Study of Ablation and Implosion Phases in Cylindrical and Star Wire Arrays

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Abdelmoula Haboub

Dr. Vladimir V. Ivanov - Dissertation Advisor

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We recommend that the dissertation prepared under our supervision by

ABDELMOULA HABOUB

entitled

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DOCTOR OF PHILOSOPHY

Dr. Vladimir V. Ivanov, Advisor

Dr. Jeffrey S. Thompson, Committee Member

Dr. Vladimir I. Sotnikov, Committee Member

Dr. Radu Presura, Committee Member

Dr. Thmasz J. Kozubowski, Graduate School Representative

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

December, 2009
Abstract

An advanced set of laser probing diagnostics was applied for the investigation of implosion dynamics and magnetic fields in cylindrical, star, and nested wire arrays at the Nevada Terawatt Facility. Plasma diagnostics at a wavelength of 532 nm provide a five-frame optical probing of the z-pinch including shadowgraphy, Faraday rotation diagnostics, interferometry, and schlieren diagnostics.

The Faraday rotation was applied for the investigation of magnetic fields and currents as well as structures in the plasma column of the precursor in wire array z-pinches. Faraday images and their complimentary shadowgrams reveal the presence of magnetic fields (B) that have opposite directions between both sides of the precursor, inside which the current was flowing since the early stage of the implosion of cylindrical and conical wire arrays. The current in the precursor plasma column was estimated to be 0.05-0.15 MA.

Measurement of the electron plasma density with regular laser interferometery meets the zero-number fringe issue on the axis of the z-pinch. We suggested a new diagnostic to record a continuous history of the interferograms and the individual evolution of the fringes. In this case, the plasma density could be measured by deriving the shift of the fringes on the slit of a streak camera.

Implosion stage was investigated in wire arrays with five-frame laser probing. Bubble-like implosion was identified as a mechanism of the mass transport in wire arrays. Development of bubbles on the breaks of the wire cores and evolution of bubbles were studied. Implosions with speeds of around 200-500 km/s were recorded in the wire arrays and the dynamics of the implosion plasma bubbles, current reconnection, as well as a
shock in the precursor were observed. The z-pinch imaging and Faraday rotation
diagnostics with 1-MA wire arrays were analyzed. A bubble-like mass transport is
observed in all types of wire arrays (cylindrical, nested, linear, etc).

A new type of “star” wire array was designed and studied. These loads consist of
multiple nested, low-wire-number, cylindrical arrays aligned azimuthally such that the
wires appear as “rays” extending from the axis of symmetry. In low wire-number star
arrays, the imploding plasma starts on the edge wires, cascades from wire to wire,
accelerating toward the center, and forms moving plasma columns with a smooth leading
edge. The cascading mode of implosion was confirmed by several optical plasma
diagnostics, including five-frame laser probing of z-pinch in three directions, an optical
streak camera, and a time-gated CCD. In star wire arrays, smoothing of plasma
instabilities was observed in the last phase of the implosion. The hydrodynamic regime of
collision mitigates the instabilities, improves the homogeneity of the imploding plasma,
and increases the radiated power in the star-like wire array. Star wire array generates a
short high power x-ray pulse. Star wire arrays could be a good alternative to single
cylindrical and double nested wire arrays in HEDP experiments.
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Chapter 1

Introduction

1.1 Dense z-pinch

A Z-pinch is a self-constricted plasma column with an axial and extremely high current flowing through it in a short time, typically a few hundred nanoseconds. This high electrical current pulse is about 1 MA in Zebra generator at Nevada Terawatt Facility (NTF), 26 MA in Z-machine at Sandia National Laboratories (SNL) [1], and 9 MA in Saturn also at SNL [2, 3]. When the current is delivered to the pinched plasma, it generates an azimuthal magnetic field that is sufficient enough to compress and confine the plasma column along the “z” direction.

Z-pinch loads consist of a variety of configurations including wire arrays, annular gas puffs fiber, thin metallic foils, and cylindrical foams. In this work, only wire array Z-pinch is our primary focus of study.

Wire array Z-pinches currently produce the world’s most powerful laboratory x-ray radiation, which is suitable for inertial confinement fusion (ICF) and other areas of high energy density physics. Implosion of wire arrays produces nanosecond x-ray pulses with energy ~ 1.8 MJ in 5 ns from a volume of 2 mm in diameter and 2 cm tall and with a power greater than 250 TW.

Wire arrays also consist of a variety of configurations including planar, cylindrical, conical, double-nested, and “star”-like wire arrays. The thin metallic wires that are configured in the arrays and used at NTF, have a diameter from 3.9 to 25 µm, depending on the metal used, and a wire number ranging from 4 wires to 32 wires. At this facility,
the wire arrays used are considered as low wire number arrays by comparison to the wire arrays used at the SNL, which are commonly called multi-wire arrays. They are generally from 200 to 300 wires. Despite the low number of wires used for implosion, the underlying physics of Z-pinches revealed at this facility is significant. The principle of how the wire Z-pinch works is illustrated in Figure 1.3.

Z-pinch is one of the earliest and most interesting types of self-constricted plasma confinement system. The first systematic attempts to characterize the self-constricted plasma configurations and Z-pinches were in 1934 [4]. From 1934 to the 1950s, Z-pinches were applied in an attempt to generate high fusion temperature and density simultaneously by heating deuterium-tritium (DT) mixtures and remaining the Z-pinch plasma in equilibrium long enough so that significant fusion can occur and then sufficient amount of fusion energy can be released [5]. Controlled fusion used magnetic fields (B) to confine the plasma of deuterium and tritium of extremely high temperature (T\textsubscript{e}), which is typically about 10\textsuperscript{8} K (10 keV). In order to achieve a sustained release of energy from a fusion reaction, the temperature (T\textsubscript{e}) needs to enable the particles to overcome the Coulomb barrier, and must be maintained for sufficient confinement time (τ), with sufficient plasma density (N\textsubscript{e}). The condition which must be met to obtain a net yield of fusion energy is known as the Lawson criterion for fusion, which is a function of the product of the time τ and the plasma density N\textsubscript{e}. The Lawson’s criterion for deuterium-tritium and deuterium- deuterium fusions are τN\textsubscript{e} \geq 10\textsuperscript{14} and τN\textsubscript{e} \geq 10\textsuperscript{16} [6] respectively.

According to thermonuclear fusion related research, the combination of both high temperature and high density sustained in equilibrium pinch is the main purpose of the
use of Z-pinches and the self-constricted plasma. However, and unfortunately, the Z-pinch formed in these thermonuclear fusion conditions, at that time, was susceptible to a large number of magnetohydrodynamic (MHD) instabilities including sausage and kink instabilities.

Among these instabilities, the m = 0 sausage instability, which occurs when an axisymmetric perturbation causes the plasma column, on some points, to become more thinner until it breaks and the plasma current is disrupted. The m = 1, or kink mode, occurs when the perturbation causes a slight bend or kink to the plasma column, where the magnetic pressure will increase inside the bends until the plasma column is broken and the current is disrupted.

These two instabilities are shown in Figure 1.1, they usually destroy the Z-pinch, limiting the radiation yields and the large amount of x-ray radiation power [7].

![Figure 1.1 (a) Sausage (m = 0) and kink (m = 1) mode instabilities in a Z-pinch, (b) optical shadowgraphy image of cylindrical wire array (W 8 x 7.3 µm) shot#960 showing at the same time the both instabilities, the sausage and the kink mode instabilities.](image-url)
One interesting phenomenon is that the sausage mode instability gave rise to voltage surges and accelerates deuterons to produce bursts of neutron radiation that was not of thermal fusion origin [5]. Consequently, the interest on the use of Z-pinches for fusion was lost for many years until the mid 1970s and early 1980s, when rapidly the short pulsed-power get developed. Wire arrays such as cylindrical loads of radius \( r \) and height \( h \) were introduced in the Z-pinch experiments, as it is shown in Figure 1.2 (a). Wire arrays use the kinetic energy of imploding plasma accelerated by the jxB force. Even though the wire array loads provide axial uniformity, the implosion stability is impacted by the azimuthal asymmetries related to the discreteness of the individual wires within the arrays. Implosion instability in the wire array may be responsible for seeding of the instabilities in the main Z-pinch [2].

In 1997, on the Saturn accelerator, these implosion non-uniformities were minimized by using wire arrays with as many as 192 wires. Increasing the wire number in wire array produced significant improvements in the pinched plasma quality, reproducibility, and x-ray output power [2, 8].
At Zebra facility, the two implosion instabilities, $m = 0$, and $m = 1$, shown in Figure 1.1 (b), were observed in several wire array Z-pincho experiments [9]. Other instabilities arise in the plasma during the ablation and implosion stages. The axial instability on individual wires depends on the axially non-uniformity of ablation mass from its plasma column. At some axial points of the corona plasma, the mass ablates faster, so the core gets burned sooner, and so this instability is seeded to the Z-pincho [10]. For Al wire arrays, at the end of the ablation phase, the characteristic wavelength of its modulation is about 0.4 mm [11]. At the beginning of the implosion phase, inhomogeneities in the plasma were observed. A current-carrying sheath is moving towards the axis of the array and snowplow the ablating mass. The period of the instability is about 2 mm, which is about 4-5 times the wavelength of the modulation of individual wire [12].
In high wire-number array experiments, at Z machine, the axial instability was seen early at the edge. The axial non-uniformity of ablation from the core gave rise to this instability.

There are several centers for fast wire array Z-pinch related research. The most advanced one is Sandia National laboratories (SNL) in Alburquerque, New Mexico, that houses the Z-machine. The Z-machine, the world’s most powerful x-ray generator, can deliver a peak current of up to 26 MA with a rise time of 100 ns through an inductive load of couple hundreds of thin metal wires, with an efficiency of 20% [1, 2]. Saturn is another Sandia generator, smaller than Z-machine, which is used to drive current pulses of up 9 MA with duration between 50 and 230 ns [2, 3]. Angara-5, in Russia, is capable to produce 3-MA load current with a rise time of about 70 ns [13]. At the Imperial College, in the UK, the Magpie generator has a peak current up to 1 MA in 250 ns [14]. At Nevada Terawatt Facility, the Zebra generator delivers a peak current up to 1 MA in pulse duration of 100 ns (1.6 MA with a current multiplier [15]). At Cornell University, the Cobra accelerator has a peak current up to 1.2 MA and rise time of 100 ns [16].

1.2 Main phases of wire array z-pinches

The main phases of implosion typically consist of four identifiable stages: the wire initiation, the ablation phase, the implosion phase, and the stagnation phase. All these basic phases of implosion were observed in all wire array Z-pinches mentioned above. Depicted in Figure 1.3 is the dynamic of the implosion in cylindrical wire arrays.
Figure 1.3 Implosion phases in a cylindrical wire array Z-pinch. (a) Wire initiation, where large currents passed through the wires creating plasma and global magnetic field. (b) Ablation phase, where the wire cores that are cold and dense remain at their original positions while the hot coronal plasma ablates due to jxB force towards the array axis. (c) Implosion phase, where wires breakage occurs, and this starts when all mass is completely ablated from some position points on the wires. (d) Stagnation phase, where the x-ray generation occurs.

In the wire initiation phase, the wires flashover in the beginning of the current pulse or on the current prepulse, which initiates the array by producing a plasma corona in few nanoseconds [17, 18]. Wires have a heterogeneous core-corona structure. The wire core is cold and dense while the coronal plasma is hot and of low density.

The high electrical current that is flowing through the wires generates a global magnetic field B that is resultant of sum of all individual magnetic fields in each wire of the wire array [19]. The field B is perpendicular to the current in each wire, which creates an inwards jxB force. During the ablation phase, the jxB force accelerates the coronal plasma around the core and towards the axis of the array, while the wire core remains stationary for about 80% of the implosion time.
The ablation rate is proportional to $I^2$ [10]:

$$V_{ab} \frac{dm}{dt} = - \frac{\mu_0 I^2}{4\pi R_0},$$

(1.1)

where $V_{ab}$ is the ablation velocity, $\frac{dm}{dt}$ is the rate of the ablation mass, $m$ is the mass per unit length, $\mu_0$ is the permeability of free space, $I$ is the current, and $R_0$ is the radius of the wire array. When the wire core runs out of mass on some position points, it starts to break up, and this triggers the implosion phase. The $jxB$ force accelerates the imploding mass. Snowplowing of the prefilled plasma plays a significant role in the implosion of the Z-pin.

The stagnation of the imploded mass at the array axis occurs with conversion of the kinetic energy into thermal energy and heating from the plasma compression. In this phase, the dense Z-pin is subjected to strong MHD instabilities, while the majority of the current flows through the central pinch.

1.3 Background and basic z-pin theory

In early works, the Z-pin was essentially abandoned as a result of large number of MHD instabilities that were experimentally and theoretically revealed. In modern Z-pin experiments, some non-uniformities can be minimized by the advance in pulse power technologies and through simulations by using accurate implosion models. The thin shell model is the simplest Z-pin model that allows easily and clearly to see the effects and possible complications of instabilities. In this model, the implosion is considered as an ideal implosion that might occur in the absences of instabilities [5].
1.3.1 Thin shell model

In the first paragraph of this chapter, the Z-pinch was described as a plasma column that is self-constricted by a high axial current, which produces an azimuthal magnetic field B. The jxB force compresses the plasma column along the z-axis as a result of the axial current j and the induced magnetic field B. In this model, the imploding plasma is assumed to remain as a infinitely thin cylindrically symmetric shell. The radial position of the plasma shell is approximated by the mass per unit length and strength of jxB force. This zero dimensional approximation is in close good agreement between the measured radius $r(t)$ and the acceleration determined from the force $J^2(t)/r(t)c^2$ and the constant mass per unit length $\mu$ [20].

With the above assumption, the equation of motion can be written as:

$$\frac{\mu d^2r}{2\pi r dt^2} = -\frac{B^2}{2\mu_0} = \frac{\mu_0 I^2(t)}{8\pi^2 r^2},$$

(1.2)

where $\mu$ is the mass per unit length, $\mu_0$ is the permeability of free space, $B = B(t)$ is the magnetic field at the surface of the pinch, and $I = I(t)$ is the pinch current.

Expression (1.2) can easily be integrated under the following boundaries conditions:

$$I = I_{\text{max}}, \quad r(0) = R_0, \quad dr(0)/dt = 0,$$

where $R_0$ is the initial plasma shell, and $I_{\text{max}}$ is the maximum current. Equation (1, 2) can be converted to dimensionless parameters in the following variable transformations:

$$r_1 = r/R_0, \quad t_1 = t/t_p, \quad I_1 = I(t_1)/I_{\text{max}},$$

where $t_p$ is the required time for $I = I_{\text{max}}$. Therefore expression (1.2) can be written as a dimensionless equation:
\[ r_1 \frac{d^2 r_1}{dt^2} = -\Pi. I_1^2(t_p), \quad (1.3) \]

where \( \Pi \) is a dimensionless factor given by:

\[ \Pi = \frac{\mu_0 I_{\text{max}}^2 t_p^2}{4\pi^2 \mu_0 r_0^2}. \quad (1.4) \]

If we assume that the current is described by:

\[ I = I_{\text{max}} \sin^2 \left( \frac{t}{2t_p} \right), \quad (1.5) \]

so the current \( I_1^2(t_p) \) has an optimum for the dimensionless factor \( \Pi \), which determines the optimization of the implosion, the current pulse amplitude and duration. In other words, to minimize the non-uniformities of the implosion, the imploding plasma should arrive at the axis at the time of corresponding to the maximum kinetic energy. This means that if the initial mass is too small, the shell will stagnate on the axis before the peak drive current, and if the initial mass is too large, this will cause the current to peak before the shell reaches the axis [20].

If we assume that the current is constant, and by introducing a dimensionless velocity \( v_1 = \frac{dr_1}{dt} \), equation (1.2) can be solved as follow:

\[ \Pi = r_1 \frac{dv_1}{dt}. \quad (1.6) \]

Upon integration \( \int_0^{v_1} v_1 dv_1 = \int_{r_1}^{1} \Pi \frac{dr_1}{r_1} \), the velocity can be expressed as follow:

\[ v_1 = \left( \frac{dr_1}{dr_p} \right)^2 = 2\Pi \ln \left( \frac{1}{r_2} \right). \quad (1.7) \]

To estimate the implosion time \( t_m \), we integrate equation (1.7)

\[ \int_0^{t_m} dt_f = \int_{r_p}^{1} \frac{dr_1}{\sqrt{2\Pi \ln \left( \frac{1}{r_2} \right)}}. \quad (1.8) \]
Therefore, the time required for the shell to be compressed to a minimum implosion radius \( r_{1m} \) is

\[
t_m = -\frac{\pi}{2\sqrt{2}} \text{Erf} \left[ \sqrt{\ln \left( \frac{1}{r_{1m}} \right)} \right].
\]  

(1.9)

### 1.4 Experimental methods for studying z-pinch plasmas

To study wire array Z-pinch plasmas, many experimental methods and techniques have been used for the investigation and diagnostics of the dense plasma parameters. Among these diagnostic techniques, there are optical, x-ray, and particle diagnostics, and for measurements of current and voltage [8]. The voltage is measured with a V-dot (capacitive divider) and resistive dividers while the current measurements are performed by B-dot (pickup coil) monitors. On Zebra generator, current through the load is measured with three differential B-dot monitors located on the anode plate at three different azimuthal locations.

For the laser probing diagnostics, the experimental methods that are used to study Z-pinch plasmas are: Dark field schlieren diagnostics, shadowgraphy, Faraday rotation diagnostics, and interferometry.

#### 1.4.1 Dark field schlieren

Dark field schlieren is an imaging technique in which a collimated laser beam is used to image electron density gradients in constricted current plasma, and to reveal the non-uniformity of the transparent plasma. This optical method relies on the transverse gradient of the index of refraction, which is associated with density gradients. If the appropriate laser light is propagated in the x direction through a transparent medium with a refraction index \( \eta (x, y) \), which varies in the y direction, the density gradients could be imaged, and the light get refracted by the following angle:
\[ \theta = \int \frac{\frac{\partial}{\partial x} \eta(x, y)}{\eta} \, dx = \frac{\Delta \eta}{\eta} \cdot l, \]  

(1.10)

where \( \theta \) is the angle of refraction, \( l \) is the interaction length in the y-direction, and \( \eta \) is the refraction index. Equation (1.10) is the angular displacement for one dimensional density gradient. Since the refraction index depends on \( x \) and \( y \), one can measure the density only by measuring the refraction of some rays, which, most of the time, cannot be identified. Therefore, expression (1.10) can be used only to determine some sensitivity of some parameters and estimate some effects.

![Diagram showing the refraction of light rays as they propagate in plasma with gradient in density. The increasing in the density gradient is in the positive direction of x-axis.](image)

Figure 1.4 Diagram showing the refraction of light rays as they propagate in plasma with gradient in density. The increasing in the density gradient is in the positive direction of x-axis.

As depicted in Figure 1.4, some rays that are propagating in plasma regions with radial density gradients, get deflected by an angle \( \theta \). At Zebra facility, the dark field schlieren diagnostic was used for imaging of low density plasma with high gradients of the electron
density. The typical experimental setup for schlieren diagnostics at 1-MA Zebra
generator is illustrated in the second chapter. It consists of a short 150-ps laser pulse at
the wavelength of 532 nm, lenses, knife edge, mirrors, and a CCD camera. The knife
edge is placed at the focal point of the lens to eliminate and block parallel rays that are
coming from undisturbed areas. In the presence of disturbances in the plasma, the rays
refract and are not stopped by the knife-edge. Refracted rays produce an image onto the
CCD camera.

1.4.2 Shadowgraphy

Laser shadowgraphy is another imaging technique used as a diagnostic for dense
plasma. Absorption in plasma creates a shadow image, which is relayed to the CCD
camera by optical system. Strong gradients of plasma density can also contribute to the
formation of the image if rays are refracted out of the acceptance angle of the beampath.
A multiframe shadowgraphy can present the dynamics of imploding plasma.

1.4.3 Interferometry

Interferometry is a common imaging technique used to measure a phase shift and
derive electron plasma density [22, 23]. There are various types of interferometers that
are used for the dense plasma diagnostics, namely, the two-beam Gamin, Michelson’s,
sharing air-wedge, and Mach-Zehnder interferometers [24].

Because the refraction index is directly related to the electron density of plasma, one
can have quantitative information about the electron plasma density by determining the
refraction index of plasma. Figure 1.5 shows a sketch of Mach-Zehnder interferometer
that is used at many facilities. It consists of a laser beam, beamsplitters, and a CCD
camera. The beamsplitter BS1 splits the laser beam on two channels. The beam splitter
BS2 is used to recombine the two beams. The interferometric pattern of plasma is relayed by lenses to the CCD camera. The introduction of a small angle between the probe and the laser beams allows the formation of straight fringes in the absence of any electron density. In the presence of plasma, a fringe shift in the interferogram is induced as result of the phase shift in the plasma.

\[ \delta = 4.46 \times 10^{-14} \lambda (\text{cm}) \int n_e (\text{cm}^{-3}) \text{dl}, \] (1.13)

where \( n_e \) is the electron number density of plasma and \( \lambda \) is the wavelength of the laser probing. When \( \lambda = 532 \text{ nm} \), we obtain:

\[ \int n_e (\text{cm}^{-3}) \text{dl} = 4.2 \times 10^{17} \delta \] (1.13)

The electron plasma density \( n_e \) can be measured by analyzing the interferograms. Once the fringe shift \( \delta \) is derived, \( n_e \) can be estimated. Abel inversion is used for the calculation of the electron density in plasma objects with cylindrical and spherical symmetry.
Earlier experiments showed that the Mach-Zehnder interferometer is too sensitive for measurements in the plasma column with the short 150-ps laser pulse at a wavelength of 532 nm. Therefore, a differential air-wedge interferometer [24], appropriate for conditions of experiments, was used to estimate the plasma density at NTF.

There are several air-wedge interferometers, namely, side-shearing, radial shearing, and polarization side-shearing interferometers [24]. The polarization side-shearing interferometer with an Iceland spar birefringent wedge allows formation of shearing interferogram in the interference of two images of an object, which are shifted with respect to each other by a certain distance.

1.4.4 Faraday effect polarimetry

The phenomenon of the Faraday effect was first seen by Michael Faraday in 1845 [25], who discovered that linearly polarized light, traveling through a transparent medium with the existence of a magnetic field $B$, experiences a net rotation $\beta$ of the plane of polarization. The amount of rotation $\beta$ is proportional to both the thickness $d$ of the transparent medium and to the strength of the magnetic field $B$,

$$\beta = V B d \ ,$$

where the constant of proportionality $V$ is the Verdet constant. Faraday rotation technique is commonly used in optical devices, such as Faraday optical isolators, to prevent unwanted self-oscillations and back-reflections. It can be also used to infer and determine the susceptibility of materials.

Faraday rotation polarimetry for the diagnostics of magnetic fields is one research method that is used successfully in many facilities, including NTF. In the Faraday magneto-optic effect, the polarization plane of the probing electromagnetic wave is
rotated. This rotation is caused by the Faraday effect in the magnetized plasma when the electromagnetic wave propagates through it [26, 27, 28, 29]. However, the rotation of the polarization plane may occur in the absence of a magnetic field. For instance, the polarization plane can be rotated by the electron number density gradient, temperature gradient, or velocity gradient. One should make sure that this rotation is really due to the existence of magnetic field in the plasma [30].

Consider an electromagnetic wave $E$, propagating through a transparent medium of plasma. The effects applied by this medium on $E$, displace the electromagnetic energy from a point $y$ to be point $y'$ defined by ($y' = y + L \theta(y)$), where $L$ is the traveled distance by $E$ in the plasma, and $\theta$ is the refraction angle of the rays defined by [31]:

$$\theta = \frac{d}{dy} \int Ndl \tag{1.16}$$

The same effect occurs in the orthogonal direction within the plasma at the coordinate $x$. So the incident electromagnetic wave at the position $(x, y)$ can be moved to other position $(x', y')$ defined by [31]:

$$(x', y') = \left( x + L \frac{d}{dx} \left[ \int Ndl \right], y + L \frac{d}{dy} \left[ \int Ndl \right] \right). \tag{1.17}$$

If the incident electromagnetic wave has uniform intensity $I_i$, the detected intensity $I_d$ can be expressed as follow [31]:

$$\frac{I_i}{I_d} = 1 + L \left[ \frac{d^2}{dx^2} + \frac{d^2}{dy^2} \right] \left( \int Ndl \right). \tag{1.18}$$

In the magnetized plasma, the electromagnetic wave $E$ get decomposed into two opposite circular polarized components, with one propagating faster than the other. This explains the physical significance of wave numbers $k_+$ and $k_-$. The magnetic field $B$ accelerates one of the components of the electromagnetic wave with respect to the other [31].
\[ \frac{E_x}{E_y} = \pm i. \]  

(1.19)

For magnetized plasma \((w \gg w_c)\) the high frequency electromagnetic wave influences the charges (electrons or ions) around the magnetic lines of force. In the case of interest, the magnetic field is parallel to the propagating electromagnetic wave \((B \perp E)\). The longitudinal mode of one component of \(E\) generates an elliptical polarization in the plane of \(k\) and \(E\), as it is depicted in Figure 1.6.

Figure 1.6 Diagram showing the Faraday polarimeter setup. After passing through the polarizer, the linear polarized beam is rotated by the polarization angle \(\beta\). The electric field \(E\) represents the propagating electromagnetic wave, which is rotated by \(\beta\).

Suppose that at \(z = 0\), the electromagnetic wave is linearly polarized and \(E_x = 0, E_y = E\), that leads to, the following equation [31]:

\[ E(0) = \frac{E}{z} [(1, -i) + (1, +i)], \]  

(1.20)

where \(z\) is the direction of propagation.

At \(z \neq 0\), equation (1.20) can be written as follow [31]:

\[ E(z) = \frac{E}{z} \left[ (1, -i) \exp \left( iN_+ \frac{w}{c} z \right) + (1, +i) \exp \left( iN_- \frac{w}{c} z \right) \right], \]  

(1.21)

where \(N_+\) and \(N_-\) are the refraction indices of the electromagnetic wave.
For magnetized plasma, the electron cyclotron frequency is

$$w_c = \frac{eB_0}{m_e c} \tag{1.22}$$

The general dispersion relation or the wave number defined by

$$k_\mp = \frac{w}{c} \left[ 1 - \frac{w_p^2}{w^2 (1 + \frac{w_c}{w})} \right]^{1/2}, \tag{1.23}$$

where \(w_p\) can be expressed as flows:

$$w_p = \sqrt{\frac{4\pi n_e e^2}{m_e}}. \tag{1.24}$$

To evaluate Faraday rotation angle in magnetized plasma, the polarization need to be characterized. If the magnetic field \(B\) is perpendicular to the \(x\)-axis, the following equation relates the transverse components of the electromagnetic wave are [31]:

$$\frac{E_x}{E_y} = \frac{iY\sin^2(\theta)}{2(1-X)\cos(\theta)} \pm i \left[ 1 + \frac{Y^2 \sin^4(\theta)}{4(1-X)\cos^2(\theta)} \right]^{1/2} \tag{1.25}$$

The Faraday rotation angle is expressed by the following equation [31]:

$$\beta = \frac{\Delta \theta}{2} = \frac{1}{2} (N_+ - N_-) \frac{w}{c} z = \frac{1}{2} \left[ \frac{Y \cos(\theta)}{(1-X)^{1/2}} \right] \frac{w}{c} z. \tag{1.26}$$

If \(X \ll 1\), the faraday rotation angle in the equation (1.23) can approximates to:

$$\beta = \frac{\Delta \theta}{2} = \left[ \frac{w_p^2 \Omega \cos(\theta)}{2w^2 c} \right] z. \tag{1.27}$$

Therefore, Faraday rotation is proportional to \(\Omega \cos(\theta)\), which is \((e/m)B\). k. Faraday rotation angle is proportional to the parallel component of the magnetic field. In the approximation \(X \ll 1\), it is also proportional to the electron density then the total Faraday rotation angle along the wave is
\[
\beta = \frac{\Delta \theta}{z} = \frac{1}{2} \int \frac{w_0^2 \Omega \cos(\theta)}{w^2 \sqrt{1 - \frac{w_0^2}{w^2}}} \frac{dl}{c}
\tag{1.28}
\]

The Polarization angle can also be written as:

\[
\beta = \frac{\Delta \theta}{z} = \frac{e}{2me} \int \frac{n_e B \, dl}{n_c (1 - n_e/n_c)^{1/2}}
\tag{1.29}
\]

\[
= \frac{e}{2me} \int \frac{n_e B \, dl}{n_c} \text{ for } \frac{n_e}{n_c} \ll 1,
\]

where \(\beta\) is measured in radians, \(\lambda\) is the wavelength of the probing beam, \(B\) is the projection of the magnetic field onto the probing direction in Gauss, \(n_e\) is the electron density of plasma in cm\(^{-3}\), and \(dl\) is an infinitesimal displacement traveled by the electromagnetic wave in cm (\(L\) is the path length).

### 1.4.5 X-ray and particle diagnostics for Z-pinches

There are many x-ray diagnostics that have been used in different facilities to investigate wire array Z and X-pinches. These x-ray plasma diagnostics include time gated and time-integrated crystal spectrometers, time-gated pinhole framing cameras, XUV spectrometers, x-ray diodes (XRDs), photoconductors detectors (PCDs), bolometers for measurements of x-ray radiation yields, soft x-ray transmission diffraction grating spectrometers, and time resolved filtered hard x-ray radiation photomultipliers as well as Si diodes. Faraday cups are used for diagnostic of particle beams from the Z-pinch. These x-ray diagnostics were used in Z machine at the Sandia National Laboratory, in ANGARA-5 facility in Moscow, in Cornell Cobra machine, in Magpie generator at Imperial College and in Zebra Generator at the Nevada Terawatt Facility.

The spatial resolution, time response, and the spectral resolution (bandwidth) are the main parameters determining the measurement accuracy that is done by the diagnostic
devise. For example, the spatial resolution for side-on time gated pinhole camera is between 100 and 250 µm [32], its response duration is between 1 to 80 ns. The response time for the PCD is less than 200 ps [33].

In wire array Z and X-pinch experiments, several plasma parameters, as well as the dense plasma properties were measured, namely the plasma temperature $T_e$, the electron plasma density $N_e$, and soft as well as hard x-ray radiation powers and energy.
1.5 Dissertation overview and goals.

The goal of this dissertation is to investigate and study the ablation and implosion phases in cylindrical and star-like wire arrays, by applying different diagnostics and experimental methods. The results of these investigations and studies are presented in the following chapters.

The second chapter is an overview of the pulse power, the Zebra generator used at the Nevada Terawatt Facility. The experimental setup for Z-pincho study will be described. Some experimental backgrounds and methods, as well as an advanced set of diagnostics that we developed and applied to investigate the wire array Z-pincho plasmas at 1-MA Zebra generator, will be described and discussed particularly the laser and the optical probing, and core x-ray diagnostics.

In the third chapter, a study of the plasma precursor in the cylindrical wire arrays will be presented. The magnetic field was investigated in the plasma column of the precursor. New diagnostic, which can precisely measure the plasma density, is introduced. It consists of developing a continuous interferometry for the ablation stage. For this purpose, a long pulse infrared laser was successfully built and tested at NTF, and that will be described in detail in this chapter.

In the fourth chapter, experimental results concerning the plasma bubble-like implosion dynamics in different wire array Z-pinches will be described and discussed.

The fifth chapter introduces new and very interesting wire arrays that were designed, developed, and studied for the first time in the 1-MA Zebra generator. These wire arrays are the star wire arrays, which demonstrate high x-ray power yields as well as smooth and minimal implosion instabilities. The cascading implosion in the star wire arrays are
described in details. This mode of implosion in this new type of wire arrays was investigated and confirmed by several diagnostics.
Chapter 2
Experimental setup for z-pinch study at 1-MA Zebra generator

This chapter describes the experimental setup, laser system, and core diagnostics used to acquire data and to study Z-pinch plasmas at 1-MA Zebra generator. An overview of the Zebra generator is given with details regarding some components of the generator. Another overview of the presented diagnostics that are used to probe the wire array Z-pinches is discussed. The rest of the chapter describes and gives more details about each plasma diagnostic that we used in our experiments at the Nevada Terawatt Facility.

2.1 The Zebra generator at the Nevada Terawatt Facility.

The implosion of a wire array z-pinch required a fast rising current, which can be provided by a short pulse and high power generator. Figure 2.1 illustrates the high-density Z-pinch II (HDZP-II) [69] current generator that was relocated to the UNR and now is also called Zebra generator. It was installed at Nevada Terawatt Facility located within the University of Nevada, Reno in order to conduct experiments with magnetically insulated transmission lines (MITL) and wire array z-pinches.

Zebra generator is a two Terawatt pulsed power accelerator which can deliver a peak current of ~ 1 MA with a rise time of 100 ns. Figure 2.2 shows Zebra current pulse regime as a function of time. In this regime, the current has a pedestal that increases for about 100 ns to about 5% of the maximum current intensity. The Zebra generator has three stages of power amplification. The first is the charging of the Marx bank that consists of thirty-two 1.3-μf capacitors, placed in an oil tank, and charged in parallel via resistors up to 85 kV, which can store energy of ~150 kJ.
Figure 2.1 Two Terawatt 1MA Zebra generator at NTF. (a) Photograph of Zebra bay area with an angle top views showing some elements of Zebra generator and diagnostics, (b) architectural concept illustrating Zebra generator with the Marx capacitor bank, the vacuum chamber, and pulse forming elements.
When the bank is triggered, the capacitors get discharged, in series, in the second stage of power amplification with a coaxial capacitor (28 nF, 2 MV) using water as dielectric and an SF₆-insulated Rimfire switch, as can be seen in Figure 2.1. When the intermediate storage capacitor is about 80% charged, the switch is electrically triggered and connects to the third stage of pulse compression. It consists of a 300 ns 1.9-Ω coaxial vertical transmission line and a self-breaking water switch.

![Figure 2.2 Zebra generator’s typical current pulses for wire array Z-pinch as a function of time.](image)

When the voltage across the switch is high enough, current will arc across the pairs of pins. The voltage breaks down the fiber providing a channel for the current that rises to ~1 MA with a rise time of ~100 ns.

The Zebra experiment chamber, as shown in Figure 2.1 (b), is located on the top of the vertical transmission line. Figure 2.3 is a conceptual schematic of the vacuum chamber, which shows the anode, cathode, and the location of the load.
The experiment vacuum chamber has 16 diagnostics ports, radially placed and equally spaced at 22.5 degrees, with alternating diameters of 7.6 cm and 5 cm. In the current configuration, the chamber wall plays the role of a current return conductor, so all diagnostics have to be installed outside of the wall, at a minimum distance of 30 cm from the chamber axis.

![Image of vacuum chamber](image)

Figure 2.3 Conceptual schematic of the Zebra experiment vacuum chamber showing its anode, cathode, and the location of the load.

### 2.2 Plasma diagnostics at 1-MA Zebra generator.

To determine the plasma parameters and study the implosion dynamics in current constricted wire arrays at NTF, many diagnostics, including current, optical, x-rays, and XUV diagnostics, were employed. Figure 2.4 is a schematic of the top view of the vacuum chamber, showing all diagnostics that were placed, in 16 different ports, radially around the Z-pinch plasma. The electrodes of the array allow an end-on (r-θ) view of the complete 2 cm x 1.6 cm volume of the wire array. Wire arrays used at Zebra Facility consist of a variety of configurations, including planar, cylindrical, conical, double nested, and “star”-like wire arrays. Typically, the thin metallic wires configured in these arrays, depending on the metal used, range from 3.9 to 25 μm in diameter, and from 4 to 32 in number per wire array. The current and voltage diagnostics are Zebra standards, and their measurements are performed in all section of Zebra generator. In the Marx section,
close to the load region and at the insulator stack, the voltage is measured with V-dot (voltage divider).

![Figure 2.4 Schematic of the top view of the Zebra vacuum chamber including all diagnostics for wire array Z-pinches.](image)

The current measurements are performed by B-dot (pickup coil) monitors. Current through the load is measured with three differential B-dot monitors located at about 15 cm from the chamber axis at three different azimuthal locations.

The following paragraphs describe the presented laser probing, optical probing, and x-ray core diagnostics used to study Z-pinch plasmas at the Zebra facility.

### 2.2.1 Laser probing diagnostics.

The optical diagnostics of plasma is based on the Nd: YAG laser with a short 150 ps pulse at the wavelength of 532 nm. The Nd:YAG laser system is commercially available from the EKSPLA company. Table 1 presents parameters of this laser.
The experimental setups that are built for the laser probing diagnostics, and used in this experimental work, have been divided into three categories: The first experimental setup is located in the Laser room, the second experimental setup is around the experiment vacuum chamber, and the third experimental setup is located in the laser probing screen box. The three groups constituting the whole experimental setup form high-resolution multi-frame imaging diagnostics that were developed at Zebra facility for the investigation of the implosion dynamics of wire arrays Z-pinch.

<table>
<thead>
<tr>
<th>Wavelength, nm</th>
<th>532</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse duration, ps</td>
<td>150</td>
</tr>
<tr>
<td>Jitter, ns</td>
<td>±1</td>
</tr>
<tr>
<td>Pulse energy, mJ</td>
<td>80</td>
</tr>
<tr>
<td>Beam diameter, mm</td>
<td>~8</td>
</tr>
<tr>
<td>Beam divergence, mrad</td>
<td>&lt; 0.5</td>
</tr>
</tbody>
</table>

Table 2.1 Specifications of the SL312 Nd:YAG Laser system used for the laser diagnostics of the Z-pinch plasmas at 1-MA Zebra generator.

The first experimental setup is depicted in Figure 2.5 and is intended to serve as a laser probing source. It includes the EKSPLA laser at a wavelength of 532 nm and a continuous wave (CW) alignment laser. Because the CW laser beam is not of a good quality, and so it needs to be treated and cleaned up. For this reason, the both lenses L1 and L2 were mounted, as well as the pinhole diaphragm PH1. The lenses L1 and L2 play the role of a telescope, while the diaphragm PH1, mounted on the focal point of the lens L1, improves the divergence of the laser beam. The laser beam coming from the laser room 112 and passing along a pipe passes through an intermediate setup mounted in an optical cabinet.
Figure 2.5 Optical scheme of the first experimental setup at the laser room 112.
The second experimental setup is mounted and distributed in five optical diagnostic blocks around the vacuum chamber, as seen in Figure 2.6.

![Figure 2.6 Photograph with an angle top view of the Zebra bay array showing the second experimental setup that is included in five optical diagnostic blocks, around the vacuum chamber.](image)

The conceptual schematic presented in Figure 2.7 illustrates the optical diagnostics of plasma, which include five-frame laser probing of the z-pinch in three directions with the angle of 22.5° between directions:

- The non-delayed and delayed laser pulses 1s, and 1ds, that pass through the first probing direction, or channel one.
- The non-delayed and delayed laser pulses, 2s and 2ds, that pass through the second probing direction, or channel two.
- The third pulsed laser beam 3 pass through the third probing direction, or channel three.
The first two probing directions are used for the four-frame shadowgraphy, or either four-frame schlieren diagnostics, or 2-frame Mach-Zehnder interferometer. The third probing direction includes shadowgraphy, Faraday rotation diagnostics, dark field schlieren diagnostics, and interferometry, see Figure 2.7.

In each Zebra shot, the short 150-ps laser pulse at a wavelength of 532 nm provides 8 high-contrast instant images of the fast moving plasma on charge-coupled device (CCD) cameras. The total of frame images was recorded in long or short pulse train. Depicted in Figure 2.8 are three optical delay lines that are arranged in a short 9-ns or long 34-ns train of five equidistant probing pulses.

Figure 2.7 Conceptual schematic of the laser probing diagnostics of plasma.
Depending on the delay and on the pulse train used for the experiment, the second experimental setup can be illustrated by two different optical schematic diagrams. Figures 2.9 and 2.10 respectively present the optical schemes of the second experimental setup for the short 9-ns and long 34-ns trains of the five equidistant probing pulses.

**Figure 2.8** Diagram showing the three optical delay lines and the corresponding pulse timing at the vacuum chamber.

5 laser pulses and three delay lines.
Figure 2.9 Optical scheme of second experimental setup for the long 34-ns trains of the five equidistant probing pulses.
Figure 2.10 Optical scheme of second experimental setup for the short 9-ns trains of the five equidistant probing pulses

The laser probing screen box represents the third experimental setup, and serves as data and image acquisition. As shown in the Figure 2.11, this experimental setup includes optics, mounts, and 8 charge-coupled device (CCD) cameras to record 8 images of the plasma. Additional equipment, for triggering as well as data recording, is included in this acquisition box such as DG 535, oscilloscope, and computers.

Laser reference images were recorded before the shot of the Zebra generator to show the initial position of the wires, to check the beam quality, and to calibrate the light intensity on CCD cameras.
Figure 2.11 Optical scheme of the laser probing screen box showing all optics, mounts, CCD cameras, and acquisition equipments.

Figure 2.12 presents the optical scheme of the dark field schlieren imaging diagnostic inside the optical screen box. It includes image-relaying lenses and a knife edge. This knife is placed on the focus of lens L2 to eliminate and block the parallel rays that are coming from undisturbed plasma. The dark field schlieren diagnostic can be established in any probing direction of the laser probing. The third probing direction includes dark
field schlieren diagnostics, shadowgraphy, Faraday rotation diagnostics, and differential interferometry.

![Diagram illustrating the dark field schlieren imaging setup.](image)

Figure 2.12 Diagram illustrating the dark field schlieren imaging setup.

The laser shadowgraphy is an imaging technique that was performed in all three directions of the laser probing diagnostics. It is similar to the dark field schlieren imaging technique, except that, in the shadowgraphy diagnostics, there is no beam stopping knife in the experimental setup.

The interferometery was applied at 1 MA Zebra generator to measure the electron plasma density. Mach-Zehnder and air-wedge differential interferometer [24] are used at Zebra facility. Mach Zehnder interferometer is too sensitive for Z–pinch plasmas and had limited applications in our experiments.

At the Nevada Terawatt Facility, the Faraday rotation technique was used to probe and investigate the magnetic fields as well as the current distributions in dense Z-pinch plasmas. The Faraday rotation diagnostic consists of a 2-channel polarimeter, sharing air-wedge interferometer, and also includes a dark field schlieren channel. A Glan prism
polarizer provides a high contrast of linear polarization, $K>10^5$, for the incident laser beam. Figure 2.13 presents an optical diagram of Faraday rotation diagnostics.

Figure 2.13 Optical schematic diagram of Faraday rotation diagnostics developed and used at Zebra Facility.

A calcite wedge is mounted after the window of the vacuum chamber and separates, angularly ($\sim 1^\circ$), two orthogonal component of the probing laser beam to form Faraday and shadow images. The same lenses are used to relay images of the plasma on two 1024x1024 pixel CCD cameras of the polarimeter. Film polarizers separate orthogonal polarizations on the CCD cameras. Narrowband interference filters block radiation of plasma. The intensity of light in the Faraday image was compared with the intensity in the shadowgram for reconstruction of the Faraday rotation angle. Part of the shadow channel beam is split into the interferometer and dark field schlieren channel.

Z-pinch plasmas are inhomogeneous and have strong gradients of electronic density. In these conditions the effect of the magnetic fields can be extracted if we compare the
identical Faraday image and shadowgram. The Glan prism polarizer G and the calcite wedge analyzer W in the Faraday channel were mismatched at \( a_0 = \pm 2.7^\circ \) to create background lighting in the Faraday image [34-37]. For \( a_0 \neq 0 \) the rotation of the polarization plane with different signs increases or decreases the intensity of light in the Faraday image. Thus, the Faraday image of the plasma appears darker on one side of an axially directed current channel and brighter on the other side.

The rotation angle \( \beta \) is reconstructed from the distribution of the light intensity in the Faraday image and the shadowgram [34]. The polarization angle of rotation \( \beta \) in the plasma is given by formula [31]:

\[
\beta = \frac{e^3 \lambda^2}{8 \pi^2 e_0 m_e c^3} \int_0^L n_e B \, dl = 2.62 \times 10^{-17} \int_0^L n_e B \, dl,
\]

(2.1)

where \( \beta \) is measured in radians, \( \lambda \) is the wavelength of the probing beam measured in cm, \( B \) is the projection of the magnetic field onto the probing direction in Gauss, \( n_e \) is the electron density of plasma in cm\(^{-3}\), and \( dl \) is an infinitesimal displacement traveled by the electromagnetic wave in cm (\( L \) is the path length).

The electron density of the plasma can be measured with interferometry. The phase shift of interferometric fringes is proportional to the electron number density \( n_e \), the phase shift \( \delta \) (in fringes) is given by formula:

\[
\delta = 4.46 \times 10^{-14} \lambda \int_0^L n_e \, dl
\]

(2.2)

To obtain the distribution of the magnetic field \( B \), the interferometric technique in parallel with the Faraday effect polarimetry needs to be used. Once the phase shift is determined, one can estimate the value of the Z-pinch plasma density. After applying the experimental method for the determination of the Faraday rotation angle, one can
estimate this polarization angle $\beta$ and therefore the magnetic field B as well as the current I inside the Z-pinchi plasma can be estimated.

The principal elements of the Faraday rotation channel are two crossed polarizers ($p_1$, $p_2$) that separate two orthogonal polarizations on two directions. A crystal wedge splits a probing pulse angularly into two beams with orthogonal polarizations. The polarizer $p_1$ is a Glan prism, located in the third direction before the vacuum chamber, while the crystal wedge $p_2$ is considered as an analyzer, located in the same port direction as $p_1$ but passed the vacuum chamber. Part of the shadow channel is split in the screen box for the shearing air-wedge interferometer and schlieren channels.

The effect of the magnetic fields can be extracted by comparing the Faraday image to its complementary shadowgraphy image before and after Zebra shot.

The linear polarized wave of the probing laser passes through the z-pinchi plasma of the wire array. In the presence of plasma, the light intensity that is passing through the Faraday channel $I_F$, after the analyzer $p_2$, is determined as follows:

$$I_F = I_o \{\sin^2(\alpha + \alpha_o) + k \cos^2(\alpha + \alpha_o)\},$$  \hspace{1cm} (2.3)

where $I_o$ is the initial light intensity in the absence of plasma, $\alpha$ is the polarization plane rotation angle in plasma with a magnetic field, $\alpha_o$ is the initial polarizer angle of mismatch, and (k) is a depolarization ratio of the probing beam. For small angles $\alpha$ equation (2.3) can be also expressed as follow [38-39]:

$$I_F = I_o \{\sin^2(\alpha + \alpha_o) + K\},$$  \hspace{1cm} (2.4)

where K is polarimeter contrast constant and $I_o$ is a new initial light intensity (after changing variables).
By considering the current carrying homogeneous plasma column with the radius $R$, and total current $I$, the magnetic field $B$ on the radius $r$ can be calculated by the formula, $B= 2r \cdot I/(cR^2)$.

### 2.2.2 ICCD and streak camera diagnostics.

A time-gated intensified CCD camera (ICCD) was used to record the optical images of the radiating plasma with a gate time of ~2 ns. The optical streak camera was used to study the continuous implosion dynamics of the wire arrays. The streak camera sweeps a duration of 300 ns over a 40 mm diameter photocathode, and were used to image the array self emission light. At the streak camera, a slit sampled across the radius of the array, producing a temporal resolution of 0.25 mm over different array diameter.

![Diagram](image)

Figure 2.14 Optical scheme of the optical diagnostic which is including an ICCD, and a streak camera to record the optical plasma of the radiating plasma and to study the continuous implosion dynamics of the wire arrays.
The streak and ICCD cameras record radiation from a direction different than the directions of the laser probing. Figure 2.14 shows the optical scheme of the optical screen box that includes an ICCD, a streak cameras, optics, mounts, and additional equipment for data acquisitions.

### 2.2.3 X-ray core diagnostics.

Wire array Z-pinches have demonstrated the capability of efficient generation of high x-ray power. In Sandia National Laboratory, the Z machine is capable of generating x-ray powers of 250 TW and x-ray energies of 1.8 MJ, while at NTF, the Zebra generator is able to produce x-ray powers of >0.5 TW and x-ray energies of 20 kJ. These radiation sources produced by Z and Zebra generators could be used in high energy density physics, radiation effects, and in inertial confinement fusion experiments.

The cylindrical and star wire arrays generate a powerful x-ray pulses including soft and hard x-ray radiation. Hence, the hard and soft x-ray diagnostics that are available at the NTF, with more relevant details will be discussed in this paragraph. X-ray plasma diagnostics on the Zebra generator, as shown in Figure 3.4, included a five-channel x-ray head, time gated pinhole camera, and x-ray spectrometers.

The five-channel head shown in Figure 2.15 is an x-ray detector array. This channel is placed at a distance of 2 meters from the load and is based on x-ray diodes (XRDs), diamond photoconductive detectors (PCDs), and energy detector bolometer. Location of x-ray diagnostics is shown in Fig. 2.4.
a) X-ray diodes (XRDs).

The XRD is an x-ray diode with a carbon photocathode and anode mesh built into the connector housing, used to measure the x-ray radiation yields from the wire array z-pinch plasmas. The XRDs are based on the emission and collection of photoelectrons from cathode under action of x-rays [33]. The photocathode consists of a diamond polished vitreous carbon disk. The carbon disk is silver epoxied to a gold-plated copper nickel stalk and acts as the center conductor for the modified N-conductor [32, 40].

![Image of XRDs](image)

Figure 2.15 An inside view of the five channel head array where the XRDs, PCDs, and bolometer are placed for x-rays probing.

![Graph of spectral response](image)

Figure 2.16 Typical spectral response of an unfiltered carbon cathode XRD as a function of the photon energy [32].
The spectral response of the XRD depends on the photon energy and varies over the range of 0.2-1.6 keV as shown in Figure 2.16 [32]. At the photon energy of 800 eV, the XRD response is about ~12 A/MW. In order to have accurate measurements of the XRD spectral responses, a cleanliness of the photocathode surface, as well as replacements and recalibrations of the XRD are required. The XRDs have a typical time response >500 ps which depends on the electron transit time between photocathode, anode and the capacitance of the detector [2]. On Zebra generator the XRDs are used with 2 µm and 6 µm Kimfol and Kapton filters for measurements of the temporal profile of the soft x-ray pulse. Power of the soft x-ray pulse was measured from the XRD filtered by the 2-µm Kimfol film and Ni bolometer.

b) Photoconductive detectors (PCDs).

The PCD is a diamond photoconducting detector used to detect the x-ray radiation pulse from the wire array Z-pinch plasmas. The diamond PCDs have some advantages compared to the XRDs, which include their ruggedness, stabilities, flat spectral response, low leakage currents, readily cleanable surface, and a short time response of <200 ps due to the short electron/hole recombination time [40].

The filters that are installed in this device allow a spectral response in the region up to 100 eV, as shown in the Figure 2.17. This Figure represents the spectral responses as a function of the photon energy.
c) **Bolometer.**

A Ni bolometer is used for energy measurements in the range from 10 eV to 4-5 keV. The bolometer is absolutely calibrated and presents time-integrated pulse with the amplitude proportional to x-ray energy. It consists of a 1 µm thin film whose resistance is linearly varied as a function the absorbed x-ray radiation [70]. The spectral response of the unfiltered Ni bolometer varies in the energy range between 0.01 eV and 10 keV. The thicknesses as well as the type of the material in the bolometer are two essential parameters that can be adjusted for accurate measurements. The incident x-ray radiation upon the thin material is heated causing resistance as well as voltage rise across the bolometer, which allows a direct measurement of the x-ray radiation yield.

Usually, the total radiating energy is measured by the Ni bolometer while the peak power of the x-ray pulse is calculated from the XRD filtered by the 2-µm Kimfol film and Ni bolometer.

Figure 2.17 Typical spectral response of unfiltered PCD as a function of the photon energy [32].
d) **Time gated x-ray pinhole framing camera.**

Time gated x-ray pinhole framing camera is used to produce an x-ray image on a micro-channel plates (MCP). At NTF, this camera is based on 6 channel MCPs with adjustable pulse duration. In our experiments it records 6x2 frames in two spectral regions with the duration of the frames from 3 to 4 ns. The inter-frame time (time between gate pulse fronts) is also changeable which are adjusted by co-axial cables. This device has being used in the experiments to get the images of x-rays in Zebra shots. The pinhole camera provides a spatial resolution of 250 µm, with time duration of the exposure 3 – 4 ns.

e) **X-ray spectrometers**

X-ray spectrometers are devices to measure and determine some characteristic of some parameters in Z-pinch experiments on Zebra generator. In our experiments, two x-ray spectrometers with convex crystals were used to investigate the properties of wire array Z-pinch plasmas. There are the time gated and time integrated spectrometers. Both they used the crystal Potassium hydrogen phthalate (KAP) as a dispersing medium. They provide a wavelength range of Al K-shell radiation, which is between 5 Å to 10 Å. They were employed to infer some physical properties of Z-pinch plasma such as the electron temperature and density. Using the crystal spectroscopy, the dispersion of the x-ray radiation follows to Bragg’s law:

\[ 2d \sin(\theta) = m\lambda \]  

(2.7)

where \( d \) is the distance between the Bragg planes of the convex crystal KAP, \( \theta \) is the grazing angle, \( d \) is a distance that is close to the x-ray wavelength, \( m \) is the order of diffraction, and \( \lambda \) is the wavelength of the diffracted light. For the convex crystal KAP
the distance 2d is about 26.62 Å and the radius of the convex crystal KAP is about 50 mm for the corresponding x-ray energies (0.8 to 3 keV).
Chapter 3

Study of the precursor in the cylindrical wire arrays

3.1 Study of magnetic fields in the precursor plasma.

The wire array Z-pinch has a complicated current distribution in different stages of implosion. In the early stages of implosion, an accumulation of mass known as “precursor” appears on the axis of the array as the result of ablated mass arrival. This precursor plasma column has been observed at small (~1 MA) [41-43], and large (~20 MA) [44] pulsed power facilities. There are many detailed studies and experiments that carefully studied the formation column on the wire array axis. However, here we focus on the magnetic field as well as the current in plasma column of the precursor.

During the ablation stage, current flows through the coronal plasma around the wires, which exhibit a complex core-corona structure [45, 46]. In this stage, part of the current can be transferred to the central plasma column. The value of current in the precursor varies from 0 to 5-15% in different loads and generators [9, 11, 47, 48]. During the stagnation stage, the majority of the current switches to the central Z-pinch. The current in the precursor can affect the radiated power and the density of the stagnated Z-pinch [41, 43, 49, 50]. For this reason, measurement of the current in the precursor plasma is important for understanding of the stagnation stage and generation of x-ray in Z-pinches.

In this chapter, magnetic fields and current were measured using the method of the Faraday rotation. The first measurements of current in the precursor of 4-wire and 8-wire arrays by this method were carried out [51]. This chapter presents systematic measurements and analysis of magnetic field in wire arrays on the 1-MA Zebra generator.
To study the magnetic fields as well as the current in the plasma column of the precursor of the wire arrays, Faraday rotation diagnostics at the NTF were developed for this purpose. Faraday images from Zebra shots with their complementary shadowgrams show a Faraday effect in the precursor plasma column of cylindrical and conical wire arrays during the ablation stage. Several examples of the Faraday rotation in the precursor plasma are presented below.

Figure 3.1 presents the plasma column of Al 16 x 15 μm cylindrical wire array from shot #508. The precursor plasma is confined in the column with a diameter of 3-4 mm. This Figure presents the Faraday image (a) and its complementary shadowgram (b), where the shadow of wires is clearly seen. By comparing these two frame images, (a) and (b), the dotted loops show a lightning on the right side and a darkening on the left side of the precursor in the Faraday image (a).

![Faraday Image](image1) ![Shadowgraph Image](image2)

Figure 3.1 One time frame of the implosion of Al 16 x 15 μm cylindrical wire array. Faraday image (a) and its complementary shadowgram (b) showing Faraday effect in the precursor. The mismatch angle between the polarizer and the calcite wedge is $\alpha_o = 5^\circ$. The pictogram in the lower right corner shows the probing direction.
The lightning and darkening on the right and left sides of the precursor indicate the inward and outward directions of the magnetic field B, respectively. In other words, the magnetic field B has opposite directions between the left and the right side on the plasma column of the precursor. This is an evidence of the current following inside the precursor plasma column since early stage of the implosion of wire array.

In fact many experiments with different type of wire arrays showed Faraday effect in the plasma column. These arrays included cylindrical with large and small diameter, and conical wire array.

Figure 3.2 Faraday Image (a) and its complementary shadowgraphy image (b) of the implosion of Al 16 x 15 µm cylindrical wire array (shot 494) showing that the Faraday effect around the plasma column of the precursor changes of sign, when the angle mismatch of the polarizers is $\alpha_o = 5^\circ$ change of sign ($\alpha_o = -5$). The pictogram in the lower right corner shows the probing direction.
Figure 3.2 presents the Faraday image (a) and the shadowgram (b) of the precursor in Al 16 x 15 μm with the view between wires. Ablation from the wires in the array forms the plasma column ~4 mm in diameter. By comparing the Faraday image and its complementary shadowgram, the Faraday effect is clearly seen in the precursor. However, the Faraday rotation effect in this Figure has a different direction because of change of the angle of mismatch between the polarizer and the calcite wedge $\alpha_0$ to a negative value $\alpha_0 = -5^\circ$.

Figure 3.3 One time frame of the implosion of Al 8 x 15 μm cylindrical wire array (shot #511). (a) Faraday image and (b) its complementary shadowgraphy image showing the Faraday effect in the edges of the plasma column of the precursor.

When $\alpha_0 = +5^\circ$, which is the case in Figures 3.1, in the Faraday image (a), there is lightening in the right side and darkening in the left side of the precursor, in comparison with the shadowgraphy image (b). When $\alpha_0 = -5^\circ$, there is a lightening in the left side and a darkening on the right side of the plasma column. In this simple way, Faraday rotation was identified from other possible optical effects.
Figure 3.3 presents another Faraday image (a) and its appropriate shadowgram (b) of the precursor in Al 8x15 μm wire array with the view between wires. The mismatch angle between the polarizer and calcite wedge $\alpha_0$ is equal to 5°, and Faraday effect is clearly seen in both edges of the plasma precursor.

The plasma jets are well seen near wires but do not produce shadow near the precursor, due presumably to smooth more laminar profile or smaller plasma density.

Figure 3.4 Five-frame laser probing of the cylindrical Al 24 x10 μm wire array (shot #662) in three directions. (3F) is Faraday rotation image and (1s), (1ds), (2s), (2ds), and (3S) are shadowgraphy images. (3F) and (3S) represent one time frame at 65 ns before the maximum of the x-ray pulse and shows current in the precursor. (e) is the timing of the laser frame images, (1) is the current at Zebra generator, and (2) is the x-ray pulse.
Figure 3.4 shows the evolution of the plasma precursor in the cylindrical Al 24 x10 µm wire array during the long 34-ns pulse train. The first frame, the shadowgraphy image (1s), shows the beginning of the formation of the precursor plasma column. 7 ns later, the plasma column appears in the shadowgraphy image (2s) to have a shaped and larger structure on the array axis.

As the mass continues to ablate off the individual wires, it flows towards the axis and forms the plasma column of the precursor, which becomes denser, as shown in the frame image (1ds). At the end of the probing pulse train, the shadowgraphy image (2ds) which is collected at 50 ns before the maximum emission x-ray pulse, illustrates and presents the structure of the plasma precursor, while material is still ablating from the wires in the wire array.

The images (3F) and (3S) are the Faraday image and its complementary shadowgram, respectively. Both of these images represent one time frame at 65 ns before the maximum of the x-ray pulse. In the image frame (3F), there are bright lightning on the right side and large darkening on the left side of the precursor. Faraday image (3F) and its appropriate shadowgram (3S) present a strong Faraday effect in the plasma column of the precursor. This indicates that even in 24–wire arrays, the magnetic fields exist and have opposite directions between the left and right sides of the precursor. This also means that the current is flowing inside of the plasma column. This shot with the cylindrical Al 24 x10 µm wire array and shot 511 with Al 8x15 cylindrical array were treated and analyzed in order to estimate the electron number density \( N_e \), the magnetic field \( B \), and the current \( I \) on the plasma precursor. The details of the calculation of these parameters are shown below. A procedure of deriving the Faraday rotation angle includes processing of four
images: Faraday and shadow images 3F and 3S from channel 3 and reference images 3F_ref and 3S_ref, recorded before the Zebra shot. Moreover, the bottom sides of the images in channel 3 were blocked with a screen installed in the beampath before the Z-pinch.

Fig. 3.5. (a) is a reference shadowgram before shot 662. (b) is a shadowgram 3S of the ablation stage in shot 662.

Fig. 3.6. (a) is the Faraday reference image before shot 662. (b) is the Faraday image 3F in shot 662 with the Al 24x10 μm wire array.
The dark areas presented in Fig. 3.5 and Fig. 3.6 allow processing of the background in areas with zero intensity of the laser beam. Images 3F and 3S in Figs. 3.5 and 3.6 were recorded in Zebra shot during the ablation stage. In these images, intensity of the dark strip includes the CCD bias, CCD noise, and a leak of throw the interference filters. Intensity of the laser beam in the Faraday channel is much smaller than in the shadow channel because of small rotation angle and the addition of plasma self radiation to the Faraday channel should be taken into account.

A relation of the intensity of the laser beam in the Faraday channel to the intensity in the shadow channel was taken from reference images. This relation was also measured from the areas free of plasma in images 3F and 3S. The images were processed with ImageJ and EXCEL programs. The intensity in the images was measured in a rectangles (R) drawn in images (a) and (b), as shown in the Figures 3.5 and 3.6. In the Faraday reference image (a), the light intensities (3fref) of the laser probing inside (R) as well as the light intensities (3fref_backgr) of the background light inside similar rectangle were measured as a function of the distances in pixels. In the Faraday image (3F), the light intensities of the plasma (3f) inside the rectangle (R) are derived as a function of the distances in pixels. For calibration and correction purposes, in a similar rectangle (R), the light intensity of the plasma self emission (3f_backgr) is measured as a function of the distance in pixels. The intensities were integrated on the vertical axis and used as lines in the EXCEL diagrams. Formulas for deriving the Faraday rotation angle $\alpha$ are presented below for small angles of rotation and mismatch.

The intensity of light on two CCD cameras 3F and 3S during the reference shot can be written as follows:
\[ I_{\text{Ref}} = I_1 \cdot (\sin^2(\alpha_0) + K) \cdot K_{\text{FF}}, \quad (3.1) \]
\[ I_{\text{Sref}} = I_1 \cdot K_{\text{SF}}, \quad (3.2) \]

where \( I_{\text{Ref}} \) and \( I_{\text{Sref}} \) are the intensities in the Faraday and shadow channels, \( K_{\text{FF}} \) and \( K_{\text{SF}} \) are absorption coefficients in filters on CCDs, \( I_1 \) is intensity of the laser beam in the reference shot, \( K \) is a contrast of the polarimeter, and \( \alpha_0 \) is the angle of mismatch.

In Zebra shot, the intensities on these CCDs are calculated as

\[ I_F = I_0 \cdot (\sin^2(\alpha + \alpha_0) + K) \cdot K_{\text{FF}} \cdot T(x), \quad (3.3) \]
\[ I_S = I_0 \cdot K_{\text{SF}} \cdot T(x), \quad (3.4) \]

where \( I_F \) and \( I_S \) are the intensities in the Faraday and shadow channels during the shot, \( I_0 \) is the intensity of the laser on the CCDs during this shot, \( \alpha \) is the angle of rotation in the magnetic field, and \( T(x) \) is the absorption profile of plasma during probing. By dividing formulas (3.1) by (3.2) and (3.3) by (3.4) and substituting \( K_{\text{FF}}/K_{\text{SF}} \) from the first relation in to the second one, we obtain the computational formula:

\[ \frac{I_F}{I_S} \cdot \frac{I_{\text{Sref}}}{I_{\text{Ref}}} = \frac{(\sin^2(\alpha + \alpha_0) + K)}{(\sin^2(\alpha_0) + K)}. \quad (3.5) \]

The intensities \( I_{\text{Ref}} \) and \( I_{\text{Sref}} \) should be cleaned of noise, bias, and other sources of the background on CCD cameras. The line with light intensity \( (3f_{\text{ref} \_ \text{backgr}}) \) was subtracted from line with intensity \( (3f_{\text{ref}}) \). For the same purpose, the amount of light intensity \( (3f_{\text{backgr}}) \) in Faraday image 3F was subtracted from the light intensity \( (3F) \). This way, the CCD bias, noise, and plasma light were subtracted. Both, the corrected intensity amount \( (3f_{\text{ref} - 3f_{\text{ref} \_ \text{backgr}}}) \) and \( (3f - 3f_{\text{backgr}}) \), as well as the light intensities \( (3f) \), \( (3f_{\text{ref}}) \), \( (3f_{\text{backgr}}) \), and \( (3f_{\text{ref} \_ \text{backgr}}) \) are presented in one diagram.
as a function of the distance in pixels. The same processing was carried out with shadowgrams 3S and appropriate reference image 3S_ref. The method of processing of Faraday images is presented below in this chapter. Two shots with cylindrical wire arrays #511 (Al 8x15 µm cylindrical wire array) and #622 (Al 24 x10 µm cylindrical wire array) are selected for processing.

Figure 3.7 presents the initial set of 8 lines for shot 511 and 4 lines with subtracted backgrounds. A shadowgram and Faraday image for this shot are presented in Fig. 3.3.

Fig. 3.7. (a) Eight lines in the diagram present intensity of the laser beam on CCD cameras in shot 511 (3s and 3f), intensities in reference images (3s ref and 3f ref), and appropriate intensities in dark areas (3s backgr, 3f backgr, 3f ref backgr, and 3s ref backgr). (b) Four lines in the diagram present intensities with subtracted backgrounds.
In Figs. 3.7, the precursor is located in the area from 50 to 250 pixels, see Fig. 3.3. The contrast of the polarimeter was measured $K = 4 \cdot 10^{-4}$.

A diagram in Fig. 3.8 (a) shows the next step in data processing. The pink red line presents a relation of intensity in the Faraday image, with a subtracted background, to intensity in the shadow image (also with a subtracted background). The blue line presents a relation of the intensity in the reference Faraday image, with a subtracted background, to the intensity in the shadow image, also with a subtracted background. This line gives an initial relation on images without plasma. The red line presents a value of the pink line divided by the value of the blue line. This line gives a relation of the arbitrary intensity of the Faraday signal to the arbitrary intensity without plasma. The last step is averaging of this line in diagram (a). It was also corrected for the additional filter, ND = 0.16, installed on the CCD of channel 3S during the shot.

![Fig. 3.8](image)

Fig. 3.8. (a) Relations of intensities with subtracted backgrounds. (b) Relation $I_F/I_S \cdot I_{Sref}/I_{Fref}$ (red line) and inversed line (green line).
The red line in Fig. 3.8 (b) presents the relation \( I_F/I_S \cdot I_{Sref}/I_{Fref} \) for calculation of the angle of rotation \( \alpha \) with formula (3.5). The green line is the inversed red line for presenting clearly the area with the opposite angle of rotation. Using equation (3.5) for relation of intensities \( I_F/I_S \cdot I_{Sref}/I_{Fref} = 4 \), one can find that \( \alpha + \alpha_0 = 10^\circ \) and \( \alpha = 5^\circ \).

Now, the magnetic field can be derived if the electron plasma density is known. To measure the plasma density with interferometry, the phase shift should be measured.

However, the interferograms of 1-MA z-pinches typically cannot be used because all fringes got disturbed. Moreover, there are no reference fringes to use to calculate the phase shift in the differential interferogram. In this case the plasma density could be estimated in shadowgrams by optical absorption at the wavelength of 532 nm.

The absorption in plasma can be estimated by the inverse bremsstrahlung formula [23]:

\[
\gamma = 8.73 \cdot 10^{-30} \cdot \lambda^2 \cdot \frac{n_e^2 \cdot Z \cdot \Lambda}{T_e^{3/2} \left( 1 - \frac{n_e}{n_c} \right)^{1/2}}.
\]

(3.6)

where \( \lambda \) is the wavelength of the probing beam in cm, \( n_e \) is the electron density of plasma in cm\(^3\), \( T_e \) is the electron plasma temperature in eV, \( \Lambda = 23 - \ln(n_e^{1/2} \cdot Z \cdot T_e^{3/2}) \) is the Coulomb logarithm, \( Z \) is the ionic charge, and \( n_c \) is the critical density of plasma. The electron plasma temperature in the precursor of the Al cylindrical wire array is estimated as \( T_e \sim 50-100 \) eV and \( Z \sim 9-10 \) [28]. The diameter of the precursor is 2.5-4 mm in the experiments. Figure 3.9 presents calculation of the transmission in plasma 3 mm of thickness with the electron temperature from 40 to 120 eV in depend on the electron plasma density. The optical transmission of the precursor plasma at the wavelength 532 nm was estimated at 0.6-0.8.
Using estimated values of the electron plasma temperature $T_e$, the diameter of the precursor, and the optical transmission of the precursor plasma measured at the wavelength of 532 nm, the electron plasma density $n_e$ can be evaluated from diagram 3.9 as $n_e = (1.5-2.5) \times 10^{19} \text{ cm}^{-3}$.

The angle of rotation of the polarization plane in plasma $\alpha$ is given by the equation

$$\alpha = 2.62 \cdot 10^{-17} \lambda^2 \int_0^L B \cdot n_e \, dl. \quad (3.7)$$

The magnetic field can be estimated with a simple model of homogeneous current-carrying plasma column. In this case the magnetic field $B$ is

$$B = 2.36 \cdot 10^{-23} \frac{\alpha}{n_e \cdot L}, \quad (3.8)$$

where $B$ is measured in Gauss, the rotation angle $\alpha$ is in degrees, $n_e$ is in cm$^{-3}$, and the path of the probing beam in plasma $L$ is in cm. For plasma parameters $n_e=2 \times 10^{19} \text{ cm}^{-3}$, $L=0.25 \text{ cm}$, and rotation angle $\alpha = 5^\circ$, the magnetic field is $B = 0.23 \text{ MG}$. The magnetic field of the plasma column with homogeneous distribution of current is

$$B = \frac{2r}{c \cdot R_0^2} \cdot I_0, \quad (3.9)$$
where \( R_0 \) is the radius of the plasma column, \( c \) is the speed of light, and \( I_0 \) is the total current. If the magnetic field \( B = 0.23 \) MG on the edge of the plasma column 0.25 cm in diameter, then the current \( I_0 = 1.4 \times 10^5 \) A. That is \( \sim 8\% \) of the maximum current in the wire array in the Zebra generator. This current can initiate current-driven instability in the precursor. This estimate of the current in the precursor in Al wire array is in good agreement with recent experiments [50]. Simulation of implosion base gives the number for the current in the precursor close to our Faraday measurements. Estimates of the current in the precursor are important for simulation of regimes of implosion and development of current-driven turbulence.

Below is another example of processing of data from the Faraday rotation diagnostic. Figure 3.10 presents the initial set of 8 lines for shot 622 and 4 lines with subtracted backgrounds. A shadowgram and Faraday image for this shot are presented in Fig. 3.4, where the precursor is located in the area from 770 to 1050 pixels. The contrast of the polarimeter constant was measured \( K = 4 \times 10^{-4} \).

A diagram in Fig. 3.11 (a) shows the next step of data processing. The green line presents a ratio of the intensity in the Faraday image, with a subtracted background, to the intensity in the shadow image, also with a subtracted background. The red line presents a ratio of the intensity in the reference Faraday image, with a subtracted background, to the intensity in the shadow image, also with a subtracted background. This line gives an initial relation on images without plasma. The thick blue line presents a value of the green line divided by the value of the red line. This line gives the ratio of the intensity of the Faraday signal to the intensity without plasma. The last step is averaging of this line in diagram (a). The red line in Fig. 3.11 (b) presents the relation \( I_F/I_S \cdot I_{Sref}/I_{Fref} \).
for calculation of the Faraday rotation angle $\alpha$ with formula (3.5). The blue line is inversed red line for presenting clearly the area with the opposite angle of rotation.

Figure 3.10 Lines representing the light intensities of the 532 nm laser beam on CCD cameras in shot 662 versus the array radius in pixels, (a) Eight lines of light intensities (3f and 3s), light intensities in reference images (3fref and 3sref), and appropriate intensities in dark area of the images (3f_backgr, 3fref_backgr, 3s_backgr, and 3sref_backgr). (b), Four lines presenting the light intensities with subtracted backgrounds. All light intensities were measured inside the same rectangle (R) (shown in Fig. 3.5 and 3.6) from the Faraday and shadowgraphy images.
Figure 3.11 Ratio of the light intensities with subtracted backgrounds in the shadowgraphy and Faraday images before after the shot of the Al 24×10 μm wire array Z-pinch as a function of the array radius in pixels (a) relations $I_S/I_F$ (green line), $I_{S\text{ref}}/I_{F\text{ref}}$ (red line), and $I_S/I_F \cdot I_{F\text{ref}}/I_{S\text{ref}}$ (blue line). (b) Relation $I_S/I_F \cdot I_{F\text{ref}}/I_{S\text{ref}}$ (red line) and inversed line (blue line).
From Figure 3.11 (b), the ratio of the intensities \( \frac{I_{\text{ref}}}{I_{\text{S}}} \) is equal to 5. Equation (3.5) can be expressed as a function of the initial given angle between the polarizer and the calcite wedge \( \alpha_0 \) as follows: \( \sin(\alpha + \alpha_0) = \left(4K + 5\sin^2(\alpha_0)\right)^{\frac{1}{2}} \). \( \alpha_0 \) is given and equal to 5°, \( K = 4 \times 10^{-4} \), then the value of the rotation angle \( \alpha + \alpha_0 \) is 8.9°, therefore the value of the Faraday rotation angle \( \alpha \) in the plasma is 3.9°.

Figure 3.12 One time frame of the implosion of conical Al 8 x 15 µm wire array, shot#584 at 10 ns before the maximum of the x-ray pulse. The frame (a) Faraday image and (b) is its complementary shadowgram showing Faraday effect in the precursor. The frame (c) is interferogram and (d) is a field schlieren image. (e) is the timing of the laser frame images, (red line) is the current at Zebra generator, and (black line) is the x-ray pulse.

A Faraday rotation in the precursor plasma was observed in cylindrical and conical wire arrays. Figure 3.12 shows a Faraday effect in the conical wire array (shot #584 from experiments of D. J. Ampleford and V. L. Kantsyrev at NTF).
The images (a-d) in Figure 3.12 present one time frame, from one shot, of the ablation stage in the conical Al 8 x 15 μm wire array at 10 ns before the maximum of the x-ray pulse. This time the frame coincides with the beginning of the precursor stage of the conical wire array. The precursor plasma column is 3-4 mm in diameter. Imprints of streams from the wires are seen in this Figure as well. By comparing the Faraday image (a) and its complementary shadowgraphy image (b), areas with lightening on the right side and darkening on the left side of the precursor are seen. It is Faraday effect that is clearly seen in both edges of the plasma precursor. This Figure indicates that current flows in the plasma column. The interferogram (c) and the dark field schlieren image (d) also show strong density perturbations developing in the precursor. The shadowgram and interferogram show that plasma jets from the wires, which may imprint the surface of the precursor [51]. All the fringes in this frame are disturbed. Therefore, there are no reference fringes to calculate the phase shift in the differential interferogram, so we present qualitative results only.

Figure 3.13 presents a one time frame, which includes a Faraday image (a) with its complementary shadowgram (b), an interferogram image (c), and a dark fields schlieren image (d). It shows the plasma column of Al 16 x 15 μm wire array when the electron plasma density is small, at the beginning of the precursor stage. A shadowgram (c) and schlieren image confirm this point. This one time frame represents an early stage of the precursor formation. Lightning on the right side and darkening on the left side indicate that current flows in the precursor since the early stage. Magnetic fields are trapped in the ablating streams that are carrying the ablated mass and current is transferred from wires.
towards the array axis. The current is transferred to the precursor even in the early precursor stage.

Figure 3.13 The images (a-d) present one time frame of the implosion of cylindrical Al 16 x 15 µm wire array. (a) is the Faraday image and (b) is its appropriate shadowgram. The angle of polarisers mismatch is 5°.

Experiments with small diameter wire array confirm transfer of current during the ablation stage. Images (a) and (b) in Figure 3.14 present one time frame, from shot #1150, of the implosion of 3-mm diameter cylindrical Al 16 x 15 µm wire array. The central area of the wire array is almost opaque for laser probing at the wavelength of 532 nm due to fast accumulating of plasma in small-diameter wire arrays. By comparing the Faraday image (a) and its complementary shadowgraphy image (b), the circles on the frame image (a) show lightening on the right side and darkening on the left side of the
axial area of the wire array. It is Faraday effect that is seen in both edges of the fast accumulated plasma in the array axis, for the mismatch angle between the polarizer and calcite wedge $\alpha_o=5^\circ$. This Figure then shows that the magnetic fields have opposite directions between the left and the right sides of the plasma formed and arrived on the axis of the array and that the current flows through this ablating plasma.

Figure 3.14 One time frame of the implosion of 3-mm diameter cylindrical Al 16 x 15 µm wire array, shot #1150. Faraday image (a) and its complementary shadowgram (b) showing Faraday effect in the axial area of the wire array.

Figure 3.15 present another example of the Faraday effect in ablating plasma. Images (a) and (b) present one time frame, from one shot, of the implosion of 8-mm diameter cylindrical Al 32 x 10 µm wire array. The central area of the wire array is opaque in both images (a) and (b). By comparing the Faraday image (a) and its complementary shadowgraphy image (b), the circles on the frame image (a) show lightening in gaps
between the wires on the right side and darkening in gaps between the wires on the left side of the wire array.

![Figure 3.15 One time frame of the implosion of 8-mm diameter cylindrical Al 32 x 10 µm wire array, shot #1233. The frame (a) is Faraday image and the frame (b) is its complementary shadowgram showing Faraday effect in the axial area of the wire array.](image)

For the angle of mismatch $\alpha_0=5^\circ$, the Faraday effect in 8-mm diameter cylindrical wire array is clearly seen between the wires on both right and left sides of the wire array and the magnetic fields have opposite directions on the left and the right sides of the wire array.

Due to complex structure of ablating plasma, our results are qualitative for shots in Figs. 3.14 and 3.15. Nevertheless, even qualitative information is important for understanding of Z-pinch physics. These results confirm for Zebra conditions, the theory developed in [46] instead [52]. Presented results show that the Faraday rotation diagnostics is a powerful tool for investigation of Z-pinch plasmas.
3.2 Development of the continuous interferometry for the ablation stage.

Optical laser diagnostics are widely used for probing Z-pinch plasmas. Measurement of the electron plasma density with laser interferometry meets a zero-number fringe issue on the axis of the z-pinch. From the ablation stage on, the density of the inhomogeneous plasma increases quickly and produces very complicated structures of fringes. The frame images (a) and (b) in Figure 3.16 present two-frame interferograms of the implosion in Al cylindrical 8-wire, 20 µm array, where the fringes are completely disturbed.

Both Mach-Zehnder and shearing interferometers were used to derive the phase shift from the interferograms then to probe the electron number density \( N_e \). Unfortunately, even two-frame interferometry cannot derive the plasma density \( N_e \) because the interferograms do not include non-perturbed reference fringes, and the plasma near the electrodes and the wires frames the axial area of the pinch. Figure 3.16 (d) illustrates how this central area of the Z-pinch in a cylindrical wire array is framed by both the plasma near the anode-cathode and by the wires. During the ablation stage, the plasma accumulates on the axis of the wire array, resulting to an abrupt jump of the phase shift from non-disturbed area to the disturbed area of the plasma.

Other attempts were tried to diagnose and probe the electron number density \( N_e \). For instance, an inverse wire array Z-pinch configuration was used [53], in which the wires form an inverse or exploding cylindrical array around a current carrying electrode on the axis. In this configuration, the magnetic field \( B \) produced by the current in the central electrode acting on the current carrying wires will produce flows of ablated plasma in the outward radial direction.
This experimental approach cannot help to measure the plasma density in the real wire array Z-pinch because the ablated plasma propagates inwards into the wire array axis. We suggested a new diagnostic to record a continuous history of the interferograms and the individual evolution of the fringes. In this case, the reference fringes are not needed and the plasma density could be measured by recording the shift of the fringes on the slit of a streak camera.

Figure 3.16 Two-frame interferograms (a) and (b) with 7 ns between frames in Al cylindrical 8-wire, 20 µm arrays by using the short 150-ps laser probing pulse. (c) is the timing of the laser frame images, and (d) is a schematic of a cylindrical wire array, where the axial area of the pinch is framed by the plasma near the electrodes and the wires.
Figure 3.17 presents a conceptual schematic diagram of this new diagnostic, showing the main components of the suggested experimental setup. It is based on the Nd:YAG laser with a long 300 ns-1 µs pulse at the fundamental wavelength of 1064 nm or the second harmonic (532 nm), Mach Zehnder interferometer, and an optical streak camera. A long-pulse laser is the core of this diagnostic. Regular Q-switch lasers cannot generate microsecond pulses. We used a commercial CW infrared Nd: YAG laser at the fundamental wavelength 1064 nm with the output power of 0.7 W as a seed laser for the two-stage amplifier. A Pockels cell cut a 0.3-1 µs pulse from the CW radiation. This pulse is amplified in a two-stage 7-pass YAG:Nd amplifier with a total gain \( \sim 10^6 \) to an energy >10mJ.

![Figure 3.17 The conceptual schematic diagram of the continuum interferometry diagnostics.](image)

A schematic representation of the optical layout of the long pulse Nd:YAG laser system is shown in Figure 3.18. This is a schematic representation of the optical elements used in the construction of the long pulse laser. The main components of this experimental setup are the CW Nd:YAG laser, the Pockels cell, two amplifiers, and Faraday isolators. For the mitigation of back-reflection, lenses were not used in the experimental setup after the Pockels cell. The two polarizers (GP1) and (GP2) in the Pockels are crossed, so that, in absence of the high voltage on KDP crystal, the horizontally polarized beam that passed through (GP1) got
completely eliminated by polarizer (GP2). The electro-optic KDP crystal is installed between polarizers (GP1) and (GP2). If an electrical half-wave voltage is applied to electrodes of the KDP crystal than the polarization of light passed the crystal is rotated in 90° and pass the second polarizer. In our laser scheme, the Pockels cell cut a single 0.3-1µs light pulse from the infrared CW radiation. The energy of the 0.5-µs pulse is $E_0 \sim 0.35$ μJ. This pulse should be amplified in $3 \times 10^5$ times to reach energy of 10 mJ. In our laser a seven-pass amplification through two amplifiers A1 and A2 with Nd:YAG crystals, 8 mm in diameter and 12 cm in length, provides a total small-signal gain $> 10^6$. Due to very high gain, Faraday isolators are used to prevent self-oscillation in the laser.

Figure 3.18 Optical schematic of the long-pulse laser designed and built at NTF.
The electric high voltage two-channels pulsed power supply for these lamp-pumped amplifiers consists of capacitor banks, charging devices, trigger and pulse forming modules, and control circuits. The high voltage pulses are applied on the flash lamps. Lamps produce light pump pulses for Nd:YAG rods in the amplifiers. The lamps are placed within a pump chamber with reflective walls, so that light pulse is absorbed in the laser rod. Excess heat from amplifiers A1 and A2 is removed by an internal cooling water unit hooked to the amplifiers through plastic tubing. This cooling unit is hooked to an additional external cooling water to stabilize the temperature in the internal cooling system.

Figure 3.19 Pin diode signal as a function of time showing the amplification of the CW infrared seeded beam by the amplifier A1 after double pass.

A small-signal gain was measured in amplifiers using the CW seed laser. With the open Pockels cell, the amplifier A1 amplifies the CW output beam as shown in Figure 3.19. This is amplification of CW by the amplifier A1 as function of time.
The pulse presents a temporal profile of the gain in the Nd:YAG rod. The pulse shape and duration are formed by the pump light pulse and a decay of the inversion population on the metastable level of Nd ions.

When the amplifier voltage is around 1300V, and after double beam pass the gain or the amplification factor is $G \sim 36$. The single-pass gain $G \sim 6$. Due to extremely small input energy amplifiers are not saturated. The gain depends on the population densities in the metastable electronic level, which depends on the intensity of the optical pumping. Power of the lamp pumping directly related to the voltage on capacitor banks in the electric power supplies. For these reasons, the gain $G$ in amplifiers was empirically measured as a function of different value of high voltage applied to the pumping lamps.

![Graph](image.png)

Figure 3.20. The double-pass gain $G_2$ in the amplifier A1 as a function of the value of the high voltage that is applied to the pumping lamps.

In order to find an optimal value of the voltage applied to the amplifier A1 which allows a good amplification of the laser pulse, the double beam-pass gain $G_2$ was measured as a
function of the voltage applied to lamps in amplifier A1. The result of these measurements is represented in Figure 3.20.

A single-pass gain $G_1 \sim 6$ is supposed to be applied to the amplifiers A1 and A2 for a suitable amplification at the voltage of $U_{A1}=1300\, \text{V}$.

We also measured a dependence of the 5-pass gain on the high voltage in the both amplifiers. A 5-pass gain $G_5$ is the amplification that was measured after four-passes through the amplifier A1 and one pass through the amplifier A2. During these measurements, the voltage applied to the amplifier A1 is maintained at the constant value $U_{A1}=1300\, \text{V}$ and the voltage on amplifier A2 was varied. Figure 3.21 represents the values of $G_5$ as a function of the high voltage that was applied for the amplifier A2. The amplifiers A1 and A2 are identical, so after five beam-passes the expected gain is $\sim 6^5$.

![Figure 3.21 The amplification gain $G_5$ after four passes of the laser pulse in the amplifier A1 and one pass in A2 as a function of different value of the high voltage $U_{A2}$.](image-url)
For the seven-pass amplification in two amplifiers pumped with voltages $U_{A1} = U_{A2} = 1300\text{V}$, the gain of $G_7 = 3 \cdot 10^5$ is expected. The real gain in the amplifier should be higher in 3-5 times to compensate passive losses in the beampath. Effect of saturation can also decrease the gain in the last pass of amplification.

Table 3.1 summarizes the calculations of the gain and energies after beam passes through the amplifiers A1 and A2. For different amplification stage, the expected gain and the energies of the long 0.5-μs amplified laser pulse were estimated in different amplification stages by neglecting losses in the laser.

Figure 3.22 Photograph of the 0.3-1μm-long pulse laser at $\lambda = 1064$ nm, showing all the optical components as well as the laser beam path.
Figure 3.23 Timing scheme diagram for triggering and monitoring the 0.3-1 µm-long pulse laser.

<table>
<thead>
<tr>
<th></th>
<th>Gain</th>
<th>Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>The initial CW laser beam</td>
<td></td>
<td>0.7 µJ</td>
</tr>
<tr>
<td>Pulsed beam amplification by the amplifier A1 after one pass</td>
<td>6</td>
<td>4.2 µJ</td>
</tr>
<tr>
<td>Pulsed beam amplification by the amplifier A1 after double passes</td>
<td>36</td>
<td>25.2 µJ</td>
</tr>
<tr>
<td>Pulsed beam amplification by the amplifier A1 after three passes</td>
<td>216</td>
<td>0.15 mJ</td>
</tr>
<tr>
<td>Pulsed beam amplification by the amplifier A1 after four passes</td>
<td>1300</td>
<td>0.9 mJ</td>
</tr>
<tr>
<td>Pulsed beam amplification after four passes by A1 and one pass by A2</td>
<td>7800</td>
<td>5.4 mJ</td>
</tr>
<tr>
<td>Pulsed beam amplification after four passes by A1 and double passes by A2</td>
<td>$4.7 \times 10^4$</td>
<td>32.7 mJ</td>
</tr>
<tr>
<td>Pulsed beam amplification after four passes by A1 and three passes by A2</td>
<td>$2.8 \times 10^5$</td>
<td>0.2 J (without gain saturation)</td>
</tr>
</tbody>
</table>

Table 3.1 The theoretical gain and energies of the amplified 0.5-µs pulsed infrared laser beam.
These passive losses include losses on mirrors and prisms, losses from the absorptions in the Nd:YAG crystal rods and Faraday isolators, and losses due to depolarization of the laser beam. Picture shown in Figure 3.22 is the long pulse laser, which is currently being completed successfully and tested for operations. The photograph represents the experimental setup of the 0.3-1μm-long pulse laser at λ=1064 nm, which shows the different optical components and the laser beam path. In reality the beam is invisible, but to simplify the description, the beam path was drawn in yellow. Figure 3.23 shows the timing scheme for triggering and monitoring the 0.3-1μm-long pulse laser.

Figure 3.24 shows the generated long pulse infrared laser, which is currently being completed and tested for operations. As shown in Figures 3.18 and 3.22, four Faraday isolators were mounted in the experimental setup to prevent self-oscillation. Faraday isolators are based on the Faraday rotation of polarization plane of the laser beam in glass placed in a strong magnetic field. The Faraday isolator consists of an input and output polarizer mismatched on 45 and a glass rod rounded by magnets. The one-pass rotation angle is 45° so that a back-reflected beam will be rotated by another 45 ° in the back pass and removed by the input polarizer. Faraday isolator transmits light in a certain direction while blocking it in the opposite direction. The purpose of using them in this pulsed infrared laser is to prevent the self-oscillations due to reflection or scattering of the laser light on surfaces of optical elements.
The Faraday isolators were properly calibrated according to the polarization type of the input beam for a maximum energy transmission and highest suppression of the back reflection. At the beginning of this laser construction, only two Faraday isolators were used in the setup. As a result many self-oscillations and noises were recorded by the infrared sensor. After adding two more Faraday isolators more and several diaphragms in the beampath, the self-oscillations were eliminated.
Figure 3.25 Two oscilloscope representations of the long 1-μs pulsed and amplified infrared laser beam showing the complete elimination of self-oscillations. In diagram (a) a strong spike due to the instant increase of the Pockels cell voltage is seen.

Figure 3.24 is the representation of oscilloscope waveforms including the laser pulse (pink line) measured by the Pin-diode, before adding of diaphragms. The yellow and dark blue pulses are the laser triggering and the Pockels cell voltage monitoring, respectively.

The pink pulse is the 1-μs pulsed infrared laser that was cut by the Pockels cell and amplified by the two amplifiers A1 and A2. The duration of the pulsed beam is ~1 μs.

The spike in the amplified pulse is due to the high voltage spike produced by the Pockels
cell. The self-oscillation shown is seen later in this Figure. After adding appropriate
diaphragms into the beam path, the self-oscillations were eliminated as it is shown in
Figure 3.25. The duration of the amplified pulse is >1 µs and the diameter of the beam is
8 mm. The spike in the beginning of the pulse is not important for experiments because
only the part of the pulse with a smooth shape will be recorded by the streak camera.
Other parts of continuum interferometry as Mach-Zehnder interferometer and streak
camera were also tested and ready for experiments. The continuum interferometry will
give quantitative information about the formation of the precursor and flows at the
ablation stage.
Chapter 4

Bubble-like implosion dynamics in cylindrical wire arrays

During the ablation phase, wires in the wire arrays, have a heterogeneous core-corona structure. The wire cores get cold and dense and remain at their original positions for the first 50-80% of the implosion time, while the plasma from the hot corona is accelerated by jxB force towards the array axis. The implosion starts when breaks arise on the wires. Previous works and studies [11, 54] show interesting details of the implosion phase that were observed by optical and x-ray probing diagnostics. During the snowplow implosion, a shock was seen in [10] by x-ray diagnostics. Several implosion models were suggested to explain the wire array physics. A snowplow-like model of implosion was suggested in [10, 55]. At the Z facility, a broad radial mass distribution during implosion was found in wire arrays [12]. Part of the wire mass does not implode and produces a trailing mass at the phase of stagnation [11, 12, 56].

Strong inhomogeneity in plasma during the implosion phase was seen in [11] with XUV pinhole camera and in [56] with optical diagnostics (“rainstorm”). Non-uniform ablation has been identified in [11] as magnetic Rayleigh-Taylor instabilities in the imploding plasma shell. Initiation of plasma inhomogeneity on the periodic structure and seeding the z-pinch was studied in [54]. Formation of the bubble at wire radius discontinuities was observed. 3-D simulations confirmed that a plasma bubble can arise at inhomogeneity in wire radius and move to the center of the array [54]. We carried out detailed investigation of the implosion dynamics with optical and laser probing diagnostics which were developed for the investigation of wire arrays Z-pinches.
at Zebra facility. Advanced diagnostics allow explanation of important detailed dynamics of mass transport and current in low number wire arrays. It was found that bubbles in plasma streams present a mass transport in wire arrays. In the Zebra generator bubbles were observed in all wire array experiments in implosion of Al, Cu, Ni, Au, Mo, Ti, stainless steel, and W loads.

Figure 4.1 Shadowgraphy images showing plasma bubbles that were seen in streams of different wire array Z-pinch plasmas.

Figure 4.1 presents shadowgrams of plasma bubbles that were seen during implosions, at The NTF, in different wire array Z-pinch plasmas. They were seen in planar [57], conical, cylindrical with a small and large diameter, double nested, and various kinds of
star wire arrays. Bubbles were also observed in conical wire arrays. Formation and development of plasma bubbles on the wire breaks, movement to the axis, and shock in the precursor were investigated in details in Al loads. The multiframe shadowgraphy was a key diagnostic in these studies. A five-frame dynamics of implosion was accompanied with interferometry, Faraday rotation and schlieren diagnostics. These diagnostics allowed unfolding fine details of bubble-like implosion in wire arrays.

Figure 4.2 presents three pairs of two-frame shadowgrams (a, b) and (c, d), and (e, f) from three different shots in Al 8x15 µm cylindrical loads with 7 ns between frames. Shadowgrams (a, b) illustrate the beginning of the implosion phase in Al cylindrical 8-wire arrays. Shadowgrams (c, d) and (e, f) present development of the plasma bubbles. The pictogram under images shows the direction of probing in the 8-wire cylindrical array.

Figure 4.2. Three two-frame shadowgrams (a, b), (c, d), and (e, f) from three shots with Al 8x15 µm cylindrical loads. The diagram (g) is the timing diagram from the first shot where frames (a, b) were taken, and a pictogram presents the direction of probing in Al 8x15 µm wire arrays. The delay between frames is 7 ns. Diamonds in timing diagram (g) present a temporal position of frames (a, b), (1) is the current pulse and (2) is the x-ray pulse.
Only three wires from the array are seen in the images because of the large magnification. It is seen in Figure 4.2 (a) that jets with the period \( \sim 0.4 \) mm flow out from lobes on plasma column around the wire. Breaks of the wire cores arise in waists on the wires. Yellow arrows in frames (a, b) show the development of the plasma bubble from the wire break. Bubbles in plasma streams indicate a burnout of the wire cores and the beginning of the implosion phase in wire arrays. In cylindrical 8-wire arrays breaks on the wire arise \(~30 \text{ ns} \) before the x-ray pulse, Figure 4.2 (g). The two-frame shadowgram (c, d) presents development and movement of the plasma bubbles. The average speed of the leading edge of these bubbles can be calculated from 2-frame shadowgrams. The blue arrow in Figure (d) shows development of the secondary bubble on the same position of the wire break. Plasma is blown from the gap toward the axis that could indicate current in wire breaks. Shadowgram (f) presents a series of bubble started later. The bubbles in shadowgram (e) interact in the axial direction with neighboring bubbles.

![Fig. 4.3. Shadowgrams from cylindrical W wire arrays with 4 wires 12 \( \mu \text{m} \) in diameter (a) and 16 wire, 4.3 \( \mu \text{m} \) in diameter (b) and a magnified fragment (c) from image (b).](image-url)
Figure 4.3 presents a shadowgrams from cylindrical W wire arrays (a, b) and a magnified fragment from image (b). The development of bubbles is very different in 4-wire and 16-wire arrays but bubbles always begin with the same initial axial scale. This fundamental scale is of 0.22-0.24 mm in W arrays and 0.4-0.45 mm in Al wire arrays.

![Figure 4.3](image)

Figure 4.4. A sketch illustrating the mechanism of the formation and development of the plasma bubbles in wire array Z-pinches.

A simplified dynamics of bubble formation is depicted in Figure 4.4. This Figure presents a suggested sketch explaining the mechanism of the formation and evolution of the plasma bubbles in wire array Z-pinches. Image (a) shows, at the ablation stage, the current j that passes through the wires and creates plasma with a “core”-corona structure. During the ablation phase, the global magnetic field B is perpendicular to the current j, and creates an inward jxB force that accelerates the formation and the transport of the plasma bubbles. These plasma bubbles that are subjected to both Ampere and jxB forces, arise on core breakages, and get accelerated towards the array axis, Fig. 4.4 (b). The observed current dynamics in low wire number array implosion include several stages. Current moves with the leading edge of bubbles at the beginning of the material movement. When the bubble reach a radial size 1-2 mm, a significant part of current
switch back to remnant plasma near the initial position of the wire. Using Faraday rotation diagnostics, a radial current flowing inside edges of bubbles and in radial plasma jets to the precursor was observed, see Figure 4.10. Bubbles deliver material and kinetic energy to the axis. Current switches to the axial plasma column when bubbles reach the precursor in Fig. 4.4 (c).

The density profile in bubbles was studied with interferometry. Figure 4.5 presents two interferograms (a) and (b) of implosion in cylindrical 8-wire and 4-wire arrays, respectively. The image (a) shows the leading edges of bubbles deliver a significant part of material from the wire to the axis. At the ablation stage, the leading edge carries much more material than plasma streams. The observed dynamics of bubbles were similar in the implosion of 4-16 wire arrays with the same mass.

![Figure 4.5 Interferograms from implosions in cylindrical 8-wire (a) and 4-wire (b) Al arrays from two shots #519 and #541. The diagram of the electron plasma (c) density is calculated along the dashed line on the interferogram (b). The pictogram in the top right in each interferogram shows the direction of the probing.](image)

Plasma streams from two wires overlap in the image (a) therefore four-wire loads with a clear inward view from the edge to the axis of the array were used for detailed investigation of mass transport. The arrows (1) in Figure 4.5 (a) point to the structure of
fingers between bubbles. Secondary bubbles in the fingers also push material towards the axis. A significant part of plasma in the side edges of bubbles is not involved in the implosion and forms the trailing mass [11]. Figure 4.5 (b) shows that the plasma density on the leading edge of the bubble from Figure 4.5 (a) is \( N_e > 10^{19} \text{ cm}^{-3} \). The plasma density inside large bubbles is below the sensitivity of the interferometer, \( N_e < 8 \cdot 10^{17} \text{ cm}^{-3} \).

Figure 4.5 (c) presents the density profile \( N_e \) as a function of the array radius \( r \). Starting from the wires towards the wire array center, the plasma density \( N_e \) increases as a function of the radius \( r \). This can be explained by the presence of the plasma bubbles in streams that are delivering material towards the wire array axis.

The average during 7 ns radial speed \( V_{av} \) of the leading edge of bubbles, measured from 2-frame shadowgrams, is presented in Figure 4.6 as a function of the initial radial size of the bubble.

![Figure 4.6 Average speed \( V_{av} \) of the bubble leading edge as function of the initial radial size \( r_0 \) of bubbles from different shots in Al wire arrays.](image-url)
This diagram shows the dependence of speed $V_a$, of the leading edge from the bubble radius $r_o$ from different shots in Al 8 and 16-wire arrays. The average speed increases when the initial radial size of the bubble increases, which indicates acceleration of material on the leading edge. By using the two consecutive shadowgraphy image frames, the measured speed of material in cylindrical 8-wire arrays is $V_{av} = (2 - 3.5) \times 10^7 \text{cm/s}$, and in cylindrical 4-wire arrays, it is $V_{av} = (2 - 6) \times 10^7 \text{cm/s}$. In these wire arrays, the measured acceleration is $a_{av} = (2.5 - 5) \times 10^{15} \text{cm/s}^2$.

Large dispersion of speed is seen on the diagram in Figure 4.6. Several sources of dispersion of bubble parameters were observed by shadowgraphy. First, the core of the wire is burnt out stochastically and bubbles start at a different time. Second, bubbles from one wire can have different speeds. These two effects are demonstrated in the two-frame shadowgram in Figure 4.7.

Figure 4.7 A two-frame shadowgram of the inhomogeneous implosion in 4-wire array, shot 541 with Al cylindrical 4x20 µm array.
Inhomogeneity of implosion is much higher in 4-wire arrays compared to 8- and 16-wire loads. Next, large variations in speed are seen from wire to wire in one wire array. Moreover, plasma inside the edges that are pushed by secondary bubbles reaches the precursor later than plasma of the leading edge.

Figure 4.8. Correlation of the implosion speed in four-wire Al cylindrical arrays with quality of the generated keV x-ray pulse.

Variation of parameters of bubbles leads to a distributed arrival of material to the axis with a total delay ~15-20 ns from the beginning to the end. For the measured speed of material ~3 \(10^7\) cm/s, the time of the bubble flight from wire to the axis is ~30 ns. This time matches to the delay presented in Figure 4.2 (g). The main x-ray pulse begins when first bubbles bring material to the precursor. The delay between the first and the last
bubbles reaching the axis can be responsible for the duration of the rising edge of the generated x-ray pulse. Indeed, the rise time of the x-ray pulse in 8-wire arrays is 15-25 ns in experiments on the Zebra generator.

The implosion quality can be connected with the speed of the bubble-like implosion. Figure 4.8 presents the implosion speed in another series of shots with Al 4-wire cylindrical arrays. Implosion in 4-wire array is not stable and shot to shot variation of parameters of the generated keV x-ray pulses is strong. Figure 4.8 shows that the quality of the implosion and generated x-ray pulse correlates to the implosion speed.

Four frames of the shadowgraphy were analyzed to measure acceleration of material imploding from the single wire in the 4-wire array. The leading edges of bubbles were identified and tracked in the four images. Average results for four bubbles with similar initial size are presented in diagrams (1) and (2) in Figure 4.9. It is seen in diagram (1) that the leading edge of bubbles accelerates mainly in the beginning of movement during several nanoseconds. The acceleration is smaller or absent in the last half of the way.

An azimuthal expansion of bubbles presented in diagram (2) also shows acceleration in the beginning of movement. Saturation of azimuthal expansion occurs because of interaction between neighboring bubbles. The value of the radial acceleration is

$$a_{\text{rad}} = 6 \times 10^{15} \text{cm/s}^2.$$ 

Current moves with the leading edge of bubbles at the beginning of the material movement. When the bubble reaches a radial size of 1-2 mm than the inductance of the loop increases and a significant part of the current switches back to the remnant plasma near the initial position of the wire. The radial current is flowing inside edges of bubbles and in radial plasma jets of the precursor. Bubbles deliver material and
kinetic energy to the axis. Current switches to the axial plasma column when bubbles reach the precursor [58].

Fig. 4.9. Dependence of the radial (1) and azimuthal (2) size of bubbles from time. Every point is averaged for 4 bubbles from one wire. Shot #540.

The Faraday rotation diagnostic was applied to study magnetic fields and current during implosion. Complementary pairs of the Faraday image and the shadowgram show the Faraday effect in Figure 4.10. Polarizers in the Faraday channel were mismatched at 3° to differentiate directions of the rotation of the polarization plane.

The four diagnostics in Figure 4.10 present plasma bubbles imploding from one wire in the Al 4-wire array. This is one time frame presenting by four complementary probing diagnostics ((a) shadowgram, (b) Faraday image, (c) interferogram, (d) the dark-field schlieren image) of the implosion in cylindrical Al 4-wire array. This Figure demonstrates that four complementary diagnostics in one time frame present fine details in the implosion of the Z-pinch.
Figure 4.10. Implosion in Al 4-wire array (shot 548) in one temporal frame presenting by four complementary probing diagnostics. a – the shadowgram; b – the Faraday image; c – the interferogram; d – the dark-field schlieren image; e – the timing diagram; f – the direction of probing. The arrow in diagram (e) presents a temporal position of the frame, (1) is the current pulse, and (2) is the x-ray pulse. The pictogram in the low right of the Figure shows the direction of the probing.

Shadowgram (a) in Figure 4.10 shows a large bubble on the top of the image which swept the precursor and arrived to the axis. The edge of the precursor (1) is seen in the lower section of the images where the small bubble didn’t reach the precursor yet. The non-simultaneous implosion was recorded in part of 4-wire arrays shots. Jet (2) flowing from the leading edge of the bubble to the precursor is seen on the interferogram in Figure 4.10 (c). In Figure 4.10 (b) the Faraday effect shows darkening and lightening in
opposite sides of the jet (2) that indicates radial current in this jet. Another jet (3) is seen inside this bubble. In Figure 4.10 (d) a schlieren image shows the jet flowing out from the gap in the wire that could indicate current in the break on the wire. The Faraday effect in the lower part of the bubble and pinching of the jet (3) also indicates radial current from the wire to the precursor.

The shadowgram in Figure 4.11 (a) shows a collision of bubbles with the precursor. The edge of the undisturbed precursor is seen in the middle of the shadowgram where the bubble didn’t reach the edge of the precursor yet. Bubbles in the top and in the bottom of the image collide with the precursor with a speed $\geq 3 \cdot 10^7 \text{cm/s}$. Lineouts in Figure 4.11 (c) from the shadowgram show that the bubbles colliding with the precursor has steep leading edges. The Alfven velocity in the Al plasma column with the electron density $N_e=10^{19} \text{ cm}^{-3}$ and $B = 0.3 \text{ MG}$ [51] is $V_A=10^7 \text{ cm/s}$. The measured speed of material during implosion is 3 times more than $V_A$ therefore a collision of bubbles with the precursor produces a shock. The shock can be an effective mechanism of plasma heating.

The Faraday image in Figure 4.11 (b) shows magnetic fields inside the imploding plasma and, presumably, presents a moment when current switches from the remnant plasma near the initial wire position to the precursor. Both, Figures 4.5 and 4.11, present the beginning of the x-ray pulse radiated in Al wire arrays.

The observed dynamics of the mass transport helps to select physical mechanisms involved in the implosion. Plasma acceleration in bubbles can be produced by the Lorentz force of the global magnetic field and by the Ampere force in the current-carrying plasma loop. Next, a significant part of current switches to plasma at the initial position of the wire. Bubbles deliver material to the axis and current switches to the axis when bubbles
reach the precursor. Bubble-like implosion is typical for all kind of wire arrays and represents a fundamental mechanism of the mass transport. In cylindrical wire arrays bubbles seed instability to the Z-pinch. Next two figures show the bubble-like implosion in planar wire arrays developed in [71, 72].

Figure 4.11 The shadowgram (a), the Faraday image (b), and the timing diagram (d) of the implosion in the Al 4-wire array (shot 541). The arrow in diagram (d) presents a temporal position of the frame, (1) is the current pulse, and (2) is the x-ray pulse. Diagram (c) presents outlines from leading edges (1,2) and the precursor (3) from the appropriate rectangles 1,2, and 3 in the shadowgram (a).

Figure 4.12 shows that the first implosion bubbles arise in breaks on the edge wires. Breaks of the wire cores arise in waists on the wires as in cylindrical arrays. Bubbles in the plasma streams indicate a burnout of cores in the edge wires, and the beginning of the implosion phase. In the 8-wire Al planar array, breaks on the wire arise 30 ns before the start of the main x-ray pulse, as seen in the timing diagram Fig. 4.12 (c). An average speed of the leading edge of bubbles $>2.5 \cdot 10^7$ cm/s was measured from two-frame
Figure 4.12 Two-frame shadowgraphy images (a) and (b) with 7 ns between frames in Al 8 x 18 μm linear wire arrays. (c) is the timing of the laser frame images. The pictogram in the lower right corner shows the probing direction.

shadowgrams. Formation of bubbles in Fig. 4.12 (a, b) is similar to formation of implosion bubbles in cylindrical wire arrays but interferometry also shows a difference. In planar arrays the phase shift in the wire breaks was <0.4 fringes compare to the phase shift ~3-4 fringes and n_e ~10^{19} cm^{-3} in cylindrical arrays. It was shown in this chapter that in cylindrical loads a significant portion of the current switches to the plasma at the initial position of the wires when bubbles reach a radial size ~1-2 mm.
Figure 4.13. Four-frame shadowgraphy images (a), (b), (c), and (d) showing imploding instability and the cascading implosion in linear Al 8 x 18 µm wire arrays. (e) is the timing of the laser frame images, (1) is the current at Zebra generator, and (2) is the x-ray pulse. The pictogram in the lower right corner shows the probing directions.
In linear arrays, a typical size of the inter-wire gap was \(~1-2\) mm, and the current, presumably, moves with the leading edges of bubbles. Assuming that current is equally distributed between the wires, one can calculate that a mutual magnetic field on the edge wire of the 1-cm 8-wire linear array is at least 3 times larger than in the 8-wire cylindrical array 1.6 cm of diameter. This higher magnetic field could prevent accumulation of plasma in breaks on the wire. In this case, the current in the linear array can move with the bubble front and does not switch back to plasma on the edges of the array. Flares in the bubbles seen in Fig. 4.12 (b) are also suggesting of magneto-Rayleigh-Taylor instabilities, which could arise because of current flowing in the leading edge of bubbles.

Figure 4.13 presents development of one implosion bubble in the 8-wire linear array with increased wire spacing near the edge. Two wire gaps near the edges were enlarged for clear viewing of details of the implosion. In Fig. 4.13 (a) the plasma bubbles from the edge wire hit the next wire in the array. Plasma moves out the left side of the column to the array center because of the momentum conservation.

The Alfven speed in the wire plasma column with the ion density \(n_i\sim10^{20}\) cm\(^{-3}\) and magnetic field \(B\sim0.2\) MG is \(V_A\sim10^6\) cm/s \(< V_{\text{plasma}}\) therefore bubbles produce a shock. The kinetic energy of bubbles, converted to the energy of the shock, breaks the core in the wire plasma column. In Fig. 4.13 (b), a part of the wire plasma column without the core begins moving to the next wire in the array. Magneto-Rayleigh-Taylor instabilities are seen in moving plasma in Fig. 4.13 (c). These instabilities produce bubbles in the moving plasma, seen in Fig. 4.13 (d). Plasma moves to the center of the array cascading from wire to wire. Due to cascading, the time of the bubble flight from the edge to the
center is larger (~30 ns) than the time of the direct flight with a speed of $2.5\cdot10^7$ cm/s (~20 ns).

Detailed investigation of the ablation and implosion phases showed also significant differences between cylindrical and linear arrays. In linear arrays, the ablation begins on the edge wires subjected to the largest mutual magnetic field [57]. As well, the implosion begins on the edge wires because of fast lost of material. At the time that plasma bubbles arise on the edge wires marking the beginning of implosion, other wires remain in the ablation phase and are still at their initial positions. The implosion bubbles start on the edge wires and cascades from wire to wire accelerating towards the array, center. It is different from implosions in the cylindrical wire array. In linear arrays the information about the character axial scale is lost every time when collision of bubbles with the next wire takes place. In Figure 4.13 bubbles with the axial size ~1.5 mm initiate the MHD instability with the scale 0.3-0.5 mm. This mechanism of rescaling of perturbation was observed in 6-10-wire linear arrays but it can be relevant also to nested and star wire arrays.

Experiments with Cu, Ni, Ti, Mo, W, stainless steel loads in the Zebra generator showed dynamics of bubbles similar to dynamics in Al loads. Bubbles snowplow ablated material at the implosion stage and accretion of material could decelerate the leading edge of bubbles.
Chapter 5

Cascading implosions in star wire arrays

5.1 Star wire arrays.

Star wire arrays were designed, developed and studied for the first time in the 1-MA Zebra generator [59]. A star wire array consists of an outer cylindrical array and more than single concentric cylindrical inner array. These arrays are 2 cm tall with different diameters. Depending on the number of the arrays and their diameters, several configurations of star arrays can be distinguished, as shown in Figure 5.1. This new type of Z-pinch loads consists of variety of configurations including triple nested, quadruple nested, five-nested, and six-nested star wire arrays.

Figure 5.1 Star wire array configurations- (a) triple Al 12-wire array with diameters 16/12/8 – (b) triple Al 24-wire array with diameters 16/12/8- (c) quadruple Al 24-wire array with diameters 16/12/8/6- (d) quadruple Al 12-wire array with diameters 16/12/8/6. The dots on the array pictogram present the initial wire positions in the star wire arrays.
We call triple and quadruple wire arrays “star” arrays because they can have only 3 and 4 wires, respectively, in the cylinder that is less than number of wires in the “ray” of the star. Probing of small-wire-number arrays allows a clear view of the wire dynamics from the edge to the center of the array. Figure 5.1 shows pictograms and pictures of several star wire array configurations, such as triple and quadruple wire arrays, which have been used at the NTF. The experiments were carried out with 2 cm tall 12-24-wire triple and quadruple star arrays with masses between 36 to 133 µg/cm and with different materials Al, W, Ni, stainless steel, Ti, and copper.

Implosions in low wire-number cylindrical arrays are inhomogeneous, non-symmetrical, involve undesired large instabilities, and lead to a smaller x-ray power comparing to multi-wire cylindrical wire arrays [2]. Double nested wire array Z-pinches produce the most powerful laboratory x-ray radiation [1, 60] and is used for inertial confinement fusion (ICF) research as well as in other areas of high energy density physics. Double nested arrays produce a shorter and more powerful x-ray pulse (>250 TW), in comparison to cylindrical arrays due to mitigation of plasma instabilities during implosion. It was found in simulations that the stagnation of the outer into the inner shell reduces plasma instabilities compared to a single array [1]. A triple nested wire array was tested in the Z generator [61] and showed a trend of shortening the x-ray pulse. Mitigation of instabilities and homogeneity of implosion can play a crucial role for increasing x-ray power in these new wire arrays. We tried to decrease implosion instabilities using multiple nesting of wire arrays at the Zebra generator.

In the first series of shots triple nested loads with diameters 16/12/8 mm were compared with double arrays (diameters of 16/8 mm) and cylindrical arrays (16 mm in
diameter). Triple arrays with 4 wires on each cylinder produced a short powerful x-ray pulse. A multiframe shadowgraphy showed that, in triple loads, implosion is directed along radial rows of wires and cascades from wire to wire to the center. Triple arrays produce x-ray pulses with higher x-ray power in 2 times compared to cylindrical arrays and ~30% more power than double nested arrays. Triple arrays also demonstrate shortening of the soft x-ray power of up to 7-12 ns in comparison with 25-35-ns pulses generated by cylindrical arrays.

Figure 5.2 presents implosion in the 8-wire double array (a) and 12-wire triple array (b). Implosions in low wire-number cylindrical arrays are inhomogeneous, non-symmetrical, and different from wire to wire. In double nested arrays implosion begins on the external cylinder. Fig. 5.2 (a) shows a double nested array when plasma of the internal cylinder begins movement to the center. The image in the dotted area shows strong plasma instabilities in the moving plasma. In triple arrays, implosion also starts on the edge wires and cascades to the center, as in planar arrays [9]. Fig. 5.2 (b) presents the last phase of implosion in the triple array. The imploding material is concentrated in the plasma column moving to the center. The image in the dotted square shows that plasma instabilities in triple array are smoothed after a collision with another wire. Plasma moves to the center like a plasma column without developed instabilities.

Rescaling of plasma perturbation is seen in triple arrays as it was observed in planar arrays. The characteristic axial scale of the instability is lost after the collision of plasma bubbles with the next wire. This prevents the generation of large-scale MHD instabilities. A scale of bubbles >1 mm is lost and the instability on the smaller scale of 0.3-0.5 mm arises.
In triple loads, the high power of the radiated x-ray pulse correlates with the low level of MHD instability. Figure 5.3 presents radiated power (a) and FWHM duration of the x-ray pulse (b) in triple, double nested, and regular cylindrical wire arrays. Diagrams (a) and (b) shows that the triple wire arrays generate x-ray pulses with significantly higher power and shorter pulse duration.

Fig. 5.2. Shadowgrams of implosion in the cylindrical 4-wire array, 4x20 µm (a), double nested Al 8-wire array with diameters of 16/8 mm, 12-µm wires (b) and in the triple 12-wire array with diameters of 16/12/8 mm, 12-µm wires (c). (d) and (e) are magnified fragments from shadowgrams (b) and (c). Pictograms in the bottom of images present directions of probing. Dashed and dotted lines show the initial position of wires and the center of arrays. The anode is at the top and the cathode is at the bottom of all images in the paper.
Several experiments were carried out with different configurations of multiple-nested wire arrays. It was found that multiple-nested arrays work well even with a low number of rays. Even three-ray loads generated x-ray power higher than cylindrical and double nested arrays. This type of loads was called as “star” wire arrays. Initial experiments helped to understand that implosion in stars are different compared to cylindrical wire array.

Fig. 5.3. Generated x-ray power (a) and pulse duration (b) in cylindrical, double nested, and triple star wire arrays.
Despite the low azimuthal symmetry, star wire arrays produce a stable x-ray pulse with the highest peak power of >0.4 TW and the shortest duration of 8-12 ns among different types of testes loads, see also Figure 5.13. This can be linked to a small level of perturbations in star wire array Z-pinch plasma. Laser probing diagnostics show improved homogeneity of imploding plasma and mitigation of instabilities in these wire arrays which have been used in ICF and other applications.

5.2 Cascading implosion in star wire arrays and mitigation of implosion instabilities in star wire arrays.

Two different implosion modes were observed in double nested wire arrays on the 1-MA Magpie generator [62]. One mode is named hydrodynamic mode of implosion or the non-transparent regime of implosion, the other is the transparent mode or the non-collision regime of implosion. In the first regime, the current switched to the inner cylinder when the plasma from the outer array reached the inner cylinder. In the second regime of implosion, the outer and inner arrays stagnated simultaneously and no collision of the arrays was observed. In multi-wire nested arrays, the inductive current division forces the current to flow mainly in the outer cylinder. The wire arrays implode in a current switching mode and the outer material passes transparently through the inner array [63, 64].

In multi-wire double nested arrays [63], the inner array is transparent to the outer array. It was suggested in [64] that the transparent mode can significantly impact the x-ray production in nested wire arrays. In this section we will show that star wire arrays implode in hydrodynamic mode. This regime of implosion differs from implosions presented in [62]. Triple and quadruple low wire-number arrays produced an enhanced x-
ray power that can be linked to mitigation of plasma instabilities in the hydrodynamic mode of implosion.

The hydrodynamic regime of implosion with cascading plasma from wire to wire was studied and confirmed in star low number wire arrays by several optical and laser probing diagnostics.

Figure 5.4 Time-gated ICCD images of implosion in star-like Al 24-wire arrays (a) with diameters 16/12/8/6 mm, 10-µm wires, (b) with diameters 16/12/8 mm, 10-µm wires. The pictograms on the right corner of the images (a) and (b) show the direction of the optical probing in each load. The timing diagrams on the bottom of the images (a) and (b) show currents (1), x-ray pulses (2), and the image frame times indicated by the arrows. The anode is at the top and the cathode is at the bottom of all images in this dissertation [63].
The five-frame laser probing of the z-pincha was used from three directions [57], which were explained early in the second chapter of this dissertation. The time-gated intensified CCD camera (ICCD) was used to record the optical images of the radiating plasma with the gate time of ~2 ns (see Fig. 5.4). The optical streak camera was used to study the continuous implosion dynamics of the wire arrays. Figure 5.4 presents time-gated ICCD emission images from two shots with Al 24x10 μm wire arrays. Figure 5.4 (a) shows the beginning of implosion. Plasma bubbles [8], arising in breaks on the edge wires, move towards the array axis and collide with the next-to-center wire. After the collision, the current redistributes between the wires. Imploding bubbles arise on the second wire and plasma cascades to the third wire toward the center of the array, as it is shown by the image (b) in Figure 5.4. This image shows strong instabilities in the imploding plasma.

![Figure 5.4](image.jpg)

Figure 5.4 Time-gated ICCD images from two shots with Al 24x10 μm wire arrays. Figure 5.4 (a) shows the beginning of implosion. Plasma bubbles [8], arising in breaks on the edge wires, move towards the array axis and collide with the next-to-center wire. After the collision, the current redistributes between the wires. Imploding bubbles arise on the second wire and plasma cascades to the third wire toward the center of the array, as it is shown by the image (b) in Figure 5.4. This image shows strong instabilities in the imploding plasma.

![Figure 5.5](image2.jpg)

Figure 5.5 Time-gated ICCD images of implosion in six nested star Al 24-wire arrays with diameters 16/14/12/10/8/6 mm, 10-μm wires (shot #1152). The pictogram on the bottom of the image shows the direction of the optical probing. The timing diagram shows current (1), x-ray pulses, and the time of image frame indicated by the arrow.
Laser probing, ICCD, and streak camera show that implosion in “star”-like loads begins on edge wires because the magnetic field and the jxB force are stronger and the loss of mass is faster on the edge of the array. The current is higher on the edge wires because of the inductive distribution on wires. The result of this distribution is shown in Figure 5.5, which represents an optical time gated ICCD image of plasma radiation from six nested star Al 24-wire arrays with diameters 16/14/12/10/8/6 mm, 10-μm wires. It shows clearly that in the early ablation stage, in star arrays, the imploding plasma starts on the edge wires and cascades from the first wire to the second wire then to the third one and the implosion cascading will continue through the rest of the wires accelerating toward the center of the array [59, 65]

Implosions in low wire-number star wire arrays are homogeneous, symmetrical, and different than the implosion in cylindrical wire arrays. In double nested arrays implosion also begins on the external cylinder, from the edge wires and cascades to the center of the arrays. Similarly, the implosion in planar wire, as shown by frame images in Figures 4.12 and 4.13, begins simultaneously on both edges and cascades from wire to wire towards the array axis. The plasma instabilities in planar array are smoothed after a collision with another wire due to rescaling of initial implosion instability [9].

Figure 5.6 presents a two-frame shadowgram of the implosion in the 3-ray 12-wire star array. Three wires from the left ray are seen in the images with the large magnification. The jxB force is stronger, the ablation rate is higher and the implosion phase begins on the edge wires. The imploding plasma from wire 1 is moving to wire 2 in the frame image (a) while wire 2 stays in its initial position. In the frame image (b) of the Figure 5.6, 7 ns later, the plasma from wire 1 has merged with wire 2 and accelerates to wire 3.
The imploding plasma bubbles move towards the array axis and collide to the next plasma column, from which other plasma bubbles get developed and accelerated to next plasma column. The characteristic axial scale of the instability is lost after the collision of plasma bubbles with the next wire.

This cascade implosion then smoothed the instabilities and prevented the generation of large-scale instabilities in the excited spectrum of MHD perturbations. A scale of bubbles ~1.1 mm is lost and the instability on the smaller scale of 0.3-0.5 mm arises. The axial
scale of the instability is lost after the collision of plasma bubbles with the next wire. This prevents the generation of large-scale instabilities in the excited spectrum of MHD perturbations. A new scale is seeded by the fundamental axial period arising on wires at the ablating phase. The final phase of the implosion is presented in Figure 5.7. The images (a),(b) and (c),(d), from Figure 5.7, present two-frame shadowgrams (with a 7-ns delay between frames) of implosion dynamics in 3-ray, 12-wire star loads. In the frame image (a) plasma from wires 1 and 2 moves to wires 3 and 4. The leading edge of the moving plasma column is very inhomogeneous and has a “bubble”-like structure. A plasma column of wire 4 is still on the initial position in this frame.

Figure 5.7. Two pairs of two-frame shadowgrams (a,b) and (c,d) from two shots in Al quadruple 12-wire arrays, 12-µm wires, 36 µg/cm. Timing of the frames to the maximum of the x-ray pulse is 24 ns (a) and 19 ns (c).
The image (b) of Figure 5.7 presents the frame 7 ns later. In this frame the plasma from wires 1-4 is collected into one plasma column near the initial position of wire 4. This plasma column is ~3 times wider than the plasma column in image 2(a). The size of the leading edge is of the order of the ion Larmour radius. The speed of ion flow $V \approx 2.5 \cdot 10^7$ cm/s was measured from the shadowgrams. An estimate for the magnetic field was obtained from the balance condition between the kinetic energy in the flow and magnetic field energy density in the plasma column. This gives for $B \approx 1$ MG a corresponding ion Larmour radius of ~0.4 mm.

A wide plasma column is also seen in the images (c) and (d) from another shot with the same type of quadruple star wire array. The two shadowgrams show a later phase of implosion when the plasma column has accumulated material from all four wires and is moving to the center of the array. Instabilities are seen in the rear edge of the plasma column but they won’t break the leading edge of moving plasma. In the image (c) the plasma column has begun movement to the center at the radius of 3 mm. The time of plasma flight is <10 ns and instabilities cannot break the plasma column during this time.

More destructive development of plasma instabilities was observed in “light” triple and quadruple wire arrays with mass 19-25 µg/cm. Laser probing shows that in light star loads instability breaks the moving plasma column before arriving to the center of the array. The enlarged plasma instability correlates with a fall of the soft x-ray power compared to wire arrays with the optimal mass and the same configuration.

The high implosion quality in star-like wire arrays can be explained by plasma homogeneity and the mitigation of instabilities. The mitigation of the imploding instability in star wire arrays could be linked to three physical mechanisms. First, a
smooth plasma column is formed in cascade implosion. Second, the time for instability development is smaller than in cylindrical wire arrays. Next, a growth rate of instability is smaller in the external magnetic field.

The first factor improves the homogeneity of imploding plasma. The rescaling of the axial period of the instability could prevent the generation of large-scale perturbations in the Z-pinch. The rescaling of the bubble-like instability with the initial scale 1-1.5 mm to the scale of the fundamental period of 0.3-0.6 mm is presented in Fig. 5.8(a). Second, a homogeneous plasma column is formed at the end of cascade implosion. These plasma columns accumulate the masses and currents of all the wires in the “ray” of the star-like array. Finally, a plasma column with a smooth leading edge is formed. This estimate correlates with the observed leading edge of the plasma column. Instabilities are small in the plasma column when it begins movement to the center. The time available for the instability growth is smaller than in large-diameter arrays because in star-like loads the plasma column starts from the radius of 3-4 mm compared to 8 mm in regular cylindrical loads. One more mechanism of stabilization of MHD instability was presented in [66].

Hybrid simulations of V. I. Sotnikov (UNR) show that if a current carrying plasma column moves in the external magnetic field then suppression of the sausage and kink instabilities, due to the flow shear in the azimuthal direction, takes place. The frames (b) and (c) in Figures 5.8 illustrate the difference in instability growth between two plasma columns. In the presence of external magnetic field $B_0$, plasma column experiences drift motion due to the $j \times B_0$ force. The flow shear connected with the plasma drift motion across the axial direction can suppress development of sausage and kink instabilities.
Fig 5.8. Shadowgram (a) presents a rescaling of the bubble-like implosion instability in the Al star-like array with a probing direction shown in the pictogram. (b, c) 3D hybrid simulation of instability development in a current carrying plasma column. (b) – no external magnetic field. (c) The plasma column moving in the external magnetic field of 0.3 MG.

The streak image in Figure 5.9 presents the continuous dynamics of implosion in the wire array. First, the optical emission begins on the outer wires. Later, radiation from the inner cylinders is seen in the image. The cascading of imploding plasma from wire to wire can be seen clearly in Figure 5.9. The formation of a plasma column is shown by arrow 1.
Figure 5.9. An optical streak image of the implosion in 3-ray quadruple star wire arrays. Shot #1246 in Al 16/12/8/6 mm, 15x12 µm star load. A pictogram on the left of the image shows the direction of the image recording [63].

The plasma column accelerating toward the center is also seen in shadowgrams [67]. Arrow 2 shows plasma from the outer wires which does not participate in the implosion. Arrow 3 shows plasma that comes to the array axis later after the main x-ray pulse and could form a trailing mass.

Several diagnostics show cascade implosion in star wire arrays. This type of implosion differs from implosions in cylindrical and multiwire double nested arrays. A simplified mechanism of the cascade implosion in wire arrays is depicted in Figure 5.10, which presents a sketch explaining the implosion in these types of wire arrays. During the ablation phase, the global magnetic field B creates an inward jxB force that transport the plasma bubbles toward the array axis. In cylindrical arrays the imploding plasma moves to the center and seed bubble instabilities to the Z-pinch. In multiwire double nested arrays the imploding plasma passes through the inner cylinder due to the transparent
regime. In stars, implosion cascade from wire to wire to the center. Implosion instabilities are mitigated during cascading.

Figure 5.10. Sketch illustrating the implosions in cylindrical (a) double nested (b), and star wire arrays (c, d).

Cascading implosion was observed in stars with Al, W, Ni, stainless steel, and other wires. Figure 5.11 presents four-frame shadowgrams of implosion of W quadruple star 19.3-μm 12-wire array, and during the 9.2 ns-short pulses of the laser probing.

The implosion begin on the edge wires and the imploding plasma start moving towards the array center by colliding with the next wires which were in their initials positions. In W star wire array the implosion also cascades from wire to wire towards the array axis.
The cascade implosion observed in W and Al star-wire arrays is similar, except in W the bubbles that are arising from the breaks of the edge wires are smaller than those that arise from the wire breakage in the Al star wire arrays. The imploding plasma that originating from the edge wires collides with the next inner wires while the inner wires stay in their initial positions. The implosion keeps cascading from wire to wire in the direction of array axis.

5.3 Z-pinch formation and x-ray generation in star wire arrays.

In the end of the implosion stage plasma columns implode and produce a plasma pinch. Figure 5.12 present four x-ray frames from the 6-frame MCP pinhole camera. Images are filtered with Be 15-µm foil (E> 0.9 keV) and Mylar 110 µm film (E> 3 keV). The pinch does not include hot spots which are typical for cylindrical wire arrays [68]. The diameter of the pinch is ~1 mm in the x-ray images.

Improved homogeneity of the imploding plasma could explain high radiated x-ray power in triple and quadruple wire arrays. Wire arrays of 24 different configurations were compared in >90 shots at the Zebra facility. Different types of loads were optimized for maximum radiated soft x-ray power. Figure 5.13 compares radiated x-ray power in star, cylindrical, double nested, and planar arrays. Radiated power was measured by the XRD with 2-µm filter calibrated with energy from the bare Ni bolometer.
Figure 5.12 (a) X-ray frames from the 6-frame MCP pinhole camera at shot#982 with Al 16/12/8/6 mm star, 12x12 µm, (b) the timing diagram.

The most effective loads in the 1-MA Zebra generator include the star, planar, and compact cylindrical wire arrays. Star wire arrays demonstrated high soft x-ray power in this series, \( P > 0.4 \) TW and produce the shortest pulse compared to other loads. This power is 50-100% higher than the power radiated in cylindrical and double nested arrays 16 mm in diameter. The soft x-ray pulse duration in star arrays is 8-14 ns. Quadruple three- and four-ray wire arrays demonstrate a good efficiency despite the poor azimuthal symmetry. Star loads have many parameters for optimization. Optimization in the Zebra generator is limited by the acceptable mass of loads that limits the wire-number in arrays to 24-32.
Optimization shows that enlarged ray-numbers in the “star” or wire-numbers in “rays” help to increase radiated x-ray power. Wire spacing in the “ray” and the diameter of the load also impact the x-ray production. Triple wire arrays with a 12-mm external diameter and compact 8-mm triple loads produce more x-ray power than 16-mm triple arrays.

Figure 5.13. (a) - dependence of power of the soft x-ray pulse from the XRD with the 2-µm Kimfol filter and Ni bolometer on the mass in 26 shots with Al wire arrays. 24-wire, 8-mm of diameter; black circle – cylindrical 16-wire, 3-mm of diameter arrays.
The star-like load is one of the most powerful sources of soft x-ray radiation in the Zebra generator. Triple, quadruple, and 6-cylinder arrays demonstrate a shortening of the soft x-ray pulse to 8-12 ns in comparison with 25-35-ns pulses generated by regular cylindrical arrays. Figure 5.14 presents a shape of soft x-ray pulses measured by the XRD with 2-µm filter. The typical durations of pulses generated by star wire arrays are 8-12 ns. These pulses are much shorter compared to pulses generated by regular cylindrical wire arrays (20-30 ns) at the Zebra generator. The soft x-ray pulse has a prepulse that could be linked to radiation during the cascade implosion. In cylindrical arrays the precursor radiates an x-ray prepulse. In quadruple 12-wire arrays a precursor plasma column is not seen in shadowgrams and x-ray images and does not radiate a prepulse. The Lorentz force prevents moving of ablating plasma to the array center like in planar arrays with the enlarged central gap [9]. That means that the prepulse is generated during the cascade implosion. Implosion in “star”-like arrays begins earlier then in cylindrical arrays because
of the enlarged mutual magnetic field on edge wires but takes more time due to the plasma cascading from wire to wire.

Experiments were carried out to understand the importance of cascading for generation of the short, powerful x-ray pulse. Figure 5.15 presents a comparison of implosions in regular stars and in “rotated“, disaligned stars. The imploding plasma cascades toward the center from wire to wire along “rays” of the “star” and forms moving plasma columns with smooth leading edges. This plasma column is seen in a two-frame shadowgram in Fig. 5.15 (a, b). Instabilities arise on the back edge of the moving plasma columns but do not impact the leading edge. Improved homogeneity of the imploding plasma can explain the high radiated x-ray power in star-like wire arrays. Figure 5.15 (e, f) presents an array with the same wires but disaligned. In star-like array, Fig. 5.15(c), every ray includes four wires. In disaligned array, Fig. 5.15(d) two wires are moved azimuthally from the initial ray to another radius. Shadowgrams (e, f) do not indicate the formation of a moving plasma column in the disaligned load. The radiated soft x-ray power drops ~2-times in implosions of disaligned loads in comparison with star-like loads with the same mass. This experiment confirms the importance of stabilization of implosion instabilities in
star-like arrays during the cascade implosion. The enhanced x-ray power generated by the star-like arrays correlates with the larger plasma density in the z-pinch.

The electron density and temperature of the Z-pinches was measured [59] using the satellite structure in [H]- and [He]-like Mg ions spectra (A. P. Shevelko, Brigham Young university). The electron density in quadruple star Z-pinches is $n_e > 2 \cdot 10^{20}$ cm$^{-3}$ in comparison with $n_e = 1.2 \cdot 10^{20}$ cm$^{-3}$ in cylindrical array 16 mm of diameter.

Figure 5.16 demonstrates shot to shot variations of the power and delay of the soft x-ray pulse in star and double nested wire arrays. Quadruple wire arrays present the smallest variation of x-ray power. The diagram (b) presents waveforms of the current and the x-ray pulse from five shots with three-“ray” quadruple arrays. The variation of the delay in star arrays (b) is much less than in cylindrical arrays (c). The duration of soft x-ray pulses in the diagram (a) is $\sim 12$ ns. A long 50-ns x-ray prepulse is radiated during the cascade implosion.

We can summarize that the high implosion quality in star wire arrays can be explained by plasma homogeneity and mitigation of instabilities. The laser probing, time-gated ICCD, and streak camera have shown that in low wire-number star arrays, the imploding plasma starts on the edge wires and cascades from wire to wire accelerating toward the center. Several physical mechanisms improve homogeneity of imploding plasma. First, the rescaling of axial period of the instability could prevent generation of large-scale perturbations in the Z-pinch. Second, a homogeneous plasma column is formed at the end of cascade implosion. This plasma column accumulates the masses and currents of all the wires in the “ray” of the star array. Finally, a plasma column with a smooth leading edge is formed. This regime of implosion differs from implosions in cylindrical arrays and
from the non-interacting implosion regimes investigated in double nested arrays [3]. The hydrodynamic regime of collision mitigates the instabilities, improves the homogeneity of the imploding plasma, and increases the radiated power in the star wire array on the 1-MA generator. Star arrays could be a good alternative to cylindrical and nested wire arrays in HEDP experiments at multi-mega-ampere generators.

Figure 5.16 (a) - shot to shot variations of the soft x-ray power in quadruple 16/12/8/6 mm arrays (squares), triple, 16/12/8 mm arrays (triangles), and double, 16/8 mm arrays (circles). b - shot to shot variations of the soft x-ray pulse delay in five shots with quadruple 12-wire, 16/12/8/6 mm arrays shown by blue squares in diagram (a). c - shot to shot variations of the soft x-ray pulse delay in four shots with cylindrical wire arrays, 16 mm in diameter.
Chapter 6

Conclusion

The ablation and stagnation stages were investigated with an advanced set of optical, laser probing, and x-ray diagnostics. Laser diagnostics were modified to reach the optimal magnification, spatial resolution, and set of frames for the investigation of wire arrays Z-pinches at Zebra facility. The Faraday rotation technique was applied systematically for the investigation of magnetic fields in the precursor in different types of wire arrays. Faraday images and their complimentary shadowgrams revealed the presence of current in the precursor of cylindrical and conical wire arrays. The magnetic field has the opposite directions on the right and left sides of the precursor, that indicates current flowing in the precursor plasma column. The Faraday effect indicates this current from the early stage of the implosion in cylindrical and conical wire arrays with wire numbers ranging from 4 to 32. The polarization angle of Faraday rotation in plasma ($\alpha$) was estimated to be between $2^\circ$ and $5^\circ$ in different shots. The magnetic field (B) as well as the current I in the plasma column of the precursor in the cylindrical wire arrays were evaluated to be $B = 0.15-0.3$ MG and $I = 0.05 - 0.15$ MA respectively.

The regular interferometry cannot be used for measurements of the electron plasma density on the axis of the wire arrays. A new diagnostic, the continuum interferometry, was developed for the ablation and implosion stages at the 1-MA Zebra generator. This diagnostic can record a continuous history of the interferograms and the individual evolution of the fringes. It is based on the long 0.3-1$\mu$s pulse laser, Mach-Zehnder interferometer, and streak camera. The unique long-pulse laser was designed and
developed at NTF. The 0.3-1µm-long pulse laser has been completed and tested for operations. It includes a CW seed laser and a seven-pass amplifier with a gain ~10^6. The continuum interferometry will give quantitative information about the formation of the precursor and flow at the ablation stage.

The fine features of the implosion stage were studied with the laser probing, including shadowgraphy, interferometry, Faraday rotation and schlieren diagnostics. Multiframe shadowgraphy allows explanations of dynamics of mass and current transport in implosions of wire arrays. It was found that the plasma bubbles are blown from breaks on the wire “core”. Bubbles indicate a burnout of the wire cores and the beginning of the implosion phase in wire arrays.

Plasma acceleration of the leading edge of bubbles is produced by the global magnetic field and by the Ampere force in the current-carrying plasma loop. Both the Ampere and Lorentz forces accelerate plasma bubbles to an average speed between 2·10^7 cm/s and 5·10^7 cm/s in a span of ~3-6 ns. In low number wire arrays, a significant part of current switches back on the plasma at the initial positions of the wires. Plasma bubbles collide the precursor with a speed >2·10^7 cm/s. The measured speed of material during the implosion is higher than the Alfven speed; therefore, a collision of bubbles with the precursor produces a shock, which can be a mechanism of plasma heating.

Plasma bubbles present a mass transport in wire arrays during the implosion. The Faraday diagnostic showed that current switches to the axis when bubbles reach the precursor. Bubbles deliver material and kinetic energy to the axis. Implosions in low wire-number cylindrical arrays are inhomogeneous and non-symmetrical, varying from
wire to wire, and are not timed. This widens the radiated x-ray pulse and decrease x-ray power.

A new type of wire array with a star configuration was designed and tested for the first time at the Zebra facility. Star wire arrays consist of multiple nested wire arrays aligned azimuthally such that the wires appear as “rays” extending from the axis of symmetry. The imploding plasma cascades to the center from wire to wire along “rays” of the “star” and forms moving plasma columns with a smooth leading edge.

Star wire arrays generate higher power yields than cylindrical and double nested wire arrays. Stars demonstrate shortening of the soft x-ray power by up to 8-12 ns in comparison to 25-35-ns pulses generated by cylindrical arrays. The high power of the radiated x-ray pulse correlates with the low level of MHD instability. Despite the low azimuthal symmetry, star wire arrays produce a stable x-ray pulse with ok highest peak power and the shortest duration of 8-12 ns (at the soft x-ray range) among different types of loads tested. This can be linked to a small level of perturbations in star wire array Z-pinch plasma.

The high implosion quality in multiple wire arrays can be explained by plasma homogeneity and mitigation of instabilities during the cascading implosion. In star wire arrays, implosion starts on the edge wires and cascades from wire to wire, accelerating toward the center. The hydrodynamic mode of implosion with cascading plasma from wire to wire, was confirmed by several optical and laser probing diagnostics. Star wire arrays implode in hydrodynamic mode. Improved homogeneity of plasma and enhanced x-ray powers were observed in these arrays, which could be a good alternative to cylindrical and nested wire arrays in high-energy density physics experiments.
Bibliography


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