White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	***June 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	S
• Interactions of plasmas and waves	
• Plasma self-organization	P
• 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:	Formation and Acceleration of Multi-ion Species Spheromak-like Compact Toroids
Corresponding Author:	David Q. Hwang
• Institution:	University of California, Davis
• email:	dqhwang@ucdavis.edu
Co-Authors:	

**(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.**

Compact toroids are self-organized dense plasmas with force-free equilibrium structures that are self-contained by strong internal magnetic fields. Compact toroids are found in both astrophysical settings, and can be created in the laboratory. Due to their robust magnetic structure, compact toroids can withstand extremely large accelerating forces. This unique feature can be relevant in simulating astrophysical phenomena, as well as in laboratory plasma experiments with direct applications, including the delivery of large quantity of ions with high kinetic energy density into magnetic fusion devices.[1-4] The understanding of the physical processes of the formation, self-organization, acceleration, and accretion of density in compact toroids represents an important scientific challenge. The most common two types of force free compact toroids are the reverse field configuration (RFC), and the spheromak. In our laboratory, we have been studying the acceleration of the spheromak-like compact toroids (SCT). Extending the experimental understanding of SCTs from purely hydrogenic to higher atomic number ions

is an important area of study with important applications to both astrophysical research, as well as a way to optimize multi-species ion delivery into terrestrial fusion devices.

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

The UC Davis Compact Toroid Injection Experiment (CTIX) research group has been studying the production and the acceleration of magnetized compact toroids for both hydrogenic and high-Z SCTs. These SCTs are typically produced by creating initially low-density, hydrogenic plasma in a magnetized formation region, then compressing and increasing the velocity of the SCT in the acceleration section. By injecting gas into the acceleration region ahead of the SCT, density as well as velocity can be increased by snowplow accretion. If the injected gas in the accelerator-region gas is high-Z, the final SCT will consist largely of non-hydrogenic ions, and can have high kinetic energy density compared to SCTs produced without snowplow accretion. Using the snowplow method, we have demonstrated the ability of CTIX, shown in Figure 1, to produce SCTs using a number of neutral gas species (H_2, He, Ar, Kr, N_2, etc.). Shown in Figure 2 are typical results of this snowplow method. Figure 2 (a) shows magnetic field and peak densities at three axial locations for a hydrogen-only SCT while Figure 2 (b) show similar data from the same axial locations, but with puffed argon in the accelerator region. Typical of most puffed shots, there is significant (~threefold) increase in the observed peak density. In this case, the majority of SCT mass is comprised of argon ions, a result which has not been possible on CTIX by direct (non-accretion) formation of argon plasma.

Figure 3 summarizes some high-performance results of accelerator-puffed operation with hydrogen, helium, neon, and argon. Using energy balance of the SCT kinetic energy density with magnetic energy density of a low-beta target plasma, experimental measurements of density and velocity can be used to estimate the magnetic field which could be penetrated. Based on these results, the current configuration of CTIX could inject high-Z particles into fields of about 0.5 Tesla. Future efforts will be made to further increase this value, by making full use of all available power, and additional high-Z ion accretion using both neutral gas and plasma sources (see below). However, in order to operate at large-tokamak fields of 5 Tesla or more, considerably larger devices than CTIX will be required.

Designing future SCT injectors will require a fundamental understanding of the processes involved. The accretion method of creating non-hydrogenic SCTs, although empirically successful, has not been systematically compared with detailed analytical or numerical models. Three potential areas of study include the ionization of the high-Z species, the magnetic field trapping of the high-Z ions, the effect of the acceleration force on the high-Z ion particle orbits, and finally the effect of SCT lifetime on the final plasma delivered to the target. Understanding of these mechanisms will be crucial in designing the larger, more powerful SCT injectors which will be required for RE mitigation in large tokamak devices, as well as other possible applications.

In non-hydrogenic plasmas, visible spectroscopic techniques offer a powerful tool for the experimental study of the accretion mechanism for the high-Z snowplow effect. The ability to measure visible spectral lines of various ionized plasma species allows the relative axial position of high-Z ions to be measured relative to other plasma quantities such as density and magnetic field strength. In addition, axial measurement of ionized-species emission can determine axial velocities from Doppler shift. Figure 4 compares the visible emission due to singly-ionized helium viewed transversely (without Doppler shift) and axially (Doppler shifted), indicating helium ion velocities of ~100 km/s, comparable to time-of-flight transverse measurements of the magnetic field. The eventual goal is the systematic determination of the distance by which high-Z ions lag behind the peak of CT magnetic field. These results can be directly compared with the results of simulation, allowing development of reliable models of high-Z ion slippage. This will in turn determine the strength of magnetic field which is required for high-Z ions to be accelerated to nearly the same velocity as hydrogenic ions.

As a part of the experiment, benchmarking magnetic PIC codes will enhance the understanding of the physical process.[5] To understand the complex accretion and acceleration issue, benchmarking computational simulation is the most effective path. There is a need to use developed codes or collaborate with computational groups to extend our experimental studies.

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

At present, the tokamak is the MFE confinement device with the parameters closest to those required for a thermonuclear reactor. Although the next-generation tokamak is expected to be able to operate at conditions close to that of a commercial reactor, a major obstacle is the appearance of plasma disruptions, which may result in a rapid loss of stored energy. Runaway electrons, driven by the large electric field inductively produced by the sudden loss of tokamak equilibrium after a major disruptive instability, have the potential to severely damage tokamaks components. Injection of compact toroids of high atomic number (high-Z SCTs) to the magnetic axis of a tokamak should be able to absorb the kinetic energy of runaway electrons by collisions and cooled by Bremsstrahlung radiation, lowering the damaging effects. This protection would not only prevent costly and time-consuming machine damage, but would also free researchers to explore more effective machine operational regimes and capabilities with less concern for avoidance of disruptions. Because SCTs can be produced using noble gas, recovery from a mitigated disruption should be more rapid without major wall gas recycling problems. The overall effect will be to permit more rapid development of the next-generation large tokamaks towards the goal of a commercial fusion reactor, whose societal benefits are clear.

References (Maximum 1 page)

1. Hammer, J.H., J.L. Eddleman, C.W. Hartman, H.S. Mclean, and A.W. Molvik, *Experimental Demonstration of Compact Torus Compression and Acceleration.* Physics of Fluids B-Plasma Physics, 1991. **3**(8): p. 2236-2240.
2. McLean, H.S., D.Q. Hwang, R.D. Horton, R.W. Evans, S.D. Terry, J.C. Thomas, and R. Raman, *Design and operation of a passively switched repetitive compact toroid plasma accelerator*. Fusion Technology, 1998. **33**(3): p. 252-272.
3. Hwang, D.Q., M. Ryutova, and H. McLean, *Penetration of a compressible magnetized plasma object into a low beta target plasma.* Physics of Plasmas, 1999. **6**(5): p. 1515-1521.
4. Degnan, J.H., J. R. E. Peterkin, G.P. Baca, J.D. Beason, D.E. Bell, M.E. Dearborn, D. Dietz, M.R. Douglas, S.E. Englert, T.J. Englert, K.E. Hackett, J. H. Holmes, T.W. Hussey, G.F. Kiuttu, F.M. Lehr, G.J. Marklin, B.W. Mullins, D.W. Price, N.F. Roderick, E.L. Ruden, C.R. Sovinec, P.J. Turchi, G. Bird, S.K. Coffey, S.W. Seiler, Y.G. Chen, D. Gale, J.D. Graham, M. Scott, and W. Sommars, *Compact toroid formation, compression, and acceleration.* Physics of Fluids B: Plasma Physics, 1993. **5**(8): p. 2938-2958.
5. Welch, D.R. and et. al. , *Lsp: a fully electromagnetic, fully relativistic 3D particle-in-cell code for advanced plasma simulations.* Presented at the HEDP Seminar, 2014.

Figures (maximum 1 page)

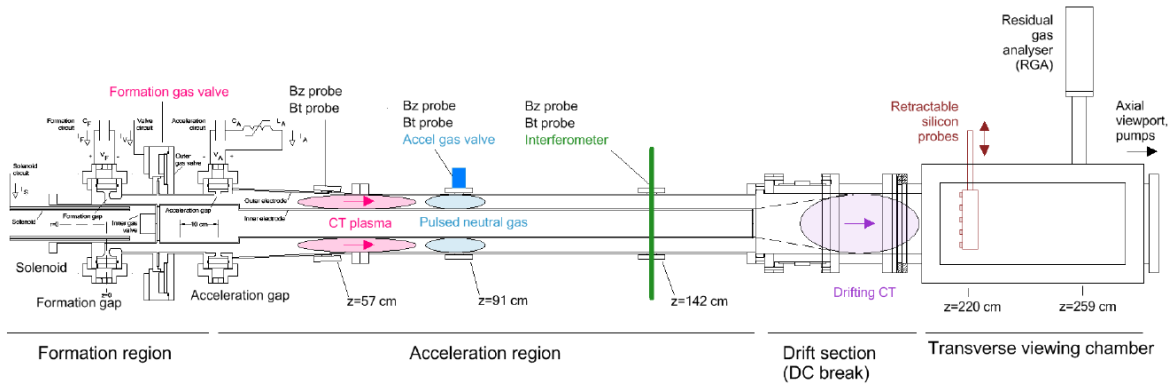
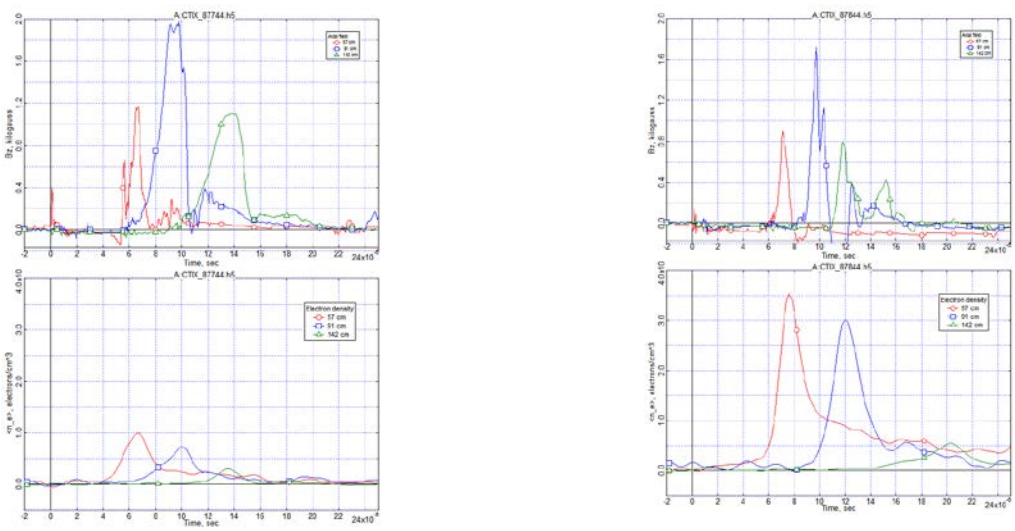


Figure 1: Schematic of CTIX



(a) (b)

Figure 2: Typical CTIX shots at 9 kV formation bank and 9 kV accelerator bank showing increased density due to accelerator-region puffing. (a) Hydrogen formation plasma, no puffing: peak density ~ 1e15 cm^{-3} at z = 57 cm (b) Hydrogen formation plasma, argon puffing; peak density ~3.5e15 cm^{-3} at z = 57 cm.

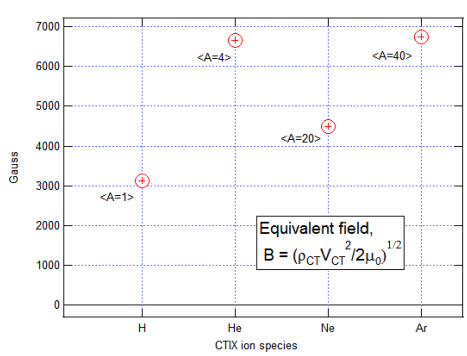


Figure 3: Results of accelerator-puffed operation with hydrogen, helium, neon, and argon in terms of the maximum magnetic field which could be penetrated by the SCT.

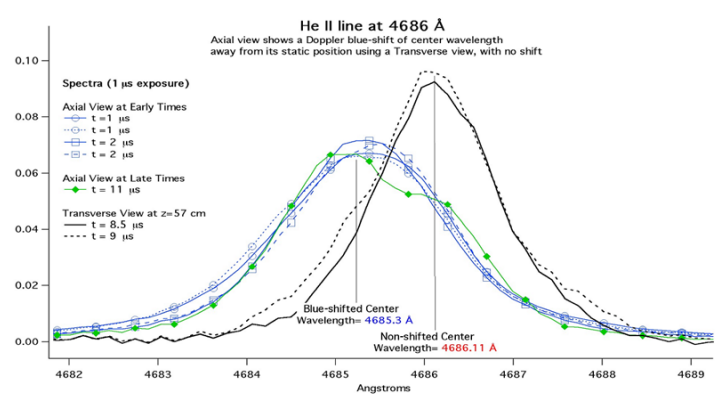


Figure 4: Transverse (black) and axial (blue, green) spectra of singly-ionized helium, showing Doppler shift due to axial velocity of approximately 100 km/s.