Modeling-challenge paradigm using design of experiments (DOE) for spacecraft immersed in nonstationary, between-regimes, flowing plasma

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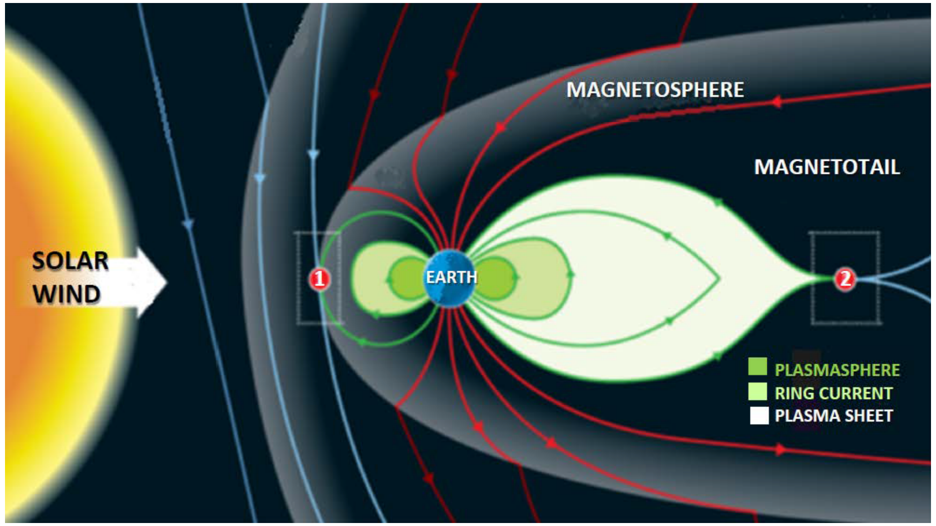

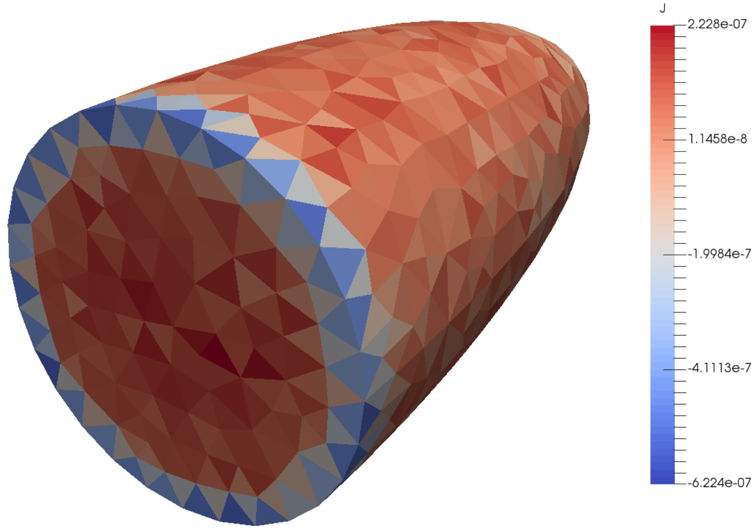

Methodologies for active experiments in space and in the lab

Space Observation

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Lab Experiment

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Analytical Theory

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Numerical Simulations

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Design of Experiments (DOE) [think of a "wind tunnel"]

Design of Experiment (DOE) methodology

Define standard experimental conditions and measurements to be modeled numerically and computationally simulated. Calibrated sensor-level lab measurements (sensor units) provided as data set, without quantity-level, plasma-parameter-specific interpretations.

For example, a Langmuir probe measurement would not be quoted in terms of electron density, electron temperature, or plasma potential, but rather as a current-voltage trace. Similarly, results from ion or electron imagers would be represented as a particle-flux or current, measured by a detector array, rather than represented as a fluid temperature, density, and flow velocity.

Goal: "Whole-device modeling" of Spacecraft-Environment Interactions

"Computational fluid dynamics (CFD) validation cannot consist of the comparison of the results of one code to those of one experiment. Rather, it is **the agglomeration of comparisons at multiple conditions, code-to-code comparisons, an understanding of the wind tunnel corrections, etc., that leads to the understanding of the CFD uncertainty and validation of its use as an engineering tool**. Examples include comparisons of predictive CFD to subsequently acquired test data. The question is not can CFD give a great answer for one or two test cases, but can the CFD "processes" give good answers for a range of cases when run by a competent engineer? This is what validation for an intended purpose is all about."

E. N. Tinoco, Validation and minimizing CFD uncertainty for commercial aircraft applications, AIAA paper 2008-6902. Presented at the 26th AIAA Applied Aerodynamics Conference, August 18-21, Honolulu, Hawaii (2008)

Project Goals & Scientific Impact: Whole-device modeling

Decipher, relate, quantify, and predict the mechanisms operating & processes occurring in nature and address intermediate-regime, non-ideal conditions and the associated challenges of additional physical phenomena that create significant problems in computational science and engineering.

Extend the ability to document and achieve accuracy in representing variables, conditions, processes, and dynamics well beyond the inference of a physical parameter from an invasive sensor interpreted with the help of theory.

Thus, an interpolated environment can be constructed volumetrically.
In this case, the environment of a spacecraft immersed in an inhomogeneously perturbed plasma environment,
can be reconstructed using instrument data processed to sensor units at original spatio-temporal resolution but without a requirement of having theory-interpreted derived values of each specific physical quantity!

Project Goals & Scientific Impact align with SHIELDS

The LANL SHIELDS Project: Space Hazards Induced near Earth by Large, Dynamic Storms: Understanding, Modeling, Predicting
V. K. Jordanova, Space Science and Applications, LANL, at 2016 SHIELDS Workshop 4-8 April 2016

Develop a new modeling capability of the complex near-Earth environment for space assets protection and Space Situational Awareness (SSA):

Transformational: from correlative to causal understanding of a complex system, exciting new physics addressing interactions across multiple scales/plasma regimes

Application: mitigate spacecraft charging effects, assist spacecraft designers, forensic analysis of space system failures

+ address intermediate-regime, non-ideal conditions and the associated challenges of additional physical phenomena that create significant problems in computational sci. & eng.

Outstanding science questions related to storm/substorm dynamics we will answer:

What determines where and when hot plasma is injected into the inner magnetosphere?

How are the injected particles transported, and how does the magnetosphere respond?

What waves do the injected particles excite and how do these waves feed back on the acceleration and loss of the particles?

Observations are inadequate to address these questions globally, modeling is the only way!

Advantage of DOE over conventional validation

Action Plan: A conducting sphere and cylinder under the conditions of nonstationary, between-regimes, flowing plasma is adopted as a test case for a modeling-challenge paradigm based on DOE methodology.

Action Plan: Identify modeling challenges for more complex codes by including the kinetic nature of the plasma sheath and capturing non-monotonic profiles of density and E field from analytical predictions that are sufficiently non-ideal to potentially distinguish one numerical simulation approach from another.

Action Plan: Facilitate a RED-team/BLUE-team challenge that addresses specific questions in Spacecraft-Environment Interactions and assesses the capability of models to describe those non-straightforward conditions.

Benefit: Streamlined model/simulation development.

Start small with proof-of-principle experiment

Koepke/Marchand-Coordinated Modeling-Challenge Facility
on Spacecraft-Environment Interactions

using laboratory facilities at West Virginia University and high-performance-computing facilities at University of Alberta and LANL.

Even if 1st formal collaboration is between Koepke-Marchand, there could be a portal, with level-1B data downloadable by anyone interested, onto which any participant could contribute simulation results. Such "users" have no financial obligation, but benefit scientifically/mutually with us (collaboration expansion).

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Grow, inclusively, as demand dictates into a
Community-Coordinated Modeling-Challenge Facility
on Spacecraft-Environment Interactions

using laboratory facilities nationwide and high-performance-computing facilities at several institutions.

Solar Wind Facility, K. Wright, T. Schneider, J. Vaughn, P. Whittlesey

Applied Space Environments Conference: Measurements, Models, Testing, and Tools, 15-19 May 2017, Huntsville, AL

Historically, NASA's MSFC has operated a Solar Wind Facility (SWF) to provide long term particle and photon exposure to material samples. The requirements on the particle beam details were not stringent as the cumulative fluence level is the test goal. Motivated by development of the faraday cup instrument on the NASA Solar Probe Plus (SPP) mission, the MSFC SWF has been upgraded to included high fidelity particle beams providing broadbeam ions, broadbeam electrons, and narrow beam protons or ions, which cover a wide dynamic range of solar wind velocity and flux conditions. The large vacuum chamber with integrated cryo-shroud, combined with a 3-axis positioning system, provides an excellent platform for sensor development and qualification. This short paper provides some details of the SWF charged particle beams characteristics in the context of the Solar Probe Plus program requirements. Data will be presented on the flux and energy ranges as well as beam stability.

Flowing Plasma Interaction with an Electric-Sail Tether Element, Todd Schneider, Jason Vaughn, Ken Wright, Allen Andersen, Nobie Stone

Applied Space Environments Conference: Measurements, Models, Testing, and Tools, 15-19 May 2017, Huntsville, AL

Motivated by interest in advancing the development of electric sails, a set of lab tests has been conducted at MSFC to study the interaction of a drifting plasma with a sheath formed around a small diameter tether element biased at positive voltages. The lab test setup was created with Debye length scaling in mind to offer a path to extrapolate (via modeling) to full scale electric sail missions. Using a Differential Ion Flux Probe (DIFP), the interaction between a positively biased tether element and a drifting plasma has been measured for several scenarios. Clear evidence of the tether element sheath deflecting ions has been obtained. Maps of the flow angle downstream from the tether element have been made and they show the influence of the plasma sheath. Finally, electron current collection measurements have been made for a wide range of plasma conditions and tether element bias voltages.

A fleet of CCMCF-ready facilities exists

MSFC's Heliopause Electrostatic Rapid Transit System (HERTS) Facility

TABLE I. COMPARISON OF PARAMETERS: E-SAIL AND LABORATORY

	Parameter	Value	Comment
E-Sail Mission	Proton Speed	400 - 450 km/s	~1000 eV
	Density	~5/cm^3	
	Electron Temp.	~12 eV	
	Ion Temp.	~10 eV	
	Debye Length	~10 m	
	Tether Diameter	~7.5x10^{-5} m	~75 microns
	Tether Bias (+)	>10 kV	
Laboratory Low Energy Analog	Ion Speed	~19 - 38 km/s	~80 - 300 eV
	Density	~1x10^6/cm^3	
	Electron Temp.	< 1eV	
	Ion Temp.	<< 1eV	
	Debye Length	< 1 cm	>> Tether Dia.
	Tether Diameter	~1mm	
	Tether Bias (+)	100 - 300 V	> Ion Energy

MSFC's Solar Wind Facility

Vacuum chamber: 4 ft diameter x 8 ft long cylinder; LN_2 cold shroud; quartz windows for solar photon input; base pressure at low 10-7 Torr with oil-free pumping

Ion source: Modified Kaufman-type with 10 cm diameter, collimating, matched grid set; housing electrically isolated from chamber; energy and flux computer controlled

Electron source: biased filament accelerates electrons through grounded anode screen; energy and flux computer controlled

Peabody Scientific ion source: water cooled Duo-plasmatron source with steering and focusing in drift tube; pin-hole aperture can be installed in chamber for pencil beam; energy computer controlled

Translation and Rotation Stages: X- and Z- motion at 4000 steps/inch; rotation at 40 steps/degree; all motion computer controlled

Helmholtz Horizontal Coils: Octagon shaped at 11' by 11' dimension with 9 turns of 12 gauge wire; computer controlled wire current

Helmholtz Vertical Coils: Square shaped at 6 ft by 6 ft dimension with 8 turns of 12 gauge wire; computer controlled wire current

Two CCMCF devices are under assembly at WVU

WVU's Blue Tank

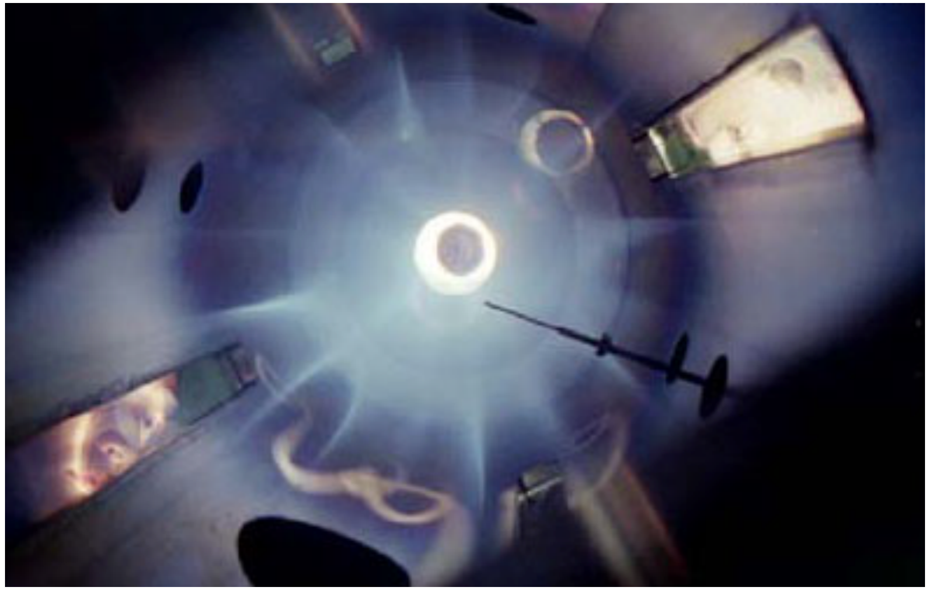
Vacuum chamber: 0.5 m dia x 1.0 m long cylinder; base pressure at low 10-7 Torr with oil-free pumping

Plasma source: Hot-filament discharge, Mini-helicon plasma thruster

Translation and Rotation Stages: X- and Z- motion; all motion computer controlled

Helmholtz Horizontal-Field Coils: Circular, 1.2 m dia, 0.5 T

Helmholtz Vertical-Field Coils: Circular, 1.8 m dia, 0.1 T



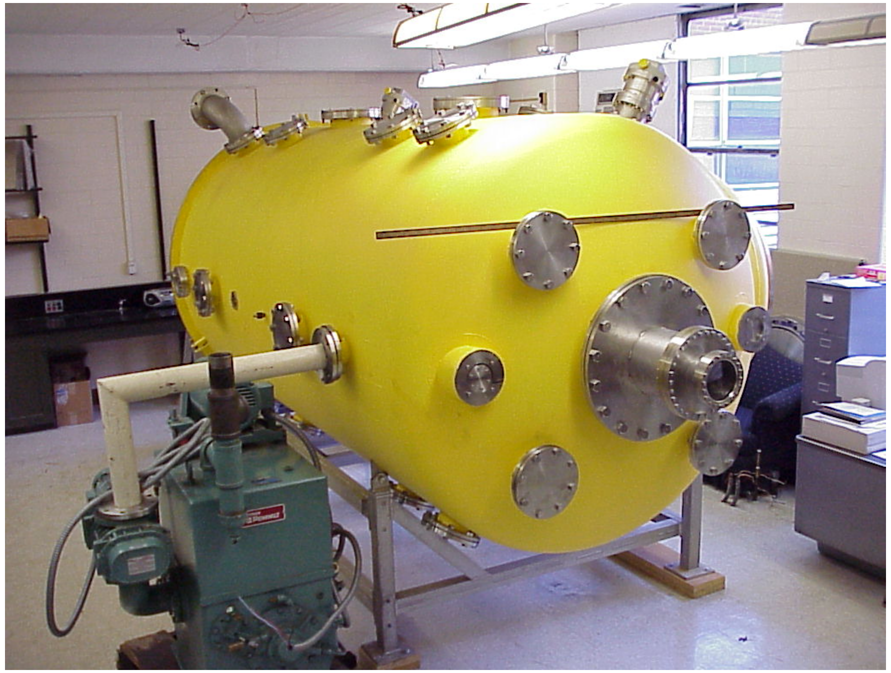
WVU's Gold Tank

Vacuum chamber: 2 m dia x 4 m long cylinder; base pressure at low 10-7 Torr with oil-free pumping

Plasma source: Large-diameter planar helicon antenna, hot cathode/mesh anode, washer gun, Q hot plate

Translation and Rotation Stages: X- and Z- motion; all motion computer controlled

Helmholtz Horizontal-Field Coils: Circular, 1.8 m dia, 0.1 T



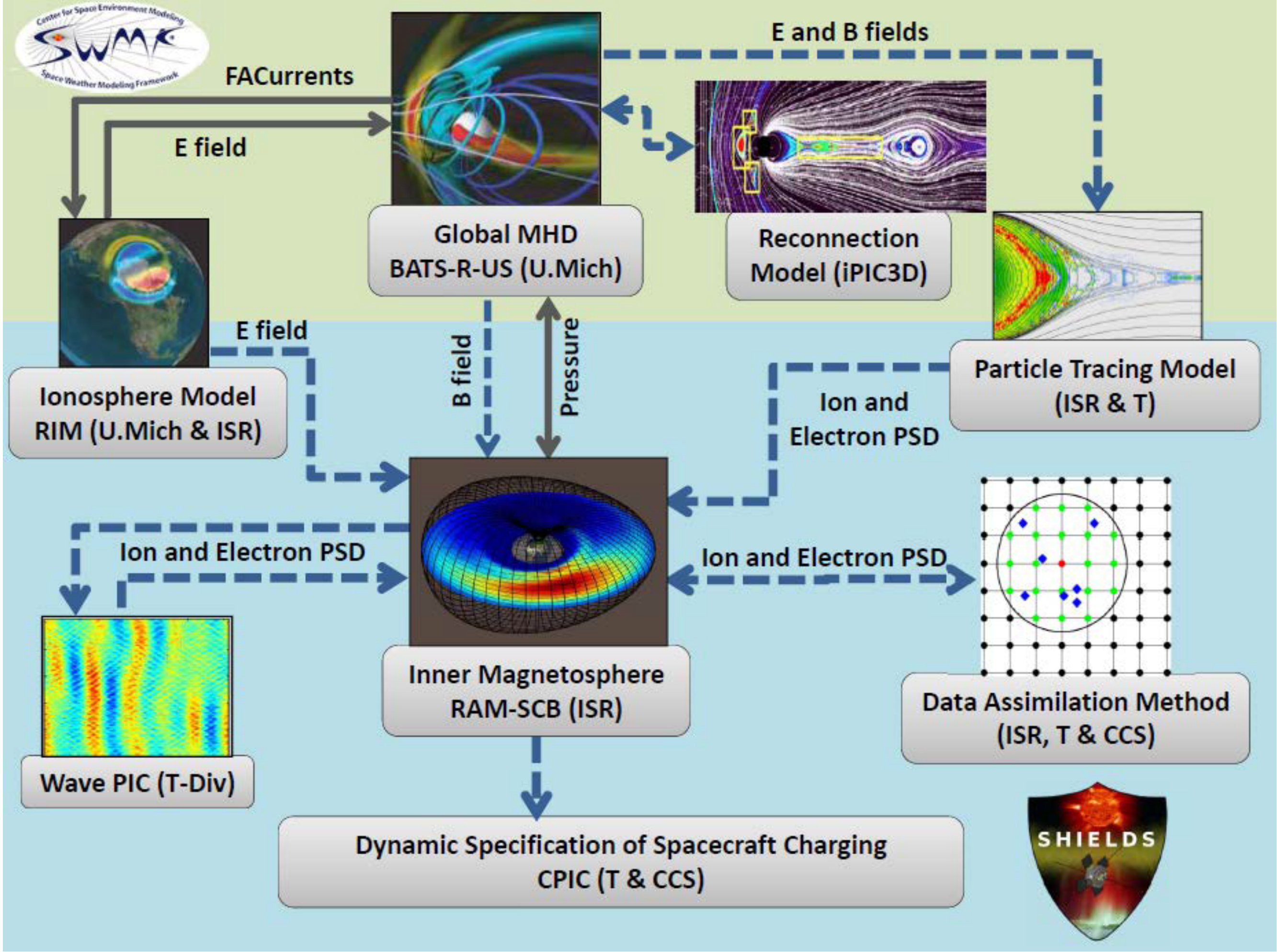
Infrastructure for a Community-Coordinated Modeling-Challenge Facility (CCMCF)

- Open to the entire stakeholder community. Allow any model to be tested against measurements. A success metric is the realized testing-and-evaluation cycle time.
- Ability to install and de-install test articles expeditiously to support high-frequency, short-duration tests focused in areas where primary uncertainties exist;
- Ability to rapidly prototype and manufacture models that reflect the design changes that get instantly transmitted by the customers of the test facility to their testing experimentalists using the latest in compatible CAD/CAM and model shop tools and materials;
- Ability to efficiently modify test conditions or proceed through a test point matrix to minimize time and effort spent while also maximizing respect of the DOE considerations;
- Convenient and thorough diagnostic-tool accessibility;
- Connectivity to high-performance computing capabilities to integrate and merge computational science and engineering simulations and test data;
- Advances in data mining and data merging software as an integral part of the facility data systems to enable rapid analyses of the variances along response surfaces; and
- Virtual presence, networking, and connectivity to achieve a fully integrated Developmental and Operational Test (DT/OT) approach in an inter-operable environment.

Bridging macro-and micro-scale models, combined with data assimilation tools

The LANL SHIELDS Project: Space Hazards Induced near Earth by Large, Dynamic Storms: Understanding, Modeling, Predicting

V. K. Jordanova, Space Science and Applications, LANL, at 2016 SHIELDS Workshop 4-8 April 2016



Whereas the SWMF
(Space Weather Modeling Framework)

- captures rapid particle injection and acceleration during a substorm and
- includes plasma wave generation and their feedback on the particles,

CCMCF needs to

- merge numerical simulation and testing to validate regional modeling
- incorporate the complexity of real **profiles**
- capture the coupling inherent in real **profiles**, and
- interpret holistically the deviations from ideal **profiles**.

CCMCF projects: Achieve a 2-way coupling between sensor data and simulation

The space environment affects spacecraft materials and equipment and a spacecraft and a rocket influences the space environment. The inclusion and joint analysis of both aspects of spacecraft/environment interaction problem promotes the optimization and effectiveness of interpreting the experiments to understand the operating mechanisms and relevant processes.

1. Achieve a fully self-consistent "two-way" coupling between symmetric plasma conditions and probe detection. ⇒ Demonstrate how a probe can measure its own surroundings by quantifying the perturbation inflicted onto the plasma and the probe signal by the presence of the probe itself.

2. Achieve a fully self-consistent "two-way" coupling between asymmetric plasma conditions and probe detection. ⇒ Quantify the perturbation inflicted onto a probe measurement by the presence of inhomogeneous, nonstationary, between-regimes, flowing plasma.

CCMCF projects align with SHIELDS projects

The LANL SHIELDS Project: Space Hazards Induced near Earth by Large, Dynamic Storms: Understanding, Modeling, Predicting
V. K. Jordanova, Space Science and Applications, LANL, at 2016 SHIELDS Workshop 4-8 April 2016

Spacecraft surface charging: interaction of a plasma with material objects, additional scales due to the object: 'more' multiscale!

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Spacecraft charging is platform dependent

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LANL state-of-the-art Curvilinear PIC (3-D, parallelized, multigrid) will be used to perform simulations of spacecraft charging for the specific geometry & material properties of [Van Allen] Probes

•

+ merge numerical simulation and testing to validate regional modeling that incorporates the complexity of real **profiles**, to capture the coupling inherent in real **profiles**, and to interpret holistically the deviations from ideal **profiles**.

CCMCF Infrastructure – Facility team

Mark Koepke (WVU, USA): Q machine, helimak, stellarator, theta- and z-pinch, and mirror-trap devices; hot and cold cathode, washer-gun, dc/rf/pulsed plasma sources; innovative probe, EEDF, IEDF, spectroscopic analysis, laser-induced fluorescence, interferometry, imaging, phase-resolved optical emission spectroscopy diagnostics

Vladimir Demidov (WVU, USA): Langmuir probe theory, application, innovation; spectroscopic analysis of plasma; gas sensors, helimak devices, and dc discharges; turbulence-induced transport; atomic & molecular physics

Earl Scime (WVU, USA): Space instruments, spacecraft design, lab experiments (reversed-field pinch, helicon anntennae, double layers, plasma processing); microwave, probe, and laser-aided diagnostics of electrons, ions, and neutrals

Julian Schulze (WVU, USA): Plasma-on-surface interaction, rf-plasma sources, partially ionized plasma diagnostics and simulation

Shunjiro Shinohara (TUAT, Japan): helicon sources, thrusters, & applications, space simulation chamber design, fabrication, operation, and diagnostic characterization

Kevin Ronald (Univ. Strathclyde, UK): Electron beam injection, coherent beams and radiation, microwave diagnostics, and Cherenkov, Bremsstrahlung, and Free Electron Laser interactions between a beam and an electromagnetic wave.

CCMCF Infrastructure – Mod/Sim team

Richard Marchand (Univ. Alberta, Canada)

Herbert Gunnel (Belgian Institute for Space Aeronomy, Brussels, Belgium)

Dimitris Vassiliadis (WVU, Morgantown, USA)

hopefully, someone from SHIELDS

CCMCF Infrastructure – Analytical Modeling team

Xin Chen and G. Sanchez-Arriaga (Universidad Carlos III de Madrid)

Models will contribute comparison results with experiments having passive and active instruments, detectors, and boundaries

The level of realism and sophistication expected from these models should exceed a minimum, in terms of geometry and physical processes.

Geometry: Models should be able to account for the main components of the experiments, including the vacuum vessel itself, objects representing satellites or satellite components (antennas, booms, solar panels), satellite instruments (Langmuir probes, energy analyzers, or flow meters, particle imagers), as well as any invasive instruments used to monitor experimental plasma conditions.

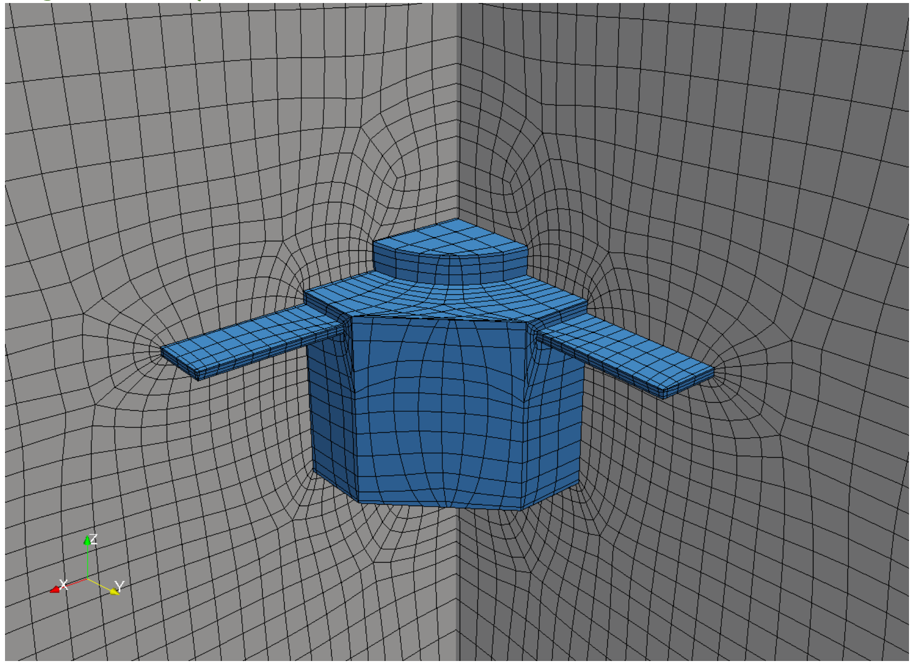
Physics: Depending on the experiment, models would also need to account for relevant physical processes occurring in the experiments, including charging, the formation of electric sheaths, the emission of secondary and photo-electron, and the reflection of charged particles at surfaces. They should be able to account for different surface materials properties and conditions, such as conductivity (perfect, finite or dielectric), depending on the experiment.

Modeling and Simulation resources

Nascap-2k, SPIS, PTetra, and EMSES, suitable for a wide range of problems, could be made available. PTetra, developed by one of us (RM) would be one of the models applied to the experiments. SPIS, an open source model, would also likely be used.

Other models, developed and under development, simulate specific conditions, such as the collection of current by a spherical probe in a flowing plasma, and could be part of CCMCF.

Curvilinear PIC (CPIC)*, suitable for CCMCF, is a flexible, fully kinetic, 3D electrostatic PIC code in general curvilinear geometry for plasma-material interaction studies



Features of CPIC:

-Optimal design choices

-Non-uniform, structured meshes: fast solvers

-Curvilinear formulation: particles move in uniform mesh

-Optimal, scalable solver based on multigrid

-Parallelized

-Multi-block meshes

-Enables tackling a broad set of plasma-material interaction problems

*Delzanno et al, IEEE Trans. Plasma Sci. (2013); Meierbachtol et al., ASEC 2017.

Start small with proof-of-principle experiment

Consider the spacecraft to be a spherical or cylindrical Langmuir probe and consider the spacecraft-environment interaction to be the flowing plasma immersing the probe. The interaction comprises alterations in particle trajectories near the probe and changes in the probe's charge state, consequently inducing spatio-temporal structuring of proximity-plasma parameters and enhanced or suppressed probe-surface absorption and emission of particles.

Secondary electron emission physics and SEE coefficient, with DOE

A computationally assisted spectroscopic technique to measure secondary electron emission coefficients in radio frequency plasmas, M Daksha et al., J. Physics D: Appl. Phys. 49, 234001, 2016.

The effect of realistic heavy particle induced secondary electron emission coefficients on the electron power absorption dynamics in single- and dual-frequency capacitively coupled plasmas, M Daksha et al., Plasma Sources Sci. Technol. 26, 085006, 2017

Experimental benchmarks of kinetic simulations of capacitively coupled plasmas in molecular gases, Z. Donko et al., Plasma Phys. Contr. Fusion, to appear 2017.

Justify the DOE conditions with analytical theory

To account for the influence of the plasma sheath on Langmuir probe current collection, use the Orbital-Motion-Limited (OML) model. To treat the self-consistent case of Orbital Motion Theory (OMT) for a monoenergetic attracted species, use the Bernstein and Rabinowitz model. To extend OMT for Maxwellian plasma and arbitrary probe radius normalized to Debye length, use the Laframboise model.

Use Robertson's approach to restore applicability even when limited by the reliance on assumptions of idealized collected-particle energy distribution functions with respect to the probe's bias voltage, of negligible population of trapped particles in bounded orbits that do not strike the probe surface, of time-stationary and negligible-flow conditions, and of unmagnetized-orbit trajectories. To a large extent, between-regime cases can be predicted by numerical solutions to idealized models.

Calculate non-monotonic radial profiles of potential surrounding the probe by including non-negligible space charge effects

To improve accuracy and increase precision, use the Sanchez-Arriaga code to include non-negligible space charge effects and to unambiguously calculate non-monotonic radial profiles of potential. All 3 references self-consistently solve the Vlasov-Poisson system based on a full-kinetic OMT model for cylindrical emitters and non-emitters to unify the Langmuir probe and emissive probe under a single framework. This model confirms the electron-trajectory trapping and ion-trajectory reflection near the probe that results in enhanced-from-background particle density at the probe front side.

G. Sanchez-Arriaga, A direct Vlasov code to study the non-stationary current collection by a cylindrical Langmuir probe 2013 Phys Plasmas 20 013504

G. Sanchez-Arriaga and D. Pastor-Moreno, Direct Vlasov simulations of electron-attracting cylindrical Langmuir probes in flowing plasmas 2014 Phys Plasmas 21 073504

Xin Chen and G. Sanchez-Arriaga, Orbital motion theory and operational regimes for cylindrical emissive probes 2017 Phys. Plasmas 24 023504

Experimental Platform

Begin with magnetic-field free, time-stationary, partially ionized plasma at rest in the laboratory frame of reference and incorporate capabilities that permit dimensionless-parameter regimes and spatio-temporal complexity to be scanned incrementally. A triple-plasma-region device separates, by a biasable mesh defining each of the two interfaces [1-3], an ionization-free region from two outboard, multi-dipole-confinement, hot-filament discharge plasmas. Each of the three regions has a cylindrical surface of alternating magnetic dipoles that causes particle reflection, forms the plasma's radial boundary, and leaves the core of the plasma magnetic-field free. Design, incorporate, and test the ability to adjust ambient magnetic field, electron density and temperature, collisionality, and plasma flow speed [4].

[1] Leung, K. N., R. D. Collier, L. B. Marshall, T. N. Gallaher, W. H. Ingram, R. E. Kribel, and G. R. Taylor (1978), Characteristics of a multidipole ion source, Rev. Sci. Instrum., 49, 321.

[2] Coakley P and Hershkowitz Laboratory double layers 1979 Phys Fluids 22 1171

[3] Hershkowitz, Review of recent laboratory double layer experiments 1985 Space Sci Rev 41 351

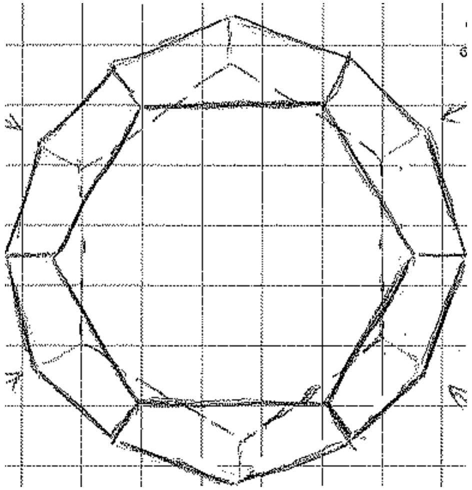
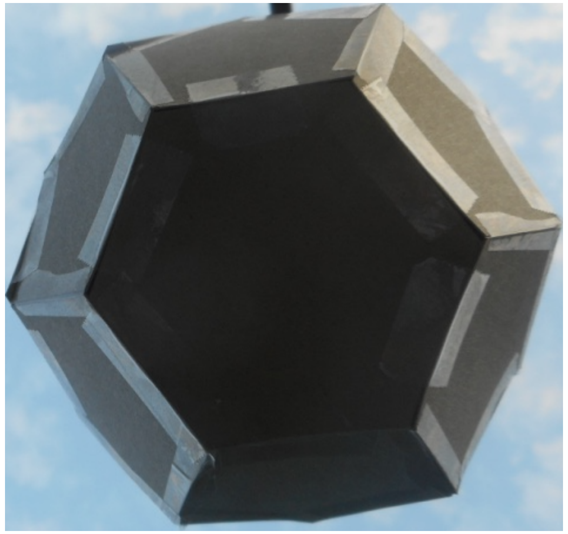
[4] Batishchev O V, Minihelicon plasma thruster 2009 IEEE Trans Plasma Sci 37 1563

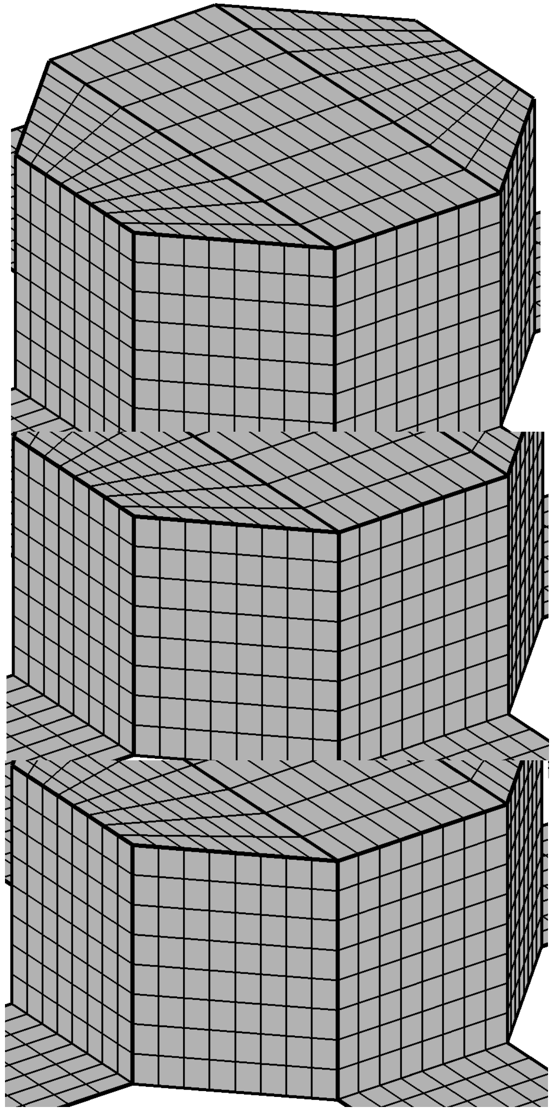
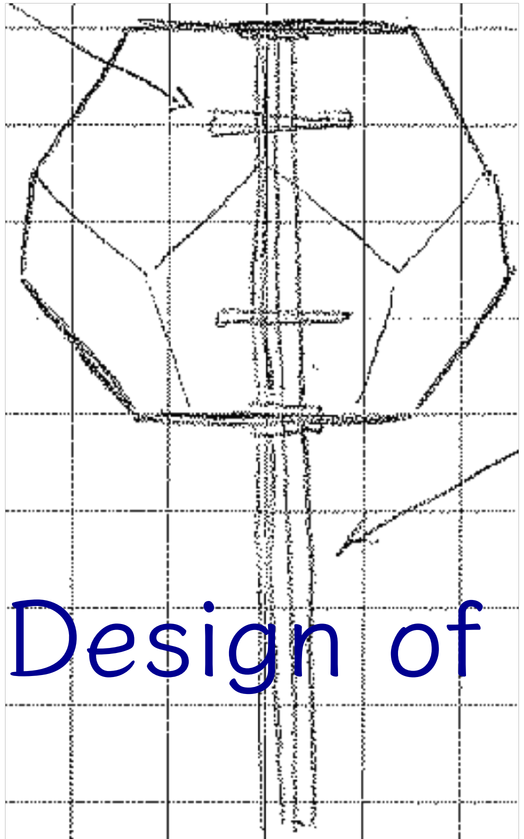
The featured diagnostic tool for employing the modeling-challenge paradigm is the spacecraft (i.e., the probe) itself, in either its spherical or cylindrical manifestation.

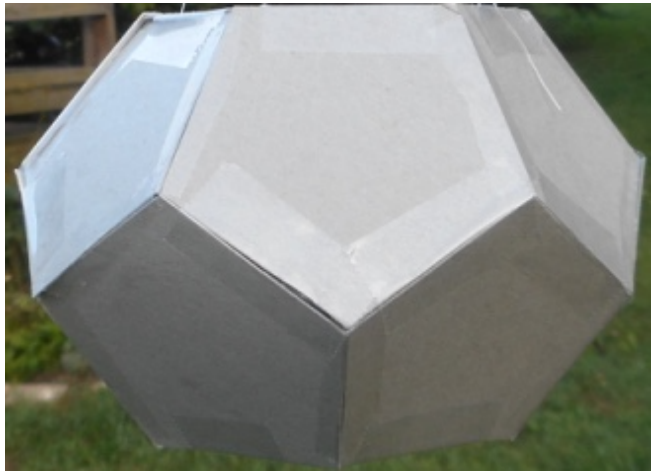
At first, diagnostic apparatus, for unmagnetized-orbit and magnetized-orbit cases, includes movable Langmuir probe of various designs, moveable retarding field energy analyzer, and optical emission spectroscopy. Additional diagnostics will come online later.

The surface of the probe is strategically segmented, with each segment being electrically isolated from others and being independently biasable with respect to electrical ground or to space potential.

The designed segmented probe shell is illustrated (next page) for spherical and cylindrical geometries. Each segment's raw current-voltage trace is an entry to the subfile of sensor data that constrain the numerical simulations.

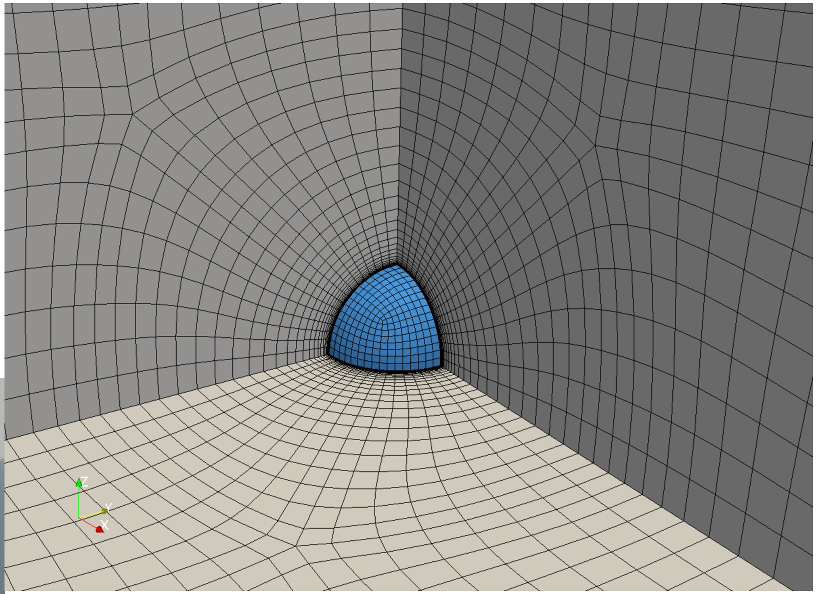


Design of segmented spherical/cylindrical probes

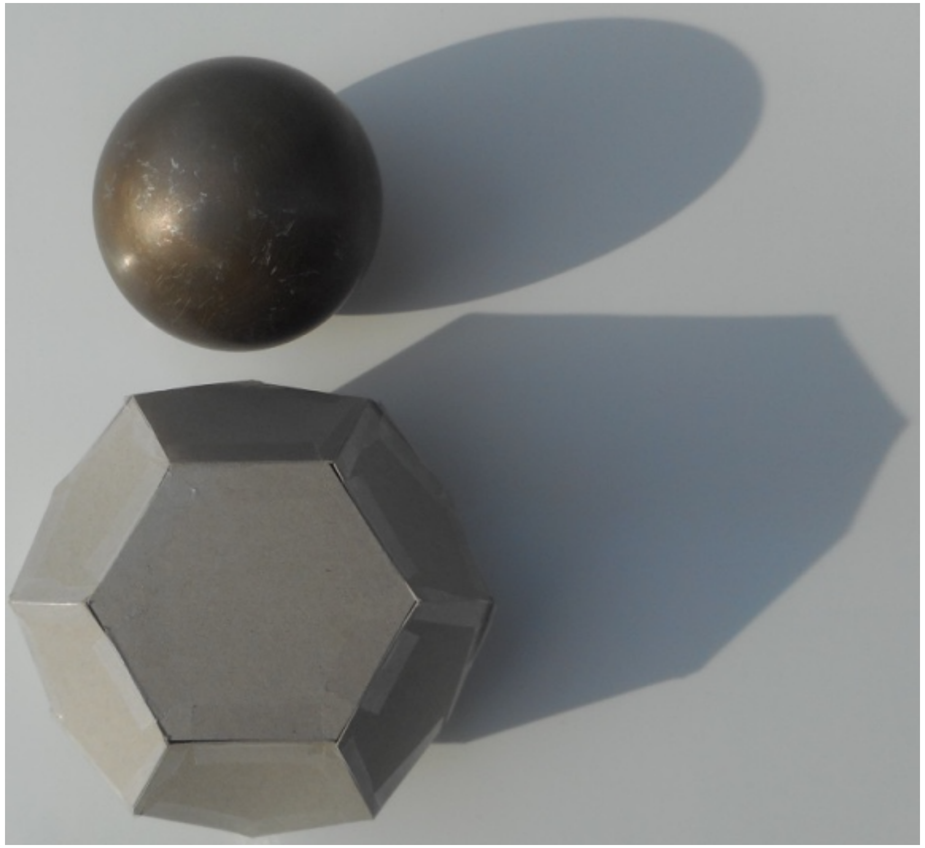
12-sided = 10 pentagons + 2 hexagons

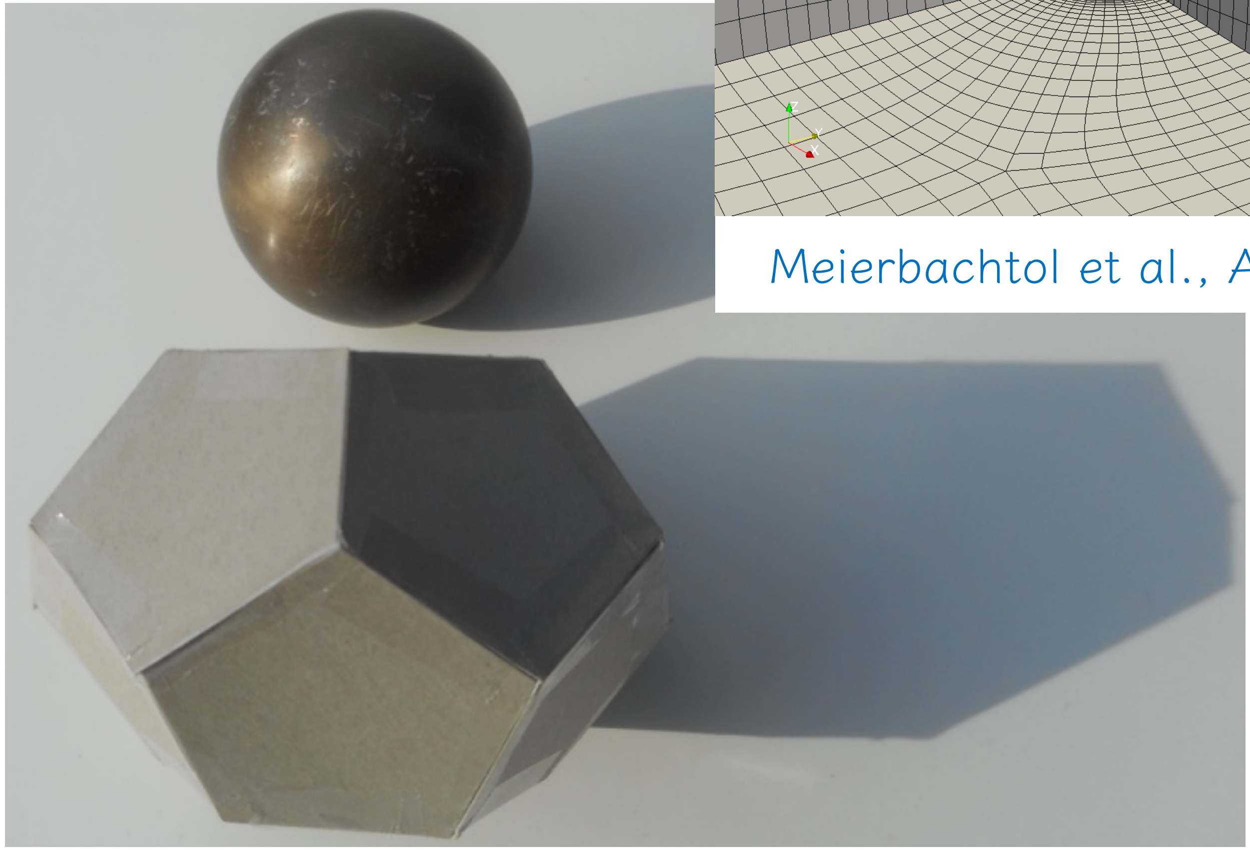
Segment a sphere and acquire 12 I-V traces

The sphere is a low resolution model
of the cupcake shape, whereas
the cupcake shape is a low resolution model
of the sphere.



Meierbachtol et al., ASEC 2017





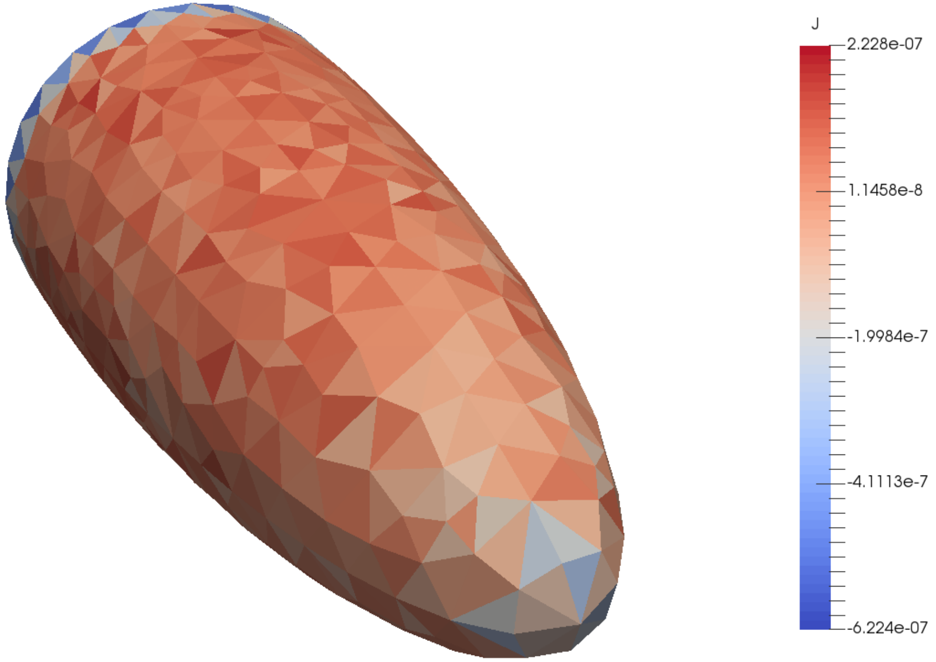
CPIC, based on 1st-principles kinetic methods and developed for curvilinear & multi-block mesh, maintains physics and geometric accuracy.

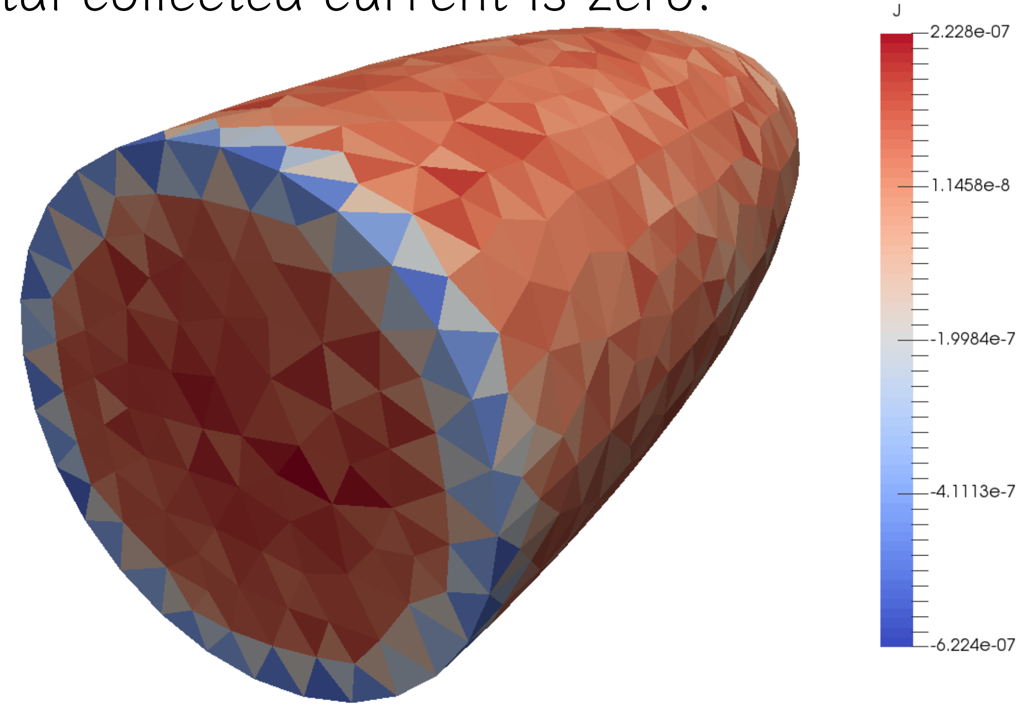
The Curvilinear particle-in-cell (CPIC) plasma-material interaction code has been modified for improved flexibility, and adapted here in studying spacecraft surface charging. The accuracy of the code physics and geometric representation were verified against a theoretical solution for the charging of a perfectly conducting sphere. Numerical results demonstrating the capabilities of the code in the case of simplistic spacecraft geometry were provided.

Collin Meierbachtol, Daniil Svyatsky, Gian Luca Delzanno, Louis Vernon, and David Moulton 2017 Numerical Simulations of Spacecraft Charging, Applied Space Environments Conference: Measurements, Models, Testing, and Tools, 15-19 May 2017, Huntsville, AL.

For a given charge on a conductor, E field is larger at edges and corners of a flat-faced segmented spherical probe, affecting the distribution of collected current.

Richard Marchand computed the collected J/area using PTetra simulations for a floating ogive-shaped conductor immersed in a stationary unmagnetized Maxwellian plasma. The parameters assumed in the simulation are 100% H^+ fully ionized plasma-electron density = ion density = 2.5×10^9 m^{-3}, Te = Ti = 0.1eV. Length of the ogive: 4-cm. Radius of the cross section at the back: 1cm. Floating potential = -0.38V. The current density is in units of A/m^2. Total current collected = 0. Negative current is collected at the edge and the tip of the ogive, where the electric field (directed toward the ogive) is strongest, and positive current is collected elsewhere where the surface is less sharp or less curved. Note also the large statistical errors in the current collected per unit surface area. This is due to the near cancellation of positive and negative current in this case where the total collected current is zero.





Publicity, recruitment, funding

Conferences, workshops, agencies

AGU, APS-GEC, APS-DPP, Bringing Space Down to Earth (April), Active Experiments in Space,

NSF, DOE-SC-FES, NASA

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Proposal (inclusive participation)

NSF-DOE Partnership, PI: Koepke, Co-PI: Marchand, Co-I: Demidov

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Communication and organization

Establish virtual presence, networking, and connectivity to achieve a fully integrated Developmental and Operational Test (DT/OT) approach in an inter-operable environment

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Point of contact: Mark.Koepke@mail.wvu.edu, 304-293-4912

Conclusion

Compelled by high experimental feasibility and feature-rich predictions of tell-tale inhomogeneity where homogeneity otherwise abounds in conventional modeling, we conceive the proof-of-principle exercise to be a conducting sphere and a cylinder under the conditions of nonstationary, between-regimes, flowing plasma for a modeling-challenge paradigm based on design of experiments (DOE) methodology that merges numerical simulation and testing.

After a proof-of-principle phase dedicated to generating evidence for streamlining the Model/Simulation development process associated with spacecraft-environment interactions, such a methodology could serve to enable fundamental scientific research essential to accomplish the NASA mission or to certify performance-acceptability standards on instruments.

End

Mott-Smith, H. M., and I. Langmuir 1926 Phys. Rev. 28, 727

Allen, J. E., R. L. F. Boyd, and P. Reynolds 1957 Proc. Phys. Soc. London, Sect. B 70, 297

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