Research Challenges in Magneto-Inertial Fusion
White Paper for *Frontiers of Plasma Science Panel*

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(Limit text to 3-pages including this form. Font Times Roman size 11.
1 page of references and 1 page of figures may also be included. *Submit in PDF format*.)

- ***Describe the research frontier* and importance of the scientific challenge.**

Inertial Confinement Fusion (ICF) is a grand challenge for high-energy-density science. In traditional ICF [1], alpha heating is achieved by producing T ~ 4 keV hot spot surrounded by a high areal density (ρR ~1 g/cm^2) of cold fuel, requiring hot-spot pressures above 400 Gbar. In Magneto-Inertial Fusion (MIF) [2], the pressure and areal density requirements are relaxed by the presence of a magnetic field strong enough to magnetically confine charged particles within a radius smaller than the fuel radius. The key parameter for MIF is thus BR rather than ρR, and for BR >0.5 MG-cm, the magnetic field effectively traps electrons, 1 MeV tritons, and fusion-produced alpha particles for almost arbitrarily small ρR. Consequently, thermal conduction losses are reduced and trapped alpha particles return much of their energy to the burning plasma. Operating at intermediate plasma density and pressure regimes between traditional magnetic confinement fusion and ICF systems, MIF concepts achieve self-heating at pressures of only ~5 Gbar, with GJ-scale yields appearing possible. Ongoing experiments demonstrate good inertial and magnetic confinement, stable implosions, and promising yields, but challenges remain in optimizing preheat, mitigating mix, and understanding fundamental plasma physics and magneto-hydrodynamic behavior in these extreme conditions.

• ***Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.***

The Magnetized Liner Inertial Fusion (MagLIF) concept described in [3-5] and illustrated in Fig. 1 includes three stages: magnetization, preheat, and implosion/compression. Ongoing experiments on Sandia's Z use external coils to produce axial magnetic fields of about 10 T in ~2 mg/cm^3 deuterium gas fuel fills. The gas is contained by a cylindrical beryllium liner and thin plastic windows covering a laser entrance hole (LEH) at the top of the target. Magnetization occurs over μs time scales to ensure field penetration through the liner into the fuel and is followed by the ~20 MA, 100-ns-risetime current pulse of the Z machine, which exerts a radially compressive **J**x**B** force on the cylindrical target. Just as the inner surface of the target begins to implode, the 2-4 kJ, few-ns Z-beamlet laser is fired into the LEH to preheat the fuel. The axial magnetic field inhibits thermal conduction losses from the preheated fuel as the ~50 ns implosion compresses both the fuel and the axial magnetic field, heating the fuel at stagnation to fusion-relevant temperatures over 1-2 ns.

All three elements of the MagLIF concept work in concert to produce the desired end state: Preheating significantly reduces the compression ratios required to reach multi-keV temperatures at stagnation, enabling slow (~10 cm/μs) implosion velocities and thick liners (R/ΔR = 6) that ensure both stability and good radial inertial confinement of the stagnating fuel. Magnetization insulates the preheated fuel during the implosion, traps fusion products at stagnation, and appears to stabilize the implosion, leading to helical structures [6] more benign than the m = 0 Magneto-Rayleigh Taylor instabilities that tear apart unmagnetized implosions. The cylindrical implosion flux-compresses the initial axial magnetic field with almost the same efficiency as it compresses the fuel, producing kT-scale fields at stagnation that effectively insulate the hot stagnation plasma and trap charged fusion products.

Initial experiments on Z have produced D-D fusion yields up to 2x10^{12} from stagnation columns diagnosed to have temperatures of 2 – 3 keV, fuel densities near 0.3 g/cm^3, liner areal densities of ~1 g/cm^2, and field-radius products of ~0.4 MG-cm [7-9], with about a third of the initial fuel mass participating in the burning core. Axial confinement is provided by the ~0.3 g/cm^2 areal fuel density along the ~1 cm axial dimension of the implosion, while radial confinement is achieved through a combination of the high BR, which traps almost half of the 1 MeV tritons produced by the D-D reactions, and the high areal density of the liner, which provides inertial confinement over the few-ns stagnation duration.

While these initial experiments support the basic principles underlying MIF and offer encouraging evidence that high BR can ease the pressure requirements of traditional ICF, the yields achieved to date remain 10x or more below the simulation predictions. This is attributed to a combination of poor laser coupling and mix of undetermined origin. Laser-only experiments at both Z and Omega indicate that only ~10-20% of the laser energy was coupled to the fuel in the early experiments, that increasing the delivered energy of an unconditioned laser beam also increases mix, and that improved coupling is possible with improved beam conditioning. Significant mix in the early experiments was evidenced by emission lines from highly charged transition metals that exist as impurities in both the LEH material and the liner. High-Z mix is especially harmful if it occurs during the preheat stage, since radiation losses over the ~50 ns implosion are not inhibited by the axial magnetic field and can lead to much lower stagnation temperatures.

Experiments to investigate and improve both preheat and mix through laser and target design changes are scheduled on Z for the near future. If both issues are successfully addressed, D-D neutron yields above 10^{13} (~10^{15} D-T) appear feasible with present capabilities. Planned facility improvements increasing the delivered current, initial magnetic field, and laser energy may enable D-T-scaled yields of ~10^{16} (100 kJ) at Z over the next few years. Simulations indicate that self-heating, high-yield experiments will require approximately threefold increases in driver and laser energies.

Progress in Sandia's Magneto-Inertial Fusion effort is aided by ongoing and planned experiments on Z-Beamlet, Omega, and NIF that will explore the preheat stage of MagLIF, including its scaling to larger targets and higher laser energies. "Mini-MagLIF" experiments using laser-driven cylindrical implosions and a MIFEDS-produced field (which was shown to enhance yields in a direct-drive spherical implosion [10]) are planned on Omega. Fundamental research in magneto-hydrodynamics and radiation physics are ongoing at several MA-class pulsed-power facilities at the University of Michigan, Cornell University, and University of Nevada-Reno. An intermediate-scale (~10 MA) pulsed power facility would provide opportunities for experiments much closer to those currently performed on Z, accelerate progress in the fundamental understanding of magnetized plasma and its scaling with driver energy, and provide a critical training ground for students interested in magneto-inertial-fusion.

Advances in target fabrication, diagnostic, simulation, and theory capabilities could also substantially accelerate progress in MagLIF. Cryogenic fuel layers inside the cylindrical targets would provide a buffer against wall mix and could reduce or eliminate preheat losses from laser-plasma interactions with the LEH window by enabling thinner windows. Buried-layer capabilities for the liners would enable diagnostics of deep mix and refine understanding of the liner conditions at stagnation. Increasing the spatial and temporal resolution of existing neutron and x-ray diagnostics would help refine understanding of the stagnation conditions in the MagLIF experiments. Increasing detector sensitivities would enable better diagnostics of failure modes and might enable in-situ measurements of laser-fuel coupling, mix, and the evolution of the plasma during the implosion. Improved absolute calibrations of x-ray diagnostics, especially measurements of crystal reflectivities, would increase confidence in the diagnosed fuel densities and temperatures at stagnation. Increased spectral resolution in the 5-8 keV photon range might enable direct measurements of the flux compression at stagnation. Theoretical investigations and focused experiments to validate stopping powers, electron-ion equilibration, and transport in high-energy-density and high-field environments would increase basic understanding of MagLIF and other ICF plasmas. On the simulation front, improved understanding of laser-plasma interactions, dynamic mixing at the fuel-liner interface, and three-dimensional effects would increase predictive capability and support the scaling calculations that will determine requirements for a future facility.

- ***Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit*.**

Laboratory fusion opens a prospect of clean nuclear energy without the proliferation and safety risks associated with fission. Within the field of fusion concepts, magneto-inertial fusion offers some unique advantages: it operates on much smaller scales and higher power densities than traditional magnetic confinement fusion, potentially reducing facility size and cost. And it operates with higher efficiencies (gain) and yields than traditional inertial confinement fusion, easing requirements for high repetition rates. Burning MagLIF plasmas would also produce sufficient energy to drive fundamental science experiments exploring material in extreme high-temperature, high-density, and high-field regimes not achievable by other means and would enable research critical for stockpile stewardship.

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Figures (maximum 1 page)

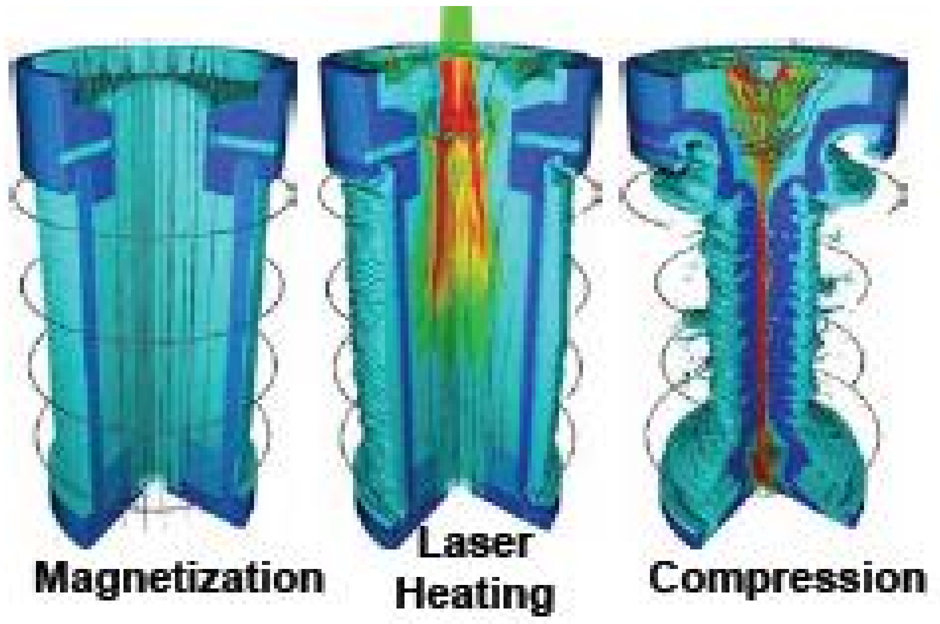

Fig. 1. Three stages of a MagLIF implosion: 1) Magnetization of DD fuel in a cylindrical metal liner followed by 2) laser heating of the fuel and 3) pulsed-power-driven compression of both fuel and field.