

# Plasma/Electrode Interactions in High Current Environments

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FA9550-11-10241; Dr. Sayir Ali (Program manager)



**Status Quo:** 15-25 A dispenser cathodes, 30000 hour lifetime, little understanding of key plasma-surface interactions.

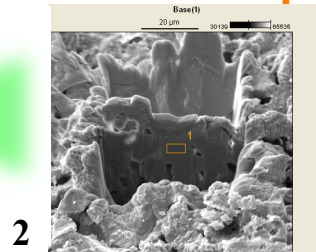
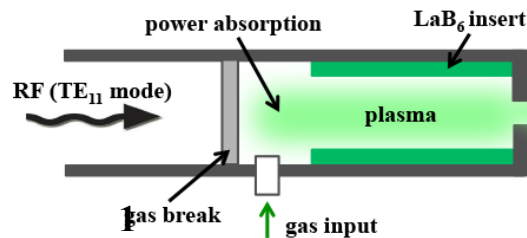
**New Insights:** Models of plasma-surface interactions and material transport reveal how to control current attachment; novel cathode designs exploit fundamental understanding

**Project Goals:** Validate models of plasma-surface interactions and transport and develop new high-risk cathode concepts to enable a 10X increase in cathode current capability and power and 3X increase in lifetime

## New Cathode Concepts (Part 1)

**Approach:** Distill decades-long experience in electric propulsion, use state-of-the-art simulation tools, dedicated experiments and advanced diagnostics to define, develop and test new high-risk cathode concepts that rely on novel methods to control the current attachments in high-current hollow cathodes.

**Recent Accomplishments:** Completed detailed numerical simulations of the RF field structure in the first new high-risk concept: the RF-Controlled Hollow Cathode (RFCHC). Used resulting insight to develop a design of the RFCHC and a dedicated experiment to study it. Started the construction of the experiment.

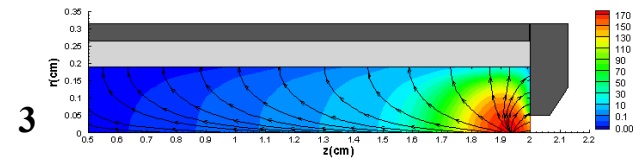


## Critical Problems in Material Transport (Part 2)

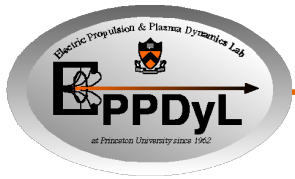
**Approach:** Use of state-of-the-art analytical techniques to understand degradation of barium dispenser and LaB6 emitter surfaces due to plasma interactions; plasma modeling tools to define the xenon plasma environment, and models of minor species transport to understand where erosion products go.

**Recent Accomplishments:** SEM and TEM analysis of LaB6 cathodes suggests L enrichment on surface exposed to plasma, modeling indicates L is likely recycled in discharge very effectively while B is lost, critical measurements of emitter temperature in LaB6 cathodes is underway.

**Publications:** M. Plasek, B. Jorns, E. Choueiri and J. Polk "Exploration of RF-Controlled High Current Density Hollow Cathode Concepts" AIAA-2012-4083  
Abstracts submitted to 2013 JPC and IEPC.



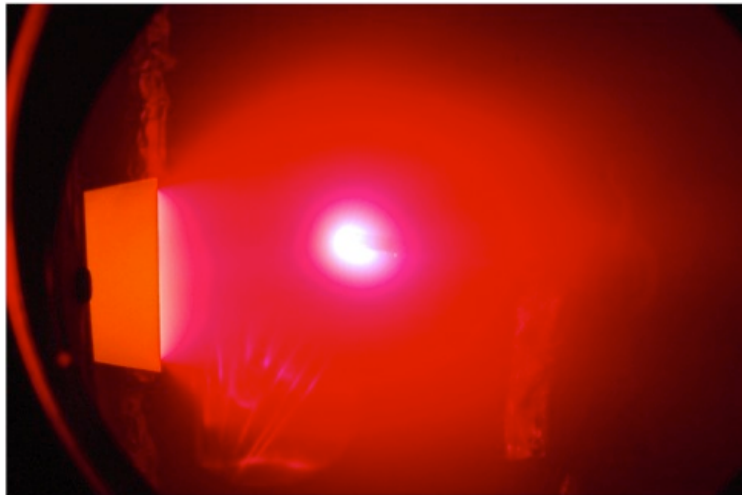
Figures: 1. The the RF-Controlled Hollow Cathode (RFCHC) concept. 2) LaB6 emitter surface samples removed with FIB for depth profiling, and 3) Model of xenon plasma in hollow cathode.



*AFOSR Program Review on Materials and Processes Far From Equilibrium*  
*Feb. 15, 2013*



# Plasma/Electrode Interactions in High Current Density Environments

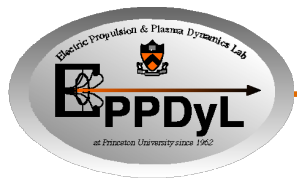


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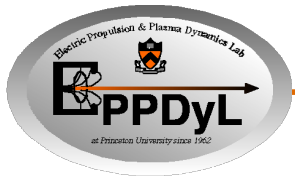
Program Manager: **Dr. Ali Sayir**



# Practical Motivation



- Critical Air Force missions will rely on high current-density ( $10\text{-}100\text{ A/cm}^2$ ) devices, such as high-power ( $10\text{-}200\text{ kW}$ ) plasma thrusters compact pulsed power systems and plasma switches.
- Electrodes, and specifically cathodes, are the most highly stressed components of these high current-density devices (HCDD).
- Presently cathodes were derived from thermionic emitters developed for vacuum tube applications in the 1950's. The next generation of cathodes will be based on a deeper understanding of Plasma-electrode interactions (PEI).



# Fundamental Motivation

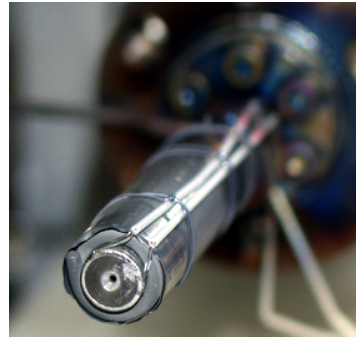
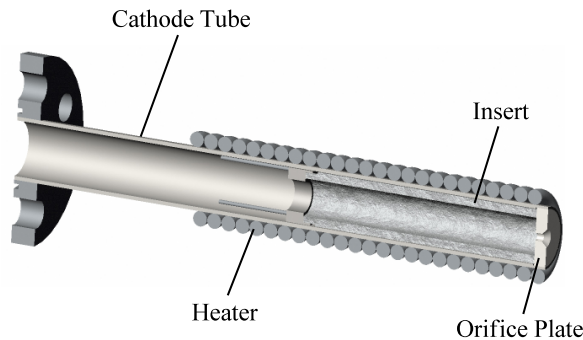


**Cathodes provide a rich area for investigation of fundamental plasma-material interaction problems**

- **Plasma discharges create a harsh environment for emitter materials (erosion)**
  - High temperature
  - Ion bombardment and sputtering
  - Chemical erosion processes
- **The plasma has an enormous effect on material transport (where erosion products go)**
  - Ionization of evaporated emitter material
  - Electric field effects on transport
  - Suppression of chemical reactions due to buildup of products
- **Surface modification impacts device performance (effects of erosion)**
  - Increases operating temperature *or*
  - Decreases current emission capability
  - Makes ignition difficult
  - Ultimately limits life of cathode

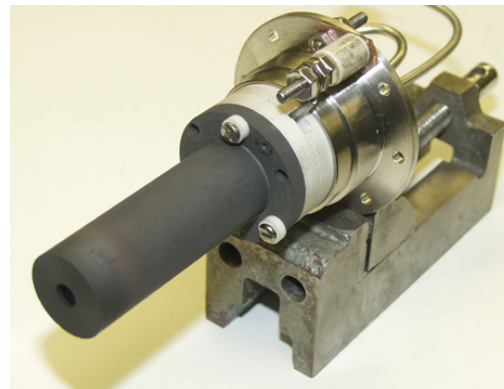
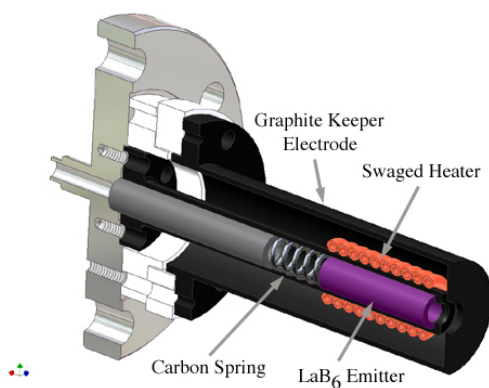
# An Overview of Thermionic Cathode Types

## Dispenser Cathodes

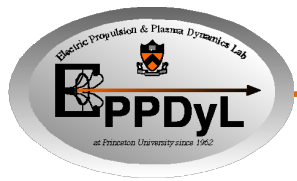


- A low work function emitter surface is formed by a refractory metal substrate with a monolayer of electropositive atoms (e.g. Ba)
- Electropositive “activator” atoms are lost by desorption from the hot surface
- The activator atoms must be replenished by a supply source in the interior

## Bulk Emitter Cathodes



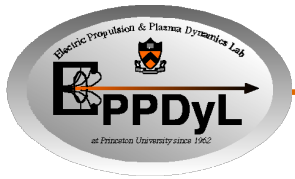
- The emitter surface is a bulk material with a relatively low work function (e.g. lanthanum hexaboride)



# High-Risk Cathode Concepts



- In addition to applying the tools we develop to optimize hollow cathodes with a more conventional design, we intend to explore high-risk but potentially high-payoff solutions.
- Among these are the following radical concepts, based on distilling our decades-long experience in electric propulsion.
- Main feature is control of the current attachment dynamics.



# Defining the Objective



**Can we lower the peak current density while maintaining the same discharge current?**

- lower emitter evaporation rate, increased lifetime<sup>8</sup>
- lower temperature, increased maximum current<sup>9</sup>

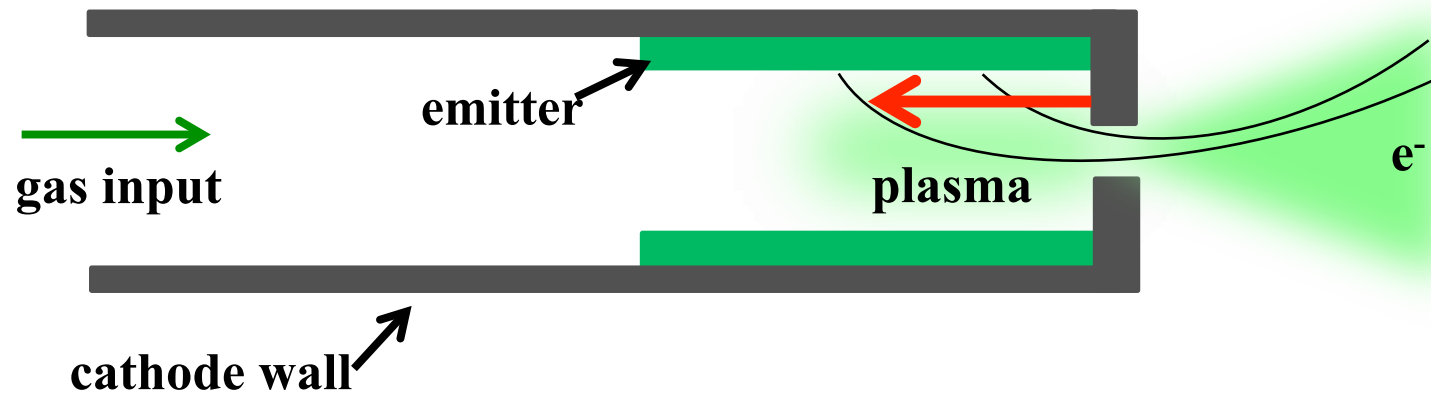
**Increase emission area**

**(8) Goebel, et al., *Journal of Propulsion and Power*, May 2007.**

**(9) Goebel, Jameson, and Hofer, *Journal of Propulsion and Power*, March 2012.**

## Defining the Objective

**Increase the emission area of the  
insert**

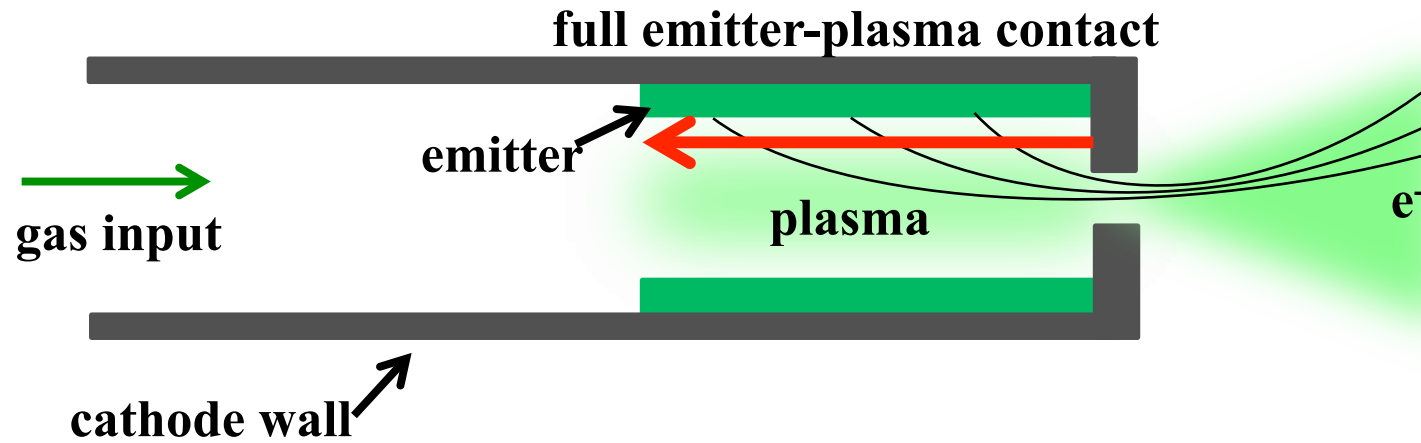


**Can we control the depth of the  
plasma attachment?**

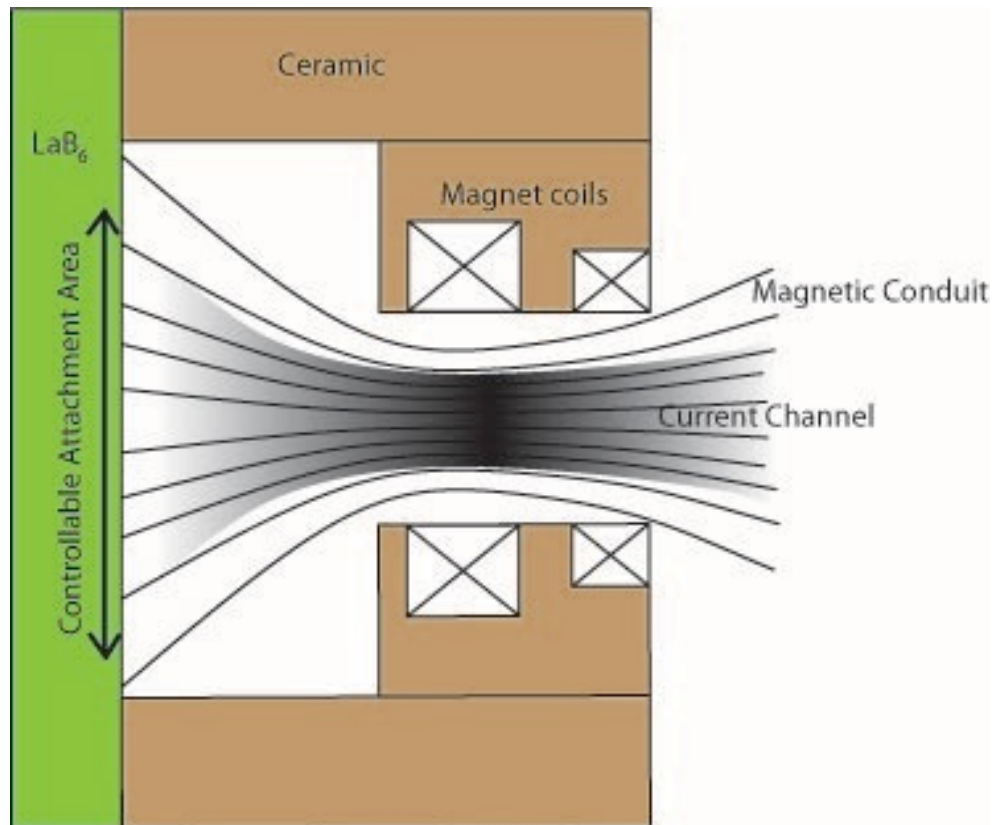


## Defining the Objective

# Increase the emission area of the insert



# High-Risk Cathode Concept I: The Magnetically Choked Cathode (MCC)

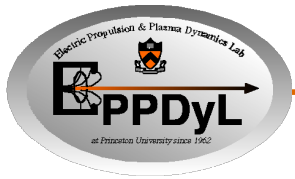


## Potential Advantages

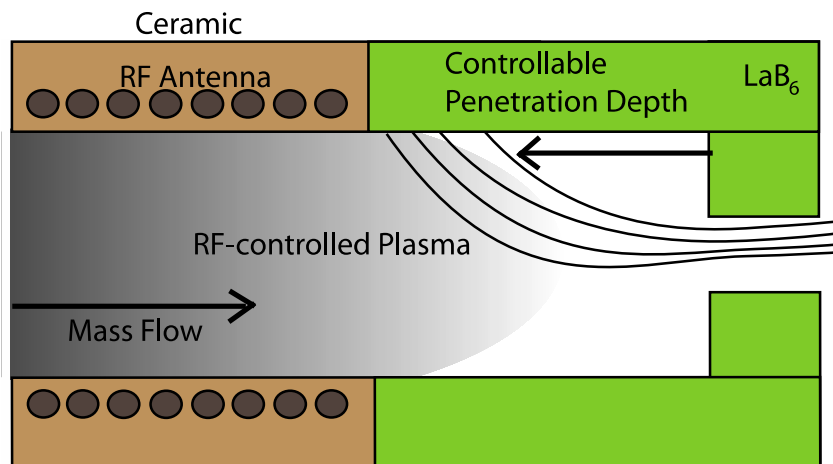
- Provide a controllable magnetic conduit for the electron current to be conducted to a large  $\text{LaB}_6$  or dispenser cathode plate.
- Controlling the B field and its topology allows controlling the dynamics of the current and the extent of the attachment area on the cathode plate
- B field plays a role similar to that of a nozzle for a choked compressible fluid flow.
- Possible modes: “magnetic nozzle”, “Magnetic cusp”, and “pseudo-mirror”.
- Favors “recycling” of eroded emitter material.

## Potential Challenges

- Electron mirroring



## High-Risk Cathode Concept II: The RF-Controlled Hollow Cathode (RFCHC)

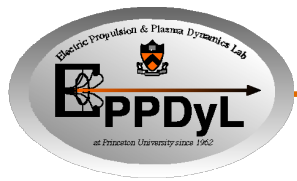


### Potential Advantages

- Controlling the mass flow and the RF field allows controlling the penetration of the RF-created plasma downstream into the hollow cathode.
- Controlling the downstream plasma penetration would allow controlling the current penetration depth.

### Potential Challenges

- Power/complexity cost

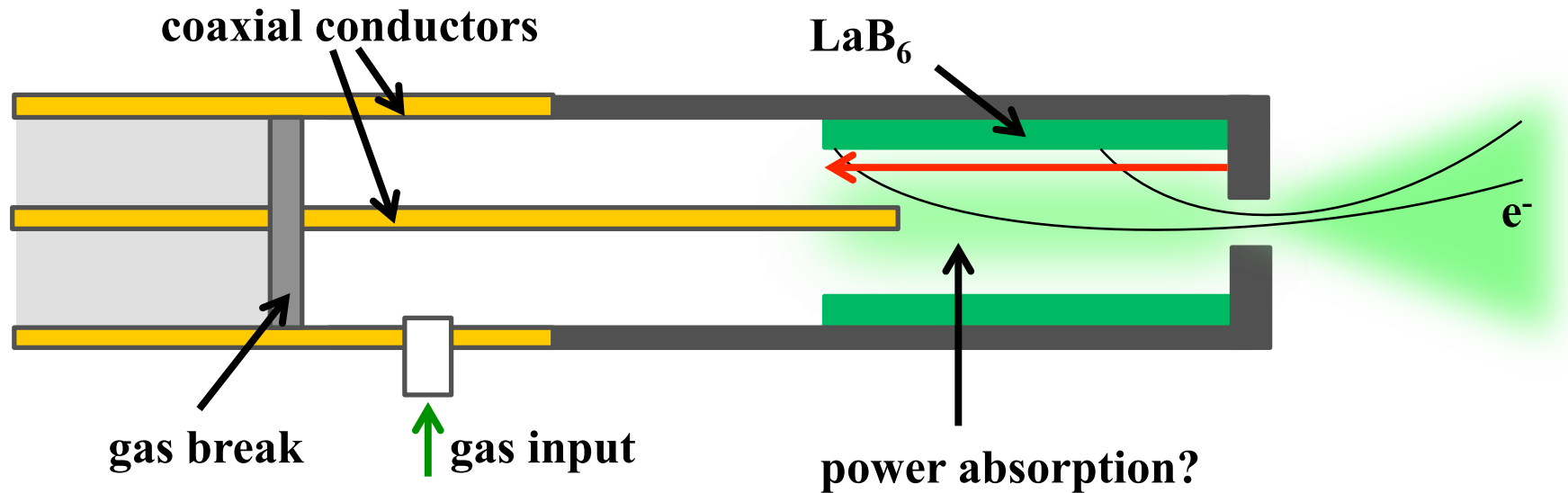


## High-Risk Cathode Concept III: The “Liquid Cathode”

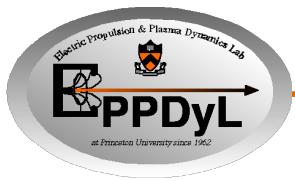


- Relies on attaching the current on liquid metals for applications where the use of such materials will be allowable (e.g. when the same liquid metals are used as propellant).
- The plasma/liquid metal interface opens up a new dimension in current attachment control that has not been explored before.
- We will study both passive methods, e.g.
  - liquid evaporation,
  - dynamic self-adjustment of emission areaand active control, e.g.
  - magnetic constriction and enlargement of the attachment areasto explore the feasibility of such novel cathodes using metals with relatively modest melting point (e.g. bismuth, lithium, zinc, and tin), especially bismuth, which of interest to Hall thrusters.

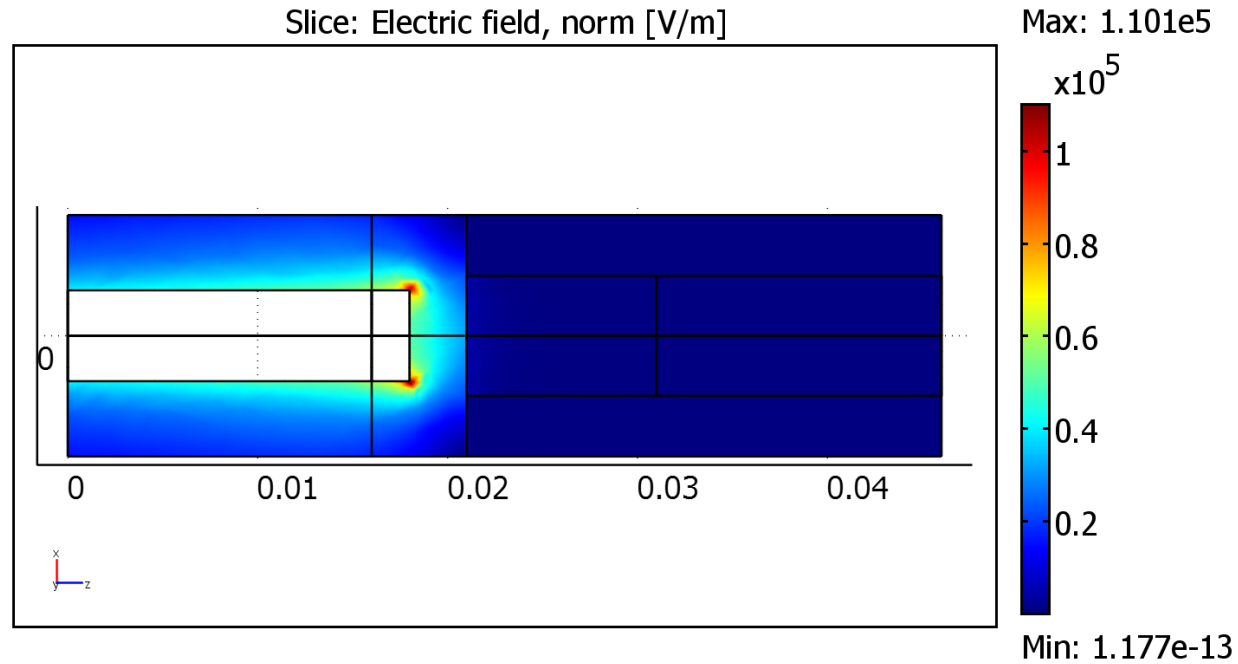
## RF-Controlled Hollow Cathode (RF-CHC)



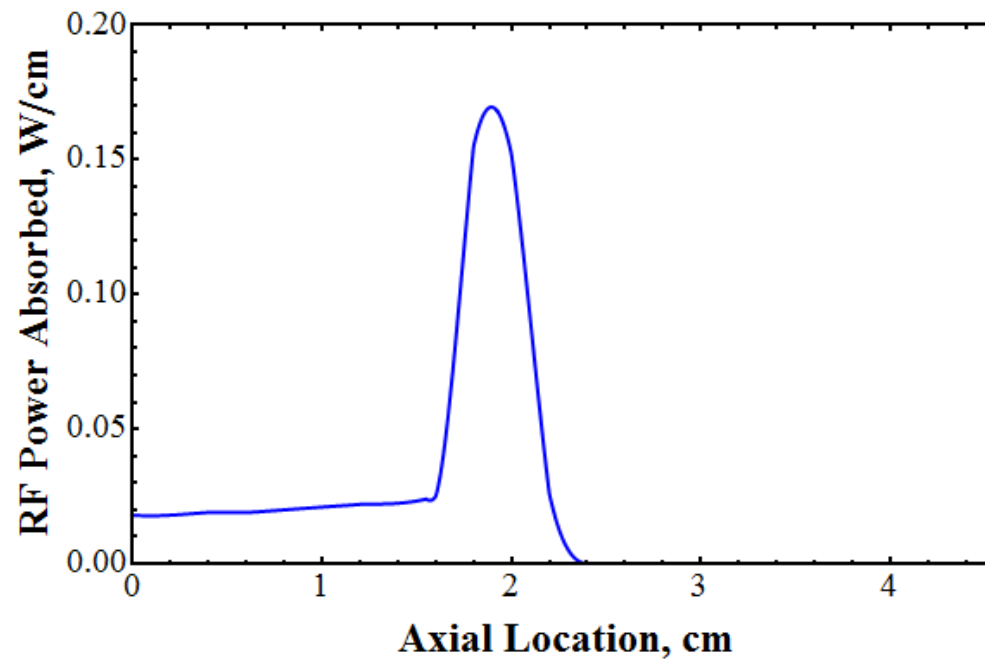
**Coaxial-Cathode Mating Configuration  
of the RF-CHC**

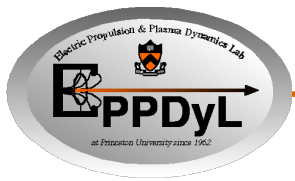


## Electric Field Magnitude

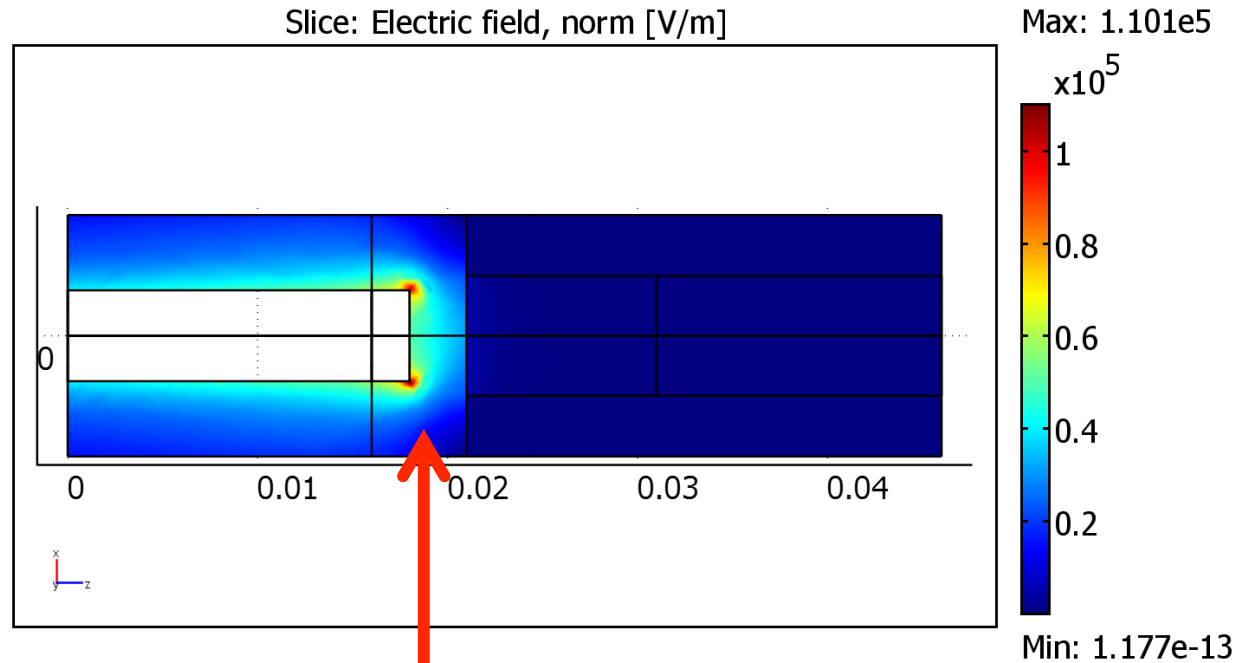


## RF Power Absorbed

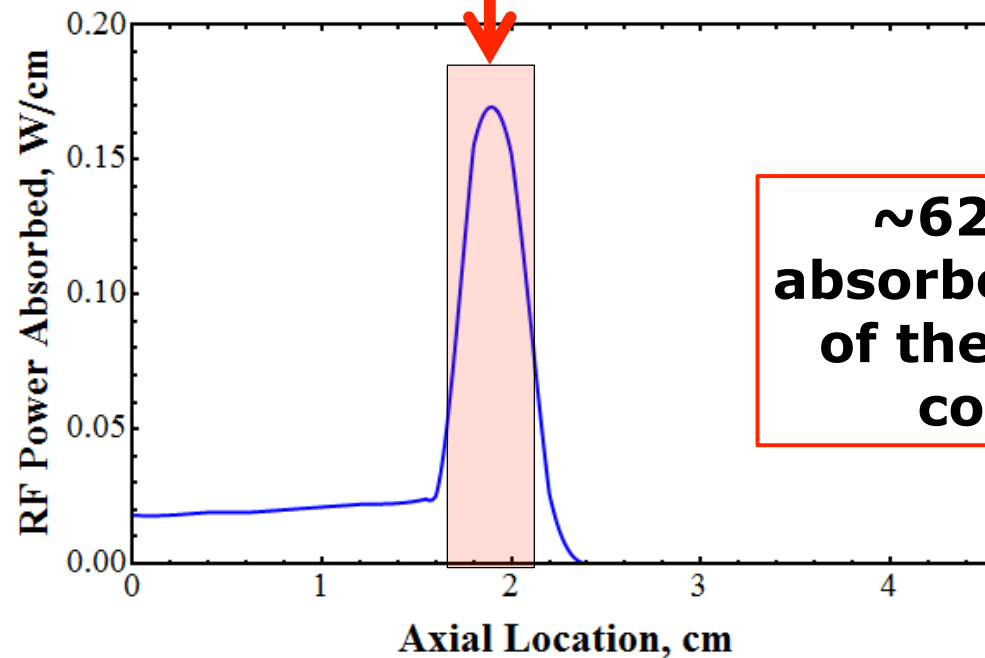




## Electric Field Magnitude



## RF Power Absorbed



**$\sim 62\%$  of power  
absorbed within 2 mm  
of the inner coaxial  
conductor tip**



# Conclusions from Coaxial-Cathode Modeling



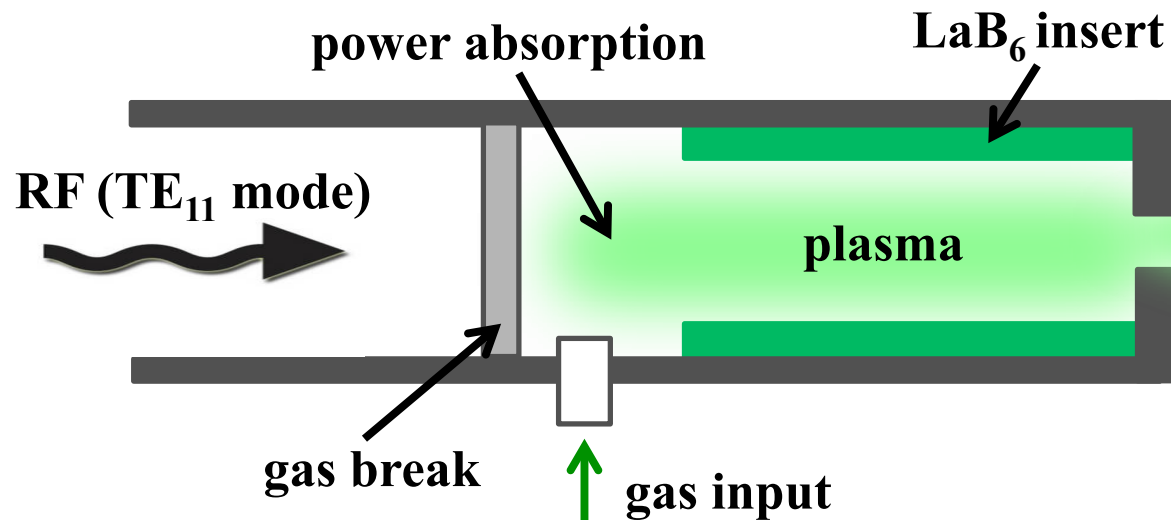
- **Localized, high absorption possible with single-stage configuration**
- **Inner conductor acts as a stinger**
- **RF heating of insert prior to plasma ignition is unlikely due to low power absorption**
- **RF breakdown of xenon gas is feasible within typical baseline parameters**





## Waveguide Configuration RF-CHC

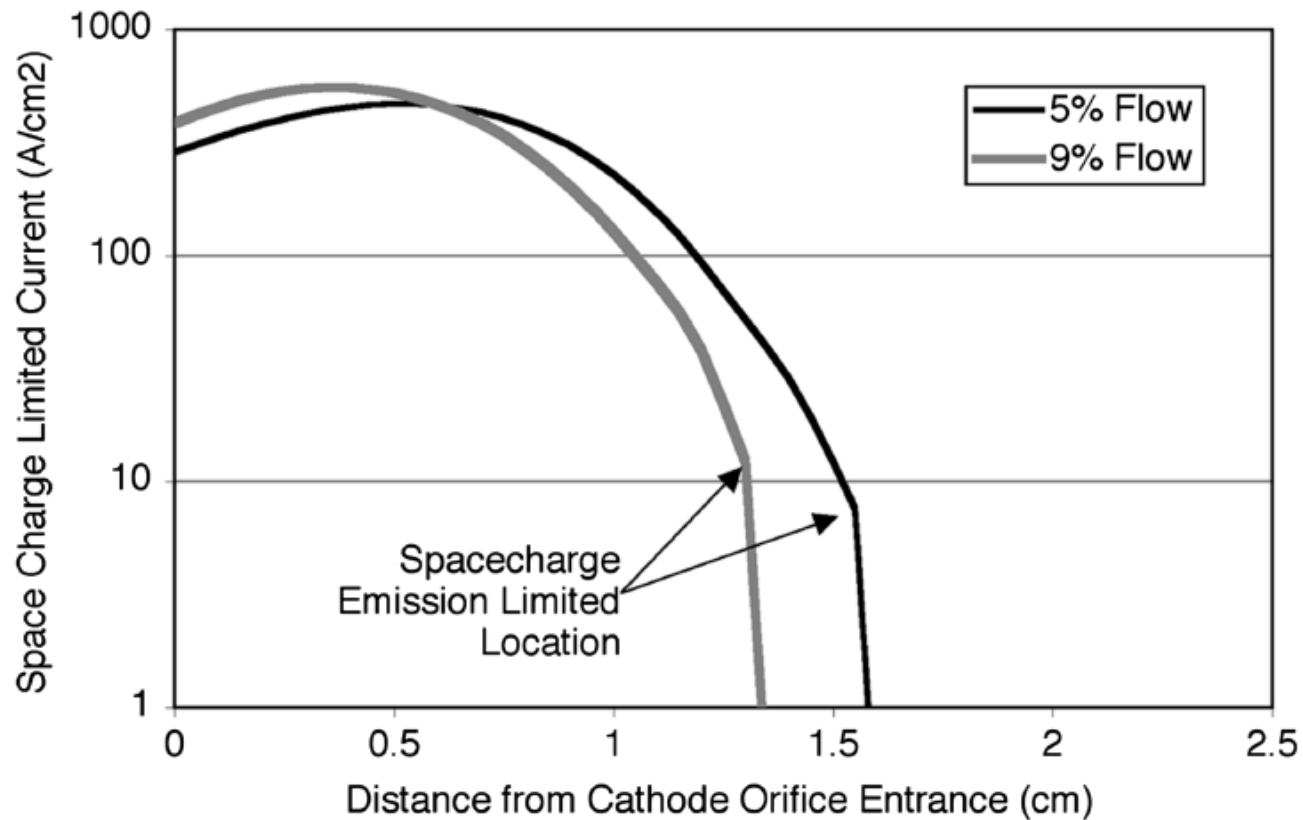
- Instead of coaxial input, use circular waveguide-cathode mating
- Option of right angle coaxial-to-waveguide transition upstream



# Space-Charge Limited Current Density

$$J_e = \frac{\kappa}{2} n_i e \sqrt{\frac{kT_e}{m}} \approx \frac{1}{4} n_e e \sqrt{\frac{kT_e}{m}}$$

Ref. 2



Ref. 2

# Space-Charge Limited Current Density

$$J_e = \frac{\kappa}{2} n_i e \sqrt{\frac{kT_e}{m}} \approx \frac{1}{4} n_e e \sqrt{\frac{kT_e}{m}}$$

Ref. 2

Maximum Current Density	Plasma Density (T <sub>e</sub> =1.2eV)	Plasma Density (T <sub>e</sub> =2eV)
1 A/cm <sup>2</sup>	5.4e17 m <sup>-3</sup>	4.2e17 m <sup>-3</sup>
10 A/cm <sup>2</sup>	5.4e18 m <sup>-3</sup>	4.2e18 m <sup>-3</sup>
20 A/cm <sup>2</sup>	1.1e19 m <sup>-3</sup>	8.4e18 m <sup>-3</sup>
100 A/cm <sup>2</sup>	5.4e19 m <sup>-3</sup>	4.2e19 m <sup>-3</sup>

**Goal: n<sub>e</sub> = 10<sup>18</sup> - 10<sup>19</sup> m<sup>-3</sup>**



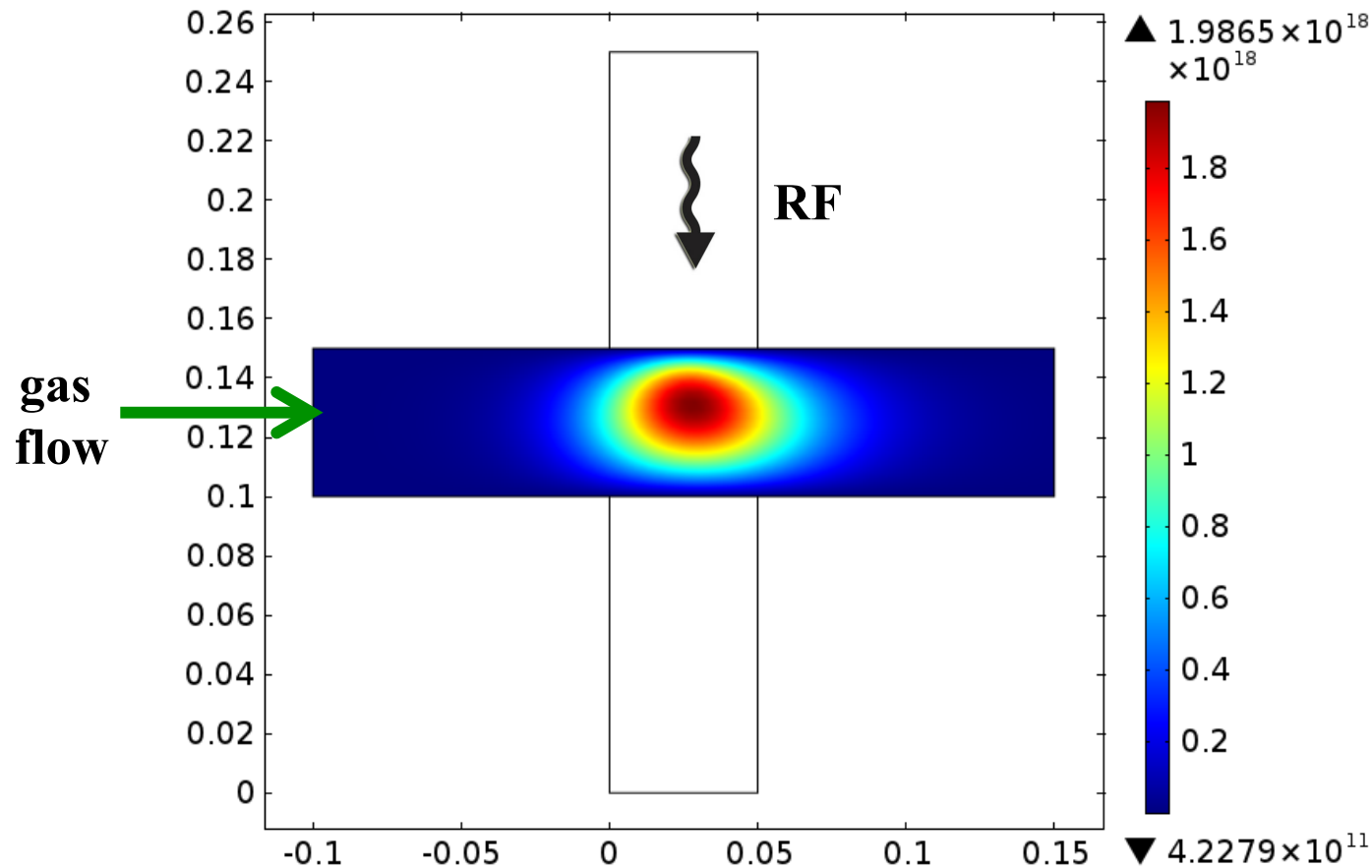
# Modeling - Large Example Plasma ( $n_e \sim 2 \times 10^{18}$ )



2.45 GHz microwave source      1 kW input power  
1 torr neutral gas pressure      10

m/s Ar flow to right

Time=0.01    Surface: Electron density ( $1/m^3$ )



# Plasma Modeling – Baseline Cathode Dimensions

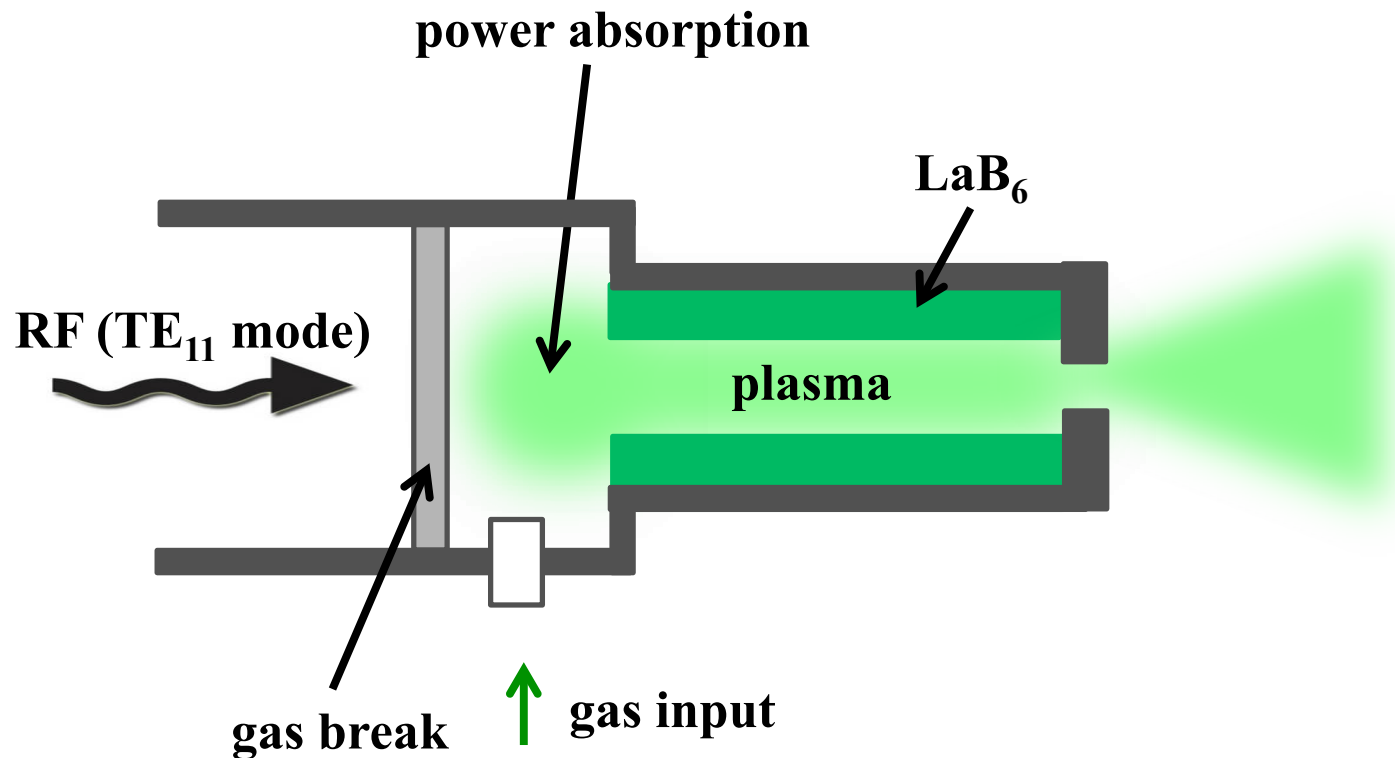


- **Similar to larger scale plasmas (mm vs. cm)**
- **Higher RF frequency, higher gas pressures produces higher plasma densities**
- **Max plasma density  $10^{19} \text{ m}^{-3}$  and  $\sim 10^{18} \text{ m}^{-3}$  within  $\sim 2 \text{ cm}$  radius possible in waveguide configuration**



## Waveguide Configuration RF-CHC

- To take advantage of common X-band ( $\sim 9.4$  GHz) radar RF use larger diameter waveguide (to stay above cutoff frequency)



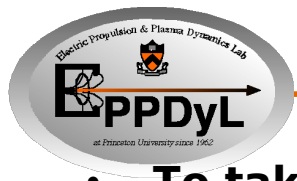


# RF-CHC Design



- Dense plasma generated in waveguide, 1-2 cm drift into insert
- RF plasma allows 10-20 A/cm<sup>2</sup> upstream
- Reasonable RF source: X-band 9.4 GHz, on order of 100 W, higher frequency sources can be tested
- Refractory metal cathode, graphite insert spacers, LaB<sub>6</sub> insert, alumina dielectric window/gas break





# Waveguide Configuration RF-CHC Dimensions



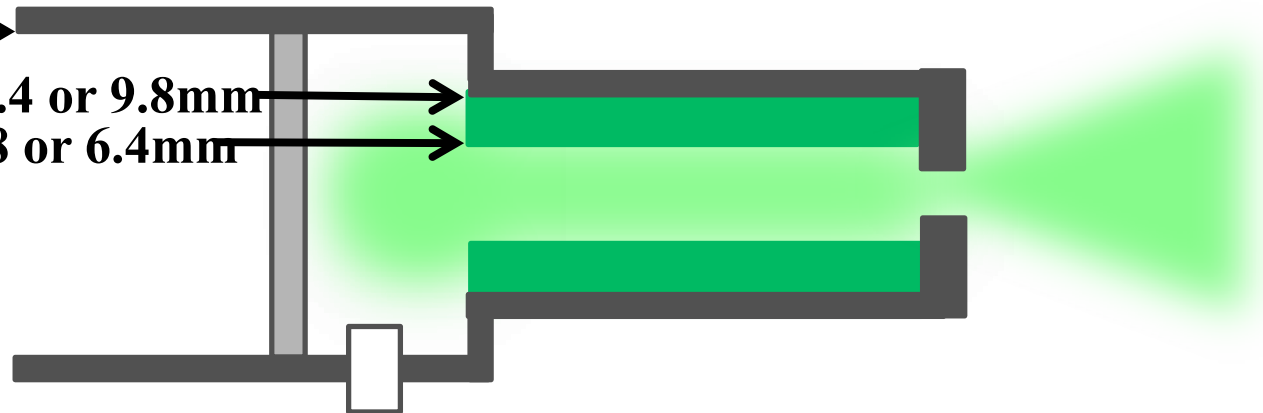
- To take advantage of common X-band ( $\sim 9.4$  GHz) radar RF use larger diameter waveguide (to stay above cutoff frequency)

**Cathode IR**

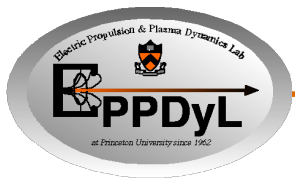
= 11.5mm →

Insert OR = 6.4 or 9.8mm →

Insert IR = 4.8 or 6.4mm →





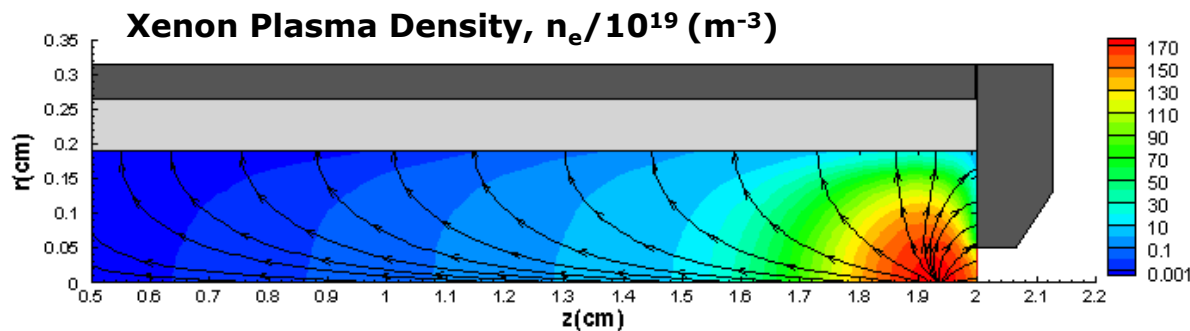


# Impact of Lack of Knowledge



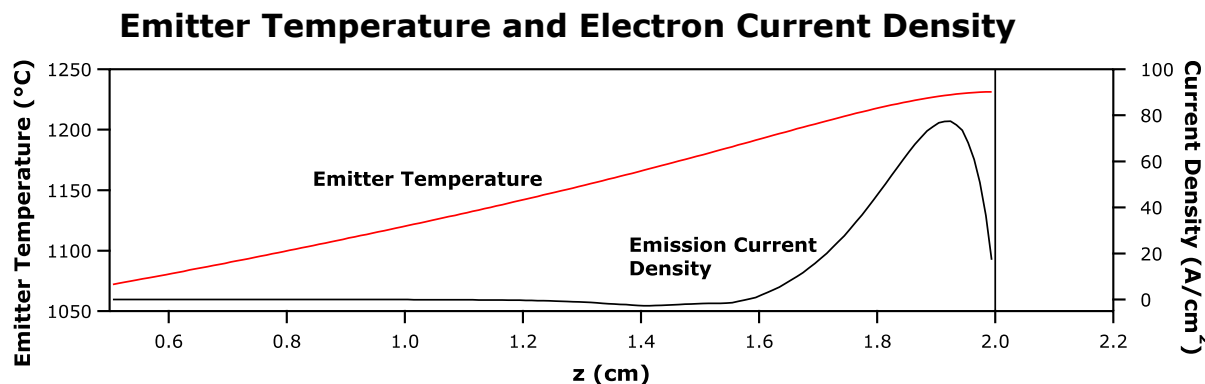
**There is no systematic design methodology for gas discharge cathodes because fundamental processes are not understood**

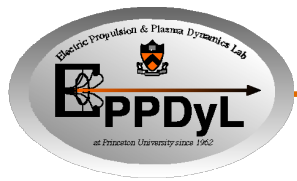
**State-of-the-art hollow cathodes exploit only a small part of the emitter area**



**Critical gaps in knowledge**

- Fundamental material properties of promising emitter materials
- Processes that control the plasma-surface contact area
- Material transport processes that determine cathode life
- Plasma modification of emitter surfaces





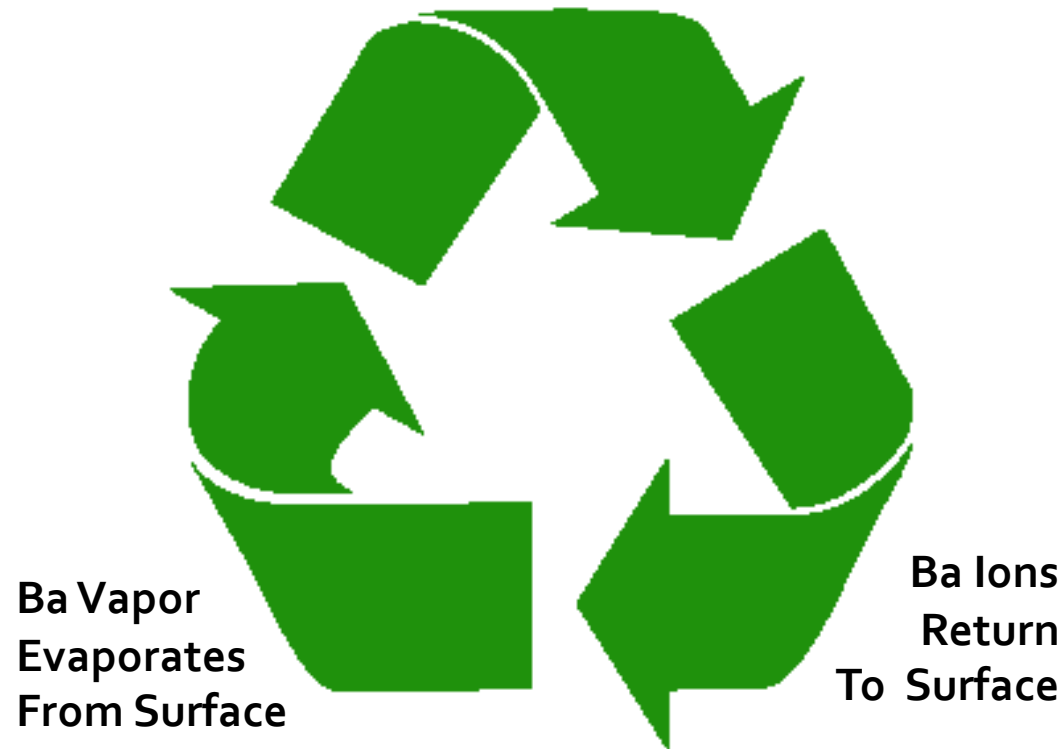
# Tools We're Applying to Fill The Knowledge Gaps



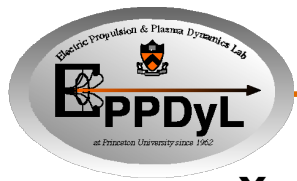
- **State-of-the-art surface and thermochemistry analysis techniques to determine fundamental properties**
  - $\text{LaB}_6$  evaporation rates and products
  - $\text{LaB}_6$  cathode surface stoichiometry and work function
  - Barium depletion depth in dispenser cathodes
  - Surface state of advanced dispenser cathodes such as Ba on O on W-Ir or W-Os (mixed metal matrix cathodes)
- **State-of-the-art radiometric measurement techniques to determine the emitter temperature**
- **State-of-the-art hollow cathode plasma codes to understand plasma contact area on the emitter**
- **Plasma transport models and surface kinetics models to understand the flow of erosion products through the plasma and the effect that has on the emitter surface state**
  - Barium transport in xenon plasmas
  - La and B transport in xenon for  $\text{LaB}_6$  hollow cathodes
  - Tungsten transport in xenon dispenser cathodes
- **Integration of the various models into design codes to develop advanced hollow cathodes**

# Green Cathodes: Reduce, Reuse, Recycle

Ba Is Ionized in Xe Plasma



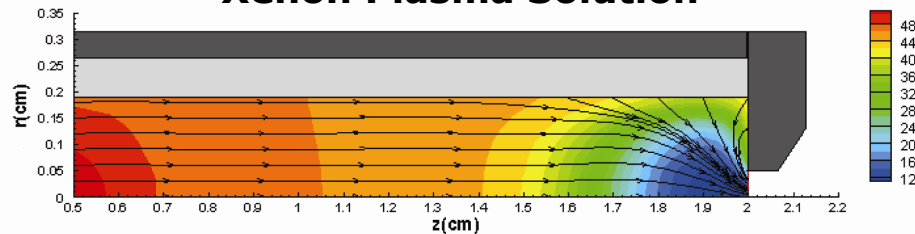
**Plasma reactions and plasma-surface interactions have a major (and beneficial, if properly exploited) effect on cathode operation**



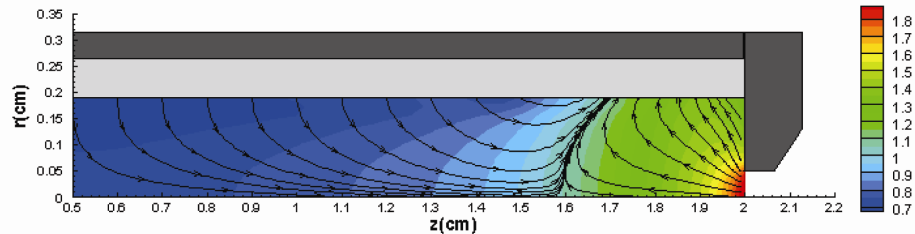
# Previous Work on Dispenser Cathodes Shows Barium is Effectively Recycled



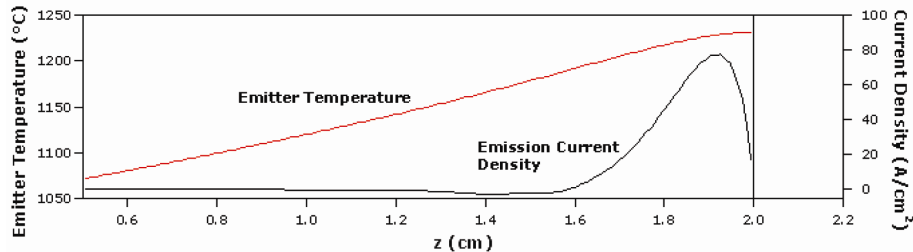
## Xenon Plasma Solution



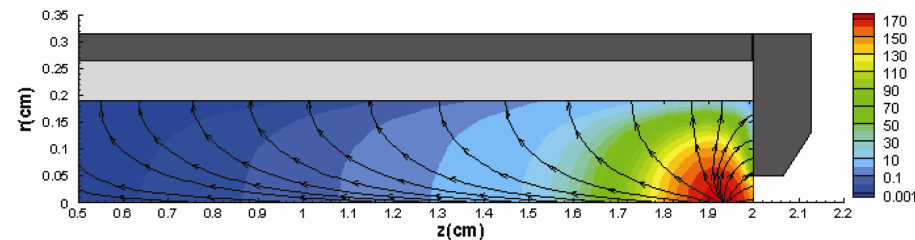
(a) Xenon neutral density contours,  $n_{Xe}/10^{21} \text{ (m}^{-3}\text{)}$  and neutral flux streamlines.



(b) Electron temperature contours (eV) and electron current streamlines.

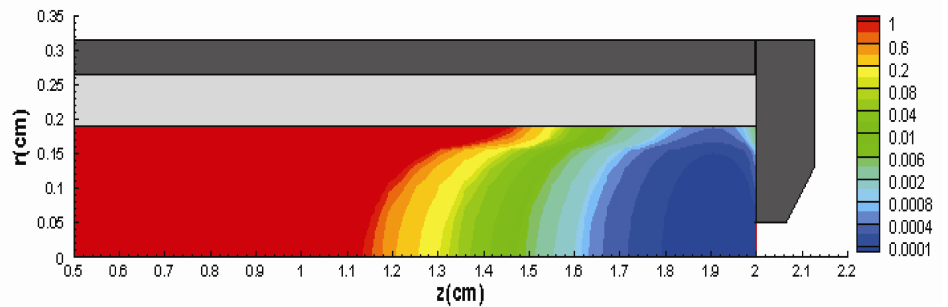


(c) Emitter temperature profile and electron emission current density.

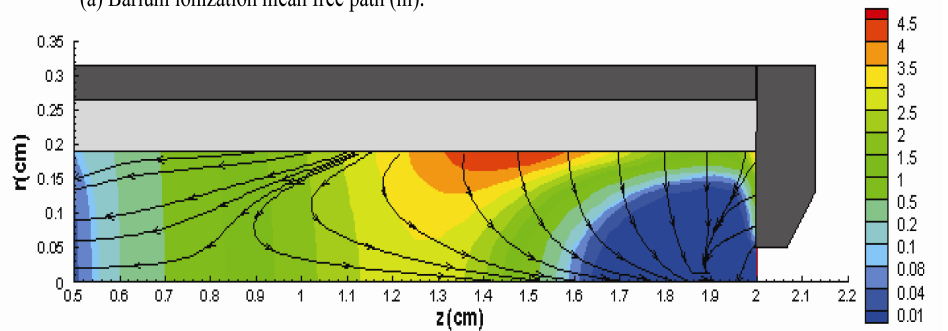


(d) Plasma density,  $n_e/10^{19} \text{ (m}^{-3}\text{)}$  and ion current streamlines.

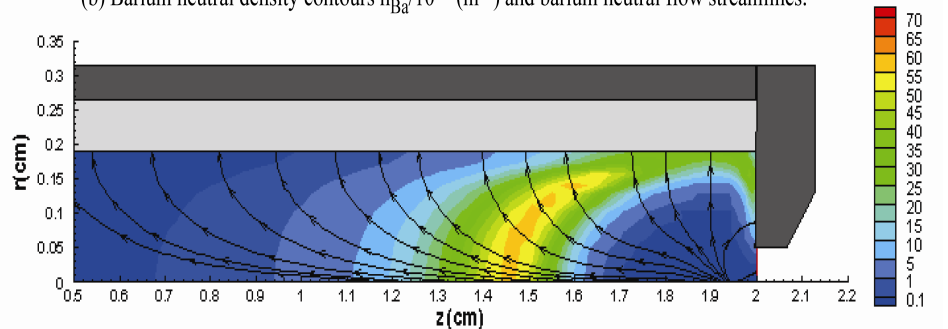
## Barium Transport in Xenon Plasma



(a) Barium ionization mean free path (m).



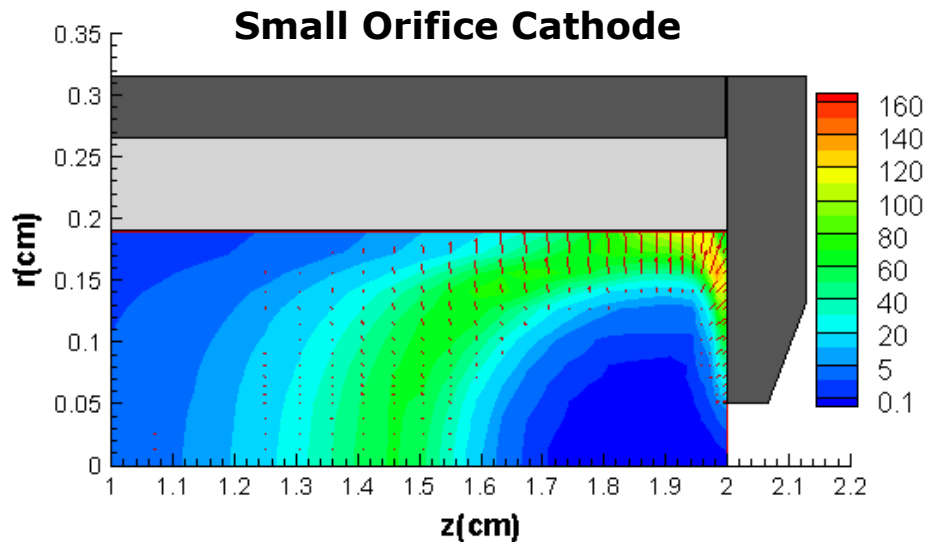
(b) Barium neutral density contours  $n_{Ba}/10^{16} \text{ (m}^{-3}\text{)}$  and barium neutral flow streamlines.



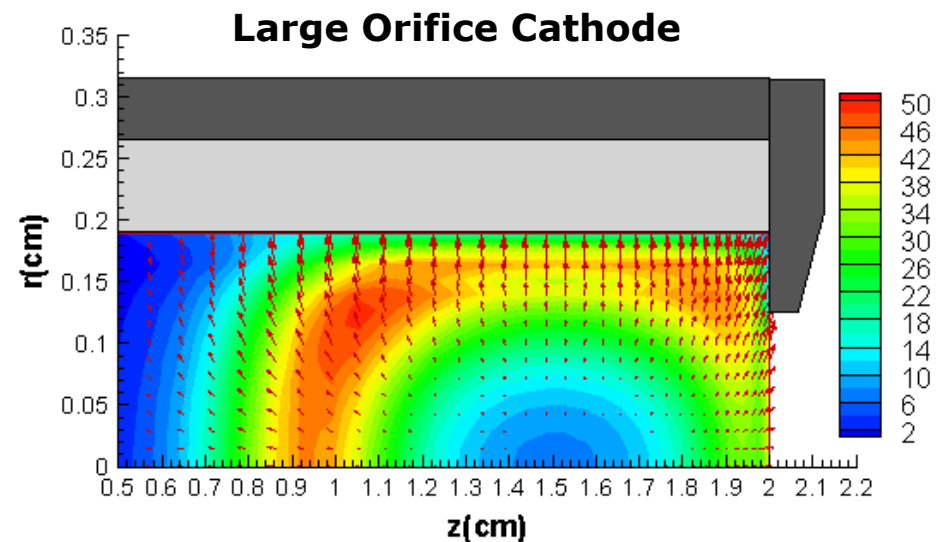
(c) Barium ion density contours  $n_{Ba^+}/10^{14} \text{ (m}^{-3}\text{)}$  and barium ion flow streamlines.



# Barium Recycling Can Be Influenced by the Cathode Design



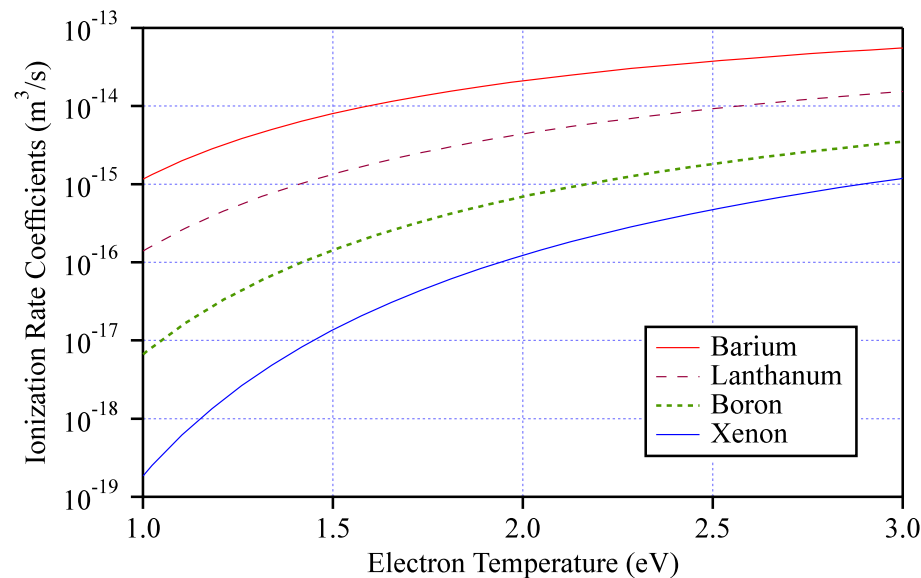
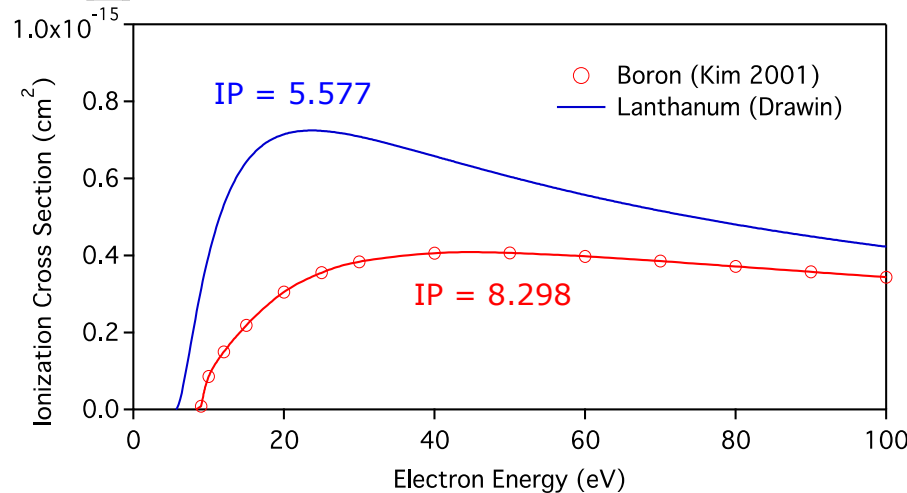
Barium Ion Density,  $n_{Ba}/10^{14} \text{ (m}^{-3}\text{)}$



Barium Ion Density,  $n_{Ba}/10^{14} \text{ (m}^{-3}\text{)}$

- **Greater Ba loss out of the larger orifice because:**
  - The internal gas pressure is lower, and the plasma penetrates further
  - The peak plasma density is lower
- **However, the cathode temperature is lower! Multi-dimensional design space**

# Cross Sections and Rate Coefficients for La and B



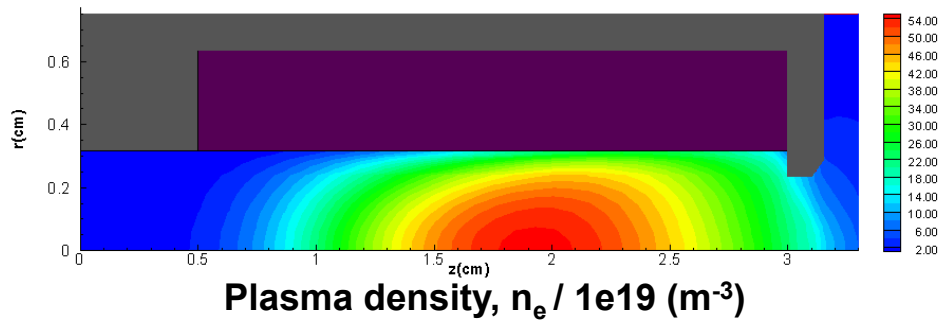
- **No data on ionization cross sections for La and B**
  - La values based on Drawin cross-section; should be refined
  - B values based on Kim model, which agrees well with other models and data for Al, Ga, In (other elements in the same column)
- **B cross section is surprisingly large because of autoionization from excited states**
- **La expected to behave like Ba, not clear for B**



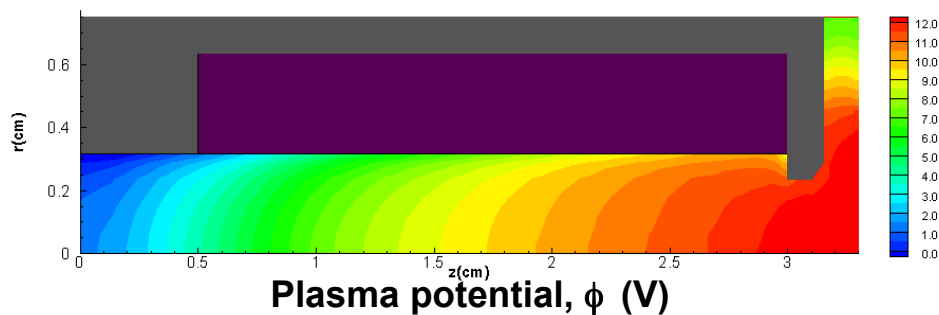
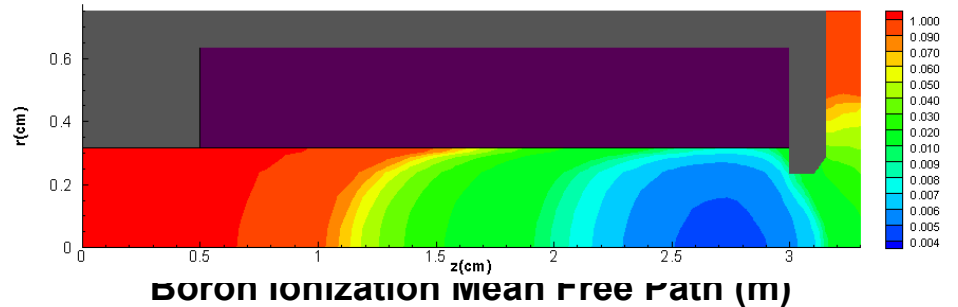
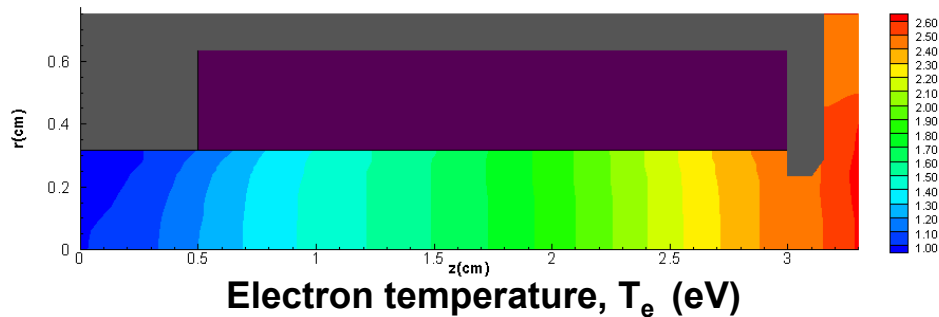
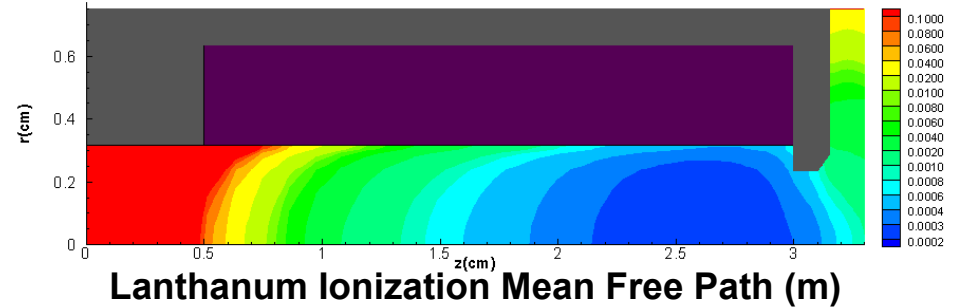
# Current Focus is on Lanthanum Hexaboride Cathodes



**Xenon Plasma Solution**



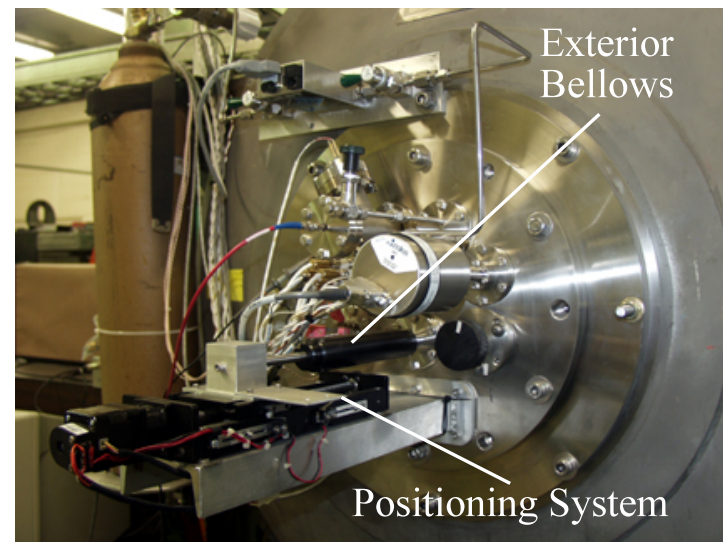
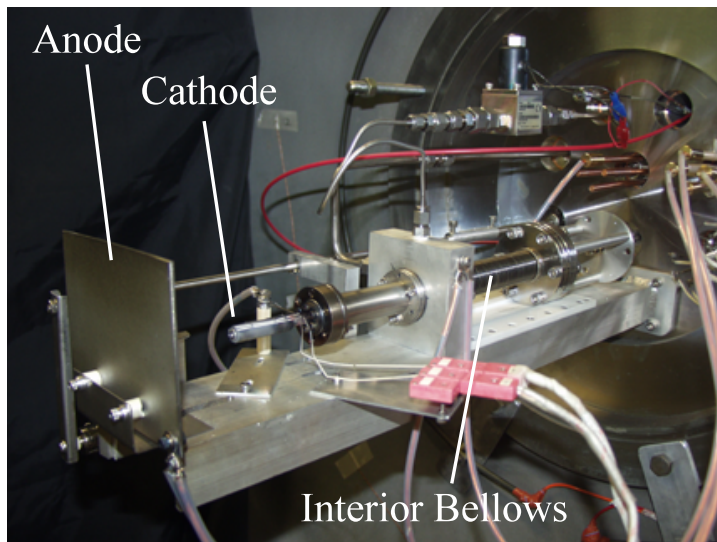
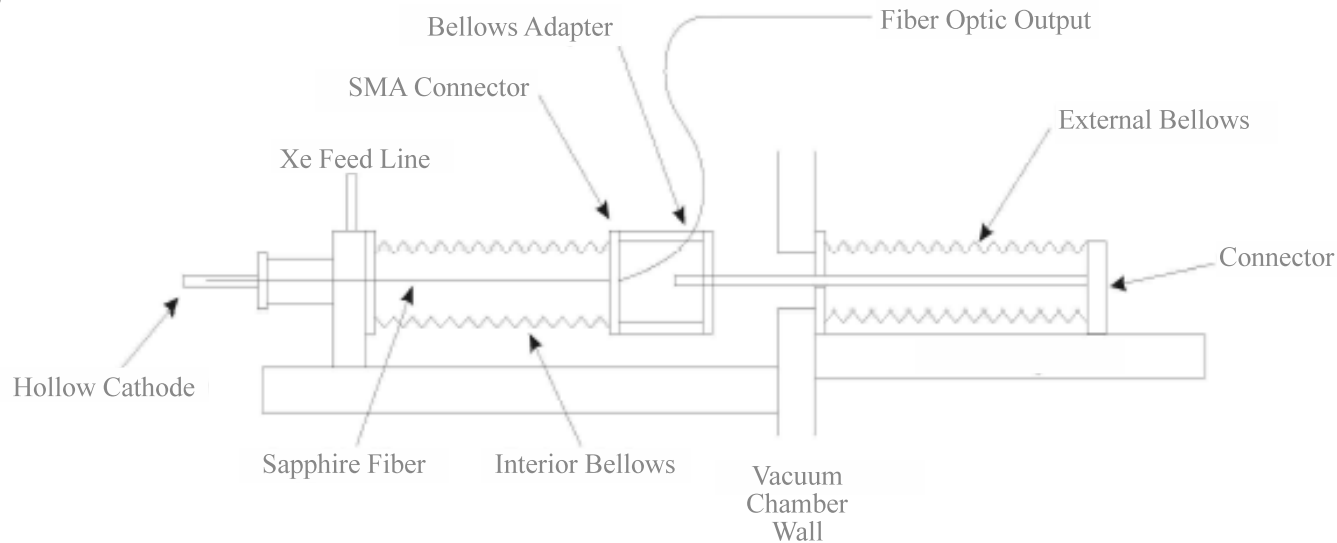
**La and B Transport in Xenon Plasma**



- Lanthanum MFP is  $< 1 \text{ mm}$ ; likely to be ionized and very effectively recycled in discharge
- Boron MFP is  $\geq 4 \text{ mm}$ ; most evaporated boron will be lost through orifice
- Currently modifying Ba transport code to model details of La and B transport



# Emitter Temperature, a Key Parameter, Is Being Measured with a Novel Fiber Optic Probe Technique



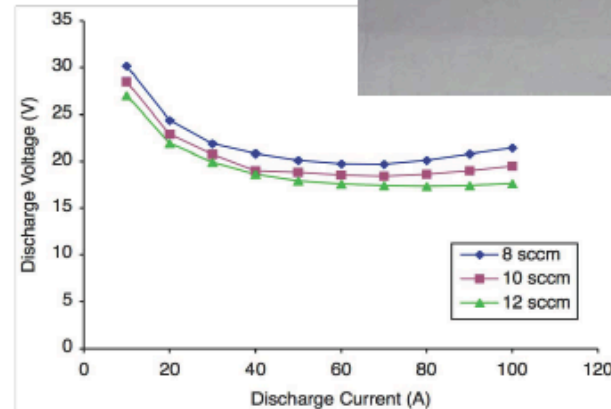
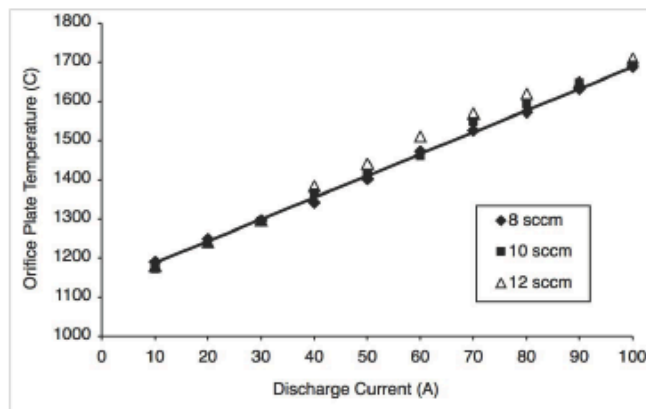
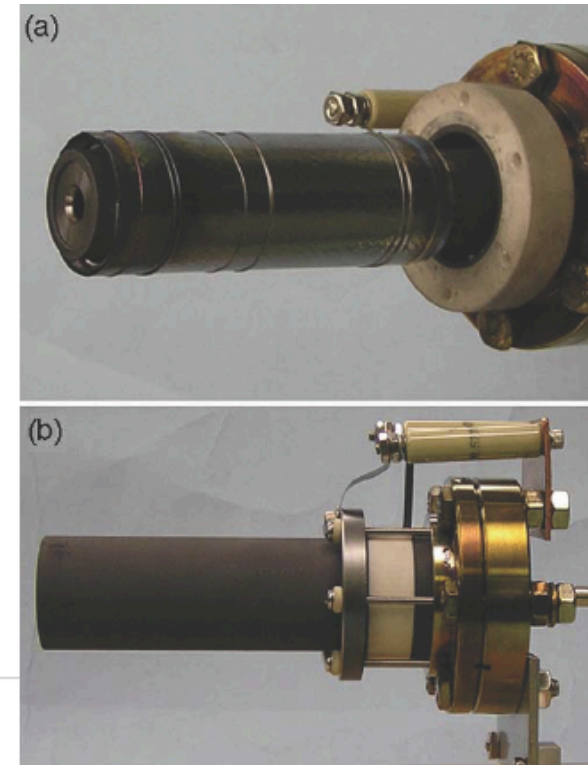


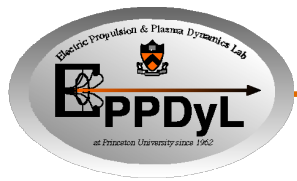


# Characterization of an Insert from a High Current LaB6 Cathode



- Parameters
  - Discharge current 20 to 100 A
  - Max O.D. = 3 cm keeper
  - $\approx 10$  cm long
- Design
  - 5 mm dia. cathode orifice, 9 mm keeper orifice
  - 1.27-cm insert outer diameter, 2.5 cm long
  - 5 cm<sup>2</sup> insert inner area
  - Nominal - 20 A/cm<sup>2</sup> @ 100 A discharge
  - $\approx 1700$  °C insert temperature
- Performance
  - Orifice temperature  $\leq$  insert temperature
  - In life test at MSFC

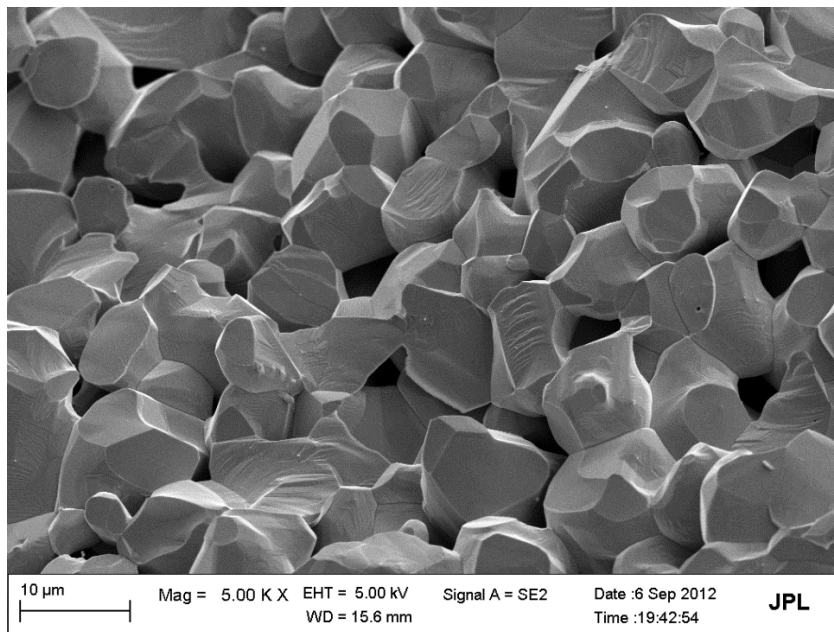




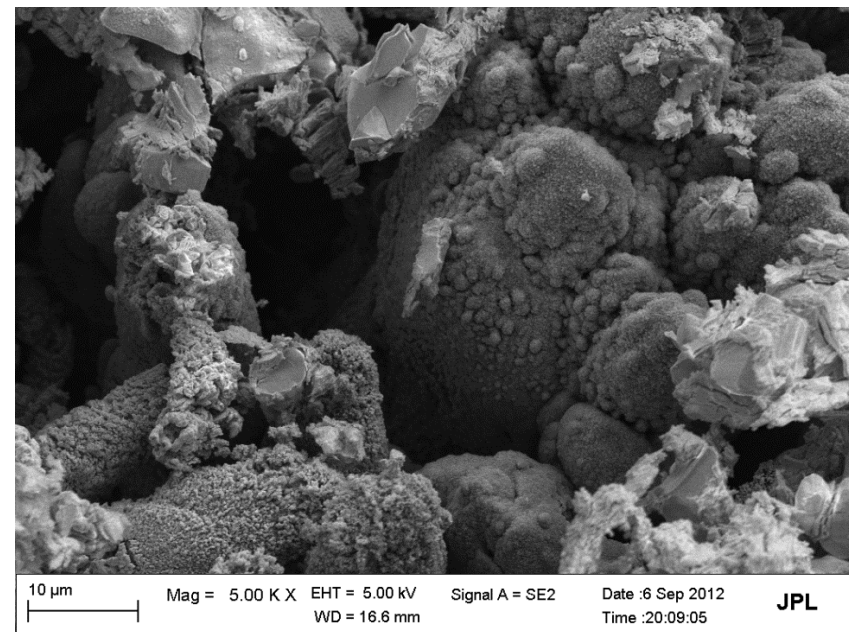
# Comparison of a Pristine $\text{LaB}_6$ Surface with the Emitter Surface after $\sim 250$ Hours



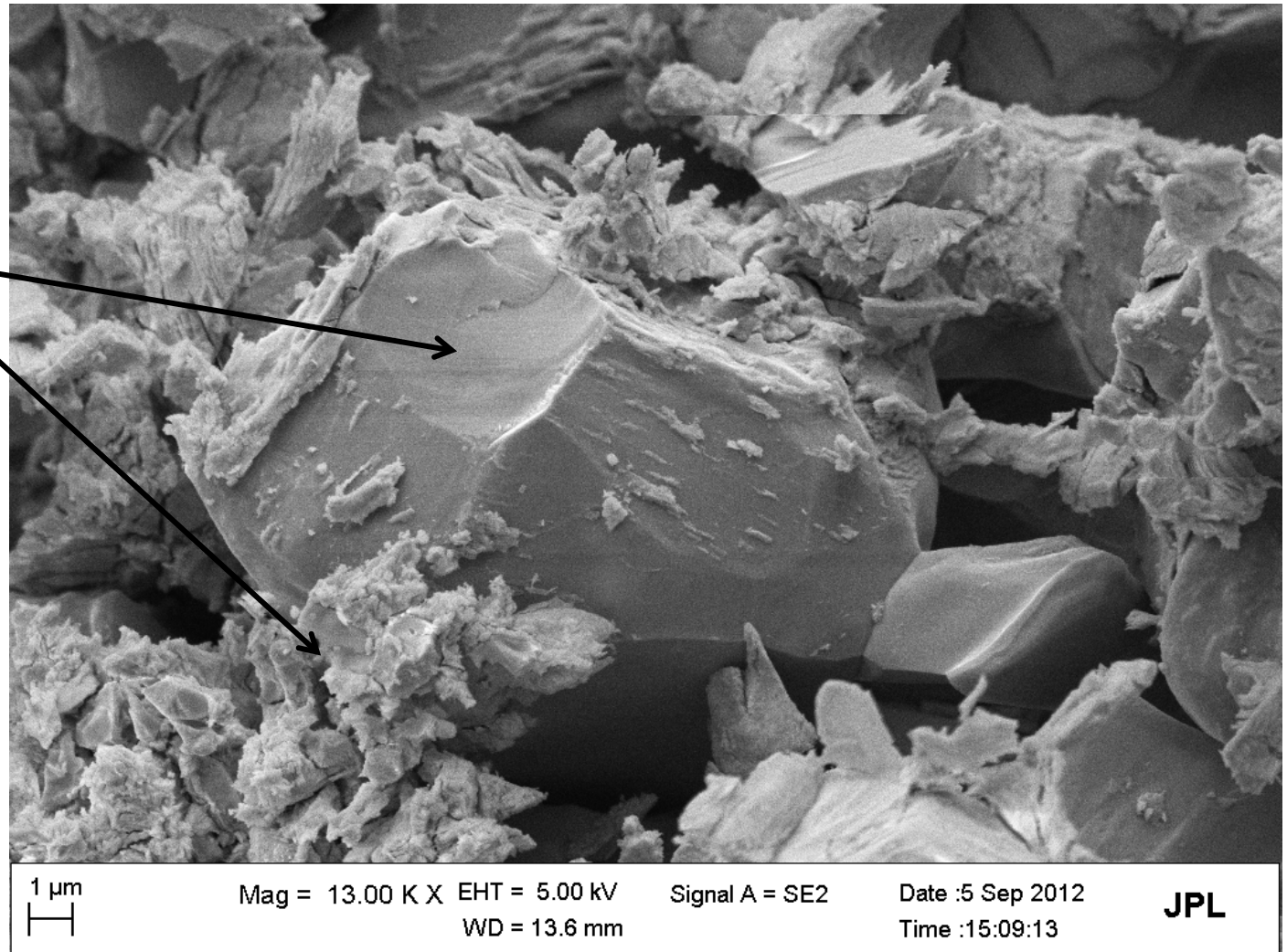
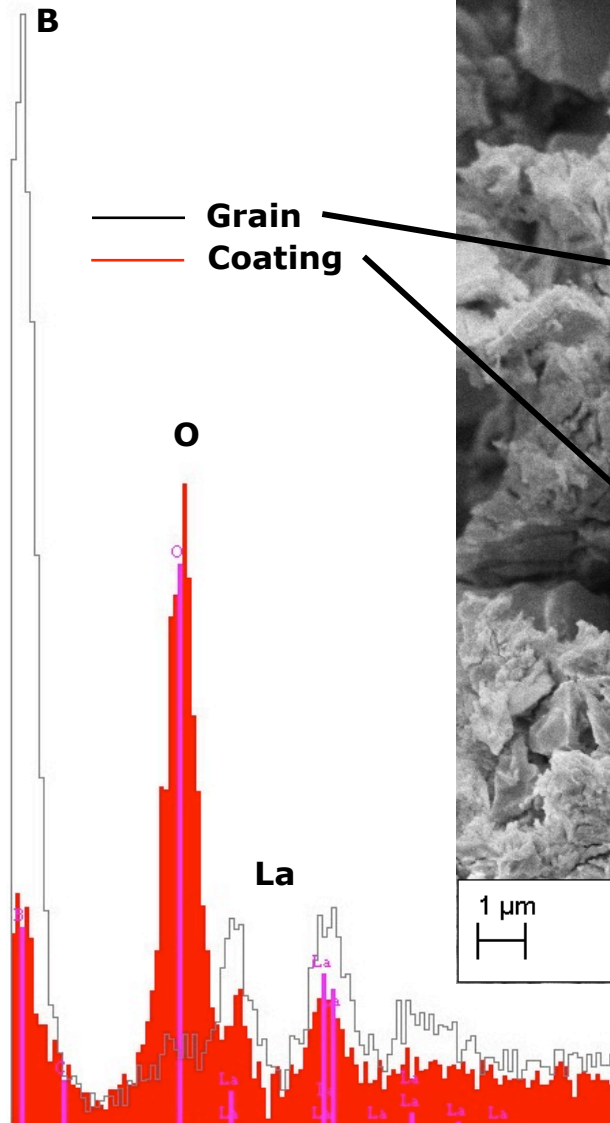
**Fresh Fracture 5000X**



**Inner Diameter 5000X**



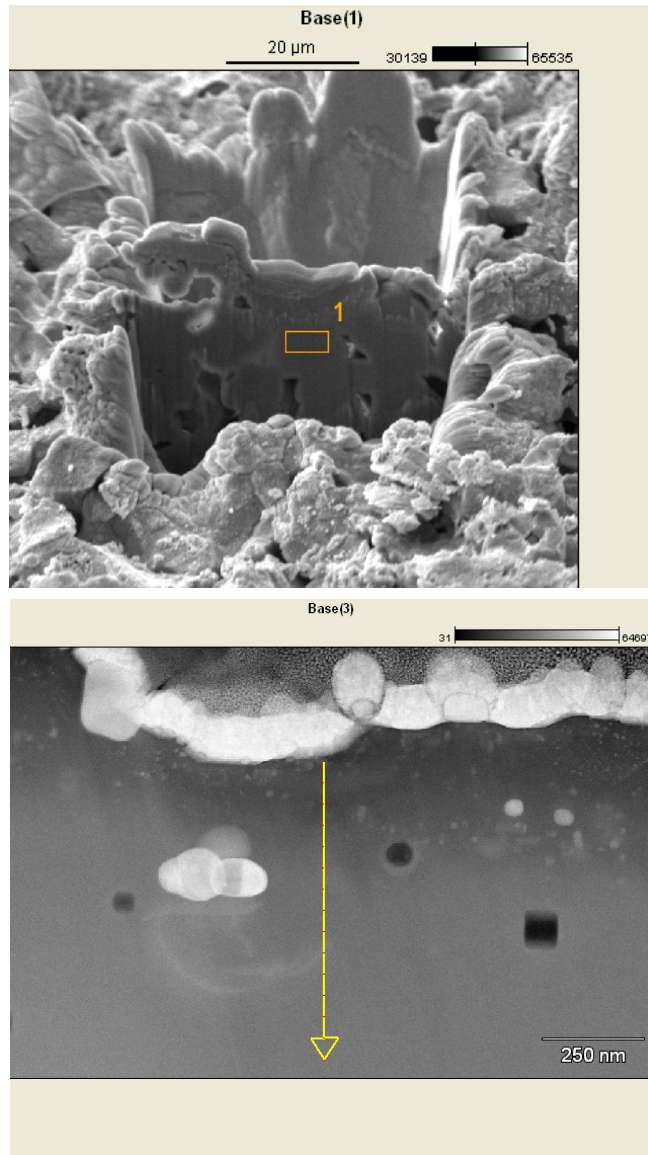
# EDS Spectra Comparison Indicates Coating is Rich in O and La



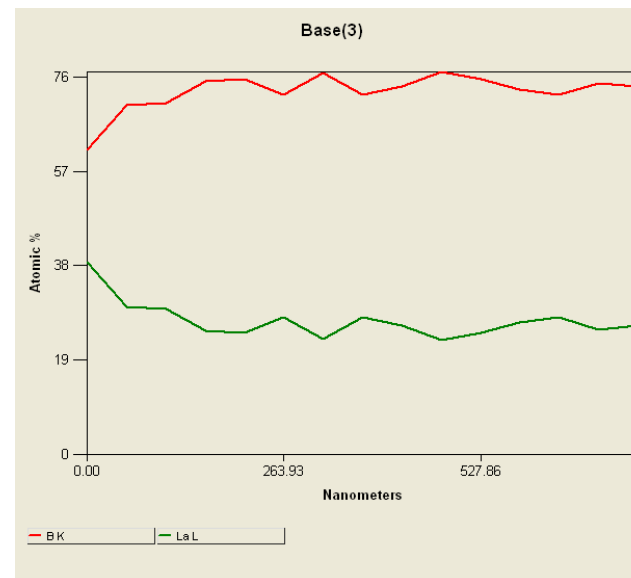


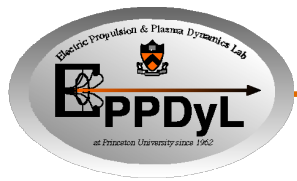


# New Depth Profile Results Indicate Lanthanum Enrichment Near the Surface



- **LaB6 cathode emitter from ~250 hour test was sent to Alp Sehirlioglu for analysis**
  - Samples removed from surface with FIB
  - Cross sections examined with EDS at high resolution to identify changes in stoichiometry near surface
- **Preliminary results suggest enrichment in top 100 nm**

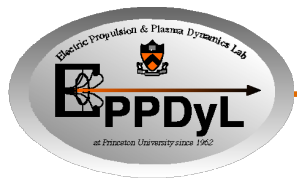




# Diagnostic Needs



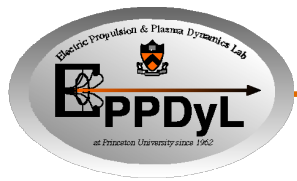
- **Depth profiling capability to determine composition underneath suspected LaO layer**
- **Ability to perform model experiments:**
  - Synthesis of relevant surfaces by deposition of La on hot LaB6 surface
  - Surface analysis tools to determine composition as surface evolves
  - Diagnostics such as UPS to measure work functions of synthesized surfaces
  - Mass spectrometry to determine vaporization rates and vapor content of synthesized surfaces
- **Resulting data would be extremely valuable in refining model boundary conditions**



# Conclusions



- **Plasma-materials interactions are central to the operation of cathodes, a key component in many devices of interest**
- **Fundamental studies of the material properties, transport processes, and surface kinetics can yield the understanding required to properly design cathodes**
- **Combined experiments and modeling are required**
- **Novel cathode concepts and new materials can improve cathode life by exploiting our evolving picture of plasma-material interactions**
  - Modeling and diagnostics results indicate that lanthanum is recycled in LaB6 cathodes. This can be exploited to reduce erosion of the high temperature emitter with proper design.
  - Emitter temperature is the primary driver of cathode life, and direct measurements of the temperature distribution are being used as an input to the plasma model, to determine evaporation rates, and as an indicator of how well the emitter surface is being used in a given design.
- **Near-term plans:**
  - Detailed modeling of La and B transport in LaB6 cathode plasmas and identification of methods to minimize erosion
  - More detailed depth profiling to determine stoichiometry changes (presumably as a result of lanthanum recycling)
  - Further temperature characterization combined with thermal modeling to better understand emitter temperature and its effect on cathode lifetime



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(Continued)



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