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Preface: Radiation from high energy density plasmas

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The first article to envision High Energy Density (HED) physics as a new discipline was by Edward Teller in the proceedings of an international summer school held in honor of Enrico Fermi in 1969.[1] Ten years later, facilities were in place for experiments and diagnostics of HED plasmas, and the "National Laser User Facility" was established in the Laboratory for Laser Energetics at the University of Rochester.[2] Since the turn of the present century, the U.S. Federal government commissioned a number of executive level reports that have highlighted the special nature and significance of HED physics.[3–8] This subject is now recognized as a truly distinct research field and refers to physical systems whose energy density is of order 10^{11} J/m^3, equivalent to a pressure of ∼1 Mbar or more. A reading of these reports and the recent textbook by Drake[9] shows that such a condition covers a vast array of physical objects, from laboratory plasmas created by lasers of high intensity or high energy, or by pulsed power drivers, to astrophysical objects such as stellar and planetary centers, supernovae, and gamma ray bursts. One of the primary means of understanding the nature and processes in HED systems is through their emission of radiation, either photons or particles. This Special Topic Section is focused on the radiation from laboratory created HED plasmas.

In general, the radiation from laboratory HED plasmas is not in equilibrium. For photons, this means that the radiation does not have a blackbody spectrum, the plasma is not in local thermodynamic equilibrium (non-LTE), and the spectrum is dominated by line emission. In some HED plasmas, the electrons themselves have a non-Maxwellian distribution due to beams and/or laser acceleration. This causes further deviations from Boltzmann and Saha equilibrium populations. To determine the physical parameters of the HED plasma from the emitted spectra, one needs to compute the ionization kinetics from fundamental microscopic processes based on calculations in atomic physics. Furthermore, the plasma may be in motion, magnetohydrodynamic (MHD) compression as in a Z-pinch, or undergo rapid intense heating due to laser deposition. Thus, radiation from a HED plasma can involve an interacting set of physical processes encompassing atomic physics, non-LTE ionization kinetics, radiation transport, and plasma dynamics.

The first international workshop on Radiation from High Energy Density Plasmas (RHEDP) was held on March 15–18, 2011 in Reno, NV. Twelve presentations from this workshop were published among the articles in volume 8 of the journal *High Energy Density Physics*. The second international RHEDP workshop was held on April 2–5, 2013 in Stateline, NV, and sixteen articles based on presentations at this workshop were published as a Special Topic Section in *Physics of Plasmas*, volume 21, starting on page 031101, 2014. The third international RHEDP workshop occurred during June 9–12, 2015 and was likewise held in Stateline, NV. The scientific topics for these workshops include the study of radiation from laboratory plasmas, such as wire-array or gas-puff pinches and high-energy lasers, short-pulse laser interactions, and photo-ionized plasmas. The focus was on emission and absorption spectroscopy, radiative shocks, radiation MHD simulations, non-LTE atomic kinetics, radiation transfer, detailed X-ray and EUV synthetic spectra, "cold" characteristic lines (K-α lines), x-ray line polarization, line broadening, diagnostic interpretation of spectroscopic data, and the efficiency/development of new x-ray K- and L-shell radiation sources. The guest editors are pleased to have this second Special Topic Section in *Physics of Plasmas* devoted to the research of the third RHEDP workshop. Among the 55 oral and poster presentations, 12 invited, peer-reviewed articles comprise this Section. These represent on-going research at universities, Department of Energy, and Department of Defense national laboratories.

As mentioned above, there are two laboratory technologies that couple energy into ordinary matter and produce HED plasmas: pulsed power and high energy/power lasers. In pulsed power z-pinch experiments, the magnetic field of an axial current implodes material into the HED state. The largest such device is the ∼25 MA refurbished Z (ZR) generator at Sandia National Laboratories (SNL). On the other hand, lasers produce HED plasmas by absorption of their energy and direct heating of the target material. The highest energy laser (∼1.8 MJ) is the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL). The first paper of this Special Topic Section by Dasgupta *et al.*[10] assembles data for the efficiency and high energy photon yields from the ZR generator and NIF. They find that the K-shell yield over the range 1 to ∼22 keV falls off differently on the ZR generator as a function of increasing atomic number (13 to 47) than on the NIF, though of course the basic processes of atomic physics leading to radiation are not different. To address this issue, their research focuses on the L-shell (1.5–2.5 keV) and K-shell (≥13 keV) radiated spectra of Kr from gas puffs on the ZR generator and gas-filled epoxy pipes on the NIF. Non-LTE simulations and comparisons of synthetic spectra with observations are used in the analysis of the experiments. They find that the time integrated Kr L-shell spectra from the ZR generator could only be matched by allowing for the dynamics of the plasma during the radiation pulse, while the time integrated Kr K-shell data from the NIF indicate a hot core surrounded by a cooler envelope over the pulse duration. The different behavior in K-shell yields appears due to the mechanism of HED production, namely, the two step process of thermalization of ion kinetic energy at implosion and subsequent electron thermal equilibration on the ZR generator versus the one step process of laser heating of electrons on the NIF.

The following three papers continue with laser-produced HED plasmas. There is interest in developing more efficient and higher energy (>10 keV) K-shell radiation sources. Kemp *et al.*[11] propose using moderate levels of magnetic fields (<50 T) in sub-quarter-critical laser heated targets in order to inhibit thermal losses to the pipe walls. Simulations with the HYDRA code suggest >50% increase in the electron temperature and 2–3 times enhancement of the laser to x-ray conversion efficiency for Kr gas filled targets on OMEGA and Ag($\geq$ 22 keV) foam targets on the NIF. There is an interesting trade-off in the efficiency in that the volume of the heated region is smaller with magnetic fields while the temperature is higher. High spectral resolution and high signal-to-noise line shape spectroscopy is a powerful tool to determine electron density and electron temperature of the high-density laser-produced plasma. This is demonstrated by Beiersdorfer *et al.*[12] in long-pulse and short-pulse experiments on the Orion Laser Facility at AWE, UK. In particular, He-β resonance and Li-like satellite line spectra of Cl and Cr from laser-irradiated foil targets are collected by a newly developed, high-resolution x-ray spectrometer and are analyzed in this paper. In the case of a short-pulse irradiated Cr foil, they find that He-like Cr is produced at a density of almost 8 g/cm^3, i.e., solid density. Instead of a foil target, the experiments of Schultz *et al.*[13] focus the fs Leopard laser at the University of Nevada, Reno, onto gas jets from a nozzle. Specifically, Ar, Kr, and Xe linear gas jets, as well as two triple mixtures of the three gases, are irradiated to produce an x-ray generating plasma. Prior to the laser-plasma experiments, the density of the gas jets is measured via optical interferometry, and the presence of clusters formed during the supersonic expansion is detected by Rayleigh scattering. When irradiated by the laser, the mixtures exhibit a higher x-ray yield than pure Xe, even with a low percentage of Xe. For the gas jets, the coefficient of conversion was as high as 0.03%. Interestingly, anisotropy of radiation with respect to the laser beam polarization direction is observed in all measured spectral regions (1.4 keV to >9 keV).

We next turn to those papers that employ pulsed power to create HED plasmas. In such drivers, the peak yields of the Ar K-shell ($\geq$3 keV) scale as the square of the load current and are said to be in the efficient regime with ~30% of the total radiated energy emerging above 3 keV. This corresponds to >300 kJ on the ZR generator for an Ar gas puff comprised of two annular shells. Harvey-Thompson *et al.*[14] present four experiments on the ZR generator to test whether the yield from a double shell Ar gas puff could be increased with the use of a central Ar jet. They find that if the mass ratio of the outer-to-inner shell is 1:1.6, then the implosion is sufficiently stable against the Magnetic Rayleigh-Taylor (MRT) instability and follow the current scaling with or without a central jet. But if the mass ratio is 1:1, then the K-shell yield decreases by more than a factor of two without the central jet. In the two shots with a central jet, its linear mass was the same. Simulations with the 3D GORGON MHD code agree with the data. A companion paper by Tangri *et al.*[15] models the same shots with the non-LTE MACH2-TCRE MHD simulation code. In addition to matching the experimental results, simulations are described for the 1:1 shell mass ratio but with a larger total mass in order to see if it is the lack of a central jet or the lower total mass of the 1:1 configuration that leads to the poor performance. The modeling results indicate that by increasing the total mass of the 1:1 load to be similar to that of the 1:1.6 shots, one can recover the large K-shell yield but not the K-shell power. Thus, the power is more sensitive to the initial density profile in a gas puff than the yield. As in the previous two papers, the next one also examines the impact of a central jet in an Ar z-pinch but on the smaller current generator COBRA (~1 MA) at Cornell University. Instead of varying the mass ratio of the outer-to-inner shell of a double puff, Ouart *et al.*[16] keep the shell mass ratio at 1:1 and vary the mass of the central jet. Based on the analysis of the Ar K-shell with a non-LTE synthetic spectra model, they find that the shot with the largest mass in the central jet also produces the highest average power. Because of the comparatively low current on COBRA, the K-shell radiation is in the inefficient regime where bright spots dominate the emission.

University-scale pulsed power facilities readily accommodate research on novel loads and alternative generators. The remaining five papers present examples of this advantage. Planar Wire Array (PWA) z-pinch loads consist of sets of parallel wires arranged in planes that are separated by an inter-plane gap. Safronova *et al.*[17] report on multi-PWAs using the Load Current Multiplier (LCM) to reach ~1.8 MA on the Zebra generator at the University of Nevada, Reno. The LCM allows the implosion of much larger size wire array loads than was possible with the standard current of 1 MA (3 or 6 mm between the outer planes). Using modified multi-plane PWAs with the distance between the outer planes up to 19 mm, two new approaches are developed and tested in this paper: (i) simultaneous study of implosion and radiative characteristics of different materials in wire array Z-pinch plasmas in one shot; and (ii) investigation of larger sized wire arrays to enhance energy coupling to plasmas and provide better diagnostic access. High linear radiation yields up to 30 kJ/cm were measured. The paper by Stafford *et al.*[18] also presents the results of the experiments at enhanced current on the Zebra generator using the LCM but with very different wire loads, namely, X-pinches that consist of wires arranged to cross at the midpoint of the anode-cathode gap. In particular, X-pinches from Cu, Ti, and alloyed Ti wires with different masses are tested to optimize and achieve the largest radiation yield of 19 kJ/cm. The linear radiation yield from the optimized X-pinches produced at Zebra with the LCM increased 50% compared to shots without the LCM. They show that time gated data are able to provide a significant understanding of the evolution of the X-pinch with the enhanced current. During X-ray bursts, the changes in multiple properties of the plasma are observed, including the size of the radiation source, the electron temperatures of the plasma, and the line opacity in the plasma. One issue with X-pinches is their long-lasting electron beam emission, which tends to limit their applicability as a point projection radiography source. Collins *et al.*[19] examine an alternative design by laser cutting a Cu foil into an X-pinch with the size of the contact point at tens of microns. Experiments on the 250 kA GenASIS driver at the University of California, San Diego, demonstrate that the radiation pulse from the foil-cut X-pinch is confined to a reproducible, short ~3 ns burst. Matching of synthetic spectra with the SCRAM code to the data reveals the presence of a micron scale plasma of temperature ~1 keV at 10% of solid density. These conditions are impressive given the limited current available.

The future of pulsed power for z-pinches may lie with Linear Transformer Drivers (LTDs). These low impedance generators offer the advantage of a smaller footprint to reach a given peak current but may be susceptible to a large current turnover at implosion as the load undergoes a large inductance change. It is thus important to understand how pinches behave on an LTD. Steiner *et al.*[20] use the MAIZE LTD (~1 MA) at the University of Michigan to study the implosion of double planar wire arrays (DPWAs) composed of stainless steel wires. A circuit model is developed for the LTD, and together with the current waveforms, x-ray diode emission, and shadowgraphy, the temporal increase in the load inductance is determined. The results indicate that the load did pinch, but the peak current is lower and the risetime longer than for similar loads on a comparable Marx generator like ZEBRA. In the last article of this Special Section D, Yager-Elorriaga *et al.*[21] employ non-imploding Al liner-plasmas to study the dominance and stabilization of helical structures that appear in the presence of axial magnetic fields on the MAIZE facility. Applying a small external axial magnetic field of 1.1 T generated a small amplitude, helically oriented instability structure that is interpreted as an $m = +2$ helical mode. The kink-seeded liners show highly developed helical structures growing at the seeded wavelength of $\lambda = 1.27$ mm. Their observations find that the direction of the axial magnetic field plays an important role in determining the overall stabilization effects; modes with helices spiraling in the opposite direction of the global magnetic field showed the strongest stabilization. These results may have implications for inertial confinement fusion in the MagLIF concept.

The third international RHEDP Workshop was organized and chaired by Alla Safronova of UNR, with co-chair John Giuliani of NRL. Other scientific committee members included: Farhat Beg of UCSD, Christopher Deeney of NSTec, and Keith LeChien of DOE/NNSA. This meeting was supported by the U.S. Department of Energy, National Nuclear Security Agency.

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