Shedding new light on old mysteries of z pinches

New quantitative data from Z-machine experiments [1] and advanced three-dimensional calculations [2,3] being presented at the American Physical Society's Division of Plasma Physics meeting promise to shed new light on some of the old mysteries of z pinches. The largest fast z-pinch facility in the world is the "Z-machine" at Sandia National Laboratories, NM. *Z* is a 20 million Ampere, 100 nanosecond, 11 million Joule pulsed power facility that has been used to produce >200 trillion Watts and 1-2 million Joules of soft x rays in the 0.1-10 keV range. One of the applications for *Z* is inertial confinement fusion (ICF), in which the x rays are used to compress the fuel in a deuterium-containing capsule to the extreme conditions required for laboratory fusion reactions to occur.

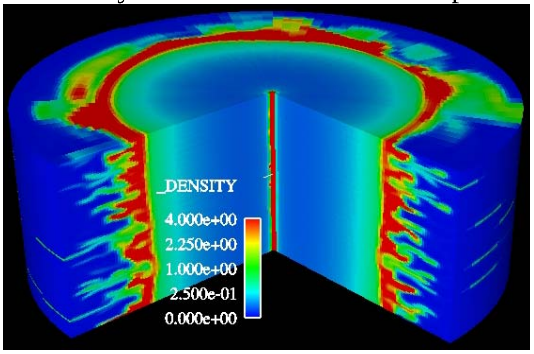
A standard load for ICF research experiments on the *Z*-machine is a 20 mm diameter cylindrical array of 300 fine tungsten wires that are anywhere from 5 to 11.5 microns in diameter (a human hair is usually ~100 microns thick). As current passes through the wire array, it melts and vaporizes the wires into plasma and also generates a powerful magnetic field surrounding the array. The interaction of the current with the magnetic field squeezes and compresses the wire array plasma toward its axis (usually called the z-axis, hence the name z-pinches). This process is analogous to squeezing a cylinder of soft play-dough in one hand by tightening your grip. The tungsten plasma heats rapidly as it is compressed on the z-axis, where it emits soft x rays in a few billionths of a second.

In ideal "thin-shell" models, the tungsten plasma would be compressed as a thin shell toward the axis during the entire 100-ns implosion time (imagine a hollow cylinder of play-dough in one hand that you crush by slowly tightening your grip.) In reality, for the first 50-80 ns, the wires are cooking off ("ablating") mass that fills the interior of the shell and the outer boundary of the shell remains at its initial position. Eventually random wire segments cook off all their mass, and the outer boundary starts to move. Axial and azimuthal variations in the mass ablation rate cause portions of the outer boundary to implode before other parts, which creates a complex, three-dimensional (3D) network of trailing mass behind the main imploding front. Following our play-dough analogy, instead of squeezing a hollow cylinder in the grip of one hand, imagine trying to quickly crush a semi-solid cylinder of play-dough with the fingertips of both hands. Play-dough will squeeze past your fingertips because it is not possible to press uniformly everywhere on the play-dough, so instead of a nice compressed column you will wind up with a messy 3D object. Unlike most play-dough, plasma can be compressed (i.e., its volume can change). The work done by the magnetic field in moving and compressing the plasma causes it to heat up and radiate away that heat as x rays.

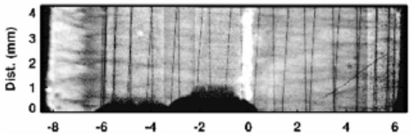
In new experiments [1] researchers estimated the work done on wire-array plasmas up through the end of the main radiation burst by the magnetic field, which essentially amounts to measuring how tightly the plasmas were compressed during this time. In tests with a partly "incompressible" 1-mm diameter rod on the array cylindrical axis, they were able to satisfactorily explain the radiation emission during the main burst of x rays by the observable magnetic work done on the plasma. Without the rod on axis to limit the compression of the magnetic field, the arrays radiated 75% more energy and it was difficult to explain the main x-ray burst on the basis of the observable plasma compression. In both cases the total radiation emitted by the z-pinch was about twice that of the main radiation burst, but after the main radiation burst the plasma column on axis begins to go unstable. Additional work can be done by the magnetic field as it drives the instabilities. Understanding the late-time radiation is of less practical importance as it comes too late to help with ICF capsule implosions. The researchers present a variety of data, including the first experimentally-measured mass-density profile of an imploding wire-array z-pinch, which are being used to constrain simulation models (e.g., [2,3]).

In new calculations [2,3] the mass ablation phase, during which mass fills in the interior of the wire array, is modeled with a mass-inflow boundary condition. This simplifying step allows researchers to focus on the ensuing implosion phase and the 3D web-like structure of trailing mass that develops behind the imploding plasma sheath. The trailing mass can play a strong role in the development of Rayleigh-Taylor (RT) instabilities on the imploding plasma sheath. (These instabilities can be thought of as plasma squeezing between your fingers if you tighten your grip on play-dough in one hand—the play-dough that squeezes past your fingers does so all at one position along the axis). In the absence of trailing mass, current flows only in the imploding sheath, leading to strong RT growth. With trailing mass the current can “relax” off the imploding sheath and into the trailing mass (i.e., after squeezing for a little bit, you loosen your grip and tighten your grip again on the plasma that initially squeezed past your fingers). This results in lower RT growth in the sheath.

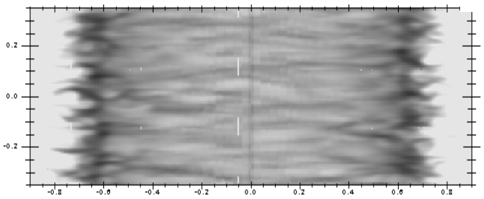
These calculations appear to quantitatively reproduce for the first time the complex 3D structures seen in experimental radiographs of wire array implosions on the *Z* machine. Moreover, they are capturing the trends in the experimentally measured radiation data with the on-axis rods. The success of these new techniques, which are based on high-resolution, three-dimensional magneto-hydrodynamic codes, may soon result in accurate and predictive modeling of wire-array z-pinch implosions. Such a predictive capability is important for understanding how z-pinch radiation scales with increasing current and will ultimately allow us to estimate the pulsed power machine parameters required for ICF.



Z-pinch simulation showing the density of the imploding plasma sheath and trailing mass.



Experimental radiographic image.



Simulated radiographic image of modeling.

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[1] GI1.00005 D.B. Sinars, “Radiation energetics of inertial confinement fusion relevant wire-array z pinches,” 11:30 AM Tuesday, November 13, 2007
[2] GI1.00006 E.P. Yu, “Investigation of trailing mass in Z-pinch implosions and comparison to experiment,” 12:00 PM Tuesday, November 13, 2007
[3] PP8.00039 R.W. Lemke et al., “Validation of an ablation model for simulating wire array z-pinches,” 2:00 PM Wednesday, November 14, 2007

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