White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	June 15, 2015

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

Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	
Poster	
Either Oral or Poster	
Will not attend	X

Title:	Three-dimensional ion and neutral acceleration due to localized electric fields in plasmas
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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.**

Free standing, localized and strong ($\sim T_e/\lambda_D$) electric fields in plasmas are referred to as "double layers" [1]. Though these structures have been known to exist since the early studies of plasmas, the physics governing their appearance, particle acceleration, and subsequent instabilities is poorly understood. Recently, spontaneous double layer formation has been observed both in the cores of, and in the expansion regions of helicon plasma devices [2-4]. Their location, strength and saturation have been investigated with probes and optical diagnostics. Streaming instabilities [5] and electron heating [3,4,6] appear to play important roles in determining the steady-state properties of these double layers. However, many mysteries remain. In expanding plasmas, multiple energetic ion populations are observed downstream [5]. Because of the multiple and overlapping ion populations arising from the double layer, the total ion velocity distribution is easily misinterpreted as being representative of a single, hot, ion population (Figure 2). The spatial and temporal structures of these multiply accelerating double layers, and their dependence on the upstream plasma parameters are unknown. Thus, it is unclear how these ion populations are accelerated. The challenge is to measure the full three-dimensional plasma structure and ion acceleration (Figure 1) in an expanding plasma double layer.

Understanding double layers is especially timely given the strong interest in particle acceleration in the ionosphere, solar flares and wind, and reconnection outflow regions [7-11]. In each of these applications, double layers have been a controversial proposed mechanism. Part of the controversy is driven by the fact

that thorough diagnosis of said phenomena *in situ* is notoriously difficult to perform, and is impossible to perform in a controlled fashion. Thus, laboratory investigation of double layers in a controlled experiment that highlights the 3D physics will provide key insights into how particles are accelerated in all directions and how these energetic particles drive further instabilities in the plasma. The identification of double layer creation in reconnection exhausts is a very recent development [11] and highlights the breadth and potential significance of this area of research.

Another important region of localized electric fields in plasmas is called the "presheath" [12]. These regions, upstream from some double layers in expanding plasmas, as well as near material boundaries, consist of weak electric fields that extend, in helicon plasmas, over several ion-neutral collision lengths [2,6] (Figure 3). These structures provide a unique opportunity to investigate ion-neutral coupling in flowing plasmas. The ions, accelerated by the weak electric fields, drag the neutrals via momentum-transfer collisions, thus accelerating the neutral fluid flow and modifying both the ion and neutral velocity distribution functions. The coupling of ion and neutral flows is critical in partially ionized flowing systems, such as cool accretion disks [13-15]. Despite this, the coupling mechanism is typically approximated with simplistic collisional cross section or frequency terms in fluid models without rigorous understanding of the accuracy of such numbers and models.

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

Measurement of the full three-dimensional plasma structure and ion acceleration in an expanding plasma double layer will require both electric probes to measure the local electric potential in the double layer and laser-induced fluorescence to non-perturbatively measure the ion velocity distribution [16-18]. These investigations will require upgrades to diagnostic equipment currently available on the HELIX-LEIA expanding helicon plasma source at West Virginia University to allow for detailed, multi-dimensional measurements of the plasma throughout the throat of the expansion region.

In addition, by directly measuring the evolution of ion and neutral velocity distribution functions in presheath structures in low temperature helicon plasmas, the coupling mechanisms between the species can be directly probed in different gases, and in gases of multiple species. Thus, the assumptions underlying models of partially ionized systems in the laboratory and astrophysical environments can be directly tested. To achieve this, novel laser diagnostic techniques for both ions and neutrals will need to be developed, such as for helium ions and xenon neutrals. In addition to investigating the fundamental physics of ion and neutral coupling, these experiments would be the first to directly measure neutral acceleration indirectly driven by electric fields.

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

It is rare when a laboratory apparatus can directly contribute to current debates on astrophysical phenomena. In the case of the diagnosis of electric field effects in plasmas, the helicon laboratory source with laser-induced fluorescence is ideally suited to this task. The recent discoveries of double layers in helicon sources have coincided with the latest developments in laser-induced fluorescence measurements of novel ion and neutral species, only now allowing for full characterization of ion-neutral coupling in the plasma. Further studies will directly contribute to our understanding of particle energization in astrophysical processes; helping to explain some of the most fundamental events observed in our near-space environment.

Additional impacts include the potential for contributing to research on helicon double-layer thrusters, a novel, electrodeless spacecraft thruster design that utilizes double layers as a propellant-acceleration mechanism. Such thrusters are currently undergoing vigorous research and have the potential to revolutionize interplanetary space travel for both manned and unmanned spacecraft due to their high efficiency, high specific impulse, and lack of material wall erosion [19]. Thus, this research has a potentially far-reaching and interdisciplinary societal benefit by investigating the physics of the acceleration mechanisms crucial for optimizing the double layer thruster designs.

References (Maximum 1 page)

[1] N. Hershkowitz, Space Science Reviews **41**, 351 (1985).

[2] X. Sun, A. M. Keesee, C. Biloiu, E. E. Scime, C. Charles, A. Meige, & R. Boswell, Physical Review Letters **95**, 025004 (2005).

[3] M. U. Siddiqui & N. Hershkowitz, Physics of Plasmas **21**, 020707 (2014).

[4] S. Ghosh, K. K. Barada, P. K. Chattopadhyay, J. Ghosh, & D. Bora, Plasma Sources Science and Technology **24**, 034011 (2015).

[5] J. Carr Jr., M. E. Galante, R. M. Magee, D. McCarren, E. Reynolds, E. E. Scime, S. Sears, R. W. VanDervort, Physics of Plasmas **20**, 113506 (2013).

[6] M. U. Siddiqui, J. F. Kim, C. D. Jackson, & N. Hershkowitz, Plasma Sources Science and Technology **24**, 015022 (2015).

[7] R. E. Ergun, C. W. Carlson, J. P. McFadden, F. S. Mozer, L. Muschietti, I. Roth, & R. J. Strangeway, Physical Review Letters **81**, 826 (1998).

[8] R. E. Ergun, Y.-J. Su, L. A. Andersson, C. W. Carlson, J. P. McFadden, F. S. Mozer, D. L. Newman, M. V. Goldman, & R. J. Strangeway, Physical Review Letters **87**, 045003 (2001).

[8] R. W. Boswell, E. Marsch, & C. Charles, The Astrophysical Journal **640**, L199 (2006).

[9] T. C. Li, J. F. Drake, & M. Swisdak, The Astrophysical Journal **757**, 20 (2012).

[10] H. Zheng, S. Y. Fu, Q. G. Zong, Z. Y. Pu, Y. F. Wang, & G. K. Parks, Physical Review Letters **109**, 205001 (2012).

[11] J. Egedal, W. Daughton, & A. Le, Nature Physics **8**, 321 (2012).

[12] N. Hershkowitz, Physics of Plasmas **12**, 055502 (2005).

[13] O. M. Blaes & S. A. Balbus, The Astrophysical Journal **421**, 163 (1994).

[14] J. F. Hawley & J. M. Stone, The Astrophysical Journal **501**, 758 (1998).

[15] B. P. Pandey & M. Wardle, Monthly Notices of the Royal Astronomical Society **371**, 1014 (2006).

[16] A. M. Keesee, E. E. Scime, & R. F. Boivin, Review of Scientific Instruments **75**, 4091 (2004).

[17] Z. Harvey, S. Chakraborty Thakur, A. Hansen, R. Hardin, W. S. Przybysz, & E. E. Scime, Review of Scientific Instruments **79**, 10F314 (2008).

[18] N. Gulbrandsen, Å. Frederiksen, J. Carr Jr., & E. Scime, Physics of Plasmas **22**, 033505 (2015).

[19] C. Charles, Plasma Sources Science and Technology **16**, R1 (2007).

Figures (maximum 1 page)

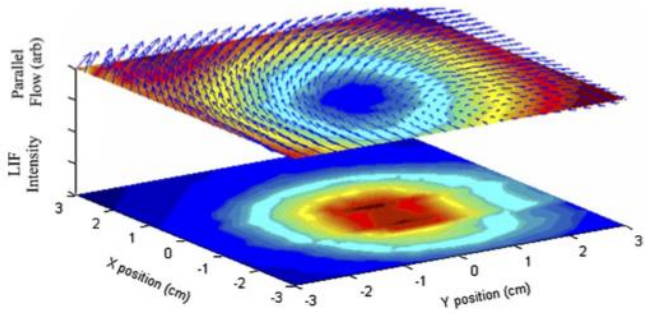

Figure 1: 3D ion flow in a 2D plane using LIF in the HELIX helicon source at WVU.

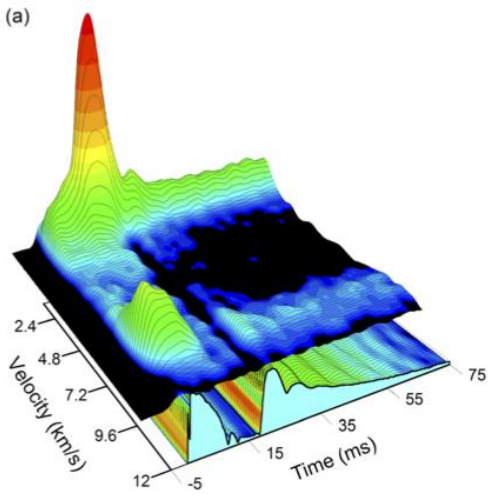

Figure 2: Evolution of ion beams measured with LIF in time due to double layer in a pulsed expanding helicon source at WVU [5].

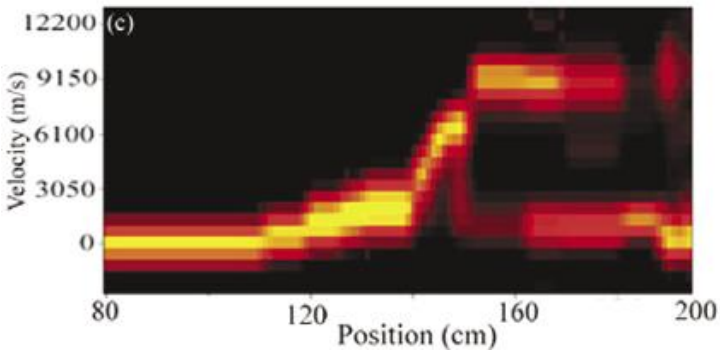

Figure 3: 1D ion acceleration through an expanding double layer, showing weak upstream pre-sheath acceleration (100-140 cm) [2].