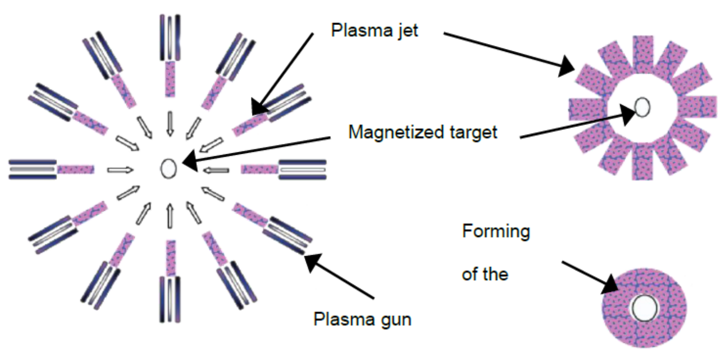
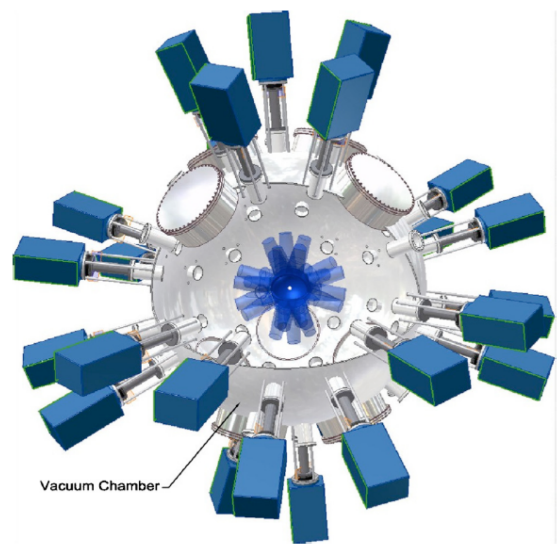
DOE Award Number:	DE-SC0003560
Recipient:	Dr. Jason Cassibry
Project Title:	F/DOE/Formation of Imploding Plasma Liners for Fundamental HEDP Studies and MIF Standoff Driver Concept Exploration
PI:	Dr. Jason Cassibry
Team Members:	Dr. Milos Stanic, Richard Hatcher

Summary of Effort:

The Plasma Liner Experiment (PLX) [1,2] is designed to simulate spherically imploding plasma liners that are characteristic of plasma jet driven magneto inertial fusion (PJMIF) as well as astrophysical phenomena such as accretion disk formation and the merging of astrophysical jets. This is accomplished via a spherical array of centrally-convergent plasma jets which merge with one another to form an imploding plasma liner. These jets are mounted within a 3 m diameter spherical vacuum chamber which has ports for up to 30 plasma guns as well as multiple ports for mounting of diagnostic equipment. Figure 1 demonstrates a 2-D cutaway of the creation and implosion of plasma liner upon a magnetized plasma target [3] while Figure 2 shows a diagram of the experimental apparatus [1].





Figures 1 and 2: (Left) Illustration of the formation of an imploding plasma liner created created by a spherical array of inwardly directed, merging plasma jets. (Right) Diagram of PLX experimental vacuum chamber with mounted plasma guns. Larger ports are used to mount diagnostic machinery.

PLX is designed to permit laboratory access to high density plasmas with number densities of 10^{23} m^{-3} to 10^{27} m^{-3} at peak compression. Therefore, direct measurement with physical probes is impractical; optical diagnostics are required to probe the resulting environment. Experimental design and full interpretation of results are complicated by wide deviations from ideal gas behavior and increasing optical opacity toward the higher end of the PLX density and energy ranges, necessitating accurate modeling of these extraordinary conditions.

SPHC, an implementation of smoothed-particle hydrodynamics (a mesh-free Lagrangian CFD method), has been utilized for the theoretical and modeling effort in support of PLX [4, 5]. This grant has enabled the extension of SPHC (version 1.20) in order to capture the behavior of the high energy density plasmas that PLX observes. These extensions include: implementation of tabular plasma equation of state (EOS) and multiple ionization states, electron thermal conduction, and optically thin/optically thick radiation transport. These tables were generated for the element argon using PROPACEOS ((PRism OPACity and Equation Of State code) from Prism Computational Sciences [6], then modified in MATLAB.

The tables are produced by supplying PROPACEOS with a range of input temperatures and densities.

In this case, we selected a temperature range of 0.01 eV to 1.0 MeV and a number density range of 10^7 cm^{-3} to 10^{23} cm^{-3}. We specify that the output be supplied in a 200 x 200 grid with respect to T and ρ for argon assuming local thermodynamic equilibrium (LTE), and request tables for total pressure (P), total internal energy (e_{int}), ionization fraction (Z), multi-group Rosseland opacities (a), and integrated Planck opacities (a). For multi-group Rosseland opacities, we request that the photon energy spectrum be divided up into ten groups, each group having it's own 200 x 200 table, in order to safely account for differential scattering and absorption of various light frequencies in the optically thick case. Integrated Planck opacities, which are used in the optically thin case, can safely be collapsed into a single group table since differential effects are relatively insignificant in that limit.

The MATLAB script converts the PROPACEOS tables from their original state, where the values of pressure, internal energy, and opacity are functions of temperature and density (e.g. $P = P(T,\rho)$ and $e_{int} = e_{int}(T,\rho)$), so that pressure, opacity, and temperature are listed as functions of internal energy and density (e.g. $P = P(e_{int},\rho)$ and $T= T(e_{int},\rho)$). This is done over *log* space using MATLAB's *interp* function. Both the original and modified files are loaded into SPHC in the form of C header files, and EOS lookups within the program were accomplished via addition of routines to handle bilateral interpolation of the PROPACEOS table entries. The source files are then compiled using the Portland Group C compiler, generating a binary Linux executable file.

Verification and validation simulations carried out via the extended SPHC match well with both analytic solutions of a fully-characterized analytic system (e.g. the Noh problem [7, 8]) as well as early PLX experimental data from laser interferometry studies (1D single jet propagation, 2-jet merging) [9] and plasma jet simulations using other codes [3] (LSP, a particle-in-cell code [10], and Nautilus, a finite-volume code [11, 12]). Important findings include determination of an empirical scaling law [3] and observation of the strong influence of the newly included thermal and radiation transport mechanisms on the collapse of a plasma jet-driven imploding liner which leads to higher peak densities and lower peak temperatures than would otherwise be expected [3].

The tools and experience generated through this work are applicable to a wide range of plasma physics and engineering problems beyond the scope of PLX. In addition, this work has enabled or inspired a similar extension of other fluid dynamics codes, including Nautilus. The bulk of this work was carried out through the doctoral dissertation project of Dr. Milos Stanic, whose final report is heavily referenced throughout this document and whose results represent the bulk of the work generated by this grant.

Model Description

SPHC (produced by Stellingwerf Associates) is an implementation of smoothed-particle hydrodynamics. Smoothed-particle hydrodynamics (SPH) is a mesh-free Lagrangian model of computational fluid dynamics where the points of interest, the titular “particles”, move along with the fluid elements [13]. SPH was created with the intent to improve solutions in certain situations where problems arise with traditional Eulerian methods. The particles are analogous to the mesh cells in an adaptive-mesh Eulerian code; increasing the density of SPH particles in a region increases the resolution of the simulation at that location. Extending the analogy with mesh elements, the particles each represent portions of the moving fluid, carrying a fraction of the total fluid mass, each having a spherical volume defined by the smoothing length h_s (which often varies with time and density), and and each bearing values for thermodynamic quantities of interest including pressure, temperature, and density. In order to maintain resolution in areas of interest with high flow rates, such as near defined free surfaces or regions with high pressure and density gradients, particles can be added via the process of "particle splitting." For each time step, the particles are advanced by via the Navier-Stokes equations for mass, momentum, and energy. If radiation is to be accounted for in the simulation, then the equations for local losses from ionization, radiative diffusion, conduction, and radiation can also be applied to the particles for both optically thick and optically thin plasmas (see [3] for an in-depth discussion of relevant radiation physics).

SPH advantages include natural conservation of mass (since the code needs only to keep track of all particles to ensure the absence of mass leakage), natural creation of free surfaces between two fluids with large density differences (the lighter fluid is represented as empty space), and ease of pressure calculations (calculated via summation of weighted neighbor particle contributions rather than via solution of systems of linear equations). However, a drawback of SPH is that relatively higher "resolution" is required to match the resolution of an equivalent Eulerian simulation.

As noted above, values of ρ, P, and T are determined in the regions in-between particles via interpolation using the SPH kernel approximation method (the "smoothing" referred to in the title). Adapting the detailed explanation in [3], we note that any field variable function can be expressed as the integral of the product of the function with the Dirac delta function δ.

$$f(\boldsymbol{x}) = \int_{\Omega} f(\boldsymbol{x}')\delta(\boldsymbol{x} - \boldsymbol{x}')d\boldsymbol{x} \tag{1}$$

$\boldsymbol{x}$ is the particle position vector and Ω is the volume over which the product is integrated. The true value of $f(\boldsymbol{x})$ can be approximated if we replace the delta function with the kernel function W which has the following properties:

$$\int_{\Omega} W(\boldsymbol{x} - \boldsymbol{x}', h_s)d\boldsymbol{x}' = 1 \tag{2}$$

$$\lim_{h \to 0} W(\boldsymbol{x} - \boldsymbol{x}', h_s) = \delta(\boldsymbol{x} - \boldsymbol{x}') \tag{3}$$

$$W(\boldsymbol{x} - \boldsymbol{x}', h_s) = 0 \text{ , when } |\boldsymbol{x} - \boldsymbol{x}'| \geq kh_s \tag{4}$$

where h_s is the smoothing length and k is a coefficient with determines the support domain boundary (usually equal to 1 or 2). Carrying out this substitution, and bracketing $f(\boldsymbol{x})$ to represent the Kernel Approximation Operator (KAO), we get:

$$< \boldsymbol{f}(\boldsymbol{x}) >= \int_{\boldsymbol{\Omega}} \boldsymbol{f}(\boldsymbol{x}')\boldsymbol{W}(\boldsymbol{x} - \boldsymbol{x}', \boldsymbol{h_s})\boldsymbol{dx}' \tag{5}$$

We can now invoke the particle approximation via the definition of the definite integral as a summation:

$$< \boldsymbol{f}(\boldsymbol{x}) >= \int_{\Omega} \boldsymbol{f}(\boldsymbol{x}')\boldsymbol{W}(\boldsymbol{x}-\boldsymbol{x}', \boldsymbol{h_s})\boldsymbol{dx}' \approx \sum_{j=1}^{N} f(\boldsymbol{x}_j) W(\boldsymbol{x}-\boldsymbol{x}_j, h_s)\Delta V_j \tag{6}$$

ΔV_j is the volume of particle j, and by the definition of mass and density, $m_j = \Delta V_j \rho_j$. So:

$$< f(\boldsymbol{x}) > \approx \sum_{j=1}^{N} \frac{m_j}{\rho_j} f(\boldsymbol{x}_j) W(\boldsymbol{x}-\boldsymbol{x}_j, h_s) \tag{7}$$

The benefit of this method becomes clear when we take the spatial derivative of the field function, which, due to the linear nature of the gradient operator, only requires that we take the gradient of the kernel function.

$$< \boldsymbol{\nabla} \cdot \boldsymbol{f}(\boldsymbol{x}) >= \sum_{j=1}^{N} \frac{\boldsymbol{m_j}}{\boldsymbol{\rho_j}} \boldsymbol{f}(\boldsymbol{x}_j) \boldsymbol{\nabla W}(\boldsymbol{x}-\boldsymbol{x}_j, \boldsymbol{h_s}) \tag{8}$$

Thus, a system of partial differential equations is simplified into a system of ordinary differential equations (Navier-Stokes plus radiative diffusion, conduction, and radiation loss calculations) with respect to time, which can then be solved via explicit integration.

The PROPACEOS-generated EOS, ionization, Rosseland multi-group opacity, and integrated Planck opacity tables, once generated, are processed into C header files and compiled into the existing SPHC code base. They replace the original hard-coded EOS for ideal gases, which was simply the ideal gas equation $p = \rho RT$. The original state of the plasma is defined via an input file supplied by the user; this input file defines the number density and temperature over the domain as a function of location. The original PROPACEOS output tables are then used to get initial values P, e_{int}, Z, and a. The absorption a is calculated after determining whether the optical thickness of the material τ_v is greater than or less than one, which determines whether the ten multi-group Rosseland opacity tables (in the thick case) or if the Planck integrated opacities (in the thin case) are employed.

From this point, the original internal architecture of SPHC calls for EOS, ionization, and opacity lookups in terms of e_{int} and T. We therefore provide modified EOS tables to supply P, T, Z, and a for all subsequent time steps. This entire process is visualized below in Figure 3 (from Ref. [3]).

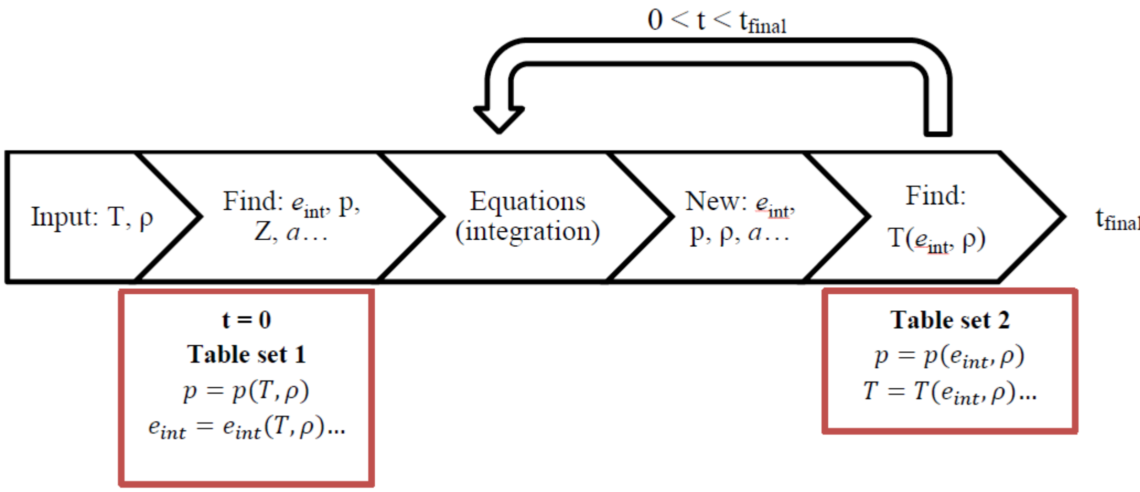


Figure 3: Illustration of SPHC main loop with focus on EOS lookup. This shows the usages of both the original EOS tables stated in terms of T, ρ and the manipulated tables stated in terms of e_{int}, ρ.

An external MATLAB tool for synthetic interferometry was developed to do SPH-style interpolation as described above on SPHC output files in order to calculate the degree to which laser beams used for interferometry measurements would be deflected. This deflection is dependent on ionization fraction and number density integrated linearly along the laser pathway. The specific methods for the experiment can be found in [8] and synthetic interferometry in [3].

Project Goals and Objectives

All objectives listed in "Revised Scope for Contract DE-SC0003560" have been accomplished. Detailed descriptions of all completed goals and V&V procedures are included in the dissertation of Dr. Milos Stanic [3]. Starting page numbers for sections describing particular completed objectives in detail are appended to the numbered descriptions from the revised scope.

1. Verification test of SPHC via the Noh Problem (p. 65)
2. Comparisons of SPHC among other codes (p. 74)
3. Development and implementation of physics models
   3.1 Tabular equation of state with multiple ionization states (p. 56)
   3.2 Electron thermal conduction (p. 42)
   3.3 Optically thin/optically thick radiation transport (p. 56)
4. Validation against the following experiments
   4.1 Jet propagation in a vacuum (pp. 87, 101)
   4.2 Merging of 2 jets (only 2 available at the time of reporting) (pp. 87, 101)
5. Plasma liner formation and implosion physics
   5.1 Ideal hydro (p. 112)
   5.2 Tabular EOS, thermal conduction, and radiative transport physics (pp. 116, 118)
   5.3 Development of scaling laws (p. 130)

Computational System Configuration

All of the simulations were carried out on a Dell Alienware platform with the following system components:
- Processor: Intel i7 Extreme Edition, 8 cores operating at 2.67 GHz
- Working memory: 6 GB DDR2 RAM
- Graphics card: nVidia GeForce GTX 480
- Hard drive: 1TB Hitachi, 7200 rpm
- OS: Linux Ubuntu 10.04 (Lucid), kernel version 2.6.32-38, Gnome 2.30.2

Collaborations Fostered by this Effort:
Dr. Doug Witherspoon (HyperV Technologies, Inc.)
Dr. Scott Hsu (Los Alamos National Laboratories)
Dr. Mark Gilmore (University of New Mexico)
Dr. Joseph MacFarlane (Prism Sciences)

Publications Produced by this Effort

Refereed Journal Publications

1. Cassibry, J. T., Cortez, R. J., Hsu, S. C., and Witherspoon, F. D., "Estimates of confinement time and energy gain for plasma liner driven magneto-inertial fusion using an analytic self-similar converging shock model," *Physics of Plasmas*, 16, 112707 (2009).
2. A. G. Lynn, E. Merritt, M. Gilmore, S. C. Hsu, F. D. Witherspoon, and J. T. Cassibry, "Diagnostics for the Plasma Liner Experiment," Review of Scientific Instruments **81**, 10E115 2010.
3. Awe, T. J., Adams, C. S., Davis, J.S., Hanna, D. S., Hsu, S. C., Cassibry, J. T., "One-dimensional radiation-hydrodynamic scaling studies of imploding spherical plasma liners," Physics of Plasmas 18, 072705, (2011). .
4. J. T. Cassibry,M. Stanic, S. C. Hsu, F. D. Witherspoon, S.I. Abarzhi, "Tendency of spherically imploding plasma liners formed by merging plasma jets to evolve toward spherical symmetry," *Physics of Plasmas*, 19, 052702, 2012.
5. Hsu, S. C., T. J. Awe, S. Brockington, A. Case, J. T. Cassibry, G. Kagan, S. J. Messer, et al., "Spherically Imploding Plasma Liners as a Standoff Driver for Magnetoinertial Fusion." *Plasma Science, IEEE Transactions On* PP (99): 1 –12. doi:10.1109/TPS.2012.2186829.
6. M. Stanic, R.F. Stellingwerf, J.T. Cassibry, S.I. Abarzhi, "Scale coupling in Richtmyer-Meshkov flows induced by strong shocks," *Physics of Plasmas*, **19**, 082706, 2012.
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9. J.T. Cassibry, M. Stanic, and S.C. Hsu, "Ideal hydrodynamic scaling relations for a stagnated imploding spherical plasma liner formed by an array of merging plasma jets," *Physics of Plasmas* **20**, 032706 (2013).

Ph. D. Dissertation

Stanic, M., "Effects of Plasma Jet Parameters, Ionization, Thermal Conduction, and Radiation on Stagnation Conditions of an Imploding Plasma Liner," Ph. D. Dissertation, Department of Mechanical and Aerospace Engineering, University of Alabama in Huntsville, Huntsville, AL, 2013.

Invited Presentations

1. S. C. Hsu, T. J. Awe, S. Brockington, A. Case, J. T. Cassibry, G. Kagan, S. J., Messer, M. Stanic, X. Tang, D. R. Welch, and F. D. Witherspoon, "Spherically Imploding Plasma Liners as a Standoff Driver for Magneto-Inertial Fusion," 38th IEEE International Conference on Plasma Science (ICOPS) and 24th Symposium on Fusion Engineering (SOFE), Chicago, IL, June 26-30, 2011.

Refereed Conference Proceedings

1. Cassibry, J. T., Stanic, M., Hsu, Scott, Witherspoon, D. and Gilmore, M., "Scaling laws for merging and implosion of discrete plasma jets," 49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, 4 - 7 January 2011, Orlando, Florida, AIAA-2011-963.
2. Stanic, M., Cassibry, J. T., Stellingwerf, R. F., Chou, C-C., Fryxell, B.J., Abarzhi, S.I., "Validation of SPHC and Crash codes in modeling of linear and non-linear Richtmyer-Meshkov instabilities," 20th AIAA Computational Fluid Dynamics Conference, 27 - 03 June 2011, Honolulu, HW, AIAA-2011-3400.
3. Loverich, J., Hakim, A., Mahalingam, S., Stotz, P. Zhou, S C.D., Keidar, M., Kandrapu, M., Zhuang, T., Cassibry, J., Hatcher, R., "Simulation of laboratory accretion disk and weakly ionized hypersonic flows using Nautilus," 42nd AIAA Plasmadynamics and Lasers Conference, 27 - 03 June 2011, Honolulu, HW, AIAA-2011-4012.

Conference Presentations without Proceedings

1. Jason T. Cassibry, Scott Hsu, Doug Witherspoon, Mark Gilmore, and the PLX team, "Hydrodynamic Modeling of the Plasma Liner Experiment, " 51st Annual Meeting of the Division of Plasma Physics, November 2-6, 2009, Atlanta, GA.
2. J.S. Davis, D.S. Hanna, T.J. Awe, S.C. Hsu, M. Stanic, J.T. Cassibry, J.J. MacFarlane, ",Numerical Modeling of Imploding Plasma liners Using the 1D Radiation-Hydrodynamics Code HELIOS" Bulletin of the American Physical Society, 52nd Annual Meeting of the APS Division of Plasma Physics, 55 (15), http://meetings.aps.org/link/BAPS.2010.DPP.JP9.41.
3. R. J. Mason, R.J. Faehl, ,R.C. Kirikpatrick, D. Witherspoon, and J. Cassibry, "Modeling of plasma jet production from rail and coaxial guns for imploding plasma liner formation," Bulletin of the American Physical Society, 52nd Annual Meeting of the APS Division of Plasma Physics, 55 (15), http://meetings.aps.org/link/BAPS.2010.DPP.UP9.114.
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5. Thomas Awe, David Hanna, Joshua Davis, Scott Hsu, Milos Stanic, Jason Cassibry, "One-dimensional numerical modeling of imploding plasma liners," Bulletin of the American Physical Society, 52nd Annual Meeting of the APS Division of Plasma Physics, 55 (15),

http://meetings.aps.org/link/BAPS.2010.DPP.UP9.166.
6. S.C. Hsu, T.J. Awe, D.S. Hanna, J.S. Davis, F.D. Witherspoon, J.T. Cassibry, M.A. Gilmore, D.Q. Hwang "Overview, Status, and Plans of the Plasma Liner Experiment (PLX)," Bulletin of the American Physical Society, 52nd Annual Meeting of the APS Division of Plasma Physics, 55 (15), http://meetings.aps.org/link/BAPS.2010.DPP.UP9.108.
7. F. Douglas Witherspoon, Richard Bomgardner, Andrew Case, Sarah Messer, Samuel Brockington, Linchun Wu, Raymond Elton, Scott Hsu, Jason Cassibry, Mark Gilmore "Overview of Plasma Guns for PLX," Bulletin of the American Physical Society, 52nd Annual Meeting of the APS Division of Plasma Physics, 55 (15), http://meetings.aps.org/link/BAPS.2010.DPP.UP9.111.
8. Elizabeth Merritt, Mark Gilmore, Alan Lynn, Bruno Bauer, F. Douglas Witherspoon, Jason Cassibry, Scott Hsu, "Diagnostics for the Plasma Liner Experiment (PLX)," Bulletin of the American Physical Society, 52nd Annual Meeting of the APS Division of Plasma Physics, 55 (15), http://meetings.aps.org/link/BAPS.2010.DPP.UP9.109.
9. J.T. Cassibry, M.D. Stanic, T.J. Awe, D.S. Hanna, J.S. Davis, S.C. Hsu, F.D. Witherspoon, "Theory and Modeling of the Plasma Liner Experiment (PLX)," Bulletin of the American Physical Society, 52nd Annual Meeting of the APS Division of Plasma Physics, 55 (15), http://meetings.aps.org/link/BAPS.2010.DPP.UP9.118.
10. J. Cassibry, R. Cortez, M. Stanic, M. Beattie, S. Thompson, R. Hatcher, R. Adams, W. Seidler, "The Case and Development Path for Fusion Propulsion," International Space Development Conference, May 22, 2011.
11. J.T. Cassibry, M.D. Stanic, R. Hatcher, S.C. Hsu, F.D. Witherspoon, M. Gilmore, W. Luo, "The Tendency of Plasma Liners Formed by Hypersonic Jets to Evolve Toward Good Spherical Symmetry During Implosion," Bulletin of the American Physical Society, 53nd Annual Meeting of the APS Division of Plasma Physics, 56 (16), http://meetings.aps.org/link/BAPS.2011.DPP.TP9.104.
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18. E. Merritt, S. Hsu, A. Lynn, A. Moser, J. Dunn, J. Davis, T. Awe, M. Gilmore, S. Brockington, F.D. Witherspoon, and J. Cassibry, in *Bulletin of the American Physical Society,* **57**(12), 54th Annual Meeting of the APS Division of Plasma Physics, October 29–November 2 *2012*; Providence, Rhode Island, http://meetings.aps.org/link/BAPS.2012.DPP.BO6.10.
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