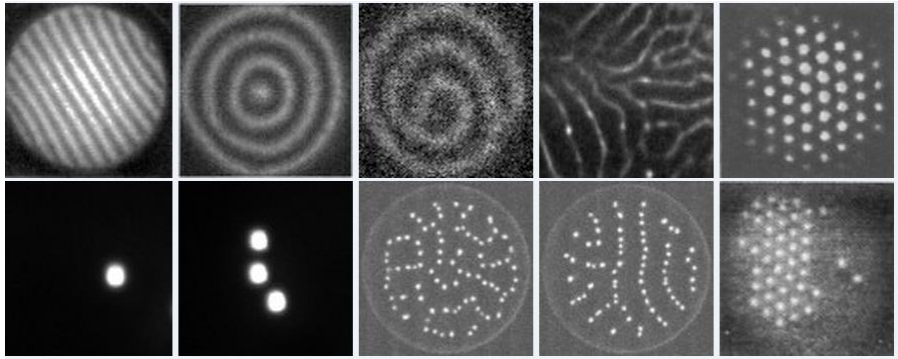
Self-organization of Microplasmas in Cathode Boundary Layer Discharges in Noble Gases and Gas Mixtures

Wei-Dong Zhu

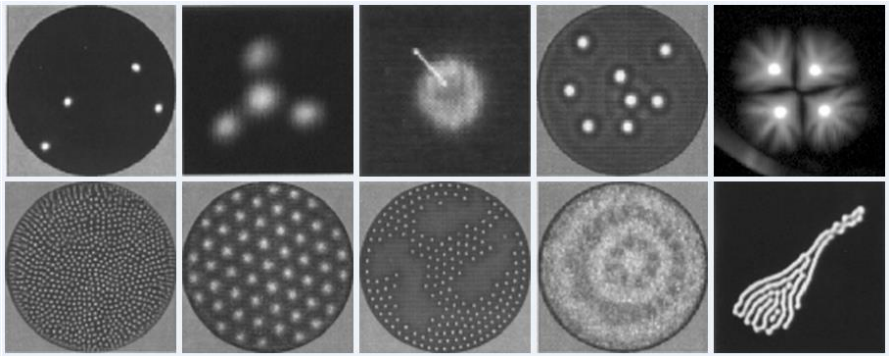
Department of Applied Science and Technology
Saint Peter's University, Jersey City, NJ, USA

Introduction

Self-organized quasi-static patterns were observed on the electrodes of gas discharge and have been studied for some time by now.

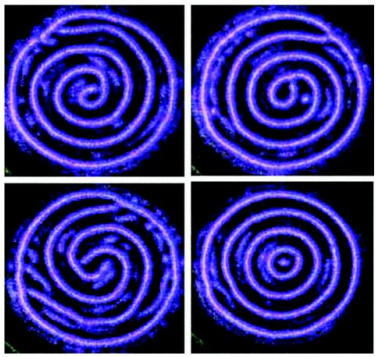


H.-G. Purwins *et al.* (dc, planar gas-discharge system with high-ohmic barrier)



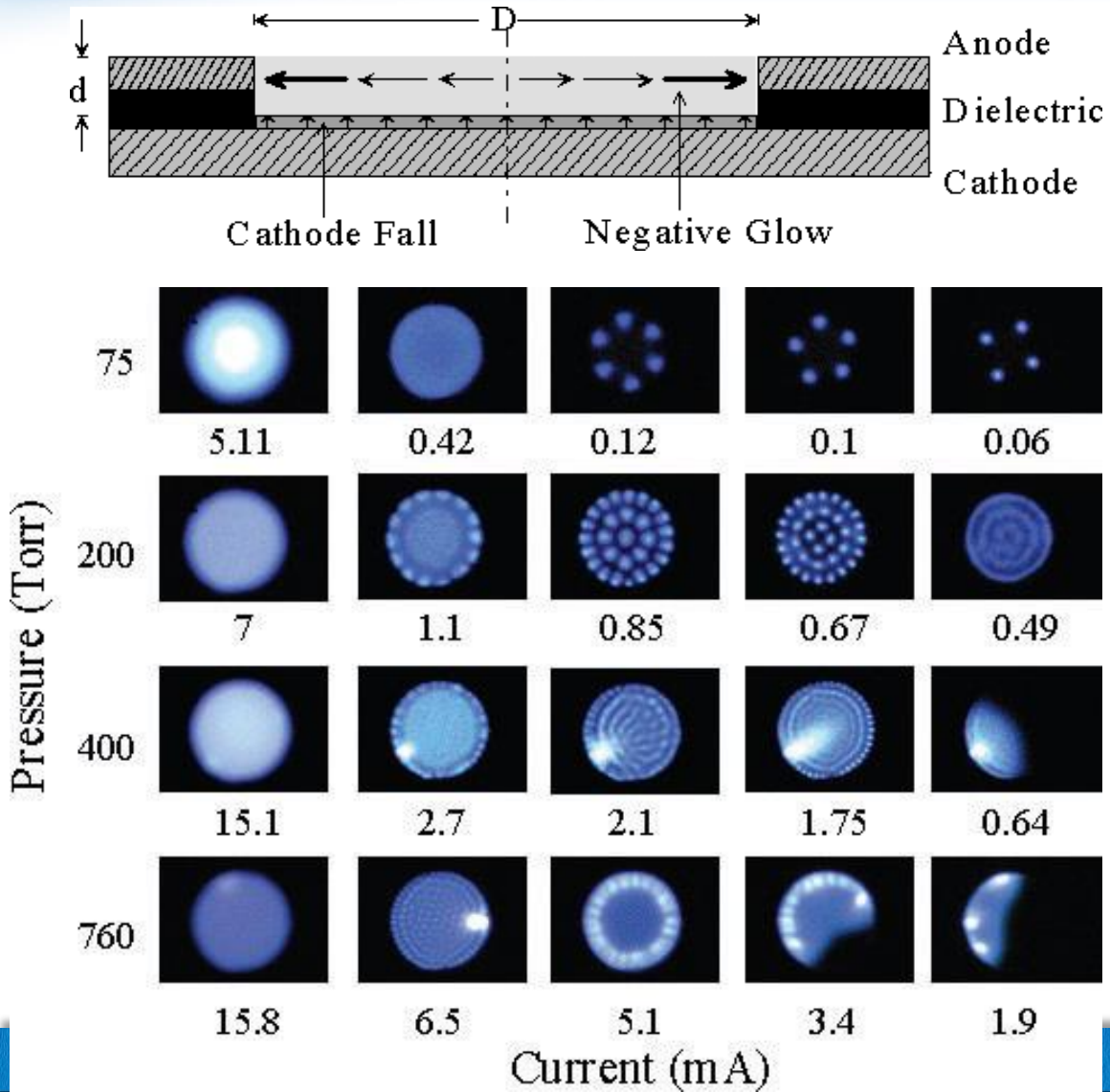
H.-G. Purwins *et al.* (ac, dielectric barrier discharge)

A.M. Astafiev *et al.* (dc, pin to water electrode)



L. Dong *et al.* (ac, dielectric barrier discharge with water electrode)

Self-organized Pattern in Cathode Boundary Layer Discharge (CBLD) - History



Anode: Molybdenum

Dielectric: Al_2O_3

Cathode: Molybdenum

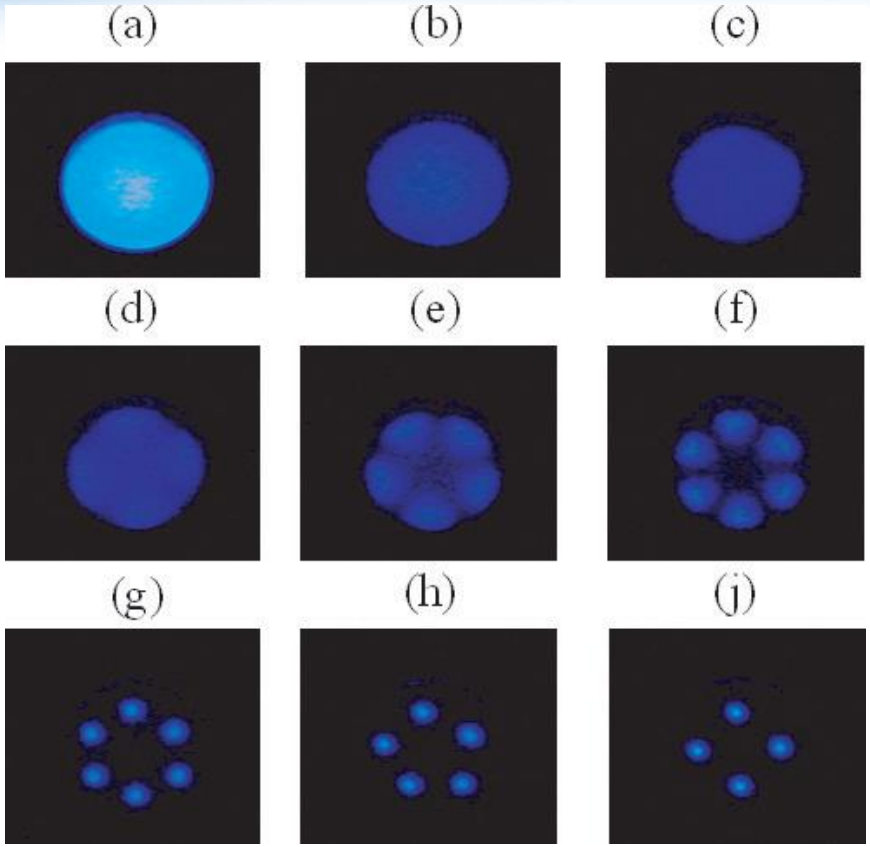
Anode opening: 0.75 - 1.5 mm

Xenon purity: 99.999%

Base pressure: 0.1 mTorr

Schoenbach et al., Plasma Sources Sci. Technol. 13 (2004) 177–185

Three Modes of Self-organized Pattern in CBLD in Xenon



Homogeneous Mode

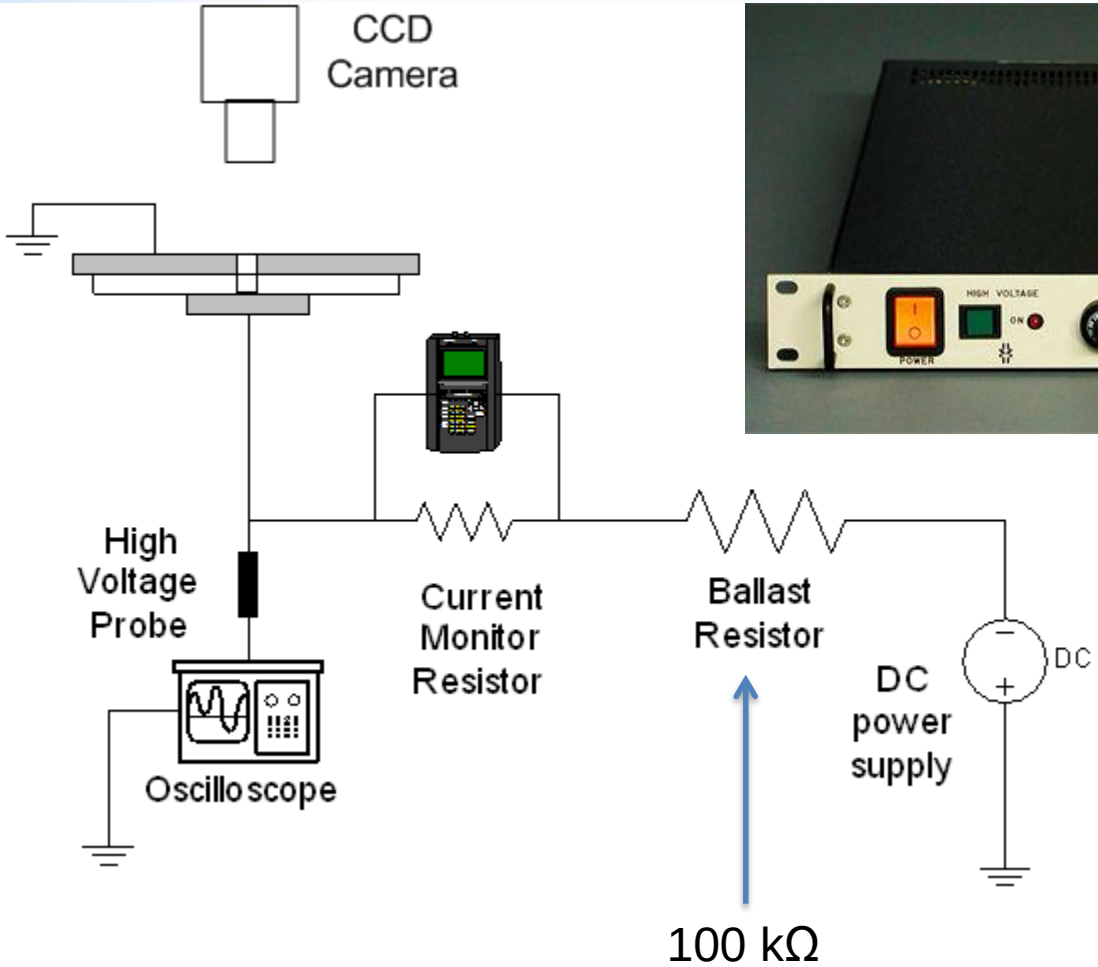
Diffuse Mode

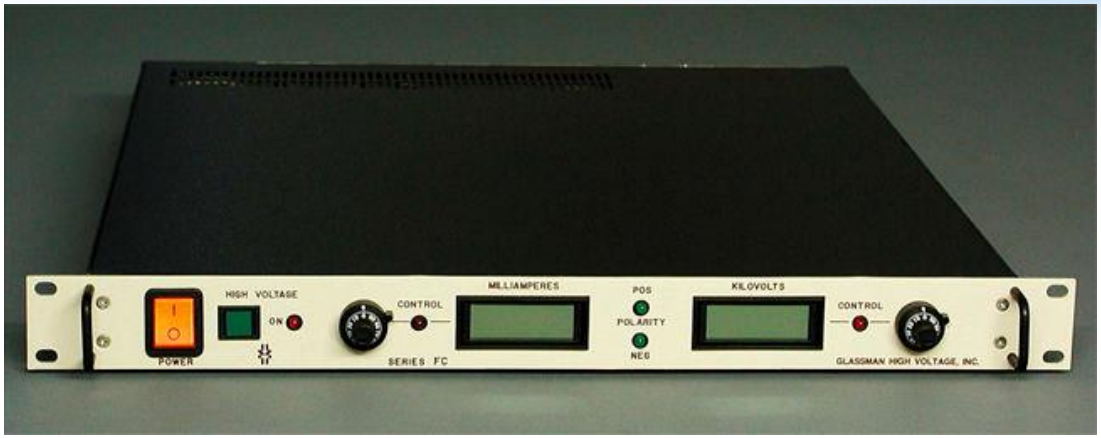
Confined Mode

Pressure: 75 Torr; Opening size: 0.75 mm

Takano et al., Plasma Sources Sci. Technol. 15 (2006) S109–S117

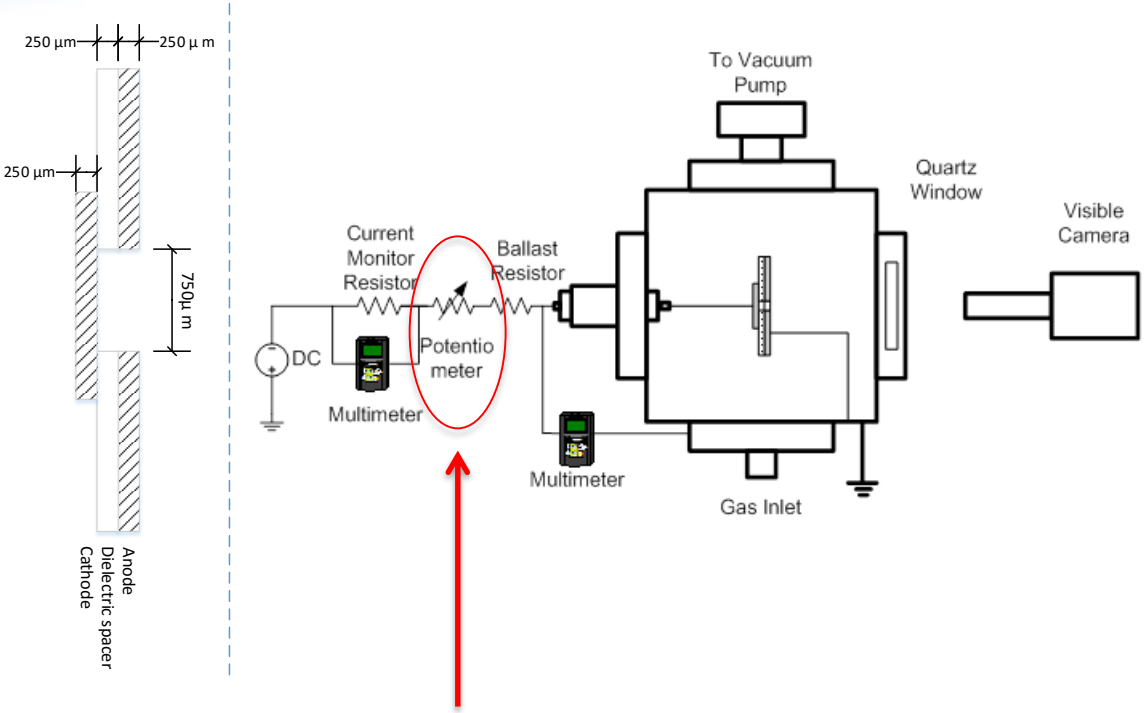
Prior Plasma Current Modulation



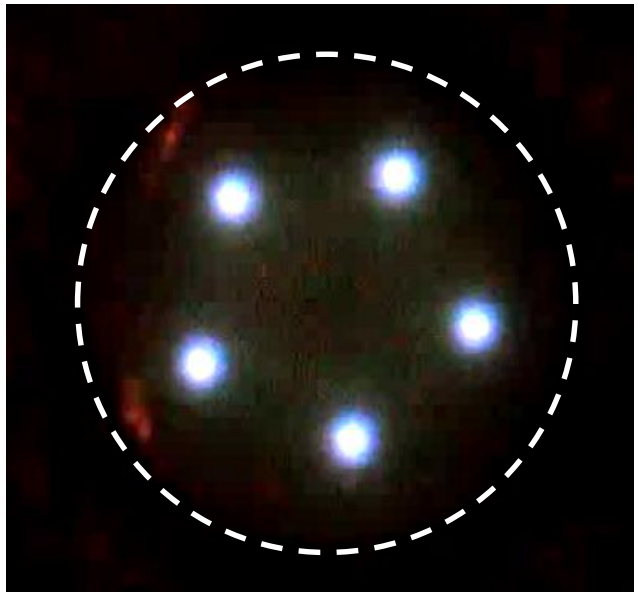


Current modulation through power supply built-in potentiometer – on the scale of tens of μA.

Fine Control of Discharge Current

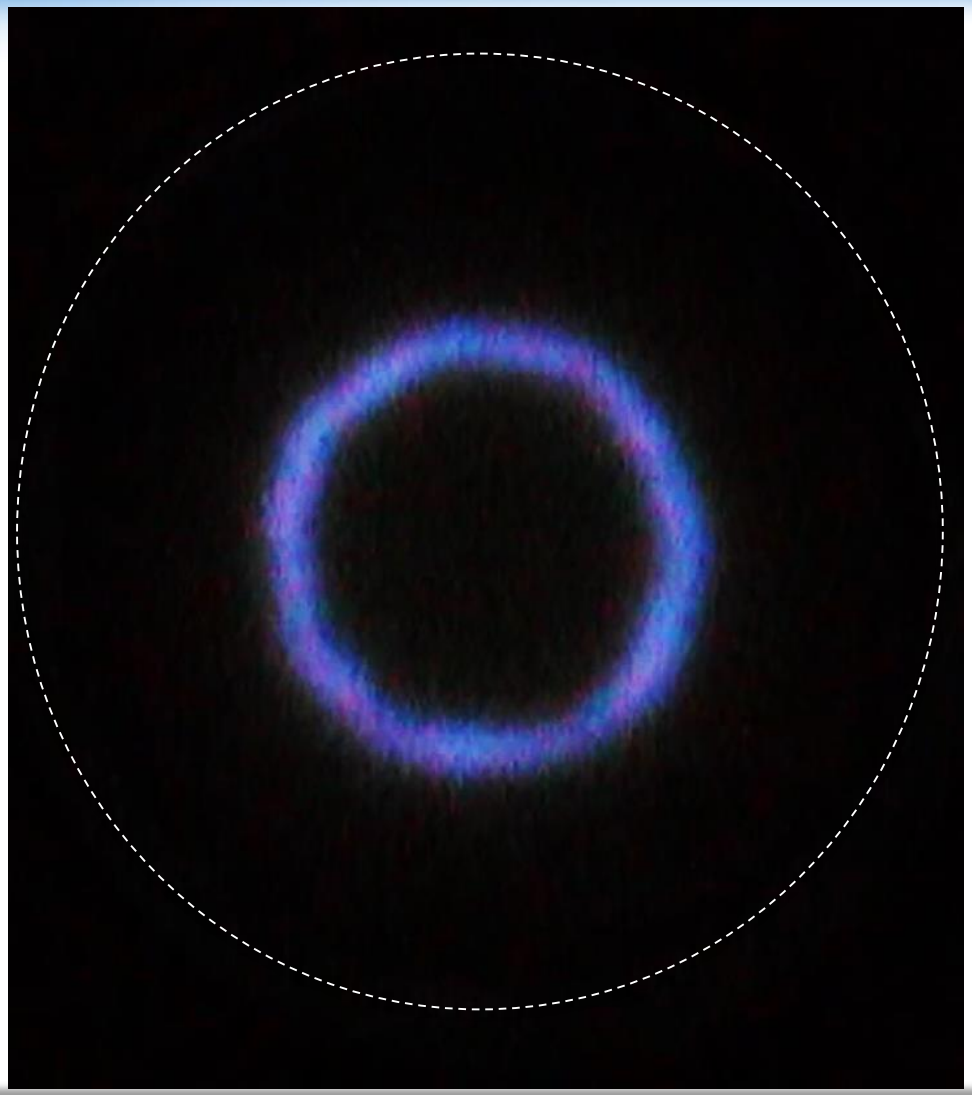


- Gas: xenon (99.999%)
- Base pressure: 0.3 mTorr
- Working Pressure: 75 Torr
- Images/videos taken with a Panasonic CCD camera (30 fps) with a telescope lens



Two 200 kΩ potentiometer added in series with the circuit → can adjust discharge current on microampere scale.

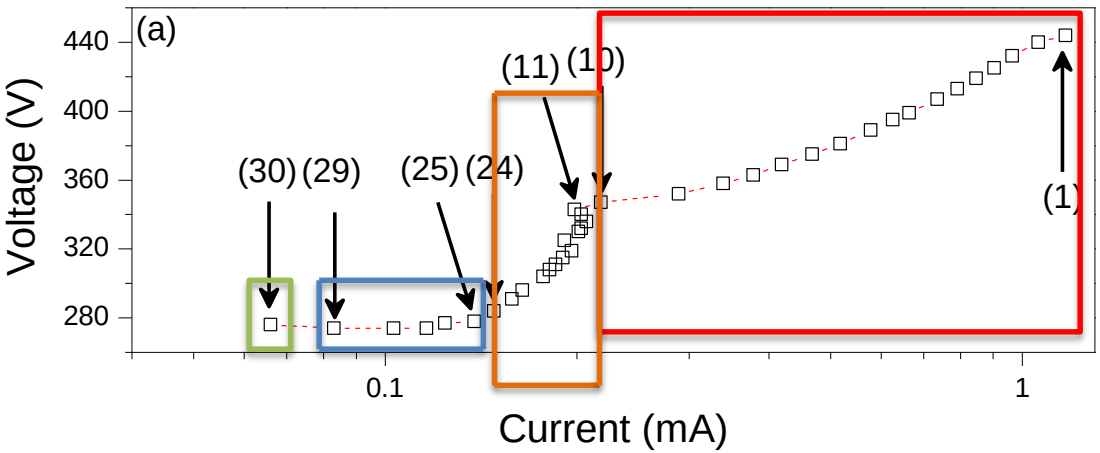
Ring Plasma Mode

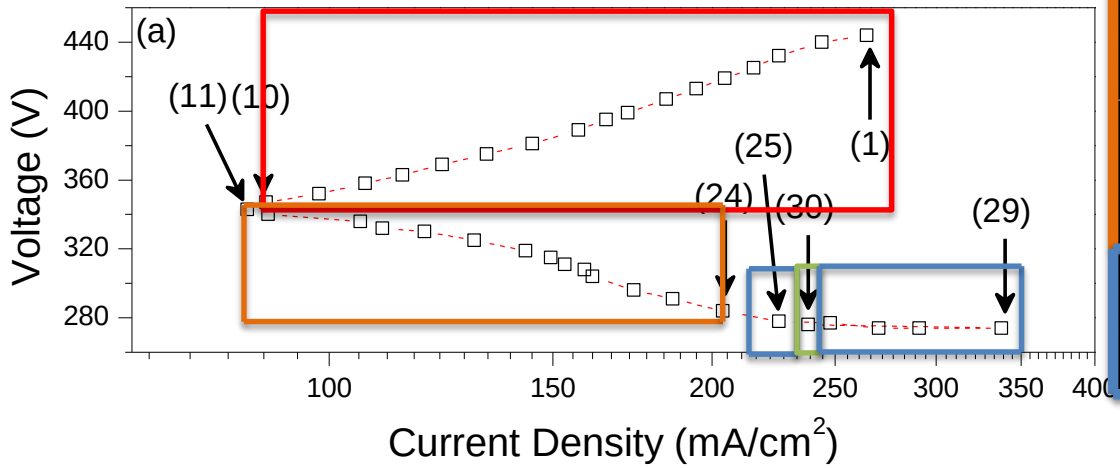


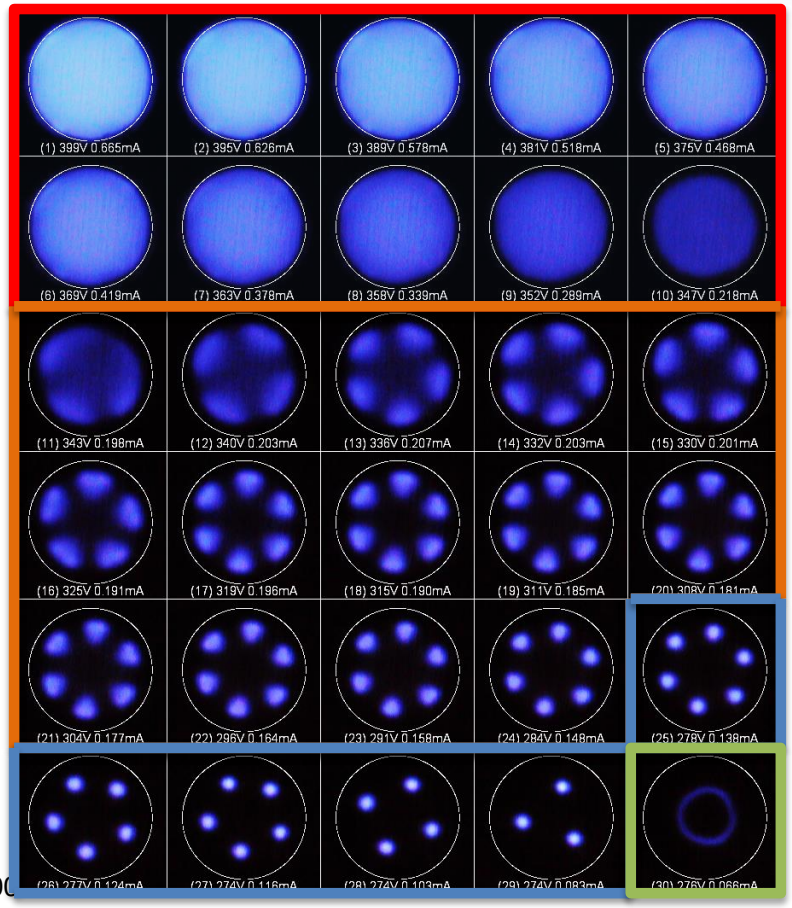
A few important observations

- Ring plasma is detached from the walls
- Ring plasma appears to be steady to naked eyes and the 30 fps CCD.
- The inner and outer diameters of the ring measure approximately 220 µm and 300 µm, respectively at a pressure of 75 Torr.
- The luminescence of the ring is weaker than that from the confined spots.
- Raising current or lowering current by adjusting the potentiometers leads to the extinguishment of the plasma or collapsing to a single spot.

CVC and CDVC

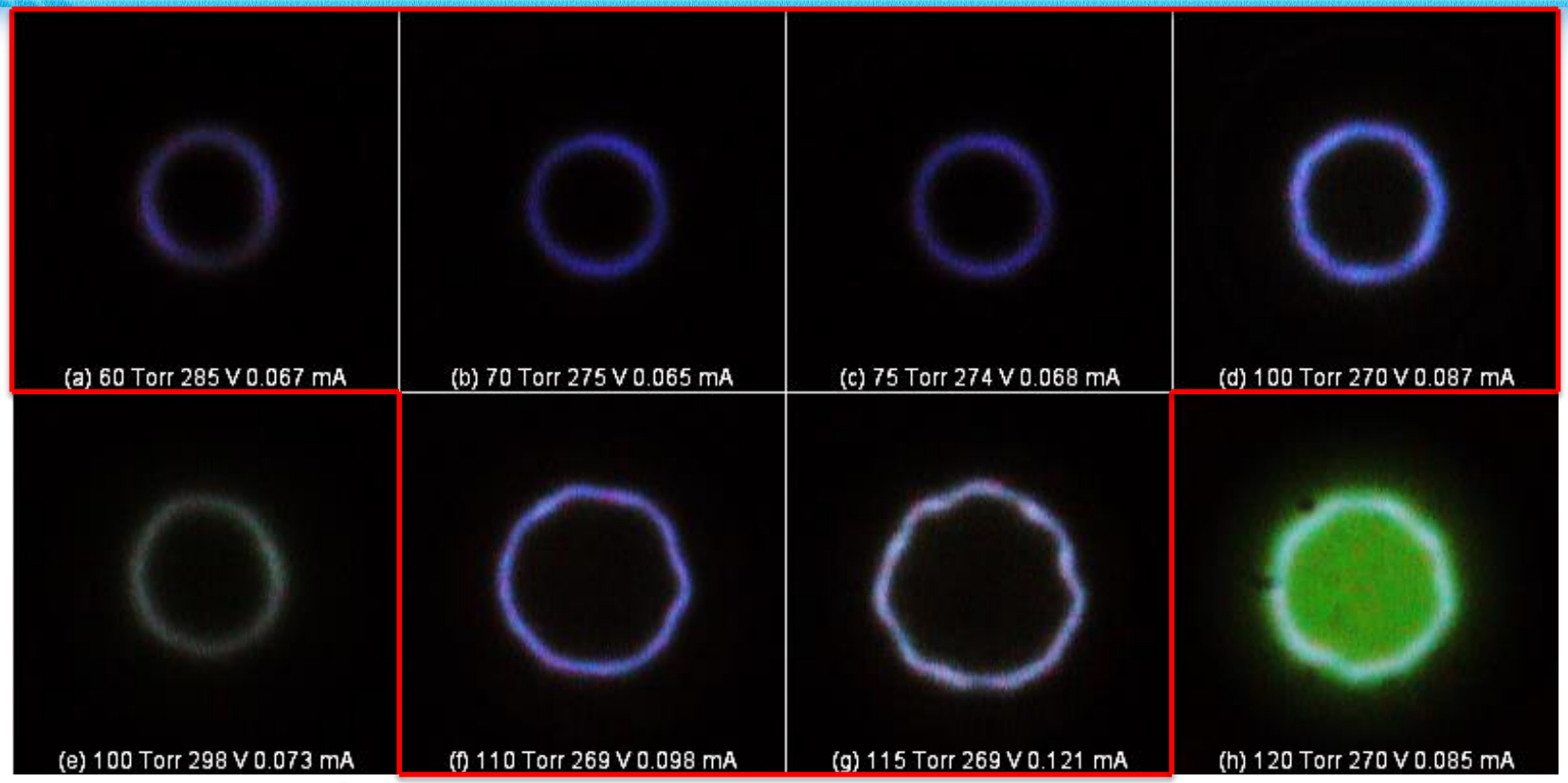






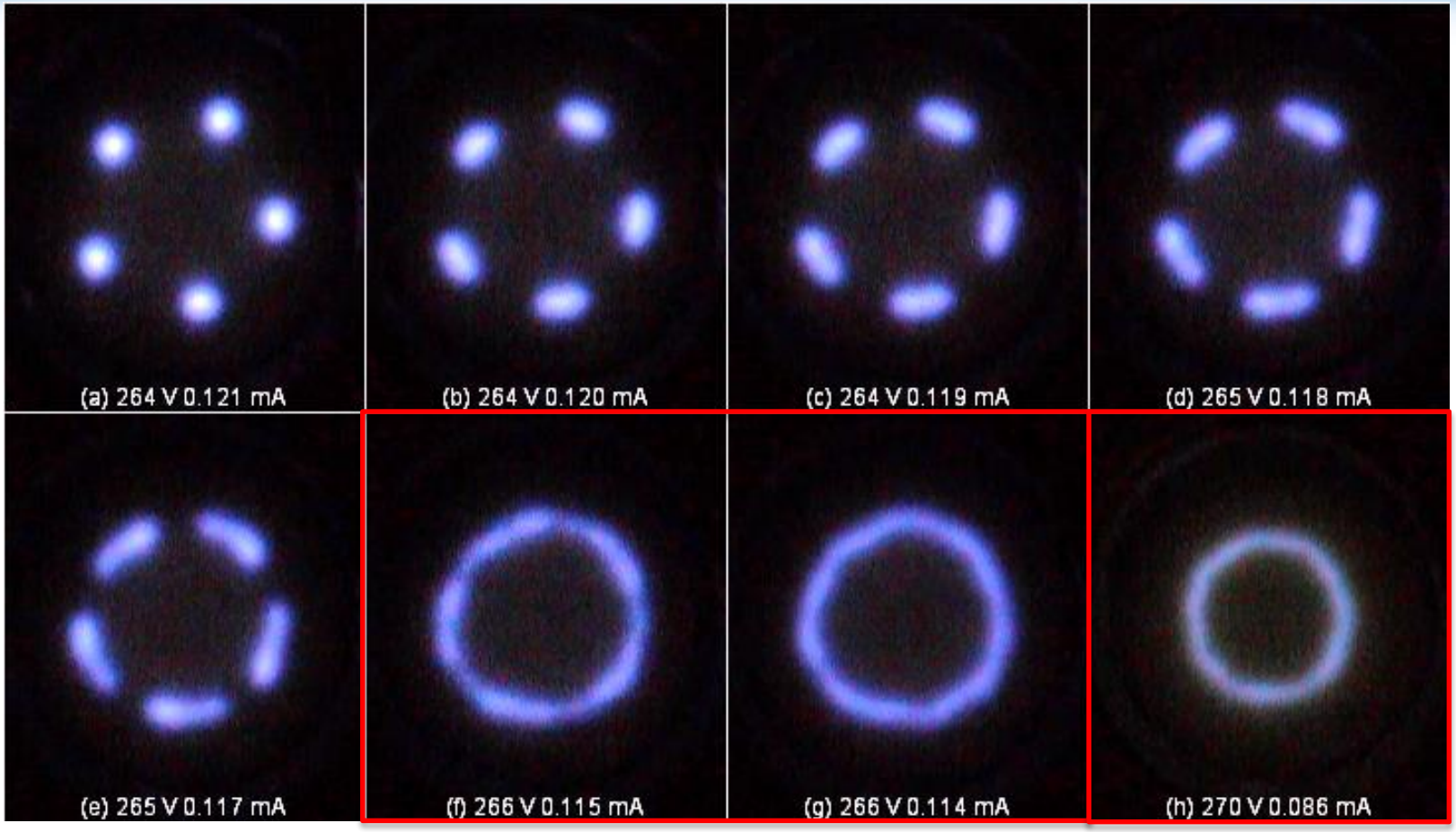
Xenon, Working Pressure: 75 Torr

Ring Plasma at Different Pressures



With 0.5% air impurity Plasma appears to be more greenish!

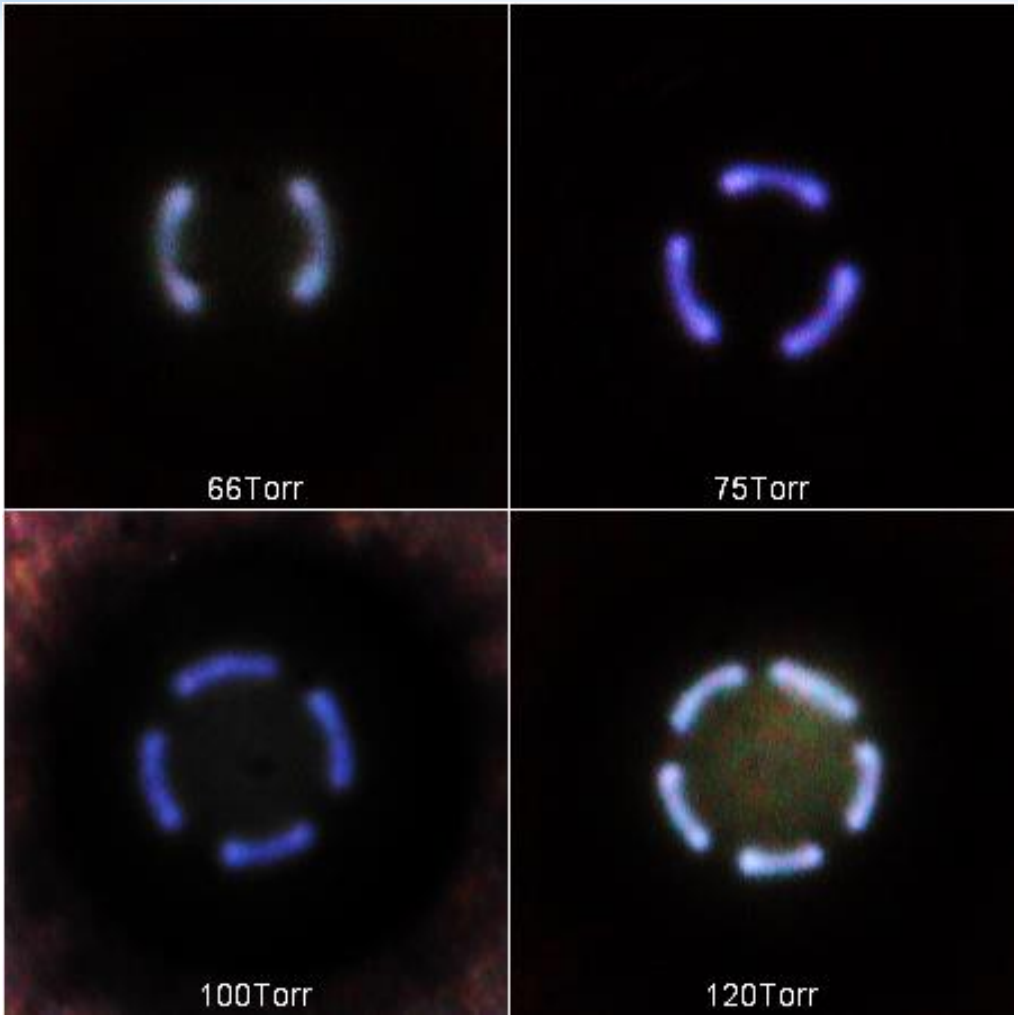
Segmented Plasma Mode (Preliminary)



Ring with nodes, reversible to segmented plasma mode

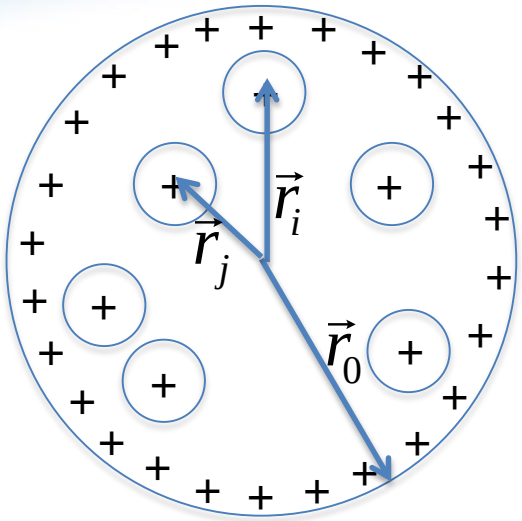
Stable

Segmented Plasma at Different Pressures



- Segmented plasma were observed at different pressures.
- They happen at the transition between the lowest number of plasma spots and the ring plasma mode.
- The lower the pressure, the fewer segment.
- We cannot rule out the motion of spots along each segment at this point

Coulomb Interaction Model (2-D)



$$H = q\sum_{i=1}^{n}\varphi_i = \sum_i \frac{q\lambda r_0}{4\pi\varepsilon}\int_0^{2\pi}(r_i^2 + r_0^2 - 2r_i r_0\cos\theta)^{-1/2}d\theta + \sum_{i\neq j}\sum_j \frac{q^2}{4\pi\varepsilon}\frac{1}{|\vec{r}_i - \vec{r}_j|}$$

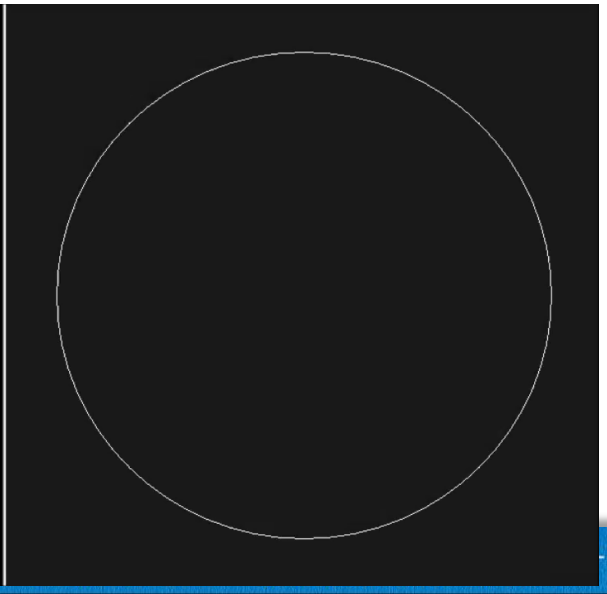
$\varphi_i -$ potential at a distance r_i from the center of the hole

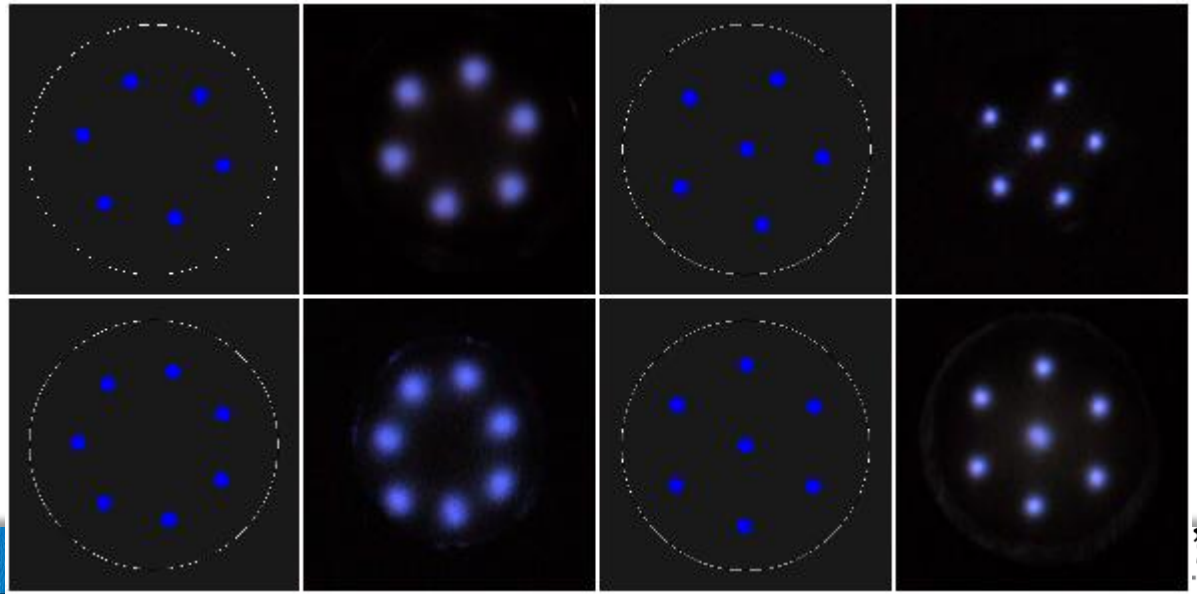
$\lambda -$ linear charge density on the dielectric wall

$\varepsilon -$ permittivity of the medium

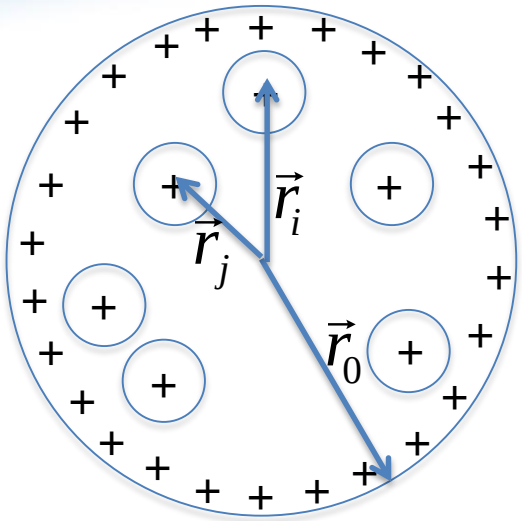
$\vec{r}_{i(j)} -$ position vector of the ith (jth) spot

$r_0 -$ radius of the hole $\quad \theta -$ polar angle





Coulomb Interaction Model (2-D)



$$H = q\sum_{i=1}^{n}\varphi_i = \sum_i \frac{q\lambda r_0}{4\pi\varepsilon}\int_0^{2\pi}(r_i^2 + r_0^2 - 2r_i r_0\cos\theta)^{-1/2}d\theta + \sum_{i\neq j}\sum_j \frac{q^2}{4\pi\varepsilon}\frac{1}{|\vec{r}_i - \vec{r}_j|}$$

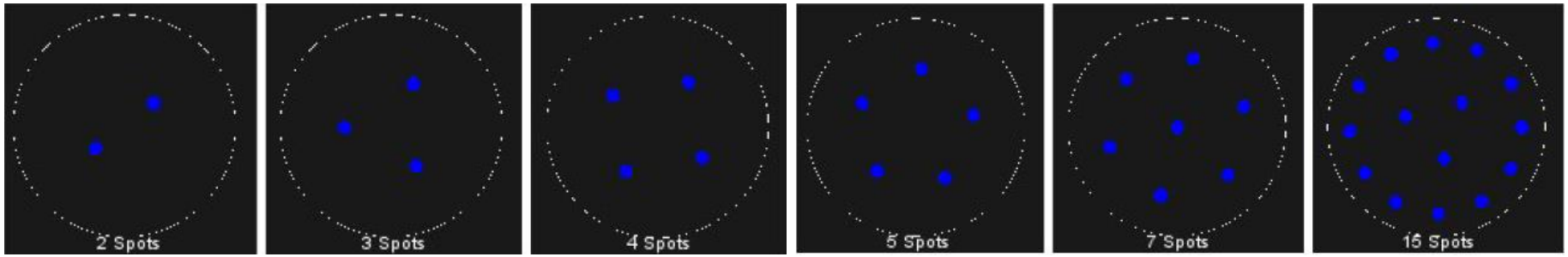
$\varphi_i -$ potential at a distance r_i from the center of the hole

$\lambda -$ linear charge density on the dielectric wall

$\varepsilon -$ permittivity of the medium

$\vec{r}_{i(j)} -$ position vector of the ith (jth) spot

$r_0 -$ radius of the hole $\quad \theta -$ polar angle



Self-Consistent Model of DC Glow Discharge

Considering a single ion species (Xe_2^+, Kr_2^+) and the electrons

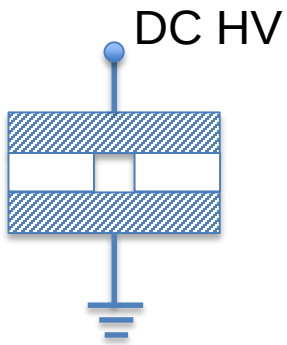
$$\nabla \cdot \vec{J}_i = n_e \alpha \mu_e E - \beta n_e n_i$$

$$\nabla \cdot \vec{J}_e = n_e \alpha \mu_e E - \beta n_e n_i$$

$$\vec{J}_i = -D_i \nabla n_i - n_i \mu_i \nabla \varphi$$

$$\vec{J}_e = -D_e \nabla n_e + n_e \mu_e \nabla \varphi$$

$$\varepsilon_0 \nabla^2 \varphi = -e(n_i - n_e)$$

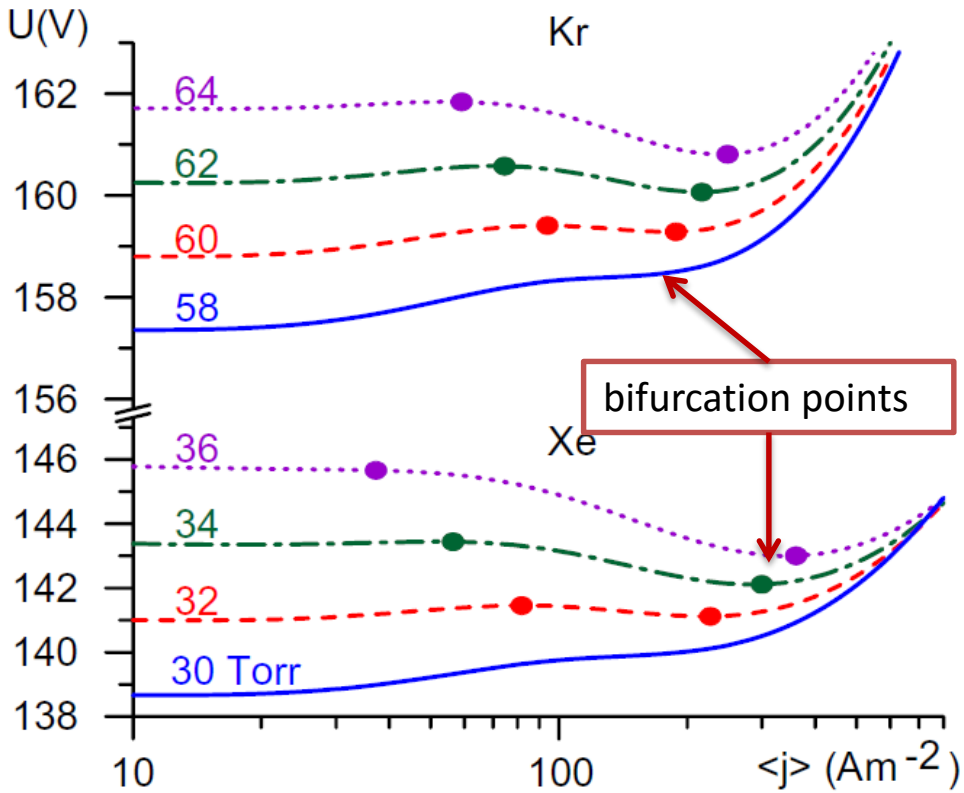


Boundary Conditions:

$$z = 0: \ \frac{\partial n_i}{\partial z} = 0, \ J_{ez} = -\gamma J_{iz}, \ \varphi = 0$$

$$z = h: \ n_i = 0, \ \frac{\partial n_e}{\partial z} = 0, \ \varphi = \mathrm{U};$$

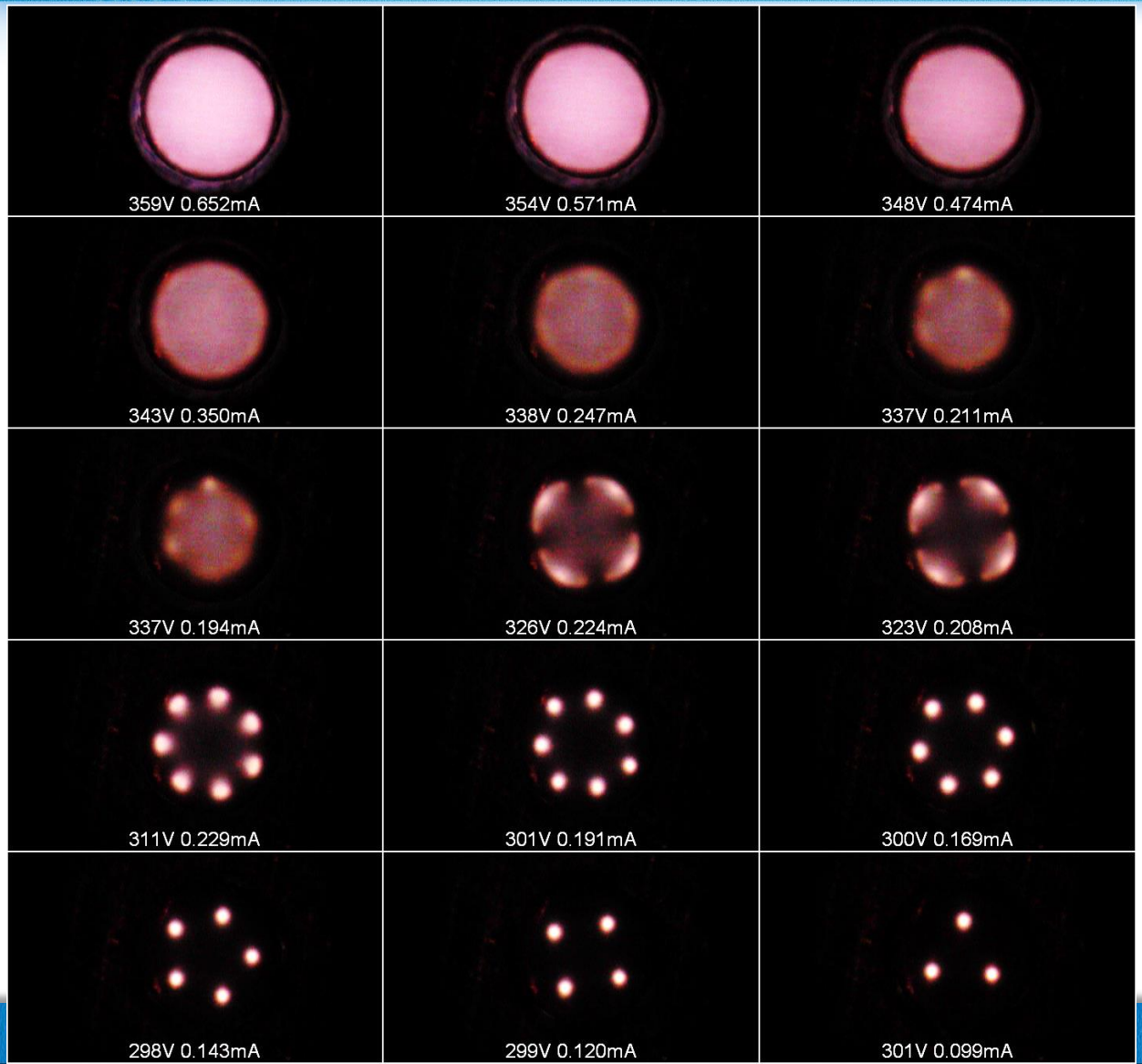
$$r = R: \ \frac{\partial n_i}{\partial r} = \frac{\partial n_e}{\partial r} = 0, \ J_{ir} - J_{er} = 0$$



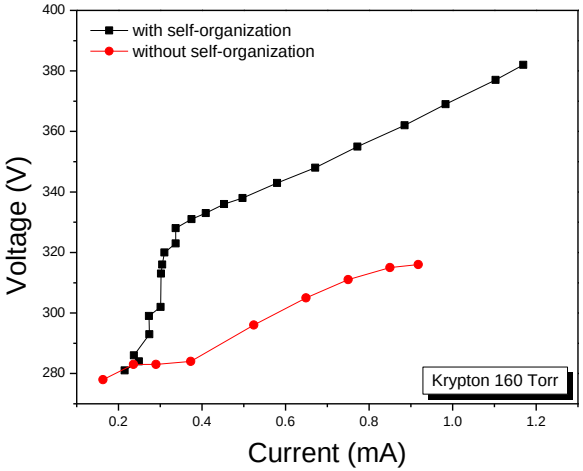
Bifurcation Analysis:
CDVC of the 1D mode, h = 250 μm, R = 375μm.

Zhu et al., 2014, Plasma Sources Sci. Technol. 23 054012
Almeida *et al.* 2009, *J. Phys. D: Appl. Phys.* 42 194010

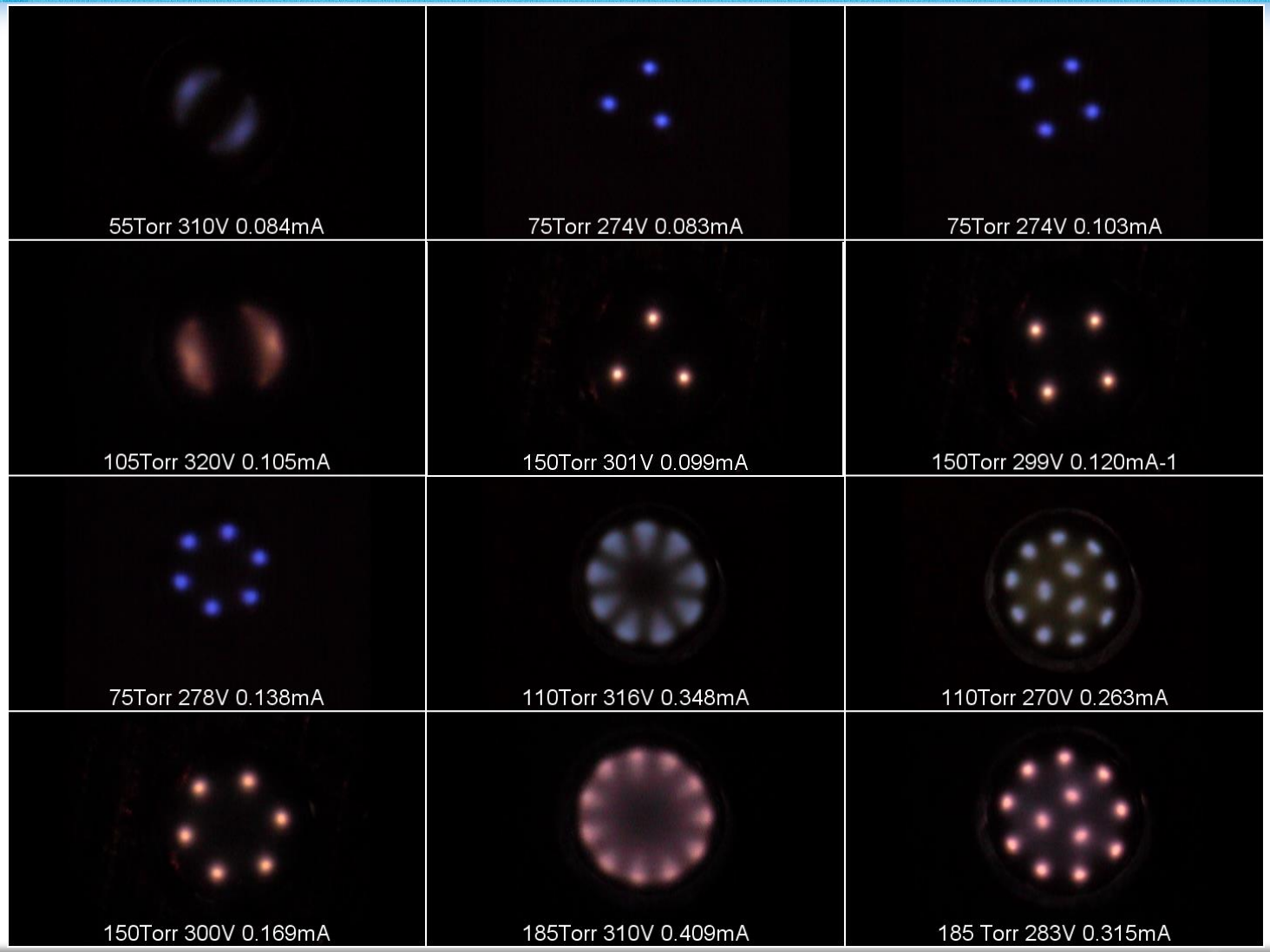
Self-Organization in Kr at 150 Torr



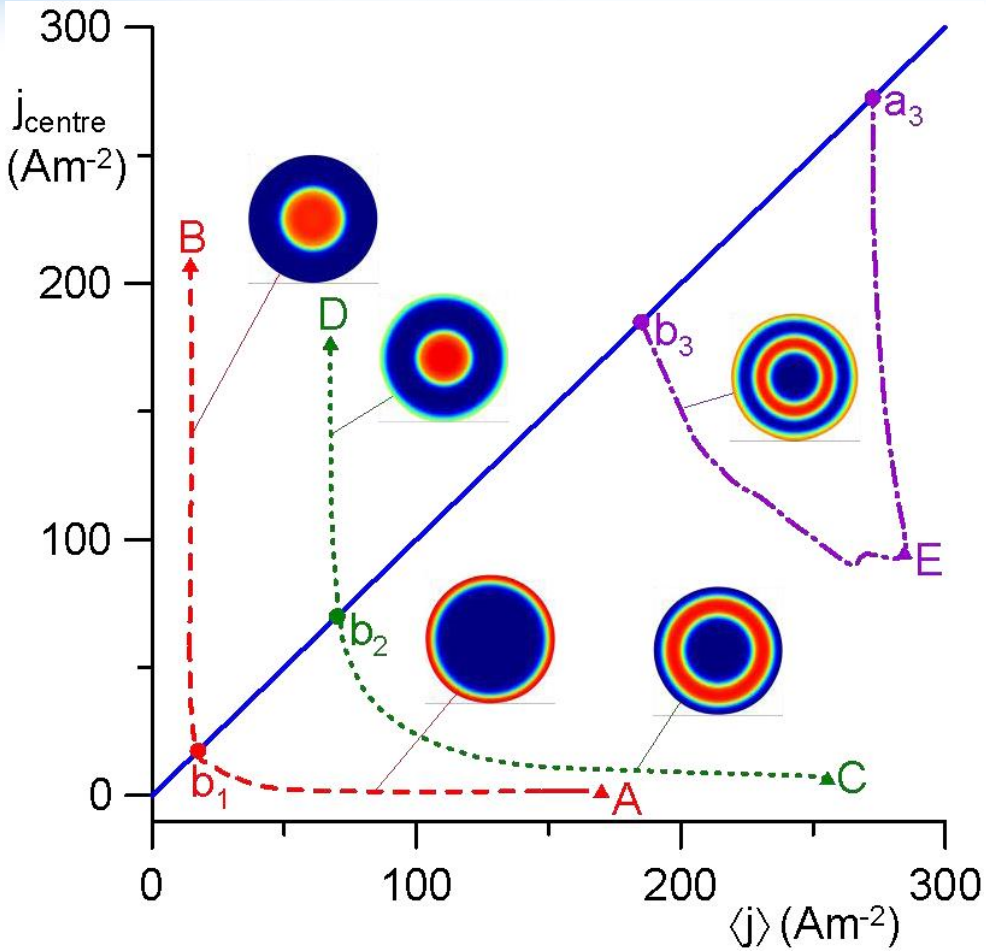
- Harder to produce than in xenon.
- May need cathode pre-treatment with xenon plasma for minutes
- A top dielectric layer to extend the dwelling time of electrons is helpful.



Parallel between Kr and Xe (Pressure Doubling)



Detailed Self-Consistent Model



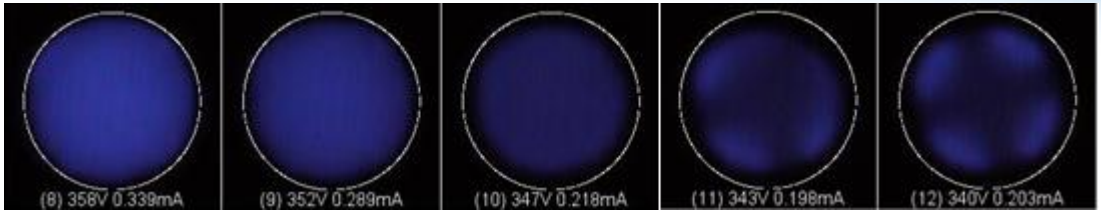
$$Xe + e^- \rightarrow Xe^+ + e^- + e^-$$
$$Xe^* + e^- \rightarrow Xe^+ + e^- + e^-$$
$$Xe_2^* + e^- \rightarrow Xe_2^+ + e^- + e^-$$

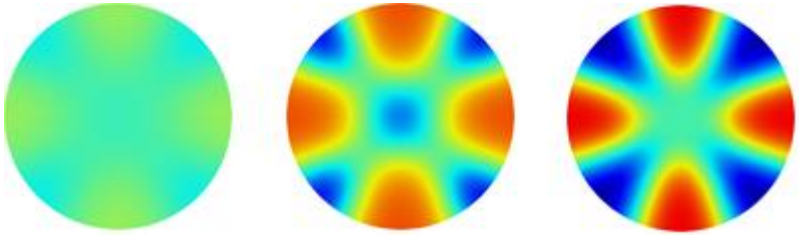
$$Xe + e^- \leftrightarrows Xe^* + e^-$$
$$Xe^+ + Xe + Xe \rightarrow Xe_2^+ + Xe$$
$$Xe^* + Xe^* \rightarrow Xe^+ + Xe + e^-$$
$$Xe_2^+ + e^- \rightarrow Xe^* + Xe$$
$$Xe^* \rightarrow Xe + \phi$$
$$Xe_2^* \rightarrow 2Xe + \phi$$
$$Xe^* + Xe + Xe \rightarrow Xe_2^* + Xe$$

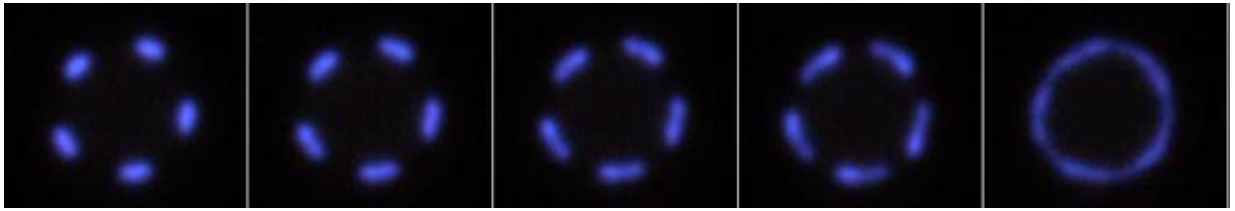
Almeida et al., 2013, *Physics of Plasmas* 20, 102013

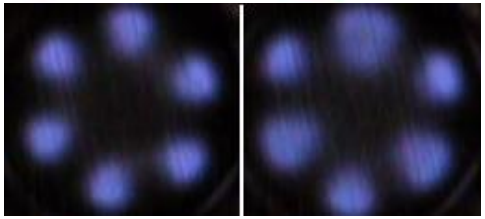
Further Comparison with the Modeling Data

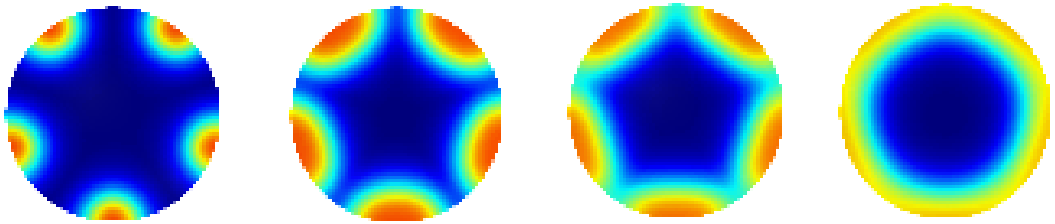
Data between modeling and experiment are qualitatively comparable

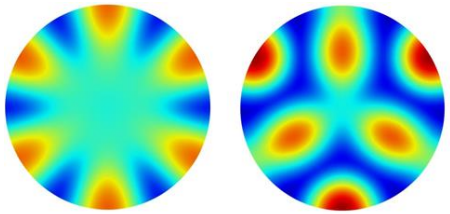












Courtesy of M. S. Benilov

Benilov *et al.*, 2014 Spring Meeting of German Physical Society

Summary and Outlook

- ✓ By adding two 200 kΩ potentiometers, we were able to fine tune discharge current at microampere scale
- ✓ Ring plasma mode and segmented plasma mode and other interesting patterns in CBLD in xenon were observed
- ✓ Self-organization in CBLD in krypton was observed and comparable to those in xenon at double the gas pressure
- ✓ Experimental results match with self-consistent modeling data qualitatively

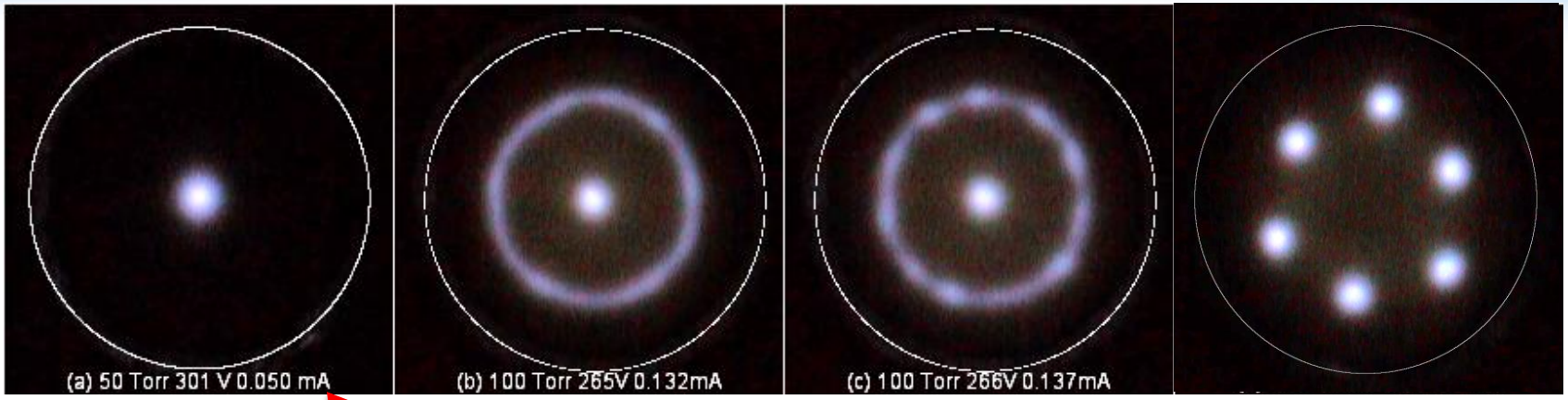
Future Work

- ❑ Transition from homogenous mode to diffuse mode.
- ❑ Fast imaging of the ring and the segmented plasma modes.

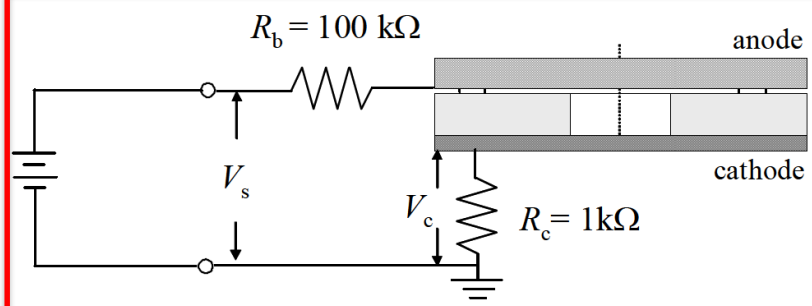
Acknowledgement

- Prof Karl Schoenbach (Old Dominion University)
  - for introducing me to self-organization of plasmas and for encouraging me to pursue this research.
- Prof. Mikhail Benilov and Prof. Pedro Almeida (University of Madeira)
  - for countless constructive discussions over Skype

Other Interesting Modes



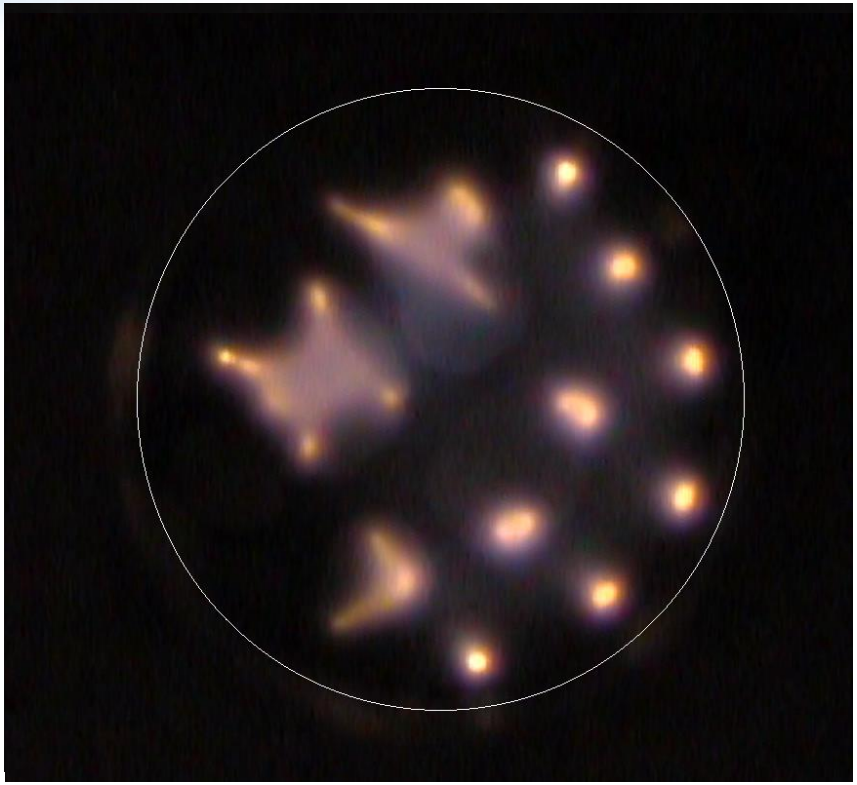
Single spot mode | Target plasma mode | Target with nodes | Alternative 6-spot

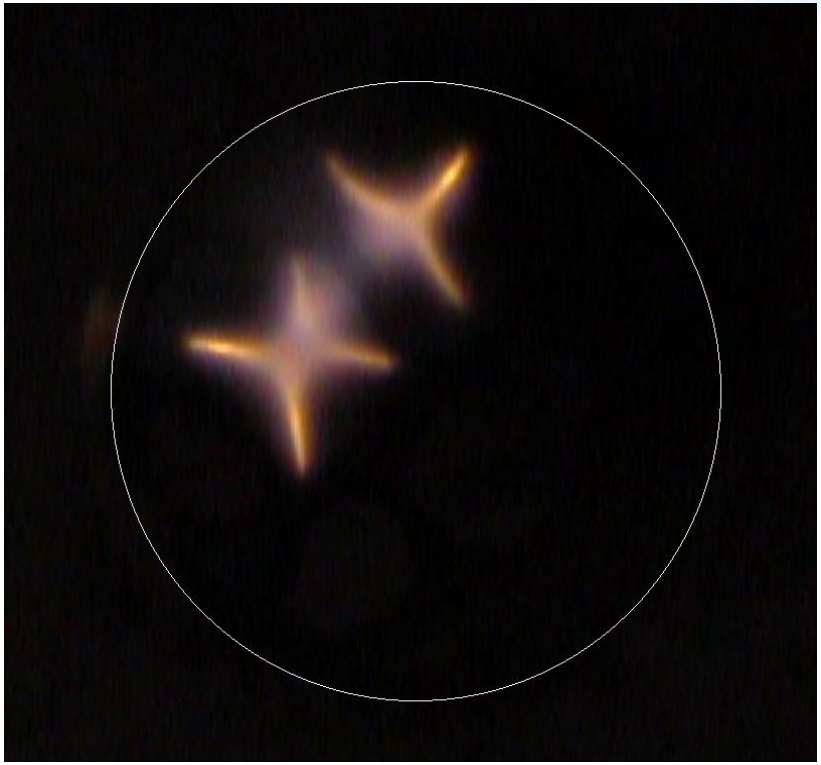


Observed only in a plane-to-plane structure or CBLD with opening diameter ~ 300 microns

Takano, Ph.D. thesis (2007)

Other Interesting Modes



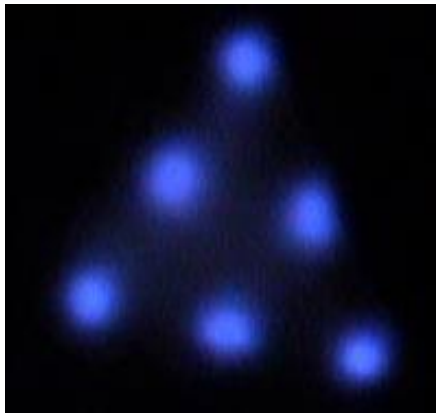


Krypton 250 Torr (Cathode Surface damaged)

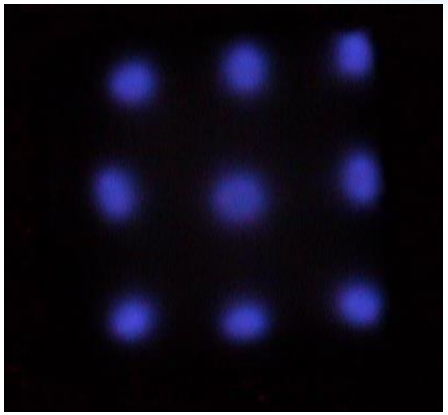
- Possibility to pre-pattern the surface to control spot locations

Other Interesting Modes

Xe, 45 Torr, Cathode Well, circular hole, stable

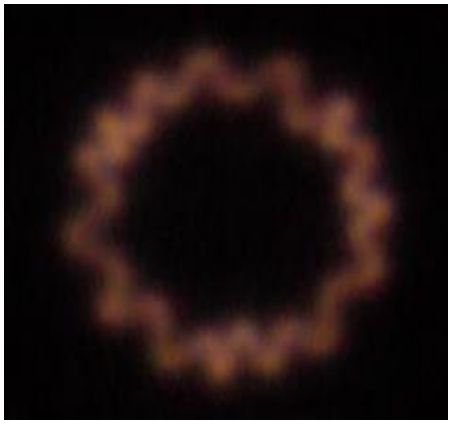


Xe, 100 Torr, CBLD, triangular hole, stable



Xe, 80 Torr, CBLD, square hole, stable

Xe, 130 Torr, CBLD, circular hole, steel cathode, unstable



Kr, 175 Torr, CBLD, circular hole, unstable