White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	***7/22/2015***

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	S
• Interactions of plasmas and waves	
• Plasma self-organization	
• Statistical mechanics of plasmas	P

Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	
Poster	
Not able to attend	X

Title:	Stopping power in dense plasmas
Corresponding Author:	Alex B. Zylstra
• Institution:	Los Alamos National Laboratory
• email:	zylstra@lanl.gov
Co-Authors:	R. Rygg, L. Benedict, F. Graziani, G. Collins (LLNL) R. Leeper, J. Fernandez, S. Palaniyappan, A. Hayes, H. Herrmann, A. McEvoy (LANL) J. Frenje, C. Li, R. Petrasso (MIT) P. Grabowski (UC Irvine) S. Hansen (SNL) S. Glenzer (SLAC)

(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.**

Studying charged-particle stopping in dense plasmas is relevant to fundamental plasma physics and to the potential realization of laboratory-scale thermonuclear fusion. Dense plasmas in the warm-dense matter (WDM) regime, approximately solid density and tens of eV temperature, are of great interest as a probe of stopping-power theories, with broader physics relevance to nonequilibrium statistical mechanics [1], dense plasma transport properties [2–4], and bound-free transitions in WDM plasmas [5]. Accurate theory for bound-free transitions is required to interpret data obtained with common laser-plasma diagnostics including Thomson scattering [6] and opacity-based areal density techniques [7].

In inertial confinement fusion (ICF), spherical implosion heats and compresses a small volume of fuel to, in principle, spark a runaway thermonuclear burn wave [8–10]. This burn wave propagates via fusion-produced energetic α particle self-heating. Understanding the transport of these α's in plasmas at extreme conditions is required to accurately model ignition experiments at the National Ignition Facility (NIF)

[11], where significant α self-heating has recently been achieved [12]. Charged-particle transport in and heating of dense plasmas is also highly relevant to alternative particle-beam-driven inertial fusion designs such as heavy-ion fusion [13] and proton fast ignition [14,15].

The stopping of energetic charged particles has been studied in cold (room-temperature) material for a century [16]; there, the energetic particle loses energy to bound electrons, for which theoretical models [17,18] are fit to a significant experimental database [19]. In a plasma, an energetic particle simultaneously interacts with a large number of particles via the Coulomb force, over a volume with dimensions given by the screening length (Debye- Hückel or Thomas-Fermi). Typically the stopping is treated as either a summation of two-body (binary) collisions [20–22], or a dielectric (density) response [22–25].

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

Prior work has measured charged-particle stopping powers in low-density plasmas at various conditions [26-31]. This work is a critical test of transport theories in 'classical' plasmas, but rigorous tests of stopping theory in dense plasma are needed. Experiments at Titan have probed relevant conditions, but with large uncertainties [32]. Recent experimental work on the OMEGA laser facility has obtained high-quality data for stopping power in the warm-dense-matter (WDM) regime for the first time[33]. In those experiments, x-ray isochoric heating was used to generate a Be plasma at Te = 32 eV and ne = 3×10^{23} 1/cm^3. Simultaneously, a thin-glass exploding-pusher implosion was used as a source of charged particles[27], in particular the 14.7 MeV protons from the D^3He reaction. Example data for cold and heated Be subject targets are shown in Fig. 1, showing excellent data quality.

These plasmas can be understood by the dimensionless parameters for degeneracy (θ) and coupling (Γ_e):

$$\theta = \frac{k_B T_e}{E_F}, \quad \Gamma_e = \frac{e^2}{a(k_B T_e + E_F)}$$

where θ is the ratio of the thermal to Fermi energy (E_F), and Γ_e is the ratio of the electron interparticle Coulomb potential energy to average kinetic energy ($k_B T_e + E_F$), where $a=[3/(4\pi n_e)]^{1/3}$ is the Wigner-Seitz radius. At the OMEGA experimental conditions, $\theta \approx 2$ and $\Gamma_e \approx 0.3$, indicating moderate degeneracy and coupling. The parameter space for the degeneracy and coupling versus electron density and temperature is shown in Fig. 2, with the OMEGA work and prior experiments marked.

The fundamental challenge to advancing the frontier in this field is to develop platforms for both generating dense plasmas of interest, which are uniform and quiescent, and charged-particle sources for probing the plasma. We expect that engagement with the HED community, and use of several facilities, will lead to complementary platforms for probing this physics. At the OMEGA laser, experiments using radiatively-heated WDM[33] and implosions [31] have begun. These platforms can be used to probe additional materials and conditions. On the NIF, a team is developing platforms using shocked planar targets to create WDM plasmas at higher densities (more degenerate and strongly-coupled than OMEGA). A D^3He proton source is also being developed[34]. Experimental platforms probing stopping power using fusion-generated particles to probe a high-ρR implosion[35], or using reaction-in-flight charged particles in a cryogenic layered implosion[36], are also being developed for OMEGA and the NIF. Finally, concepts for the Trident facility are being explored, which could use fully-ionized heavy-ion beams, generated with the short-pulse laser, to explore both stopping power and recombination rates in WDM plasma. This approach aims to use each facilities' strength to explore various regions of the parameter space, for both target and projectile conditions.

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

Energy transport in dense plasma is a fundamental challenge, both theoretically and experimentally. Modern high-energy-density plasma facilities provide a new opportunity for rigorous experimental validation of these theories. Charged-particle stopping is directly applicable to the transport of particles in these plasmas. More broadly, it provides a unique experimental test of general collisional transport, as these theoretical models are applicable to other critical quantities like the thermal and electrical conductivities in dense plasma.

This research has a direct and immediate impact upon the present effort to achieve break-even inertial fusion implosions in the laboratory. In an inertially-confined plasma, the fusion alpha self-heating must overcome energy loss mechanisms to 'bootstrap-heat' the plasma. The heating rate depends on the transport of the DT fusion alpha particles, while the energy loss mechanisms depend on energy transport phenomena like the thermal conductivity and electron-ion equilibration rate. As igniting implosion designs depend implicitly on theories for these quantities, validating the theories is critical to increasing our confidence in the implosion designs. Alternatively, if the transport physics is different than expected, alternate implosion designs may be found with better performance than current experiments.

These dense plasmas studied in this work are also relevant to the cosmos. With HEDP facilities we can study plasmas at conditions equivalent to stellar interiors, novae, or the universe during the big bang. Astrophysical understanding of these systems relies upon models of their interior behavior, which is not directly observable. By increasing our understanding of dense plasma physics, the communities' confidence in these models will be likewise increased.

References (Maximum 1 page)

[1] R. Zwanzig, Nonequilibrium Statistical Mechanics (Oxford University Press, New York, 2001).
[2] Z. Donkó and B. Nyíri, Phys. Plasmas 7, 45 (2000).
[3] J. Daligault and G. Dimonte, Phys. Rev. E 79, 056403 (2009).
[4] L. X. Benedict et al., Phys. Rev. E 86, 046406 (2012).
[5] S. Vinko, O. Ciricosta, and J. Wark, Nat. Commun. 5, 3533 (2014).
[6] G. Gregori, S. H. Glenzer, W. Rozmus, R. W. Lee, and O. L. Landen, Phys. Rev. E 67, 026412 (2003).
[7] S. J. Rose, J. Phys. B 25, 1667 (1992).
[8] J. Nuckolls, L. Wood, A. Thiessen, and G. Zimmerman, Nature (London) 239, 139 (1972).
[9] J. Lindl, Phys. Plasmas 2, 3933 (1995).
[10] S. W. Haan et al., Phys. Plasmas 2, 2480 (1995).
[11] G. Miller, E. Moses, and C. Wuest, Nucl. Fusion 44, S228 (2004).
[12] O. Hurricane et al., Nature (London) 506, 343 (2014).
[13] S. Humphries Jr., Nucl. Fusion 20, 1549 (1980).
[14] M. Tabak, J. Hammer, M. E. Glinsky, W. L. Kruer, S. C. Wilks, J. Woodworth, E.M. Campbell, M.D. Perry, and R. J. Mason, Phys. Plasmas 1, 1626 (1994).
[15] M. Roth et al., Phys. Rev. Lett. 86, 436 (2001).
[16] N. Bohr, Philos. Mag. 30, 581 (1915).
[17] H. Bethe, Ann. Phys. (Berlin) 397, 325 (1930).
[18] F. Bloch, Ann. Phys. (Berlin) 408, 285 (1933).
[19] J. Ziegler, J. Biersack, and U. Littmark, The Stopping and Range of Ions in Matter (Pergamon, New York, 1985).
[20] B. Trubnikov, Particle Interactions in a Fully Ionized Plasma (1965).
[21] C. K. Li and R. D. Petrasso, Phys. Rev. Lett. 70, 3059 (1993); 114, 199901(E) (2015).
[22] P. E. Grabowski, M. P. Surh, D. F. Richards, F. R. Graziani, and M. S. Murillo, Phys. Rev. Lett. 111, 215002 (2013).
[23] J. Lindhard, Mat. Fys. Medd. K. Dan. Vidensk. Selsk 28, 1 (1954).
[24] J. Jackson, Classical Electrodynamics (Wiley, New York, 1975).
[25] G. Maynard and C. Deutsch, Phys. Rev. A 26, 665 (1982).
[26] D. H. H. Hoffmann, K. Weyrich, H. Wahl, D. Gardés, R. Bimbot, and C. Fleurier, Phys. Rev. A 42, 2313 (1990).
[27] J. Jacoby et al., Phys. Rev. Lett. 74, 1550 (1995).
[28] M. Roth, C. Stöckl, W. Süß, O. Iwase, D. O. Gericke, R. Bock, D.H.H. Hoffmann, M. Geissel, and W. Seelig, Europhys. Lett. 50, 28 (2000).
[29] D. G. Hicks et al., Phys. Plasmas 7, 5106 (2000).
[30] A. Frank et al., Phys. Rev. Lett. 110, 115001 (2013).
[31] J. A. Frenje et al., submitted to Phys. Rev. Lett. (2015).
[32] F. Graziani et al., High Energy Density Phys. 8, 105 (2012).
[33] A.B. Zylstra et al., Phys. Rev. Lett. 114, 215002 (2015).
[34] J.R. Rygg et al., private communication (2015)
[35] A. McEvoy and H. Herrmann, private communication (2015)
[36] A. Hayes et al., arXiv preprint arXiv:1411.6971 (2014).

Fig 1: Parameter space, showing contours of constant degeneracy (θ, black) and coupling (Γ_e, magenta) as functions of electron density and temperature. Previous experiments[26–31] are shown in the blue points (blue shaded region for Ref. 31), and this work is shown by the red points. A typical range for WDM ($n_e = 10^{22} - 10^{24}$ 1/cm^3, $T_e = 1-100$ eV) is shown by the green shaded box, while typical parameters for the ICF hot spot (HS) and dense fuel (DF) are shown by green points.

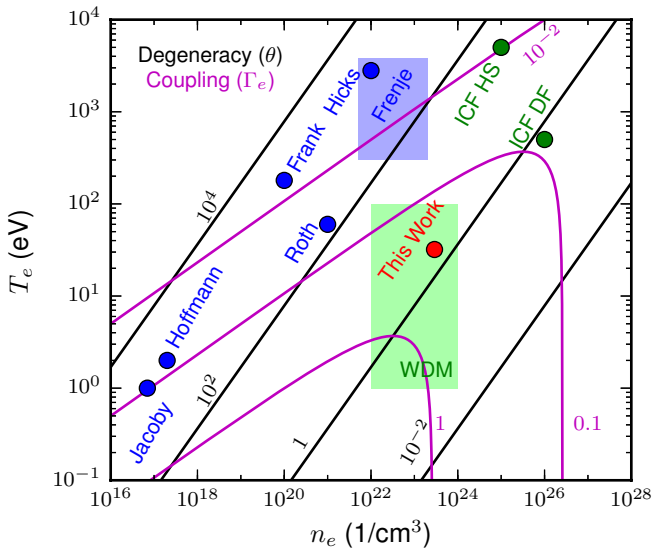
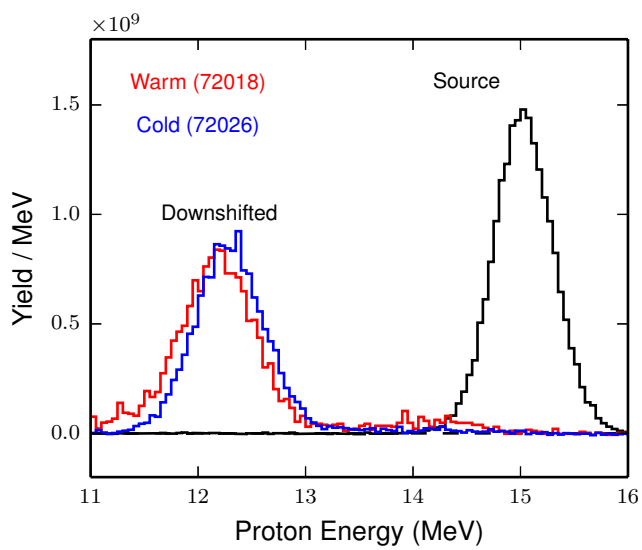
Fig 2: Proton spectral data from OMEGA for a heated (warm) Be target (shot 72018, red) and an undriven (cold) Be target (shot 72026, blue). For each shot, the proton source spectrum (black) is measured directly by 3 detectors.