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Editorial for special issue on Z-pinches

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Fast Z-pinches, plasma implosions driven by MA-level ~100-ns duration current pulses, are an active research area with applications to a broad range of High Energy Density Physics studies, including investigations of properties of materials at extreme pressures,[1] opacities of various plasmas at conditions found in stellar interiors,[2] and scaled modelling of astrophysical magnetohydrodynamics.[3] The ability of fast Z-pinches to generate extremely bright pulses of X-ray radiation is of significant interest for Inertial Confinement Fusion (ICF) studies. The highest X-ray powers and yields are achieved using wire-array Z-pinch loads, which are capable of generating 2-MJ, 250-TW,<10-ns X-ray pulses at the largest currently operating pulsed power facility, the 25-MA Z machine at Sandia National Laboratories (New Mexico, USA). The physics of wire-array loads continue to attract significant interest from the Z-pinch community, with research aiming to further improve their operation.

This special issue of Matter and Radiation at Extremes on Z-pinches presents seven papers discussing various aspects of Z-pinch physics. Studies discussed in these papers were performed in research groups working in the USA, China, UK, and Russia, using a variety of pulsed power facilities, including the second-largest Z-pinch facility in the world, the 8-MA Julong-1 facility [also known as PTS (Primary Test Stand) facility] in China (the 8-MA to 10-MA Saturn facility is still in operation at Sandia National Laboratories).

The paper by Li *et al.*[4] presents a concise overview of the Z-pinch research performed at different institutions and universities in China. A significant part of the article is devoted to the computational studies of the dynamic hohlraum concept. They describe investigations of the coupling of Z-pinch implosion energy to a fusion capsule driven by a radiative shock formed at the stagnation of a wire-array plasma with a foam cylinder. Experimental studies of dynamic hohlraum loads were performed at the 8-MA Julong-1 facility. The paper provides detailed information on the radial structure and azimuthal symmetry of the radiating shock propagating through the dynamic hohlraum foam and discusses the relation between the X-ray pulse-shape and the wire-array implosion dynamics. The paper also contains a nice review of earlier studies of the plasma dynamics and X-ray production in wire-array Z-pinches, summarizing results obtained at the 1.5-MA QiangGuang-1 [Xi'an, Northwest Institute of Nuclear Technology (NINT), China], 2-MA S300, 4-MA Angara-5 (Kurchatov, Russia), and 8-MA Julong-1 facilities [Mianyang, China Academy of Engineering Physics (CAEP), China]. In addition to describing the progress in the understanding of traditional wire array configurations, the paper presents investigations of quasi-spherical, wire-array Z-pinch loads. It also describes an impressively broad range of diagnostics used in various experiments.

The papers by Wang *et al.*,[5] and by Wu *et al.*[6] summarize Z-pinch studies performed at Tsinghua and Xi'an Jiaotong Universities, respectively. A significant fraction of work at Tsinghua University concentrates on the studies of plasma formation in wire arrays. These include measurements of the properties of precursor plasmas and of the wire cores for standard wire-array loads performed with X-pinch radiography and laser probing. They also demonstrate how a modification of the load geometry, the addition of a flashover switch inserted into the cathode, can lead to full vaporization of W wires and suppression of the core-coronal plasma structure. Other areas of research at Tsinghua University include underwater wire explosions for shock-wave generation and explosions of Ti wires in a nitrogen atmosphere for nano-powder production. The main experimental effort at Xi'an Jiaotong University is directed towards the development of wire-array loads with wires pre-conditioned by a controllable current pre-pulse. The new Qin-1 facility allows the coupling of a small pre-pulse generator (10 kA, 20 ns) with a 0.8-MA, 100-ns main generator. Experiments investigate conditions required for the axially uniform vaporization of the wires and the merging of closely spaced wires as a first step towards formation of cylindrical plasma loads. Experiments with implosions of pre-conditioned, 2-wire loads demonstrate the suppression of the ablation stage and a significant change in the implosion dynamics, thus creating an interesting experimental platform for studies of Magneto-Rayleigh-Taylor instability.

The paper by Shelkovenko *et al.*,[7] presents a review of different types and configurations of X-pinches, which are a special class of Z-pinch loads often used as a radiation source for X-ray radiography at 1-keV to 10-keV photon energies. The authors present scaling arguments for obtaining an optimal X-pinch performance and maximizing X-ray output while retaining the few-micron size of the emitting spot as required for many applications. The operation of X-pinches at high currents (>1 MA) requires a significant increase of the load mass, and the results presented in this paper demonstrate that a careful arrangement of the wires in the crossing region allow for the achievement of good performance at currents up to ~2 MA. The paper also describes the novel "hybrid" X-pinch design, which reliably produces a single bright spot for radiography applications and is a promising configuration for developing an in-vacuum reloadable radiographic system.

The paper by Ivanov *et al.*[8] presents an overview of the studies of several wire array Z-pinch configurations performed at the 1-MA Zebra facility at the University of Nevada, Reno. The main feature of this work is the use of multiple laser probing diagnostics covering a broad range of wavelengths (213 nm, 266 nm, 532 nm, and 1064 nm), and the authors present measurements with Faraday rotation, interferometry, shadowgraphy, and Schlieren diagnostics. Laser imaging of wire arrays performed simultaneously along several chords, providing important information on 3-D structures, that develop in the final stages of the implosions. The paper also presents detailed investigations of the implosion dynamics of single and nested arrays, the cascade implosions of star-shaped arrays, and measurements of the current division between the stagnated and the trailing lower density plasma.

The paper by Romanova *et al.*,[9] presents investigations of electrical explosions of wires in air at atmospheric pressure. It concentrates on the processes determining the duration of the current pause developing due to the dramatic fall in the material conductivity at the liquid-vapor phase transition. Laser probing measurements obtained by the authors demonstrate the presence of a droplet-vapor mixture in the wire explosion products, and the formation of the tubular mass profile with reduced density at the axis. One of the important results of this research is the demonstration that the secondary discharge, terminating the current pause, occurs inside the tubular core and not along the boundary between the wire material and the surrounding air.

The paper by Spielman and Reisman[10] is devoted to an extremely important power-flow issue for multi-MA pulsed-power facilities. This issue is related to the power flow in magnetically insulated transmission lines (MITLs) that may limit the delivery of electrical power to Z-pinch loads at higher currents and voltages. Next-generation Z-pinch drivers will operate at currents greater than 50 MA. The required spatial compression of the energy delivered by the generator to a small-diameter Z-pinch load is achieved using MITLs. This paper presents an approach to MITL design which, according to the authors, is more theoretically based than that commonly used. The paper gives the results of circuit simulations that, in detail, describe the performance of MITLs. The design process is illustrated in this paper by two example solutions for a 15-TW, 10-MA generator: one solution for a constant-impedance MITL and a second solution for variable-impedance MITLs operating with Z-pinch loads. The paper suggests that variable-impedance MITLs have the potential for significantly reducing the inductance of the vacuum section of the driver. The authors note the similarity of the constant-impedance design to the well-tested Z-machine MITL, which supports the technical strength of the proposed design process.

The present understanding of the physics of high-Z, Z-pinches suggest that the scaling of X-ray energy and X-ray power yields beyond the 2 MJ and 200 TW of Z is very likely. Drivers at the level of ~45 + MA will be able to radiate X-ray energies of ~8 MJ and X-ray powers of 800 TW. In addition, higher current drivers enable a wide range of more complex Z-pinch loads due to the larger load masses allowed. This is particularly of interest in dynamic hohlraum loads, MagLIF loads, and multiple-shell Z-pinch loads. Z-pinch opacities and other plasma physics issues need to be studied to address radiative efficiency issues for the massive, >20-mg loads. There are important power-flow concerns that could impact our ability to deliver the required current to the Z-pinch loads. These issues include: insulator voltage hold-off, MITL power flow, post-hole convolute scaling, and high-current-density limits near the load. Taken together, there is a significant research effort required before the 45-MA experiments can be conducted with acceptable risk. Even with this required research, Z-pinches will remain the most efficient method of converting electrical energy to kinetic energy and to X-rays. The sheer magnitude of the X-ray energies and X-ray powers that can be generated ensure interest in this field. Finally, Z-pinches remain a viable, even likely, approach to thermonuclear fusion.

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