Experimental Investigation of the Properties and Phase State of Thick Aluminum Surfaces Pulsed to Megagauss Level Magnetic Field in a Z-Pinch Geometry

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Physics

by THOMAS J. AWE

Dr. R. E. Siemon/Committee Chairman and Dissertation Advisor
Dr. B. S. Bauer/Dissertation Advisor

December, 2009
THE GRADUATE SCHOOL

We recommend that the dissertation prepared under our supervision by

THOMAS J. AWE

entitled

Experimental Investigation of the Properties and Phase State of Thick Aluminum Surfaces Pulsed to Megagauss Level Magnetic Field in a Z-Pinch Geometry

be accepted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Richard E. Siemon, Ph.D., Advisor

Bruno S. Bauer, Ph.D., Committee Member

Roberto C. Mancini, Ph.D., Committee Member

Richard A. Wirtz, Ph.D., Committee Member

Dhanesh Chandra, Ph.D., Graduate School Representative

Marsha H. Read, Ph. D., Associate Dean, Graduate School

December, 2009
Thermal transformation to plasma of an aluminum surface pulsed to multi-megagauss magnetic field is observed to occur when the surface field reaches a threshold level of 2.2 MG. Magnetic field ($B$) is pulsed on the surface of cylindrical metallic rods. Rods are thick—with radii ($R$) exceeding the magnetic field penetration depth ($\delta_B$). Ohmic heating is confined to a skin layer, with $\delta_B$ determined by diffusion and hydrodynamic processes. Initial rod diameters ($D_0$) ranging from 2.00 to 0.50 mm are pulsed with 1.0 MA peak current by the Zebra z-pinch. Due to Zebra’s high transmission line impedance (1.9 ohm), the current waveform is insensitive to $D_0$. The Zebra current, $I(t)$, consistently rises exponentially to 100 kA (with rise time $\tau=13$ ns), and then linearly from 100 to 900 kA for 70 ns, with $\frac{dI}{dt} = 1.1 \times 10^{13}$ A/s, to a maximum current of 1.0 MA. By
altering $D_0$, a variety of magnetic field and current density profiles are examined. For $D_0$ of 2.00 and 0.50 mm, magnetic field rise rates ($\partial B/\partial t$) vary from 30 and 80 MG/µs, and peak surface fields reach 1.5 and 4 MG, respectively. Novel contact configurations and load surface profiles mitigate plasma formation from contact arcing or electric-field-driven electron avalanche, ensuring that plasma forms thermally—a result of ohmic or compression heating.

Aluminum plasma is observed through a variety of independently measured phenomena. First, for rod surfaces pulsed above the magnetic field threshold ($B_s > B_{\text{threshold}} = 2.2$ MG), multi-eV brightness temperatures ($T_{BB}$) are observed, clearly indicating plasma for aluminum. For example, peak $T_{BB}$ reach 20 and 36 eV for 1.00 and 0.50 mm rods, respectively. Plasma forms at lower current and reaches higher temperatures as $D_0$ is decreased. Second, aluminum ion species are distinguished via extreme ultraviolet (EUV) spectroscopy. Line spectra from Al$^{3+}$ and Al$^{4+}$ ions are obtained. The average ion charge and line ratios depend strongly upon temperature, and taking the ratio of line intensities results in an estimated peak plasma temperature of 15±1 eV for 1.00-mm-diameter rods. Third, EUV photon flux consistent with multi-eV temperature is recorded by Al or Si/Zr filtered photodiodes sensitive to photon energies from 16 to 73 eV, or 60 to 100 eV, respectively. Fourth, magnetohydrodynamic (MHD) instabilities form. Instability development depends on the conductivity of the low density expanding surface material. High resistivity vapor interacts weakly with magnetic field; therefore, flute instabilities are attributed to surface plasma. For those rods which do not reach $B_{\text{threshold}} = 2.2$ MG, no evidence of surface plasma is obtained. For 2.00-mm-diameter rods, which reach peak surface field of only 1.7 MG, surface temperatures
remain cool (peak $T_{BB} = 0.7 \text{ eV}$), no EUV emission can be measured, and even while carrying 1.0 MA of current, and after significant radial expansion, no surface instability is observed.

The experiment offers the first detailed study of plasma formation by pulsed magnetic field on a thick metallic surface carrying a skin current. The magnetic field threshold for plasma formation, surface brightness temperature, radial expansion velocity, instability growth, and ionization state have been measured. The effects of hardware design, load geometry, Al alloy, and surface smoothness have been carefully examined, creating a dataset that can be used for the design of practical systems. The experiment has achieved thermal, uniform, and symmetric plasma formation, providing a meaningful comparison for MHD simulations.
DEDICATION

To my mother, who taught me to never save for later what could be done immediately. And, to my father, who taught me that every project should be done right, no matter how long it takes. Together, these traits have accounted for the majority of any success I have had in physics.

To my fiancé, Jen. Completing this dissertation has required extraordinary patience; listening to me talk about it has undoubtedly taken much more. Your love, support, and patience throughout this process have been truly amazing.
ACKNOWLEDGMENTS

I have greatly enjoyed working on the research team led by Professors Bauer and Siemon. I would like to begin by thanking Professors Fuelling and Makhin for many enjoyable conversations and for their constant support and encouragement. I would also like to thank Professor Lindemuth who has always been a valuable resource. I’ve enjoyed working with, and extend my thanks to fellow graduate students T. Goodrich, M. Angelova, and J. Billing.

Our experiments could not have been successful without the assistance of the dedicated Zebra staff, including T. Adkins, A. Astanovitskiy, S. Batie, B. Le Galloudec, D. Macaulay, V. Nalajala, and many others. I would also like to thank Professors Presura and Ivanov, and their students, for help during experiments, and for many useful technical discussions.

The quality of our research has been immeasurably aided by the computational work of our collaborators. I would like to thank Drs. Atchison, Frese, and Garanin for working diligently (and typically in their free time) to help us better understand the many intricacies of our experiment.

I would like to extend many thanks to Dr. Reinovsky, who enabled the UNR-Megagauss Experiments modeling workshops, provided us with precision machined barbell loads, and funded my travel to Novosibirsk, Russia, where I presented experimental results at the 2008 Megagauss Conference.

Finally, I would like to extend my deepest gratitude to Professors Bauer and Siemon. I thank them for continually showing patience and respect toward any idea, question, or concern that I brought to them. I thank them for granting me independence and a chance for leadership before I necessarily deserved it. I thank them for the opportunity to work by their side regularly—an experience many graduate students do not have—I’ve learned far more physics in our frequent interactions than in any classroom. It is because of all that my advisors have taught me, that I enter the next phase of my scientific career with confidence and excitement.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Title page</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Committee Approval page</td>
<td></td>
</tr>
<tr>
<td>Copyright page</td>
<td></td>
</tr>
<tr>
<td>Abstract</td>
<td>i</td>
</tr>
<tr>
<td>Dedication</td>
<td>iv</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>v</td>
</tr>
<tr>
<td>Table of Contents</td>
<td>vi</td>
</tr>
<tr>
<td>List of Tables</td>
<td>ix</td>
</tr>
<tr>
<td>List of Figures</td>
<td>x</td>
</tr>
<tr>
<td>Introduction</td>
<td>1</td>
</tr>
</tbody>
</table>

**Chapter I: Fundamentals of the Experiment: Thick-Rod Z-Pinches** 8

- Section I.A: Electric and Magnetic Fields in a Simple Static Z-Pinch 9
- Section I.B: Magnetic Diffusion 15
- Section I.C: Z-Pinch Equilibrium 29
- Section I.D: Z-Pinch Stability 32
- Section I.E: Resistivity and Equation of State 35

**Chapter II: The Zebra Facility** 49

- Section II.A: The Zebra Machine and Facility Infrastructure 49
- Section II.B: The Zebra Current 55
- Section II.C: Diagnostic Triggering and Timing 65
TABLE OF CONTENTS (Continued)

Chapter III: Experimental Design and Hardware Performance 68

Section III.A: Megagauss Field and Skin Current on a Stable Rod Surface 69
Section III.B: Hardware Designs to Mitigate Non-Thermal Plasma 72
Section III.C: Hardware Performance—Non Thermal Plasma Formation 83
Section III.D: Hardware Performance—Heating and Emission Uniformity 90
Section III.E: The Effect of Surface Smoothness 105
Section III.F: Concluding Remarks on Load Hardware 112

Chapter IV: Surface Temperature Estimates from Visible Light Radiometry 113

Section IV.A: Basic Photon Statistics 114
Section IV.B: Visible Light Radiometry Diagnostics—MG-(I-III) 126
Section IV.C: Brightness Temperature Calculation—MG-II & MG-III 156
Section IV.D: Brightness Temperature Calculation—MG-IV 158

Chapter V: Measurement of Extreme Ultraviolet Emission 168

Section V.A: EUV Photodiodes 169
Section V.B: EUV Spectroscopy 176
Section V.C: Temperature Estimates via Spectroscopy 182

Chapter VI: Surface Expansion and Stability 187

Section VI.A: Diagnostic Overview 188
Section VI.B: Data Analysis: Image Interpretation and Sources of Error 197
Section VI.C: Radial Expansion Results 204
Section VI.D: Pinch Instabilities 214
<table>
<thead>
<tr>
<th>TABLE OF CONTENTS (Continued)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chapter VII: Magnetic Field Threshold for Plasma Formation</strong></td>
</tr>
<tr>
<td>Section VII.A: Magnetic Field Threshold for Plasma Formation</td>
</tr>
<tr>
<td>Section VII.B: Sensitivity to Small Changes in Initial Rod Diameter</td>
</tr>
<tr>
<td><strong>Chapter VIII: Summary of Results, Remaining Questions, and Future Work</strong></td>
</tr>
<tr>
<td>Section VIII.A: Summary of Results</td>
</tr>
<tr>
<td>Section VIII.B: Remaining Questions and Future Work</td>
</tr>
<tr>
<td>Section VIII.C: Conclusion</td>
</tr>
<tr>
<td><strong>Appendix: Commonly used Symbols</strong></td>
</tr>
<tr>
<td><strong>References</strong></td>
</tr>
</tbody>
</table>
List of Tables

| Table II.1: Port assignments for diagnostics used in MG-(I-IV) | 54 |
| Table III.1: Photodiode voltages used to determine the relative intensity of the two images from the two-frame ICCD | 101 |
| Table IV.1: Geometry of radiometric diagnostics and setup for MG-(II-IV) | 138 |
| Table IV.2: Calibrated ND filter values (Source: 532 nm) | 144 |
| Table IV.3: Calibrated ND filter values (Source: Wratten #58 filtered strobe) | 148 |
| Table VI.1: Shadowgram resolution | 191 |
| Table VII.1: Rod parameters at the time of plasma formation | 223 |
# List of Figures

| Intro.1: | Wall plasma interaction in an MTF system | 3 |
| Intro.2: | Similarity of flux compression and thick-rod experiments | 5 |
| I.1: | Geometry of a z-pinch | 10 |
| I.2: | Magnetic diffusion: Separable solution | 19 |
| I.3: | $T(B)$: Knoepfel estimate | 21 |
| I.4: | Magnetic diffusion: Constant boundary condition | 26 |
| I.5: | Current density and ohmic heating: Constant B.C | 28 |
| I.6: | Desjarlais: Warm dense Al, conductivity vs. density | 43 |
| I.7: | Phase plot for Al from the Sesame database | 44 |
| I.8: | Al resistivity tables | 47 |
| II.1: | Drawing of the Zebra z-pinch | 51 |
| II.2: | Zebra Chamber: Anode-cathode configuration and diagnostic ports | 53 |
| II.3: | Bdot configuration in the anode plate | 56 |
| II.4: | Raw differential Bdot voltages | 57 |
| II.5: | Calibrated differential Bdot voltages and calculated current | 58 |
| II.6: | Reproducibility of the Zebra current | 60 |
| II.7: | All shot averaged $I(t)$ measurements: MG-III and MG-IV | 62 |
| II.8: | Evidence that the Zebra current is unaffected by $D_0$ | 63 |
| II.9: | Campaign averaged $I(t)$ measurements: MG-(II-IV) | 64 |
| II.10: | Time between LWVdot pulse and $I(t=100 \text{ ns})=500 \text{ ka}$ | 66 |
## List of Figures (Continued)

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>III.1</td>
<td>Maximum magnetic field obtainable on a stable surface</td>
<td>71</td>
</tr>
<tr>
<td>III.2</td>
<td>Simple-straight-rod load mounted in GRAV hardware</td>
<td>75</td>
</tr>
<tr>
<td>III.3</td>
<td>Simple-straight-rod load mounted in KE hardware</td>
<td>76</td>
</tr>
<tr>
<td>III.4</td>
<td>Barbell load mounted in KE hardware</td>
<td>77</td>
</tr>
<tr>
<td>III.5</td>
<td>Hourglass load mounted in KE hardware</td>
<td>78</td>
</tr>
<tr>
<td>III.6</td>
<td>Measurements of initial rod diameters</td>
<td>82</td>
</tr>
<tr>
<td>III.7</td>
<td>Imaged PMT diagnostic</td>
<td>84</td>
</tr>
<tr>
<td>III.8</td>
<td>Operation of a PMT</td>
<td>84</td>
</tr>
<tr>
<td>III.9</td>
<td>PMT signals</td>
<td>86</td>
</tr>
<tr>
<td>III.10</td>
<td>Dependence of PMT turn-on-time on shot hardware</td>
<td>88</td>
</tr>
<tr>
<td>III.11</td>
<td>Dependence of PMT and photodiode turn-on-time on hardware</td>
<td>89</td>
</tr>
<tr>
<td>III.12</td>
<td>Schematic of an intensifier head unit</td>
<td>92</td>
</tr>
<tr>
<td>III.13</td>
<td>ICCD optics used in MG-(I-II)</td>
<td>93</td>
</tr>
<tr>
<td>III.14</td>
<td>Gated images of early emission from different types of rods</td>
<td>94</td>
</tr>
<tr>
<td>III.15</td>
<td>Two-frame ICCD optics</td>
<td>96</td>
</tr>
<tr>
<td>III.16</td>
<td>Function of a field lens</td>
<td>97</td>
</tr>
<tr>
<td>III.17</td>
<td>Light transmission flow chart for two-frame ICCD optics</td>
<td>98</td>
</tr>
<tr>
<td>III.18</td>
<td>Average photodiode voltage for 1.00 mm rods (MG-II)</td>
<td>100</td>
</tr>
<tr>
<td>III.19</td>
<td>ICCD images during plasma formation from 1.00 mm rods</td>
<td>103</td>
</tr>
<tr>
<td>III.20</td>
<td>Emission uniformity as measured by linear photodiode array</td>
<td>105</td>
</tr>
</tbody>
</table>
# List of Figures (Continued)

| III.21: | ICCD images of (LANL) ultra-smooth barbell loads | 107 |
| III.22: | Typical nonuniform emission from hourglass and barbell loads | 109 |
| III.23: | Visible microscope image of 1100-alloy Al barbell | 110 |
| III.24: | Non-uniform emission and jetting from rod with grooves | 111 |
| IV.1:  | Spectral emissive power vs. wavelength for a blackbody | 120 |
| IV.2:  | Peak wavelength of the Planck distribution | 122 |
| IV.3:  | Streaked visible light spectrum | 124 |
| IV.4:  | Visible light radiometry diagnostic: MG-I | 127 |
| IV.5:  | Photodiode voltages for MG-I hourglass loads | 129 |
| IV.6:  | Visible light radiometry diagnostics: MG-II and MG-(III-IV) | 131 |
| IV.7:  | Visible radiometry detector heads: MG-II and MG-(III-IV) | 133 |
| IV.8:  | Photodiode responsivity and Wratten filter transmission | 135 |
| IV.9:  | Charge drawn from bias capacitors in MG-III diode array | 137 |
| IV.10: | Comparison of visible light radiometry data: MG-II and MG-III | 139 |
| IV.11: | Setup for ND filter calibration | 143 |
| IV.12: | Setup for photodiode linearity testing | 146 |
| IV.13: | MG-II BPX 65 linearity testing: Data | 149 |
| IV.14: | MG-II BPX 65 linearity testing: Results | 150 |
| IV.15: | MG-III A5C-38 linearity testing: Data | 151 |
| IV.16: | MG-III A5C-38 linearity testing: Results | 152 |
## List of Figures (Continued)

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>IV.17</td>
<td>MG-III A5C-38 “R-Factor”</td>
<td>153</td>
</tr>
<tr>
<td>IV.18</td>
<td>MG-III average diode voltage for different $D_0$</td>
<td>156</td>
</tr>
<tr>
<td>IV.19</td>
<td>MG-III average brightness temperature for different $D_0$</td>
<td>158</td>
</tr>
<tr>
<td>IV.20</td>
<td>Addition of ND filter to diode array for MG-IV measurements</td>
<td>159</td>
</tr>
<tr>
<td>IV.21</td>
<td>Validity of the nonlinearity correction: MG-III $T_{BB}(t)$ data</td>
<td>161</td>
</tr>
<tr>
<td>IV.22</td>
<td>MG-IV $T_{BB}(t)$ data</td>
<td>165</td>
</tr>
<tr>
<td>IV.23</td>
<td>MG-IV low temperature $T_{BB}(t)$ data</td>
<td>167</td>
</tr>
<tr>
<td>V.1</td>
<td>EUV photodiode array</td>
<td>170</td>
</tr>
<tr>
<td>V.2</td>
<td>Visible and EUV photodiode measurements</td>
<td>172</td>
</tr>
<tr>
<td>V.3</td>
<td>Spectral responsivity for EUV diodes</td>
<td>173</td>
</tr>
<tr>
<td>V.4</td>
<td>Estimate of EUV diode response as a function of rod temperature</td>
<td>175</td>
</tr>
<tr>
<td>V.5</td>
<td>EUV spectrometer</td>
<td>177</td>
</tr>
<tr>
<td>V.6</td>
<td>EUV spectra for 1.00 mm rods</td>
<td>180</td>
</tr>
<tr>
<td>V.7</td>
<td>Absorption spectral for 0.50 and 0.64 mm rods</td>
<td>181</td>
</tr>
<tr>
<td>V.8</td>
<td>PrismSPECT calculations of ionization fraction</td>
<td>182</td>
</tr>
<tr>
<td>V.9</td>
<td>Histograms of ICCD images</td>
<td>184</td>
</tr>
<tr>
<td>VI.1</td>
<td>Schematic of Ekspla optics near Zebra vacuum chamber</td>
<td>189</td>
</tr>
<tr>
<td>VI.2</td>
<td>Typical layout of a CCD coupled streak camera</td>
<td>193</td>
</tr>
<tr>
<td>VI.3</td>
<td>Magnification of streak camera electron optics</td>
<td>196</td>
</tr>
</tbody>
</table>
### List of Figures (Continued)

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>VI.4</td>
<td>Plot profile of a high quality shadowgram</td>
<td>198</td>
</tr>
<tr>
<td>VI.5</td>
<td>Plot profile of a shadowgram with laser speckle</td>
<td>201</td>
</tr>
<tr>
<td>VI.6</td>
<td>Results of tests which confirm shadowgram image mixing</td>
<td>203</td>
</tr>
<tr>
<td>VI.7</td>
<td>Plot profile of a shadowgram with image mixing</td>
<td>204</td>
</tr>
<tr>
<td>VI.8</td>
<td>Laser and ICCD $R(t)$ data from MG-III and MG-IV</td>
<td>209</td>
</tr>
<tr>
<td>VI.9</td>
<td>Radial expansion as recorded by the Imacon 500 streak camera</td>
<td>209</td>
</tr>
<tr>
<td>VI.10</td>
<td>$\Delta R(t)$ as determined from MG-IV shadowgrams</td>
<td>210</td>
</tr>
<tr>
<td>VI.11</td>
<td>Schematic of the hypothesized cool sheath geometry</td>
<td>213</td>
</tr>
<tr>
<td>VI.12</td>
<td>Instability growth as indicated by laser shadowgraphy</td>
<td>215</td>
</tr>
<tr>
<td>VI.13</td>
<td>Edge width vs. time for different $D_0$</td>
<td>217</td>
</tr>
<tr>
<td>VI.14</td>
<td>Experimental instability growth rates scale with $R_0$</td>
<td>218</td>
</tr>
<tr>
<td>VI.15</td>
<td>Initial surface smoothness affects instability amplitude</td>
<td>219</td>
</tr>
<tr>
<td>VII.1</td>
<td>Plasma formation evident as an abrupt increase in $\partial T_{BB}/\partial t$</td>
<td>222</td>
</tr>
<tr>
<td>VII.2</td>
<td>Variation in time of plasma formation</td>
<td>225</td>
</tr>
<tr>
<td>VII.3</td>
<td>Variation in time of plasma formation depends upon $D_0$</td>
<td>225</td>
</tr>
<tr>
<td>VII.4</td>
<td>Variation in time of plasma formation observed in EUV data</td>
<td>226</td>
</tr>
</tbody>
</table>
**Introduction**

If, when, and how plasma forms from a metallic surface driven by intense current is an important question for both basic science and for applications. The question of the conductivity of a metal surface under conditions of pulsed megagauss magnetic field has been posed since at least 1959 [1], when Fowler, Garn, and Caird produced fields above 10 MG by explosively driven magnetic flux compression. The conductivity of warm dense aluminum remains uncertain [2]. An important part of the challenge has been uncertainty as to the state of the metal: liquid, vapor, warm dense matter, plasma, or a mixture of these. Understanding plasma formation and developing predictive capability for the resultant evolving plasma is an ongoing fundamental physics challenge. An unsolved problem is the generation and evolution of plasma from the surface of thick metal carrying an ultra-high skin current. Even for systems that can be described by radiation-magnetohydrodynamics (R-MHD), the complex interplay of magnetic diffusion, hydrodynamics, and radiative energy transfer is a challenge to model, especially because the material properties vary rapidly in space and time.

Radiation-magnetohydrodynamics and intense current are vital to a wide variety of applications, including wire-array z-pinches, magnetically insulated transmission lines [3], recyclable transmission lines [4], dense plasma foci [5], ultra-high magnetic field generators [6], and magnetized target fusion systems [7,8,9]. While there exists a large volume of experimental data pertaining to volumetrically ohmically heated thin wires [10,11,12,13], experimental data for surface-heated thick metal have not been available. Plasma formation from a metal in the “thick-rod,” or “liner,” or “surface-heating” regime (where current flow and ohmic heating are confined to a skin layer of thickness $\delta_B$) is far
less certain than for volumetrically-heated thin wires, even for an order-of-magnitude higher linear current density (and surface magnetic field). This is due in part to the continued availability of underlying cold metal, whose high electrical conductivity reduces the surface electric field and ohmic heating to values that may be marginal for plasma to form. Detailed understanding of the ohmically driven phase changes at the surface of thick metal pulsed with high field is critical to the engineering of practical devices.

The interplay of intense magnetic field and ohmically heated conductor is a significant physical process in magnetized target fusion (MTF), a type of magneto-inertial fusion (MIF), where magnetized plasma is compressed by an imploding, flux conserving metallic liner (Fig. Intro.1). As the liner implodes, the internal magnetic field is compressed to the megagauss level while a fraction of the flux diffuses into the interior wall. The magnetic field acts to suppress losses associated with electron thermal conduction to the liner wall [14], but as the magnetic field is compressed the induced eddy currents cause intense ohmic heating and phase changes in the material.
Fig. Intro.1: Schematic of wall plasma interaction in an MTF system. Liner compression of magnetized plasma involves a multitude of physical processes at the metal-fusion fuel interface. The properties of the liner surface determine amount of material able to cross magnetic field lines and contaminate the fusion fuel.

For metallic liners, if the energy deposition is sufficient, a thin layer of metallic plasma may form at the wall surface [15]. Complicated processes that are dependent upon the electrical conductivity of both the metallic plasma sheath (if plasma forms) and the interior conductor determine the level of current shunted to the liner plasma, the spatial distribution of electrical energy deposited by ohmic heating, and the expansion of the metallic plasma (or metallic vapor) across the confining magnetic field. The details of these diffusion processes, and the amplitude of hydrodynamic instabilities, dictate the amount of liner material able to mix with and contaminate the fusion fuel [16,17]. These complex phenomena determine the maximum time for which the fusion fuel can be held at high pressure before severe high-Z contamination occurs, and may ultimately determine the success of a MTF system.
The present hypotheses regarding the ionization of thick metal surfaces exposed to intense magnetic field have been summarized by Garanin et al. [18]. With theory and computations that included the effects of thermal conduction, radiation transfer, and dynamic resistivity, they studied the diffusion of megagauss magnetic field into a metal and the resultant plasma formation. Conflicting basic descriptions on if, when, and how plasma forms were summarized. One common view is that when a metal surface is ohmically heated to the boiling point, a resistive metal vapor is emitted which expands freely through the magnetic field, carrying little current, and remaining cool [19]. Under such conditions, no plasma forms. Others argue that even for lower fields of about 1 MG, plasma forms on a metal surface, and the majority of the current is shunted to the plasma. In this case, ohmic heating of the plasma is high, and the plasma sheath becomes hot and highly radiating. Garanin’s work suggests (in contrast to both arguments) that the expanding vapor will ionize only if the magnetic field strength is sufficiently high. Plasma formation is due to seed photoionization from nearby radiating metal of electronvolt temperature, in conjunction with ohmic heating from the current induced as the vapor moves across magnetic field lines. Initially, plasma forms in a thin surface layer, is of low density, and since the interior metal is also a good conductor, carries only a small fraction of the current. The electrical energy deposition is spatially distributed, and plasma temperatures remain fairly low. It is concluded in [18] that plasma will form on a copper surface for fields in excess of about 1.5 to 3-MG, depending upon the rise-rate of the applied field ($\partial B/\partial t$).

Due to the shortage of available data and remaining theoretical uncertainties, experimental investigation of magnetic-field-driven diffusion and hydrodynamic
processes are of fundamental importance. To examine the interplay of thick metal and ultra-high magnetic field in a configuration relevant to MTF, experiments which compress magnetic flux (without fusion fuel) inside of an imploding metallic liner have been designed and modeled at UNR [20,21]. In such experiments, the dynamics and phase state of the inner liner surface would be examined. Many of the physical conditions achieved during flux compression are also present in a geometrically simple z-pinch configuration where megagauss magnetic field is pulsed on the surface of a thick conducting rod (Fig. Intro.2). In both systems, conductors are pulsed to high field by fast-rising currents that flow nonuniformly in a skin layer (MTF liners are driven with relatively slow—of order 10 µs—current pulses on the outer wall, but the eddy currents in the inner liner wall rise rapidly during the final stages of compression [22]). For each configuration, high current densities drive phase changes in the metal, and place megagauss level field at the material-vacuum interface. Late-time dynamics involve low-density surface plasma being decelerated by magnetic forces, resulting in the formation of flute-mode instabilities.

Fig. Intro.2: Schematic demonstrating that a “thick-rod” megagauss experiment accesses much of the same physics as a magnetic flux compression experiment, but through a simplified approach.
The pulsed-rod configuration has several advantages. First, detailing complex surface phenomena is a greater challenge in the case of liner-driven magnetic flux compression, since the surface of interest is enveloped by liner material and moves at supersonic velocity. Next, flux compression requires a long-pulse, ultra-high-current driver such as Shiva Star [23] or Atlas [24] to accelerate the massive liner to high kinetic energy. To pulse high field on a rod, a short-pulse, lower-current driver, such as the Zebra generator is acceptable. The total energy delivered to the load is reduced, resulting in a relatively non-destructive experiment with increased shot repetition rate and reduced cost per-shot. Finally, load fabrication is simplified for the pulsed-rod geometry, further reducing shot costs.

The “UNR-Megagauss Experiments” examine megagauss physics using the pulsed-thick-rod geometry and have obtained results that can readily be used to validate R-MHD codes, or to design MTF systems. Rod surfaces are pulsed with ultra-high field by the University of Nevada Reno-Nevada Terawatt Facility (UNR-NTF) Zebra generator [25,26], which delivers a repeatable 1.0 MA, 100 ns rise time current pulse. Novel loads and coupling hardware configurations limit non-MHD precursor plasma formation. “Hourglass” and “barbell” loads (details in Ch. III) transition smoothly to small diameter, and use buried current joints to mitigate plasma formation from non-thermal effects such as electric-field-driven electron avalanche and contact arcing [27]. The Alfvén transit time for selected rod diameters is sufficiently long to limit the growth of instabilities until after the time of plasma formation [16], increasing the likelihood that one-dimensional modeling is relevant to at least this time. Measurements are made to infer the surface magnetic field ($B_s$), time of plasma formation ($t_{\text{plasma}}$), surface brightness temperature
(T_{BB}), spectrum of emitted radiation, uniformity of surface heating, radial expansion velocity, and growth rate of instabilities. Parametric studies in dJ/dt and dB/dt (where J and B represent the current density and magnetic field strength, respectively) are conducted by varying the initial load diameter from 0.50 to 2.00 mm (with a repeatable current pulse), allowing access to qualitatively different regimes. Peak surface magnetic fields range from 1.5 to 4 MG; levels which [18] suggests are needed to form surface plasma. The experiment confirms the prediction that plasma will form only when the field strength reaches a magnetic field threshold level (B_{threshold}). Thermal plasma forms on the surface of thick 6061-alloy Al rods only when the magnetic field strength reaches B_{threshold}=2.2 MG, independent of the initial rod diameter.
Chapter I: Fundamentals of the Experiment: Thick-Rod Z-Pinch

In the UNR-Megagauss Experiments, the interaction of pulsed ultra-high magnetic field with current carrying conductors is examined. Megagauss level magnetic field is pulsed on the surface of metallic rods in the z-pinch geometry. Rods are thick, with radii greater than the conductivity and rise-time-dependent magnetic field penetration depth ($\delta_B$). Hydrodynamic and diffusion processes are important, and the phase changes in the rod in large part determine its dynamics.

Fundamental to the experiment are aspects common to the physics of z-pinches, and to the physics of ultra-high magnetic fields. An enormous amount of research has focused on thin-wire ($D_0 \leq 100 \, \mu m$) z-pinches, where high current is pulsed through either a single wire, or an array of wires. In such experiments, plasma forms at magnetic field below the megagauss level. What ultimately drives plasma formation in the thin wire configuration remains a challenging question, but plasma likely forms as a result of non-thermal processes, such as the electrical breakdown of desorbed surface impurities. The UNR-Megagauss Experiments seek to examine thermal plasma formation. Recent theoretical conjecture concluded that thermal plasma will form from a thick metal surface when the magnetic field reaches 1.5 to 3.0 MG [18]. Ohmic heating for moderate magnetic field can be accurately modeled, but for ultra-high magnetic field, the material will undergo phase changes. The resulting large temporal and spatial variations in temperature and density make simulations challenging. The evolution of a current-carrying thick metal, subject to ultra-high magnetic field is uncertain.

To aid in the understanding of experimental design, and in the interpretation of experimental results, the chapter develops simple models which may be used to estimate
the properties of a z-pinch. Where possible, the models will be used to distinguish the behavior of thin wires from thick rods. First, electric and magnetic field equations are derived. Next, magnetic diffusion is considered and analytic solutions are derived for the simplest cases. Pressure equilibrium in a z-pinch is then discussed. Analytic solutions are obtained after applying many simplifying assumptions (e.g., constant resistivity, zero velocity, etc.). At the end of the chapter, ohmic-heating-induced changes in phase state are considered, and equation of state and resistivity models are discussed.

Section I.A: Electric and Magnetic Fields in a Simple Static Z-Pinch

A z-pinch carries axial current which generates an azimuthal magnetic field (Fig. I.1). Current flows upward through a large diameter “return conductor” and downward from the anode plate to cathode plate through an axially centered conducting rod. The central conductor is the actual “pinch,” and is aptly named since the axial current and azimuthal magnetic field result in a radially directed “J-cross-B” force which acts to pinch the material. Fig. I.1 displays the magnetic and electric field configurations, along with the direction of current flow.
Fig. I.1: Current, electric field, and magnetic field configuration of a simple z-pinch. The diagram matches the polarity of the Zebra pulsed z-pinch. It is assumed that the positive z-axis points downward so as to eliminate a large number of (−) signs that would otherwise be carried through the derivations to follow.

To simplify the derivation of field equations, first assume a steady-state equilibrium (\( \mathbf{v} = 0 \)). Further, assume a simple current configuration where the total current is spread uniformly throughout a cylindrical shell spanning from inner radius \( r_i \) and outer radius \( R \). The current density is then,

\[
J_z = \frac{I}{\pi(R^2 - r_i^2)} \quad \text{for} \quad r_i < r < R
\]

\[
J_z = 0 \quad \text{for} \quad r < r_i \quad \text{and} \quad r > R
\]

In the limit that \( r_i \to 0 \), current flows uniformly (thin-wire limit). In the limit \( r_i \sim R \), current flows in a skin layer of thickness \( \Delta = R - r_i \) (thick-rod limit). The current distribution in a real conductor is determined by diffusion processes, which are considered later. Assume constant resistivity (\( \eta = \text{constant} \)), with the axial electric field.
and current density related by the simplified Ohm’s Law, \( E_z = \eta J_z \). The axial electric field inside the rod is then,

\[
E_z = \eta J_z = \frac{\eta I}{\pi (R^2 - r_i^2)} \quad \text{for} \quad r_i < r < R
\]

Also, with the current density defined, the magnetic field is immediately found by application of Ampere’s law.

\[
\begin{align*}
B_\theta &= 0 \quad \text{for} \quad r < r_i \\
B_\theta &= \frac{\mu_0 I}{2\pi r} \left( \frac{r^2 - r_i^2}{R^2 - r_i^2} \right) \quad \text{for} \quad r_i < r < R \\
B_\theta &= \frac{\mu_0 I}{2\pi r} \quad \text{for} \quad r > R
\end{align*}
\]

By setting \( r_i = 0 \), the magnetic field for uniform current density is obtained. The relationships above are also valid for time-dependent current, \( I(t) \).

The radial electric field \( (E_r) \) has recently been shown to play an important role in the evolution of thin-wire z-pinches, affecting plasma formation and implosion dynamics (for wire-array z-pinches). For wire-array z-pinches, the radial electric field is generally of negative polarity. Recent experiments \([28]\) were conducted with a special “hollowed out” anode-cathode configuration which allowed the radial electric field to switch polarity at the axial half-plane of the array. The study found a fascinating and surprising result. The section of the array with positive polarity matched the implosion dynamics (wire core size and ablation rate) of a typical negative polarity array. The section with negative polarity displayed a factor of three reduction in core size, and reduced ablation. Separate x-ray pulses originated from each section of the array. Changes in electron emission associated with the polarity of the radial electric field may play an important role in thin wire plasma initiation, and therefore the dynamics of the pinch. Other radial
electric field effects have been reported. In [29], a positive polarity radial electric field is shown to enhanced energy deposition is a single-wire pinch. In [30], axial symmetry in the radiation from a wire-array z-pinch is shown to depend upon the magnitude of the radial electric field.

The radial electric field at the surface of a single-rod z-pinch is derived in order to determine its impact, if any, on the dynamics of the rods examined in the UNR-Megagauss Experiments. To do so, Laplace’s equation is solved for \( V(r, z) \) in the vacuum between the rod outer surface \((r=R)\) and the inner surface of the return conductor \((r=b)\). The potential of the return conductor is assumed zero \((V(b,z)=0)\). The electric field at \(r=R\) is

\[
E_z(R) = \frac{\eta I}{\pi (R^2 - r_i^2)} \quad \text{(I.4)}
\]

And, \( V(R, z) = -\int_0^z E_z(R) \cdot dz = -\frac{\eta I z}{\pi (R^2 - r_i^2)} \bigg|_0^z = -\frac{\eta I z}{\pi (R^2 - r_i^2)} \quad \text{(I.5)}
\]

Now, Laplace’s equation is solved for the boundary conditions above:

\[
\nabla^2 V = \frac{1}{r} \frac{\partial}{\partial r} \left[ r \frac{\partial V}{\partial r} \right] + \frac{1}{r^2} \frac{\partial^2 V}{\partial \theta^2} + \frac{\partial^2 V}{\partial z^2} = 0 \quad \text{(I.6)}
\]

The potential has no theta-dependence, so the equation simplifies to:

\[
\frac{1}{r} \frac{\partial}{\partial r} \left[ r \frac{\partial V}{\partial r} \right] + \frac{\partial^2 V}{\partial z^2} = 0 \quad \text{(I.7)}
\]

Next, it is assumed that the potential has the simple separable form:

\[
V(r, z) = z \cdot f(r) \quad \text{(I.8)}
\]
Upon inserting this potential function into Eqn. I.7, ‘z’ cancels, and the resulting simple ODE for \( f(r) \) is found.

\[
\frac{\partial^2 f(r)}{\partial r^2} = -\frac{1}{r} \frac{\partial f(r)}{\partial r} \Rightarrow f(r) = A \ln(B \cdot r)
\]  

(I.9)

Therefore,

\[
V(r, z) = z \cdot A \ln(B \cdot r)
\]  

(I.10)

Applying the boundary condition \( V(b, z) = 0 \), gives \( B = (1/b) \). Applying the boundary condition,

\[
V(R, z) = -\frac{\eta l z}{\pi (R^2 - r_i^2)}
\]  

(I.11)

gives,

\[
A = -\frac{\eta l}{\pi (R^2 - r_i^2)} \left[ \ln \left( \frac{R}{b} \right) \right]^{-1}
\]  

(I.12)

Finally the potential function is found.

\[
V(r, z) = -\frac{\eta l z}{\pi (R^2 - r_i^2)} \frac{\ln(r/b)}{\ln(R/b)}
\]  

(I.13)

Next, differentiation with respect to ‘\( r \)’ results in the equation for the radial electric field:

\[
E(r, z)_r = -\frac{\partial V(r, z)}{\partial r} = -\frac{\eta l z}{\pi (R^2 - r_i^2)} \frac{1}{\ln(R/b)} \frac{1}{(r/b)} \frac{1}{b} = \frac{\eta l z}{\pi (R^2 - r_i^2)} \frac{1}{\ln(R/b)} \frac{1}{r}
\]  

(I.14)

Similarly, differentiation with respect to ‘\( z \)’ results in the equation for the axial electric field:

\[
E(r, z)_z = -\frac{\partial V(r, z)}{\partial z} = \frac{\eta l}{\pi (R^2 - r_i^2)} \frac{\ln(r/b)}{\ln(R/b)}
\]  

(I.15)
Eqn. I.15 is equivalent to Eqn. I.4 at the rod surface \((r=R)\), as it must be. Eqn. I.14 shows the radial electric field decreases rapidly with increased wire diameter. Assuming uniform current density \((r_i=0)\), the radial electric field at the rod surface falls proportional to:

\[
E(R, z) = \frac{\eta I_z}{\pi (R^2) \ln(R / b)} \frac{1}{R} \frac{1}{R^3 \ln(R / b)}
\]

(\text{I.16})

While references [28] and [30] examine the effects of the radial electric field on wire-array z-pinches, reference [29] examines single, 20 µm titanium wires pulsed to 3 kA. The single-wire result is more readily compared to the UNR-Megagauss Experiment, and is considered in detail here. Using the parameters in [29] to find the maximum electric field: \(\eta = 5.6 \times 10^{-7} \, \Omega \cdot \text{m}, \, z = 0.02 \, \text{m}, \, R = 10 \, \mu \text{m}, \, b = 0.3 \, \text{m} \) (actually not given, set equal to \(b_{\text{Zebra}}\)), \(I = 3 \, \text{kA}\), the radial electric field is \(E_r = -1.4 \times 10^9 \, \text{V/m}\). Using the parameters of the UNR-Megagauss Experiments: \(\eta = 2.8 \times 10^{-8} \, \Omega \cdot \text{m}, \, z = 0.007 \, \text{m}, \, R = 500 \, \mu \text{m}, \, b = 0.3 \, \text{m}, \, I = 1.0 \, \text{MA}\), the radial electric field is \(E_r = -7.9 \times 10^4 \, \text{V/m}\). Due to the strong dependence on pinch radius, the radial electric field in the UNR-Megagauss Experiments is \(\sim 10^4\) times below the electric field estimated in [29], despite the much larger magnitude of the Zebra current. The radial electric field present in the UNR-Megagauss Experiments is well below that required for electric-field-driven breakdown, and likely plays a negligible role in plasma formation from thick rods.

The basic field structure has been outlined for the simple case of constant current density flowing only in a surface layer of thickness \((\Delta = R - r_i)\). To summarize, the following field configurations have been obtained:
Magnetic Field
\[ B_\theta = 0 \quad \text{for} \quad r < r_i \]
\[ B_\theta = \frac{\mu_0 I}{2 \pi r} \frac{(r_i^2 - r^2)}{(R^2 - r_i^2)} \quad \text{for} \quad r_i < r < R \]  
\[ B_\theta = \frac{\mu_0 I}{2 \pi r} \quad \text{for} \quad r > R \]  

(I.17)

Electric Field
\[ E(r, z) = -\frac{\partial V(r, z)}{\partial r} = \frac{\eta I z}{\pi (R^2 - r_i^2) \ln(R / b)} \frac{1}{(r / b)} \frac{1}{b} = \frac{\eta I z}{\pi (R^2 - r_i^2) \ln(R / b) R} \]
\[ E(r, z) = -\frac{\partial V(r, z)}{\partial z} = \frac{\eta I}{\pi (R^2 - r_i^2) \ln(R / b)} \ln(r / b) \]  

(I.18)

Through order-of-magnitude estimates, it has been shown that the radial electric field is likely of little consequence in the UNR-Megagauss Experiments.

Section I.B: Magnetic Diffusion

Next, the diffusion of a pulsed current into a finite resistivity conductor is considered. In this case, the radially distribution of current and field is dictated by diffusion processes. Again, it is assumed that the velocity is everywhere zero. Furthermore, since the UNR-Megagauss Experiments examine rods with radii much greater than the magnetic field penetration depth (to be shown), the early magnetic diffusion and subsequent joule heating can be studied (with small error) by considering planar geometry \((B \text{ is a function of only } x \text{ and } t)\). Under these assumptions, analytic solutions for the magnetic field distribution, current density, electric field strength, and ohmic heating are found.
The diffusion equation is derived using Maxwell’s equations and a simplified version of Ohm’s law.

Maxwell’s Equations

\[ \nabla \cdot E = \frac{\rho}{\varepsilon_0} \]  \hspace{1cm} (I.19)

\[ \nabla \cdot B = 0 \]  \hspace{1cm} (I.20)

\[ \nabla \times E = -\frac{\partial B}{\partial t} \]  \hspace{1cm} (I.21)

\[ \nabla \times B = \mu_0 J + \mu_0 \varepsilon_0 \frac{\partial E}{\partial t} \]  \hspace{1cm} (I.22)

Ohm’s Law

\[ E = \eta J \]  \hspace{1cm} (I.23)

Charge neutrality is assumed (\( \rho = 0 \)); Eqn. I.19 becomes \( \nabla \cdot E = 0 \). Furthermore, the displacement current is often negligible in comparison to current density, except in cases of very rapidly varying fields. Setting the displacement current to zero is valid for experimental conditions, as can be seen by comparing \( J = E/\eta \) and \( \varepsilon_0 (\partial E/\partial t) \) in Ampère’s Law. Essentially, \( 1/\eta \) is compared with \( \varepsilon_0 /\tau \), (where \( \tau \approx 100 \text{ ns} \) is a reasonable characteristic time for the experiment). Clearly, the displacement current contribution is negligible, and Eqn. I.22 becomes \( \nabla \times B = \mu_0 J \). Combining Eqns. I.(21-23) results in the equation for magnetic field diffusion.

\[ \nabla \times E = -\frac{\partial B}{\partial t} \rightarrow \frac{\partial B}{\partial t} = -\nabla \times E = -\nabla \times \eta J = -\nabla \times \left[ \frac{1}{\mu_0} \left( \nabla \times B \right) \right] \]  \hspace{1cm} (I.24)

or,

\[ \frac{\partial B}{\partial t} = -\frac{1}{\mu_0} \nabla \times \left[ \eta \left( \nabla \times B \right) \right] \]  \hspace{1cm} (I.25)
Eqn. I.25 governs the one-dimensional diffusion of magnetic field into a semi-infinite slab of static material. Next, in order to find analytic solutions to the equation above, the resistivity is assumed constant in space in time. This assumption cannot be justified. In the UNR-Megagauss Experiments, intense ohmic heating leads to the release of low density vapor from the rod surface, and eventually the development of surface plasma. Associated with these changes, resistivity changes by many orders of magnitude. The assumption is even more strongly violated in the case of thin wires, where ablated wire material and surface impurities can be ionized by electrical breakdown at very low current. A low density, expanding plasma corona forms, and resistivity falls rapidly as the corona is heated [31,32]. The resistivity of the layered “core-corona” pinch (which develops nearly instantly) varies rapidly in both space and time. Nonetheless, as a first approximation, the resistivity is assumed constant, but results must be considered with great caution. For constant resistivity, $\eta$ can be pulled out of the cross product.

$$\frac{\partial B}{\partial t} = -\frac{\eta}{\mu_0} \nabla \times (\nabla \times B)$$

(I.26)

Now, $\nabla \times (\nabla \times B) = \nabla (\nabla \cdot B) - \nabla^2 B$ and, $\nabla \cdot B = 0$, so Eqn. I.26 takes the familiar form of a diffusion equation.

$$\frac{\partial B}{\partial t} = \frac{\eta}{\mu_0} \nabla^2 B$$

(I.27)

This equation applies to multi-dimensional diffusion, but one-dimensional diffusion is considered here. Therefore, Eqn. I.27 may be written:

$$\frac{\partial B(x,t)}{\partial t} = \frac{\eta}{\mu_0} \frac{\partial^2 B(x,t)}{\partial x^2}$$

(I.28)
**Solution by Separation of Variables:** Assume \( B(x,t) = X(x)T(t) \)

Applying the standard technique of separation of variables to Eqn. I.28 results in the following conditions:

\[
\frac{1}{\tau} \frac{dT}{dt} = \frac{\eta}{\mu_0} \frac{d^2X}{dx^2}
\]  

(I.29)

Separate equations for the spatial and temporal dependence of \( B \) are then found (with non-physical terms eliminated):

\[ T(t) = C_1 \exp(t/\tau) \quad \text{and} \quad X(x) = C_2 \exp\left(-\sqrt{\mu_0/\eta} \cdot x\right) \]  

(I.30)

Combining the results gives:

\[ B(x,t) = C \exp(t/\tau) \exp\left(-\sqrt{\mu_0/\eta} \cdot x\right) \]  

(I.31)

Assume an exponentially rising boundary condition of the form \( B(0,t) = B_0 \exp(t/\tau) \).

The solution is then:

\[ B(x,t) = B_0 \exp(t/\tau) \exp\left(-\sqrt{\mu_0/\eta} \cdot x\right) \]  

(I.32)

Where \( \sqrt{\mu_0/\eta} \equiv 1/\delta_B \) is the reciprocal of the standard magnetic diffusion skin depth \( \delta_B \).

The magnetic field distribution as given by Eqn. I.32 is plotted for several different times in Fig. I.2. The following parameters have been used: \( B_0 = 0.1 \text{ T}, \quad \tau = 13 \text{ ns}, \) and \( \eta = 2.8 \times 10^{-8} \Omega \cdot \text{m} \). These parameters are chosen to be somewhat relevant to the conditions in the UNR-Megagauss Experiments. The characteristic time \( (\tau = 13 \text{ ns}) \) is that for the least-squares fit of an exponential to the Zebra current \( I(t) \), as it rises from 20 to 200 kA. The resistivity \( (\eta = 2.8 \times 10^{-8} \Omega \cdot \text{m}) \) is that of cold aluminum. For these conditions, at
At $t=78$ ns, the magnetic field has become appreciable several 10s of microns below the surface (Fig I.2). Therefore, for thin wires, current flow has reached the axis, and the current density is more uniformly distributed. For the thick rods examined in the UNR-Megagauss Experiments, with initial rod radii of order 500 $\mu$m, the field is confined to a comparably thin surface skin layer, and no current flows on axis.

Fig I.2: Magnetic field penetration for the separable solution to the diffusion equation.

Eqn. I.32 has features which are clearly non-physical. First, since the temporal portion of the solution is exponential (based on the chosen boundary condition), the field is non-zero at $t=0$. Second, since the spatial portion of the equation is constant, the shape of the field distribution is constant, and is simply multiplied by a time-dependent factor. Despite these clear inaccuracies, the solution does have sensible features. The field decays when moving deeper into the material, and increases with time as the applied field grows. Also, due to the simplicity of the solution, other important parameters such as ohmic heating and material temperature are readily derived.
First, with the magnetic field known, the current density may be found. Using Eqn. I.32 along with Ampere’s law (with the displacement current set to zero) the current density is found:

\[
J = \frac{1}{\mu_0} \frac{\partial B}{\partial x} = -\frac{1}{\mu_0} B_0 \sqrt{\mu_0 / \eta \tau} \exp(t / \tau) \exp\left(-\sqrt{\mu_0 / \eta \tau} \cdot x\right) = -\frac{\sqrt{\mu_0 / \eta \tau}}{\mu_0} B(x, t) = -\frac{B(x, t)}{\sqrt{\mu_0 \eta \tau}}
\]  

(I.33)

The ohmic heating, or the ohmic power input per cubic meter given by \(P = \eta J^2\), becomes:

\[
P_j(x, t) = \eta \frac{B_0^2}{\mu_0 \eta \tau} \exp(2t / \tau) \exp\left(-2\sqrt{\mu_0 / \eta \tau} \cdot x\right) = \frac{1}{\mu_0 \tau} B^2
\]  

(I.34)

Ohmic heating is independent of \(\eta\), and proportional to \(B^2\). The dependence on \(\tau\), which is associated with the rise time of \(B\), shows that ohmic heating is higher for faster rising currents. Next, if the specific heat of the material is assumed constant, the material temperature can be calculated.

If \(C_v = \frac{\partial E}{\partial T}\) then \(\frac{P}{C_v} \approx \frac{\partial T}{\partial t}\), so

\[
\frac{\partial T}{\partial t} \approx \frac{P(x, t)}{C_v} = \frac{1}{C_v} \frac{\eta B_0^2}{\mu_0 \eta \tau} \exp(2t / \tau) \exp\left(-2\sqrt{\mu_0 / \eta \tau} \cdot x\right) = \frac{1}{C_v \mu_0 \tau} B^2
\]  

(I.36)

Integrating with respect to ‘t’ gives:

\[
T(x, t) \approx \frac{1}{C_v \mu_0 \eta \tau} \frac{\tau}{2} \exp(2t / \tau) \exp\left(-2\sqrt{\mu_0 / \eta \tau} \cdot x\right) = \frac{1}{2C_v \mu_0} B^2
\]  

(I.37)

The temperature is independent of \(\eta\), and proportional to \(B^2\). The temperature solution shows material dependence only through the specific heat. Since temperature relates to the total energy gain rather than the rate at which the energy enters the system,
the factor $\tau$ is not present. The insensitivity to $\tau$ arises in part because of the nature of the method used to find the solution. By assuming that the magnetic field function is separable, the field distribution does not change in time. This essentially has the effect of eliminating thermal conduction, or other transport processes, in the material. This is not a large source of error, at least for cool aluminum, where the magnetic skin depth is 15 times larger than the thermal skin depth [33].

The derivation above, which finds that temperature grows proportional to $B^2$, is often referred to as the “Knoepfel estimate,” and has been derived in texts by, for example, Knoepfel [33] and Herlach [34]. The Knoepfel $T(B)$ curve for aluminum, using $C_v=2.42\times10^6$ J/(K·m³) is given in Fig. I.3. Results from this simple model will be compared in detail to experimental temperature measurements in Ch. IV.

![Knoepfel Estimate: Temperature vs. Magnetic Field](image)

Fig. I.3: Knoepfel estimate of temperature vs. magnetic field for aluminum.

Because the Knoepfel estimate is derived for a semi-infinite half space, it applies only in the thick-rod limit. For thin wires, where current reaches the axis, current density
increases, and material temperatures exceed those found by the Knoepfel estimate. To see this, assume (as above) that an exponentially rising field is applied to the surface of a conductor. However, now consider the case where the field is applied to the surface of a thin wire with $\delta_B >> R$. An exponentially rising surface field (on a static pinch) implies an exponentially rising current:

$$I(t) = I_0 \exp(t / \tau)$$  \hspace{1cm} (I.38)

Then, with $\delta_B >> R$, the current density is uniform \{ $J(t) = I(t) / (\pi R^2)$ \} and the joule heating becomes:

$$P_j(x,t) = \eta J^2 = \eta \left( \frac{I_0}{\pi R^2} \right)^2 \exp(2t / \tau)$$  \hspace{1cm} (I.39)

Similar to the integration of Eqn. I.36, $P_j/C_v$ is integrated with respect to time to find the temperature:

$$T(t) = \frac{1}{C_v} \int_0^t P_j(x,t) dt \approx \left( \frac{\eta \tau}{\mu_0} \right) \left( \frac{1}{R^2} \right) \left( \frac{2}{\mu_0 C_v} \right) \left( \frac{\mu_0 I_0}{2 \pi R} \right)^2 \exp(2t / \tau) = \left( \frac{\delta_B}{R} \right)^2 \frac{2 [B(t)]^2}{\mu_0 C_v}$$  \hspace{1cm} (I.40)

The solution has form similar to the Knoepfel estimate; however, in the thin-wire limit, the term $(\delta_B/R)^2$ is included. Therefore, for thin wires with $\delta_B >> R$, the temperature greatly exceeds that of the thick rod.

The differences in the rates of heating for thin wires and thick rods shown by Eqns. I.37 (thick) and I.40 (thin), explain why thin wires “explode” and thick rods are nearly in pressure equilibrium. With particle pressure proportional to $T$, the material pressure is proportional to $B^2$ for both thick rods and thin wires. The addition of the multiplier $(\delta_B/R)^2$ for thin-wire heating, which can be very large, creates material
pressures which greatly exceed the magnetic pinching pressure \((B^2/2\mu_0)\); therefore, thin wires explode.

General Solution by Laplace Transforms

Due to the non-physical aspects of the separable solution, a solution more relevant to the experiment is sought. The diffusion equation can be solved via several different mathematical techniques, but here, the Laplace Transform is used. For details on the properties of the Laplace Transform, see for example [35,36,37]. The problem is defined as given:

\[
\frac{\partial B(x,t)}{\partial t} = \frac{\eta}{\mu_0} \frac{\partial^2 B(x,t)}{\partial x^2} \tag{I.41}
\]

\(\Rightarrow\) Initial condition: \(B(x,t=0) = 0\)

\(\Rightarrow\) Boundary condition: \(B(x = 0,t) = f(t)\)

The transform will operate on the variable ‘\(t\),’ so that the variable ‘\(x\)’ is treated as a constant under the operation. Then:

\[
L_x \left[ \frac{\partial B(x,t)}{\partial t} \right] = sU(x,s) - B(x,0) \text{ and } B(x,0) = 0 \text{ so } L_x \left[ \frac{\partial B(x,t)}{\partial t} \right] = sU(x,s) \tag{I.42}
\]

\[
L_x \left[ \frac{\eta}{\mu_0} \frac{\partial^2 B(x,t)}{\partial x^2} \right] = \frac{\eta}{\mu_0} \frac{d^2 U(x,s)}{dx^2} \tag{I.43}
\]

The transform of \(\frac{\partial^2 B(x,t)}{\partial x^2}\) takes the simple form shown because the operation does not act on the variable \(x\). The boundary condition must also be transformed:

\[
B(x = 0,t) = f(t) \Rightarrow L_x \left[ B(x = 0,t) \right] = U(x = 0,s) = L_x \left[ f(t) \right] = F(s) \tag{I.44}
\]
By using the Laplace transform, the partial differential equation of variables \( x \) and \( t \), has been changed into an ordinary differential equation of variable \( x \). The problem to solve becomes:

\[
sU(x, s) = \frac{\eta}{\mu_0} \frac{d^2U(x, s)}{dx^2}, \text{ or after slight reorganization: } \frac{d^2U(x)}{dx^2} = \frac{\mu_0}{\eta} U(x) \quad (I.45)
\]

\( \rightarrow \) Boundary condition: \( U(x=0, s) = F(s) \)

This ODE has the simple solution:

\[
U(x) = F(s) \exp \left[ -\frac{\mu_0 x^2}{\eta} \right] \quad (I.46)
\]

Using the inverse Laplace Transform, the variable, ‘\( s \),’ is transformed back to the time variable.

\[
B(x, t) = L^{-1}[U(x)] = L^{-1} \left[ F(s) \exp \left( -\frac{\mu_0 x^2}{\eta} \right) \right] = L^{-1}[F(s)] * L^{-1} \left[ \exp \left( -\frac{\mu_0 x^2}{\eta} \right) \right] \quad (I.47)
\]

Where the symbol * represents the finite convolution of the two functions. Now, the inverse transforms of the two functions are found:

\[
L^{-1}[F(s)] = f(t) \text{ and,}
\]

\[
L^{-1} \left[ \exp \left( -\frac{\mu_0 x^2}{\eta} \right) \right] = \sqrt{\frac{\mu_0}{\eta}} \frac{x}{2\sqrt{\pi}} \exp \left( -\frac{\mu_0 x^2}{4\eta t} \right) \quad (I.48)
\]

Using the definition of the convolution:

\[
(f \ast g)(t) = \int_0^t f(t - \tau) g(\tau) d\tau \quad (I.49)
\]

The solution:
\begin{equation}
B(x,t) = \frac{\sqrt{\mu_0/\eta} \cdot x}{2\sqrt{\pi}} \int_0^\infty \left\{ f(\tau)(t-\tau)^{3/2} \exp\left(-\frac{\mu_0 x^2}{4\eta(t-\tau)}\right) \right\} d\tau
\end{equation}

Where \( f(t) \) is the boundary condition for the applied field. The equation must be solved numerically for all but the simplest forms of \( f(t) \). Consider, for example, that \( f(t) = B_0 = \text{constant} \). In this case, the field becomes,

\begin{equation}
B(x,t) = \frac{\sqrt{\mu_0/\eta} \cdot x}{2\sqrt{\pi}} \int_0^\infty \left\{ B_0(t-\tau)^{-3/2} \exp\left(-\frac{\mu_0 x^2}{4\eta(t-\tau)}\right) \right\} d\tau
\end{equation}

Using the change of variable \( u = \sqrt{\frac{\mu_0 x^2}{4\eta}} (t-\tau)^{-1/2} \)

The integral may be written:

\begin{equation}
B(x,t) = \frac{2B_0}{\sqrt{\pi}} \int_{\sqrt{\frac{\mu_0 x}{2\eta}}}^\infty \exp(-u^2) d\tau
\end{equation}

With solution,

\begin{equation}
B(x,t) = B_0 \text{erfc} \left[ \sqrt{\frac{\mu_0 x}{\eta}} \frac{x}{2\sqrt{t}} \right]
\end{equation}

Using \( B_0 = 1.0 \) T and \( \eta = 2.8 \times 10^{-8} \Omega \cdot m \), the curves in Fig. I.4 are obtained for the magnetic field at \( t = 10, 100, 200, \) and \( 300 \) ns.
Fig. I.4: Magnetic field distribution for constant surface magnetic field

Now, with the analytic solution for the magnetic field known, the current density is calculated using:

\[ J = \frac{1}{\mu_0} \frac{\partial B}{\partial x} \]  (I.55)

The magnetic field solution contains the error function, the derivative of which is not easily evaluated. Eqn. I.53 may be differentiated with respect to \( x \), but integrals with respect to \( t \) are not readily evaluated. As a second method of evaluation, \( B \) may be written in terms of the series expansion of the error function, and differentiated term by term. Using,

\[ \text{erfc}(z) = 1 - \frac{2}{\sqrt{\pi}} \left( z - \frac{z^3}{3} + \frac{z^5}{10} - \frac{z^7}{42} + \frac{z^9}{216} - \ldots \right) \]  (I.56)

and,
\[
B(x,t) = B_0 \text{erfc} \left[ \sqrt{\frac{\mu_0}{\eta}} \frac{x}{2\sqrt{t}} \right] = B_0 \text{erfc} \left[ a \ x \right] \text{ where } a \equiv \sqrt{\frac{\mu_0}{\eta}} \frac{1}{2\sqrt{t}} \quad (I.57)
\]

Then \( J \) becomes:

\[
J(x,t) = -\frac{2B_0}{\mu_0 \sqrt{\pi}} \left( a - a^3 x^2 + \frac{a^5 x^4}{2} - \frac{a^7 x^6}{6} + \ldots \right) = -\frac{2B_0}{\mu_0 \sqrt{\pi}} \sum_{n=0}^{\infty} \frac{(-1)^n a^{2n+1} x^{2n}}{n!} \quad (I.58)
\]

For the diffusion problem under consideration, where \((t<<1 \text{ s}, x<<1 \text{ m})\), \(a^{2n+1}\) grows large at nearly the same rate as \(x^{2n}\), so the sum must be carried to large ‘\(n\)’ in order to gain an accurate solution for \(J\). Therefore, it is more straightforward to simply numerically differentiate \(B\). Since the magnetic field strength varies smoothly with \(z\), no large errors should arise from numeric differentiation. Several current density and ohmic heating curves are shown in Fig. I.5.
Fig. 1.5: (a) Current density and (b) ohmic heating distributions at different times for a constant magnetic field boundary condition.
To find the temperature, the ohmic heating is integrated with respect to time. The series solution for $J$ is again used.

$$T \approx \int \frac{P(x,t)}{C_v} dt = \frac{1}{C_v} \int \eta J^2 dt = \frac{1}{C_v} \int \eta \left[ -\frac{2B_0}{\mu_0 \sqrt{\pi}} \sum_{n=0}^{\infty} \frac{(-1)^n a^{2n+1} x^{2n}}{n!} \right]^2 dt \quad (I.59)$$

This integral can be numerically evaluated. Based on the nature of the joule heating for the constant boundary condition, where the maximum power input is at $x=0$ for all times, it is clear that peak temperature will occur at the surface, with a sharp drop in temperature when moving deeper into the material. As time passes, the current is spread throughout the conductor, and the energy is distributed.

To obtain solutions for $B$, $J$, $P$, and $T$, which more nearly approximate experimental conditions, the function $f(t)$ in Eqn. I.50 would be changed to match the profile of the pulsed surface magnetic field. Analytic solutions exist for sinusoidal boundary conditions, therefore, via superposition, boundary conditions which approximate experimental conditions may be constructed (for constant $\eta$).

Section I.C: Z-Pinch Equilibrium

With an appropriate current distribution, a pinch can be held in equilibrium. In this section, a model for equilibrium is developed using the equations of ideal MHD. In Eqns. I.(60-63), $\rho$ is the mass density, $u$ is the fluid velocity, $\sigma$ is the charge density, $n$ is the electron number density, and $e$ is the electron charge. Other quantities are named in a manner consistent with other portions of this document.
Mass continuity equation:

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \]  \hfill (I.60)

Charge continuity equation:

\[ \frac{\partial \sigma}{\partial t} + \nabla \cdot (J) = 0 \]  \hfill (I.61)

Single fluid equation of motion:

\[ \rho \frac{du}{dt} = \rho \left( \frac{\partial u}{\partial t} + u \cdot \nabla u \right) = \sigma E + J \times B - \nabla p \]  \hfill (I.62)

Generalized Ohm’s Law:

\[ E + u \times B = \eta J + \frac{J \times B - \nabla p_e}{ne} \]  \hfill (I.63)

Assume that the local charge density is everywhere zero (charge neutrality). Also, assume the fluid velocity is everywhere zero.

\[ \frac{\partial u}{\partial t} = u = \sigma = 0 \]  \hfill (I.64)

Assuming steady-state behavior amounts to seeking an equilibrium condition where magnetic and material pressure gradients are equal everywhere, as will be shown. Under these assumptions, the single-fluid equation of motion, (with isotropic pressure assumed) simplifies:

\[ \nabla p = J \times B \]  \hfill (I.65)

Then, along with the two Maxwell equations for \( B \) (steady-state)

\[ \nabla \times B = \mu_0 J \quad \text{and} \quad \nabla \cdot B = 0 \]  \hfill (I.66)
the magnetic field, current density, and scalar pressure are found to be interconnected. Inserting Ampere’s Law into the pressure-balance equation gives, after slight manipulation:

\[ \nabla p = J \times B = \frac{1}{\mu_0} \left( \nabla \times B \right) \times B = \frac{1}{\mu_0} \left[ \left( B \cdot \nabla \right) B - \nabla \left( B^2 / 2 \right) \right] \]

\[ \Rightarrow \nabla \left( p + \frac{B^2}{2\mu_0} \right) = \frac{1}{\mu_0} (B \cdot \nabla) B \] (I.67)

The left hand side (LHS) shows that the plasma pressure and magnetic field pressure are coupled if the velocity is to remain zero. The right hand side (RHS) gives the contribution to the pressure-balance condition resulting from the bending or compression of magnetic field lines. The RHS may sometimes be ignored, however, here cylindrical geometry is of interest, and the term must be included to account for the curvature of the azimuthal magnetic field. Equation I.67 therefore is examined in full form.

In the LHS of Eqn. I.67, all variations in pressure and azimuthal magnetic field are assumed to be in the radial direction. Therefore, \( \nabla \to \partial / \partial r \). The RHS of Eqn. I.67 can be simplified in the following manner:

\[ \frac{1}{\mu_0} (B \cdot \nabla) B = \frac{1}{\mu_0} \left( B_\theta \hat{\theta} \cdot \nabla \right) B_\theta \hat{\theta} = \frac{1}{\mu_0} B_\theta \nabla \cdot \frac{1}{\mu_0} B_\theta \hat{\theta} \nabla \left( B_\theta \hat{\theta} \right) = \frac{1}{\mu_0} B_\theta \frac{1}{r} \frac{\partial}{\partial \theta} \left( B_\theta \hat{\theta} \right) \]

\[ = \frac{1}{\mu_0} B_\theta \frac{1}{r} \left( \frac{\partial B_\theta}{\partial \theta} \hat{\theta} + B_\theta \frac{\partial \hat{\theta}}{\partial \theta} \right) = \frac{1}{\mu_0} B_\theta \frac{1}{r} (0 - B_\theta \hat{r}) = -\frac{1}{\mu_0 r} B_\theta^2 \hat{r} \] (I.68)

Where the identity: \( \partial \hat{\theta} / \partial \theta = -\hat{r} \) has been used. Finally the LHS and RHS are brought together and integrated with respect to \( r \) to find:

\[ \frac{\partial}{\partial r} \left( p + \frac{B^2}{2\mu_0} \right) = -\frac{1}{\mu_0 r} B_\theta^2 \Rightarrow p(r) = p_0 - \frac{B_\theta^2(r)}{2\mu_0} - \frac{1}{\mu_0} \int_{r_0}^r \frac{B_\theta^2}{r} \, dr \] (I.69)
This solution is valid for any field profile. Assume $B_0$ has the form of Eqn. I.17. Then,

$$p(r) = p_0 - \frac{1}{2\mu_0} \frac{\mu_0^2 I^2}{4\pi^2 r^2 (R^2 - r_i^2)^2} (r^2 - r_i^2)^2 - \frac{1}{\mu_0} \int_{r_i}^r \left[ \frac{\mu_0^2 I^2}{4\pi^2 r^3 (R^2 - r_i^2)^2} (r^2 - r_i^2)^2 \right] dr$$

$$\Rightarrow p(r) = p_0 - \frac{\mu_0 I^2}{4\pi^2 (R^2 - r_i^2)^2} \left[ r^2 - r_i^2 \left( 1 + 2 \ln \left( \frac{r}{r_i} \right) \right) \right]$$

(I.70)

In the thin-wire limit (uniform current density, $r_i = 0$), the result reduces to,

$$p(r) = p_0 - \frac{\mu_0 I^2 r_i^2}{4\pi^2 R^4}$$

(I.71)

The pressure at the material-vacuum interface ($r = R$) must equal zero, so $p_0$ is easily solved for. The resulting pressure profile is commonly referred to as the “Bennett Equilibrium [38].”

$$p(r) = \frac{\mu_0 I^2}{4\pi^2 R^4} \left( 1 - \frac{r^2}{R^2} \right)$$

(I.72)

For a static pinch with uniform current density, the magnetic field inside the conductor will grow linearly with $r$ while the pressure falls as $(1-r^2/R^2)$ until reaching the edge, where $p(R)=0$. While “estimates based on this assumption are often correct only with an order of magnitude…they are convenient and, therefore, conventionally used [39].”

Section I.D: Z-Pinch Stability

The work of the previous section shows that theoretically, a z-pinch can be held in equilibrium at arbitrarily high pressures. According to the Lawson Criterion [40], if fusion plasma (fuel) can be held at sufficiently high density for a sufficient amount of time, fusion breakeven can be achieved. The high pressures associated with the magnetic field, made the simple z-pinch one of the first designs tested for the realization of the
thermonuclear fusion as an energy source. The failure of this geometrically simple system lies in the instability of the pinch. The Bennett profile, while in force balance, is highly unstable. If a radial perturbation is introduced into the pinch, the perturbation will grow. For example, imagine the pinch has a location with slightly reduced radius. At that location, since the surface radius is reduced, the local surface magnetic field is increased, resulting in greater local magnetic pressure. Therefore, the local constriction is pinched smaller still, providing positive feedback, and leading to exponential growth of the perturbation.

The “flute instability” of a simple z-pinch is discussed in many introductory texts [39,41,42]. Here a brief derivation of the growth rate of the flute instability is presented. For more detailed derivations, the reader is directed to the listed references. For more advanced discussion of pinch instabilities, see for example [43,44,45,46,47].

The gravitational Rayleigh-Taylor instability is observed in ordinary fluids, and occurs when a heavy fluid is supported above a lighter fluid. The heavy fluid can be in equilibrium with the lighter fluid (the lighter fluid will be compressed until its pressure can support the mass of the heavier fluid), however, the interface between the two fluids is unstable. If a perturbation (or ripple) is introduced at the interface, the heavy fluid will gravitationally fall through the lighter fluid. The interface is said to be unstable, since in this configuration, the interface perturbation will grow. In contrast, if a light fluid is supported by a heavy fluid, a perturbation at the interface will decay away, and the configuration is stable. For the unstable configuration, it is easily shown (see the textbook references above) that the growth rate of the perturbation ($\gamma$) is given by $\gamma=(g/s)^{1/2}$ where $g$ is the gravitational force, and $s$ is the scale length of the fluid density gradient.
It is well known from basic plasma physics that charged particles will follow magnetic field lines, and if the field lines are curved, the plasma will experience an associated “centrifugal force.” This force, in plasma, acts similar to the gravitation force. External gravitational forces applied perpendicular to magnetic field lines introduce a charged particle drift given by:

\[ v_{D,g} = \frac{Mg \times B}{eB^2} \]  

(I.73)

The drift associated with field line curvature and gradients is given by

\[ v_{D,B} = \frac{M}{e} \left( \frac{v_\perp^2 + v_\parallel^2}{R_c^2 B^2} \right) \]

(I.74)

where \( R_c \) is the radius of curvature of the pinch.

Aside from multiplicative factors, the two drift velocities carry the same basic form. Therefore, \( z \)-pinches, with curved field lines, experience Rayleigh-Taylor-like instabilities associated with field-line curvature. Such instabilities are known as flute instabilities. By averaging over the distribution of particle velocities, it can be shown that Eqns. I.73 and I.74 are equivalent if \( g \) is written as \( \frac{2p}{(\rho R_c)} \). Therefore, the growth rate for the flute instability of a \( z \)-pinch may be written as:

\[ \gamma = \left( \frac{g}{s} \right)^{1/2} \sim \left( \frac{2p}{s \rho R_c} \right)^{1/2} \sim \left( \frac{2(\partial p/\partial r)}{\rho R_0} \right)^{1/2} \]  

(I.75)

Where \( p/s \) has been set approximately equal to \( \partial p/\partial r \) and \( R_c \) set equal to \( R_0 \) (the outer radius of the pinch). Instabilities grow faster in low density, small radius pinches, when large pressure gradients exist. Therefore, in the UNR-Megagauss Experiments, as the rod diameter is increased, one-dimensional behavior should extend later into the experiment.
However, due to the square root in equation I.75, there is only a factor of 2 difference between the instability growth rate predicted for 0.50 and 2.00-mm-diameter rods.

Section I.E: Resistivity and Equation of State

This section begins by deriving simple models for the conductivity of solids and plasmas. Such models are well known, and carefully detailed in a number of texts. The discussion of conductivity based on the electric-field-driven flow of free electrons closely follows the presentation of the subject in [33,48]. Next, an equation for the resistivity of fully ionized plasma is presented. This result is also well known, and is presented in commonly used plasma physics text books [41,42]. The resistivity of cool metal and fully ionized plasmas are well known. It is for material in the intermediate, warm-dense-matter regime, where the resistivity is not yet well understood. At the end of this section, the work of Desjarlais, who modeled the conductivity of Al in this difficult intermediate regime, is discussed.

**Solid State Resistivity**

Assume a potential difference $V$ is applied to the ends of a one-dimensional object of length $L$. The electric field and resultant force and acceleration on the electrons in the object are given by:

$$E = -\nabla V = -\frac{V}{L}$$

(I.76)

and,
Assuming the atoms remain in a stationary lattice, the electrons are accelerated for a time \( \Delta t \) (the mean time between collisions with a lattice atom) referred to as the collision time. The component of velocity related to the electric field will then increase from 0 to \( a \Delta t \), with the average velocity equal to half the final velocity, or

\[
v_{\text{average}} = \frac{1}{2} a \Delta t
\]  

Rather than using the average time between collisions to calculate the average velocity, it is more appropriate to use the actual times and then take the average \([48]\). This amounts to a factor of 2 correction to the average velocity,

\[
v_{\text{average}} = a \Delta t \equiv v_D
\]  

This is defined as the drift velocity. The drift velocity then relates to the applied electric field and the collision time through

\[
v_D = \left( \frac{e}{m} \right) \Delta t \equiv \mu_e E \quad \text{where} \quad \mu_e \equiv \frac{e}{m} \Delta t
\]

Where \( \mu_e \) is defined as the electron mobility. With the electron drift velocity specified, the associated current density can be related to the number density of the free electrons, \( N_e \), by

\[
J = N_e e v_D = N_e e \left( \frac{e}{m} \right) \Delta t \equiv \left( \frac{N_e e^2 \Delta t}{m} \right) E = \sigma E \quad \text{where} \quad \sigma = \frac{1}{\eta} \equiv \frac{N_e e^2 \Delta t}{m} = \mu_e \cdot N_e e
\]

The electrical conductivity \((\sigma = 1/\eta)\) determines the current density for a given electric field strength, and is proportional to the available number of free electrons, their mobility, and their charge. The thermal velocity does not affect the current density, as thermal
motions are random. The mobility of electrons in metals is typically not very large, so
the high conductivity of metals is due primarily to the large number of free electrons.

Above, the simple solid-state conductivity model was derived by defining a
characteristic time between electron collisions with lattice atoms. The result, Ohm’s
Law, states that the current density is proportional to the electric field through the
conductivity. But, the characteristic time between collisions should depend upon the
applied electric field because it is the strength of the field that determines the acceleration
of the electrons, which should determine the time between collisions. It is perhaps more
physical to consider the inter-atomic spacing of the lattice, \(d\) (since there is no reason to
think that the inter-atomic spacing should be affected by the strength of the applied
electric field). Then, the characteristic time is related to \(d\) by:

\[
\Delta t = \frac{d}{(v_{\text{thermal}} + v_D)}
\]  

\hspace{1cm} (I.82)

Now, the conductivity depends upon \(\Delta t\), and \(\Delta t\) depends upon \(v_D\), and since, as stated,
\(v_D\) depends upon the applied electric field, we see that the conductivity does indeed
depend upon the electric field strength, in disagreement with the simple version of Ohm’s
Law. How then is Ohm’s Law commonly used, with seemingly high applicability?
Ohm’s Law in standard form holds only if the characteristic time depends weakly on \(v_D\),
which is true if \(v_D \ll v_{\text{thermal}}\). If this simple model is applied to aluminum, the electron
mobility is \(\mu_e \approx 0.013 \text{ m}^2\text{V}^{-1}\text{s}^{-1}\), resulting in a drift velocity of 0.013 m/s for an applied
1.0 V/m field. The thermal velocity of the electrons in aluminum can be approximated
by the thermal velocity of an ideal gas, \(v_{\text{thermal}} = (3kT/m)^{1/2}\), which is roughly \(10^5\) m/s at
room temperature. Therefore, \(v_{\text{thermal}}\) exceeds \(v_D\) by seven orders of magnitude, and \(\Delta t\) is
virtually unaffected by the applied electric field, which is why Ohm’s Law holds for most applied fields.

Since $\Delta t$ decreases with $v_{\text{thermal}}$, and $v_{\text{thermal}}$ increases with temperature, the electrical conductivity of a metal is expected to decrease with temperature. The conductivity may be written,

$$\sigma \equiv \frac{N_e e^2 d}{\sqrt{3mkT}}$$  \hspace{1cm} (I.83)

This simple formula predicts that the conductivity of a metal will decrease with the square root of temperature, due to the increased thermal speed decreasing the free-electron charge mobility.

As discussed in Section I.B, if current flows through resistive material, the material is ohmically heated. Even in the simple conductivity models developed above, it is shown that as the material temperature increases, the resistivity increases. More complicated theoretical models, and experimental results show that in the solid state, conductivity changes with both temperature and density (Eqn. I.84).

$$\sigma = \frac{\sigma_0}{1 + \beta c_v T \left( \frac{\rho}{\rho_0} \right)^\alpha}$$ \hspace{1cm} (I.84)

where $\sigma_0$ is the room temperature conductivity, $c_v$ is the specific heat, $\beta$ is the material dependent “heat coefficient,” $\rho_0$ is the initial density, and $\alpha$ is the material dependent “pressure coefficient.” The conductivity may also vary with magnetic field. It is stated in the text by Knoepfel, that for an applied 1 MG magnetic field, the conductivity of
room temperature Cu can change by nearly 20%. However, as the conductor is heated, this effect diminishes.

Eventually, if the energy deposition associated with ohmic heating is sufficient, the metal will undergo phase changes. During the transition from solid to liquid, a discontinuous increase in resistivity occurs, associated with the increases in “disorder scattering” as the ordered lattice is eliminated [49]. As the material is heated further, vapor will form. If ultra-high magnetic field is present, as the vapor expands, decreases in density, and continues to ohmically heat, the vapor can ionize, forming high-conductivity plasma [18]. In this regime of uncertain phase, conductivity calculations become difficult because the material can undergo large changes in density, temperature, and ionization state. Before discussing the conductivity of a metal as it progresses through this complicated region of phase space, a brief digression is made to derive the “Spitzer” resistivity of fully ionized plasma.

**Plasma Resistivity**

The resistivity of fully ionized plasma can be derived from basic collision theory. First, the equations of motion (Eqn. I.62) are written in two-fluid form (independent equations for electrons and ions).

\[
\begin{align*}
&Mn \left[ \frac{du_i}{dt} \right] = en(E + u_i \times B) - \nabla p_i + P_{ie} \\
&mn \left[ \frac{du_e}{dt} \right] = -en(E + u_e \times B) - \nabla p_e + P_{ei}
\end{align*}
\]

(I.85)
The final terms on the RHS of each equation represent momentum gain (or loss) from one fluid through interaction with the other fluid. By conservation of momentum, these terms must be equal and opposite ($P_{ei} = -P_{ie}$). The momentum gain may be written in terms of the collision frequency and fluid velocity. For the electron fluid,

$$P_{ei} = mn(u_i - u_e)\nu_{ei}$$  \hspace{1cm} (I.86)

Furthermore, on physical grounds, the interaction term must be proportional to the Coulomb force, the number of particles squared, and the relative velocity of the fluids. Defining the constant of proportionality ($\eta$) as the specific resistivity, it is found that,

$$P_{ei} = \eta e^2 n^2 (u_i - u_e)$$  \hspace{1cm} (I.87)

Eqns. I.86 and I.87 together imply that the resistivity is related to the collision frequency by,

$$\eta = \frac{mv_{ei}}{n e^2}$$  \hspace{1cm} (I.88)

Next, as is typical in the development of Coulomb collision models, an impact parameter ($b$) and effective impulse time are defined. The change in the electron’s momentum due to the Coulomb interaction can be shown to be:

$$\Delta (mv) \approx \frac{e^2}{4\pi e_0 bv}$$  \hspace{1cm} (I.89)

If the collisions are assumed to be large-angle, where the electron changes direction by nearly 90º, then the change in momentum is of the same order as the initial momentum (if
the electron elastically collides and changes direction by 180°, then the change in momentum is twice the initial momentum). Then, for large-angle collisions,

\[ \Delta(mv) \approx mv \approx \frac{e^2}{4\pi\varepsilon_0 b v} \Rightarrow b = \frac{e^2}{4\pi\varepsilon_0 m v^2} \]  

(I.90)

The collision cross section is then,

\[ \sigma_e = \pi b^2 = \frac{e^4}{16\pi\varepsilon_0^2 m^2 v^4} \]  

(I.91)

and the collision frequency is expressed as,

\[ \nu_e = n \sigma_e v \]  

(I.92)

Assuming a Maxwellian velocity distribution with \( v = (kT_e/m)^{1/2} \), the resistivity can be written,

\[ \eta = \frac{\pi e^2 m^{3/2}}{(4\pi\varepsilon_0)^{3/2} (kT_e)^{3/2}} \]  

(I.93)

For fully ionized plasma, the resistivity is proportional to \( T_e^{-3/2} \), resulting in a rapid decrease in plasma resistivity as the temperature increases.

Finally, as was shown by Spitzer [50], a correction should be added to account for the significant contribution (due to the extended influence of the Coulomb force) of small angle collisions. The final “Spitzer Resistivity” is given in Eqn. I.94.

\[ \eta = \frac{\pi Ze^2 m^{3/2}}{(4\pi\varepsilon_0)^{3/2} (kT_e)^{3/2} \ln \Lambda} \]  

where \( \Lambda = 12\pi n\lambda_D^3 \)  

(I.94)

Where \( \lambda_D \) is the Debye length. As shown in [42], the value of \( \ln \Lambda \) does not change much over typical plasma parameters. Therefore, based on the large number of simplifying
assumptions already made in developing the model, it is typically acceptable to set \( \ln \Lambda = 10 \). Also included in Eqn. I.94 is the atomic number \( Z \) (for the case of non-hydrogen plasmas).

**Warm Dense Matter Resistivity**

Calculating the resistivity of metal as it transitions from solid state to plasma poses a significant challenge. Statements alluding to the challenges associated with this regime include:

“In the high temperature and low density well-ionized plasma limit, the resistivity of plasma adopts the well established Spitzer-like dependence of \( T^{-3/2} \). Between these two well-established limits, around the implied resistivity maximum at 1–10 eV, there is considerable uncertainty (particularly at densities lower than solid) with more than an order of magnitude difference between theoretical models.”


“As the temperature of the ohmically heated conductor becomes higher than the boiling point, the surface starts boiling off; the dense vapor then expands and is gradually transformed into a highly conducting plasma. Study of the properties of the electric conductivity and, in general, of transport coefficients across these phase changes is a rather arduous problem. In general one tries to approach it from a practical side by giving empirical laws.”


The conductivity of warm-dense aluminum for densities ranging from solid density \( \rho_0 \) to nearly \( \rho_0/1000 \), and temperatures ranging from 0.5 to 3 eV, is considered by Desjarlais, Kress, and Collins [2]. They “perform ab initio molecular dynamics (MD) simulations within the framework of the finite temperature density functional theory (FT-DFT) of Mermin” to obtain ion configurations for the conductivity calculation. The
Kubo-Greenwood formula (also referred to as the optical conductivity) is then used to determine the electrical conductivity. Here, their method is not described in detail, but their commonly used results are examined. In Fig. I.6 is a replica of a plot displayed in [2]. Most, but not all of the data contained in the original figure has been hand-fit to generate the plot below. The caption from [2] is quoted below the replicated figure.

Fig. I.6: (caption quoted from [2]) “Aluminum dc electrical conductivity versus density for data and calculations at 6 kK (diamonds), 10 kK (triangles), 20 kK (squares), and 30 kK (stars). Calculation results are in red; the data from the experiments of DeSilva and Katsouros are in gray (6 and 20 kK) and black (10 and 30 kK).”

The plot is presented as in the original paper, with the exception of the lines and text shown in green, which have been added for clarity. Experimental data is shown in black
and gray, while simulation results are show in red. Data point shapes are coded according to temperature: diamonds→0.5 eV, triangles→1.0 eV, squares→2.0 eV, and stars→3.0 eV. As shown in the upper right hand corner of the plot, near solid density, the conductivity varies inversely with temperature. For slightly lower densities, experiment and simulation show strong agreement, and the conductivity falls with density, with little temperature dependence. According to the paper, in this region, $\sigma \sim \rho^{7/3}$. As the density falls further still, the dependence of conductivity upon temperature grows. At $\rho_0/100$, the theoretical ratio of the conductivity for 0.5 eV to 3.0 eV is between 50 and 100. At high temperature, the conductivity stabilizes with falling density, while at low temperature, the conductivity roughly follows the $\sigma \sim \rho^{7/3}$ curve to lower density. This feature may correspond to the transition from vapor to plasma. Fig. 1.7 displays a phase plot for Al from the Sesame database (plot courtesy of Professor V. Makhin). The transition to plasma occurs at lower temperatures for lower densities (as indicated by the $Z=1$ line). The lower ionization state results in fewer free charge carriers, and decreased conductivity for constant density but lower temperature.
Fig. I.7: (Plot courtesy of Professor V. Makhin) Phase plot for Aluminum from the Sesame database.

In the quote by Chittenden it is stated that there may be order-of-magnitude differences in conductivity models for warm dense matter. This point is displayed by the plots in Fig. I.8, where resistivity contours are plotted on a density (kg/m$^3$)-temperature (eV) plot. Plot (a) is generated from the work of Desjarlais, and plot (b) from the work of Garanin (plots generated by M. Angelova using TRANCE [51]). The differences in the conductivity models lead to significant differences in simulation results [52].
Rising $\eta$

Falling $\eta$

$\eta=10^{-8} \Omega \cdot m$

$10^{-7}$

$10^{-6}$

$10^{-5}$

$10^{-4}$

$10^{-3}$

$10^{-2}$

$10^{-1}$

$10^0$

$10^1$

$\rho_0/10$

$10^{2}$

$10^{3}$

$10^{4}$

$10^{5}$

$10^{6}$

$10^{7}$

$10^{8}$

$10^{9}$

$10^{10}$
While the conductivity models displayed in Fig. I.8 contain significant differences, they agree qualitatively. For example, the shape of the resistivity contours in the low-density region give information about how material is heated, and why plasma may form. Recall that ohmic heating is given by $P_j = \eta J^2$, and that $E = \eta J$, therefore, $P_j = E^2 / \eta$. Now, assume constant electric field strength. For densities below approximately $\rho_0 / 10$, the resistivity falls with increasing temperature (blue arrow, Fig. I.8:(a)) with little density.
dependence. As the resistivity falls, $P_j = E^2/\eta$ increases, resulting in further temperature increase. Therefore, in this portion of phase space, the feedback is positive, and temperatures grow rapidly. Heating in this regime will eventually lead to sufficiently high temperatures for thermal breakdown and plasma formation. In contrast, for higher densities, as the temperature increases, the resistivity increases (red arrow, Fig. I.8:(a)), resulting in lower energy input. This negative feedback results in decreased heating. Plasma formation in the UNR-Megagauss Experiments likely occurs in material with sufficiently low density to enable positive feedback.

Clearly, when considering the complexity of the problem, and the uncertainty of the conductivity of heated Al, an accurate calculation of magnetic diffusion and ohmic heating proves difficult. In a rod pulsed to ultra-high magnetic field, individual and complex trajectories through phase space of each layer of material must be considered simultaneously (since material is coupled through transport phenomena). The analytic solutions derived in this chapter cannot possibly describe such complex processes, but do offer a qualitative picture of rod heating and dynamics. Even with state-of-the-art simulations, the uncertainty of the state and conductivity of the heated rod can lead to large differences in results. The UNR-Megagauss Experiments offer a dataset which can be compared against equation-of-state and material-properties models, possibly leading to improved predictive capability.
Chapter II: The Zebra Facility

The UNR-Megagauss Experiments use the Zebra z-pinch [25,26] to pulse high magnetic field on the surface of thick conducting rods. The machine is used in short-pulse mode, delivering a peak current of approximately 1.0 MA. The current rises linearly for approximately 70 ns at $\frac{dI}{dt} = 1.1 \times 10^{13}$ A/s from 100 to 900 kA. Zebra is a high-impedance driver (1.9 $\Omega$), with the load essentially acting as a short circuit. Therefore, minor changes in impedance associated with different initial rod diameter have no observable affect on the current profile. While the impedance mismatch is electrically inefficient, the consistency of the current profile for rods of variable diameter makes Zebra ideal for parametric studies in $dJ/dt$ and $dB/dt$.

This chapter offers an overview of the Zebra facility. First, Zebra’s major electrical components are described, and the power flow from the charging capacitors to the load is discussed. Next, the Zebra load chamber is detailed with particular attention given to diagnostic access. Then the Zebra current pulse delivered to the load is considered. The configuration of Bdot probes near the load region is detailed, and the method for using raw Bdot signals to determine the load current is outlined. The shot-to-shot variation in current is examined with plots and statistics. Finally, the triggering of diagnostics and synchronization of data are overviewed.

Section II.A: The Zebra Machine and Facility Infrastructure

The Zebra z-pinch delivers 1.0 MA of current to the load via three stages of power amplification. The first stage consists of (32) 1.3 $\mu$F capacitors in a Marx configuration. Initially the capacitors are in parallel with an effective capacitance of
1.3×32 µF=41.6 µF. The capacitors are rated for a maximum charge of 100 kV, but are typically charged only to 85 kV (significantly extending the capacitor lifetime), with total stored energy \(E=CV^2/2\) of 150 kJ. Ultimately, the capacitors are discharged in series to deliver a high-voltage pulse \((32\times85 \text{ kV}=2.7 \text{ MV})\), through a self-breaking gas switch to a 28 nF, 3.5 MV coaxial capacitor. The capacitor is immersed in de-ionized water with a low frequency dielectric constant of 80, and is discharged through an SF\textsubscript{6}-insulated Rimfire switch. When the Rimfire switch is triggered, the electrical energy is delivered to the third amplification stage; a 50 ns, 1.9 Ω vertical transmission line and an eight channel self-breaking water switch. Due to Zebra’s high transmission-line impedance (1.9 ohm), the large-diameter loads examined in the UNR-Megagauss Experiments effectively create a short circuit, and the current waveform is insensitive to the initial rod diameter \(D_0\). The Zebra current, \(I(t)\), consistently rises exponentially to 100 kA (with rise time \(\tau=13 \text{ ns}\), and then linearly from 100 to 900 kA for 70 ns, with \(dI/dt=1.1\times10^{13} \text{ A/s}\), to a maximum current of 1.0 MA \((I_{\text{max}}\sim1.2 \text{ MA if capacitors are charged to 100 kV})\). Electrical power flow is measured throughout the machine with inductive B\textsubscript{dot} (current) and capacitive V\textsubscript{dot} (voltage) probes. A detailed drawing of Zebra’s major electrical components is available on the NTF’s website \([53]\) and shown Fig. II.1. The site includes further machine details, and lists and describes the facilities core diagnostics (available to all users of the Zebra facility).
The vertical transmission line (Fig. II.1) delivers high voltage to the anode plate which is positioned above the cathode inside the vacuum chamber. The center conductor of the vertical transmission line is held at negative potential with respect to the grounded anode plate. The load is electrically connected from the anode to the cathode at the axial center of the chamber. The anode-cathode configuration inside the vacuum chamber is displayed in Fig. II-2(a) [53]. The outer wall of the chamber acts both as the return conductor, and as the vacuum vessel. Pressure in the vacuum chamber must fall below $10^{-5}$ Torr before a shot is allowed, in part to reduce the likelihood of insulator stack flashover, but also to reach typical vacuum levels required for safe (high voltage) MCP operation. The Zebra vacuum chamber is evacuated using mechanical, turbo, and cryo-pumps.
A key advantage of the pulsed-rod experimental configuration over the imploding-liner experimental configuration (discussed in the introduction of this dissertation) is increased diagnostic access. The center of the load is vertically aligned with the center of the chamber’s 16 diagnostic ports, which are evenly spaced at 22.5° intervals. Of these ports, 8 are 2” diameter, 7 are 3” diameter, and 1 (south) has been increased to 4” diameter to allow coupling to the beam tube of the Leopard laser. The ports are named according to the geographic direction of the vector from chamber center to port center. The naming convention is as listed in Table II-1, and as labeled in Fig. II-2(b) [27]. Several ports are dedicated to core diagnostics, yet many remain available for supplemental diagnostics. Table II-1 lists the use of each port in each of the four experimental campaigns.
Fig. II.2: (a) Cutout of Zebra chamber. Vacuum vessel (gray), mesa or cathode (blue), and anode plate (red). Load assembly is mounted at chamber center between the cathode and anode plate. (b) Bird’s eye view of the Zebra vacuum chamber showing 16 load-level diagnostic ports.
<table>
<thead>
<tr>
<th>Port Location</th>
<th>Port Diam.</th>
<th>USE: MG-I</th>
<th>USE: MG-II</th>
<th>USE: MG-III</th>
<th>USE: MG-IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>3&quot;</td>
<td>ICCD/Streak</td>
<td>ICCD/Streak</td>
<td>ICCD/Streak</td>
<td>ICCD</td>
</tr>
<tr>
<td>NNE</td>
<td>2&quot;</td>
<td></td>
<td>EUV Spectrometer</td>
<td>Array Detector</td>
<td>EUV Spectrometer &amp; EUV diode array</td>
</tr>
<tr>
<td>NE</td>
<td>3&quot;</td>
<td>Nikon Camera (PD)</td>
<td>3X diode Array &amp; PMT #2</td>
<td>Array Detector</td>
<td>Array Detector</td>
</tr>
<tr>
<td>ENE</td>
<td>2&quot;</td>
<td>Ekspla Ch 2 Out</td>
<td>Ekspla Ch 2 Out</td>
<td>Ekspla Ch 2 Out</td>
<td>Ekspla Ch 2 Out</td>
</tr>
<tr>
<td>E</td>
<td>3&quot;</td>
<td>Ekspla Ch 1 Out</td>
<td>Ekspla Ch 1 Out</td>
<td>Ekspla Ch 1 Out</td>
<td>Ekspla Ch 1 Out</td>
</tr>
<tr>
<td>ESE</td>
<td>2&quot;</td>
<td>Ekspla Ch 3 Out</td>
<td>Ekspla Ch 3 Out</td>
<td>Ekspla Ch 3 Out</td>
<td>Ekspla Ch 3 Out</td>
</tr>
<tr>
<td>SE</td>
<td>3&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SSE</td>
<td>2&quot;</td>
<td></td>
<td></td>
<td></td>
<td>Optics for fiber to spectrograph</td>
</tr>
<tr>
<td>S</td>
<td>3&quot;</td>
<td></td>
<td></td>
<td></td>
<td>CW backlighter—ICCD</td>
</tr>
<tr>
<td>SSW</td>
<td>2&quot;</td>
<td>EUV Diode Array</td>
<td>EUV Diode Array</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SW</td>
<td>3&quot;</td>
<td>Nikon Camera (PD)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WSW</td>
<td>2&quot;</td>
<td>Ekspla Ch 2 In</td>
<td>Ekspla Ch 2 In</td>
<td>Ekspla Ch 2 In</td>
<td>Ekspla Ch 2 In</td>
</tr>
<tr>
<td>W</td>
<td>3&quot;</td>
<td>Ekspla Ch 1 In</td>
<td>Ekspla Ch 1 In</td>
<td>Ekspla Ch 1 In</td>
<td>Ekspla Ch 1 In</td>
</tr>
<tr>
<td>WNW</td>
<td>2&quot;</td>
<td>Ekspla Ch 3 In</td>
<td>Ekspla Ch 3 In</td>
<td>Ekspla Ch 3 In</td>
<td>Ekspla Ch 3 In</td>
</tr>
<tr>
<td>NW</td>
<td>3&quot;</td>
<td></td>
<td></td>
<td></td>
<td>PMT #1 and #2</td>
</tr>
<tr>
<td>NNW</td>
<td>2&quot;</td>
<td></td>
<td></td>
<td></td>
<td>Vis. Spect. Fiber &amp; PMT #1</td>
</tr>
</tbody>
</table>

**Table II.1:** Port assignments for diagnostics used in MG-(I-IV).

An assembly of steel rails referred to as the “space frame” surrounds the Zebra vacuum chamber area (not shown in Fig. II.1). The rails are used for the mechanical support of diagnostics. The space frame is anchored to the concrete floor of the Zebra bay basement rather than to the machine itself, to decouple diagnostics from the mechanical shocks endured by Zebra during a discharge.

Multiple screen enclosures are available throughout the Zebra lab for EMI shielding of sensitive electronic devices. A 4’ by 6’ optical table is positioned north of the Zebra vacuum chamber, and is used to mount optical components for imaging to the ICCD and streak cameras located in the northwest optical screen box. The northwest optical screen box and east laser screen box are constructed atop optical tables, allowing convenient mechanical mounting of the cameras and optical components they contain. Digitizers are available in all screen enclosures, and data is saved to a server after each shot.
During experiments, day to day operations are shared by Zebra support staff and experimental personnel. Prior to each shot, Zebra staff conducts electrical tests, and performs a series of safety inspections and sweep procedures. Trained personnel then control the charging and firing of the machine. After the shot, digitizer signals are saved to the Zebra server by the support staff while image files are saved by the experimental team. Between shots, the Zebra chamber is vented, opened, and cleaned. Debris shields (glass slides which protect chamber windows from metal vapor) are replaced. A new load is inserted, the chamber closed, and the machine is again pumped down to vacuum. Tasks associated with the “turn-around” of the machine are shared by Zebra staff and the experimental team. Zebra is currently a single-shift facility, with shots performed from approximately 8:30 am to 5:00 pm. After diagnostics have been installed and the experiment is running smoothly, 4 shots per day is readily accomplished. If a load is inserted into the machine in the evening, and a shot can be taken immediately in the morning, 5 shots can be accomplished in a problem-free day.

Section II.B: The Zebra Current

The Zebra current is measured near the load by three differential Bdot probes [54]. The probes are positioned in the anode plate at 120° intervals, and at a distance of either 13 or 17 cm from the central axis of the pinch (Fig. II-3). Each probe is composed of two independently calibrated flux loops which are overlaid but wound in opposite directions. The loops are then potted in the probe body, which are “keyed” to ensure that the flux loop orientation is correct. Differential probes are designed to reduce the influence of noise by taking advantage of common-mode rejection. Since the voltages induced from
the changing magnetic field will change sign based on the polarity of the flux loop, but the electrical noise will not, electrical noise can be removed by inverting one signal, and then averaging. Signals from each flux loop are acquired by the “TLS #2” digitizer in the main data-acquisition screen box.

Fig. II.3: (Drawing courtesy of B. Le Galloudec) Anode plate configuration showing location (values in inches) of Bdot probes in the anode plate.

With knowledge of the internal construction of the probe, and its location in the anode plate, the load current may be inferred from the induced Bdot voltage. Considered here are the signals from load Bdot #4 (position D in Fig. II.3); signals from other probes are treated similarly. Raw voltage curves from the independent flux loops of load Bdot
#4 are plotted in Fig. II.4 (shot 1891 of MG-IV). Due to the opposite polarity of the separate flux loops, the primary induced voltages are of opposite sign.

**Fig. II.4:** Raw signals obtained from dual flux loops of differential load Bdot #4 (shot 1891 of MG-IV).

Next, the raw data is corrected for any DC offset that may exist. If the offset is not removed, the deduced current will have superimposed a nonphysical linear function which is zero at the beginning of the trace, and has slope equal to the offset value (due to integration). While the data in Fig. II-4 is plotted from 200 ns, the record actually begins at −400 ns. To determine the DC offset value, data is averaged from −400 ns to −230 ns. The average value is then subtracted from the entire curve. Next, data is multiplied by calibration constants which relate to the physical construction of the flux loops (calibration completed by Team Specialties [55]), and their location and orientation in the Zebra vacuum chamber. Also, the time axis is shifted to account for cable delays. The resulting offset, calibrated, and time-shifted curves are plotted in Fig. II.5 (red and blue).
Both curves now initially fall negative, since the calibration constant of the probe takes into account flux-loop polarity.

![Calibrated Signals-Differential Load Bdot #4](image)

**Fig. II.5:** Calibrated Bdot voltages (red and blue), which are then averaged (green) and integrated to find the final current from load Bdot #4 (purple). The common mode signal, which represents the noise reduction attained through use of differential loops, is also plotted (light blue).

Next, the two calibrated signals are averaged (Fig. II.5, green). The average curve is smoother than the individual flux loop curves, due to the removal of electrical noise by common mode rejection. The average curve is numerically integrated by evaluating the zone-centered Riemann sum (average value of neighboring data points). The resulting current vs. time curve for load Bdot #4 is displayed in purple in Fig. II.5. Three current vs. time curves (one for each probe) are generated for each shot. This work required to generate the three current profiles from the raw Bdot signals is typically completed by B. Le Galloudec.
The “shot average” current is found by averaging the currents deduced from the three load Bdot measurements. Typically, the currents from the three probes match quite well. For example, Fig. II.6 (a) displays the three current traces (one per Bdot) and the shot average current for shot 1869. The data has been time-shifted so that $I_{\text{avg}}(100\text{ns})=500 \text{ kA}$, which is how the experimental time base has been (arbitrarily) defined. In MG-IV, current vs. time measurements have been obtained for 29 shots. In Fig. II.6 (b) the peak current from each probe is plotted (by shot index). Also included in the plot is the peak of the average current for each shot. The plot displays variation in peak current measurements within a single shot, and from shot to shot. Of the 29 shots, LB4, LB5, and LB6 measure the highest peak current 17, 8, and 4 times respectively. This could represent actual asymmetry in current flow, or inaccuracies in probe calibration.
Fig. II.6: (a) Currents from 3 load Bdot signals of shot 1869, along with the “shot average” current given by the average of the 3 current traces. (b) Maximum current for each shot in MG-IV, showing probe-to-probe variation in current for each shot, and shot-to-shot variation in current throughout the campaign.

After determining the shot average current and time-shifting all signals so that $I_{\text{shot}}(100\text{ns})=500\text{kA}$, the “campaign average” current $I_{\text{camp}}(t)$ is determined. All (shot average) $I_{\text{shot}}(t)$ traces for MG-III and MG-IV are plotted in Fig. II.7:(a-b). Campaign
average curves are shown in red (dashed, bold curve). Whenever possible, shot data is referenced to the $I_{\text{shot}}(t)$ curve rather than the $I_{\text{camp}}(t)$ curve. For example, if an ICCD image from shot ‘A’ is known to be taken at $t=t_1$, when reporting the load current for that image, $I_{\text{shot-A}}(t_1)$ is used rather than $I_{\text{camp}}(t_1)$. $I_{\text{camp}}(t)$ is used in computational modeling, and for more general analysis.
Fig. II.7: (a) All shot currents and the campaign average current for MG-III. The average maximum current was 990 kA with (standard deviation) $\sigma_\Delta=30$ kA. (b) All shot currents and the campaign average current for MG-IV. The average maximum current was 1049 kA with $\sigma_\Delta=20$ kA.
As mentioned in the opening of this chapter, Zebra is a high-impedance machine. Therefore, the current delivered to the load is independent of $D_0$ since the small change in load impedance has negligible effect. This assertion is confirmed by the experiment. Plotted in Fig. II-8 are peak current values for all shots in MG-III. Data is plotted according to shot number, with data markers specified by load type. There is no clear correlation between peak current and $D_0$. The only data in the graph that appears systematic in any way is the gradual degradation in peak current throughout the campaign.

![MG-III: $I_{\text{max}}$ Vs Shot Number--Grouped by Load Type](image)

**Fig. II.8.** Peak current for all shots in MG-III. No correlation between $D_0$ and peak current is observed.
Fig. II.9: Campaign average current for MG-II through MG-IV. The maximum of the average current was 937 kA in MG-II, 990 kA in MG-III, and 1049 kA in MG-IV. Little change in the current profile is observed for $I(t)$ below 500 kA.

The Zebra current pulse was quite stable throughout the UNR-Megagauss Experiments; however, subtle changes in the current pulse have been observed. First, as shown in Fig. II.9, the campaign average current has increased slightly from one campaign to the next. Since the machine is charged and triggered manually, this may result from slight changes in the charge voltage, etc., as dictated by the operator. An automated system which triggers when specified charge voltages are obtained would eliminate variability associated with the operator. Probe calibration constants could also change with time. For example, the probes, which are mounted directly in the current carrying surface of the anode plate, are covered with a thin foil which could change in thickness over the course of many shots. Second, in MG-IV, the current is observed to occasionally crowbar at an abnormally high level. Comparing the data in Fig. II.7:(a) with the data in
Fig. II.7:(b) shows that this behavior did not occur in MG-III. The high crowbar current may be the result of changes made to the Zebra post-shot maintenance plan. In MG-(I-III), the cathode structure (known as the “mesa”) was removed and scrubbed after every shot, and the insulator stack was wiped with alcohol. And, after every 4th shot, the stack was scrubbed with an alcohol soaked Scotch bright pad and wiped clean. In MG-IV, the cleaning procedure was reduced. The mesa was only removed at the end of each day, at which point a full scrub (with a Scotch bright pad) was completed. Depending on the number of shots per day, the machine was discharged up to 5 times without cleaning. Perhaps the increased metallic debris on the stack rings effects stack flashover, and late-time Zebra crowbar behavior. Despite these peculiarities, the Zebra current has been adequately consistent throughout the UNR-Megagauss Experiments.

Section II.C: Diagnostic Triggering and Timing

To accurately interpret experimental results, diagnostic data must be well synchronized to the Zebra current. The time base of the Zebra current is defined as: $I(t=100 \text{ ns}) = 500 \text{ kA}$. Many diagnostics are triggered by the voltage pulse generated from the Low-Water-Vdot (LWVdot) probe. This probe is located in the Zebra water tank, and produces one of the earliest available low-jitter signals. If the delay between the LWVdot signal, and the time that the load current reaches 500 kA is known, the “load time” at which data was acquired may be inferred. The delay between the initiation of the LWVdot signal and the time that the load current reaches 500 kA is generally near 300 ns, but has jitter which must be accounted for. These delays, for all shots in MG-IV,
are plotted in Fig. II.10. Delays ranged from 289 to 303 ns. The average delay for these data was 295 ns (red) and the standard deviation was $\sigma = 3.3$ ns.

**Fig. II.10:** Time delay between the onset of the LWVdot pulse and the time at which the load current $I = 500$ kA for 26 shots in MG-IV.

In order to determine the “load time” of an image or signal (the time at which a physical event occurred, at the location of the load), Zebra jitter must be taken into account, along with all cable and other propagation delays. Diagnostic setup, including, for example, cable delays, optical time of flight, and delay generator setting, is well documented, allowing the physically relevant load time for each dataset to be determined. For images, such as those recorded by the ICCD, or laser shadowgrams, the physically relevant time was that moment when the light was emitted from (ICCD) or absorbed by (shadowgraphy) the rod. Where possible, diagnostics are timed to the load current using multiple paths to ensure accuracy. For example, the time of an ICCD image can be found either by tracing cables from the LWVdot trigger pulse, or from the output pulse generated by the instrument when the intensifier head is gated. To ensure correlation of signals in multiple screen boxes, identical timing fiducials are delivered to each location. The fiducials are generated from fiber-coupled fast photodiodes (high-speed Si detector—Thorlabs item number: DET10A) which are sensitive to channel 3 (otherwise unused) of the Ekspla laser pulse (see Ch. VI for a description of the Ekspla laser
diagnostic). The Ekspla laser generates a 150 ps pulse, faster than the 1 ns rise-time of the photodiodes. These fiducials precisely record a single event, and allow the timing of that event to be recorded by multiple digitizers placed throughout the lab. The fiducials have decreased uncertainty in synchronization between diagnostic signals and the Zebra current pulse.
Chapter III: Experimental Design and Hardware Performance

The UNR-Megagauss Experiments are designed to access physical parameters relevant to the aluminum liners used in the Magnetized Target Fusion (MTF) experiment under development, in conjunction with Los Alamos National Laboratory (LANL), at the Shiva Star pulsed-power facility at the Air Force Research Laboratory (AFRL) [56,57]. In MTF, the state of the inner liner wall during compression of the magnetized plasma is uncertain [15]. The interaction of the inner liner wall with the compressed, megagauss magnetic field may ultimately determine the length of time which the plasma can be held at high density and temperature. Much of the physics associated with the interaction of the magnetic field with the inner liner wall during magnetic flux compression can be studied by pulsing high field on the surface of a thick-metal rod (see the introduction to this dissertation). Ideally, for the experiment to examine liner physics issues using the simple pulsed-rod geometry, the following conditions are to be achieved:

(1) Megagauss level magnetic field on rod surfaces \( B_s \geq 1 \text{ MG} \)

(2) Nonuniform current density in a surface skin layer \( \delta_b < R \), to access the “thick-rod” or “liner” or “surface-heating” regime.

(3) Surface stability through the time of plasma formation \( R/V_A \geq t_{\text{plasma}} \). Comparisons with one-dimensional modeling (commonly used to study liner physics and MTF) are then more relevant.

(4) Avoidance of non-MHD plasma sources, such as arcing electrical contacts, or electric-field-driven electron avalanche

(5) Rod surfaces smooth enough to avoid multidimensional effects such as highly nonuniform heating or hydrodynamic jetting.

In this chapter it is shown that, due to the high magnitude and short rise-time of the Zebra current, goals (1-3) may be simultaneously achieved. As a consequence, Zebra
creates a high-electric-field environment, which can result in non-thermal plasma production from such sources as electric-field-driven electron avalanche, or arcing current contacts. Such mechanisms of plasma formation are not of primary interest here, and are not incorporated into MHD models; therefore, these sources of plasma are to be avoided. To mitigate non-thermal plasma formation, carefully configured load profiles and electrical contacts are used to achieve condition (4). The most commonly used load hardware configurations will be detailed. Load hardware performance is evaluated with multiple diagnostics, including imaged photomultipliers, a two-framed, gated, intensified imaging system, and a 38 element fast photodiode array. While certain hardware profiles are shown to effectively mitigate non-thermal plasma, some profiles are challenging to machine. Occasionally load surface irregularity causes nonuniform heating and, in the most severe cases, hydrodynamic jetting. The impact of surface smoothness on rod evolution will be discussed, with data from ultra-smooth loads (fabricated by the MST-7 precision fabrication team at LANL [58]) compared against data from loads with standard surface finish.

Section III.A: Megagauss Field and Skin Current on a Stable Rod Surface

Aluminum surfaces are pulsed to high field by the Zebra generator, which delivers a repeatable 1.0 MA current pulse (Ch. II). To examine surface physics relevant to the liners used in MTF, current should flow nonuniformly in a skin layer, and multi-megagauss level magnetic field should be pulsed on the rod’s surface [59]. The Zebra current, which rises from 100 to 900 kA in 70 ns at \( \frac{dI}{dt} = 1.1 \times 10^{13} \) A/s, allows both conditions to be simultaneously achieved. The average Zebra current \( I(t) \) is least-
squares-fit with an exponential function as it rises from 20 to 200 kA. The resulting function, \( I(t) \approx I_0 \exp(t/\tau) \) with \( \tau = 13 \) ns, corresponds to a magnetic field penetration depth of \( \delta_B = 0.017 \) mm in cold aluminum. Due to ohmic heating, the field will penetrate into hot, resistive aluminum, with \( \delta_B \) many times greater than that of cold aluminum [2], of order 0.1 mm. Therefore, the initial rod diameters examined, which ranged from 0.50 to 2.00 mm, are large enough for current to flow in a skin layer \( (\delta_B < R_0) \). For a 1.0-mm-diameter current channel carrying 1.0 MA the surface field is \( B_s = \mu_0 I/2\pi R = 4.0 \) MG. Therefore, rods with initial diameter \( (D_0) \) of order 1 mm meet the high-field and surface-heating requirements when pulsed with the Zebra current.

At pressures associated with megagauss level field, metals are stressed well beyond their yield strength, and fluid instabilities can develop. For example, the pressure associated with a 1.0 MG magnetic field \( P_B = B^2/(2\mu_0) = 4 \) GPa, while the yield strength of 6061-alloy Al is 290 MPa [60]; therefore, the metal acts as a fluid. As the field increases, sausage and kink mode instabilities develop [61]. Unstable surfaces are difficult to diagnose, their parameters are difficult to interpret, and as instabilities progress, one-dimensional modeling becomes less relevant. Therefore, an experimental configuration which allows for the examination of stable surfaces pulsed to high field is sought. In a 2008 *Journal of Fusion Energy* article [16], Professor R. E. Siemon comments on the stability of a z-pinch, and shows that for a given current profile, there is a maximum achievable magnetic field that can be pulsed on a stable rod surface. The paper analyzes rod stability for a variety of pulsed power drivers. The growth time for instabilities is assumed to equal \( R/V_A \) where \( R \) is the rod radius, \( V_A \) is the Alfvén velocity \( (V_A = B_s/\sqrt{\mu_0\rho}); B_s \) is the surface magnetic field strength, and \( \rho \) is the material density).
A plot displaying contours of minimum rod radius and maximum $B_s$ is included in the article (Fig. 1 in the article), and has been replicated below (Fig. III.1).

**Fig. III.1:** Contours of maximum surface magnetic field and minimum rod radius as constrained by stability. Points derived from the rise time and maximum current of several pulsed power systems are included.

Fast rising high magnitude current sources may achieve ultra-high field on a stable surface. In this regard, the Sandia Z Machine [62] is quite impressive, with the ability to achieve over 10 MG on a stable surface. Long pulse drivers such as Atlas [63] or Shiva Star [64] have reduced capability, because the slow-rising pulse requires a large-diameter rod for stability, thus reducing $B_s$. A low-current driver such DPM-15 [16] is incapable of achieving megagauss field on a stable surface.

The UNR-Megagauss Experiments pulse high field on the surface of conducting rods using the Zebra z-pinch. Again, to maintain stability, the penetration depth ($\delta_A$) of the
Alfvén wave should be less than $R$. To estimate $\delta_A$, assume that a rod of radius $R$ is pulsed with a current source rising linearly at $dI/dt$ to a desired field strength $B_s$. The time ($t_B$) required for the surface magnetic field to reach $B_s$ is,

$$t_B = \frac{2\pi RB_s}{\mu_0(dI/dt)}$$  \hspace{1cm} (III.1)

At time $t_B$, $\delta_A$ is then,

$$\delta_A = V_A t_B = \frac{B_s}{\sqrt{\mu_0 \rho}} t_B$$  \hspace{1cm} (III.2)

Where $\rho$, and $\mu_0$ are mass density, and permeability of free space, respectively. Using the density of aluminum at standard temperature and pressure ($\rho=2700$ kg/m$^3$), and setting $B_s=200$ T (2 MG), $dI/dt = 1.1\times10^{13}$ A/s (that of Zebra), and $R = 0.5$ mm, it is shown that $\delta_A < 0.2$ mm. Therefore, the Zebra z-pinch simultaneously satisfies the megagauss surface field, skin-current, and stability conditions for Al rods with $D_0$ near 1.0 mm.

Section III.B: Hardware Designs to Mitigate Non-Thermal Plasma

The substantial magnitude and short rise time of the Zebra current enables megagauss field to be pulsed on the surface of a thick, stable conductor, but also introduces large electric field. As a consequence, non-thermal plasma can be created due to electric-field-driven electron avalanche or photoionization from arcing electrical contacts. A quite comprehensive discussion of vacuum breakdown in high voltage devices is given by Cuneo [65]. The importance of contact mating has been demonstrated for thin wires, where soldered contacts result in enhanced energy deposition for single wires [66], and specialized fixturing results in decreased wire-plasma material and increased peak x-ray
power for dynamic hohlraums [67]. In the UNR-Megagauss Experiments, current joint arcing is observed to initiate plasma formation on rod surfaces far from the source of the arc, possibly by photoionization. High voltage breakdown phenomena are observed from simple loads, but are significantly reduced or even eliminated when using carefully configured load profiles and electrical contacts. The most common hardware configurations are displayed in Figs. III.(2-5) (mechanical drawings courtesy of Professor S. Fuelling). Hardware configurations vary both by central load profile (simple-straight-rod, barbell, or hourglass), and in the hardware used to couple the central load to the Zebra anode-cathode gap (gravitational or penetrating knife-edge). Specifics of the hardware configurations are described in the paragraphs to follow (also see [27]).

Two varieties of hardware have been used to couple central load profiles to the Zebra anode-cathode gap. Gravitationally bound (GRAV) coupling hardware (Fig. III.2) relies only on gravity for the mating of current joints. The tight-fitting but non-compressed contacts exhibit significant arcing, which initiates precursor plasma formation on rod surfaces far from the location of the arc. Data pertaining to the performance of this hardware is presented in Section III-C. Penetrating knife-edge (KE) coupling hardware (Figs. III.(3-5)) was developed to eliminate the non-thermal plasma produced by poor contact mating. KE hardware uses several machine screws to compress large-diameter stainless steel knife-edge rings (0.25 mm high) through the aluminum oxide layer on the anode and cathode plates, decreasing contact resistance. On the anode side, the current is carried through a 40-40 wire per inch Cu-wire mesh. The mesh allows for the slight compression of the anode-cathode gap which occurs as the Zebra vacuum chamber is evacuated. A set of 6 #8-32 bolts are used to both securely fasten the small-diameter
edge of the Cu mesh to the anode assembly, and compress the knife-edge ring through the aluminum oxide surface of the anode plate. A zoomed view of the configuration of the anode plate, Cu mesh, and knife-edge ring is given in Fig. III.3:(b). Similarly, the cathode assembly uses a knife-edge ring but requires no Cu mesh. A zoomed view of the cathode assembly is given in Fig. III.3:(c).

Compressed knife-edge coupling hardware mitigates one source of non-thermal plasma, but arcing is also observed from the small-diameter rod-to-anode-cathode contacts of simple-straight-rod loads (Fig. III.2). Evidence of arcing from these current joints is presented in Section III.C. Hourglass and barbell loads eliminate this source of non-thermal plasma. Hourglass loads are machined from a single 3-inch-diameter 6061-alloy Al cylinder, and therefore have no contacts near the straight-central-rod section of the load, completely eliminating the current joint. Barbell loads are machined from 6-mm-diameter Al cylinders (1100 or 6061-alloy), and can be mated to either GRAV or KE hardware. Barbell loads, like straight rod loads, have exposed electrical contacts, but since the anode-cathode contacts are at 6 mm diameter, the local contact resistance and current density is reduced. The radial transitions of hourglass and barbell loads, as well as of the anode and cathode plates used in KE hardware, are made smoothly to avoid electric field enhancement. Hourglass loads and barbell loads mounted in KE hardware reduce or eliminate the arcing that is observed from simple-straight-rod loads and from GRAV hardware. Performance results for all hardware configurations are discussed after detailing the hardware naming convention, and discussing certain machining trends associated with different load geometries and machinists.
Fig. III.2: Simple-straight-rod load mounted in gravitationally bound (GRAV) hardware. Anode-cathode hardware relies only on gravity for current joint mating. The central rod makes small-diameter slip-fit electrical contacts with the 1.0-mm-diameter bores drilled through the anode and cathode plates. Arcing is observed from both the power flow coupling hardware, and from the rod to anode-cathode contacts.
Fig. III.3: (a) Simple-straight-rod load mounted in compressed knife-edge (KE) hardware. The coupling hardware uses several machine screws to compress a large-diameter stainless steel knife-edge through the aluminum oxide layers on anode and cathode plates. Boxes indicate approximate zoomed regions (zoomed views are from slightly different perspective angle). (b) Zoomed view of anode plate assembly including Cu mesh and knife-edge. (c) Zoomed view of cathode plate assembly including knife-edge.
Fig. III.4: (a) Drawing of a barbell load mounted in KE hardware. The coupling hardware is the same as that described in Fig. III.2. The anode and cathode plates are slightly modified with a conical protrusion near the center. The barbell load to anode-cathode contact is made with a 6.0-mm-diameter slip-fit contact. (b) Photograph of a constructed barbell load mounted in KE hardware. The three rods surrounding the load are known as fixturing rods, and are used for mechanical stability during construction of the load, and while placing the load in the Zebra anode-cathode gap. The fixturing rods are removed after the load has been secured in the Zebra vacuum chamber.
Fig. III.5: (a) Drawing of an hourglass load mounted in KE hardware. The coupling hardware is the same as that described in Fig. III.2. No load to anode-cathode contacts exist, as the rod, anode plate, and cathode plate are machined as a single body from a 3-inch-diameter Al cylinder. (b) Photograph of an hourglass load. (c) Engineering drawing of an hourglass load with measurements in millimeters.
In order to efficiently refer to different load hardware during shot planning and data analysis, the following naming convention was used:

Material Type–Alloy–Load Profile–Surface Finish–Requested $D_0$ [Machinist]

Material Type
- A=Aluminum
- C=Copper
- W=Tungsten
- S=Tin

Alloy
- 1=Aluminum 1100
- 6=Aluminum 6061
- *=Unknown/Unspecified

Load Profile
- W=Simple-straight-rod
- B=Barbell
- H=Hourglass
  Note: Simple-straight-rods are designated ‘W’ since they were initially called wires. Now “wire” is used for conductors in the thin wire limit ($\delta_B>R_0$).

Surface finish
- P=Pulled/Extruded,
- T=Turned on a lathe

Requested Initial Load diameter
—#.## mm

Machinist or Machine shop
- [L]=MST-7 at LANL
- [P]=Physics machine shop at UNR
- [R]=Remarc Inc. of Reno, NV
- [S]=Professor Stephan Fuelling
  NOTE #1: Pulled straight rods do not include this label since there is no machinist
  NOTE #2: This label is not used for MG-(I-II) since all loads were either pulled or fabricated by the UNR Physics machine shop
As an example, a 1.00-mm-diameter 6061-alloy Al barbell load machined by Remarc Inc. is named: A6BT-1.0 [R]. When necessary, the coupling hardware type is also included at the end of the label (KE for knife-edge hardware, GRAV for gravitationally bound hardware). This addition is not often necessary, since only KE hardware has been used since MG-II.

Experiments have examined loads of varying profile, initial diameter, and material. These loads are extruded, or turned (machined on a lathe). Turned loads have been manufactured in a number of different machine shops, using different machining techniques, over the course of several years. Loads were fabricated at the UNR Physics machine shop (P), Remarc Inc. of Reno, NV (R), MST-7 at Los Alamos National Laboratory (L), and by Professor Stephan Fuelling of the UNR Physics Department (S). Materials of different strength and hardness were used. Since these loads can be challenging to fabricate, it is to be expected that the loads may not be delivered precisely as requested. Figs. III.4:(a-d) display information regarding the consistency in delivered rod diameter over these multiple variables, by plotting the ratio of the measured initial rod diameter to the requested initial rod diameter. Typically, the measured rod diameter is determined from Ekspla reference shadowgrams (see discussion of the shadowgraphy diagnostic in Ch. VI), and when possible, confirmed by visible light microscope images. Data are grouped according to load type, initial rod diameter, and machinist.
MG-I: Measured $D_0$ (Ekspla-Ref)/Req. $D_0$

MG-II: Measured $D_0$ (Ekspla-Ref)/Req. $D_0$
Fig. III.6: Measured initial rod diameter (as determined by Ekspla reference shadowgrams) divided by requested rod diameter. Data points are grouped by requested initial rod diameter, and the manufacturer of the loads. (a) MG-I; all loads machined by the UNR Physics machine shop or pulled. (b) MG-II; all loads machined by the UNR Physics machine shop or pulled. Turned wires are machined significantly larger than requested. (c) MG-III data. This dataset includes the full set of initial rod diameters. (d) MG-IV data; LANL fabricated loads show surprising spread in measured initial rod diameter.
Several notes are made concerning the data presented in Fig. III.4:(a-d):

1. Machined simple-straight-rods exceed their requested $D_0$. 1100-alloy Al machined simple-straight-rods are larger than 6061-alloy Al machined simple-straight-rods, likely because 1100-alloy is softer, and more difficult to machine to small diameter.

2. The physics machine shop consistently fabricates larger diameter loads than Remarc for the same requested $D_0$.

3. The loads from MST-7 at LANL (while remarkably smooth) display a large spread in initial rod diameter.

   The data presented in Fig. III.4:(a-d) shows the importance of measuring the actual rod diameter prior to each shot. For example, when determining radial expansion rates (Ch. VI), the change in radius ($\Delta R=R(t)-R_0$) is reported as a function of time rather than the radius itself. In this way, the slight variations in $D_0$ introduce less error.

Section III.C: Hardware Performance—Non Thermal Plasma Formation

Non-thermal precursor plasma is observed at low load current from the small-diameter contacts of simple-straight-rod loads, and from the low-pressure current joints of GRAV hardware. Hourglass and barbell loads in KE hardware reduce or eliminate non-thermal plasma formation from contact points. Plasma initiation is examined by multiple diagnostics. First, two imaged, high-gain photomultiplier tubes (PMTs) are used to examine the onset of visible emission from different sections of the load (Fig. III.6). Load light was imaged to the face of optical fibers, which transport light to individual PMTs located in a screen box. PMT #1 was sensitive to light from the center of the rod section of the load, while PMT #2 was sensitive to light from the cathode current joint. A cartoon of the diagnostic setup is shown in Fig. III.7.
Fig. III.7: Cartoon of high-gain PMT pair used to measure the time and location of first light emission. A single lens is used to image load light to the face of two optical fibers. The first fiber collects light from the center of the rod, and carries this light to PMT#1. The second fiber collects light from the rod to cathode contact. This light is carried to PMT #2. Data collected by the PMTs gives information about the high-voltage performance of load hardware.

Fig III.8: (a) (Left) Schematic describing the operation of a photomultiplier tube. Light is incident upon a photocathode, which converts photons to electrons. The electrons are accelerated through the dynode chain by a strong electric field. As electrons move from one dynode to the next, secondary emission causes the number of electrons to grow exponentially. The resulting output is a voltage pulse which may be proportional to the light level incident upon the photocathode. (b) (Right) Picture of a PMT used in the experiment.
Comparison of the turn-on-time of the two PMT's confirms the presence of arcing at the small-diameter contacts of simple-straight-rod loads. The high gain of the PMT's allows relatively small light intensity emitted from an electrical arc (small when compared to the light emitted after bulk heating has occurred) to induce a fast-rising pulse in the detector. As seen in Fig. III.9, light from the current joint is emitted some 40 ns prior to light from the axial center of the simple-straight-rod load. In contrast, the barbell load shows nearly simultaneous emission from the two locations. For both load types, the center focused PMT measures no light until the load current reaches approximately 500 kA ($t=100$ ns). For the barbell load, the contact PMT shows first light at nearly the same moment, whereas for the wire load, emission from the cathode contact is much earlier, when the load current has only reached roughly 100 kA.
Fig. III.9: First light emission from the center of the rod section of the load and from the cathode current joint as indicated by high-gain PMTs. (a) PMT and photodiode data from a simple-straight-rod load mounted in KE hardware. (b) PMT and photodiode data from a barbell load mounted in KE hardware.
Photomultiplier data from many combinations of central load profile and coupling hardware are presented in Fig. III.10, and show that the time and location of first light emission is hardware dependent. To the left (early emission) lies data from all loads (simple-straight-rod or barbell) coupled to GRAV hardware (Fig. III.2). To the right (late emission) lies data from all hourglass loads and all barbells coupled to KE hardware (Fig. III.(4-5)). Data in the centrally located purple box pertains to 7.0-mm-long straight-rod loads coupled to KE hardware (Fig. III.3). Early emission is detected from both the contact region and load center for all loads in GRAV hardware. Straight rods mounted in KE hardware show early emission from the small-diameter cathode contact, but emission is delayed from the rod center. Barbell and hourglass loads with KE hardware show delayed emission from both load regions, indicative of delayed or eliminated precursor plasma formation. The tendency for larger-diameter loads to emit light at higher current is observed for loads coupled to KE hardware. This trend is not clear for loads coupled to GRAV hardware, suggesting that early emission results from (voltage dependent) non-thermal processes rather than from (current-density-dependent) ohmic heating.
Fig. III.10: Time and location of first light emission as indicated by the turn-on-time of imaged PMTs. Data presented for the multiple combinations of central load profile and anode-cathode hardware used in MG-II. Red stars indicate data pairs where the center PMT observed light earlier than the cathode PMT.

Next, visible photodiode data are added to the PMT data. In MG-II, 3 BPX-65 fast photodiodes were used to measure emission from the rod at three separate locations: 2.0 mm above rod center, rod center, and 2.0 mm below rod center (see Section IV.B). The photodiodes, with orders of magnitude lower gain than the PMTs, only observe the strong emission due to bulk ohmic heating. The data in Fig. III.11 indicate the time that photodiode signals first rise above the noise (or, assuming blackbody emission, when the
rod surface reaches approximately 0.5 eV). Five data points from each shot (2 PMT, 3 photodiode) are included in each row of the plot in Fig. III.11.

**Fig. III.11:** PMT and photodiode turn-on-times for 1.00-mm-diameter rods examined in MG-II. The plot can be divided into 6 regions. Each region pertains to a specific hardware feature.

Fig. III.11 has been divided into 6 regions (A-F). The data contained in each region is specific to a certain hardware feature, as described in the list below:

A. PMT data (from both rod center and cathode current joint) for barbell and simple-straight-rod loads in GRAV hardware.

B. Photodiode data for barbell and simple-straight-rod loads in GRAV hardware (same shots as in region A)

C. Cathode PMT data from simple-straight-rod loads mounted in KE hardware (plus one outlying photodiode data point).

D. Center PMT data, and photodiode data from simple-straight-rod loads mounted in KE hardware (same shots as in region C).

E. EMPTY (no data at early time for hourglass loads or barbell loads in KE hardware).

F. All signals (PMT and photodiode) for hourglass loads and barbell loads in KE hardware. No low current emission is detected for these loads, even by the high-gain PMTs.
Combining the information in Figs. III.(10-11) allows conclusion to be drawn about the performance of the central load and coupling hardware combinations used in MG-II.

1. Loads mounted in GRAV hardware (simple-straight-rod or barbell) emit light at low current from both the cathode contact and the central portion of the load (region A).

2. Simple-straight-rod loads mounted in KE hardware emit early light from the cathode contact, but display delayed emission from the center of the rod (region C and D).

3. Conclusions 1 and 2 suggest that arcing rod to anode-cathode contacts of simple-straight-rod loads do not cause precursor plasma formation at the center of the rod; however, GRAV hardware does. It is concluded that the plasma formation from GRAV hardware effects the full load assembly, causing plasma to form (perhaps due to photoionization) on surfaces far from the location of the arc.

4. For hourglass loads and barbell loads mounted in KE hardware, precursor plasma formation has been mitigated or eliminated. PMT signals are delayed, and rise only slightly before the photodiodes observe bulk heating (regions E and F).

5. Precursor plasma formation does not have a profound effect on the bulk heating of rod surfaces, since the turn-on-time of the photodiodes is quite independent of the turn-on-time of the PMTs. This conclusion requires the following qualifier: The 3 photodiodes used in MG-II were individual elements, which have been found to respond somewhat differently to the same light pulse. The alignment method used for these detectors was also imprecise and variable. The large spread in MG-II photodiode turn-on-time is not observed in later experiments which use a consistently well aligned single substrate photodiode array with high element-to-element response uniformity. Whether the observed spread in MG-II data is due to the detectors used, or due to variable load hardware performance is uncertain.

Section III.D: Hardware Performance—Heating and Emission Uniformity

The data obtained from the imaged PMTs and photodiodes shows that simple electrical contacts will arc in Zebra’s high-electric-field environment. To support this conclusion, and to examine heating along the full length of the rod surface, an Andor iStar intensified CCD camera has been used to capture high temporal and spatial resolution images of surface emission. Due to the high-gain intensifier, the instrument can capture features of low-intensity emission. The basic components of an intensifier
head are displayed in Fig. III.12. An image is incident upon the photocathode, where photons are converted to photoelectrons. Electrons are swept by a strong electric field from the photocathode to the Microchannel Plate (MCP). As electrons move through the fine array of MCP channels, secondary emission occurs. For the instrument used, the MCP gain may be altered from 0 to 255 using the Andor iStar software (changing the voltage applied to the MCP). With the gain set to 0, 60, 120, 180, and 240 the number of counts per photoelectron is 1, 4, 16, 64, and 256, respectively. The gain curve approximately fits the function: \((\text{counts/photoelectron}) = 2^{(\text{gain}/30)}\). The electrons emitted from the MCP are again accelerated by a strong electric field to a phosphor, where they are converted to photons. A fiber optic output window couples the phosphor to a CCD, where the image is recorded. The CCD readout of the iStar system consists of a 1024×1024 element array of 13 µm square pixels. The CCD array is well matched to the grid of MCP channels. In MG-I through MG-III, the minimum gate width (the time that high voltage is applied to the MCP—the exposure time of the instrument) was 5 ns. In MG-IV, diagnostic improvement enabled a 2 ns minimum gate.
Fig. III.12: Schematic of an intensifier head unit. Incident photons are converted to electrons by the photocathode, and the number of electrons grows exponentially when passing the MCP. Electrons are converted back to photons by a phosphor, which is coupled to a CCD by a fiber optic output window.

The optical system used to image load light to the ICCD is shown in Fig. III.13:(a). The first optic in the system is a 1000 mm focal length, 2” diameter lens placed 1.00 m from the center of the Zebra chamber. With the object distance equal to the focal length, light is imaged to infinity. The semi-parallel rays can propagate any distance desired, at which point a second converging lens is placed in the path. For the system used, the second lens was placed at 3.0 m. For this lens the object distance is infinite, and an image is created one focal length behind the lens at 4.0 m. This system allows great flexibility, but significant vignetting occurs as shown by the ray diagram in Fig. III.13:(b).
Fig. III.13: (a) Imaging system to the ICCD for MG-I and MG-II. (b) Ray diagram for the system in (a), which shows that off-axis rays are lost to vignetting.
Fig. III.14 displays images obtained in MG-II using the optical system shown in Fig. III.13:(a) and the Andor iStar ICCD camera. The system was capable of 5 ns temporal resolution and achieved 90 µm spatial resolution. The images support the conclusions drawn from the PMT analysis. First, simple-straight-rod loads consistently show arcing from current joints. Furthermore, ICCD images show that arcing associated with GRAV hardware leads to highly nonuniform emission along the length of the rod (Fig. III.14:(a)). Barbell and hourglass loads have dark current joints and emit more uniformly along the length of the central rod section.

**Fig. III.14:** Early emission captured by a 5 ns time-gated intensified CCD camera (a) $D_0=1.00$ mm simple-straight-rod load in GRAV hardware at 663 kA (b) $D_0=1.00$ mm simple-straight-rod load in KE hardware at 674 kA (c) $D_0=1.00$ mm barbell load in KE hardware at 528 kA (d) $D_0=1.59$ mm hourglass load at 836 kA.
While barbell and hourglass loads coupled to KE hardware eliminate non-thermal plasma production at contacts, early emission from localized hot spots are observed in ICCD images (Fig. III.14:(c)). Early surface emission generally consists of a combination of low-intensity background and relatively high-intensity hot spots. In order to study the evolution of hot spots and other surface emission features, an optical system was designed to allow a single ICCD camera to capture two high-resolution, gated images per shot. The two images are separated temporally, but originate from precisely the same rod location. To accomplish this, surface emission is lens relayed to a pellicle splitter which divides the light into two optical paths. “Non-delayed” light is reflected from the splitter and imaged directly to the camera. “Delayed” light is transmitted through the splitter, lens relayed through an extra 8.0 m (26.7 ns delay) loop, and then, after passing through the backside of the same splitter, focused beside the non-delayed image on the ICCD’s photocathode. Field lenses are used in the extended optical path to reduce vignetting. A schematic and photograph of the 2-frame ICCD optical system used in MG-III are displayed in Fig. III.15.
At the pellicle splitter 92% of the light passes and is relayed through an extra 8m path length. When it passes the splitter a second time (rejoining the 8% of light which was reflected), the two images are focused side by side, passing the remainder of the optics together, but temporally displaced by 26.7 ns.

**Fig. III.15:** (a) Schematic of the optical splitter system used to capture two (temporally separate) load images per shot with a single intensified CCD camera. (b) Photograph of the delay optics, installed in the Zebra laboratory.

Due to the lengthy optical path length of the delay leg, field lenses are required to maintain high image quality. Field lenses are placed in image planes, and used to image one imaging lens onto the next. In this way, vignetting does not occur, and off-axis rays propagate through the system. The function of a field lens is shown in Fig. III.16. Black
lines represent off-axis rays. Dashed black lines show the path of the off-axis rays with no field lens in the system, while solid black lines show the path with the field lens in place. The off-axis ray at the top of imaging lens 1 is lost via vignetting if the field lens is not present. Blue lines represent on-axis rays. For these rays the field lens has no effect. It is for this reason that the field lens is necessary. With a long optical path, and no field lenses, a disproportionate number of on-axis rays make it through the system in comparison to off-axis rays, and information about emission uniformity is lost.

**Fig. III.16:** Ray diagram showing the use of field lenses to eliminate vignetting. Field lenses were used in the MG-III and MG-IV ICCD optics.

Aside from high resolution, the two-frame imaging systems must be designed to allow:

1. Sufficiently high image intensity so that the imaged rod emission is brighter than background light.

2. Comparable intensity of the two images (delayed and non-delayed), so that the finite dynamic range of the ICCD allows for 2 high-contrast images.

The imaging system used in earlier experiments supplied sufficient image intensity to the ICCD. A simple comparison between the throughput of the earlier setup and the new optics will ensure that images remain sufficiently intense. The first optic in the single-image system was a 2” diameter lens positioned a distance $d=1.00$ m from the load. The
two-frame system is designed with a 2" diameter lens at a distance $d=2.00$ m from the load. Solid angle varies as $1/d^2$, so (since the lens diameter is unchanged) the two-frame system gathers four times less light than the single-frame system. Furthermore, this light must be shared by two images. It is assumed that the single-frame system has no losses, and the quantity of light entering the first optic of this system is defined as 100%. The quantity of light entering the first optic in the two-frame system is then 25%. An intensity “flow chart” through the two-frame systems has been constructed (Fig. III.17).

![Light transmission in MG-III two-frame optical design](image)

**Fig. III.17:** Light transmission flow chart for the two-frame optical system. The chart shows how light is distributed among the four different images (2 ICCD images, 2 streak camera images). Quantities relate to intensities in the MG-II system.

In the MG-II system, a 50-50 splitter was used to send half of the light to the streak camera, and half of the light to the ICCD. The high intensity to the streak camera caused saturation, so an ND 1.0 filter (factor of 10 reduction) was placed in the optical path; therefore, relevant to the percentages shown in Fig. III.17, in MG-II, 50% of the light was...
delivered to the ICCD, and $50\%/10=5\%$ was delivered to the streak camera. The MG-III design has $7.1\%$ delivered the streak camera; an insignificant difference from the MG-II intensity. Next, $14.2\%$ of the light is delivered to the ICCD as a part of the delayed image. This is down by a factor of $50/14.2=3.5$ from the MG-II level. This reduction is easily accounted for by increasing the ICCD’s MCP gain. Only $1.3\%$ of the light is delivered to the ICCD as the non-delayed image, however, the photons comprising this image will be emitted from the rod at higher current, and thus the image will be higher intensity. The variation in the intensity ratio of the delayed and non-delayed images is considered next. If the difference in intensity is too great, the limited dynamic range of the instrument will not allow for optimal image contrast.

To obtain two high quality images per shot with a single ICCD camera, the intensity of the two images should be comparable. With fixed optics, the intensity ratio will depend upon when during the Zebra current rise the images are obtained. Information from visible light radiometry measurements made in MG-II allows acceptable image exposure times to be chosen. Since both the ICCD and photodiodes are sensitive to visible light only, it is assumed in this analysis that the voltage driven in the diodes increases in direct proportion with the counts recorded by the CCD pixels. Most images recorded by the single-frame system used in MG-II were taken in the time span between 90 and 110 ns (recall that $I(t=100\text{ ns})=500\text{ kA}$). In the (MG-III) two-frame system, the photons in the delayed image will emerge from the rod 26.7 ns earlier than those in the non-delayed image. From the photodiode curve show in Fig. III.18, and the data in Table III.1, if the delayed image is captured at 100 ns, the non-delayed image (assuming a 50-50 splitter) will be nearly 20 times brighter at 127 ns. If the delayed image is captured
after 125 ns, when the sharp rise in emission intensity has begun, the non-delayed image (assuming a 50-50 splitter) will only be 5 times brighter (or less, for later exposures). Therefore, the time that the ICCD is set to trigger greatly affects the intensity ratio of the images. Based on this analysis, the first splitter in the optical system was chosen to transmit 92% of the light, and reflect 8%. In this way, with the ICCD triggered early in the current rise (first image at $t \sim 100$ ns), the non-delayed image will have roughly 2 times more counts than the delayed image. If the ICCD is triggered later in the current rise (first image at $t \sim 125$ ns), the non-delayed image will have roughly 2 times fewer counts than the delayed image. Due to the high dynamic range of the instrument’s 16 bit analog-to-digital converter, these ratios are acceptable, and the contrast of the images obtained was generally high.

Fig. III.18: Average voltage measured by visible light photodiodes in MG-II ($D_0=1.00$ mm). The curve represents variation in rod emission intensity as a function of time, and allows determination of the intensity ratio of the two images record by the two-frame ICCD system.
Table III.1: Diode voltage values taken from the curve in Fig. III.18 at specified times. The ratio of the voltages in columns 2 and 4 indicates the emission intensity ratio from the rod for the times shown. This ratio can be used to determine the relative intensity of the two images captured by the ICCD.

<table>
<thead>
<tr>
<th>Early Image Time (ns)</th>
<th>Early Voltage (V)</th>
<th>Late Image Time (ns)</th>
<th>Late Voltage (V)</th>
<th>Voltage Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.055</td>
<td>127</td>
<td>1.04</td>
<td>18.9</td>
</tr>
<tr>
<td>105</td>
<td>0.114</td>
<td>132</td>
<td>1.65</td>
<td>14.5</td>
</tr>
<tr>
<td>110</td>
<td>0.23</td>
<td>137</td>
<td>2.52</td>
<td>11.0</td>
</tr>
<tr>
<td>115</td>
<td>0.363</td>
<td>142</td>
<td>3.18</td>
<td>8.8</td>
</tr>
<tr>
<td>120</td>
<td>0.543</td>
<td>147</td>
<td>3.83</td>
<td>7.1</td>
</tr>
<tr>
<td>125</td>
<td>0.828</td>
<td>152</td>
<td>4.34</td>
<td>5.2</td>
</tr>
<tr>
<td>130</td>
<td>1.36</td>
<td>157</td>
<td>4.83</td>
<td>3.6</td>
</tr>
<tr>
<td>135</td>
<td>2.12</td>
<td>162</td>
<td>5.2</td>
<td>2.5</td>
</tr>
<tr>
<td>140</td>
<td>2.99</td>
<td>167</td>
<td>5.57</td>
<td>1.9</td>
</tr>
</tbody>
</table>

The MG-IV optical splitter system was similar to the MG-III system, but with the following modifications:

1. The f=1000 mm lenses were replaced with f=500 mm lenses (the diameter remained 2”), in an attempt to reduce the diffraction limit of the system to below the pixel size of the ICCD. The first optic in the system moved closer to the load, from 2.00 m to 1.00 m. Therefore, the light through the system was increased by a factor of 4.

2. The delay leg was reduced from 8.00 to 6.00 m, reducing the time delay from 26.7 to 20.0 ns.

3. A laser line filter (Thorlabs item number: FB500-40) was added to the system, and placed immediately in front of the ICCD camera. The transmission of the filter was centered at 500 nm, with 40 nm FWHM transmission (maximum transmission 50% at λ=500 nm). The filter was added to reduce chromatic aberration. Even though chromatic doublet lenses are used throughout the system, the focal length remains wavelength dependent. For example, for the specific lens used, \( f(\lambda = 520 \text{ nm}) = 499.8 \text{ mm} \), while \( f(\lambda = 620 \text{ nm}) = 500.2 \text{ mm} \). Laser line filters are designed for normal incidence light. With an f-10 imaging system (f-number=lens focal length/lens diameter), light rays are sufficiently parallel to allow use of a normal incidence filter.

4. Irises were added to some lenses, reducing their effective diameter to 1.0”. The irises were added to reduce spherical aberration (although, this increases the diffraction limit).
The optical magnification was increased:
   i. MG-III $M=1.67$ for both images
   ii. MG-IV $M=3.21$ for delayed image, $M=2.84$ for non-delayed image

The changes made to the optical system enabled higher resolution images to be obtained in MG-IV. The best system resolution achieved was 30 µm. The resolution during most shots is estimated at 40-50 µm. Resolution is quantified by using a backlit razor edge as the object, and observing the spread of the edge in the captured image.

As observed in images from both the MG-III and MG-IV two-frame systems, for those loads which form plasma, early nonuniform emission becomes more uniform as the surface temperature increases. For example, Fig. III.19 displays four images of 1.00-mm-diameter rods at different load currents (Figs. III.19:(top right) and III.19:(bottom right) are separate images of the same rod—shot 1877). Spotting, typical of low surface temperature, is displayed in Fig. III.19:(a). As the current grows, the transformation to plasma begins and the rate of surface heating increases. In Fig. III.19:(b), at an average surface temperature of 0.8 eV (temperature estimates are discussed in Ch. IV), plasma has formed on some of the surface, but the majority of the surface remains cool (dark). Fig. III.19:(c) shows that at 1.8 eV the surface is predominately plasma, with the observed “fracture” pattern possibly what remains of the thin, resistive aluminum oxide layer which forms on all rod surfaces. Finally, at 7.0 eV, Fig. III.19:(d) displays highly uniform plasma emission. The observed tendency towards uniformity as the surface temperature increases supports the applicability of one-dimensional modeling.
Fig. III.19: ICCD images of $D_0=1.00$ mm rods details features of rod surface emission. The rod first emits light from hot spots. These hot spots give way to a fracture pattern. The rod surface becomes progressively more uniform as the Zebra current increases.

By collecting images from a large number of shots, a statistically supported description of the evolution of rod surface emission is gained. However, it is also valuable and confirmatory to continuously examine the evolution of the rod surface during a single shot. Albeit with low spatial resolution, axial variation in surface emission is continuously measured with high temporal resolution by a 15 element, linear, fast-photodiode array. Emission from the rod surface is lens relayed to a linear photoconductive diode array (OSI Optoelectronics model A5C-38). Fig. III.20:(a) is drawn approximately to scale, with the filled rectangles representing the emitter area that each of the 15 active array elements (of 38 total) view in the case of a 1.00-mm-diameter barbell load. As shown, the system magnification is large enough for the load image to
fill the width of each array element from the onset of the experiment (or after minimal expansion for \(D_0=0.50\) mm and \(D_0=0.64\) mm rods). The emitter area is then well defined, and the radial expansion of the rod needn’t be considered in surface temperature calculations (see Ch. IV for further details). Each element of the array integrates the intensity emitted by a 160 µm section along the length of the rod. Therefore, the spatial resolution of the instrument does not allow measurement of the fine-scale emission features shown in ICCD images, but can measure large-scale temperature gradients, and their progression in time.

Fig. III.20:(b) displays the emission intensity (a.u) measured from 11 separate locations along the length of a \(D_0=1.00\) mm barbell load. Data is present for active elements 3-13, and plotted in 20 ns increments. In each group, there are 9 bars; the first (leftmost) bar corresponds to \(t=100\) ns (\(I=500\) kA), bar 2 (2\(^{nd}\) bar from the left) corresponds to \(t=120\) ns, and so forth. Curves connect the bars and represent variation in emission intensity as a function of axial location for each of the 9 plotted times. The displayed dataset was chosen because of the particularly nonuniform emission observed from \(t=120\) ns (red line) to \(t=140\) ns (dark green line). Emission uniformity for each plotted time is quantified by calculating the standard deviation of the 11 intensity values, and dividing by their average value. This quantity is found to be 0.72, 0.24, and 0.06 at 120, 140, and 200 ns respectively, demonstrating the trend towards uniform emission at late time. In general, the emission uniformity increases with temperature for those rods which form surface plasma during the linear current rise. Data from the two-frame ICCD and the multi-element photodiode array show that although surface emission may be nonuniform early in the current rise, these features tend to decay rather than grow. The
tendency towards emission uniformity supports the applicability of one-dimensional modeling.

Fig. III.20: Linear diode array: (a) Detector geometry in the image plane for \( D_0 = 1.00 \) mm barbell loads. (b) Emission data from 11 axial locations show that early nonuniformity along the length of the rod tends to equilibrate by the time of peak temperature.

Section III.E: The Effect of Surface Smoothness

The majority of the loads examined in the UNR-Megagauss Experiments were shaped loads (barbell or hourglass) machined locally by the UNR Physics machine shop, or Remarc Inc. Machining aluminum into long, sub-millimeter diameter rods is challenging, and occasionally rods contain macroscopic surface irregularity. As discussed in Section III.D, early emission from rod surfaces often includes localized hot spots, and less often, large axial temperature gradients along the length of the rod. These features have been observed by multiple diagnostics to gradually equilibrate with their surroundings as the load current increases. Surface irregularity has been considered as a possible reason for hot spot initiation. This supposition was tested in recent experiments by examining a series of extremely smooth barbells. The loads were machined by the precision machining team of MST-7 [58] at Los Alamos National Laboratory. Despite
sub-micron scale surface irregularity, these rods showed low intensity spotting qualitatively similar to much rougher (locally machined) rods with 25 micron scale surface irregularity. All ICCD images presented in Fig. III.19 are of Remarc manufactured 6061-alloy Al, $D_0=1.00$ mm barbell loads. In Fig. III.21, ICCD images of LANL manufactured 6061-alloy Al, $D_0=1.00$ mm barbell loads are presented. Although the LANL barbells are significantly smoother, hot spots again form, and the characteristic scale of surface irregularity is similar to that of the Remarc loads. Based on this observation, hot spots are likely not the result of macroscopic surface irregularity. Hot spot formation may be associated with the internal grain structure of the metal, in which case, machining smoothness would have no effect. This possibility has not been examined in detail.
Fig. III.21: ICCD images of ultra-smooth LANL fabricated 6061-alloy Al, $D_0=1.00$ mm barbell loads. Emission features are similar to those of loads with rougher surfaces (see Fig. III.19). (E)=Early image from delayed path; (L)= Late image from non-delayed path.
While minor surface irregularity seems to have little influence on the evolution of the rod, larger machining artifacts are observed to have profound effects. The type of surface irregularity tends to be specific to the load type. Hourglass loads commonly emit strongly from a screw-like surface pattern (Fig. III.22:(a)). This pattern likely matches the final paths made by the cutting tool during machining. Barbell loads commonly emit strongly from the ends of the straight central section of the rod (Fig. III.22:(b)). Pre-shot microscope images of barbells (Fig. III.23) often show a reduced diameter groove cut into the barbell near the ends of the straight central section (microscope images are not available for hourglass loads). The images shown (Fig. III.23) are of an 1100-alloy Al barbell. The low strength and softness of 1100-alloy Al often results in a poorer surface finish than similarly machined 6061-alloy Al loads. The grooves (red arrows) may result from extra time spent by the cutting tool at these locations, or due to increased stiffness of the rod near the ends (the rod may deflect away from the tool elsewhere, leaving a slightly larger diameter). The grooves result in increased local current density and ohmic heating.
Fig. III.22: Typical nonuniform emission from loads with surface irregularity (a) Hourglass load with “screw” pattern left by the final passes of the cutting tool. (b) Barbell load with machined grooves at the top and bottom of the straight central rod section of the load.
Fig. III. 23: Microscope image of an 1100-alloy Al barbell load with severe pitting (green arrow) and grooves (red arrows) machined near the top and bottom of the central straight rod section of the load (the central portion of the rod is not shown).

Surface imperfections in the load displayed in Fig. III.23 resulted in early heating at the locations of grooves, and subsequent late-time jetting (Fig. III.24). It will be shown in Ch. VI that $D_0=1.00$ mm rods form vapor at around $t=70$ ns. After this point, the surface expands at a near constant velocity of 3.0 km/s until the time of peak current. After peak current, the expansion velocity increases to greater than 10 km/s. The shadowgram in Fig. III.24:(c) displays the rod surface profile at $t\approx180$ ns, or about 15 ns
after peak current. For this image, the central portion of the rod has expanded to $D=2.17$ mm, while the upper jet has reached $D=3.08$ mm. This average velocity of the jets is estimated at 10 km/s during the Zebra current rise (although the time that the jet formed is unknown, but likely somewhat before 70 ns). In figure III.24:(d), the rod has expanded to 3.11 mm, with the jets no longer at larger radius than other portions of the surface. Based on these images, the jet first moves through the magnetic field at high velocity, and then essentially stops (or perhaps re-pinches), as the remainder of the rod material continues to expand. Such jets could be intentionally formed by machining precise grooves into the rod surface. This would allow examination of the interaction of megagauss magnetic field and dense plasma jets. Such studies may be of interest to those studying plasma jet dynamics through megagauss fields [68].

**Fig. III.24:** Evolution of the rod shown in Fig. III.23. (a) Ekspla laser reference image of the rod ($I=0$). (b) ICCD image at $t \sim 90$ ns, $I=400$ kA, showing increased heating and emission from the machined grooves. (c) Shadowgram at $t \sim 180$ ns ($I \sim 950$ kA, after peak current) showing hydrodynamic jetting from location of machined grooves. (d) Shadowgram at $t \sim 205$ ns, showing that the central section of the rod has comparable diameter to the location of the earlier observed jets.
Section III.F: Concluding Remarks on Load Hardware

This chapter has presented data related to the performance of a variety of load hardware configurations. The data has shown that local arcing from—(1) GRAV hardware and (2) anode-cathode contacts of simple-straight-rod loads—can initiate precursor non-thermal plasma formation along the length of the rod. For these reasons, GRAV hardware and simple-straight-rod loads have not been used since MG-II. Barbell loads in KE hardware, and hourglass loads have displayed nearly identical behavior, with no non-thermal plasma observed. Hourglass loads are challenging to fabricate, requiring several hours of meticulous hand machining. Barbell loads can be machined in approximately 10 minutes, and can be turned in an automated lathe (by Remarc). Barbell loads can also be machined from 1100-alloy Al. 1100-alloy Al hourglass loads cannot currently be created because: (1) 1100-alloy Al is likely too fragile to support the massive anode and cathode ends during machining (2) The required 3” diameter 1100-alloy Al cylinders are not commercially available. For these reasons, barbell loads mounted in KE hardware have become the standard load type used in the UNR-Megagauss Experiments. Only barbells in KE hardware have been examined in MG-(III-IV), and have continued to display favorable performance. As diagnostics continue to progress, it may be worthwhile to reexamine the hourglass load, to determine if differences in the evolution of the two load types can be observed.
Chapter IV: Surface Temperature Estimates from Visible Light Radiometry

Radiation emitted from a body offers information about the state of the radiating material. Parameters such as material temperature and ionization state may be deduced from measurements of intensity as a function of wavelength. In this section, an estimate of the surface brightness temperature \( T_{BB} \) of the aluminum rod is made by sampling radiation from a 70 nm band centered on 530 nm in the visible portion of the spectrum. Blackbody theory is used to interpret the radiometric data. It is assumed that the radiation reaching the detector is emitted from a very thin layer of oscillators near the surface of the rod. Since a blackbody is a perfect emitter, a real body will emit less than a blackbody, and the assumption therefore results in an underestimate of the actual temperature. This underestimate becomes more severe as the optical thickness of the surface material decreases (becomes more optically thin). It will be shown, by theoretical consideration and experimental support, that for visible radiation, the blackbody assumption is reasonable for the parameters of the experiment.

The chapter begins with a short derivation of blackbody theory based on photon statistics. Use of the resulting Planckian blackbody formula to deduce a surface brightness temperature is outlined. After the theoretical development, the generic components of a radiometric device are overviewed, followed by specific details of those diagnostics used in the UNR-Megagauss Experiments. It was discovered that the photodiode array used in MG-III responds non-linearly to high levels of illumination. After careful calibration of the detector, an appropriate transfer function was applied to the data to correct for nonlinear response. Agreement was then found between the MG-III temperature estimates and earlier measurements. The agreement was validated
with temperature measurements made in MG-IV, using the same detector, but operated at lower intensity (to ensure linear response). The resultant surface brightness temperature estimates from each diagnostic will be reported and discussed.

**Section IV.A: Basic Photon Statistics**

In this section, a brief discussion of blackbody theory is presented. A more complete derivation of blackbody theory is presented in Reif [69]. Furthermore, the theory is considered from a clear physical point of view in Modest [70], and is applied to a variety of different physical situation in Zel’dovich and Raizer [71]. Also, a tutorial paper on radiation transport in dense plasmas by Apruzese et. al. [72] is very informative.

Blackbody theory may be derived from fundamental statistical mechanics. The fundamental postulate of statistical mechanics states that for an isolated system of particles in equilibrium, any possible configuration (which satisfies macroscopic conditions such as, e.g. total energy) is equally probable. Conservation laws, along with definitions of entropy and temperature in terms of the total number of accessible states ($\Omega$), allow introduction of the “canonical distribution.” The canonical distribution enables calculation of the probability, $P_r$, that a large ensemble of particles is in state $r$:

$$P_r = \frac{\exp(-\beta E_r)}{\sum_r \exp(-\beta E_r)}$$

(IV.1)
In Eqn. IV.1, $\beta = 1/kT$ and $E_r$ is the energy of state $r$. The canonical distribution is easily converted into the “partition function.” To do so, note that the average energy of the system is:

$$\overline{E} = \sum_r E_r P_r = \frac{\sum_r \exp(-\beta E_r) E_r}{\sum_r \exp(-\beta E_r)} \quad \text{(IV.2)}$$

Now,

$$\sum_r \exp(-\beta E_r) E_r = -\sum_r \frac{\partial}{\partial \beta} \exp(-\beta E_r) = \frac{\partial}{\partial \beta} Z \quad \text{where} \quad Z \equiv \sum_r \exp(-\beta E_r) \quad \text{(IV.3)}$$

With the partition function ‘$Z$’ defined, the average energy is written simply as,

$$\overline{E} = \frac{\sum_r \exp(-\beta E_r) E_r}{\sum_r \exp(-\beta E_r)} = \frac{ZE_r}{Z} = -\frac{1}{Z} \frac{\partial Z}{\partial \beta} \quad \text{(IV.4)}$$

The concepts and mathematical formalism of the canonical distribution and partition function may be applied to the radiation field emitted from a heated body. Here, the behavior of a large ensemble of photons is analyzed. Quantum mechanical arguments determine the way the number of energy states accessible to each photon are “counted,” and ultimately determine the structure of the distribution. Photons have spin=1 so multiple particles can occupy the same state, and an ensemble of photons is therefore governed by “Bose-Einstein Statistics.” The possible quantum states of a single particle will be denoted by $r$. The energy of a particle in state $r$ is ‘$\epsilon_r$’ and the number of particles is ‘$n_r$.’ Let $N$ be the total number of photons in the ensemble. Then

$$N = \sum_r n_r \quad \text{(IV.5)}$$
For a photon distribution, $N$ is not a conserved quantity, since photons may be emitted or absorbed. Therefore $n_r$ can attain any integer value. The energy of state $r$ is then $\varepsilon_r n_r$ and the partition function is written:

$$Z = \sum_r \exp(-\beta \varepsilon_r n_r) \quad \text{(IV.6)}$$

With a clever manipulation of the partition function (see, e.g., [69]), it can be shown that the average number of photons in state $r$, (with energy $\varepsilon_r$) is given by the well known “Planck Distribution.”

$$\overline{n_r} = \frac{1}{\exp(\beta \varepsilon_r) - 1} \quad \text{(IV.7)}$$

Clearly, as $T \to 0$, $\beta \to \infty$, and $\overline{n_r} \to 0$. Conversely, as $T$ grows large, so too does $\overline{n_r}$.

Consider an enclosure with walls in thermodynamic equilibrium at temperature $T$. The walls of the container emit and absorb photons continuously, reaching equilibrium with the radiation field. Since radiation cannot escape, the enclosure is a perfect absorber, and is therefore a blackbody. To remain in equilibrium, and at temperature $T$, the walls must emit and absorb photons at equal rates, so the enclosure is also a perfect emitter—A blackbody is a perfect absorber and emitter. A real body must radiate less than a blackbody at the same temperature. For example, a real body at temperature $T_1$ will emit the same amount of radiation as a blackbody at $T_2$, where $T_1 > T_2$ (the difference between $T_1$ and $T_2$ depends on the characteristics of the emitter). If the radiation is sampled, and interpreted using the blackbody assumption, the deduced temperature is $T_2$, so the material temperature is underestimated. As the emission spectrum escaping from
the rod surface moves further from the characteristics of a blackbody, the underestimate of temperature becomes progressively worse.

Consider an ensemble of photons inside of (and in thermodynamic equilibrium with) an enclosure. Represent the photons as a collection of standing waves bounded by the enclosure. Assuming a rectangular enclosure simplifies the mathematics and quickly leads to quantization of wave number (and photon energy). Counting the total number of accessible states, gives the total number of photons within the energy range $\varepsilon \rightarrow \varepsilon + d\varepsilon$ (frequency range $\nu \rightarrow \nu + d\nu$). With the number of photons with energy in the specified range known, the spectral energy density is found as:

$$u(\nu, T) = \frac{8\pi \hbar \nu^3}{c^3} \frac{1}{\exp(h\nu/kT) - 1}$$  \hspace{1cm} (IV.8)

Eqn. IV.8 expresses the energy radiated at wavelength $\nu$, per unit volume, per unit wavelength. To determine the spectral intensity, Eqn. IV.8 is simply multiplied by the speed of light, and divided by $4\pi$ (since the radiation is emitted equally in all directions). Therefore, the intensity radiated by a blackbody is given by

$$I(\nu, T) = \frac{c}{4\pi} u(\nu, T) = \frac{2\hbar \nu^3}{c^2} \frac{1}{\exp(h\nu/kT) - 1}$$ \hspace{1cm} (IV.9)

The radiation intensity is independent of angle. In the UNR-Megagauss Experiments it is assumed that the majority of observable radiation is emitted from a thin layer of surface material. Therefore, surface brightness is of interest, and according to Lambert’s Law, the intensity emitted from a surface does depend upon the angle between surface normal and direction of emission. This rather subtle distinction is discussed in detail in
where the (directionally dependent) emittance of a body, $i_v$, is related to the spectral intensity by,

$$i_v = I(v, T) \cos \theta$$  \hspace{1cm} (IV.10)

Therefore, when viewing perpendicular to the surface normal, the intensity decreases to zero. The curved rods examined in the UNR-Megagauss Experiments are viewed from a distance much greater than the radius of curvature of the rods. Based on Eqn. IV.10, one may conclude that images obtained should be brightest in the center, and gradually grow dark towards the edges. The emittance, however, is defined per unit surface area, and due to the curvature of the rod, when moving towards the edge, the projected area grows, canceling the directional dependence of emittance. Therefore, even though the emittance approaches zero towards the rod edge, the effective area viewed approaches infinity, and the emission intensity is uniform across the curved rod surface.

Finally, with careful analysis of the subtleties associated with Lambert’s Law (see e.g., Section II.7 of [71]) it can be shown that the radiant energy flux emitted from a blackbody surface differs from the equation for volume radiation (Eqn. IV.9) by a factor of $\pi$. The equation for surface emission is given by Planck’s Law.

$$I_{BB,v}(v, T) = \frac{c}{4} u(v, T) = \frac{2\pi \nu^2 dv}{c^2} \frac{1}{\exp(h\nu/kT) - 1}$$  \hspace{1cm} (IV.11)

The radiant energy flux is the emitted energy per unit time, per unit surface area, per unit frequency. To make use of this law to deduce a brightness temperature, a radiation detector must be well characterized in terms of temporal and spectral response, emitter area viewed, and solid angle subtended.
Eqn. IV.11 is expressed in terms of frequency but may also be written in terms of wavelength. Since the equation represents the spectral emissive power, the conversion to a similar formula based on wavelength cannot be found by simply replacing $\nu$ with $c/\lambda$. First, the total emissive power may be found by integrating Eqn. IV.11 over all frequencies:

$$E_{BB,\nu}(T) = \int_0^{\infty} 2\pi \frac{\hbar \nu^3}{c^2} \frac{1}{e^{\hbar \nu/kT} - 1} d\nu$$  \hspace{1cm} (IV.12)

The integral expression may then be converted using variable substitution. Since the photon frequency is related to wavelength by $\nu = c/\lambda$, differential elements are related by $d\nu = -(c/\lambda^2) d\lambda$. Also, since $\nu$ is inversely proportional to $\lambda$, the limits of integration will run $\infty \to 0$ rather than from $0 \to \infty$. The result is the following integral expression in terms of wavelength:

$$E_{BB,\lambda}(T) = \int_0^{\infty} 2\pi \frac{\hbar(c/\lambda)^3}{c^2} \frac{1}{e^{\hbar c/\lambda kT} - 1} \frac{c}{\lambda^2} d\lambda = \int_0^{\infty} 2\pi \frac{\hbar c^2}{\lambda^5} \frac{1}{e^{\hbar c/\lambda kT} - 1} d\lambda$$  \hspace{1cm} (IV.13)

Therefore, the spectral emissive power (emitted energy per unit time, per unit surface area, per unit wavelength) is given by the integrand of Eqn. IV.13, or by,

$$I_{BB,\lambda}(\lambda, T) = \frac{2\pi \hbar c^2}{\lambda^5} \frac{1}{e^{\hbar c/\lambda kT} - 1}$$  \hspace{1cm} (IV.14)

The Planck distribution is plotted vs. wavelength for several different temperatures in Fig. IV.1. The curves for temperatures ranging from 0.5 to 2.0 eV are normalized to the peak of the 2.0 eV distribution, with all higher temperatures curves being self-normalized. The total emitted radiation increase with temperature, and the average photon energy increases (shifts to shorter wavelength or higher frequency).
Fig. IV.1: Normalized emissive power vs. wavelength for a blackbody at multiple temperatures. Curves for temperatures at or above 2.0 eV have been self normalized to a maximum value of 1. Curves below 2.0 eV have been normalized to the 2.0 eV curve.

Integration of the spectral emissive power over all frequencies gives the total emissive power, or the emitted energy per unit time, per unit surface area.

\[
P_{BB}(T) = \int_{0}^{\infty} E_{BB,\nu}(T, \nu) \, d\nu = \int_{0}^{\infty} \frac{2\pi h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1} \, d\nu = \sigma_{SB} T^4
\]  \hspace{1cm} (IV.15)

Eqn. IV.15 is the well known Stefan-Boltzmann Law, and shows that the total emissive power from a blackbody is proportional to \( T^4 \). The constant of proportionality, \( \sigma_{SB} \), is known as the Stefan-Boltzmann constant, and is equal to \( 5.670 \times 10^{-8} \) W/m\(^2\)K\(^4\). The total emitted radiation from a blackbody increases rapidly with temperature.

As displayed in Fig. IV.1, the peak of the distribution shifts to shorter wavelength as the blackbody temperature \( T_{BB} \) increases. The frequency of the distribution peak is found by differentiating the integrand of Eqn. IV.12 with respect to \( \nu \) and setting the result to zero, which leaves the simple expression:
\[ e^x = \frac{3}{3-x} \quad \text{where} \quad x = \frac{h\nu}{kT} \]  

(IV.16)

With solution

\[ x = \frac{h\nu}{kT} = \frac{2.82}{kT} \]  

or  

\[ v_{\text{max}} = \frac{2.82kT}{h} \]  

(IV.17)

In Fig. IV.2, the blackbody temperature is plotted vs. the corresponding wavelength of the distribution peak. The plot contains wavelength ranges which are commonly used to categorize radiation. Also plotted are the sensitivity ranges (rectangles) of several diagnostics used in the UNR-Megagauss Experiments. Where the \( T_{BB}(\lambda_{\text{max}}) \) curve passes through the rectangles indicates the blackbody temperature for which the diagnostic is optimized. For example, the visible light radiometry diagnostic is optimized for temperatures near 1 eV. The EUV diagnostics are better suited for temperatures near 10 eV. The blackbody distribution is broad (Fig. IV.1), so diagnostics can be useful in examining material temperatures well outside their optimized wavelength.
Since diagnostics can sample only a limited range of photon energies, often a simplified version of the blackbody formula can be employed when analyzing data. For example, if a detector samples high energy photons in comparison to the photon energy of the distribution peak for the given material temperature, then $h\nu >> kT$, and Eqn. IV.9 simplifies to Wien’s Displacement Law:

$$E_{BB,\nu}(T,\nu) = \frac{2\pi h\nu^3}{c^2} e^{-h\nu/kT} \quad \text{for} \quad h\nu >> kT$$  \hspace{1cm} \text{(IV.18)}

In the other limit, for relatively low energy photons ($h\nu >> kT$) the exponential term in Eqn. IV.9 can be Taylor expanded, since for small $x$, $e^x \approx 1 + x + x^2/2! + ...$. Retaining only the first two terms, Eqn. IV.11 simplifies to the Rayleigh-Jeans Law:

$$E_{BB,\nu}(T,\nu) = \frac{2\pi h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1} \approx \frac{2\pi h\nu^3}{c^2} \frac{1}{1 + h\nu/kT} = \frac{2\pi v^2 kT}{c^2} \quad \text{for} \quad h\nu << kT$$  \hspace{1cm} \text{(IV.19)}
Making use of these approximations requires knowledge of the radiation spectrum, and the frequency response of the detector. If the radiating body is relatively hot, the detector will measure photons in the lower energy tail of the distribution, and the Rayleigh-Jeans Law may be used. In this case, as the temperature of the body increases, the intensity in the sensitivity range of the detector will grow linearly with $T_{BB}$ (Eqn. IV.19). If the radiating body is relatively cool, the detector will see sparingly few photons, as shown by the exponential dependence of Wien’s Law. As the temperature of the body is increased, the distribution will shift to lower frequencies, and eventually into the sensitivity range of the detector, resulting in an exponential increase in intensity with $T_{BB}$ (Eqn. IV.18).

Both approximations are useful for interpreting data obtained in the UNR-Megagauss Experiments. Observe in Fig. IV.2, that for a 2.0 eV blackbody, the peak of the distribution is at 220 nm, between the spectral response ranges of the EUV diodes (at higher photon energy) and the visible light photodiodes (at lower photon energies). As the blackbody temperature is increased, the intensity to the EUV diodes will grow approximately exponentially with $T_{BB}$ (Wien’s Law) as the sharp, high-photon-energy edge of the distribution shifts to shorter wavelength. At the same time, the intensity to the visible photodiodes will grow linearly with $T_{BB}$ (Rayleigh-Jeans Law) as the broad, low-photon-energy tail of the distribution increases in number density in proportion to temperature.

The mathematical methods required for using blackbody theory to determine the temperature of a radiating body have now been covered. The question of how closely the radiation escaping the rod surface resembles the radiation emitted from a blackbody remains unanswered. Support of the blackbody assumption in the visible portion of the
radiation spectrum has been obtained. Continuum emission has been observed with time-resolved spectroscopy (a Horiba Jobin Yvon CP140 visible light imaging spectrograph coupled to a streak camera). The wavelength scale of the system has been calibrated with multiple laser lines (Fig IV.3), which also enables an estimate of the spectral resolution. Assuming the spectral width of the laser lines are finer than the resolution of the instrument, the width of the streaked spectral line (from the laser) is approximately equal to the instrument’s spectral resolution. The spectral scale of the CCD readout is calibrated at 1.76 px/nm. The laser line widths average 16 pixels (however, the resolution tends to improve with increased wavelength). The system resolution is therefore approximately 9 nm. To within the resolution limits of the instrument, line-free continuum emission is observed for 1.00-mm-diameter rods (Fig. IV.3).

![Streaked visible light spectrum from a 1.00-mm-diameter 6061-alloy Al rod. Continuum emission is observed. Colored lines indicate the laser lines used to calibrate the instrument. Spectral resolution is estimated at 9 nm.](image)

**Fig. IV.3:** Streaked visible light spectrum from a 1.00-mm-diameter 6061-alloy Al rod. Continuum emission is observed. Colored lines indicate the laser lines used to calibrate the instrument. Spectral resolution is estimated at 9 nm.
Aside from the observation of continuum emission, if the spectral response of all elements in the diagnostic system is known, the time-dependent emission intensity as a function of wavelength can be reconstructed from the data. Completing this work will be difficult if not impossible for the data obtained with the streaked spectrograph, since the streak camera (which was on loan from LANL) was not properly calibrated or flat-fielded before being returned to LANL. However, in MG-IV a similar diagnostic was fielded, with the streak camera replaced by an A5C-38 linear photodiode array. While the array cannot match the spectral resolution of the streak camera, it does offer well characterized spectral response, and high element-to-element response uniformity. The loss of spectral resolution is not critical, since the earlier data has already confirmed continuum emission.

The spectral distribution inferred from this instrument can be compared against the blackbody spectrum. If the time varying spectrum can be fit to the Planck distribution, and the shift of the distribution from red to blue as the rod is heated can be observed, this would further validate use of the blackbody assumption to determine the brightness temperature. Preliminary results, which have been compared with modeling [73], suggest that the brightness temperature varies with photon frequency. This is due to the strong ($\nu^{-3}$) frequency dependence of the bremsstrahlung absorption coefficient. Modeling estimates show that temperature gradient scale lengths in the edge plasma are comparable to the optical depth. Therefore, harder photons originate from deeper in the plasma layer, where the material may be appreciably cooler, resulting in a wavelength dependent brightness temperature. Full details of this diagnostic, and its analysis will be included in Ms. Tasha Goodrich’s Master’s Thesis.
Section IV.B: Visible Light Radiometry Diagnostics—MG-(I-III)

Under the assumption of blackbody radiation, a diagnostic with well characterized geometry, and known spectral response, can be used to deduce the brightness temperature of the radiating object. The rod is assumed to radiate as a blackbody, so the spectrum of photons is fully defined for a given temperature. Experimentally, light is incident upon a photodiode, and the diode current is measured. In order to interpret that measurement as a temperature, the diagnostic setup must be well characterized. Photons will be emitted through $4\pi$ Steradians, a small fraction of which will be collected by the diagnostic. The solid angle of the system will be determined by the location and effective f-stop of a lens. The area of the rod imaged to the detector is defined by the system magnification, and the active area of the photodiode. A filter may be used to select a well defined bandpass of photons, and the transmission percentage of this filter as a function of wavelength must be known. Finally, an estimate of losses associated with reflections from windows, lenses, etc. must be included. With each of these factors known, the total number of photons (per unit wavelength, per unit time) incident upon the active area of the detector can be determined. The responsivity function of the detector allows conversion from watts of light per unit wavelength to diode current. Therefore, based on the measured diode current, the temperature of the rod can be calculated.

Different versions of fast-photodiode-based radiometric diagnostics were used in each experimental series. Next, a short description is given for the diagnostics used in MG-I followed by more complete descriptions of the diagnostic used in MG-II and MG-III.
Diagnostic Description—MG-I

Initial surface luminosity measurements were made in MG-I using a slightly adapted 35-mm Nikon F camera body and a BPX-65 photodiode. Load light was imaged onto the face of a 600 μm diameter silica fiber, which was directed to the NW optical screen box and coupled to the active surface of a BPX-65 fast photodiode. Fiber optic coupling eliminated the need for EMI shielding, as all electronic components were located in a screen box. This system allowed for simple optical alignment through the viewfinder of the camera body. Also, the built in f-stop allowed simple adjustment of the system solid angle, and thus the light intensity to the detector. This was a critical system component, since prior to the first experiment, opinions on expected surface temperature varied widely. Fig. IV.4 shows a sketch of important optical components.

Fig. IV.4: Important optical components of the radiometric diagnostic fielded in MG-I.
A 55 mm Micro NIKKOR lens was used. Due to use of an extension tube, the magnification was not the same as that listed on the barrel of the lens, however, good resolution was demonstrated, and the actual magnification can be deduced. During the experiment, the distance from the front of the camera lens to the rod was about 14.5 inches. By reconstructing this setup after the Zebra experiment, it was shown that upon back illuminating the 600 µm fiber, the size of the spot generated at a distance of 12” to 14” (allowing for uncertainty in the setup) was $4.1 \pm 0.15$ mm in diameter. Therefore, the system magnification is approximately $M=0.6/4.1=0.15$. The magnification introduces an uncertainty associated with the expansion of the rod. With $M=0.15$, a 1.00-mm-diameter rod initially fills only 150 microns of the 600 µm diameter fiber. This introduces large error in the inferred temperature, as the emitter area is not well known. First, there is error in the measurement of the radial expansion of the rod. Second, if the system is not perfectly aligned (with the rod image centered on the fiber), further error is introduced. Furthermore, it became clear during the experiments that although the fiber coupling at the camera body was quite rigid, the transmission from the fiber to the photodiode was sensitive to small motion of the fiber. This introduced significant error, which changed from shot to shot.

Significant sources of error contributed to high uncertainty in the measured temperature, but the MG-I diagnostic was able to capture essential qualitative emission information. Fig. IV.5 shows diode voltage vs. time for all hourglass loads examined in MG-I. The peak temperature was estimated to reach 20 to 30 eV. The large level of variation in the signals likely was due to changes in fiber-to-diode coupling efficiency.
Several conclusions were drawn from the MG-I $T_{BB}$ measurements, all of which have been supported or confirmed by data obtained in later experiments. Conclusions from of MG-I 1.00-mm-diameter dataset include:

1. Emission is too low to be measured until the load current reaches approximately $I=500$ kA. Thereafter, rapid heating is observed.

2. Peak temperatures exceed 10 eV, and may reach 30 eV (peak temperature estimates for $D_0=1.00$ mm rods was $20\pm10$ eV)

3. Peak temperatures are observed to occur near the time of peak current.

**Diagnostic Description—MG-II & MG-III**

The visible light radiometry diagnostics fielded in MG-II and MG-III were similar in many ways. First, both diagnostics eliminated the need for fiber optic coupling, which was determined to be the largest source of error in MG-I measurements. Load light was imaged directly to the photodiodes, which were located near the Zebra vacuum chamber. Furthermore, each system used large optical magnification, so that the image of the unexpanded rod was wider than the active area of the photodiode ($D_0=0.50$ mm and
$D_0=0.64$ mm rods are an exception, and require slight expansion before their images fill the diode). In this way, radial expansion measurements (with associated error) are not included in brightness temperature estimates. Finally, both diagnostics contained multiple active photodiodes, enabling luminosity measurements at several axial locations.

The upper portion of Fig. IV.6 displays the design of the diagnostic used in MG-II. The assembly is housed in a 2” diameter Al tube. At the front of the housing is a mechanical mount to hold a 50.8 mm diameter, $f=250$ mm lens. The object distance was 333 mm and the image distance 1000 mm, resulting in $M=-3.0$. The Al tube provides a rigid mechanical mount, as well as EMI shielding. The tube is fastened to the Zebra diagnostic space frame via plastic mounts to provide electrical isolation, further reducing EMI. The back of the tube attaches to the multi-layered diode housing. The outer shielding is made from a 6” length of Al pipe similar to that used for the main section of the diagnostic, and provides an initial layer or electrical shielding. Inside of the pipe is a tight fitting plastic sleeve, which serves to electrically isolate the internal electronics enclosure from the outer shielding. The diodes and electronics are mounted in a 2.25” diameter Al pipe, fitted with aluminum caps in front and back. Three BPX-65 diodes are mounted in the front cap and four BNC bulkhead connectors are mounted in the back cap. RG-232 double braided coaxial cables run from the back plate to the NW optical screen box. The cables are wrapped in 2 more layers of braided shielding, but the braid is stopped short of the internal circuit enclosure to isolate electronic components from the currents induced on the shielding. The use of multiple layers of fully isolated shielding resulted in very low electrical noise (noise level below 10 mV).
Fig. IV.6: Mechanical design of radiometric diagnostic used in MG-II (top) and that used in MG-III through MG-IV (bottom). At the center is a diagram of the circuits used for each diagnostic.
The lower portion of Fig. IV.6 displays the design of the diagnostic used in MG-(III-IV). A larger EMI enclosure was needed to house the slightly larger diode array, but the system design was quite similar to that of the MG-II diagnostic. Again, a central EMI enclosure housed all electrical components, and the enclosure was electrically isolated from the outer shielding. Rather than mounting the imaging lens to the EMI enclosure (as in the MG-II design), in the MG-III design, the lens was mounted directly to the outer wall of the Zebra chamber. This allows the shielding enclosure to be considerably more compact. The outer enclosure is constructed from 1/16” thick aluminum sheet metal, and aluminum angle brackets. Since the enclosure contains many seams, the entire assembly is shrouded in Cu mesh. The mesh begins at the face of the diagnostics, runs the full length of the coaxial cables, and is finally secured to the outer wall of the inlet to the digitizer’s screen box.

The primary difference between the MG-II and MG-III diagnostics was use of significantly different detectors. In MG-II, (3) BPX-65 detectors (the same as those used in MG-I) were used to capture light from three rod locations: 2.5 mm above rod center, rod center, and 2.5 mm below rod center (Fig IV.7(a)). In MG-III, a single substrate, 38 element (only 15 of which were activated) photoconductive array was used (model A5C-38 from OSI Optoelectronics, Fig. IV.7(b)).
The 3-diode detector head was designed in the following way. Optical fibers (600-µm-diameter silica) were placed above and below the array of photodiodes. With the center of fiber 1 at \( z = 0 \), diodes 1, 2, 3, and fiber 2 were centered at \( z = 4.5 \), 10.5, 16.5, and 21 mm, respectively. With proper alignment of the \( M = -3 \) system, diode 2 views the axial center of the rod, with the other diodes viewing 2.0 mm off center, and the fibers viewing 3.5 mm off center. In Fig. IV.7(a) an image of a 7.0-mm-long simple-straight-rod load is superimposed over the diode array (approximately to scale). With \( M = -3 \), the width of the rod’s image is three times greater than the width of the 1.0 mm square active area of the BPX-65 diode, so radial expansion needn’t be considered in temperature calculations. This detector head was designed for hardware with a 7.0-mm-long anode-cathode gap, which was often used in MG-II. For such loads, the light incident on the optical fibers originated from the anode and cathode electrical contacts of the load. This light was sent to PMT’s which recorded emission from arcing electrical contacts (see Ch. III for results). The fibers were also used for diagnostic alignment. Prior to each shot, the opposite ends of the fibers were illuminated with laser light. The light was
emitted by the ends of the fibers mounted in the detector head, and imaged (through the lens) to the load. The result—two small points of laser light imaged onto the rod surface. This light is easily viewed through a neighboring chamber port, allowing the diagnostic to be properly positioned.

The diode array used in MG-III, similar to the detectors in MG-II, offers high-speed performance and low cross talk, but adds increased axial resolution and high element-to-element response uniformity. The array elements are 4.39 mm wide, so a large magnification of \( M = -5.6 \) was used to fill the active area of the elements from the onset of the experiment. In MG-(III-IV), \( D_0 \) as small as 0.50 mm were examined. With \( M = -5.6 \), and perfect optical alignment, the rod diameter must reach nearly 0.8 mm before the image fills the diode element. The smaller diameter rods are observed to expand rapidly, and the image will fill the detector well before peak current, however, slight errors may exist at early times for 0.50 and 0.64-mm-diameter rods. In Fig. IV.7(b), an image of a 1.00-mm-diameter barbell load is superimposed over the array (approximately to scale). The 15 active array elements are indicated by red rectangles. Since the face of the diode array is easily observable (upon removal of the Wratten #58 filter), alignment of the detector to the rod is simply accomplished by reflecting a bright light source off of the rod and viewing the position of the resulting rod image on the face of the array. This alignment method was fast, and effective.

To infer the emission intensity of the rod surface from photodiode data, the responsivity of each detector must be known as function of photon frequency. The responsivity curves, along with the transmission curve for the Wratten #58 filter (taken
from manufacturer datasheets) are plotted in Fig. IV.8. The detector’s responsivity curves are nearly identical for those wavelengths which the Wratten #58 filter transmits.

**Fig. IV.8:** BPX-65 and A5C-38 detector responsivity (A/W) and Wratten #58 filter transmission as functions of wavelength.

The driving circuits for each of the (3) BPX-65 diodes used in MG-II, and each of the (15) active element of the A5C-38 array used in MG-III are displayed at the center of Fig. IV.6. The bias voltage was reduced from 20 V (BPX-65) to 10 V (A5C-38) to comply with manufacturer recommendations. The change from a 100 nF (MG-II) to a 2 nF (MG III) bias capacitor was inadvertent. The intention was to use a 200 nF capacitor, but the label of the capacitor was misread. This appears to be of little consequence; it can be shown that the available charge from the 2 nF capacitor falls only slightly during the times of interest in the experiment. Fig. IV.9 shows experimental diode current profiles (averaged over several shots) for the different $D_0$ examined in MG-III. These curves are integrated with respect to time to determine the total charge drawn from the capacitor as a
function of time \( Q(t) = \dot{I}(t) dt \). The data shows that approximately 20% of the 20 nC total charge has been used by the time of peak temperature for \( D_0 = 0.50 \) mm rods (less for larger rods). Tests conducted after the experiment used a fast strobe source to examine the effect of such charge reduction, or equivalently, bias voltage reduction. With the strobe flashing, the bias voltage was gradually reduced (by reducing the voltage of the power supply). Little change was observed in the measured diode current as the bias voltage was reduced from 10 to 8 V (20% reduction, similar to experimental conditions). Upon reaching approximately 6 V, the peak of the pulsed diode current began to fall. Since the rise time of the strobe is slow in comparison to the rise time of emission from the rod, this test cannot definitively determine whether or not bias reduction affects experimental results. If the MG-III detector was used to measure higher intensity radiation (or longer light pulses) the bias capacitance would need to be increased. The detector used in MG-III was again used in MG-IV, but in MG-IV measurements, the diode current was nearly 20 times lower due to incorporation of an ND 1.3 filter and reduced solid angle (see Section IV.D), making the low bias capacitance irrelevant.
Fig. IV.9: Average diode current vs. time for rods of different initial diameter (MG-III). Diode currents are integrated to find the total charge drawn from the bias capacitor as a function of time. At peak intensity, nearly 20% of the total charge has been drawn from the bias capacitor in the case of the (brightest) 0.50-mm-diameter rods.

The optical and geometric characteristics of the radiometric system must be known to deduce the brightness temperature, \( T_{BB}(t) \), from raw signals. Geometric features of the radiometric diagnostics used in the UNR-Megagauss Experiments are compared in Table IV.1. Equations IV.(20-22) are used to calculate the system magnification, solid angle, and emitter area, respectively. For the solid angle calculation, the aperture normal is considered to be parallel to the optical path.

\[
M = -\frac{s_i}{s_0} \tag{IV.20}
\]

\[
\Omega = \iint_S \hat{n} \cdot d\mathbf{a} = \frac{\text{Aperture Open Area}}{(\text{Aperture to Source Distance})^2} \tag{IV.21}
\]
\[ Emitter \text{ Area} = \left( \frac{ElementLength}{M} \cdot \frac{ElementHeight}{M} \right) = \frac{DetectorElementArea}{M^2} \]  

(IV.22)

<table>
<thead>
<tr>
<th>Imaging System</th>
<th>MG-II</th>
<th>MG-III</th>
<th>MG-IV: Small Aperture</th>
<th>MG-IV: Large Aperture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lens Focal Length</td>
<td>250</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Lens Radius (mm)</td>
<td>22.5</td>
<td>76.2</td>
<td>76.2</td>
<td>76.2</td>
</tr>
<tr>
<td>Object Distance (mm)</td>
<td>406</td>
<td>346</td>
<td>350</td>
<td>350</td>
</tr>
<tr>
<td>Image Distance (mm)</td>
<td>1200</td>
<td>1930</td>
<td>2053</td>
<td>2053</td>
</tr>
<tr>
<td>Aperture Defining Solid Angle</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radius (mm)</td>
<td>22.5</td>
<td>25.4</td>
<td>17.9</td>
<td>25.4</td>
</tr>
<tr>
<td>Distance from Source (mm)</td>
<td>406</td>
<td>300</td>
<td>295</td>
<td>300</td>
</tr>
</tbody>
</table>

| Detector Characteristics     |        |        |                       |                       |
| Length (Single Element) (mm)  | 1      | 4.39   | 4.39                  | 4.39                  |
| Height (Single Element) (mm)  | 1      | 0.89   | 0.89                  | 0.89                  |
| Active Area (mm²)             | 1.00   | 3.91   | 3.91                  | 3.91                  |
| Number of Active Elements     | 3      | 15     | 14                    | 14                    |
| Active Element Separation in Image Plane (mm) | 7.5 | 1.98 | 1.98 | 1.98 |
| Bias Voltage                  | (-) 20 V | (-) 10 V | (-) 10 V               | (-) 10 V               |

| Calculated Quantities         |        |        |                       |                       |
| Magnification                 | -2.96  | -5.58  | -5.86                 | -5.86                 |
| Solid Angle (Steradians)      | 9.649E-03 | 2.252E-02 | 1.156E-02             | 2.252E-02             |
| Emitter Area (Square meters)  | 1.15E-07 | 1.26E-07 | 1.14E-07              | 1.14E-07              |
| Active Element Separation in Object Plane (mm) | 2.54 | 0.35 | 0.34 | 0.34 |
| Solid Angle \times Emitter Area | 1.10E-09 | 2.83E-09 | 1.32E-09              | 2.56E-09              |

Table IV.1: System parameters of the visible light radiometry diagnostics used in MG-(II-IV).

The bottom row of the table displays the value of the subtended solid angle multiplied by the (per element) emitter area for each system. For the same light source, this number shows (ignoring the slight difference in responsivity of the two detectors) that the system used in MG-III should record a diode current \( \frac{2.83}{1.10} = 2.57 \) times greater than that recorded by the system used in MG-II. The comparison of the average diode current for 1.00-mm-diameter rods in MG-II and MG-III is plotted in Fig. IV.10, and shows to the
contrary that the diode currents recorded in MG-II were actually higher than those recorded in MG-III.

Fig. IV.10: Average diode current vs. time for 1.00-mm-diameter rods in MG-II and MG-III (using different diagnostics). Based on system specifications, the MG-III diode current was expected to exceed the MG-II diode current by a factor of 2.57.

The diode currents measured in MG-II were, on average, 2.37 times higher than those measured in MG-III ($D_0=1.00$ mm). Since the MG-III current should be 2.57 times higher than the MG-II current, data suggests that rod temperatures in MG-II were a factor of $2.37 \times 2.57 = 6.1$ higher than rod temperatures in MG-III. Temperature estimates from MG-I and MG-II data were consistent to within measurement accuracy, and no other diagnostics used in MG-III showed signs of reduced surface temperature. It is therefore highly unlikely that such a change in temperature occurred. If the discrepancy were simply due to mathematical error, multiplying by a constant would bring the curves into agreement. Fig IV.10 also includes the MG-III diode current multiplied by a factor of 2.37. The curve peaks now reach the same value, but the waveforms are significantly
different. The observed inconsistency is therefore not due to simple mathematical error.
An extensive performance study was conducted to determine the cause of the
disagreement. Results from this work are presented next, before reporting final surface
brightness temperature estimates.

**Diagnostic Performance and Calibration**

The first test of photodiode performance was to verify manufacturer responsivity
curves at low intensity. A “VLM High Quality Laser Diode Module” (Coherent Inc.,
Part No. 0222-482-00) emits 4.2 mW±4% at 635 nm and was used as a calibration
source. The laser beam cross section spans 5.0 mm×1.2 mm; larger than the active area
of the detectors (A5C-38: 4.39 mm×0.89 mm, BPX-65: 1.00 mm×1.00 mm). To ensure
all laser light reached the detector, the beam was focused through a \( f=1000 \) mm lens, with
the detectors placed one focal length behind the lens. Both detectors are capacitively
biased, and cannot measure the intensity of a CW source. Therefore, the CW output of
the laser diode was modulated with a spinning-mirror beam chopper. Assuming 8%
losses for both the lens and the beam chopper, nominally 3.55 mW reaches the detector.
Diode currents measured 1.32 and 1.36 mA for the MG-II BPX-65 diode and MG-III
A5C-38 array detector, respectively. For 635 nm light, the responsivity is 0.37 and
0.41 A/W for the BPX-65 and A5C-38 detectors, respectively (Fig. IV.8). The power
measured by each detector is therefore 3.57 mW (BPX-65) and 3.32 mW (A5C-38). The
slight differences between the measured and expected values are within the accuracy of
the test. Therefore, the diode response curves are accurate at low intensity (for red light).
Next, to test the linearity of photodiode response, a higher power laser was used to drive the detectors to higher diode current. With a stable source, the intensity delivered to the detectors can be systematically reduced by inserting well characterized ND filters into the beam path. The output power of the laser, as well as the wavelength dependent attenuation of the ND filters must be known. A NIST traceable (Thorlabs model PM1000) optical power meter system (coupled to a S121B silicon power meter optical head) was used for optical power measurements. The power meter is listed accurate to ±5%. As a first test, the output power of the 4.2 mW (±4%) VLM laser diode was measured. The damage threshold of the measurement device’s optical head is listed as 50 W/cm$^2$ (500 mW/mm$^2$). The average intensity of the low-power, large-cross-section beam of the laser diode is 0.7 mW/mm$^2$ (715 times below the damage threshold). The laser is therefore safe for direct incidence on the detector.

The VLM output, as measured by direct incidence to the power meter, fully stabilized to 4.429 mW after 10 minutes of continuous operation. With 5% measurement accuracy, the output power is known to lie between 4.21 and 4.65 mW. The laser output power (4.2 mW±4%) is between 4.0 to 4.4 mW. The two ranges of uncertainty overlap from 4.21 to 4.4 mW, so to within the device tolerances, agreement is gained. Since the power meter is NIST traceable, results from this instrument will be used, with 5% measurement uncertainty assumed.

Next, with the stable VLM laser diode source, multiple ND filters (Thorlabs Item number: NEK01S—Box of 10 unmounted absorptive 2" x 2" ND Filters of varying attenuation) were inserted into the beam path, and power levels were recorded. The ND filters were shown to match the manufacturer specified attenuation ratings to better than
±4%. Since the calibration was done for 635 nm light, and these values are not used in
the analysis to follow, further details are not given. Similar calibrations were completed
for 532 nm laser light; these results are used to calibrate experimental diagnostics, and
are discussed in detail next.

A 532 nm, 46.9 mW laser was used to drive the photodiodes to higher diode current.
To complete linearity tests, the ND filters must first be calibrated for this specific source.
Again, the NIST traceable power meter was used. The laser, with a 1.0 mm beam
diameter, has an average beam intensity of 64 mW/mm². This is only a factor of 7.8
below the damage threshold of the optical head of the power meter. The beam is not
perfectly uniform, and the highest intensity locations could exceed the damage threshold.
Therefore, to ensure the safety of the detector, the beam was expanded. As simple beam
expander in the “Galileo configuration” was used (Fig. IV.11(b)). The distance between
the two lenses is equal to the focal length of the converging lens minus the absolute value
of the focal length of the diverging lens; the beam is expanded by the ratio of the absolute
value of the two focal lengths. The lenses used were $f=-200$ mm and $f=750$ mm, so the
beam diameter expanded from 1.0 mm to 3.75 mm. The intensity therefore decreases by
a factor of $3.75^2=14$. The intensity of the expanded beam is then a factor of 110 below
the damage threshold. Since high intensity is not required for filter calibration, as a
further precaution, (for the safety of both instrumentation and personnel), the laser was
immediately attenuated by an ND filter, which was always in place during laser
operation. The final setup used for filter calibration is shown in Fig. IV.11(a).
The filters to be calibrated were placed in filter holder #2. When calibrating filters ND 2.0 and below, an ND 1.0 filter was mounted in filter holder #1, reducing the power level to below 5 mW (for safety). When calibrating higher ND filters, two laser shutters...
were first closed, and then the ND 1.0 filter was replaced with the higher order test filter.

Data for two rounds of testing are presented in Table IV.2.

<table>
<thead>
<tr>
<th>Filter ND</th>
<th>Tuesday Evening</th>
<th>Wednesday Morning</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P (mW): ND 1.0 only</td>
<td>P (mW): filter added</td>
</tr>
<tr>
<td>0.1</td>
<td>3.985</td>
<td>3.254</td>
</tr>
<tr>
<td>0.2</td>
<td>3.977</td>
<td>2.476</td>
</tr>
<tr>
<td>0.3</td>
<td>3.975</td>
<td>2.049</td>
</tr>
<tr>
<td>0.4</td>
<td>3.973</td>
<td>1.492</td>
</tr>
<tr>
<td>0.5</td>
<td>3.973</td>
<td>1.277</td>
</tr>
<tr>
<td>0.6</td>
<td>3.974</td>
<td>0.927</td>
</tr>
<tr>
<td>1.3</td>
<td>3.97</td>
<td>0.224</td>
</tr>
<tr>
<td>2</td>
<td>3.968</td>
<td>0.0295</td>
</tr>
</tbody>
</table>

Table IV.2: ND filter calibration to 532 nm laser light. The calibrated values for green light differ from manufacturer specified ND values more so than do the calibrated values for red light. This is to be expected, as the manufacturer specifies ND levels for 633nm light.

After calibrating the filter attenuation of a 532 nm laser source, linearity tests were conducted. The setup displayed in Fig. IV.12 was used. The signal was modulated using a fan blade as a beam chopper (instead of the much faster spinning mirror chopper, which was inoperable during the time of the tests). The slow fan blade resulted in a 10 µs rise-time of the laser pulse. This adversely affected the array detector tests, since the bias capacitance for each array element was only 2 nF. With such low stored charge \(Q=20 \text{ nC}\), the bias voltage was significantly reduced during the rise of the laser pulse. Array detector test data are therefore valid only for small diode currents (which require less stored charge). During the tests, it was clear which results were valid. As the edge of the fan blade sweeps through the beam profile, an increasing amount of light reaches the detector, and the diode current rises. Eventually, the full beam reaches the detector for a lengthy period of time (until the next blade enters the beam path). While the beam is unblocked, the photodiode current should remain constant. If the measured peak diode
current remains constant for some time, the diode is adequately biased. If the bias capacitor has been discharged to low voltage, after peak intensity has been reached (full beam), the diode current will immediately begin to fall exponentially. In these cases, the peak has been reduced by an unknown amount due to reduced bias on the diode. Only those data which show a period of constant current are included in this analysis.
Fig. IV.12: (a) Setup used for photodiode linearity testing. The output power of the 532 nm laser was observed to slowly, but continually decay. Therefore, the laser output power was measured immediately before and after the linearity tests (the detector head was removed during tests), bounding the output power of the laser to minimize the uncertainty associated with the laser decay. (b) Photodiode current as a function of calibrated ND level. The plot shows linear response of all detectors for low intensity light.
Fig. IV.12(a) displays a plot of diode current vs. calibrated ND value for 3 individual detectors. The plot includes data obtained with the BPX-65 diode used in MG-II, the A5C-38 detector used in MG-III, and a third detector, constructed from a previously unused BPX-65 diode. Diode current is plotted on a logarithmic scale (ND is also logarithmic). Sources of error include variation in laser output and errors in filter calibration. Data shows that, to within measurement accuracy, the BPX-65 detectors respond linearly for diode current up to at least 9 mA, while the array detector responds linearly up to at least 1 mA (the array detector could not be tested at higher current due to insufficient bias capacitance). Both experimental detectors have exhibited agreement with their manufacturer specified responsivity curves, and have also displayed linear response to low intensities. A higher intensity source is needed to test conditions closer to those experienced during the UNR-Megagauss Experiments.

To test the response of the detectors at experimentally relevant intensity, a fast strobe lamp was used. The lamp offers several advantages over the laser sources, including higher output power, faster pulse rise (~1 µs), and the elimination of (eye) safety hazards. The strobe emits light from an arc discharge. The arc measures approximately 1 mm × 5 mm and was one-to-one imaged through a single lens to the detector. A low f-number system, which subtends a large solid angle, was used to deliver high intensity to the detectors. The unlabeled lens had approximate characteristics of $f \sim 50$ mm and $D \sim 25$ mm.

Using the strobe system, the MG-II BPX-65 photodiode measured a maximum diode voltage of 12.2 V (244 mA on 50 Ω). This exceeds the diode currents measured in the UNR-Megagauss Experiments ($I_{\text{max}} \sim 150$ mA). Due to the excess intensity, a
Wratten #58 filter was placed in the optical path, making the test more relevant to the experimental data. The ND filters must again be calibrated, this time for the unknown spectral output of the strobe pulse through a Wratten #58 filter.

To calibrate, ND filters were placed in the path between the highly repeatable strobe pulse and the photodiode, and diode voltage curves (measured by a digitizer) were saved and plotted together on the same axis. Data was analyzed under the assumption that all strobe pulses were identical. The independent curves were multiplied by separate constants, chosen so that all curves overlapped the low diode current curve obtained when the strobe passed through ND 1.0 and ND 1.3 filters. Appropriate constants were found by using a least-squares-fit procedure. Only 150 ns of the rising edge of the pulses were fit to one another, since during these early times, illumination levels were sufficiently low to ensure that all data was acquired in the linear operating regime of the detector. The constants ‘C’ (found by the least squares fit) were then converted to “calibrated ND” values by evaluating $\log_{10}(C)$. Three series of tests were completed for each filter. The resulting ND filter values, calibrated for the Wratten #58 filtered strobe source are listed in Table IV.3.

<table>
<thead>
<tr>
<th>Specified ND</th>
<th>AVG Calibrated ND</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.087</td>
</tr>
<tr>
<td>0.2</td>
<td>0.179</td>
</tr>
<tr>
<td>0.3</td>
<td>0.329</td>
</tr>
<tr>
<td>0.4</td>
<td>0.338</td>
</tr>
<tr>
<td>0.5</td>
<td>0.389</td>
</tr>
<tr>
<td>0.6</td>
<td>0.510</td>
</tr>
<tr>
<td>1.0</td>
<td>0.876</td>
</tr>
<tr>
<td>1.3</td>
<td>1.222</td>
</tr>
</tbody>
</table>

**Table IV.3:** ND values calibrated for the Wratten #58 filtered strobe source.
With the calibrated ND values measured, the raw voltage curves were multiplied by $10^{\text{calibrated ND}}$, and plotted on the same axes. If the strobe output is perfectly repeatable, the filters perfectly calibrated, and the detector perfectly linear, the resulting curves should perfectly overlap. The results for the MG-II BPX-65 detector are displayed in Fig. IV.13.

**Fig. IV.13:** Curves obtained by flashing light from a fast strobe on the MG-II BPX-65 detector. Light passes through different ND filters to drive different levels of diode current. Data is then multiplied by $10^{\text{calibrated ND}}$. If the resulting curves overlap, the detector response is linear for the examined intensities.

The curves are labeled according to the manufactured specified ND values rather than the calibrated ND values for simplicity. The curves do not perfectly overlap as a result of detector nonlinearity, variable strobe output, improper filter calibration, or a combination of these. If the differences were due to nonlinearity, the least attenuated (highest intensity) curves should have the lowest peak voltage (at high intensity, nonlinearity will result in lower than expected diode current [75]). In Fig. IV.14, the peak value of each curve in Fig. IV.13 is plotted vs. the calibrated ND value of the filter used to obtain the
curve. The data does not depend on the attenuation level of the filter. Therefore, the spread in the data is due to random changes in the strobe output pulse, or other sources of measurement error, and not a result of photodiode nonlinearity. The peak voltages shown have a 1-sigma spread of 5.5%, which must be taken into account when determining the error associated with the calibration of the detector.

![Graph](image.png)

**Fig. IV.14:** Peak values of the curves in Fig. IV.13, plotted vs. the calibrated value of the ND filter used to obtain the curve.

Similar tests examined the MG-III photodiode array. For these high intensity tests, the 2 nF bias capacitor was replaced with a 100 nF capacitor. For low intensity pulses, no change in behavior was observed as a result of the change to the circuit. Applying the same procedure and analysis as described for the BPX-65 detector, the data plotted in Fig. IV.15 were obtained.
Fig. IV.15: Curves obtained by flashing light from a fast strobe on the MG-III A5C-38 detector. Light passes through different ND filters to drive different levels of diode current. Data is then multiplied by $10^{\text{Calibrated ND}}$. If the resulting curves overlap, the detector response is linear for the examined intensities.

The performance of the A5C-38 photodiode array is qualitatively different than that of the BPX-65 diode (compare Figs. IV.13 and IV.15). For the photodiode array, nonlinear response is observed for high intensity. Curves obtained at high intensity (low attenuation) fall below the other curves at early time. In Fig. IV.16, the peak value of each curve in Fig. IV.14 is plotted vs. the calibrated ND value of the filter used to obtain the curve.
**Fig. IV.16:** Peak values of the curves in Fig. IV.15, plotted vs. the calibrated value of the ND filter used to obtain the curve.

For filters with attenuation level ND 1.3 and above, the response is linear, as indicated by the small random variation in normalized peak voltage values. For lower attenuation (higher incident intensity) the detector responds nonlinearly, as indicated by the steady decline in normalized peak voltage with reduced attenuation. The data in Fig. IV.16 can be used to estimate the reduction in diode current associated with the observed nonlinear response, as a function of incident intensity. If the detector responds linearly for all light levels, the full curve would be nearly flat with only small deviations from a constant value. This constant value is approximately 19.98, and is found by averaging all data points (Fig. IV.16) from the linear operating regime (above ND 1.3). All peak voltage values are then divided by this average amount. This result is then plotted vs. the maximum voltage of the raw (non-normalized) curves in Fig. IV.17. The deviation from linearity begins when the peak diode voltage reaches ~1.5 V (~30 mA). The ratio then increases proportional to the diode voltage. The resulting reduction factor or “R-Factor” for data in the nonlinear regime (raw voltages 1.5V and above) is estimated by the linear trendline shown in Fig. IV.17.
The equation for the linear trendline (Fig. IV.17) defines the “R-factor” and gives a means to calculate expected deviation from linear response as a function of diode voltage. For voltages 1.46 V and above, the R-factor is found by inserting the measured voltage value \( V_M \) into the following equation (R-factor = 1 at 1.46 V).

\[
R - \text{Factor} = 5.23 \times V_M - 6.64
\]  

(IV.23)

This factor must be multiplied by the measured voltage to determine the voltage that would have been obtained had the detector responded linearly. Let the expected voltage (for linear response) be \( V_L \), then,

\[
V_L = \begin{cases} 
V_M (5.23 \times V_M - 6.64) = 5.23 \times V_M^2 - 6.64 \times V_M & \text{for } V_M > 1.46 \text{ V} \\
V_M & \text{for } V_M < 1.46 \text{ V} 
\end{cases}
\]

(IV.24)

Applying this simple formula to the data obtained in MG-III creates an unnatural transition between the raw and adjusted data. This is due in part to the simplistic application of the linear formula for the reduction factor (and the absence of any
correction below 1.46 V). A smoother transition is made if the two linear functions are bridged by a quadratic function. To find an appropriate quadratic function, let

\[ y_1 = 1 \]
\[ y_2 = 5.23 \cdot x - 6.64 \]
\[ y_{fit} = ax^2 + bx + c \]  \hspace{1cm} (IV.25)

Now, choose a point \( x_1 \) where:

\[ y_1(x_1) = y_{fit}(x_1) \quad \text{and} \quad \frac{dy_1}{dx}_{x=x_1} = \frac{dy_{fit}}{dx}_{x=x_1} \]  \hspace{1cm} (IV.26)

And a point \( x_2 \) where:

\[ y_2(x_2) = y_{fit}(x_2) \quad \text{and} \quad \frac{dy_2}{dx}_{x=x_2} = \frac{dy_{fit}}{dx}_{x=x_2} \]  \hspace{1cm} (IV.27)

By equating the functions and derivatives at the two points, the following four equations are found:

\[ 1 = ax_1^2 + bx_1 + c \]
\[ 5.23 \cdot x_2 - 6.64 = ax_2^2 + bx_2 + c \]
\[ 0 = 2ax_1 + b \]
\[ 5.23 = 2ax_2 + b \]  \hspace{1cm} (IV.28)

Solving these equations for the constant coefficients \( a, b, \) and \( c \) gives:

\[ a = \frac{2.615}{x_2 - x_1} \]
\[ b = -\frac{5.23x_1}{x_2 - x_1} \]
\[ c = 1 + 2.615 \cdot \frac{x_1^2}{x_2 - x_1} \]  \hspace{1cm} (IV.29)

The values where the functions meet (\( x_1 \) and \( x_2 \)) may now be chosen. In order for the functions and their slopes to be equal at a single point, the locations of \( x_1 \) and \( x_2 \) must be equidistant from 1.46 (1.46 is the value where \( y_1 \) and \( y_2 \) are equal). If \( x_2 - x_1 \) is small, the quadratic function will run very close to the two linear functions, and the transition is still unnaturally abrupt. If the \( x_2 - x_1 \) is large, the transition is smooth, but the quadratic
function no longer closely approximates the R-factor. The values ultimately chosen were $x_1=1.0$ V and $x_2=1.92$ V; therefore, $a=2.842$, $b=-5.685$, and $c=3.842$. With $x_1=1.0$, the raw voltage is unaltered below 1.0 V, and measurements are not manipulated for temperatures relevant to plasma formation (shown to be approximately 0.7 eV, or 95 mV). The quadratic function never deviates far from the linear functions, but creates a smooth transition between raw and corrected data. The final transform formulas are given by Eqns. IV.30.

$$V_L = \begin{cases} V_M & \text{for } V_M < 1.0 \text{ V} \\ V_M \times \left\{2.842 * V_M^2 - 5.685 * V_M + 3.842\right\} & \text{for } 1.0 < V_M < 1.92 \text{ V} \\ V_M (5.23 * V_M - 6.64) & \text{for } V_M > 1.92 \text{ V} \end{cases} \quad \text{(IV.30)}$$

Voltage profiles, averaged for each $D_0$, and corrected for nonlinearity, are plotted in Fig. IV.18. No correction is required for the 1.59 and 2.00-mm-diameter rods since they remain cool enough for linear response. The adjusted peak voltage for 1.00-mm-diameter rods is approximately 17 V. The peak voltage measured for 1.00-mm-diameter rods with the MG-II detector was approximately 6.5 V. This is in rough agreement with the expectation that the MG-III detector should record a diode current 2.57 times greater than the MG-II detector ($6.5 \times 2.57 = 16.7$). With the primary source of difference between MG-II and MG-III data discovered (nonlinear response of the MG-III detector), temperature vs. time results will now be presented.
Fig. IV.18: MG-III average diode voltages for different initial rod diameters. The data has been “corrected” to account for nonlinear photodiode response by applying Eqns. IV.30 to raw voltages.

Section IV.C: Brightness Temperature Calculation—MG-II & MG-III

Diode voltage data may be used to determine the brightness temperature of the radiating material at the rod surface. To do so, blackbody emission is assumed, photodiode responsivity and filter transmission curves (Fig. IV.8) are applied, and the geometric specifications shown in Table IV.1 are used. An Excel spreadsheet has been constructed to complete the brightness temperature calculation. First, a temperature is chosen. The spectral Planck distribution (Eqn. IV.12) is evaluated for this temperature in 10 nm increments. The responsivity and filter transmission percentage are also recorded every 10 nm and are then convoluted with the Planck distribution. The result is integrated over all wavelengths, arriving at the diode current per unit Steradian, per unit emitter area, for a blackbody at the chosen temperature, $T_{BB}$. This quantity is multiplied by the system specific solid angle and emitter area, as well as by 0.78 to account for
losses associated with transmission through the debris shield, vacuum chamber window, and lens. The resulting diode current is multiplied by 50 to convert current to voltage over 50 $\Omega$. Aside from entering the temperature, the spreadsheet completes this calculation automatically. Sets of tabulated data are generated, which allow conversion from measured diode voltage to estimated brightness temperature, for each diagnostic.

After subtracting the DC offset from the raw diode voltages (and applying the linearity correction to MG-III data), Excel’s vertical lookup function uses the tabulated data to convert from diode voltage to $T_{BB}(t)$. The tabulated data can be fit with polynomial equations (Eqns. IV.31). The equations show that the Raleigh-Jeans Law is valid for most of the data obtained, since for temperatures above 2 eV, voltage is linearly proportional to temperature

**MG – II**

\[
T[eV] = -10575 \times V^4 + 2730.9 \times V^3 - 262.81 \times V^2 + 15.696 \times V + 0.3686 \quad \text{for} \ 0 < T < 1.0
\]

\[
T[eV] = -1.2393 \times V^2 + 3.6533 \times V + 0.6385 \quad \text{for} \ 1.0 < T < 2.0
\]

\[
T[eV] = 2.53 \times V + 0.9 \quad \text{for} \ 2.0 < T < 5.0
\]

\[
T[eV] = 2.42 \times V + 1.06 \quad \text{for} \ 5.0 < T < 40
\]

**MG – III**

\[
T[eV] = -221.79 \times V^4 + 150.22 \times V^3 - 37.965 \times V^2 + 5.9689 \times V + 0.3686 \quad \text{for} \ 0 < T < 1.0
\]

\[
T[eV] = -0.183 \times V^2 + 1.397 \times V + 0.683 \quad \text{for} \ 1.0 < T < 2.0
\]

\[
T[eV] = 0.965 \times V + 0.89 \quad \text{for} \ 2.0 < T < 4.0
\]

\[
T[eV] = 0.925 \times V + 1.05 \quad \text{for} \ 4.0 < T < 40
\]

Finally, $T_{BB}(t)$ curves are obtained. Plotted in Fig. IV.19 are average $T_{BB}(t)$ curves for $D_0=0.50, 0.64, 0.80, 1.00, 1.25, 1.59$, and $2.00$ mm, from MG-III, and $D_0=1.00$ mm from MG-II. The $T_{BB}(t)$ data contains information related to the plasma formation time and variation in heating. Due to the increased uncertainty in the MG-III data associated with
nonlinear response, these features will be discussed in detail using MG-IV data.

**Fig. IV.19:** Average $T_{BB}(t)$ for $D_0=0.50$, 0.64, 0.80, 1.00, 1.25, 1.59, and 2.00 mm, from MG-III, and $D_0=1.00$ mm from MG-II. The MG-II data has been time shifted. The reason for this time shift is discussed in Section IV.D.

**Section IV.D: Brightness Temperature Calculation—MG-IV**

Due to the multiple sources of uncertainty introduced by the nonlinear response of the detector used in MG-III, results must be corroborated. A slight modification was made to the visible light radiometry diagnostic from MG-III to ensure that the detector operates linearly in MG-IV. Half of the active elements (1-8) were covered with an ND 1.3 filter (actually calibrated for white light, through a Wratten #58 filter at ND 1.222).
Fig. IV.20: Schematic of the diode array used in MG-IV. Half of the elements were covered with an ND 1.3 filter. The filtered elements remain at low intensity, and operate linearly. The unfiltered elements are able to measure low rod temperatures.

The factor of $10^{1.222}=16.67$ in attenuation due to addition of the filter reduces the diode current (elements 1-8) to levels below the measured onset of nonlinearity at ~30 mA. Unfiltered elements will respond nonlinearly at high temperatures (as in MG-III), but operate linearly with high signal-to-noise ratio at low (<2 eV) temperatures. This configuration allows examination of low rod temperatures with the unfiltered elements, and also peak plasma temperatures with the filtered elements. If the signal had been reduced for all diode elements (by, for example, reduction in solid angle) low temperature data would have been indistinguishable from noise. To correlate the data between the two sections of the diode array, it is assumed that $T_{BB}$ are comparable along the full length of the rod. This has been confirmed by data from MG-III as discussed in Section III.C.
The MG-IV setup allows for a direct check of the non-linearity correction applied to the MG-III data. Using data from a single shot, voltages from filtered elements (1-8) and unfiltered elements (9-15) are averaged. The average filtered voltage is then multiplied by 16.67 to account for the ND filter attenuation (Fig. IV.21, red curve), while the average unfiltered voltage is “corrected” using formulas IV.28 (Fig. IV.21, purple curve). Assuming that the top and bottom halves of the rod are at the same temperature, the two curves should overlap if the correction formulas and ND filter calibration are correct. Fig. IV.21 displays data for the 8 shots which allowed this direct comparison to be made.
Fig. IV.21: The configuration of the array detector in MG-IV allows the validity of the nonlinearity correction formulas (Eqns. IV.28) to be directly evaluated. If the formulas are valid, the purple and red curves should match well.
Two features of the data in Fig. IV.21 are noted:

1. The time axes have not been shifted to the standard $I(100 \text{ ns})=500 \text{ kA}$

2. For the 0.50 and 0.80-mm-diameter rods, an aperture was placed in the system to further decrease the incident intensity (the ND 1.3 filter, which was difficult to replace, did not attenuate enough for the array to operate linearly at peak temperature for these rods). Therefore the conversion from voltage to brightness temperature is not the same for these rods and the 1.00-mm-diameter rods (see “small aperture” and “large aperture” columns of Table IV.1).

The data in Fig. IV.21 shows that the nonlinearity correction formulas are reasonably successful in recovering peak temperatures. However the nonlinear response is found to reduce the slope of the rising diode current. This creates an increasing time-lag which was not accounted for in the correction formulas. This is the largest remaining error associated with the observed nonlinearity of the MG-III measurement.

The filtered elements of the MG-IV detector were operated at low enough intensity to ensure linear response. Therefore, the errors associated with the linearity correction are eliminated from the MG-IV data. To convert from diode voltage to temperature, methods similar to those described in Section IV.B are applied. In MG-IV, the aperture which defined the system solid angle was smaller for 0.50 and 0.80-mm-diameter rods than for 1.00 and 2.00-mm-diameter rods. Separate conversion tables have been generated for the two setups. This information is included in Table IV.1. The photodiode responsivity and filter transmission curves shown in Fig. IV.8 are again used in the MG-IV temperature calculation. Finally, the data from filtered cells (1-8) are multiplied by 16.67 before converting to temperature to account for filter attenuation. Conversion to temperature is completed using tabulated data and Microsoft Excel’s “vlookup” function. Again, the tabulated data have been fit with polynomials (Eqns. IV.32).
**MG—IV**

**Small Aperture**

\[
T[eV] = -4743.2 \cdot V^4 + 1493.9 \cdot V^3 - 175.57 \cdot V^2 + 12.836 \cdot V + 0.3686 \quad \text{for } 0 < T < 1.0
\]

\[
T[eV] = -0.8465 \cdot V^3 + 3.0043 \cdot V + 0.638 \quad \text{for } 1.0 < T < 2.0
\]

\[
T[eV] = 2.0986 \cdot V + 0.8955 \quad \text{for } 2.0 < T < 4.0
\]

\[
T[eV] = 1.9915 \cdot V + 1.0897 \quad \text{for } 4.0 < T < 40
gpe (IV.32)
\]

**Large Aperture**

\[
T[eV] = -328.17 \cdot V^4 + 201.53 \cdot V^3 - 46.18 \cdot V^2 + 6.5831 \cdot V + 0.3686 \quad \text{for } 0 < T < 1.0
\]

\[
T[eV] = -0.2227 \cdot V^3 + 1.5408 \cdot V + 0.638 \quad \text{for } 1.0 < T < 2.0
\]

\[
T[eV] = 1.0763 \cdot V + 0.8955 \quad \text{for } 2.0 < T < 4.0
\]

\[
T[eV] = 1.0215 \cdot V + 1.0889 \quad \text{for } 4.0 < T < 40
\]

The MG-IV \( T_{BB}(t) \) curves in Fig IV.22:(a-e) are obtained. Figures IV.22:(a-d) show \( T_{BB}(t) \) for rods with similar initial diameter. In Fig. IV.22:(e), the average \( T_{BB}(t) \) for all initial rod diameters are plotted together.
Fig. IV.22: (a) MG-IV $T_{BB}(t)$ for $D_0=0.50$ mm rods. (b) MG-IV $T_{BB}(t)$ for $D_0=0.80$ mm rods. (c) MG-IV $T_{BB}(t)$ for $D_0=1.00$ mm rods. (d) MG-IV $T_{BB}(t)$ for $D_0=2.00$ mm rods. (e) MG-IV average $T_{BB}(t)$ for $D_0=0.50$, 0.80, 1.00, and 2.00 mm rods.
The following comments are made with regard to the data in Figs. IV.22:(a-e):

1. Similar to the data from MG-III (Fig. IV.19), plasma forms earlier and reaches higher temperature for smaller rod diameters.

2. For those rods which form plasma, temperatures quickly rise to greater than 10 eV. Peak temperatures are slightly higher in MG-IV than in MG-III. This is likely the result of inaccuracies in the MG-III data associated with photodiode nonlinearity, however, the increase in the average peak Zebra current from 990 kA (MG-III) to 1050 kA (MG- IV) could also play a role. Furthermore, if the ND filter is inaccurately calibrated, errors will result.

3. The 2.00-mm-diameter rods remain cool, with peak $T_{BB}=0.7$ eV. Due to the low level of radiation emitted from these cool rods, the data has relatively poor signal-to-noise ratio.

4. As shown in Figs. IV.22:(a-d), $T_{BB}(t)$ data for rods with similar initial diameter compare quite well. Temperatures rise above the noise at nearly the same time and reach approximately the same maximum value. The consistency of $D_0=1.00$ mm data is higher than that of $D_0=0.50$ mm data, likely due to the increased machining consistency for larger diameter rods. The strong agreement in the time of first light emission for the $D_0=0.80$ mm rods is not physical. Data for $D_0=0.80$ mm rods were obtained in the final four shots of MG-IV. In those shots, data was acquired by a Zebra staff member who failed to properly acquire select digitizer channels. As a consequence, no $T_{BB}(t)$ data is available for shot 1898, and no Zebra current time-base is available for shots 1896 and 1897. The data from shot 1899 was acquired correctly, and the curve is properly timed to the Zebra current. The other curves are simply time shifted so that the rising edges of all light pulses align with the rising edge of shot 1899.

Finally, data from unfiltered cells (9-15) allow inspection of low temperature behavior. Shown in Fig. IV.23 are $T_{BB}$ profiles for 0.50 and 1.00-mm-diameter rods (MG-IV). This data allows inference of the plasma formation time. The data is shown here for completeness, but is not currently discussed in detail. Low temperature data will be discussed primarily in Ch. VII, and used to determine the time of thermal plasma formation. Low temperature measurements will also be discussed briefly during the analysis of extreme ultraviolet diode data (Ch. V).
**Fig. IV.23:** Low temperature measurements for 0.50 and 1.00-mm-diameter rods (MG-IV). This data will be discussed in detail in Chapters V and VII.
Chapter V: Measurement of Extreme Ultraviolet Emission

Extreme ultraviolet (EUV) diagnostics, fielded in MG-III and MG-IV, enable determination of the composition and ionization state of surface plasma. Data also confirm the high temperatures inferred from visible light radiometry. First, a McPherson Model 310/g grazing incidence spectrometer, equipped with a multi-strip multichannel plate detector (MCP) is sensitive to photon energies in the band from 70 to 150 eV (8 to 18 nm). The spectrometer is capable of resolving $\lambda/\Delta\lambda \approx 400$ at $\lambda = 30.4$ nm when the entrance slit is set to 30 $\mu$m (at $\lambda = 11.0$ nm, $\lambda/\Delta\lambda \approx 300$) and observes line emission from Al$^{3+}$ and Al$^{4+}$ ions. Second, broadband EUV photodiodes, filtered with 200 nm of Al or 100 nm of Si and 200 nm of Zr, are sensitive to photon energies from 16 to 73 eV, or 60 to 100 eV, respectively. The diodes record an EUV photon flux consistent with multi-eV temperatures.

EUV diagnostics were primarily designed and fielded, and their data analyzed by Professor S. Fuelling of the UNR Physics Department. Detailed descriptions of the diagnostic and analysis have been presented in unpublished reports [76], and only a general description of this work is presented here. This chapter focuses on Professor Fuelling’s results, and their application to increased understanding of the experiment as a whole. The chapter begins with a brief description of the broadband EUV photodiodes. The data from these diodes is used to confirm the plasma formation time and material temperatures measured by visible light radiometry. Next, an overview of the EUV spectrometer is presented, and the acquired spectra discussed. While the identified ion species (Al$^{3+}$ and Al$^{4+}$) are sensible considering the temperature of the rod surface, several (perhaps) unexpected results are obtained. First, while emission lines are
observed for $D_0=0.80$ mm and $D_0=1.00$ mm rods, absorption spectra are observed for smaller rods, suggesting that a high temperature “core” may be backlighting a cooler, yet ionized, plasma sheath. Also, while temperature estimates obtained by evaluating line-intensity ratios are consistent with 15 eV plasma (similar to inferred temperatures by other diagnostics), the line ratios remain approximately constant; that is, for all spectra obtained, the intensity ratio of Al$^{3+}$ and Al$^{4+}$ lines is essentially the same, with no observed dependence on $D_0$, or on the level of the Zebra current. This suggests constant plasma temperature, in disagreement with the continually varying temperatures deduced from other measurements. The chapter will include detailed discussion of these, and other results from the EUV diagnostics.

Section V.A: EUV Photodiodes

Four silicon photodiodes with directly deposited filters measure higher energy photons. Two of the photodiodes are filtered with a 200 nm layer of Al while two others are filtered with 100 nm of Si and 200 nm of Zr. Detected photon energies range from 16 to 73 eV, or 60 to 100 eV, respectively. The diodes, purchased from International Radiation Detectors, Inc. (IRD) have 1.0 mm × 1.0 mm active area. The filters are directly deposited and “light tight” in that all photons must pass through the filters to be detected. In MG-III, the diodes were mounted approximately 40 cm from the rod, while in MG-IV (due to the high intensities observed in MG-III) the diodes were to 5 m from the load. Due to the close proximity between the diagnostic and the load, the MG-III setup required static debris shielding. To accomplish this, four fused-silica capillaries from Polymicro Technologies, LLC were placed directly in front of the diodes. The
capillaries, with an inner diameter of 0.70 mm are mounted in V-grooves which have been machined into an aluminum cylinder. All capillaries point to the center of the rod, as directed by the V-grooves, which are aligned with an axially centered laser pointer. The V-grooves, and the capillaries are slightly curved. Therefore, the debris from the load is deposited inside the capillary before reaching the photodiode while, after multiple grazing-incidence reflections inside the capillary, the EUV radiation reaches the photodiode. The MG-III diagnostic setup is shown in Fig. V.1. In the MG-IV setup, with the diodes positioned 5 m from the load, a fast pneumatic valve shields debris, and the capillaries are removed from the system.

**Fig. V.1:** (Drawing courtesy of Professor S. Fuelling) Cut-away view of the EUV photodiode array. The curved capillaries, which mount in a curved V-groove, point to the rod surface. Debris is deposited along the inner capillary surface. EUV radiation reaches the photodiodes via multiple grazing-incidence reflections along the capillary inner surface. The silicon chips of the EUV photodiodes are mounted directly onto vacuum SMA feedthroughs. The filter material is directly deposited onto the SMA/photodiode assembly. The EUV photodiodes are mounted on an ISO 60 blank flange.
EUV emission reaches measurable intensity only after visible light radiometry measurements indicate the brightness temperature exceeds 2.0 eV. A lower bound on the surface temperature of the rod has been estimated by measuring the spectral radiation intensity escaping the rod and calculating $T_{BB}(t)$ using the Planckian blackbody formula (see Ch IV). An optically thin body radiates less than a perfect blackbody; therefore, $T_{BB}$ underestimates the actual temperature by an amount related to the optical depth of the evolving surface material [71]. This underestimate is more severe for higher energy photons, which have longer mean free path, and the material is therefore more optically thin. Nonetheless, the higher energy EUV photon flux should increase with temperature, and for the dense plasma under consideration, emission should remain low until temperatures exceed approximately 1 eV and plasma has formed (see Section IV.A for a discussion of the distribution of photon energies as a function of blackbody temperature).

Shown in Fig. V.2 are averaged EUV diode voltage traces and $T_{BB}$ curves for $D_0=0.50$ mm and $D_0=1.00$ mm 6061-alloy Al rods (MG-IV). The MG-IV $T_{BB}(t)$ curves could be replaced with MG-III curves, with no effect on this analysis, since the low temperature behavior of $T_{BB}$ for MG-III and MG-IV are nearly identical (agreement to within 2 ns, to be discussed in Ch. VII). EUV curves differ from MG-III to MG-IV; changes to the diagnostic setup allow much higher intensity to reach the MG-III detector. The reduced MG-IV voltages rise above the noise later in the current rise; however, even in MG-III the EUV signals rise after the visible diode signals. Two $T_{BB}$ curves are shown for each load diameter, since low temperature and high temperature measurements are inferred from filtered (relatively low incident intensity, measures high $T_{BB}$) and unfiltered
(relatively high incident intensity, measures low $T_{BB}$) sections of the visible photodiode array (see discussion in Section IV.D). Comparison of the EUV voltages, and the low temperature $T_{BB}$ measurements show that detectable EUV emission is observed only after $T_{BB}(t)$ exceeds 2.0 eV.

**Fig. V.2:** Visible light $T_{BB}(t)$ [eV] curves and Al-filtered EUV diode $V(t)$ curves. Data for 0.50 and 1.00-mm-diameter rods are included. The Zebra current is also plotted. At low temperature, the abrupt increase in $\partial T_{BB}/\partial t$ indicates the formation of surface plasma (see Ch. VII). EUV emission is observed only after plasma has formed and $T_{BB}$ exceeds 2.0 eV.

EUV emission is observed only after $T_{BB}$ exceeds 2.0 eV, in agreement with simple analysis. Order-of-magnitude estimates of the diode current expected for a given material temperature may be completed. Similar to temperature estimates made from visible light radiometry, the Planck distribution (blackbody emission) is used to define the emission intensity in the spectral range of the EUV diodes. For visible light, support of the blackbody assumption is obtained experimentally (time-resolved spectroscopy) and
computationally (simulation estimates of the photon mean free path suggest the blackbody approximation is reasonable for visible radiation [77]). For EUV emission, the distribution of radiation is clearly not governed by the blackbody formula, as line emission is observed via spectroscopy (details in Section V.B). Nonetheless, for this simple estimate, blackbody emission is assumed. The spectral response of the detectors is well known, and shown in Fig. V.3. For this approximation, only the Al-filtered diodes are considered, and their responsivity is assumed constant at 0.12 A/W for photon wavelengths ranging from 17 to 78 nm. Zero sensitivity is assumed for photon wavelengths outside this spectral range.

Fig. V.3: Spectral responsivity curves for Al and Si/Zr filtered EUV photodiodes used in MG-III and MG-IV.

Next, estimates of the system solid angle and viewed emitter area are made. In MG-III, the diodes were mounted behind glass-capillary debris shields, which define the solid angle of the system. The cross sectional area of the capillary opening is 3.85×10^{-7} m^2, and is located approximately 0.3 m from the rod surface. The system solid angle is then:
\[ \Omega = \oint_S \frac{\hat{n} \cdot da}{R^2} = \frac{\text{Capillary Open Area}}{(\text{Source Distance})^2} = \frac{3.85 \times 10^{-7} \text{ m}^2}{(0.3 \text{ m})^2} = 4.3 \times 10^{-6} \text{ SR} \quad (V.1) \]

A loss of 50% is assumed for propagation down the capillaries. The setup allows radiation from the full length of the rod to reach the detector. Therefore, the emitter area is given by the rod diameter (1.00 mm) multiplied by the rod length (7.0 mm), or \( A_E = 7 \times 10^6 \text{ m}^2 \). These numbers may be used, along with the detector responsivity (Fig. V.3) and the blackbody formula (Eqn. IV.12) to approximate expected Al-filtered EUV diode voltages as a function of temperature. Fig. V.4 presents the expected diode voltage vs. rod temperature based upon this analysis. The two curves are identical, however, the blue curve is plotted for the primary vertical scale and shows low temperature behavior, while the red curve is plotted for the secondary vertical scale and shows high temperature behavior. At lower temperature (blue curve), the diode bandpass is at higher energy than the distribution, so the signal grows exponentially with increasing temperature (Wien’s Displacement Law). At high temperature (red curve), the diode bandpass is at lower energy than the distribution, so the signal grows linearly with increasing temperature (Rayleigh-Jeans Law).

To extend this analysis to the MG-IV setup, the voltage is reduced by a factor proportional to the ratio of system solid angles \( \Omega_{MG-IV} = 4 \times 10^{-8} \) and increased by a factor of 2 due to the removal of the capillaries. Therefore, the MG-IV signals are expected to be roughly \( 2 \times (4e-8/4.3e-6) = 1.9\% \) of the MG-III signals.
Fig. V.4: Al-filtered EUV diode voltage vs. temperature for the setup used in MG-III, based upon simple estimates.

The diode voltage at low (<7 eV) temperature displayed in Fig. V.4 explains two features common to the MG-III EUV diode signals. First, the Al-filtered EUV diode signals rise to observable voltage only after brightness temperatures reach several eV. The expected diode voltage at 1 eV is only 3 µV, but by 2 eV, the expected signal increases several orders of magnitude to a measurable 20 mV. By 7 eV, the anticipated diode voltage has reached the limiting photodiode bias voltage of 50 V. Saturation at or before 50 V is commonly observed in MG-III data, however, signals sometimes do not reach the saturation voltage. The simple analysis considered here would suggest that the diode should always saturate. Possible reasons that the EUV photodiodes do not saturate are:

1. Rough estimates were made, particularly with respect to the capillaries. However, any errors associated with geometry and/or loss should affect the entire $V(T)$ curve, not just the high temperature portions of the curve. Transmission through the capillary could, however, be a strong function of photon frequency.
2. Assuming blackbody emission gives a lower bound of the material temperature. Or, from the opposite perspective, assuming blackbody emission gives an upper bound of the diode voltage. Therefore, as the material becomes increasingly optically thin to higher energy photons, the diode measurements may fall well below that expected for blackbody emission. This effect could become more pronounced as the material temperature increases, since higher temperatures may correlate with decreased edge density of the radiating plasma.

3. The diodes were not replaced after every shot and may sustain damage during a shot. The photodiodes were exposed to pulsed intensities far higher than they were designed for. Damage may occur from exposure to such high intensities, effecting performance on the subsequent shot. This issue could be examined experimentally by comparing the response of new diodes to those which have previously been exposed to the high intensity and harsh EMI environment present during a Zebra shot.

Although questions concerning the EUV photodiode data remain, the diodes do show an EUV photon flux consistent with multi-eV temperatures. The EUV diodes rise only after visible light radiometry measurements suggest surface temperatures have exceeded approximately 2.0 eV. Therefore, although work is required to interpret a temperature from the EUV diode measurements, they are confirmatory that multi-eV plasma exists on the rod surface.

Section V.B: EUV Spectroscopy

EUV emission is measured by a McPherson Model 310/g grazing incidence spectrometer equipped with a six-strip MCP (Model 40.6-MCPH, from X-ray Specialty Instruments). The MCP strips are DC biased to 400 V. An electronic gate increases the voltage to 900 V for 5 ns, activating the MCP strips. Cables are used to delay the time between the gating of each strip by 10 ns. Only the four center strips of the MCP are illuminated in the experimental setup, allowing 4 spectral “snapshots” over the course of
30 ns. The spectrometer, with a 600 g/mm iridium coated grating with a blaze angle of 2° (blaze wavelength at 10.14 nm) was sensitive to photon energies in the band from 70 to 150 eV (8 to 18 nm). Gold strips coated with CsI on the photocathode improve sensitivity in the EUV. The MCP phosphor is coupled to a 3:1 fiber optic reducer and then lens-coupled with two F/1.2 Nikkor camera lenses to a Peltier-cooled CCD camera (Finger Lakes Instruments, Max Cam-II). The CCD camera is equipped with a 1-mega pixel Marconi chip CCD47-10 with a 16-bit A/D converter achieving 14-bit dynamic range. The MCP-CCD assembly is shown in Fig. V.5.

**Fig. V.5.** (Drawing courtesy of Professor S. Fuelling) MCP-CCD assembly. Six SMA connectors at that back flange of the MCP-CCD assembly provide electrical connection to the MCP strips. Input power passes an EMI filter. The CCD camera is controlled via a 20 m long fiber optic USB Extender (Model M2-100 from Opticis). The trigger is delivered to the Max-Cam II controller via a fiber optic cable (after conversion to 5 V TTL).
The MCP is assembled to a 4 5/8” Conflat flange that houses the 3:1 fiber optic reducer, the high voltage vacuum feedthrough for the phosphor, and the six MCX type coaxial miniature RF connectors for the six MCP strips. A 3” diameter, 5-m-long beam tube vacuum-couples the spectrometer to the Zebra vacuum chamber. A bellows near the chamber decouples the instrument from mechanical stresses and shocks. Near the spectrometer is a fast pneumatic valve, which closes after EUV emission is recorded, but before debris reaches the spectrometer, protecting the instrument (and the EUV photodiodes in the MG-IV configuration).

The spectral region between 8 and 18 nm is recorded. This region is chosen because it contains spectral emission lines from Al$^{3+}$, Al$^{4+}$, and Al$^{5+}$ (Al IV, V, and VI). Furthermore, the grating efficiency drastically decreases below 8 nm. Increased background from zero order light hitting the MCP assembly becomes dominant below 8 nm. The selected spectral range is ideally suited for the temperature of the aluminum plasma formed in the UNR-Megagauss Experiments.

Careful signal processing is required to interpret spectra from the CCD images. Images are first background subtracted to remove the effects of both stray light and x-ray artifacts. X-ray photons incident upon the CCD create saturated pixels. After integration, these pixels create unit-width peaks, which mimic spectral lines, and therefore must be removed. After mapping the CCD column number to a wavelength scale, spectral images are converted to EUV spectra. Professor Fuelling’s calibration work included:

1. Correction to the ideal dispersion formula for a grazing incidence spectrometer due to the projection onto the flat MCP surface.
2. Correction for errors in the spectrometer input angle, grating tilt and offset, MCP location, tilt, and offset with respect to the Rowland circle, etc.

3. Correlation with data from measurements of other “test spectra,” at other wavelengths.

Professor Fuelling found the spectral features of the aluminum ions to be correctly identified using the web-based NIST atomic database [78]. Only spectra from Al$^{3+}$ and Al$^{4+}$ ions were observed in the spectral range between 8 nm and 18 nm. Impurity lines from, for example, magnesium, oxygen or carbon, could not be identified (possibly due to the overall weak recordings). Spectra from a 1.00-mm-diameter barbell load are shown in Fig. V.6. The data is obtained near peak current (peak temperature), where the emission is highest. Included in the plot are calculated spectra from PrismSPECT [79], a commercial collisional-radiative spectral analysis code, which was used to estimate the plasma temperature. Temperature estimates from spectroscopy are discussed in Section V.C.
Fig. V.6: (Data courtesy of Professor S. Fuelling) Average EUV spectra, gated near peak current, from $D_0=1.00$ mm 6061-alloy Al barbell loads in knife-edge hardware. The data (thick line) are presented along with a PrismSPECT-calculated spectrum for 15 eV temperature (thin line) and the wavelength and magnitude of Al$^{3+}$ and Al$^{4+}$ lines obtained from the NIST Atomic Spectra Database (vertical dashed lines). PrismSPECT calculations assume a 1.0 µm thick plasma layer with density $5\times10^{-3}$ g/cm$^3$.

Emission lines dominate the spectra of 1.00-mm-diameter rods, as displayed in Fig. V.6. In contrast, rods with $D_0$ of 0.50 and 0.64 mm often display absorption spectra (Fig. V.7). Absorption spectra will only exist if radiating material below the surface acts to “backlight” cooler surface material. The cooler surface material must remain ionized, since the absorption lines are at wavelengths related to Al$^{3+}$ and Al$^{4+}$ ions. It has been hypothesized that such a temperature profile may exist for smaller diameter rods (and not larger rods) due to the turbulent interchange with magnetic field that occurs for the highly unstable small diameter rods. While this may be the case, it is interesting to note that the
1D modeling (which cannot include instability effects) of Professor Garanin of VNIIEF has shown a “double peaked” temperature profile (even for 0.50 and 1.00-mm-diameter rods) with the interior peak approximately 100-200 µm below the rod surface at $t=200\text{ ns}$ [80]. His simulations suggest that the interior temperature peak is at slightly lower temperature than the surface plasma. Nonetheless, the qualitative description of the temperature profile is interesting. This configuration could create the “backlighter effect” necessary to produce absorption spectra. Further work is required to determine why smaller diameter rods should develop such a temperature distribution. Furthermore, even if high temperature aluminum plasma exists below the surface, it is not clear that the opacity of the surrounding material should allow these photons to escape the surface. Extensive modeling work is required to unfold these complex interactions.

**Fig. V.7:** (Plot courtesy of Professor S. Fuelling) Spectra of 0.50 and 0.64 mm rods show absorption lines. Larger diameter rods display emission spectra. Lines from the NIST database [77].
Section V.C: Temperature Estimates via Spectroscopy

Analysis of the intensity ratio of lines present in EUV spectra allow the temperature of the radiating material to be inferred. The average ion charge and line intensity ratios depend strongly upon temperature [77]. Therefore, the ratio of measured line intensities can be used to deduce material temperatures. Displayed in Fig. V.8 are ionization fractions calculated in PrismSPECT for a 1.0-µm-thick layer of \(5 \times 10^{-3}\) g/cm \(\rho_0/540\) density Al.

![Simulation Parameters: Density: 5x10^-3 g/cm^3, Thickness: 1 µm, Non-LTE](Plot courtesy of Professor S. Fuelling) Ionization fraction as a function of plasma temperature from PrismSPECT, assuming radiation originates from a 1-µm-thick layer of \(5 \times 10^{-3}\) g/cm density Al.

**Fig. V.8:** (Plot courtesy of Professor S. Fuelling) Ionization fraction as a function of plasma temperature from PrismSPECT, assuming radiation originates from a 1-µm-thick layer of \(5 \times 10^{-3}\) g/cm density Al.

Experimental data is well matched (Fig. V.6) to simulation results when \(T=15\) eV. The temperature estimate is in agreement with visible light radiometry measurements (see Ch. IV). However, spectra obtained at different times, for different rod diameters, also show line-intensity ratios which correspond to 15 eV Al plasma. This does not agree with visible light radiometry results which show continuously changing surface
temperature and, for example, 35 eV peak temperature for $D_0=0.50$ mm rods. Several hypotheses have been proposed to describe the constant 15 eV temperature estimated by EUV spectroscopy:

**Hypothesis #1:** The increasing temperature inferred from visible light measurements is not due to increasing plasma temperature, but rather due to an increasing fraction of the rod surface area being converted to plasma.

This is conceivable, since the visible photodiode array determines a spatially averaged temperature for a rather large surface area of $1.26 \times 10^{-7}$ m$^2$. Also, recall (see Ch. III) that near the time of plasma formation ICCD images first show hot spot emission, which gradually becomes spatially uniform (Fig. III.19, re-displayed below). Fig. V.9 displays 60,000 pixel histograms for rod sections of each of the upper two images displayed in Fig. III.19. The images chosen (1878-early and 1877-early) may be compared directly, since both images are from the delayed ICCD optics, both used an ICCD gain of 225, and both used the same laser line filter. Comparing the histograms, two conclusions are immediately drawn: (1) An increased number of pixels are illuminated in the later image. (2) The brightest pixels are much brighter in the later image than in the earlier image (increased plasma temperature). Data from these images do not support hypothesis #1. Since each ICCD pixel also integrates over a finite surface area, the hypothesis is not fully refuted; however, it appears highly unlikely that constant temperature (but growing surface area) plasma exists.
Fig. III.19: ICCD images of $D_0=1.00$ mm rods detail features of rod surface emission. The rod first emits light from bright hot spots. These hot spots give way to a fracture pattern. The rod surface becomes progressively more uniform as the Zebra current increases.

Fig. V.9: Histograms of the upper two images in Fig. III.19. The histograms show that as the Zebra current increases, more cells are illuminated, and the counts per pixel increases (increased plasma temperature).
**Hypothesis #2:** Emission lines do not originate from the rod surface, but rather originate from arcing contacts, or other plasmas in the Zebra chamber.

This is possible, since the configuration of the spectrometer allows radiation from areas far from the rod surface to reach the grating. Spectral measurements are composed of both continuum background and line spectra. As the rod heats, the background continuum grows, but the line-intensity ratio does not change. Therefore, perhaps the growing continuum is due to the increasing temperature of the rod surface, while the line emission is due to some peripheral (nearly constant temperature) radiation source. This hypothesis is unlikely, since 2.00-mm-diameter rods, which do not reach temperatures sufficient for measurable EUV emission, show no spectral lines. This suggests that line emission does indeed originate from the rod surface; therefore, hypothesis #2 is likely unfounded.

**Hypothesis #3:** The material conditions assumed in the PrismSPECT calculation should be altered both as a function of time, and for different initial rod diameters.

In all cases, calculations assume radiation originates from a 1.0-µm-thick layer of $5 \times 10^{-3}$ g/cm density Al. These conditions undoubtedly are imperfect for any $D_0$ and should be altered to account for the different surface parameters of different $D_0$. While simple estimates would assume little change in surface material associated with rod diameter, the observation of emission spectra from 1.00-mm-diameter rods, but absorption spectra from 0.50 and 0.64-mm-diameter rods, shows that reality is far more complex. Large changes in plasma density or plasma layer thickness would alter the temperature associated with a given line-intensity ratio (although temperature is the
dominant parameter). Further theoretical and computational work is required to test this hypothesis.

The newly fielded EUV diagnostics have confirmed the high temperatures and plasma formation times observed by visible light radiometry, and have allowed ion species present in the aluminum plasma to be identified. These diagnostics have provided irrefutable evidence of bulk plasma heating and the presence of Al plasma. Further theoretical and computation effort is warranted to understand the surface conditions which enable absorption spectra. Also, continued efforts are required to understand the constant temperature result obtained by evaluating line-intensity ratios.
Chapter VI: Surface Expansion and Stability

Time resolved measurement of the rod radius as a function of time, $R(t)$, is used to calculate such quantities as the radial expansion velocity and surface magnetic field strength. In the UNR-Megagauss Experiments, time-resolved measurements of $R(t)$ have been made with three diagnostics:

1. Laser shadowgraphy—Two shadowgrams of the rod per shot in MG-(I-IV)
2. Visible light gated imaging (ICCD)—One image per shot in MG-(I-II); Two images per shot in MG-(III-IV)
3. Visible light streaked radial expansion—Continuous measurement of $R(t)$ at a single axial rod location in MG-(I-III)

Diagnostics which measure self emission (ICCD and streak) detail the radial edge of the outermost radiating material. Shadowgrams detail the edge of the outermost absorptive material. Whether or not these two edges coincide depends upon the optical depth and other radiative properties of the surface material. To within experimental accuracy, the emitting edge and absorptive edge coincide, however, there is evidence that absorptive material may exist at a slightly larger radius than the outermost emitting material.

This chapter begins with a description of the laser shadowgraphy and streaked-expansion diagnostics (for details on the ICCD diagnostic, see Ch. III). The methods for analyzing the images from each diagnostic are discussed, and data are presented. The rate of radial expansion and particularly the occurrence of radial acceleration show the effect of surface plasma. Next, data on z-pinch instabilities are presented. As instabilities can be “seeded” by surface irregularity, instability formation on precision
machined rods (LANL) is compared with instability formation on rougher, locally machined rods.

Section VI.A: Diagnostic Overview

Laser Shadowgraphy

Laser shadowgrams are created by backlighting the rod with a short pulse of visible laser light. The plane of the rod is imaged to multiple CCD cameras, obtaining digital shadowgrams. The backlighter source is an Ekspla manufactured Class IV Nd:YAG (532 nm) laser (referred to in this text as “Ekspla”) [81]. Ekspla delivers a maximum energy of 100 mJ in a 150 ps pulse. The laser pulse is split at multiple locations, traveling separate and different optical path lengths, allowing images to be captured at several times. The optics are capable of generating interferograms and schlieren images. However, as discovered in MG-I, due to the sharp density gradient at the edge of the rods surfaces, these more advanced diagnostic techniques provided little additional information. Therefore, in MG-(II-IV) only the shadowgraphy diagnostic was fielded. Typically, four shadowgrams per shot are obtained, only two of which are at high resolution. A section of the optical system used to create shadowgrams is displayed in Fig. VI.1.
Fig. VI.1: (Schematic by Dr. V. Ivanov) Schematic of the Ekspla laser optics near the Zebra vacuum chamber.

Shadowgrams are generated by using a large cross section (expanded) laser beam to backlight the rod, creating a shadow. The plane of the load is then imaged to a CCD camera. Since laser light is delivered in a single, high intensity, 150 ps pulse, there is no need for a gated, intensifying MCP. As shown in Fig. VI.1, polarizing beam splitters are used to create multiple beam paths. The images are split in the following manner: After light passes diaphragm D1, the beam is incident upon SPC1, where p-polarized light passes, and s-polarized light is transmitted. The transmitted light travels around the delay path. Typically, in the UNR-Megagauss Experiments, the (adjustable) delay length was set to 25 ns. Both paths (non-delayed and delayed) will encounter the beam splitting
cube (orange square, marked BSC). Non-delayed light transmitted through the BSC creates path 2 (Image 2), while non-delayed light reflected from the BSC creates path 1 (Image 1). Delayed light transmitted through the BSC creates path 1d (Image 1d), while delayed light reflected from the BSC creates path 2d (Image 2d). In MG-(I-III), if the laser pulse in path 1 encounters the load at $t=t_0$, pulses 2, 1d, and 2d encounter the load at $(t_0+9)$ ns, $(t_0+25)$ ns, and $(t_0+34)$ ns, respectively. In MG-IV, the timing of the four pulses was changed to $t_0$, $(t_0+2)$ ns, $(t_0+25)$ ns, and $(t_0+27)$ ns. The change was made for reasons associated with the resolution of images 2, and 2d, which will be discussed below.

As limited access users of the Zebra facility, the shadowgraphy setup “inherited” from the previous experiment was generally only fine tuned; image magnification and resolution were essentially pre-determined. Images 1 and 1d are captured by high resolution 1536×1024 pixel CCD cameras whereas images 2 and 2d are captured with 768×512 pixel CCDs. The optical system has greater magnification for images 1 and 1d. Due to the higher resolution CCDs, and the increased magnification, the resolution of images 1 and 1d significantly exceed the resolution of images 2 and 2d. The table below lists the image resolution in pixels per millimeter (px/mm) for the individual optical paths in the UNR-Megagauss Experiments.
Table VI.1: Pixels per millimeter for Ekspla shadowgrams obtained in each of the UNR-Megagauss Experiments.

<table>
<thead>
<tr>
<th>Campaign</th>
<th>Camera</th>
<th>Resolution (Px/mm)</th>
<th>Campaign</th>
<th>Camera</th>
<th>Resolution (Px/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MG-I</td>
<td>1</td>
<td>126.3</td>
<td>MG-III</td>
<td>1</td>
<td>130.2</td>
</tr>
<tr>
<td>MG-I</td>
<td>1d</td>
<td>127.7</td>
<td>MG-III</td>
<td>1d</td>
<td>31.7</td>
</tr>
<tr>
<td>MG-I</td>
<td>2</td>
<td>27.2</td>
<td>MG-III</td>
<td>2</td>
<td>134.3</td>
</tr>
<tr>
<td>MG-I</td>
<td>2d</td>
<td>26</td>
<td>MG-III</td>
<td>2d</td>
<td>31.7</td>
</tr>
<tr>
<td>MG-II</td>
<td>1</td>
<td>48.2</td>
<td>MG-IV</td>
<td>1</td>
<td>146.6</td>
</tr>
<tr>
<td>MG-II</td>
<td>1d</td>
<td>46.3</td>
<td>MG-IV</td>
<td>1d</td>
<td>139.7</td>
</tr>
<tr>
<td>MG-II</td>
<td>2</td>
<td>33</td>
<td>MG-IV</td>
<td>2</td>
<td>X</td>
</tr>
<tr>
<td>MG-II</td>
<td>2d</td>
<td>32.9</td>
<td>MG-IV</td>
<td>2d</td>
<td>X</td>
</tr>
</tbody>
</table>

Increasing the number of px/mm allows resolution of finer surface features. The resolution of the data obtained in MG-II was particularly coarse. Data from images 2 and 2d are typically of little quantitative interest in comparison to images 1 and 1d due to reduced resolution, however, their low magnification enables a large field of view, and a record of qualitative information not available from images 1 and 1d. As mentioned in the paragraph above, in MG-IV, images were captured at \( t_0 \), \((t_0+2\) ns), \((t_0+25\) ns), and \((t_0+27\) ns). In this way, images 1 and 2, as well as images 1d and 2d, nearly coincide. Therefore, high resolution, small field of view (1 & 1d), and low resolution, large field of view (2 & 2d) images are obtained, at nearly the same load current. Quantitative analysis of radius vs. time and of instability formation presented in the sections to follow uses MG-(III-IV) data from images 1 and 1d. Data from MG-III and MG-IV are of primary interest due to the scan in \( D_0 \) completed in those experiments. Also, the advancements made to the ICCD optics prior to MG-III allow an interesting comparison to be made between absorption and emission characteristics of the rod surface.
Visible Light Streaked Imaging

In MG-(I-III), a visible light streak camera was used to track the radial expansion of the rod as a function of time. The optics used to image load light to the ICCD were also used to image light to the input slit of the streak camera (see Figs. III.13 and III.15). In MG-I, a Cordin Model 163 Image Converter streak camera was used, while in MG-(II-III) an Imacon 500 streak camera was used. Both instruments are coupled to CCD cameras, which capture images of the streak camera MCP phosphor. The Cordin streak camera was on temporary loan from LANL. It was used to record radial expansion during MG-I and output from the visible light spectrograph during MG-II (Fig. IV.3). The Cordin camera was returned to LANL prior to MG-III. The Imacon streak camera was used to measure radial expansion in MG-(II-III), but was in a state of disrepair; most importantly, the diagnostic has very high trigger jitter (perhaps ±100 ns). The large trigger jitter often resulted in lost data, as the instrument either triggered earlier than expected, resulting in a dark streak, or later than expected, resulting in data collection after the time of interest. To increase the likelihood of collecting interesting data, the sweep speed was set slow (increased ns/mm) so that the time span of data collection was maximized. This decreases the temporal resolution of measurements, creating large uncertainty in inferred velocities. Also, due to the trigger jitter, the instrument could not be synchronized in the standard way. External timing fiducials, which are described next, were incorporated into the diagnostic to enable synchronization to the Zebra current.
Fig. VI.2: Typical layout of a CCD-coupled streak camera. The configuration of both the Cordin and Imacon streak cameras are well represented by the figure.

Synchronization of the Imacon streak camera is accomplished by pulsing (well timed) Ekspla laser light to the input slit of the streak camera. Laser light from (unused, as a backlighter) Ekspla Ch. 3 (Fig. VI.1) is incident upon two optical fibers located near the Zebra vacuum chamber. The fibers have different lengths, so two short (150 ps) bursts of light illuminate the input slit, and are recorded as two (temporally separate) vertical lines on the CCD readout. Using two pulses of light allows examination of shot-to-shot variation in sweep speed (ns/mm). The sweep speed remained constant throughout the experimental campaign. Errors associated with this timing method are substantial (±10 ns), and include uncertainty in Ekspla timing, uncertainty in the propagation delay of the fibers, and error associated with the width of the vertical fiducial lines recorded by the streak system. MG-I data obtained with the Cordin streak camera had higher timing accuracy, but poorer optical resolution than data obtained in subsequent experiments. Data from the well-timed Cordin streak camera confirms that the first light observed by the streak camera is coincident with the first light observed by visible light photodiodes. While the Imacon and Cordin streak cameras have different gain, the rise of the radiation emitted from rod surfaces is abrupt, so correlation between the turn-on-time of streak
images and photodiode signals can be used to ensure semi-accurate timing of Imacon data.

Other problems adversely affect the quality of data obtained by the Imacon streak camera. First, the placement of the camera in the optical screen box makes the entrance slit difficult to view (by the operator). In consequence, image placement on the slit is viewed using a mirror. Furthermore, the focus mode of the instrument is inoperable, amplifying the challenges associated with alignment. These factors make optimizing image alignment and focus difficult tasks. Since the ICCD and streak camera use the same imaging system, the magnification to the streak camera is assumed to match that of the ICCD. Magnification from the streak slit to the CCD camera has been measured. During this effort another problem with the instrument was discovered, as discussed in the following paragraph.

The magnification from the streak camera’s input slit to the CCD camera has been examined by placing four thin wires across the entrance slit of the streak camera. Wire locations and separations were determined by capturing and analyzing microscope images of the wires across the slit (Fig. VI.3(a)). Wire separations were found to be:

1. Wire 1 → Wire 2: 2.51 mm
2. Wire 2 → Wire 3: 2.70 mm
3. Wire 3 → Wire 4: 2.24 mm

The wires were present on the streak slit in shots 1465-1476. Not all shots provided useable data due to trigger jitter, however, the data shown in Fig. VI.3:(b) were obtained. Wire separations deduced from the data in Fig. VI.3:(b) do not match those determined
from microscope images (Fig. VI.3:(a)). Furthermore, the location of the shadows and their relative separation (in pixels) change from shot-to-shot. To see this, compare the data from shot 1470 with that from shot 1471. The centers of wire 1 shadows are well aligned at pixel 206. However, the shadow of wire 4 lies at pixel 407 in shot 1470, and at pixel 401 in shot 1471. This indicates that the magnification through the electron optics is not reproducible.
Fig VI.3: Fine wires added to streak slit are used to determine the magnification from streak slit to CCD readout. (a) Microscope image of fine wires mounted to the streak camera input slit. (b) Streak of radial expansion with shadows cast by the fine wires placed on the streak slit. (c) Data from 8 shots shows that the wire shadows shift, and the gap between wires changes: the electron optics in the streak tube do not function properly, or reproducibly.
One positive result was found during the streak camera analysis. As shown in Fig. VI.3:(b), the shadows case by the wires run parallel, and are straight (for a single shot) which indicates that while the electron optics change from shot-to-shot, during a single sweep, the focusing is constant. Therefore, while quantitative analysis and shot-to-shot comparisons of data from this diagnostic are difficult, qualitative arguments can be made. For example, streak images can be used to show when (to within the rather poor time-resolution of the diagnostic) radial acceleration occurs (Fig. VI.9).

Section VI.B: Data Analysis: Image Interpretation and Sources of Error

Rod radii are inferred from the location of rod edges in laser shadowgrams and ICCD images. The software package ImageJ [82] has been used during image analysis. To determine an edge, the following steps are completed:

1. For ICCD images, background subtraction is completed. A selection is made far from those pixels associated with emission from the rod. The mean number of counts is found and subtracted from all pixels in the image. Due to the large variations in background intensity associated with laser speckle, background subtraction is not completed for shadowgrams.

2. The image is adjusted for brightness and contrast. This does not change any of the data (pixel counts remain as recorded), but rather alters the display cutoff for dark and bright pixels. The image is adjusted so that the displayed edge contrasts strongly with the background.

3. The image is rotated so that the rod edges run vertically. ImageJ performs a bilinear interpolation when rotating the image. The accuracy of the interpolation will degrade
with the rotation angle, but generally small rotations of a few degrees or less are required, and errors remain small. In some instances, the rods are tapered with constant $\partial R/\partial z$, or the rods are curved. Tapered rods are aligned with the error shared by both sides of the rod, rather than aligning so that one side is vertical.

4. A selection rectangle is place over the rotated image which captures a significant portion of the rod length (generally 700 rows), at a width somewhat larger than that of the rod. A plot profile is generated from the selected pixels. The plot profile averages the number of counts of each pixel in the selected columns.

![Fig. VI.4: (a) Rod shadowgram with the selection rectangle shown. (b) Plot profile of the data contained within the rectangle shown in (a), used to determine the edges of the rod.](image)

5. Four pixel numbers are selected from the plot profile. Pixel “A” (left edge) corresponds the start of the transition from laser backlighter to rod shadow, and “B” (left edge) to the end of this transition. Pixels “C” and “D” are similarly chosen, only on the right edge. The diameter is then defined as:

$$\text{Diameter} \equiv \text{AVG}(C,D) - \text{AVG}(A,B),$$

where $\text{AVG}(C,D)$ is the average of pixel numbers C and D.
Determining the location of an edge is often challenging due to a number of possible sources of error or confusion, including:

1. Machining imperfections (radius is a function of $z$ and/or loads are curved)
2. Optical resolution—Optics not focused to rod edge, aberrations, etc.
3. Pixel size—Limits resolution of CCD
4. Laser speckle (shadowgraphy) or nonuniform emission (ICCD)
5. Surface plasma has unknown optical depth
6. Surface instabilities develop, making determination of edges challenging
7. Image mixing (shadowgraphy)

With regard to each of the aforementioned challenges, the following comments are made:

**Machining Imperfections**

A variety of machining imperfections have been observed. First, the rod may not be machined to the requested rod radius. This issue is in part a result of the large number of different machine shops and machinists involved in load fabrication. A detailed discussion of machining accuracy and consistency for different load types is found in Section III.B. The initial rod diameter must be accounted for in the radial expansion analysis.

Rods may also be tapered, with nearly constant $\partial R/\partial z$, or may be machined with random perturbations along the surface. The radii of these loads are difficult to quantify. Generally, in the case of minor axial variation, the edge diameter is simply averaged along the length of the rod. If distortions are severe, the data may be excluded from consideration. Occasionally deep grooves are machined into the surface. Grooves
undergo early heating which can cause jetting. These effects appear to remain localized during times of interest; therefore data from such loads can be salvaged by analyzing a smaller section of the rod length.

**Optical Resolution**

The optical resolution of the laser shadowgraphy diagnostic has been discussed previously. The uncertainty in $D(t)$ measurements are estimated at 40 µm and 30 µm for MG-III and MG-IV data, respectively. The optics to the intensified CCD camera were discussed in Ch. III. Advancements were made to the ICCD optics between each experimental series. The uncertainty in $D(t)$ measurements are estimated at 50 µm and 25 µm for MG-III and MG-IV data, respectively. The estimate of 25 µm is a best case estimate (40 µm uncertainty was commonly achieved in shot data).

**Pixel Size**

The high resolution CCD’s used for channels 1 and 1d of the shadowgraphy diagnostic (1536×1024 px) and the ICCD (1024×1024 px) are not a limiting factor in the system resolution. As shown in Table VI.1, the laser system results in a magnification of approximately 7.5 µm/px, so each pixel can resolve significantly finer detail than the achieved optical resolution. Similarly, the ICCD magnification resulted in 7.8 µm/px resolution in MG-III, and 4.1 µm/px (delayed image) or 4.6 µm/px (non-delayed image) in MG-IV. All values are considerably better than the optical resolution. This shows that pixel size is not a limiting factor in image resolution.
Laser Speckle or Nonuniform Surface Emission

Laser speckle can introduce significant error in the edge analysis of shadowgrams. Images are analyzed by hand, and there is unavoidable human error. While the edges represented by the plot profile in Fig. VI.4 are easily located, those in Fig. VI.5 are difficult to define. Laser speckle becomes increasing more difficult to interpret as instabilities develop on the surface, as the physical source for reduced contrast (instability) and the diagnostic source (speckle) are a challenge to distinguish.

![Shadowgram of a rod with surface instability and large laser speckle.](image)

**Fig. VI.5:** Shadowgram of a rod with surface instability and large laser speckle. The plot profile associated with this image is difficult to interpret. Edge locations determined from such images will have increased uncertainty.

Nonuniform surface emission makes the edge analysis of ICCD images more challenging, since dark locations of the rod are indistinguishable from background. Typically, a large fraction of the rod length is selected, and a plot profile is used to average the pixel counts along each included column. Averaging will result in reduced contrast (sloping plot profile edges), due to the dark portions of the rod surface being indistinguishable from background. For these images, the standard analysis method is...
altered, and the outermost bright portions are used to determine the rod edge. Plot profiles are generated from small sections of rod length, where both edges appear to be illuminated. Several sections are analyzed, and the maximum diameter is used.

**Surface Plasma has Unknown Optical Depth**

If laser light (532 nm) is able to penetrate the surface, light will be transmitted through edge material, resulting in low contrast shadowgram edges. Similarly, if a cool sheath of material is present at the outer diameter of the rod, with hot, highly radiating material below, the rod edges in ICCD images will display poor contrast. These possibilities are discussed in Section VI.C, after \( R(t) \) measurements are presented.

**Surface Instabilities Develop**

Surface instability formation has the effect of reducing the slope of plot profile edges of both shadowgrams and ICCD images. The width of the plot profile edge grows as the instabilities grow, and is somewhat indicative of the amplitude of the surface disruption. FWHM measurements are still used to determine the rod diameter after instabilities develop. Therefore, measurements track the diameter of an averaged edge. Material will exist outside, and voids will exist inside, the reported \( R(t) \).

**Image Mixing**

The Ekspla optical system (Fig. VI.1) uses polarizing splitters to create separate optical paths of linearly polarized laser light. These splitters are “leaky” when improperly aligned. The Glan prisms (used as polarization splitters in the Ekspla
diagnostic) are composed of two right angled prisms, separated by an air gap along their long faces. At the interface of the prisms, s-polarized light is reflected and p-polarized light is transmitted. The prism must be precisely aligned to accomplish near complete polarization splitting. In MG-IV, a simple test was completed to determine if leakage was occurring. Laser reference images were taken with the laser paths that create either images 1 and 2, or images 1d and 2d, blocked. With stop A in place (Fig. VI.1), image 1D should contain no laser light, while with stop B in place, image 1 should contain no laser light. Fig. VI.6 shows the results of the test. With stop A in place, a shadow of the rod is still clearly observed by image 1d (Fig. VI.6:(b)). Therefore, light from the non-delayed path is mixing with the delayed path. Since Fig. VI.6:(c) shows only a very weak shadow, it appears the polarized light for the delayed image is not mixing into non-delayed images significantly. Mixing creates a “double exposure” resulting in temporal mixing of data. Image 1D will show shadows from both delayed and non-delayed light. This problem will be rectified in future experiments by adding properly oriented polarizers in front of the CCD cameras.

Fig. VI.6: Images captured during tests of polarizer performance indicate leakage.
An example of an image with mixing is shown in Fig. VI.7 (shot 1866). The outermost unstable surface is from the intended 1d shadowgram. The inner straight edged shadow is the result of the unintended mixing of image 1. The displayed plot profile also shows the double edge associated with image mixing.

**Fig. VI.7:** Shadowgram 1d from shot 1886 shows the effect of mixing from image 1. The double edge associated with image mixing is clearly observed in the plot profile.

Section VI.C: Radial Expansion Results

Change in radius vs. time measurements from the two-frame ICCD and laser shadowgraphy are presented in the following 7 plots (one plot for each $D_0$ examined in the UNR-Megagauss Experiments). Change in radius is defined as $\Delta R(t) = R(t) - R_0$, where $R_0$ is the initial rod radius determined from laser reference images (See Ch. III). $R_0$ is measured separately for each shot, and for each image (1 or 1d). Confirmatory measurements are also made with a visible light microscope prior to experiments [83]. The average of the initial radius determined from laser reference images 1 and 1d is used as the initial radius in ICCD measurements (the ICCD cannot produce high resolution pre-shot reference images). Data pertaining to shot-to-shot variation in $D_0$ has been
presented in Ch III. Due to the significant variation in $D_0$, $\Delta R(t)$ is plotted rather than $R(t)$, since to first approximation, $\Delta R(t)$ eliminates the effect of machining variability from the expansion analysis. This also allows a more relevant comparison to be made between the surface expansion characteristics of the 7 different (nominal) $D_0$ examined. Clearly, the initial rod diameter effects rod dynamics, but the small deviation from the requested $D_0$ is considered a secondary effect, since experimental results show clear grouping of properties such as brightness temperature, time of plasma formation, etc. according to requested $D_0$.

In Fig. VI.8:(a-g) lines connect the two data points obtained from a single diagnostic (ICCD or Ekspla) during a single shot. Red lines are used for MG-III laser data, turquoise for MG-III ICCD data, green for MG-IV laser data, and black for MG-IV ICCD data. The slope of each line represents the average velocity of the rod radius over the time span between two points (time span is 25 ns for laser shadowgrams, 26.7 ns for MG-III ICCD images, and 20 ns for MG-IV ICCD images). No data is included from MG-II due to the relatively poor resolution of each diagnostic during that experimental series (Table VI.1). MG-I laser data is included for $D_0=1.00$ mm rods. During MG-I, mostly $D_0=1.00$ mm rods were examined, and due to the large number of data points, lines are eliminated to avoid clutter. ICCD data is not included for $D_0=2.00$ mm rods, as they emit weakly, and only low contrast images have been obtained. Measurement uncertainty in $R(t)$ (double for $D(t)$) is estimated at 20 and 25 $\mu$m for MG-III laser and ICCD data, respectively, and 15 and 15 $\mu$m for MG-IV laser and ICCD data, respectively. Quoted uncertainty pertains to the highest quality images obtained. The factors discussed in Section VI.B can cause the uncertainty to increase substantially. Measurement
uncertainty becomes particularly large after macroscopic surface instabilities develop, as determination of the edge location is challenging.
Fig. VI.8(a-g): Laser and ICCD $\Delta R(t)$ data from MG-III and MG-IV, plotted together. Separate plots are included for all initial rod diameters examined ($D_0=0.50, 0.64, 0.80, 1.00, 1.25, 1.59,$ and $2.00$ mm).

Fig. VI.9: Radial expansion determined from Imacon 500 streak data obtained in MG-II.
Fig. VI.10: $\Delta R(t)$ as determined from MG-IV shadowgrams. This is the highest resolution, most well timed radial expansion data obtained in the UNR-Megagauss Experiments. Peak current occurs at approximately 170 ns. The effect of flux pulling out of the conductor is clearly seen in the radial expansion of $D_0=1.00$ mm rods. The expansion of $D_0=2.00$ mm rods, which form no plasma, is unaffected by changes in $\partial I/\partial t$.

The data presented in Figs. VI:(8-10) allow several conclusions to be drawn:

1. The expansion dynamics of the rod are primarily determined by the non-plasma material below the rod surface. Rods expand monotonically, with no evidence of re-pinching after surface plasma forms. The highest quality expansion data (highest resolution, largest dataset for comparison) was obtained by the shadowgrams in MG-IV (Fig. VI.10). Expansion velocities are similar for $D_0=1.00$ mm and $D_0=2.00$ mm rods at 2.8 km/s and 3.6 km/s, respectively, during the linear rise of the Zebra current (and prior to instability formation on $D_0=1.00$ mm rods). However, when $\partial I/\partial t$ decreases, and eventually becomes negative, flux begins to leave the rod. As this occurs, $D_0=1.00$ mm rods show significant radial acceleration while the
velocity of $D_0=2.00$ mm rods remains constant. The dependence of surface dynamics on $\partial I/\partial t$ is attributed to the presence or absence of surface plasma in the following way—Initially, due to the inverse relationship between current density and rod radius, $D_0=1.00$ mm rods experience higher ohmic heating, and begin expanding (after vaporizing) at lower current when compared to $D_0=2.00$ mm rods. Plasma eventually forms on the surface of the $D_0=1.00$ mm rod, increasing the local current density and pinching force. However, the plasma layer is thin, and, due to its low density, remains significantly more resistive than cool metal. Therefore, while the pinching force pins the plasma layer against the internal vapor, keeping it thin and causing fluting, the field diffuses through the plasma quite easily, and does not have a significant effect on the overall expansion of the rod. For example, no evidence of re-pinching has been observed. Therefore, during the current rise, the material below the surface determines the expansion dynamics, and velocities are similar for 1.00 and 2.00-mm-diameter rods. However, when the current begins falling, and flux is removed from the rod, the presence of the plasma layer is clearly observed. The plasma layer now experiences reduced pinching, and can expand relatively freely (plasma could also be “pulled” outward by the expanding field lines, depending on their relative velocity). Due to the high plasma temperature (peak $T_{BB}=20$ eV for $D_0=1.00$ mm), the thermal velocity is high, and the plasma surface quickly accelerates to near 10 km/s. In the case of the $D_0=2.00$ mm rods, with no surface plasma, the expanding field lines have little effect on the resistive surface vapor, and the velocity remains constant.
2. *There is significant spread in the data.* Part of the spread may result from shot-to-shot variation in rod expansion, especially after the onset of large-amplitude surface instability. However, other inconsistencies exist, and could be the result of poor diagnostic performance. For example, recall that the lines plotted in Figs. VI.8:(a-g) join the two data points obtained during a single shot, from a single diagnostic. Occasionally, image 1d in shot ‘x’ will closely match the exposure time of image 1 in shot ‘y’ (shadowgraphy). While measured radii may differ due to shot-to-shot variation, over many shots, these variations should be random. However, in the MG-III shadowgraphy data, $R(t)$ as determined from image 1 consistently exceeds similarly timed measurements determined from image 1d. This inconsistency is not observed in MG-IV data, suggesting error in the MG-III measurement. Perhaps the observed inconsistency is a result of leakage through polarizers, which has been discussed previously.

3. *While results are qualitatively similar, rod radii inferred from ICCD images are consistently smaller than radii inferred from shadowgrams.* Results do agree to within measurement accuracy, however, the source of the difference is unknown. Inconsistent measurements could result from inaccurate calibration, inaccurate timing, or other errors. However, it is possible that the difference is due to a “cool sheath” surrounding a core of hot, radiating material. A possible core-sheath configuration is displayed in Fig. VI.11.
Fig. VI.11: Schematic of the hypothesized “core-sheath” configuration.

The path length (through the sheath) which laser light, or light from the hot core must traverse in order to be detected, as a function of the variable $x$, can be found. The detectors are distant, so the value of $y$ depends to first order, only on $x$ (and constants). First, for self emission, only $x < r$ need be considered, since negligible radiation originates from the cool sheath. The minimum path length occurs at $x=0$ \{ $y(x=0)=\delta$ \}, and the path length increases with $x$, as shown by Eqns. VI.1. Since $y$ increases with $x$, it is possible that light from the center of the core would escape, while light from the edge of the core would be absorbed by the effectively thicker sheath at that location.
For $x < r$

\[ r = R - \delta \]
\[ y = d - s \]
\[ d^2 = R^2 - x^2 \]
\[ s^2 = r^2 - x^2 = (R - \delta)^2 - x^2 \]
\[ y = d - s = \sqrt{R^2 - x^2} - \sqrt{(R - \delta)^2 - x^2} \]  \hspace{1cm} (VI.1)

Next, for laser light, if $x < r$, no laser light can be transmitted, since the core is optically thick. However for, $x > r$, $y = d$, but must be multiplied by 2 to account for negative $y$ values. The result is simply:

For $x > r$

\[ y = 2\sqrt{R^2 - x^2} \]  \hspace{1cm} (VI.2)

As $x \to R$, $y \to 0$; therefore, shadowgrams may also represent a smaller than accurate radius, since laser light may be transmitted through edge material. Yet, if the described “cool sheath” configuration does occur, shadowgrams must measure larger radii than self emission images. However, the sheath must be quite thin or hot enough to radiate, or no light emitted by the core material would be able to escape, and self emission images would be dark.

Section VI.D: Pinch Instabilities

Surface plasma is indicated by the development of instabilities, whose formation depends on the conductivity of the expanding material [61]. Resistive vapor will move freely through the surrounding high magnetic field, while low density conductive plasma will interact with the field, and magnetic Rayleigh-Taylor instabilities will develop. The
effect of surface plasma is demonstrated in Fig. VI.12, which displays surface structure near the time of peak current for 0.80, 1.25, and 2.00-mm-diameter rods. The $D_0=0.80$ mm rod forms surface plasma early in the current rise, and the surface grows highly unstable. The $D_0=1.25$ mm rod forms surface plasma at higher current and instability amplitudes near the time of peak current are observable, but small. In contrast to both, the $D_0=2.00$ mm rod forms no surface plasma, and remains stable even after significant radial expansion.

![Fig. VI.12: Instability growth as indicated by laser shadowgraphy. (a) $D_0=0.80$ mm near peak current, (b) $D_0=1.25$ mm near peak current (c) $D_0=2.00$ mm near peak current. Dashed lines indicate the initial rod diameter. Rods which form surface plasma are $m=0$ unstable, while rods form no plasma show no instability formation even when carrying 1.0 MA of current, and after significant radial expansion.](image)

As discussed in Section I.D, the curved magnetic field lines of a z-pinch initiate flute mode instabilities. Simple linear instability analysis shows the surface perturbations will grow exponentially in time with growth rate $\gamma$ (in units of s$^{-1}$), given by:

$$\gamma = \left( \frac{2(\partial p / \partial r)}{\rho R_0} \right)^{1/2}$$  \hspace{1cm} (VI.3)
Therefore, the perturbation amplitude will grow according to,

\[ A(r, t) = A_0(r) \exp(\gamma t) \]  

(VI.4)

Data from multiple shots have been used to estimate instability growth rates for rods of different initial diameter. The time dependant amplitude of surface instability has been approximated in the following way—When determining \( D(t) \), four data points (A, B, C, and D) are obtained from the plot profile generated for each shadowgram (Fig. VI.4). Two points are obtained for each rod edge, and indicate where the transition from dark to bright (or bright to dark) begins. From these four points, the FWHM value is used to determine \( D(t) \). However, evaluating \( B-A \), or \( D-C \) gives the width of each edge. As macroscopic surface instabilities develop, the edge width grows. Plotted in Fig. VI.13 are average edge widths (in mm) vs. time for all MG-III rods. Exponential trendlines have been fit to the data, which have been grouped by \( D_0 \). An edge width, growing approximately exponentially in time is observed for rods with \( D_0=0.50, 0.64, \) and 0.80 mm (which form plasma early in the experiment). Exponentials are also fit to \( D_0=1.00 \) and \( D_0=1.25 \) mm data. These rods also form plasma, but with larger \( D_0 \), not only do they form plasma later in the experiment, but they also have lower theoretical growth rates (Eqn. VI.3), and surface instabilities are quite small (or undetectable) for the data obtained.
Fig. VI. 13: Edge width vs. time for different $D_0$ evaluated in MG-III.

For those $D_0$ which display clear edge growth, an exponential trendline has been fit to the data, obtaining the experimental growth rate. From equation VI.3, theory predicts $\gamma$ is proportional to $R_0^{-1/2}$, or $R_0$ is proportional to $1/\gamma^2$. Strong agreement with this prediction is found in the experimental data, as shown in Fig. VI.14, where $1/\gamma^2$ has been plotted vs. $R_0$ for $D_0=0.50, 0.64$, and $0.80$ mm rods.
The data presented in Figs. VI.13-14 were obtained for barbell loads machined locally. Since instabilities require an initial perturbation to grow, rods machined with smoother surface finish should display reduced instability amplitude for the same Zebra current. The effect of surface smoothness on instability amplitude was observed in MG-IV (Fig. VI.15), where ultra-smooth barbells machined at LANL were examined. The ultra-smooth, diamond turned rods, fabricated in MST-7 at LANL display a smooth surface at considerably higher current than do rougher rods. Those rods manufactured by the UNR Physics machine shop display reduced instability amplitude (for the same current) when compared to barbells fabricated by Professor Fuelling. This could be due to surface smoothness; however, the rods machined by Professor Fuelling reached near the desired 0.50-mm-initial-diameter. UNR Physics loads had rod diameters larger than the requested 0.50-mm-diameter, which would also contributed to delayed instability growth.

![Graph](image)

**Fig. VI. 14:** Experimental growth rates scale with $D_0$ in agreement with theory.
Fig. VI.15: ICCD images of \( D_0 = 0.50 \) mm rods examined in MG-IV. Initial surface smoothness affects the amplitude of surface instabilities.
Chapter VII: Magnetic Field Threshold for Plasma Formation

That plasma can form from the surface of thick aluminum when pulsed to ultra-high magnetic field has been definitively confirmed. For rods with initial diameter $D_0 \leq 1.25 \text{ mm}$, evidence of plasma is obtained through a variety of measurements. As indicated by visible light radiometry, surfaces reach brightness temperatures ($T_{BB}$) which clearly indicate plasma for Al (see Ch IV). For example, peak temperatures reach 20 eV for $D_0 = 1.00 \text{ mm}$ rods. By decreasing $D_0$ plasma forms at lower Zebra current and peak temperatures increase. Also, multiply ionized Al (predominantly Al$^{3+}$ and Al$^{4+}$) is observed with time-resolved EUV spectroscopy, and a large flux of higher energy photons is detected with broadband EUV photodiodes for $T_{BB} \geq 2.0 \text{ eV}$ (See Ch V). Furthermore, for those rods which form plasma, pinch instabilities are recorded with gated imaging and laser shadowgraphy, and radial acceleration is observed when the Zebra current begins to fall (see Ch VI). While plasma forms from rods with $D_0 \leq 1.25 \text{ mm}$, plasma is not observed from $D_0 = 2.00 \text{ mm}$ rods, which remain cool (peak $T_{BB} = 0.7 \text{ eV}$), emit insufficient EUV radiation for detection, form no observable surface instabilities, and expand at constant velocity even after the Zebra current falls.

The diagnostics fielded in the UNR-Megagauss Experiments allow the time of plasma formation to be inferred. The onset of thermal plasma is evident in temperature profiles obtained by visible light radiometry, as an abrupt increase in $\partial T_{BB}/\partial t$ when $T_{BB}$ reaches about 0.6 to 0.9 eV, for $D_0 \leq 1.25 \text{ mm}$. With the time of thermal plasma formation known, the time-dependent value of the surface field, $B_s(t)$ is determined by time-resolved measurements of the discharge current, $I(t)$, and the surface radius, $R(t)$. The time of plasma formation, surface temperature history, radial expansion characteristics, surface
magnetic field rise rate ($\partial B_s/\partial t$), and magnetic field maximum ($B_{\text{max}}$), vary with $D_0$. Despite these differences, it is found that plasma forms from a 6061-alloy Al surface when $B_s$ reaches a threshold level of 2.2 MG, quite independent of the initial rod diameter. This is the first experimental measurement of the magnetic field threshold for plasma formation from a thick metallic surface.

Section VII.A: Magnetic Field Threshold for Plasma Formation

The onset of thermal plasma from rod surfaces is evident in the optical photodiode signals as an abrupt increase in $\partial T_{BB}/\partial t$ when $T_{BB}$ reaches about 0.6 to 0.9 eV, for $D_0 \leq 1.25$ mm (Fig. VII.1). Due to electromagnetic noise, $T_{BB}$ below 0.4 eV cannot be measured. After $T_{BB}$ rises above the noise level, a period of slow heating is observed, until $T_{BB}$ reaches 0.6 to 0.9 eV. $\partial T_{BB}/\partial t$ then increases by approximately an order of magnitude. The relatively slow heating phase is attributed to diffusive heating as the magnetic field penetrates through resistive Al vapor. The duration of resistive heating is extended for larger $D_0$ (Table VII.1). This is reasonable, since $P_J(r,t) = \eta(r,t)(J(r,t))^2 \approx \eta(r,t) \cdot \{I(t)/(\pi D_0 \Delta(t))\}^2$ varies inversely with $D_0^2$ (where $\Delta(t)$ is the increasing thickness of the current carrying skin layer). The abrupt increase in $\partial T_{BB}/\partial t$ which follows is attributed to a corresponding abrupt decrease (greater than 10 orders of magnitude [52]) in resistivity associated with the formation of plasma. The energy deposited by ohmic heating increases when the resistivity falls. This is made clear by expressing ohmic heating as $P_I = E^2/\eta$ (using, $E = \eta J$). If the electric field strength is assumed constant, but the resistivity falls by 10 orders of magnitude, the ohmic heating will increase drastically, spurring the sharp increase in $\partial T_{BB}/\partial t$. The observed plasma
formation temperature is consistent with calculations of the conductivity of warm, dense aluminum at below one-tenth solid density \([2]\). This supports experimentally determining the plasma formation time \((t_{\text{threshold}})\) and magnetic-field threshold \((B_{\text{threshold}})\) via the inflection in \(T_{\text{BB}}(t)\).

Fig. VII.1: Shot averaged brightness temperature profiles. The onset of thermal plasma is evident as an abrupt increase in \(\partial T_{\text{BB}}/\partial t\) when \(T_{\text{BB}}\) reaches about 0.6 to 0.9 eV, for \(D_0 \leq 1.25\) mm. Data from MG-III (solid lines) and MG-IV (dashed lines) are consistent.

Quite independent of \(D_0\) (perhaps surprisingly), thermal plasma forms when \(B_s\) reaches \(B_{\text{threshold}}=2.2\) MG (Table VII.1). As mentioned previously, by decreasing \(D_0\), the rate of energy deposition via ohmic heating \(P_J(r,t)=\eta(r,t)(J(r,t))^2\approx\eta(r,t)\cdot\{I(t)/(\pi D_0\Delta(t))\}^2\) increases. Melting, vaporization, and plasma formation occur earlier (at lower Zebra current). For plasma to form, ohmic heating must exceed energy losses associated with expansion, thermal conduction, and radiation. For each \(D_0\), the material takes a different trajectory (through \(\rho-T\) space), with multiple orders of magnitude changes in resistivity.
and heat capacity in the skin layer, yet the formation of plasma remains highly connected to the value of $B_s$. The surface magnetic field is calculated using the radius $R(t)$ observed in gated imaging and laser backlighting, and the load current $I(t)$ deduced from differential magnetic (Bdot) probe measurements. Rods with $D_0=0.50, 0.64, 0.80, 1.00$, and 1.25 mm form plasma when the $B_s$ reaches 2.0, 2.1, 2.2, 2.3, and 2.2 MG, respectively. Plasma formation depends strongly upon $B_s$, but weakly upon magnetic field rise rate ($\partial B_s/\partial t$ decreasing with increasing $D_0$ from 80 to 30 MG/µs) or upon non-planar effects associated with small radius. This is the first experimental measurement of the magnetic field threshold for plasma formation from a thick metallic surface.

<table>
<thead>
<tr>
<th>$D_0$ (mm)</th>
<th>Time span of resistive heating (ns)</th>
<th>Plasma formation time (ns)</th>
<th>Expanded diameter (mm)</th>
<th>Load current (kA)</th>
<th>Surface field (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>8</td>
<td>92</td>
<td>0.79</td>
<td>375</td>
<td>197</td>
</tr>
<tr>
<td>0.64</td>
<td>14</td>
<td>97</td>
<td>0.90</td>
<td>466</td>
<td>207</td>
</tr>
<tr>
<td>0.80</td>
<td>18</td>
<td>102</td>
<td>0.97</td>
<td>527</td>
<td>217</td>
</tr>
<tr>
<td>1.00</td>
<td>26</td>
<td>118</td>
<td>1.24</td>
<td>703</td>
<td>226</td>
</tr>
<tr>
<td>1.25</td>
<td>38</td>
<td>135</td>
<td>1.59</td>
<td>873</td>
<td>219</td>
</tr>
</tbody>
</table>

**Table VII.1:** Rod parameters at the time of plasma formation. Plasma is shown to form when the magnetic field strength at the expanding rod surface reaches approximately 2.2 MG.

**Section VII.B: Sensitivity to Small Changes in Initial Rod Diameter**

Small changes to experimental parameters (such is ~10 µm changes in $D_0$) are observed to systematically affect data obtained by multiple diagnostics, demonstrating a high level of measurement sensitivity. Shot-to-shot variation in the time of plasma formation can be attributed primarily to variation in the initial rod diameter, and/or variation of the Zebra current pulse. For example, consider the $T_{BB}$ curves for $D_0=1.00$ mm rods displayed in Fig. VII.2. $T_{BB}$ data for the 15 separate $D_0=1.00$ mm rods
examined in MG-IV are displayed. The time at which these rods reach $T_{BB}=1.0$ eV is spread over 11 ns from 116 to 127 ns. How then, considering this variation, has it been concluded that a magnetic field threshold exists? Recall from Ch. III, that measured rod diameters often differ from their nominal value by 10’s of microns, and occasionally by over 100 µm. For example, in MG-IV, for those rods which were nominally machined to 1.00-mm-diameter, measured rod diameters ranged from 0.94 to 1.13 mm. These changes in $D_0$ result in corresponding variation in the time at which thermal plasma forms. The time that each rod reaches $T_{BB}=1.0$ eV (Fig. VII.2) has been plotted vs. the rod’s measured $D_0$ (Fig. III.6) in Fig. VII.3. With the exception of 3 outliers, it is clear that those rods with large initial diameter reach 1.0 eV at later time. The affect of variations in the Zebra current pulse are also observed. The rod surface examined in shot 1883 forms plasma last of all $D_0=1.00$ mm rods due to an abnormally low Zebra current pulse (Fig II.7:(b)).
Fig. VII.2: Temperature profiles for all 0.50 and 1.00-mm-diameter rods examined in MG-IV. Variation in the time of plasma formation is observed.

Fig. VII.3: Measured $D_0$ vs. the time that $T_{BB}$ reaches 1.0 eV for $D_0=1.00$ mm rods (MG-IV). The plot demonstrates (with the exception of 3 outliers) that differences in plasma formation time are due to small variations in $D_0$. The experiment and diagnostics are sensitive to small changes in initial conditions.
The influence of variation in initial rod diameter on surface dynamics is observed by multiple diagnostics and extends late into the experiment. The correlation found between measured $D_0$ and $T_{BB}$ is also found in EUV diode data. As shown in Fig. VII.4, those rods which reach 1.0 eV later in time (according to visible light radiometry) also emit delayed EUV radiation. Since EUV emission is observed only after significant heating, small changes in $D_0$ can be observed to affect plasma properties late in the experiment.

![Graph: Time $T_{BB}(t)$ Reaches 1.0 eV Vs Time Al-EUV Diode Reaches 1.0 V](image)

**Fig. VII.4:** The time that $T_{BB}=1.0$ eV is plotted vs. the time that Al-filtered EUV diode voltages reach 1.0 V for all $D_0=1.00$ mm rods in MG-IV. Visible light radiometry and Al-filtered EUV diode data independently observed delayed heating associated with small increases in $D_0$.

The effect of small changes in initial rod diameter (of order 10µm) are observed to affect the time of plasma formation, and the time that surface plasma reaches multi-eV temperature. Several conclusions follow:

1. The experiment and its diagnostics are sensitive to small changes in initial conditions.
2. The Zebra current pulse is sufficiently repeatable to allow small variations in $D_0$ to have a clear, systematic affect on the evolution of the rod surface.

3. The novel load hardware developed for the UNR-Megagauss Experiments successfully mitigates non-thermal plasma. Changes in ohmic heating associated with small changes in $D_0$ are clearly observed. Such trends cannot be observed in data from simple straight rod loads, or in data from loads mounted in GRAV hardware (See Ch. III). For these hardware types initial surface plasma is the result of contact arcing, not thermal processes. For these data, the correlation between delayed plasma formation (heating) and small increases in $D_0$ is unclear.
Chapter VIII: Summary of Results, Remaining Questions, and Future Work

In this final chapter experimental results are first summarized. Then remaining questions and future work are presented together. Finally, concluding remarks are made.

Section VIII.A: Summary of Results

MTF liner physics is being cost-effectively studied by using the 1.0-MA Zebra z-pinch to observe the effect of pulsed multi-megagauss magnetic field on the surface of thick aluminum rods. Ideally, in order for the experiment to examine liner physics issues using the simple pulsed-rod geometry, the following conditions should be achieved:

1. Megagauss level magnetic field on rod surfaces ($B_S \geq 1$ MG)
2. Nonuniform current density in a surface skin layer ($\delta_B < r$), to access the “thick-rod” or “liner” or “surface-heating” regime.
3. Surface stability through the time of plasma formation ($r/V_A \geq t_{\text{plasma}}$). Comparisons with one-dimensional modeling (commonly used to study liner physics and MTF) are then more relevant.
4. Avoidance of non-MHD plasma sources, such as arcing electrical contacts, or electric-field-driven electron avalanche.
5. Rod surfaces smooth enough to avoid multidimensional effects such as highly nonuniform heating or hydrodynamic jetting.

It has been shown that due to the high magnitude and short rise-time of the Zebra current, conditions (1-3) are simultaneously achieved for rods with $D_0$ ranging from 0.50 to 1.00 mm. The Zebra generator delivers a repeatable 1.0 MA current pulse which rises from 100 to 900 kA in 70 ns at $dI/dt=1.1\times10^{13}$ A/s. The average Zebra current $I(t)$ rises from 20 to 200 kA approximately as $I(t)=I_0 \exp(t/\tau)$ with $\tau=13$ ns, which corresponds to a magnetic field penetration depth of $\delta_B = 0.017$ mm in cold aluminum (or $\delta_B \sim 0.1$ mm in
hot resistive Al). Therefore, those rod diameters examined, which ranged from 0.50 to 2.00 mm, are large enough for current to flow in a skin layer ($\delta_B < r$), yet small enough for megagauss magnetic field to be generated on the surface ($B_s = 4\,\text{MG}$ for $I = 1.0\,\text{MA}$, $R = 0.50\,\text{mm}$). To maintain stability, the penetration depth ($\delta_A$) of the Alfvén wave should be less than $R$. Now, $\delta_A = V_A t_B = B_s t_B / \sqrt{\mu_0 \rho}$ where $V_A$ is the Alfvén velocity and $t_B$ is the time required for the surface magnetic field to reach $B_s$ (determined by the rod radius and driver current). For a $R = 0.5\,\text{mm}$ Al rod at standard temperature and pressure, driven by the Zebra current, $\delta_A \leq 0.2\,\text{mm}$. Therefore, the Zebra $z$-pinch can simultaneously satisfy the megagauss surface field, skin current, and stability conditions for Al rods with $D_0$ near 1.0 mm.

To avoid non-MHD plasma sources (condition 4), a significant portion of early experimental effort was directed towards developing and testing load hardware. To determine if, when, where, and how plasma first forms from differently designed hardware, several diagnostics were developed. First, a pair of imaged, high gain PMTs examined the onset of visible emission from separate sections of the load. PMT #1 was sensitive to light from the center of the rod section of the load, while PMT #2 was sensitive to light from the rod-to-cathode current joint. Comparison of the turn-on-time of the two PMTs confirms the presence of arcing at the small-diameter contacts of simple-straight-rod loads. It was also shown that GRAV hardware generates precursor plasma which alters the time of plasma formation along the full length of the rod.

To study contact arcing and the evolution of other nonuniform surface emission features, an optical system was designed which allows a single ICCD camera to capture two high-resolution, gated images per shot. The two images are separated temporally,
but capture emission from precisely the same section of the rod. For those rods which form plasma, early nonuniform emission becomes more uniform as the surface temperature increases. Second, axial variation in visible light emission from the rod surface was continuously examined (during a single shot), albeit with low spatial resolution, by an imaged, 15 element, linear, fast-photodiode array. The emission history of the rod surface recorded by the linear diode array supports the conclusion from two-frame imaging that emission uniformity increases with time.

To obtain a dataset suitable for comparison with one-dimension modeling, rod surfaces should be sufficiently smooth to maintain predominantly one-dimensional behavior until the time of plasma formation. While nonuniform heating can result from machining artifacts, as detailed previously, such nonuniformity generally does not persist. A small subset of rods (typically composed of difficult to machine 1100-alloy Al) contain severe surface irregularities, which clearly result in late-time multi-dimensional behavior (jetting). Moderate surface roughness (pits or bumps) were shown to have no clear effect on surface heating near the time of plasma formation. Precision machined rods from LANL showed similar early surface emission characteristics to rods with much rougher surfaces. It has been hypothesized that early emission nonuniformity may correlate with the internal grain structure of the material, but this has not yet been examined in detail.

The dataset obtained in MG-I and MG-II allowed determination of which hardware was most effective for studying the phase state of thick metal pulsed with ultra-high magnetic field. Well machined barbell and hourglass loads coupled to KE hardware demonstrate consistent mitigation of non-thermal plasma and repeatable heating and expansion characteristics. In comparison to hourglass loads, barbell loads are easier to
machine, generally have a smoother surface, and can be constructed from 1100-alloy Al. For these reasons, the barbell load in KE hardware was used exclusively in MG-(III-IV). With the hardware issues resolved, later experiments focused on important physics issues. These experiments examined the effect of variations in current density and magnetic field rise rate by completing a scan of different initial rod diameters. Rods with $D_0$ from 0.50 and 2.00 mm reach peak $B_S$ of 4 and 1.5 MG, respectively, corresponding to $\partial B_S/\partial t$ from 80 to 30 MG/µs on the expanding surfaces. The phase state of thick Al surfaces under varying conditions of pulsed magnetic field was examined.

That plasma can form from the surface of thick aluminum when pulsed to ultra-high magnetic field has been definitively confirmed. For rods with initial diameter $D_0 \leq 1.25$ mm, evidence of plasma is obtained through a variety of independent measurements. As indicated by visible light radiometry, surfaces reach temperatures ($T_{BB}$) which clearly indicate plasma for Al (See Ch IV). For example, peak temperatures reach 20 eV for $D_0=1.00$ mm rods. By decreasing $D_0$ plasma is observed at lower Zebra current, and peak temperatures increase. Also, multiply ionized Al (predominantly Al$^{3+}$ and Al$^{4+}$) is observed with time-resolved EUV spectroscopy, and a large flux of higher energy photons is detected with broadband EUV photodiodes for $T_{BB} \geq 2$ eV (See Ch V). Also, for those rods which form plasma, pinch instabilities are recorded with gated imaging and laser shadowgraphy, and radial acceleration is observed when the Zebra current begins to fall (See Ch VI). While plasma forms from rods with $D_0 \leq 1.25$ mm, plasma is not observed from $D_0=2.00$ mm rods, which remain cool (peak $T_{BB}=0.7$ eV), emit insufficient EUV radiation for detection, form no observable surface instabilities, and expand at constant velocity even after the Zebra current falls.
The onset of thermal plasma is evident in temperature profiles obtained by visible light radiometry as an abrupt increase in $\partial T_{BB}/\partial t$ when $T_{BB}$ reaches about 0.6 to 0.9 eV, for $D_0 \leq 1.25$ mm (See Ch. VII). With the time of thermal plasma formation ($t_{\text{plasma}}(D_0)$) known, the time-dependent value of the surface field ($B_s(t)$) is determined by time-resolved measurements of the discharge current $I(t)$ and the surface radius $R(t)$. $T_{BB}(t)$, $R(t)$, $t_{\text{plasma}}$, $\partial B_s/\partial t$, and $B_{\text{max}}$ vary with $D_0$. Despite these variations, it is found that plasma forms from a 6061-alloy Al surface when $B_s$ reaches a threshold level of 2.2 MG, quite independent of $D_0$. This is the first experimental measurement of the magnetic field threshold for plasma formation from a thick metallic surface.

A question of primary importance for metallic-liner-driven MTF is to what extent liner material is able to cross magnetic field lines and mix with the compressed fusion fuel. A critical measurement in the UNR-Megagauss Experiments is that of the expansion of surface material through the surrounding magnetic field. It was shown in Ch. VI that, while surfaces remain quasi-one-dimensional, and while the Zebra current is rising, rod radii expand at ~3km/s (relatively independent of $D_0$ or $T_{BB}$). For $D_0 = 2.00$ mm rods, ~3 km/s radial velocity is observed for times extending well beyond that of peak current. For rods which form plasma, initial radial velocities are also measured at ~3 km/s; however, the radial expansion velocity of these rods eventually increases.

The acceleration observed for those rods which form surface plasma can be attributed to two mechanisms: (1) As large amplitude surface instabilities form, the surface material can interchange with magnetic flux. (2) Near the time of peak current, when magnetic flux begins to move out of the material, the surface plasma layer experiences reduced
pinching, and accelerates to some fraction of its sound speed. Measurements indicate that \(D_0=1.00\) mm rods, with maximum \(T_{BB}=20\) eV, and \(D_0=2.00\) rods, with maximum \(T_{BB}=0.7\) eV, expand at nearly the same \(\sim3\) km/s velocity until the time of peak current. After peak current, \(D_0=2.00\) mm rods continue to expand at 3 km/s while \(D_0=1.00\) mm rods accelerate to near 10 km/s. This suggests that while the current is rising, if plasma forms, it is pinned against the interior warm dense Al. Even though the plasma layer has high conductivity, it is thin enough for the magnetic field to diffuse through easily, so it cannot hold back the expansion of the material below the rod surface. The “snow plow effect” of the interior material determines the rate of radial expansion. Smaller diameter rods accelerate when large amplitude surface instabilities form (before peak current). Therefore, while the magnetic field is rising, and before instabilities dominate the surface, the expansion of the inner wall of an MTF liner may be driven primarily by the dynamics of the buried warm dense matter. The thin layer of surface plasma which will form (as a result of the growing multi-megagauss magnetic field) may have little effect.

The carefully diagnosed UNR-Megagauss Experiments have obtained previously unknown results concerning the interaction of conductors carrying an ultra-high skin current and megagauss magnetic field. Important design and engineering efforts resulted in effective methods to reduce or eliminate the influence of non-MHD plasmas, even in the high electric field environment created by the Zebra generator. Time-resolved measurements of the discharge current, expanding rod radius, and surface brightness temperature have allowed inference of the phase of the rod surface. The first experimental measurement of the magnetic field threshold for thermal plasma formation from a thick metallic surface has been obtained \((B_{\text{threshold}} = 2.2\text{ MG})\). EUV spectroscopy
measurements have determined which ion species are present in the plasma (Al\textsuperscript{3+} and Al\textsuperscript{4+}). Detailed measurements of phase, temperature, velocity, and ionization state of a thick metal surface as a function of intense pulsed magnetic field are informing radiation MHD modeling and will facilitate the design and engineering of practical devices.

**Section VIII.B: Remaining Questions and Future Work**

A fundamental goal of the UNR-Megagauss Experiments has been to determine the phase state of a thick metal surface pulsed to ultra-high magnetic field. The experiment confirmed that plasma will form, but only when the surface magnetic field reaches a threshold level of 2.2 MG. Multiple results (summarized in the previous section) will aid in the design and engineering of practical devices, including MTF systems. However, many questions remain unanswered, several of which are considered below:

**Question #1:** Is the blackbody assumption, which has been used to infer the surface brightness temperature ($T_{BB}$), reasonable?

It has been assumed, when calculating the surface brightness temperature, that visible radiation escaping the rod surface is Planckian. This assumption has not yet been verified. A visible light spectrograph coupled to a visible streak camera has recorded predominantly continuum spectra; however, the spectral distribution has not been measured. The data obtained by the streak camera system is difficult to interpret since the spectral responses of system components (other than the spectrograph) are not well characterized. The streak camera/CCD system was on loan from LANL and has been returned. Therefore, the opportunity to fully calibrate the system has passed.
**Future Work:** In MG-IV, the output of the visible light spectrograph was recorded by an A5C-38 single substrate linear photodiode array (the same model as that used for visible light radiometry). While this detector does not offer the spectral resolution of the streak camera, it has high element-to-element response uniformity and the frequency dependent responsivity has been calibrated by the manufacturer. The photon frequency range incident upon each element has been calibrated using a monochromator. Therefore, the current driven in each channel can be used to interpret the spectral “shape” of the photon distribution as a function of time. The spectral shape should match that of the Planckian distribution if the blackbody assumption is reasonable. The instrument was fielded in MG-IV by Professor Siemon and Ms. Tasha Goodrich (Graduate Student, UNR Physics). The data is currently being interpreted, and no results are available at this time. Conclusions drawn from this effort will be included in Ms. Goodrich’s Master’s Thesis, and will be important in determining the accuracy of experimental temperature measurements.

**Question #2:** What is the (temporally and spectrally dependent) emissivity of the rod surface?

It has been assumed, when calculating the surface brightness temperature, that the emissivity of the rod surface is unity. Emissivity is defined as the ratio of the radiation emitted by a body to the radiation emitted by a blackbody at the same temperature. The emissivity of oxidized Al at room temperature is ~0.2, and grows with increasing temperature prior to melt [84]. The emissivity of the warm dense Al is not well known.
If the emissivity of the surface is not unity, the interpreted temperature will fall below the actual material temperature by an unknown amount. Furthermore, the emissivity will be time and (photon) frequency dependent.

**Future Work:** A diagnostic measuring the reflectivity ($r(\lambda, T)$) of the rod surface could be fielded to gain information about the emissivity ($\varepsilon(\lambda, T)$). By assuming $\varepsilon(\lambda, T)=1-r(\lambda, T)$, the emissivity can be determined from the reflectivity. For example, laser light can be reflected from the rod surface, and the reflected light measured by a PMT. If the rod surface emits nearly as a blackbody (a perfect absorber) the rod will absorb the majority of the incident light. The measurement may be quite difficult. First, light will be scattered due to surface roughness. Second, since the surface is expanding, if alignment is imperfect, the direction of reflected light will change. Third, since emissivity is a function of wavelength a spectroscopic approach should be taken (for example, multiple laser lines could be used). In order to field an informative emissivity diagnostics, these issues must be carefully considered.

**Question #3:** What determines the spatial distribution of the observed early emission nonuniformity?

Early images of emission from rod surfaces display nonuniform hot spot emission. It was hypothesized that the nonuniformity may be due to surface roughness. However precision (diamond turned) rods from MST-7 at LANL, which are remarkably smooth, show similar emission characteristics to much rougher surfaces. A second hypothesis is
that the nonuniformity is directly connected with the internal grain structure of the rod material. This hypothesis has not been tested.

**Future Work:** The internal grain structure of the Al rods examined in the UNR-Megagauss Experiments will be characterized by a materials group at UNR [85]. With the grain structure known, it may still be challenging to correlate those data with experimental results. Perhaps more conclusive would be to (in future experiments) examine Al rods composed of differently treated Al (rolled or extruded, vs. cast, for example) with different internal grain structure. Different emission patterns may be observed.

**Question #4:** Why does the EUV spectrometer measure emission lines for 0.80 and 1.00-mm-diameter rods, but absorption spectra for 0.50 and 0.64-mm-diameter rods?

As suggested in Ch. V, absorption spectra may result if a relatively cool plasma sheath is backlit by interior, hotter plasma. It is unclear why the existence of this configuration should depend upon $D_0$. Perhaps, such a configuration can exist only after large instabilities develop, allowing mixing of different layers of material. This is supported by spectra obtained in MG-IV, which showed emission lines at low current (when instability amplitudes are small) for $D_0=0.50$ mm rods.

**Future Work:** This question appears difficult to answer experimentally. If absorption spectra result only in the case of large amplitude surface instability, careful measurements may allow observation of these phenomena. Loads could be constructed
with a buried layer of tracer material. If this material were mixed with surface material (due to instabilities) the spectra specific to the tracer material could be observed, and the material interchange could be studied. It would also be interesting to examine spectra from \( D_0=1.00 \text{ mm} \) rods after the onset of large amplitude instabilities to determine if absorption lines are present. Furthermore, continued modeling effort is warranted to study the radiation transport occurring in the outer rod material.

**Question #5:** Calculating the intensity ratio of \( \text{Al}^{3+} \) and \( \text{Al}^{4+} \) lines allows estimation of the temperature of the radiating material. Why does this estimate consistently give a temperature of 15 eV when other diagnostics show a wide range of plasma temperatures?

**Future Work:** Several hypotheses have been offered to explain this observation (Ch. V).

In order to determine the temperature based upon line-intensity ratios, assumptions are made about the radiating material (such as layer thickness and density). It has been suggested that continued work with PrismSPECT be completed, where, rather than assuming the same radiating layer thickness and density for all rods, densities and opacities calculated from MHD simulations should be used to determine the PrismSPECT input parameters.

**Question #6:** Measurements of \( \Delta R(t) \) from laser shadowgraphy and self-emission imaging differ. Are the differences due to measurement error, or the presence of an optically thin “cool sheath?”

Consistently, rod radii inferred from ICCD images are slightly smaller than radii inferred from shadowgrams. However, the results agree to within measurement accuracy. The difference could be due to inaccurate calibration or other errors. However, as
discussed in Ch. VI, it is possible that the difference is due to a “cool sheath” at the rod surface. This sheath may absorb or deflect laser light, yet emit weakly, and would therefore not be recorded by ICCD images. This may account for the difference in $\Delta R(t)$ measurements.

**Future Work:** High resolution measurements of surface density as a function of radial location would determine whether or not a cool sheath exists. This could be examined with higher energy photons. A new diagnostic is being brought on-line at the Zebra facility that will allow shadowgrams or interferograms to be created using pulsed UV laser light [86]. Furthermore, point-source x-ray radiography diagnostics, using either the 10-terawatt Tomcat laser, or the 100-terawatt Leopard laser are being developed. These probing diagnostics would allow examination of the density distribution of the outer layers of rod material. Furthermore, if the resolution of both ICCD images and laser shadowgrams can be increased, measurement uncertainty would be reduced, and the source of the difference between the two measurements could be discovered.

**Question #7:** For 2.00-mm-diameter rods, which do not form surface plasma, surfaces remain stable, even when carrying 1.0 MA of current, and after the radius has expanded by 100s of microns. The bulk of the current is therefore likely flowing below the rod surface. Has the current carrying material below the surface gone unstable?

**Future Work:** The NTF’s Leopard laser [87] is capable of probing material below the rod surface via x-ray or proton radiography. The laser can deliver 20 J of 1054 nm light in a sub-picosecond pulse. A target intensity of $10^{19}$ W/cm$^2$ may be achieved if the on-target focus can reach 10s of microns. Laser interaction with a foil can produce
100-1000 keV electrons, which will create a large electrostatic field capable of extracting protons from the foil, which would then be accelerated to 10 MeV. Similar methods for creating energetic proton beams have been demonstrated with other ultra-short pulse lasers [88,89]. Time-resolved proton radiographs would enable time-resolved measurement of density, electric field, and magnetic field. Furthermore, the Leopard laser may be used to provide a powerful x-ray backlighter. The energetic electrons (created in the laser-foil interaction) will emit bremsstrahlung radiation and also excite ionic states, which will provide intense $K$-shell line radiation. Due to issues with focusing the laser beam in the Zebra chamber, these capabilities do not yet exist. If Leopard-laser-driven x-ray and/or proton radiography diagnostics are brought on-line, a small diameter, unstable surface may be discovered below the smooth outer surface of $D_0=2.00$ mm rods. This would be the first known observation of such phenomena.

Section VIII.C: Conclusion

In conclusion, for $\partial B_s/\partial t$ ranging from 30-80 MG/µs, thermal plasma is observed to form from a 6061-alloy Al surface when $B_s$ reaches 2.2 MG. The existence of a plasma formation threshold at the few MG level is in qualitative agreement with recent theoretical and computational results for Cu [18]. The experiment offers the first detailed examination of the pulsed-magnetic-field threshold for plasma formation from a thick metallic surface. Non-thermal plasma production has been mitigated or even eliminated with specialized load hardware. For $B_s$ below 2 MG, sub-eV temperatures persist, and no evidence of plasma is observed. Thermal plasma forms from a 6061-alloy Al surface when $T_{BB}$ reaches approximately 0.7 eV during the linear current rise, at which point
rapid surface heating occurs. For $D_0=1.00$ mm rods, at the time of peak current (1.0 MA), $B_s$ is 3.0 MG, $T_{BB}$ is 20 eV, and $\text{Al}^{3+}$ and $\text{Al}^{4+}$ ions observed in approximately equal abundance. Prior to the observation of large amplitude instability, aluminum surfaces expand at 3 km/s while the Zebra current rises. Detailed measurement of phase, temperature, velocity, and ionization state of a thick Al surface as a function of pulsed ultra-high magnetic field is informing radiation MHD modeling, and will facilitate in the design and engineering of practical devices, including MTF systems.
# Appendix: Commonly used Symbols

A list of commonly used symbols are included below for reference. These symbols are used throughout the text, and are not defined in each occurrence. Infrequently used symbols are typically defined within the text, and thus are not included in the list below.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta_B$</td>
<td>Magnetic field penetration depth</td>
</tr>
<tr>
<td>$t_{\text{plasma}}$</td>
<td>Time of plasma formation</td>
</tr>
<tr>
<td>$B$</td>
<td>Magnetic field</td>
</tr>
<tr>
<td>$B_{\text{threshold}}$</td>
<td>Magnetic field threshold for thermal plasma formation</td>
</tr>
<tr>
<td>$B_s$</td>
<td>Surface magnetic field</td>
</tr>
<tr>
<td>$E$</td>
<td>Electric field</td>
</tr>
<tr>
<td>$V$</td>
<td>Electrostatic potential</td>
</tr>
<tr>
<td>$I$</td>
<td>Current</td>
</tr>
<tr>
<td>$I_{\text{max}}$</td>
<td>Maximum current</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Characteristic rise time of the Zebra current</td>
</tr>
<tr>
<td>$J$</td>
<td>Current density</td>
</tr>
<tr>
<td>$P_j$</td>
<td>Ohmic heating</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature</td>
</tr>
<tr>
<td>$T_{\text{BB}}$</td>
<td>Brightness Temperature</td>
</tr>
<tr>
<td>$D_0$</td>
<td>Initial rod diameter</td>
</tr>
<tr>
<td>$R_0$</td>
<td>Initial rod radius</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Electrical resistivity</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Electrical conductivity</td>
</tr>
<tr>
<td>$\sigma_\Delta$</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Mass density</td>
</tr>
<tr>
<td>$p$</td>
<td>Material pressure</td>
</tr>
<tr>
<td>$P_B$</td>
<td>Magnetic field pressure</td>
</tr>
<tr>
<td>$e$</td>
<td>electron charge</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Growth rate for instabilities</td>
</tr>
<tr>
<td>$g$</td>
<td>Gravitational force</td>
</tr>
<tr>
<td>$\sigma_{\text{SB}}$</td>
<td>Stephan-Boltzmann constant</td>
</tr>
<tr>
<td>$Q$</td>
<td>Charge</td>
</tr>
<tr>
<td>$V_A$</td>
<td>Alfvén velocity</td>
</tr>
<tr>
<td>$v_D$</td>
<td>Drift velocity</td>
</tr>
<tr>
<td>$v_{\text{thermal}}$</td>
<td>Thermal velocity</td>
</tr>
<tr>
<td>$u$</td>
<td>Fluid velocity</td>
</tr>
</tbody>
</table>
REFERENCES


[52] Paper to be published by e.g. Lindemuth, Siemon, Makhin, Atchison, Garanin, Frese.


[55] Team Specialty Products Corporation, *Albuquerque, New Mexico 87123, USA*


[58] http://www.lanl.gov/mst/groups.shtml


[73] R. E. Siemon, private communication


[81] Professor V. Ivanov is the researcher most responsible for the Ekspla diagnostic.
[82] Image processing program developed by the NIH. http://rsbweb.nih.gov/ij/

[83] Work completed in part by Ms. Tasha Goodrich or Ms. Jaspreet Billing


