Restoring High-Resolution Electron Spectra from the CASSIOPE/e-POP Suprathermal Electron Imager

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Department of Physics and Astronomy

Acknowledgments:

- The work was supported by the Canadian Space Agency
- e-POP team produced a new quaternions data product to support the project

DASP Workshop 2024, February 20 – 23, 2024

Introduction

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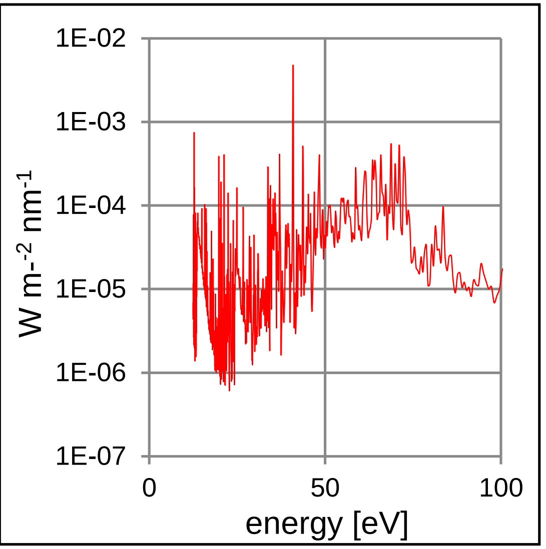
15.4 (3.8 Lyman Alpha) mW/m²



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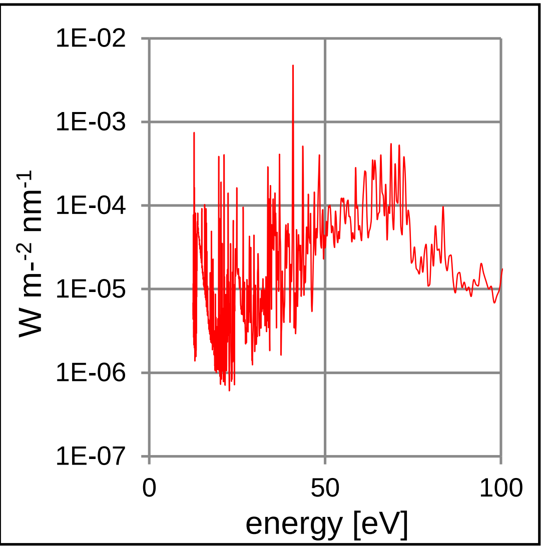

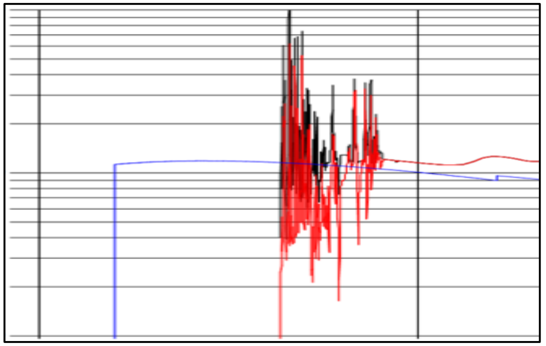

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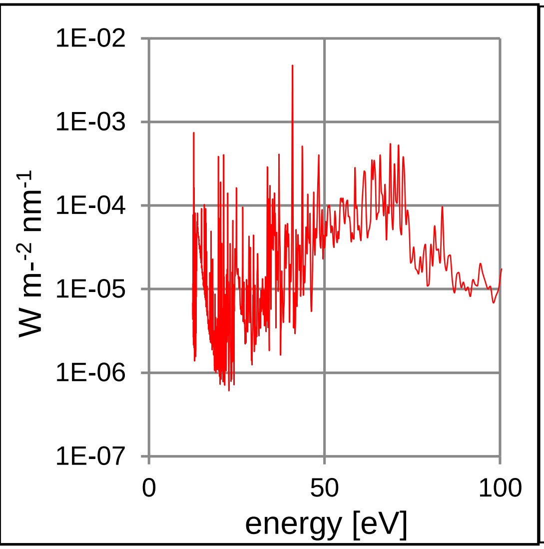
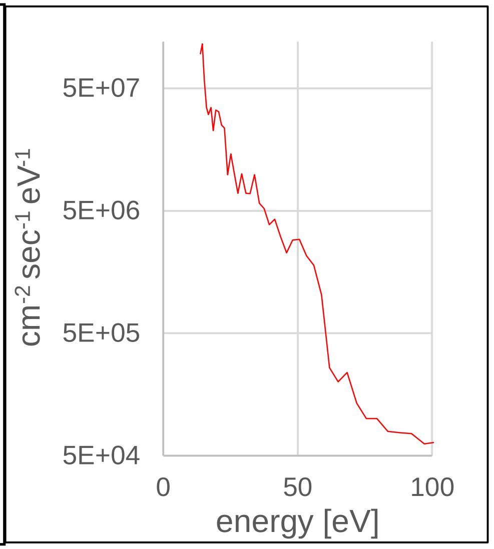
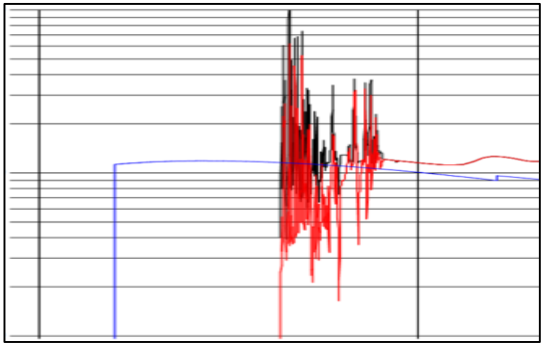
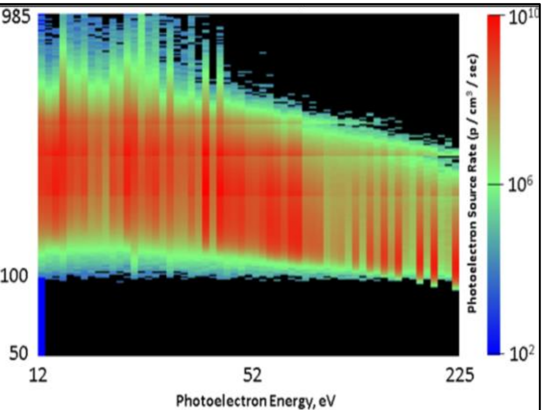


Photoelectron Spectrum







Plasma Factory: Photoelectron Production & its Spectra Altitude Profile.

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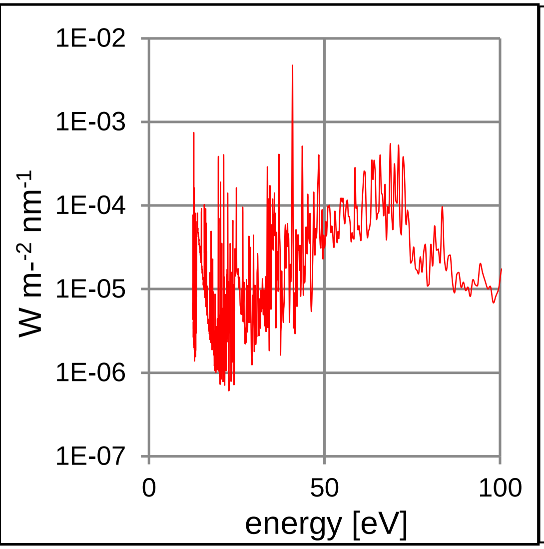

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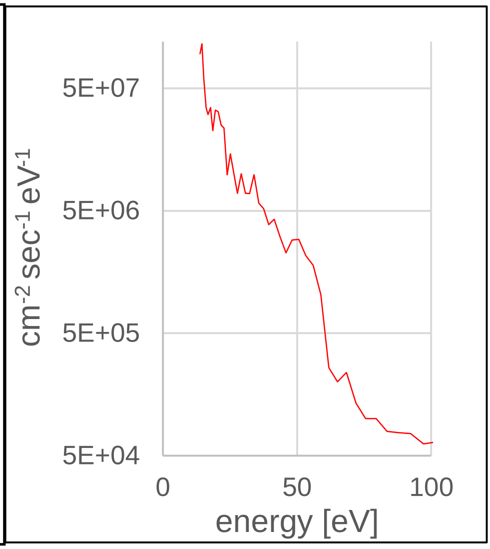
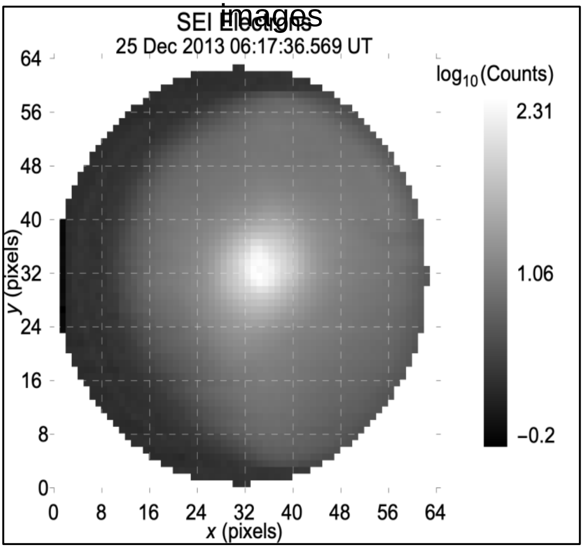
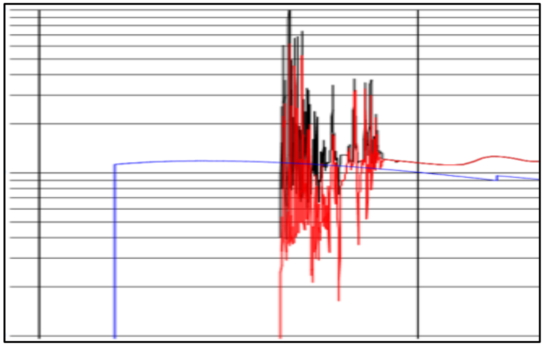
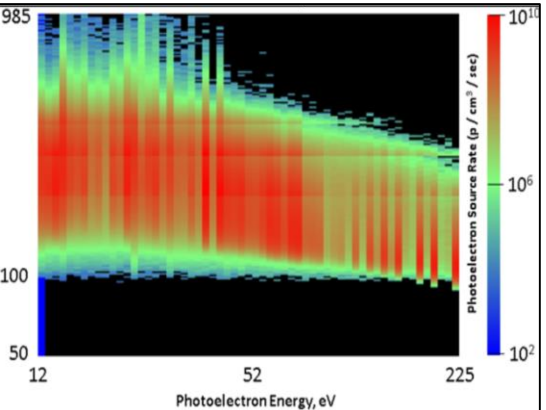


An average of 100 SEI images







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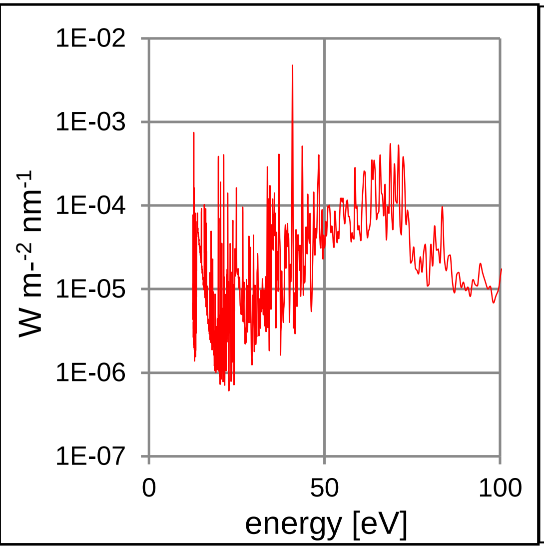

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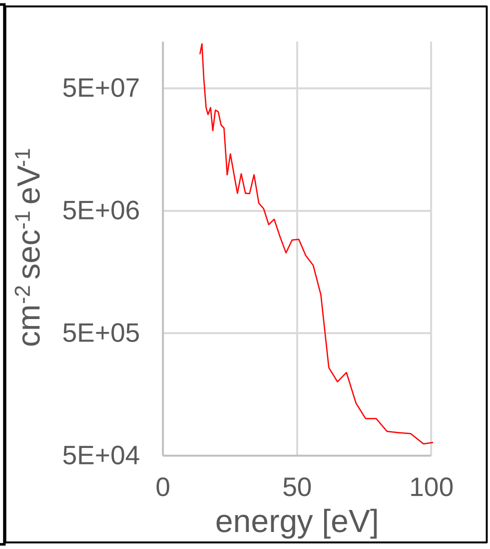

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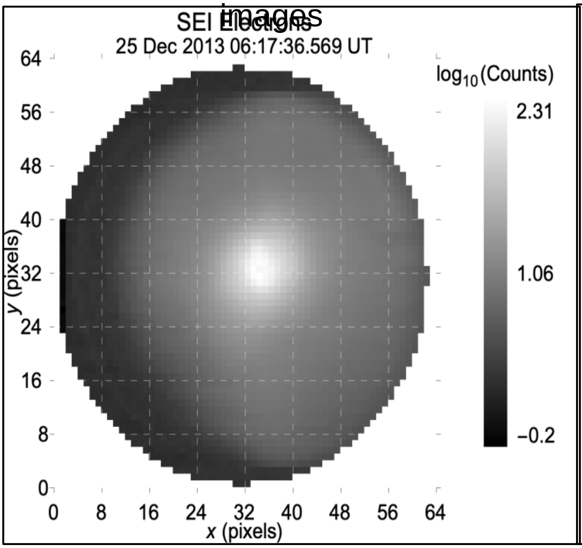
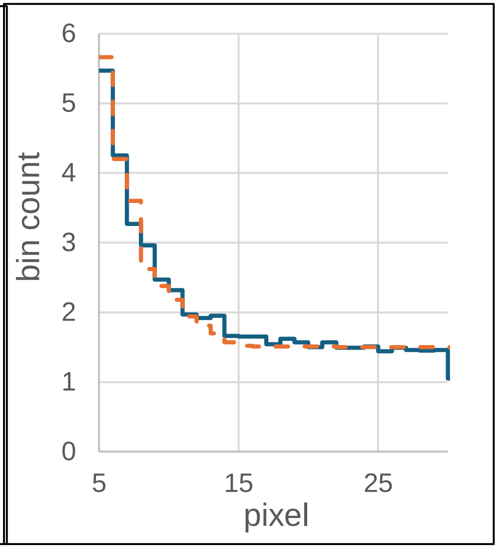
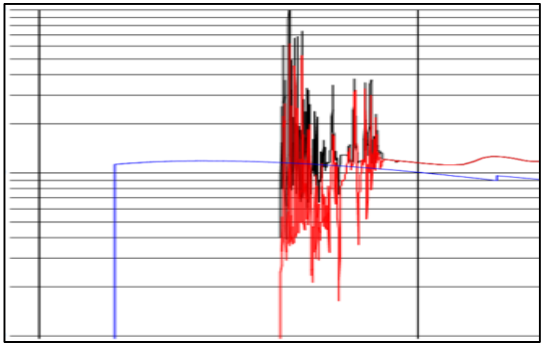
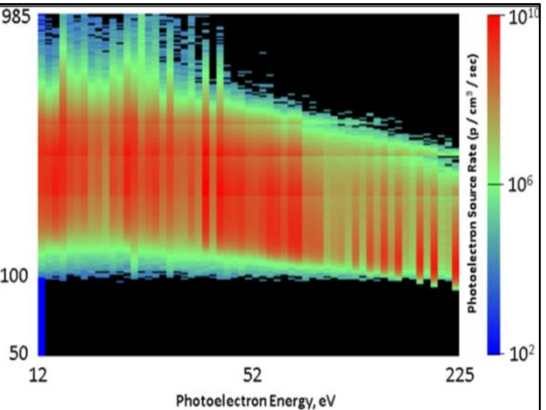


Convoluted Electron Spectra







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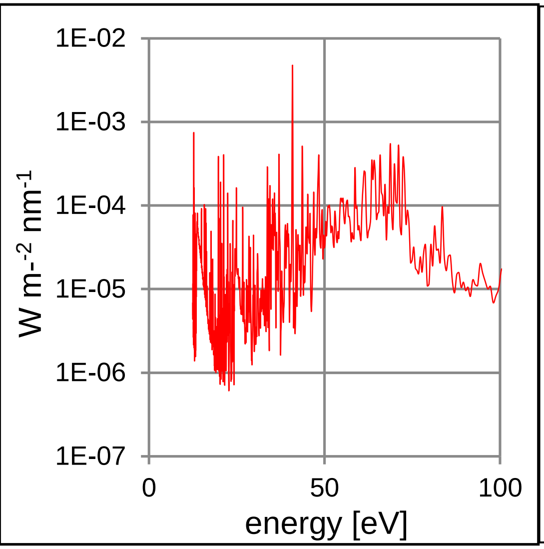

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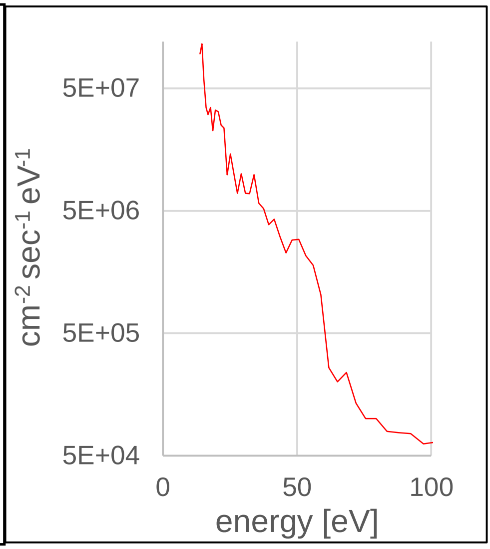

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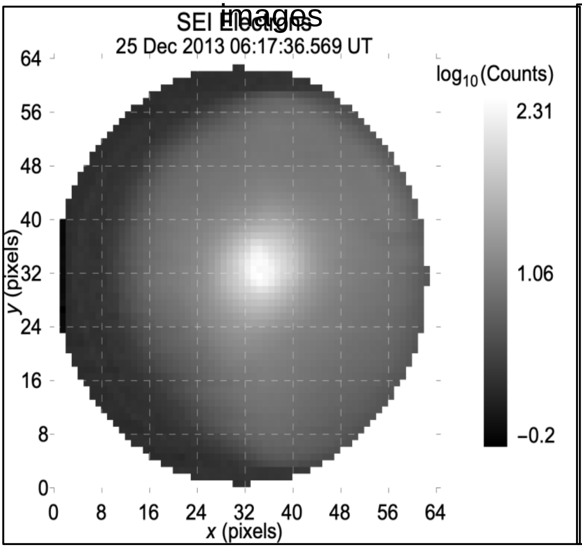

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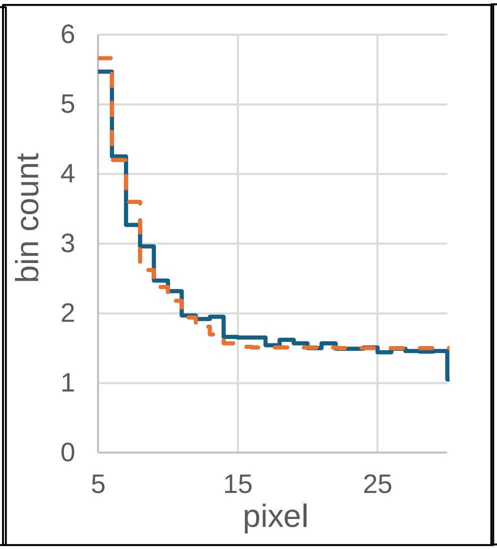
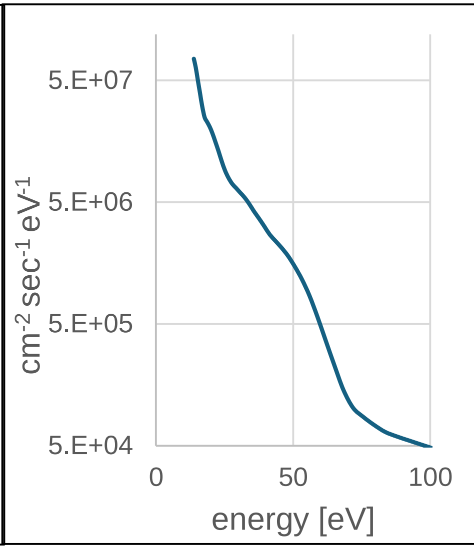
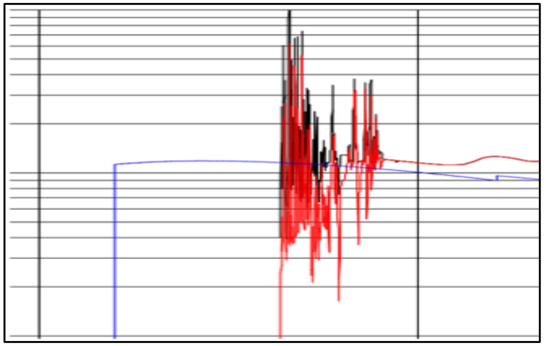
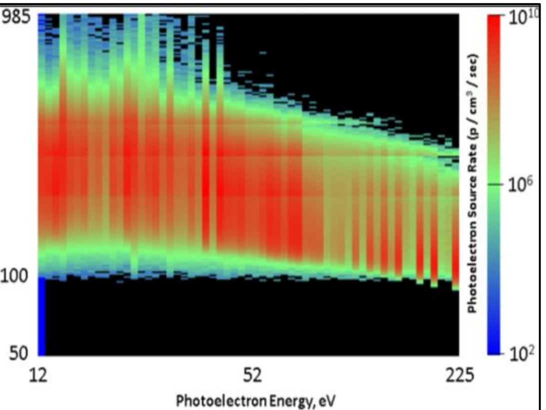


Deconvoluted Electron Spectrum







Plasma Factory: Photoelectron Production & its Spectra Altitude Profile.

Deconvolution an Electron Spectrum from an SEI Image Based on the **Point-Spread Functions**:

1. Debye Shielding of the SEI Instrument by its high negative voltage (strongly-coupled plasma).
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3. Photoelectron propagation in the SEI strong electric field.

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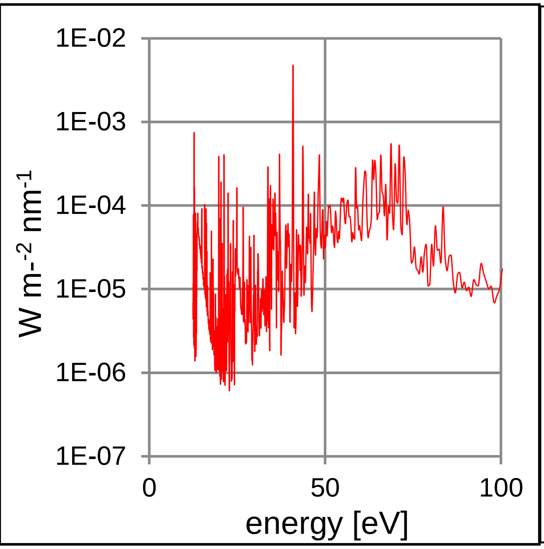

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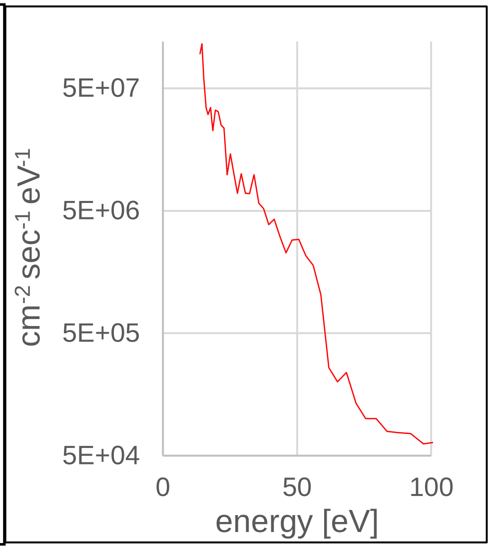

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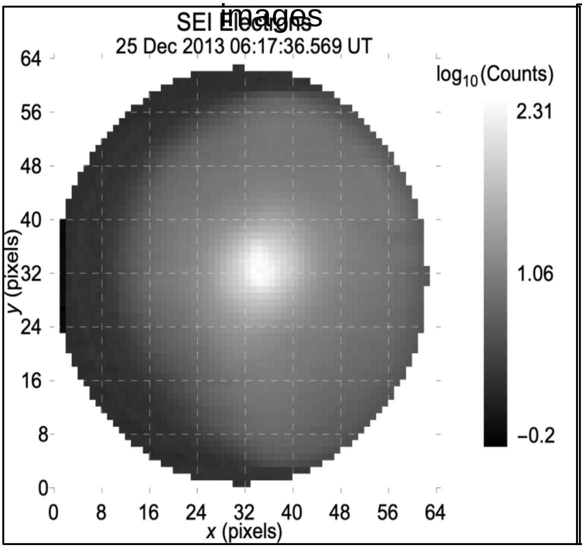

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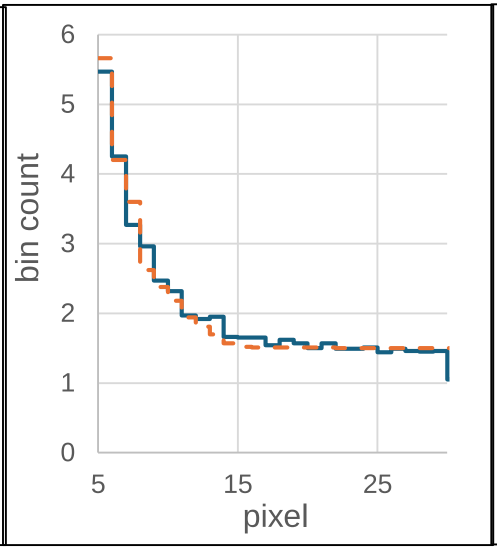

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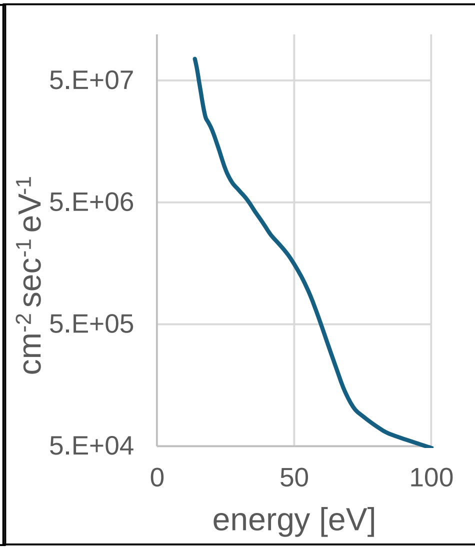

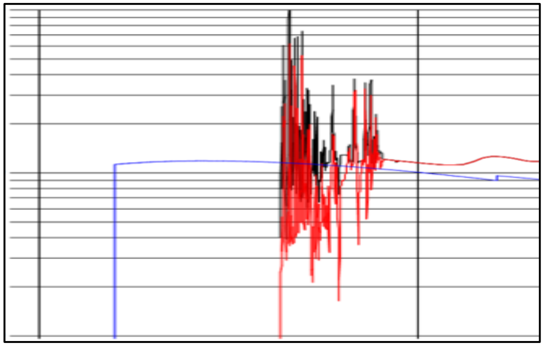

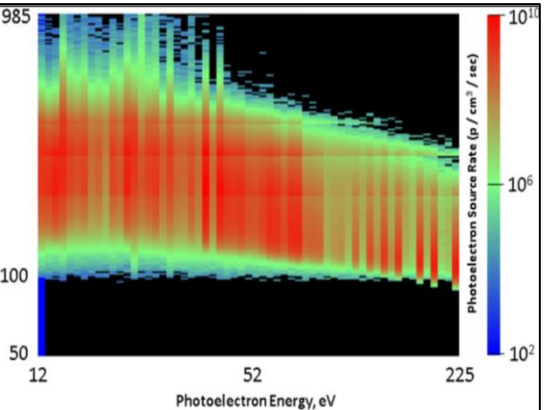

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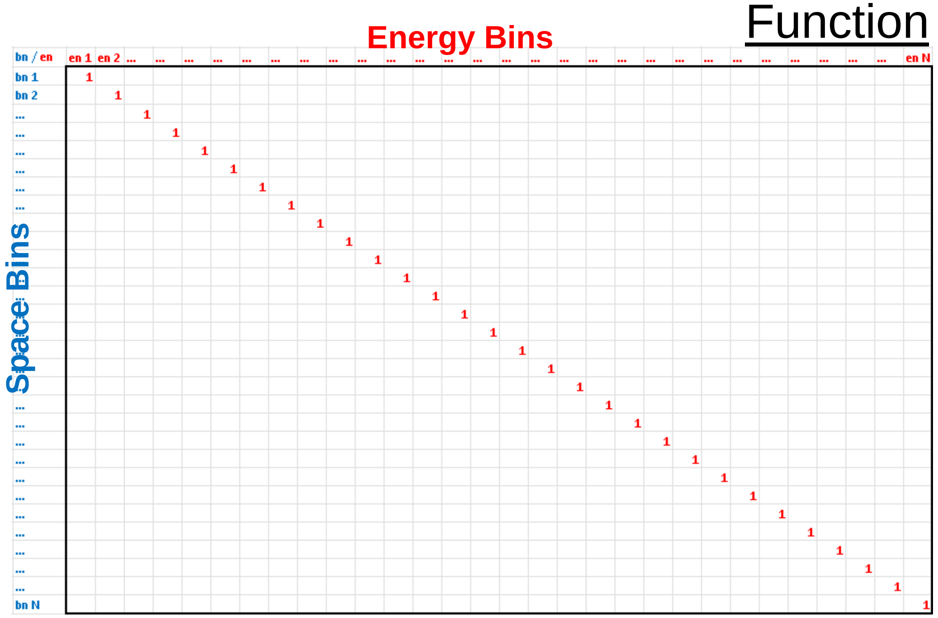
Satellite potential is CRUCIAL

for the **Point-Spread Function** reliable calculations:

Particle Analyzers

Particle Analyzers

Electrostatic Analyzer: Point-Spread Function



Energy Bins

Space Bins

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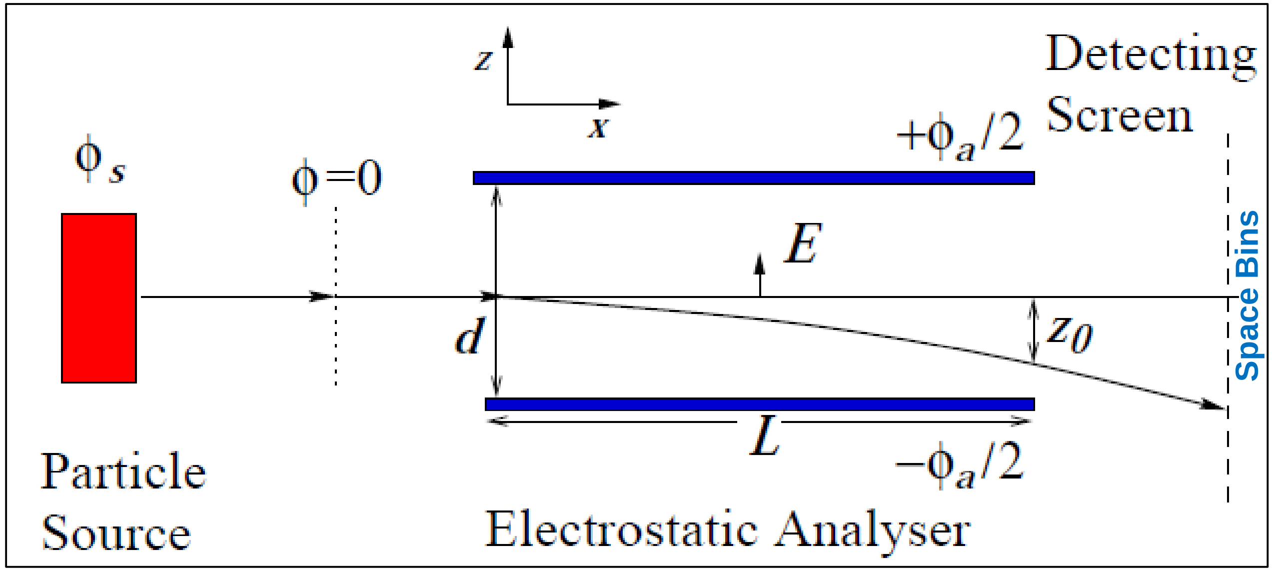
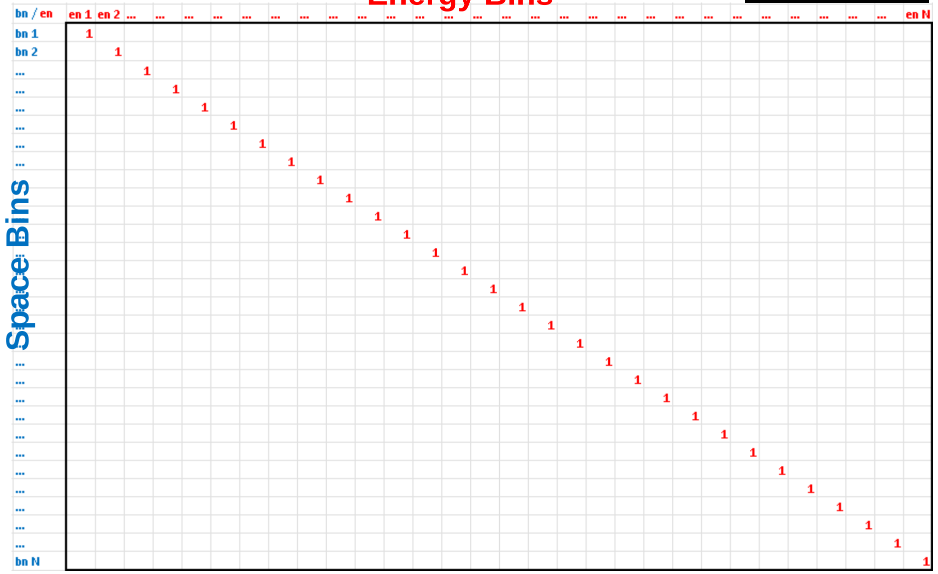


Particle Energy

$$z_0(W) = \frac{1}{4}\frac{qE}{W}L^2$$

Particle Analyzers

Electrostatic Analyzer: Point-Spread Function



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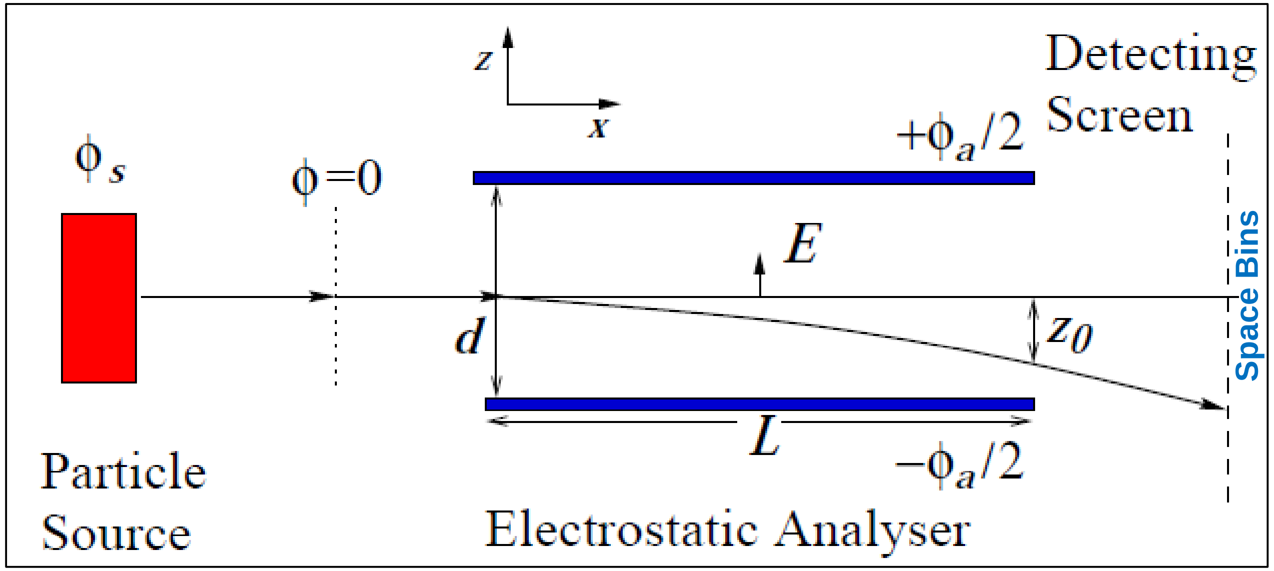

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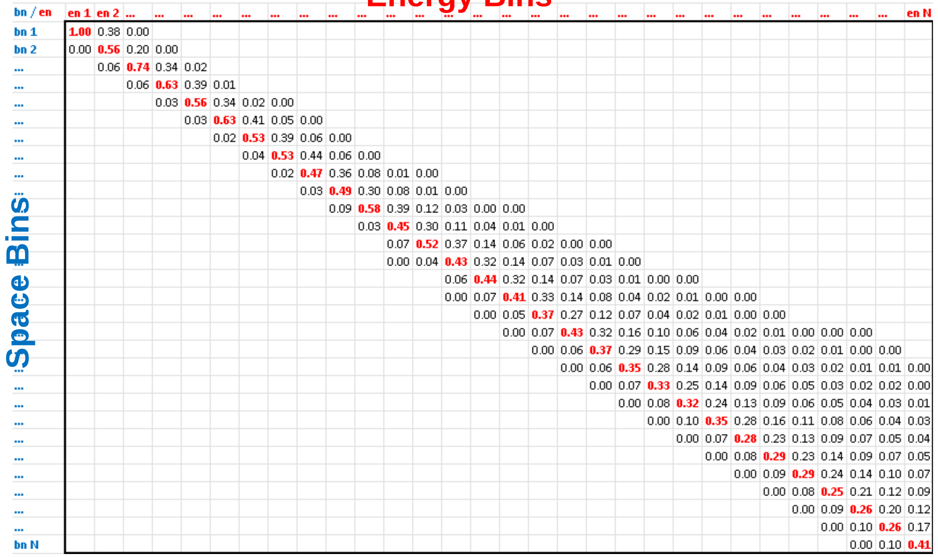

Energy Bins

Space Bins

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...												0.00	0.04	**0.43**	0.32	0.14	0.07	0.03	0.01	0.00									
...														0.06	**0.44**	0.32	0.14	0.07	0.03	0.01	0.00	0.00							
...														0.00	0.07	**0.41**	0.33	0.14	0.08	0.04	0.02	0.01	0.00	0.00					
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...																	0.00	0.06	**0.37**	0.29	0.15	0.09	0.06	0.04	0.03	0.02	0.01	0.00	0.00
...																		0.00	0.06	**0.35**	0.28	0.14	0.09	0.06	0.04	0.03	0.02	0.01	0.01	0.00
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...																						0.00	0.07	**0.28**	0.23	0.13	0.09	0.07	0.05	0.04
...																							0.00	0.08	**0.29**	0.23	0.14	0.09	0.07	0.05
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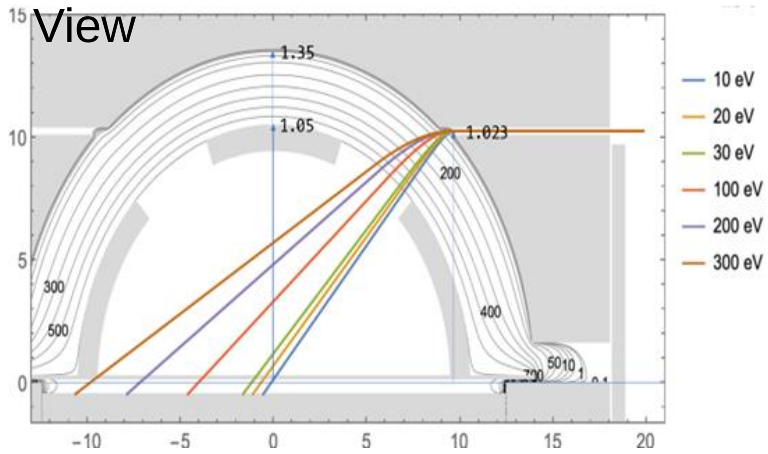
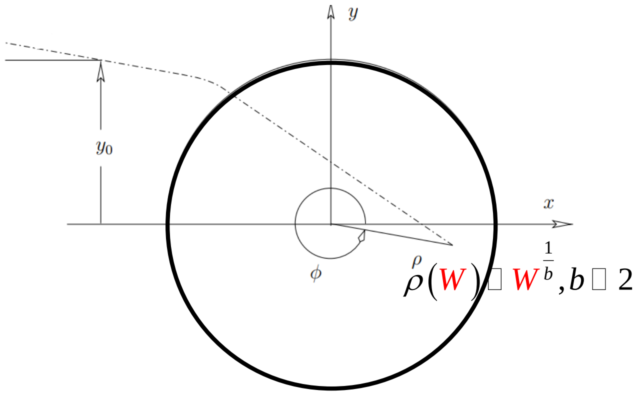
Whalen Analyzer Side-View



Side-view section (x − z plane) with **on-axis** particle trajectories of different energies.

Whalen Analyzer Top-View

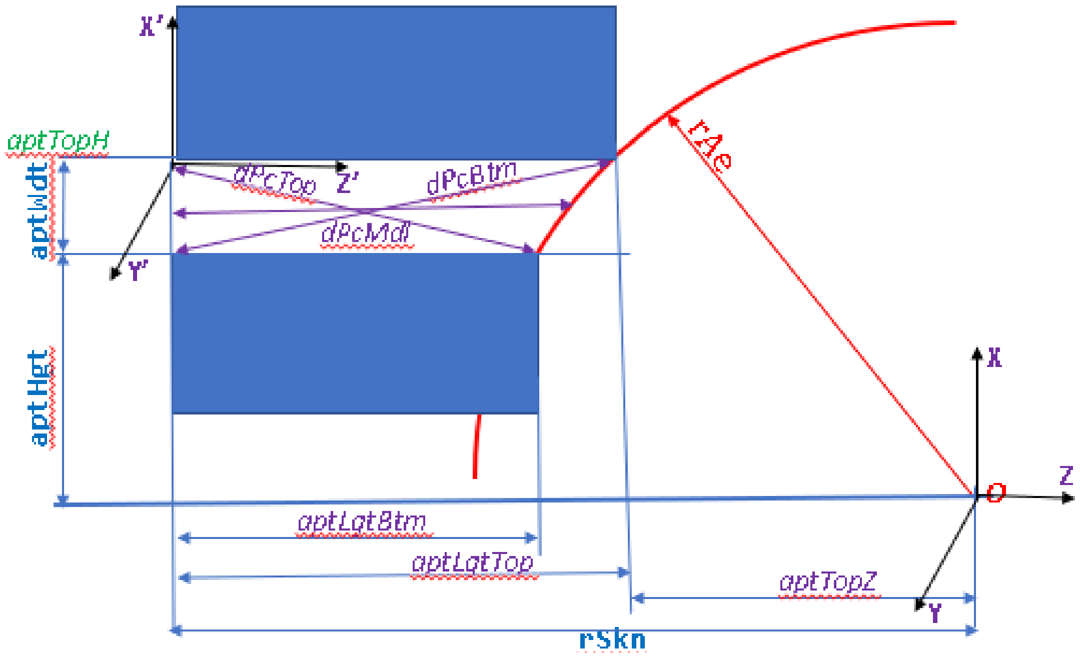


$$\rho(W) \propto W^{\frac{1}{b}}, b \approx 2$$

Top-view section (x − y plane), with a sample **off-axis** particle trajectory indicated by the dot-dashed line.

Knudsen, at al., 2015, “*The CASSIOPE/e-POP suprathermal electron imager (SEI)*”

Collimator Angular Distributions at the Detector Aperture



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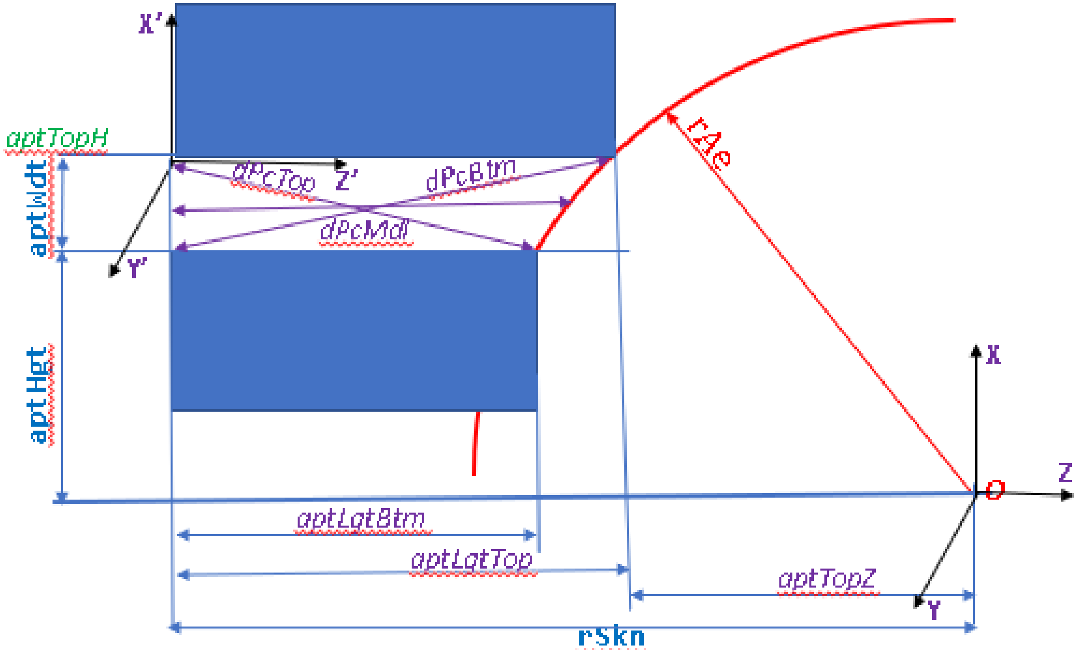

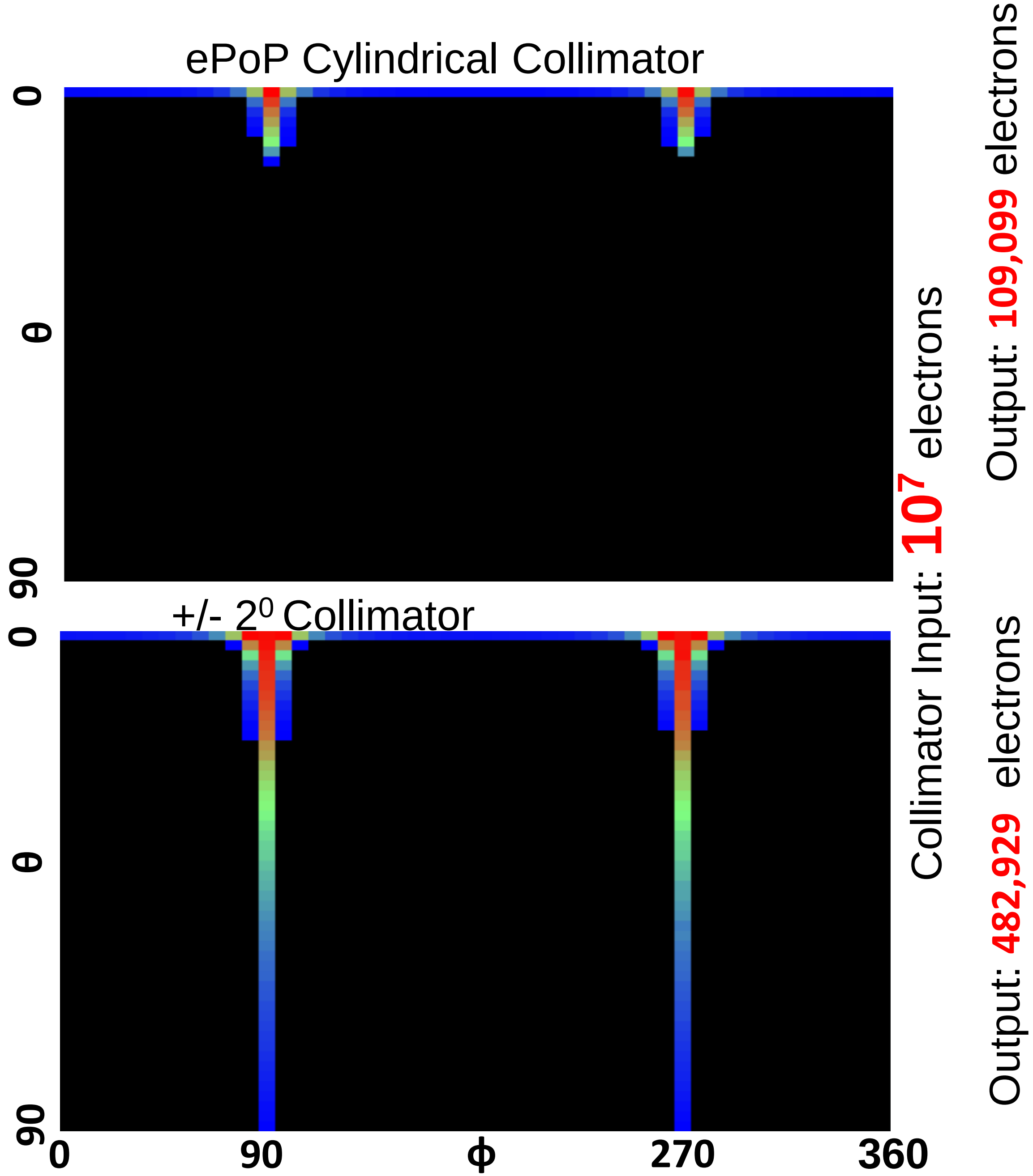

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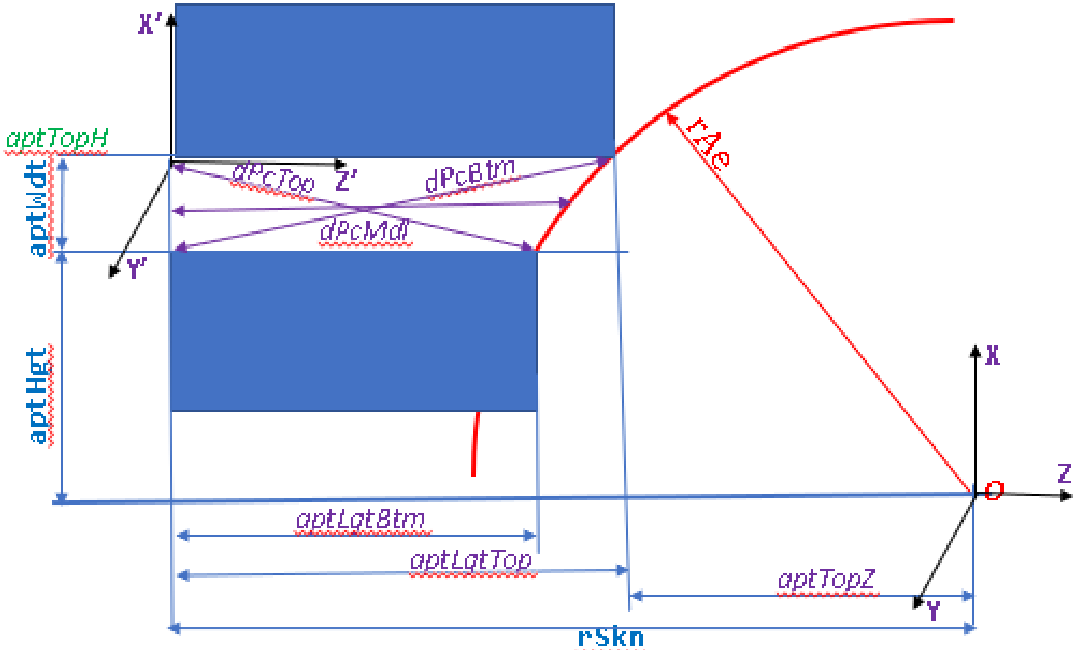
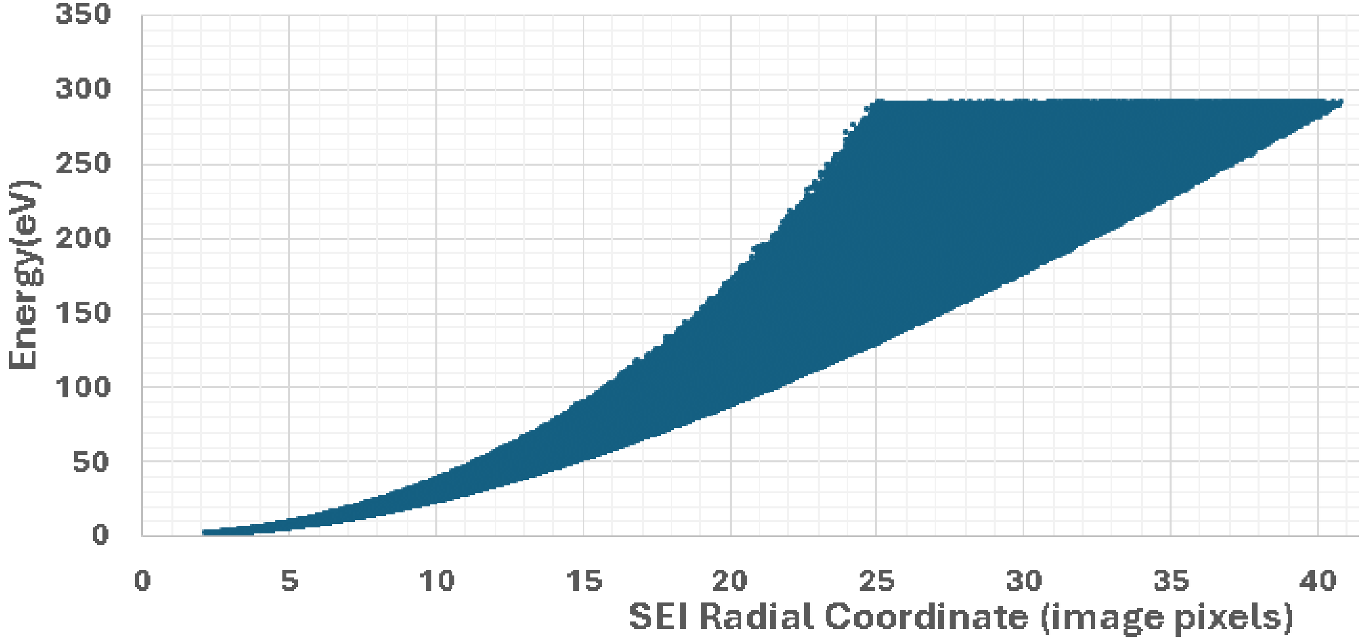
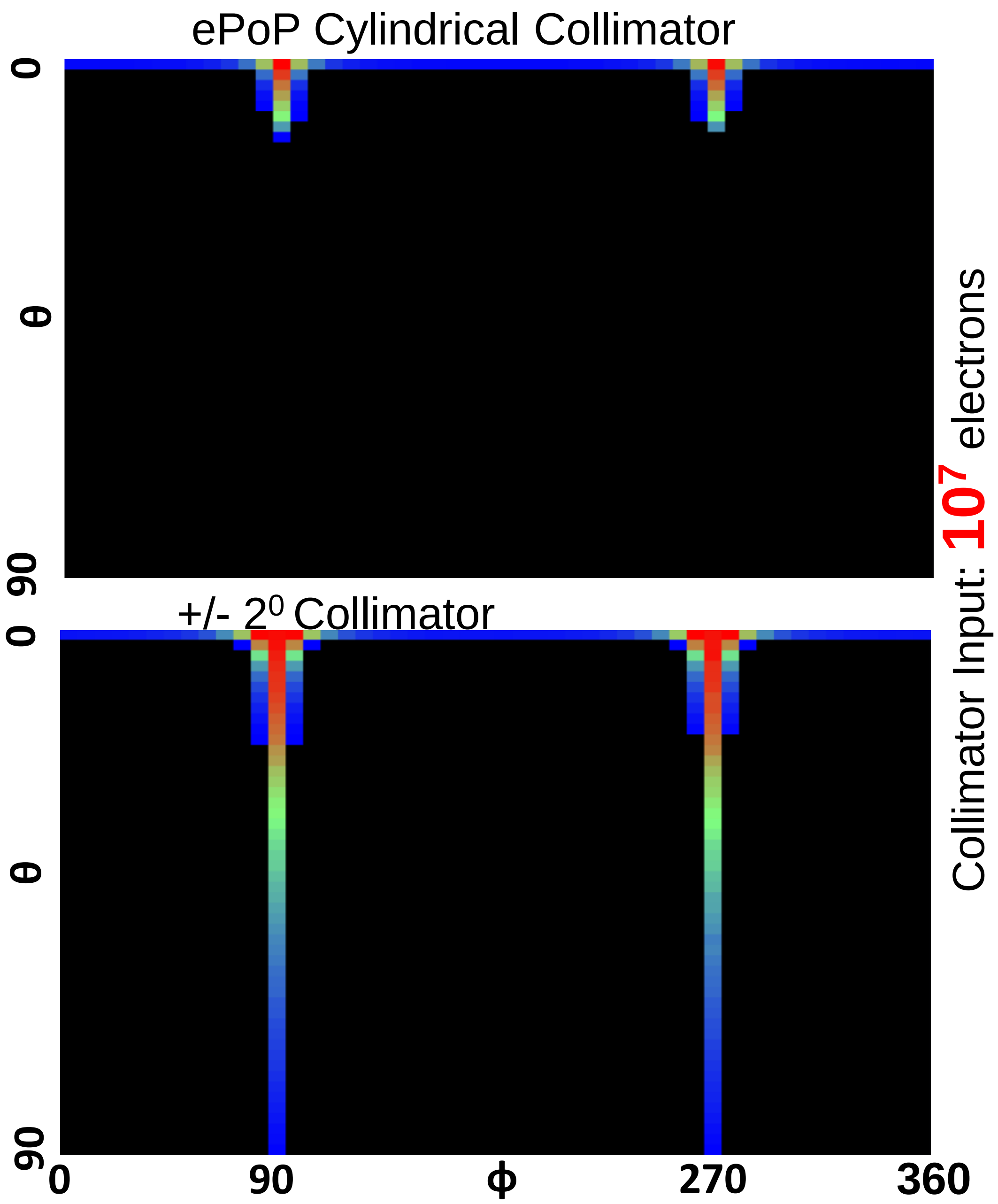






Collimator Input: 10^7 electrons

Output: 109,099 electrons

Output: 482,929 electrons

SEI Shielding in the Strongly Coupled Plasmas

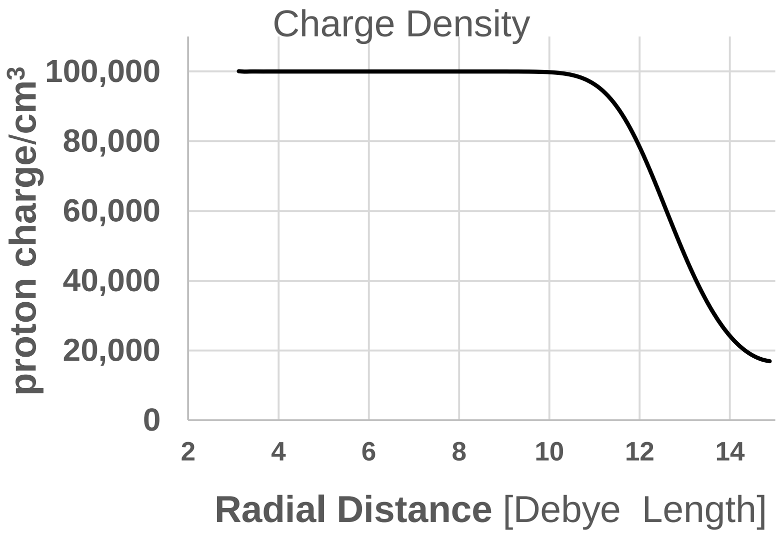
Poisson–Boltzmann equation in vector form:

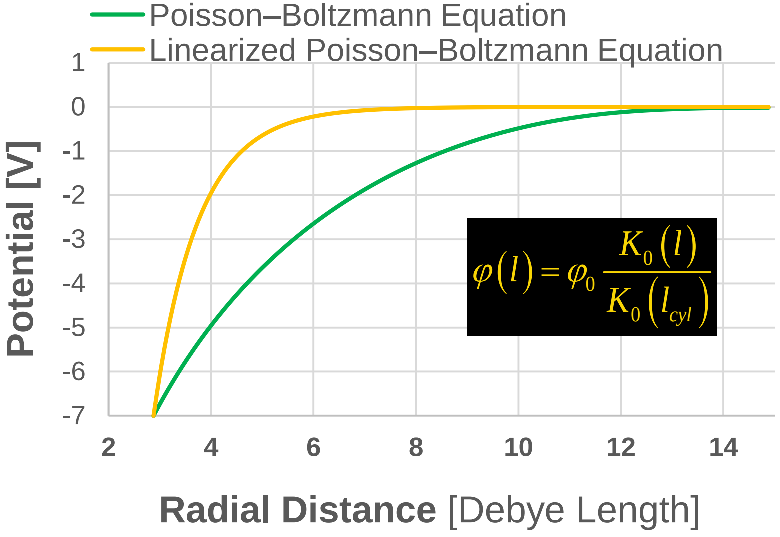
$$\nabla^2\varphi(\vec{r})=4\pi e n_0\left(\exp(\chi)-1\right), \chi=\frac{e\varphi(\vec{r})}{k_BT}<0$$

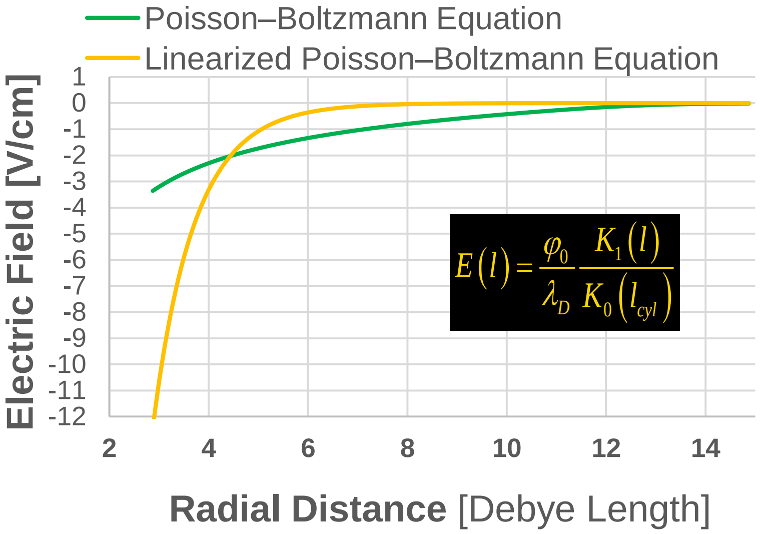
Parameter	Value
Electron Temperature	900 K
Plasma Density	100,000 cm-3
Debye Length	0.6547 cm
Cylinder (SEI) Radius	1.8825 cm
Cylinder Potential	-7 Volt

Poisson–Boltzmann equation in cylindrical coordinates:

$$\frac{d^2\chi(l)}{dl^2}+\frac{1}{l}\frac{d\chi(l)}{dl}=e^{\chi(l)}-1; l=r/\sqrt{\frac{k_BT}{4\pi e^2 n_0}}$$

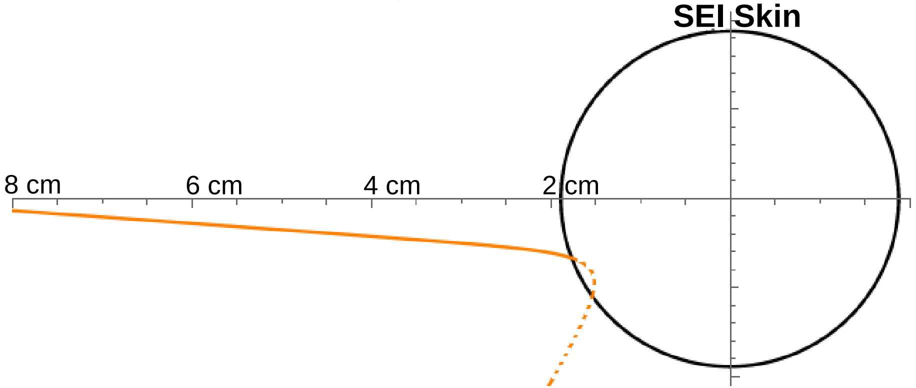






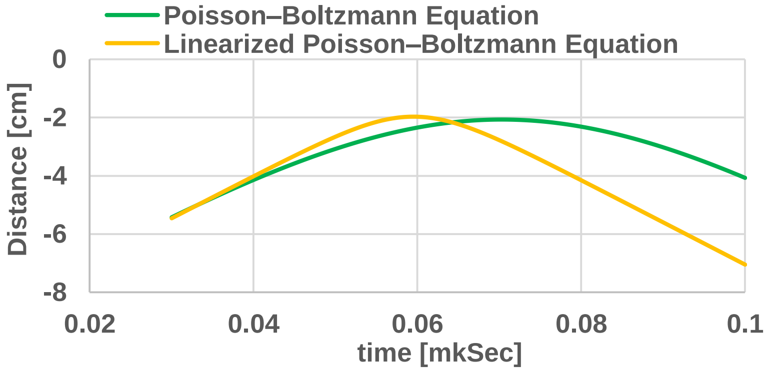
Linearized Poisson–Boltzmann Equation

15 eV, 230 cm/μS



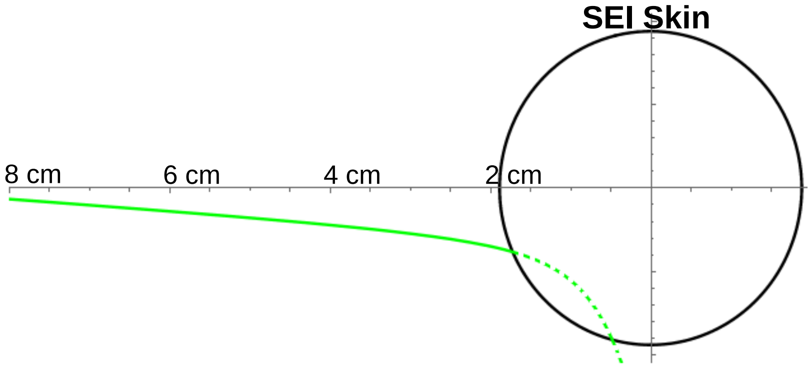
Electron Trajectories in the SEI Electric Field

7 eV, 157 cm/ μS



Exact Poisson–Boltzmann Equation

15 eV, 230 cm/ μS



Electrons Deflection by the SEI Skin External Electric Field

Conservation of Density in Phase Space, or the Liouville Theorem: The distribution function is **constant** along any trajectory in phase space in the incompressible dynamical systems.

Lemma: Electron probability to hit the detector Eff_{Cyl} *for the* **isotropic** incoming electron flux in the **infinite** cylindrical geometry depends on the electron initial **energy** w and the probe **potential** φ (in respect to the ambient plasma) and **does not depend** on the **shape** of the electric field:

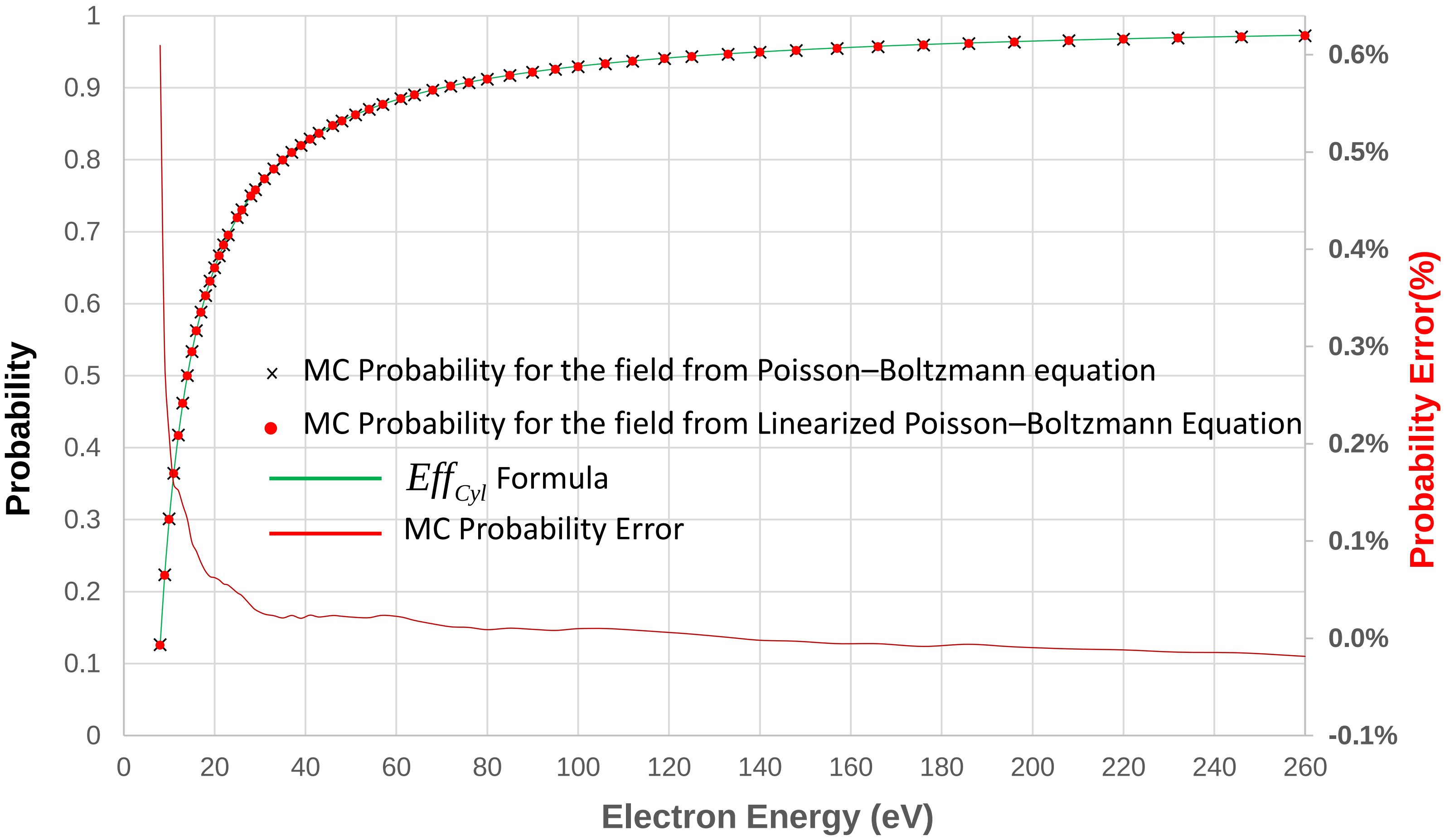
$$Eff_{Cyl} = \frac{\int_{2\pi} I_{\hat{\Omega}}(w,\varphi)\,\vec{j}\left(\hat{\Omega}\right)\cdot\hat{n}\;d\hat{\Omega}}{\int_{2\pi} \vec{j}\left(\hat{\Omega}\right)\cdot\hat{n}\;d\hat{\Omega}} = \ldots = 1-\frac{e\cdot\varphi}{w},\ w\in[e\cdot\varphi..\infty]$$

where $\hat{\Omega}$ is a unit vector of an electron direction, $\vec{j}$ is an external electron current density entering a cylindrical region, $\hat{n}$ is a normal vector to the surface of a cylinder and $I_{\hat{\Omega}}(w,\varphi)$ is an indicator function that maps elements of directions to **one** if electron with energy w hit the detector in the presence of the electric field, and **zero** for the rest of directions.

Prove Idea: The derivation for the probability to hit the detector assumes that any final direction at the collimator entrance at a given energy has the same probability (or distribution, according to the Liouville Theorem), except **prohibited** final directions, when electron can't penetrate sensor's electric field if it's traced back to space.

Compare with Mott-Smith and **Langmuir**, **1926**,"*The Theory of Collectors In Gaseous Discharge*":
"*Special properties of the Maxwellian distribution: If the sheath has **axial symmetry** so that the equipotentials are coaxial circular cylinders, it is found from **simple mechanical principles** that the **condition** for a positive or a negative ion **to reach the collector depends not upon the nature of the field of force along the whole orbit**, but **only** upon the **initial** and **final potentials** and the **initial velocity** of the ion on entering the sheath*".

MC Simulations of Electron Probability to Hit Detector



MC Simulation Parameters	Value
Electron Temperature	**900** K
Plasma Density	**100,000** cm-3
Debye Length	**0.6547** cm
Cylinder (SEI) Radius	**1.8825** cm
Cylinder Potential	**-7** Volt

Leap-Frog trajectory calculations of isotopically distributed electrons coming from infinity and propagation in the radial electric field of the infinite right cylinder with the radius 1.8825 cm, electric potential -7[V], and plasma parameters from the table. Ten million electrons for each of 59 energies ranging from 8 to 260 eV were traced for two electric field models applied: One for the solution of the Poisson–Boltzmann equation , and one for the solution of the linearized Poisson–Boltzmann equation.

Conclusions

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1. Photoelectron Production and Transport First-Principles Calculations:

**** Plasma Factory ****

Done.

Not Covered in DASP-2024

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2. Debye Shielding in the Strongly Coupled Plasmas:

**** SEI Point-Spread Function ****

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Will be Presented Tomorrow

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**** SEI Photoelectron Spectra Deconvolution ****

Work in progress:

Satellite Potential Needed …

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4. A photoelectron model may help to explain the need in practice for a large negative faceplate bias to enable estimation of ion density

**** Satellite Instrument Shielding in the Strongly Coupled Plasma ****

Work in progress:

Satellite Potential Needed …