White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	**2015-06-19**

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

Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	**X**
Poster	
Either Oral or Poster	

Title:	**Experimental studies of charged-particle stopping in weakly to moderately coupled plasmas**
Corresponding Author:	**Johan Frenje**
• Institution:	**Massachusetts Institute of Technology**
• email:	**jfrenje@psfc.mit.edu**
Co-Authors:	**Chikang Li, Maria Gatu Johnson, Fredrick Seguin, Richard Petrasso, Brandon Lahmann, Hong Sio, Alex Zylstra, Siegfried Glenzer, Rip Collins, Ryan Rygg, Frank Graziani, Paul Grabowski, Riccardo Betti**

(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.***

Experimental studies of charged-particle stopping in weakly to moderately coupled plasmas

Over the last few decades, charged-particle stopping in weakly to strongly coupled plasmas has been the subject of extensive analytical and numerical studies [1-13]. Although numerous efforts have been made to theoretically describe the behavior of charged-particle stopping in ICF-relevant plasmas, no rigorous experimental validation of these theories and models exists. Our recent experimental work, described below, makes possible the first quantitative experimental assessment of the characteristics of charged-particle stopping in WDM, with Γ of ~30%, and around the Bragg peak in weakly coupled plasmas (Γ~0.1–5%).

Experimental studies of ion stopping in plasmas can focus on measurements of dE/dx of ions in partially ionized Warm Dense Matter and dE/dx of charged fusion products leaving ICF implosions to characterize ion stopping around the Bragg peak. Resulting data would be used to validate and differentiate various plasma-stopping-power theories, which will be very important both for ICF and for basic science. In particular, arriving at an understanding of alpha-particle stopping near the Bragg peak in dense and degenerate plasmas is crucial for ICF hot-spot ignition [3], where the range of DT-α must be matched to the hot-spot ρR for efficient bootstrap heating.

a) Research using the Warm Dense Matter (WDM) platform

MIT has developed a platform at OMEGA for studying charged-particle stopping power in WDM plasmas (see Fig. 1). As charged-particle stopping in partially ionized and microscopically inhomogeneous WDM plasmas is very challenging to describe theoretically [2], this type of platform is ideal for validating various plasma stopping-power formalisms. Using this platform, we have conducted preliminary measurements of charged-particle stopping in WDM plasmas. As shown schematically in Fig. 1, 30 OMEGA beams illuminated the outside of a Ag-coated cylinder. This generated Ag L-shell emission that radiatively heated an inner cylinder of Be to WDM conditions – solid density and tens of eV in temperature (Γ~30%) [14]. A D^3He-gas-filled exploding pusher was used as a charged-particle source [15], and the produced D^3He-protons were observed to exhibit different stopping in the warm (heated) and cold beryllium cases. This platform can be used for the following research.

<u>1. Studying dE/dx in partially ionized plasmas:</u> Most theories of charged-particle stopping in partially ionized plasmas treat the free-electron and bound-electron contributions separately. In our first set of stopping power studies of partially ionized WDM, Be^{2+} was used. The two remaining bound electrons significantly contributed to the total stopping power (~1/3 of the total), making this measurement a sensitive probe of partial-ionization effects. We would take our studies of charged-particle stopping in partially ionized WDM to the next level by changing the material in the target to alter the bound electron configuration. Li and C will be used as target materials, since the former will have a mixture of H-like and He-like states at achievable temperatures, and the latter will have primarily He-like ions at a higher nuclear charge than Be. These data will be the best available for understanding charged-particle stopping in partially-ionized material. To diagnose plasma conditions in these experiments, x-ray Thomson scattering and x-ray absorption spectroscopy of a dopant would be used.

<u>2. Studying dE/dx with degenerate electrons:</u> The WDM dE/dx platform will be modified to probe the physics of degenerate electron stopping, which is essential for understanding alpha transport in degenerate cold fuel. The effect of density (degeneracy) can be directly probed by using pure C cylinders of varying density but constant ρL. Low-density foams of C (~50mg/cc), graphite (~2.1g/cc), and possibly diamond (~3.5g/cc) will be used as target materials. The Fermi pressure, proportional to $n^{5/3}$, would change by a factor of 2.3 between graphite and diamond. Once again, X-ray Thomson scattering or absorption spectroscopy will be used to measure the electron temperature, with the platform designed for uniform temperature and varying density.

<u>3. Studying dE/dx with slow test particles:</u> Using low-density foams to generate WDM with a Γ of about 10% will allow the use of lower-energy test particles. In particular, we would use DD-tritons, D^3He-

alphas, and DD-protons to probe the stopping power in WDM for test-particle velocities down to $v_i \sim 2v_{th}$. Plasma stopping power in this regime where the test particle velocity is comparable to the thermal electron velocity is critical to hot-spot ignition designs. By using slower test particles, the shape of the stopping-power curve closer to the Bragg peak will be studied. This experiment will be analogous to the proposed stopping power studies using the ICF implosions discussed in the next section.

b) Research using the ICF implosion platform

Plasma-stopping-power experiments were conducted at OMEGA using an ICF-implosion platform [16]. In these experiments, the energy loss of four charged fusion products were used to study the characteristics of charged-particle stopping around the Bragg peak for weakly-coupled plasmas with a Γ in the range of 0.1–5%. The reactions we studied are

$$D + D \rightarrow t\,(1.01\text{MeV}) + p\,(3.02\text{MeV}) \quad (1)$$
$$D + {}^3He \rightarrow {}^4He\,(3.71\text{MeV}) + p\,(14.63\text{MeV}). \quad (2)$$

Measured energy loss of these four charged particles is illustrated in Fig. 2 for a low-temperature implosion and for a high-temperature implosion, both generating a similar ρR. As shown, the DD-tritons, DD-protons and D^3He-alphas display significantly larger energy loss in the low-temperature case than in the high-temperature case. This is caused by the fact that v_i (the ion velocity) ~ v_{th} (the electron thermal velocity) for the DD-tritons, D^3He-alphas and DD-protons, which thus probe the Bragg peak in the low-temperature case, while $v_i << v_{th}$ in the high-temperature case. The D^3He-protons, on the other hand, exhibit a similar energy loss in these two cases, which is explained by their higher velocity. A parameterization of the classical stopping power [11] and Brown-Preston-Singleton (BPS) [5] formalism was used to model the energy-loss data. The solid (dashed) curves are the BPS (MD) modeled fits to the data. These curves were obtained by integrating the plasma-stopping power functions over an assumed T_e and ρR, which were adjusted until best fits to the data were obtained. The plasma conditions inferred from the fits are shown in each figure, clearly indicating that the plasma-stopping-power function depends strongly on T_i, T_e and ρR (or n_e). It is also clear from these data that the ions and electrons have not equilibrated during burn and that T_e and T_i are quite different.

In those experiments, T_e and n_e could not be measured. In proposed experiments, $T_e(r,t)$, $n_e(r,t)$ and also ρR will be measured accurately at various plasma conditions using x-ray techniques [12] and spectrometry of secondary neutrons [17] to fully constrain and differentiate the various plasma stopping power theories.

Comprehensive charged-particle stopping data around the Bragg peak ($v_i \sim v_{th}$) will be obtained using the ICF implosion platform and used to validate and differentiate various plasma-stopping-power theories that have been central to the discussion in the literature [1-13]. To achieve this, implosions of thin glass-capsules (~3um thick) filled with argon-doped D^3He gas will be used to generate weakly-coupled plasmas with a Γ in the range of 0.1–1%, at which the various plasma-stopping-power theories differ substantially around the Bragg peak. Spatially and temporally resolved x-ray spectroscopy of the argon emission [18-19] and secondary neutron measurements will be used to determine $T_e(r,t)$, $n_e(r,t)$ and fuel ρR, which will fully constrain the electron component of the plasma-stopping-power modeling.

We will also explore charged-particle stopping power for progressively higher Γ values (1% – 5%). Implosions of 4-7 μm thick CH- and glass-capsules filled with D^3He gas are planned to be used. The measurements require the Multiple Nuclear Burn History Diagnostic currently being developed by MIT, and also the complete set of charged-particle spectrometers routinely used at OMEGA. $T_e(r,t)$, $n_e(r,t)$ and ρR of the fuel will be measured once again using spatially and temporally resolved x-ray spectroscopy of the argon emission from the fuel and spectrometry of secondary neutrons . X-ray absorption spectroscopy of a titanium dopant in the CH shell will also be made to diagnose the electron density and temperature in the remaining shell [20].

References

1. H. Bethe, "Zur Theorie des Durchgangs schneller Korpuskularstrahlen durch Materie", ***Ann. Physik*** vol. **397**, Issue 3, 325 (1930).
2. T.A. Mehlhorn, "A finite material temperature model for ion energy deposition in ion-driven inertial confinement fusion targets", ***J. Appl. Phys***. **52**, 6522 (1981).
3. T. Peter and J. Meyer-ter-Vehn, "Energy loss of heavy ions in dense plasma. I. Linear and nonlinear Vlasov theory for the stopping power", ***Phys. Rev. A*** **43**, 1998 (1991).
4. C.K. Li and R.D. Petrasso, "Charged particle stopping powers in inertial confinement fusion plasmas", ***Phys. Rev. Lett.*** **70**, 3059 (1993).
5. L.S. Brown, D.L. Preston, R.L. Singleton, "Charged particle motion in a highly ionized plasma", ***Phys. Reports*** **410**, 237 (2005).
6. D.O. Gericke, M. Schlanges, W.D. Kraeft, "Stopping power of a quantum plasma – T-matrix approximation and dynamical screening", ***Phys. Letters A*** **222**, 241 (1996).
7. G. Zwicknagel, "Theory and simulation of heavy ion stopping in plasma", ***Laser and Part. Beams*** **27**, 399 (2009).
8. G. Maynard and C. Deutsch, "Energy loss and straggling of ions with any velocity in dense plasmas at any temperature", ***Phys. Rev. A*** **26**, 665 (1982).
9. G. Maynard and C. Deutsch, "Born random phase approximation for ion stopping in an arbitrarily degenerate electron fluid", ***J. Physique*** **46**, 1113 (1985).
10. G. H. Zimmerman, LLNL report, UCRL-JC-105616 (1990).
11. P.E. Grabowski, M.P. Surh, D.F. Richards, F.R. Graziani and M.S. Murillo, "Molecular Dynamics Simulations of Classical Stopping Power", ***Phys. Rev. Lett.*** **111**, 215002 (2013).
12. R. T. Nagayama, R. C. Mancini, R. Florido, D. Mayes, R. Tommasini, J. A. Koch, J. A. Delettrez, S. P. Regan and V. A. Smalyuk, "Direct asymmetry measurement of temperature and density spatial distributions in inertial confinement fusion plasmas from pinhole space-resolved spectra", ***Phys. Plasmas*** **21**, 050702 (2014).
13. A.C. Hayes, LANL report, LA-UR-13-22639 (2013).
14. S.H. Glenzer, G. Gregori, R.W. Lee, F.J. Rogers, S.W. Pollaine and O.L. Landen, "Demonstration of Spectrally Resolved X-Ray Scattering in Dense Plasmas", ***Phys. Rev. Lett***. **90**, 175002 (2003)
15. C.K. Li, F.H. Séguin, J.A. Frenje, J.R. Rygg, R.D. Petrasso, R.P.J. Town, P.A. Amendt, S.P. Hatchett, O.L. Landen, A.J. Mackinnon, P.K. Patel, V.A. Smalyuk, J.P. Knauer, T.C. Sangster and C. Stoeckl, "Monoenergetic proton backlighter for measuring E and B fields and for radiographing implosions and high-energy density plasmas (invited)", ***Rev. Sci. Instrum.*** **77**, 10E725 (2006).
16. J. A. Frenje, P.E. Grabowski, C.K. Li, F. H. Seguin, A. B. Zylstra, M. Gatu Johnson, R. D. Petrasso, V. Yu. Glebov ad t. C. Sangster, "Measurements of Ion Stopping around the Bragg Peak in High-Energy-Density Plasmas", submitted to ***Phys. Rev. Lett***. (2015).
17. M.D. Cable and S.P. Hatchett, "Neutron spectra from inertial confinement fusion targets for measurements of fuel areal density and charged particle stopping powers", ***J. Appl. Phys.*** **62**, 2233 (1987).
18. T. Nagayama, R.C. Mancini, R. Florido, R. Tommasini, J.A. Koch, J.A. Delettrez, S.P. Regan and V.A. Smalyuk, "Processing of spectrally resolved x-ray images of inertial confinement fusion implosion cores with multimonochromatic x-ray imagers", ***J. Appl. Phys.*** **109**, 093303 (2011).
19. S.P. Regan, J.A. Delettrez, R. Epstein, P.A. Jaanimagi, B. Yaakobi, V.A. Smalyuk, F.J. Marshall, D.D. Meyerhofer, W. Seka, D.A. Haynes Jr., I.E. Golovkin and C.F. Hooper Jr., "Characterization of direct-drive-implosion core conditions on OMEGA with time-resolved Ar K-shell spectroscopy", ***Phys. Plasmas*** **9**, 1357 (2002).
20. V.A. Smalyuk S. B. Dumanis, F. J. Marshall, J. A. Delettrez, D. D. Meyerhofer, S. P. Regan, T. C. Sangster, B. Yaakobi and J. A. Koch, "Radial structure of shell modulations near peak compression of spherical implosions", ***Phys. Plasmas*** **10**, 820 (2003).

Figures

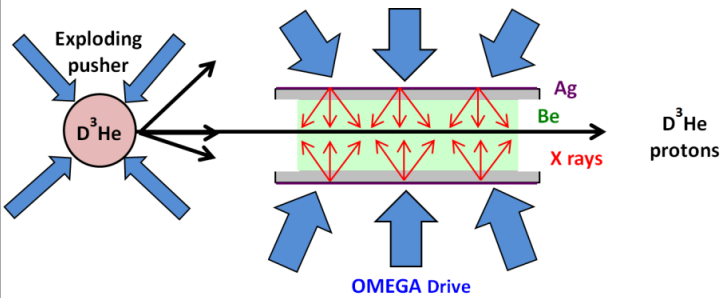

FIG. 1. Experimental geometry for the charged-particle dE/dx measurements in WDM that were made at OMEGA with a plasma-coupling parameter of around 30%. Future experiments will explore alternative materials such as Li, LiH, and C in the place of Be in this configuration. This would also require alternative x-ray sources such as Al, Si, or Ti in place of Ag.

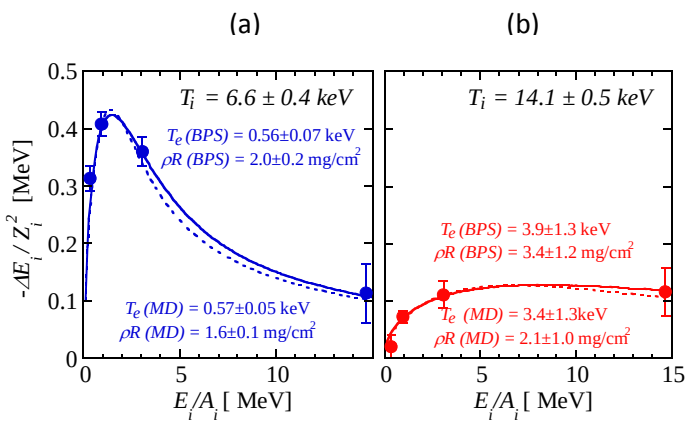

FIG. 2. Measured and modeled charged-particle stopping ($-\Delta E_i/Z_i^2$ versus E_i/A_i) for (a) a low-T_i experiment, and (b) a high-T_i experiment (similar ρR). The solid (dashed) curve represents the BPS (MD) stopping-power modeling. In future experiments, $T_e(r,t)$ and $n_e(r,t)$ and ρR will be measured accurately at various plasma conditions to fully constrain and differentiate the various plasma stopping power formalisms. From left to right, the four data points are for 1-MeV t, 3.7-MeV α, 3-MeV p, and 15-MeV p.