White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	***July 23, 2015***

Indicate the primary area this white paper addresses by placing "P" in right column.
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• Plasma Atomic physics and the interface with chemistry and biology	
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• Plasma self-organization	
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	"X"
Oral	X
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Title:	**Magnetized Inertial Confinement Fusion**
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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.**

In magnetized inertial confinement fusion (MICF), initial imposed seed magnetic fields of 10-100T that can compress to greater than 10^4 T (100 MG) under implosion can relax the minimum areal densities, temperatures and pressures required for ignition and propagating burn in inertial confinement fusion (ICF) targets. The goal of ICF – i.e., ignition of around a milligram of deuterium-tritium (DT) fusion fuel with net fusion energy gain – is one of the grand challenges of science. The ignition campaign on the National Ignition Facility (NIF) with cryogenic-DT targets has returned experimental data of unprecedented value and diagnostic precision. The quality of NIF implosions have progressed substantially but the fuel is compressing to only around one-half that required and the fusion yield remains a factor of around ten lower than required for ignition and propagating thermonuclear burn. Continuing progress is evident by the highest fusion yield shots now showing clear evidence of the initial stages of "boot strapping" or self heating by alpha particle deposition in the DT "hot spot" [1]. It is in this transitional regime that MICF can play a major role in that it may permit the recovery of ignition, or at least significant alpha particle heating, in such capsules that would otherwise fail to burn because of adverse hydrodynamic instabilities [2].

The potential advantages of compressed magnetic fields in ICF were recognized some four decades ago [3,4] followed by a number of numerical studies [5,6,7,8] and recent concept [9,10]. Magnetizing a

plasma with compressed field B reduces electron heat conduction perpendicular to the field as $k_{\perp}\nabla T_e$ where $k_{\perp}=k/(1+(w_{ce}t_{ei})^2)$ and where k is the normal (no field) thermal conductivity, w_{ce} ($\sim B$) is the electron gyrofrequency in the magnetic field and t_{ei} the electron-ion collision time [11]. Electron confinement and suppression of perpendicular electron heat conduction are achieved for $w_{ce}t_{ei}>1$ requiring compressed fields in the vicinity of $\sim 10^3$ T (10 MG). Stronger compressed fields of the order of $\sim 10^4$ T (100 MG) can localize the deposition range of charged fusion burn products within the hotspot to around that of their gyro orbits $(2mE)^{1/2}/qB$.

In the compression of an ICF capsule in an initial applied magnetic field, the highly conducting plasma is characterized by a large Magnetic Reynolds Number – the ratio of the magnetic advection to magnetic diffusion. Given typical ICF capsule implosion times are ~15 ns while magnetic resistive diffusion times are ~ms, the flux is effectively frozen in and the magnetic field is compressed to high factors that depend on the particulars of the implosion geometry. Thus, in such highly compressed fields, the plasma conditions for ignition and burn are relaxed because of range shortening and magnetic mirror trapping of fusion alpha particles, suppression of electron heat conduction and potential reduction of hydrodynamic instability growth [2]. More generally, such applied fields may permit attainment of ignition and burn in targets redesigned to operate under reduced drive and/or lower convergence ratios. The seed field can also suppress laser-plasma instabilities conditions in indirect-drive hohlraums such as stimulated Raman and Brillouin scattering and that cause laser backscatter efficiency loss and hot electron preheat of the capsule [12].

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

The 10's of Tesla magnetic field required for MICF on NIF with indirect-drive targets can be obtained with a single-turn coil wound on the hohlraum driven by a pulsed power supply. Fig. 1 shows an in-progress design to be fielded on NIF in 2016-17. The DT fuel capsule is mounted in the center of the cylindrical hohlraum and the coil is designed to produce an applied axial seed magnetic field of ~50-70T in the hohlraum volume for a few microseconds during which time the capsule is imploded on the field via the laser-driven hohlraum x-rays. Fig. 2 illustrates 2-D radiation-hydrodynamic simulations of such a magnetized DT fusion capsule where its fusion yield is plotted as a function of increasing perturbation roughness on the capsule outer surface for initial seed fields in the range of 0 to 100T [2] The major effect of the applied field is a shift of the ignition cliff to the right – the capsule can now attain ignition and appreciable yields at perturbation parameters that would otherwise result in only low yield and no ignition. Simulations also suggest that the frozen-in field may suppress the Rayleigh-Taylor (R-T) instability itself. This is shown in Fig. 3 where low mode perturbations of mode number $L=2\pi/\lambda$ of 12 and 24 were applied with high initial amplitude of 6μm to the capsule inner ice surface at time zero. Note that at stagnation, the cases with applied field have truncated the R-T instability growth into the hotspot because the spike growth has to expend energy to bend the frozen-in field lines. This stabilization should be even more effective at higher mode numbers (i.e., shorter wavelengths)

Laser-driven magnetic flux compression within a cylindrical ICF target has been performed on the OMEGA laser facility, where a pair of small co-located Helmholtz coils generated a initial seed field of ~16 T at the coils, ~9 T at the target and achieved a field compression factor within the target of $\sim 10^3$ - see Fig. 4 [13,14]. In laser-driven magnetized implosions in spherical geometry on OMEGA, a magnetic seed field of ~8 T was generated in a spherical CH target containing 10 atm of D_2 gas by a single coil with diameter around twice that of the target [15]. A co-located pulsed power supply (45 kA, 350 ns) was timed to coincide with the OMEGA laser target compression beams (~4 ns implosion time). The compressed field attained a maximum central value of 8000 T (80 MG). As a result of the hot-spot

magnetization, electron radial heat losses were suppressed and observed ion temperatures and neutron yields were enhanced by 15% and 30%, respectively, relative to non-magnetized controls.

An analogous approach was employed using magnetized cylindrical implosions at the Z magnetic pinch facility at SNLA [16], demonstrating the basic proof of concept of MagLIF, a future full scale, high gain burning system [9,10]. In the Z implosions, the neutron yield increased by 2 orders of magnitude when a pre-imposed magnetic field of 10 T was imposed into the Be shell with a deuterium hot spot fill gas. Even a 10-fold increase in yield at NIF would push these implosions into the beginning stages of ignition and propagating burn in a magnetized HED plasma.

Conventional pulsed power technology should be appropriate for seed fields in NIF hohlraum volumes approaching 100T. Above this limit, very high seed fields may be attainable for MICF with laser-driven coils due to their very low inductance and high current rise. Daido et al. demonstrated a field of 60 T (0.6 MG) at the center of a laser-driven, 2-mm-diam one-turn coil [17]. Fujioka et al. have demonstrated laser-generated seed fields over 1000 T (10 MG) in a ~1mm capacitor-coil system using 1 kJ, 1.3 ns, 0.1-$4x10^{16}$ W/cm^2 beams from the GEKKO-XII laser [18,19] They measured an average field of ~880 T at 850 mm from the coil and peak fields of 1500 T at 650 mm. In this regard, the NIF hohlraum itself might serve as a single turn solenoid containing a narrow insulating gap at the wall parallel to the hohlraum axis and driven one or more quads of NIF beams for $B_0 \geq 100$ T

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

Magnetized inertial confinement fusion may be viewed as a hybrid of the features of ICF and magnetic confinement fusion and therefore is a very rich physics area for future research both experimentally and theoretically. Given it potentially offers a route to ignition and fusion energy gain in ICF platforms that otherwise would be sub marginal in performance, it may offer an earlier route to achieving thermonuclear burn and, therefore could potentially accelerate progress in inertial fusion energy.

Development of such experimental capabilities on NIF, OMEGA and Z would also enable other discovery science research areas in strongly magnetized plasmas including (1) collisionless shocks in background fields (applications to gamma-ray bursters, supernova remnants), (2) instabilities in magnetic stagnation of plasma flows (applications to solar-terrestrial magnetosphere, heliosphere), (3) astrophysical jets (applications to accretion columns, white dwarfs, etc), and (4) exploding plasma collisionless shocks and EMP in high altitude phenomena. These application areas typically require 10's of Tesla in $\leq$cm^3 volumes so, for example should be well positioned to be explored on NIF with the presently envisaged pulse power magnetic field systems (Fig 1)

References

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Figures

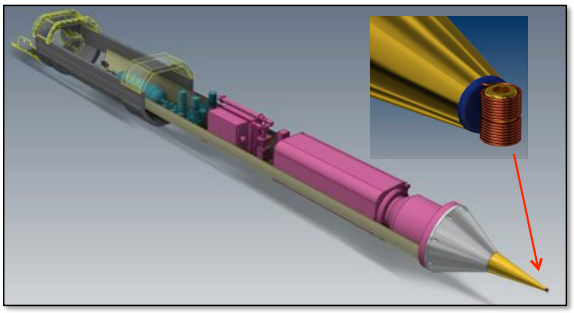

Fig. 1. Pulsed power supply and hohlraum/coil configuration for magnetized indirect-drive targets on the National Ignition facility. Hohlraum design fields are 50T, 70T maximum

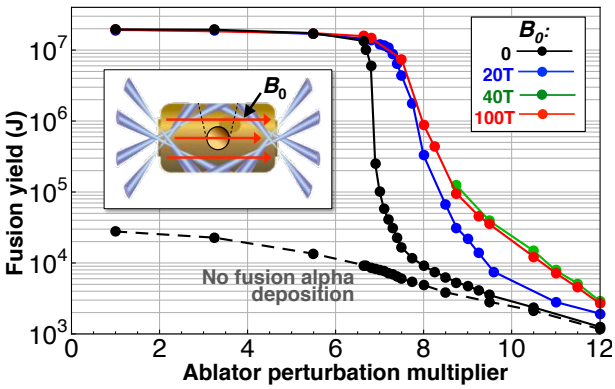

Fig. 2 Fusion yield versus amplitude multiplier on capsule outer surface perturbation under initial seed magnetic fields from 0 to 100 T for a NIF cryogenic DT fusion ignition target. (Simulations from the LASNEX 2-D radiation hydrodynamics code [2])

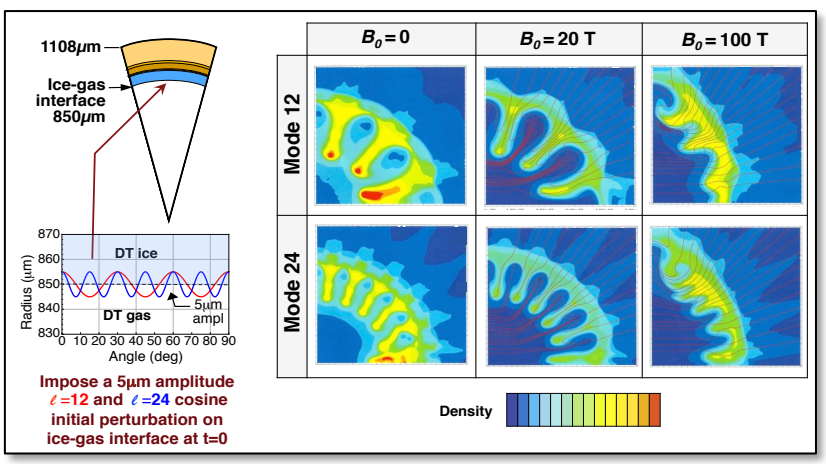

Fig. 3. Density contours at ignition (Ti=12keV) for imposed single-mode perturbations of 5μm initial amplitude on the ice-gas interface at t=0 for imposed magnetic fields of 0-100 T. Suppression of the RT instability with B is due to the field-line bending energy that must be expended
(2-D LASNEX)

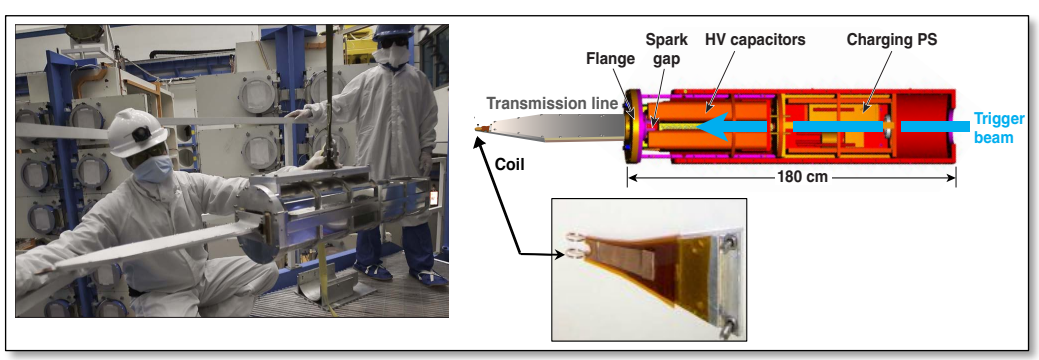

Fig. 4. The MIFEDS pulsed-power-driven coil system at the OMEGA laser facility