White Paper for *Frontiers of Plasma Science Panel*

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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	S
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• Plasma self-organization	
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	"X"
Oral	
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Title:	The microphysics of inertial fusion ignition
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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 an inertial confinement fusion (ICF) implosion, the initial laser energy is transferred to the fuel through a complex chain of energy conversion processes.[1] When laser energy of ~1.6 MJ is incident on an ignition hohlraum, it is absorbed collisionally and reemitted as x rays with approximately 75% efficiency.[2] Losses include back-scattered light and the acceleration of non-thermal, high-energy electrons that can preheat the capsule, making compression more difficult. The transport of x-ray energy from the hohlraum wall to the capsule results in ~140 kJ of energy absorbed at the ablation front of the ignition capsule.[3] Modeling the emission, absorption and propagation of x-rays in the hohlraum requires accurate LTE (local thermodynamic equilibrium) and non-LTE opacities, and equation of state (EOS) for regions of both pure and mixed materials.[4-10] Understanding the effects of "hot-electrons" requires an understanding of electron transport in a wide range of hohlraum plasma states. Ablation of the capsule surface, which drives the implosion, depends on x-ray absorption and reemission, and on the ionization

state and sound speed of matter near the ablation front. These quantities control the "rocket effect" that accelerates the fuel to a kinetic energy of ~15 kJ.[3]

During the early stages of the implosion, the x-ray energy increases with time, driving a series of shock waves through the ablator and into the DT fuel. The cold DT fuel is compressed to a dense, nearly Fermi-degenerate layer on the interior of the ablator shell, and then accelerates to peak velocities of near 370 km/s at 10-20 g/cm^3 and ~10 eV. During this phase, the stability of the fuel-ablator interface depends on the density profile of the ablator and fuel, which are set by the x-ray absorption, thermal transport, and EOS. At stagnation, the hot spot must reach ~100 g/cm^3, and 5 keV, while the dense fuel surrounding it must reach ~1kg/cm^3 at just ~300 eV. At these extreme conditions, there is little data to constrain physical models. Hotspot initiation is then a race between energy production and transport, including nuclear reaction rates, thermal transport from the hotspot into the cold fuel, electron-ion equilibration, ion stopping power, and x-ray emission and reabsorption.[1] It may also be that other physical processes, not traditionally part of the radiation-hydrodynamic description of ICF implosions, are important to optimizing ignition implosions (i.e. ion kinetics, large electric or magnetic fields, viscosity, correlated fluctuations, etc). While a significant theoretical effort has produced the physical models integral to ICF capsule design, these models have little benchmarking data at the extreme conditions accessed by ICF implosions. With recent investments in HED facilities, we can for the first time produce accurate data of ultra-dense matter with atoms brought together much closer than the Bohr radius producing new quantum matter with chemistry determined by core electrons to hot plasmas with gradients, fields and energy production giving rise to new correlated behavior yet harnessed.

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

To make progress on the timescale relevant to the national ignition facility (NIF), this white paper will hopefully engage scientists and capabilities from around the world to provide benchmarking data (NIF, Omega, LCLS, ALS, XFEL, GSI, APS, Z, MagPi, Orion, Gekko, etc) and make theory/simulation advances (i.e. LSP, Fokker-Plank, quantum molecular dynamics, path integral Monte Carlo, Purgatorio) to improve predictive modelling for optimizing inertial fusion ignition experiments. Several areas of focused effort are required including equation of state (Fig. 1) experiments/theory including (1) the hot low density plasma regime, characteristic of the ablating plasma shell or the hot plasma forming the incipient stages of the stagnating hotspot, (2) the warm dense matter regime (10eV and 10 g/cc) characteristic of the imploding fuel and ablator shell in flight, and (3) ultra high density hydrogen, to 1.5 Kg/cc and 100 eV.[4-10] The LTE radiative properties of the hohlraum and ablator shell materials (Au, U, C, Si, Ge, Be) for a wide range of conditions, especially in the vicinity of .1-1 g/cc and 300 eV material conditions, and the opacity of hydrogen in the degenerate 4000 x compressed fuel. The non-equilibrium radiation production and transport for high Z materials such as Au and U, which are commonly used for radiation hohlraums for x-ray driven inertial fusion experiments, at conditions of the electron temperature of 100 eV to 5 KeV and electron densities ranging from 10^{21}-10^{23}/cc (Fig. 2).[1,11,12] The transport quantities describing energy flow within the hotspot including thermal conduction, electron-ion equilibration, alpha stopping power, and Bremsstrahlung emission for hotspot conditions (Fig. 3).[1,15-30]

To generate benchmarking data for these physical quantities requires a wide variety of new techniques, making this a key scientific challenge of our time. In some cases accurate diagnosis of the plasma conditions is the main challenge, and in other cases it is not clear we can even generate a particular state of matter given today's capabilities. With a new generation of benchmarking data, we will be able to produce a new generation of theoretical tools to describe such phenomenon. In addition to this new frontier enabled by today's HED capabilities, we are in a situation similar to when Kamerlingh Onnes liquefied He or when Bragg realized diffraction could unveil hidden symmetries in solids. This allows us to address basic questions implicit to inertial fusion.

• What is the largest hydrogen density one can achieve in the laboratory and what limits this achievable density?
• What is the largest energy density gradient one can achieve in ignition scale implosions, how long can one sustain such a gradient, and what are the main mechanisms limiting or eroding such gradients?
• What is the largest entropy gradient one can achieve in ignition scale implosions, how long can one sustain such a gradient, and what are the main mechanisms limiting or eroding such gradients?
• How predictive and realistic can we expect the hydrodynamic approximation to be for inertial fusion?

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

Providing the first benchmark data for microphysics quantities integral to todays inertial fusion effort will provide an improved understanding for achieving and sustaining thermonuclear burning plasmas in the laboratory and prepare us for how to use such states of matter. An inertially confined thermonuclear burning plasma provides a unique environment in terms of extreme temperature and density conditions and also in terms of the flux of energy and particles. At present the modeling of burning plasma behavior relies on a hydrodynamic description. Benchmarked and accurate physical models integral to our hydrodynamic simulation tools will provide an important first step in developing a predictive understanding for controlled inertial fusion and will lead to a deeper understanding of the limitations of the hydrodynamic approximation for such applications.

Looking further to the future, controlled optimization of thermonuclear burning plasmas on NIF will allow the opportunity to study still more extreme physics from higher-pressure science to perhaps burning of pure deuterium. Pure deuterium burn is important in energy generation (by reducing the neutron flux) and has implications for scientific experiments, as the conditions generated appear to allow investigation in the laboratory of intense broadband quasi-isotropic radiation fields of extraordinary intensity. For NIF the peak intensity is of order 10^{20}Wcm^{-2}, whereas for pure deuterium burning capsules the intensity would be greater than 10^{22}Wcm^{-2} which is comparable to that delivered from the highest intensity laser today. Because it is broadband and quasi-isotropic the physics of the interaction of this ultra-intense radiation with matter is expected to be very different to that from a laser.

Finally, harnessing thermonuclear energy from inertial fusion implosions for energy will likely require a world-wide effort to optimize, control, and use the extreme energy densities produced in inertial fusion implosions. Central to such optimization will be a deep understanding of the microphysics implicit in such inertial fusion implosions. Because of several recent investments in high energy density facilities, producing benchmark data to enable a new generation of microphysical models for inertial fusion is within reach.

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Fig. 1 Ablator and fuel states in an ICF implosion: Summary of pressure–density states of CH ablators (left) and temperature-density states for the hydrogen fuel (right). The CH figure shows the shock Hugoniot (pink dashed curve), the cold curve (blue solid line), and the trajectory for one particular CH zone a few microns from the DT-CH interface in an ignition simulation. The hydrogen figure shows the compression path for a DT zone again a few microns from the DT-CH interface. The only data constraining these EOS models is on the Hugoniot to 10 Mbar for CH and 3 Mbar for D_2.

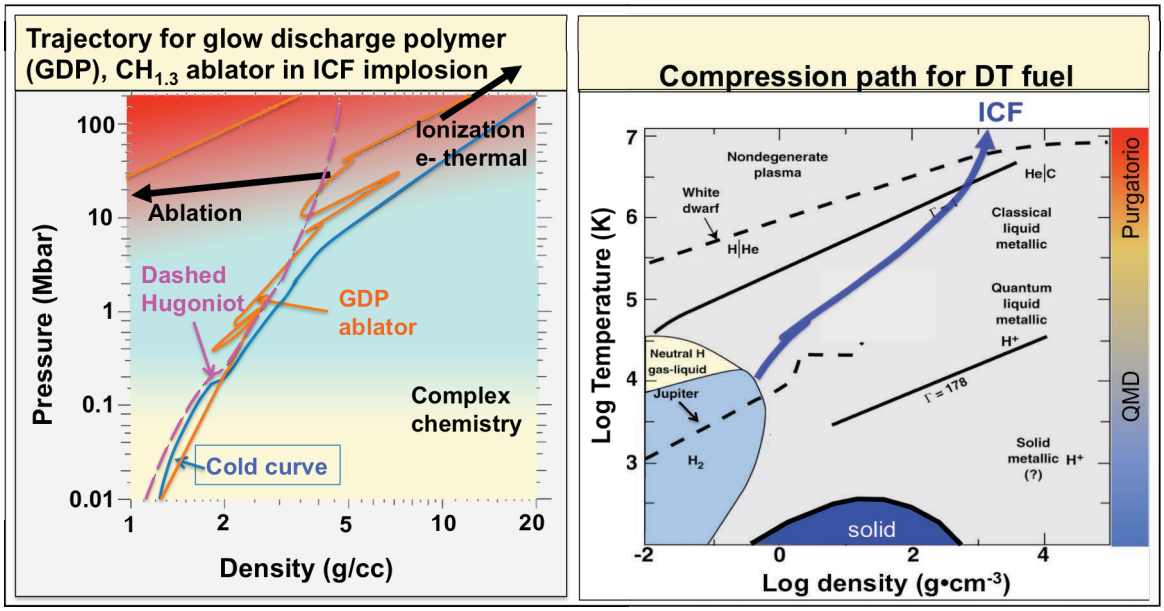

Fig. 2 Physical properties for x-ray hohlraum performance (left) and states important for radiation production/transport in a NIF scale hohlraum (right): (left) hohlraum wall (green), UV laser light (blue), ablator (red).

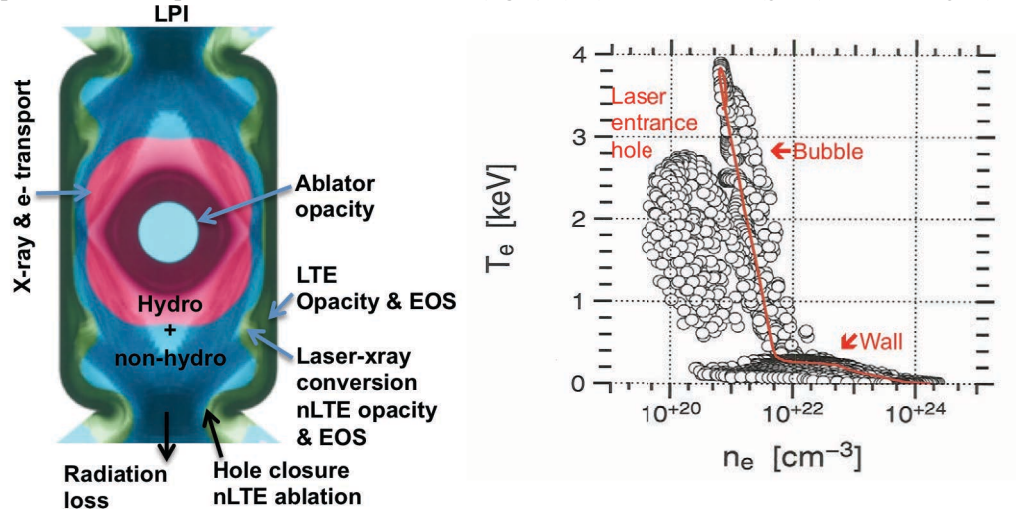
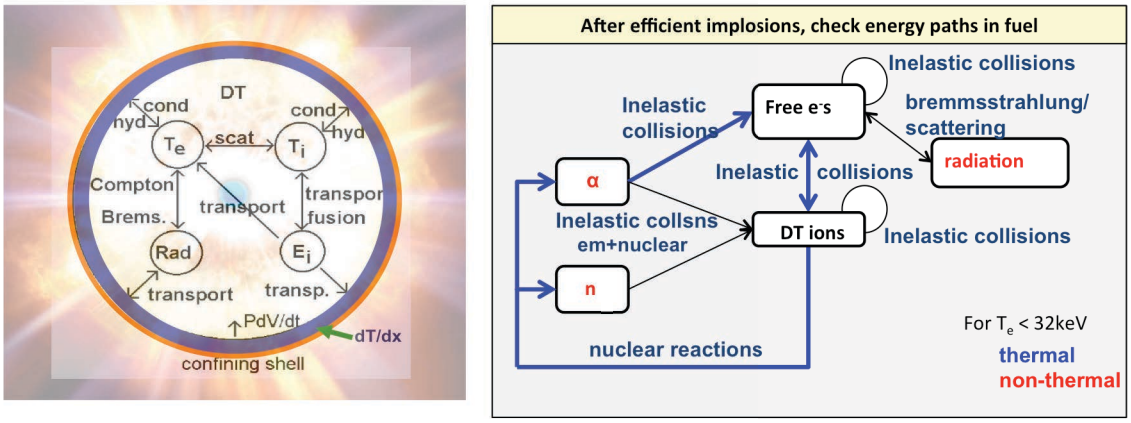
Fig. 3 Energy pathways for a fully assembled inertial fusion hotspot: These energy-transport processes in the hydrodynamic approximation, thermal/electrical conduction, radiation, viscosity, electron-ion equilibration and particle stopping, Bremsstrahlung radiation, determine how energy is transferred and redistributed in the an implosion and in the resulting imploded core. These energy partition pathways must be understood and properly controlled to guide the energy toward desired paths for nuclear combustion.