Air Force Research Laboratory

Using Computer Simulation to Understand Active Experiments

AFRL HERITAGE | 1917–2017

100 YEARS OF U.S. AIR FORCE SCIENCE & TECHNOLOGY

Active Space Experiments Workshop

Santa Fe NM

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leidos

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Integrity ★ Service ★ Excellence

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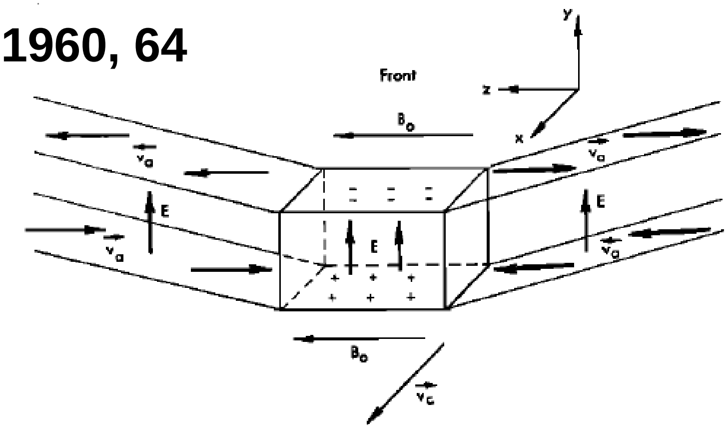
Outline

- Early years, electron beam rockets and big balloons
- SPEAR, Space Power Experiment Aboard Rockets
- Wake Shield
- NASCAP, POLAR, DynaPAC, Nascap-2k
- DSX
- TSS
- Momentum coupling in plasmas

ECHO I & II

Passive communication reflector satellites, 1960, 64

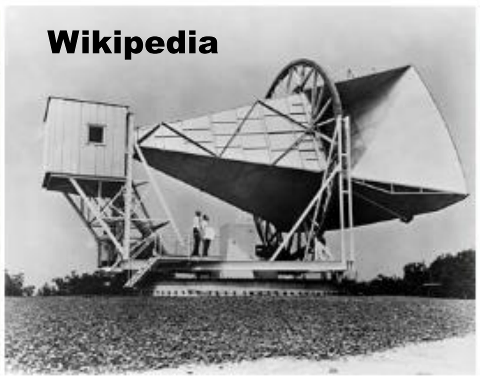
- High LEO (1000 km+) 47^{O} & 80^{O} inclination
- Successful voice (big bounce) transmission
- Led to first considerations of Alfven J x B drag
- No plasma drag reported, but photon pressure was measured
- More later



Alfvén wings generated by an ideal conductor in a collisionless plasma, Drell, S., H. Foley, and M. Ruderman. "Drag and propulsion of large satellites in the Ionosphere: An Alfvén propulsion engine in space," JGR, 1965.

Echo 2 inflated prior to launch in 1964

People



Holmdel Horn Antenna constructed for Project Echo and later used to discover the cosmic microwave background radiation.

This AT&T/Bell Labs video shows the first voice transmission via satellite and the engineers who conducted the effort.

Echo 1 - 1960 issue

Electron Beam Rockets

- Broad interest in electron beams for field line mapping, artificial aurora (Hess, 68), and perhaps plasma physics in space.
- Linson (69) review of electron collection
  - I-V characteristics of space platform and environment will determine charging.
  - Beard & Johnson (similar to Langmuir & Blodget, Langmuir & Mott-Smith)
    - Ignore B, compute the sheath, plasma electron current to/thru sheath
    - Quasi-analytic sheath model
  - Parker & Murphy
    - Analytic dynamical limit on electron collection based on conservation of canonical angular momentum
  - Suggested turbulence
    - Q = $\omega_{pe}^2/\omega_{ce}^2 = c^2/v_A^2 > ½$, conductive
    - Q < ½ , magnetic insulation
- The question of would beam emitting rockets collect enough current was replaced by why did they sometimes collect so much?

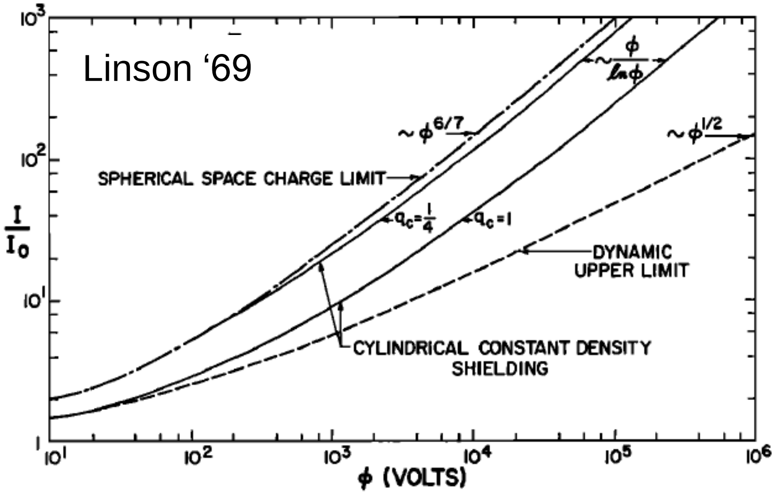


Fig. 3. Comparison of the predictions of the three models discussed in the text. Their asymptotic behavior for large ϕ is shown. The dot-dash curve represents the absolute upper limit to the current which the satellite can attract and, for constant potential, scales like $I_0^{-4/7}$. The normalized voltage ϕ_0 defined in equation 8 has been taken to be 178 volts. A change in the constant q_c displaces the solid curve horizontally by the appropriate factor.

Electron Beam Rockets

Hess (71) Artificial Aurora Experiment

- Taking no chances with insufficient return current
- First e-beam rocket?
  - Aerobee rocket, Wallops Island, Jan 69
  - 9 KV, 490 mA electron beam
  - 290 km altitude
  - Faint "aurora" streaks were observed for the highest power beams
  - Possible, but inconclusive VLF detected
  - Collector partially deployed, ultimately wrapped around payload
  - No apparent beam instability
  - No serious charging (details unpublished)

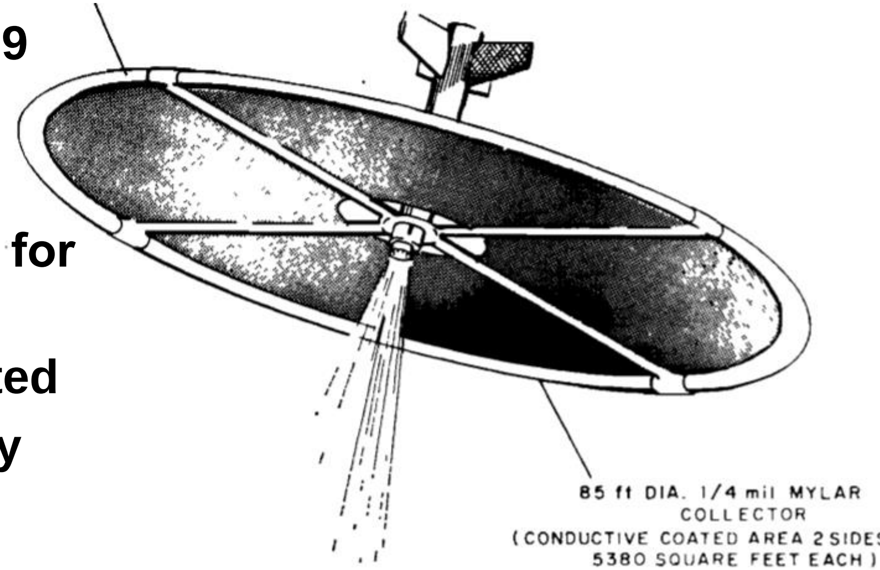
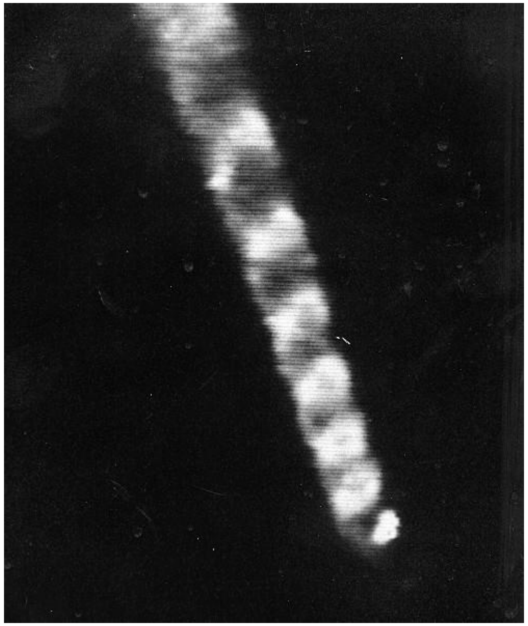


Fig. 7. The collector screen in the deployed configuration used to collect current to keep the rocket near electrical nutrality.

ECHO Rocket Series, 1-7

- **By 1980, there had been an about 25 particle beam rockets including ECHO 1-5 (mostly electrons)**
  - **Artificial aurora, conjugate returns, other effects observed**
  - **Beam currents up to 800 mA, 40 keV**
  - **Quiescent return currents to bodies 1-10 mA**
  - **Observed and estimated body potential < 40 V**
  - **Mostly below 300 km**
  - **Suggested puzzle solutions: Beam plasma discharge, Control gas ionization. No definitive models or measurements.**
  - **Negative charging showed accelerated ion spectrum**
  - **Electron spectra always hot and down to 0 eV.**
- **ECHO 7**
  - **Launched Feb 9, 1988, at from the Poker Flat, Alaska**
  - **Apogee of 292 km, 3 payload sections**
  - **40 keV, 250 mA (AFGL built) electron gun beam**
  - **5 kV (inst. limit) charging observed at 300km**
  - **Reduced to few 100V by ACS gas release**



Onboard observation of
ECHO 7 beam
100 km, 36 kV, 180mA, 150 ms

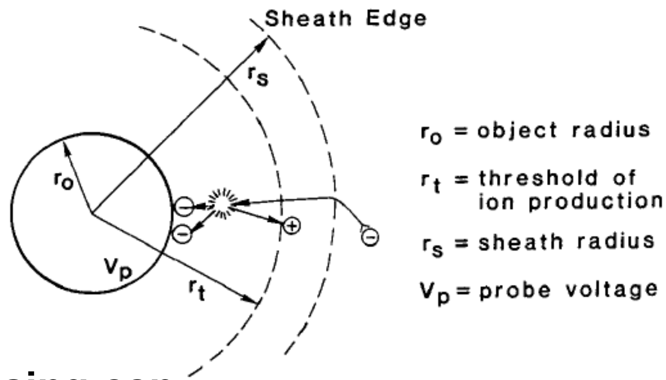
Winckler, J. R., Arnoldy, R. L., & Hendrickson, R. A. Echo 2: A study of electron beams injected into the high-latitude ionosphere from a large sounding rocket. *Journal of Geophysical Research*, *80*(16), 2083-2088, 1975.

Winckler, J.R., P. Malcolm, R. Arnoldy, W. Burke, K.Erickson, J. Ernstmeyer, R.Franz, T. Hallinan, P. Kellogg, S. Monson, K. Lynch, G. Murphy, and R. Nemzek, ECHO 7, An Electron Beam Experiment in the Magnetosphere, *Eos, Vol. 70(25), 1989*

Israelson, G. A., & Winckler, J. R. (1979). Effect of a neutral N2 cloud on the electrical charging of an electron beam-emitting rocket in the ionosphere: Echo IV. *Journal of Geophysical Research: Space Physics*, *84*(A4), 1442-1452.

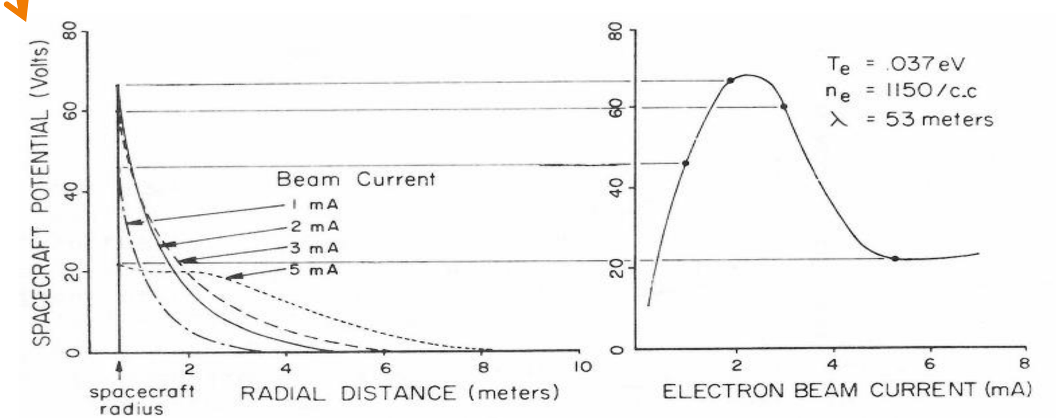
Space Charge & Discharge

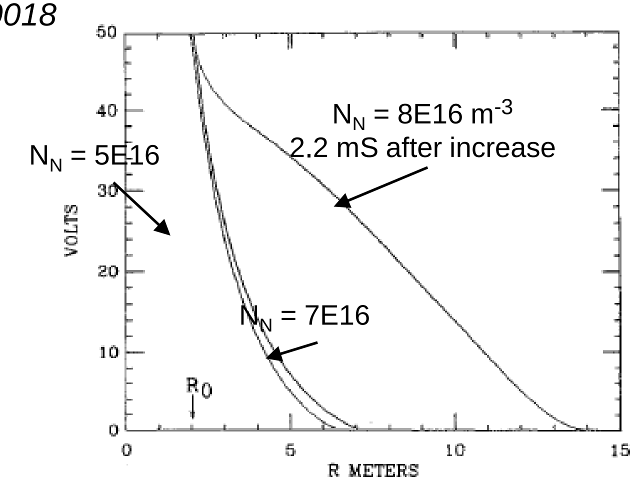
- **The low charging potential of electron beam rockets seemed related to low altitudes, RSC gas jets**
  - **But the ionization rates did not work.**
- **Two independent efforts showed that ions born in the electron collecting sheath move out slowly**
  - **Positive space charge destabilizes sheath (explodes).**
  - **8 x 10^{16} m^{-3} ≈ 10^{-8} Torr ≈ 160 km**
  - **1% of density needed for Paschen breakdown**
- **Even above 200 km, and w/o gas jet operation, outgassing can provide enough neutral density to discharge a sounding rocket**



Cooke, D., I. Katz, Ionization-Induced Instability in an Electron Collecting Sheath, *J. Spacecraft & Rockets,* 1988

Lai, S., H. Cohen, K. Bhavnani, M. Tautz, Sheath Ionization Model of Beam Emissions from Large Spacecraft, *Proc of Spacecraft Charging Interactions Technology, 1983, AFGL-TR-85-0018*



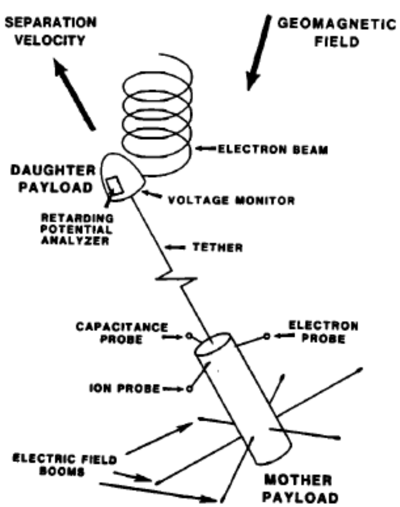


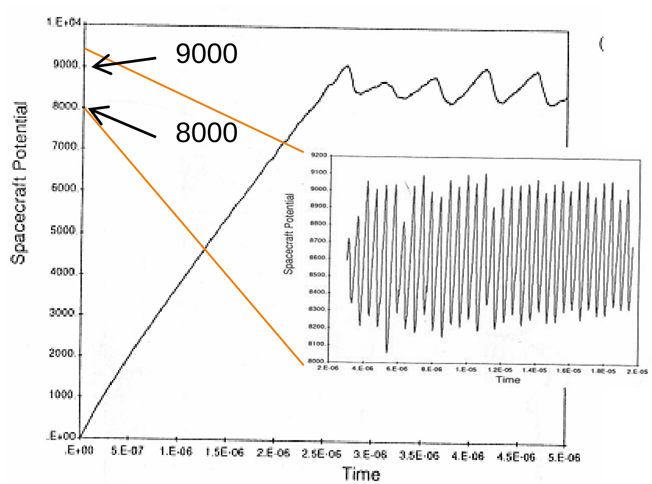
And then there was MAIMIK
14 kV charging with 8 keV e-beam

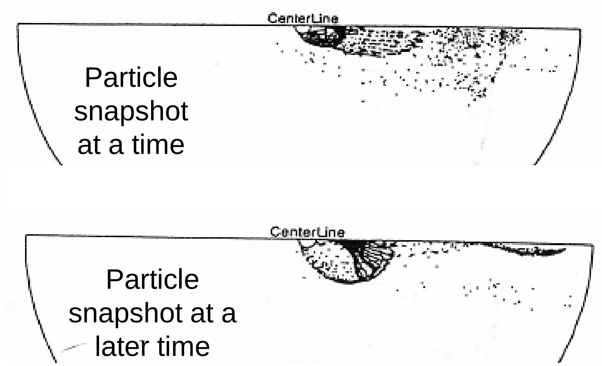
Mother-daughter tethered sounding rocket, launched Nov. 1985 from Norway

- **Mother-daughter potential measured during electron beam emission**
- **Potential as high as 14 kV measured during emission of 8 keV, 0.8A electron beam**
- **Low plasma density measured by EISCAT (< 10^4 /cc)**
- **Estimated plasma thermal current integrated over a L-B type sheath < 2% I_{beam}**

- **2D axisymmetric PIC simulation (Mandell & Katz)**
  - **Dipole oscillation of trapped electron beam cloud, above-below-above... the rocket**
  - **Broadened electron distribution with energized fraction sufficient to escape and maintain supercharged potential**





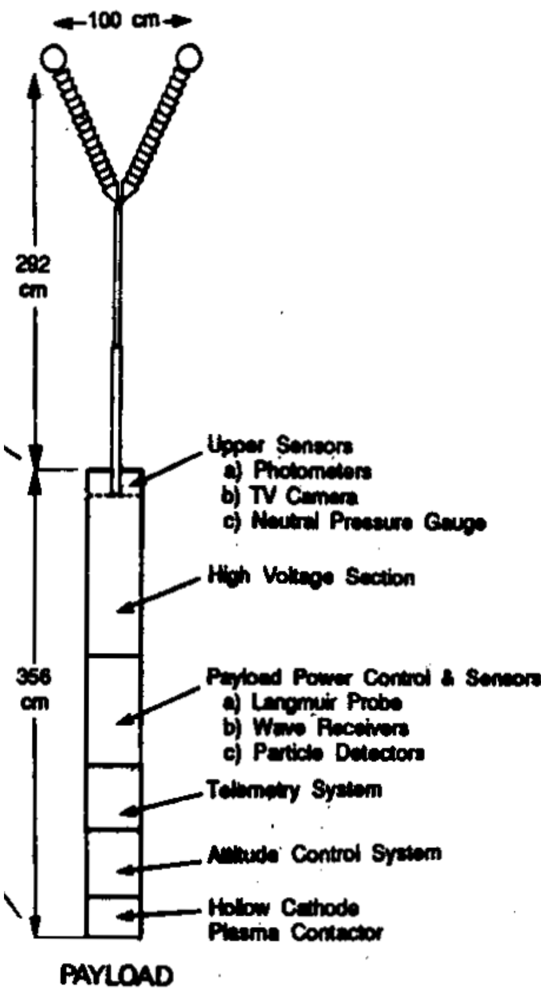


Denig, W.F., N. Maynard, W. Burke, B. Maehlum, Electric Field Measurements During Supercharging Events on the MAIMIK Rocket Experiment, *JGR, V96(A3), 1991*

Mandell, M.J., I. Katz, Dynamics of Spacecraft Charging by Electron Beams*, Proc of Spacecraft Charging Technology Conference, 1989, PL-TR-93-2027*

S.T. Lai and J. Wang. Supercharging - Theory and Simulations, 36th AIAA Aerospace Sciences Meeting and Exhibit, *https://doi.org/10.2514/6.1998-987*

SPEAR
Space Power Experiments Aboard Rockets



SPEAR-1

SPEAR-1,2,3 was an SDIO science program to pioneer high voltage and current technology for space

- **Insulated & pressurized systems would be too heavy**
- **Use the vacuum (with conductive plasma)**
- **The terrestrial insulation and rocket communities were brought together to develop guidelines for plasma engineering**
  - **Design of insulator bushings to hide triple points**
  - **Sheath physics, including bi-polar sheath**
  - **Still mysterious neutralization**
  - **Neutral gas effects, both outgassing & RCS jets**
  - **Paschen type breakdown between spheres**

SPEAR - 1

- **Launched Dec 1987, Wallops Island, 370 km.**
- **46 kV between probes and/or rocket body**
- **No breakdown in space (common in chamber testing)**
- **A hollow cathode failed, and did not hold rocket V≈0**
- **Neutral pressure stayed above 10^{-5} Torr**
- **Plasma currents were linear w Voltage and effected by angle to B, but never magnetically insulated**

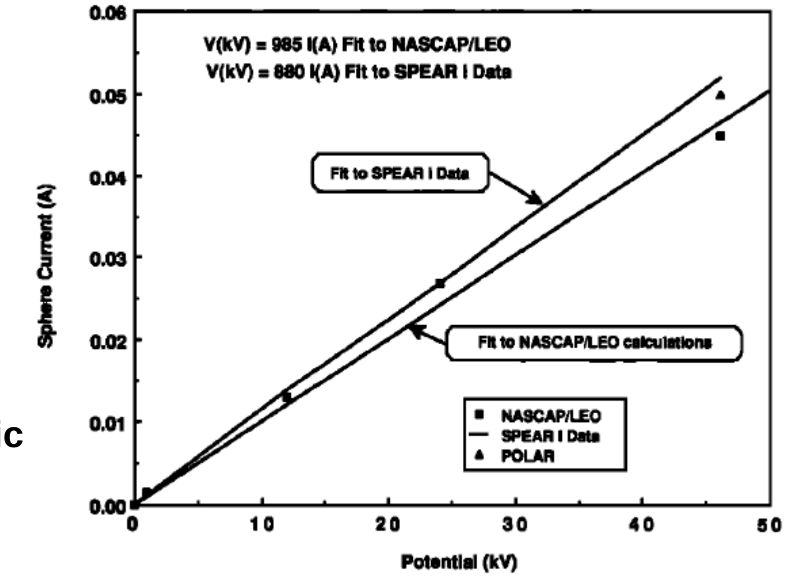
SPEAR-1 Bipolar Sheath

Results & Analysis

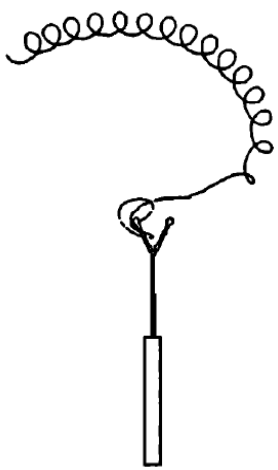
- The boom insulators worked as designed
- The current-voltage characteristic was linear
  – Both PM & PB currents should grow less than linear with Voltage.

$$I_{PM} = \frac{1}{2} I_{LB} \frac{\omega_{pe}}{\omega_{ce}} \left(\frac{kT_e}{eV}\right)^{1/4} \qquad I_{LB} = 4\pi J_{th} R_O \lambda_D \frac{\omega_{pe}}{\omega_{ce}} \left(\frac{eV}{kT_e}\right)^{\beta}$$

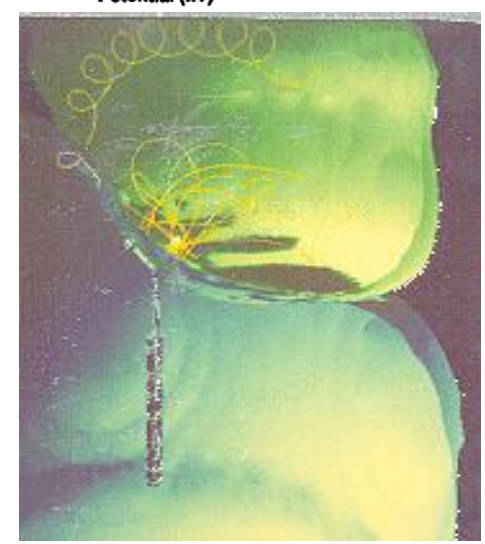
$$3/4 < \beta < 6/7$$



- POLAR II simulation
  – Bipolar distorted sheath limits symmetry and magnetic shielding, increasing collection efficiency w larger V
  – Angular momentum, canonical or otherwise is a property of field symmetry, not the particle.
  – As the ion energy impacting the body increases, ion generated secondary yield increases
  – Linear finite-element, multi-grid, charge stabilized. Trajectories tracked from sheath edge
  – Steady State, electrons behave classically and turbulence not need
- NASCAP-LEO Analytic space charge formula, sheath edge particle tracking for currents



NASCAP-LEO



Katz, Jongeward, Davis, Mandell, Kuharsky, Lilley, Raitt, Cooke, Torbert, Larson, Rau, “Structure of the Bipolar Sheath Generated by SPEAR I,” *JGR, 94(A2)* 1989.

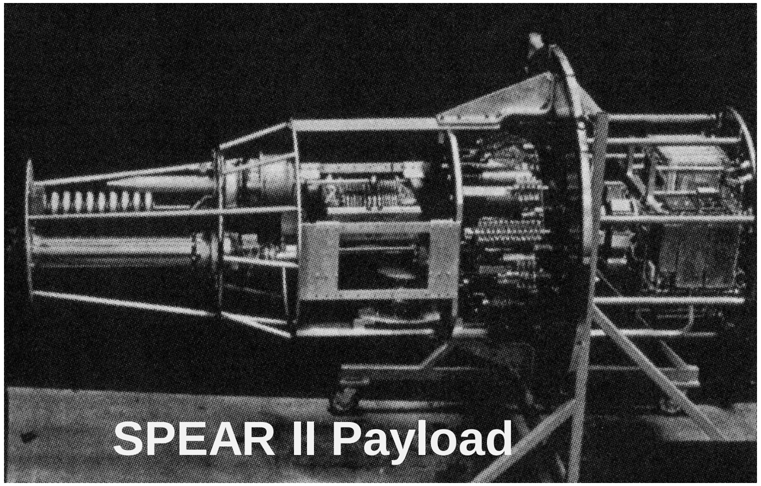
DynaPAC Applications

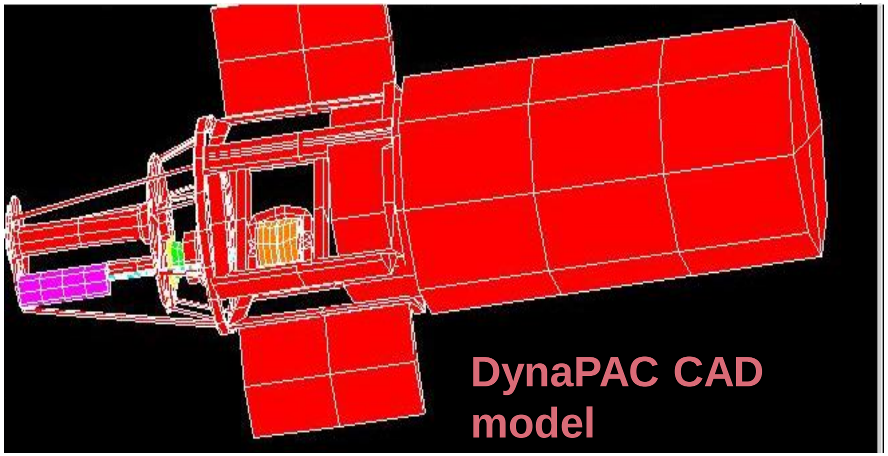
SPEAR - II

- Pulsed power components in space, 100 KV
- No oil, no water, no pressurized gas, no foam
- It will breakdown, but after how long? Long enough?
- Launch failure
- Extensive chamber testing & model agreement validated designs

DynaPAC (Dynamic Plasma Analysis Code)

- Evolved from POLAR II, Full explicit & hybrid PIC, extended CAD capability

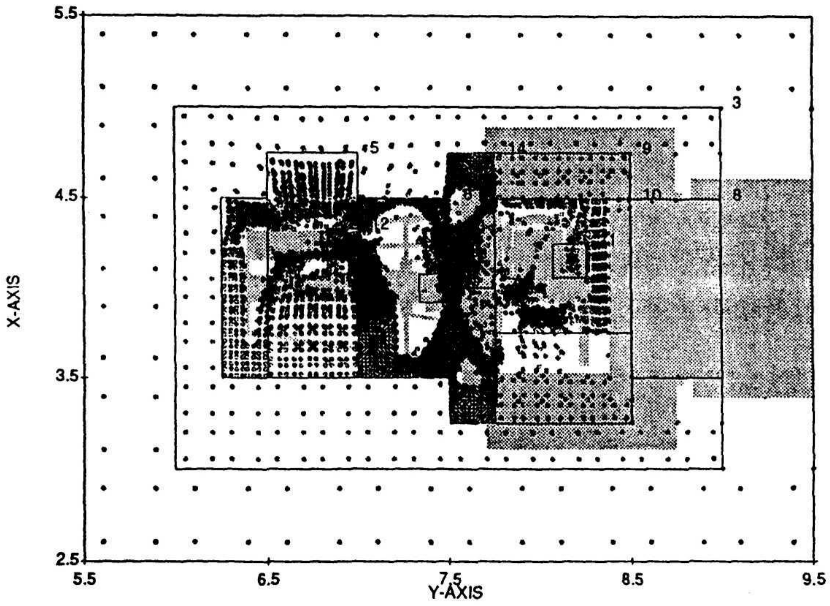




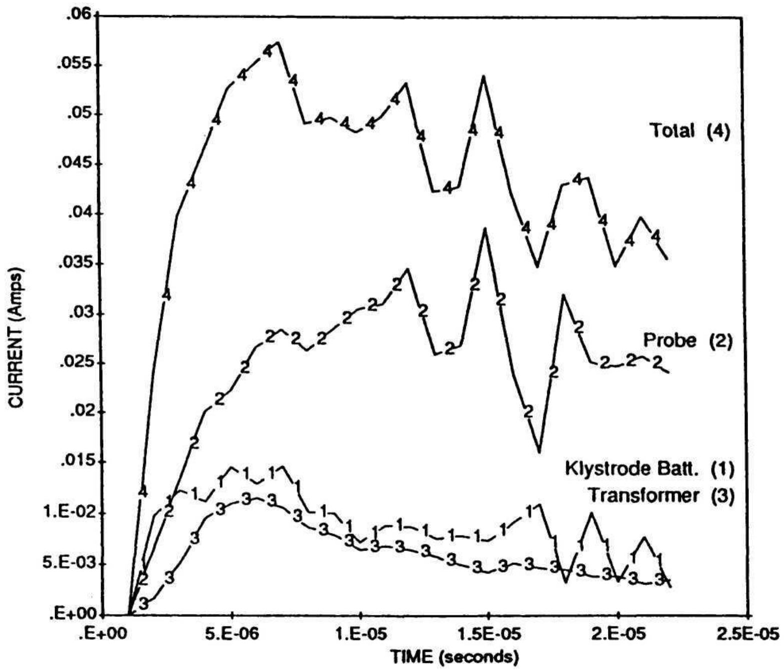
Cohen, Lehr, Engle, "SPEAR II High Power Space Insulation, Texas Tech Univ. Press, 1995

DynaPAC Applications

SPEAR-II PIC Simulation



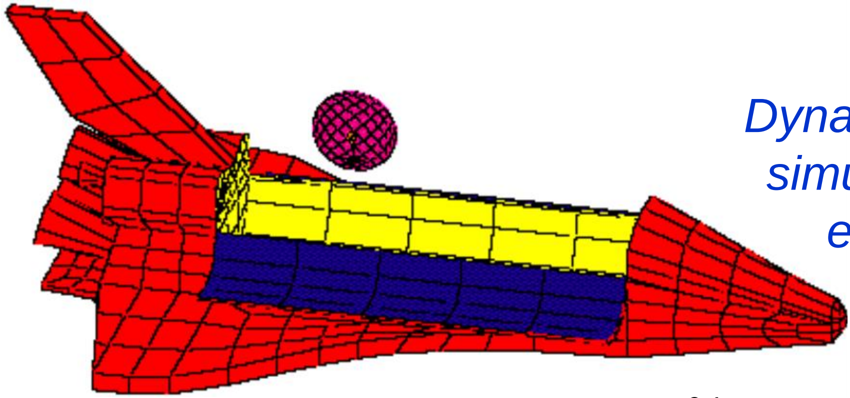
Ion macroparticles 3 μs into simulation. Original distribution represented constant ion density.



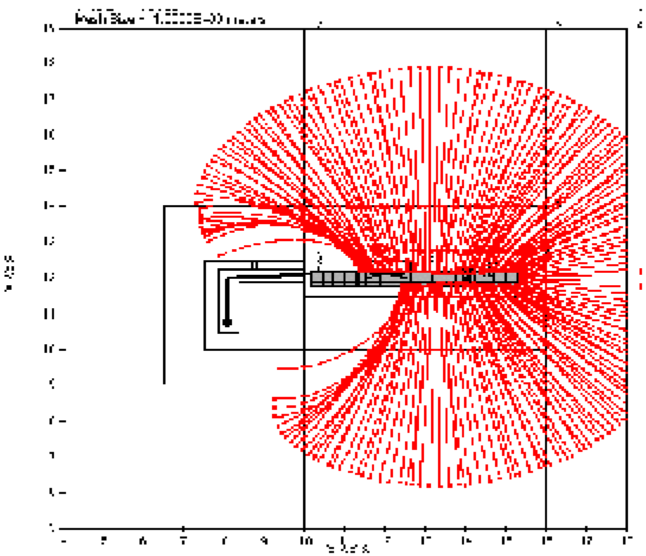
Calculated ion currents to the SPEAR-II high voltage components.

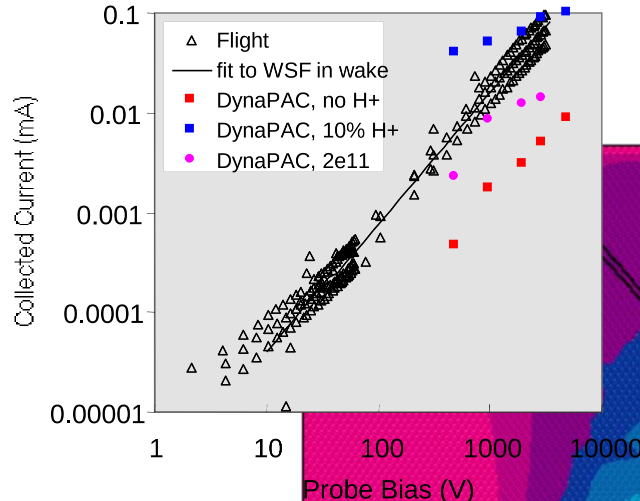
SPEAR-II was lost on launch, but (CAD aided) designs to hold off breakdown were developed and validated in chamber testing

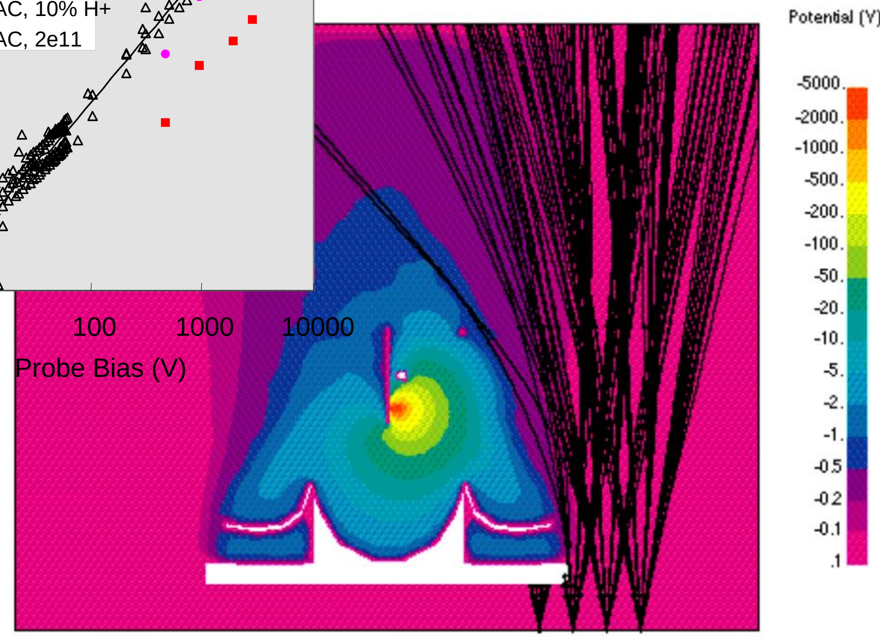
DynaPAC Applications



DynaPAC multi-sub-grid resolution enables the simulation of the CHAWS high voltage probe experiment on the Wake Shield Facility (STS60 and STS69)



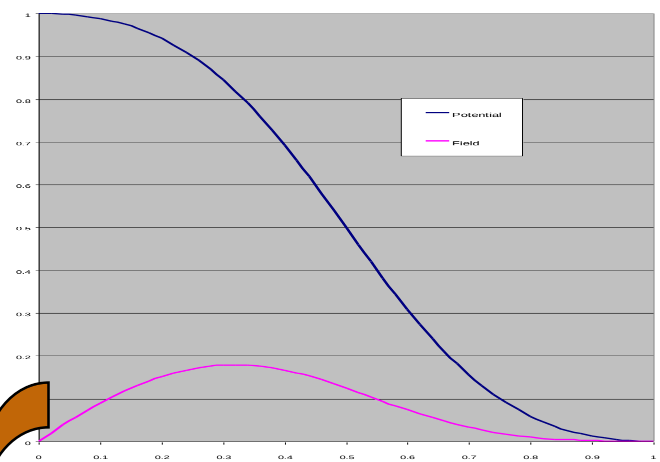


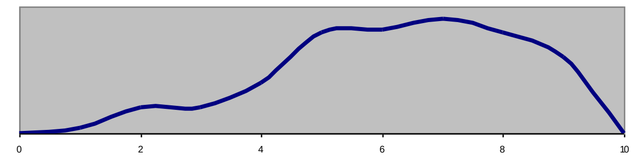


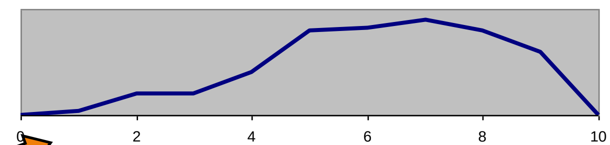
DynaPAC simulation of the 3D ion sheath surrounding the SPEAR-III sounding rocket experiment

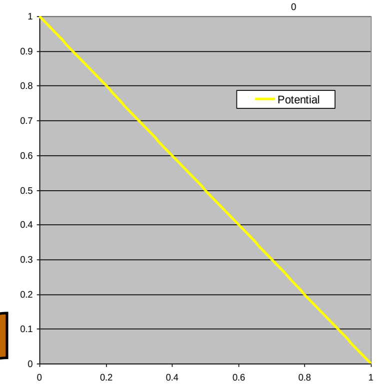
DynaPAC Innovations Continuous Electric Field

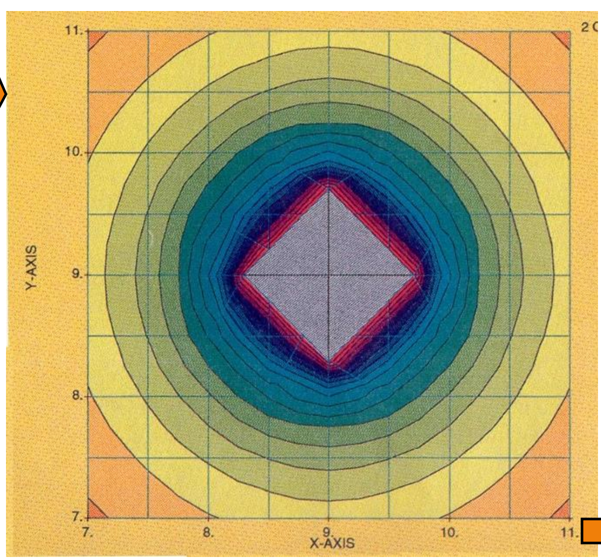
Non-linear finite element interpolants yield continuous electric field

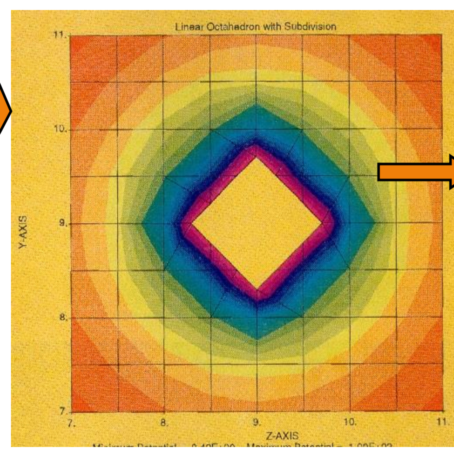




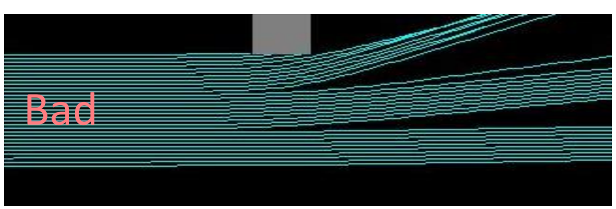


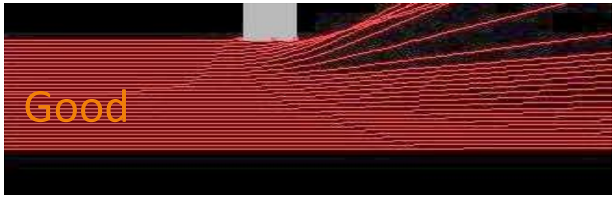




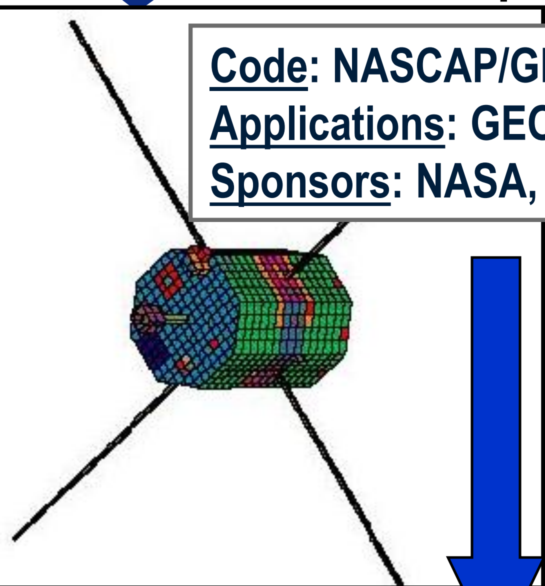


Linear Finite Elements lead to piece-wise continuous potential, piece-wise *discontinuous* electric field and unphysical beaming



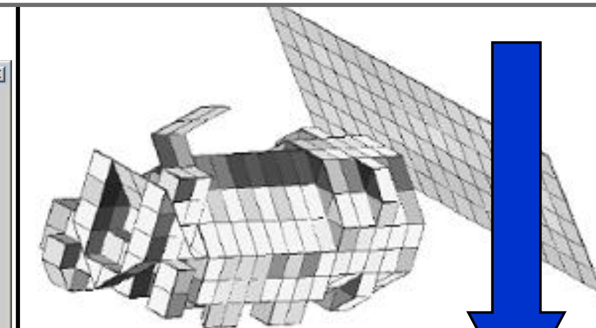


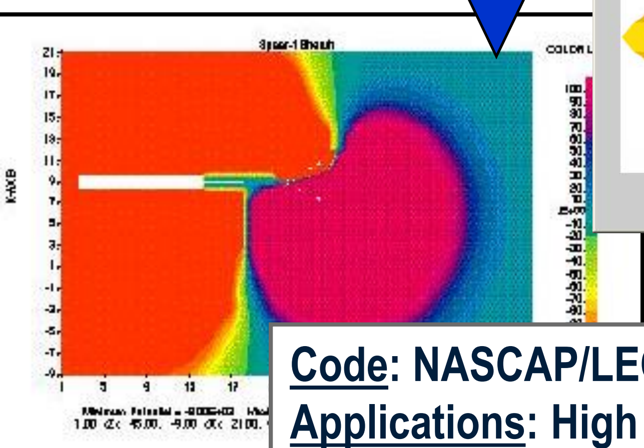
Nascap-2K Replaces Earlier Spacecraft-Plasma Codes

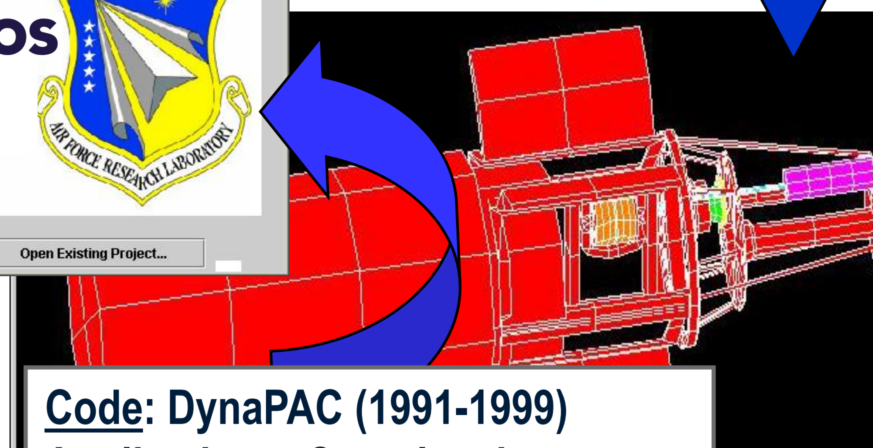


Code: NASCAP/GEO (1976-1984)
Applications: GEO S/C Charging
Sponsors: NASA, Air Force

Code: POLAR (1978-1991)
Applications: Auroral Charging, Wakes
Sponsor: Air Force







Code: NASCAP/LEO (1980-1991)
Applications: High Voltage Current Collection in Dense Plasma
Sponsor: NASA

Code: DynaPAC (1991-1999)
Applications: Complex dense plasma phenomena
Sponsor: AFRL

Boundary Element Method Equations & Implicit Charging

In GEO, where space charge may be neglected, rather than a global gridded field solution, the BEM uses Coulomb's law to sum over all sources of surface charge for the field at a specific point (grid-less).

$$V = \frac{q}{4\pi\varepsilon_0 r} \longrightarrow (4\pi\varepsilon_0)V_i = \sum_j \int d^2 r_j \frac{\sigma_j}{r_{ij}}$$

$$E = \frac{q}{4\pi\varepsilon_0 r^2} \longrightarrow (4\pi\varepsilon_0)\mathbf{E}_i = \sum_j \int d^2 r_j \frac{\sigma_j}{r_{ij}^3}(\mathbf{r}_i - \mathbf{r}_j)$$

$$V_i = [\mathbf{C}^{-1}]_{ij}\,\sigma_j \qquad \mathbf{E}_i \cdot \mathbf{n}_i = \mathbf{F}_{ij}\sigma_j \qquad \mathbf{E}_i \cdot \mathbf{n}_i = \mathbf{F}_{ik}\mathbf{C}_{kj}V_j$$

$$q_i = A_i (E \cdot n)_i + C_{ic}(V_i - V_c) \qquad \text{(insulators)}$$

$$I_i(V_i, (E \cdot n)_i) = A_i F_{ik} C_{kj} \dot{V}_j + C_{ic}(\dot{V}_i - \dot{V}_c) \qquad \text{(insulators)}$$

Discretize and Implicitize: $I(t+\Delta t) \approx I(t) + dI/dV\,(V(t+\Delta t) - V(t))$

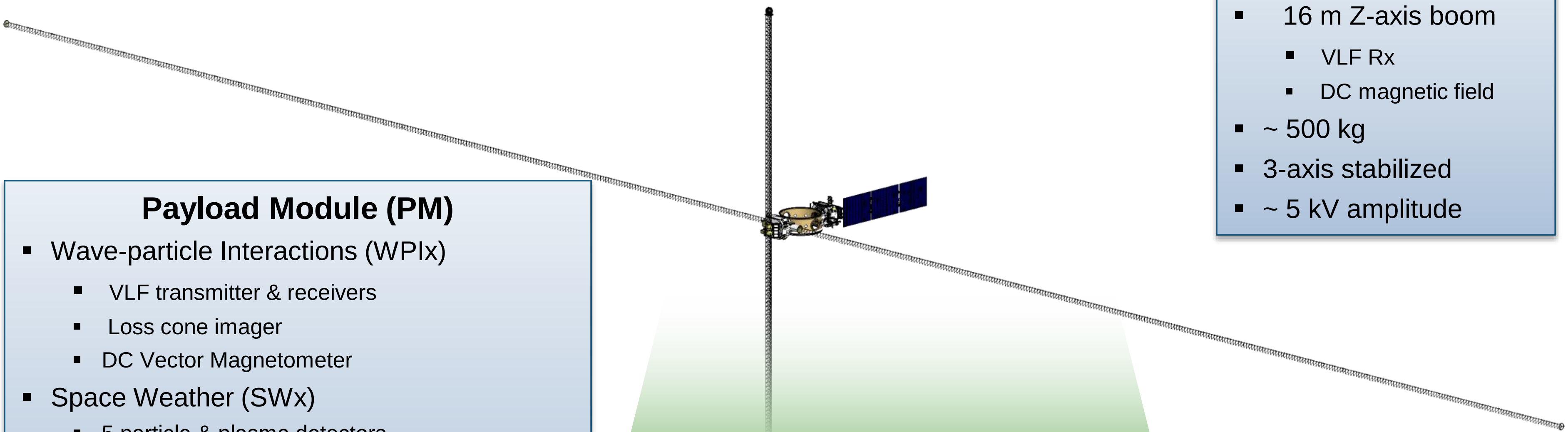
A bit more Math: $V(t+\Delta t) = V(t) + I(t)/[\mathbf{G} - \mathbf{I}']$

Where **G** is a 'round-up' of all the capacitance-like terms (all the math) and the current derivative, **I′ =** ***dI/dV***, contains all the physics.

DSX Spacecraft
A really big VLF antenna

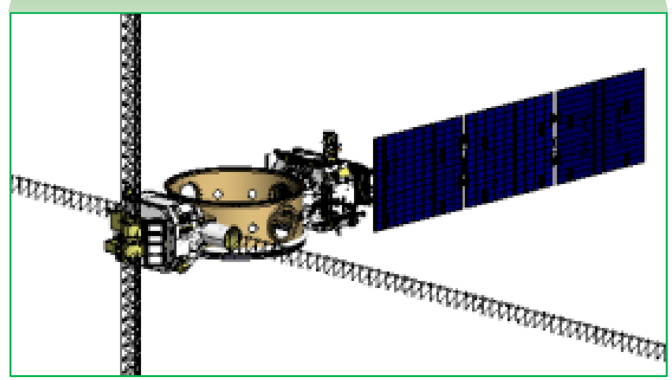
Largest unmanned self-supporting structure ever flown in space

- 80 m Y-axis boom
  - VLF Tx & Rx
- 16 m Z-axis boom
  - VLF Rx
  - DC magnetic field
- ~ 500 kg
- 3-axis stabilized
- ~ 5 kV amplitude



Payload Module (PM)

- Wave-particle Interactions (WPIx)
  - VLF transmitter & receivers
  - Loss cone imager
  - DC Vector Magnetometer
- Space Weather (SWx)
  - 5 particle & plasma detectors
- Space Environmental Effects (SFx)
  - NASA/Goddard Space Environment Testbed
  - AFRL effects experiment
- NASA/JPL deployable structures payload



Avionics Module (AM)

- Attitude Control System
- Power
- Thermal Control
- Communications
- Computer/Avionics
- Experiment Computer
- Space Weather (HEPS)

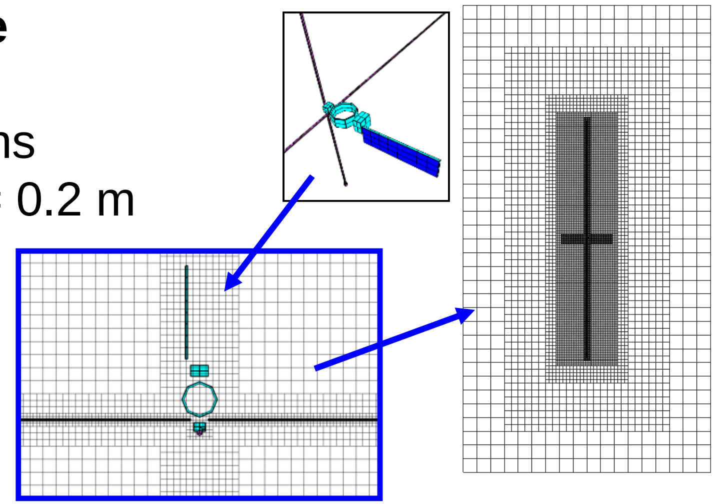
First spacecraft design with integrated ESPA Ring

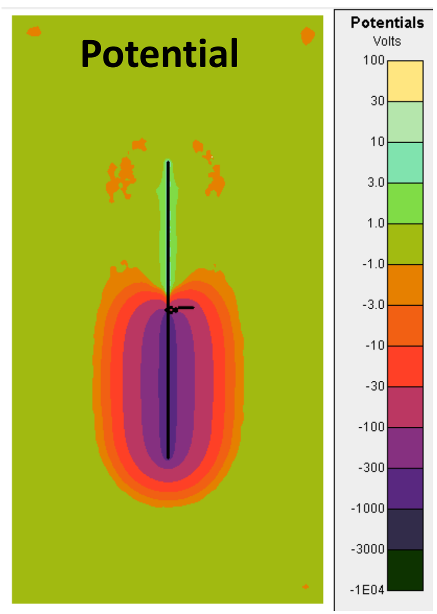
Dynamic Sheath Simulation with Nascap

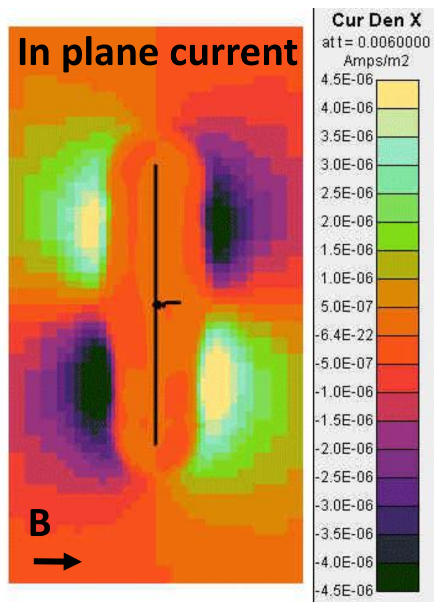
leidos

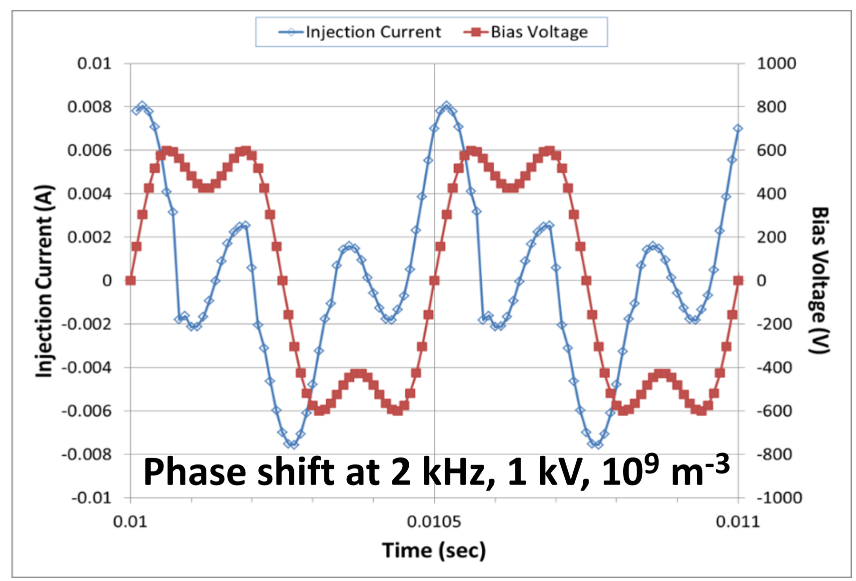
Sheath physics is key to antenna performance

- Investigation with Nascap
- 3D finite element PIC and hybrid PIC simulations
- Full scale, 5 kV, nested grids 15 cm – 5 m, λ_D = 0.2 m
- **Plasma power loss:** < 1 W (preliminary)
- Antenna + volume/shielding currents hand off to cold-plasma EM solver









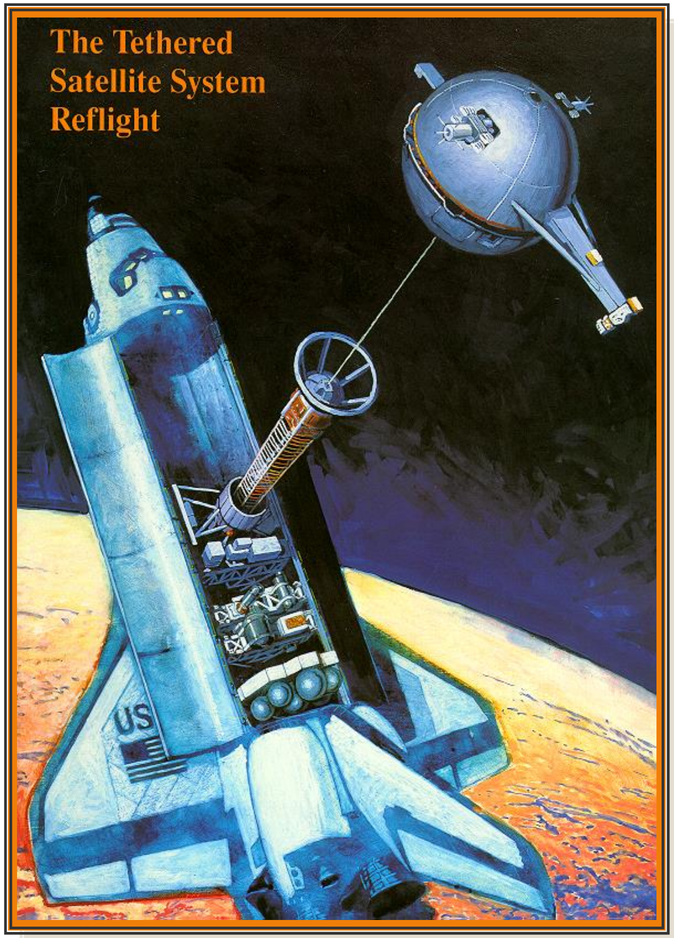
Numeric models in Nascap-2k

- Environment integrals (*NASCAP/GEO & POLAR*)
- Implicit charging algorithm (*NASCAP/GEO*)
- Finite element method (*NASCAP/GEO*)
- Multiply nested grids (*NASCAP/LEO*)
- Space charge stabilization (*POLAR*)
- Matrix elements for "special elements" (*NASCAP/LEO*)
- Strictly continuous electric fields (*DynaPAC*)
- Third order particle tracking (*DynaPAC*)
- Boundary element method (*Nascap-2k*)
- Moment conserving particle injection, splitting, chemistry (Nascap-2k)
- Object Toolkit (*Nascap-2k*)
- Orbit Averaging blends, PIC → Cloud in Cells → Steady State Trajectory (Nascap-2k) Where we started and still very efficient
- Pseudopotential fluid current calculation (for DSX)

Electrodynamic Tethers

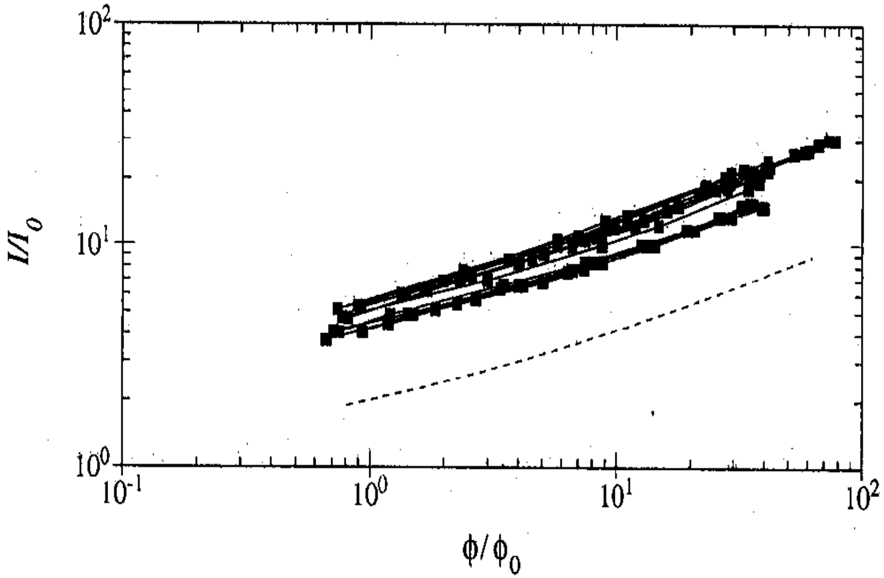
The TSS1 (1992) and TSS-1R (1997) space shuttle missions demonstrated

- Viable concept for extracting or adding orbital energy
- Space Shuttle charging
- Techniques for electron emission and ion collection at shuttle (and tether) end
- Enhanced magnetized probe collection
- There was and still is no theory for the positive bias Langmuir probe in a flowing plasma
- Electrodynamic plasma coupling theory was not adequate for experiment prediction
- Much more

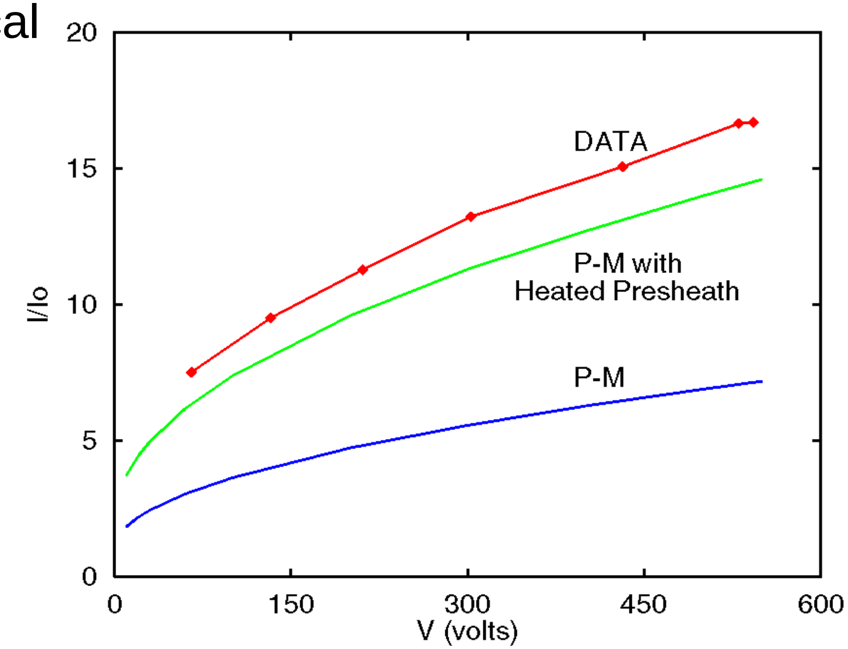


TSS-1R Current Collection During Electron Gun Emission

- TSS-1R data showed enhancement over Parker-Murphy, P-M, canonical angular momentum conservation theory, ranged from 2.2 to 2.9.
- Data groups best when normalized to local plasma parameters
- Data does not show dependence on Alfven speed or D region conductivity
- Results do scale like P-M.



TSS-1R data normalized by thermal current and electron temperature [Thompson et al., 1998]



Early TSS-1R data by Wright et al. [1997]
Heated pre-sheath model, Cooke & Katz ['98]
$I = ½\, I_{P\text{-}M}\, (1 + (1 + 2E_{Ram}/5T_O)^{½})$

The (Alfvén) Wing model (Drell et.al.) Recall ECHO I-II & TSS-1R

Current closure through polarization current

$$j_p = \left(\rho / B^2\right)\left(\frac{dE_y}{dt}\right) \qquad \frac{dE_y}{dt} = \frac{dE_y}{dy}\frac{dy}{dt}$$

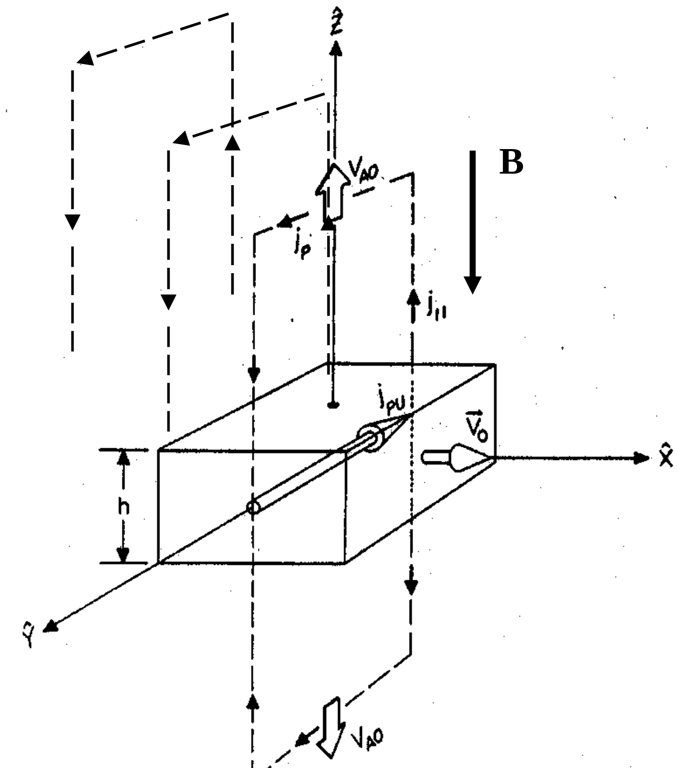
- With high field aligned mobility, $E = v_o \times B$ is constant below the $j_{//}$ front, and the front moves at $v_{//}$
- Integrate cloud and front along Z.

$$hj_{pu} = \int j_p dz = \int j_p v_{ll} dt = \int \left(v_{ll}\rho / B^2\right) dE = \left(\rho / B\right) v_{ll} v_O$$

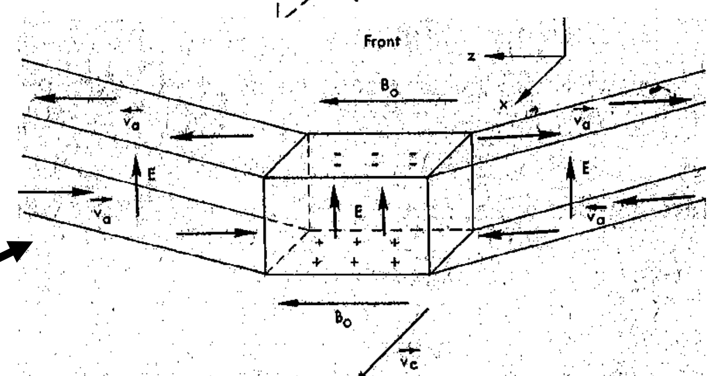
- The braking force on the cloud plasma is

$$\mathbf{j_{pu}} \times \mathbf{B} = -\left(\frac{2}{h}\right)\rho v_{ll} v_O$$

- Drell, Foley and Ruderman [1965] first performed this analysis for ECHO I-II with the conjecture that $v_{//} = v_A$
- With the realization that a tether more readily generates Whistler waves than Alfvén waves interest waned, but the conjecture has never been validated.
  - **They botch a space-charge limiting test**

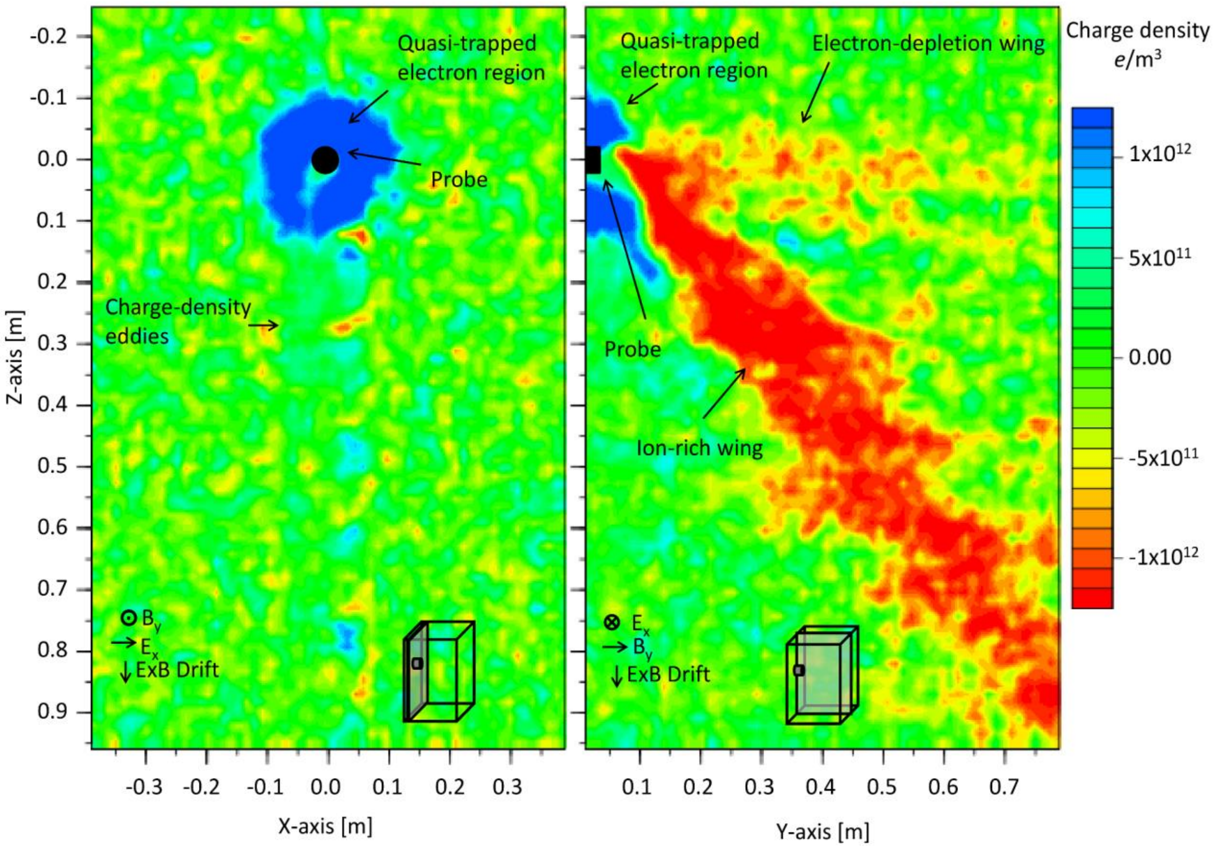


Alfvén Wings



Simulation of a positive probe in a flowing magneto-plasma with ICEPIC

Under-dense strongly magnetized plasma



Four regions:

- Quasi-trapped electron region
- Electron depletion wing
- Ion-rich wing
- Wake region
- Ion cyclotron wake eddies
  - characteristic wavelength

$$\lambda = 2\pi U_{drift}/\omega_{ci}$$

- No magnetic perturbation observed

$$r_e < \lambda_D < r_i < r_P$$

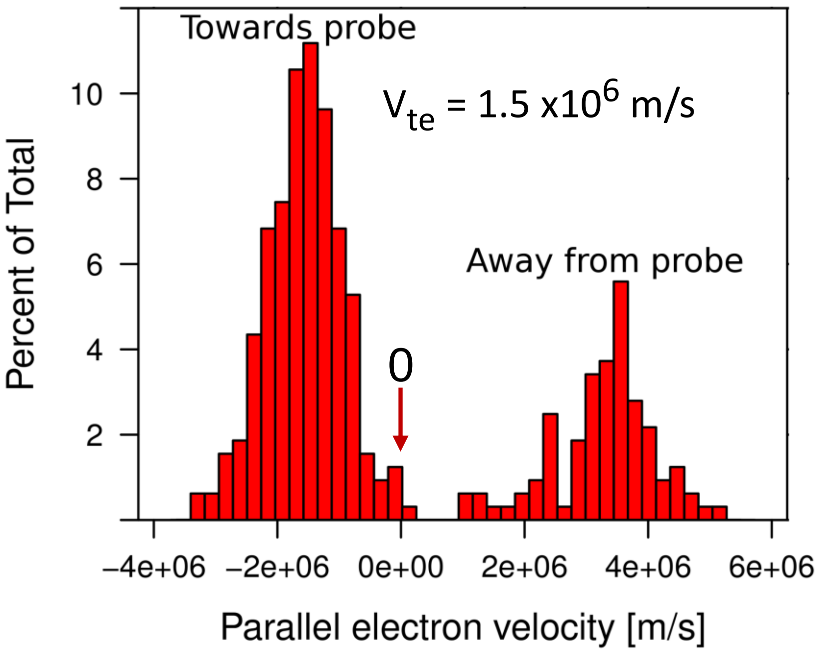
Charge Density Cross−Sections: $t = 6.05 \times 10^{-6}\ s$ with $V_p = 200$ V

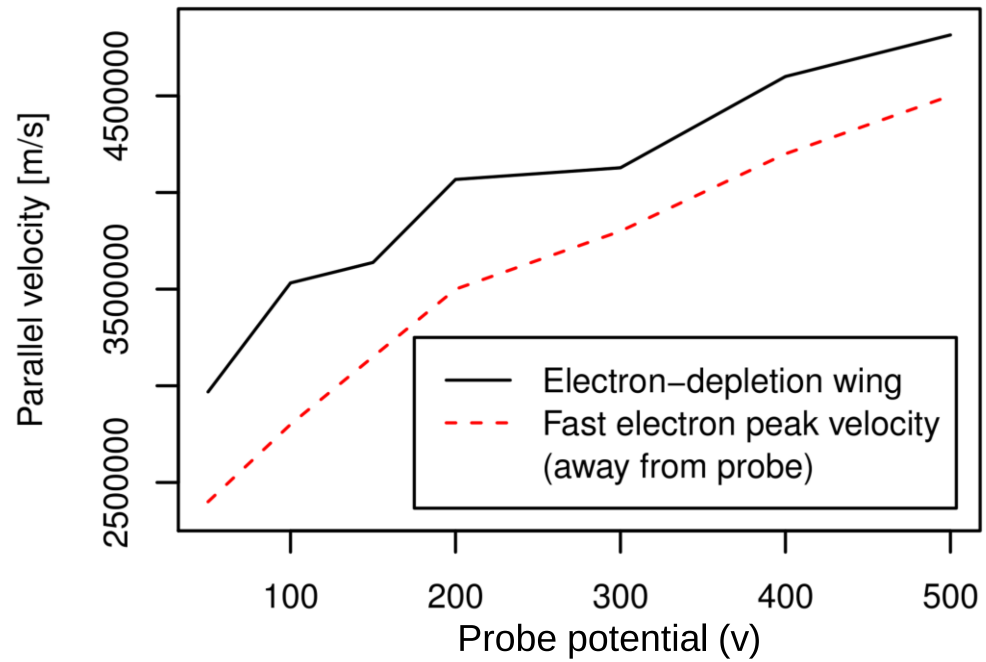
Dynamics of positive probes in under-dense, strongly magnetized, E X B drifting cc plasma: Particle-in-cell simulations, Jonathon R. Heinrich and David L. Cooke, *Physics Of Plasmas* 20, 093503 (2013)

ICEPIC (Improved Concurrent Electromagnetic PIC), J. Blahovec, L. Bowers, J. Luginsland, G. Sasser, and J. Watrous, IEEE Trans. Plasma Sci. 28, 821 (2000).

Simulation using ICEPIC
Under-dense strongly magnetized plasma

Electron Depletion Wing



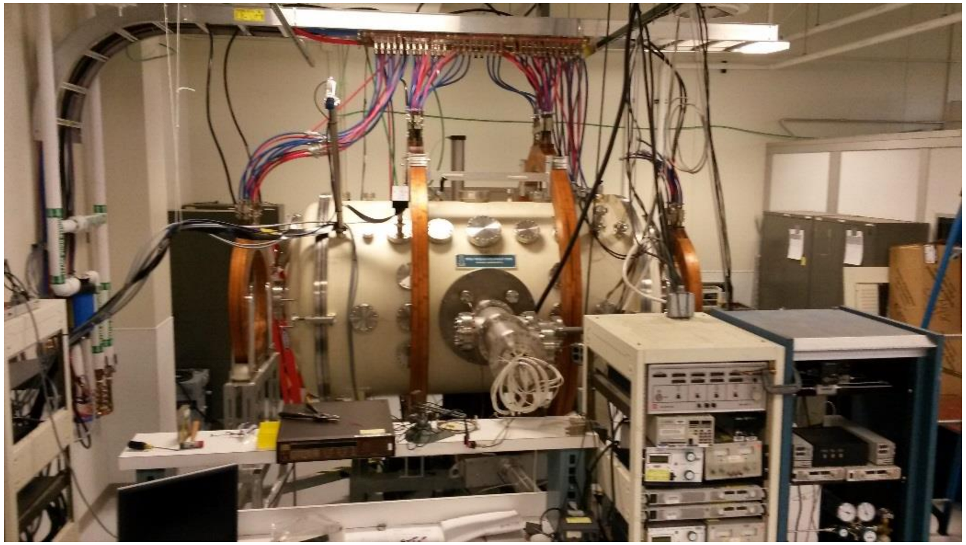


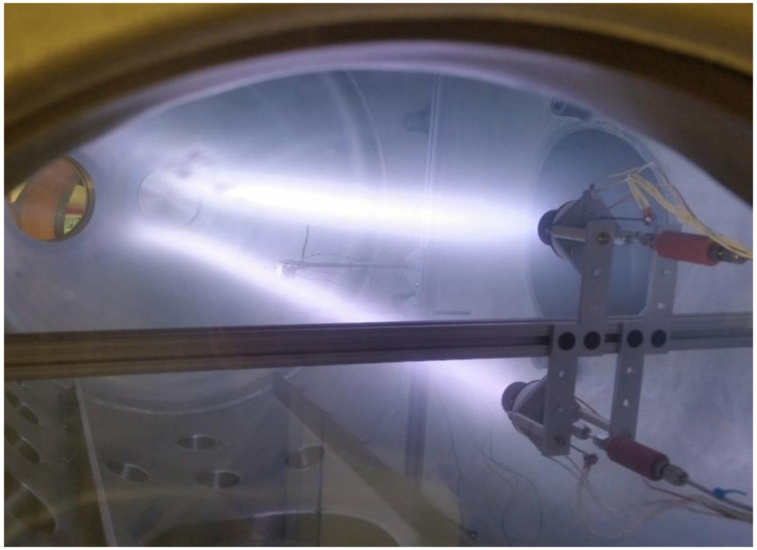
- Two populations of electrons in electron depletion wing.
- Secondary fast population propagating away from probe found on trailing edge of depletion wing.

- Propagation velocity of electron depletion wing follows velocity of secondary fast electrons.
- Secondary electrons originate from the quasi-trapped region.

Dynamics of positive probes in under-dense, strongly magnetized, E X B drifting cc plasma: Particle-in-cell simulations, Jonathon R. Heinrich and David L. Cooke, *Physics Of Plasmas* 20, 093503 (2013)

E x M Plasma Device EMPD

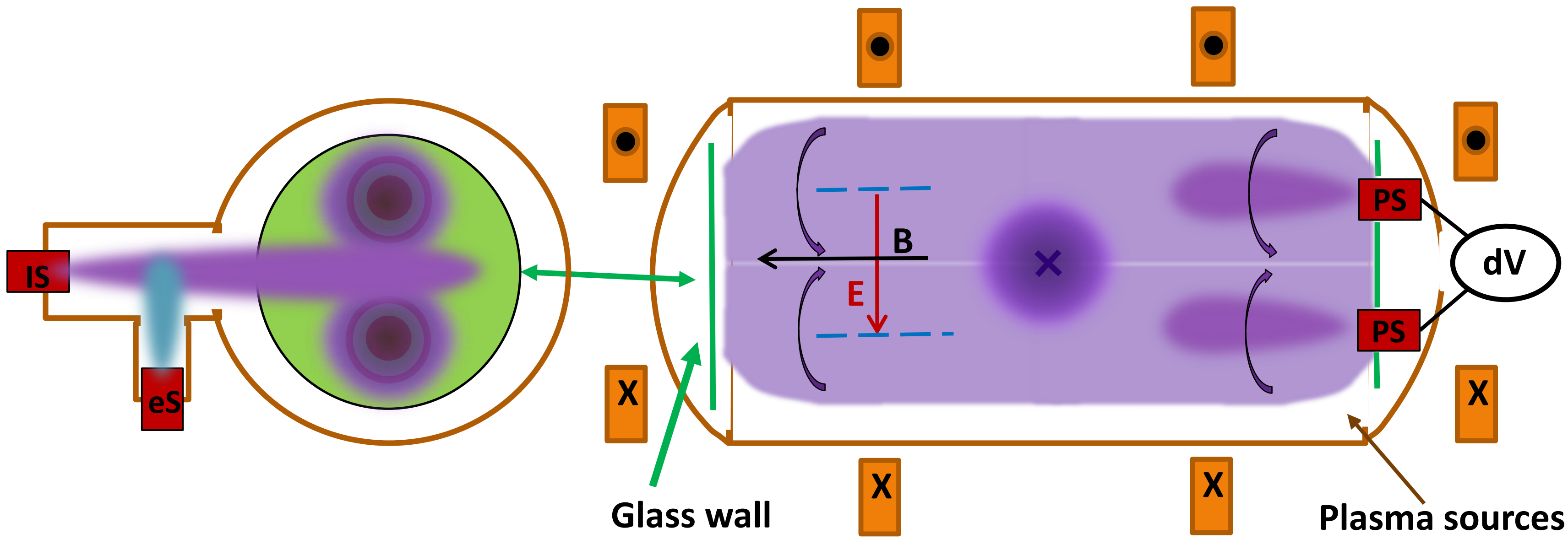




New facility at AFRL Kirtland AFB, Space Vehicles Directorate

- 2m x 1m chamber, 300 G,
  - Glass inner doors to support transverse **E**
- Plasma sources
  - Hollow cathode light sabers (shown) – Helicon in development
- Planned experiments
  - ExB drifting plasma to explore wings (Thermal vs Alfven)
  - Spinning CIV limited plasma

Spinning Plasma Experiment ExB Pinch Roller



Objectives

- Plasma wing experiments
- Positive probe in flowing magnetoplasma
- Twin rotating columns for ExB boundary condition (Mach = 1 due to CHX)
- Injected Ions, $\boldsymbol{v}_D$ = E/B, Mach >1

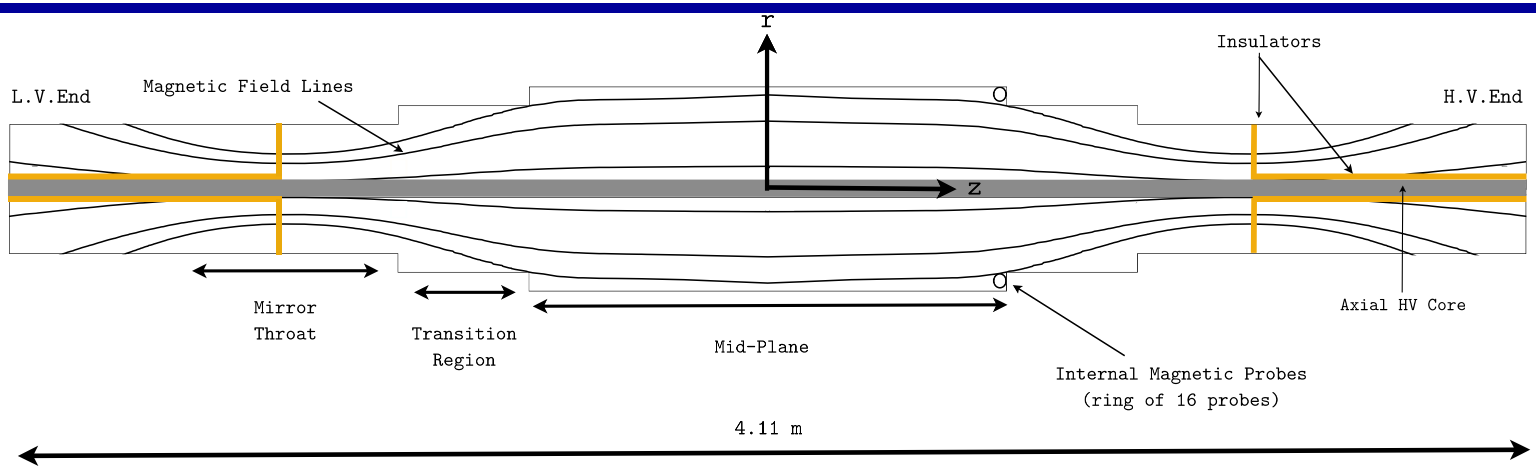
Plasma sources

- Hollow Cathodes
- Helicon
- Bad Magnetron (sandbox effort)

Diagnostics

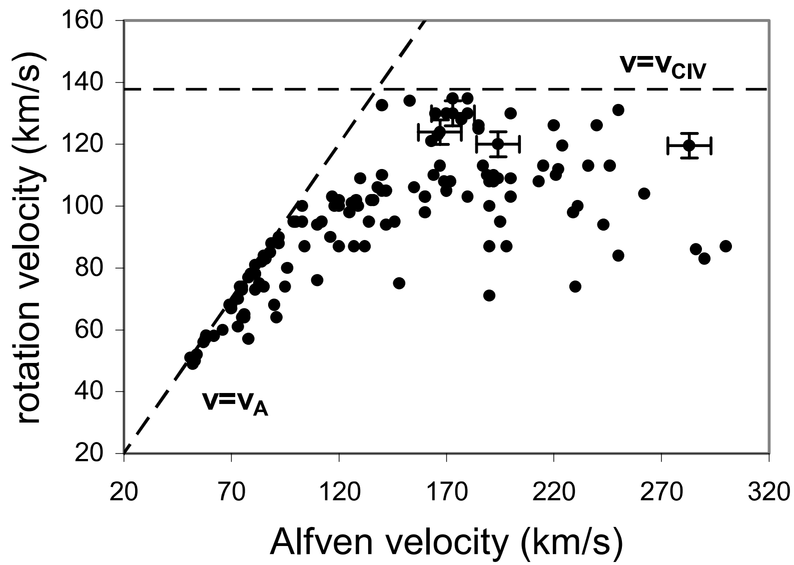
- Motion system (2x 2D, translation + rotation)
- 16 channel, HV, Low I, analog multiplex switch
- Keithley 237
- Cyl Langmuir Probes
- MACH probes
- Emissive probes
- Rogowski coils
- Doppler spectroscopy (later, $$)

Maryland Centrifugal eXperiment (MCX)



MCX was designed to test supersonic plasma rotation for plasma confinement. The experiment suffered from a limit on the rotation velocity consistent with CIV at the insulators. (1)

- Magnetized plasma is observed to rotate with equal angular velocity along shaped field lines.
- Plasma velocity in the low field region was limited to a rotation corresponding to the CIV limit at the insulators in the high field region.
- The effect was observed using hydrogen and helium with the expected reduction in velocities in helium. (2)



(1) Ellis *et al*, Physics of Plasmas 12 055704 (2005)
(2) C. Teodorescu *et al*, Physics of Plasmas, **17**, 052503 (2010)

Summary

- The utility of computer simulation in support of active experiment is not controversial
  - Less common is a commitment to build on a government owned legacy capability, i.e., Nascap. Turning Science into Engineering for over 30 yrs
  - Not just about Nascap
- Reviewed grounding of (+/-) charged rocket bodies in LEO
  - Much not mentioned
  - Now have a good understand of the physics
  - Captured in numerical models for future engineering needs
- HV & Wakes
- No discussion of plumes, but Nascap does that
  - Hall Thrusters in GEO
- Touched on numerical techniques
  - Steady State is still very important, PIC if really needed,
  - Heuristic algorithms can best illustrate the physics and run on your phone.
- DSX, VLF transmitter or plasma heater?
- Outstanding problem of a positive body in flowing magnetoplasma

Questions, Answers?

A Problem with Drell

Drell, Foley, and Ruderman, *Drag and propulsion in the ionosphere: An Alfven propulsion engine in space*, JGR, 1965

Calculated the Aflvén wing current to the Echo 1 balloon

The current of 0.2 amp/4 × 10⁶ cm² < 0.1 μamp/cm² is well below the space charge limit. To show this, we compute the thickness of the ion sheath surrounding the conducting surface of the Echo 1 in order to neutralize the electric field in the plasma. It is, by Gauss' law,

$$l = \frac{E}{2 \times 4\pi n_{\mathrm{ions}} e} = \frac{v_c B}{8\pi e c n_{\mathrm{ions}}} \approx 10^{-1} \text{ cm}$$

where we used $n_{\mathrm{ions}} \sim n_{\mathrm{electrons}} \sim 5 \times 10^3/\mathrm{cm}^3$ at 1600 km altitude. Thus we have a potential drop of 3 volts occurring in a distance of 0.1 cm from the surface of Echo, and through this drop a current of hundreds of microamperes can flow before being limited by space charge according to Child's law.

Space-charge limited current test

- At 5×10^3/cc, and T_e= 1.0 eV (not specified in Drell),
  - J_{the} = 0.013 μA/cm²
  - The Alfven wings give 0.1 μA/cm²
- Two mistakes
  - Incorrect sheath & space-charge limit,
  - **Not recognizing the thermal current is the constant that sets the sheath size.**
- Sheath calculation
  - They get D_S = 0.1 cm assuming constant ion density
  - Child sheath at 3 Volts, λ_D = 10 cm, D_S = 29 cm
  - $D_S = 1.26\,\lambda_D \left(eV / kT \right)^{3/4}$ (using thermal current)
- Many citations (over 100) using $v_{//} = v_A$,
  - Borovsky, *Limits on cross field propagation ..*, Phys. Fluids, 1987, (excellent on this problem)
  - Goertz and Machida, *Asymptotic state of CIV* , JGR, 1985
  - Haerendel,G., *Alfvén's Critical Velocity Effect Tested in Space*, Z. Naturforsch., 1982.

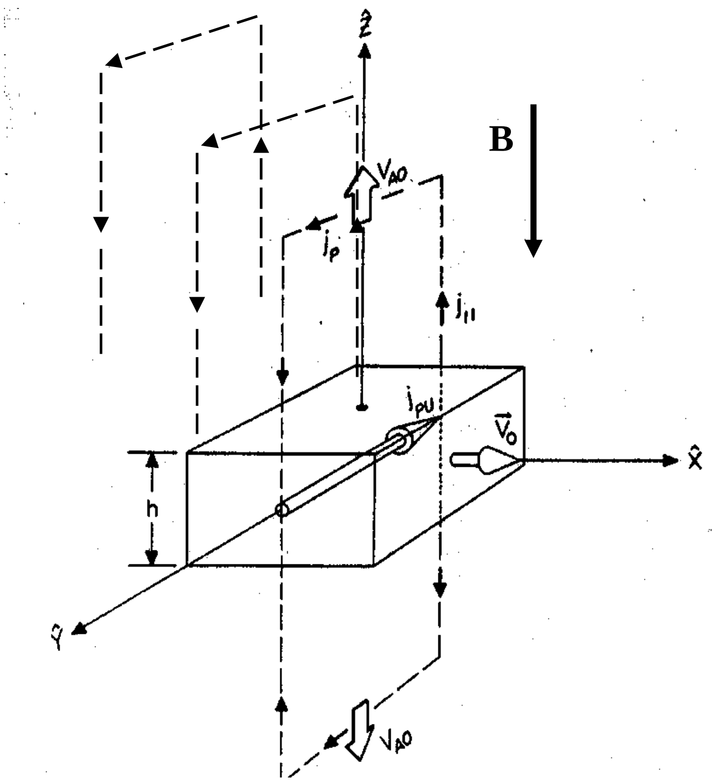
A Thermal Wing model

- Current closure still through polarization current
- Charges in the background plasma are only motivated by their thermal current

$$v_{ll} = v_{th} = \sqrt{kT_e/2\pi m_e}$$

$$j_p = \left(\rho/B^2\right)\left(dE_y/dt\right)$$

$$hj_{pu} = \int j_p dz = \int j_p v_{ll} dt = \int \left(v_{ll}\rho/B^2\right) dE = (\rho/B) v_{ll} v_O$$



- The braking force $F = \mathbf{j_{pu}} \times \mathbf{B} = -\left(2/h\right)\rho v_{ll} v_O$
- Compare the Thermal force to the Alfven force

$$F_{th}/F_A = v_{th}/v_A = \left(1/B\right)\sqrt{\mu_O \rho_i k T_e / m_e} = \sqrt{\beta\left(m_i/m_e\right)}$$

- For the Drell case (10^3/cc and T = 1.0 eV)
  - $F_{th}/F_{vA} = 0.001$
  - Higher in the plasmasphere we get up to 0.1
  - But in troughs and pauses, $\rho \rightarrow 0$, and $v_A \rightarrow \infty$