A Vector Neutral Particle Spectrometer for Space Environment Measurements

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Space Dynamics LABORATORY

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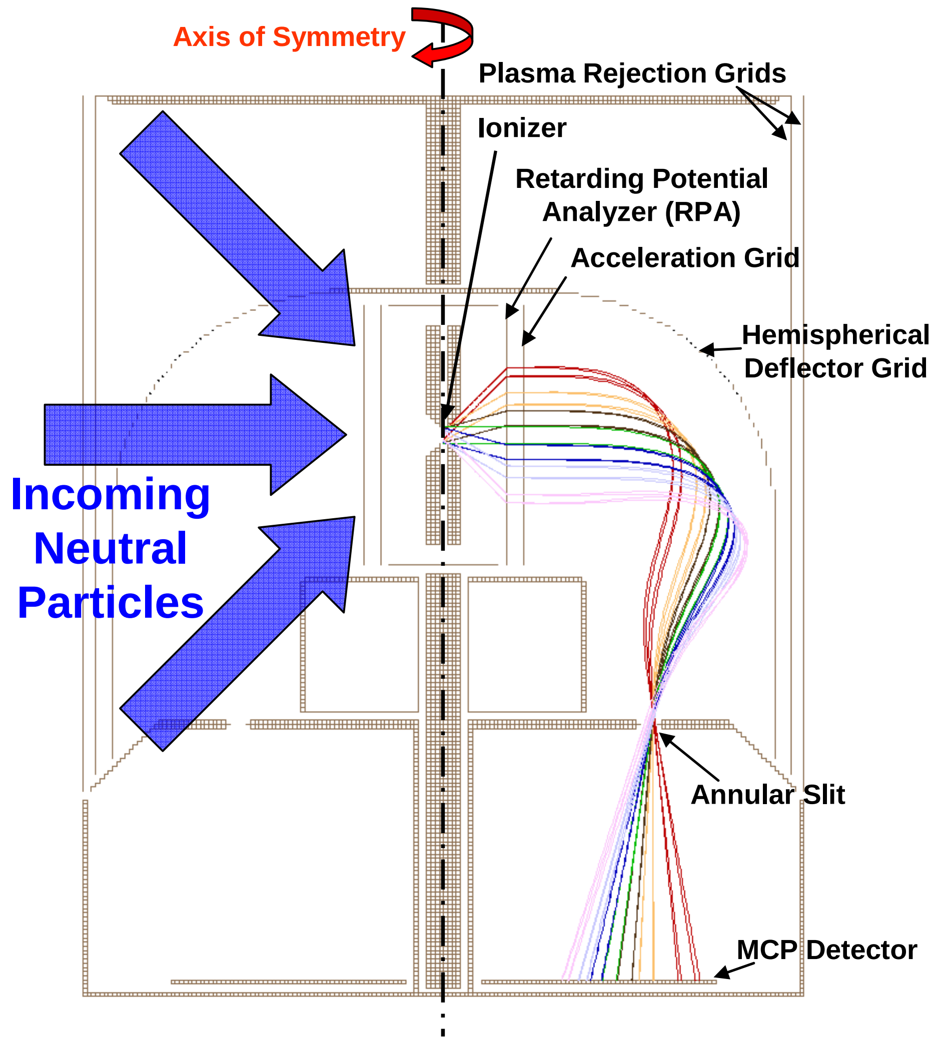
Objectives

- Goal: Develop a new class of *in situ* neutral particle detector for measurements of the neutral atmosphere and orbital environment
  - Neutral density, including reactive species
  - Velocity and energy distribution
  - Composition
- Desired instrument characteristics
  - High field-of-view without moving parts
    - Accommodation on a variety of spacecraft, including sounding rockets
    - 100% duty cycle, even on spinning satellites
  - Imaging capability
    - Induced environment applications (outgassing, rendezvous / docking, etc.)
    - Spatial discrimination of background
    - Neutral wind measurements
  - Maximum sensitivity and dynamic range for a wide range of altitudes
  - Autonomous operation and low demand on spacecraft resources

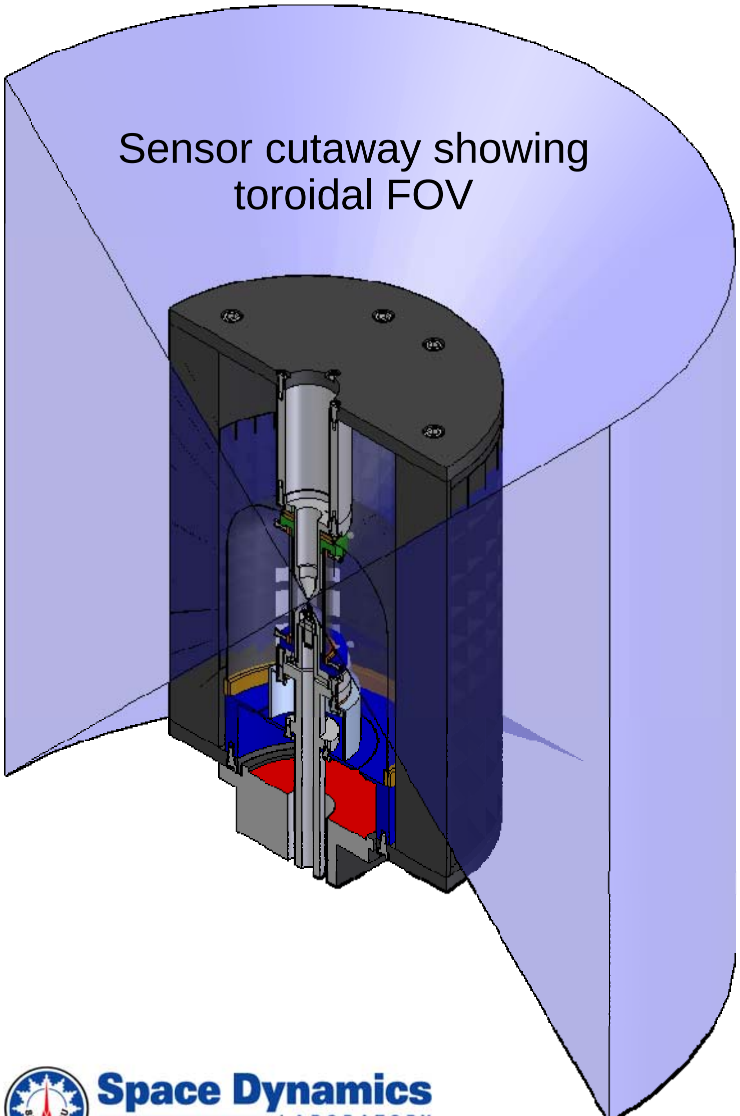
VNPS Concept

- High FOV (2.8π sr)
  - Central, open ionizer
  - Transparent mesh-based ion optics
- Ionizer
  - Compact, well-defined electron impact ionization volume
  - Collisionless 'fly-through' ionization for accurate reactive species measurement
  - COTS LaB_6 thermionic emitter, interchangeable with Spindt cathode array for long operational lifetime and reduced power requirements
  - Pierce-type electron focusing optics design
- Ion optics
  - Retarding potential analyzer (RPA) for energy analysis and rejection of local outgassing background
  - Acceleration grid generates trajectories directed radially outward from central axis of sensor
  - Deflection grid redirects and focuses ions to UV-attenuating slit
  - Field-free region for dispersion and/or TOF analysis
- Detector
  - Microchannel plate detector for single ion counting
  - Crossed delay-line anode allows imaging readout
- Background reduction
  - Black collimator for solar UV suppression (not shown)
  - Plasma grids reject ambient ions and electrons



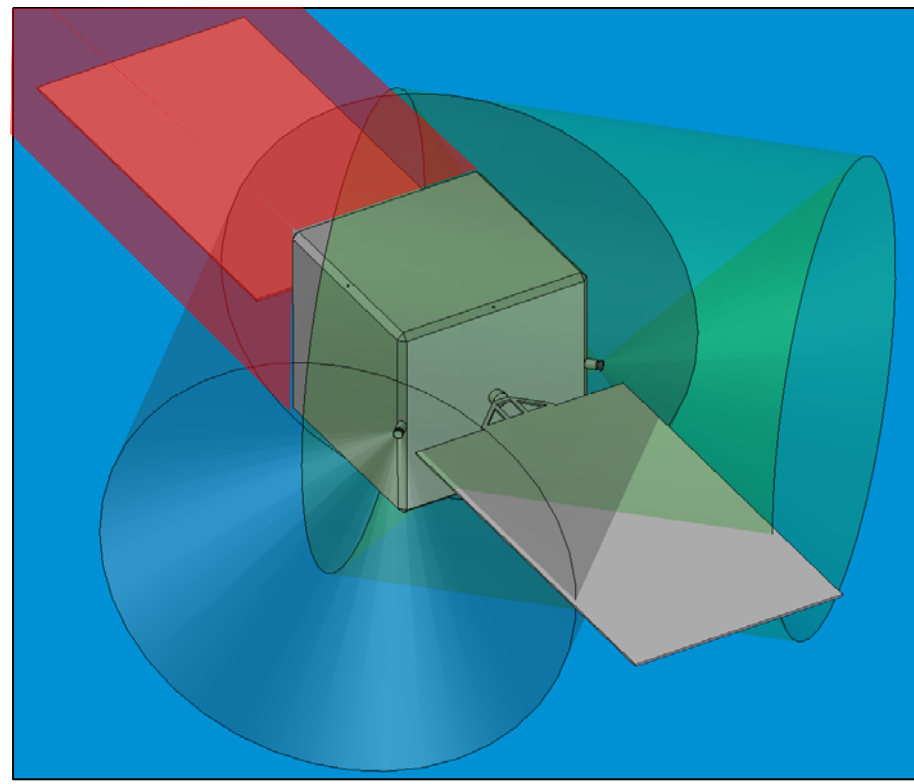
Ion optics design (SIMION trajectories)

Field of View and Spacecraft Accommodation

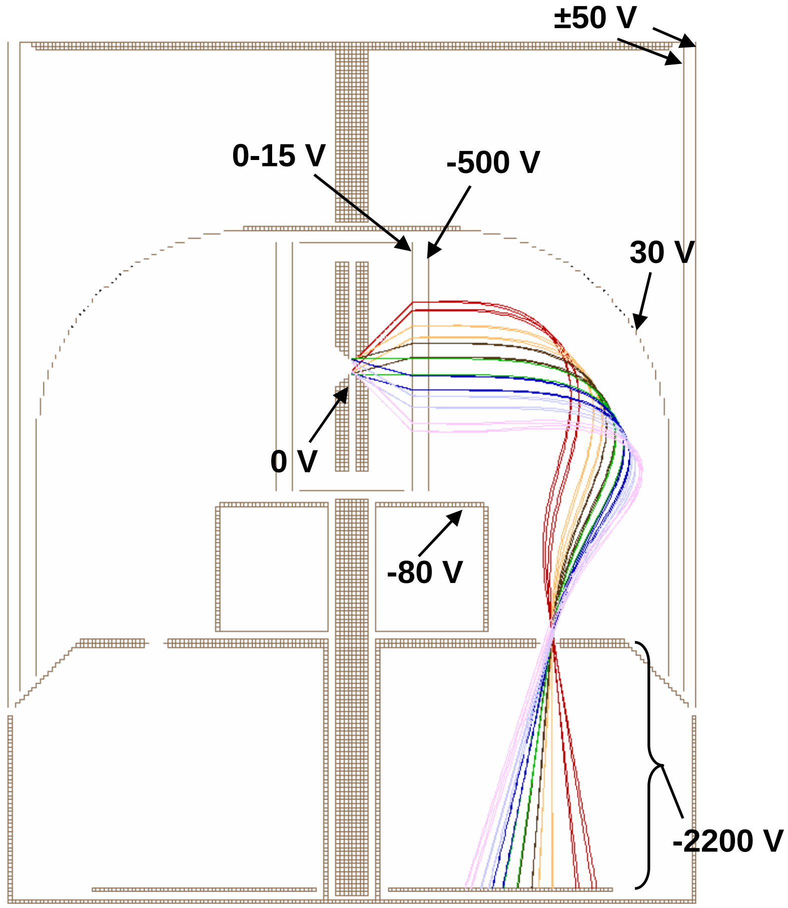


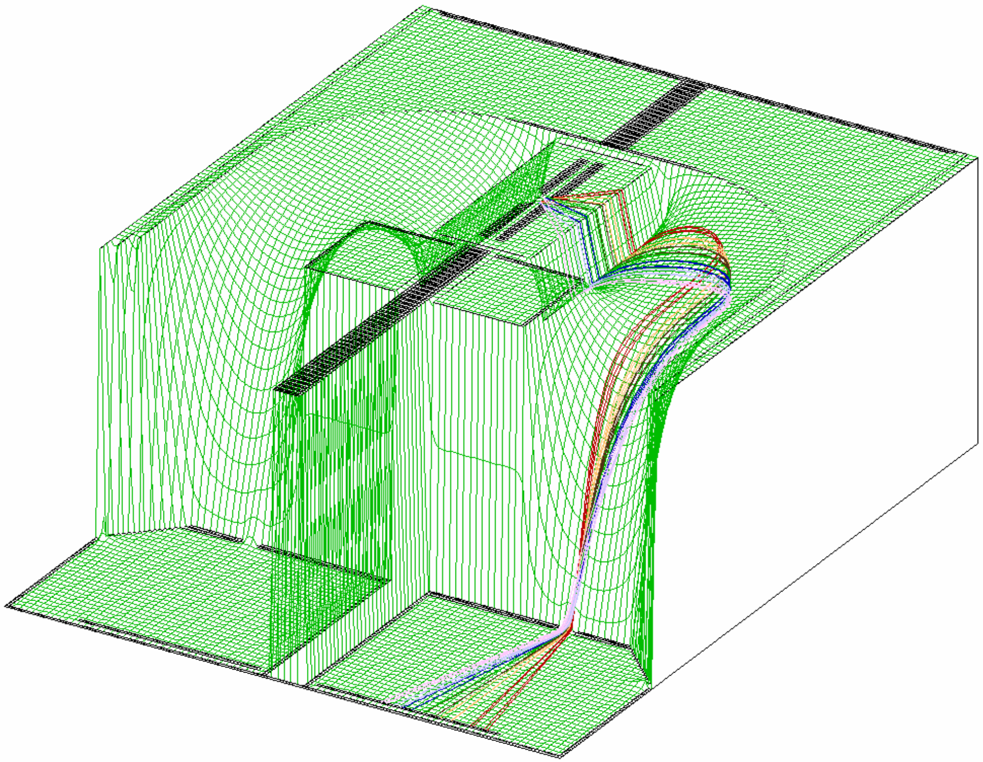
Sensor cutaway showing toroidal FOV

Two sensors oriented on satellite vertices with primary axes normal to each other, yielding 4π sr FOV (GPS)



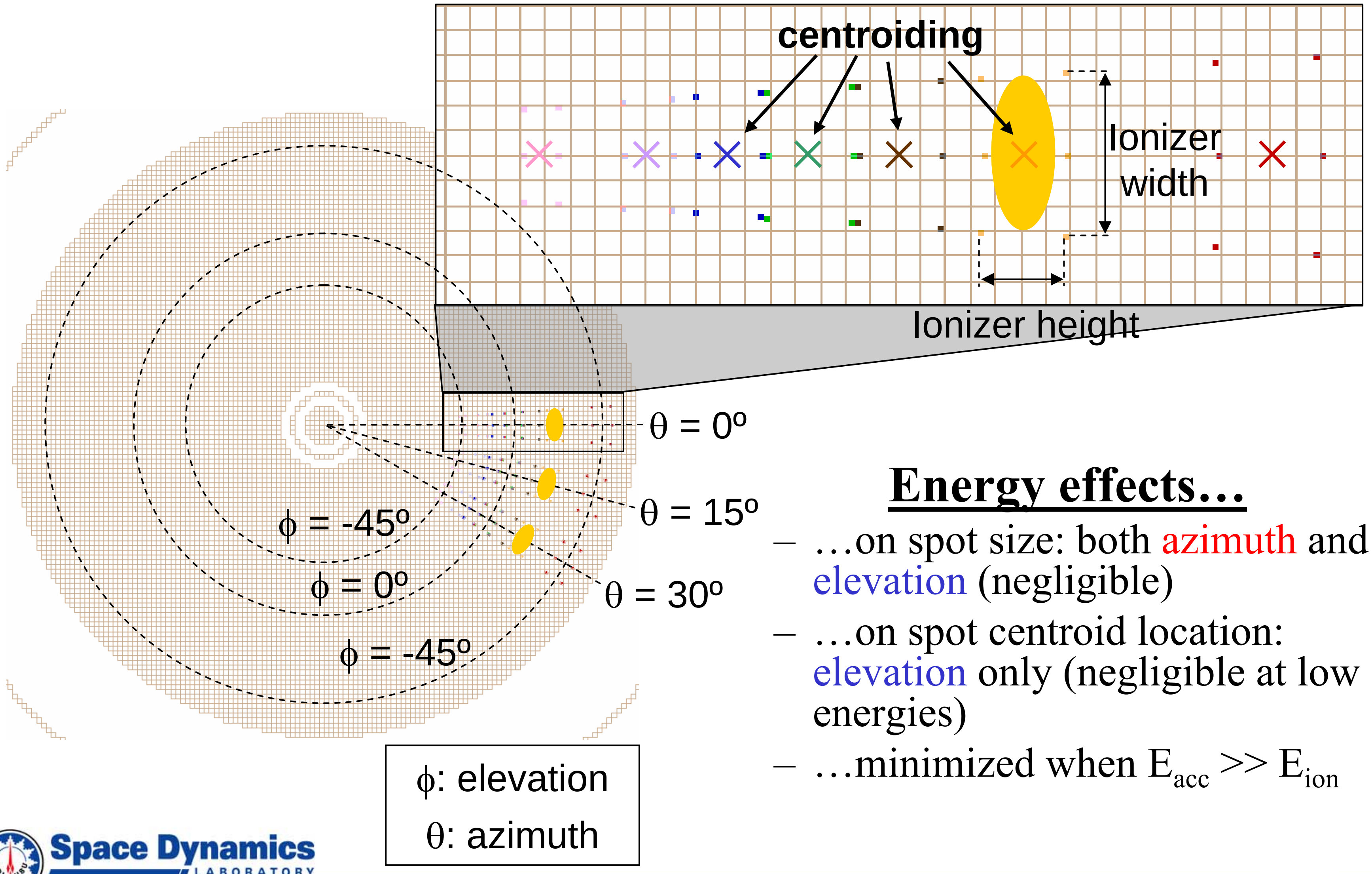
Sensor Potentials and Electric Fields





SIMION potential map

Imaging Performance

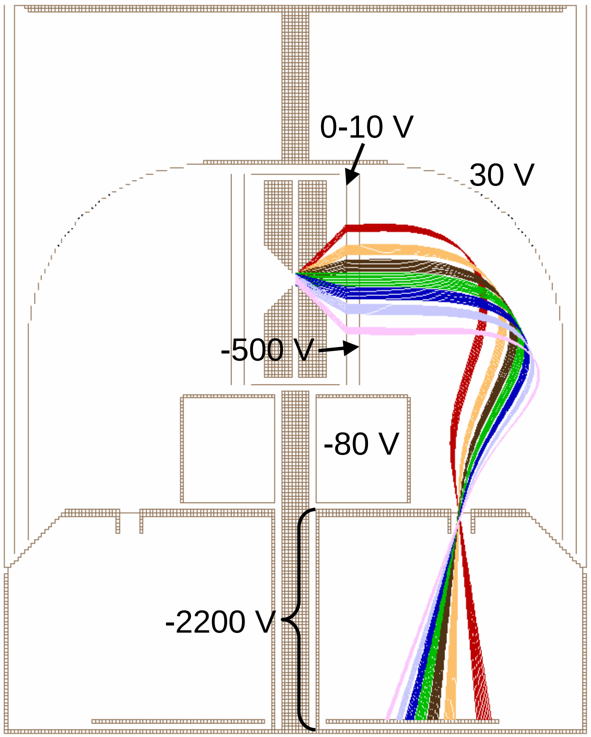


Energy effects…

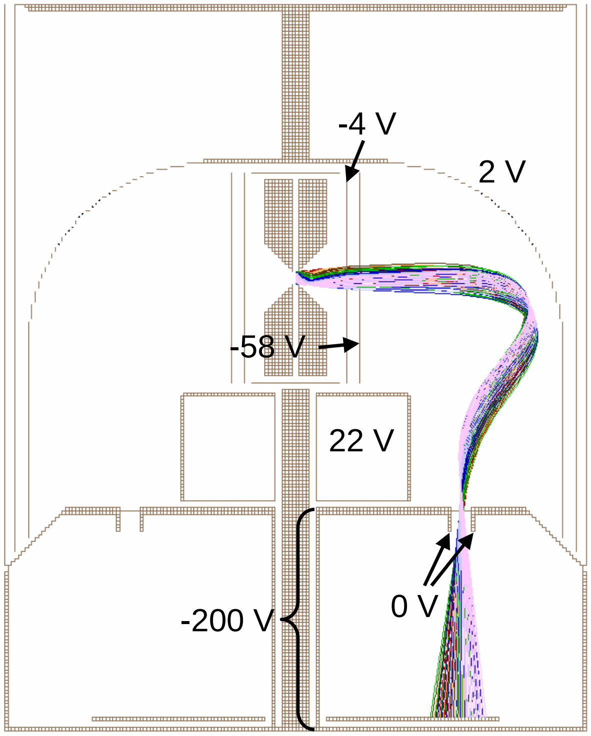
- …on spot size: both azimuth and elevation (negligible)
- …on spot centroid location: elevation only (negligible at low energies)
- …minimized when $E_{acc} >> E_{ion}$

Modes of Operation

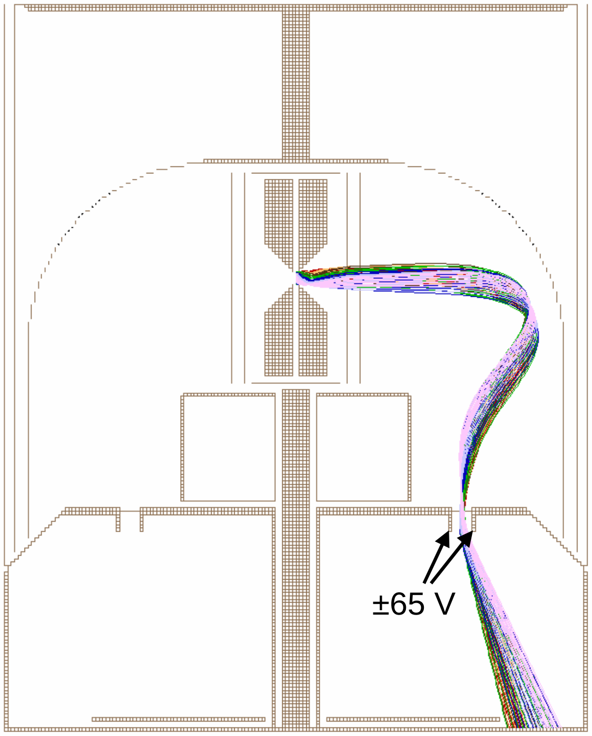
Imaging Mode



TOF Mode, Beam 'On'

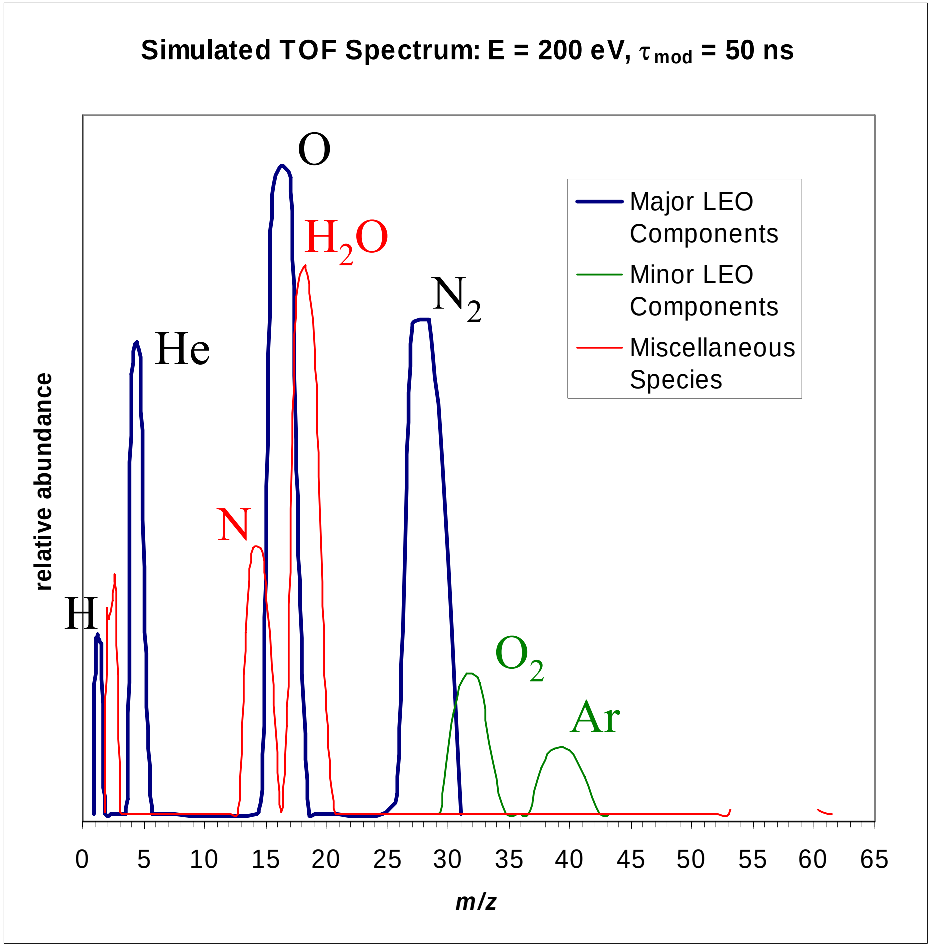


TOF Mode, Beam 'Off'



TOF-MS Capability

- Beam modulation at annular slit allows time-of-flight analysis, even over short (3 cm) drift length
- Duty cycle
  - Traditional operation: ~4% to *m/z* 50, 2% to *m/z* 200; ***mass dependent.***
  - Pseudorandom modulation / Hadamard Transform: 50%; ***mass independent***. No limit to mass scanning range.
- Mass resolution determined primarily by modulation bin width
- *Sensor design not optimized for TOF-MS performance*



*0.03 – 2 eV ions, all elevation angles (±45º)

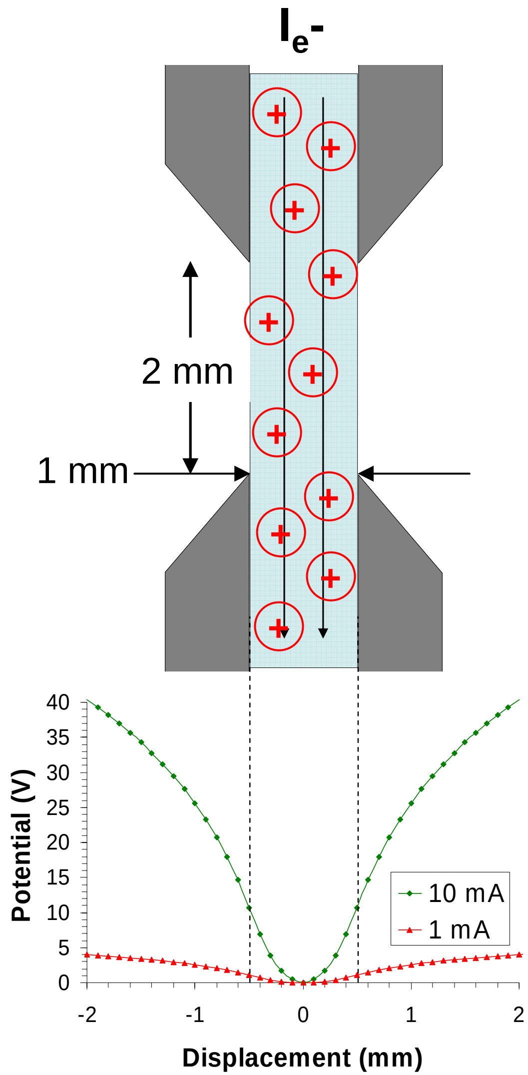
Ion Optics Performance Summary

- **Field of view**
  - ϕ: ±45º, θ: 0-360º
  - 2 properly oriented sensors cover 4π sr with 41.4% FOV overlap
- **Angular resolution**
  - With centroiding
    - Elevation: ~1º @ 0-1 eV, ~5º @ 0-5 eV
    - Azimuth: no limit
  - Single ion detection
    - Elevation: ~10-14º
    - Azimuth: ~8-9º
- **Theoretical ion transmission**
  - ~50-70% (angle dependent)

Total angular resolution will optimally be detector-limited, and will only *improve* with the use of multiple sensors

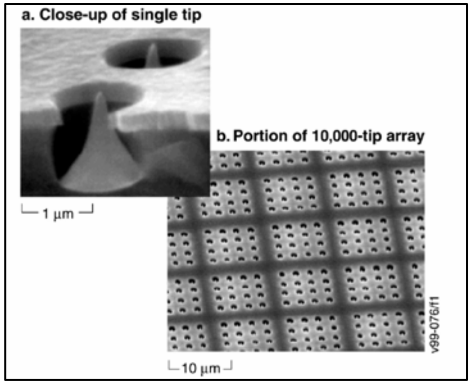
Ionizer Design Challenges

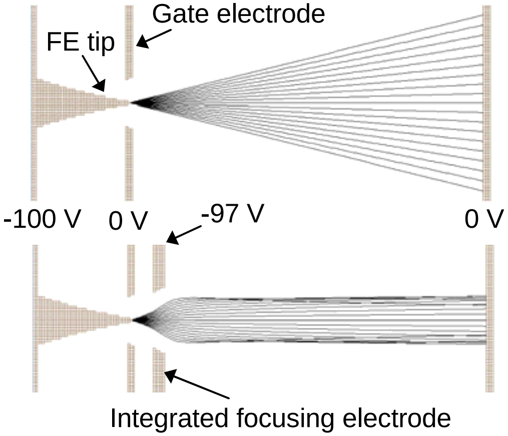
- Ionizer design goals
  - ≥1 mA, 70-200 eV, 1 mm diameter, 2 mm long electron beam (open ionizer)
- Space charge forces
  - **Repulsive** → electron beam divergence
    - Requires focusing optics
    - Must limit electron path length
    - Increased electron energy somewhat beneficial
  - **Attractive** → ion trapping (unintended RPA) or trajectory deflection (degradation or loss of imaging)
    - Potential well depth scales with beam current
    - Compensation by ionization of background gas occurs to some degree (pressure and time dependent)
    - Possible advantages: ion accumulation for increased sensitivity, alternate approach to TOF-MS



Electron Emission Sources

- **Field emission (Spindt cathode array)**
  - Very high electron current densities - up to 2000 A/cm^2 ($\leq$20 A from 1 mm cathode)
  - "Cold cathode" operation, low power requirements
  - Long lifetime (demonstrated continuous operation - years)
  - High initial kinetic energies
    - COTS cathodes produce electron beams of high divergence
    - Requires integrated focusing electrode for low-energy collimated beam
- **Thermionic emission (LaB_6 cathode)**
  - Current densities up to 30 A/cm^2 ($\leq$30 mA from 330 μm cathode)
  - Low initial kinetic energies (thermal distribution)
  - High temperature operation (1700-1900 K), moderate power requirements (heating current ~ 2 A @ 2.5 V)
  - Short lifetime at high currents (100's of hours)
  - Relatively inexpensive and replaceable
- **Goal: Develop robust, plug-and-play ionizer**





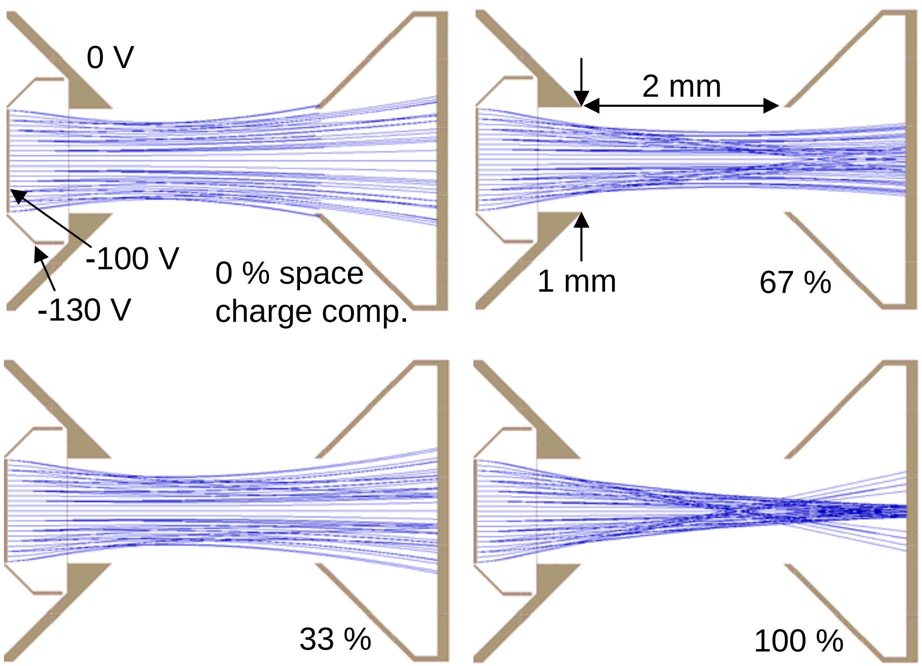
Prototype sensor:
LaB_6 cathode

Flight sensor: Spindt cathode

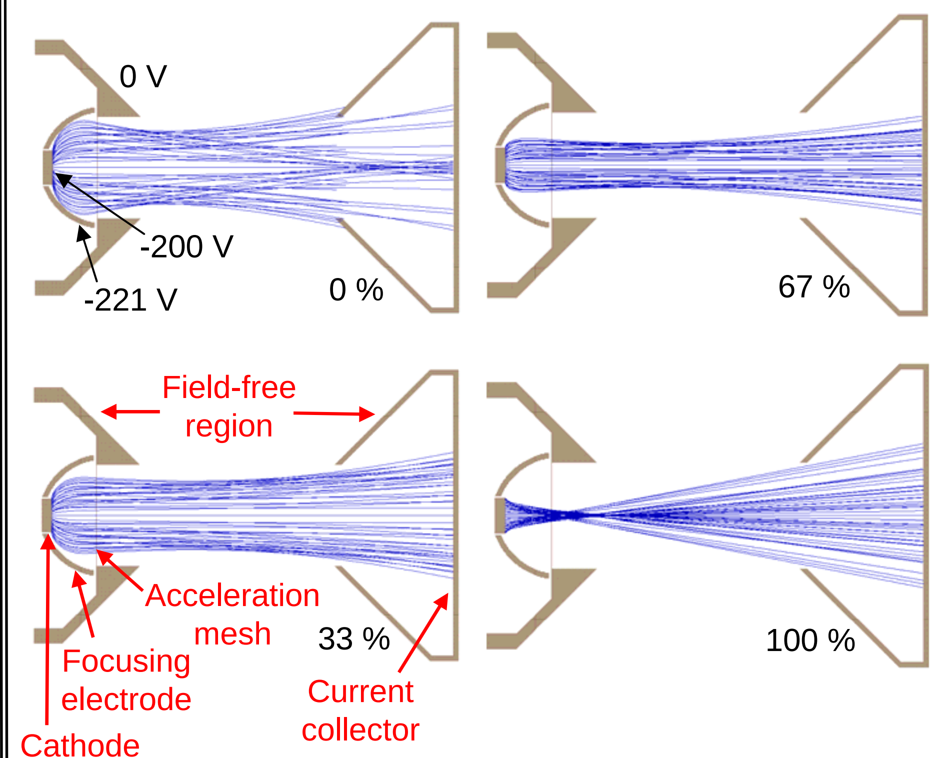
Electron Focusing Optics Design and Analysis

10 mA, 200 eV electron beams with varying degrees of space charge compensation:

Spindt cathode field emitter (100 eV initial KE)

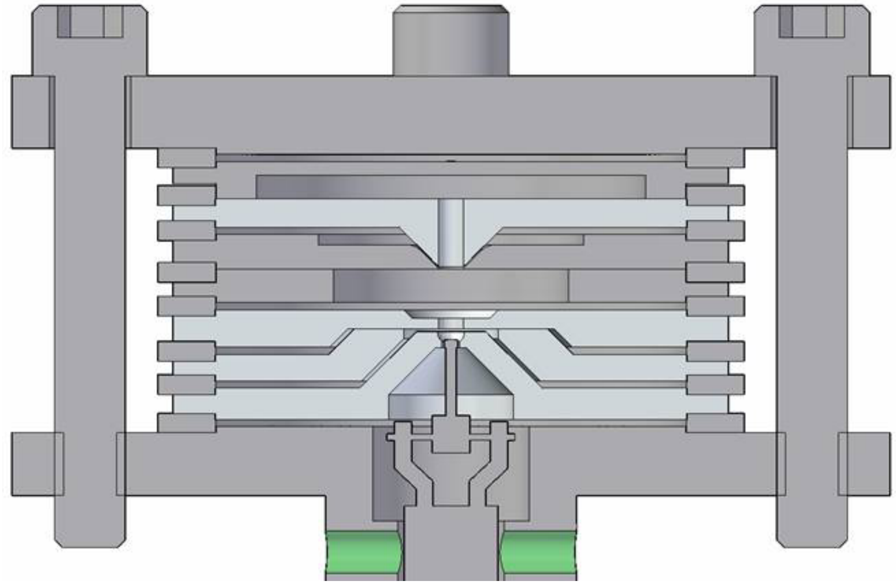


LaB_6 thermionic emitter (0.2 eV initial KE)

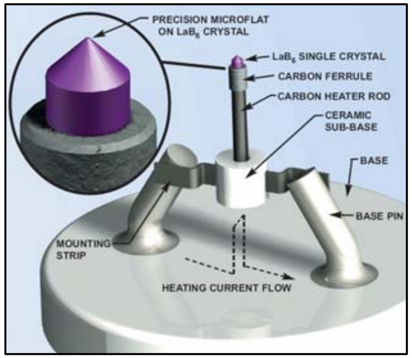


Electron Beam Testing

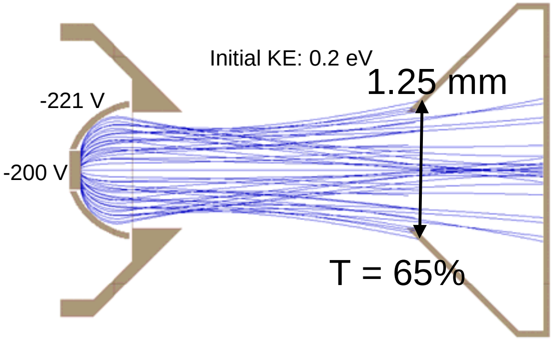
Ionizer 'lens stack' prototype for electron focus testing:

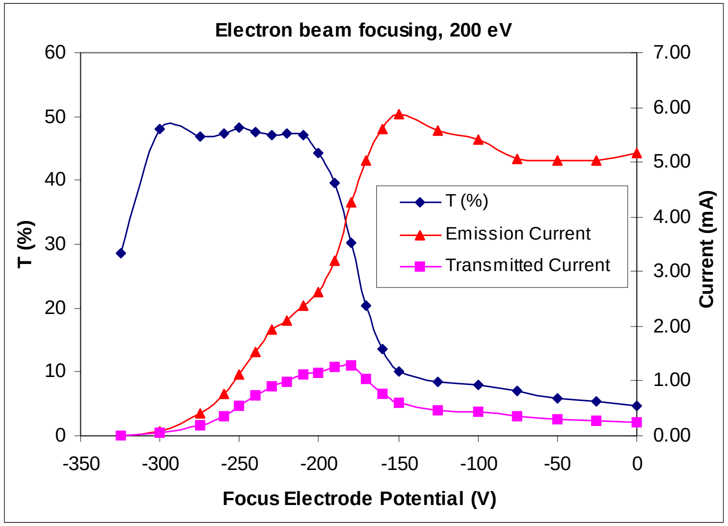


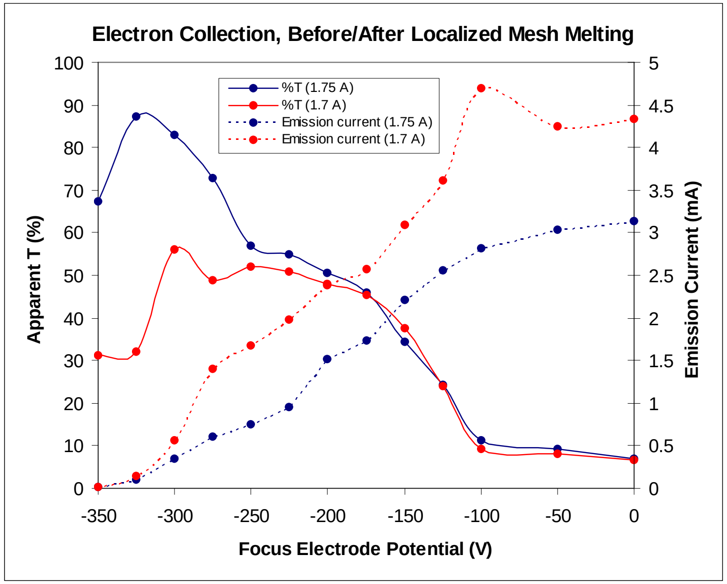
LaB_6 cathode (Kimball Physics):



Observed transmission for an apparently well-focused beam:

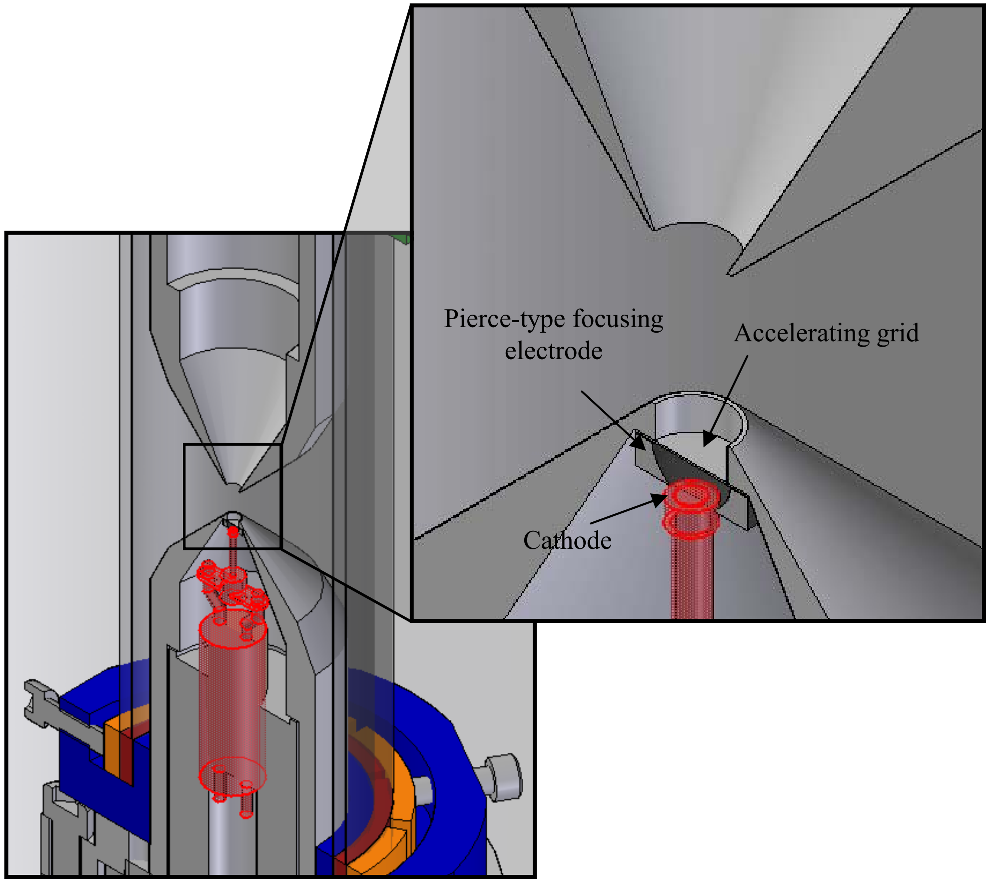




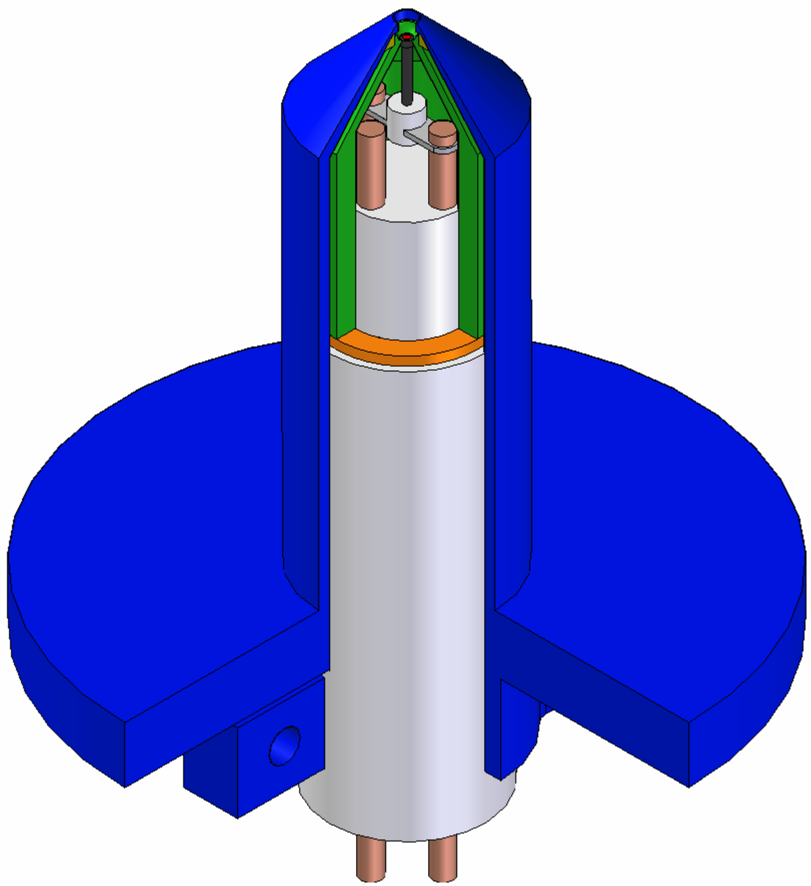


Ionizer Mechanical Design

Ionizer assembly and electron focusing optics



Custom ceramic base and heat-sink design



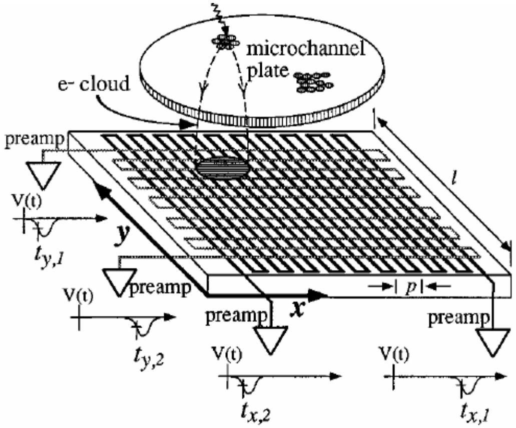
MCP-XDL Detector

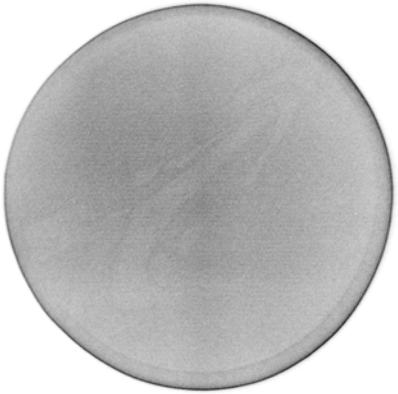
MCP-XDL (Sensor Sciences)

XDL Theory of Operation

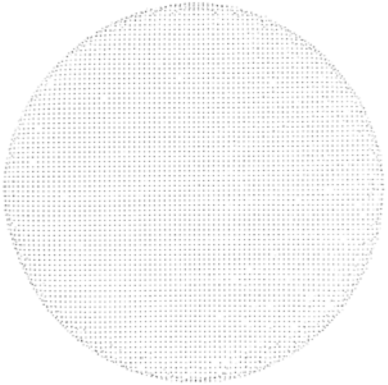
Crossed delay lines allow spatially sensitive readout of MCP

Coincidence loss becomes significant at count rates above ~100 kHz





Uniform detector response

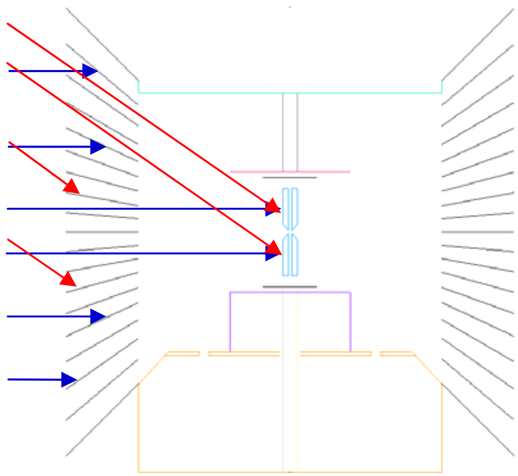


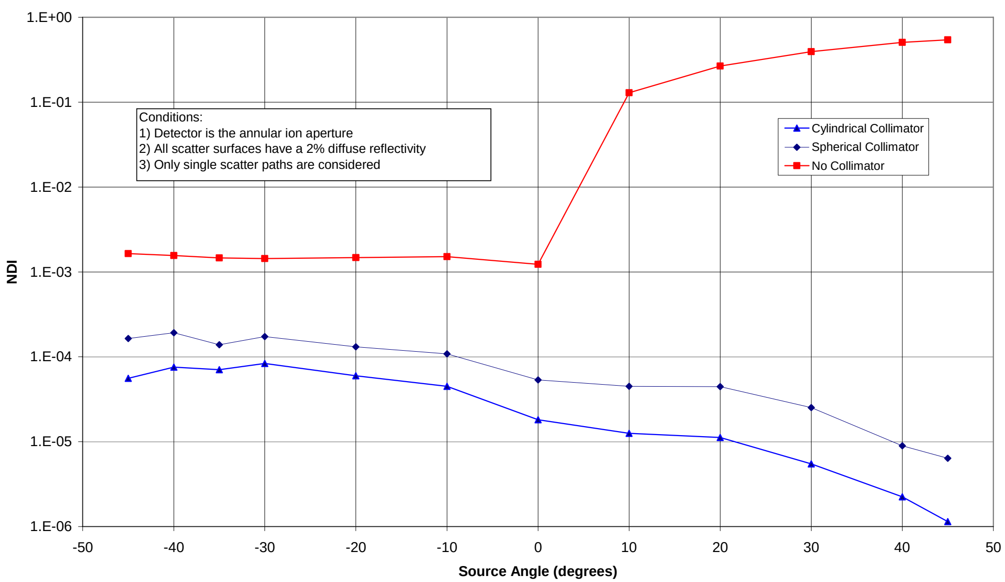
10 µm resolution mask produces 37-50 µm FWHM spots

Low background count rates: 5 s^{-1} @ 4400 V

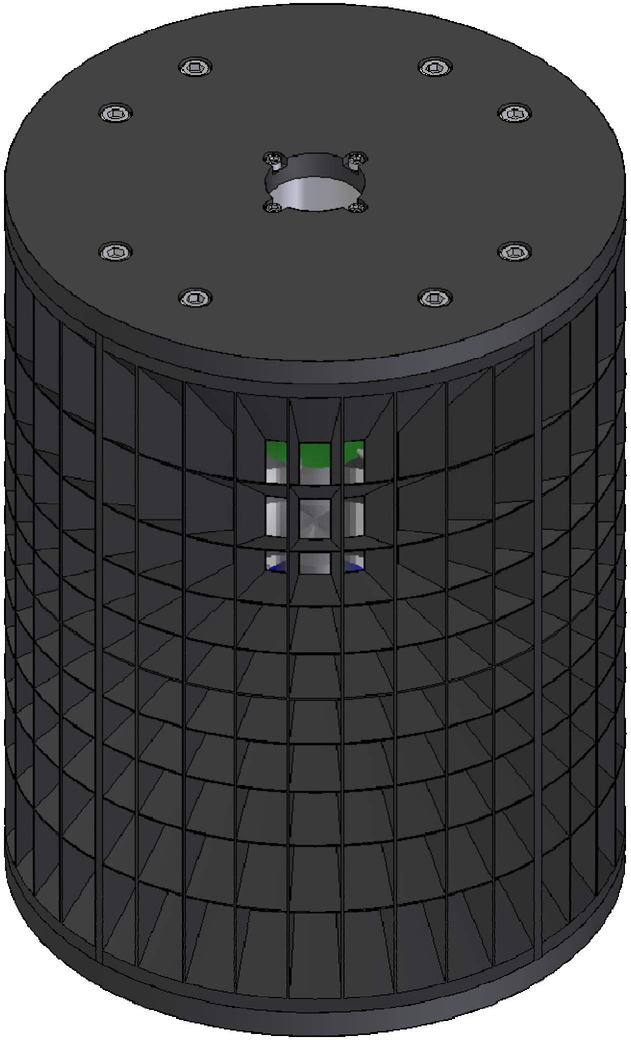
UV Attenuation

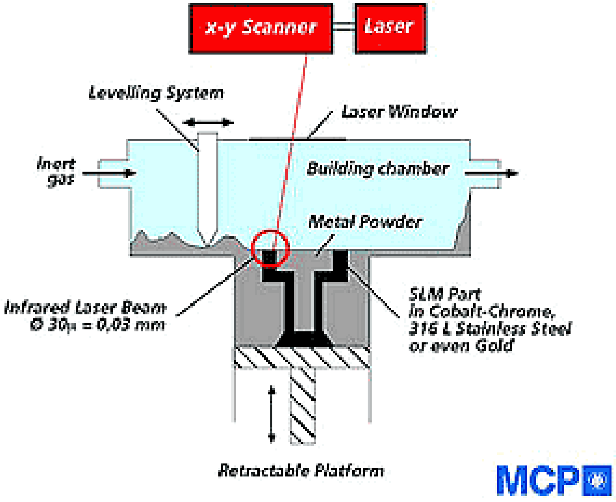
- Flux of UV photons reaching detector must be minimized to maintain low background rates
  - α-Lyman (sun): ~10^{11} ph/cm^2/s
  - Bacground reduction improves sensitivity
- UV flux into sensor acceptance area reduced by a converging collimator
- Direct illumination of the detector eliminated by incorporation of slits, baffles, and coatings
- Stray-light modeling used to predict performance



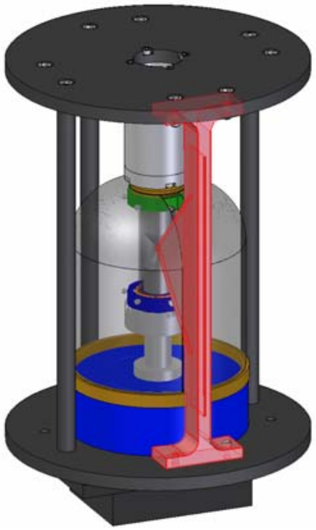


Collimator Design and Fabrication

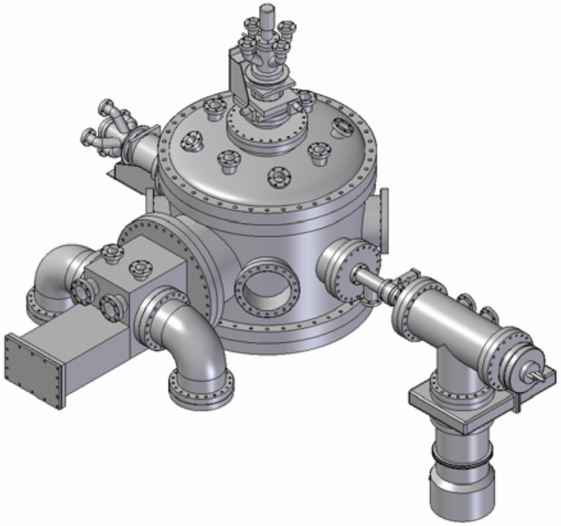




Sources for Sensor Testing

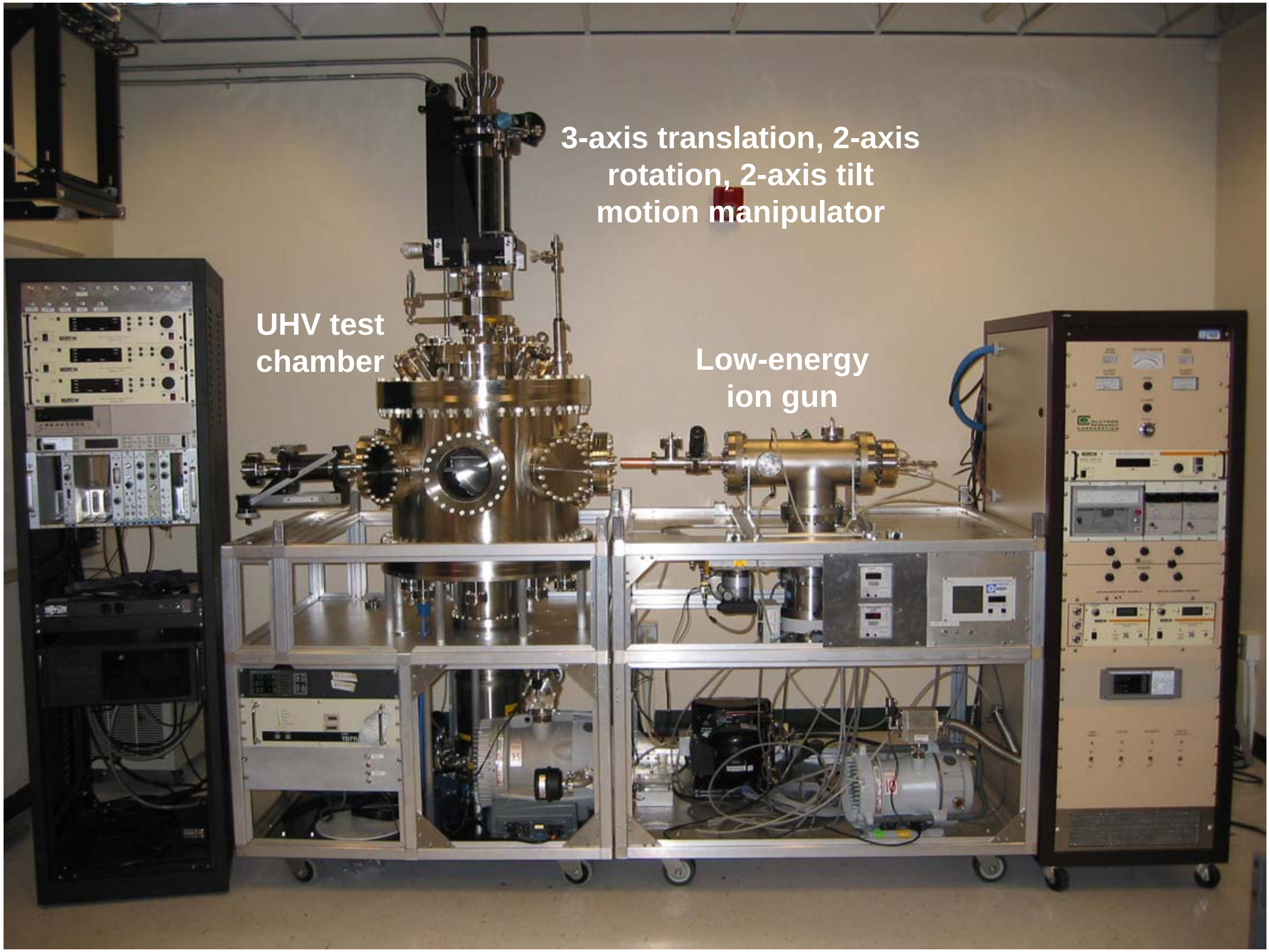


- Ion beam (ion trajectory validation)
  - Tunable energy and current
  - Narrow energy distributions (~0.5 eV FWHM)
  - Decouples electron beam space charge effects
  - Requires low-profile, field-free entrance slit to prevent ion deflection by electrostatic potentials on meshes
  - Beam characteristics are strongly dependent on energy

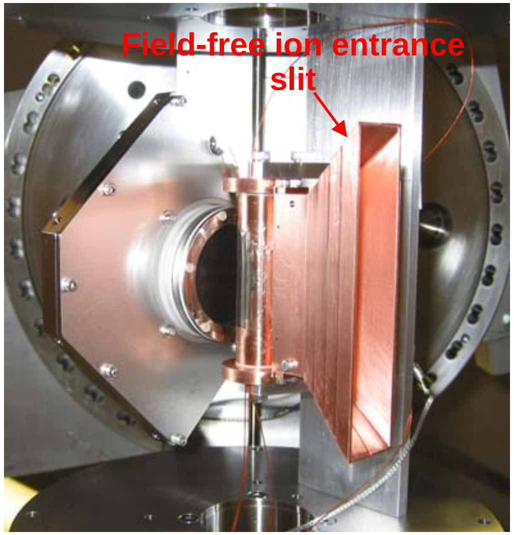


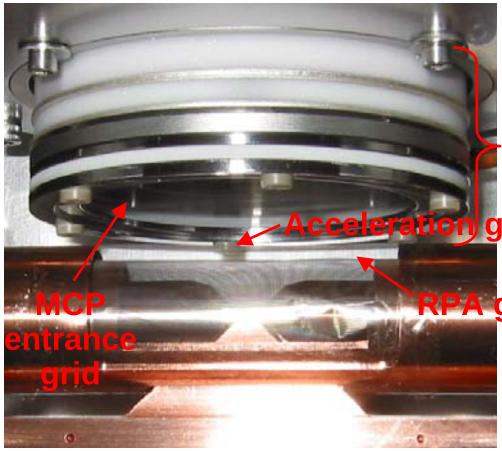
- Neutral beam (ionizer and integrated sensor testing)
  - Energy range limited, but sufficient for effective sensor testing (~0-10 eV)
  - Extremely narrow energy distributions possible
  - Beam profile is independent of energy
  - Necessary for investigation of electron beam space charge effects and integrated sensor testing

SDL Ion Optics Test Facility



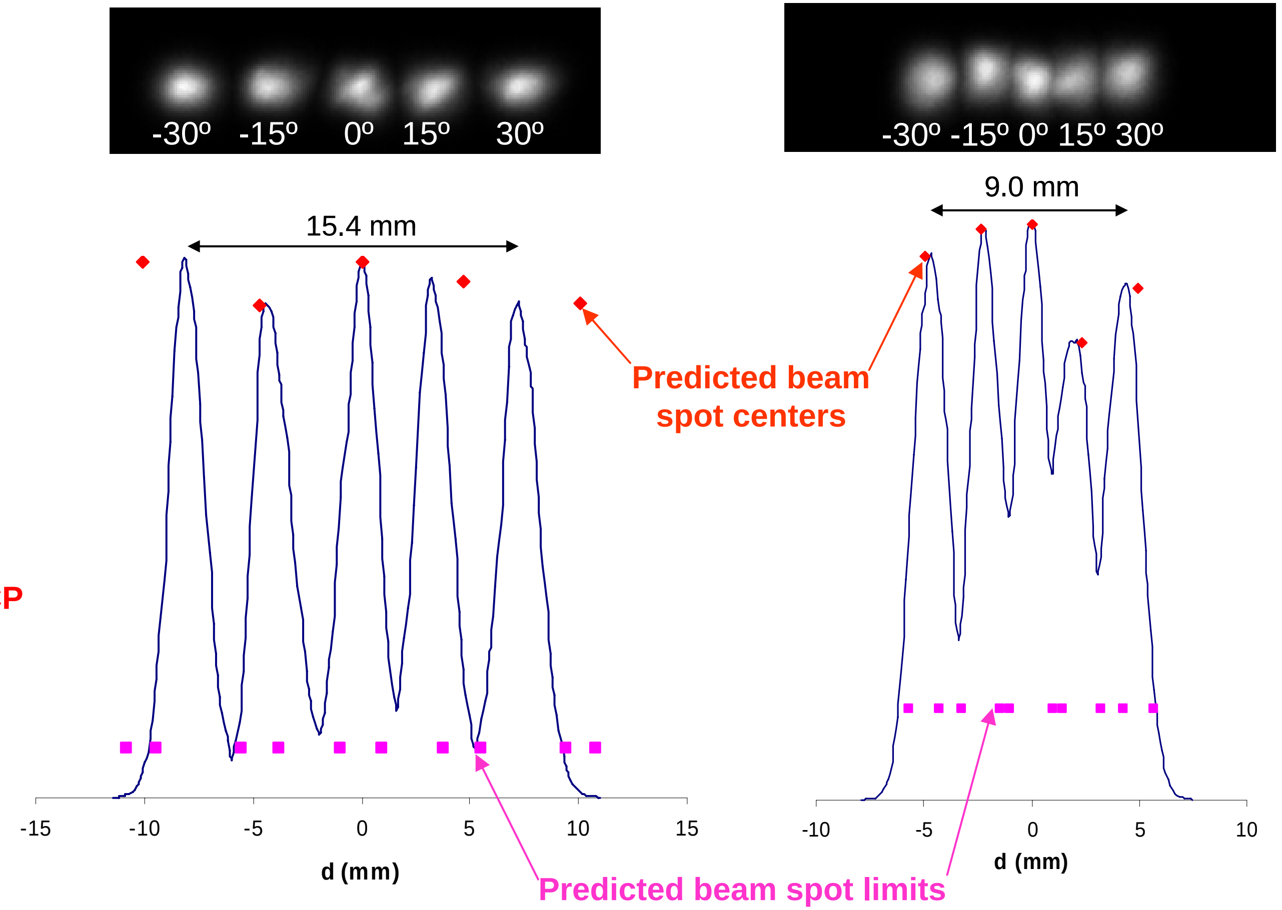
Ion Optics Testing





5 eV Ar$^+$, 0 V acceleration potential

5 eV Ar$^+$, 500 V acceleration potential



Conclusions

- We have designed and modeled a novel, high field-of-view Vector Neutral Particle Spectrometer for measurements of the orbital environment
- We have demonstrated the production of a focused electron beam suitable for use in open ionizers
- SDL has developed laboratory test facilities for the experimental validation of mass spectrometers and ion optics systems
- Preliminary studies indicate excellent agreement between predicted and observed performance of the VNPS

Supplementary Slides

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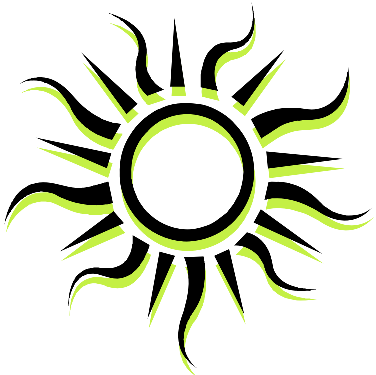
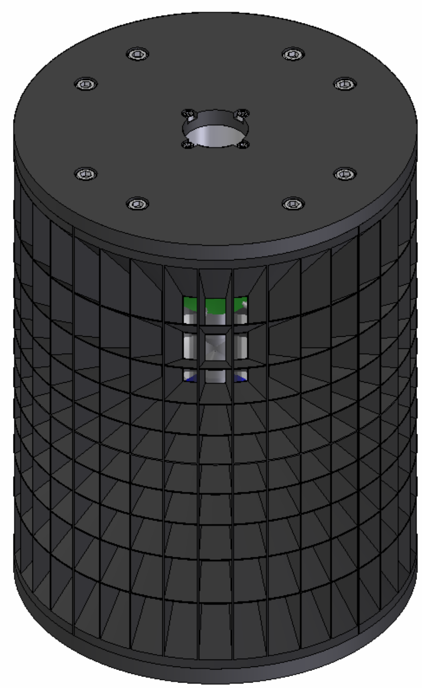
System Thermal Design



Radiation from sun:
38.2 watts

Assume:
-Full cross sectional area
-Solar absorptivity = .97



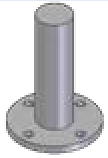
Radiation to space:
47 watts

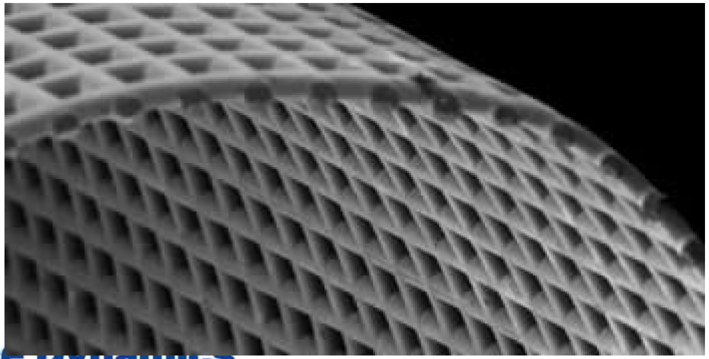
Assume:
-View Factor to space = 1.0
-Emissivity = .97
-Collimator operating at 30ºC

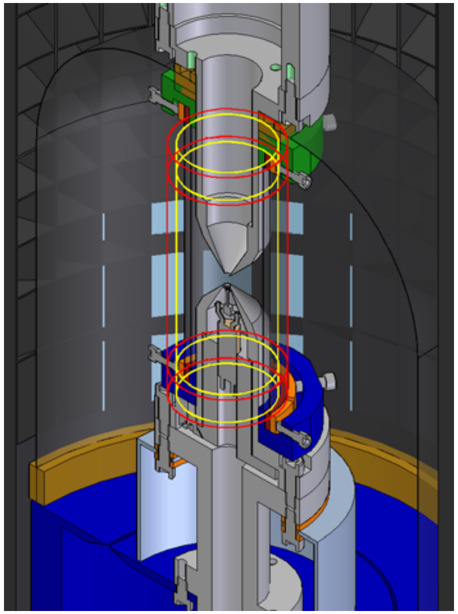
Fabrication of Curved Meshes

Manufacturing Method

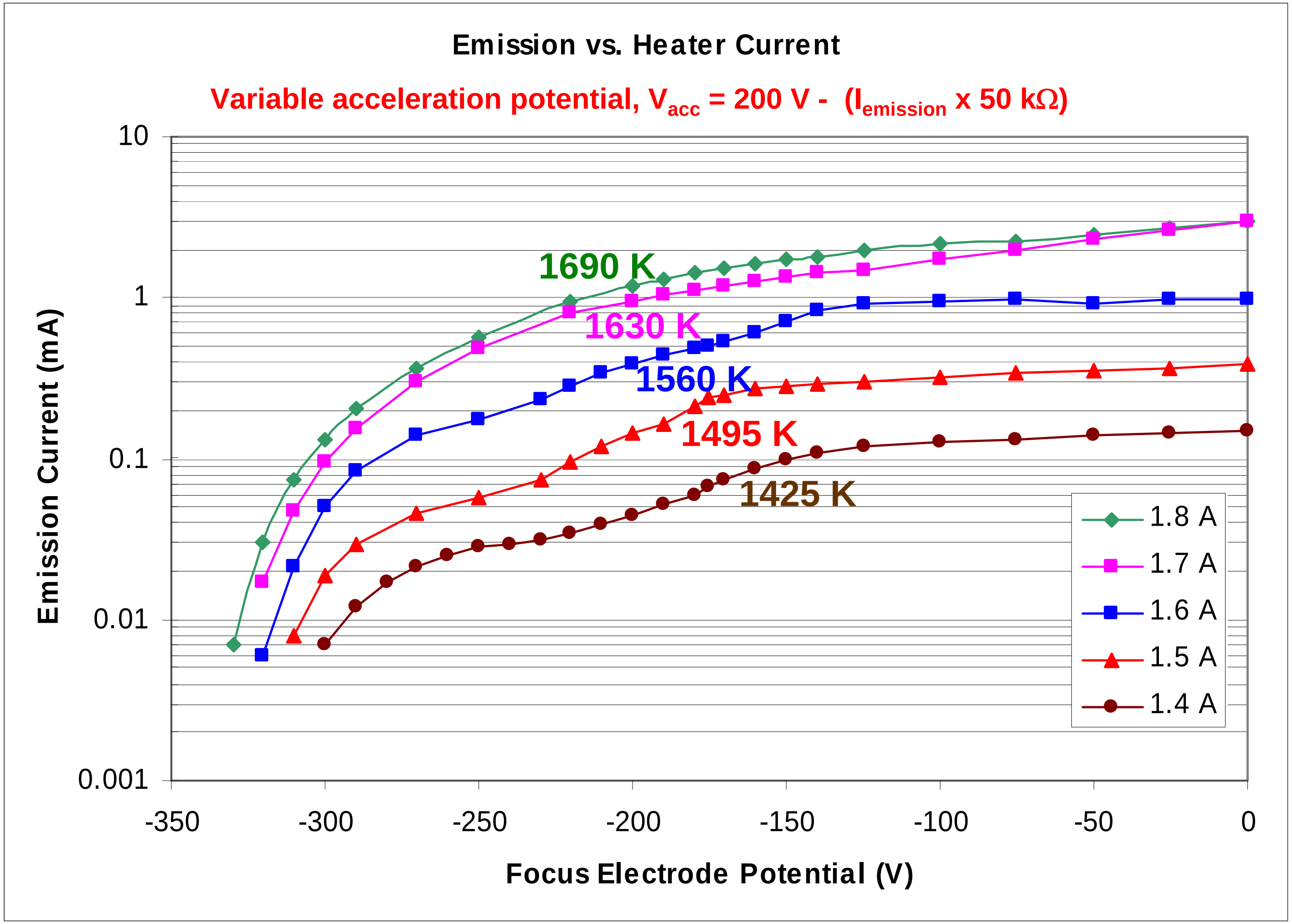
- Construct solid SST mandrel at SDL
- Send to Precision E-Forming for nickel striking
- Send to Intelligent Micro Patterning for 3D lithography
- Send to Precision E-Forming for 3D electroforming
- Return to SDL for part removal and installation



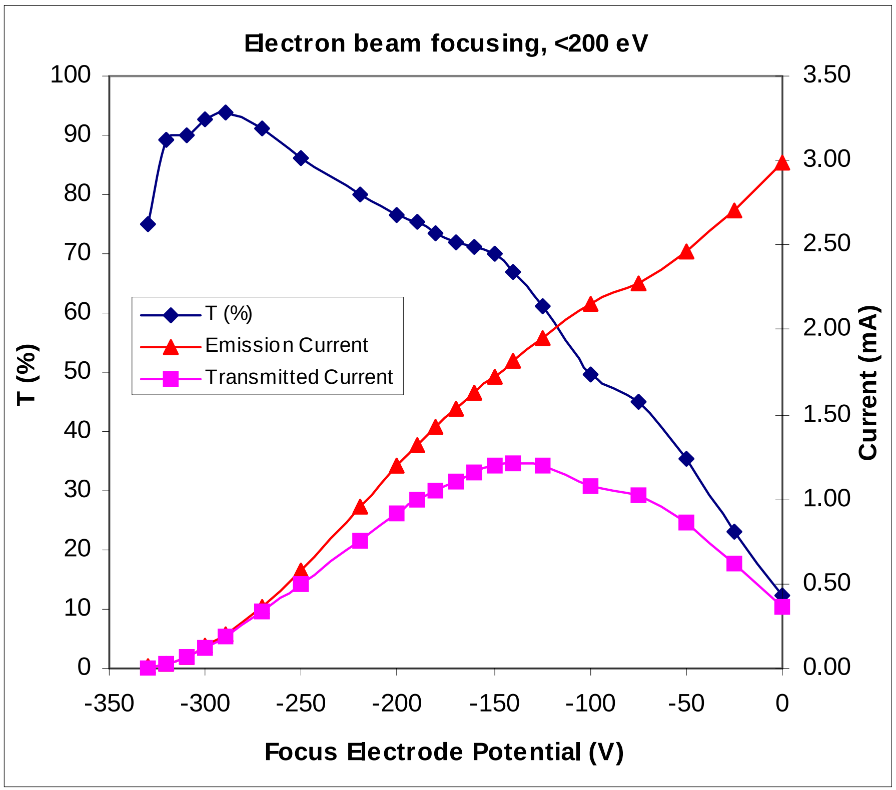


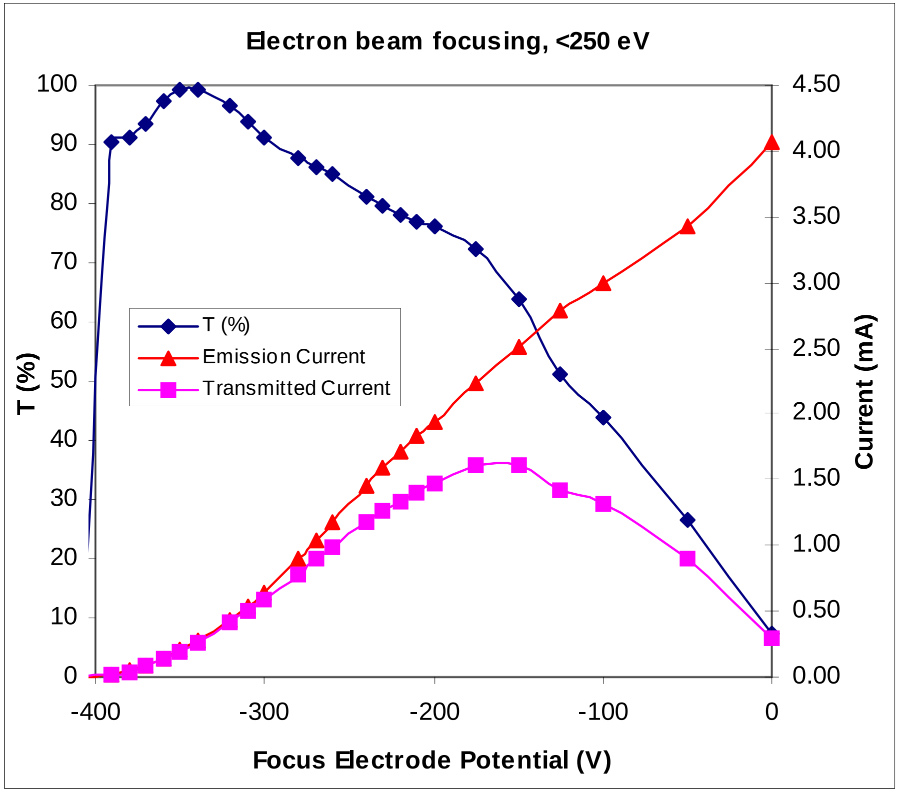


Emitter Current Saturation Curves



Electron Beam Focusing





*Assuming $\%T_{actual} = \%T_{observed} / 0.7$

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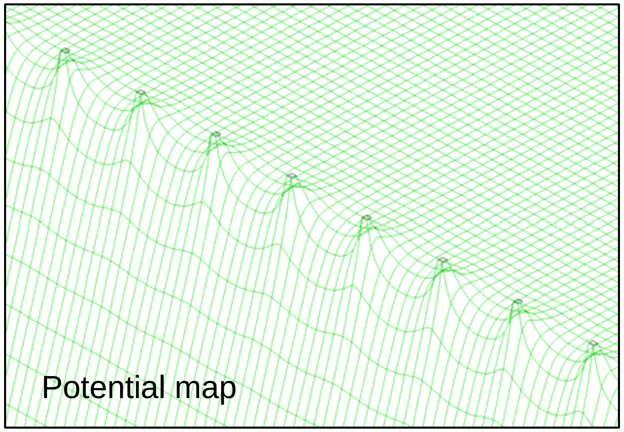
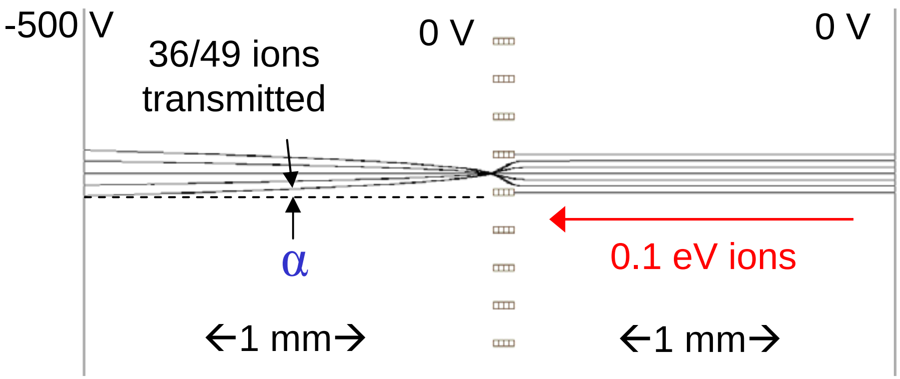
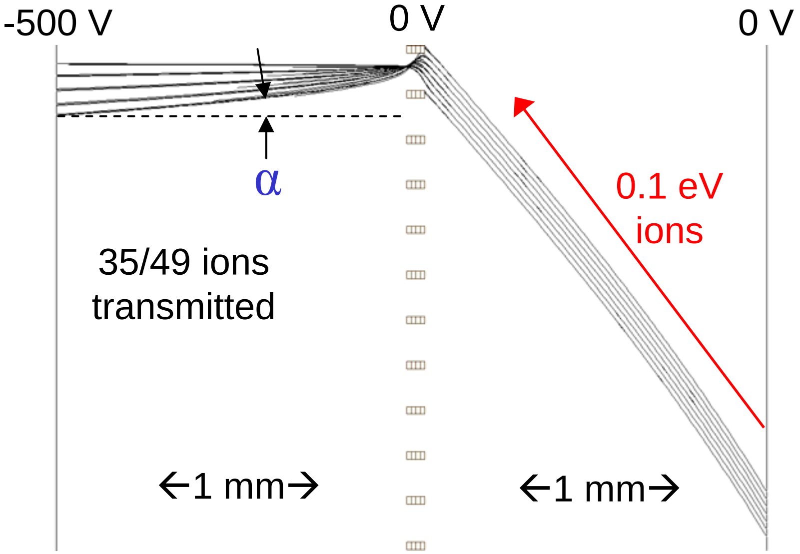
Ion Optics Challenges {*Solutions*}

- Non-ideal grids (field penetration)
  - Micro-lensing → ion trajectory deflections {*minimize electric fields, optimize individual meshes*}
    - Mean **α** ≤ 2.5º
  - Effective grid potential < applied potential {*determine this relationship as a function of electric field for a given grid*}
    - Field penetration is localized; effective potential barrier is predictable and "smooth"



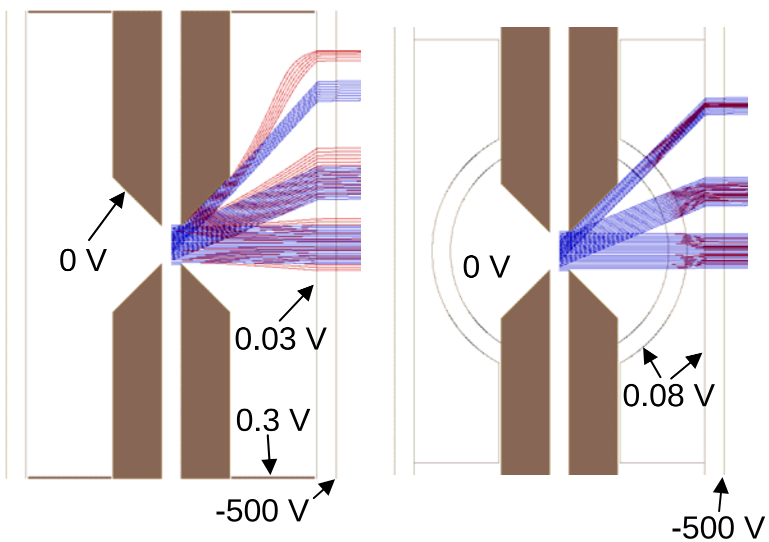




*cross sections of 3D simulations

More Ion Optics Challenges {*Solutions*}

- Entrance angle effects
  - Non-uniform low-energy ion filtering {*end-cap electrodes*}
- Energy effects
  - Non-uniform potential gradients and ion trajectories {*spherical energy analyzing grids*}



Ion energies: 0.1 eV, 0.5 eV

Potential map