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# Pulsed-power-driven high energy density physics and inertial confinement fusion research[a)]

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The Z accelerator [R. B. Spielman, W. A. Stygar, J. F. Seamen *et al.*, *Proceedings of the 11th International Pulsed Power Conference, Baltimore, MD, 1997*, edited by G. Cooperstein and I. Vitkovitsky (IEEE, Piscataway, NJ, 1997), Vol. 1, p. 709] at Sandia National Laboratories delivers ~20 MA load currents to create high magnetic fields (>1000 T) and high pressures (megabar to gigabar). In a z-pinch configuration, the magnetic pressure (the Lorentz force) supersonically implodes a plasma created from a cylindrical wire array, which at stagnation typically generates a plasma with energy densities of about 10 MJ/cm$^3$ and temperatures >1 keV at 0.1% of solid density. These plasmas produce x-ray energies approaching 2 MJ at powers >200 TW for inertial confinement fusion (ICF) and high energy density physics (HEDP) experiments. In an alternative configuration, the large magnetic pressure directly drives isentropic compression experiments to pressures >3 Mbar and accelerates flyer plates to >30 km/s for equation of state (EOS) experiments at pressures up to 10 Mbar in aluminum. Development of multidimensional radiation-magnetohydrodynamic codes, coupled with more accurate material models (*e.g.*, quantum molecular dynamics calculations with density functional theory), has produced synergy between validating the simulations and guiding the experiments. Z is now routinely used to drive ICF capsule implosions (focusing on implosion symmetry and neutron production) and to perform HEDP experiments (including radiation-driven hydrodynamic jets, EOS, phase transitions, strength of materials, and detailed behavior of z-pinch wire-array initiation and implosion). This research is performed in collaboration with many other groups from around the world. A five year project to enhance the capability and precision of Z, to be completed in 2007, will result in x-ray energies of nearly 3 MJ at x-ray powers >300 TW.
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## I. INTRODUCTION

The z pinch was one of the earliest techniques used as an attempt to heat plasmas to thermonuclear temperatures.[1] As an alternative to these direct heating mechanisms, Sandia National Laboratories began a program in the 1970s on the Proto II (Ref. 2) pulsed power generator to study the efficacy of using x rays from pulsed-power-driven z-pinch implosions to compress a DT-filled spherical capsule. In a z pinch, the azimuthal magnetic field associated with the axial flow of current through a cylindrically symmetric plasma creates a magnetic pressure ($\mathbf{J}\times\mathbf{B}$ or Lorentz force) that accelerates the plasma radially inward at high velocities. X rays are produced when the imploding plasma stagnates on the cylindrical axis of symmetry. While this research path was put on hold in 1983 because of the belief that ions offered a more reasonable route to inertial confinement fusion (ICF), z-pinch research continued on fast ($\leqslant$100 ns) pulsed power generators in order to create intense, energetic x-ray sources for radiation-material interaction studies. A wide variety of cylindrical z-pinch loads were used in these early experiments, including thin annular foils, gas puffs, low-density foams, and low-number wire arrays.[3] The z-pinch loads efficiently converted 10–15% of the stored electrical energy into x rays, and the x-ray power was roughly equal to the electrical power that drove the z-pinch implosion. A breakthrough in the x-ray power was achieved in 1995 when a series of experiments[4] performed on the 7 MA, 20 TW electrical Saturn[5] pulsed power generator revealed that the x-ray power from an imploding z pinch could be greatly enhanced by using a cylindrical array containing a very large number of wires ($\geqslant$100). This breakthrough technology (Fig. 1) was quickly adapted for testing at higher currents when a

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[a)] Paper AR1 1, Bull. Am. Phys. Soc. **49**, 19 (2004).
[b)] Invited speaker.

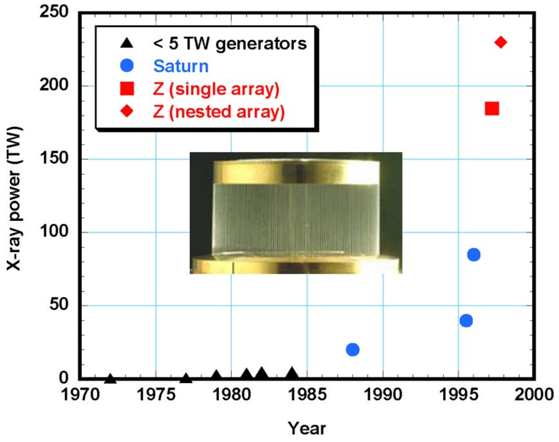

FIG. 1. Gas puff implosions on Saturn in 1988 provided a significant increase in x-ray power over early, smaller pulsed power generators (Gamble II, Pithon, Proto II, Blackjack, Double Eagle). High-number wire arrays (192-wire Al and 120-wire W) increased the x-ray power on Saturn to 85 TW in 1995. This technology has produced over 200 TW x-ray sources with nested wire arrays on the Z facility. Inset shows photograph of a single wire array.

modification[6] of the Particle Beam Fusion Accelerator (PBFA II) (Ref. 7) to allow z-pinch experiments was completed in October 1996.

Research in high energy density physics (HEDP) encompasses a regime that is typically associated with energy densities $\geqslant 10^5$ J/cm$^3$=1 Mbar.[8] At the time that the review article[9] on Sandia z pinches as intense x-ray sources for HEDP applications was written in 1996, the z-pinch mode of PBFA II [the 20 MA PBFA Z, now called Z (Ref. 6)] had been operational for one month, and x-ray energies >1.6 MJ and powers >160 TW had been produced from wire-array z-pinch sources. Subsequently, x-ray powers in excess of 200 TW were obtained using nested arrays of 200–400 wires.[10]

In this paper we review progress on ICF and HEDP experiments in pulsed power and research on radiation science, z-pinch physics, diagnostic development, and modeling and simulation that pertains to these experiments. Three major diagnostic improvements in the experiments occurred after 1997. (1) The multi-kilojoule, multi-terawatt (0.3–20 ns) Z Beamlet Laser[11] (ZBL), originally a scientific prototype at Lawrence Livermore National Laboratory for the laser system of the National Ignition Facility[12] (NIF), was completed and implemented at Z. Moreover, an associated high-spatial-resolution, monochromatic spherical crystal imaging system for backlighting that was pioneered for z pinches on smaller facilities[13] became operational[14] with ZBL. (2) Spectroscopic diagnostics to determine absorption and emission from photoionized z-pinch plasmas were added.[15–17] (3) Shockless pressure-loading techniques were developed to measure dynamic materials properties based on isentropic compression and magnetically launched flyer plates.[18,19] Experiments in magnetically driven HEDP and radiation-driven ICF have stimulated advances in simulation and modeling. These advances have included (1) detailed circuit models of Z,[20,21] (2) two-dimensional (2D) simulations of the hohlraum and capsule system,[22–24] (3) interpretation of wire-array implosions and materials equation-of-state (EOS) experiments via 2D and three-dimensional (3D) magnetohydrodynamics (MHD) codes,[25–30] (4) development of theories to explain the complex wire-array dynamics,[31–36] and (5) generation of accurate, first-principles-based quantum molecular dynamics calculations of the electrical, optical, and thermodynamic properties of metals.[37]

The advances in modeling and simulation, in turn, have led to more sophisticated HEDP experiments on Z and the approval of and commencement of a refurbishment of Z,[38] which is scheduled for completion in early 2007, and to the design of a high-energy petawatt capability for ZBL to extend the photon energy available for radiography experiments and enable fast ignition[39] experiments. The refurbishment of Z is being designed to deliver 26 MA load currents to a 4 cm diameter, 2 cm long wire array and should produce soft x-ray pulses approaching 300 TW. Other complementary research efforts have included an *in situ* cryogenic cooling system[40] on Z, advances in the design and fabrication of large ICF capsules and uniform foams by General Atomics and Schafer Corporation,[41] and use of Z to obtain accurate EOS and phase transition measurements[42] for a variety of ICF- and HEDP-relevant materials.

Selected pulsed-power-driven HEDP and ICF research on Z during the last few years is reviewed in the following sections. Section II describes the progress on ICF experiments and simulations to achieve high-temperature implosions and symmetric drive, as well as initial work on pulsed-power-driven fusion fuel assembly techniques for fast ignition[39] concepts. Section III reviews radiation science and plasma spectroscopy on Z. Section IV describes progress in understanding z-pinch physics and Sec. V reviews the advances in measuring, simulating, and modeling the properties of dynamic materials. The paper concludes (Sec. VI) with a short summary of the ongoing effort, which began in 2002, to improve the capability of Z.

## II. INERTIAL CONFINEMENT FUSION

The flexible, efficient x-ray sources demonstrated on Z have sparked interest in several z-pinch fusion concepts. In this section we summarize results of high-temperature capsule implosions in the dynamic hohlraum configuration, radiation symmetry studies in the double-ended hohlraum configuration, and z-pinch-driven hemispherical compression studies for a fast ignition concept in which the compressed core of the fuel would be further heated by a short-pulse laser beam.

### A. High-temperature capsule implosions with dynamic hohlraums

In a z-pinch dynamic hohlraum (DH) a high-Z, high-opacity, annular plasma formed from a cylindrical array of wires stagnates on an inner cylinder of low-density, low-Z foam (Fig. 2). The impact of the high-Z plasma shell on the foam launches a radiating shock that propagates toward the cylindrical axis of symmetry. The high-opacity pinch plasma traps the radiation and serves as the hohlraum wall. This concept was independently developed[9,43] in the late 1970s to

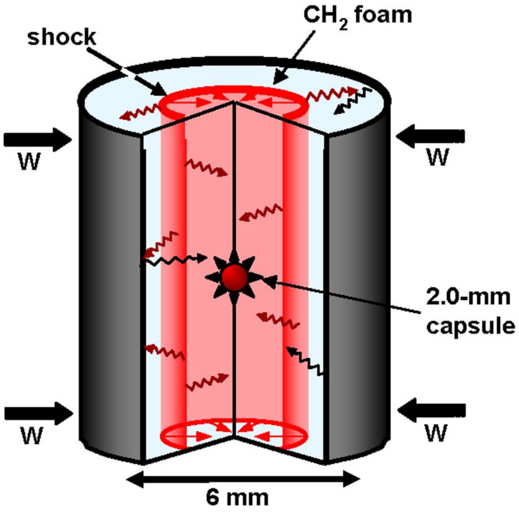

FIG. 2. Schematic of z-pinch-driven dynamic hohlraum configuration showing imploding tungsten shell that launches a radiating shock in a low-density foam. The shock creates the x-ray environment that implodes a spherical capsule on the cylindrical axis of symmetry.

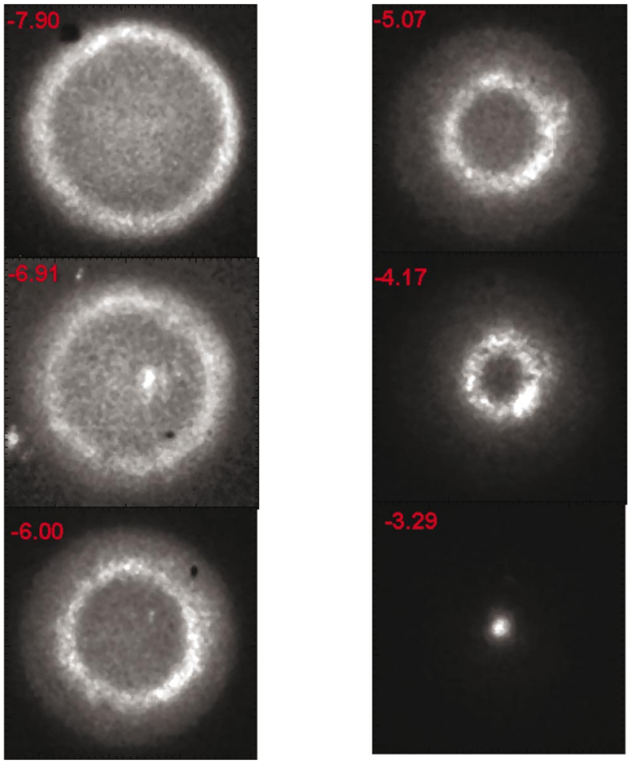

FIG. 3. (Color). End-on x-ray images of radiating shock in low-density foam of a dynamic hohlraum on Z at times from 7.9 to 3.29 ns before peak of radial x-ray intensity.

early 1980s by researchers at Sandia, Los Alamos National Laboratory, and in Russia. The dynamic hohlraum is an efficient means of delivering intense radiation from the z pinch to a capsule embedded within the foam: 3 mm diameter capsules in recent experiments absorbed ~80 kJ of x rays. As reviewed below, x-ray spectroscopy and imaging, combined with detailed one-dimensional (1D) and 2D simulations, have provided a benchmarked understanding of dynamic hohlraum physics. Although many challenges remain, this improved understanding has enabled us to tailor capsule implosions to produce measurable thermonuclear neutron yields from x-ray-driven capsule implosions on Z.

In the first DH experiment on Z, x rays exiting the end of the dynamic hohlraum were used as a source for radiation physics experiments.[44] The encouraging results then motivated interest in diagnosing conditions within the hohlraum itself.[45] A DH was created by accelerating a tungsten z-pinch plasma onto a cylindrical (10 mm diameter), $5\ \mathrm{mg/cm^3}$ $CH_2$ foam. Time-resolved x-ray images of self-emission from a radiating shock propagating at $\sim 35\ \mathrm{cm}/\mu\mathrm{s}$ in the foam showed that the shock was remarkably uniform with an annular width less than $\sim 200\ \mu\mathrm{m}$ (Fig. 3). The narrow width implied that variations in shock launch time or shock strength along the 15 mm tall foam, induced by hydromagnetic Rayleigh–Taylor instabilities in the accelerated tungsten plasma or by any other nonuniformity, were quite small. (The corrugated structure associated with the instabilities had been expected to imprint on the shock.) Furthermore, 2D LASNEX (Ref. 46) simulations accurately reproduced (Fig. 4) the measured spatial profile of the shock self-emission and shock propagation through the hohlraum.[23,24] The simulations also indicated that the shock characteristics were insensitive to the instability amplitude and that the interaction of the tungsten plasma with the ablated foam tamped the instability. The relatively smooth magnetic pressure largely determined the shock conditions. The small effect of pinch nonuniformities on the radiating shock was an important breakthrough for DH ICF.

The relatively large (10 mm diameter, 15 mm tall) dynamic hohlraums in these experiments reached ~135 eV peak radiation drive temperatures, too low for capsule implosions capable of emitting measurable x rays or fusion neutrons. However, the insights gained by comparing the data to

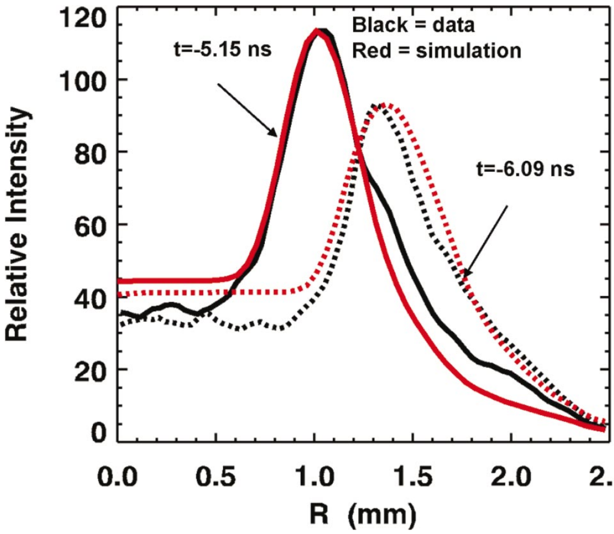

FIG. 4. (Color). Comparison of measured intensity of x rays emitted from radiating shock (black) to simulated intensity (red) on Z at two different times (6.09 and 5.15 ns) before peak of radial x-ray intensity for a dynamic hohlraum.

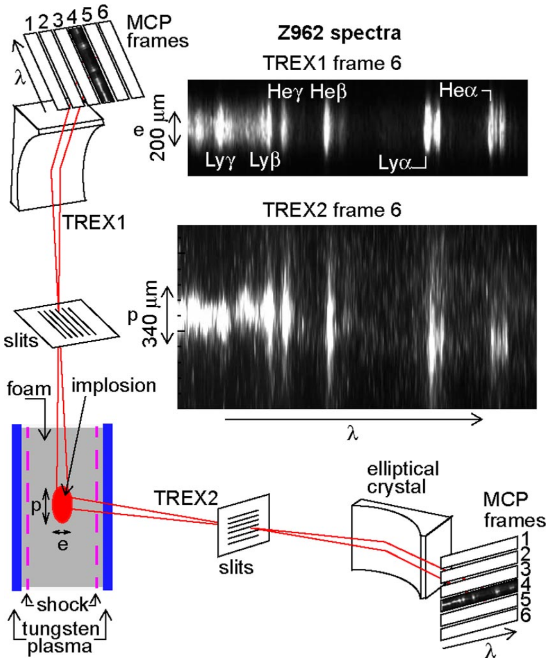

FIG. 5. Schematic setup of spectroscopic experiment on Z. Time-resolved, high-spatial-resolution elliptical crystal spectrometers are oriented to measure the implosion core size along the equatorial axis *e* and polar axis *p*, respectively, inside the dynamic hohlraum. Microchannel plate frames record space-resolved spectra at 1 ns intervals. Ar spectra were recorded at peak emission time.

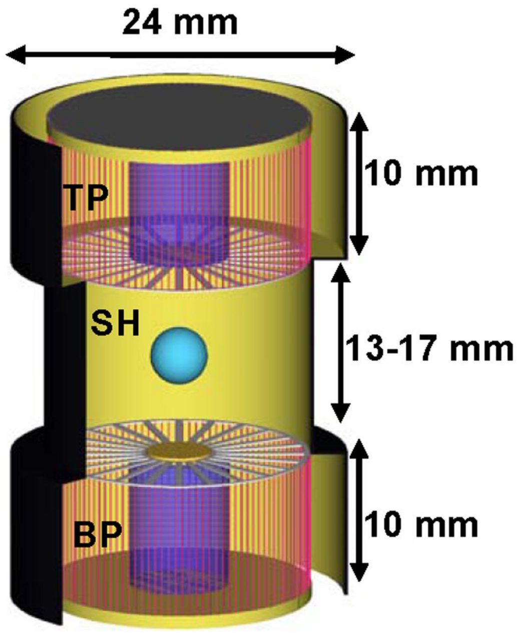

FIG. 6. Schematic of high-yield double-ended hohlraum configuration, driven by a double-sided pulsed-power feed architecture. TP denotes top pinch and primary hohlraum, SH denotes central secondary hohlraum containing the DT-filled capsule, BP denotes bottom pinch and primary hohlraum. Radial-spoke electrodes and on-axis shine shields located at either end of the secondary hohlraum separate the top and bottom z-pinch implosion and stagnation regions from the capsule.

simulations motivated new hohlraum and capsule designs[23] that could produce measurable x-ray emission from the imploding capsule core and thereby provide data on electron temperature, electron density, and symmetry.

A cylindrical hohlraum tends to drive a spherical capsule with equator-hot radiation that, if uncorrected, would produce an implosion elongated along the cylinder axis. However, symmetry corrections, including radiation shields and noncylindrical foams, require diagnostics that can measure the effects of such corrections. Published laser-driven capsule implosions[47] have shown that x-ray core imaging data of the equatorial radius $r_e$ as compared to the polar radius $r_p$ reflect the x-ray drive asymmetry. Applying such methods to the DH was complicated by the difficulty in viewing the capsule implosion through the luminous, high-opacity z-pinch plasma (Fig. 2). However, a second-generation series of experiments that used 6 mm diameter, 12 mm tall, 14 mg/cm$^3$ $CH_2$ foam with ~2 mm diameter CH-shell capsules filled with $CD_4$ or $D_2$ and a trace amount of argon successfully recorded (Fig. 5) time- and space-resolved x-ray spectra from the tracer atoms.[48] In these experiments the radiation temperature peaked at 215 eV. This technique required two separate spectrometers, one viewing along the polar axis and the other along the equatorial plane, to determine the $r_e/r_p$ ratio. The two spectra lay the foundation for a future tomographic reconstruction of the 2D electron density $n_e$ and temperature $T_e$ spatial profiles within the implosion core and have already benchmarked the accuracy of 1D and 2D LASNEX simulations.

The measured peak average core density and temperature in these experiments were $n_e \sim (1-3) \times 10^{23}/\text{cm}^3$ and $T_e \sim 0.8-1.1$ keV. By leveraging the understanding provided by the x-ray imaging data and comparisons of the $n_e$ and $T_e$ data to LASNEX simulations, the performance of the implosion core was optimized to obtain the first measurements of thermonuclear neutrons from a z-pinch-driven ICF capsule implosion in 2003.[49] Neutron energy and yield data verified that the energy (2.45 MeV) and isotropic nature are consistent with a thermonuclear origin. Based on neutron time-of-flight measurements of the energy spectrum, the ion temperature is $4.5 \pm 1.5$ keV. More evidence of the thermonuclear character came from the addition of trace amounts of xenon to the standard $D_2$+Ar fill. The xenon cooled the implosion core and reduced the thermonuclear neutron yield by a factor of ~20, in agreement with simulations.[49]

In experiments with z-pinch and plasma focus devices over many years, the neutrons had been nonthermonuclear;[50] directed energetic ions created during plasma disruption resulted in nonthermal ion-beam-generated DD neutrons. In addition to being thermonuclear, the measured neutron yields in the DH experiments $(1-5 \times 10^{10})$ were also the largest produced in any[51] laboratory x-ray-driven $D_2$ implosion.

## B. Symmetric drive with double-ended hohlraums

The double-ended hohlraum (DEH) approach to pulsed-power-driven high-yield ICF described by Hammer *et al.*[52] uses a z-pinch-driven vacuum hohlraum at each end of a central coaxial hohlraum containing the ICF capsule (Fig. 6). For high yield, the calculations predict that two z pinches with peak electrical currents of 63 MA would release a total of 16 MJ of x rays in a shaped pulse, driving the secondary hohlraum to 220 eV radiation temperatures. About 1 MJ of x rays are absorbed by a 5 mm diameter cryogenic DT-filled capsule, which is ablatively driven to a convergence ratio of 35, igniting a central hot spot from which the fusion burn propagates radially outward with a total fusion yield of 400 MJ. This ICF approach separates the physics issues associated with the z pinch, hohlraum, and capsule, allowing some independent optimization and validation of each component.

Over the past five years, z-pinch-driven vacuum hohlraums have been extensively characterized on Z. Experiments have measured the z-pinch power, primary hohlraum radiation temperatures, and primary-to-secondary hohlraum coupling efficiency for configurations relevant to this concept.[53–55] The relationship of the measured pinch power history to the hohlraum temperatures is well understood (±20% in flux) within zero-dimensional hohlraum power balance models,[55,56] 2D time-dependent view-factor calculations,[57] and 2D radiation-hydrodynamics (RHD) simulations.[54] This same research also demonstrated adequate radiation flow through the radial-spoke electrode separating the primary and secondary hohlraums. The measured effective radiation transmission through the beryllium spokes $[>(71\pm7)\%]$ is sufficient for capsule implosion experiments, agrees with 2D RHD simulations,[54] and scales to high yield.[52] From a hohlraum energetics standpoint, the remaining key question relates to the scaling of pinch performance (as discussed in Sec. IV) from the 20 MA level presently possible on Z to the 63 MA level envisioned for high yield with a DEH.

Capsule radiation symmetry is a crucial physics issue for this concept because central hot-spot ignition capsules typically require $<1-2\%$ overall fluence asymmetry (*e.g.*, the point design capsule for the NIF tolerates $<1\%$ time-averaged asymmetry[58]). The polar angle distribution of radiation fluence on a spherical capsule in an axisymmetric hohlraum is typically expressed in terms of Legendre polynomials $P_j$. For double-pinch hohlraums, odd Legendre mode asymmetry ($P_1$, $P_3$, *etc*.) results from power imbalance and mistiming of the two z pinches, whereas even Legendre mode asymmetry ($P_2$, $P_4$, *etc*.) is governed by hohlraum effects (geometry, time-dependent wall albedo, and wall motion). Time-dependent 2D view factor and 2D RHD simulations have predicted that superimposed primary and secondary wall reemission onto the capsule creates a radiation drive with a uniformity that depends on the primary and secondary geometry.[57,59] Self-backlit foam ball burnthrough experiments have partially validated these simulation techniques, demonstrating gross modifications of radiation symmetry via geometric changes in single-pinch hohlraums.[60]

Two advances have enabled high-quality capsule implosion experiments in a DEH of the same physical scale as the high-yield concept: (1) development of a robust double-pinch wire-array load for Z and (2) adaptation of ZBL (Ref. 11) for 5–7 keV x-ray backlighting on Z. Shown schematically in Fig. 7, the double-pinch wire-array load[54,61] provides balanced upper and lower pinch x-ray power histories such that the upper and lower primary hohlraum wall emission temperatures agree within ±5% instrumental error bars. The flux asymmetry as measured by foam ball burnthrough was $<15\%$ maximum-to-minimum in double-pinch hohlraums,[59,60] at the limit of detection for the self-backlit technique. Higher resolution techniques were therefore needed to measure the predicted 2–4% fluence asymmetry levels.[61]

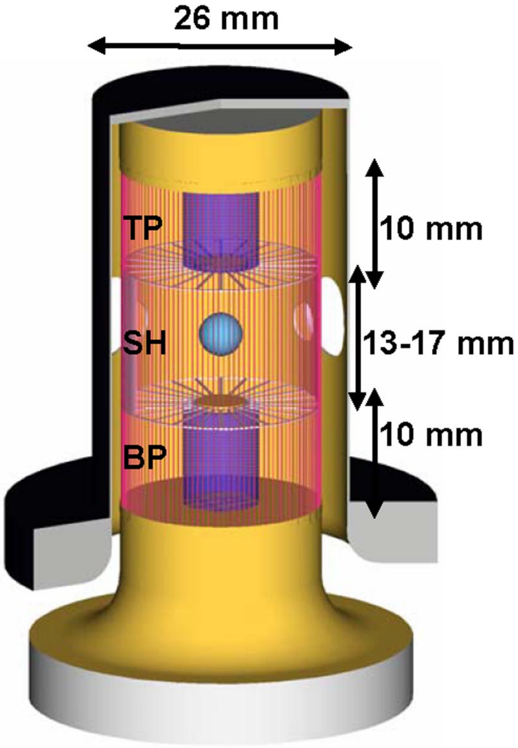

FIG. 7. Schematic of double-ended hohlraum configuration as fielded on Z. Hohlraum is driven from the bottom by a single-sided pulsed-power feed architecture. Secondary hohlraum is attached to a single tungsten wire array that is strung the entire length of the load and forms the top and bottom pinches. Electrical current flows up the bottom pinch, around the outside of the secondary hohlraum, up the top pinch, and returns via the outer wall of the hohlraum.

ZBL provided high-resolution capsule symmetry diagnosis by creating high-energy (4.7–6.7 keV) x rays for point projection backlighting of the capsule implosions. X-ray backlit imploding capsules as a symmetry diagnostic has its origins in laser-driven hohlraums,[62] where ultrathin spherical shells have been used to measure radiation asymmetries, particularly higher order $P_6$ and $P_8$ modes. The use of highly collimated shielding to reduce the high-energy bremsstrahlung background and an electromagnetically driven fast shutter for debris mitigation[63] allow high-contrast film images to be obtained in the harsh multi-megajoule x-ray environment of Z. Backlit capsule images with 50 $\mu$m spatial resolution and 0.6 ns temporal resolution have enabled measurements of in-flight distortions at the percent level[64] in z-pinch-driven hohlraums. A hohlraum length scan demonstrated the behavior as a function of convergence ratio and hohlraum geometry.[65] This demonstration of capsule asymmetry trends with hohlraum geometry is somewhat analogous to earlier

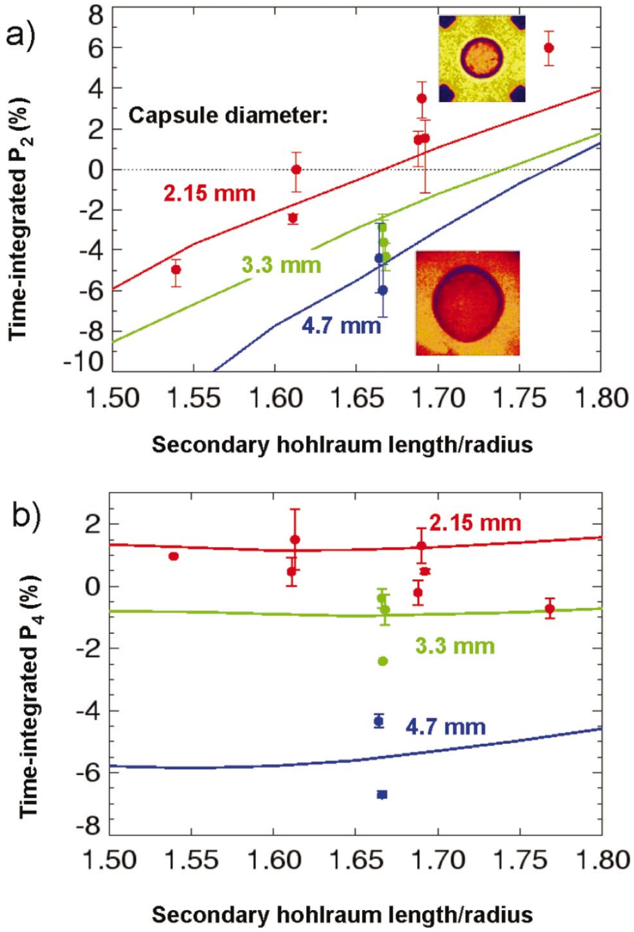

FIG. 8. (Color). Time-integrated radiation asymmetry in Legendre modes $P_2$ and $P_4$ for double-ended hohlraum on Z. Data points with error bars are from Z experiments, solid lines are from time-dependent view-factor simulations. (a) $P_2$ mode vs secondary hohlraum length-to-radius ratio for different capsule sizes. Insets show two example backlit capsule images. (b) Same plot for $P_4$ mode.

laser-driven hohlraum experiments that demonstrated symmetry control via laser pointing, hohlraum length variation, and shine shields.[66]

The combination of a robust double-pinch hohlraum with now-routine x-ray backlighting has enabled quantitative studies of capsule drive asymmetry over a range of hohlraum parameters and capsule sizes. Experiments in symmetry tuning with 2.15 mm diameter plastic ablator capsules absorbing 5–7 kJ of x rays have demonstrated $P_2$ symmetry control to ±2%,[67] maximum-to-minimum fluence asymmetry of $3.0 \pm 0.7\%$ for the most symmetric cases,[68] and convergence ratios of 14–21 inferred from the size of the assembled ablator plasma in x-ray backlit images.[64] Larger-diameter (4.7 mm), thin-shell (25–30 $\mu$m) capsules are currently being used to study radiation symmetry control via hohlraum geometry tuning at a high-yield-relevant case-to-capsule radius ratio of ~4. Figure 8 shows the measured time-integrated $P_2$ and $P_4$ asymmetry modes as functions of both the capsule diameter and the secondary hohlraum length-to-radius ratio. Also plotted for comparison are the results of time-dependent view-factor calculations,[59] which show reasonable agreement with the sensitivity to both hohlraum length and case-to-capsule ratio. Including the effects of time-dependent wall motion was a key to obtaining this level of agreement with the data. The 2.15 mm diameter capsule data in Fig. 8(a) show that the time-integrated $P_2$ asymmetry can be zeroed by the proper choice of hohlraum length (with all other parameters held constant), in agreement with calculations.[67] Experiments are currently underway to investigate the use of hohlraum geometry (length, on-axis shine shield radius, and thickness) to tune symmetry for the larger 4.7 mm diameter capsules and to compare the measured trends with simulations.

As seen in Fig. 8(b), the $P_4$ mode is more weakly dependent on hohlraum length than $P_2$ for the 2.15 mm diameter capsules and may be unacceptably large for the 4.7 mm diameter capsules. ($P_4$ asymmetry at a level of 5% would, in fact, cause the baseline high-yield capsule to fail.) Conventional symmetry control methods such as hohlraum geometry design and additional $P_4$-specific permanent shine shields are being investigated. In addition, capsule shimming experiments in collaboration with Lawrence Livermore National Laboratory are validating a $P_4$ control method that is applicable not only to z-pinch ICF but also to heavy-ion fusion and possibly to ignition on the National Ignition Facility. Originally conceived as part of a heavy-ion fusion target design,[69] a thin (submicrometer) layer of high-Z material with angular-dependent thickness directly deposited on the ablator surface may allow percent-level early-time asymmetries to be nullified with the least overall energetics penalty. Backlit shimmed-capsule experiments in the DEH on Z are currently validating this concept at drive temperatures similar to the foot pulse required for ignition capsules. In addition to the physics issues being tested via comparisons of simulated and experimental backlit images, practical issues of target fabrication, capsule mounting, and capsule orientation are being addressed.

DEH implosion experiments with deuterium-filled, 3.3 mm diameter capsules designed to absorb 14 kJ of x rays have also begun on Z as an integrated test of drive temperature and symmetry. These capsules are complementary to the thin-shell symmetry diagnostic capsules described above. At this capsule size, the time-integrated $P_2$ and $P_4$ asymmetries may be tuned to low enough levels (see Fig. 8) to permit convergence ratios of 10–20 with measurable neutron yields for comparison with 2D calculations. High-sensitivity neutron detectors are being designed and calibrated to measure expected DD thermonuclear neutron yields of $>1 \times 10^6$ for these integrated tests.[70]

The ability to separate the physics issues for the DEH has allowed progress in understanding on several fronts over the last five years, as summarized in a recent conference paper.[71] The experimental hardware, diagnostics, and simulation capability development have produced understanding of hohlraum energetics at the 15–20% level and of low-mode capsule asymmetry at the 2% level. Mature DEH capsule symmetry experiments are now exploring the subtle effects of small changes in hohlraum geometry and the use of submicrometer shim layers for early-time symmetry control with applications to multiple indirect-drive ICF approaches. Finally, the systematic trends in radiation asymmetry measured in the Z DEH are being used for quantitative validation of models that will be used to design hohlraums and capsules for higher-current z-pinch accelerators.

### C. Fast ignition

Short-pulse laser-matter interactions produce electron[72] or ion[73] beams that can heat high-density compressed matter to high temperatures and therefore reduce the implosion symmetry, compressed fuel density, and radiation pulse shape requirements for hot-spot ignition of the fuel core. The advent of the technology to produce large-aperture, high-energy ($>1$ kJ), short-pulse (femtosecond to picosecond) lasers with high peak powers (100 TW–1 PW) has renewed interest in the decade-old fast ignition concept[39]for ICF.

In 2001 a short-pulse laser energy coupling efficiency of 30% to a compressed ICF capsule was demonstrated at the Institute for Laser Energetics in Japan. This efficiency was obtained by imploding the capsule along the surface of a 60°, high-Z cone by direct laser drive.[74] The high-Z cone maintained a path free of low-density plasma so that the laser could be focused onto the dense core of the implosion.

In a series of Z experiments, z-pinch-driven secondary hohlraums using wire-array z-pinch sources[54,55,60] (as discussed in Sec. II B) are being applied to indirect-drive capsule implosion concepts compatible with fast-ignition fuel heating.[75,76] Hemispherical capsules can be imploded on a planar surface with the x-ray drive,[75] and the capsule implosion symmetry controlled with the hohlraum geometry.[60,75,76] Achievable capsule symmetry in optimal systems is being measured using the high-spatial-resolution crystal imaging system for backlighting.[14]

A cryogenic $D_2$ capsule[77] is being developed with a thin inner shell to contain the $D_2$ layer, based on the system previously developed[40] for cryogenic $D_2$ EOS measurements on Z.[19,78,79] Radiation symmetry control in this system may be sufficient to produce densities of $135\ \mathrm{g/cm^3}$ for a compressed fuel $\rho r$ of $0.8-1.1\ \mathrm{g/cm^2}$ with hemispherical implosions on the refurbished Z.[76] Dynamic hohlraum drive[23,45,48,76,80,81] (as discussed in Sec. II A) can produce higher radiation temperatures than vacuum hohlraum drive and may produce densities of up to $300\ \mathrm{g/cm^3}$ (a $\rho r$ of $1.3\ \mathrm{g/cm^2}$ at 180 eV).

Recently, state-of-the-art simulations of the coupling of a short-pulse, high-intensity laser pulse to matter[82] with the LSP code[83] have been used to model the fast ignition experiments of Kodama *et al.*[74] The development of a high-energy (2 kJ), short-pulse (petawatt) laser coupled to the refurbished Z should allow exploration, on the 2008 time frame, of fast ignition science issues such as the production of high-energy electron and ion beams, beam-matter coupling at high densities and temperatures, and fuel heating and sub-ignition fusion neutron yields.[84]

## III. RADIATION SCIENCE AND PLASMA SPECTROSCOPY ON Z

X-ray generation, propagation, heating, and ionization contribute to the formation and evolution of many laboratory and astrophysical plasmas. The interpretation of ICF and astrophysical observations must often rely on RHD simulations that depend on an accurate treatment of radiation absorption and reemission properties. The measurement of these properties, which are controlled by the atoms composing the plasma, is a central aspect of radiation science, and the data are of special importance when multiple radiation and hydrodynamic phenomena are intermingled. The properties must often be approximated, and the suitability of such approximations can be tested in radiation science experiments. Plasma spectroscopy is a key diagnostic, and the information quality is only as good as the atomic and plasma physics models used to interpret the data.

Rapid progress in radiation science has occurred in the last two decades[85–88] because of the development of high-intensity lasers and atomic models to analyze complex spectra. However, the available radiation source energy limited the experiments that were feasible. With the advent of the intense x-ray burst emitted by z-pinch plasmas at Z in 1996, a new capability became available.[89] In “ride-along” experiments (defined as experiments that are performed in such a way that they do not interfere with the principal experimental objective of the Z shots), material samples can be exposed to a radiation flux equivalent to a 20–70 eV blackbody.[90] In dedicated Z experiments, samples can be exposed to much higher radiation temperatures. The flux level in Z ride-along experiments is comparable to present-day laser plasma experiments.[85–88] However, the larger sample size and longer radiation pulse possible with z pinches (typically by an order of magnitude) allow measurement of radiation conditions in multiple samples simultaneously, achievement of more uniform conditions, and a closer approach to steady state results. A typical radiation-science configuration on Z (Fig. 9) consists of a sample located 1–10 cm away from the z pinch, where it is heated to 10–100 eV by the pinch radiation. The spectrally resolved absorption is measured by aiming x-ray spectrographs through the sample at the pinch. The pinch plasma thus both heats the sample and serves as a backlighter.

With the addition of an extremely bright, broad-wavelength-coverage backlighter, opacity measurements are especially promising on high-current z-pinch generators. Development of the capability to measure opacities in relatively uniform samples (spatially and temporally) over a wide spectral range on these generators will enhance the understanding of the atomic physics of HEDP plasmas. The opacity of a material controls the flow of energy within the plasma and hence can strongly influence the radiation hydrodynamics in ICF hohlraums and z pinches and as well as in astrophysical plasmas. The first opacity experiment on a Sandia pulsed power accelerator was in 1995 on Saturn. The iron opacity data obtained[91] resulted in improved computer code models to simulate the behavior of Cepheid variable stars. More recently, we have been developing the capability on Z to obtain accurate opacity data for medium- and high-atomic-number materials that are heated by the z-pinch radiation source. For example, the opacity of a medium-Z atom with a partially filled *M* shell, bromine, was measured on Z using CH-tamped NaBr foil samples.[92] The CH tamping of the foils allowed higher densities to be accessed. The electron tem-

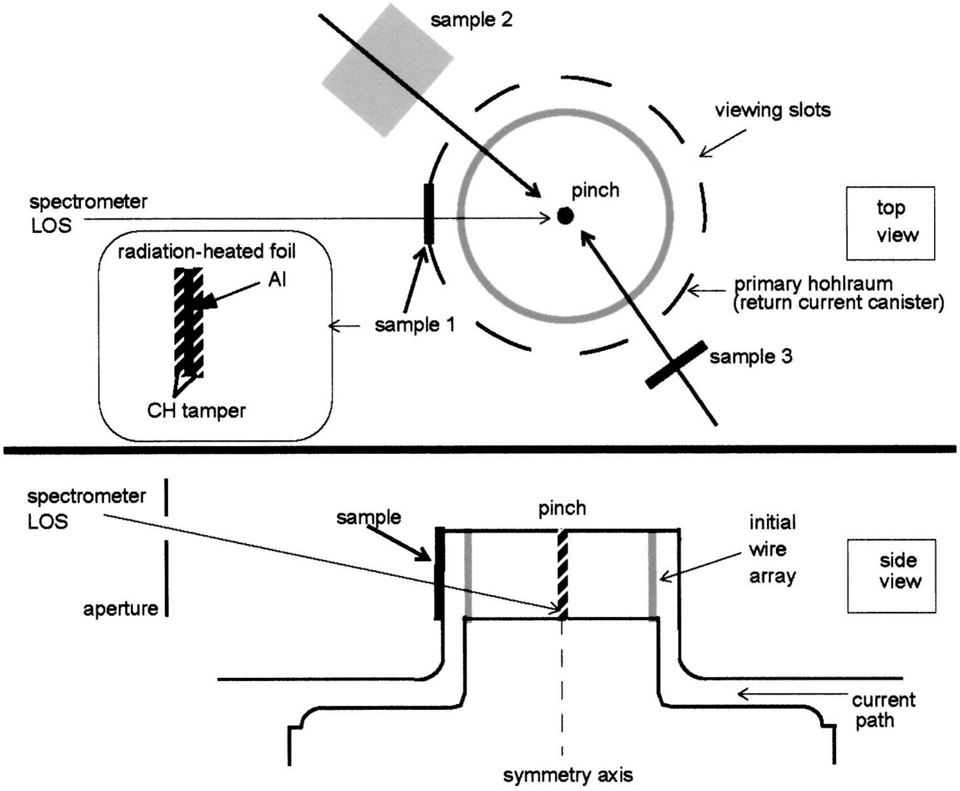

FIG. 9. Schematic diagram of radiation science experiments on Z using z-pinch x-ray source shows top and side views. Multiple samples located outside the primary hohlraum are heated by x rays and diagnosed using the z-pinch source as a backlighter for absorption spectroscopy.

perature and density of the foil (50 eV and $3\times10^{21}/\mathrm{cm}^3$) were diagnosed from the spectral lines of the relatively well understood (low-Z) sodium, and the opacity of Br under these known plasma conditions was determined from the absorption spectra. Recent work has focused on measuring the opacity of CH-tamped Fe+Mg foils at temperatures corresponding to the radiation zone in the sun. The technique used for these measurements is similar to that in Ref. 92. The temperature and density are determined from the Mg spectral lines, and iron opacity models are tested with the Fe absorption spectra. In this study, the dynamic hohlraum x-ray source appears promising for heating samples to an electron temperature of ~150 eV. Once fully developed, such a capability can be used to investigate many materials of interest to high energy density physics. For example, this capability could be used to develop models that elucidate the role of opacity in the performance of an ICF capsule that contains a medium-Z dopant in the outer shell.

The large sample size and brightness of the z pinch as a backlighter are also being exploited in a novel method to measure reemission from radiation-heated gold plasmas.[89] A CH-tamped, layered foil with Al+$\mathrm{MgF_2}$ faces the radiation source. A gold backing layer that covers a portion of the layered foil [Fig. 10(a)] absorbs radiation from the z-pinch source and provides reemission that further heats Al+$\mathrm{MgF_2}$. The Al and Mg heating is measured using space-resolved $K_\alpha$ absorption spectroscopy, and the difference between the two regions [Fig. 10(b)] allows the gold reemission to be determined.

Many past spectroscopy experiments have studied atomic kinetics in plasmas where the ionization distribution and excited state populations are controlled by electron collisions. Spectroscopic data are also needed to benchmark atomic physics models of photoionized plasmas—in particular, to interpret data from accretion-powered objects such as x-ray binaries and active galactic nuclei. However, such plasmas have been studied in few laboratory experiments because the incident radiation field must be intense enough that photoionization dominates over collisions, the plasma density must be relatively low ($<10^{13}/\mathrm{cm}^3$ for typical astrophysical plasmas), and the sample must be large enough at low density to provide measurable absorption or emission spectra.

Absorption and emission spectra from a photoionized iron experiment on Z have already provided charge state distribution and plasma conditions suitable for initial tests of astrophysical atomic kinetics models. The approach to generating a low-density Fe plasma[15,16] was to preheat a tamped, thin foil with low-intensity x rays from the Z run-in radiation, so the foil could expand to the desired density prior to application of the main photoionizing radiation field. For neon, a gas cell filled to the desired atomic density[17] has produced a spectrum with visible He-like and Li-like neon lines, indicating that the radiation was intense enough to ionize neon into the desired regime. Future photoionization experiments on Z may provide even stronger model tests by improving the plasma characterizations, increasing the photoionization, and possibly reducing the density. The results for Fe and Ne provide a basis for designing these improved experiments.

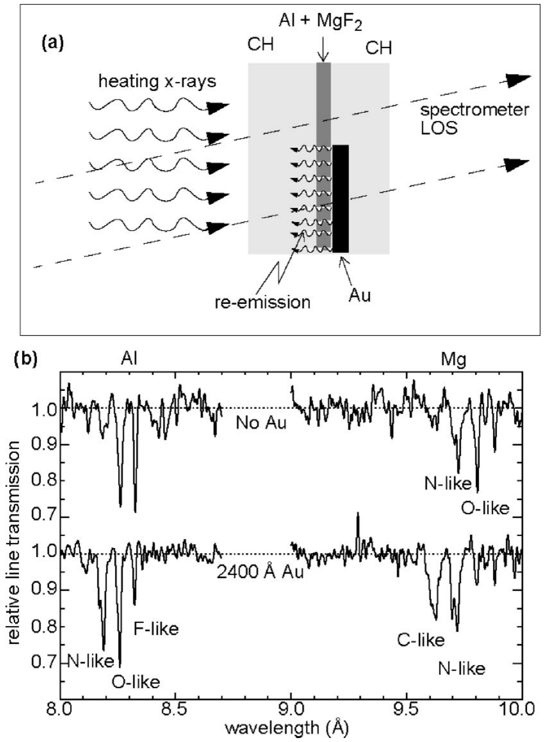

FIG. 10. (a) Sample configuration for opacity experiment on Z in which a CH-tamped, layered foil with Al and MgF$_2$ faces the radiation source. Re-emission from a gold backing layer that covers a portion of the layered foil further heats the sample. (b) Al and MgF$_2$ spectra with and without the gold backing layer.

## IV. Z-PINCH PHYSICS

Since the initial results obtained in 1995 and 1996 on Saturn[4] and Z,[10,93,94] the z-pinch community has made great strides in advancing the understanding of wire-array dynamics and developing the MHD codes required to model wire-array implosions. Experiments on the 1 MA MAGPIE facility[95] at Imperial College have elucidated the dynamics of arrays with a low number of wires.[96,97] These results confirmed earlier measurements[98–101] that the wires remain "wirelike" for a large fraction of the implosion time and ablate material in an axially nonuniform process that ejects material towards the array axis. The process was quantified[31] by introducing the "rocket model" to describe the early-time ablation dynamics of the arrays. This semiempirical description is supported by more detailed theoretical studies on wire ablation dynamics.[32,33,36] Measurements on MAGPIE also indicated that the early-time behavior delays the implosion trajectory and causes mass to be left behind during the main acceleration towards the axis.[28,31,102]

Experiments[103–108] on higher current facilities, the 3 MA Angara-5 (Ref. 109) and the 20 MA Z,[6] have indicated that the same dynamics of long wire-ablation phase, delayed array acceleration, axially nonuniform wire ablation, trailing mass, and trailing current are manifested at high currents and high wire numbers. Interpretation of the Z wire implosion experiments has been aided by the availability of the ZBL and the high-spatial-resolution, monochromatic spherical crystal imaging system.[14] The x-ray backlighting data (see Fig. 11) show the onset and growth of instabilities that produce axially nonuniform ablation of the wires and directly confirm the presence of trailing mass.[107] X-ray backlighting may also provide clues for resolving an important issue for z pinches, that is, the degradation of performance with too many wires in the cylindrical array.[110,111]

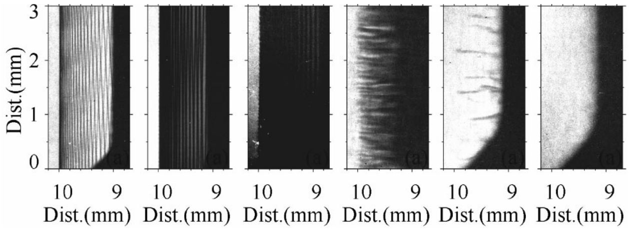

FIG. 11. Sequence of radiographs obtained with ZBL and the high-spatial-resolution, monochromatic spherical crystal imaging system shows the edges of imploding 20 mm diameter tungsten arrays on Z with high wire numbers (300 wires). The long-lived, "fingerlike" structures of trailing mass contribute to the broadening of the radial mass distribution of the wire-array plasma.

An improved understanding of wire-array physics is required to scale these sources to larger facilities for two of the ICF applications that are discussed in Sec. II. In particular, recent work suggests that the peak power from the higher-mass (5.8 mg/cm), 20 mm diameter arrays used for the double-ended hohlraum approach scales subquadratically with current.[112] This scaling may be produced by wire ablation effects[112,113] that result in trailing mass[105] and current[106] that are not coupled to the axis at peak x-ray power. As further support for the conclusion that trailing mass may result in the slower scaling of power with current,[105] lower-mass (2 mg/cm), 40 mm diameter arrays show quadratic scaling of the power and energy with current.[114] These lower-mass arrays were estimated to have only ~(36±6)% of the trailing mass of the higher-mass, 20 mm arrays.[105]

The effort to improve the performance of 20 mm diameter arrays for the double-pinch concept (Sec. II B) has been guided by these observations of discrete wire ablation and trailing material. For example, when nested arrays are used, the discrete core/corona behavior of the arrays can allow a relatively transparent mode of interaction between the arrays[115–117] rather than the inelastic collision necessitated by thin-shell approximations.[94] Recent observations of an extended ablation period and discrete inner-wire cores in a nested-array geometry for 20 mm outer-diameter, 12 mm inner-diameter nested arrays[118] confirm operation in a current transfer mode, even with high outer-wire numbers. These transparent nested arrays are being used to produce a shaped radiation pulse[119,120] for ICF hot-spot ignition.[52] A second area of research involves the use of deliberately undermassed wire arrays with short implosion times that are not well matched to the generator's current pulse. This research has demonstrated that low-mass arrays that reach peak currents of only 14 MA can radiate nearly as well as heavier arrays that reach 18 MA peak currents,[121] implying improved scaling of peak power with current.

An experiment that can be performed at high currents on Z, but not on smaller current experiments, is the comparison of the array dynamics with foil dynamics,[122] since the higher mass requirement for Z experiments enables fabrication of high quality foils. A comparison of data from foils and wire arrays of equivalent mass demonstrated that, in spite of its complex dynamics, a wire array appears to have a lower level of initial perturbation than a foil. The foil implosions may be plagued by classic hydromagnetic-Rayleigh-Taylor growth.[123] Early-time images indicate that the foil has a coherent perturbation prior to implosion. The equivalent-mass, 300 wire array has a much less pronounced level of perturbation at the same early time. Experiments and calculations are underway to understand these phenomena.

The foil implosions do, however, provide the opportunity to model the dynamics with a standard 2D MHD calculation in the *r-z* plane. Such calculations[25,26] have been successful in the past in replicating general implosion dynamics, x-ray outputs, and energetics and in contributing to the development of new load concepts (*e.g.*, nested wire arrays). Nevertheless, these calculations cannot capture the 3D nature of wire-array implosions. Over the last five years, the community has made great strides in developing 3D MHD codes to model wire arrays. Even with modern computational platforms, physics trade offs are still required to ensure reasonable run times, but recent papers[27,28] have indicated that these codes can accurately simulate the 3D dynamics of z pinches. To have a complete *a priori* predictability, however, we must fully understand what physics has to be included. For example, the natural wavelength that is selected in wire-array ablation seems consistent for a given material and generally appears to be a multiple of the wire core size.[31,107] Haines[34] has developed a theory based on a thermoelectric instability to explain this observation. In addition, Oliver[35] has pointed out the need to consider additional two-fluid phenomena in the physics of wire-corona formation, linear bubble breakthrough, and nonlinear saturation amplitudes of instabilities.

Answering fundamental questions about z-pinch physics is a challenge for facilities the size of Z because of the low experimental shot rate and the harsh x-ray environment. Small university facilities thus serve a critical role. To validate 3D codes and understand the formation of natural modes in wire arrays, innovative experimental designs are needed. Preinscribing perturbations on wire arrays provide the opportunity to address these issues. (The laser-plasma community had employed a similar technique to study the early development of Rayleigh–Taylor or Richtmeyer–Meshkov instabilities, by using preformed targets of a known wavelength and amplitude.) Recent MAGPIE experiments[124] have used chemically etched, modulated wires to provide a known initial seed for the array implosions so the behavior can be imaged and compared to 3D calculations.[29] The experiments indicated that, even with a 1 mm wavelength modulation, the natural 500 $\mu$m wavelength grew. This suggests that, in order to influence the natural wavelength and differentiate between a MHD or a thermoelectric origin, the modulations must have a wavelength significantly less than 1 mm. Techniques to produce controlled, 100 $\mu$m wavelengths are being explored. These modulated wires may also provide a method to pulse shape the x-ray output for ICF applications.[29]

Another example of the contributions that small facilities can provide is in understanding the hydrodynamics and turbulence in plasmas. Extremely detailed experiments with a 300 kA gas puff[125]at the Weizmann Institute in Israel have recently shown the details of the implosion physics and the ion heating and cooling in the stagnated z pinch. High ion temperatures have been measured by Doppler broadening over the last 20 years, but it is unclear how a local ion temperature can be differentiated from turbulence. On the Zebra[126] experimental facility at the University of Nevada, Reno, wire arrays have been imploded with a localized NaF dopant that is coated on the array with 1 mm axial extent.[127] Spatially resolved spectroscopy can measure the axial transport of NaF in the stagnated z pinch, thereby putting a bound on the wavelength of the turbulence. Future experiments will use varied dopant configurations with time-resolved imaging and high-resolution spectra to obtain data to validate the turbulence models.

ICF experiments require the use of high-Z materials such as tungsten to provide a near-Planckian x-ray source.[10,54] Mid-Z materials driven to high temperature in high-velocity implosions are used in another class of experiments[128] to produce multi-keV *K*-shell x rays for the study of material-radiation interactions. These experiments with mid-Z materials require very large diameter arrays ($>50$ mm) compared to those for ICF experiments (20 mm for vacuum hohlraums[61] and 40 mm for dynamic hohlraums[45]), and the production and radiation transport is very complex.[129] Such implosions are highly supersonic ($>$Mach 10), but must be very stable to produce the desired x-ray yields. Nested wire arrays have enabled implosions from 60 mm diameter arrays that have produced 3.7 keV iron plasmas with $6\times10^{20}/\mathrm{cm}^3$ ion densities. These nested arrays operate with very sparse wire numbers and yet can still produce x-ray pulse widths as short as 5 ns and hot plasma diameters as small as 1.5 mm. MAGPIE experiments[116,117,119] using laser imaging and Saturn experiments[130] using dopant spectroscopy have shown that such low-wire-number nested arrays operate in a current-switching mode. MHD calculations[131] indicate that the outer array material has a magnetic Reynolds number of $\sim1$ at the time of interaction, thus allowing rapid field diffusion from the outer to the inner array. In recent Z experiments nested arrays begin to lose their efficacy to improve implosion quality at large diameters ($>75$ mm).[132] Experiments are being performed to understand and mitigate this effect.

*K*-shell emitting plasmas provide unique opportunities for spectroscopic investigation of plasma parameters, and recent data have added to the understanding of z-pinch energetics. Numerous measurements have indicated that z pinches radiate more energy than can be accounted for by the radial implosion kinetic energy. Moreover, estimates of electron internal energy and pressure, when compared to the radiation rates and the magnetic pressure, indicate that the stagnated plasma should continue to compress. Experiments on Z have shown that an ion temperature of 200 keV,[133] sufficient to maintain pressure balance against the magnetic pressure on axis, is maintained during the plasma lifetime on axis. It has been proposed[134] that the high ion temperature is

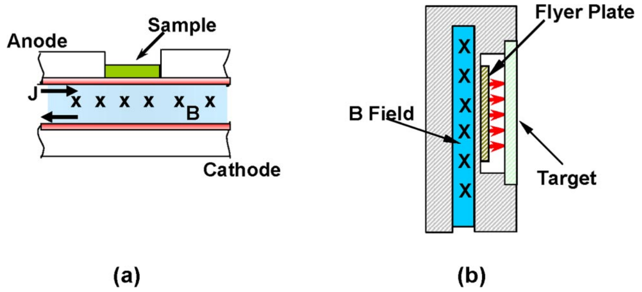

FIG. 12. Schematic of configurations fielded on Z to use the high magnetic field pressure associated with large current flow to (a) perform isentropic compression experiments or (b) accelerate flyer plate at solid density to very high velocity for impact experiments.

a signature of short-wavelength MHD turbulence.

Although much progress has been made, remaining z-pinch physics issues[135] will challenge the plasma community for the foreseeable future. These include measuring the current within the imploding z-pinch system, developing *a priori* models of implosion dynamics and plasma heating rates on axis at stagnation, and numerically modeling the cold start of wire arrays through the supersonic implosion that ends in complex radiation transport in the stagnated pinch.

## V. MEASURING, SIMULATING, AND MODELING PROPERTIES OF DYNAMIC MATERIALS

An important application of magnetohydrodynamics and the $\mathbf{J}\times\mathbf{B}$ force generated on Z is to drive material samples to high pressure to obtain EOS data. In the late 1990s, Asay *et al.*[136] proposed using the large magnetic fields produced by the 20 MA currents to generate ramp pressure loadings to megabar-class pressures (Fig. 12). Pressures of hundreds of kilobars were attained in the initial experiments.[137] At higher pressures, the sample thickness was limited to prevent shock growth.[138] Recent advances in shaping the current drive on Z have enabled isentropic compression experiments with multi-megabar pressure drives, which allow the use of much thicker material samples without shock formation. In addition, this shockless loading technique has enabled the acceleration of magnetically driven flyer plates to ultrahigh velocities ($>30$ km/s).

Hugoniot experiments using high velocity flyers have significantly improved our understanding of the behavior of liquid deuterium subject to dynamic loading. For example, in an initial series of experiments, Al flyer velocities in the range of 20 km/s (Ref. 139) produced up to 1 Mbar pressures in liquid deuterium by flyer plate impact on Z. The measured response of the deuterium[19] agreed with the deuterium EOS in the standard SESAME database[140] and with most models of deuterium, but disagreed with experimental data[141] on the Nova[142] laser. The magnetically launched flyer plates in the Z experiments were about 0.5 cm in effective diameter and a few hundred microns thick. Consequently, at impact the shock pressure drive was constant for 20–40 ns. With such long drive times, other techniques, such as reverberation and reshock, could also be employed.[78,79] These other techniques also gave data that are self-consistent with the measurements of the principal Hugoniot.

A critical regime of interest for many HEDP applications extends from moderate compression over solid density down to 100-fold expansions from solid and at temperatures from ambient up to several eV. An integral part of Sandia's pulsed power HEDP research is therefore computational modeling of the complex configurations in ICF, isentropic compression,[18] and magnetically launched flyer plate EOS experiments.[19]

For experiments on pulsed power devices, accurate computer modeling has been hampered by large uncertainties in the electrical properties of materials, particularly if the modeling begins near the cold solid state. For example, electrical conductivity measurements of metals are not available for much of this regime, and analytical results are limited by uncertainties in treating strongly coupled and degenerate, or weakly degenerate, systems. To improve the capability to simulate experiments in this warm dense matter regime, Desjarlais compared the data[143] and existing theories[144] with the Lee–More model[145] that was widely used in MHD codes. Modifications were made to the Lee–More algorithm in order to better model the physics in the vicinity of the metal-insulator transition, resulting in what is now called the Lee–More–Desjarlais, or LMD, model.[146] Subsequent MHD simulations using LMD gave a better match to experiments in the warm dense matter regime. More recently, to further improve the understanding of this warm dense matter regime, *ab initio* quantum molecular dynamics (QMD) calculations have been done for several metals.

These QMD calculations, which are based on density functional theory (DFT), provide the total energy and pressure as a function of density and temperature for a material, thereby allowing refinements to existing EOS or generation of new EOS, if needed. The QMD calculations also provide atomic configurations, electron orbitals, and density distributions that can be analyzed within the Kubo–Greenwood formalism[147] to generate electrical and optical properties of materials. Under conditions for which conductivity data is available,[143] the agreement is very good.[37] Moreover, using the QMD results, in conjunction with data and theory, the generic LMD conductivity algorithms[146]are being "tuned" to generate accurate, wide-ranging, SESAME-type tables for the conductivity. QMD-based tables for materials such as aluminum, tungsten, and stainless steel are now available, and several other materials are under active study. An EOS for stainless steel has been generated and is available in tabular format. The QMD approach is also being used to improve low-energy opacity models of both simple metals and of complex plastics and foams. An important aspect of this approach to determining the electrical, optical, and thermodynamic properties is that the physics models generated are manifestly consistent, something not usually found in standard materials libraries.

A dramatic illustration of the potential of the QMD approach is in the modeling of magnetically launched flyer plates.[30] Advanced simulation codes, such as Sandia's ALEGRA code,[148] using the newly generated conductivity

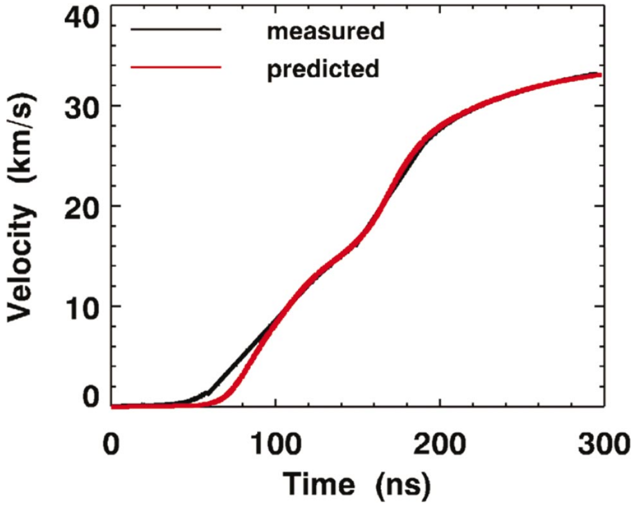

FIG. 13. (Color). Comparison of measured and predicted velocities in a dynamic materials properties experiment on Z with a 0.085 cm thick aluminum flyer plate. The multi-megabar drive pressure was obtained by shaping the accelerator current waveform to avoid shock formation in the Al.

tables and algorithms, are achieving excellent agreement with experiment, thereby permitting increasingly complex and optimized designs for experiments[30,139] and providing predictive capability. Because of progress in 2D MHD modeling and in particle-in-cell modeling of the power flow on Z,[20] it is now possible to shape the current pulse for as long as 560 ns. This capability has allowed 3 Mbar in an isentropic compression configuration for a 450 ns pulse in aluminum.[149] Analysis of the data has confirmed that the material being compressed is loaded on the isentrope.

In the last year, the improved 2D ALEGRA MHD simulations,[21,30,139] in conjunction with pulse shape optimization[20,21,150] using detailed circuit modeling of Z, have guided the design and implementation of aluminum flyers to ultrahigh velocities (up to 33 km/s so far) using shaped multi-megabar magnetic drive pressures that preclude shock formation in the flyer during acceleration and have a sufficient fraction of flyer material that remains intact at solid density to allow accurate EOS measurements. Experimentally, the desired current waveform has been achieved[151] by firing the 36 laser-triggered switches on Z in a timing sequence determined by the circuit calculations and the desired magnetic pressures have been achieved using an asymmetric load.[152] The 0.085 cm thick Al flyer was subjected to a peak magnetic pressure of ~4.8 Mbar without shock formation (shockless or quasi-isentropic acceleration). The measured flyer velocity matched the predicted waveform to better than 3% over 98% of the ~250 ns trajectory, as shown in Fig. 13. These higher-velocity flyers have created pressure states of up to 1.4 Mbar in deuterium, again confirming a stiff response by the equation of state. The Al flyers have also yielded accurate EOS data in quartz and sapphire samples at pressures of 11.5 Mbar and 14.6 Mbar, respectively. Future Z experiments using this configuration are predicted to extend the Hugoniot data for deuterium[19] and Al (Ref. 153) to 1.8 Mbar and 13 Mbar, respectively.

The advanced pulse shaping has also enabled the study of various materials and their phase transitions, especially when coupled with a preheat capability. Two examples[42] are the identification of two phase transitions in zirconium in a single loading and measurement of the variation in the phase transition pressure of tin with initial temperature.

Because the QMD/DFT simulations represent molecules, atoms, dissociation, and ionization on a self-consistent footing, they are well suited to exploring the evolution of materials through different phases. An example is the transition of liquid deuterium from molecular fluid, to atomic fluid, to plasma along the principal Hugoniot. The QMD simulations of shocked deuterium[154] have found the principal Hugoniot and reshock properties to be in very good agreement with gas gun data from Lawrence Livermore National Laboratory and with magnetically launched flyer plate data from Z.

## VI. REFURBISHMENT OF Z

Z began its service as PBFA II,[7] with initial operation in December 1985. PBFA II had been designed as a high-voltage ion beam driver (10–30 MV) for ICF research. Modifications[6] were completed in September 1996 to the power flow and transmission line sections to enable a high-current (18–20 MA) configuration to test the scaling of x-ray output from z-pinch loads as a function of current. Although these modifications were intended to be in place for just six months, the results were so successful that the pulsed-power generator was never converted back to an ion driver and the facility was renamed “Z” in July 1997.

The z-pinch applications described in this paper have brought many challenges to the facility. Today, Z must be a stable, precision platform for a large number and variety of reliable, reproducible HEDP experiments. However, its operational efficiency is limited because most of the hardware is of 1985 vintage, it was not optimized for these applications, and it was not designed for the rigors of daily use. To extend the lifetime of Z and update the pulsed power components with modern technology, a refurbishment project began in February 2002.[38] The goals are (1) to provide the capacity to perform more experimental shots, (2) to improve the overall precision and pulse shape variability for better reproducibility and data quality, (3) to increase the delivered current, and (4) to accomplish these improvements with minimal disruption to ongoing experimental programs. The refurbished components should be installed in 2006 and, after a testing phase, Z will return to full operational status in 2007. For typical z-pinch configurations, the delivered current should increase more than 30%, which corresponds to an energy increase of ~70%, thereby allowing access to a new high energy density physics regime. Moreover, the higher currents will allow access to higher-pressure EOS data.

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