Numerical Analysis on Solar Sail Charging in Interplanetary Environment

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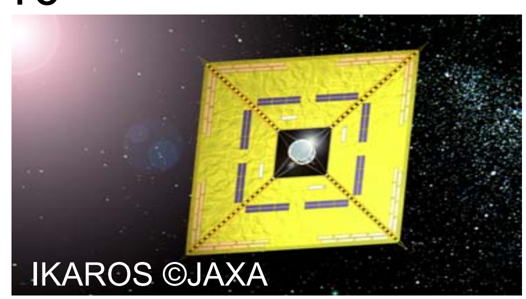
2010 Spacecraft Charging Technology Conference
2010.09.20-24 @Albuquerque

Background

- Solar sail is a candidate for interplanetary-flight spacecraft
  - Use solar radiation pressure for its thrust: ~μPa@1AU
  - Need less propellant compared to a conventional thruster (e.g. EP)
- Very unique spacecraft design
  - Large scale, ultra-thin membrane (Al-coated polyimide)
  - Area: 10x10 ~ 100x100(m^2), Thickness: ~10^{-6}(m)
- The sail would encounter various plasma environment
  - Near Earth, inferior planet, superior planet (0.5-5.0AU)
  - Interactions between a large membrane and plasmas are unique
- Previous work, Garrett & Minow provided an overall for this subject
  - NASCAP2k, PIC (particle ions & fluid electrons) (JPL TRS 1992+, 2004)
- Demonstration spacecraft had been/ will be launched in 2010
  - IKAROS (JAXA/ Solar power sail/ Venus orbit)
  - Light Sail-1(TPS/ Ultra-light sail/ Earth orbit)



These could be recognized onboard S/C now

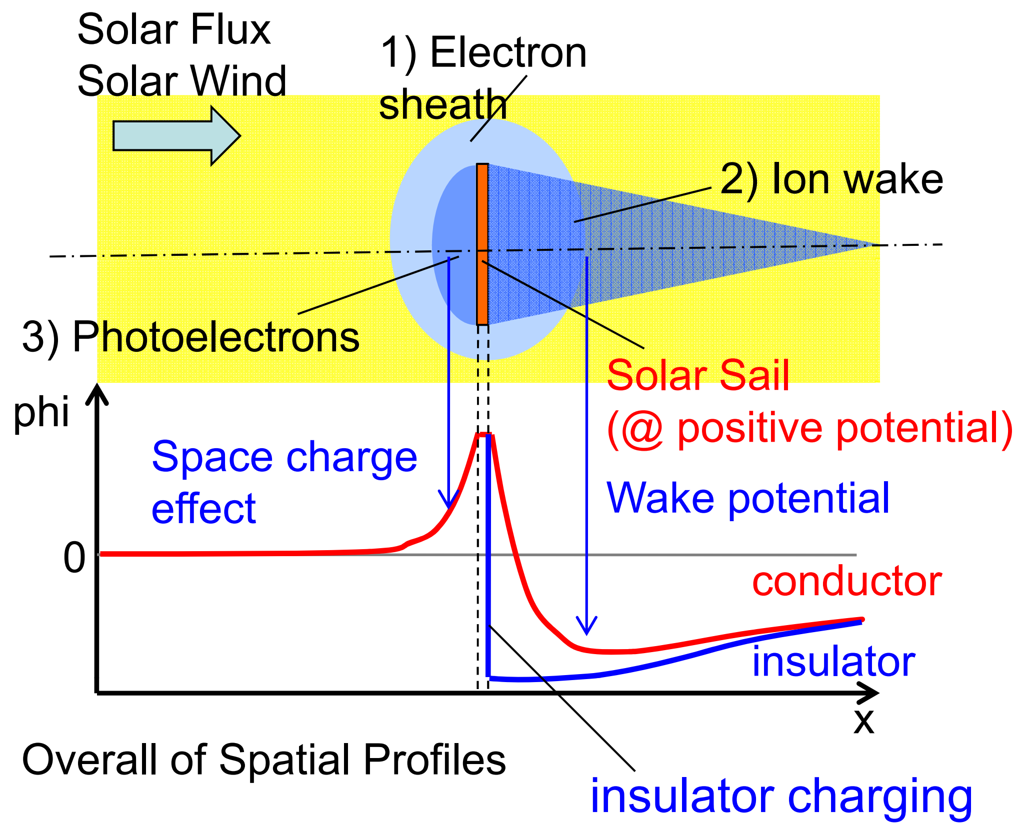
Features of the Plasma & Potential Profile

Solar wind plasmas

1) Debye length ~ L_s (sail scale length)
   - The sail potential is shielded by the plasma
   - The sail potential extends well out from the sail
2) $v_{ti} << v_d$, $v_{te} > v_d$ (v_t: thermal velocity, v_d: drift velocity)
   - Deep ion wake behind the sail

Photoelectrons

3) Emission from the ram surface (conductor: sunlit surface)
   - Diffusion around the sail: Space charge effect



Overall of Spatial Profiles

Charged particle profiles:
Characterize the current collection onto the sail

Purpose of This Study

For the payload design of a solar sail considering future interplanetary mission, both engineering & scientific purposes

We numerically provide quantitative analyses using full-particle simulation in three environments (0.5, 1.0, 3.0 AU) ;

- Spacecraft charging status
  - Floating potential, Differential voltage (rear)
  - Current collection characteristics
- Spatial distributions of charged particles and electric potential
  - Large ion wake
  - Photoelectron cloud in the vicinity of a sail

Fundamental analysis is explained at 1.0AU, results at 0.5, 3.0 AU briefly shown

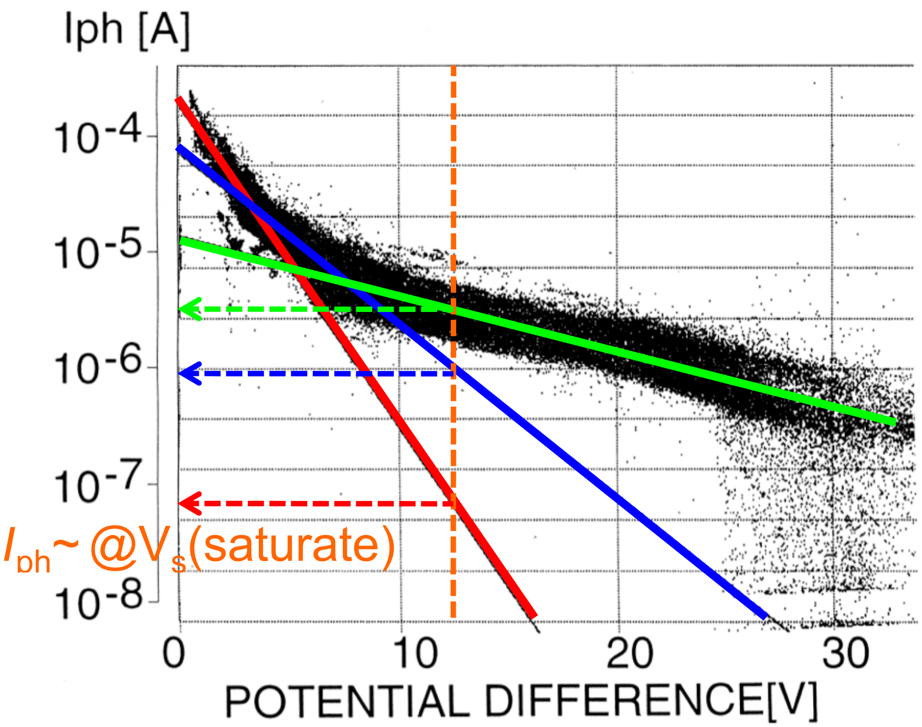
Environment Model (1/2): Solar Wind Plasma Environment Model

- Simplify plasma parameter referring to the observation data (e.g. Ulysses spacecraft)
- Solar wind plasma consists of protons and electrons
- Both protons and electrons have the same one component temperature and density
- No magnetic field

	0.5AU	1.0AU	3.0AU
plasma density [10^6 m^{-3}]	50	6	0.5
plasma temperature [eV]	40	10	5
drift velocity [km/s]		470	
mi/me (H+)		1836	
Debye length [m]	6.7	9.6	23.5

Environment Model (2/2): Photoelectron Spectrum Model

GEOTAIL spacecraft observation
(magnetosphere observation)



PE energy spectrum was estimated under tenuous plasma environment (~0.1/cc)

$$J(V_s)[\mu A/m^2] = \underline{53\exp\left(\frac{-V_s}{1.6}\right)} + \underline{21\exp\left(\frac{-V_s}{3.0}\right)} + \underline{4\exp\left(\frac{-V_s}{8.9}\right)}$$

PE dominant current collection, Vs>>+1;

Single-Maxwellian PEE must not be appropriate

We use 2-Maxwellian of 1.5 eV & 5.0 eV

T. Nakagawa et al., Earth, Planets and Space, vol. 52, pp283-292, 2000.

Algorithm of the 3-D ES full-PIC code

Parameter Input → Space Plasma; Spacecraft (S/C) Geometry; Numerical Parameters

Install Macro Particles → Ambient Plasma (Drift Maxwellian); Photoelectron (2-Maxwellian)

ES Field Computation → **ES Poisson Solver by FFT**; S/C Charge Collection/Emission; Charge Density → Electric Potential

$$-\varepsilon_0 \nabla^2 \phi = \rho \qquad \vec{\phi}_{SC} = \overleftrightarrow{C}_{SC}^{-1} \cdot \vec{\rho}_{SC} \qquad \vec{E} = -\nabla \phi$$

full-PIC
self-consistently solved

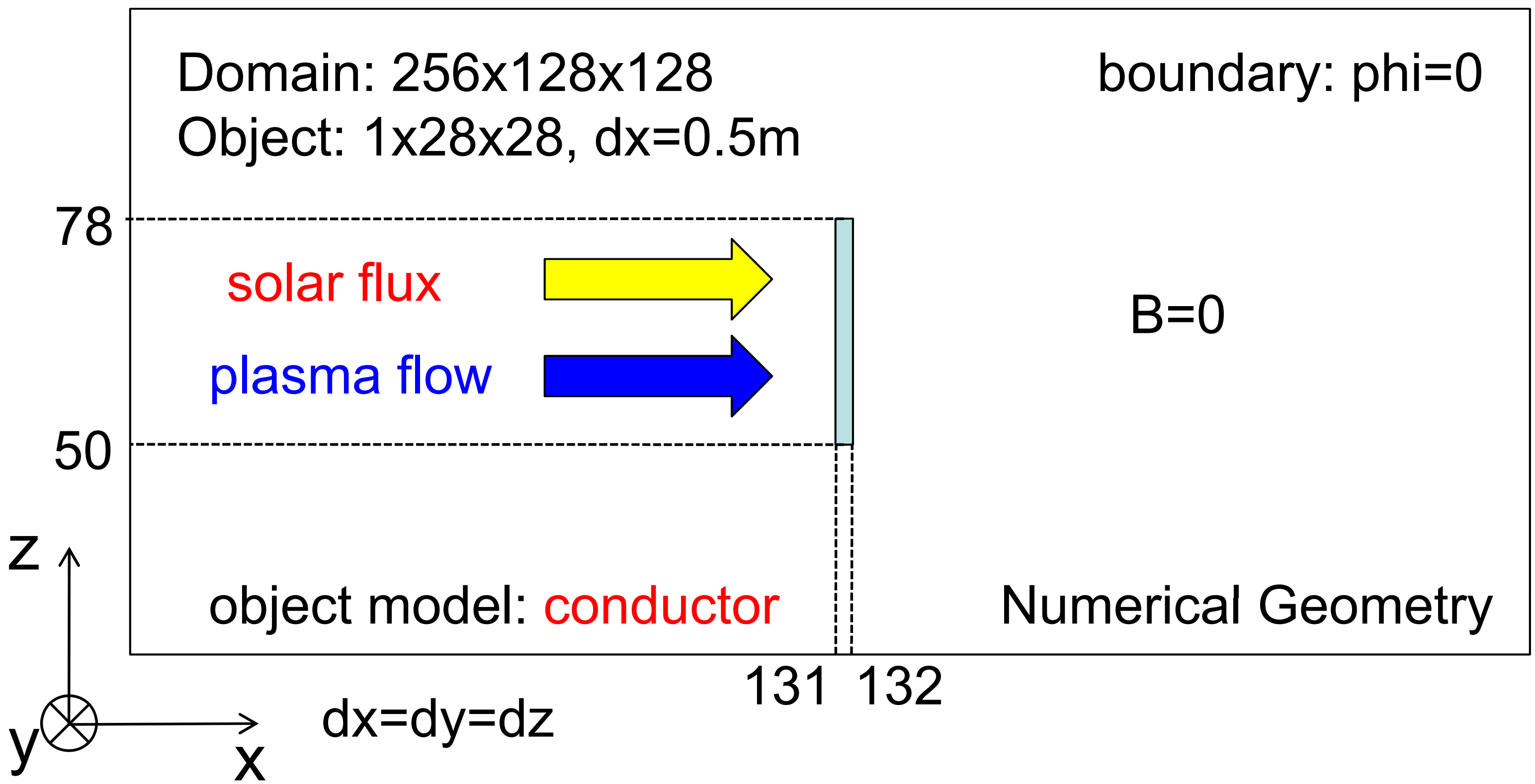
Particle Trajectories → Integrate Newton-Lorentz Equation; Explicitly Solve Electrons and Ions

$$\frac{d^2 \vec{x}_j}{dt^2} = \frac{q_j}{m_j}\left(\vec{E} + \vec{v}_j \times \vec{B}\right), \quad \frac{d\vec{x}_j}{dt} = \vec{v}_j$$

End

Numerical Domain

symmetric in Y- and Z -axes



MPI parallel computation:
Domain decomposition in X-axis

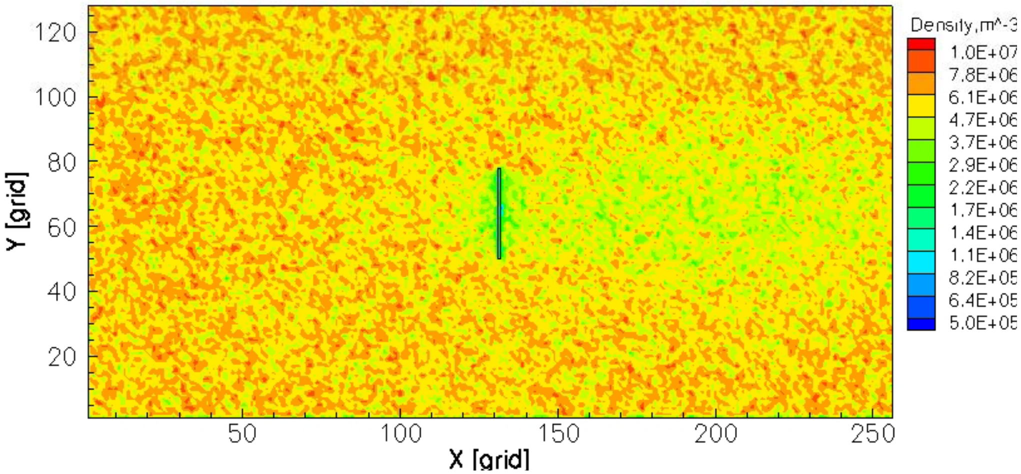
Computation Parameters

	0.5AU	1.0AU	3.0AU
plasma density [$10^6 m^{-3}$]	50	6	0.5
plasma temperature [eV]	40	10	5
drift velocity [km/s]	470		
mi/me (H+)	1836		
Debye length [m]	6.7	9.6	23.5
PE current flux [uA/m^2]	160	40	4.4
PE temperature (1) [eV]	1.5		
PE temperature (2) [eV]	5.0		
PE flux ration of PE1:PE2	9:1		
numerical domain [grid]	256*128*128		
object size [grid]	1*28*28		
dx [m]	0.5		
dt [s]	0.5×10^{-7}	1.0×10^{-7}	1.4×10^{-7}

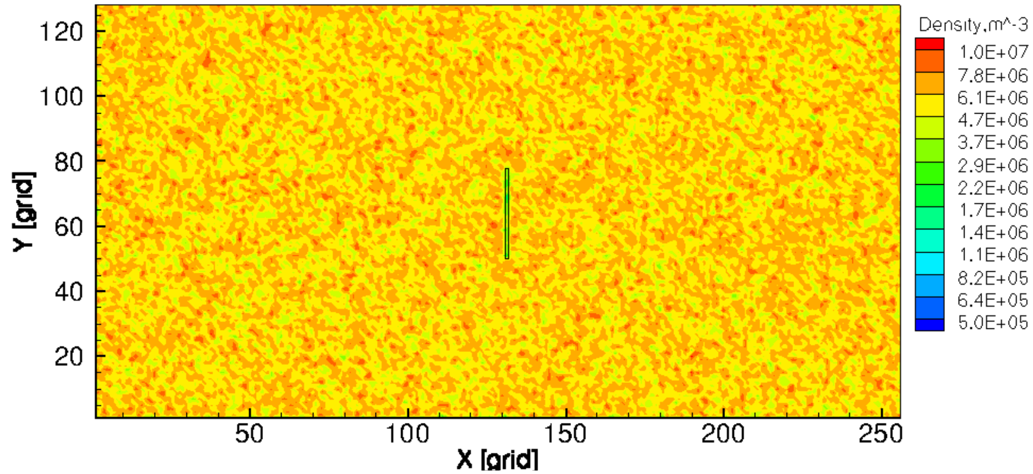
Plasma Analysis Results @1.0AU

Solar Flux & Plasma flow: left to right, T=10eV, n=6x10^{6} m^{-3}, vd=470km/s, dx=0.5m

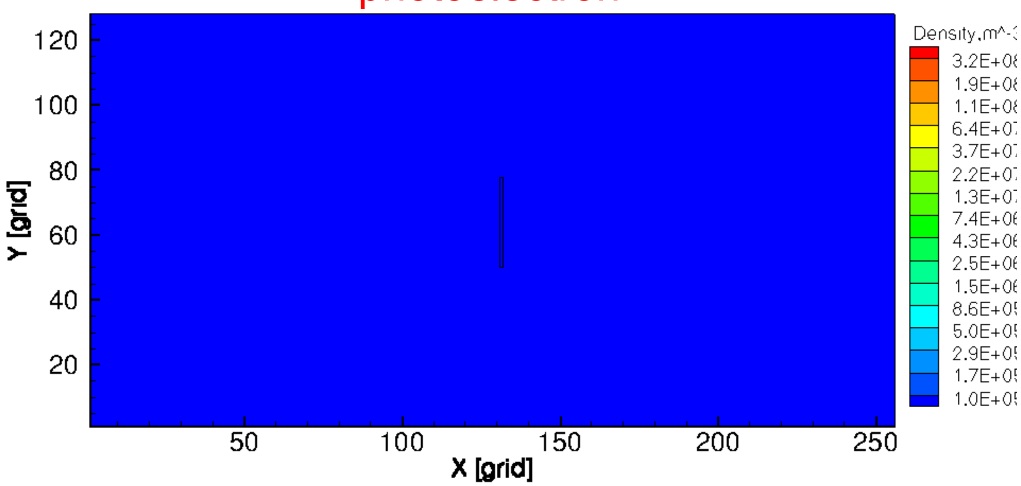
ambient electron



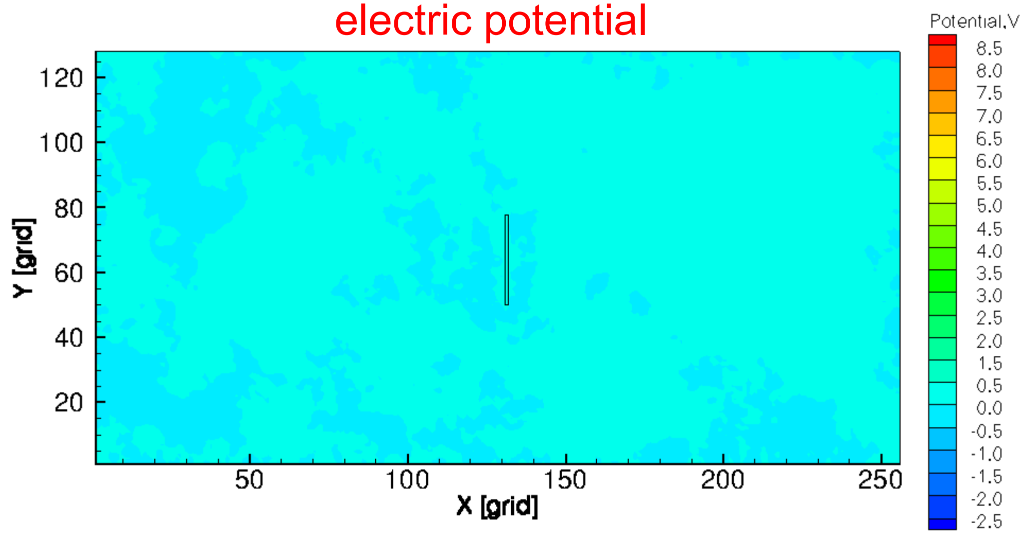
ambient ion



photoelectron

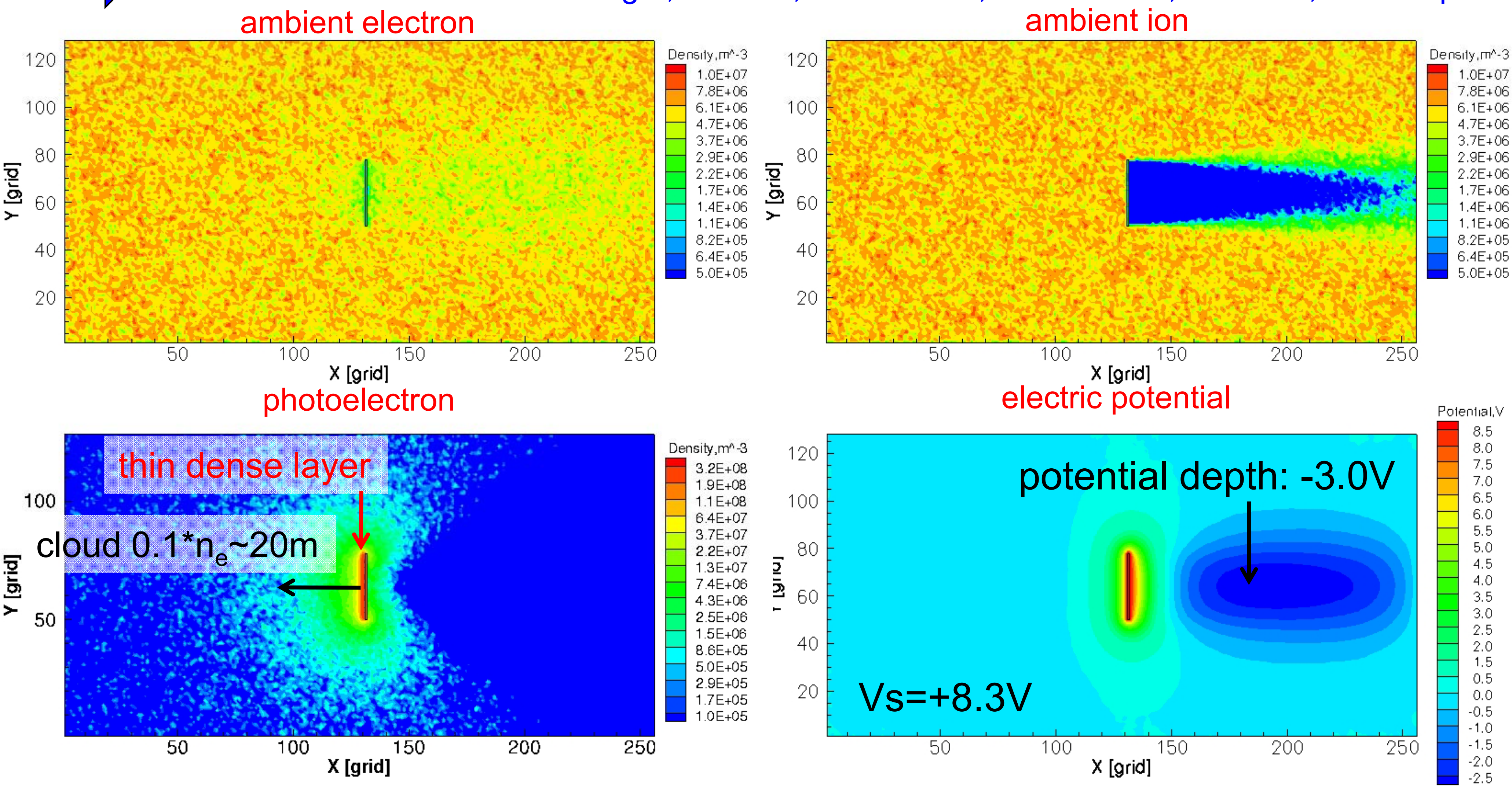


electric potential



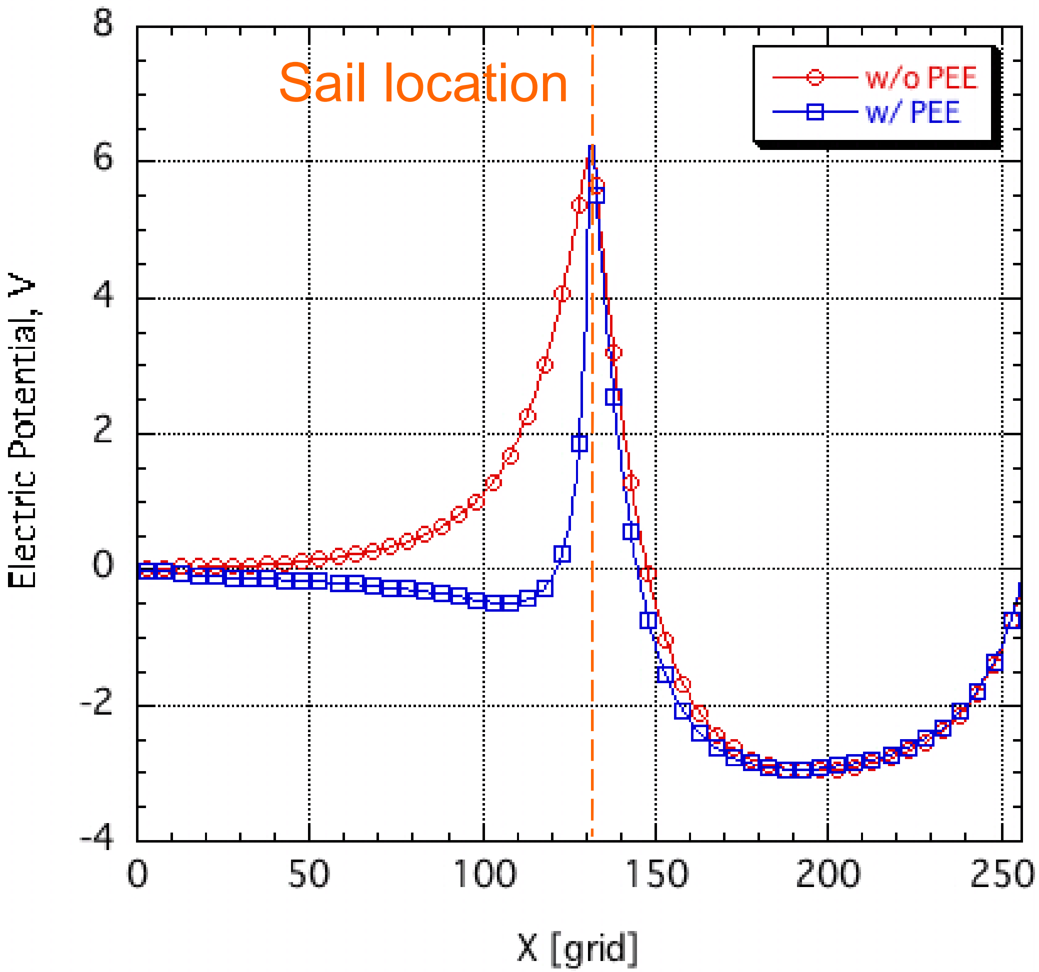
Charged Particle & Potential Profiles@1.0AU

Solar Flux & Plasma flow: left to right, T=10eV, $n=6\times10^{6}\ m^{-3}$, vd=470km/s, dx=0.5m, 2500steps



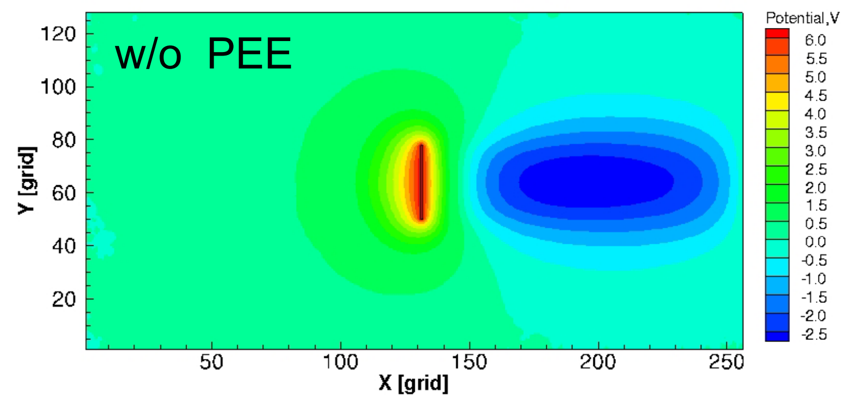
Effect of the Photoelectron Cloud: Reduction of the Electron Sheath due to PEE

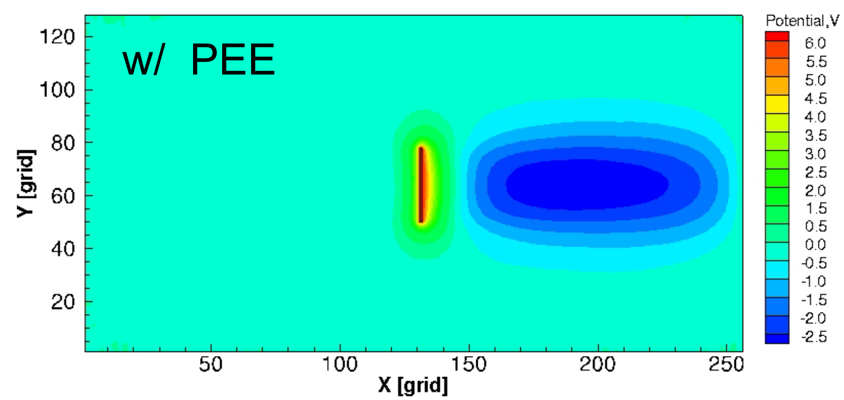
1.0AU, 1PEE(1.5eV) case



y=64, z=64 (center, dx=0.5m)

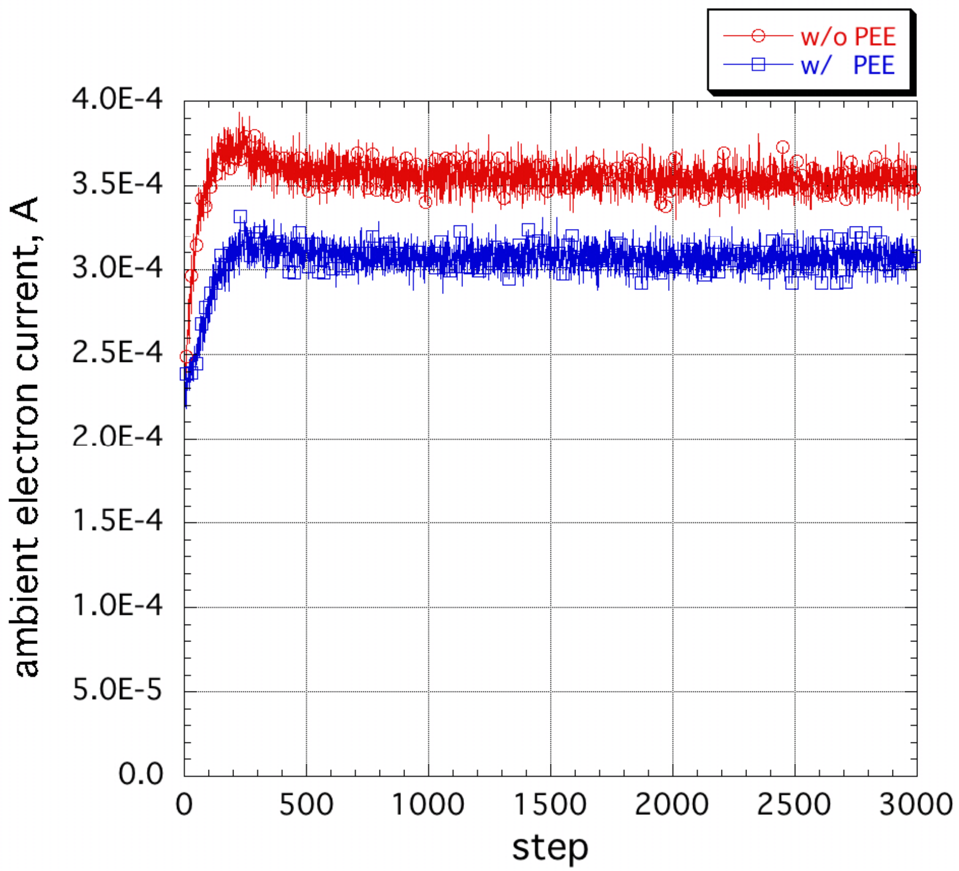
comparative computation results

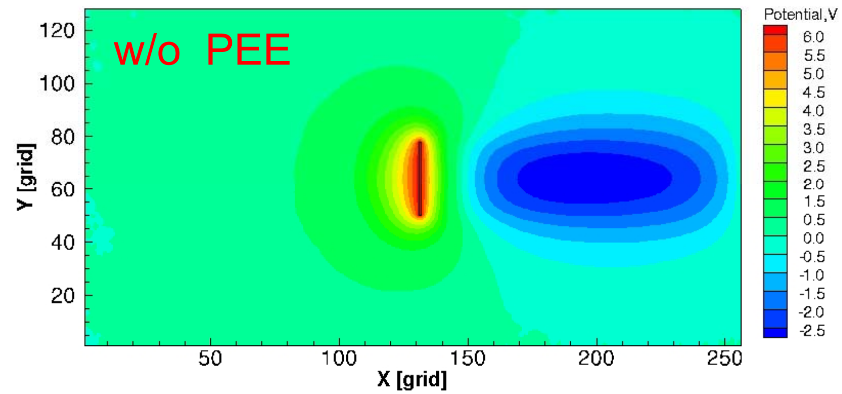


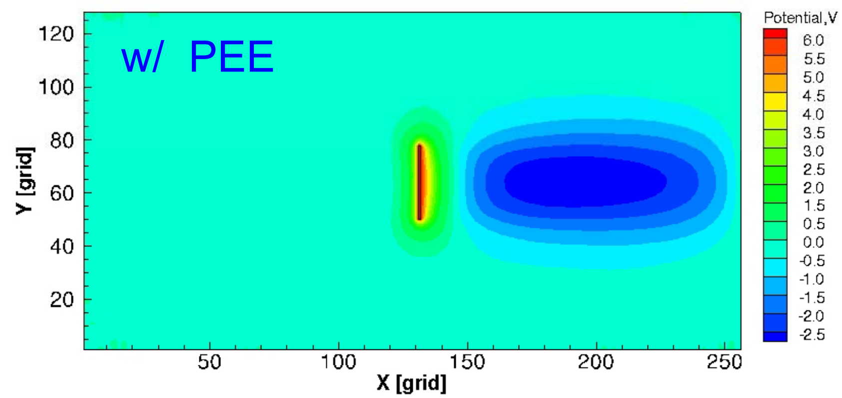


Effect of the Photoelectron Cloud: Reduced Electron Sheath Decreases I_e

smaller ambient electron current with PEE(17% lower in this case)



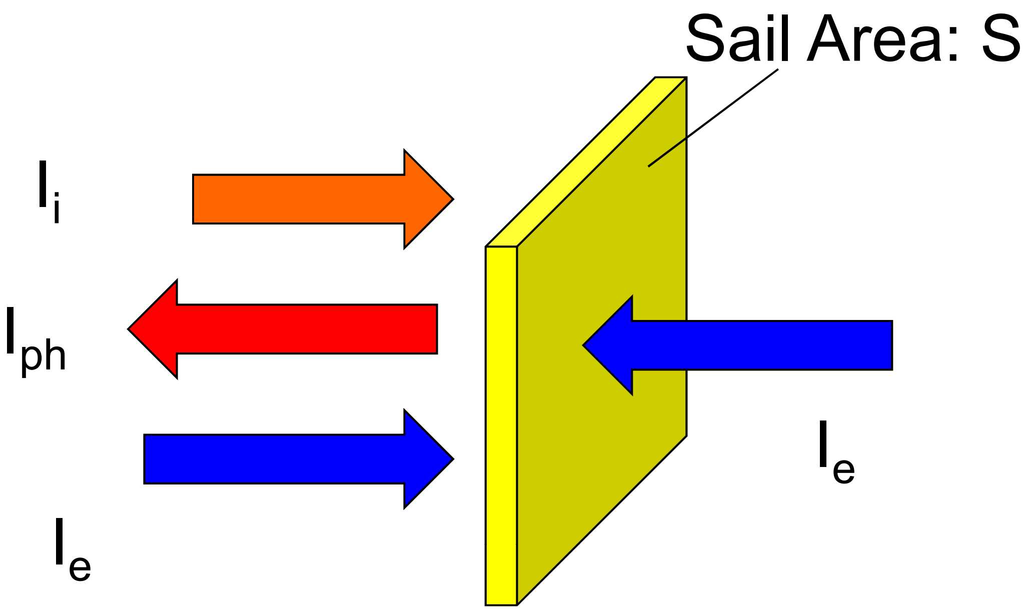




Current Collection Analysis: Brief Estimation of the Current Collection

positive source: I_i, I_{ph}

negative source: I_e



$$I_i + I_e + I_{ph} = 0$$ @Vs(saturate)

Ions: $v_{ti} << v_d$ (~beam)

$$\boxed{I_i \simeq S \cdot q \cdot n_i \cdot v_d}$$

Electrons: $v_{te} >> v_d$, Vs>0

$$\boxed{I_e \simeq -2S \cdot e \cdot n_e \cdot \frac{1}{4}\langle v \rangle \cdot f_m}$$

f_m: magnitude shows the effect of the sheath size on the current collection

thin sheath limit: $f_m = 1$

thick sheath: $f_m = (1 + eV_s / kT_e)$

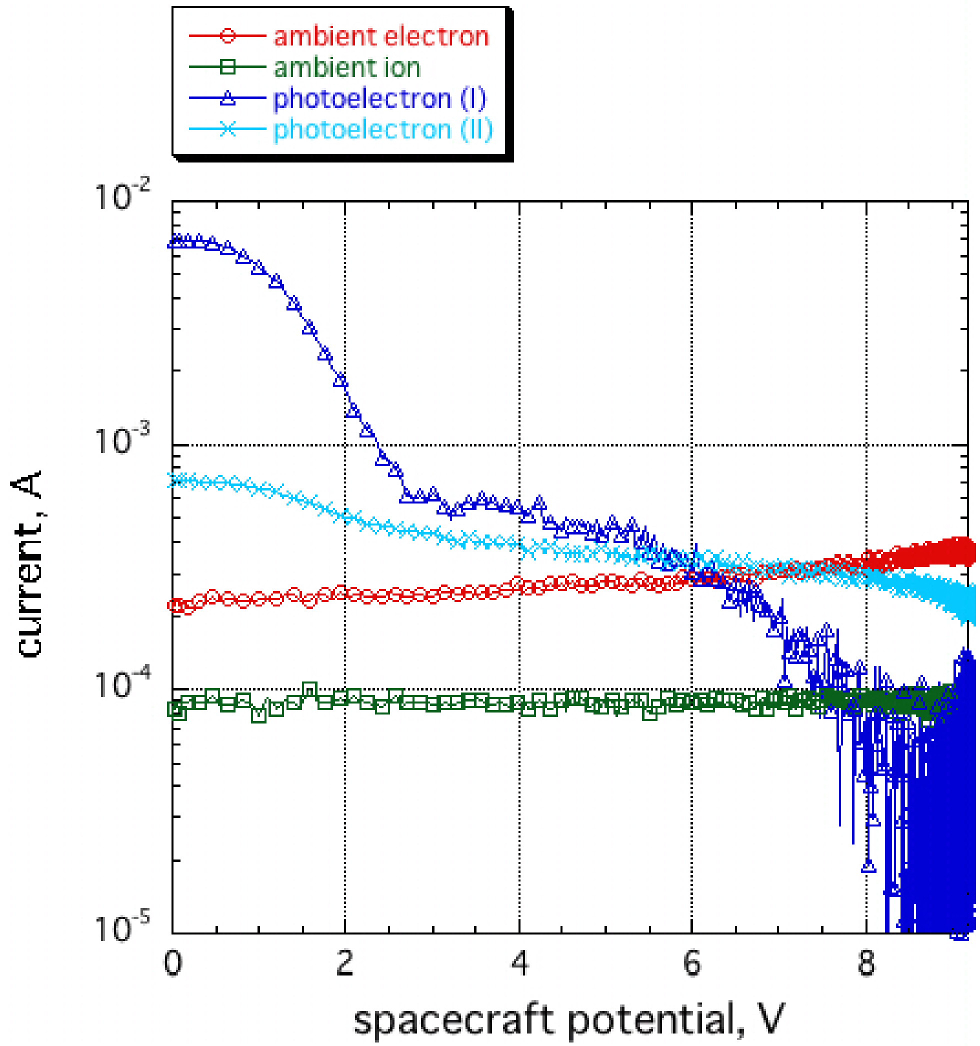
ex. spherical conductor

We show the value of fm numerically

Photoelectrons: Vs>0

$$\boxed{I_{ph} = S \cdot j_{ph0} \cdot \exp(-V_S / kT_{ph})}$$

Current Collection Analysis: Current-Voltage Characteristics @1.0AU



Saturation Value of Vs: +8.3V

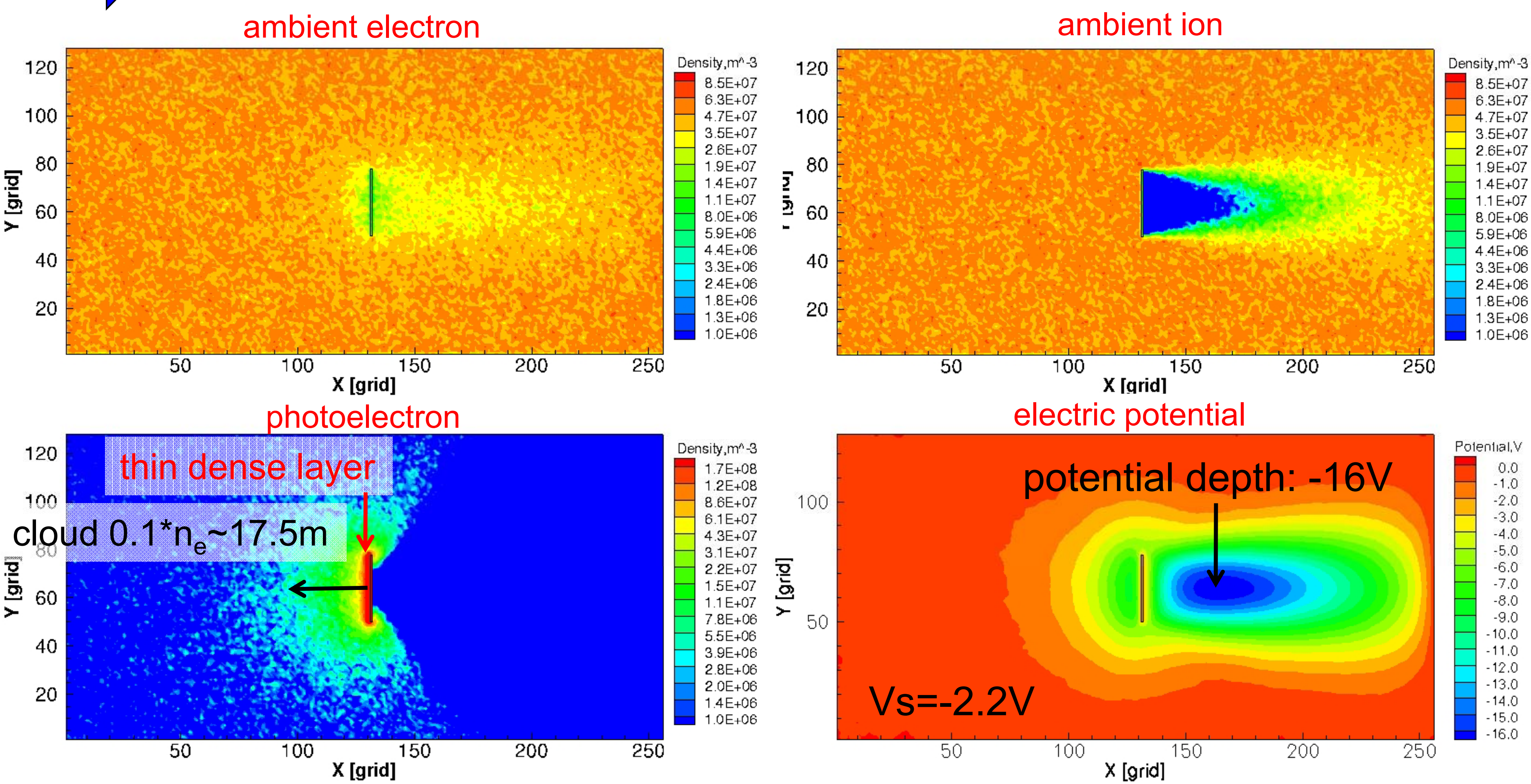
Ion Current: ~ constant

Electron Current: f_m= 1.7

Photoelectron Current: partly follows a simple exponential decrease

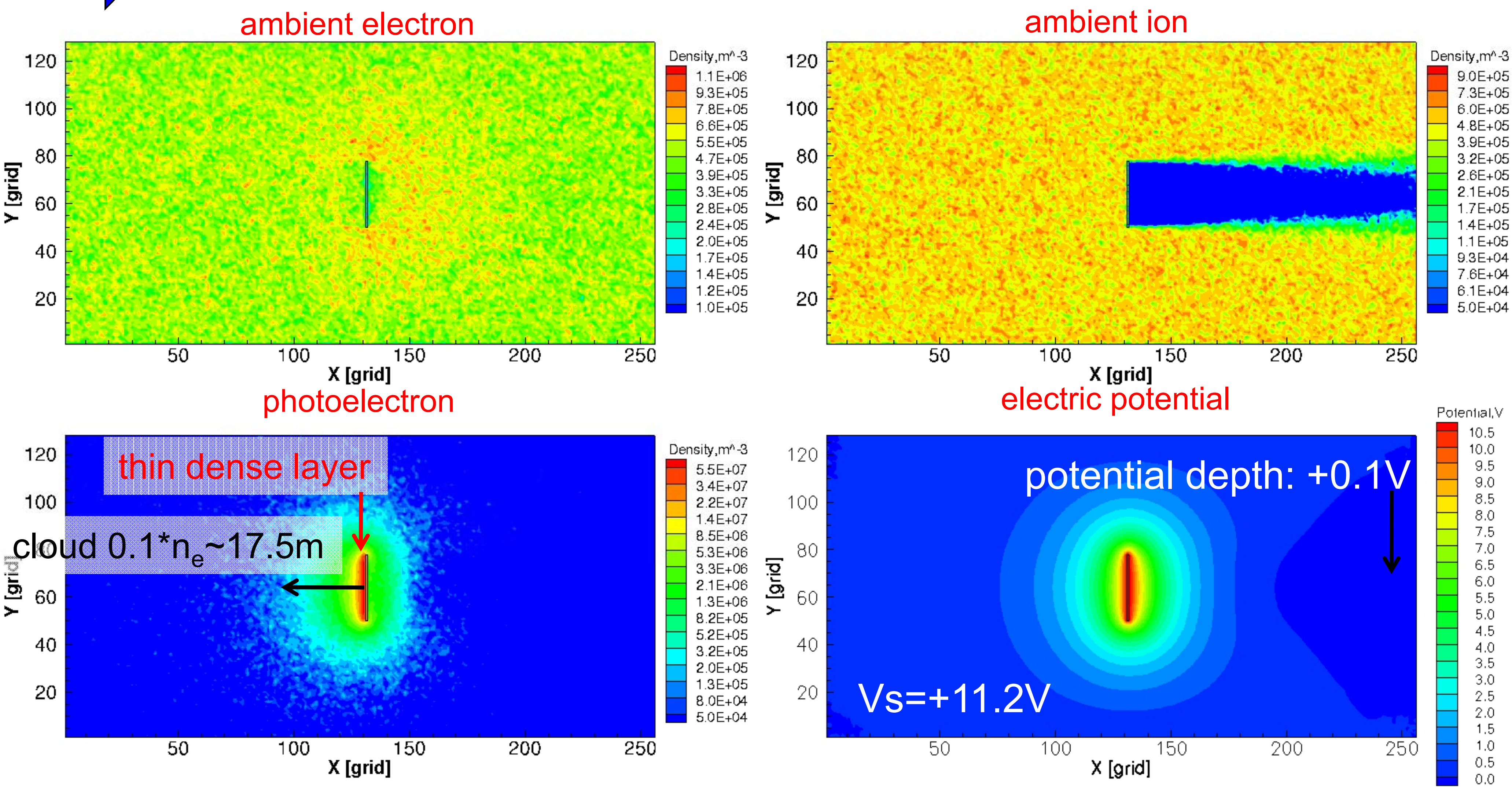
Charged Particle & Potential Profiles@0.5AU

Solar Flux & Plasma flow: left to right, T=40eV, n=50x10^{6} m^{-3}, vd=470km/s, dx=0.5m, 5000steps



Charged Particle & Potential Profiles@3.0AU

Solar Flux & Plasma flow: left to right, T=5eV, $n=0.5\times10^{6}\ m^{-3}$, vd=470km/s, dx=0.5m, 5000steps



cloud inclines to the ram side

Conclusion Remarks
Parameters Obtained from This Study

	Debye length [m]	vd/vti	wake potential [V]	S/C potential [V]	Diff. potential [V]
0.5 AU	6.7 (0.48L)	5.3	-16.0 (-0.4Te)	-2.2 V	--
1.0 AU	9.6 (0.69L)	10.8	-3.0 (-0.3Te)	+8.3 V	-15.8* (MUSCAT)
3.0 AU	23.4 (1.67L)	15.6	+0.1 (+0.02Te)	+11.2V	-11.2* (MUSCAT)

	Ie magnifi-cation: fm	PE dens layer	PE cloud (~0.1*ne)[m]	PE diffusion to the rear
0.5 AU	0.91* (Vs<0)	~1.7x10^{8}m^{-3} in 2.5m	20 (1.42L)	△partly
1.0 AU	1.7	~3.2x10^{8}m in 1.5m	17.5 (1.25L)	○
3.0 AU	2.6	~5.5x10^{7}m in 2.0m	17.5 (1.25L)	◎

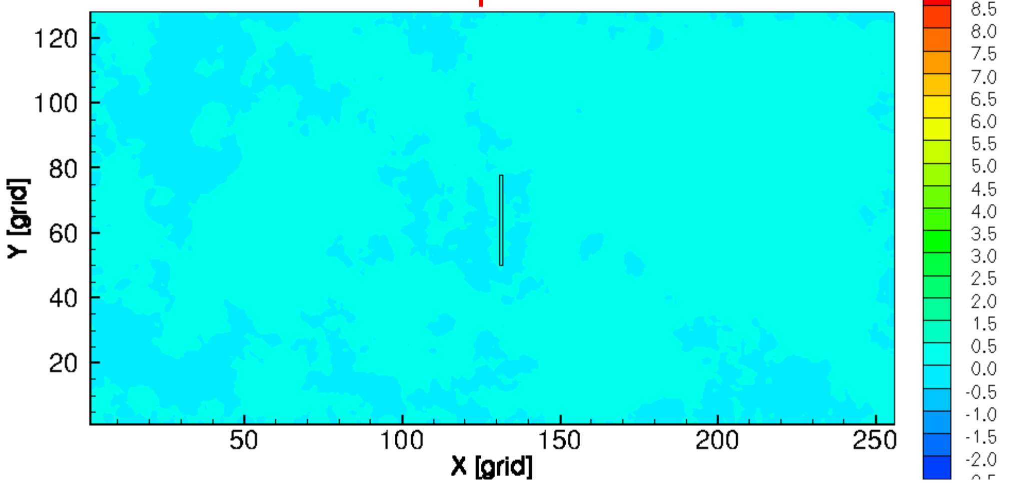
Conclusion

- We had numerically analyzed solar sail charging in interplanetary plasma environment, focusing on the spatial distribution of the charged particles around the sail. The results can provide a guideline for the solar sail design, especially for onboard electrical instruments.
- A wake potential is formed due to a large ion wake. The potential obstructs the diffusion of the photoelectrons to the rear surface of a sail. Besides, the degradation of the positive floating potential of the sail by the wake potential could not be negligible depending on its depth.
- Photoelectron cloud is formed around the sail including the downstream region. That can lead to the reduction of the electron sheath, which result in decrease of the ambient electron current collection onto the sail. The effect on the ambient electron current is numerically shown by the parameter *f*m.
- Differential voltage on the rear insulator surface of the sail will affects the wake potential and suppress the photoelectron diffusion to the downstream region of the sail.

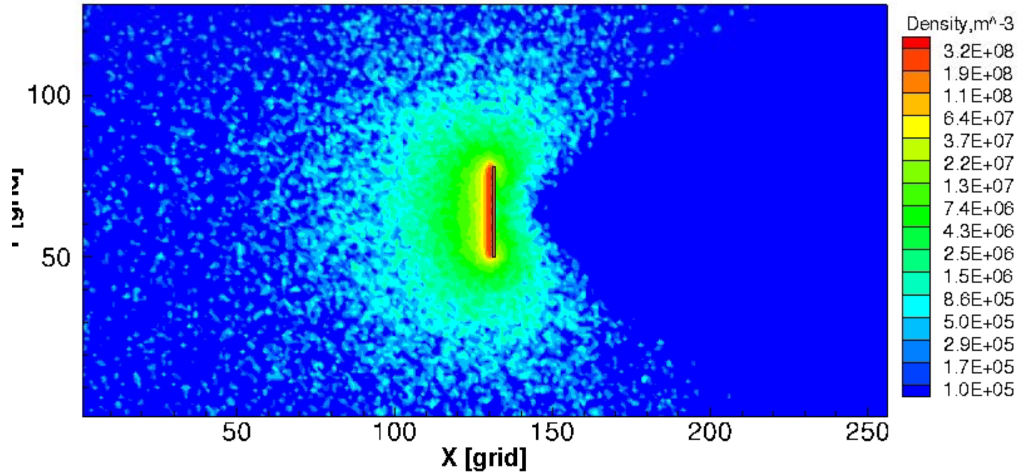
Plasma Analysis Results @1.0AU (2/2)

Solar Flux & Plasma flow: left to right, T=10eV, n=6×10^6 m^{-3}, vd=470km/s, dx=0.5m

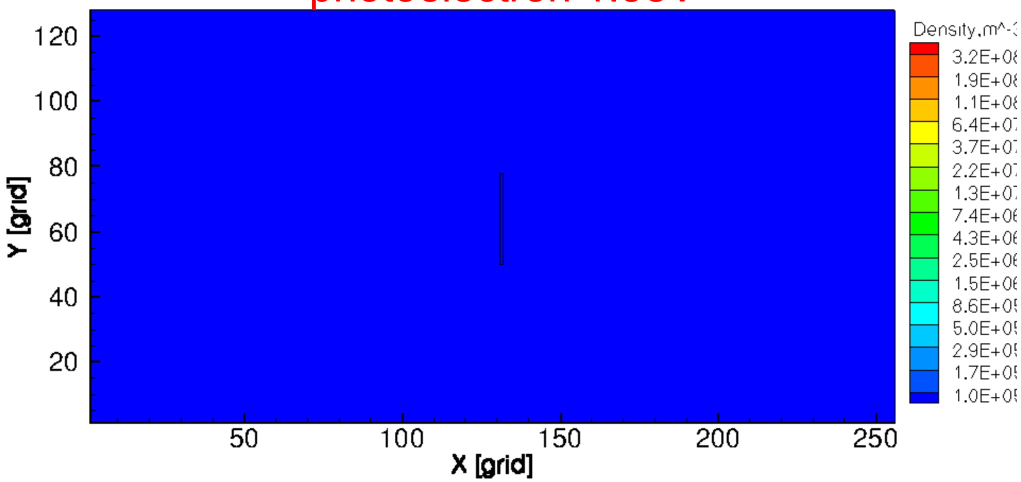
electric potential



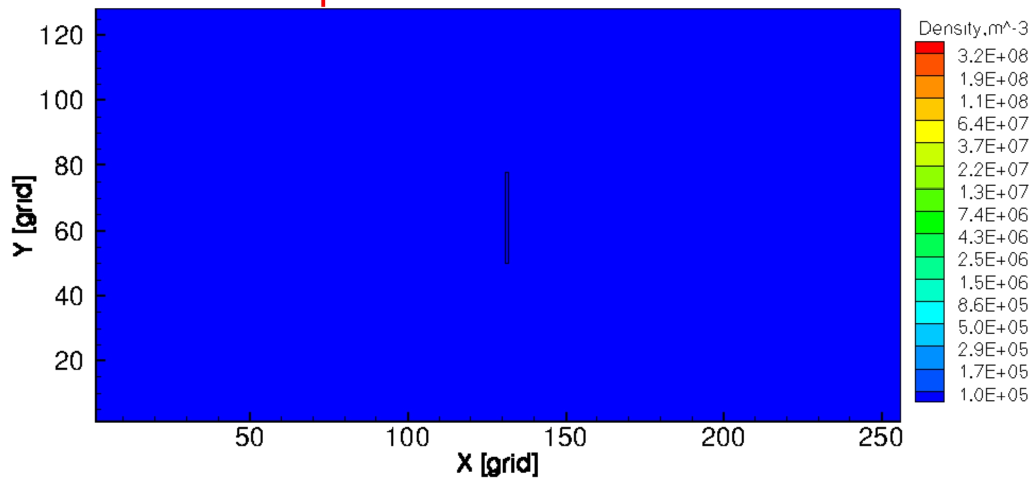
total photoelectron



photoelectron 1.5eV



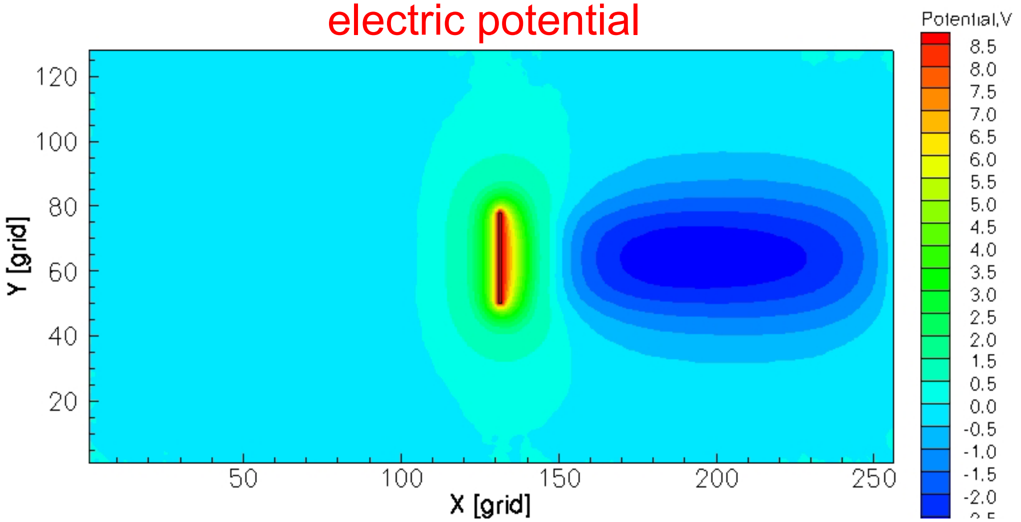
photoelectron 5.0eV



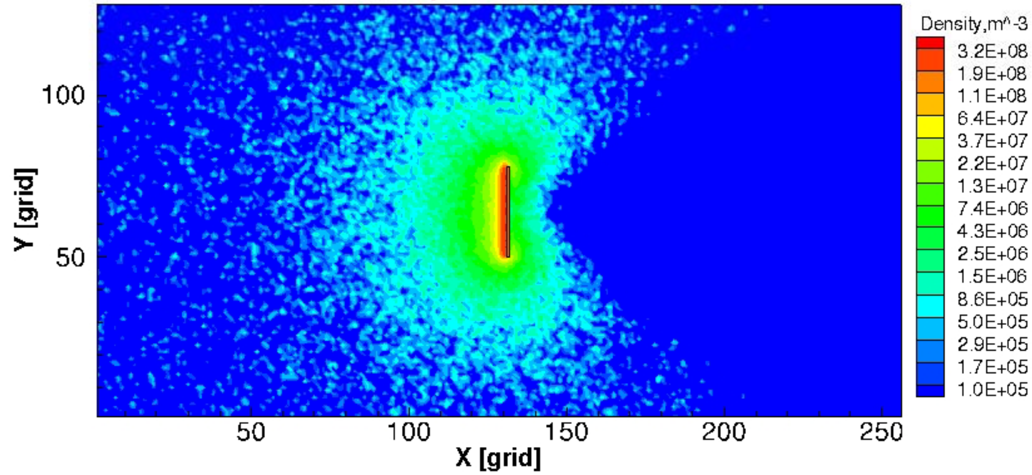
Charged Particle & Potential Profiles@1.0AU

Solar Flux & Plasma flow: left to right, T=10eV, n=6x10^{6} m^{-3}, vd=470km/s, dx=0.5m

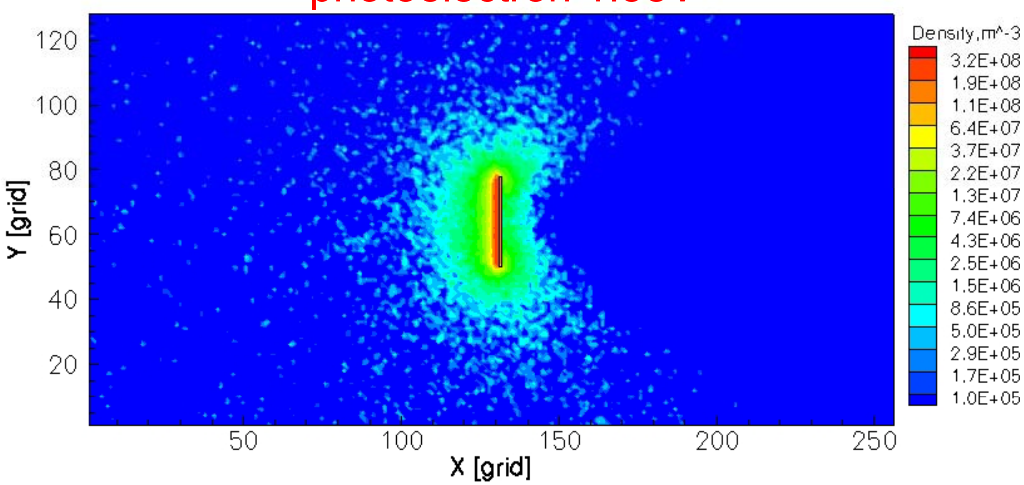
electric potential



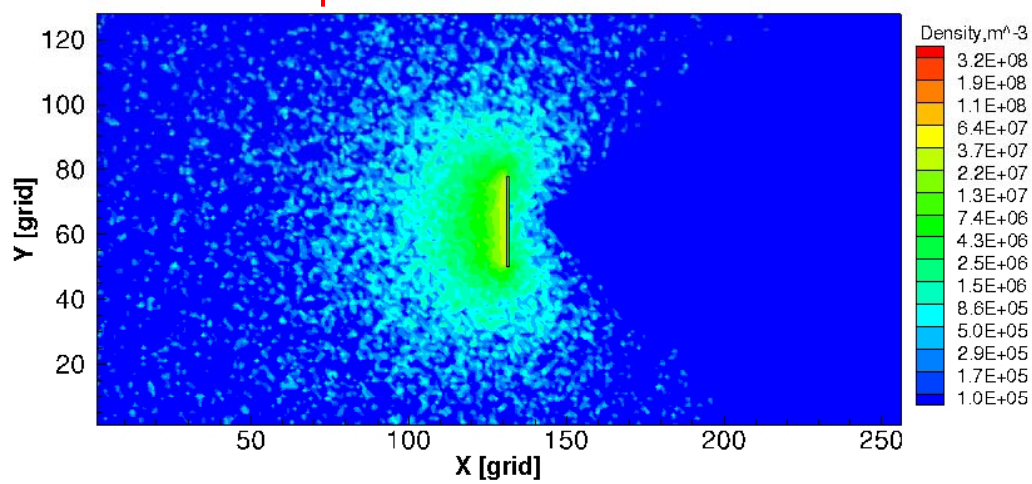
total photoelectron



photoelectron 1.5eV



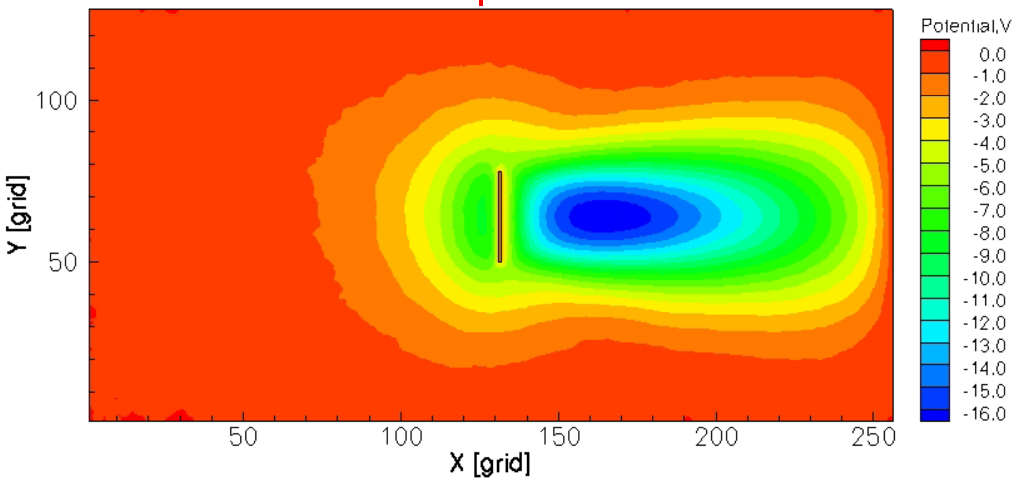
photoelectron 5.0eV



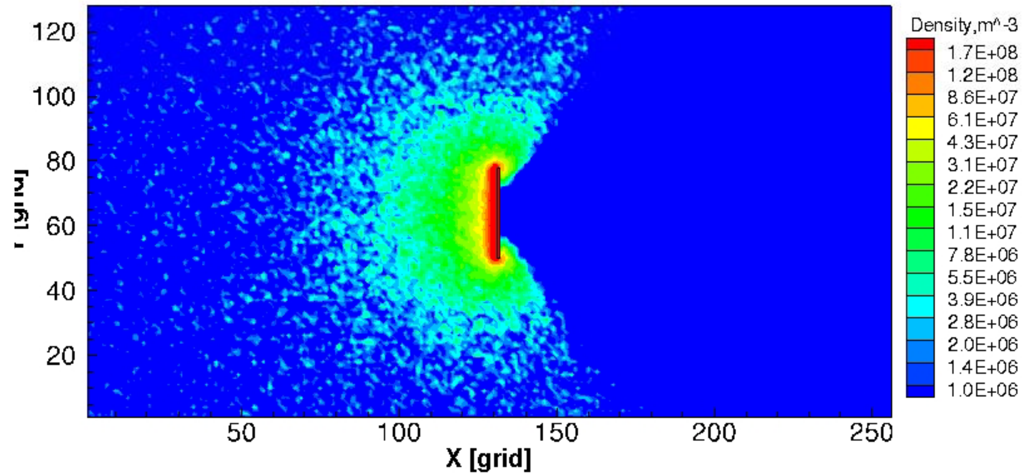
Plasma Analysis Results @0.5AU (2/2)

Solar Flux & Plasma flow: left to right, T=40eV, n=50x10^{6} m^{-3}, vd=470km/s, dx=0.5m, 5000steps

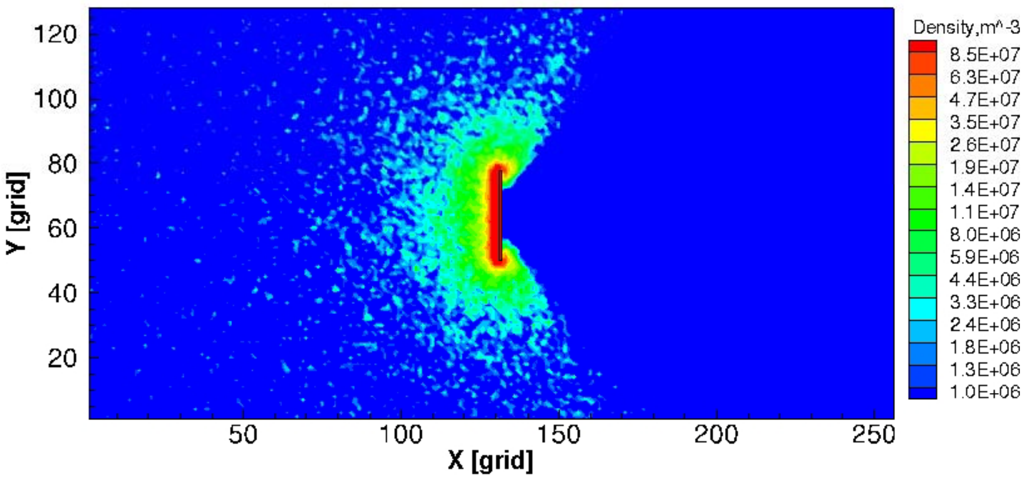
electric potential



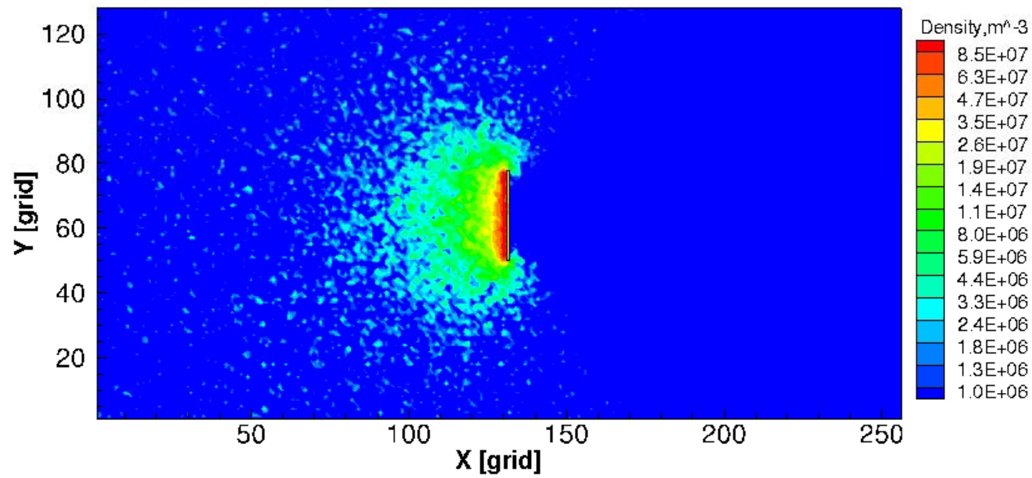
total photoelectron



photoelectron 1.5eV



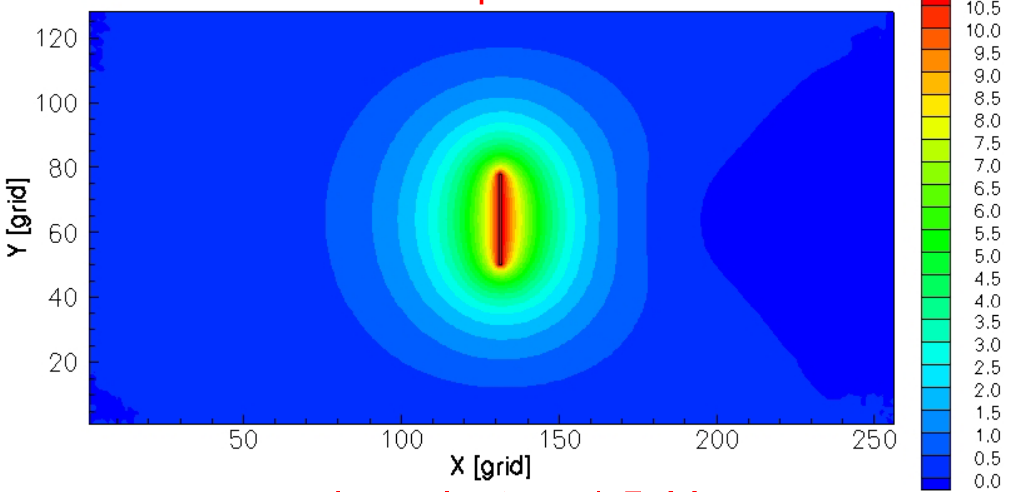
photoelectron 5.0eV



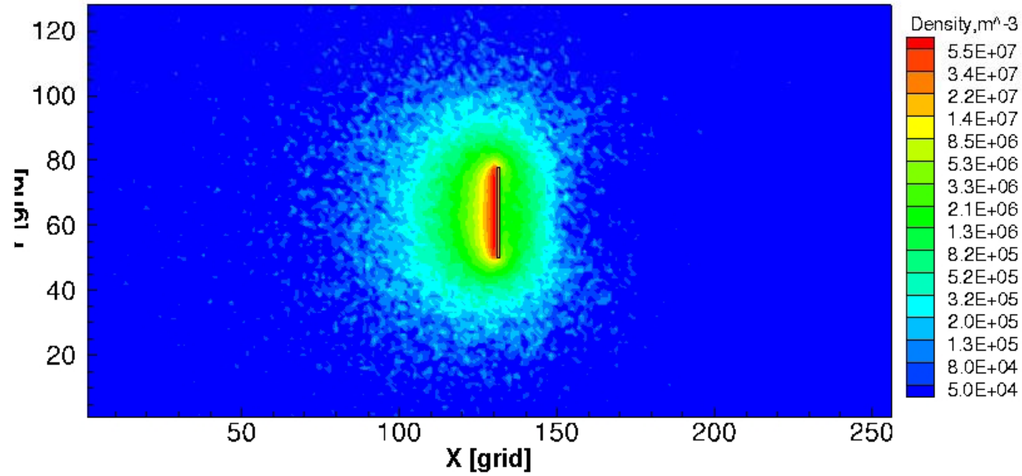
Plasma Analysis Results @3.0AU (2/2)

Solar Flux & Plasma flow: left to right, T=5eV, n=0.5x10^{6} m^{-3}, vd=470km/s, dx=0.5m, 5000steps

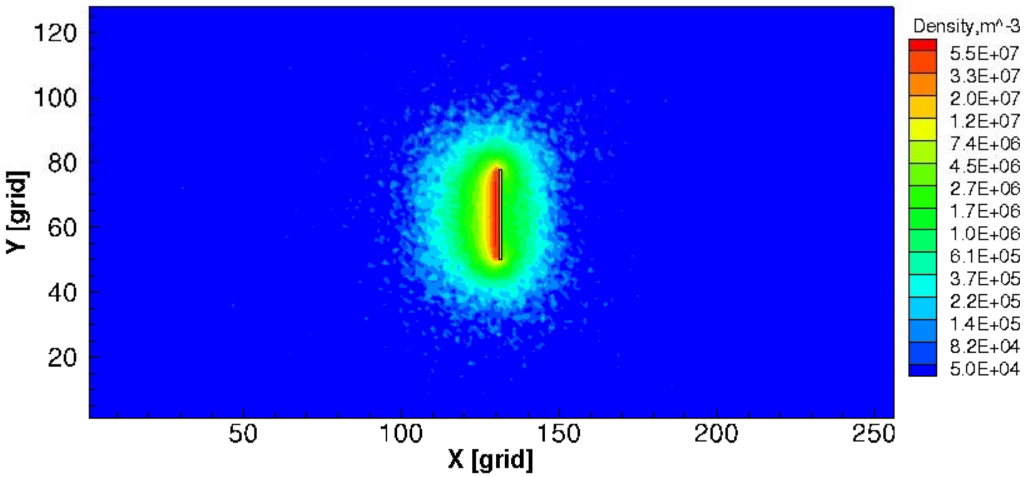
electric potential



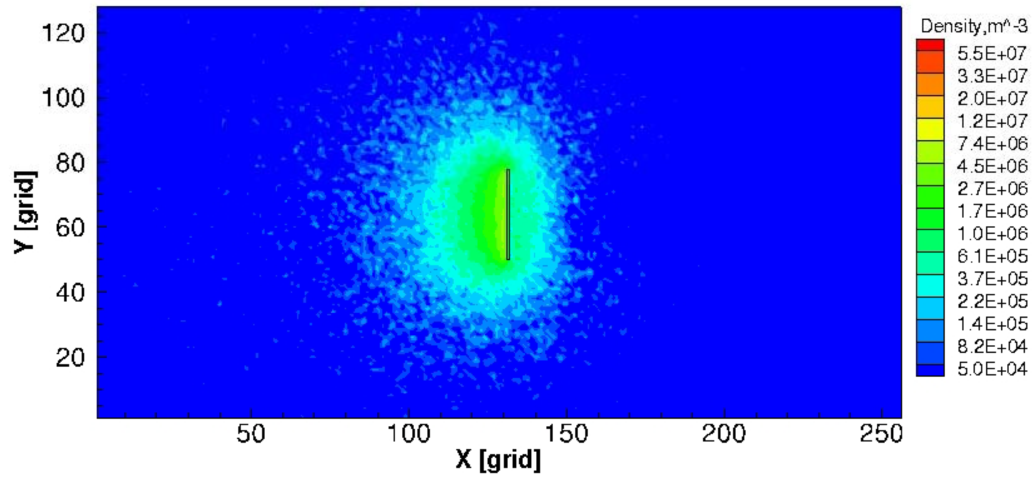
total photoelectron



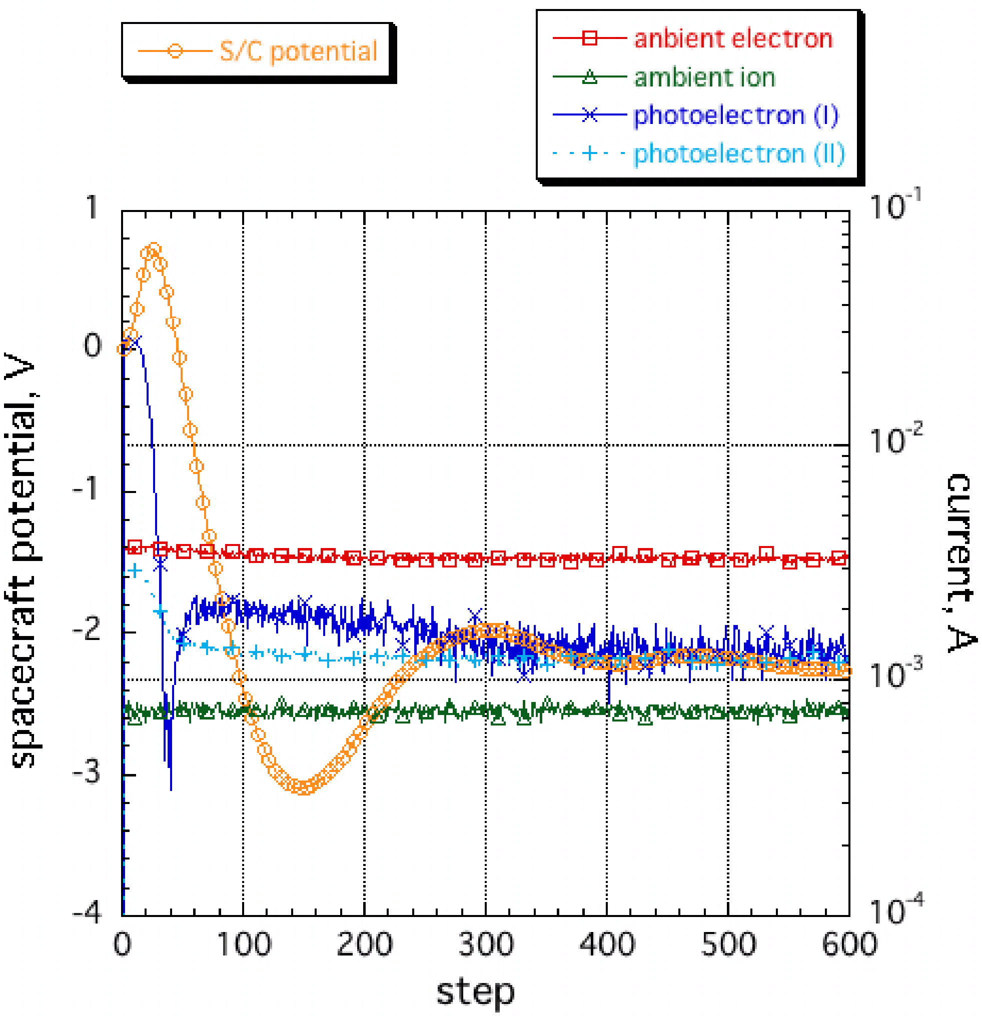
photoelectron 1.5eV



photoelectron 5.0eV



Current Collection Analysis: Current-Voltage Characteristics @0.5AU



Saturation Value of Vs: -2.2V affected by the wake potential

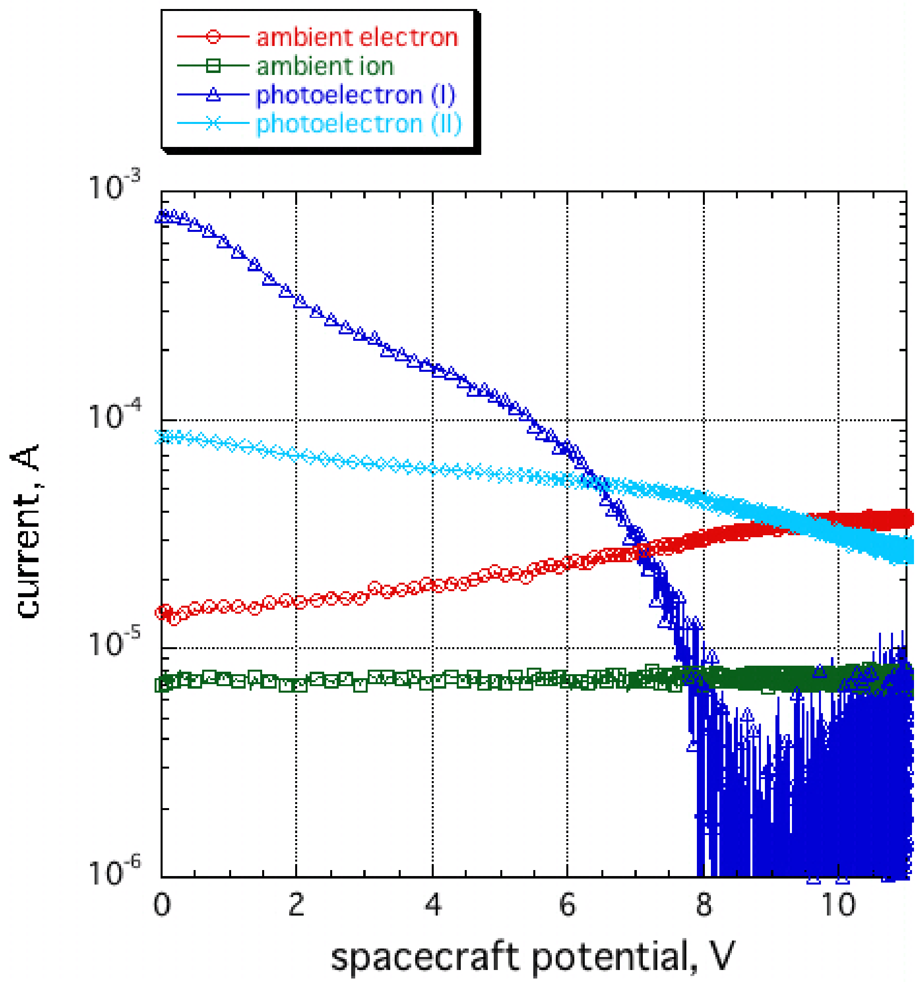
Ion Current: ~ constant

Electron Current: f_m= 0.91* (Vs<0)

Photoelectron Current:

- Iph<Iph0 at Vs<0, due to negative space potential
- $I_{PE(1.5eV)} \sim I_{PE(5.0eV)}$

Current Collection Analysis: Current-Voltage Characteristics @3.0AU



Saturation Value of Vs: +11.2V

Ion Current: ~ constant

Electron Current: f_m= 2.6

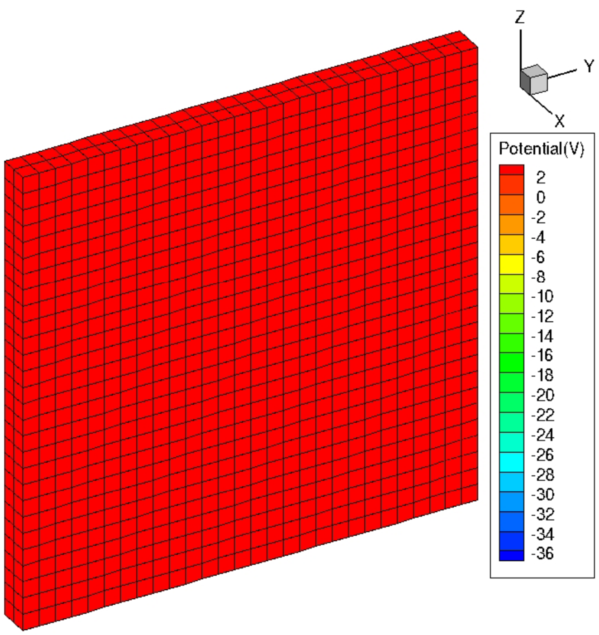
Photoelectron Current: $I_{PE(5.0eV)} >> I_{PE(1.5eV)}$@Vs(saturate)

Differential Voltage Estimated by MUSCAT

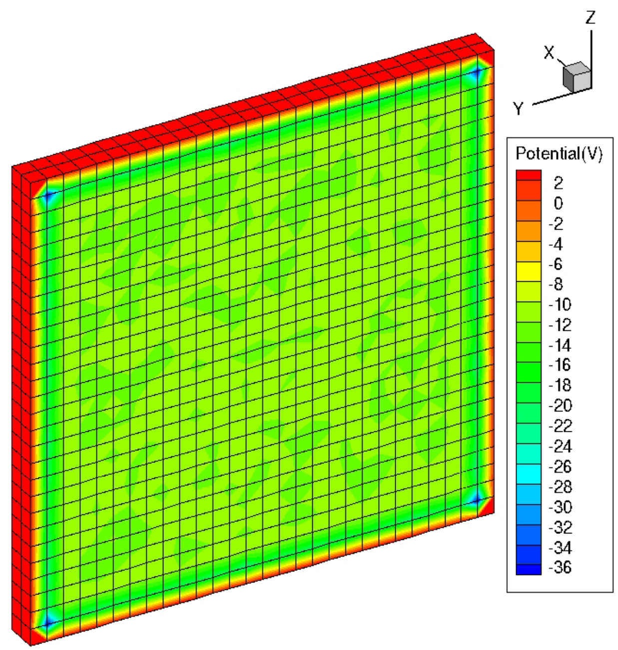
@1.0AU, 1PEE(1.5eV, Jph=1.0Jph0), t=320s

body potential: 3.2V

differential voltage: -15.2V



front:conductor

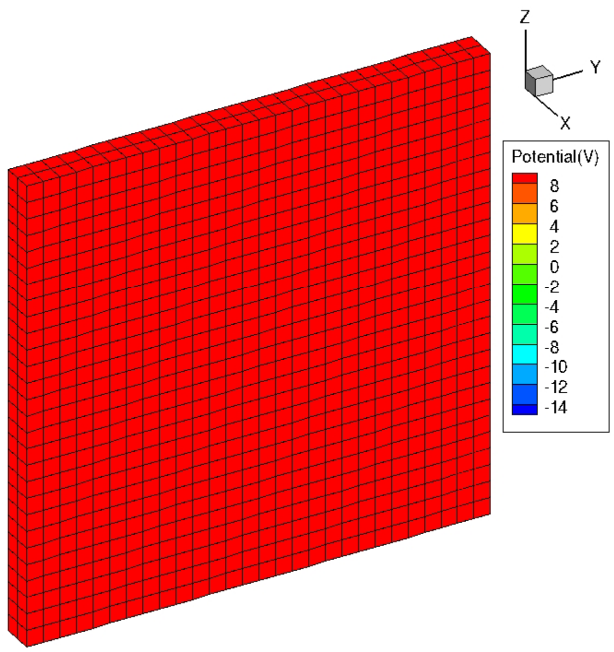


rear:7.5um Kapton

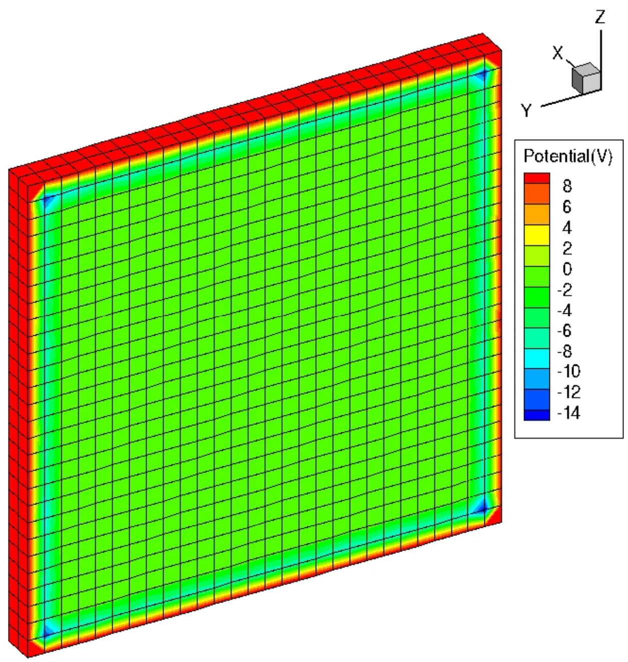
Differential Voltage Estimated by MUSCAT

@3.0AU, 1PEE(5.0eV, Jph=0.1Jph0), t=3860s

body potential: 10.3V
differential voltage: -11.8V



front:conductor



rear:7.5um Kapton