Silence is Golden: Detector Radiation Shielding at Europa for MAss Spectrometer for Planetary EXploration (MASPEX)

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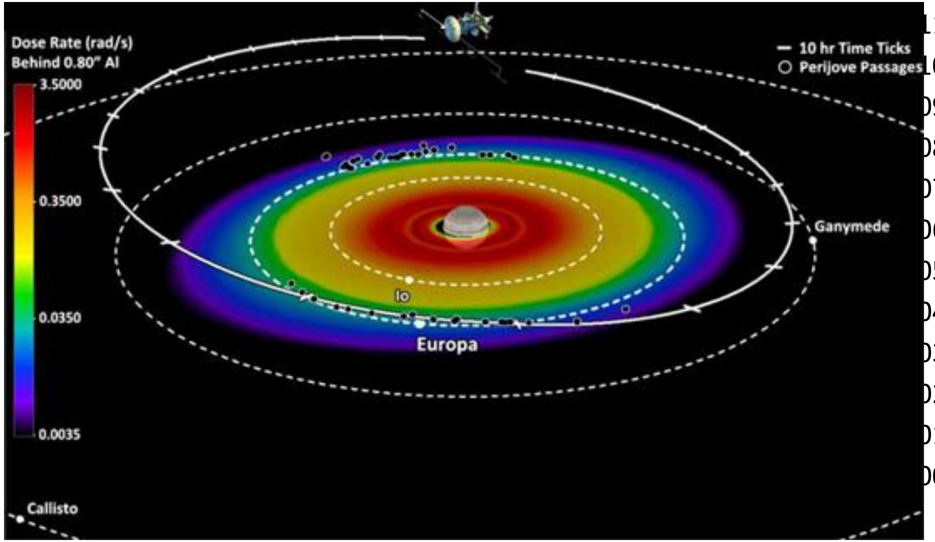
11th HEMS Workshop

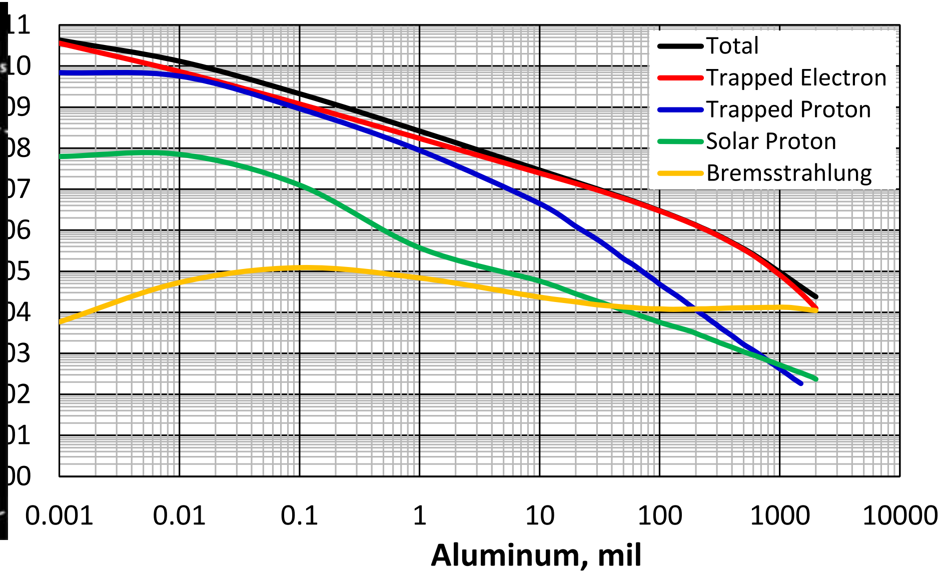
Co-authors: J. Hunter Waite, Jr., Tim Brockwell, Paul Wilson IV, Greg Miller, John Roberts, Keith Pickens, Roland Benke

Outline

- Background Information
  - Radiation at Europa
  - The MAss Spectrometer for Planetary EXploration (MASPEX) instrument
- How is Radiation-Induced Background Noise calculated?
- Experimental measurements of microchannel plate (MCP) detection efficiency
- Incorporating experimental measurements into radiation transport simulations
  - MCNP6 simulations
  - Determining noise rates at MCP detector behind a shielded instrument design
  - Effects on science goals
- Optimizing the shielding design

A major challenge (risk) of Europa Clipper Mission : Radiation





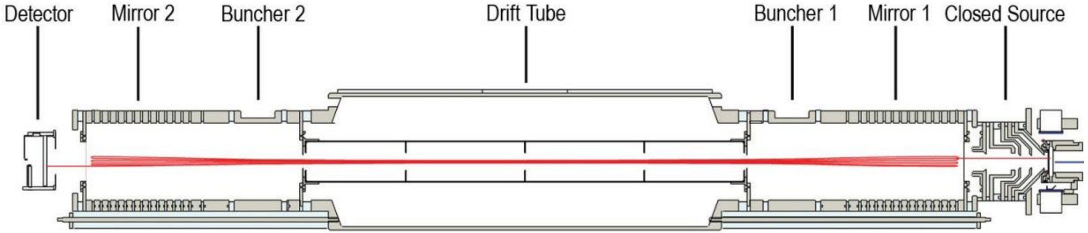
Energy, MeV

- Large flux of electrons and protons trapped by Jupiter's magnetic field.
- TID for the mission behind various Al spherical shield thicknesses seen at upper right.
- Let's put this into a real-world perspective!

Medical Procedure	Radiation Dose (mrem)
Hand or foot X-ray	0.5
Dental Panoramic X-ray	1
Single Chest X-ray	10
Upper GI	600
Whole-body CT screening	1000
Europa (1 second)	308,600 (308.6 rad(Si)/s)*
Europa (mission lifetime)	3.6×10^{13} (3.6×10^{10} rad(Si))*

*behind 0.001 mils Al and assumes that 1 rad(Si) = 1 rem

THE MASPEX instrument (Multi-bounce time-of-flight mass spectrometer (MBTOF))

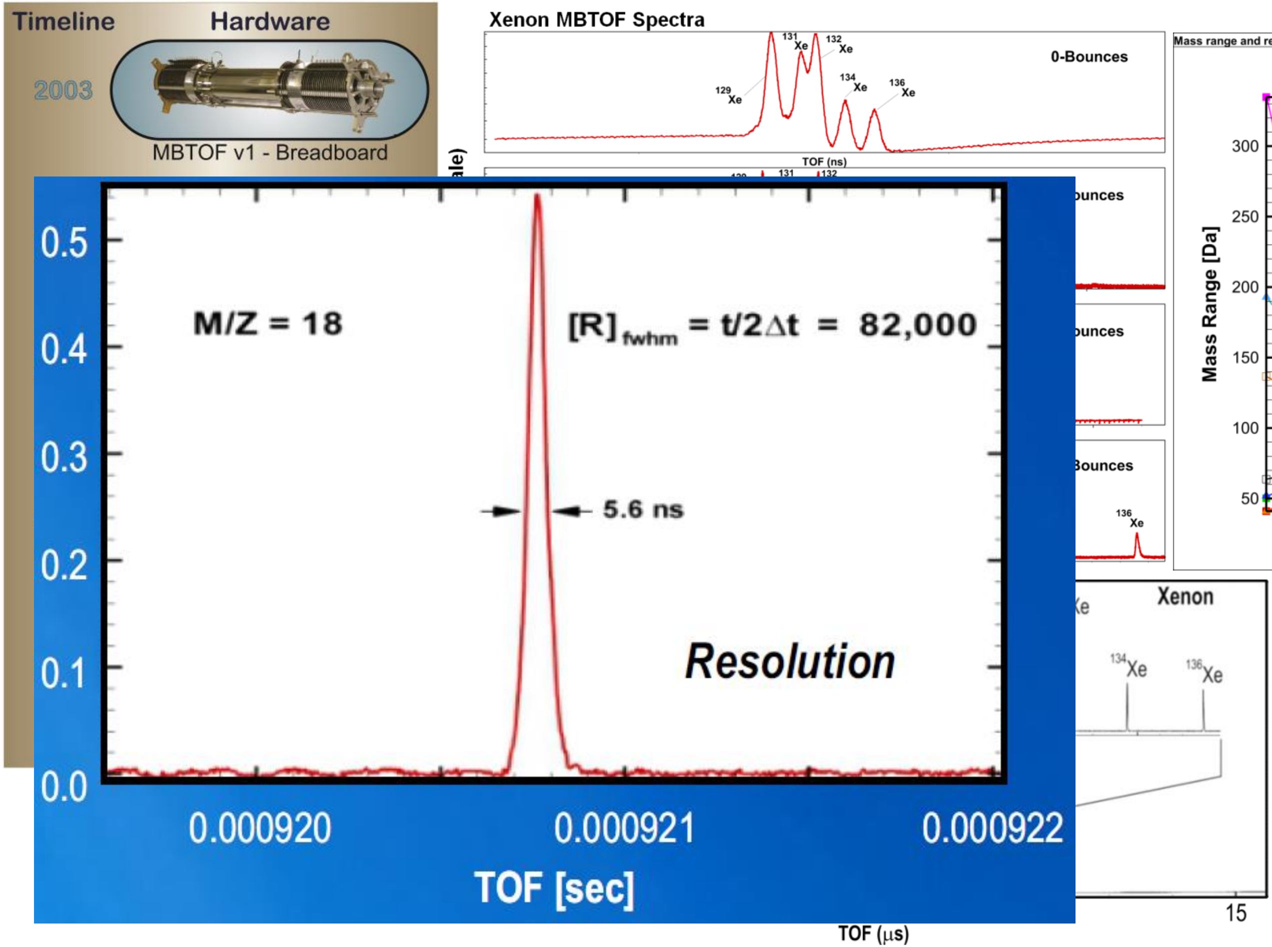


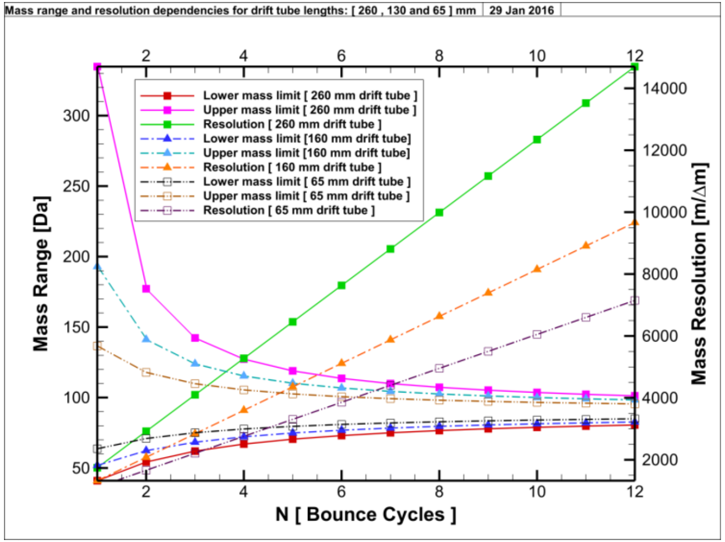
- Time-of-flight (TOF) separates ions over a flight distance according to their velocities.

$$KE = \frac{1}{2}mv^2$$

- TOF can be considered like a road race among different runners.
    - Consider 2 runners: running at 10.001 m/s and 10.000 m/s
    - Over 100 m distance, their times would be 9.999 s and 10.000 s. Would one be able to decipher the winner?
    - Over a marathon distance, the times would be 4,219.08 and 4,219.5 s. We have a winner!
    - Large footprint – how to reduce?
    - Make them run laps on track (~106)
    - Can do the same with ions

THE MASPEX instrument (Multi-bounce time-of-flight mass spectrometer (MBTOF))



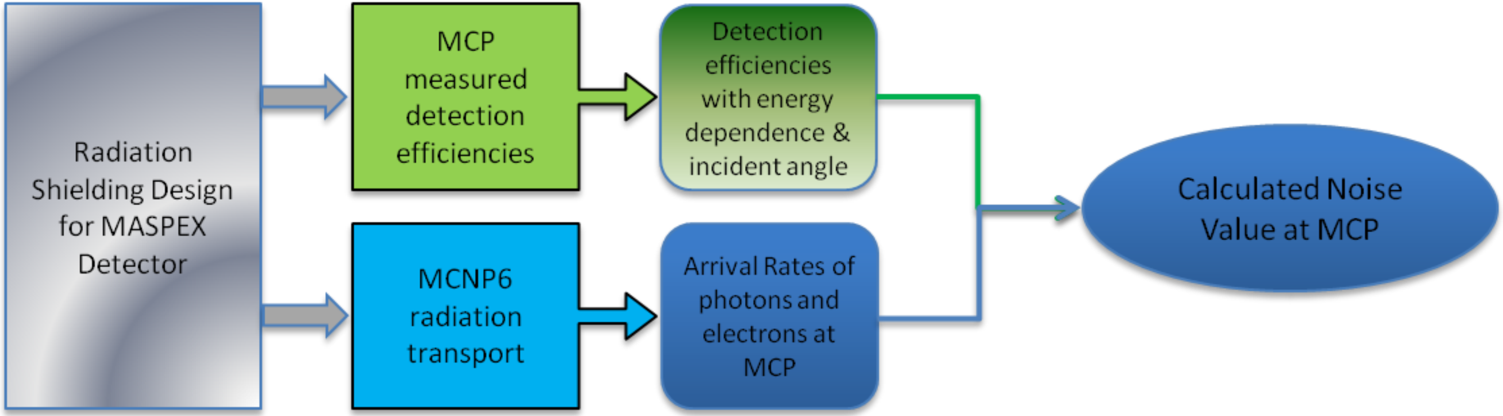


- As length increases, resolution increases, but mass range becomes truncated.

T. Brockwell et al., The mass spectrometer for planetary exploration (MASPEX), Aerospace Conference, 2016 IEEE.

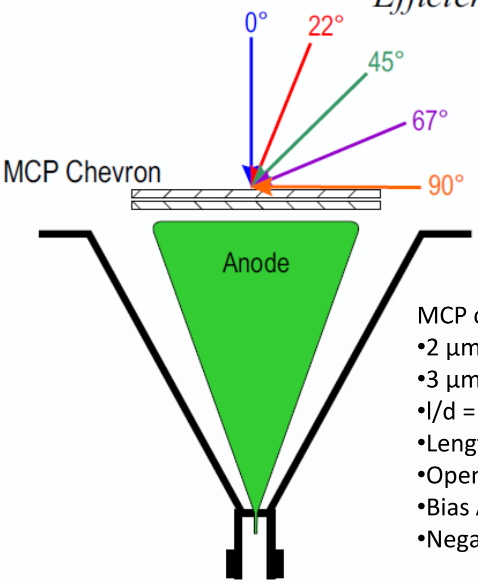
How is Radiation Induced Background Noise Calculated?

- Shielding of MASPEX MCP detector based on:
  - Measured detection efficiency to electrons and secondary photons
  - Detection efficiencies incorporate energy dependence
    - Detection efficiencies incorporate particle angle of incidence
  - MCNP6 radiation transport simulation tool results
    - Determine arrivals at detector with shielding geometries
    - Determine noise values from arrivals at detector with incorporated data on detection efficiency as a function of energy and angle of incidence



How are the detection efficiency measurements made?

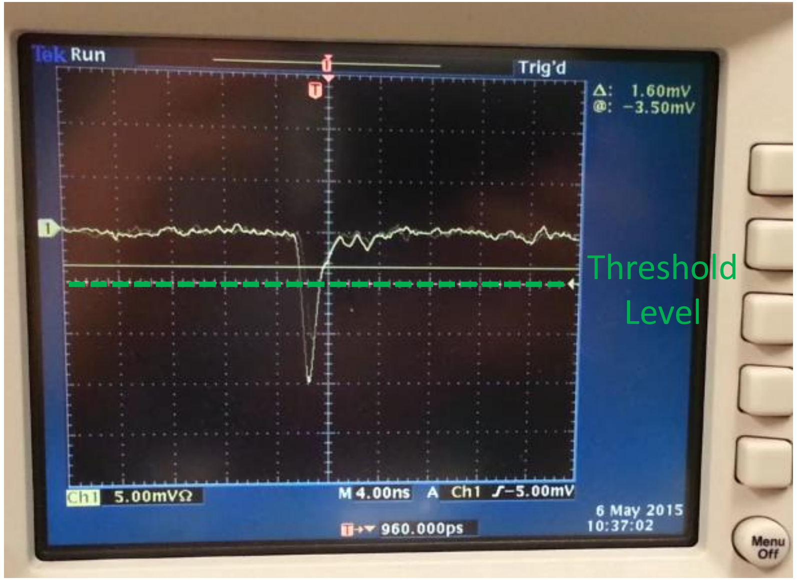
$$Efficiency = \frac{\overline{X_{cps}}}{e^{-}}$$



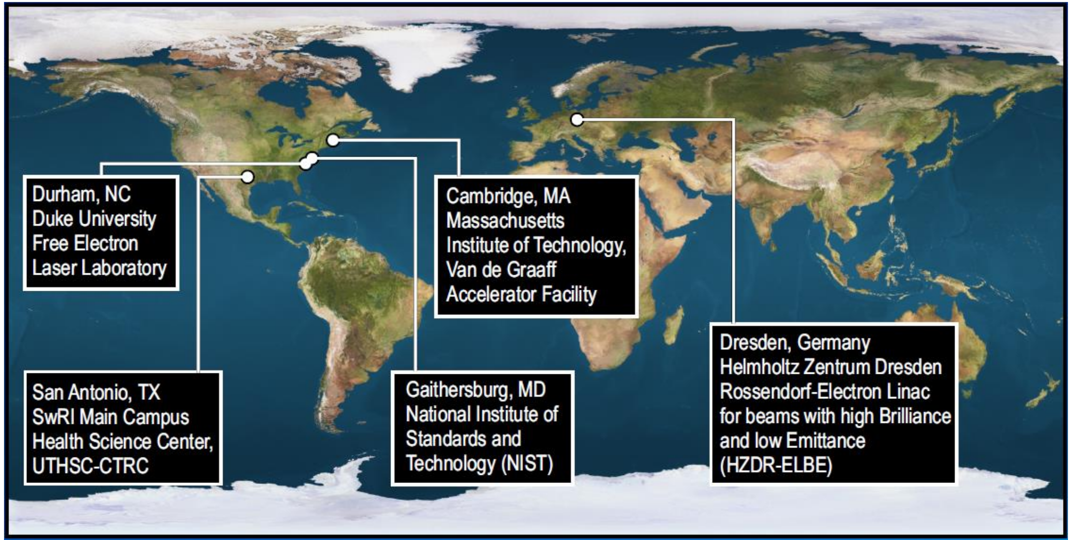
MCP characteristics
- 2 µm pore diameter
- 3 µm center-to-center (1 µm pitch)
- l/d = 75:1
- Length = 150 µm
- Open Area = ~57%
- Bias Angle = 13°
- Negative bias for + ion detection

Particle beam incident angle illustration relative to the MCP front face.
Note: MCP moves in relation to the beam.

- In normal operation, we are wanting to count ions (ionized neutral gas molecules at Europa). As such, we don't want too be penalized by counting radiation induced noise counts which are below the single events we normally want to count.



Experimental Measurements to determine Detection Efficiency of the MCP



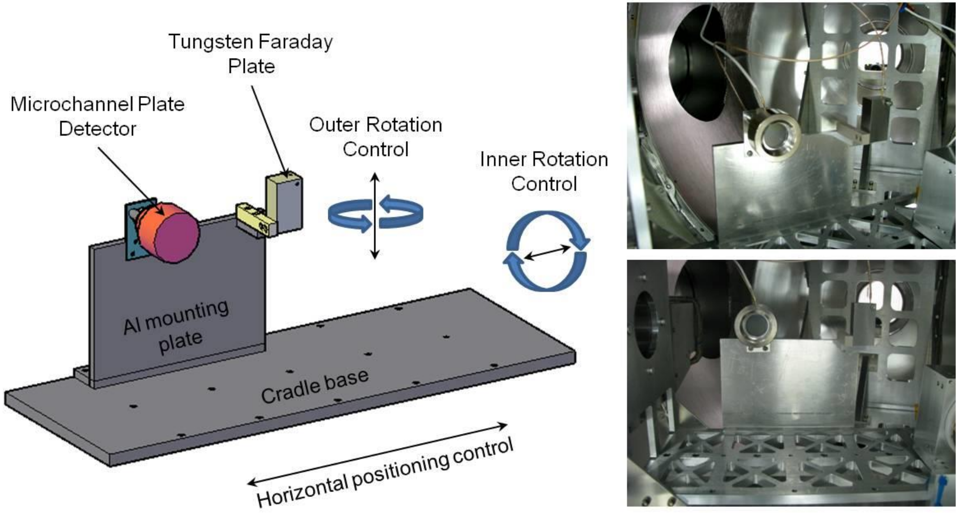
MCP detector setup has travelled 21,100 miles, 54 millionths the distance to Europa.

Experimental Facility	Particle Type	Energy Range
SwRI Electron Chamber	Electrons	1 - 30 KeV
MIT Van de Graaff Accelerator	Electrons	400 KeV - 2.6 MeV
Duke Free Electron Laser Laboratory	Photons	2.5 - 20 MeV
HZDR - ELBE	Electrons	20 - 30 MeV

Experimental Measurements (Low energy electrons)

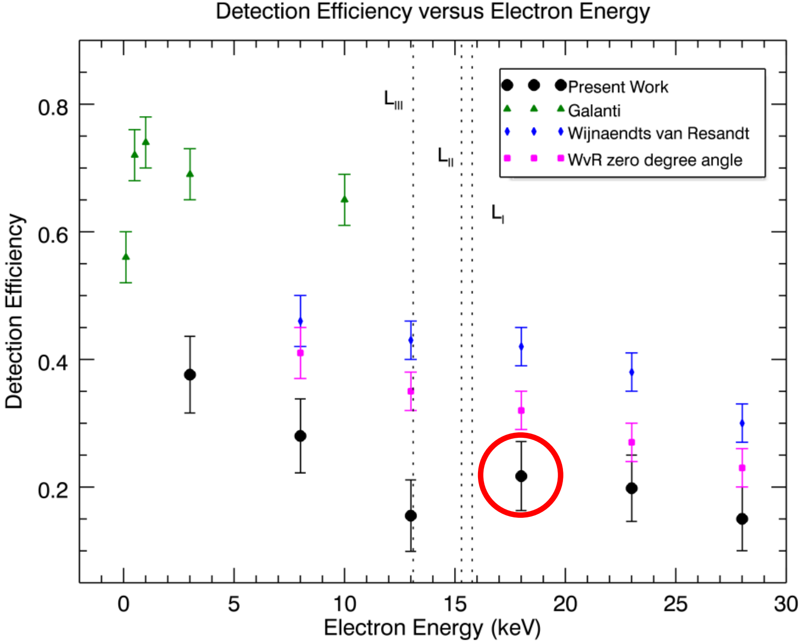
Photograph of Electron Chamber at SwRI

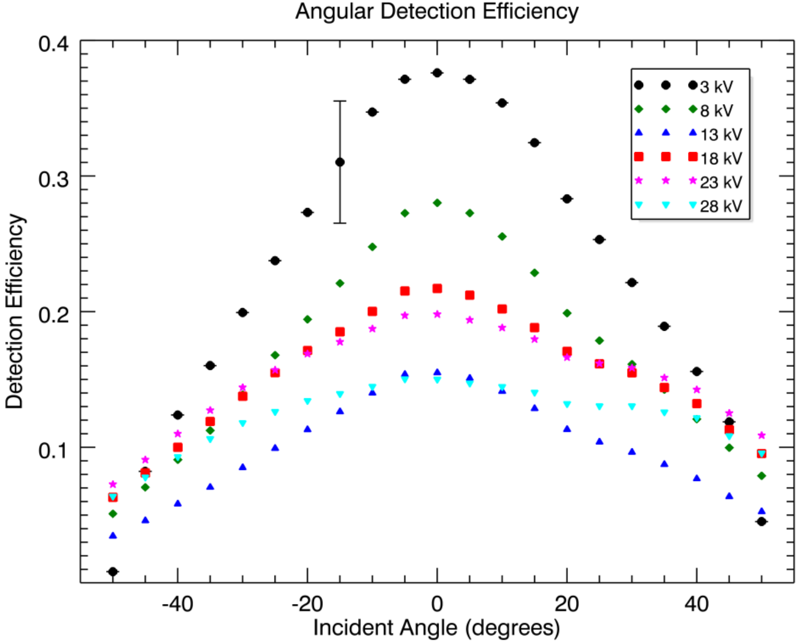
3-Axis Cradle Positioning System



- MCP detection efficiency tested in electron energy range of 3 to 28 keV
    - Angular detection efficiency tested by rotating the cradle positioning system
- Electron beam shape (diameter) determined from Quantar imaging MCP detector
    - Beam diameter confirmed at 18 mm, the active diameter of the MCP
- Electron beam current measured by Tungsten Faraday Plate
- Electron beam irradiates the MCP and we determine the counts registered above the required threshold versus the number of electrons arriving at the MCP (beam current)
    - Detection efficiency = Counts / Electron arrivals

Experimental Measurements (Low energy electrons)

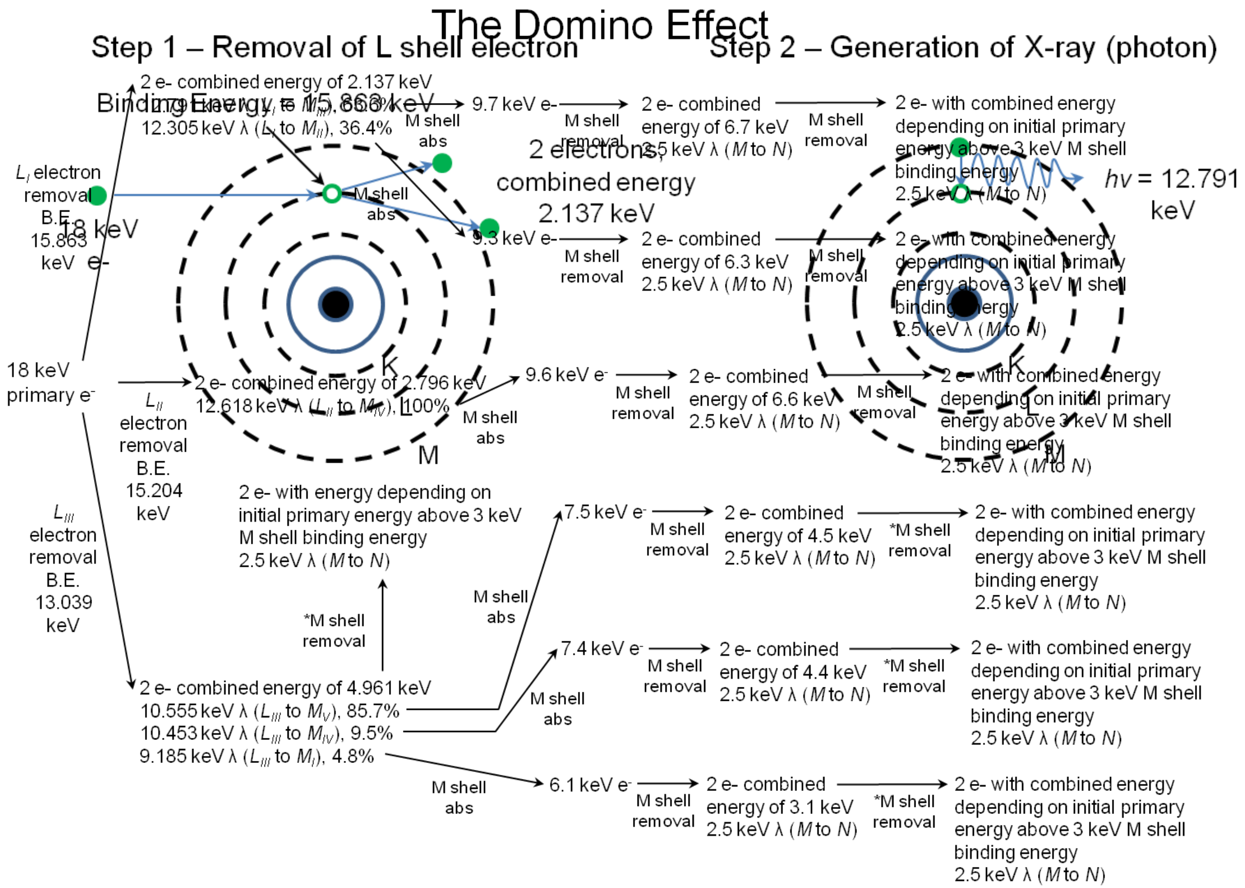




- MCP detection efficiency results as a function of electron energy presented at left (our data are the black circles)
- Overall trend: detection efficiency decreases as the electron energy increases
  - What is with the data point at 18 keV?
  - L shell electron removal from Lead – more on this on the next slide
- MCP detection efficiency as a function of incident angle at right
  - Overall trend: detection efficiency decreases as the incident angle increases (less pronounced as the electron energy increases)

Blase, R.C. et al. Microchannel plate detector detection efficiency to monoenergetic electrons between 3 and 28 keV, *Review of Scientific Instruments*, 2017, 88, 055302.
M. Galanti et al., A High Resolution, High Sensitivity Channel Plate Image Intensifier for Use in Particle Spectrographs, *Review of Scientific Instruments, 1971,* 42, 1818-1822.
R. W. Wijnaendts van Resandt, "Absolute quantum efficiencies of micro-channelplates for 8-28 keV electrons," *J. Phys. E: Sci. Instrum.*, vol. 13, pp. 1162-1164, 1980.

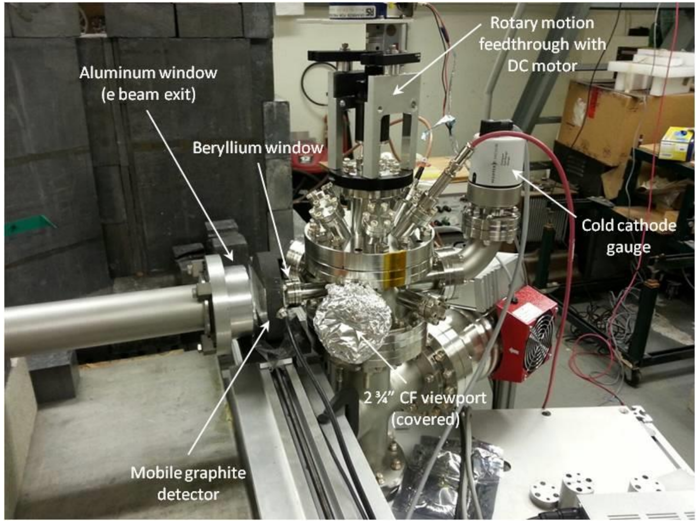
Low Energy Electrons (data at 18 keV and above)

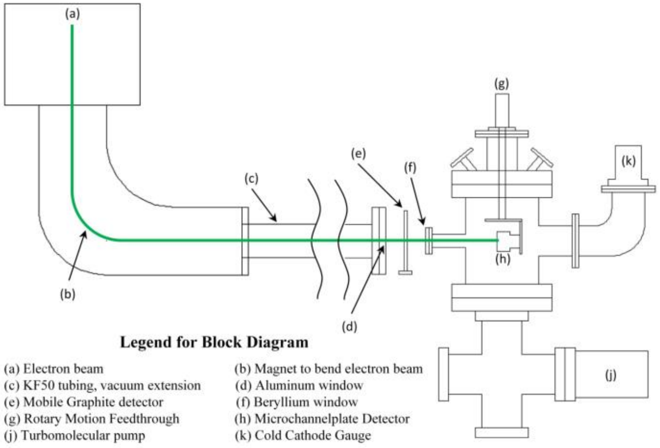


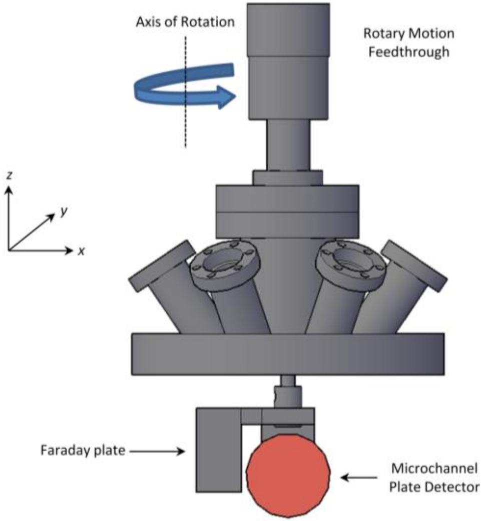
- Incident electron energy, at 13.039 keV, and above is sufficient for L shell electron removal from Lead
- Removal of the L shell electron results in two lower energy electrons and a specific X-ray being released from an M shell electron dropping down into the vacant L shell
- The released X-ray can be absorbed by the M shell from the photoelectric effect which can continue the production of secondary particles which can induce electron cascades in the MCP and produce counts
- The secondary particles and the reduced energy primary electron increase the probability of producing electron cascades in the MCP and thereby increase detection efficiency.

Blase, R.C. et al. Microchannel plate detector detection efficiency to monoenergetic electrons between 3 and 28 keV, *Review of Scientific Instruments*, 2017, 88, 055302.

Experimental Measurements at MIT (Medium Energy Electrons)



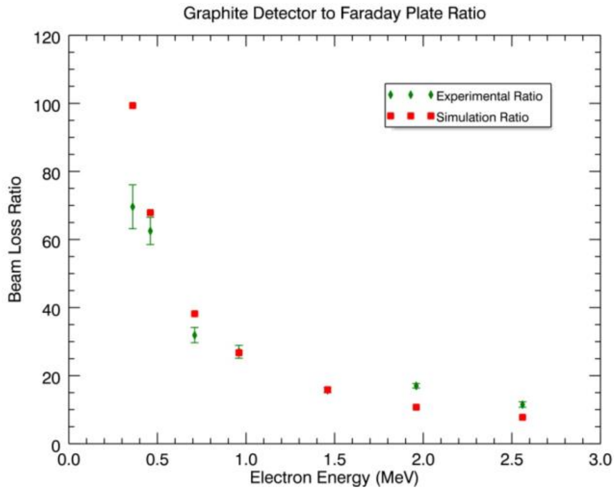


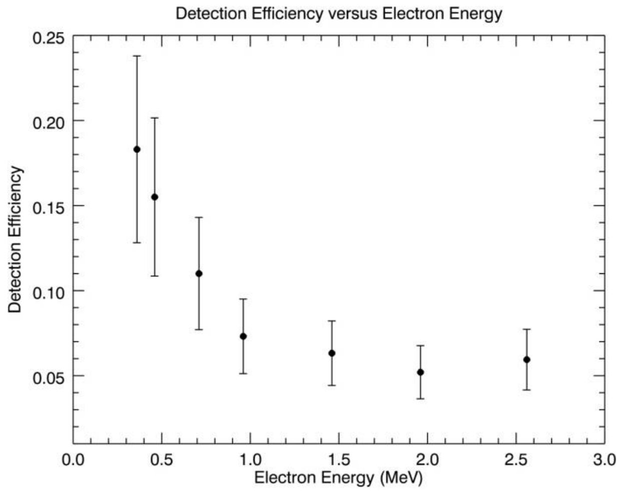


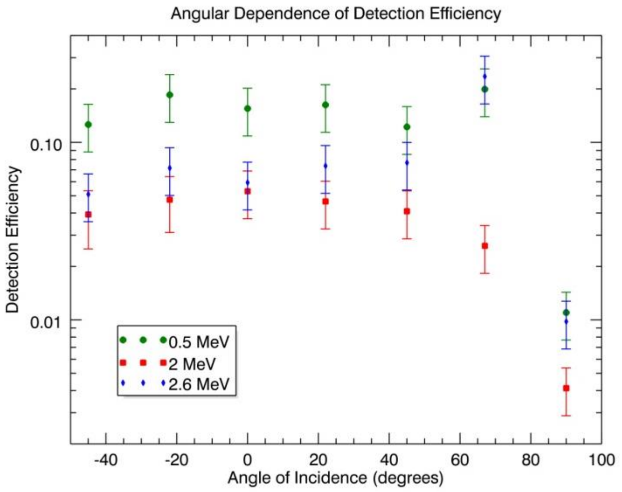
- Experimental setup shown above (left and middle)
- Electron beam exits Van de Graaff accelerator chamber (3 mils Al), enters our chamber through Beryllium window (2 mils)
  - Need to minimize this air gap while also being able to measure the electron beam current entering the Beryllium window
  - Correlated the electron beam current measured with mobile graphite detector with our internal Faraday plate
- Figure at right represents the rotary motion feedthrough to rotate the MCP in the beam line or position the Faraday plate to measure the electron beam current
- Rotary motion feedthrough motorized with DC motor to control angular position while sitting safely in the beam control room

Blase, R.C. et al. Microchannel Plate Detector Detection Efficiency to Monoenergetic Electrons Between 0.4 and 2.6 MeV, IEEE Transactions on Nuclear Science, 2015, 62 (6), 1-7.

Experimental Measurements at MIT (Medium Energy Electrons)



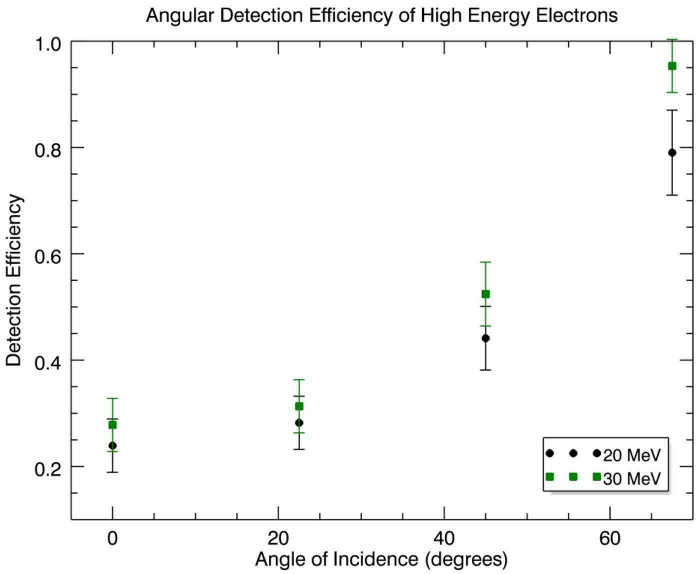




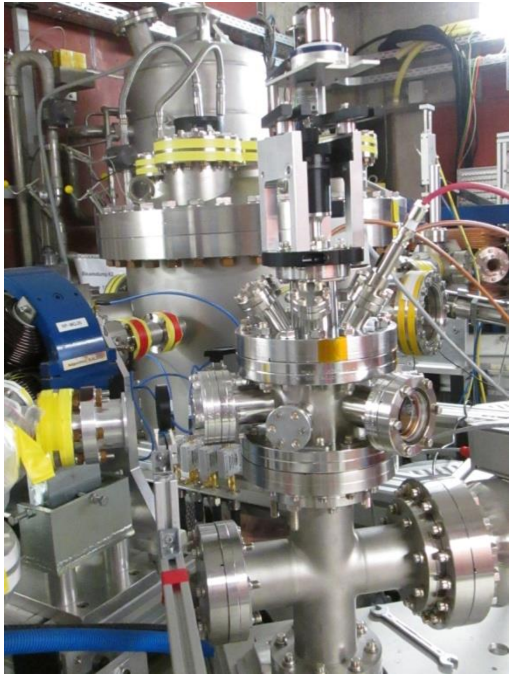
- Figure at left shows the mobile graphite detector to Faraday plate ratio in red along with MCNP6 simulations showing electron arrivals at the mobile graphite detector compared with the Faraday plate
    - Good agreement and simulation confirmation gave us high confidence in electron beam current for MCP detection efficiency measurements
- Figure in the middle displays the MCP detection efficiency as a function of electron energy
- Figure at right displays the MCP detection efficiency as a function of incident angle at three different beam energies
    - Detection efficiency as a function of incident angle remains relatively unchanged over the angles investigated

Blase, R.C. et al. Microchannel Plate Detector Detection Efficiency to Monoenergetic Electrons Between 0.4 and 2.6 MeV, IEEE Transactions on Nuclear Science, 2015, 62 (6), 1-7.

Experimental Measurements at HZDR-ELBE (High Energy Electrons)



Detection Efficiency versus angle of incidence for the two electron energies.

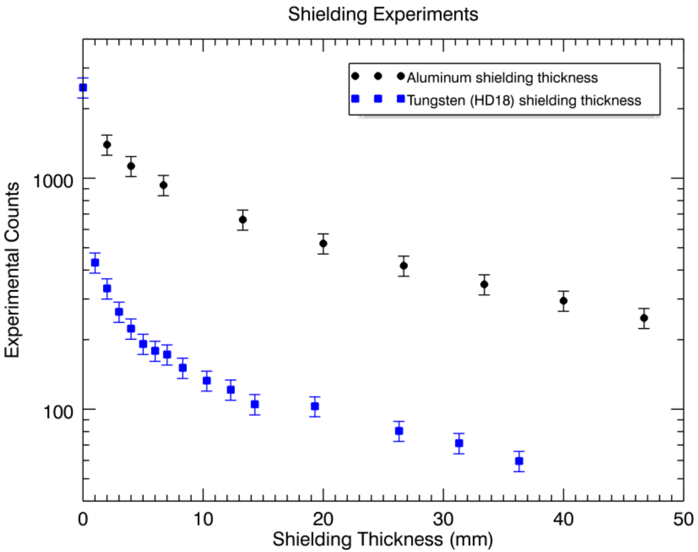


Photograph of experimental setup at HZDR-ELBE.

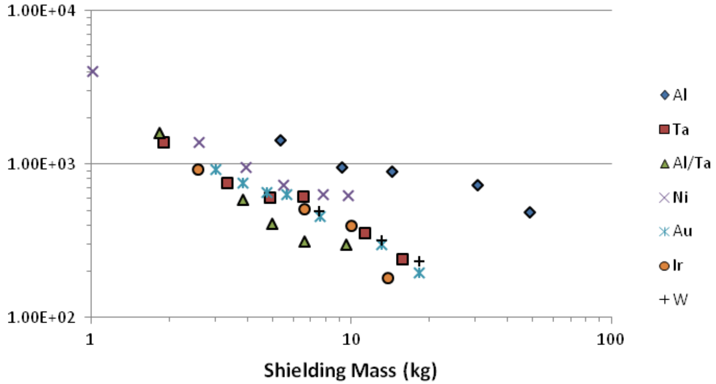
- Much like high energy photons, high energy electrons are very penetrating at large incident angles.
- Increased detection efficiency at increased incident angle (entries from the side of the MCP).

Experimental Measurements at HZDR-ELBE (High Energy Electrons)

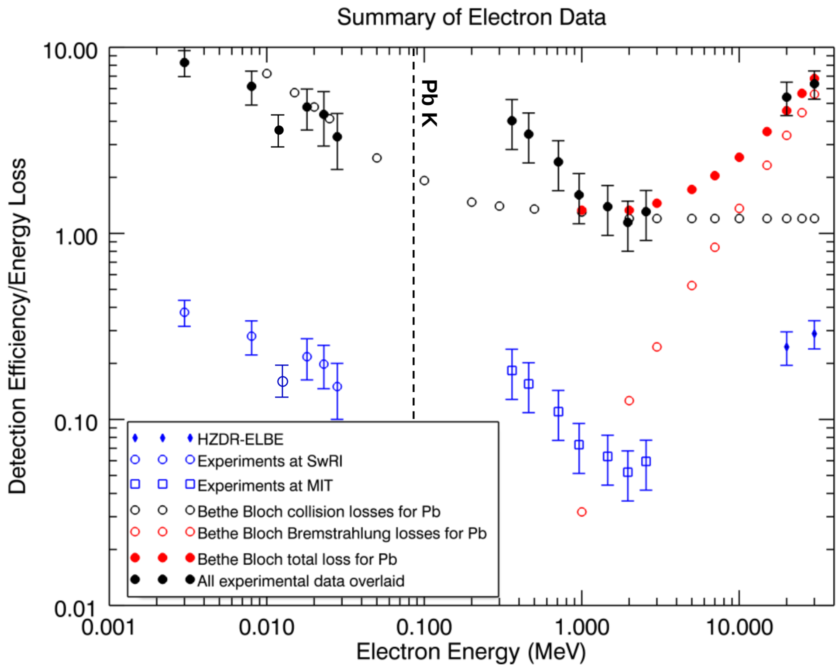
Al and Tungsten (HD18) shielding discs for shielded experimental measurements of 30 MeV beam.



Performed experiments with layered Al/W shielding discs and saw a reduction of about 3 to 5 percent with the layered shield (equivalent mass).

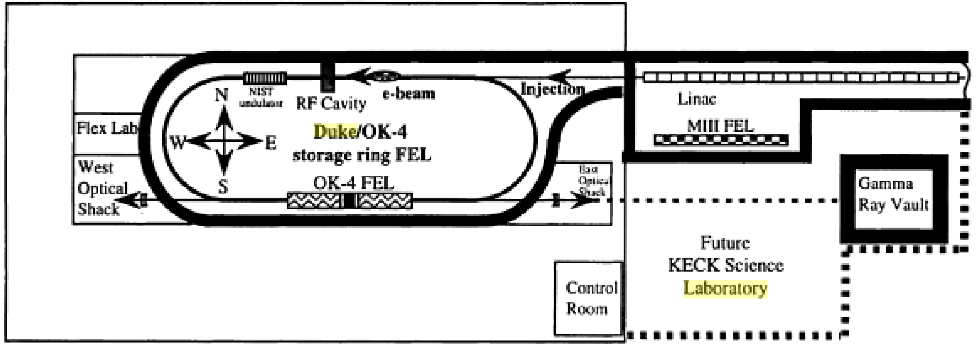


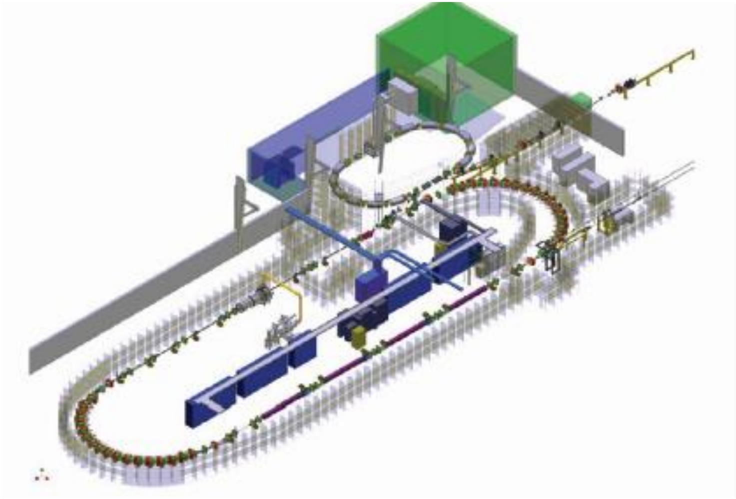
Electron Experimental Summary

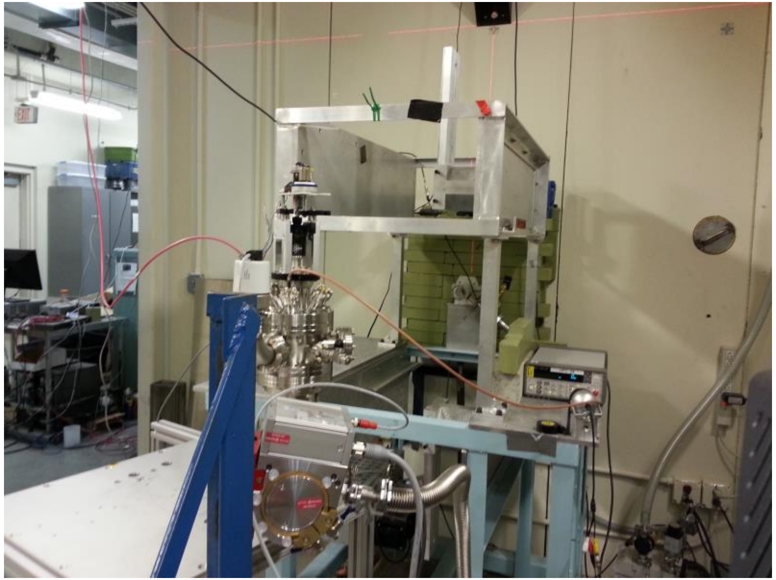


- Electron detection efficiency discontinuities due to Pb L shell and K shell (surmised, not proven experimentally).
- Bremsstrahlung production (losses) at high energy giving rise to increased detection efficiency with high energy electrons.
- Bethe Bloch collision, Bremsstrahlung, and total loss for Pb shown to illustrate the point.

Experimental Measurements at Duke Free Electron Laser (FEL) Laboratory (High Energy Photons)

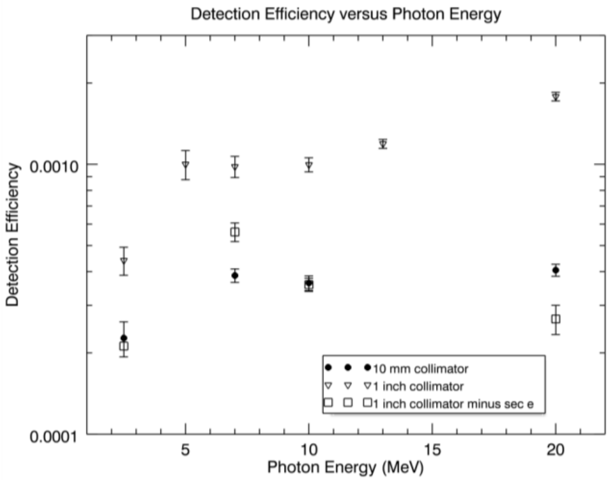


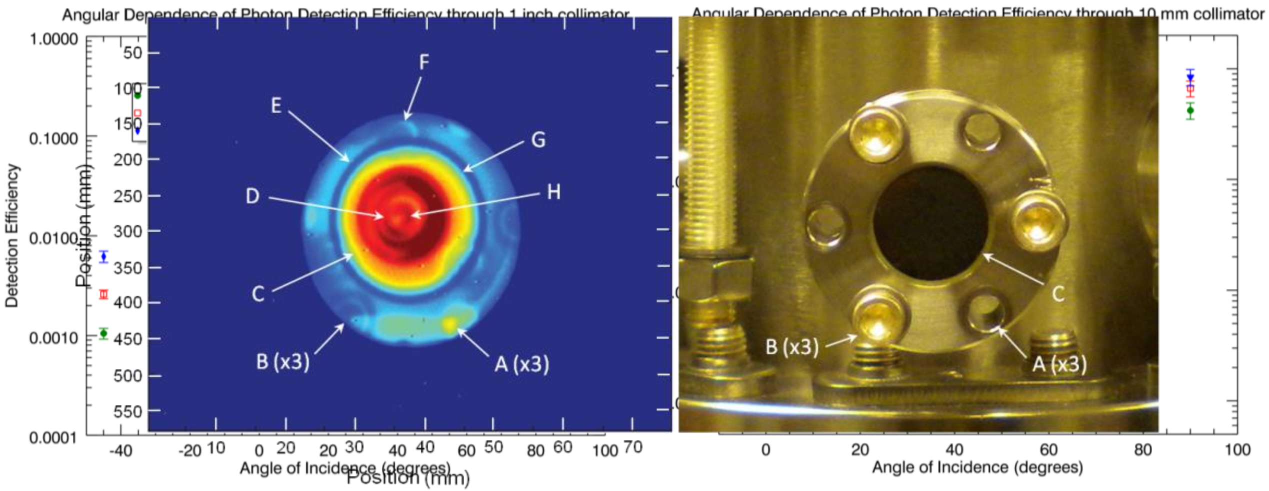




Photograph of the experimental setup in the gamma ray vault.

Experimental Measurements at Duke (High Energy Photons)



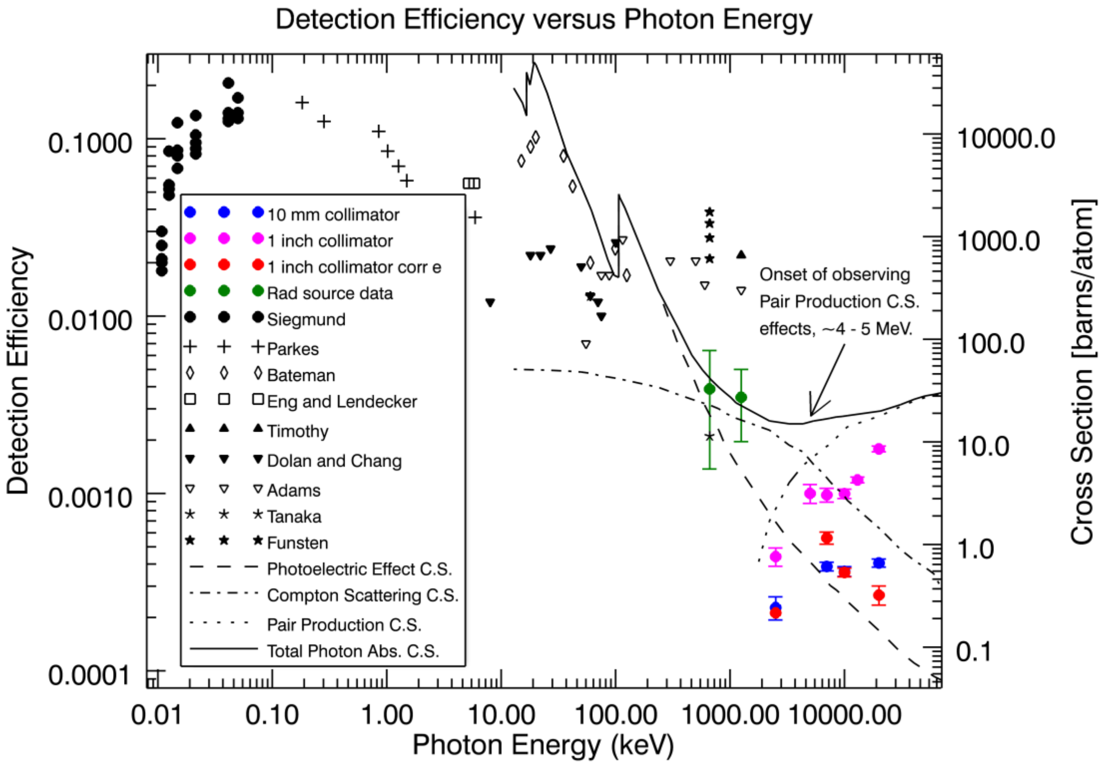


- Detection efficiency as function of photon energies through two collimating diameters shown at left
    - Efficiency begins to increase as the gamma (photon) energy increases
- Detection efficiency as a function of incident angle shown at middle for 1 inch collimator
- Detection efficiency as a function of incident angle shown at right for 10 mm collimator
    - Detection efficiency increases as a function of incident angle due to penetrating ability of high energy gammas

(A) open bolt circles (B) closed bolt circles (C) beryllium window diameter (D) detector anode outer diameter (E) outer diameter of vacuum tube (F) detector body mounting ring (G) inner diameter vacuum tube and (H) detector anode inner diameter/SMA connection in anode body.

R.C. Blase et al., Microchannel Plate Detection Efficiency to Monoenergetic Photons Between 0.66 and 20 MeV, submitted to *IEEE Transactions on Nuclear Science* (currently revising after review).

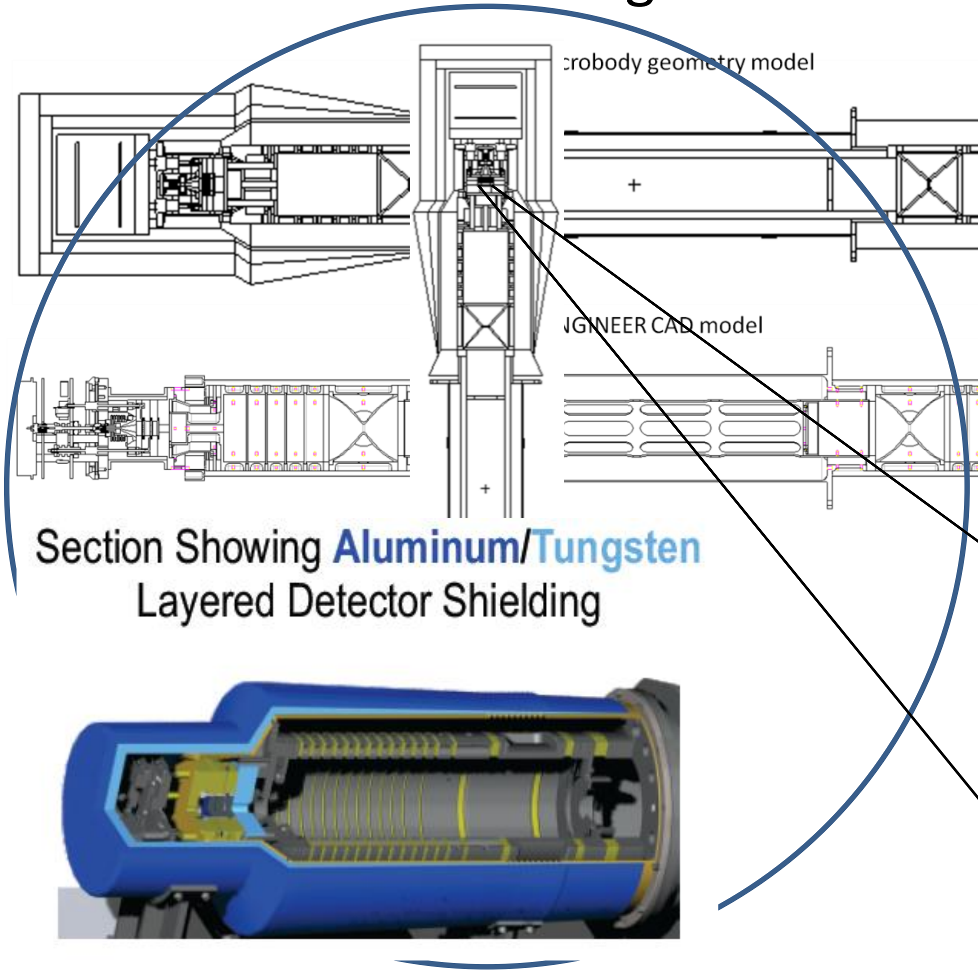
Photon Experimental Summary



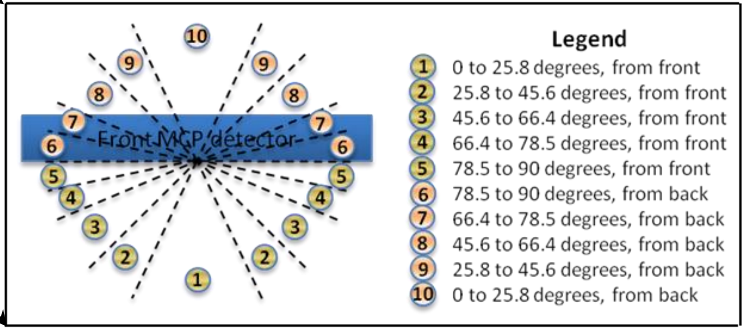
- •Overall trend: detection efficiency decreases as photon energy increases.
- •Discontinuities in this trend (jumps in detection efficiency) are due to the photoelectric effect from materials in the MCP matrix up to about 100 keV.
- •Compton scattering becomes a contributor above the 100 keV energy, but we did not observe much of an effect.
- •Above 1.022 MeV, where pair production can occur, we think we started seeing this effect around 4 to 5 MeV (data point at 5 MeV).
- •We believe this is the first reported effect of pair production observation with MCPs?? Mainly because nobody uses MCPs to measure high energy photons.

R.C. Blase et al., Comparing Measured Photon Detection Efficiencies of Microchannel Plates, to be submitted to *Nuclear Instruments and Methods.*

Modeling the entire shielded instrument



- The shielded instrument model is complex and has high fidelity.
- The shielded instrument is modeled in MCNP6 with a source sphere of electrons.
- Particle arrivals are tallied at the front MCP and binned by both energy and angle.



Noise versus Shield Mass and Its effects on Science Goals (measurements)

Shielding mass and radiation-induced noise (Hz) for a layered Al:HD18 shield at various primary electron spectra (flux curves) for the Europa environment.

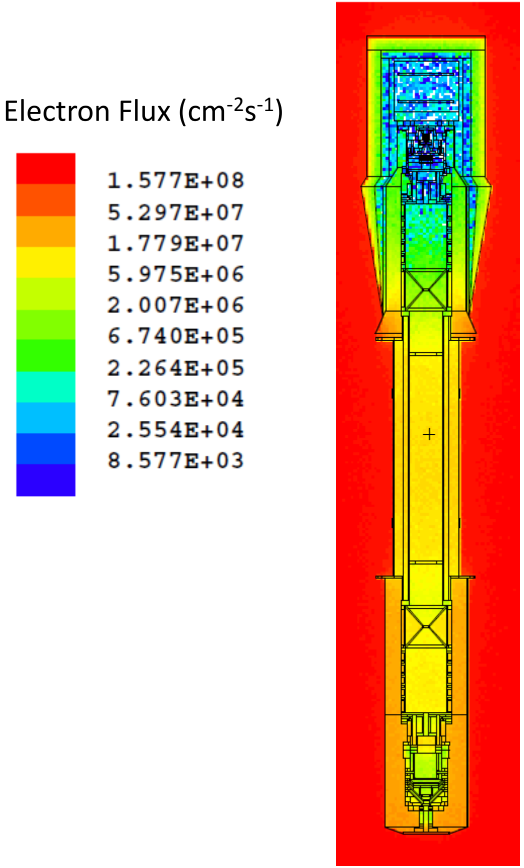
Shield Mass (kg)	Peak Average Flux	E33	E33 Europa Shielded [a]	Apoapsis
3	8,067	5,427	543	15.7
6	3,467	2,336	234	7.7
12	1,757	1,179	118	3.9

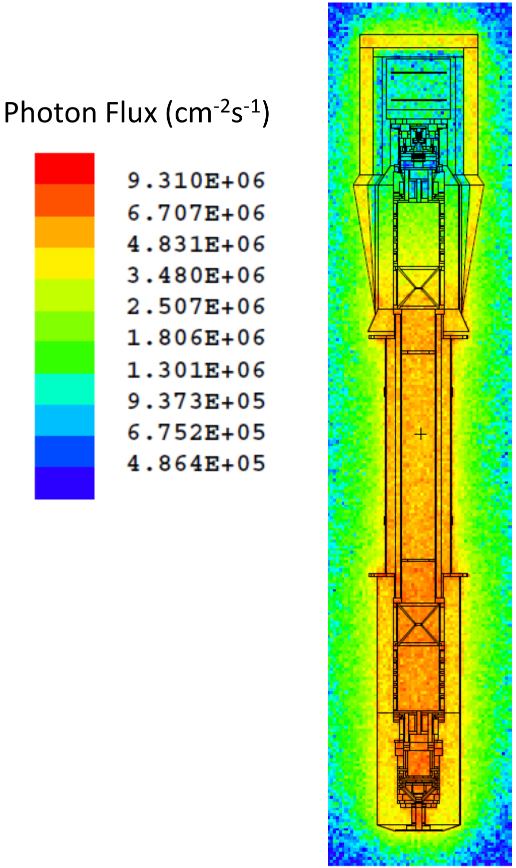
Molecular Density (cm^{-3})	Partial pressure (torr)	Maximum counts at peak centroid	Noise Counts (Hz) where signal is interfered (S/N = 3:1)	Noise Counts (Hz) where signal is interfered (S/N=10:1)
1×10^8	8×10^{-10}	342466	9.13 GHz	2.74 GHz
1×10^5	8×10^{-13}	342.466	9.13 MHz	2.74 MHz
3.5×10^3	2.8×10^{-14}	12	320,000	96,000
5×10^2	4×10^{-15}	1.8	48,000	14,400
1×10^1	8×10^{-17}	0.035	933	280

- Assumptions on calculations:
- Product of molecular density and source sensitivity gives the number of counts per second.
- The digitizer operates at 1.6 Gs/s (0.625 ns) and the mass spectrum spans a time of 50 µs. This gives 80,000 bins in the mass spectrum.
- Noise counts are evenly distributed over the 80,000 bins.
- A typical peak width for MASPEX ion signals is on the order of 6 to 20 ns. For the following calculations, we used an average peak width of 10 ns (16 bins).

With no radiation shield, all potential measurements below the green line would not be attainable.

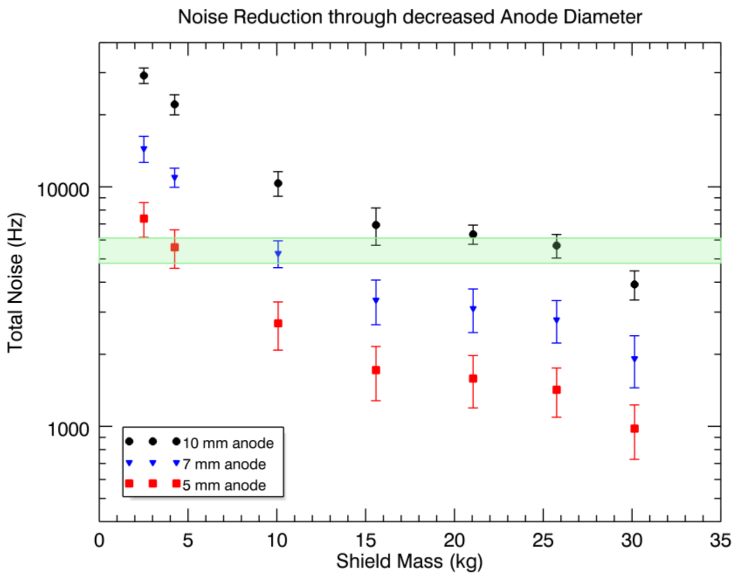
Mesh tallies in MCNP6 for particle visualization





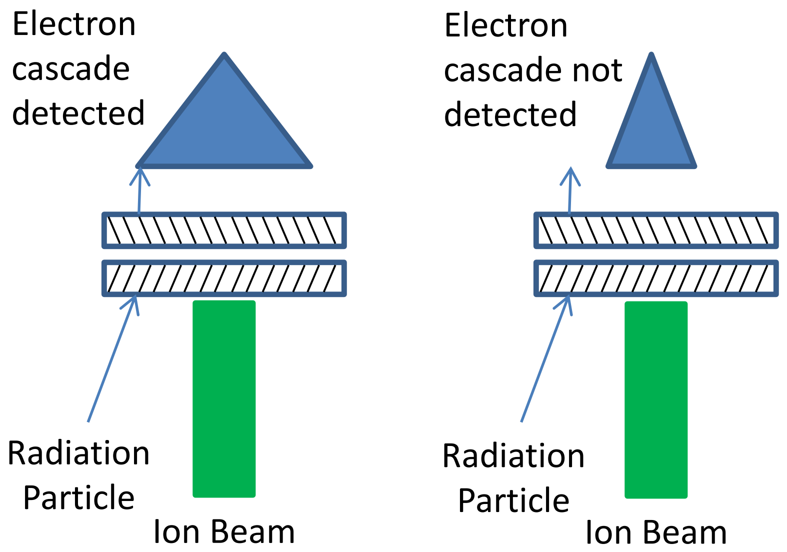
Mesh tallies show where the photons and electrons are (fluxes). Provides a “look” at where the particles are going.

Other Ways to Reduce Radiation-Induced Noise

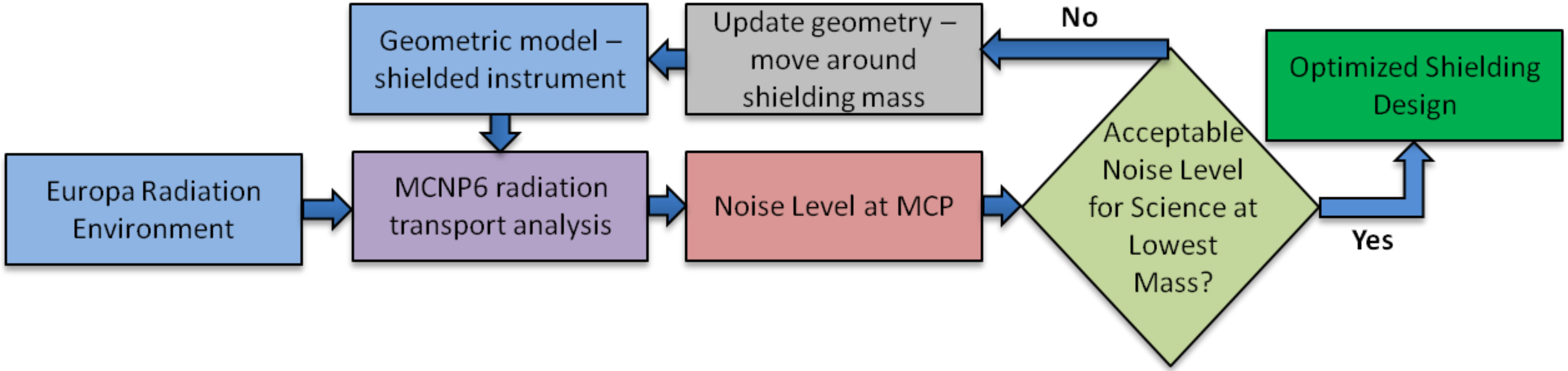


Noise versus shield mass from peak average flux Europa spectrum for three different anode diameters.

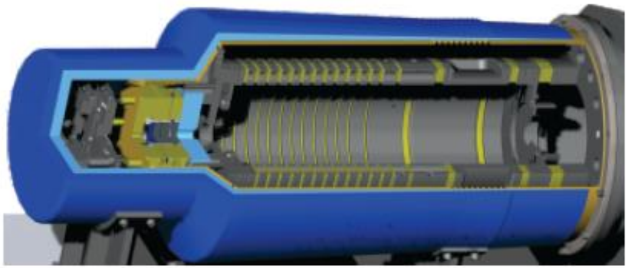
- Reduction in anode diameter reduces the radiation-induced noise by the factor r^2.
- Reduce the anode diameter as much as possible while maintaining detection of the ion beam.

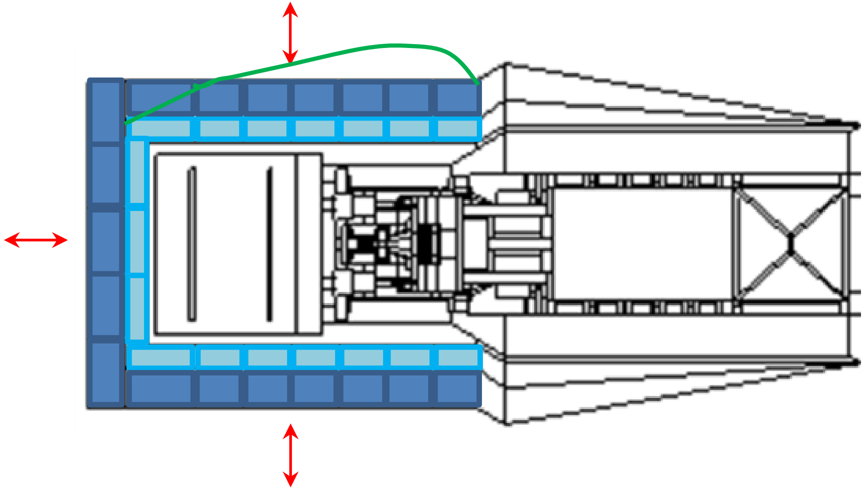


Current Work: Optimization of the Shield Design



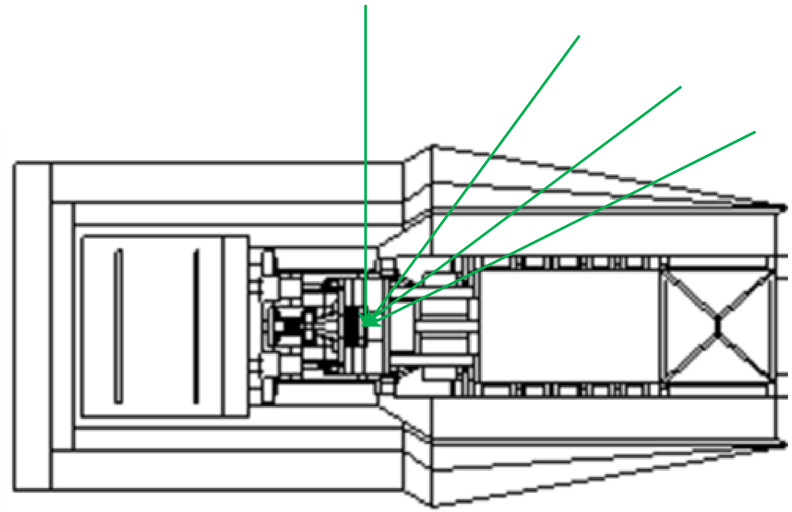
Section Showing **Aluminum**/**Tungsten** Layered Detector Shielding





Future Work: Irradiation of Shielded MCP to confirm MCNP6 simulation results

- Construct a shield around the MCP and back-half portion of the instrument and irradiate the shielded geometry at different angles and energies and compare with MCNP6 simulations for the geometry to confirm MCNP6 simulation results for the shielded instrument at Europa.



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•Tim Brockwell – Deputy PI, Instrument Scientist for MASPEX/Europa

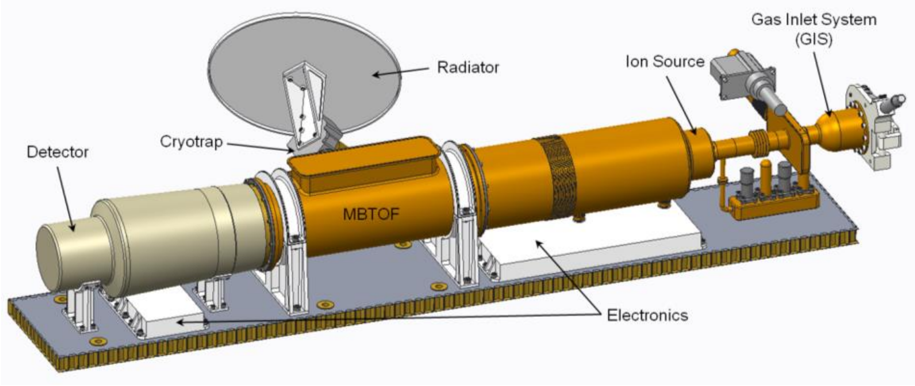
•Paul Wilson IV – Program Manager, MASPEX/Europa

•Greg Miller – Ion Optics Guru, Optics and Calibration Lead, MASPEX/Europa

•John Roberts – Mechanical Engineer, MASPEX/Europa

•Keith Pickens – Systems Engineer on MASPEX

•Roland Benke – now at Atom Consulting, LLC – colleague for all experiments presented



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