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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	"P", "S"
• Plasma Atomic physics and the interface with chemistry and biology	
• Turbulence and transport	P
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• Plasma self-organization	
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Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	O
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Title:	Ignition and burning plasmas in HED environments
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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.**

One of the grand challenges in applied plasma science is the pursuit of nuclear fusion as a source of energy. The inertial confinement fusion (ICF) path to fusion takes place in extremely high energy density (HED) conditions. The required densities of the hydrogen (D,T) fuel are very high (100-1000 g/cm^3), with electron densities of order (10^{25}-10^{26} cm^{-3}), and temperatures ranging from 50 eV to 5 keV. In the densest, "cool" regions of the hydrogen fuel, the plasma is Fermi degenerate and strongly coupled. Once nuclear burning begins, the plasma is predicted to reach temperatures of 10-30 keV. These conditions overlap with conditions in stellar interiors, hence developing the science of ICF ignition will create laboratory capabilities for studying the hot, dense plasma science of star formation, stellar interiors, stellar evolution, and stellar explosions (supernovae).

Once burning plasma conditions for ICF are achieved, a number of key questions in the science of hot, dense burning plasmas will be experimentally accessible. We will be able to test our understanding, theories, and simulations of plasma physics and mix models used in radiation-hydrodynamic codes, in the presence of burn. Of particular interest is the physics of mixing between higher Z pusher or ablator material and the burning gas. A central question is whether plasmas mix in the same way unionized fluids do. Understanding for example the Rayleigh-Taylor instability alpha bubble discrepancy between simulations and experiments needs to be resolved. The community is divided on what mix models work best and which are the most accurate. Having high quality data in the HED regime that differentiates between mix models is needed. Open questions remain in ICF on how 'chunks' of ablator penetrating the

hot spot can get dispersed or mixed throughout the hot spot, in the presence of nonlocal heat transport, species separation, and/or for Knudsen number > 1; how ablator penetration into the hot spot reaches a fully atomically mixed state in the presence of radiation, nonlocal thermal heat conduction, self-generated or compressed pre-imposed magnetic fields; and what the effective viscosity of the implosion hot spot is, and how this affects shell mix and dispersion into the hot spot. The propensity of ablator material to penetrate into the DT hot spot, driven by the Rayleigh-Taylor instability on the outside of the shell at the ablation front during the acceleration phase, and on the inside at the shell – hot spot interface during deceleration and the approach to peak compression is illustrated in Fig. 1. [1]

In addition to mixing, validation and insights into the plasma physics of hot dense environments is needed even for simple ideal plasmas where the plasma coupling is small. We have a paucity of data that validate or inform our plasma models (e.g. electron-ion coupling, thermal diffusivity, particle diffusivity, nuclear stopping powers and conductivities) even in regimes where we think the theory is well understood. When low Z and high Z ions are involved in the burning plasma and in particular when the high Z ions are not weakly coupled, the theory becomes very complex. Having accurate data of electron-ion coupling, diffusivity, stopping power and conductivity, with or without magnetic fields, is sorely needed to help guide theoretical developments.

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

Achieving a burning plasma test bed in HED conditions, optimized for the basic burning plasmas research just described, is a grand challenge. Enormous progress has been made over the past 5 years at NIF, with the highest yield shots showing clear evidence of the initial stages of "boot strapping" or self heating by alpha particle deposition from the DT hot spot, as shown in Fig. 2. [1] The plan going forward is a staged approach, starting with optimizing the hot spot, then working outwards. The relevant terminology is as follows. 'Ignition' is the condition in the fusion fuel such that the fusion power produced is greater than the rate of energy loss from the fusion region due to electron conduction losses, bremsstrahlung radiation losses, and pdV work upon expansion. 'Propagation' is the process in which an ignited mass of fusion fuel heats and sometimes additionally compresses an adjacent non-ignited mass of fusion fuel bringing it to ignition conditions. This process happening in succession over-and-over again can lead to very large fusion energy releases from a much smaller investment in energy. 'Gain' is a measure of fusion energy liberated divided by energy input into a specified region. Common gain metrics are [2] G_{fuel}, $G_{capsule}$, and G_{target} (or just G) which are the gains measured in the mass of fusion fuel, capsule, fusion target (e.g. hohlraum + capsule + fuel in the case of indirect drive. $G_{fuel} > 1$ has already been achieved. [3] Traditional hot-spot ignition on NIF requires 'ignition' in a hot-spot (~10-20 microgram of DT) that then 'propagates' into a surrounding fuel layer (~170 micrograms of DT). 'Ignition' does not guarantee 'propagation.' An ignited hot-spot produces hundreds kJ of yield whereas the energy from the hot-spot propagating into the fuel yields tens of MJ potentially. Presently, the highest yield achieved on NIF is ~26 kJ with half this yield coming from alpha-particle self-heating. [4]

The strategy for achieving burning plasmas in an ICF setting is based on a staged approach. Since ignition (and therefore propagation and gain) must start in with an igniting hot-spot, the strategy first focuses on making a hot-spot with sufficient (areal density)(temperature), $\rho R_{hs} T_{hs}$, so as to reach the ignition threshold. These hot-spot focused implosions serve as integrated implosion 'diagnostics' that will help to identify aspects of the implosions that must be corrected and serve as a test bed for proposed solutions. As more implosion control is demonstrated, the program will shift focus to improving the quality of the implosion shell, thus working towards steadily increasing the total fuel areal density, ρR_{tot}. [1,3]

In the current ICF ignition campaigns, there is a need to increase the fuel and hot spot areal densities to increase the alpha particle deposition 'boot strapping'. This will necessarily make the capsules more

prone to hydrodynamic instability growth, which when unabated, can be quite problematic (see Fig. 1). Striking the optimum balance between instabilities (or lack thereof) and density will require improved methods of experimentally imaging the shell at bang-time to know exactly how deep the shell material has penetrated into the hot spot. These improved experimental techniques will need to be developed and optimized, for the ICF experiments to push into the burning plasma regimes and ignition.

Finally, to access the frontier science of magnetized HED burning plasmas, techniques can be developed to pre-magnetize an ICF capsule shell and DT fuel, with fields in the range of 10 – 100 T. With typical capsule convergence ratios on NIF, this field could reach field strengths greater than ~10^4 T (100 MG) due to flux compression as the capsule converges. [5] Such field strengths could relax the implosion hotspot areal densities and pressures required for ignition and propagating burn by ~50%. The compressed field should be high enough to suppress transverse electron heat conduction, and to allow the resulting alpha particles from the primary D+T fusion reactions to couple energy into the hotspot even when the hot spot is highly deformed by large low-mode drive asymmetries and capsule nonuniformities. This might permit the recovery of ignition, or at least facilitate significant alpha particle heating, in sub-marginal capsules that would otherwise fail because of adverse hydrodynamic instabilities, as suggested by Fig. 3. [5] Such an approach has been pursued successfully using magnetized cylindrical implosions at the Z magnetic pinch facility at SNLA, demonstrating the basic proof of concept. [6] 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 D-D hot spot fill gas. Even a 10-fold increase in yield at NIF would push these implosions into the beginning stages of a propagating burn in a magnetized HED plasma.

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

The potential impact of this burning HED plasmas research is significant. First, the positive impact on society of achieving, understanding, and controlling energy production by fusion driven burning plasmas is enormous. Potential areas of experimental research enabled by such a burning plasmas test bed include study of HED burning plasmas; controlled thermonuclear plasma physics relevant to stellar interiors; [7] stellar and big bang nucleosynthesis; [8] the mechanisms for producing the heavy elements; [9] the dynamics of the turbulent thermonuclear flames in Type-Ia supernova; [10] and the Rayleigh-Taylor and Landau-Darius instabilities at the burn font interface in ICF and supernovae. [11]

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Figures (maximum 1 page)

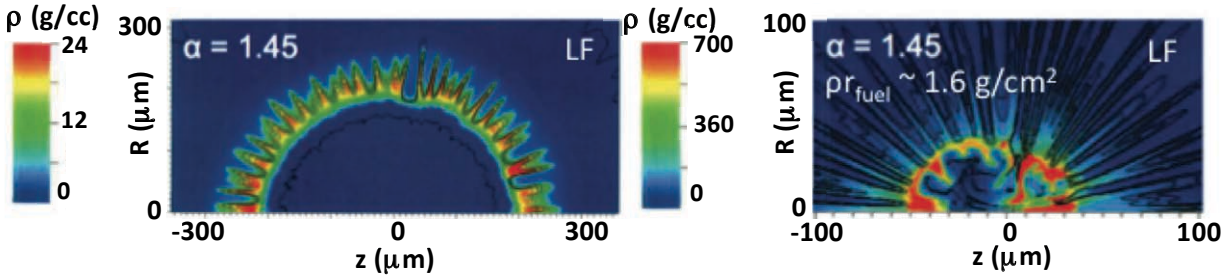

Figure 1. (a) Plots from 2D simulations of low adiabat (a ~ 1.45) cryogenic DT layered implosions on NIF. The plots show the shape of the imploding capsule shell and fuel, where the color scale is density, at peak velocity (a) and peak compression (b). [1].

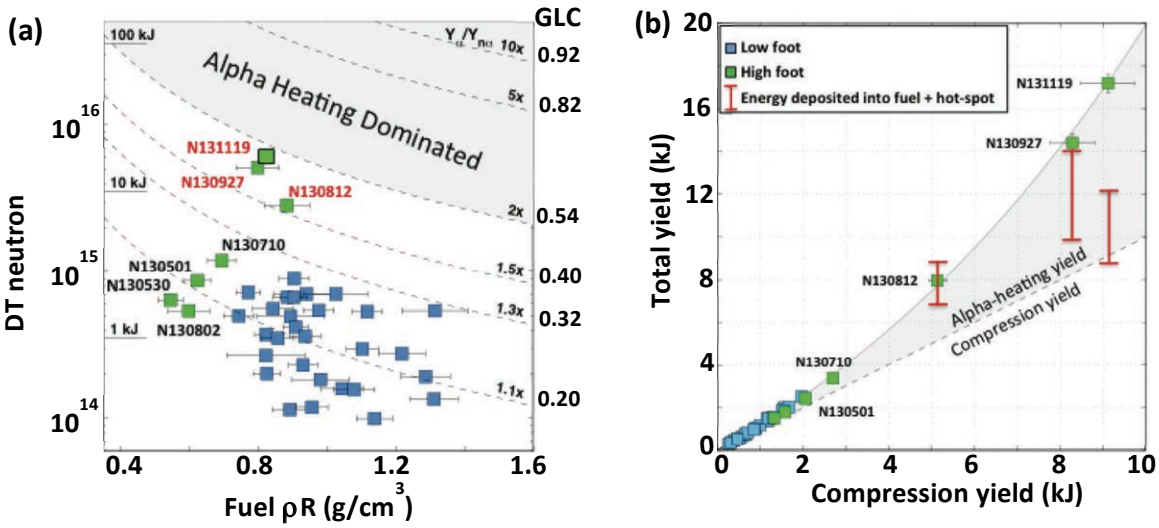

Figure 2. (a) A scatter plot of DT neutron yield vs. fuel areal density (rR), from a collection of cryogenic DT layered implosions on NIF. (b) A plot of total yield (kJ) vs compression yield without alpha heating. [1].

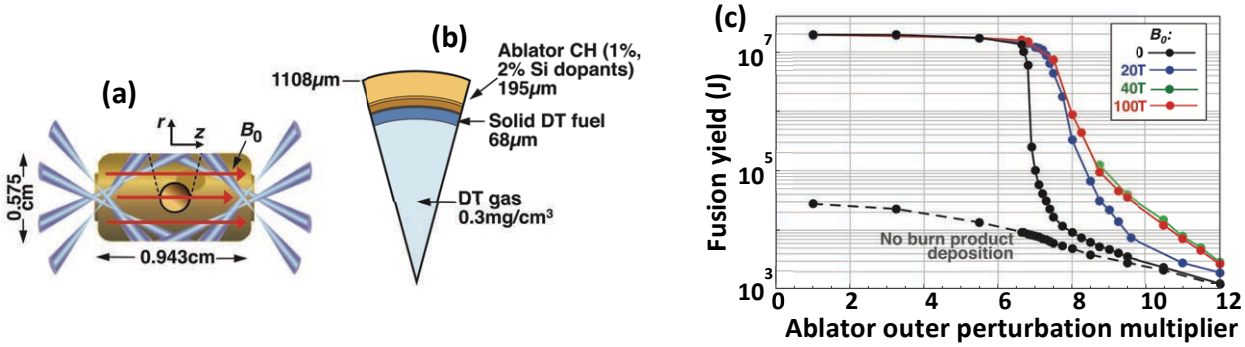

Figure 3. (a) Hohlraum and (b) capsule configuration for the 2D implosion simulations with a preimposed magnetic field. (c) Results of the 2D simulations, as a function of ablator surface roughness and strength of preimposed magnetic field. [5]