An Experimental Study to Show the Effects of Secondary Electron Emission on Plasma Properties in Hall Thrusters

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Introduction

- Electron induced SEE in insulator walls can drastically affect the energy distribution of the electrons, sheath potential, cross-field current, heat flux, and various other properties of the system [1, 2]
- The exact effects of SEE in Hall thrusters have not been well studied experimentally
- These effects can be experimentally studied by inducing SEE in insulator materials used in Hall thruster channels in a low-density background plasma using a low-energy electron gun

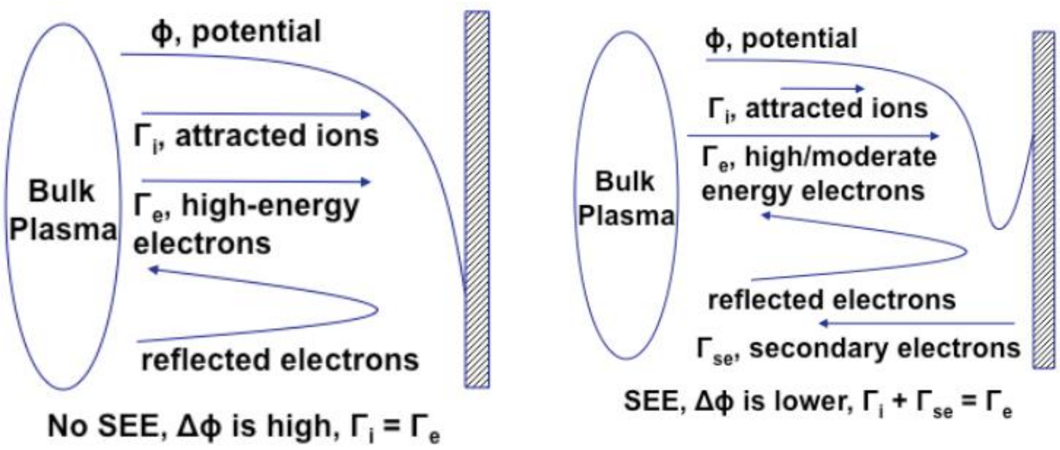


Figure: Sheath profile in absence and presence of secondary electron emission

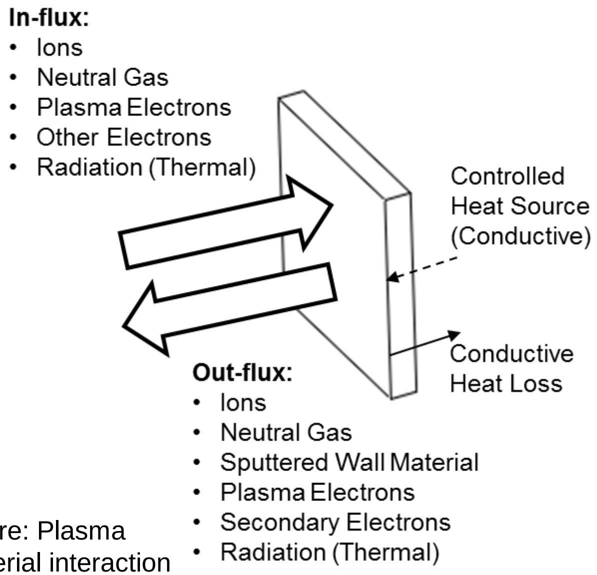


Figure: Plasma material interaction science

Motivation

- Analytical models using kinetic theory to study plasma-wall systems suggest the decrease in sheath potential, highly anisotropic, non-Maxwellian distribution of electrons with a severe depletion of high energy electrons, and increased heat and energy fluxes to the wall [3,4]
- To study the effects of SEE in Hall thrusters, ionization, strong electric and magnetic fields, and the resulting cross-field current, must be added to the simple plasma-wall system
- Simulations and experiments of the effects of SEE in Hall thrusters suggest the increased contribution of near-wall conductivity of the insulator wall to the E x B current of Hall thrusters, formation of two-stream instability due to beam-like character of the secondary electrons, and sheath instability [5, 6]
- Many of the models and simulations have little or very indirect experimental verification; therefore, experimentally studying the effects of SEE in a Hall thruster-like system is essential in verifying the results of the previous studies

Hall Thruster

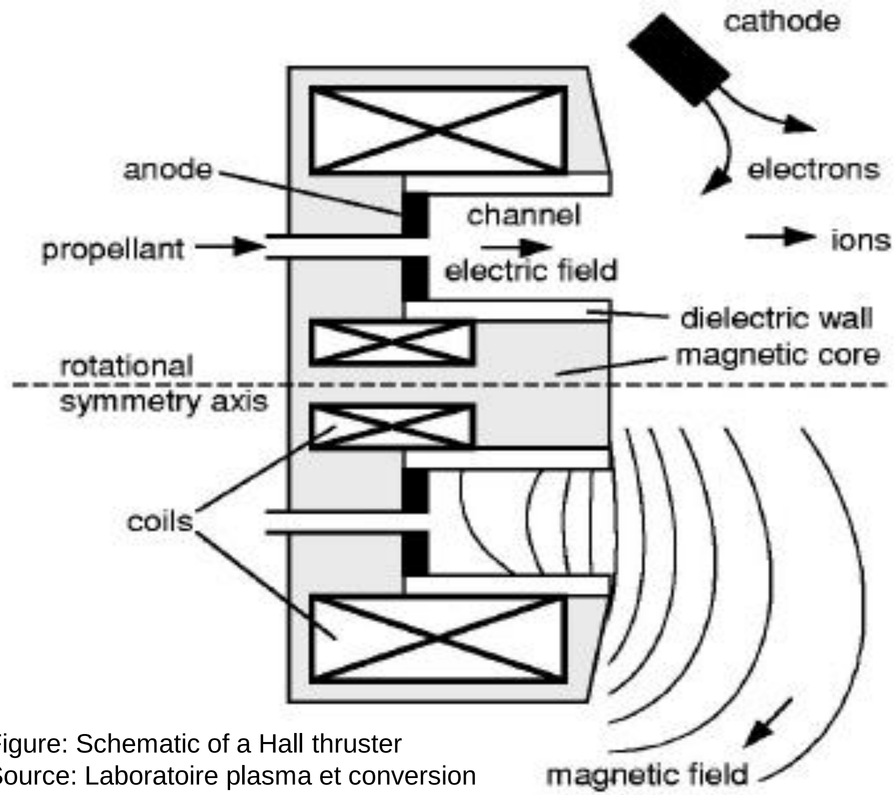


Figure: Schematic of a Hall thruster
Source: Laboratoire plasma et conversion d'energie Website (http://www.laplace.univ-tlse.fr/groupes-de-recherche/groupe-de-recherche-energetique/projets-en-cours/Propulseurs-a-effet-Hall-pour/Hall-effect-thrusters-for?lang=fr)

Figure: Photograph of the NASA 173 Mv1
Source: Plasmadynamics and Electric Propulsion Website (http://pepl.engin.umich.edu/thrusters/NASA_173Mv1.html)

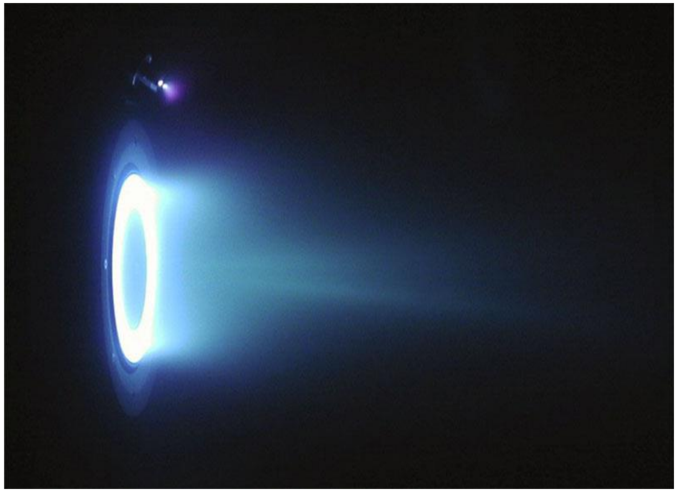


Figure: Photograph of a the NASA 173 Mv1 operating at 300 V, 15 A.
Source: Plasmadynamics and Electric Propulsion Website (http://pepl.engin.umich.edu/thrusters/NASA_173Mv1.html)

Complexity in Hall Thrusters

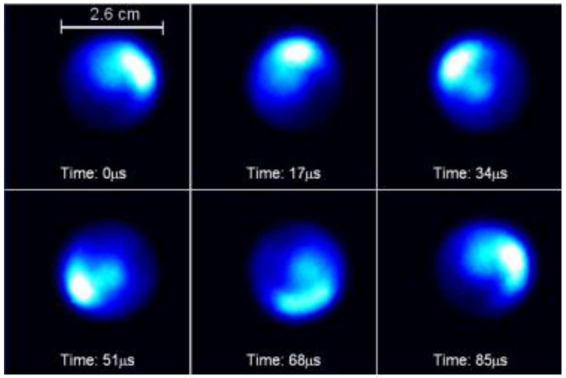
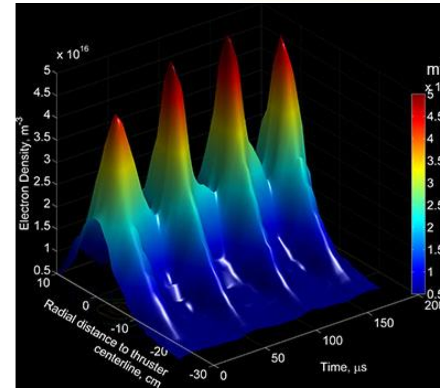


Figure: Rotating Spoke Instability (15 – 35 kHz) in ExB direction.
Source: IEPC-2011-173
Authors: Ellison, Raitses and Fisch

Figure: Radial Profile of Oscillating Plasma Waves in a Hall Thruster
Source: PEPL Website
Author: Robert Lobbia



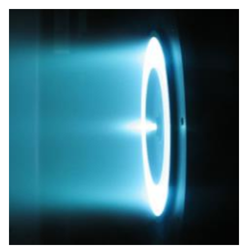
Rotating Spoke

Breathing Mode (Oscillations)

Channel Wall Sputtering

Anomalous Diffusion

Secondary Electron Emission



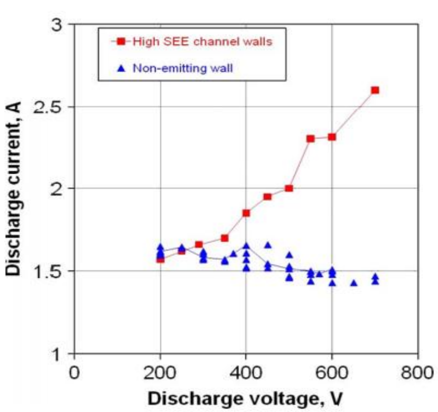
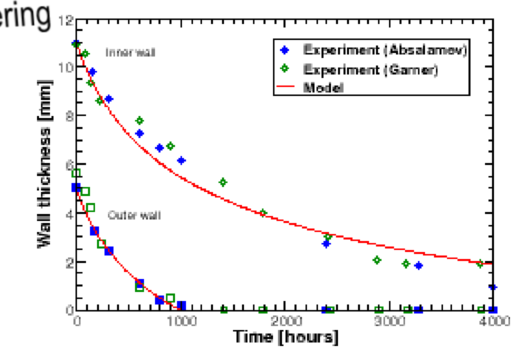


Figure: I-V Characteristics for BN and Carbon Velvet showing clear difference due to SEE
Source: IEEE Trans on Plasma Sci., 39, 4, 2011
Authors: Raitses et al.

Figure: Reduction in thickness of wall over time due to wall erosion
Source: NGPD Website
Author: Yim J. T et al.



Known Effects of SEE in Hall Thrusters

- SEE at channel walls regulates energy transport to the wall by controlling sheath potential profile
  - Leads to depletion of the tail of the EEDF
  - Saturation of the electron temperature
  - Sputtering of wall material
- SEE emission under certain conditions lead to relaxation oscillations which ultimately affects engine stability as well as possibly cross field diffusion rates
  - Can feed instabilities via two-stream interaction
- SEE controls the electrically insulating properties of Hall thruster channel (determines how large of an electric field that can be supported in the channel)
  - Emission affects near-wall conductivity
- SEE electron beam can heat plasma electrons (effect may be enhanced by SEE trapped between channel walls)

Research Benefits

- The experimental apparatus designed for this effort simulates the channel of a Hall thruster
- Isolation of the physics allows investigation of specific effects relevant to Hall discharge physics
- Results serve as a tool to validate and improve existing numerical models by providing boundary conditions and secondary electron emission yields for situations encountered in Hall thrusters
- This will allow to choose better materials for future Hall Thrusters and conditions to improve the performance and potentially the power density and life of these thrusters.
- Data gathered may also be useful in other applications such as cross field material processing tools, fusion devices, etc.

Research Goals

- **Develop a test-bed** to study the **effects of secondary electron emission (SEE) processes** on EP discharge plasmas
  - ❑ Characterize changes in electrostatic **wall sheath** due to SEE in EP relevant situations
  - ❑ Characterize changes in **electron energy distribution function** (EEDF) due to SEE injection into discharge
- Understand and investigate effects of SEE on general plasma properties and discharge characteristics
  - ❑ Quantify influence of **incident (primary) electron energy** on SEE yield in presence of plasma, E_{inc}
  - ❑ Quantify influence of **primary electron incidence angle**, θ_{inc}
  - ❑ Quantify influence of **magnetic field & topology** on plasma-wall interactions, B_0 and **B**
  - ❑ Quantify influence of **insulator temperature** on plasma-wall interactions, T_{init}
  - ❑ Quantify influence of **insulator surface roughness** on plasma-wall interactions
  - ❑ Quantify influence of **insulator morphology** (crystalline/amorphous) on plasma-wall interactions
- Utilize knowledge gained to **improve the performance and potentially the power density and life of EP thrusters**

Research Approach

- Bench-top apparatus built to <u>characterize discharge EEDF in presence of SEE </u>within a plasma environment
- Plan of action:
  - Coated filament cathode initiates transverse electric discharge, terminating at the anode
  - Low density plasma generated by filament discharge produces thick sheath
  - Electron gun will be used to generate secondary electrons from the ceramic target, which will migrate to the plasma
  - Probes will be placed to collect plasma information due to the secondary electron flux
- Diagnostics will provide:
  - <u>Sheath potential</u>
  - <u>Structure of secondary electron energy distribution</u>
- Test effects of E_{inc}, θ_{inc}, B_0, $\mathbf{B}$, T_{init} , and surface conditions on discharge properties

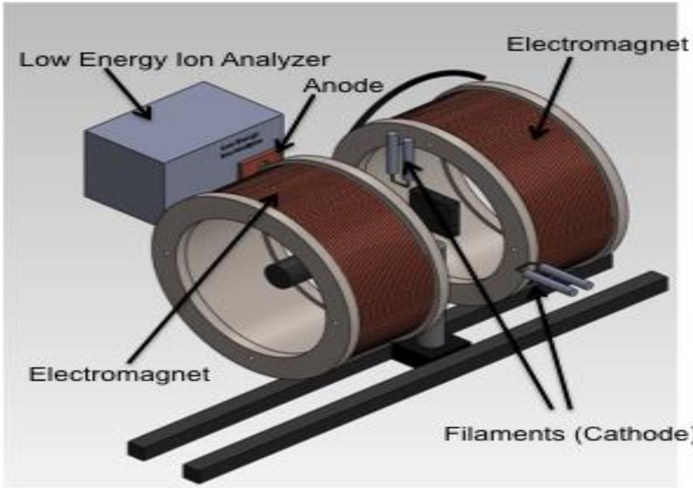


Figure: Concept Drawing

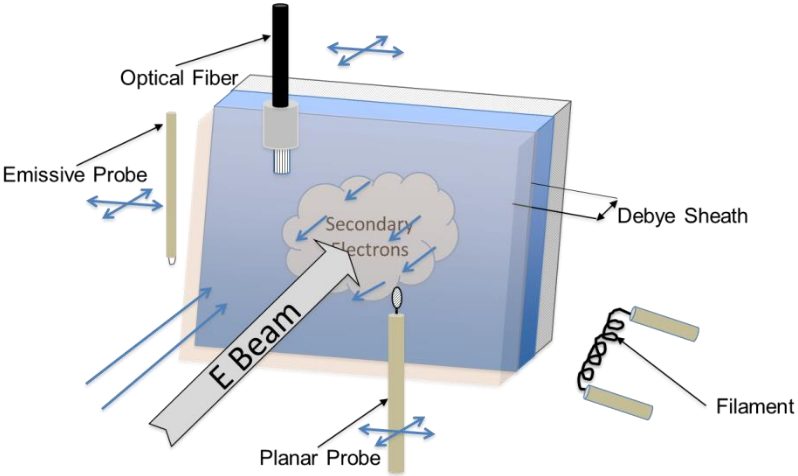


Figure: Diagnostics Plan

Experimental Setup
Drawing and Assembly

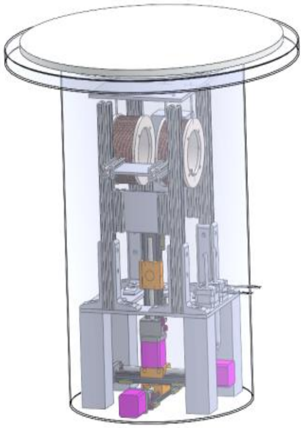


Figure: CAD drawing of the entire experiment inside the vacuum facility

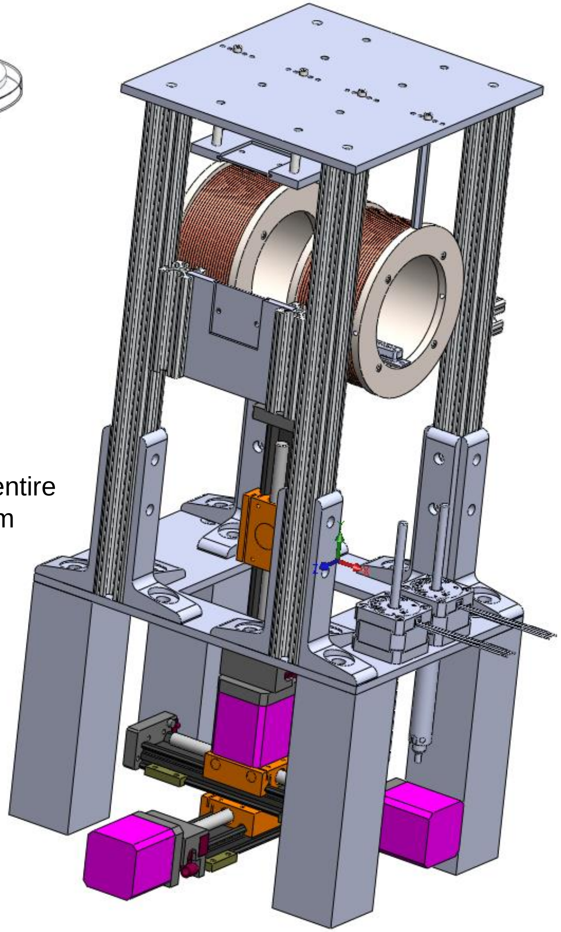


Figure: CAD drawing of the experimental setup

Figure: Vacuum facility that will house the experiment

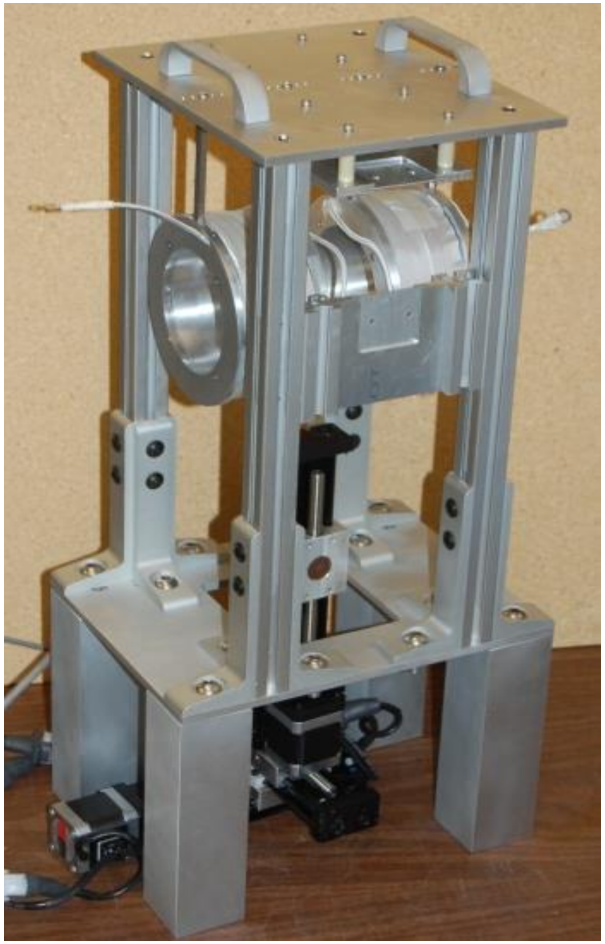
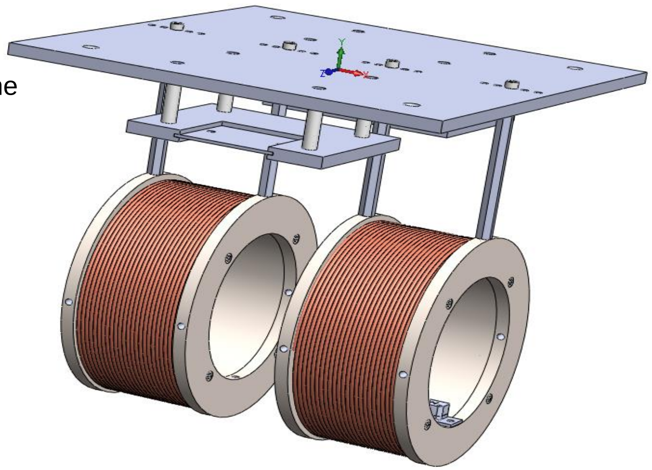


Figure: Experimental setup

Magnetic Field Characterization

- <u>Helmholtz coil</u> arrangement utilized for creating <u>uniform magnetic field</u>
  - Designed to include chamber specifications and allow sufficient space for a thick sheath measurement
- Structure allows <u>non-uniform magnetic topology</u> by varying the separation between the two electromagnets and applying unequal currents to the coil
- <u>Over 200 Gauss of magnetic field has been achieved</u> experimentally
  - Shown in the figure; simulation results in dashed lines, and experimental data by markers

Figure: CAD drawing of the Helmholtz coil used in the bench top apparatus



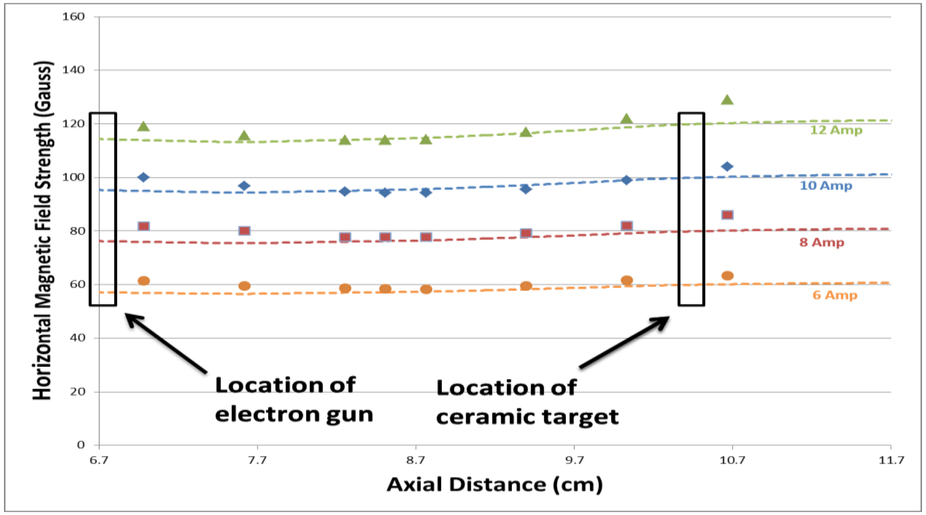


Figure: Axial magnetic field generated by the Helmholtz coil based on input current

Low Energy Electron Gun

- Electron gun fabricated using stainless steel
  - Current design accommodates 2 grid assemblies for beam acceleration and focusing
  - Design permits easy expansion of grid assemblies depending on application
- Filament driven thermionic electron beam source
  - Various tungsten wire sizes have been chosen to provide required extracted current with minimum input power
  - Other refractory materials are being investigated
  - Filament has a carbonate coating with a mixture of Barium, Strontium and Calcium [(Ba-Sr-Ca) CO_3 56-31-13%]
  - Coil geometry used to enhance emission


Figure: CAD model of the electron gun

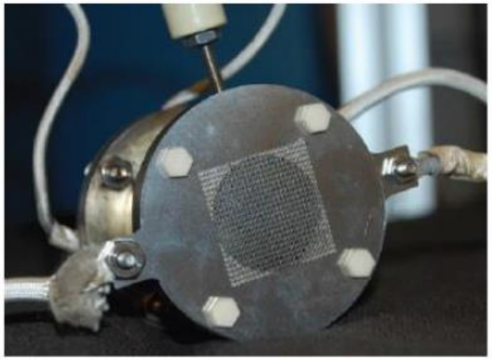


Figure: Electron gun with a high transparency grid

Electron Gun Specs

- 1% Thoriated Tungsten wire used
- Stable current demonstrated = 1 mA
- Max. current demonstrated = 4 mA (short duration)
- Filament wire diameter = 0.01 inch = 0.2794 mm
- Low frequency pulsed mode also demonstrated
- Minor focusing effects demonstrated using grids bias voltage

Figure: Various grids used to test sensitivity of electron beam based on grids

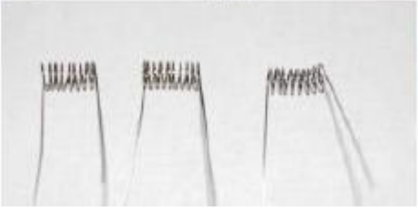


Figure: Filaments produced for thermionic emission source

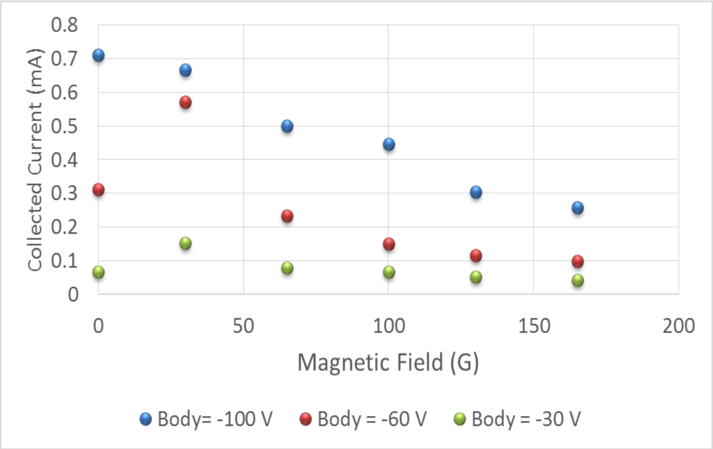
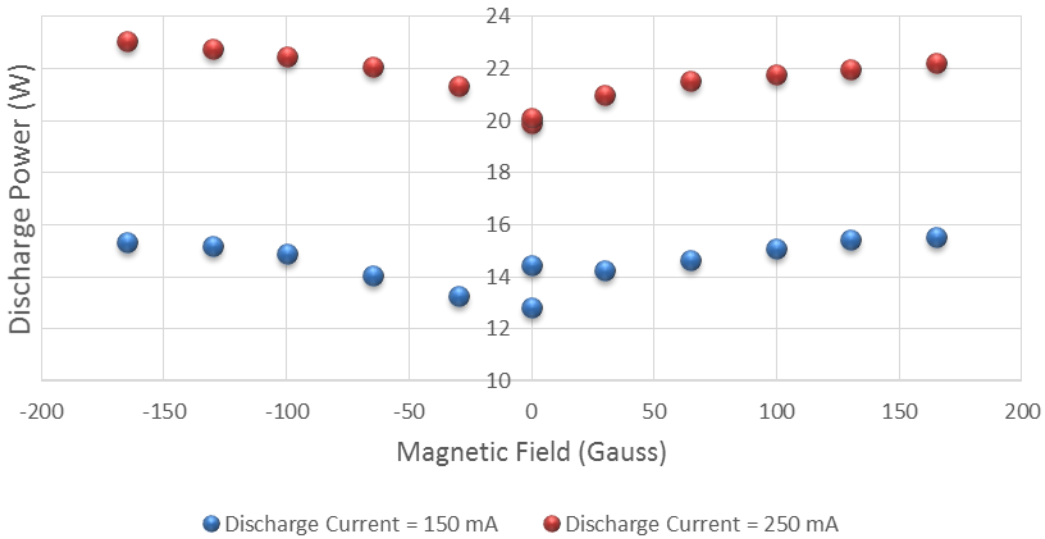


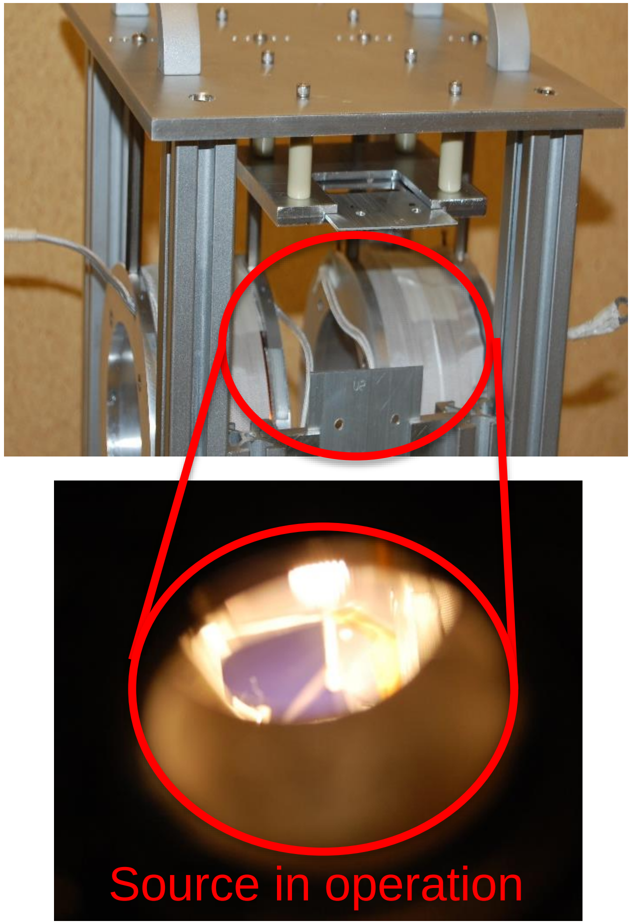
Figure: Typical reduction in collected current as a function of magnetic field.

* For plasma density of interests, the current density on the target or probe is much smaller than the primary beam emitted by the electron gun.

Discharge Preliminary Characterization

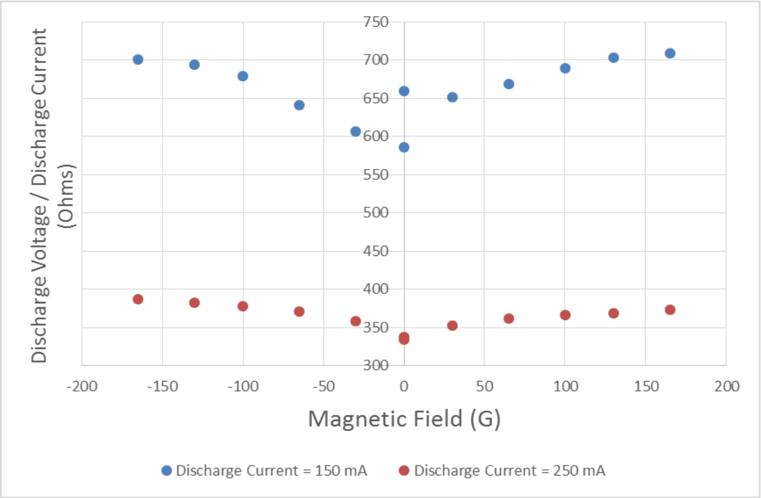
- Cross field plasma generated with densities varying from 10^7 cm^{-3} to 10^9 cm^{-3}
  - Sheath thickness ~ 1 cm range possible
- Discharge currents generated from 15 mA to 250mA
- Discharge voltage required to maintain cross field current increases with increasing magnetic field as expected of a cross field device (e.g., Hall Thruster)

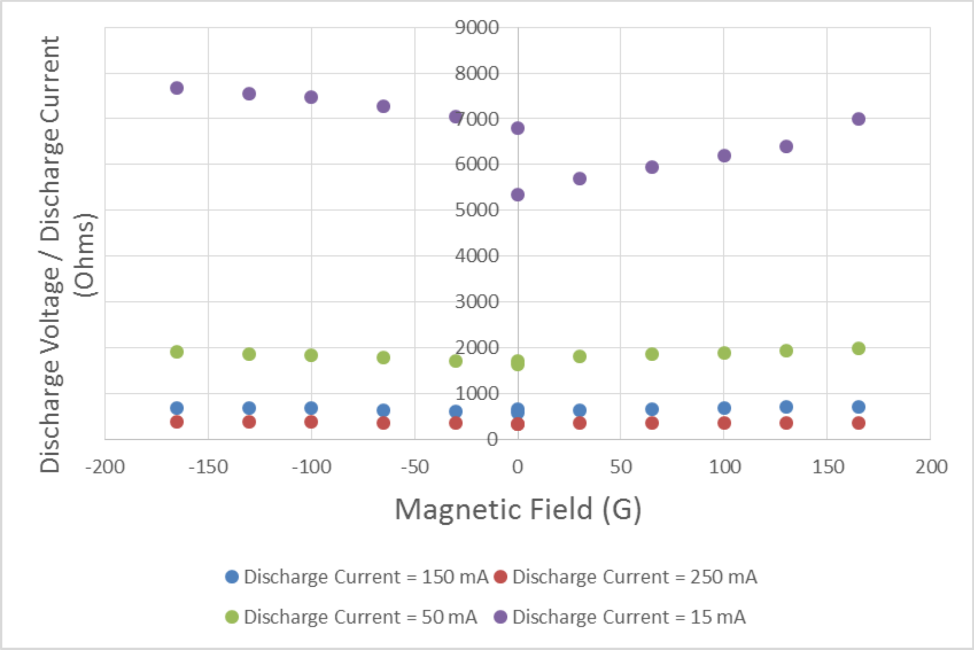


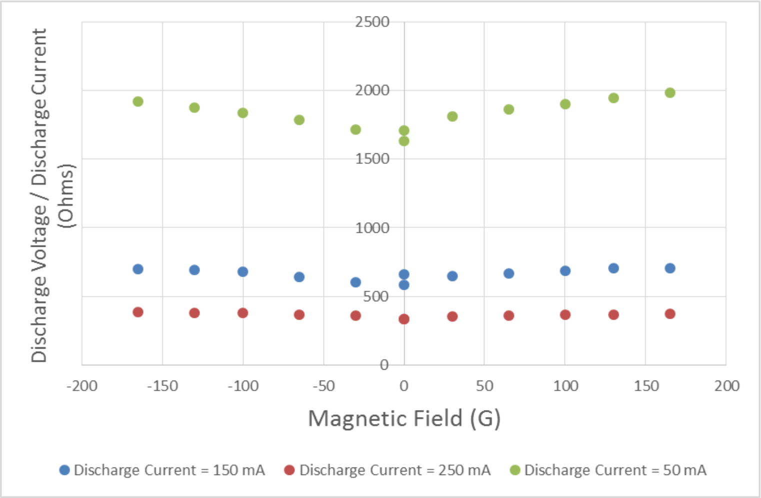


Crossed Field Impedance

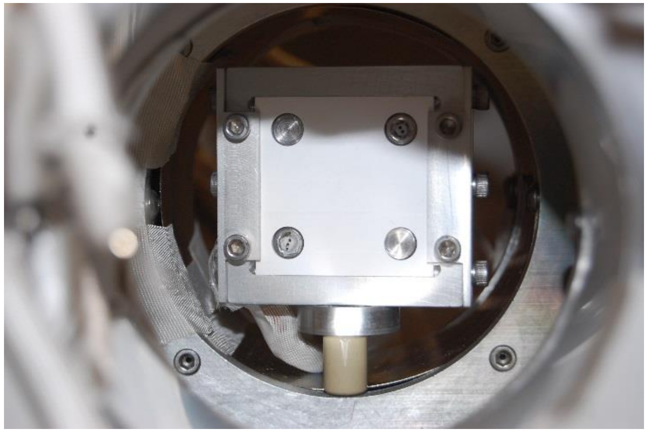
- Slope of the discharge voltage versus magnetic field strength gets steeper for decreasing discharge current

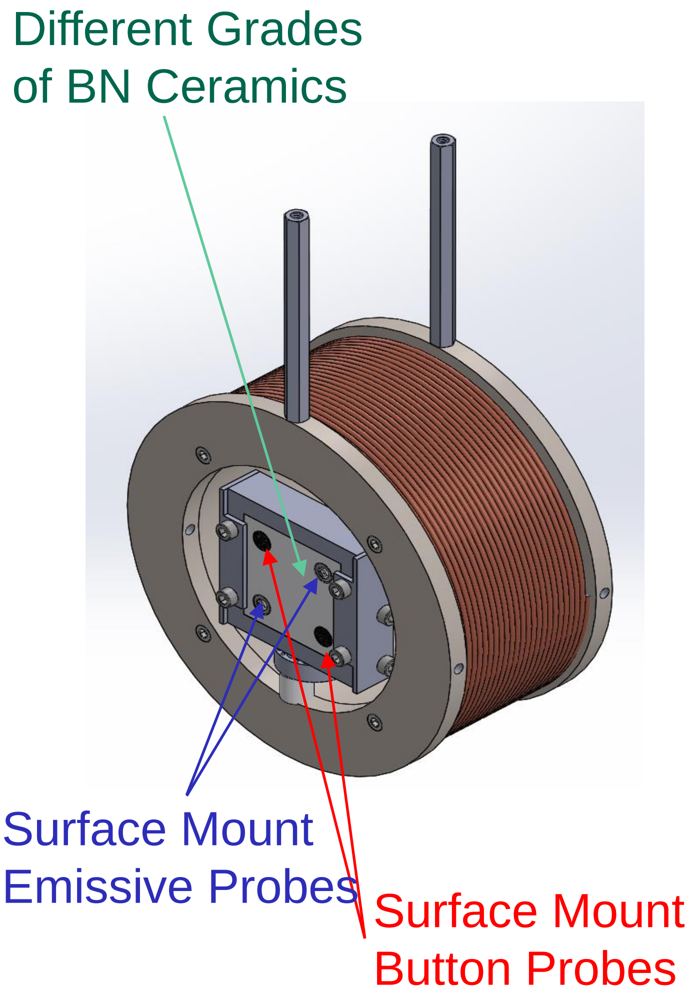




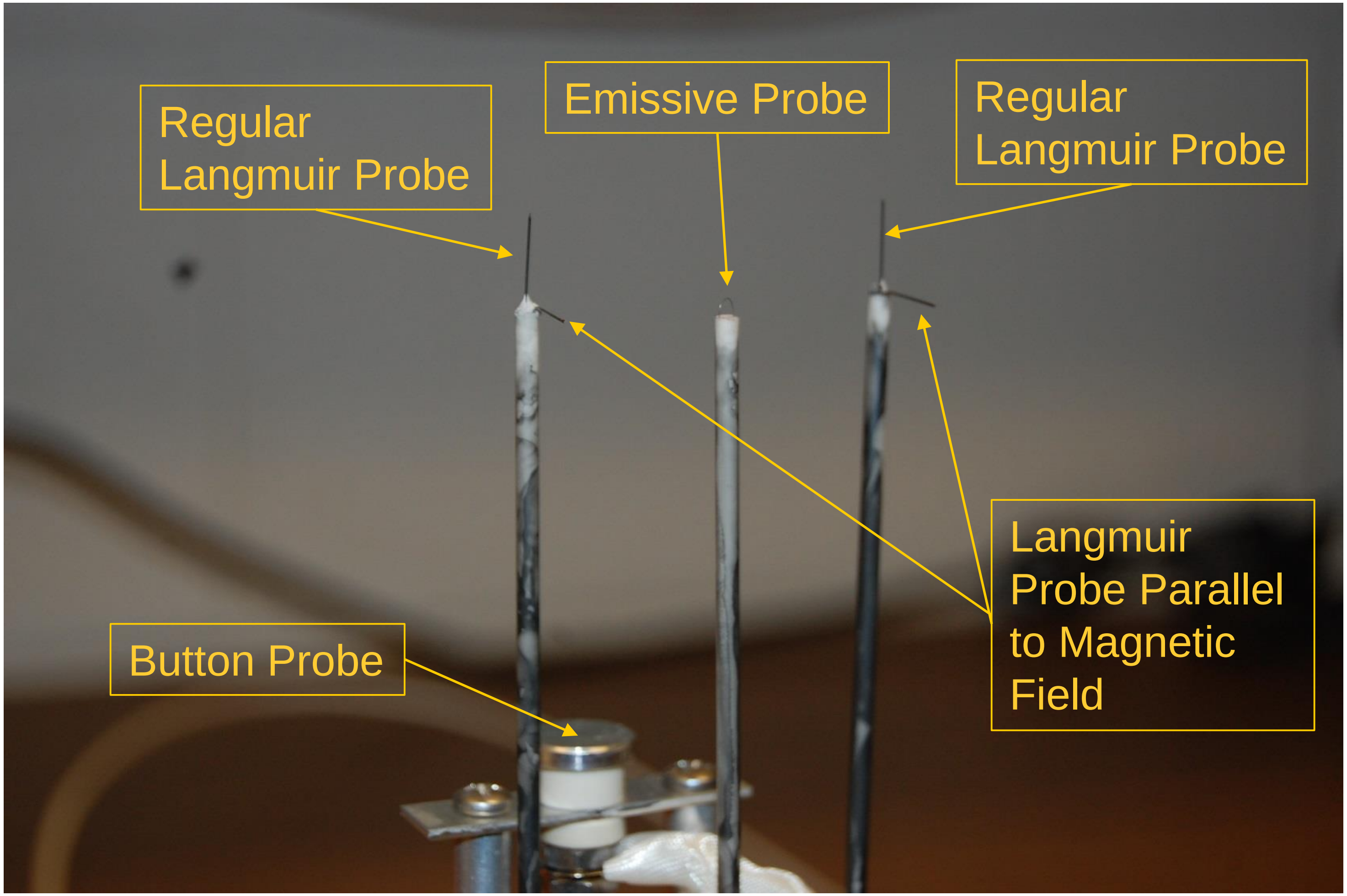


Diagnostics – Surface Mount Probes



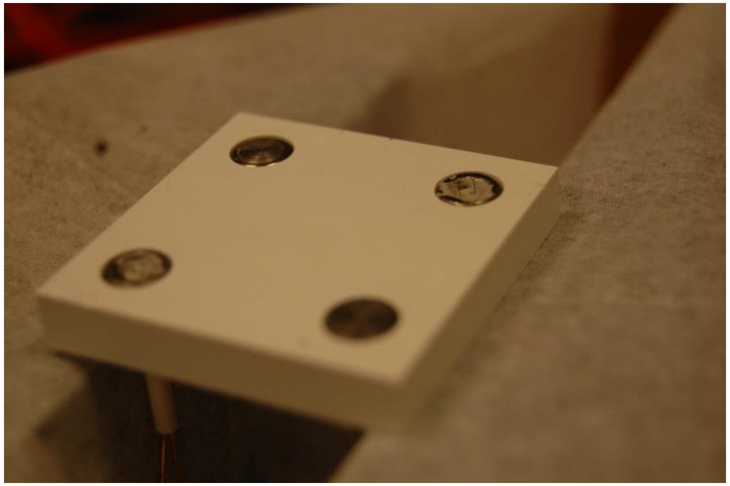


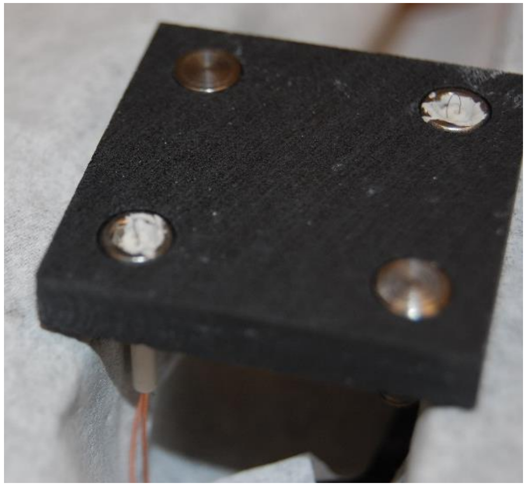
Probes to Travel in the Plasma



Materials

- To directly compare the effect of SEE due to primary electron impact, the choice of the following materials will help provide clear distinction between SEE yield and plasma change behavior.

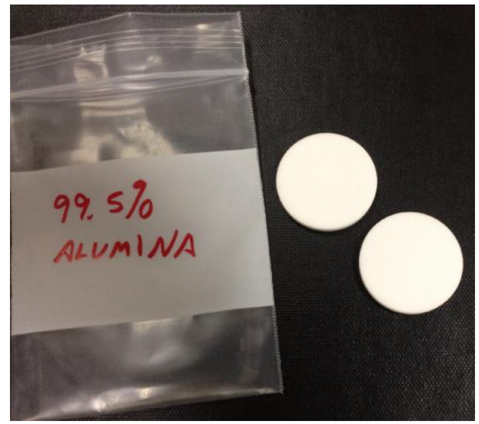


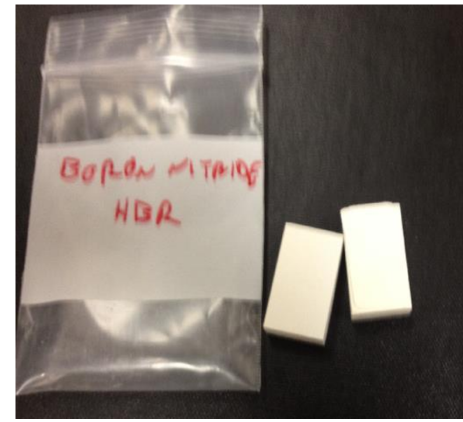


Ceramic Surface Study

(SEE Yield Dependence on Surface Properties)

- Investigate sensitivity of SEE with electron impact for ceramics of interest in the presence of a background plasma
  - BN, Alumina, Macor, Quartz
- First-order scaling of discharge characteristics extractable from experiments
- Ceramic targets characterization pre- and post-test via atomic force microscopy, SEM, profilometers (optical and tip based)
- Targets will be baked via quartz lamp pretest to desorb gaseous monolayers — control initial surface conditions and chemistry, which in turn can affect SEE yield
- For sample shown, the average surface roughness, <Ra> = 4.35E+4 Angstroms (20 measurements)
  - Ability to modify ceramic surfaces from several um to 20 nm





Materials already available at PSTL:
- Alumina (99.5% grade)
- Boron Nitride (HBR grade)

Application Requirement	Grade HBN	HBR	HBC	HBT
High Temperature Capability	Good	Better	Best	Best
Moisture Resistance	Good	Better	Best	Best
Thermal Shock Resistance	Good	Better	Best	Best
Thermal Conductivity	Best	Best	Better	Good
Electrical Resistance	Best	Best	Best	Best
Machinability	Best	Best	Best	Best
High Purity	Better	Better	Best	Best

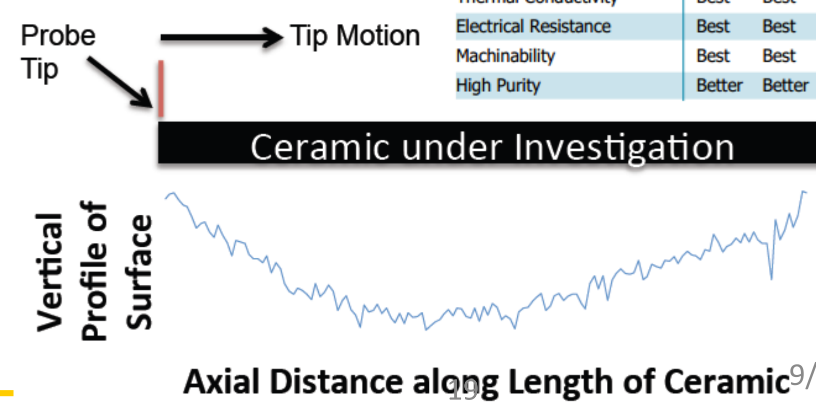
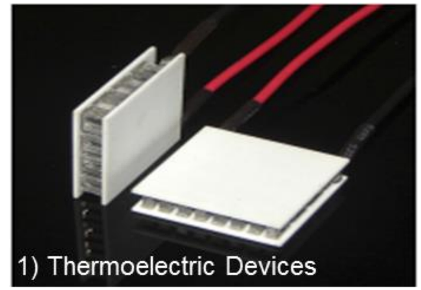


Figure: Demonstration of surface profile using Dektak

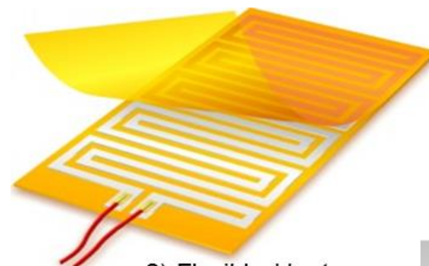
Temperature Effects

(SEE Yield Dependence on Temperature)

- Study the <u>effect of insulator temperature on the secondary electron yield</u> (SEY) is important
- Temperature will be controlled using two devices:
  - <u>Thermoelectric Devices</u>
    - Capable to go from 253 K to 413 K in vacuum
  - <u>Flexible Heaters</u>
    - Capable to go from room temperature 273 K to 473 K
- Bi-directional relay driven temperature controller is purchased for varying the temperature and studying the outgassing effects of the ceramic for the given temperature range and its impact on SEE yield



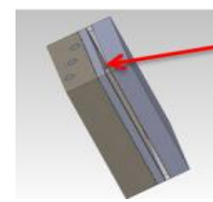
1) Thermoelectric Devices



2) Flexible Heaters

*Glass used as prototype for testing

**Back plate serves multiple purpose:
- Acts as source/sink to the thermoelectric device
- Structural support to mount to electromagnet directly or via motor



Thickness of flexible heater = 7 mils = 0.118 mm

Relay driven bi-directional temperature controller

Next Steps

- Map out sheath profile variation due to SEE in the influence of magnetic field strength, discharge current, and electron gun current
- Study the EEDF of the plasma system and variation of its behavior due to SEE based on above mentioned causes
- Relating the data acquired with physical phenomena to real world Hall thrusters modeling to understand the system better and improve performance

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Acknowledgments

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- The authors would like to thank Dr. Alec Gallimore (Aerospace Engineering, University of Michigan) for valuable insight and discussions