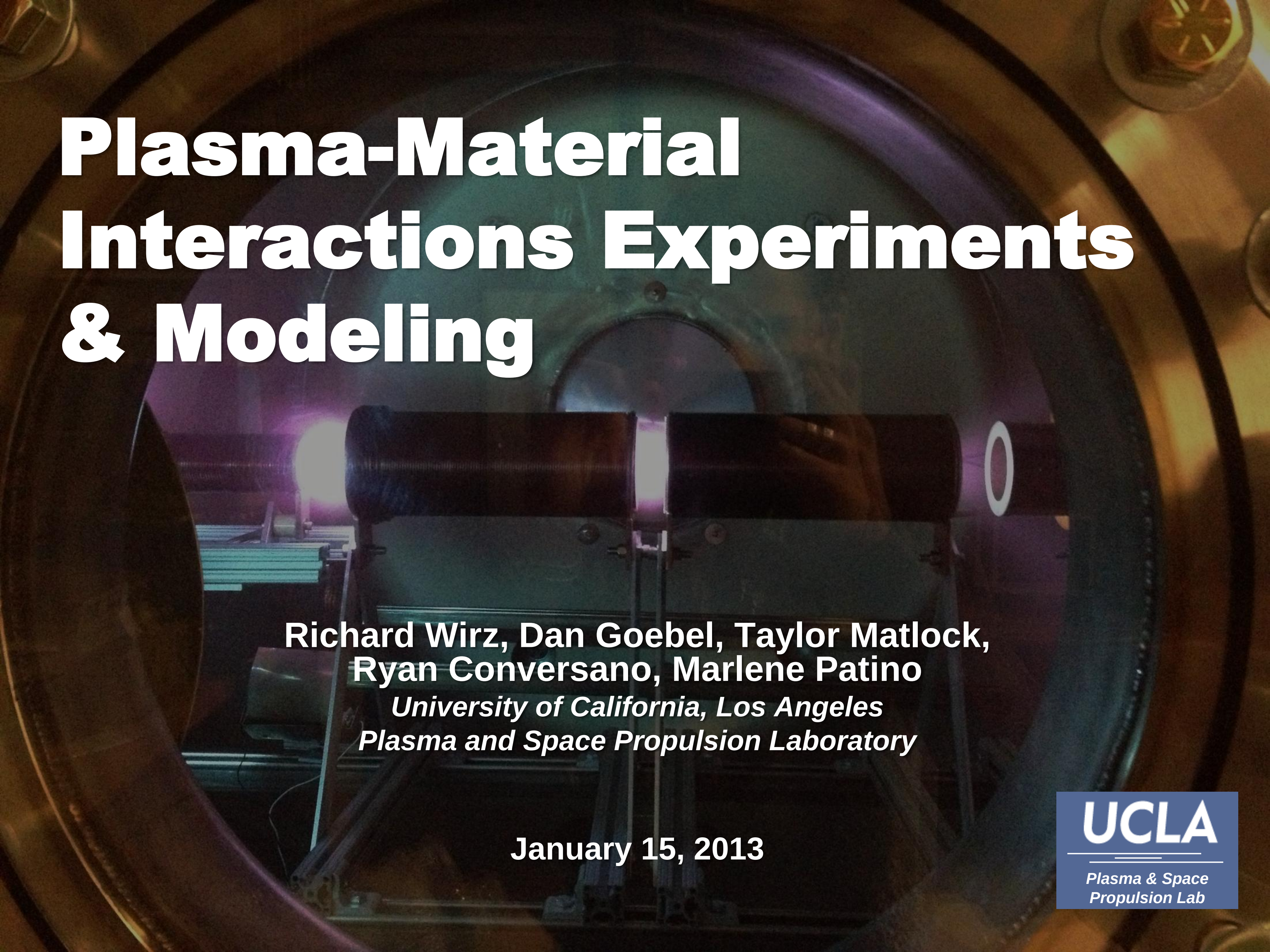

Plasma-Material Interactions Experiments & Modeling

Richard Wirz, Dan Goebel, Taylor Matlock, Ryan Conversano, Marlene Patino

University of California, Los Angeles

Plasma and Space Propulsion Laboratory

January 15, 2013

UCLA

Plasma & Space Propulsion Lab

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Status Quo:

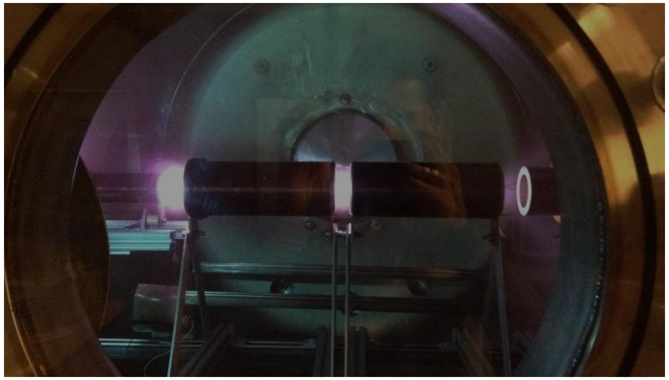
- Existing material options limit plasma thruster and high power device capabilities
- Plasma-material interactions for new material architectures require designated investigations

Research Goals:

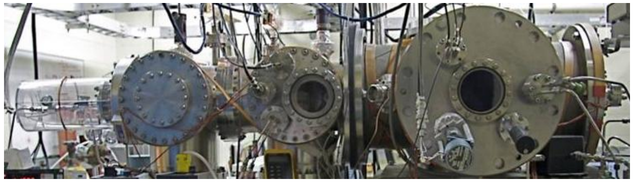
- Develop facilities specifically designed to examine plasma-material interactions for new material architectures
- Utilize a combined experimental/modeling approach to provide well-defined plasma information to sheath and material multi-scale models
- Develop precision experiment to investigate heavy particle induced electron emission

Main Accomplishments:

- Developed a high power plasma source for designated plasma-material investigations

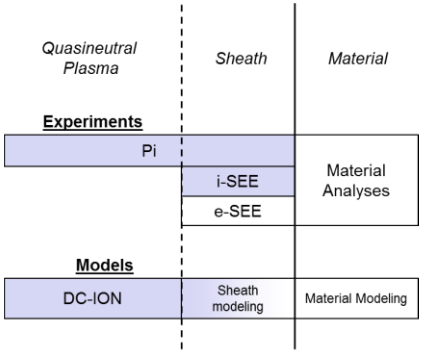


- Identified methods to improve facility, including auxiliary feed and key diagnostics
- Characterized a precision ion beam facility for investigating heavy particle induced electron emission



- Source improvement complete, beam conditioning and test article improvements underway

Project Relationship:



Key Publications:

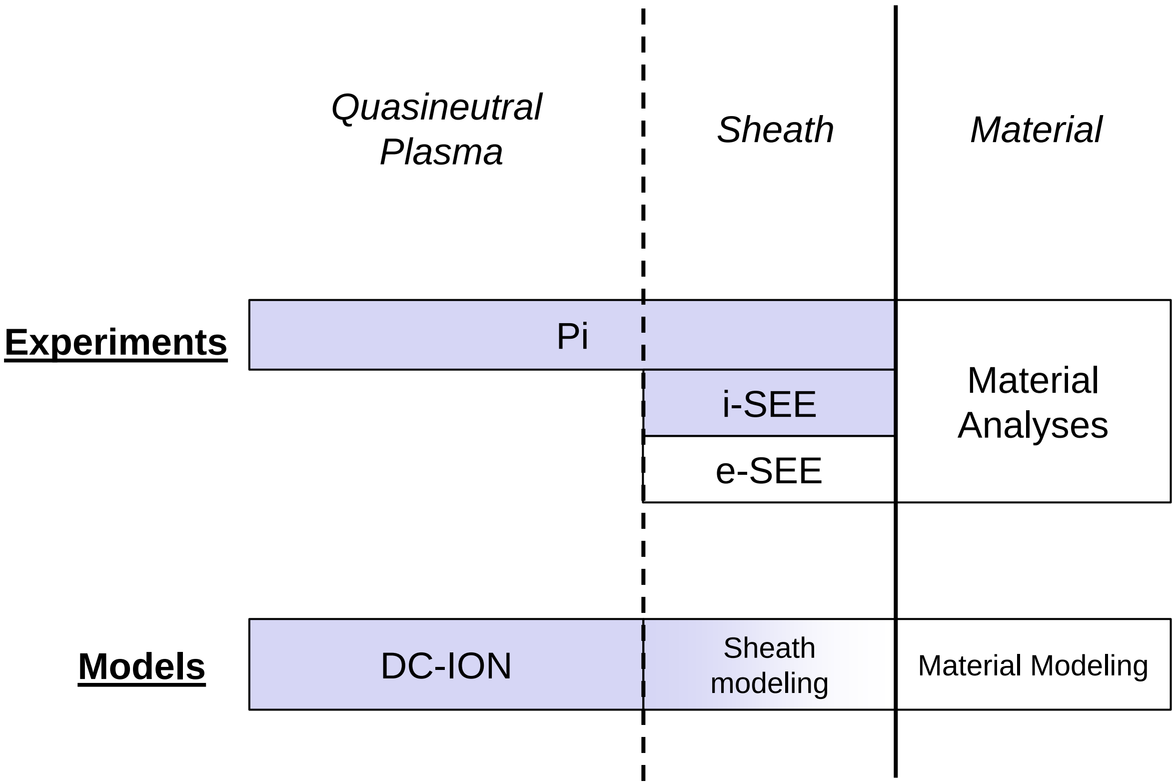
- Wirz R. E., Patino M. I., Chu L. E., Mao H-S., Araki S. J., *Plasma Sources Sci. Technol.*, Submitted Jan 2013.
- Chu E., Goebel D., Wirz R., *Journal of Propulsion and Power*, accepted Nov 2012
- Araki J., Wirz R., *Journal of Applied Physics*, accepted for publication Oct 2012

Outline

- Introduction
- UCLA-Pi
  - Experimental Facilities
  - Modeling
- Heavy Particle Induced Electron Emission
  - Ion Beam Facility and Modeling
- Wrap-up

Introduction

- Examine plasma-material interactions using combined experimental & modeling approach
- This presentation describes the “Pi” plasma source and related modeling (DC-ION)
- Also described are preliminary efforts towards ion induced SEE measurements



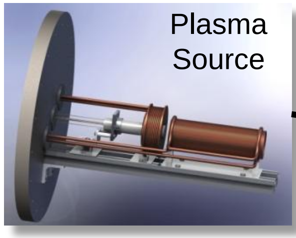
UCLA Pi: Plasma-Material Interactions Facility

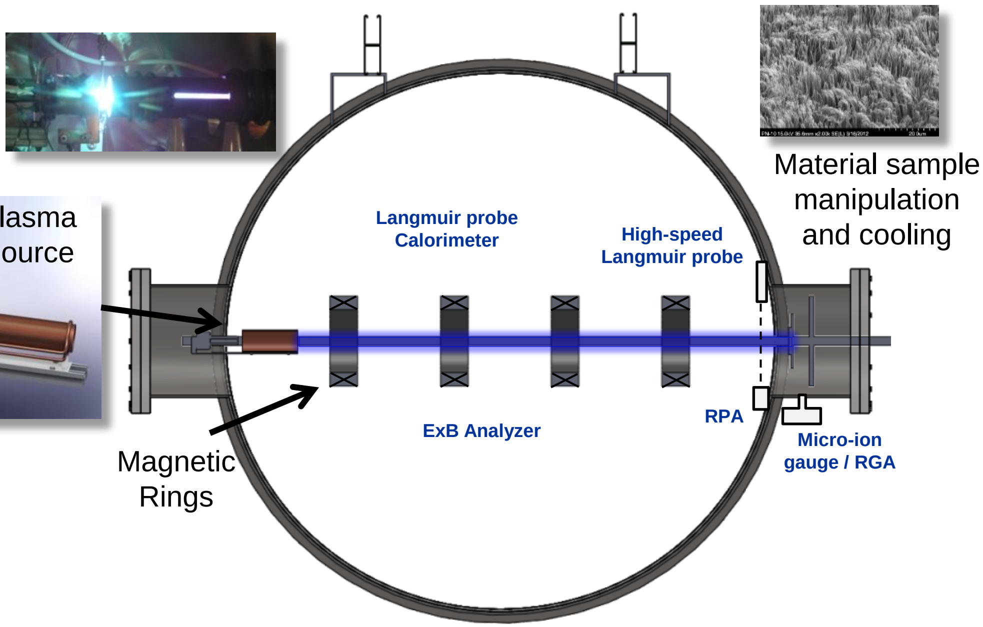
Objective: Examine the behavior of new materials for a wide range of plasma conditions

Parameter	Range
Plasma density	$\leq 1x10^{19}$ m^{-3}
Electron temperature	3 to 20 eV
Ion energy	10 to 300 eV
Ion flux to target	10^{21} to 10^{23} m^{-2}s^{-1}
Target area	≈ 5 cm^2

Plasma Diagnostic	Measurement
Micro-ion gauges	Neutral density
Langmuir/calorimeter probes	Density, T_e, total ion energy, power flux
$E\times B$ analyzer	Species mix
RGA	Neutral species and impurity levels
RPA	Ion energies

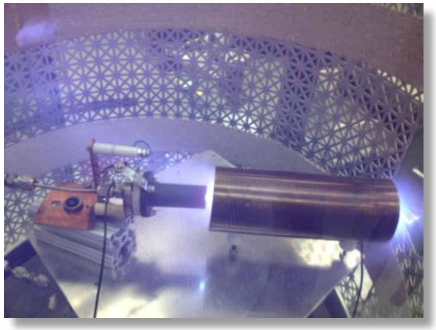
*Target capabilities

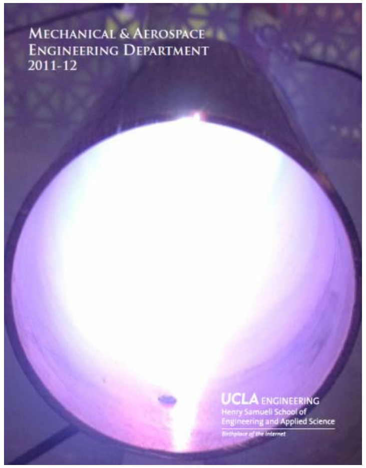




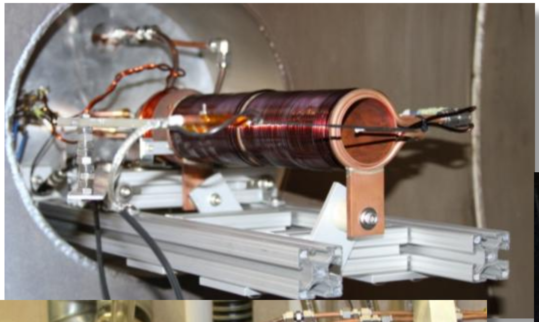
Plasma Source Development

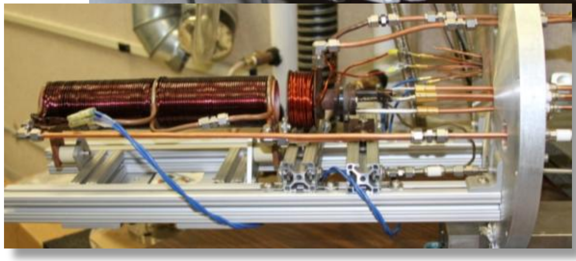
- Preliminary Cathode Tests
  - 100A hollow cathode
  - Tested in a bell jar vacuum
  - No magnetic confinement of plasma

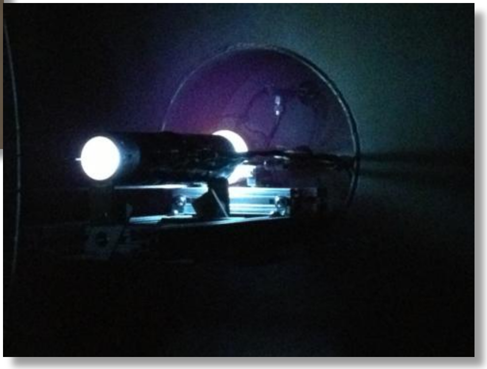




- Pi Facility Installation
  - Cathode and anode coils
  - Low 10^{-6} Torr operating pressure

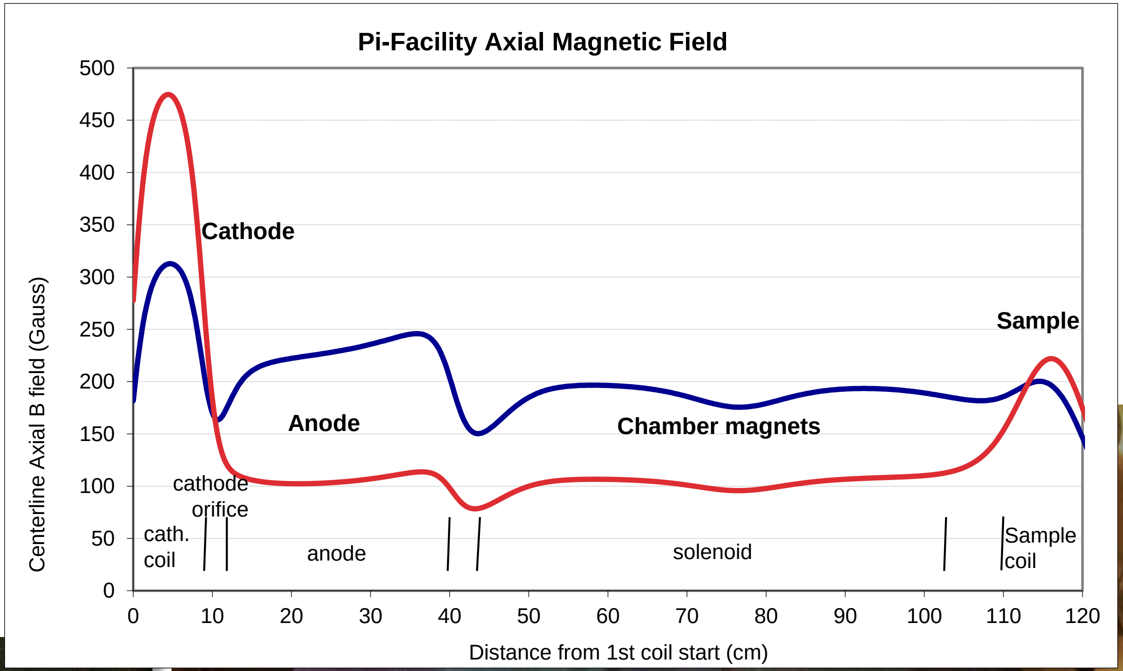


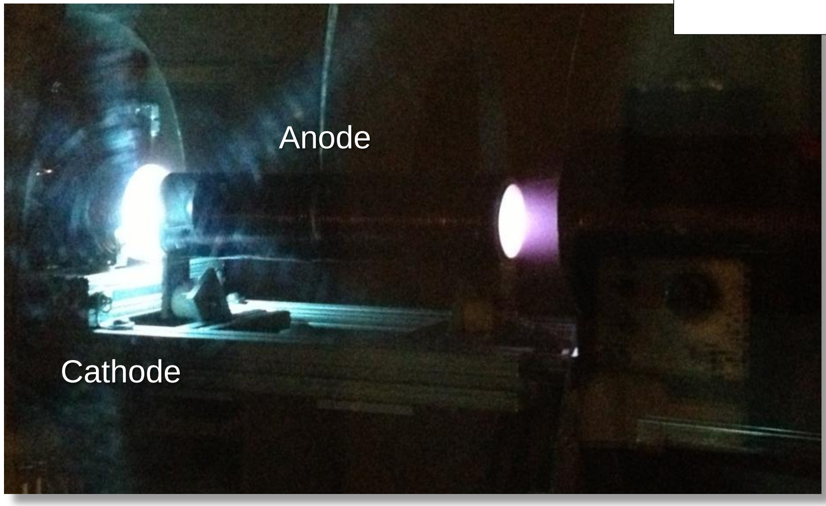


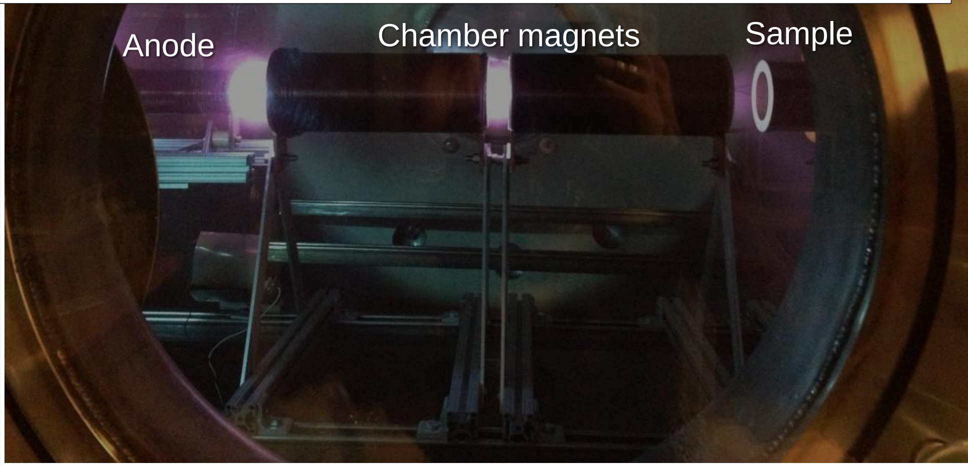


Plasma Confinement

- Multiple stages of magnetic confinement
  - Strong cathode magnet for efficient plasma extraction
  - Weaker anode magnet weak enough for current collection
  - Downstream “chamber magnets” maintain ~1” diameter plasma beam across chamber (100-200 G)
  - Sample magnet chokes beam to sample size



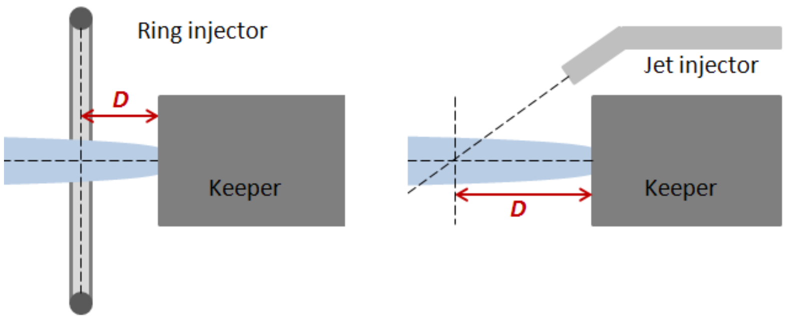


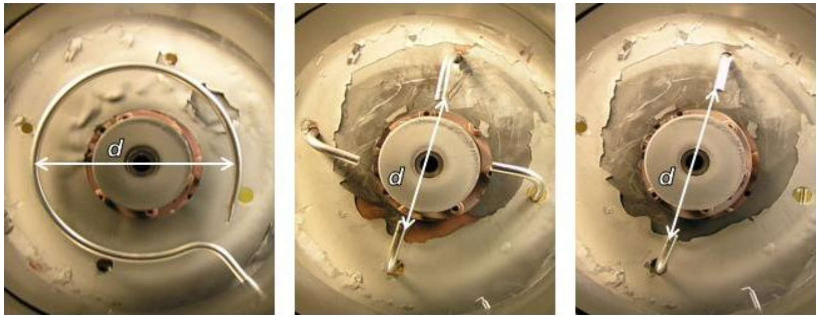


Auxiliary cathode flow injection

Objectives:
- Examine cathode discharge for auxiliary flow configurations
- Consider for improved plasma source

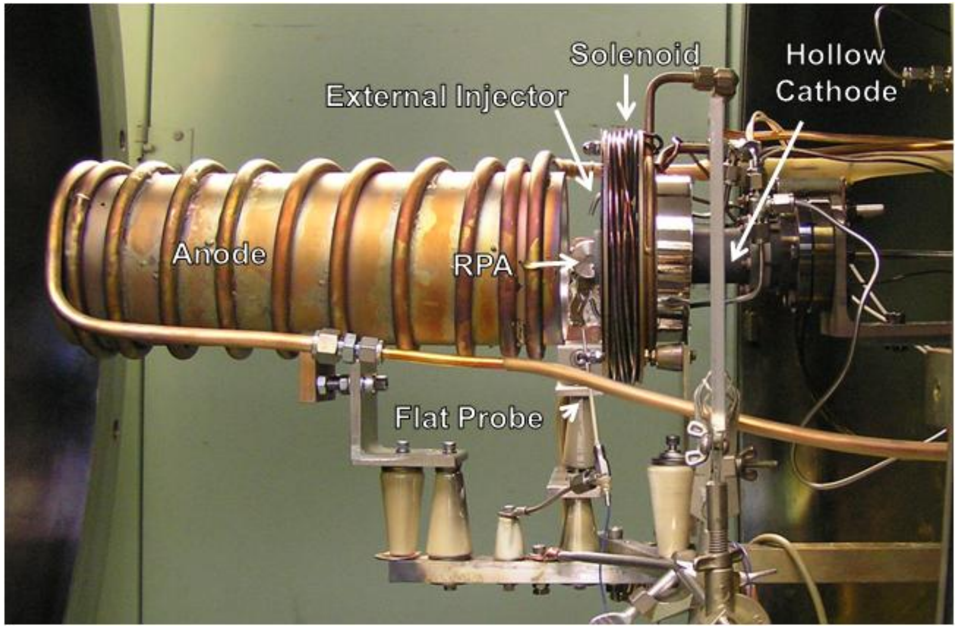
Injection techniques:





Chu E., Goebel D., Wirz R., *J. Prop. Pwr.*, accepted Nov 2012

Experimental setup:
- 250 A LaB_6 cathode
- 0.8-m-dia. by 2-m-long water-cooled anode
- 10-cm-diameter solenoid coil
- Ion energy measurements via retarding potential analyzer



Auxiliary cathode flow results

Consider external flow to reduce fluctuations and unwanted high energy ions

- Cathode results show clear reduction, especially at higher discharge currents[1]
- Fluctuation reductions shown for thruster and cathode discharges [2]

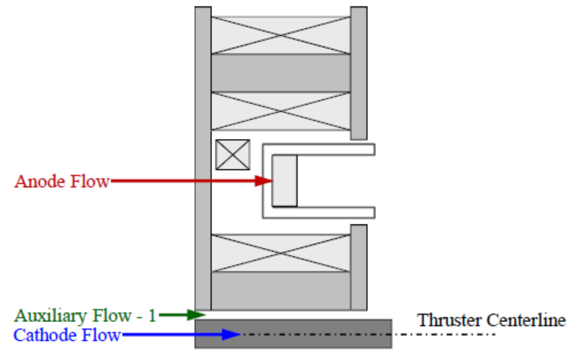


Figure 19. Schematic of the 6-kW laboratory model Hall thruster illustrating locations of propellant injection at the anode, cathode, and auxiliary port.

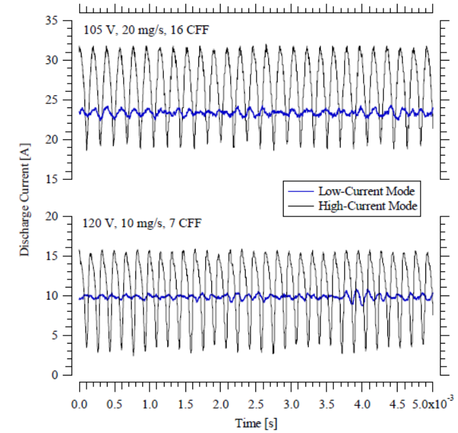
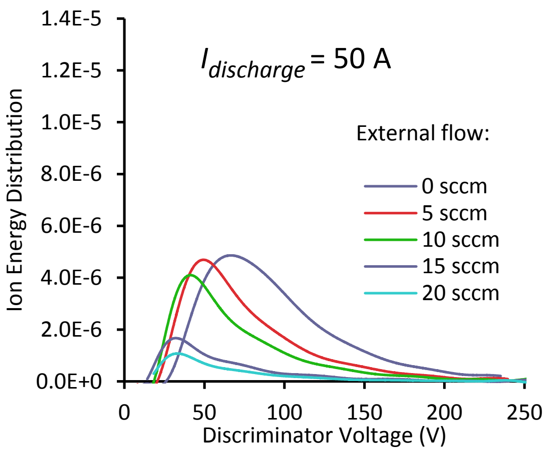
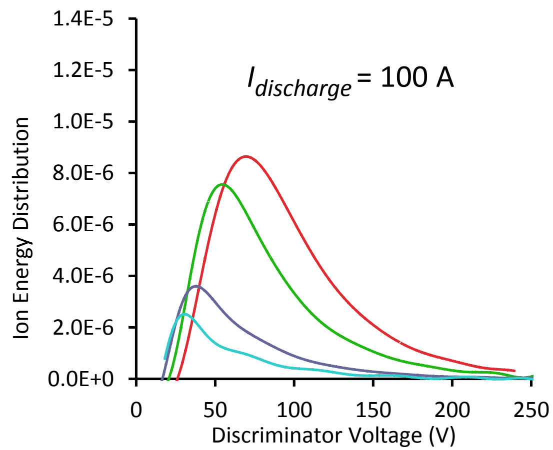


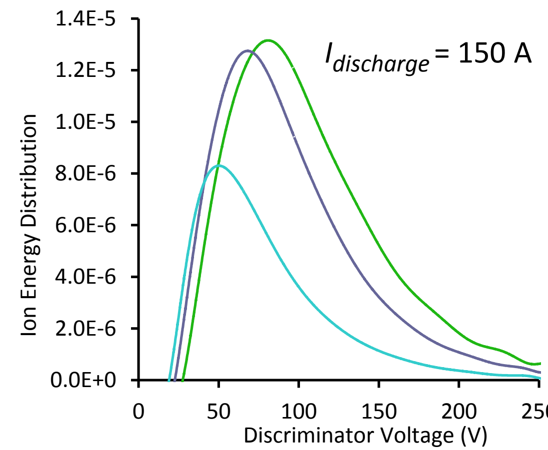
Figure 10. Comparison of discharge current oscillations in the low-current and high-current modes for 105-V, 20-mg/s, 16-CFF operation during a 5-ms time period.

[2] Brown D. L., Gallimore A. D., *IEPC-2009-074*

Cathode flow: 10 sccm



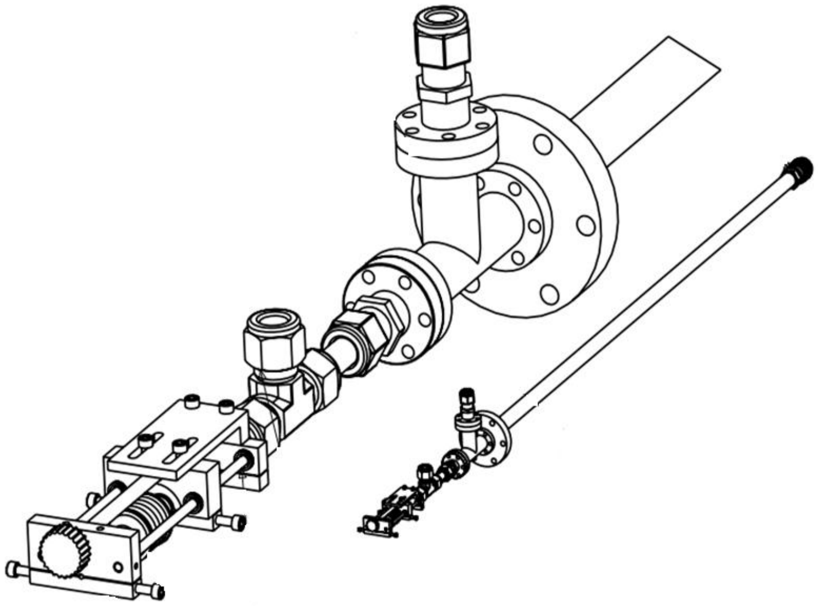




[1] Chu E., Goebel D., Wirz R., *J. Prop. Pwr.*, accepted Nov 2012

Material sample manipulator

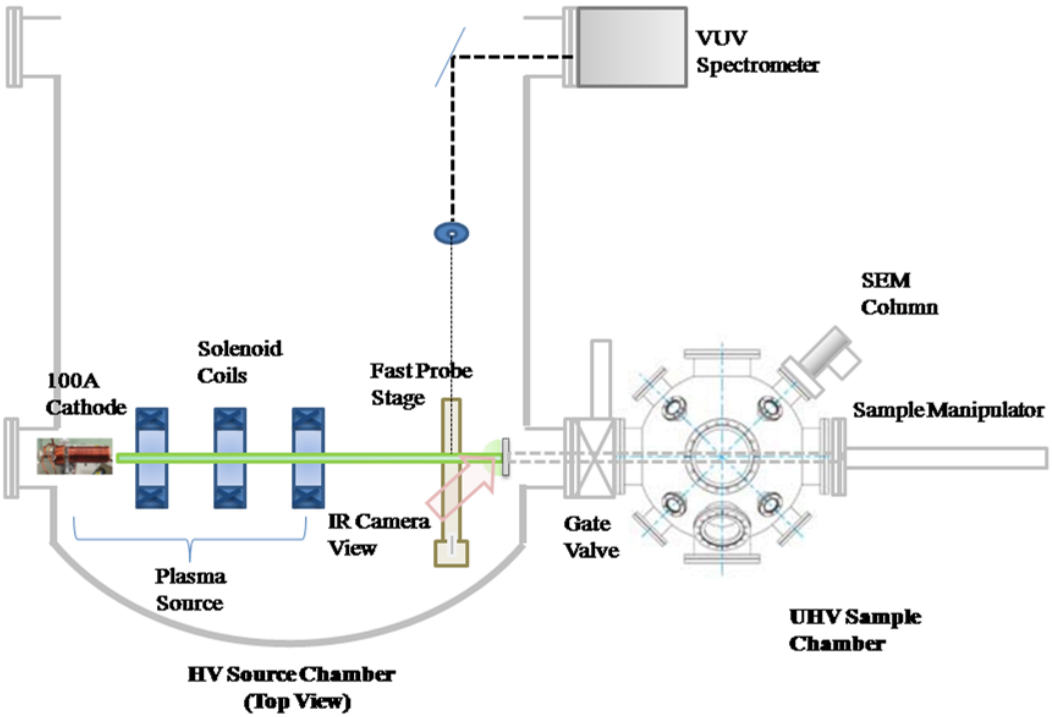
- Manipulator/holder is under construction
  - Water-cooled
- Baseline sample tests pending
- Preliminary micro-engineered material tests will follow baseline tests



UCLA-Pi Facility Diagnostics

- Current diagnostics
  - Langmuir probe
    - Plasma density/flux
    - Electron temperature
    - Spatial/temporal resolution
  - *Ex situ* SEM
    - Morphology change (pre/post)

- Possible diagnostic upgrades
  - Improved diagnostics
    - Fast probe stage
    - ExB, RPA, RPA, calorimeter
  - Attached SEM
    - Rapid morphology change
    - No atm contamination
  - VUV spectra
    - Sputtered/deposited species
    - Erosion/redeposition rates
  - IR video
    - Temperature map
    - Time resolved capture of 'hot spots'
  - <u>All to be *in situ*</u>



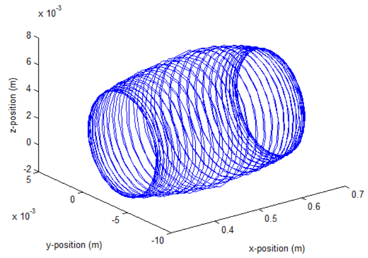
Schematic of the proposed Pi facility showing the addition of a differentially pumped UHV chamber for periodic material inspection. Current facility only includes HV source chamber.

Modeling of Pi Plasma

- Plasma conditions just upstream of the material surface will be characterized by a combination of experimental diagnostics and modeling

- *DC-ION: 2D/3D Hybrid-PIC low-temperature plasma model
  - 3D primary electron (PIC)

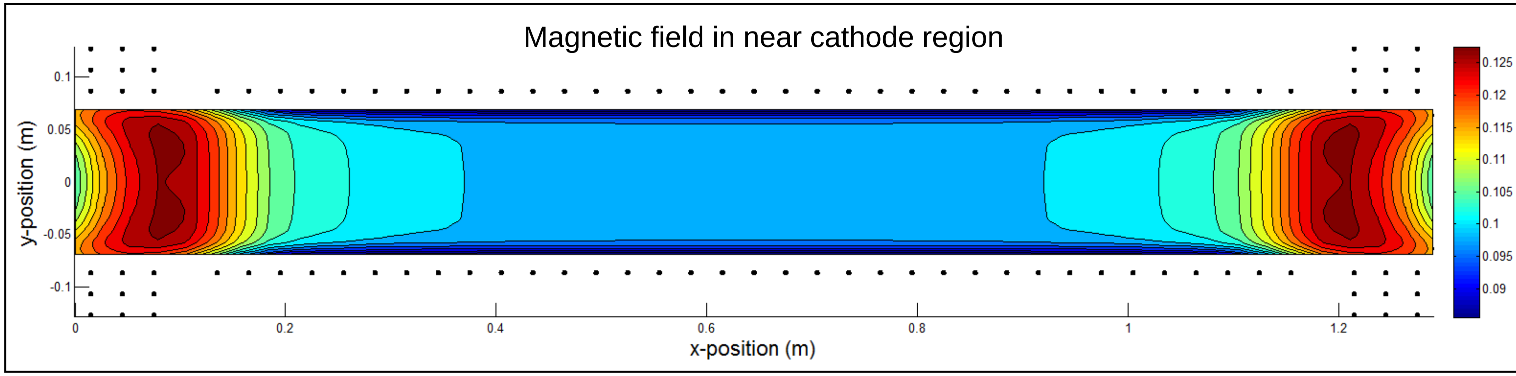
    Ionization rate for primary electrons (PIC): $\dot{n}_i^p = \left(\sum \Delta J_p^{iz}\right) / V_{cell}$
  - 2D two-fluid plasma ions and electrons



$$\text{Ion fluid: } nm_i\nu_{i-n}\mathbf{u}_i - nm_e\nu_{ei}\left(\mathbf{u}_e - \mathbf{u}_i\right) = ne\mathbf{E} + ne\mathbf{u}_i \times \mathbf{B} - k\nabla\left(nT_i\right)$$

$$\text{e}^- \text{ fluid: } nm_e\nu_{e-n}\mathbf{u}_e + \underbrace{nm_e\nu_{ei}\left(\mathbf{u}_e - \mathbf{u}_i\right)}_{two-fluid\ \text{interaction}} = -ne\mathbf{E} - ne\mathbf{u}_e \times \mathbf{B} - k\nabla\left(nT_e\right)$$

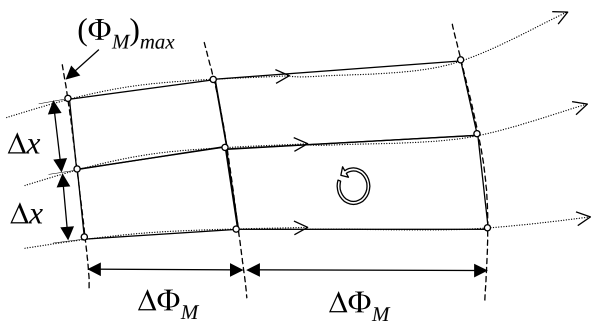
$$\text{Neutral interaction: } \nu_{i-n} \equiv \nu_{in} + \nu_{CEX} + \dot{n}_i/n \;;\; \nu_{e-n} \equiv \nu_{en} + \dot{n}_e/n$$

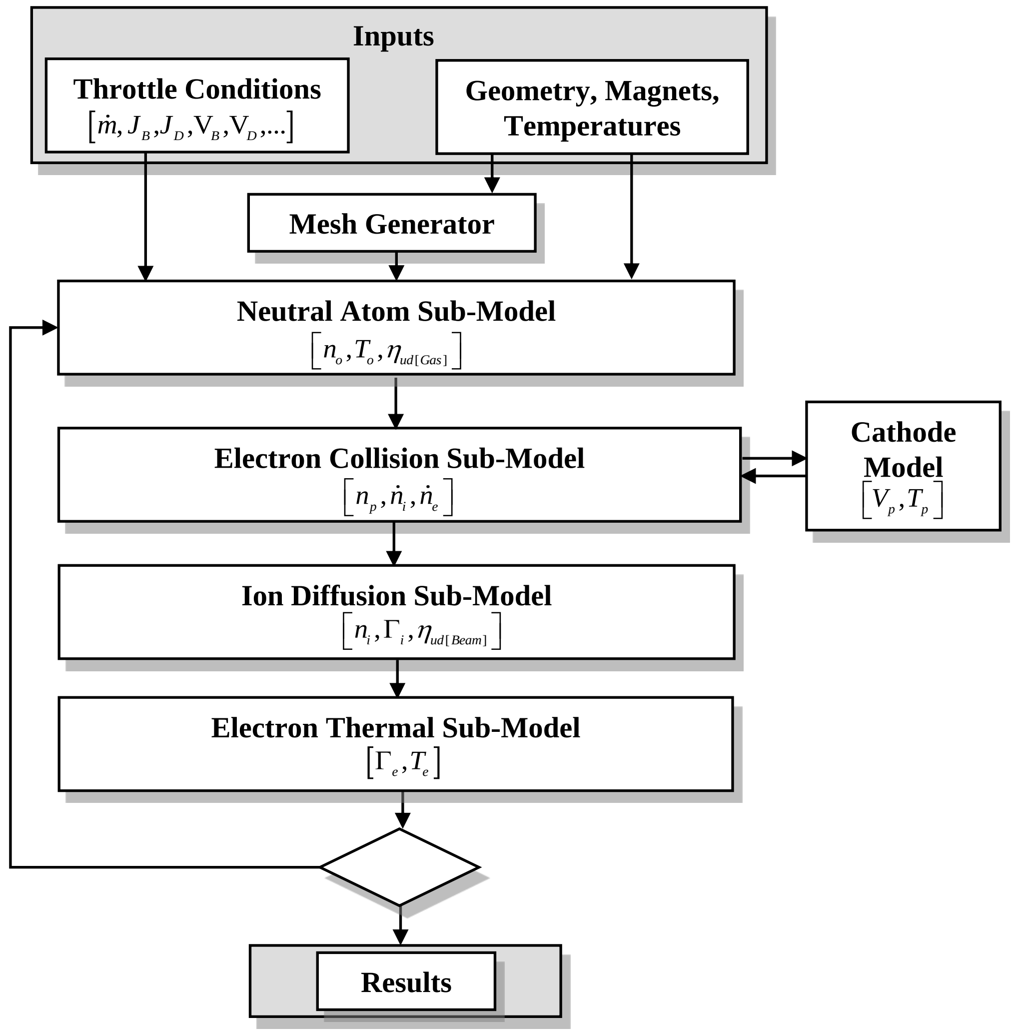


*Wirz R., *AIAA-2005-3887*

DC-ION Model (Overview)

- Hybrid code
- Multi-species
  - Neutral Atoms
  - Primary Electrons
  - Ions
  - Double Ions
  - Secondary Electrons
- Collisions
  - Elastic, ionization (+ & ++), excitation, e-e
- Magnetically aligned mesh capability





Wirz R., *AIAA-2005-3887*
Wirz R., Katz I., *AIAA-2004-4107*
Wirz R., Goebel D., *Plasma Sources Sci. Technol., 17 (2008) 035010*

Heavy Particle Induced Electron Emission

- Limited data for relevant energies/materials
- Simple theories of electron yield break down for heavy particles
  - Dominant process may change for relevant energies

E (keV)	Targets	Author	Year
1-5	U	Chen et al.	1983
2-8	**W**	Bonnano et al.	1990
10	Cu,Au,Kr(sol),Xe(sol)	Soszka et al.	1990
0.3-10	Au	Alonso et al.	1986
6-10	FeNi,Xe(sol)	Soszka et al.	1989
5-20	**Al**,Ti,Ni,Cu,Zn,**Mo**,Ag,Au,Pb	Zalm & Beckers	1984
5-20	Cu,Zn	Zalm & Beckers	1985
1.5-25	KBr,KCl,NaCl,LiF	Konig et al.	1975
40	Ge	Holmen et al.	1975
1.2-50	**Al**	Alonso et al.	1980
5-50	Cu,Au,**Mo**	Ferron et al.	1981
7.3-70	Cu	Brusilovsky & Molchanov	1971
4-80	Si	Benazeth et al.	1989
3-90	CuBe	Schram et al.	1966
20-100	Si	Fontbonne et al.	1970
0.01-0.35	**Al**	Svensson & Holmen	1982
0.1-0.4	Cu	Holmen et al.	1981
0.03-0.4	Cu	Svensson et al.	1981
0.08-1	**C**	Hasselkamp & Scharmann	1983

Survey of experiments from 1968-1990 with Xe^+ as impinging ion at energies ≤25 keV. Target materials of interest are highlighted in red. Table adapted from D. Hasselkamp, **Particle Induce Electron Emission II**, 1992

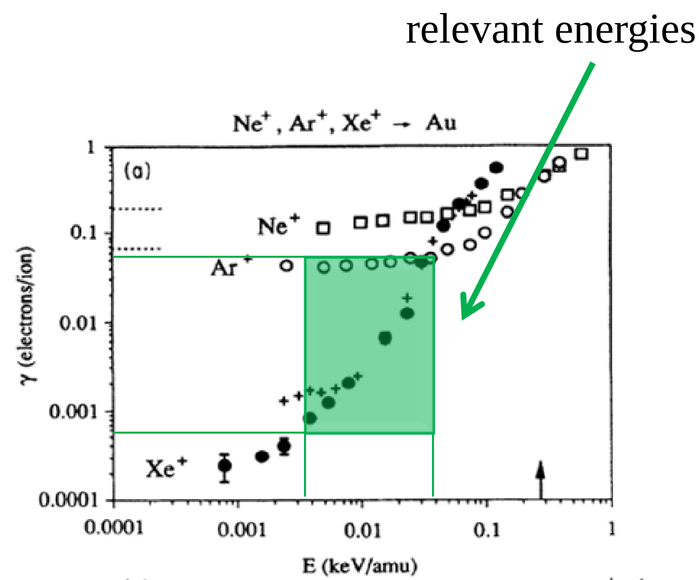


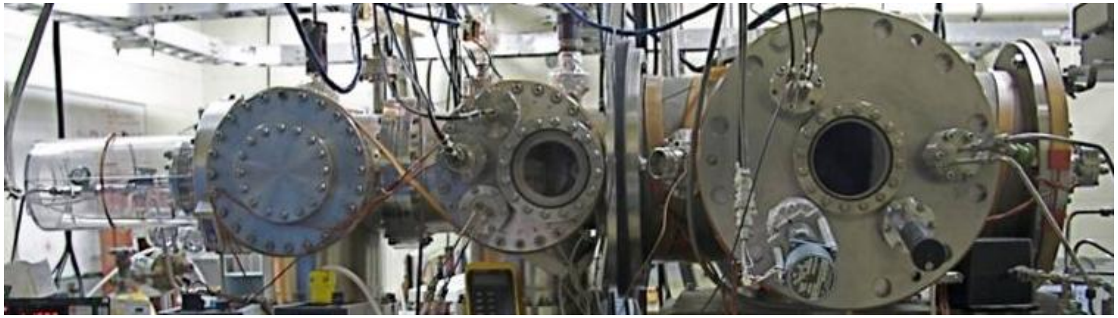
FIG. 3. (a) Total electron emission yields for Ne^+ (open squares), Ar^+ (open circles), and Xe^+ (solid circles) impact on clean polycrystalline gold vs impact energy per atomic mass unit. Crosses show results for Xe^+ from Ref. 7. Vertical arrows and dashed horizontal lines as for Fig. 2(a). (b) Ratio of emis-

G. Lakits *et al*, *Phys Rev A 42(9)*, 1990

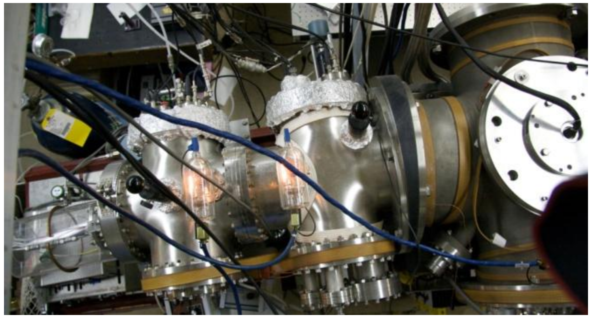
Ion Beam Facility

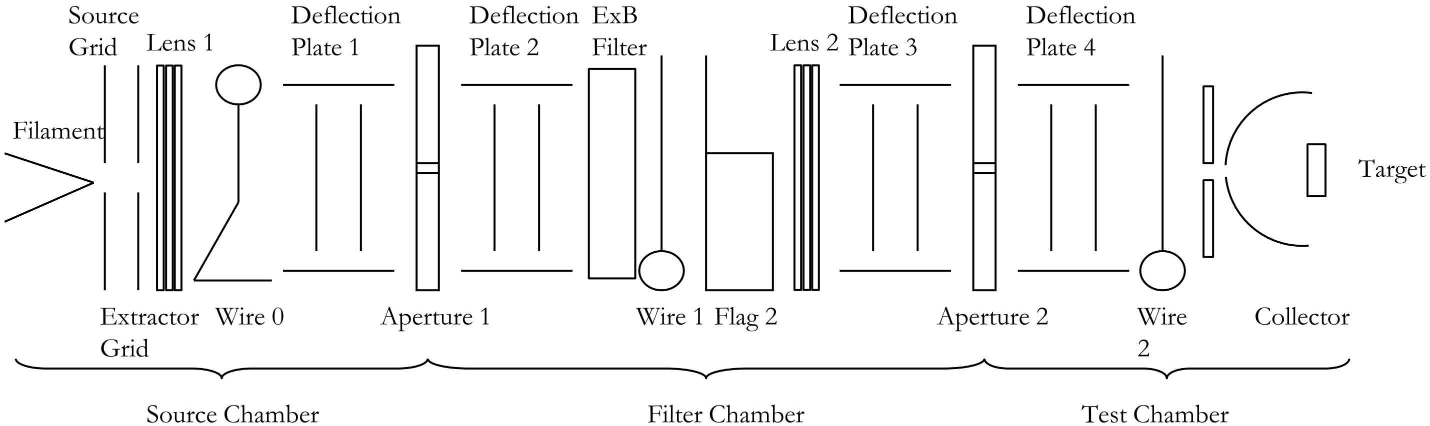
- Facility provides a well-characterized xenon ion beam
- Enables measurement of particle-induced electron emission from a variety of materials
  - Stainless steel, platinum, carbon materials, micro-architectured materials, etc.

Side View



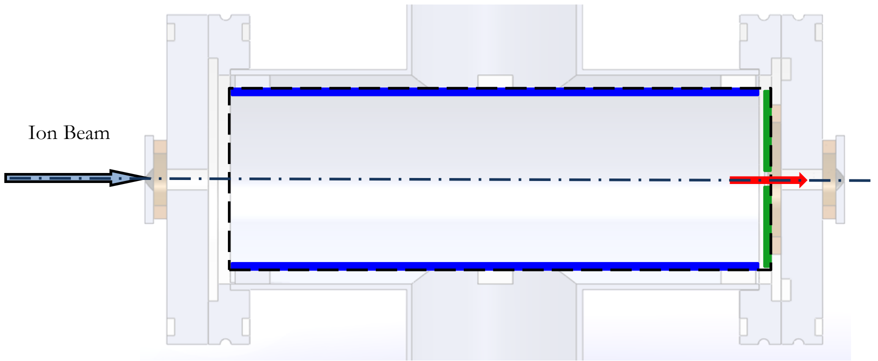
Top View

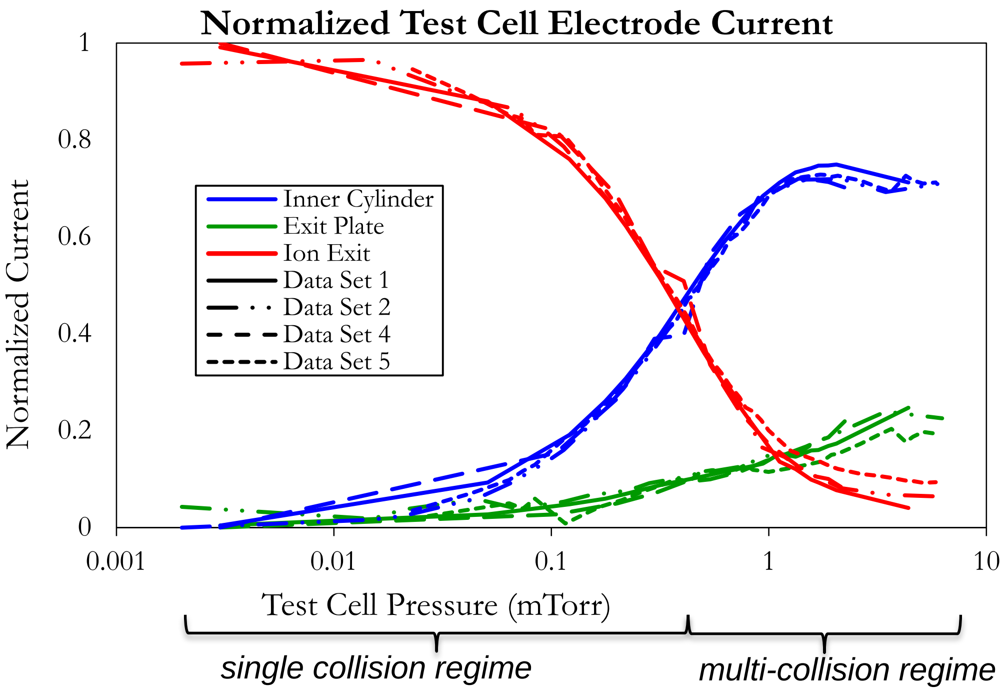




Ion Beam Characterization

- Ion beam characterized using "Test Cell" and upstream diagnostics
- Repeatable data provides expected trends for normalized data
- Improvements are needed to improve beam current and quality



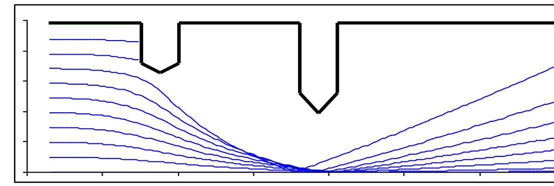


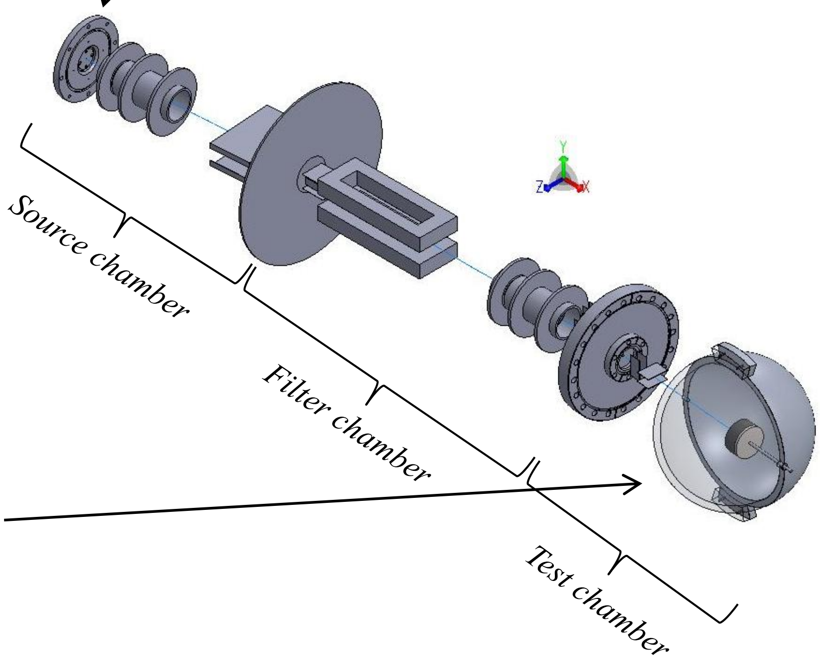
Wirz R. E., Patino M. I., Chu L. E., Mao H-S., Araki S. J., "Simple plasma experiments for investigation of plasma behavior and model validation," *Plasma Sources Sci. Technol.*, Submitted Jan 2013.

Patino M., Chu L., Wirz R., "Examination of Ion-Neutral Collisions using a Well-Characterized Plasma Experiment," 48th AIAA Joint Propulsion Conference, Atlanta, GA, 30 July - 1 August 2012, AIAA-2012-4119

Ion Beam, Current Efforts

- Improvements to ion source current and beam definition
  - Improved ion optics for source designed and built
  - Ion modeling efforts underway to improve ion beam conditioning (e.g., lenses, deflection plates, filter, diagnostics)





- SEE measurements
  - Spherical collection electrode designed for variable incident angles

Wrap-up

- UCLA-Pi
  - Vacuum System
    - Complete, fully operational
  - Plasma Source
    - 100 A cathode installed, tested, 75 A plasma demonstrated
  - Sample Manipulator
    - Under construction
  - Modeling
    - Magnetic field modeling and meshing underway
    - To be validated and used for source optimization and characterization

- Ion Beam
  - Ion Source
    - Source improvements complete
    - Beam conditioning and diagnostic improvements underway
  - Heavy particle induced electron emission
    - Experimental design underway

Related Publications/Papers

- **Journal articles**
  - Wirz R. E., Patino M. I., Chu L. E., Mao H-S., Araki S. J., “Simple plasma experiments for investigation of plasma behavior and model validation,” *Plasma Sources Sci. Technol.*, Submitted Jan 2013.
  - Chu E., Goebel D., Wirz R., “External Mass Injection to Reduce Energetic Ion Production in the Discharge Plume of High Current Hollow Cathodes,” *Journal of Propulsion and Power*, accepted Nov 2012
  - Araki J., Wirz R., “Ion-Neutral Collision Modeling Using Classical Scattering with Spin-Orbit Free Interaction Potential,” *Journal of Applied Physics*, accepted for publication Oct 2012

- **Conference papers**
  - Patino M., Chu L., Wirz R., “Examination of Ion-Neutral Collisions using a Well-Characterized Plasma Experiment,” 48th AIAA Joint Propulsion Conference, Atlanta, GA, 30 July - 1 August 2012, AIAA-2012-4119
  - D. Goebel and E. Chu, "High current lanthanum hexaboride hollow cathodes for high power Hall thrusters," in 32nd International Electric Propulsion Conference, Wiesbaden, Germany, September 11 – 15, 2011.
  - Wirz R., Chu L., Patino M., Mao H., Araki S. J., “Well-Characterized Plasma Experiments for Validation of Computational Models”, IEPC-2011-122, 32nd International Electric Propulsion Conference, Kurhaus, Wiesbaden, Germany, Sept 11-15, 2011
  - Mao H.-S., Wirz R., “Comparison of Charged Particle Tracking Methods for Non-Uniform Magnetic Fields”, AIAA-2011-3739, 42nd AIAA Plasmadynamics and Lasers Conference, Honolulu, Hawaii, June 27-30, 2011
  - Araki S. J., Wirz R., “Collision Modeling for High Velocity Ions in a Quiescent Gas” AIAA-2011-3740, 42nd AIAA Plasmadynamics and Lasers Conference, Honolulu, Hawaii, June 27-30, 2011