White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	***6/19/15***

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	X
Either Oral or Poster	
Will not attend	

Title:	**Toroidal Air Plasmas, a New Paradigm in Self Organizing, Self Sustaining Plasmas**
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- ***Describe the research frontier*** **and importance of the scientific challenge.**

The plasma community is focused on the challenge of forming and sustaining long lived, high density toroidal fusion plasmas using large tokamaks and large magnetic fields. The principles behind this class of plasma formation are largely understood and indicate desirable properties at larger scale lengths. ***Recent work by the PI has shown that a self-organized, self-sustained, self-confined toroidal plasma can be formed in air with lifetimes exceeding 10 ms with a major radius of 5- 10 cm.*** This self-organized lifetime exceeds the electron collision time by 10^6, and likely represents a new class of self-organization. We believe that basic science experiments need to be performed on this self organizing, self-sustained, self-confining plasma, as well as investigation and basic understanding of the plasma physics and the boundary conditions that sustain plasmas past the Bohm criteria on a small laboratory scale. We also believe that the scaling of the self-organized, self-sustained, self-confined toroidal plasma needs to be established by increasing the energy to the formation mechanism. This plasma formation will be simulated, investigated with high speed diagnostics, and scaled to gain an understanding of self organizing plasmas and the mechanisms that allow them to be self sustained.

The University of Missouri-Columbia (UMC) has been investigating techniques for producing self organizing, large volume, long duration, high density atmospheric air, plasma discharges. A self sustaining toroidal air plasma, or TAP, shown in Figure 1, has been developed by restricting the radial expansion of an exploding wire and subsequently accelerating it with a biased, transparent grid in ambient air. The basic research program investigated the formation of the self organizing plasma and the interaction with shock waves. The plasma so generated lasts for 10-12 ms, is formed in open atmospheric air, and does not require an external magnetic field for stability. This has many similarities to a compact toroid, for example formed in a Marshal gun, but typically at much lower pressure. ***Based on our observations and simulations, the plasma has an internal magnetic field that inhibits instabilities and dramatically improves energy confinement.***

To form the toroid, an exploding wire plasma is injected into a gridded structure or acceleration section which forms the boundary conditions for subsequent formation of the toroid. This secondary electrode is held at 250-300 V by a DC charged 8.8 mF electrolytic capacitor bank. When the plasma closes the gap between this acceleration region, the secondary capacitors discharge their stored energy through the plasma. The bulk of the plasma then exits the accelerator region, detaches from the fixture and forms the TAP, 500-1000 us after the wire explodes.

Without the accelerator region, the toroid shape does not consistently form, greatly affecting the duration of the discharge beyond detachment. Over a 20 ms period, the TAP travels approximately 60 cm, with a stable velocity of 25-35 m/s. Additionally, as shown in the last image of Figure 1, the plasma maintains its toroid shape 11 ms (or more) beyond wire vaporization. We have also injected the plasma toroid at 20-25 m/s into a quadrupole magnetic field and the resulting plasma collapse has been verified as shown in Figure 2.

Self sustaining, self organizing plasmas of this type may hold the future for long lifetime plasma physics once the chemistry, boundary conditions, and instability scaling are understood.

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

We propose to assemble a team to investigate the self organizing plasma effect using laboratory experiments and simulations. The TAP will be investigated up to atmospheric pressurein various gases and in reduced atmospheric conditions. Experiments will be conducted to probe the plasma. These include advanced chemistry experiments, perturbation of the plasma with shock waves, laser and microwave interferometry, Schlieren, magnetic mapping, high speed photography and time resolved diagnostics. The effect of the circuit and the energy transport rates into and out of the TAP will also be explored.

The team will develop hydrodynamic models integrated with fluid models coupled with experiments to understand, and develop a basic physics multidisciplinary understanding at the macroscopic and microscopic levels that allow the effects seen in the TAP to be used for fueling of Tokamaks for fusion energy.Additional applications may include low temperature plasmas for biomedical, semiconductor fabrication and deep space exploration.

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

The stability of a plasma to hydrodynamic instabilities (HI) such as the Rayleigh-Taylor, Richtmyer-Meskov (RM), and Kelvin-Helmhotz instabilities is important in many high energy density (HED) applications such as in astrophysics and fusion. In the case of fusion power, these instabilities have proven to have a larger role in performance degradation in experiments at the National Ignition Facility (NIF) than expected. It has been shown that ***in the presence of external and self magnetic fields the stability of a plasma can be improved*** but understanding these magnetic effects poses a challenge to the development of alternative fusion paths such as magnetized liner inertial fusion. In the presence of a magnetic field it has been shown that a perturbed plasma can be stable to this shock interaction. A similar response may be responsible for the stability of the TAP. Two low resolution simulations were run using the Flash code to show how MHD effects can damp the growth of instabilities on an atmospheric toroidal plasma. These are simplified 2D simulations which used a constant low strength magnetic field (Plasma Beta 316) directed along the z direction (out of the 2D plane) everywhere. The simulations were run with no viscosity or diffusion models included. Figure 3 below shows the initial conditions for the simulations. Due to the round shape of the interface not all the vorticity is conducted away from the interface in MHD shocks. Instead some vorticity remains near the edges but it is greatly diminished. The remainder of the imparted vorticity is transported to the interior of the toroid where it cannot mix the fluid. Overall, the toroid remains stable with the magnetic field at late times similar to the observed TAP behavior when directed at a shock wave from a large area shock tube, (Figure 3). Based on our experiments and the initial simulations, we have formed a field reversed configuration without external fields.

Impact: The proposed basic plasma physics program will have a significant impact on the ability to form, contain, and maintain self-assembling plasmas, inproving understanding of energy confinement and stabilization mechanisms in a broad range of parameters of practical interest and utility.

Societal Benefit: The benefit of this program go well beyond energy applications, and will enhance biomedical applications, sterilization technology, water purification, deep space exploration, fabrication of semiconductors.

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Figures and Graphs

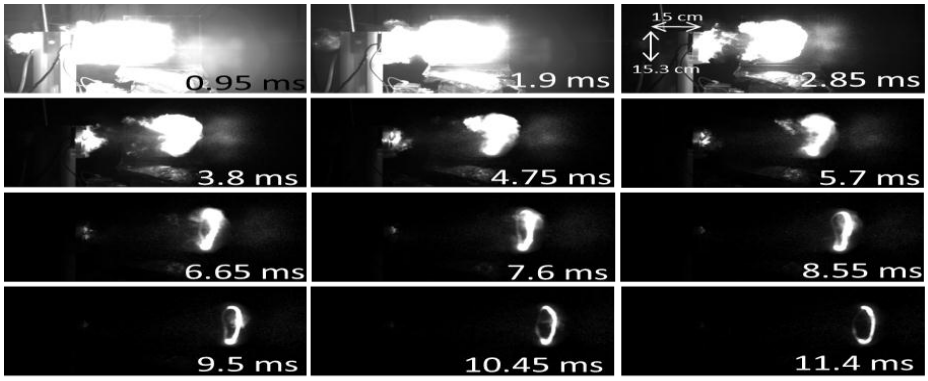

Figure 1. High Speed Photograph of the Plasma Toroid versus time and distance traveled

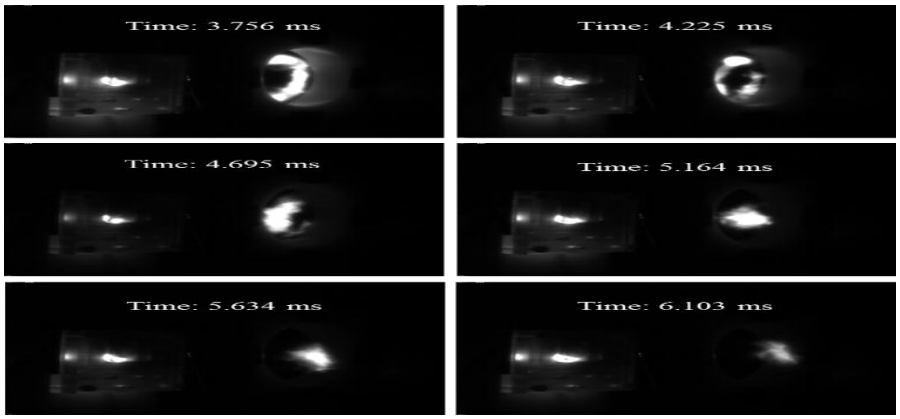

Fig. 2. High Speed images of the TAP passing through the magnetic quadrupole (from ~45º from the axis of travel) and photograph of test fixture.

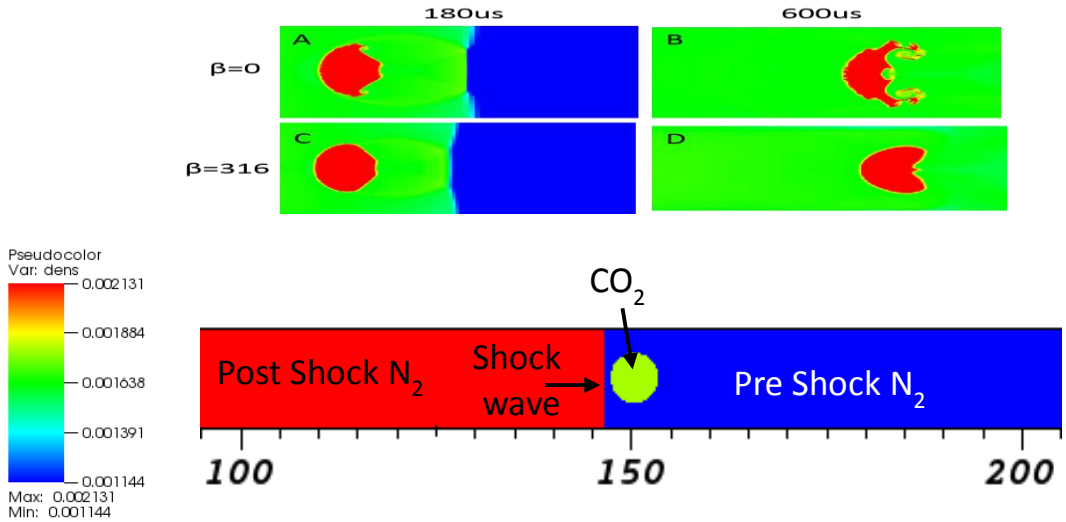

Figure 3: Density pseudocolor plots for the toroidal plasma with and without a magnetic field at early and late times after shock interaction.