

Neighboring Spacecraft Charging due to Continuous Electron Beam Emission and Impact

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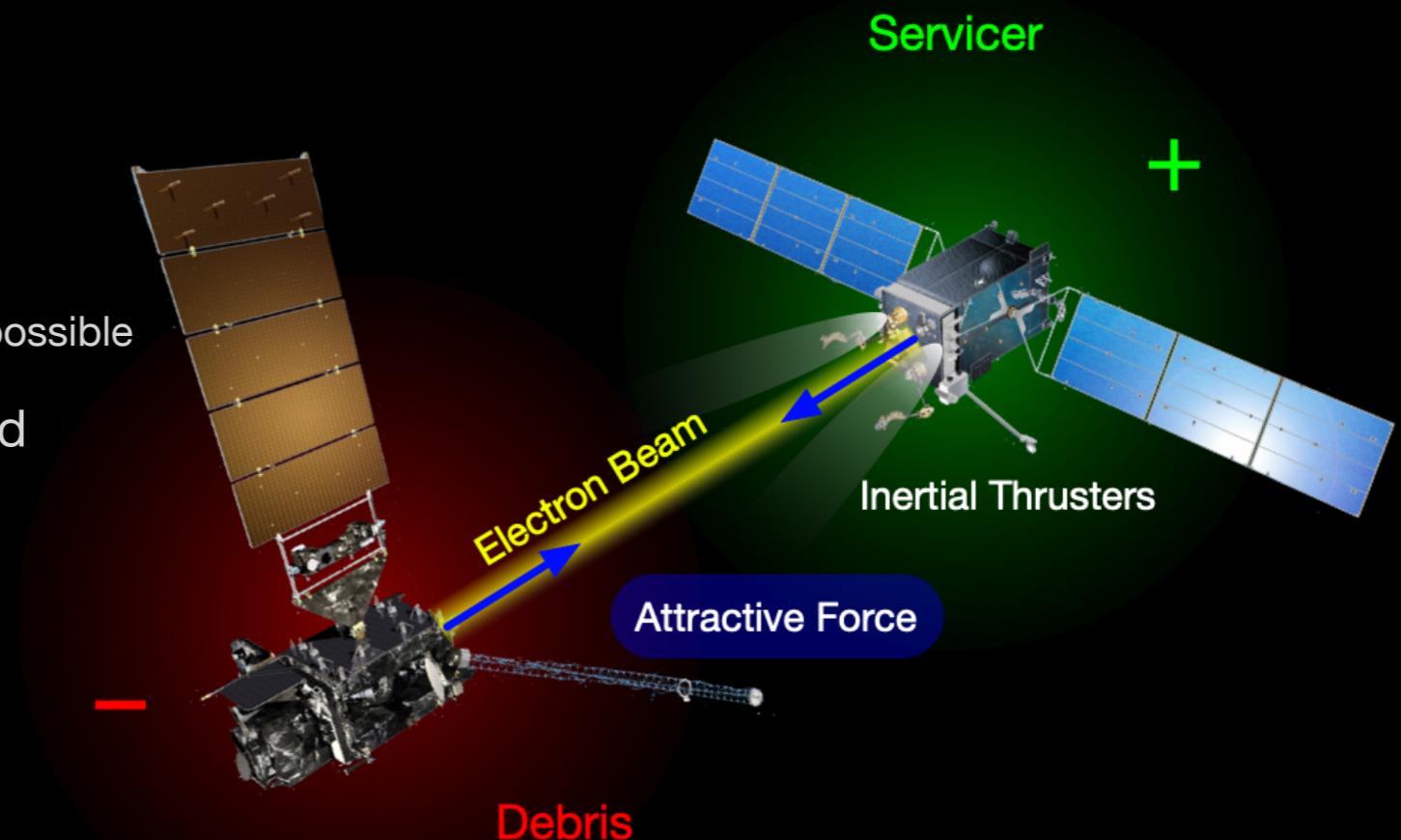
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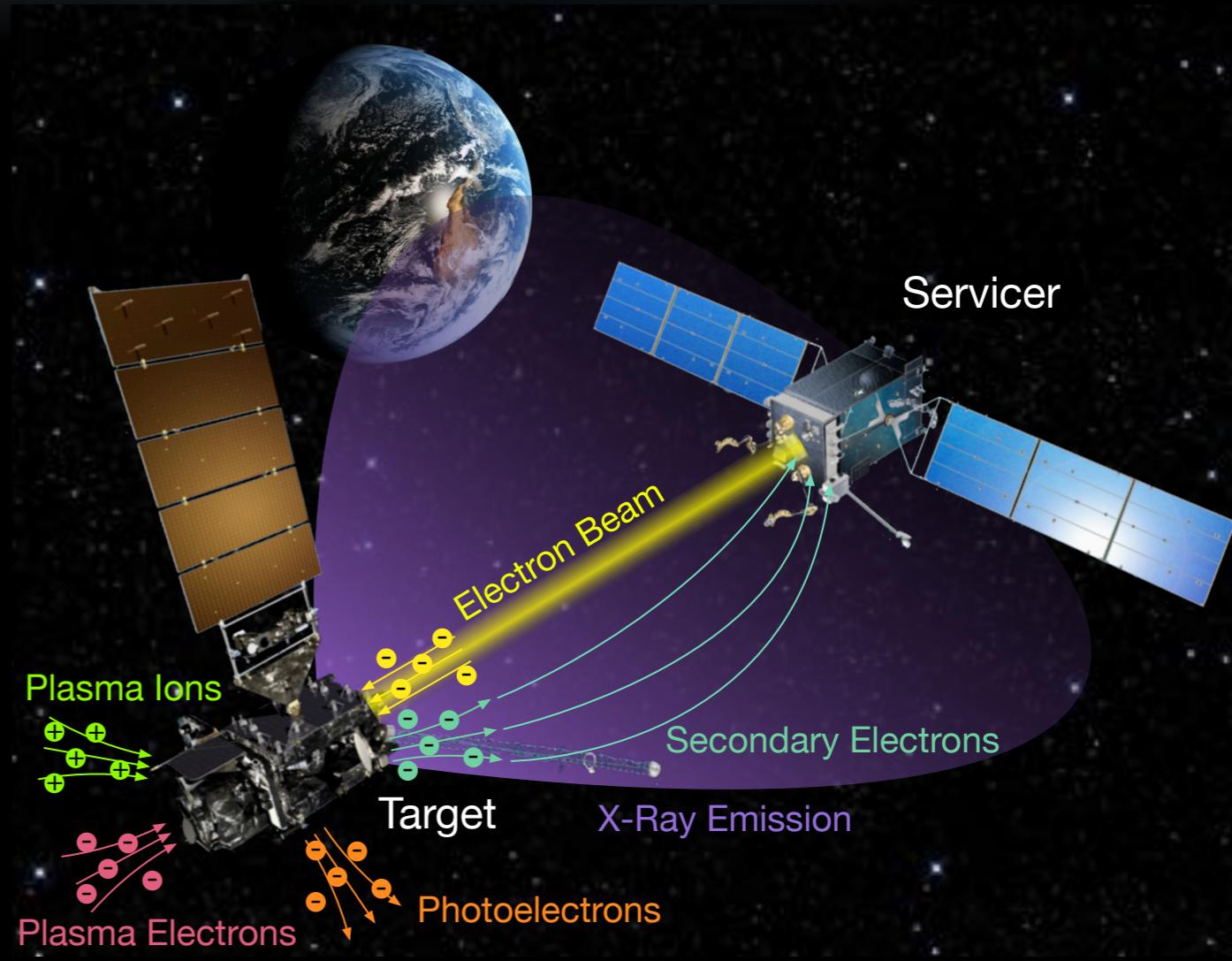
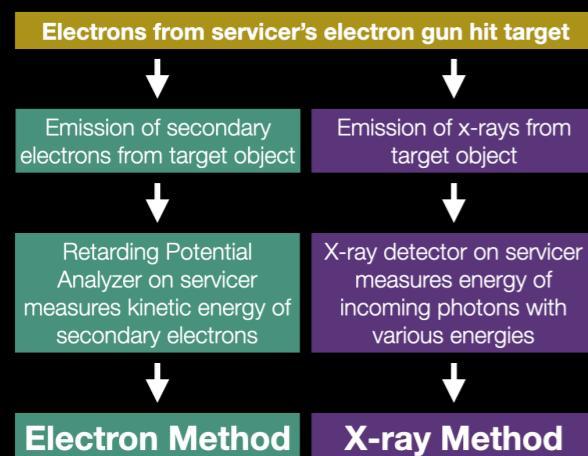
Electrostatic Tractor

- Most Active Debris Removal (ADR) methods rely on some sort of physical contact
 - Nets and harpoons might generate new debris fragments
 - High debris tumble rates complicate grappling methods
- Electrostatic Tractor: relocation of retired satellites without physical contact
 - Servicer emits electron beam onto debris, causing an attractive electrostatic force
 - Inertial thrusters to tug the debris and raise orbit
 - Detumbling of debris with electrostatic force and torque possible
- Relative motion controller feeds forward expected electrostatic force



Electrostatic Tractor: Charging and Sensing

- Most prior work assumed fixed potentials
 - How do potentials change over the duration of an orbit?
 - How do we control and maintain desired potentials?
- Need fast (simplified) charging model in order to
 - Simulate the variation of potentials and electrostatic forces over time
 - Implement a charge filter and charge controller that utilize the estimation of electric potentials
 - Study the effect of the electron beam on such electric potential sensing methods



Natural Currents

Plasma Electron Current

$$I_e(\phi) = \begin{cases} -\frac{A_p q n_e w_e}{4} e^{\phi/T_e} & \text{if } \phi \leq 0 \\ -\frac{A_p q n_e w_e}{4} \left(1 + \frac{\phi}{T_e}\right) & \text{if } \phi > 0 \end{cases} \quad w = \sqrt{\frac{8T}{\pi m}}$$

Secondary and Backscattered Electron Current due to ambient electrons

$$I_{SEE,B,e}(\phi) = \begin{cases} - \langle Y_{SEE,B,e} \rangle \cdot I_e(\phi) & \text{if } \phi \leq 0 \\ \underbrace{- \langle Y_{SEE,B,e} \rangle \cdot I_e(\phi) e^{-\phi/T_{SEE}}}_{\approx 0} & \text{if } \phi > 0 \end{cases}$$

Yield model for electron impact

$$Y_{SEE,B}(E) = 4 \cdot Y_{\max} \frac{E/E_{\max}}{(1 + E/E_{\max})^2}$$

$$\langle Y \rangle = \frac{\int_L^\infty Y(E)(E/(E \pm \phi))F(E \pm \phi)dE}{\int_L^\infty (E/(E \pm \phi))F(E \pm \phi)dE}$$

$$F(E) = \sqrt{\frac{q_0}{2\pi T_m}} \frac{E}{T} n \exp\left(-\frac{E}{T}\right)$$

Plasma Ion Current

$$I_i(\phi) = \begin{cases} \frac{A_p q n_i w_i}{4} \left(1 - \frac{\phi}{T_i}\right) & \text{if } w_i \geq v_{i,\text{bulk}}, \phi \leq 0 \\ \frac{A_p q n_i w_i}{4} e^{-\phi/T_i} & \text{if } w_i \geq v_{i,\text{bulk}}, \phi > 0 \\ A_{\text{ram}} q n_i v_{i,\text{bulk}} & \text{if } w_i < v_{i,\text{bulk}} \end{cases}$$

Secondary Electron Current due to ambient ions

$$I_{SEE,i}(\phi) = \begin{cases} \langle Y_{SEE,i} \rangle \cdot I_i(\phi) & \text{if } \phi \leq 0 \\ \underbrace{\langle Y_{SEE,i} \rangle \cdot I_i(\phi) e^{-\phi/T_{SEE}}}_{\approx 0} & \text{if } \phi > 0 \end{cases}$$

Yield model for ion impact

$$Y_{SEE,i}(E) = 2 \frac{\beta E^{1/2}}{1 + E/E_{\max,i}}$$

Photoelectric Current

$$I_{ph}(\phi) = \begin{cases} j_{ph,0} A_{ph} & \text{if } \phi \leq 0 \\ \underbrace{j_{ph,0} A_{ph} e^{-\phi/T_{ph}}}_{\approx 0} & \text{if } \phi > 0 \end{cases}$$

Charging model assumes fully conducting spacecraft

Electron Beam Induced Currents

Electron Beam Current on Servicer

$$I_{EB,S}(\phi_T, \phi_S) = \begin{cases} I_{EB} & \text{if } E_{EB} > \phi_S - \phi_T \\ \underbrace{I_{EB}(1 - e^{-(E_{EB} - \phi_S + \phi_T)/T_{EB}})}_{\approx 0} & \text{if } E_{EB} \leq \phi_S - \phi_T \end{cases}$$

Electron beam can only reach target if initial energy is greater than electric potential difference

Electron Beam Current on Target

$$I_{EB,T}(\phi_T, \phi_S) = \begin{cases} -\alpha I_{EB} & \text{if } E_{EB} > \phi_S - \phi_T \\ \underbrace{-\alpha I_{EB}(1 - e^{-(E_{EB} - \phi_S + \phi_T)/T_{EB}})}_{\approx 0} & \text{if } E_{EB} \leq \phi_S - \phi_T \end{cases}$$

Secondary and Backscattered Electron Current due to Beam Impact on Target

$$I_{SEE,B,eb}(\phi_T, \phi_S) = \begin{cases} -Y_{SEE,B}(E) \cdot I_{EB,T} & \text{if } \phi_T < 0 \\ \underbrace{-Y_{SEE,B}(E) \cdot I_{EB,T} e^{-\phi/T_{SEE}}}_{\approx 0} & \text{if } \phi_T \geq 0 \end{cases} \quad E = E_{EB} - \phi_S + \phi_T$$

Total Current and Equilibrium

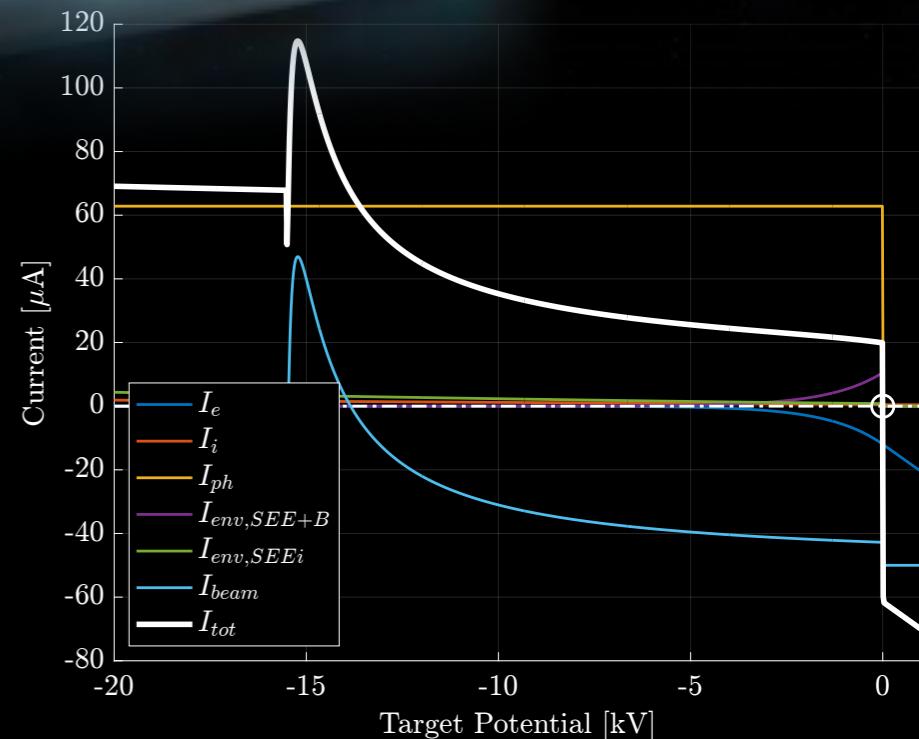
Total Current

Total Current on Servicer

$$I_{\text{tot},S}(\phi_T, \phi_S) = I_e(\phi_S) + I_i(\phi_S) + I_{ph}(\phi_S) + I_{SEE,B,e}(\phi_S) + I_{SEE,i}(\phi_S) \\ + I_{EB,S}(\phi_T, \phi_S)$$

Total Current on Target

$$I_{\text{tot},T}(\phi_T, \phi_S) = I_e(\phi_T) + I_i(\phi_T) + I_{ph}(\phi_T) + I_{SEE,B,e}(\phi_T) + I_{SEE,i}(\phi_T) \\ + I_{EB,T}(\phi_T, \phi_S) + I_{SEE,B,eb}(\phi_T, \phi_S)$$



Equilibria

Servicer Equilibrium

$$I_{\text{tot},S}(0, \phi_S) = I_e(\phi_S) + I_i(\phi_S) + I_{ph}(\phi_S) + I_{SEE,B,e}(\phi_S) + I_{SEE,i}(\phi_S) + I_{EB,S}(0, \phi_S) = 0$$

Assumption that the target potential does not influence whether or not the beam comes back to servicer

Target Equilibrium

$$I_{\text{tot},T}(\phi_T, \phi_S) = I_e(\phi_T) + I_i(\phi_T) + I_{ph}(\phi_T) + I_{SEE,B,e}(\phi_T) + I_{SEE,i}(\phi_T) + I_{EB,T}(\phi_T, \phi_S) + I_{SEE,B,eb}(\phi_T, \phi_S) = 0$$

Varying Electron Beam Current and Sunlight/Eclipse

- Higher beam current does not necessarily mean more negative target potential

- Servicer charges as well -> limits how much target can charge
- Servicer equilibrium increases with increasing beam current
- Less potential “left” for target

Requirements for multiple equilibria

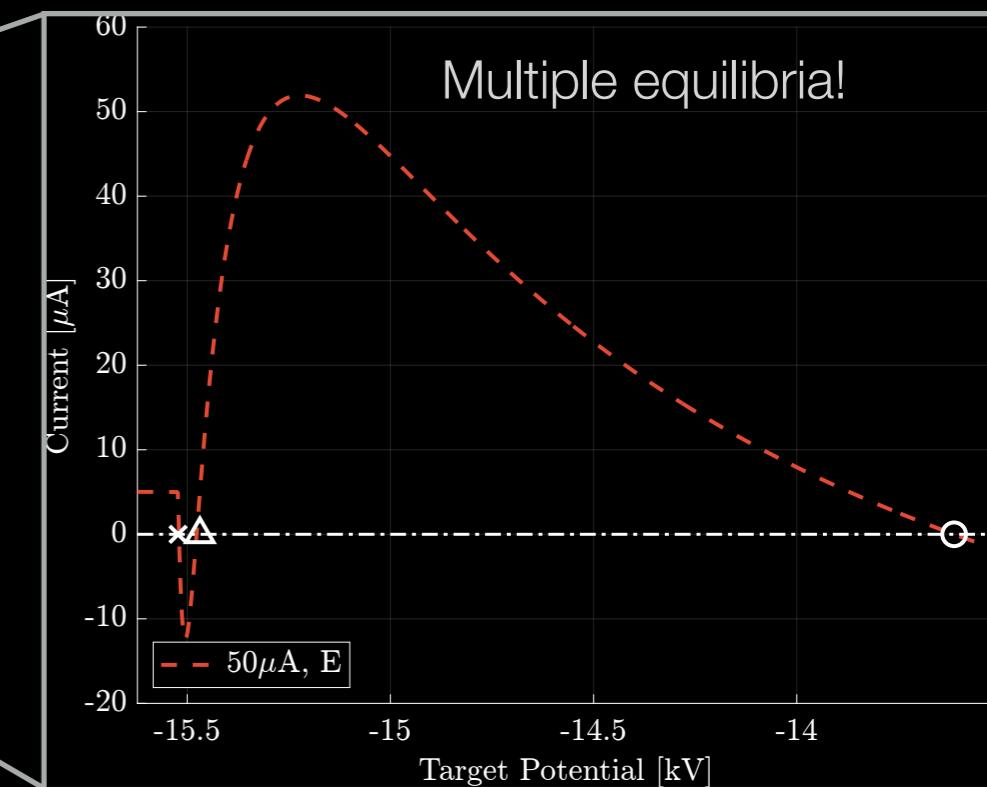
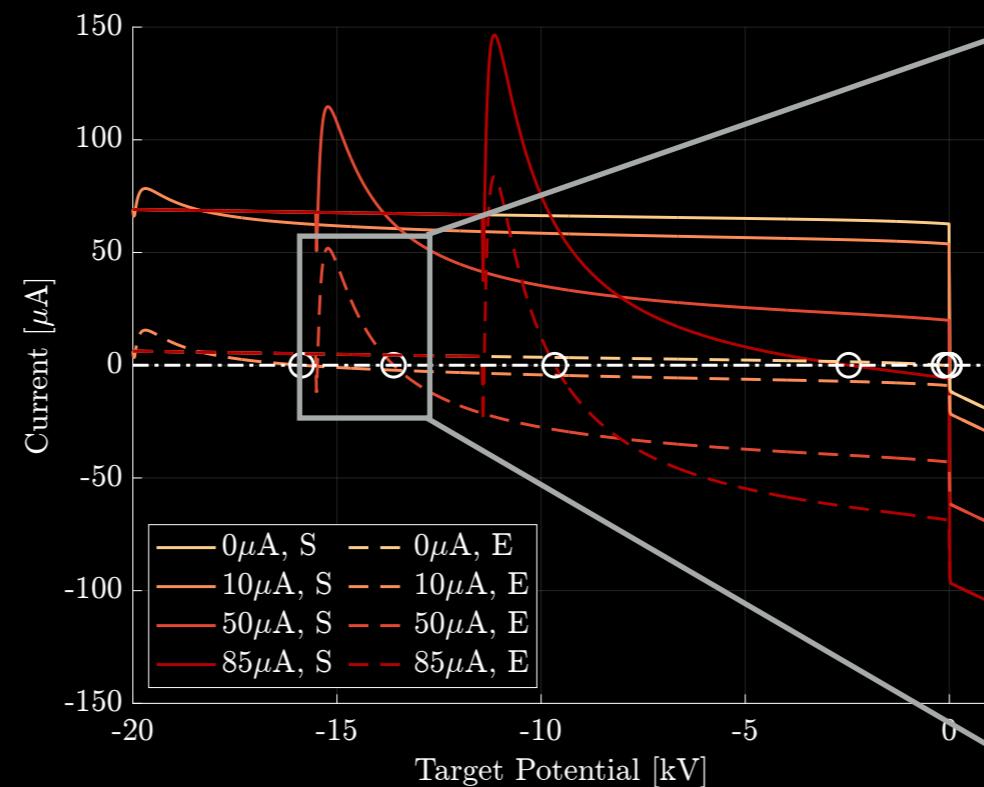
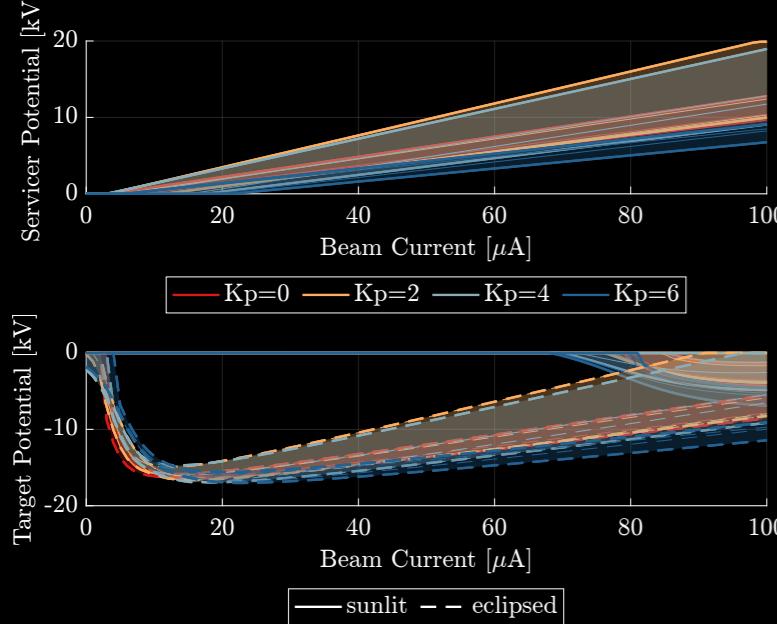
$$I_{tot,T}(\phi_T = \phi_S - E_{EB}) - I_{EB} < 0$$

$$(Y_{SEE,B,eb,max} - 1) \cdot I_{EB} + I_{tot,T}(\phi_T = \phi_S - E_{EB} + E_{max}) > 0$$

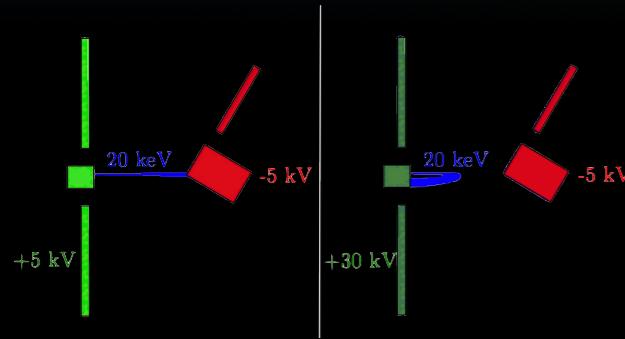
↓ rewriting

$$I_{EB} > I_{tot,T}(\phi_T = \phi_S - E_{EB})$$

$$Y_{SEE,B,eb,max} > 1 - \frac{I_{tot,T}(\phi_T = \phi_S - E_{EB} + E_{max})}{I_{EB}}$$

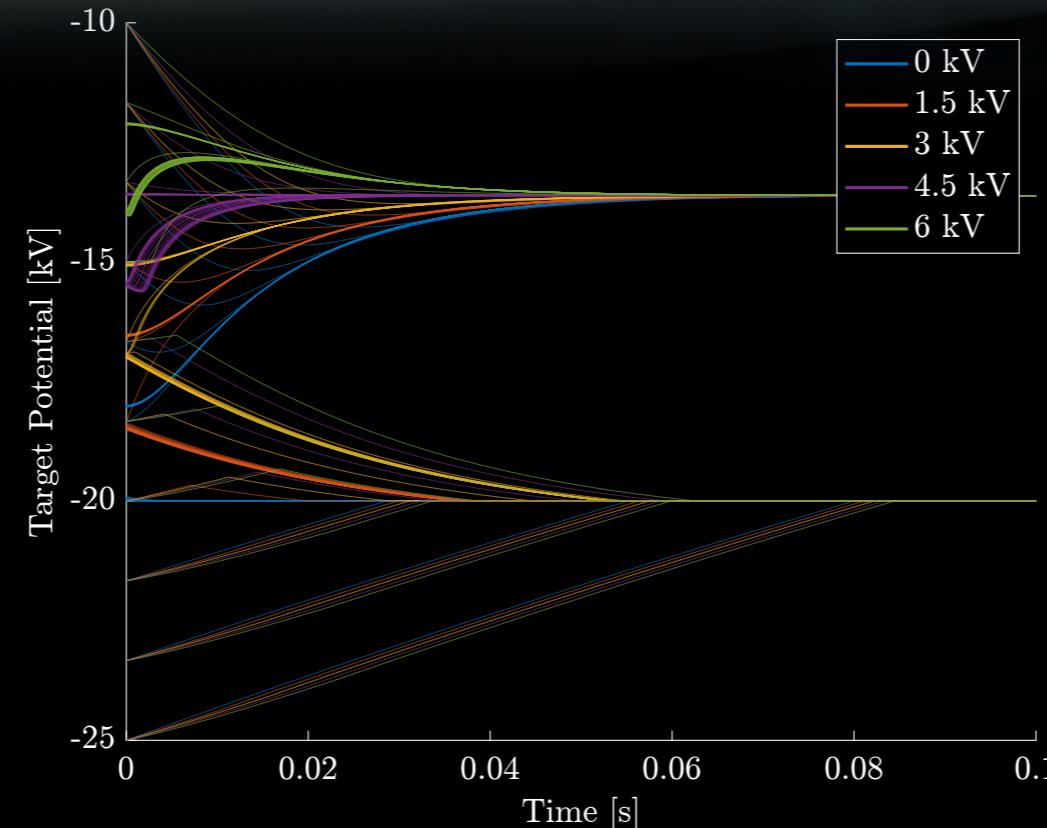


Multiple Equilibria: Regions of Convergence

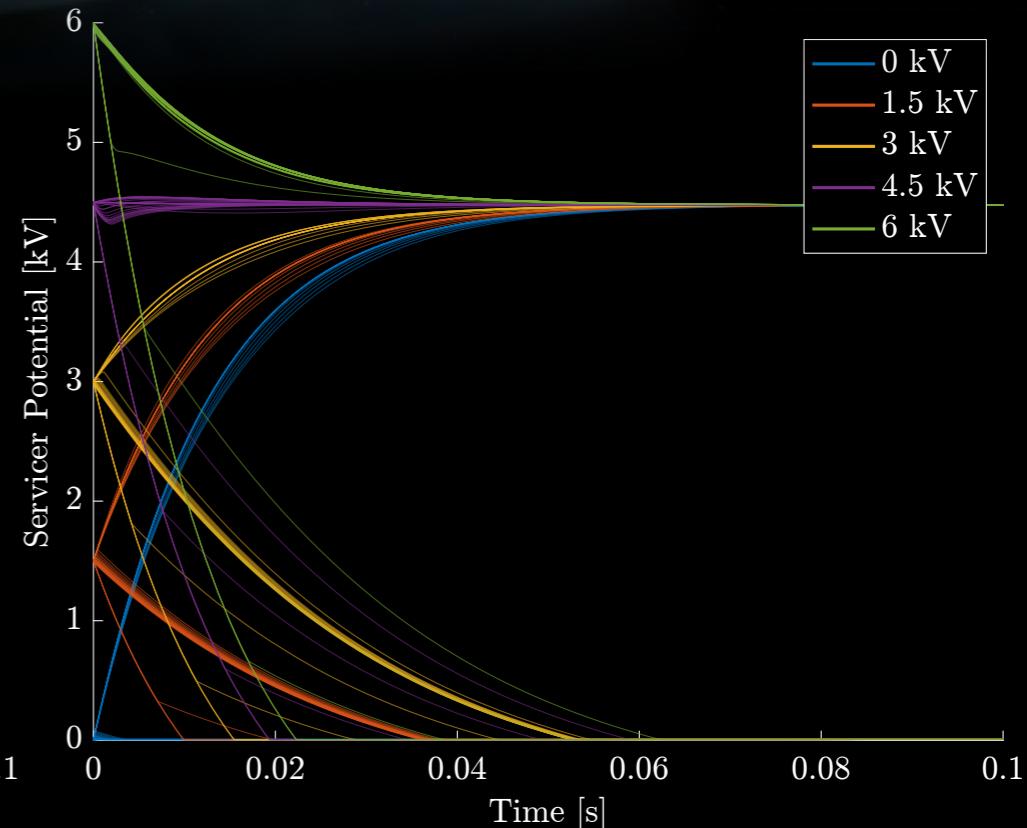


Legend indicates the initial potential of the servicer

20 keV Electron Beam



Target



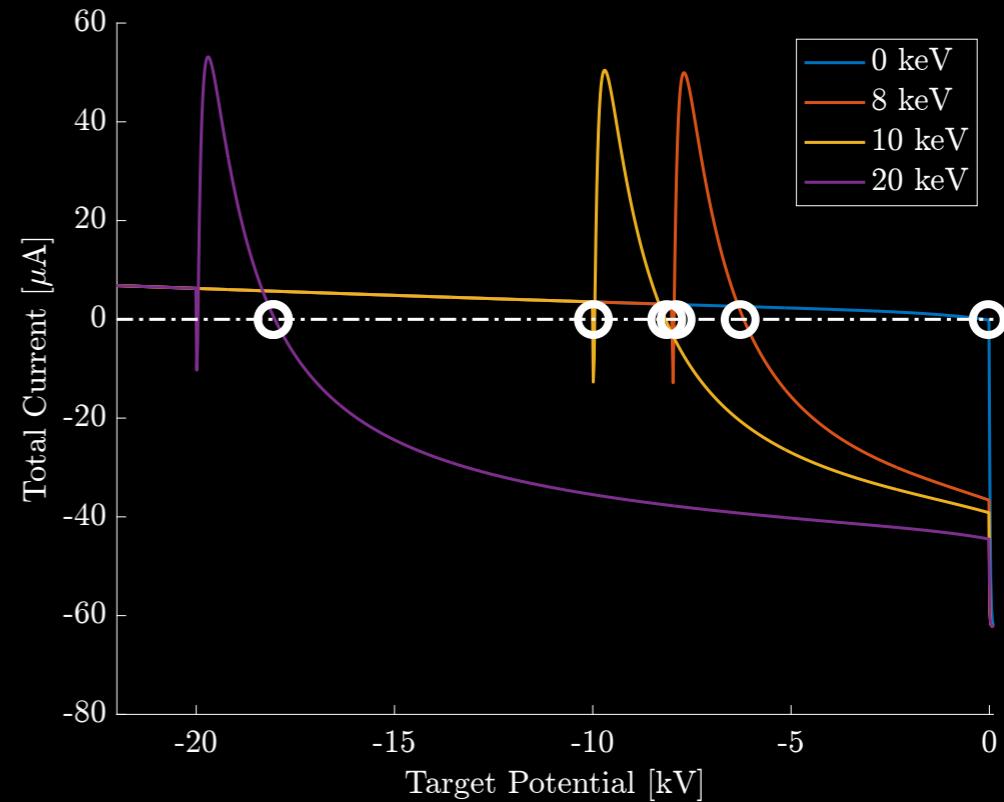
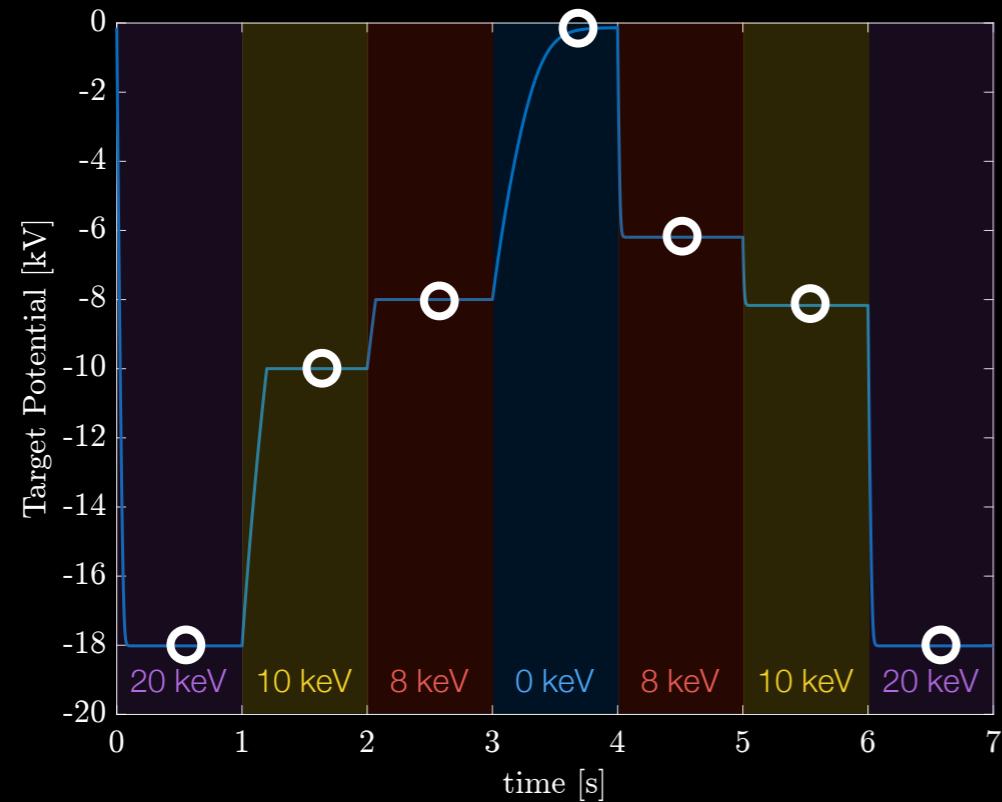
Servicer

Achieved Equilibrium depends on charging time history (initial conditions)

Can we jump from one equilibrium to the other?

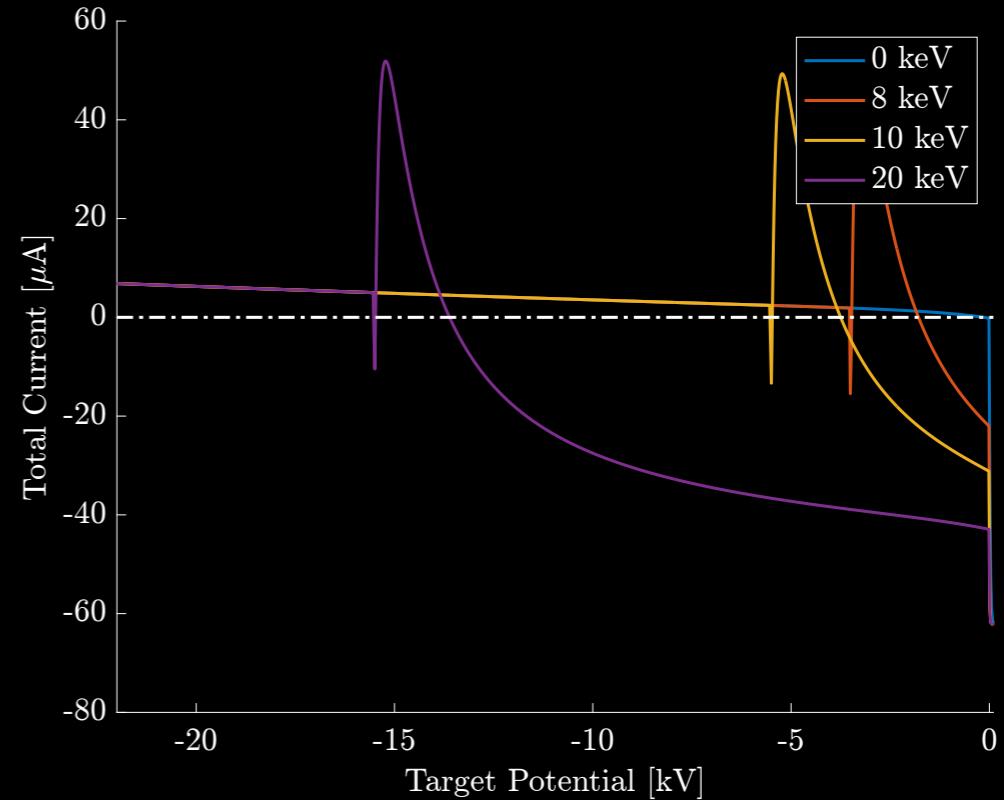
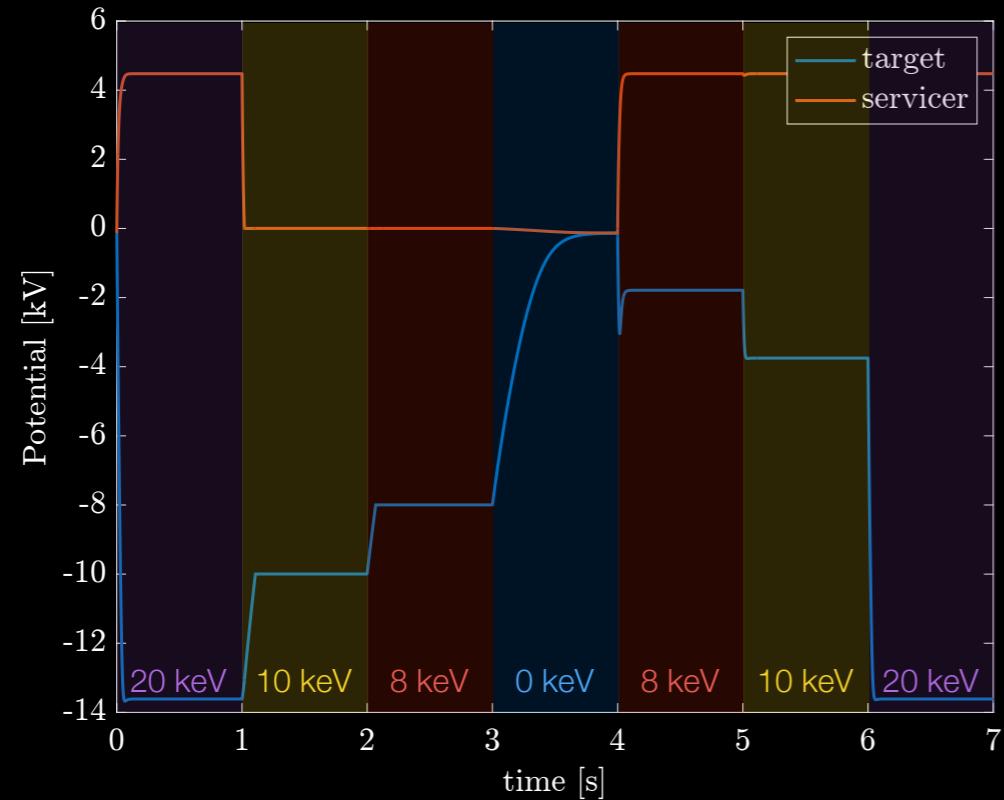
Varying the Electron Beam Energy

Servicer held at 0 V (no servicer charging)



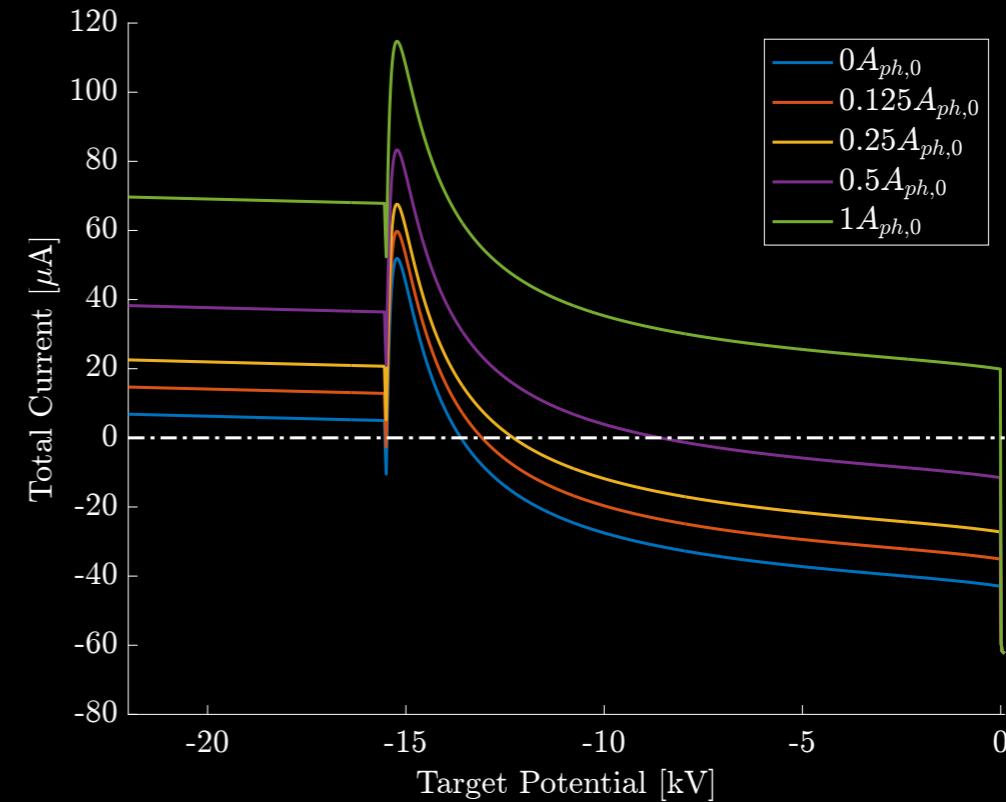
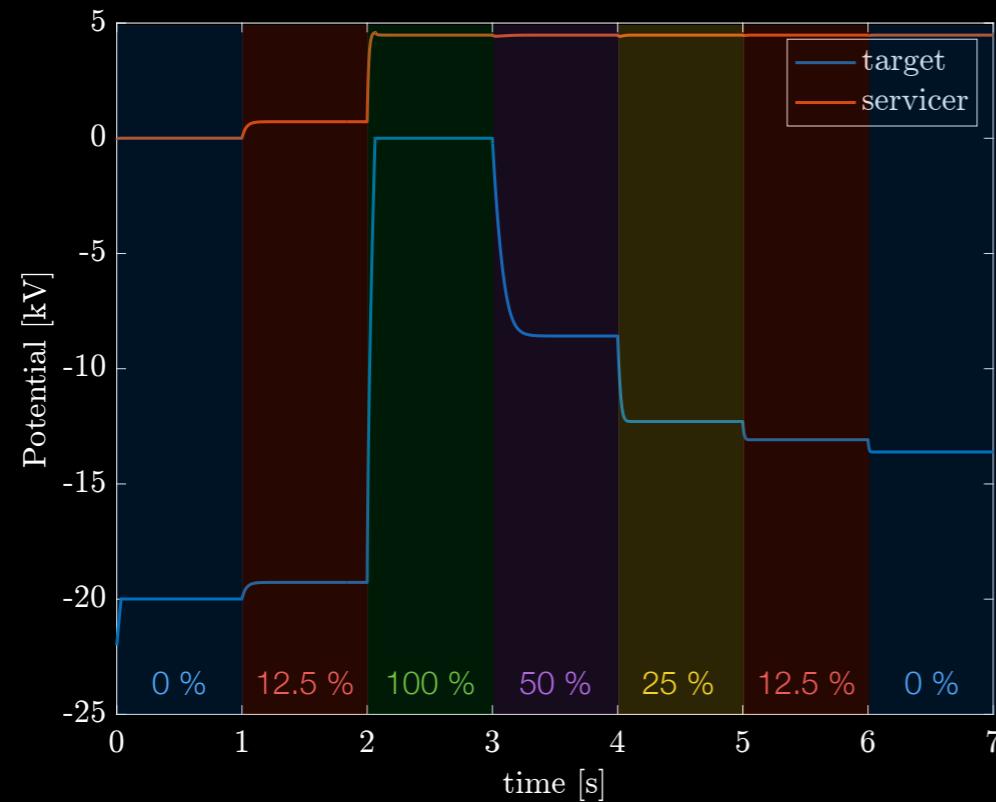
Varying the Electron Beam Energy

With servicer

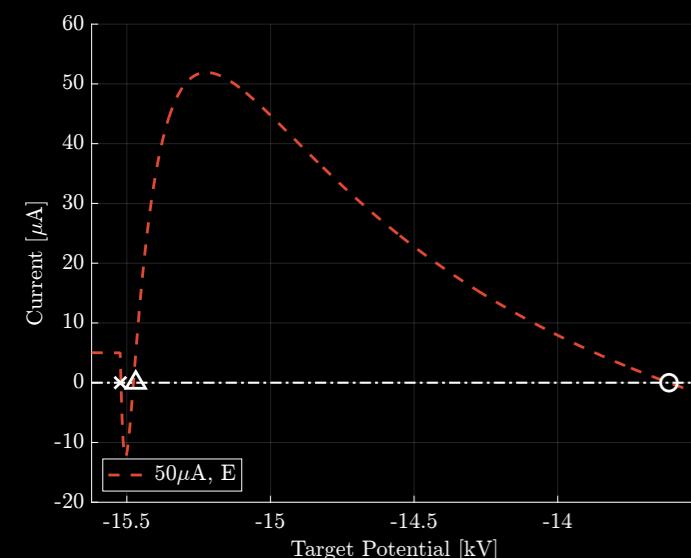


Varying the target orientation (sunlit area)

With servicer

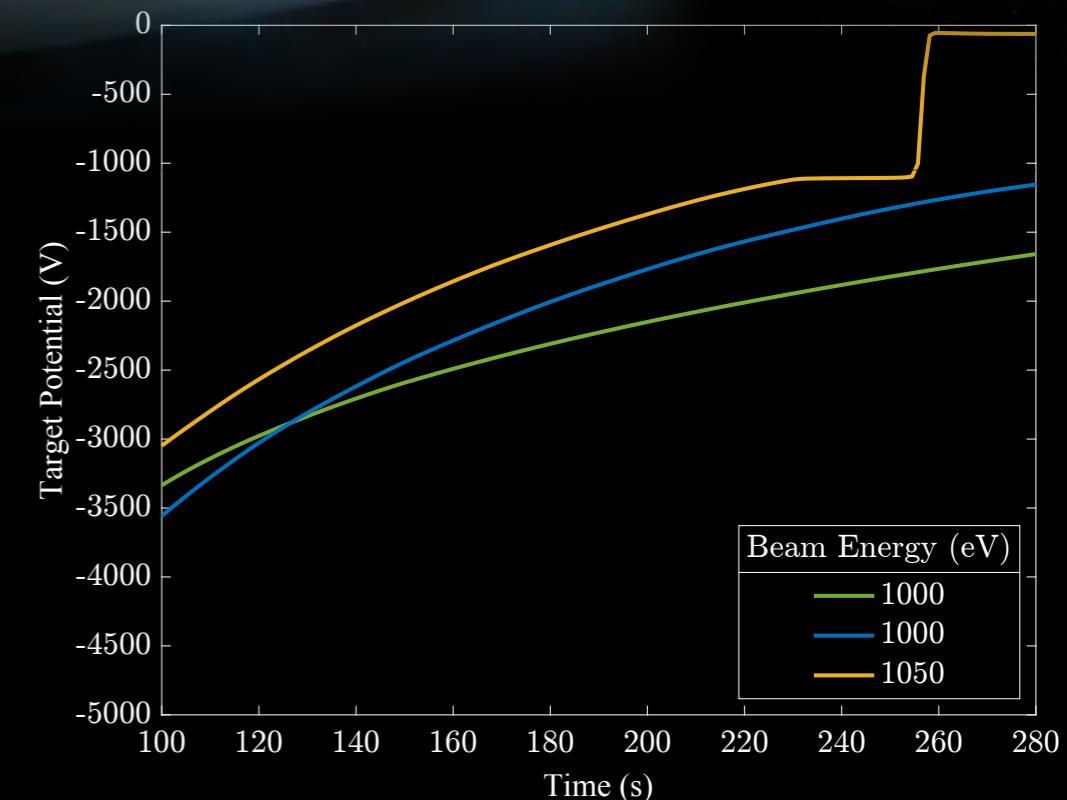


Current Noise applied to chamber-like scenario



Simulation in Matlab with current fluctuations

But these are just simulations...
Can this be observed in experiments?



Experimental data from floating potential experiments by J. D. Walker

We believe that multiple equilibria are present in this experimental data

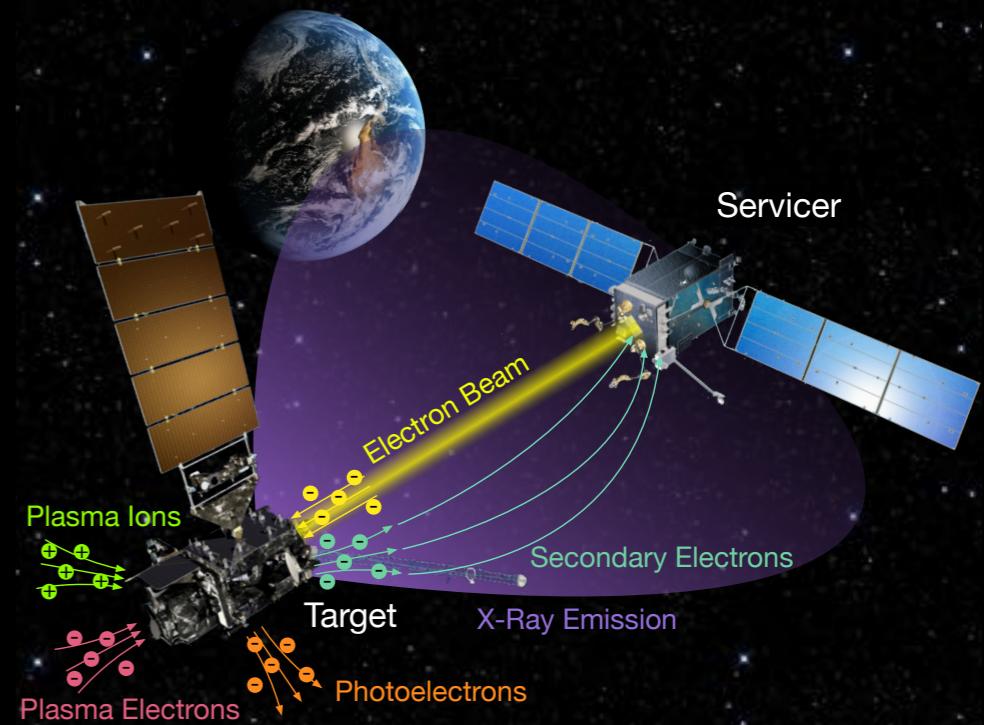
Conclusions and Future Work

- Assumption that target potential does not influence whether or not beam comes back to servicer seems to be justified for our work
 - Benefits the simplicity and efficiency of the charging model
- Multiple Equilibria may exist under certain conditions
 - Converged potential depends on charging history (initial conditions)
 - Possible to jump from one equilibrium to another when
 - Beam parameters are varied (pulsed): beam current and beam energy
 - Orientation of spacecraft changes (and consequently intensity of photoelectric current)
 - Significant current fluctuations are present
 - Servicer Potential changes (acts like change in beam energy)
 - ... ?
 - Possibly observed multiple equilibria in experimental data
- Possible utilizations of multiple equilibria (and significance for simulations)
 - Open loop charge control at left-most equilibrium (we know the value of this equilibrium, we just need to get it there)
 - Needs to be considered for simulations (which equilibrium do we want to compute)
 - Need to be aware what could cause a jump to another equilibrium (beam parameters, ...)
 - ... ?

Requirements for multiple equilibria

$$I_{EB} > I_{tot,T}(\phi_T = \phi_S - E_{EB})$$

$$Y_{SEE,B,eb,max} > 1 - \frac{I_{tot,T}(\phi_T = \phi_S - E_{EB} + E_{max})}{I_{EB}}$$





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Questions?



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Backup Slides

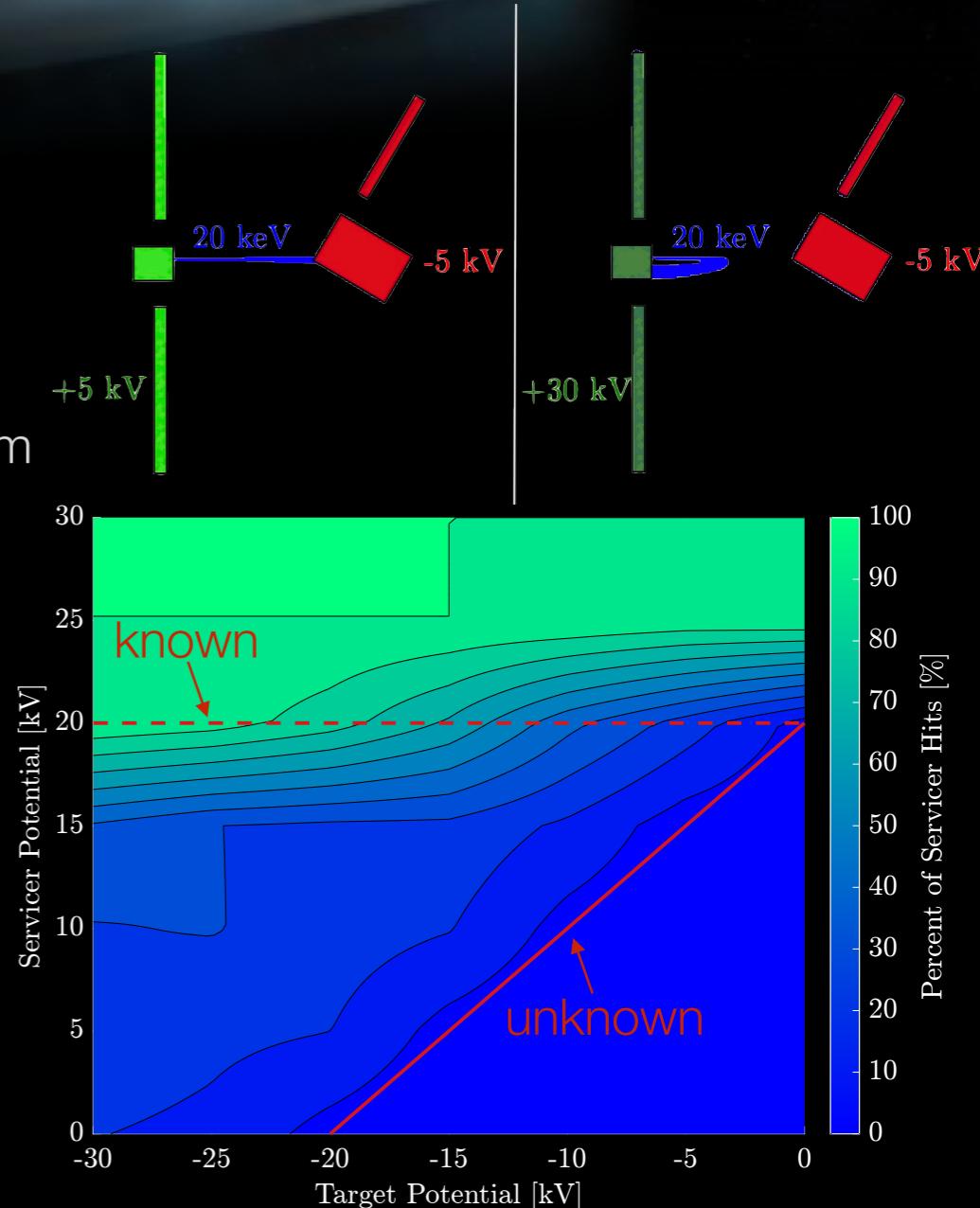
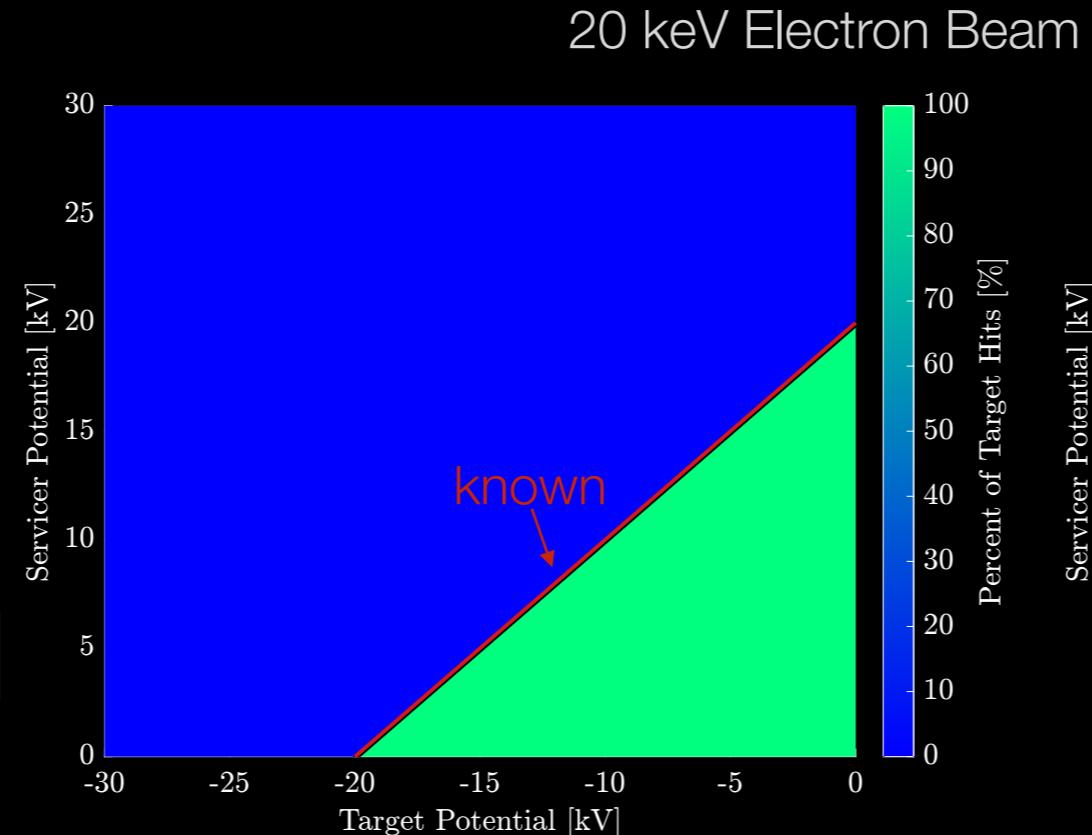
Justification of Electron Beam Assumption

- Simulation in SIMION Particle Tracing Software to investigate beam landing location (does the beam hit servicer or target?)

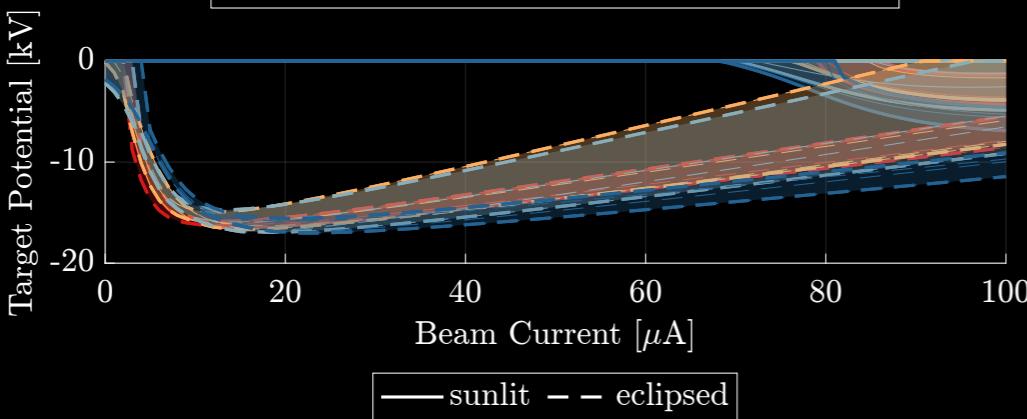
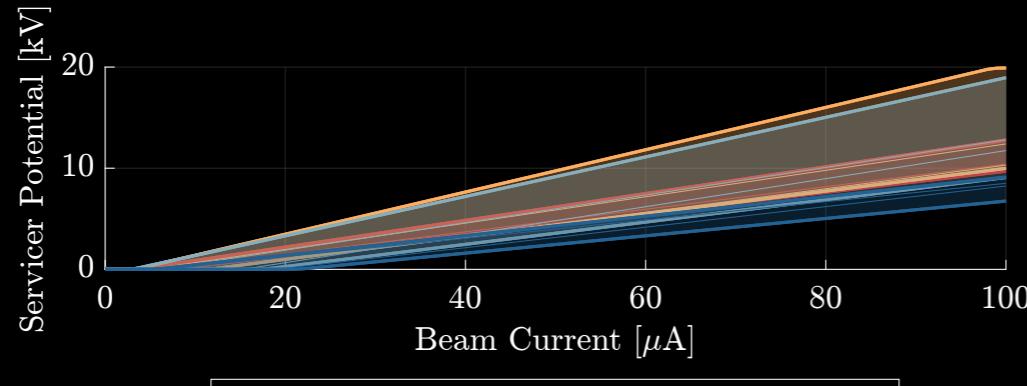
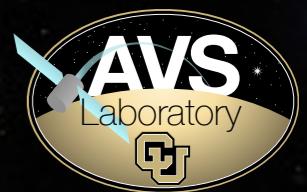
Good agreement with assumption from previous slide!

- Electron Beam Energy: 10, 20, 30 keV
- Target Potentials: -30 kV to 0 kV
- Servicer Potentials: 0 kV to 30 kV
- Separation Distance: 15, 20, 30 m
- Varying Target Orientations

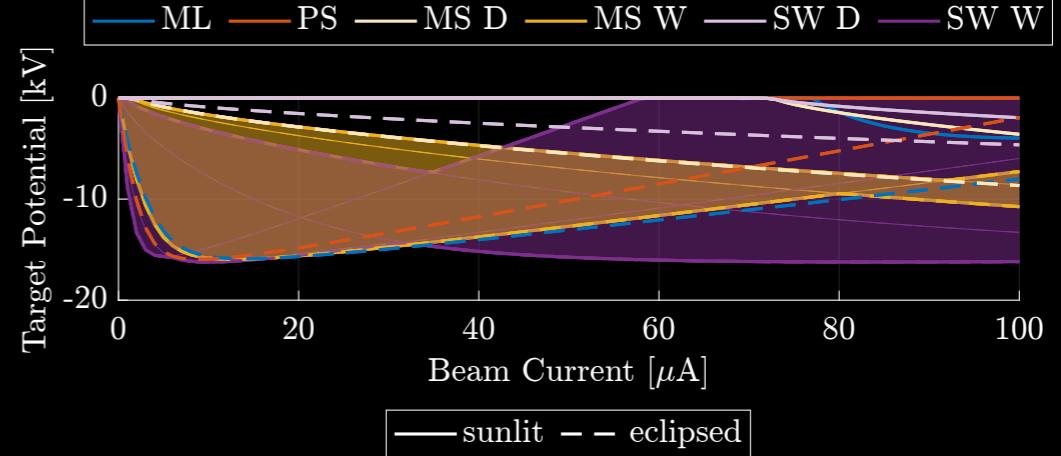
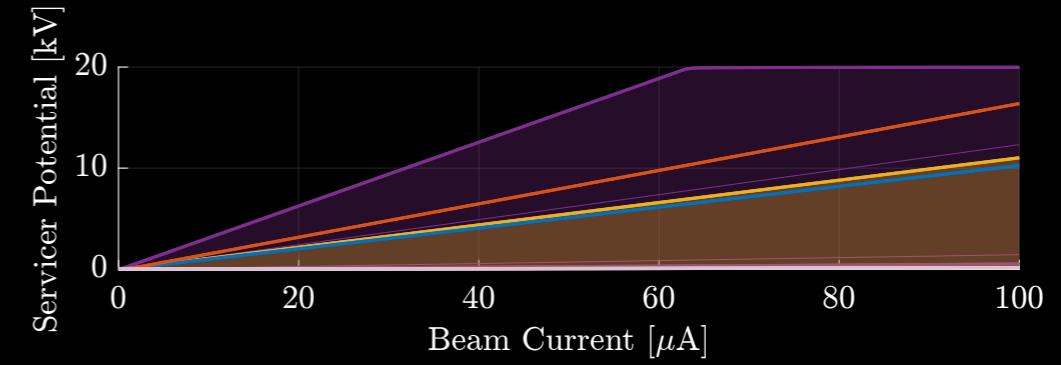
Plots show number of hits averaged over all distances and orientations



Equilibrium Potential vs. Electron Beam Current

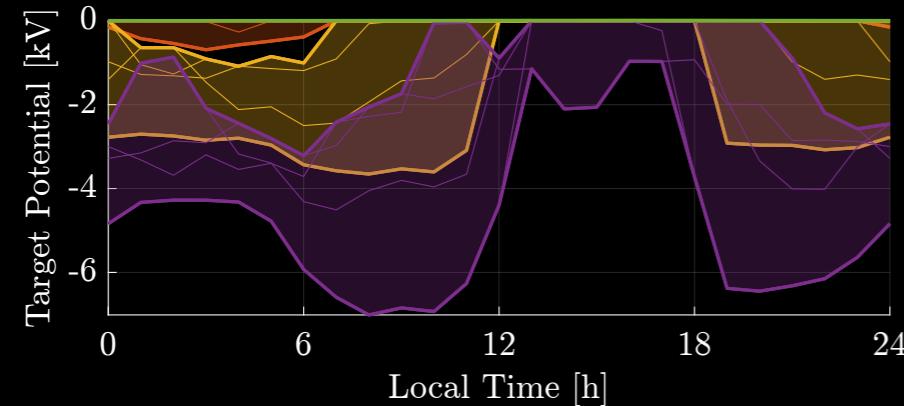
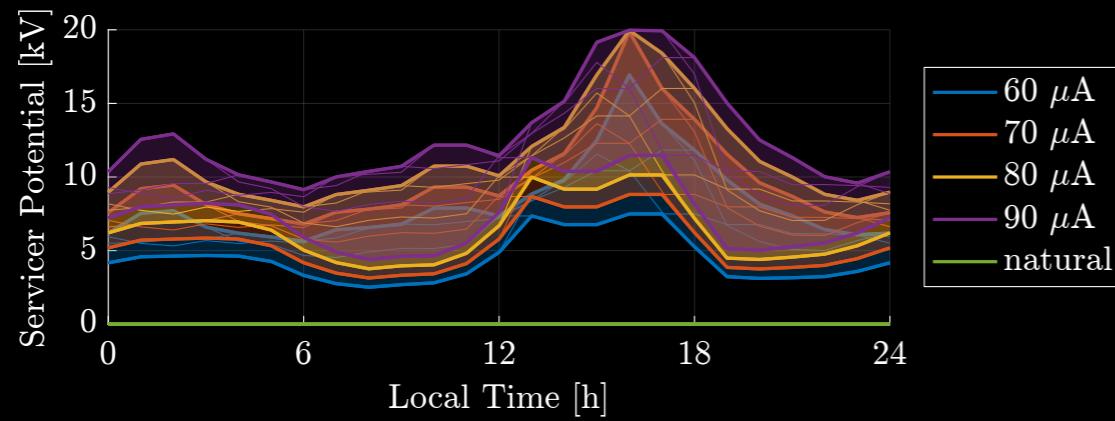


GEO

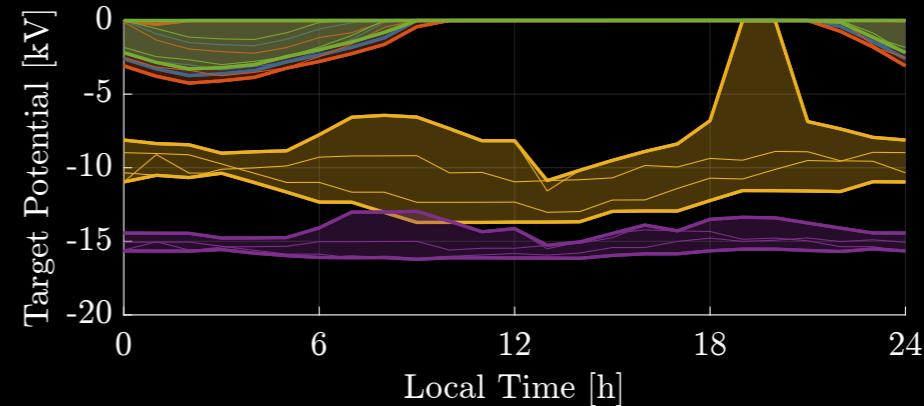
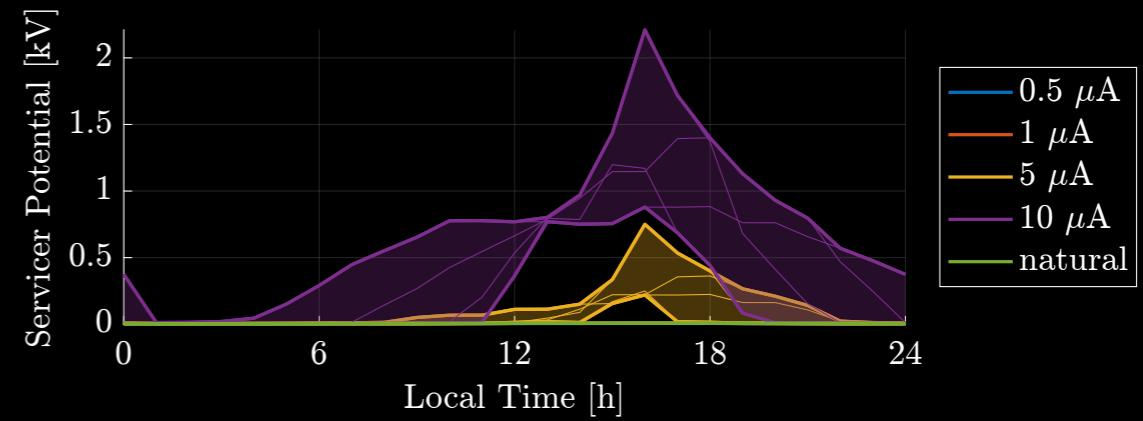


Cislunar

Equilibrium Potential vs. GEO Local Time

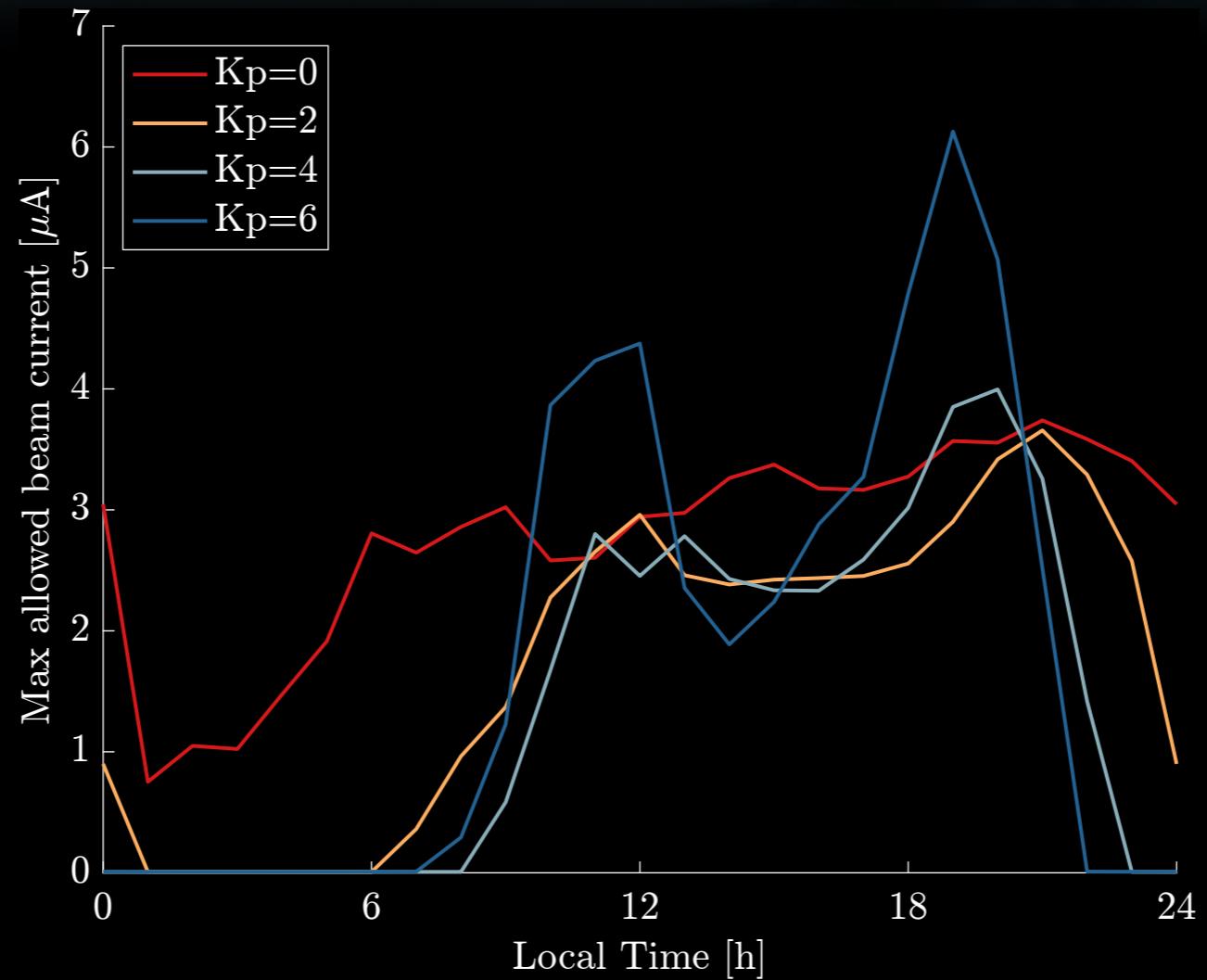


In Sunlight



In Eclipse

Maximum allowed beam current to not charge target



Charged Particle Yield

$$\text{CPY} = \frac{I_{\text{tot},T}}{I_{EB}} + 1$$

