

Lunar Vehicle Active Charge Control System (LVACCS)+

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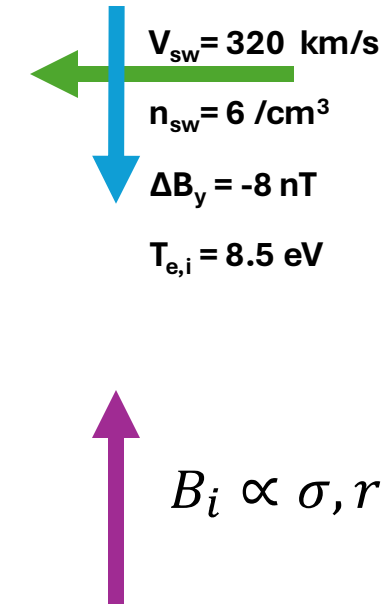
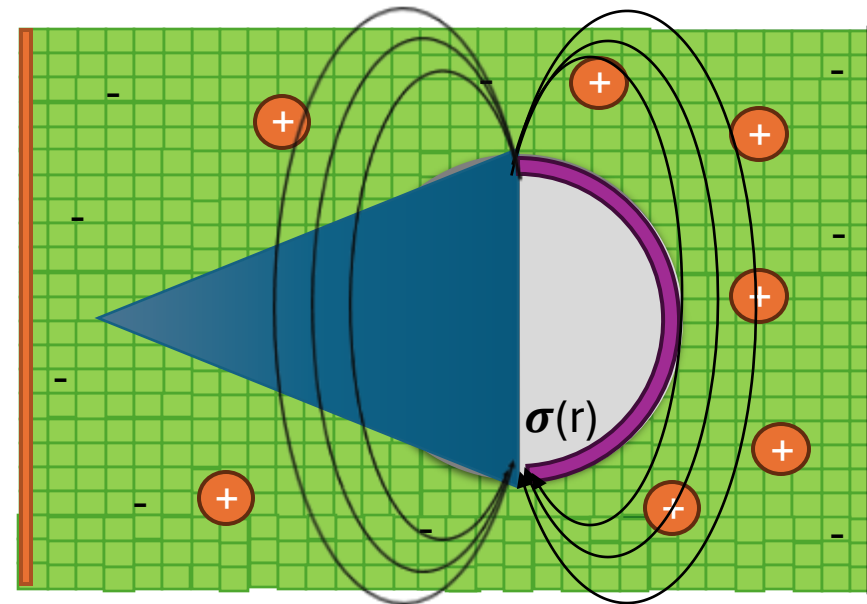


Outline

- The Lunar Induced Magnetic Field & Plasma Wake Interactions
- Lunar Plasma Environments for NASA Crewed Missions
- Open Questions
- Lunar Vehicle Active Charge Control System (LVACCS)
 - Objectives
 - Capabilities
 - Development Plan
- Conclusion

Transient Plasma Hybrid Kinetic Induction Model

General SW Case, Perpendicular
AMITIS, Fatemi et al., 2017

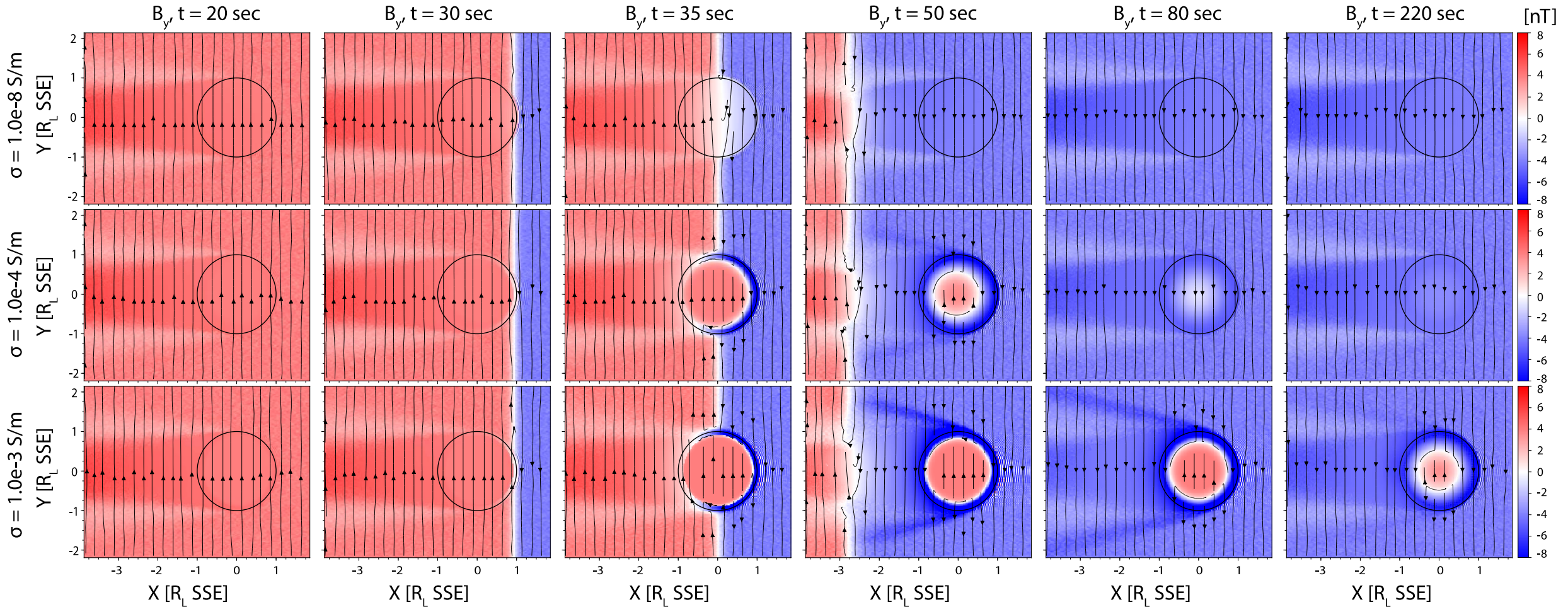
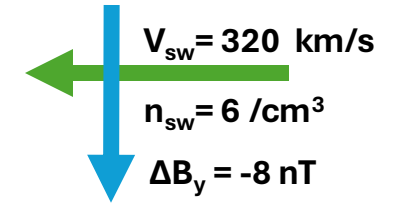


- Cell size: 50 km ($\sim 0.028 R_L$)
- 16 macroparticles (only protons) per cell
- $t_{step} = 0.001 \text{ s}$
- $0 < t < \sim 300 \text{ s}$, $t = 24 \text{ s}$ IMF discontinuity
- $\sigma_1 = 1.0 \text{ e} - 8, 1.0 \text{ e} - 4, 1.0 \text{ e} - 3 \text{ [S/m]}$
- At $t = 0$, $B_{IMF} = [0, +4, 0] \text{ nT}$
- At $t = 24 \text{ s}$, $B_{IMF} = [0, -4, 0] \text{ nT}$
- $\Delta B_y = -8 \text{ nT}$
- $\sigma_{vac} = 2.0 \text{ e} - 7 \text{ [S/m]}$

- Conducting radius (r_1) = 1,600 km ($\sim 0.91 R_L$, or ~ 32 cells), $\sim M_{ind} = 1.64 \text{ e} 17 \text{ A m}^2$ (Fatemi et al., 2015; Saur et al., 2010).
- Resistive crust ($1 \text{ e} - 8 \text{ S/m}$) radius = 150 km (~ 3 cells crust). $R_L = 1750 \text{ km}$.
- Model captures inductive and plasma response self-consistently
- SSE Coordinate System: Selenocentric Solar Ecliptic ($+X_{SSE}$ points towards the sun)

Fuqua Haviland et al., 2019. GRL.

Results: Time Dependence

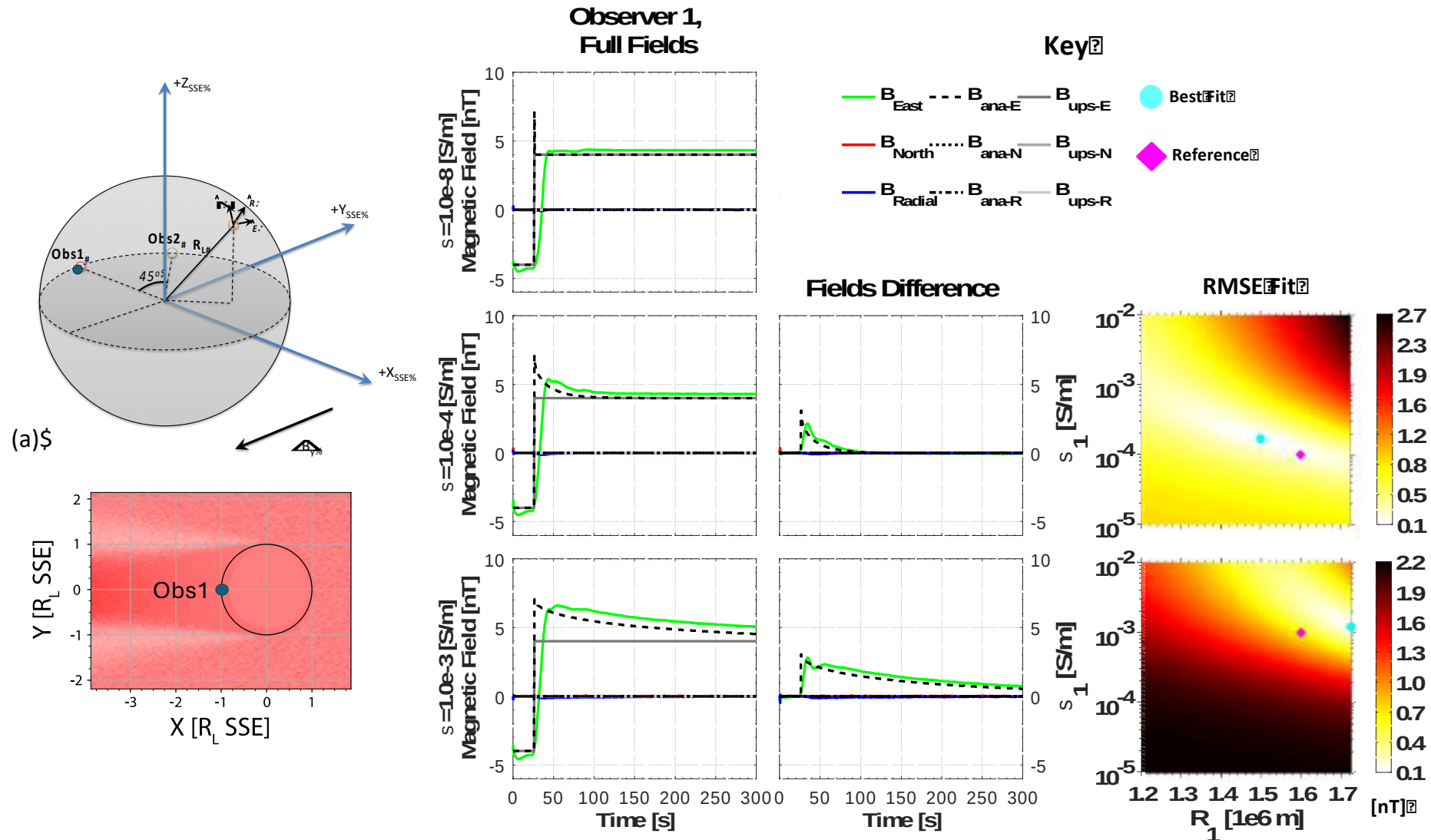


SSE Coordinate System (+ X_{SSE} points towards the sun)

$R_L = 1850 \text{ km}$

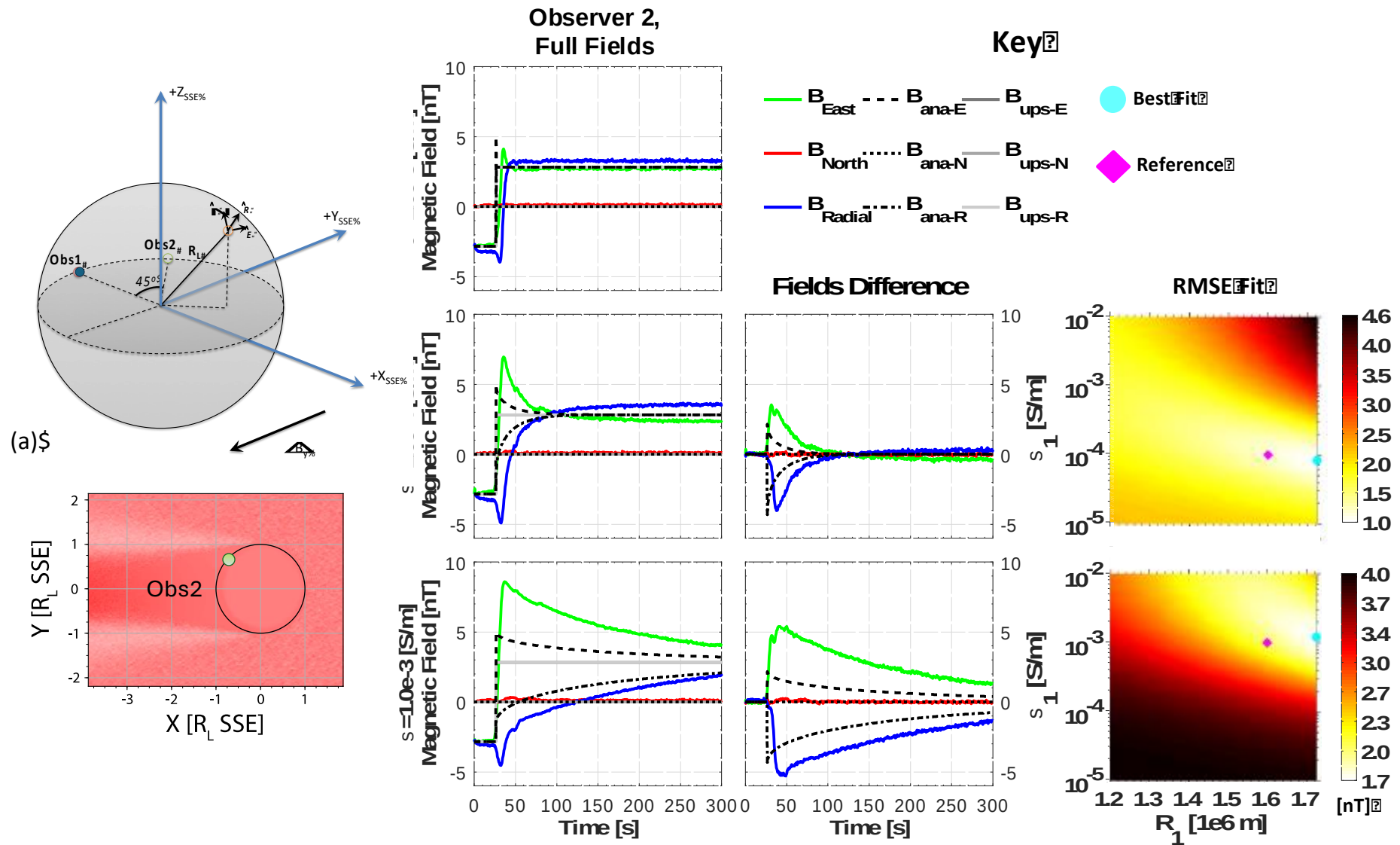
Fuqua Haviland et al., 2019. GRL.

Results: Case Study 1 Time Series



Fuqua Haviland et al., 2019. GRL.

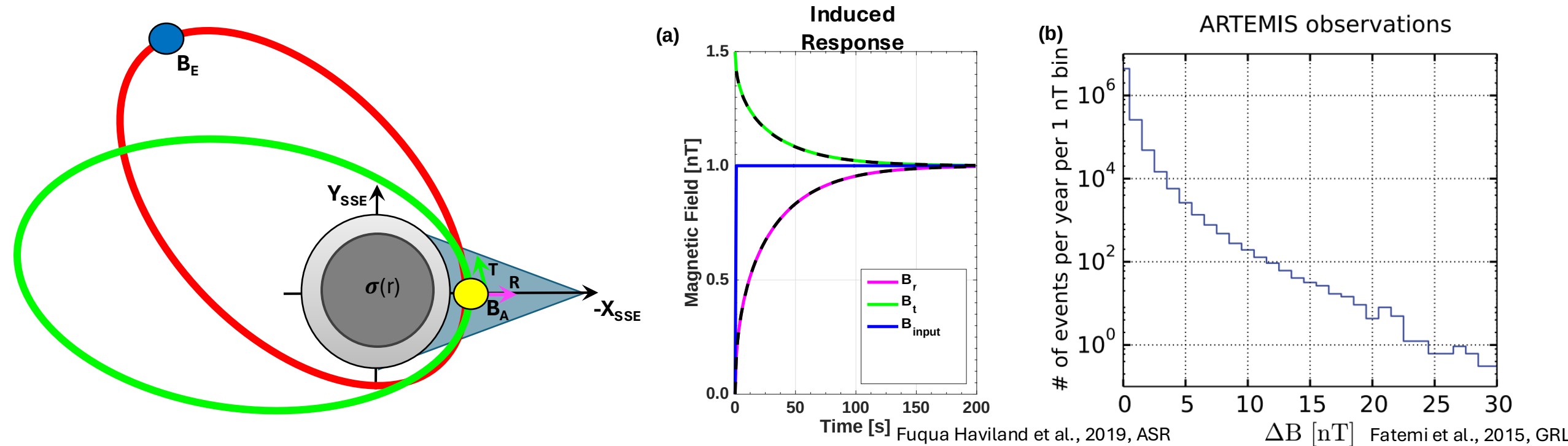
Results: Case Study 2 Time Series



Fuqua Haviland et al., 2019. GRL.

Nightside Time Domain Electromagnetic Sounding with ARTEMIS: Challenges of Isolating Induction from the Lunar Interior

Heidi Fuqua Haviland (NASA MSFC), Andrew Poppe (UCB SSL), Shahab Fatemi (Univ. of Umea)



Goal is to identify induction from the lunar interior within ARTEMIS FGM data where the plasma environment is quiet and there is no inference from crustal magnetic fields. Use measured induction to perform geophysical inversion to constrain electrical conductivity as a function of depth. Focus on sounding mantle depths. Will not be able to sound the core with ARTEMIS due to limited duration of the periselene passes.

ARTEMIS Wake Summary Plots Event 1

Visual Inspection: Wake Summary Plots

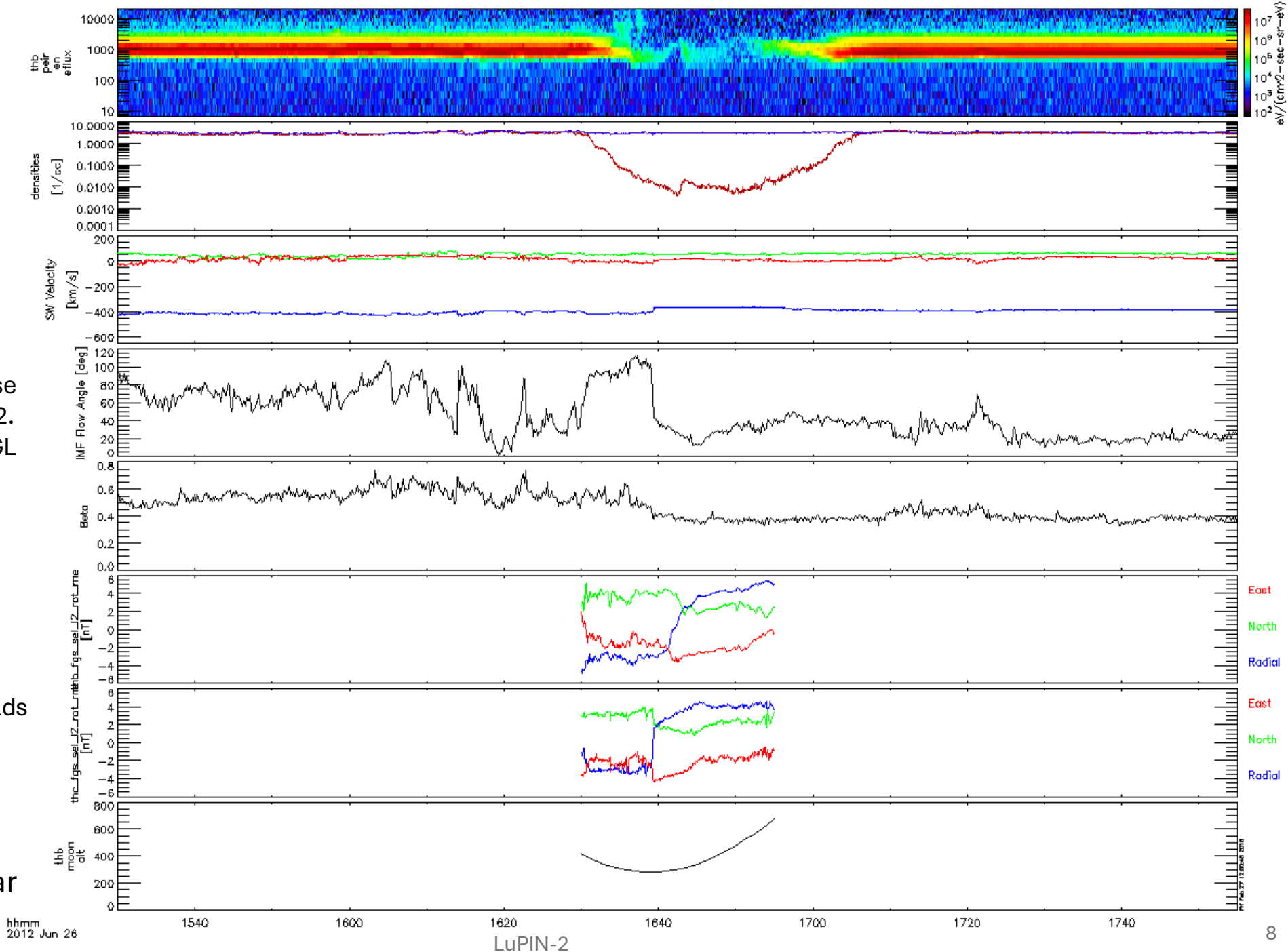
ARTEMIS plasma & fields processed data:

1. Load, process, and plot datasets:
 - Lower probe: FGL L1 w/eclipse corrections, Ref Probe FGL L2.
 - RNE coordinate transform FGL SEL
2. Also considering times of CMEs or other space weather event.

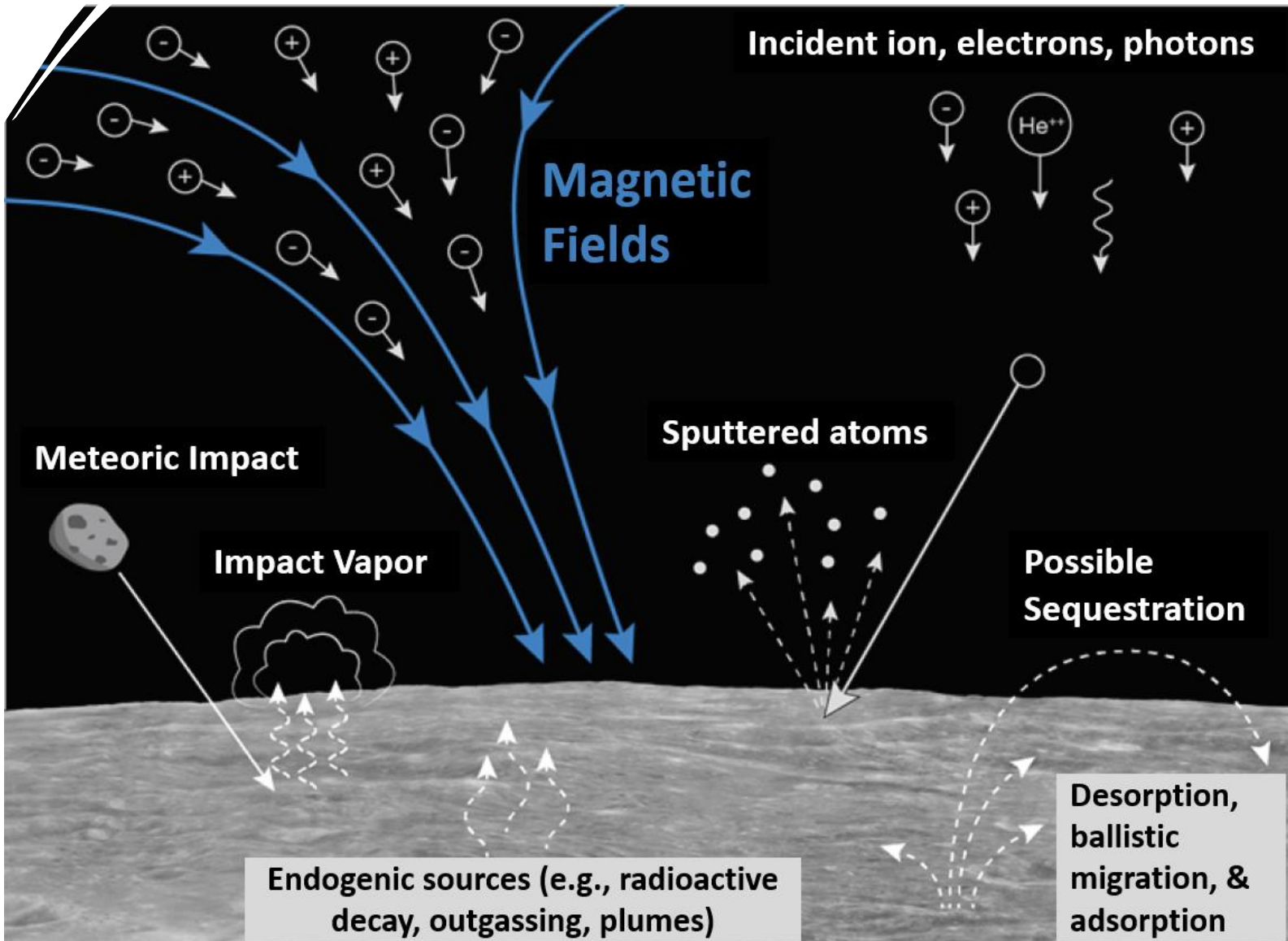
Potential sources of plasma challenging sounding:

- Limb shocks
- Particle reflections from crustal fields
- And others

Project is in work and will
continue analyzing data to
isolate induction from the lunar
interior.



Plasma Environment



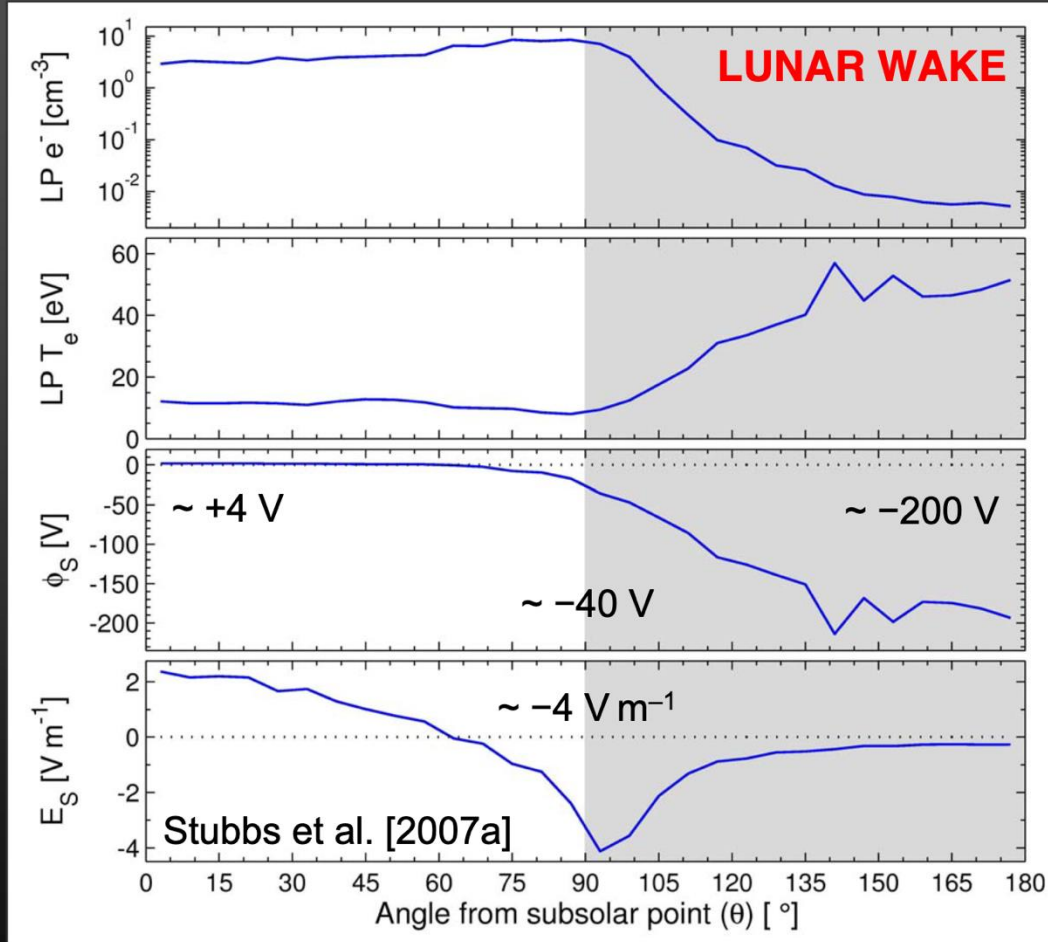
Multiple processes contribute to the formation and evolution of surface boundary exospheres (NASA, 2023).

Interest in the role lunar crustal magnetism and surface charging plays in the plasma environment.

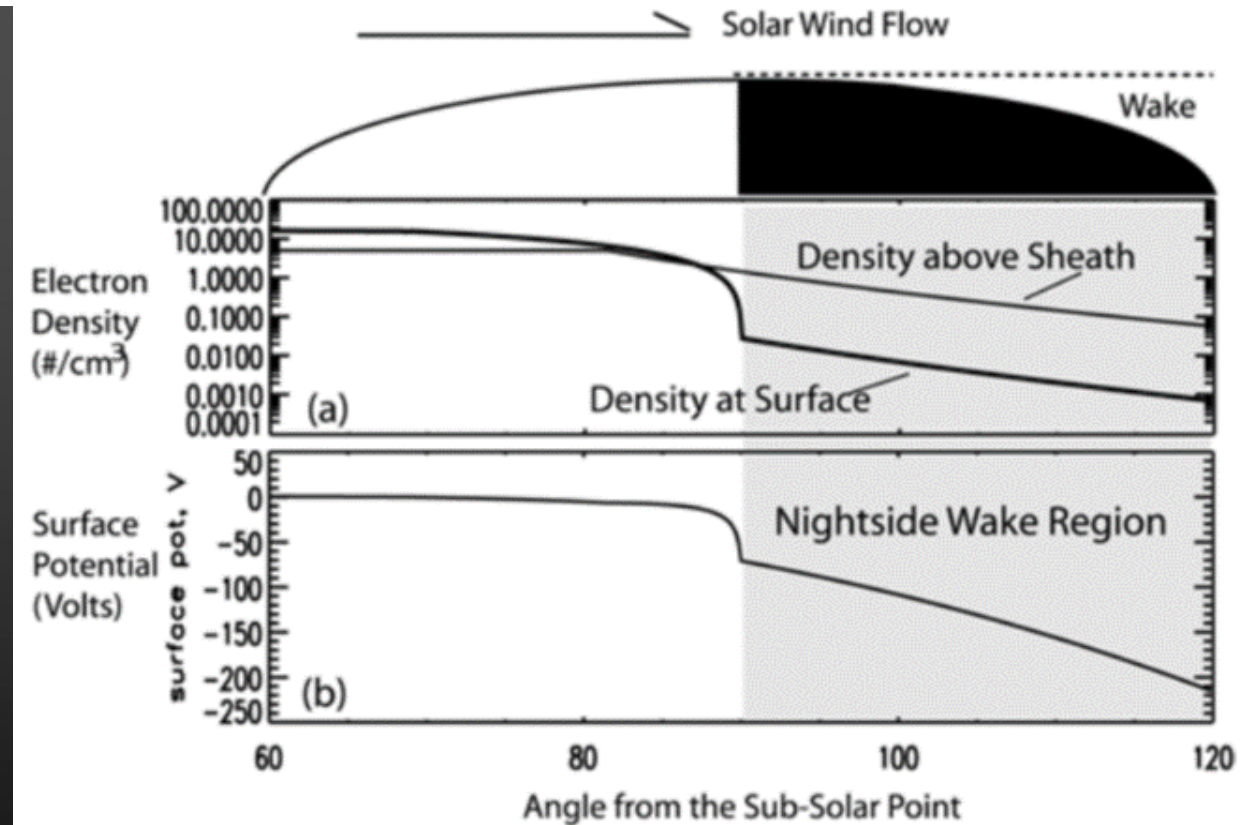
Lunar Surface Charging in the Solar Wind

Lunar Prospector
Electron Observations

Surface Charging
Predictions

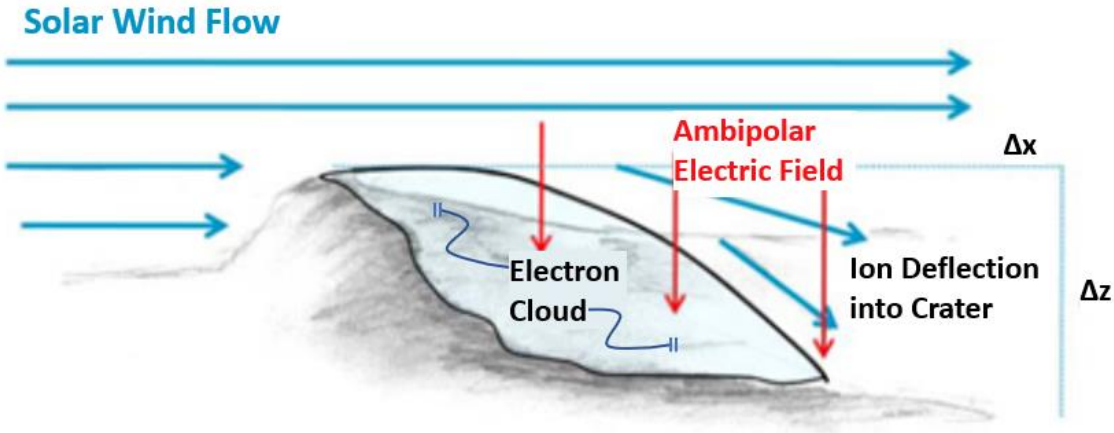


Using Lunar Prospector Data to make surface charging predictions (Stubbs et al., 2007a).

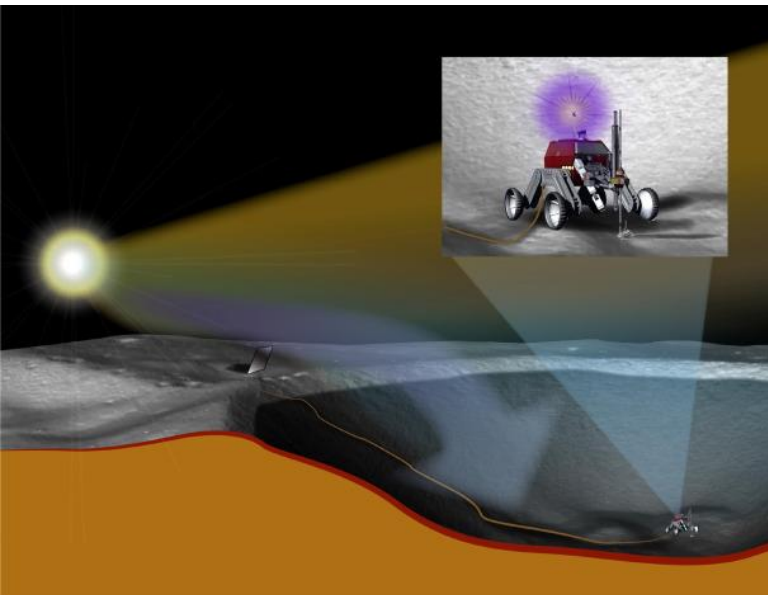


Modeled surface potential changes with local time (Farrell et al., 2008).

Polar Plasma



Polar plasma environment when exposed to the solar wind flows obliquely to the surface causing mini-wake features to form on the downward edge of vertical obstructions such as crater walls or behind large boulders, etc (Farrell et al., 2010). Mini wakes have been shown to influence even small scale features (Zimmerman et al., 2011).



Rhodes et al (2020) estimate a drill to accumulate $-3.3 \mu\text{A}$ of triboelectric current and the drill at near and far edges of a simulated Shackelton crater reach potential are estimated to reach values on the order of a million volts (negative) over the course of 10 s.

Lunar Plasma Environments for NASA crewed Missions

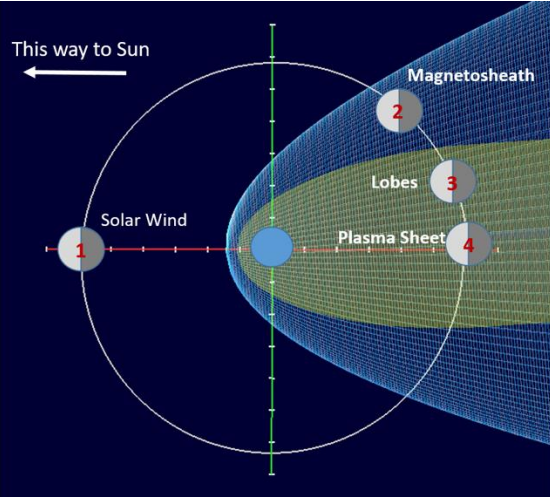
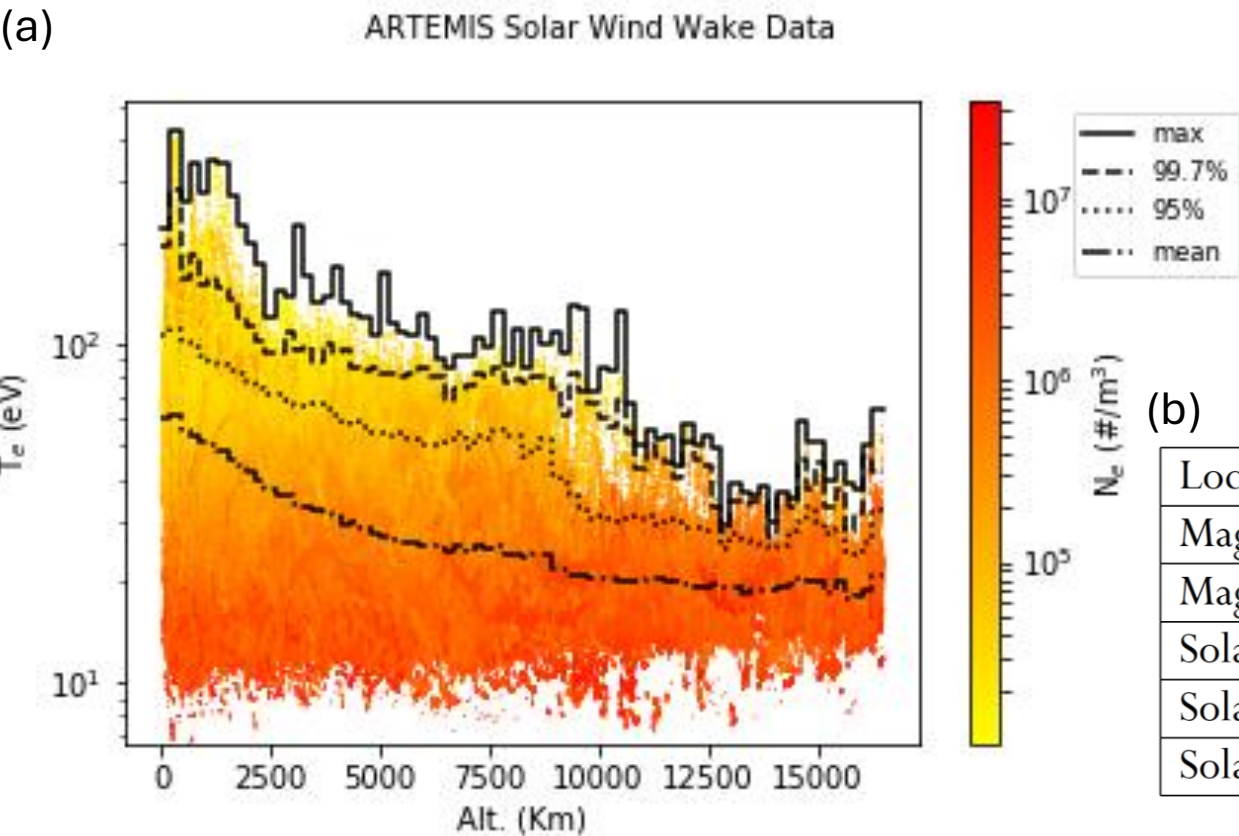


Fig.20 Lunar surface potentials according to

Location	Sunlight (V)	Darkness/shadow (V)
Magnetotail Lobe	0	-100
Magnetotail Plasma Sheet	0, -500 (rare)	-1000
Solar Wind	0	- 500 , -4500 (rare)
Solar Wind Terminator (SZA > 60)	- 50	-200
Solar Wind Local Surface Wake	- 50	-100

(a) Electron temperature versus altitude for plasma in the solar wind wake. (b) Lunar surface potentials according to location (Willis, Emily M., et al (In Prep). “**Lunar Plasma Environment for NASA Crewed Missions**”; Willis, Emily M., et al (2019). “A Comparison of ARTEMIS Data with the Lunar Plasma Design Environment for NASA Crewed Missions”. In: Applied Space Environments Conference 2019. M19-7402.)

Key Open Questions

1. What is the lateral and vertical extent of the Procellarum KREEP Terrain (PKT) in the upper mantle?
2. What is the global extent of the discontinuities in the upper mantle?
3. Does a partial melt region exist in the lower mantle?
4. What is the nature and extent of the lunar core?
5. How do the induced fields interact with wake fields?
6. Do crustal magnetic fields play a role in PSR water retention and shielding?
7. Plasma observations taken directly from the surface is needed to validate simulations of the surface plasma environment.

EM Sounding is a powerful tool capable of constraining the electrical conductivity of the Moon, and hence, temperature, core thickness, mantle, and crust/PKT structure at depth.

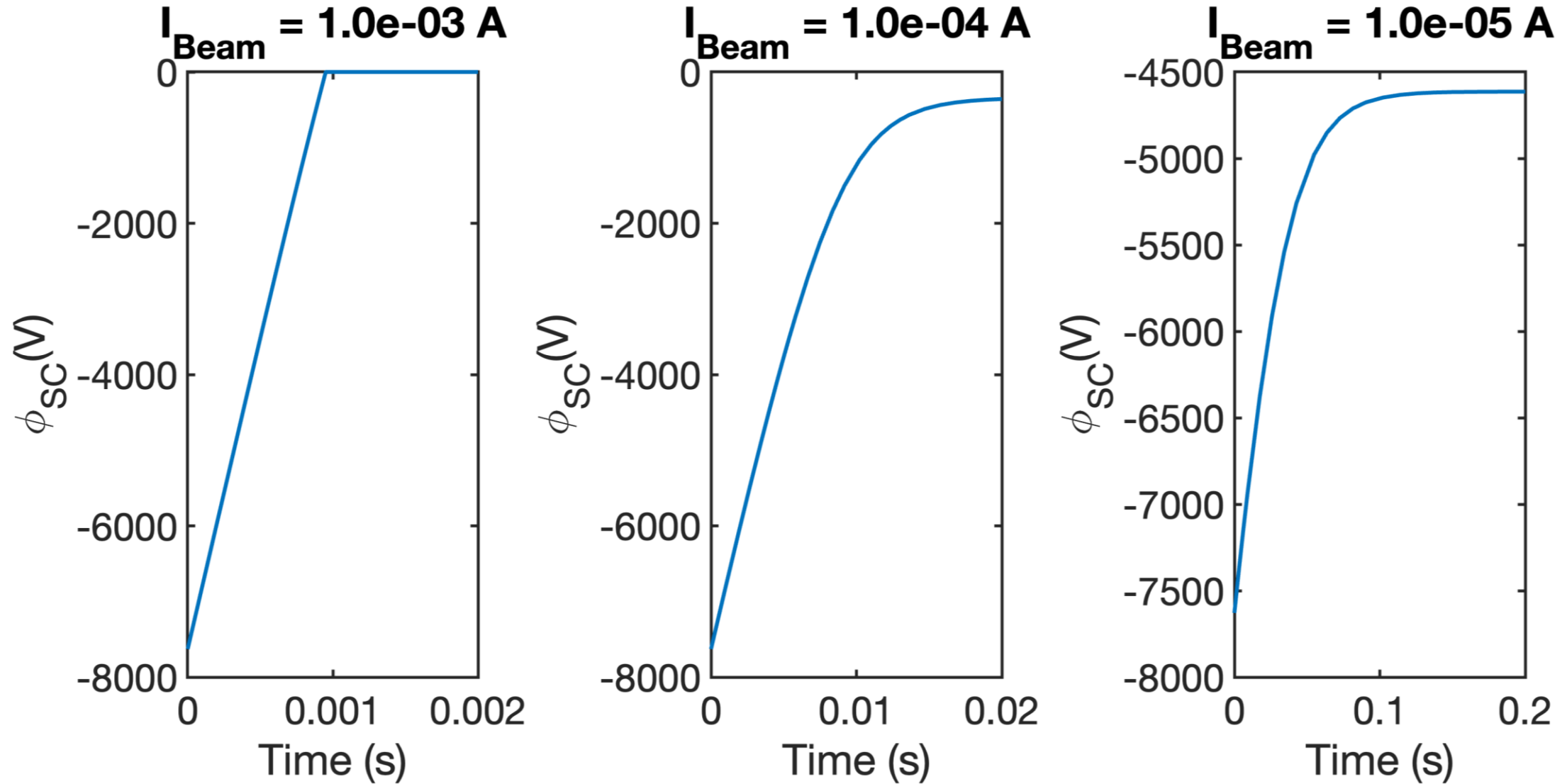
Lunar Vehicle Active Charge Control System (LVACCS) Motivation

- In very low density plasma environments ($n \lesssim 10^2 \text{ cm}^{-3}$) vehicle charging can:
 - invalidate plasma probe measurements (Waets et al., 2019)
 - degrade avionics performance (Bialke et al., 2019)
 - lead to a complete system failure (Leach, 1995)
- Traditional methods measure vehicle potential with a charged particle detector or with a reference conductor at the end of a long boom.
 - Limitations: requires vehicle in sunlit (Mullen, 1982)
- Vehicle potential is often required to process space plasma environment data (e.g., McFadden et al., 2008); Calibration is often accomplished with spacecraft charging models (Johansson et al., 2020).
 - The lunar plasma environment is constantly changing, thus, this approach becomes increasingly more difficult with each new space environment to be explored.
- **A real-time in situ space situational awareness instrument is needed.**

Lunar Vehicle Active Charge Control System (LVACCS) Overview

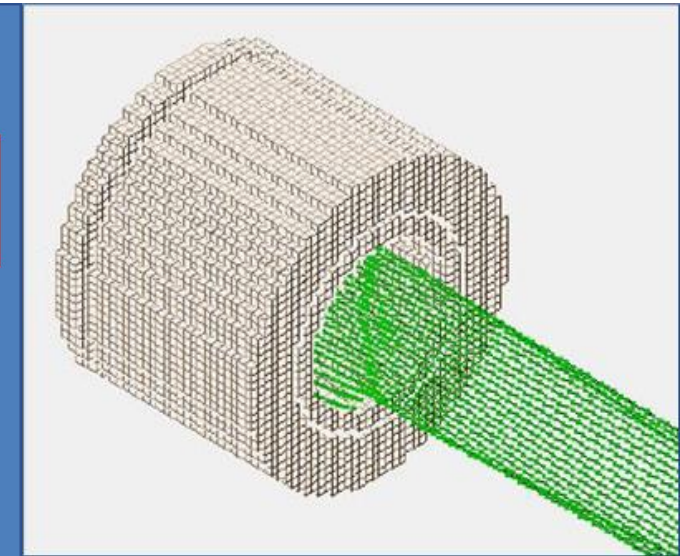
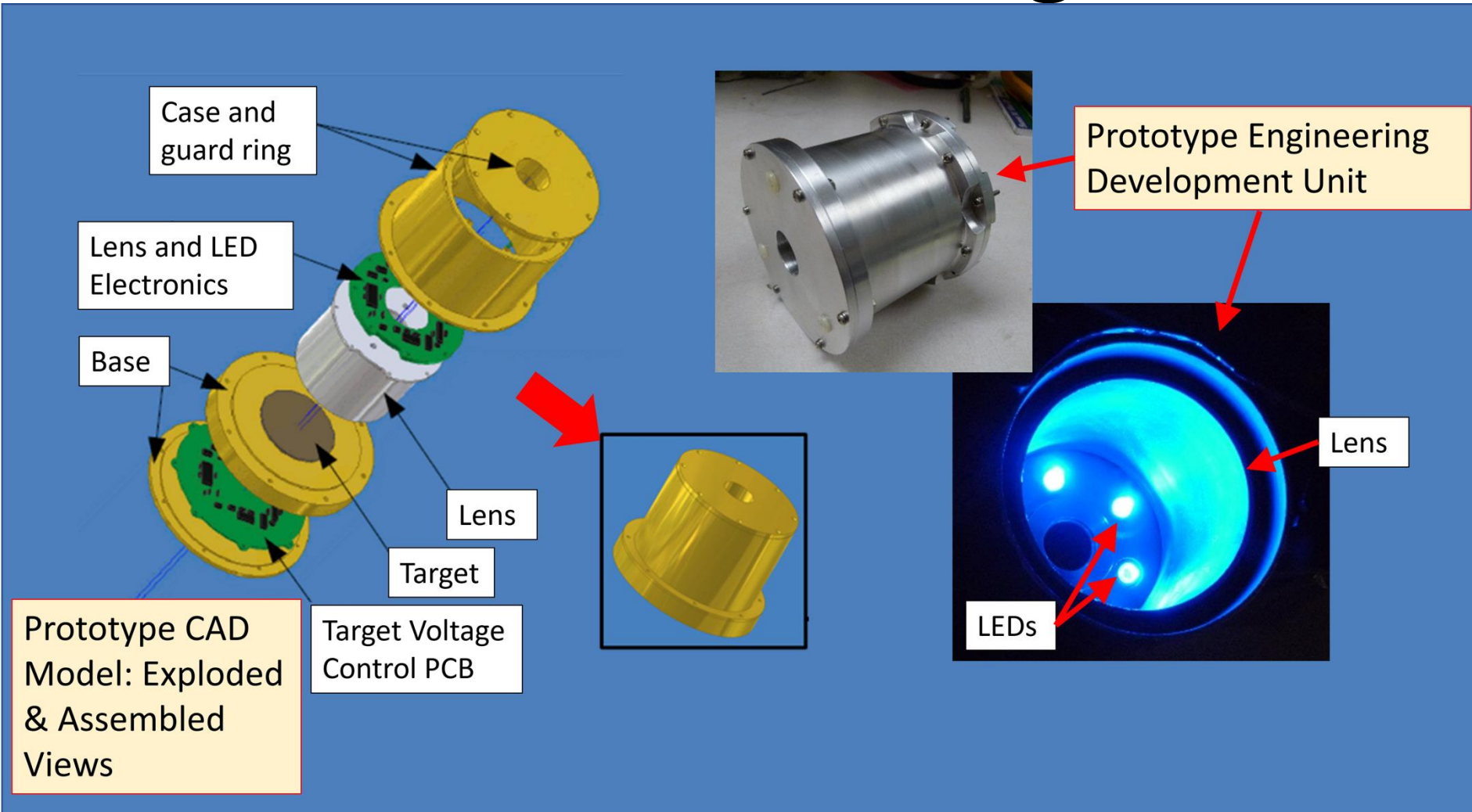
- **LVACCS:**
 1. Measures the electric frame potential of the vehicle for both positive and negatively charged conditions.
 2. Discharge any negatively charged vehicle.
 3. Safely charge the vehicle to a known positive potential.
- LVACCS has received a NASA PICASSO instrument development grant. TRL 2 (current) to TRL 5 in 2026.
- The LVACCS consists of Collimated Photoelectron Gun (**CPEG**) with Spacecraft Charge Detection (**SCD**).
- Very low resource (size, mass & power) instrument approach.

LVACCS discharging shadowed spacecraft



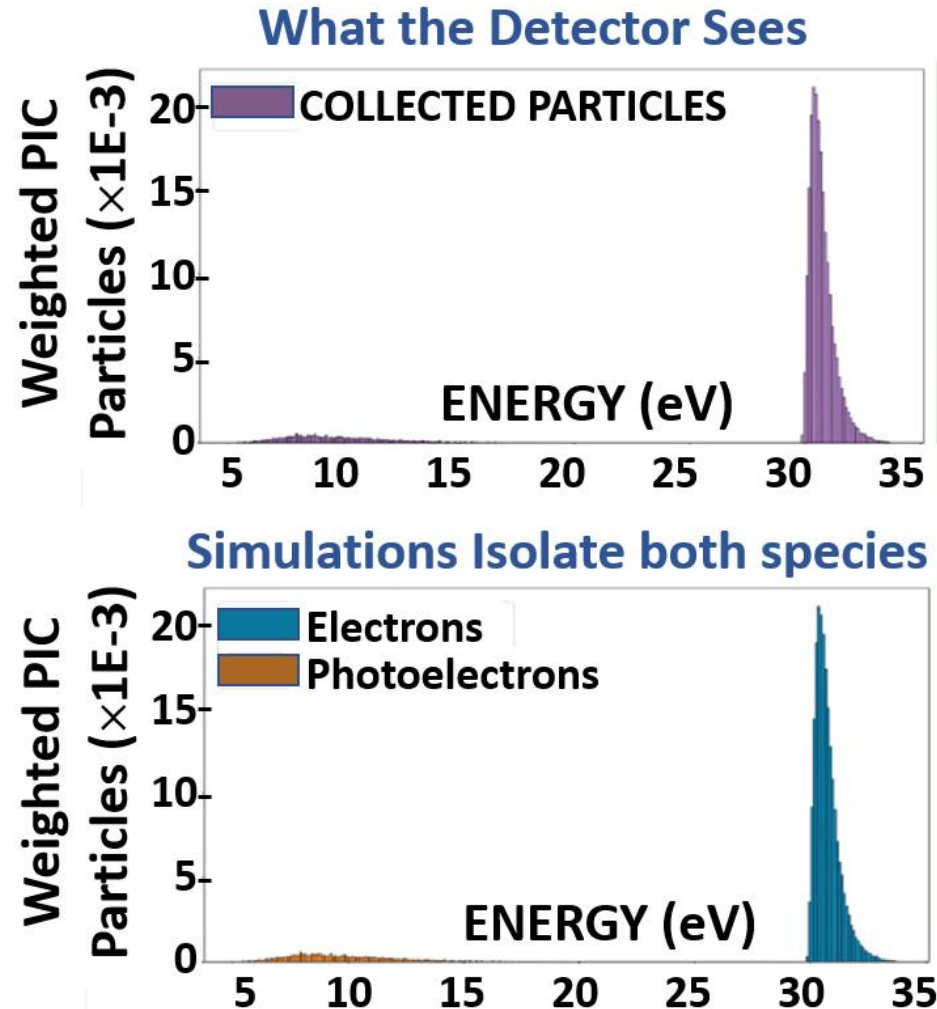
Modeled discharge characteristics of LVACCS operating at various beam currents for plasma density of 100 cm^{-3} .

CPEG Mechanical Design

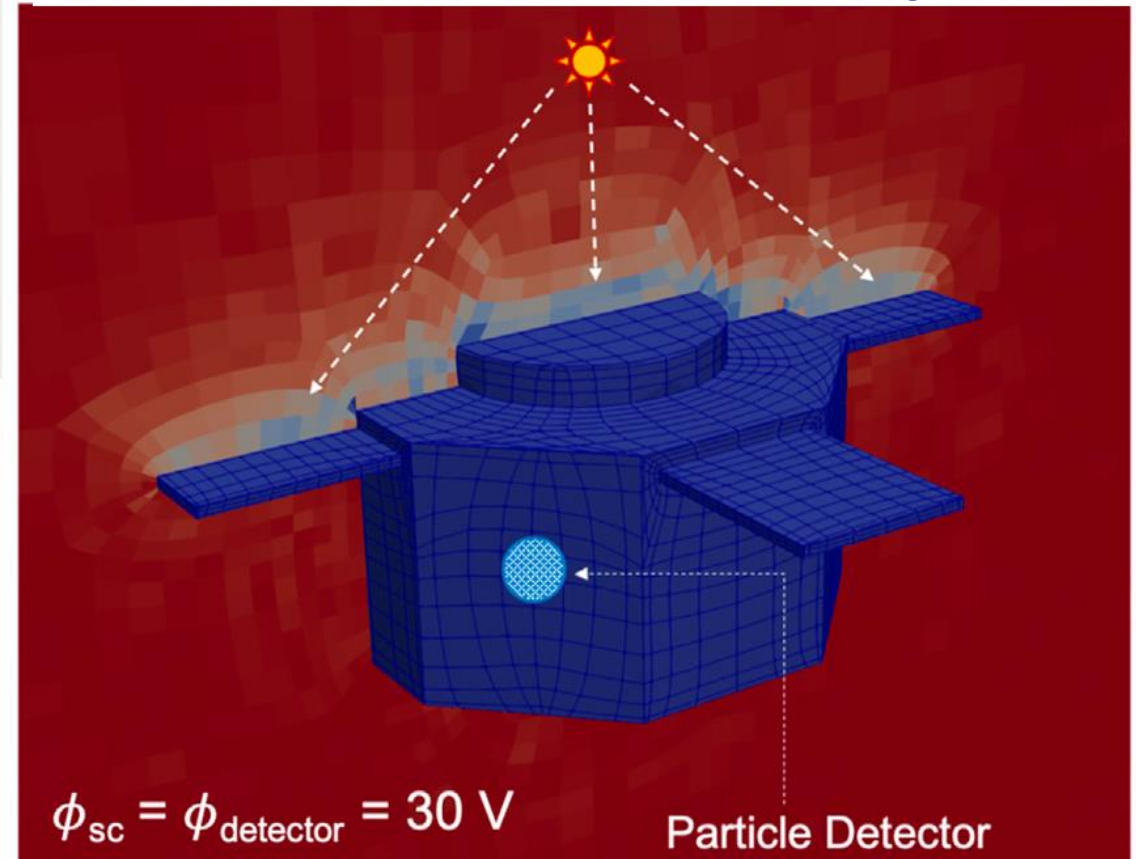


CPEG CAD model in exploded and assembled views are on the left. An Engineering Development Unit is shown on the right. Blue (460 nm = 2.7 eV) LEDs were used with a LaB6 target (work function = 2.5 eV.)

LVACCS Charging Simulation

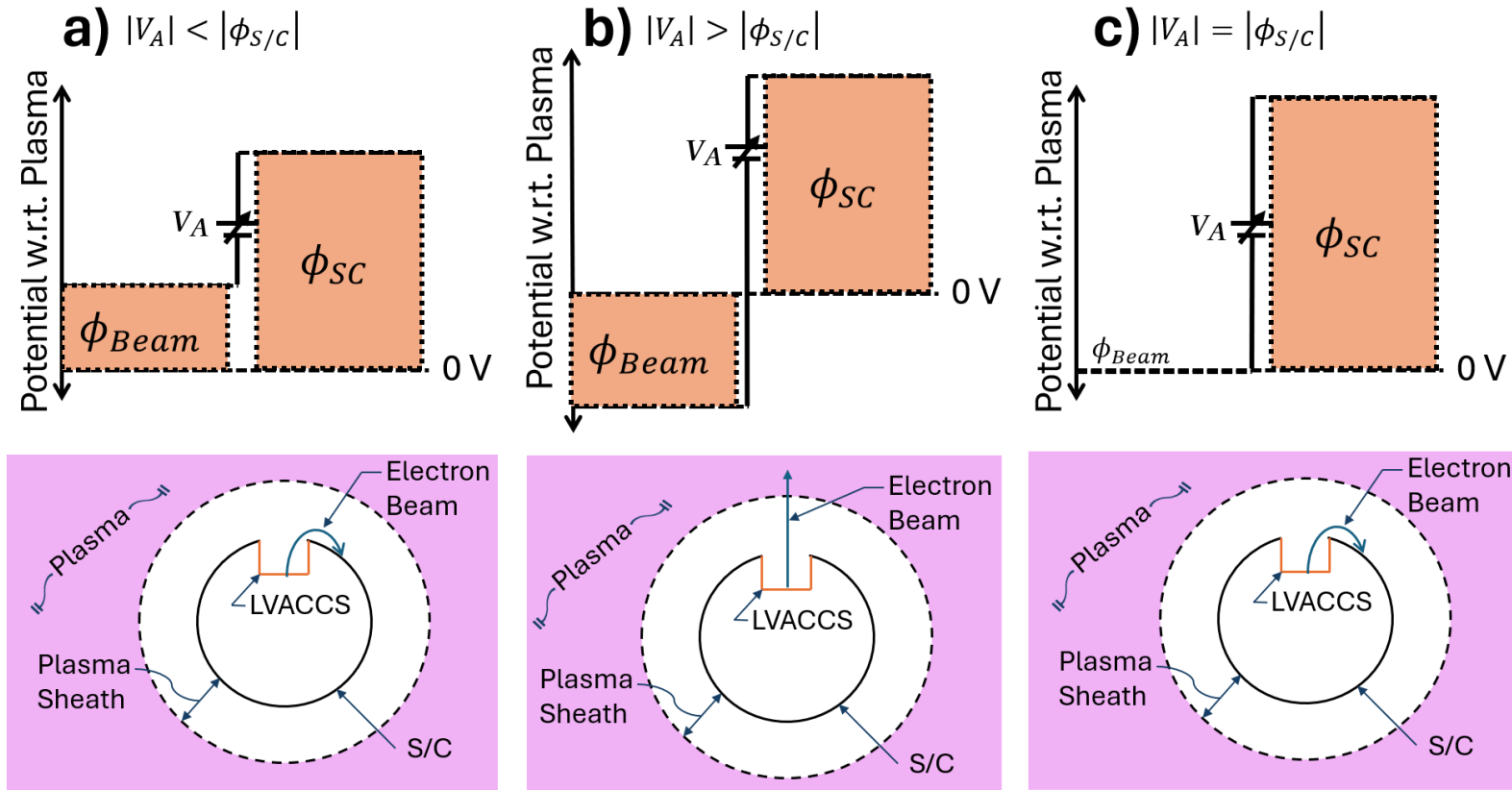


Kinetic Simulation: Van Allen Probe Spacecraft



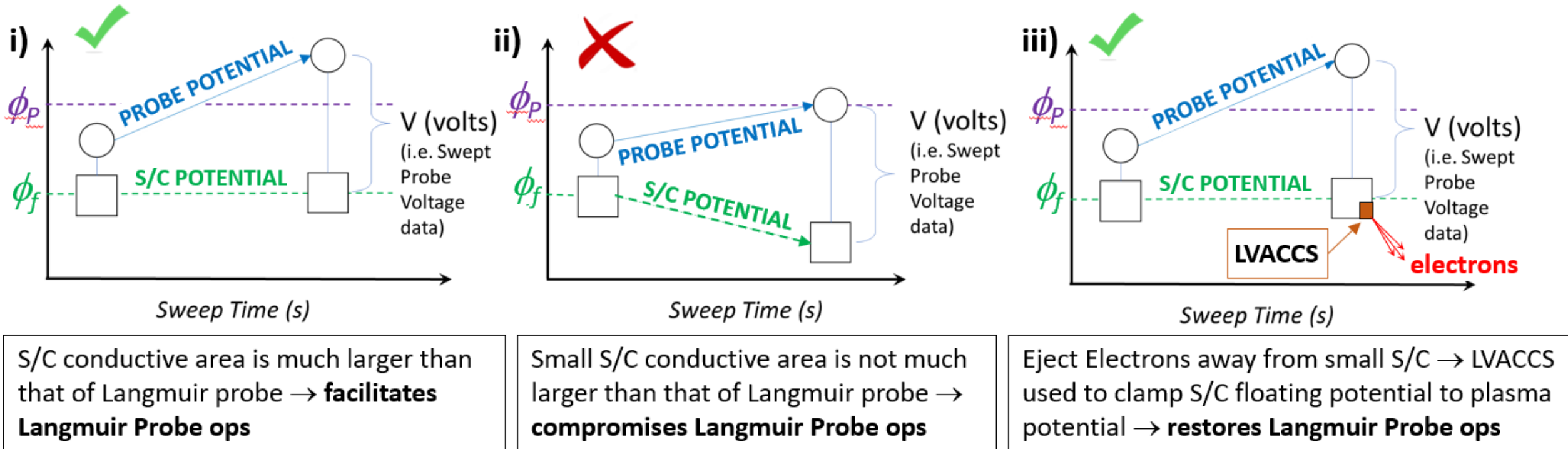
Kinetic simulations demonstrating that active spacecraft charge control can positively bias the spacecraft chassis to detect cold electron populations in the magnetosphere (Maldonado et al., 2023). LVACCS will charge vehicles tens of volts positive as part of positive vehicle potential determination.

LVACCS Measurement Technique



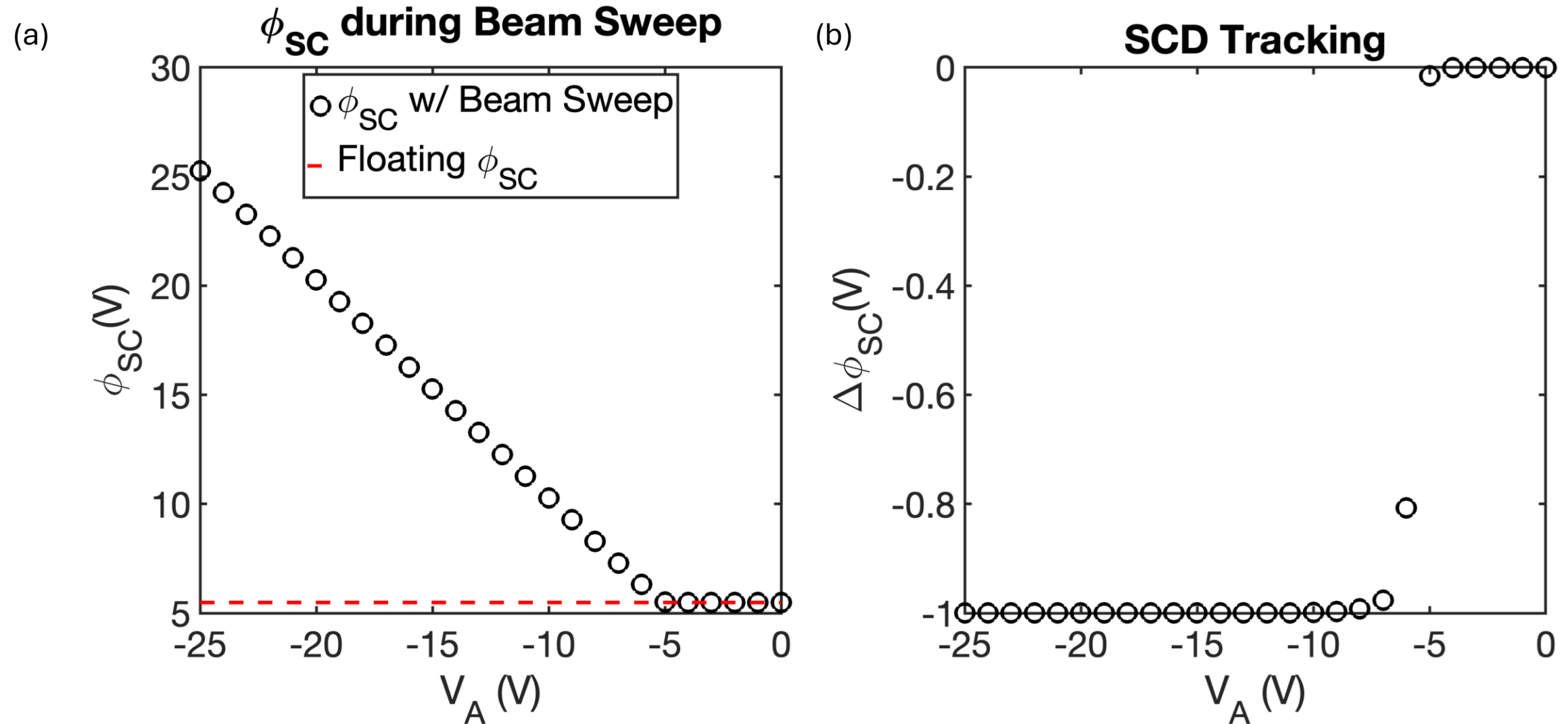
Requirements for LVACCS electron beam escape from plasma sheath surrounding vehicle. V_A is applied to bias the LVACCS electron beam cathode (ϕ_{Beam}) and vehicle frame (ϕ_{SC}). (a) V_A is negative, but beam potential is more positive than plasma potential. Electron beam returns. (b) V_A is negative, and beam potential is more negative than plasma potential. Electron beam escapes. (c) Spacecraft charges positively due to electron beam escape and LVACCS measures a change in potential. Electron beam returns.

LVACCS: Concept of Operations



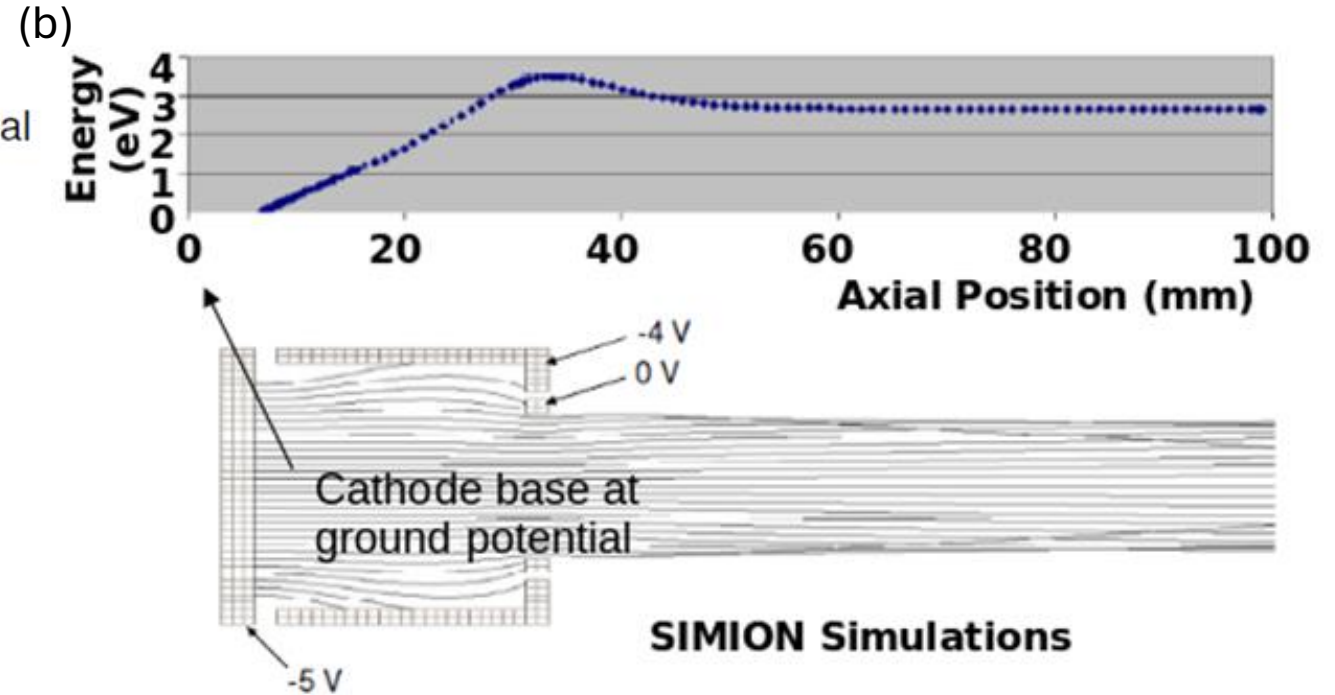
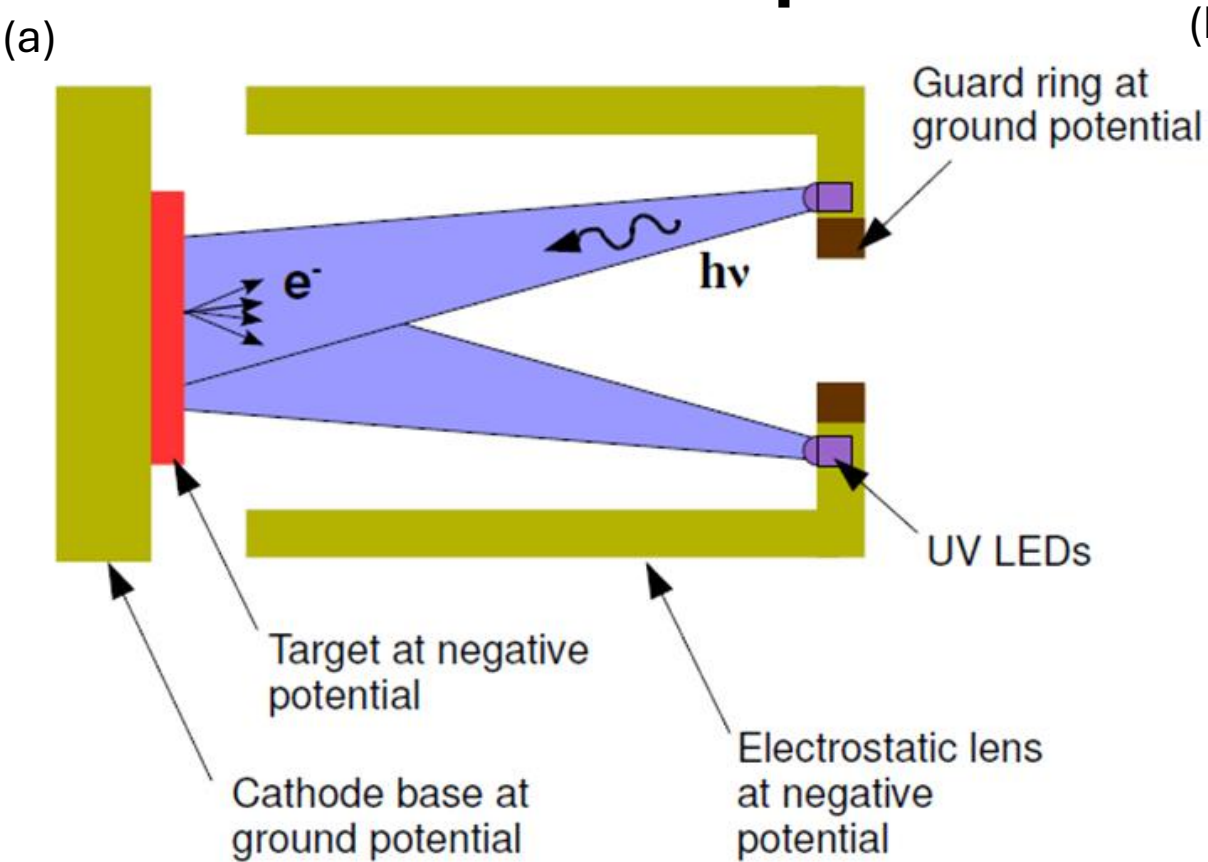
The LVACCS photoelectron beam mitigates induced negative charging due to Langmuir probe operation on small spacecraft platforms. A similar technique was employed with thermionic emission on QB50 CubeSats that utilized the m-NLP system (Hoang et al., 2019).

LVACCS Sweeping from a Sunlit Spacecraft



LVACCS positive vehicle potential estimate. (a) The vehicle potential as the LVACCS is swept from 0V to -25V. (b) The theoretical SCD measurement. Note that there is no measured change in potential until the LVACCS begins to charge the vehicle.

CPEG Concept



(a) shows axial cross-section of cylindrical geometry, where UV LEDs illuminate a target that is electrically isolated from the cathode base. The electrostatic lens is used to focus the photoelectrons into a beam. (b) Results from SIMION calculations show a laminar electron beam (bottom) and the effective axial energy of the electrons (top).

Expected LVACCS Performance

Characteristic	Performance
Electron Beam	
Beam Current	1 mA
Stabilization Time	$< 100 \mu\text{s}$
Spacecraft Charge Detection	
Voltage Range	$-1 \text{ kV to } 25 \text{ V}$
Settling Time	$\leq 500 \mu\text{s}$

Target Destination	Earth magnetosphere, Lunar orbit and surface, interplanetary
Start TRL	2 (SCD) / 6 (CPEG) / 2 (LVACCS)
End TRL	5 (SCD) / 6 (CPEG) / 5 (LVACCS)
Anticipated Benefits	Application of system in space environment to enable ambipolar measurements of vehicle potential and discharging of negative vehicle charging when ambient plasma density is $\lesssim 10^2 \text{ cm}^{-3}$.

Science Traceability Matrix

Example Lunar Surface Mission		Subsystem	Segment	
Observation Approach	Measurement Objectives	Instrument	Platform	Space System Requirements
1. Influence of local and regional crustal magnetism on surface sheath structure?				
Observations of surface potential near a crustal magnetic field	Measure space vehicle potential from -1kV to +25V, accuracy to within 10% or 10V, whichever is smaller	LVACCS	Lander and Rover	- Simultaneous Lander/Rover Operation at least one Lunar Day - Rover operates at least 10 m from Lander

Near Term Dust/Plasma/Fields Observations on CLPS Deliveries

- TO2 IM/IM1, Intuitive Machines, Malapert A, South Pole, launched & landed in Feb 2024.
 - Radio-wave Observations at the Lunar Surface of the photo Electron Sheath (ROLSSES): Low-frequency radio astronomy receiver system measuring the Electron sheath density and scale height; dust impacts
- TO 19-D/Blue Ghost 1, Fire Fly, landing near Mare Crisium, this year:
 - Lunar Magnetotelluric Sounder (LMS): Electric & Magnetic fields
 - Electrodynamic Dust Shield (EDS)
- TO CP-11/IM3, Intuitive Machines, landing in Reiner Gamma, next year:
 - Lunar Vertex (PRISM1): Lander & rover magnetometers (VML, VMR), ion-electron plasma spectrometer (MAPS), cameras on the lander, and a multispectral microscope on the rover
 - KASI's Lunar Space Environment Monitor (LUSEM), solid state telescopes, Charged particles of ≥ 50 keV, separating ions and electrons
- TO CP-12, Draper, Schrodinger:
 - LuSEE-Lite: electric and magnetic field environment of the lunar surface from DC to 20 MHz. The payload consists of a fluxgate magnetometer, a search coil magnetometer, and a 7-meter-tall vertical monopole.
 - Lunar Interior Temperature and Materials Suite (LITMS)(PRISM1): Lunar Magnetotelluric Sounder and Heat Flow Probe + Sounder and Drill
- TO CS-3/Blue Ghost 2, Fire Fly, Farside:
 - LuSEE Night: Low frequency radio astronomy ($< \sim 50$ MHz) with standalone operations through the lunar night, four monopole antennas to operate continuously for 1 year independently from the lander.
- TO CP-21, Vendor TBD, landing on the Gruithuisen Domes:
 - ROLSES 2
- TO CP-22/IM4, Intuitive Machines Nova-C lander to Mons Mouton, South Pole 2027:
 - Magnetometer

<https://science.nasa.gov/lunar-science/clps-deliveries/>

Summary & Forward Work

- The conducting lunar interior induces a transient magnetic dipolar field that couples with the nightside plasma wake.
 - Need for characterizing the background plasma in magnetic sounding.
- Surface plasma data is needed for surface charging considerations.
- LVACCS is science enabling technology that opens avenues for new research in low density plasma environments such as the terrestrial and planetary magnetospheres, the near-lunar space environment, and interplanetary space.