White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	***6/19/2015***

Indicate the primary area this white paper addresses by placing "P" in right column.
Indicate secondary area or areas by placing "S" in right column

	"P", "S"
• Plasma Atomic physics and the interface with chemistry and biology	
• Turbulence and transport	
• Interactions of plasmas and waves	S
• Plasma self-organization	P
• Statistical mechanics of plasmas	

Indicate type of presentation desired at Town Hall Meeting.

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Oral	
Poster	
Either Oral or Poster	X

Title:	
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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.**

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

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

Measurements of time-resolved 3D field structures in high-energy-density plasmas

High-energy-density (HED) plasma physics includes physical regimes in which coupling of plasmas to electromagnetic fields can significantly alter the plasma dynamics. Gradients in electron pressure, temperature, and composition can generate electric fields; the Biermann battery effect can generate magnetic fields, which are advected by plasma flows. Once in place, magnetic and electric field structures modify the dynamics of the plasma: for example, magnetic fields are known to reduce the thermal conductivity and the diffusion rate. Such self-generated and magnified plasma magnetic fields are hypothesized to provide the source for cosmic magnetic field structure on the galactic scale. Electromagnetic instabilities such as the Weibel instability in counter-propagating collisionless shock formation are under experimental investigation to evaluate their proposed role in the acceleration of cosmic rays. [1, 2] Magnetic fields are generated by and modify the dynamics of Rayleigh-Taylor instability growth in plasmas. [3, 4] The magnetic field dynamics are particularly fundamental to experimental studies in Z-pinch plasmas, for which magnetic pressure drives the implosion. Understanding the structure and evolution of fields in HED plasmas is an essential area of research for both laboratory astrophysics and inertial confinement fusion (ICF).

Several techniques have been used for probing electromagnetic field effects on HED facilities. Inductive "B-dot" probes have been applied to measure magnetic fields in low-density plasmas for the study of turbulent magnetic field amplification. [5] These measurements record time-resolved local magnetic field strength and direction, but are limited to structures on the scale of millimeters and can significantly perturb the experiment. In deflectometry, high-energy charged particles passing through electromagnetic fields are deflected by the Lorentz force, and the magnitude of the deflection can be inferred from the recorded image of these particles and the geometry of the system. If more than one species or energy of particle is used simultaneously, the degeneracy between deflection by electric and magnetic fields can often be broken, allowing inference of the path-integrated magnetic- or electric-field strength. The use of fusion products for charged-particle deflectometry is now well-established at OMEGA, [6, 7, 8] and is currently being developed at the NIF. [9] The use of deuterium and ^{3}He gas-filled shock-driven implosions as backlighters has been particularly successful: these targets produce substantial yields of DD-fusion protons (3.0 MeV), D^{3}He-fusion protons (14.7 MeV) and D^{3}He-fusion alpha particles (3.6 MeV), all of which may be measured using CR-39 nuclear track detectors, [10] with spatial resolution of ~40 microns and time resolution less than 100 ps. Example D^{3}He-proton backlighting data of magnetic field structures formed in collisionless shock experiments on OMEGA are shown in Figure 1. Alternative sources include the Target-Normal Sheath Acceleration (TNSA) effect produced by irradiation of a thin foil by a short-pulse petawatt beam, which generates protons in a broad spectral distribution up to several tens of MeVs. [11] TNSA backlighting produces images with spatial resolution of less than 10 microns, however images can be difficult to interpret due to nonuniformity of the source. [12] Recent evidence suggests that quasi-monoenergetic high-energy proton distributions may be produced using the related breakout afterburner (BOA) effect. Lastly, polarimetry has been used to image the Faraday rotation of probe beams in the context of pulsed power machines to diagnose magnetic fields. [13] This technique, in combination with a coaxial measurement of the electron areal density using interferometry, can produce time-resolved images of the line-integrated magnetic field strength. Faraday rotation requires penetration of the plasma with a polarized probe beam, which in the context of laser-generated HED plasmas at OMEGA and the NIF necessitates 3ω (351-nm) or 4ω (263-nm) lasers. Such probes have been implemented on the OMEGA-EP laser for interferometry. [14] The Faraday rotation angle scales proportionally to ω^{-2} and systems implemented using 3 or 4ω probes would require angular resolution much smaller than 1 percent. Deflectometry and polarimetry provide at best line-integrated magnetic- and electric-field strength along a single line-of-sight. However, the experiments being probed generally have complex, 3-dimensional field structure that evolves over time, which is impossible to evaluate using the current technologies.

The development of techniques to measure the time-dependent, three-dimensional structure of the electromagnetic field strength in HED plasmas will significantly advance the frontiers of plasma self-organization and plasma-electromagnetic field coupling. All three of the techniques currently in use – inductive measurements, deflectometry and polarimetry – have the potential for significant advances in the next decade.

Inductive measurements are limited primarily by the size, bandwidth, and survivability of the current B-dot probes. Advances in 3D printing and micro-robotics have the potential to improve the repeatability of these probes and reduce their size to sub-millimeter scales. The primary challenges involve engineering effort to minimize size, maximize bandwidth, and to use new manufacturing methods to increase reliability and reduce costs. The development of repeatable arrays of smaller, faster inductive probes will significantly advance low-density and low-temperature plasma studies for turbulent magnetic field generation and amplification.

Deflectometry studies will dramatically advance with the development of multiple simultaneous lines of sight on a single experiment. Figure 1 shows that various lines of sight generate different and complementary information on the field structures. Multiple, simultaneous lines of sight provide the potential for tomographic reconstruction of the full field structure from data, which is impossible with only a single projection. Currently, simultaneous D^3He-fusion radiography and TNSA radiography is possible by joint operation of the OMEGA and OMEGA-EP lasers, if sufficient care is taken to prevent cross-talk between the detectors, however tomographic reconstruction of 3D structures require the simultaneous operation of at least 3 lines of sight. On the NIF, the development of a D^3He-fusion backlighter for radiography is underway and makes use of six quads to drive the backlighter capsule. Using this design, deflectometry images can in principle be simultaneously recorded along four independent D^3He-fusion backlighting lines of sight, while still leaving half of the NIF beams to drive an experiment of interest. Such an experiment requires the development of new target positioning capabilities: at least five targets are needed. Additional diagnostic instrument manipulators (DIMs) are also required to position the diagnostic detector packages. The development of NIF ARC short-pulse capability, which compresses one NIF quad into a petawatt-scale short-pulse beam, will introduce TNSA capability at the NIF for a complementary deflectometry technique. Algorithms for tomographic reconstruction are well established for x-ray transmission imaging, and will be adapted for the analysis of this data to infer for the first time fully 3-dimensional field features in HED plasmas.

The implementation of a 4ω polarimetric imager will offer an additional, independent diagnostic for magnetic field structure. The probe beam, optical infrastructure, and detector technology required for this measurement has already been developed at OMEGA-EP, making this site a prime candidate for the first demonstration of HED physics studies using polarimetry. Technical challenges for this work include the improved accuracy and uniformity of sub-degree polarization measurements. This and several related optical probe diagnostics could be translated to the NIF to provide an advanced new diagnostic capability for plasmas with electron density below 10^{22} cm^{-3}.

This program will clarify many outstanding questions in ICF, HED and laboratory astrophysics. Strong magnetic field structures have been documented in and around ICF capsules and hohlraums, [15, 8] but their impact on experiments has not been extensively studied. Electric fields provide a unique signature for composition or charge-state gradients in plasmas and will constrain models of ion diffusion at these interfaces, which are currently under development. Volumetric imaging of field structures will dramatically advance studies of field generation and amplification in plasmas, with the potential to constrain models of cosmic ray and seed field generation. These techniques will significantly aid in the development of magneto-inertial fusion experiments, which potentially offer a more robust path to fusion ignition and high-gain on current facilities. In general, the probing of three-dimensional electromagnetic field structure will significantly advance knowledge and capability in HED and ICF science.

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Figures (maximum 1 page)

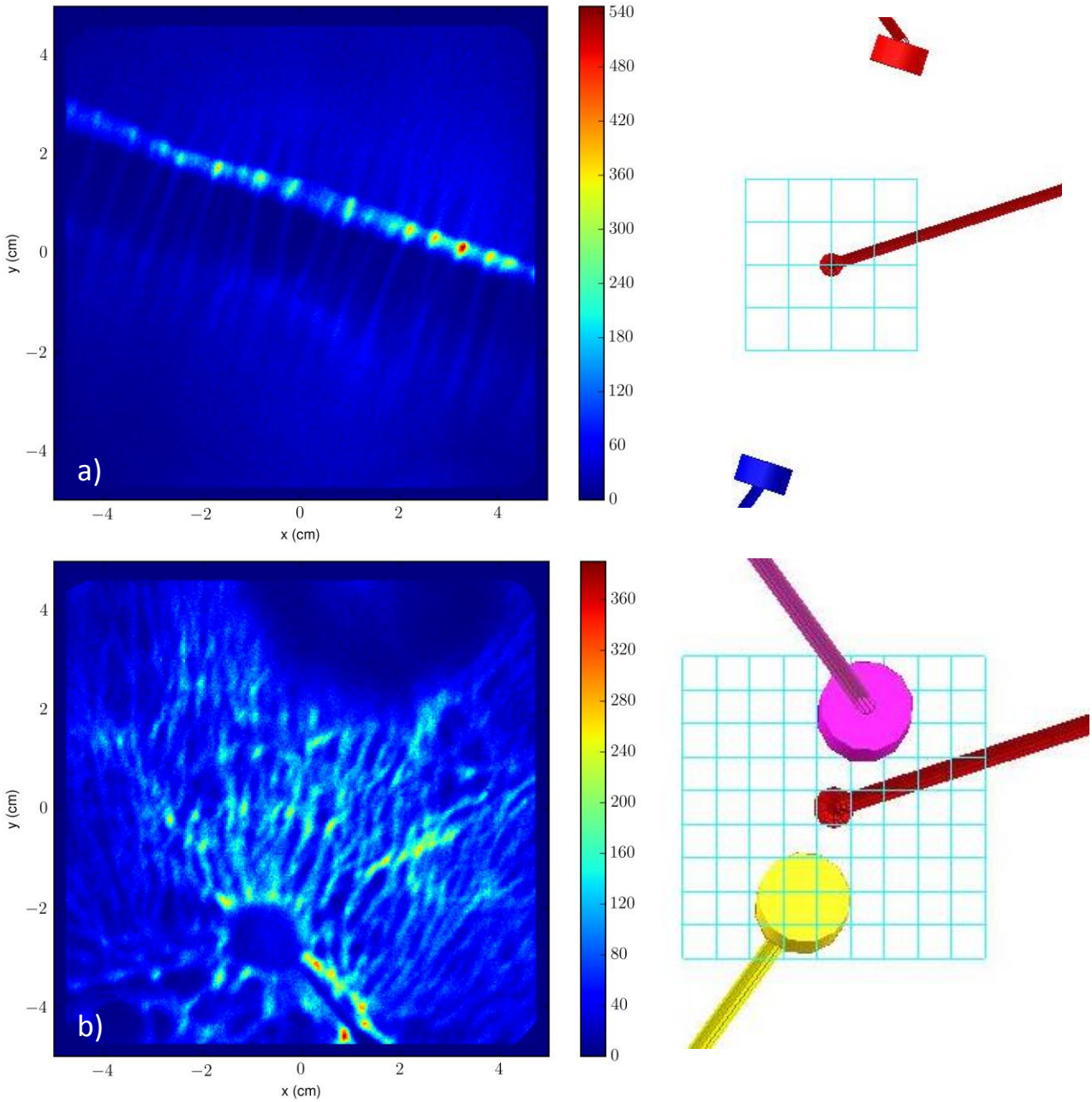

Figure 1: Example deflectometry images of magnetic field structures created by colliding plasma jets with a) side-on and b) rotated perspectives, on different but comparable shots at the OMEGA laser; projection of the target positions into the detector plane for the two experiments is shown on the right. Protons from the D^3He-fusion reaction (E = 14.7 MeV) are deflected by magnetic fields, and the proton flux in the image plane is analyzed to infer the path-integrated magnetic field strength. Because the signal is path-integrated, different lines of sight provide different and complementary information regarding the field structures. Future implementation of simultaneous imaging along 3+ lines of sight will allow tomographic reconstruction of the 3D field structures in comparable experiments on the NIF.