White Paper for *Frontiers of Plasma Science Panel*

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	"P", "S"
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• Turbulence and transport	
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• Plasma self-organization	P
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Title:	Self-organization of Microplasmas in Cathode Boundary Layer Discharges in Noble Gases and Gas mixtures
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Self-organization of Microplasmas in Cathode Boundary Layer Discharges
In Noble Gases and Gas mixtures

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- ***Describe the research frontier*** **and importance of the scientific challenge.**

Self-organized pattern formation has been observed in various areas including biology, chemistry, mathematic and physics. In electrical transport systems, self-organization was observed in e.g. magnetically confined plasmas, arc discharges, longitudinal discharge tubes, dielectric barrier discharges (DBDs) and cathode boundary layer discharges (CBLDs). These electrical discharges present physical systems which both show different processes of pattern formation and allow for a good theoretical and experimental treatment. Compared to self-organization of high temperature plasmas, self-organization of non-thermal microplasmas at elevated to atmospheric pressures are less understood, probably due to the complex environment they present.

Cathode boundary layer discharges (CBLDs) differ from conventional plane-to-plane plasma devices as the anode side is open with no obstruction for the light and reactive species generated within the plasma cavity. A schematic diagram of the CBLD is shown in Figure 1. They can be operated in various atomic and molecular gases up to and beyond atmospheric pressure, although self-organized pattern formation was only observed experimentally in heavy noble gases (Xe and Kr) up to this point (see exemplary images in Figure 2 [1]), with high purity xenon being the easiest self-organization forming medium. Due to the asymmetry of the electrode arrangement (i.e. anode opening versus plenary cathode), modeling of this kind of discharges is rather challenging. Most of the modeling work is still limited to the plane-to-plane structure. Modeling work by Benilov on a plane-to-plane structure suggests that these patterns should be observed in other noble gases too [2], but the onset pressure to observe self-organized pattern formation is inversely related to the atomic number of the noble gas. These claims are yet to be confirmed experimentally.

Furthermore, preliminary results indicate that self-organized pattern may form only on particular cathode materials (such as molybdenum, tungsten, titanium and silver, etc.) [3]. Table 1 summarizes the appearance of self-organization on a few cathode materials tested so far. Cathode properties such as conductivity, secondary electron emission coefficient, and magnetic permeability were not considered carefully, if at all in modeling work. Better understand this information may guide the design of the plasma reactors targeting at particular applications where self-organization may or may not be desired.

Preliminary results also indicate self-organized plasma spots confined to predefined cathode patterns is possible. Figure 3 shows the plasma spots formed in a thermally damaged region on a molybdenum cathode. Despite most of the research on self-organization in CBLD used circular openings, periodic appearance of plasma spots was also observed in an elongated square trench (with a length-to-width ratio as high as 130) with a blank molybdenum cathode [4]. At pressure below 100 Torr in xenon, the locations of the single-filed spots were rather predictable. The control of the location of the plasma spots is extremely important for applications such as periodic signal modulation by the plasmas.

Mixture of noble gases or noble gas with molecular gases may lead to other interesting pattern formation which may result in better control of the light emission and local reactive species generation. This however is not yet explored extensively.

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

To advance the current research in self-organized pattern formation in CBLD in noble gases and noble gas mixtures, we intend to approach in the following ways:

1. Work closely with modelers (Prof. Pedro Almeida and Prof. Benilov) on incorporating cathode material properties into their "self-consistent model of DC glow discharge" model to better predict the pattern formation in CBLD. We also intend to develop in-house modeling via COMSOL multiphysics.
2. Design and manufacture novel CBLD reactors to increase the number density of high energy electrons as well as their dwelling time in the plasma reactor, by for example, mechanically polish the cathode to mirror-like surface, or adding an additional dielectric layer on top of the anode. This will certainly be communicated to the modelers to be included in the consideration of the models.
3. Purposely predefine patterns on cathode surface and further explore elongated square trench structure to better control the location of the plasma spots.
4. Explore the mixture of noble gases and noble gas with molecular gases and pattern formation.

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

Although this research is focused on self-organization in CBLD, the research results may help understand self-organization in other plasma systems, or even in other disciplines. The size of these plasma spots inversely scale with pressure and may reach a few tens of or even single digit microns in diameter at atmospheric pressure. Each spot is a strong vacuum ultraviolet light emitter, which may be used for maskless pattern transfer to certain materials. The regular appearance of the patterns may be used for small signal modulation.

Furthermore, this research will be carried out at Saint Peter's University – a Hispanic serving liberal art university. Research opportunities will be presented to exclusively to (underrepresented minority) undergraduate students for them to experience this research frontier. Being exposed to this research in their undergraduate years, will likely increase their interest in the plasma science area, which will in turn lead to their further study or work in the area of plasma science in general and help advance this field.

References (Maximum 1 page)

[1] W. Zhu. Self-Organized Pattern Formation in Cathode Boundary Layer Discharges in Xenon and Krypton. In proceeding of the 8th International Workshop on Microplasmas, May 11-15, 2015, Newark, NJ, USA

[2] M.S. Benilov. Multiple solutions in the theory of dc glow discharges and cathodic part of arc discharges. Application of these solutions to the modeling of cathode spots and patterns: a review. Plasma Sources Sci. Technol. 23 (2014) 054019

[3] P. Niraula. Experimentation and Modeling of Self-Organization in Cathode Boundary Layer Discharge in Noble Gas. Undergraduate Honor Thesis, 2015. Saint Peter's University, Jersey City, NJ, USA

[4] W. Zhu, N. Takano, K.H. Schoenbach, D. Guru, J. Mclaren, J. Heberlein, R. May and J.R. Cooper, Direct Current Planar Excimer Source, Journal of Physics D: Applied Physics, 40 (2007) 3896

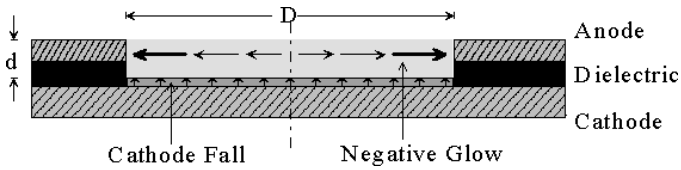

Figure 1. A schematic diagram of the cathode boundary layer discharge (CBLD).

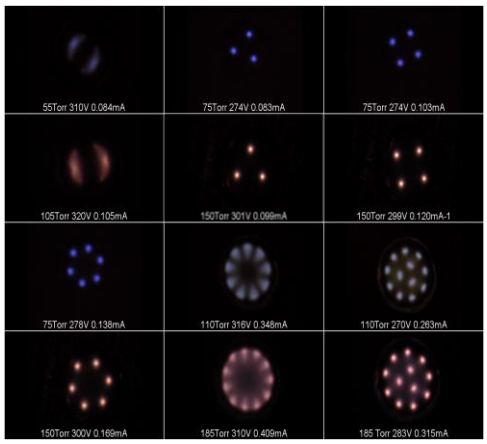

Figure 2. Exemplary self-organization photos of microplasmas in CBLD in xenon (1st and 3rd rows) and in krypton (2nd and 4th rows)

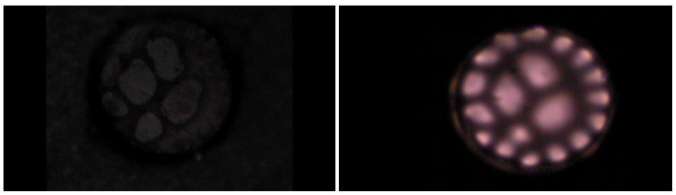

Figure 3. Plasma spots form in thermally damaged regions on the cathode.

Element	Work Function (eV)	Self-Organization
Aluminum (Al)	4.28	Not Observed
Copper (Cu)	4.65	Not Observed
Hafnium (Hf)	3.9 ± 0.1	Observed
Molybdenum (Mo)	4.6 ± 0.15	Observed
Silver (Ag)	4.26	Observed
Titanium (Ti)	3.96 ± 0.04	Observed
Tungsten (W)	4.55	Observed
Zinc (Zn)	4.33	Not Observed

Table 1. Summary of self-organization in xenon on different cathode materials