Breakthrough in Z-pinch implosion stability opens new path to fusion

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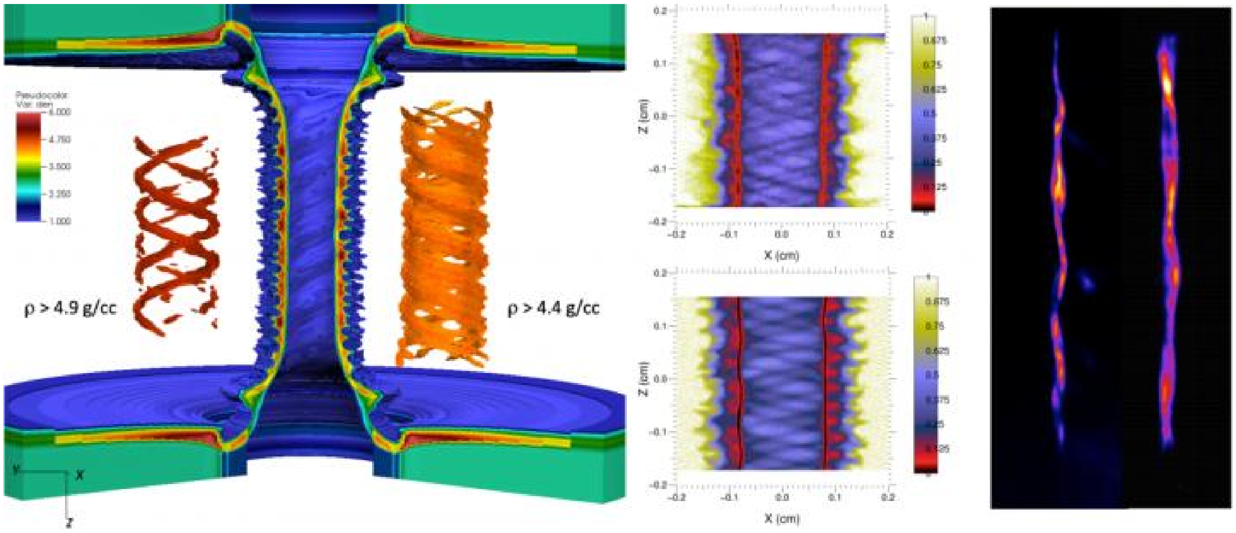

Simulated density profiles highlight the helical instability growth in the Z-pinch;(Center) Experimental [top] and synthetic [bottom] x-ray transmission radiographs of the helical perturbation in the liner during the implosion; (Right) Experimental [left] and synthetic [right] x-ray emission images of the hot plasma at stagnation and peak fusion burn. Credit: Sandia National Laboratories

Using magnetic field thermal insulation to keep plasmas hot enough to achieve thermonuclear fusion was first proposed by the Italian physicist Enrico Fermi in 1945, and independently a few years later by Russian physicist Andrei Sakharov. An approach known as magneto-inertial fusion uses an implosion of material surrounding magnetized plasma to compress it and thereby generate temperatures in excess of the 20 million degrees required to initiate fusion. But historically, the concept has been plagued by insufficient temperature and stagnation pressure production, due to instabilities and thermal losses in the system.

Recently, however, researchers using the Z Machine at Sandia National Laboratories have demonstrated improved control over and understanding of implosions in a Z-pinch, a particular type of magneto-inertial device that relies on the Lorentz force to compress plasma to fusion-relevant densities and temperatures. The breakthrough was enabled by unforeseen and entirely unexpected physics.

The researchers' approach to fusion relies on laser preheating of the fuel contained within a solid cylindrical metal liner, both of which are pre-magnetized by a magnetic field of 100,000 Gauss—a crucial distinction. Applying a force of 20 million Amperes over 100 nanoseconds causes the liner to implode, compressing the plasma and raising temperatures to 30 million degrees and magnetic flux to 100 million Gauss. When the fusion yield is large enough, such an enormous magnetic field is able to trap the heat given off by the fusion reactions and "boot-strap" itself to higher temperatures, leading to ignition of the fuel.

According to existing theory, however, the imposed magnetic field should not have significantly impacted the growth of the instabilities that normally shred the liner and prevent high levels of compression during the implosion. But, while fusion plasmas are subject to various forms of instability, referred to as modes, not all these instabilities are detrimental. The pre-magnetized system demonstrated unprecedented implosion stability due to the unpredicted growth of helical modes, rather than the usual azimuthally-correlated modes that are most damaging to implosion integrity. The dominant helical modes replaced and grew more slowly than the so-called "sausage" modes found in most Z-pinches, allowing the plasma to be compressed to the thermonuclear fusion-producing temperature of 30 million degrees and one billion times atmospheric pressure. The origin of the helical modes themselves, however, remained a mystery.

Advanced simulations of the system solved the mystery by uncovering the origin of the helical instability growth that enabled high temperatures, magnetic fields, and plasma pressures from such high-convergence implosions. The researchers achieved the critical new breakthrough when they included effects from the plasma and magnetic field in the transmission line that delivers the intense current pulse to the implosion region. They found that the plasma outside the liner participated in an upper hybrid oscillation and bombarded the liner, resulting in a helically correlated perturbation to the liner early in time that overrides other perturbations. The new perturbation source was also found to be the previously unexplained origin of the ubiquitous "sausage" fundamental mode that has historically dominated and spoiled the Z-pinch implosion dynamics in the un-magnetized versions of these systems.

Once they included the new physics in the modeling, the researchers were able to reproduce and explain the two-dozen observables from the magnetized liner inertial fusion experiments at the Z Machine. The implosions were found to efficiently convert liner kinetic energy into the internal energy of the fusion fuel and confirm the system behaved as expected and could scale to higher yields on future facilities. Since the thermonuclear hot spot produced the expected stagnation pressure and was not dominated by 3D instability, it is now thought to provide the basis for a promising route to achieve higher thermonuclear fusion yields in the laboratory.

More information: meetings.aps.org/Meeting/DPP16/Session/UI3.6

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