Active space experiments with relativistic electron accelerators

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Acknowledgements: J. Borovsky (SSI), F. Lucco Castello (KTH), G. Miars, O. Leon, B. Gilchrist (U. Michigan), V. Roytershteyn (SSI) + CONNEX team

Outline

I. Electron beams for space physics

II. Magnetic-field-line connectivity

- CONNEX mission concept
- Spacecraft-charging

III. Wave-generation

- Beam-plasma coupling efficiency
- Beam-PIE rocket experiment

IV. Summary

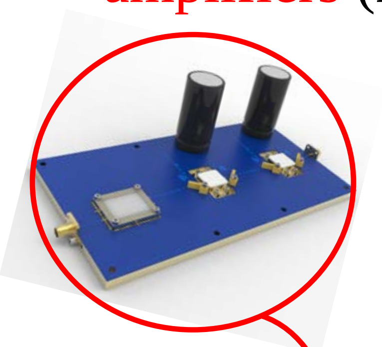
There is renewed interest in space experiments with e-beams, driven by new technological developments

- Rich history of active space experiments with e-beams [from 70s to early 90s]: ~10s keV, <~1 A
  - Vehicle charging: CHARGE, SCATHA, STS 3
  - Beam-environment interactions: ARAKS, POLAR, APEX
  - VLF emissions: SEPAC, SPACELAB 1-2
  - Magnetospheric (radiation belt) physics: ECHO
- Vehicle charging is an issue
  - All these experiments (but SCATHA) were in the high-density ionosphere
  - 6 mA beam on SCATHA caused permanent failure of 3 payloads
- New emerging applications would require operating e-beams in the low-density magnetosphere.
  - Catastrophic spacecraft charging is a major concern
  - Called for as unsolved problem in the Decadal Survey of Space Physics

Enabling technology: compact relativistic e- accelerators

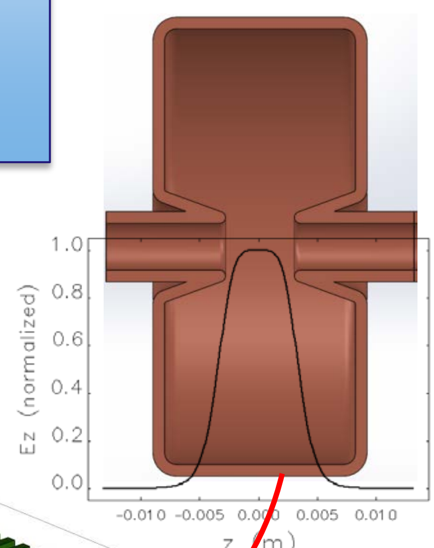
- Substantially reduce spacecraft-charging problems
    - Less current for the same amount of power
- We are currently testing low-voltage, high-power 5.1-GHz solid-state amplifiers (HEMTs) driving accelerator cavities

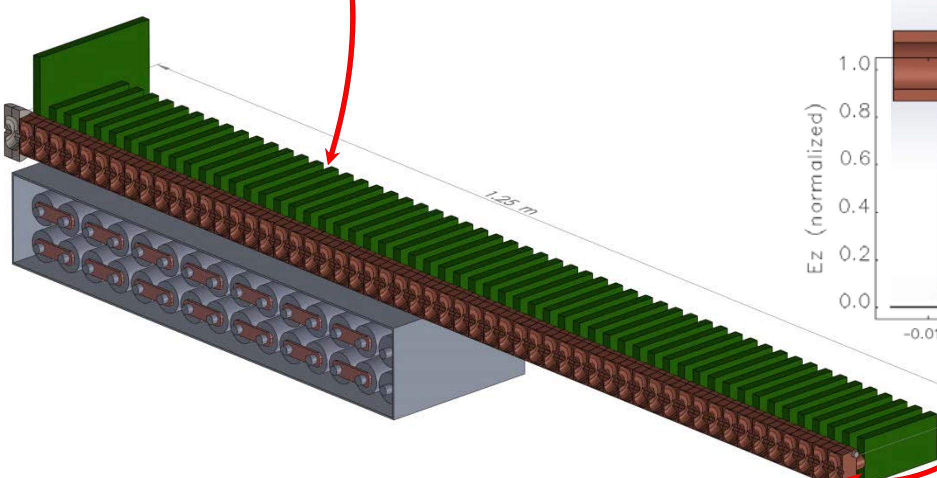
Accelerator	Estimates
Total Beam Energy	1 MeV
Length	1.25 m
Weight	31 kg
Beam Power	10 kW peak 1 kW average
Number of Cells	55
Voltage per Cell	18 kV



Each cell driven by 500-W High-Electron Mobility Transistor (HEMT)

5.1-GHz accelerator cell





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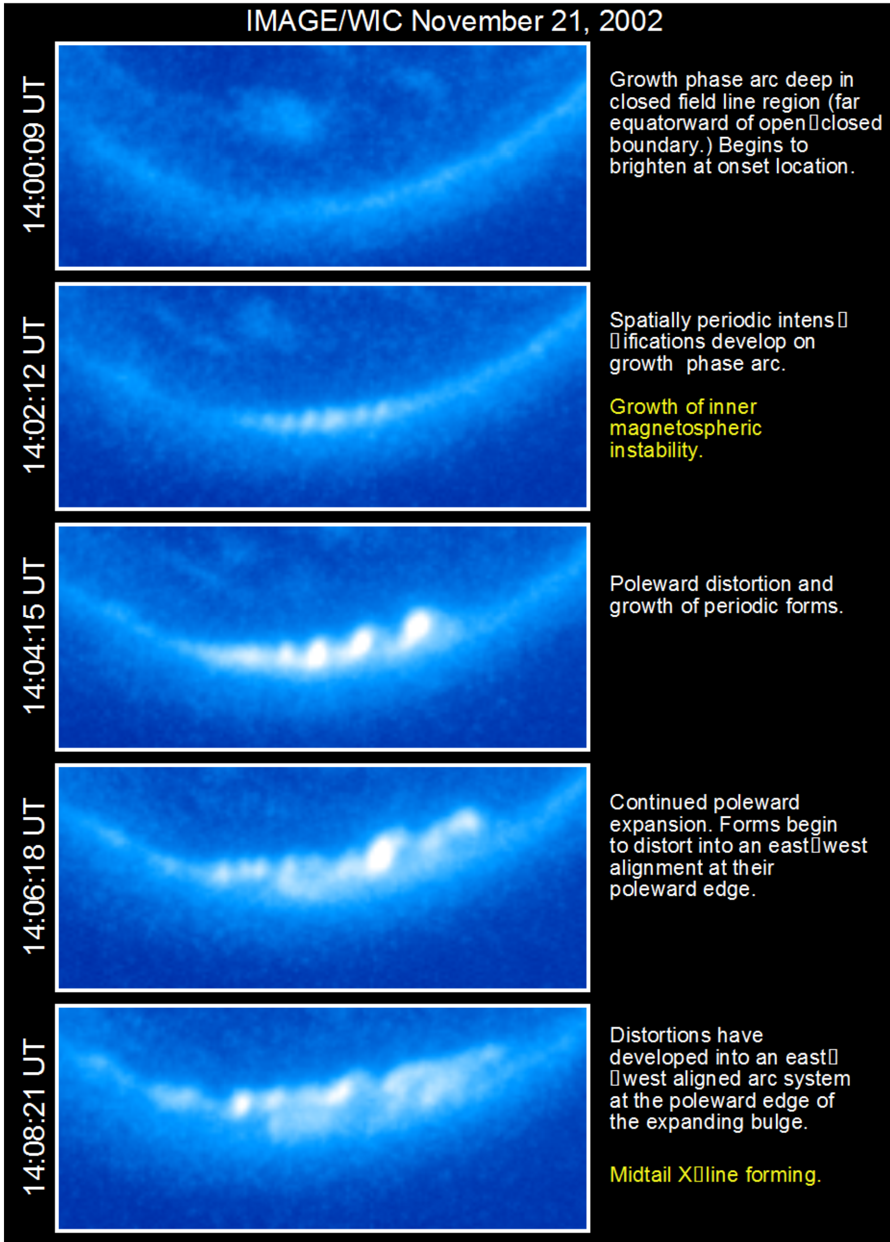
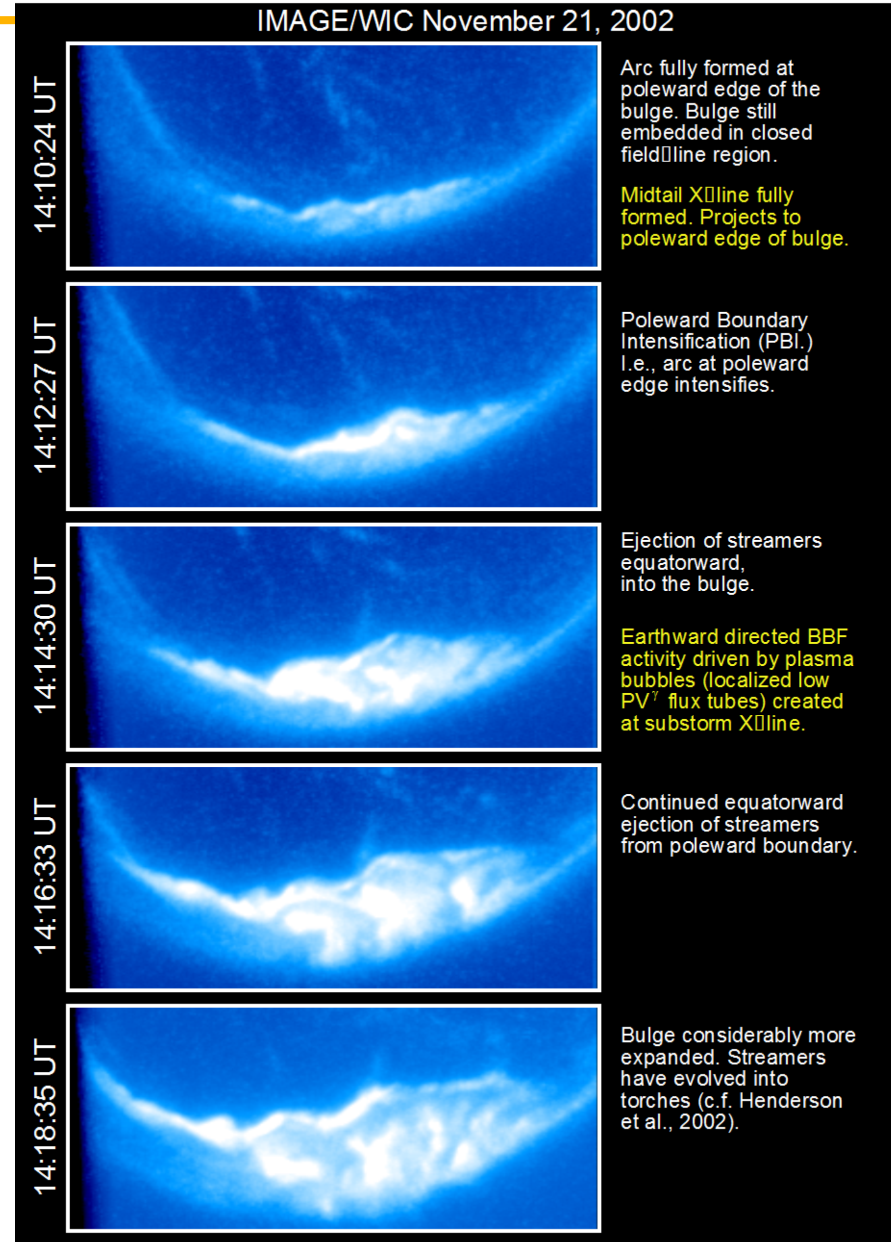
e-beam could be used to establish magnetic field line connectivity unambiguously and address longstanding magnetosphere-ionosphere coupling questions

When geomagnetic activity turns on, auroral arcs emerge, migrate, become unstable and turn into chaos

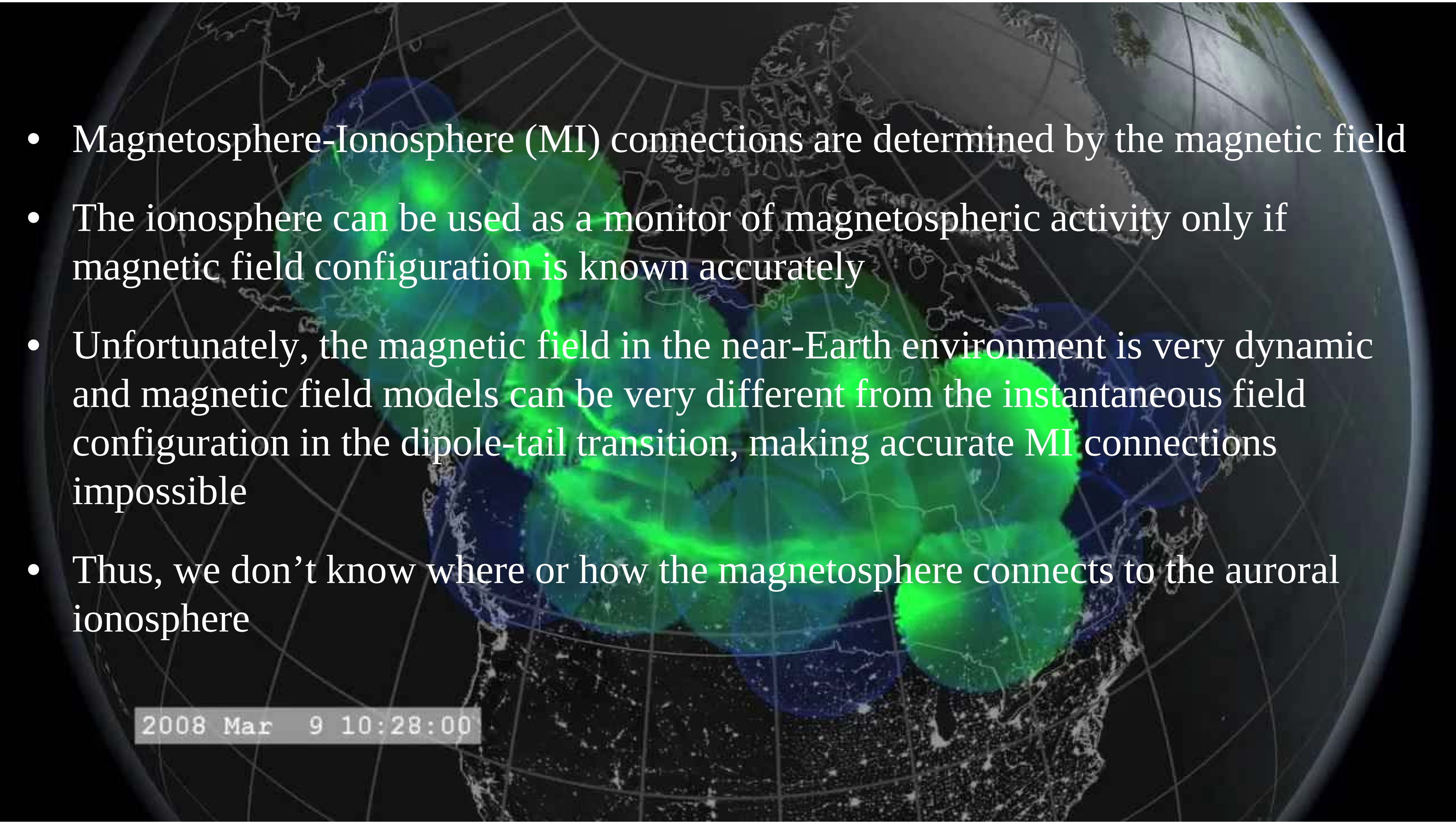




Connecting the dynamic magnetosphere and the auroral ionosphere: How? When? Where?

- Aurora: most-visible manifestation of complex processes operating in the distant MS
- If we understood the processes that produce arcs, we could use the aurora to visualize the processes ongoing in MS
- Long-standing mysteries
  - How do the magnetospheric processes produce conditions where auroras can occur?
  - How accurately can ionospheric and auroral observations specify the state of the magnetosphere?
- We could solve these mysteries by measuring critical MS gradients (pressure, anisotropy, flow and magnetic shear, field-strength) at the site of auroral arcs

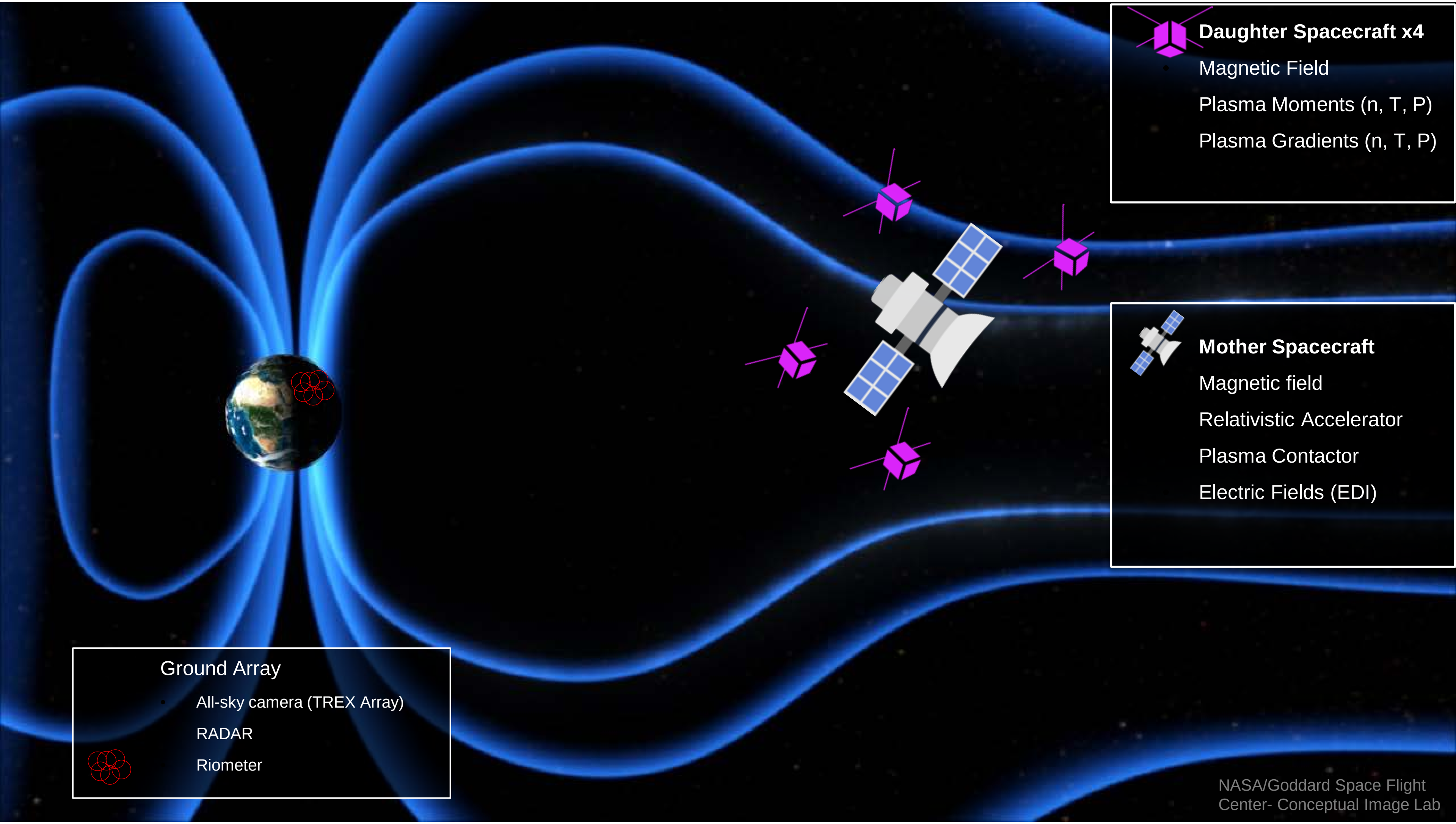
Unfortunately, so far, we cannot determine when our spacecraft are in the equatorial source region of auroral arcs



- Magnetosphere-Ionosphere (MI) connections are determined by the magnetic field
- The ionosphere can be used as a monitor of magnetospheric activity only if magnetic field configuration is known accurately
- Unfortunately, the magnetic field in the near-Earth environment is very dynamic and magnetic field models can be very different from the instantaneous field configuration in the dipole-tail transition, making accurate MI connections impossible
- Thus, we don't know where or how the magnetosphere connects to the auroral ionosphere

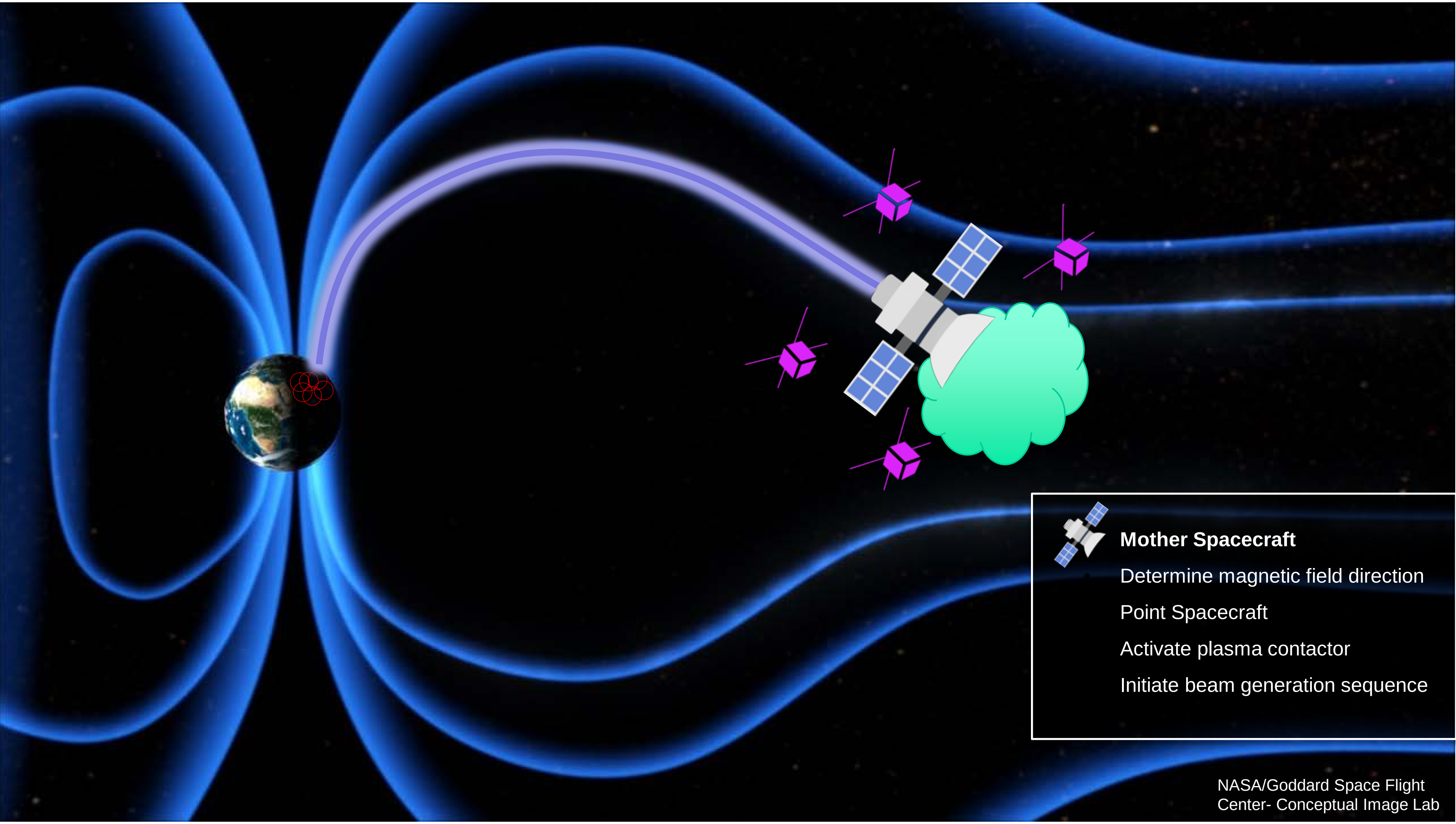
How to solve the magnetic-connectivity problem and answer MI coupling questions? 1. Record Magnetospheric and Ionospheric Context

CONNection EXplorer (CONNEX)



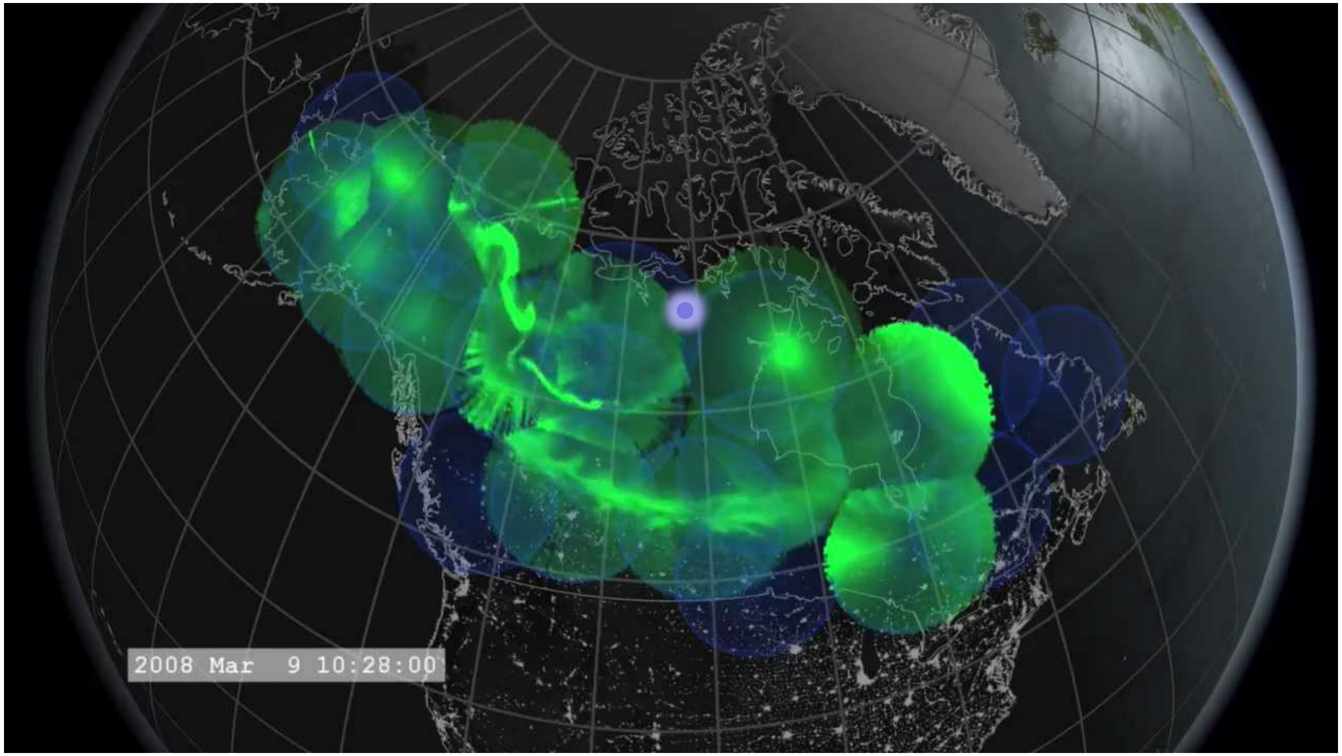
2. A mapping sequence is triggered through a timed command plan or scientist in the loop activation

CONNection EXplorer (CONNEX)

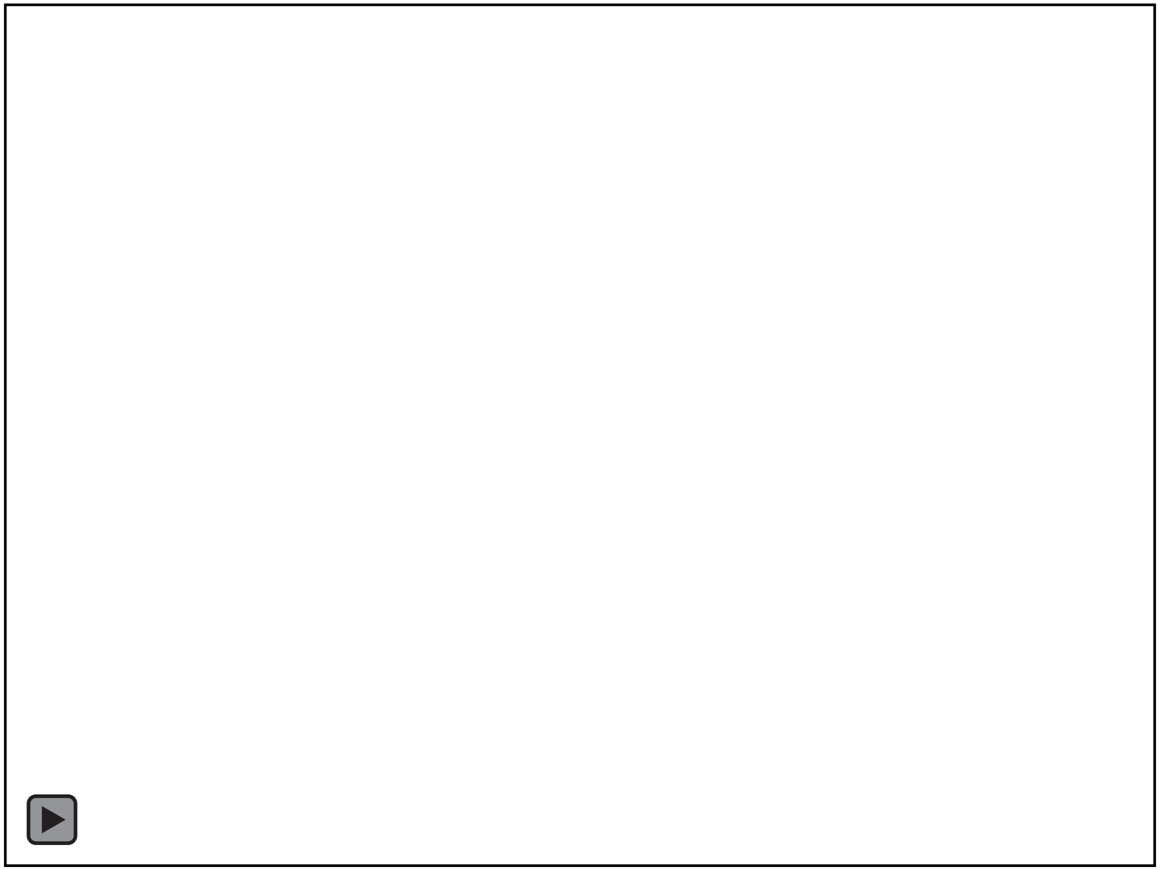


3. A beam burst arrives at ionosphere at regular intervals providing real-time assessments of spacecraft location in ionospheric coordinates.

- **Beam traverses magnetic field line**
  - Stability
  - Deposition and detection
- **Beam deposits energy creating light**
- **Beam is detected by all-sky cameras in auroral context**
- **Investigating RADAR possibilities incoherent scatter, SuperDARN**

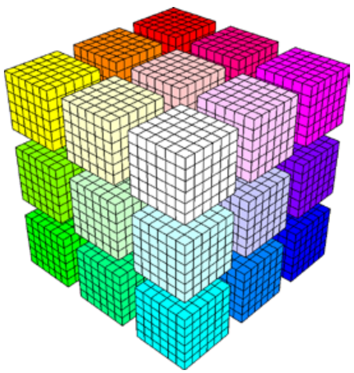


Spacecraft charging is the major obstacle to operating high-power e-beams in the low-density magnetosphere



Charging studies with Curvilinear PIC (CPIC)

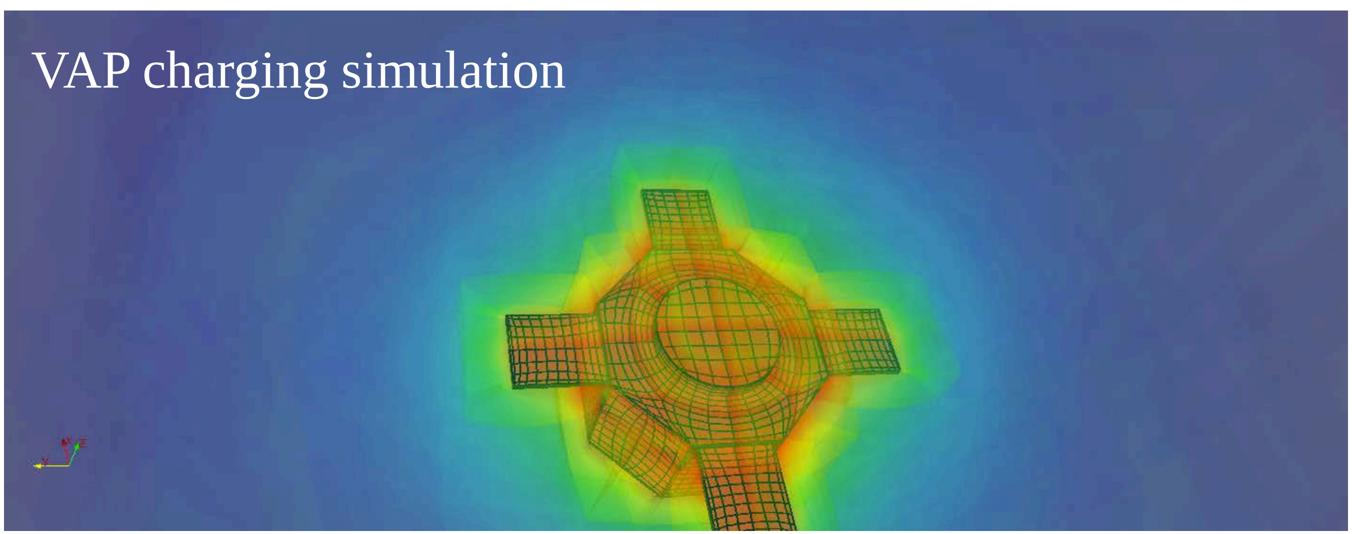
- Solves kinetic equations in the electrostatic limit: Particle-In-Cell technique
- Mesh: multiple structured, connected blocks



mapping

Delzanno et al., IEEE (2013)
Meierbachtol et al., JCP (2017)

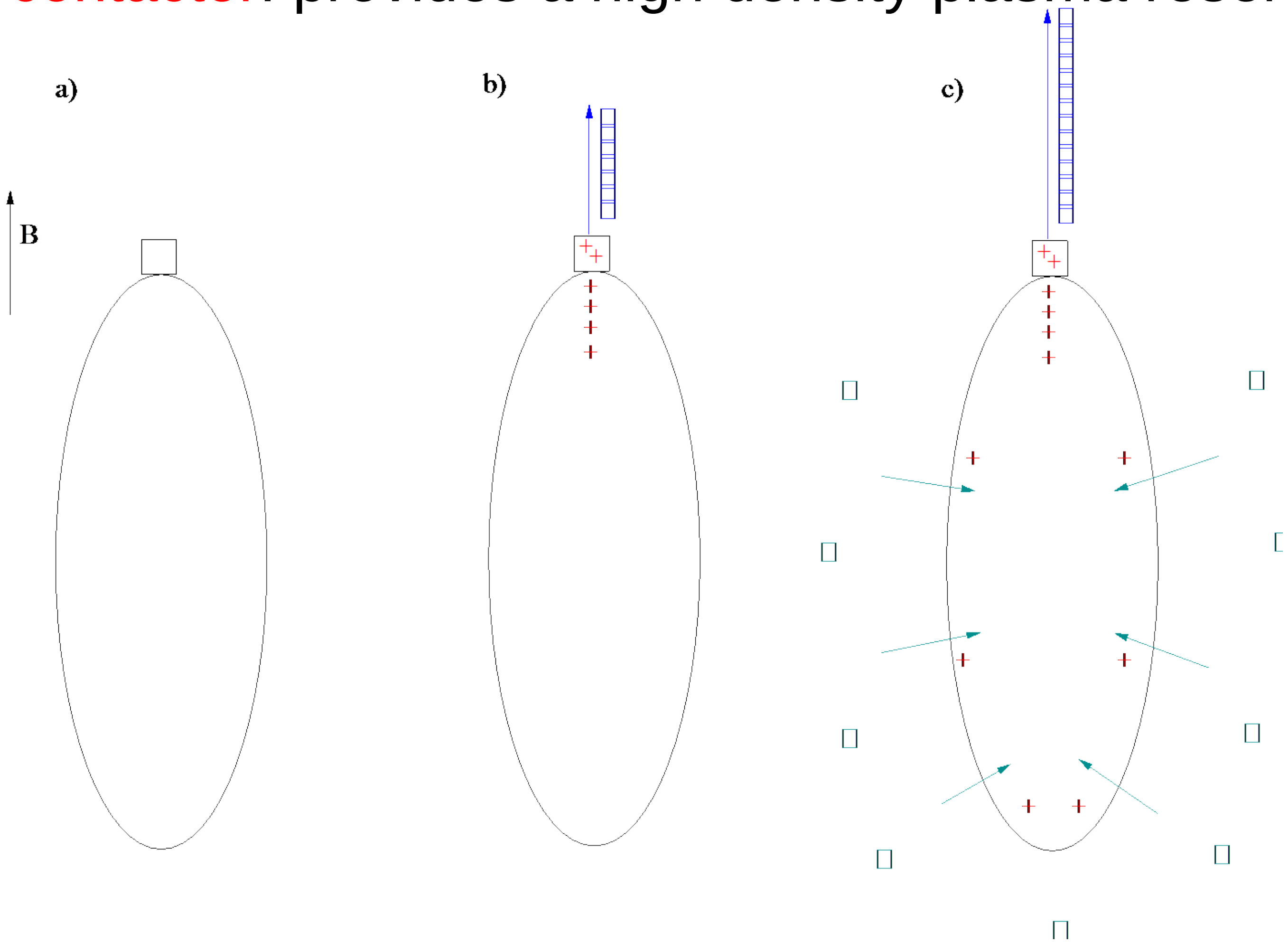
- Avoids inefficiencies of unstructured-mesh PIC
- Estimated speed-up: **>5x** (particle mover)
- Highly-parallelized



A mitigation strategy based on plasma contactor as electron collector …

- Plasma contactor: provides a high density plasma reservoir

Km-sized cloud



$I_b/I_{cont}>1$

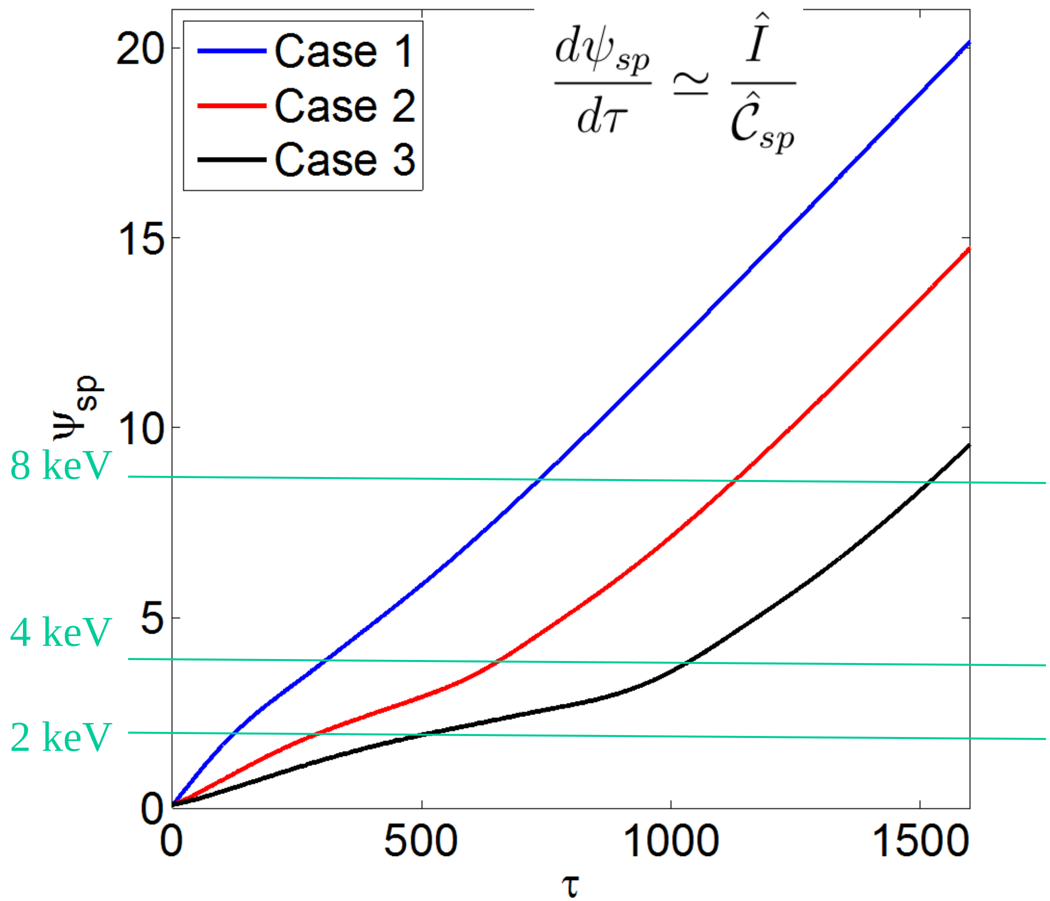
... would not work! $I_b/I_{cont}=2$

- PIC simulations:

contactor, spacecraft and beam

- Contactor fired before beam
  - 3 initial configurations with different size of contactor cloud
- Fire electron beam
  - with contactor on

- Contactor fails to draw a large current from background



G.L. Delzanno, J.E. Borovsky, M.F. Thomsen, J.D. Moulton, E.A. MacDonald, *Future beam experiments in the magnetosphere with plasma contactors: How do we get the charge off the spacecraft?*, Journal of Geophysical Research, 120 (5), 3647 (2015)

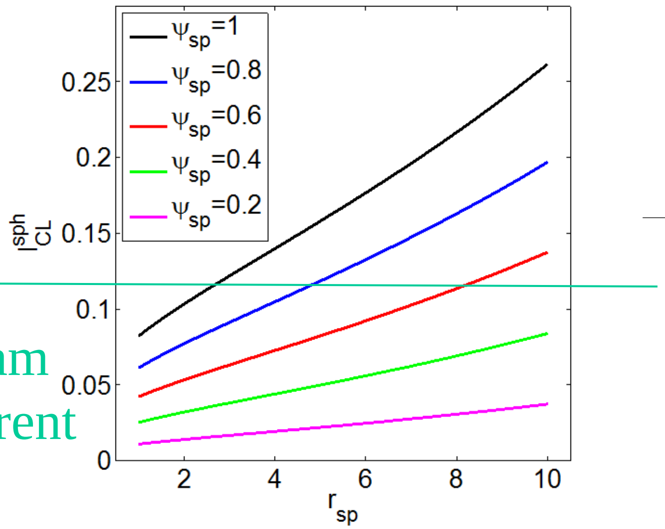
G.L. Delzanno, J.E. Borovsky, M.F. Thomsen, J.D. Moulton, *Future beam experiments in the magnetosphere with plasma contactors: The electron collection and ion emission routes*, Journal of Geophysical Research, 120 (5), 3588 (2015)

In a different parameter regime, $I_b/I_{cont}<1$, the beam can be emitted

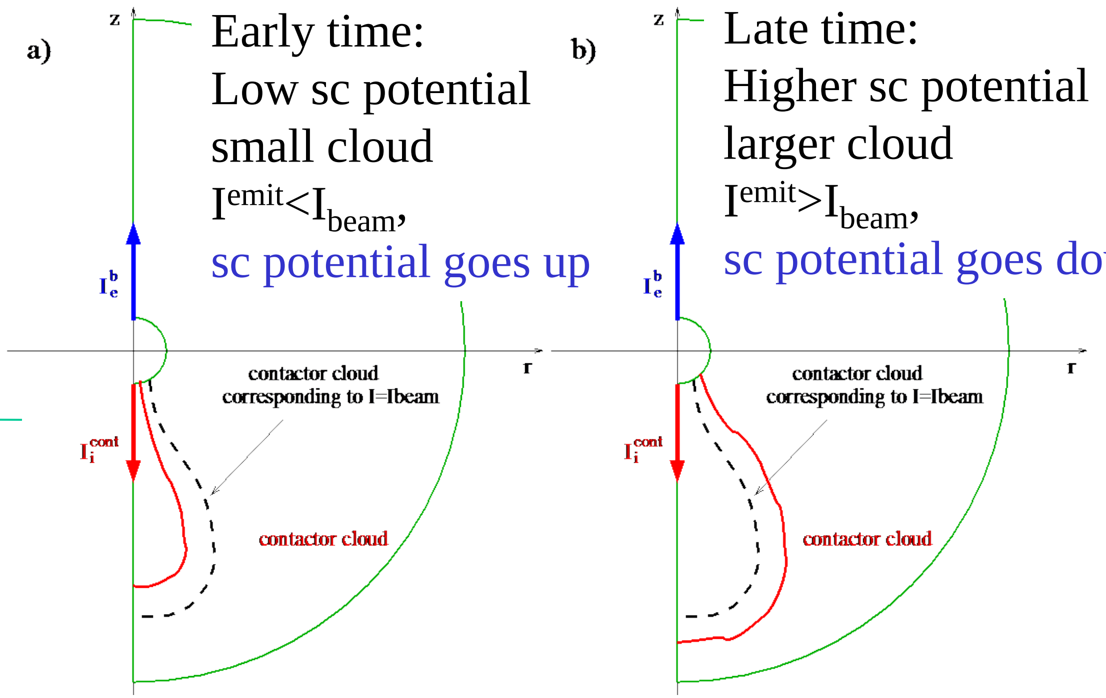
The contactor can be used to emit ions (and not to collect electrons!)

Interpretation in terms of Child-Langmuir (CL) law in spherical geometry

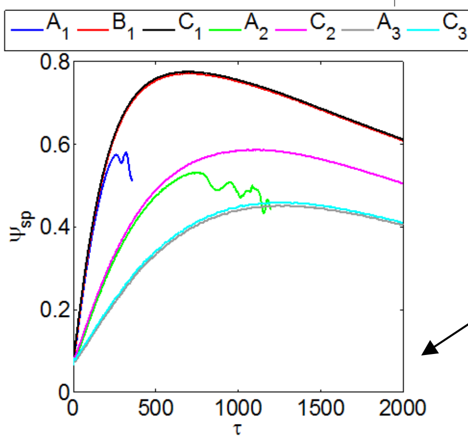
CL current



Beam current



$I^{emit} = I^{emit}$ (spacecraft potential, plume geometry, ion drift velocity)



<1/100 of real experiment

early-vs-long time evolution?
role of simulation boundary?

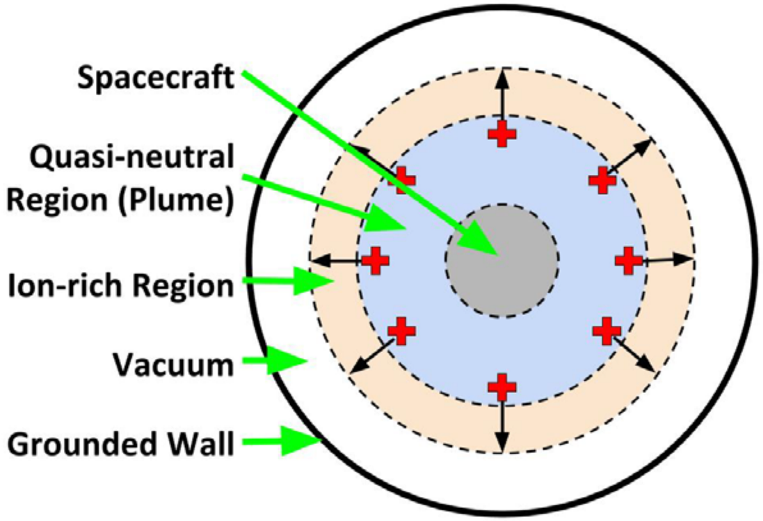
A simple semi-analytical model for the transient of the sc potential in response to e-beam emission has been developed

- Main assumptions of the model:
  - Perfect spherical symmetry → 1D
  - Focus on contactor ion **dynamics** → slow → $I_b = I_i$, $I_e = 0$
  - e-beam leaves system instantaneously

- Model's parameters
  - Radius of the quasi-neutral cloud, $\hat{r}_{qn}$: If $I_i = I_b$ the plasma electron current is zero and $\hat{r}_{qn}$ is constant

$$\hat{r}_{qn} = \hat{r}_{qn,0}$$

  - Radius of the ion front, $\hat{r}_i$
  - Potential of the ion front, ψ_i
  - Spacecraft potential, ψ_{sc}



Sc initially emits only a neutral contactor plasma. After some time, it also emits an e-beam

Runs in secs/minutes on laptop vs weeks of PIC on IC clusters

Model summary

- Model:

$$-\hat{r}_{qn} = \hat{r}_{qn,0}$$

$$-\frac{\mathrm{d}^2\hat{r}_i}{\mathrm{d}\tau^2} = \frac{m_i}{m_e}\frac{\mathcal{Q}_0 + \hat{I}_b\tau}{4\pi\hat{r}_i^2}$$

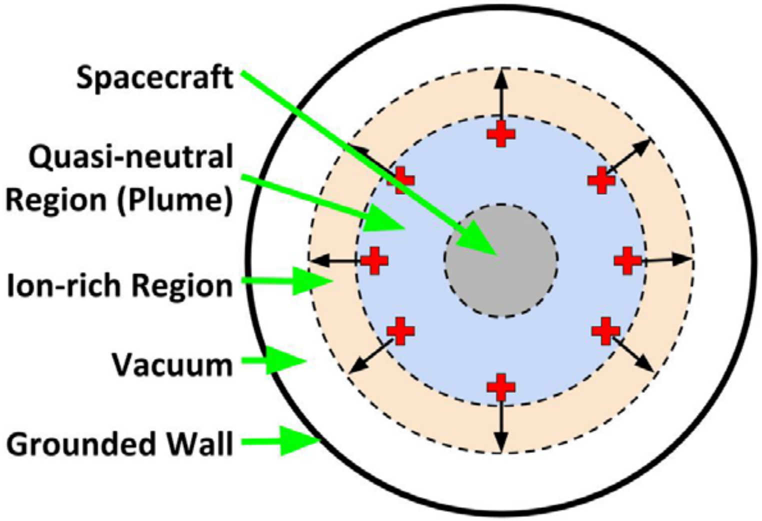
$$-\psi_i = \frac{\mathcal{Q}_0 + \hat{I}_b\tau}{4\pi}\frac{\hat{r}_2 - \hat{r}_i}{\hat{r}_2\hat{r}_i}$$

$$-\frac{1}{\hat{r}^2}\frac{\mathrm{d}}{\mathrm{d}\hat{r}}\left(\hat{r}^2\frac{\mathrm{d}\psi}{\mathrm{d}\hat{r}}\right) = \hat{J}_{qn,e}f(\hat{r},\psi_{sc}) - \frac{\hat{I}_i}{4\pi\hat{v}_d\hat{r}^2}\left(1 + \frac{\psi_{sc} - \psi}{\mathcal{K}_i}\right)$$

$$\psi(\hat{r}_i) = \psi_i$$

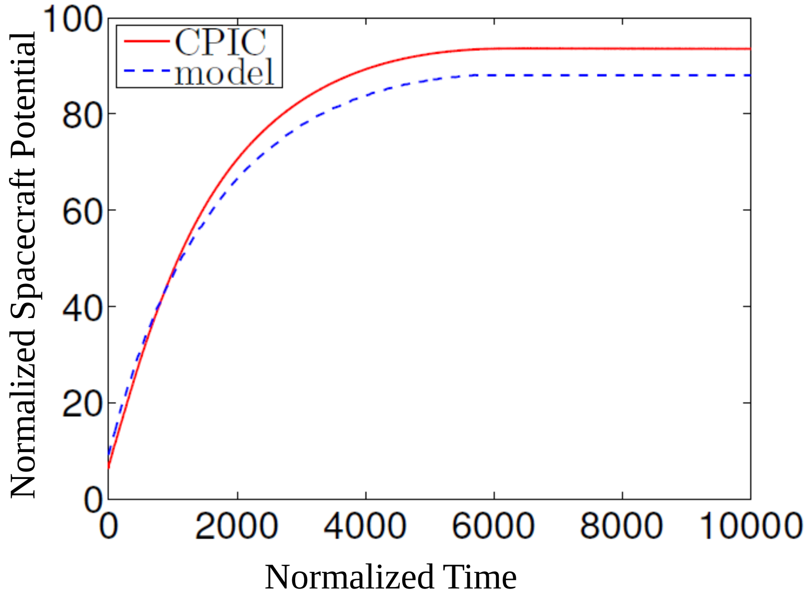
$$\mathrm{d}\psi/\mathrm{d}\hat{r}|_{\hat{r}=\hat{r}_{qn}} = 0$$

← c.f. Child-Langmuir law



- Initial conditions taken from PIC, we need to define $r_{qn,0}$, $r_{i,0}$, $v_{i,0}$ and $\mathcal{Q}_0$

Good agreement between model and simulations



Quantity	Symbol	NORM	REF	DIM	Unit
Spacecraft radius	$\hat{r}_1$	8.9	2.4e-3	1	m
Outer radius	$\hat{r}_2$	890	2.4e-3	100	m
Injection area	$\mathcal{A}$	995	1.2e-2	12.7	m^2
Electron temperature	$\hat{T}_e$	1	2.3	2.3	eV
Ion temperature	$\hat{T}_i$	0.2	2.3	0.5	eV
Electron thermal velocity	$\hat{v}_{th,e}$	1	640	640	km/s
Ion thermal velocity	$\hat{v}_{th,i}$	5.4e-3	640	3.4	km/s
Ion drift velocity	$\hat{v}_d$	5.5e-2	640	35	km/s
Electron current	$\hat{I}_e$	560	1.3e-2	7.2	mA
Ion current	$\hat{I}_i$	77.6	1.3e-2	1	mA
Beam current	$\hat{I}_b$	77.6	1.3e-2	1	mA
Contactor expansion time	τ_c	1.5e3	1.8e-7	0.3	ms
Beam emission time	τ_b	1e4	1.8e-7	1.8	ms

- To mimic conditions in space, we let the outer boundary $r_2 \rightarrow \infty$.
- If we assume to emit the beam for 0.5 s ($\tau = 2.5 \cdot 10^6$) the spacecraft would charge the spacecraft to a potential of 700 V (ψ_{sc} = 315).
- Taking into account that the expansion is not radial (via PIC simulations) leads to 1.1 kV, much smaller than the beam energy for a relativistic beam!
- The beam would be easily emitted. This is a major result for CONNEX!

Experimental design: testing ongoing at U. Michigan

Large Vacuum Test Facility (LVTF)
6 meter x 9 meter cylinder
Largest of its kind in academia

Cathode Test Facility (CTF)
0.7 meter x 1.5 meter cylinder
Cost effective and good availability

Objective: laboratory validation of contactor-based ion emission

$I^{emit}=I^{emit}$ (spacecraft potential, plume geometry, ion injection velocity)

Team: G. Miars, O. Leon, B. Gilchrist

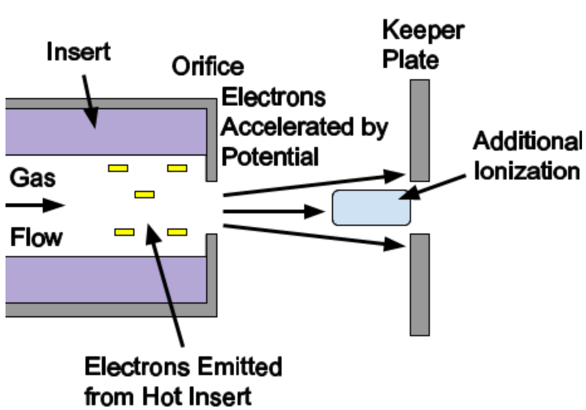
Experimental results summary

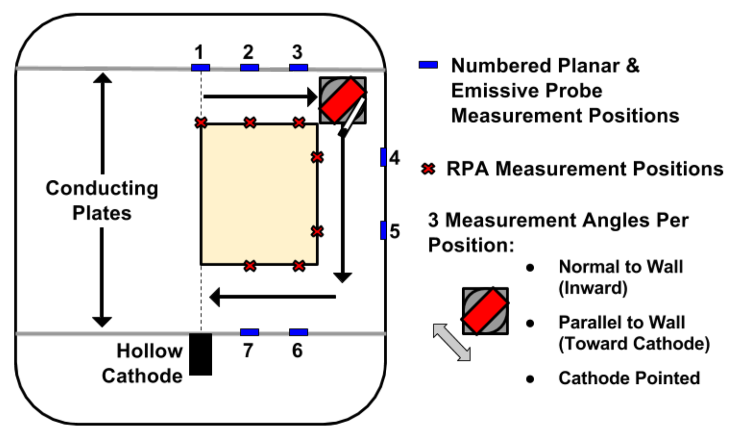
- Extensive measurements solidify and extend interpretation of the ion emission model

$I^{emit} = I^{emit}$ (spacecraft potential, plume geometry, ion drift velocity)

- Ion emission from quasi-neutral plasma appears space-charge-limited
- Discrepancy attributed to fast electrons

Position	Measured Emission (nA)	Theoretical/ Measured Emission
1	50	66.0
2	210	13.8
3	270	5.2
4	430	1.2
5	290	0.7
6	240	0.5
7	320	1.2





Other challenges

A. Beam propagation. POC: Ennio Sanchez, SRI, ennio.sanchez@sri.com
- Modification of the loss cone for relativistic electrons
- Ballistic propagation to the ionosphere

B. Beam deposition. POC: Bob Marshall, UCo, Robert.Marshall@colorado.edu
- How much energy can be deposited in the atmosphere? Needs ~10 kW
- Prediction of generated signal
- Prediction of ground detection performance (optical and radar)
- Indicates that the beam spot is detectable

C. Accelerator maturation. POC: Dinh Nguyen, LANL, dcnguyen@lanl.gov
- Successfully demonstrated 20 keV energy gain in single cavity
- Building/testing 10 cavity prototype by summer 2018 (LANL/SLAC)

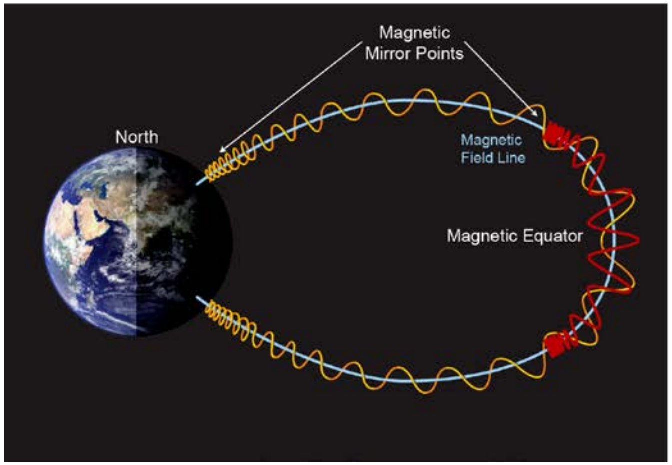
We are making progress in mitigating all these challenges!

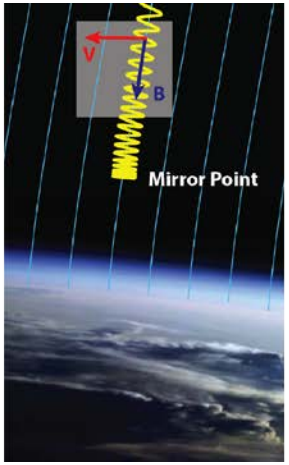
CONNEX PI: Eric Dors, LANL, edors@lanl.gov

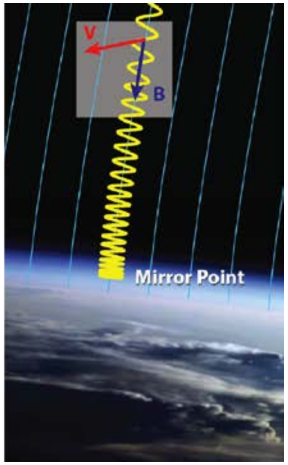
e-beam could be used for radiation-belt-remediation

e-beams could be used for radiation belt remediation

- Natural radiation belt: MeV
- Gyro, bounce and drift motion
- Artificial radiation belt. Remediation
- Wave-particle interaction (pitch-angle scattering) to precipitate energetic particles
- Use e-beams to stimulate wave emission
    - Cherenkov or cyclotron emission
    - Beam-plasma instabilities







In the following we will take a look at Cherenkov (mostly) radiation theory

Radiation theory: pulsed beam aligned to B

- Developed in the 60s [McKenzie, 63; Mansfield, 67; Harker&Banks, 84+]
- Beam point pulses act as a current source
- Plasma responds with characteristic frequencies driven by resonances
  - Resonance $\omega = k_{\parallel} V_p$
  - Linear response: cold plasma theory
- Radiated power

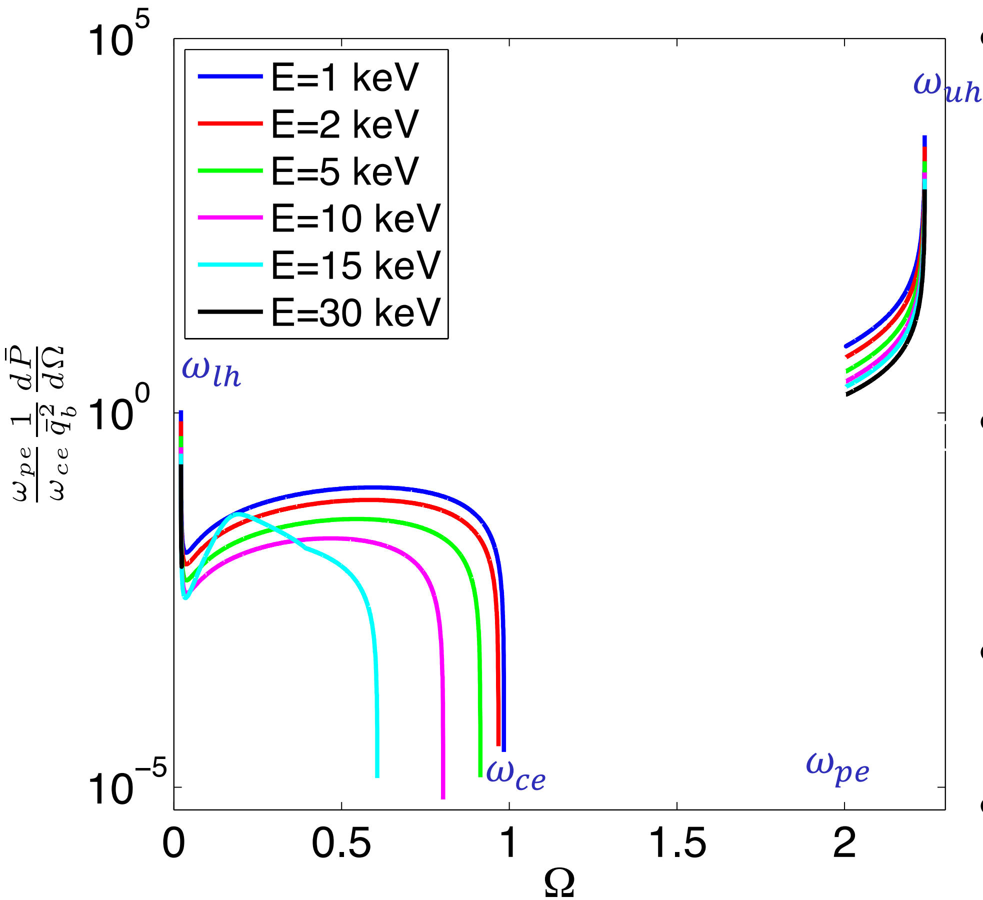
$$P(t) = \sum_{j=1}^{N_p} \sum_{p=1}^{N_p} \frac{q^2 V_j}{4\pi\varepsilon_0 c^2} \int d\omega |\omega| \underbrace{\exp\left[i\frac{\omega}{V_p}(z_{p0} - z_{j0})\right]}_{\text{Spatial coherence}} \underbrace{\exp\left[i\omega\left(1 - \frac{V_j}{V_p}\right)t\right]}_{\text{Temporal coherence}} \frac{\sum_{l=1}^{2}(-1)^l T_{33}(n_l)}{\varepsilon_1 \left(n_2^2 - n_1^2\right)}$$

Spatial coherence

Temporal coherence

Farrell&Goertz 90
Harker&Banks 84, …

Two coupling regimes



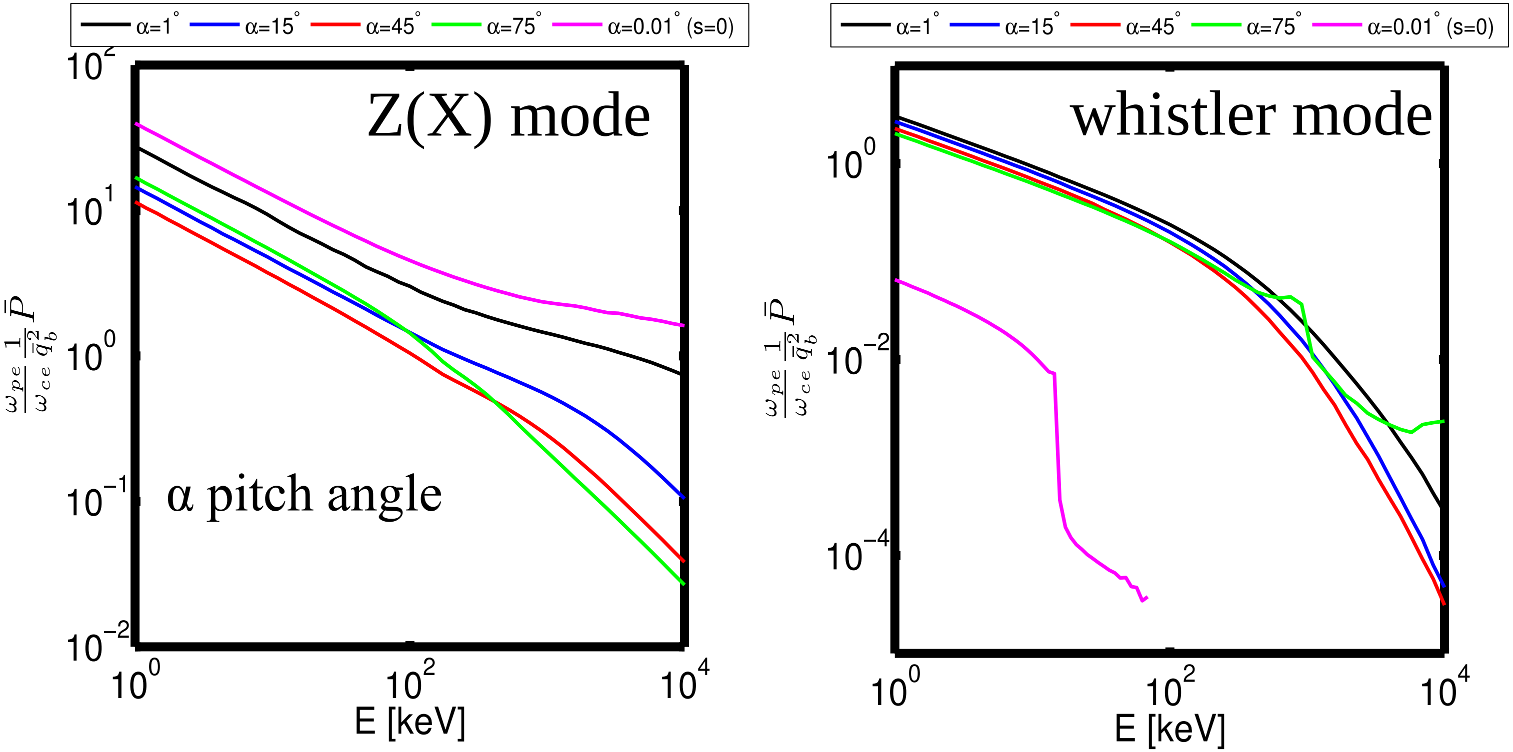
- Whistler and X modes
  - Whistler energy-range is limited
  - Space nomenclature: X→slow Z
- Resonances
  - Lower-hybrid frequency
  - Upper-hybrid frequency
- Yields logarithmic singularities for field-aligned beam
- The total power diverges

$$\Omega = \frac{\omega}{\omega_{ce}} \qquad P \propto \int \frac{d\bar{P}}{d\Omega} d\Omega$$

$\omega_{pe}/\omega_{ce}=2$, $m_i/m_e=1836$

Finite pitch angle yields finite total radiated power

- Several mechanisms can yield a finite radiated power:
  - Finite pitch angle, nonlinearities, kinetic physics, collisions …
  - Finite pitch angle: resonances are still present, but are now integrable



Can we really trust total radiated power with finite pitch angle? In general NO!

- Cold-plasma theory breaks down at resonances. Need simulations!

Simulations

- SpectralPlasmaSolver (SPS): solves kinetic equations with spectral expansion of the distribution function in moments [Delzanno, JCP 15; Vencels et al, J. Physics 16]

$$f_s(x,v,t) = \sum_{n=0}^{N_H-1} \sum_{k=-N}^{N} C^s_{n,k}(t)\Psi_n(\xi_s)\Phi_k(x)$$

- Velocity discretization: Hermite or Legendre
- Spatial discretization: Fourier or Finite Elements
- Fully-implicit time discretization
- Naturally bridges between fluid (few number of moments) and kinetic (large number of moments). Optimal way to include microscopic physics in large-scale simulations (?)
- To test radiation theory:
  - Stop expansion at 4 Hermite modes: fluid treatment
  - Consider low beta: cold plasma
  - Regularization of resonances achieved by non-linear effects

SPS simulations (used as a 2-fluid solver)

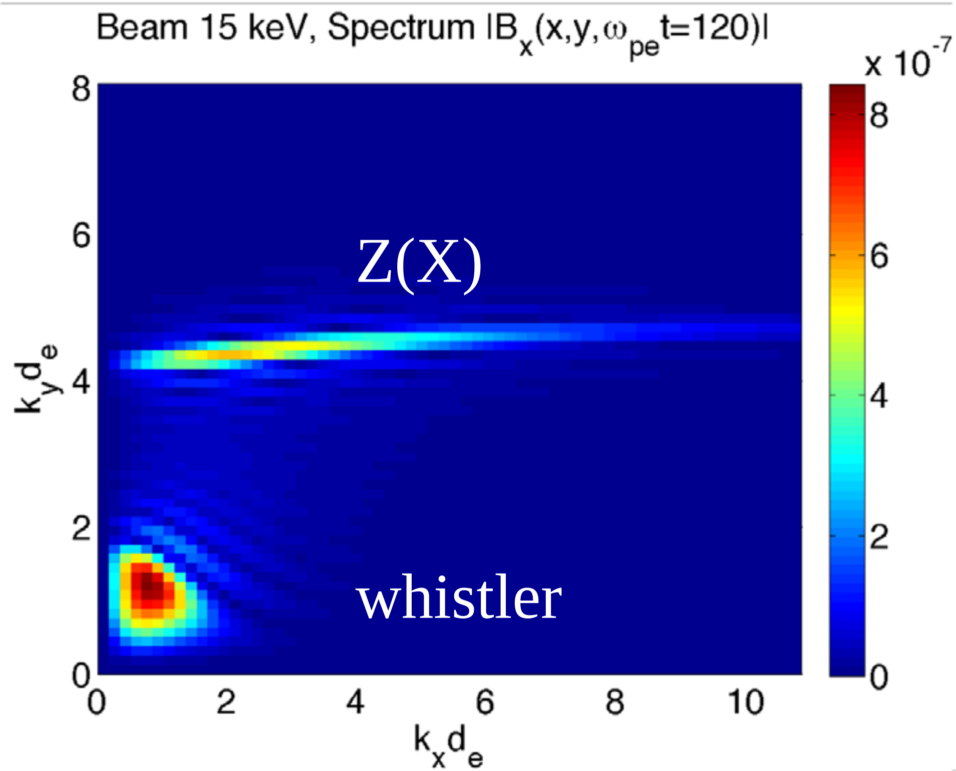
$\omega_{pe}/\omega_{ce}=2$,
$m_i/m_e=1836$,
$\beta_{\|e}=10^{-4}$,
$T_{\|e}/T_{\perp e}=1$,
$T_e/T_i=1$

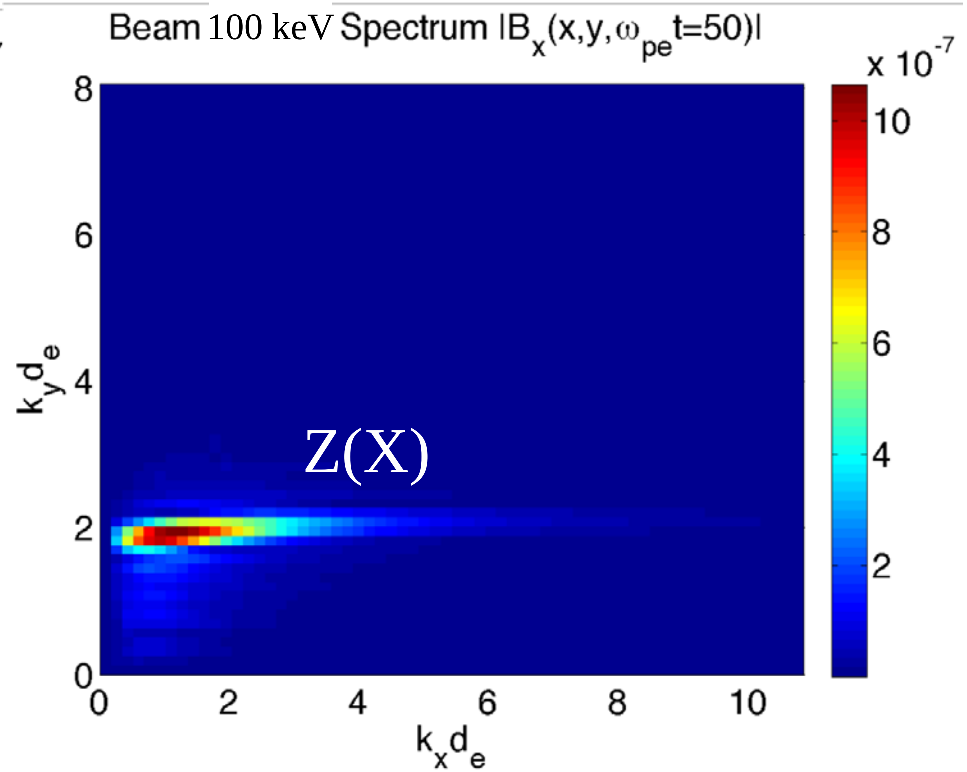
Point pulse

SPS more efficient than PIC (statistical noise!)

100 keV beam

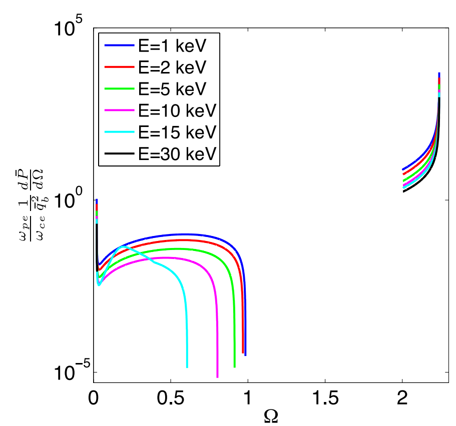
Spectra: 15 keV and 100 keV



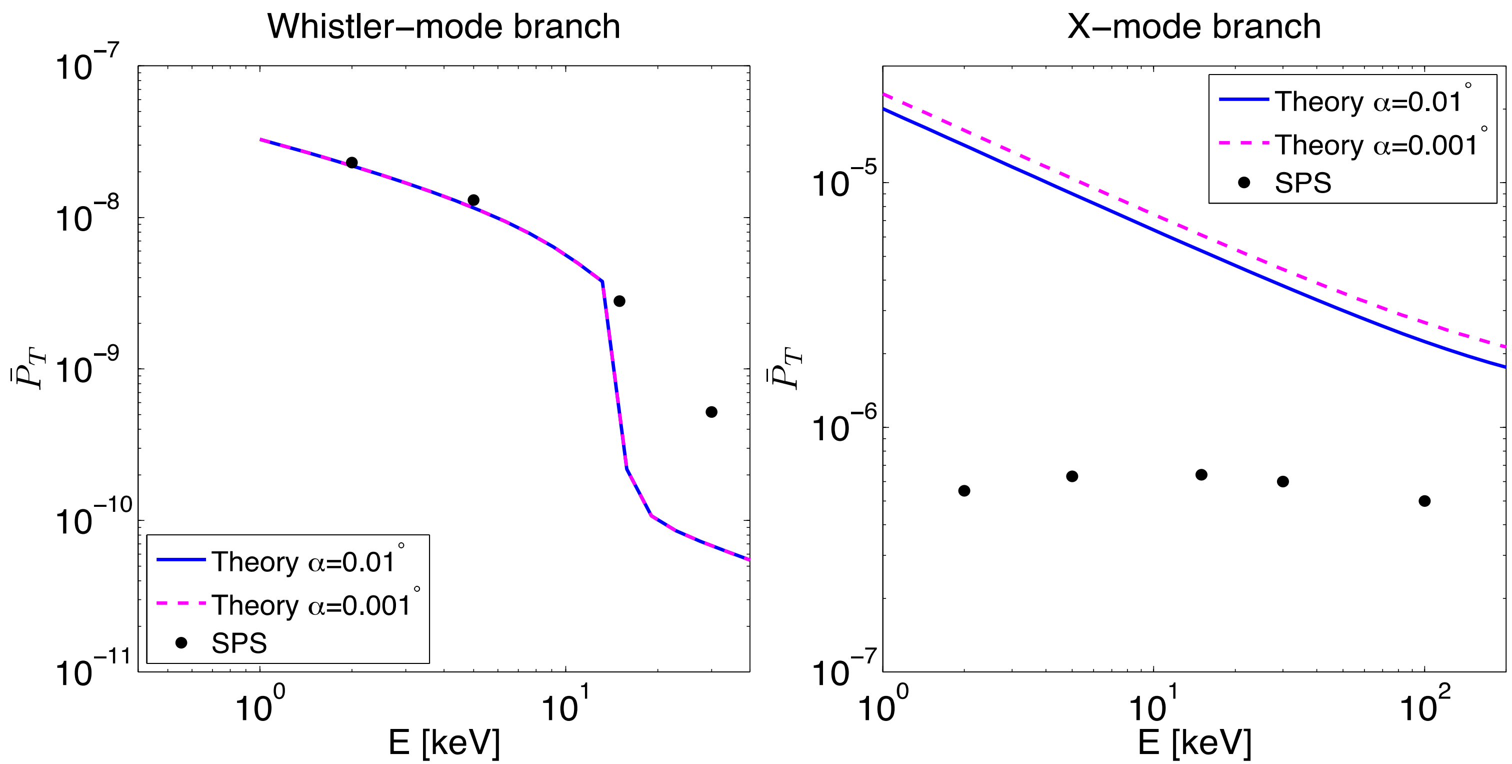


Small amplitude for large $k_x = k_\perp$

Theory might overestimate radiated power



Total radiated power

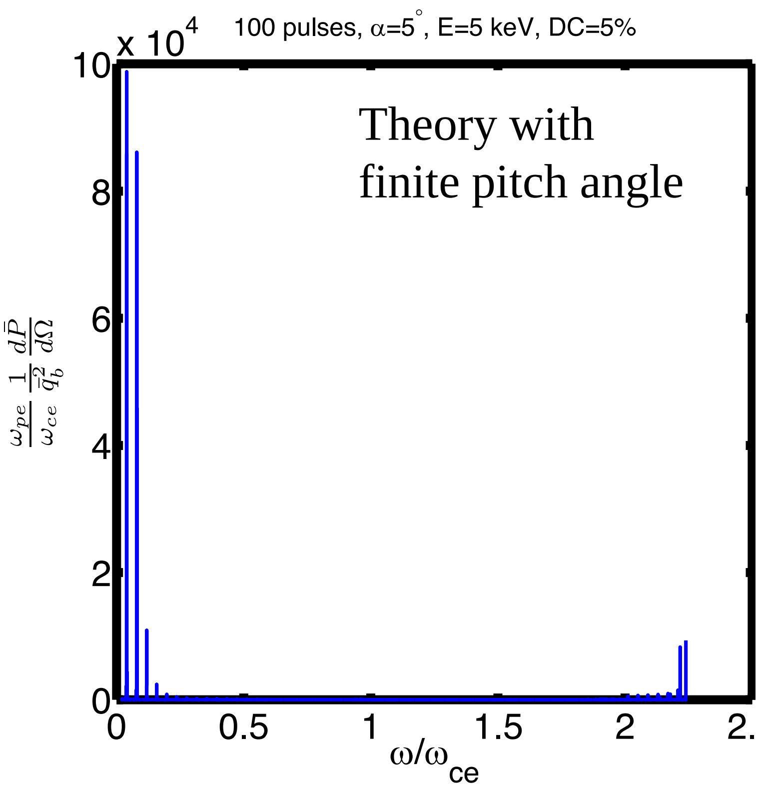


- Whistler: good agreement between theory and simulations
    - Contribution around resonance not important
- Z(X)-mode: theory overestimates radiated power
- Simulations confirm that Z(X) mode dominates radiation (20-100 higher)
    - Many rocket/shuttle experiments focused on whistler

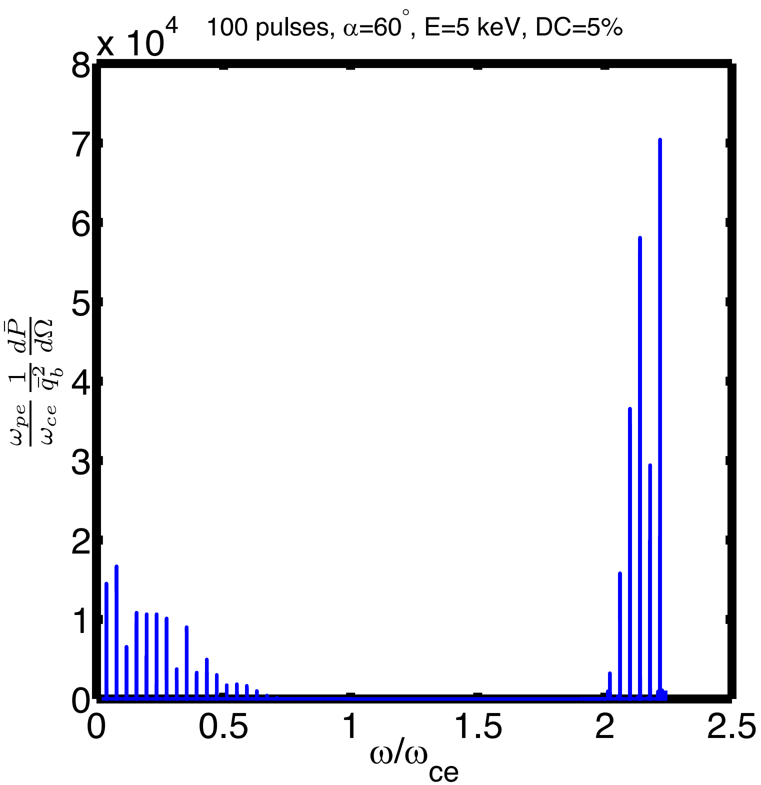
Coherence effects are important: beam modulation or pitch angle allow one to select between the 2 regimes

Minipulse: T_{mini}=1 μs.
$V_{beam}T_{mini}$=71 m

100 pulses suitably separated
5 kHz modulation



selects whistler



selects X

Wave-particle interaction

- Test particle simulations in a prescribed wave field
- Single, monochromatic wave: fix B_{rms}=60 nT, use cold-plasma theory to fix other amplitudes. Fix background B_z=45,000 nT
- Objective: reduce pitch angle by 3 deg to induce precipitation
  - Particles lost in the atmosphere (100 km) have pitch angles 66° at 500 km and 61° at 700 km
  - Particles mirroring at 200 km have pitch angles 69° at 500 km and 64° at 700 km
- Move 500 electrons with given initial energy and pitch angle, and random initial position and gyro-phase
- For a given pitch angle, energy is computed from the first cyclotron resonance:

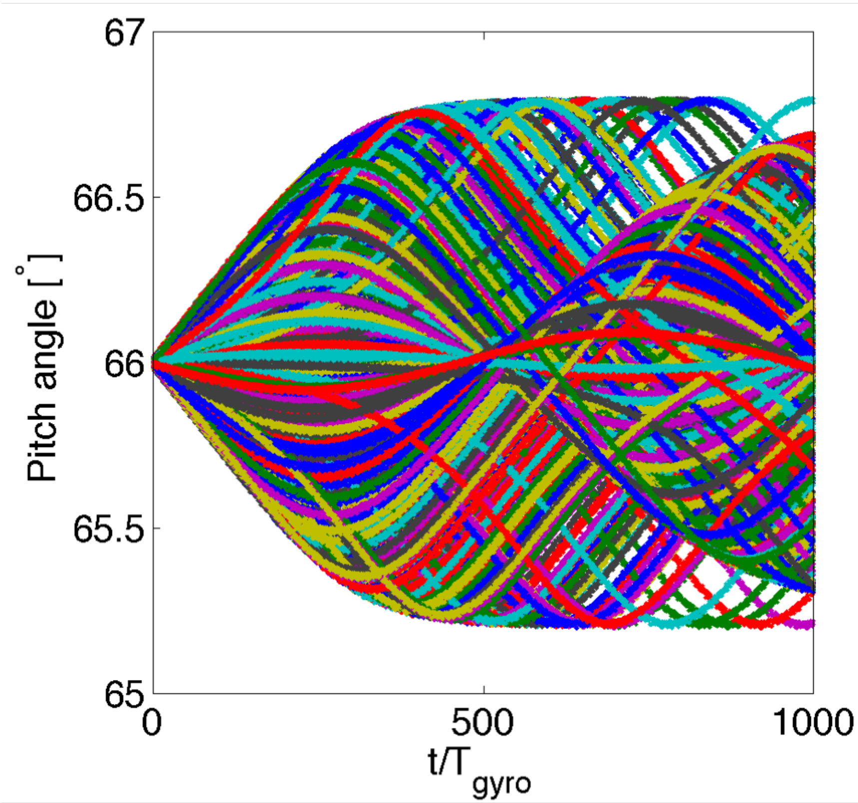
$$\omega - k_{||} v_{||} = \frac{\omega_{ce}}{\gamma}$$

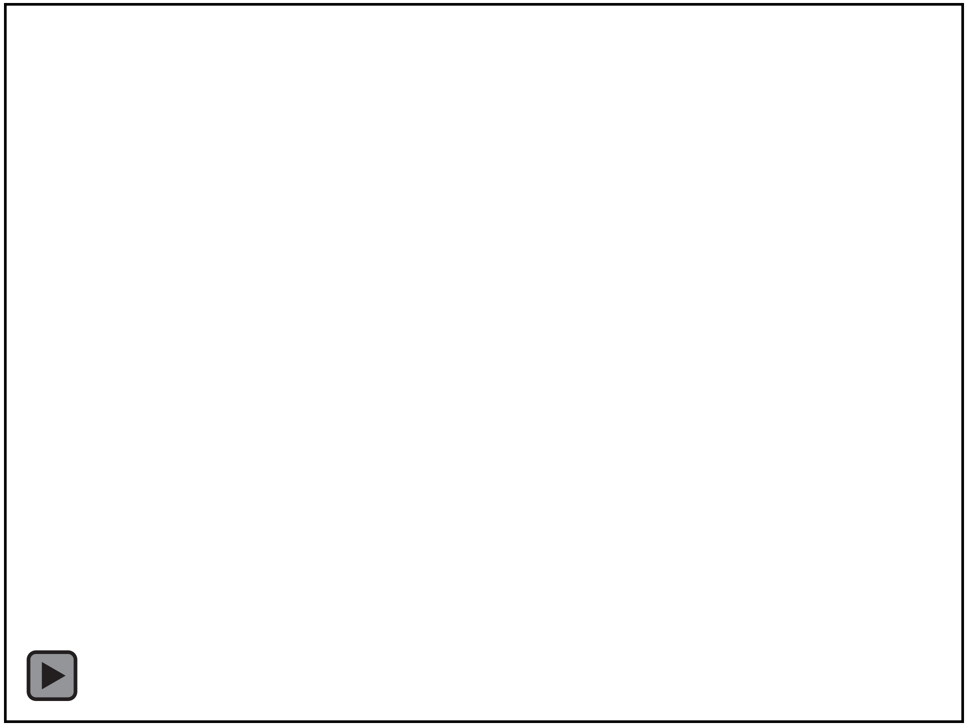
beam (ω, $k_{||}$)   Background particle ($v_{||}$, γ)

SHIELDS

Whistler mode:

E(0)=3.7 MeV; α(0)=66°; $\omega=0.045\omega_{ce}$

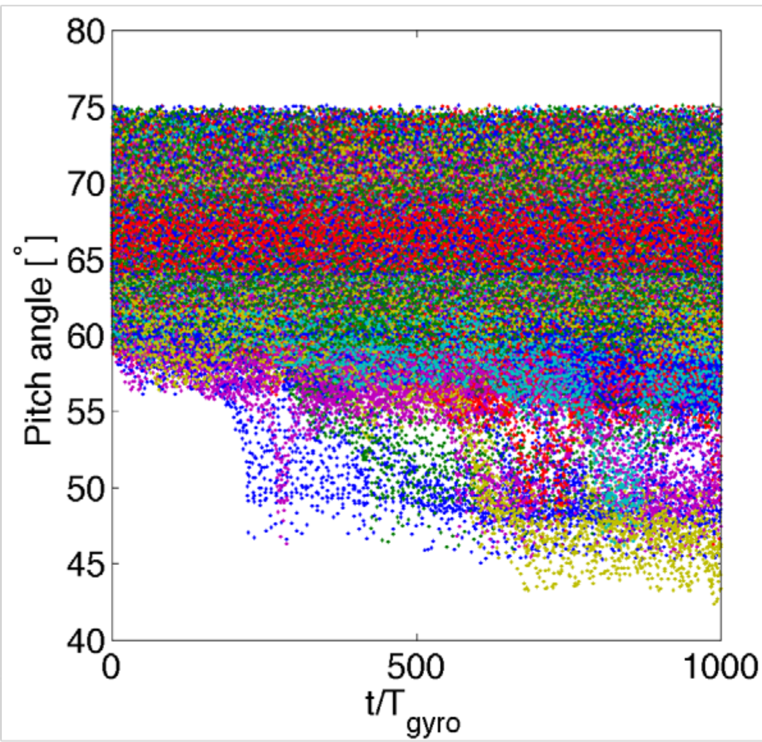


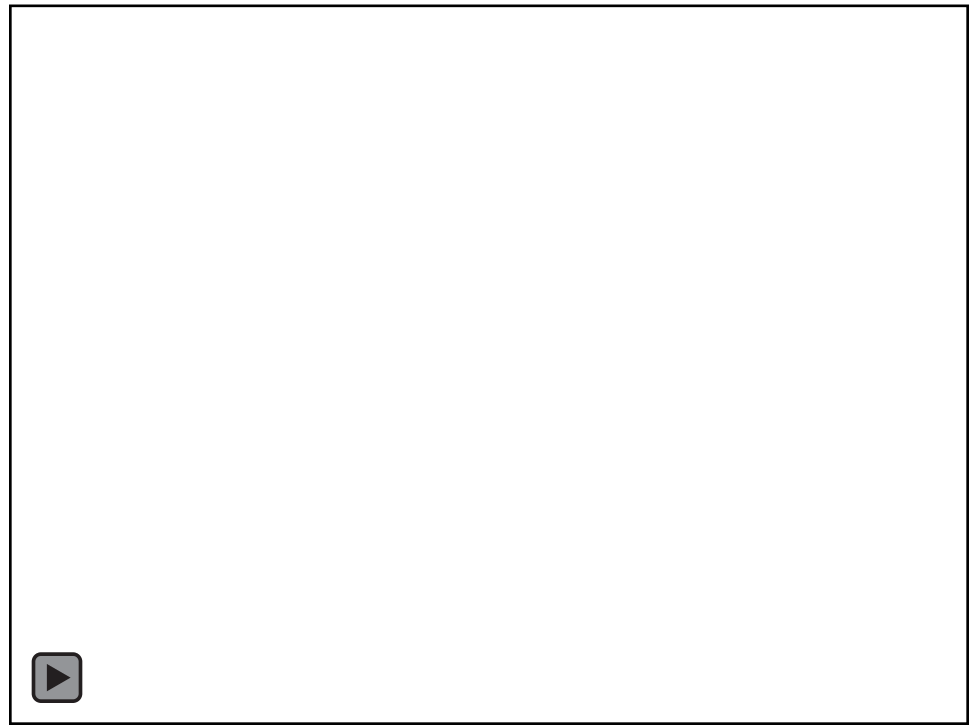


With these parameters, can’t get 3 deg changes in pitch angle necessary for precipitation

Z(X) mode:

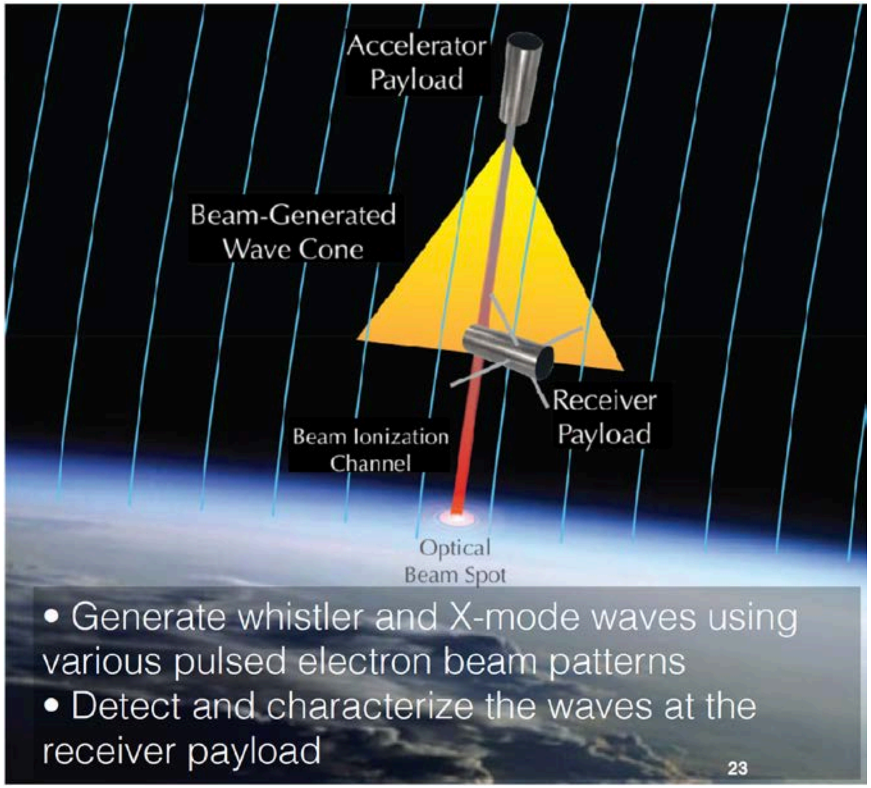
E(0)=31 keV; α(0)=66°; $\omega=2.2\omega_{ce}$

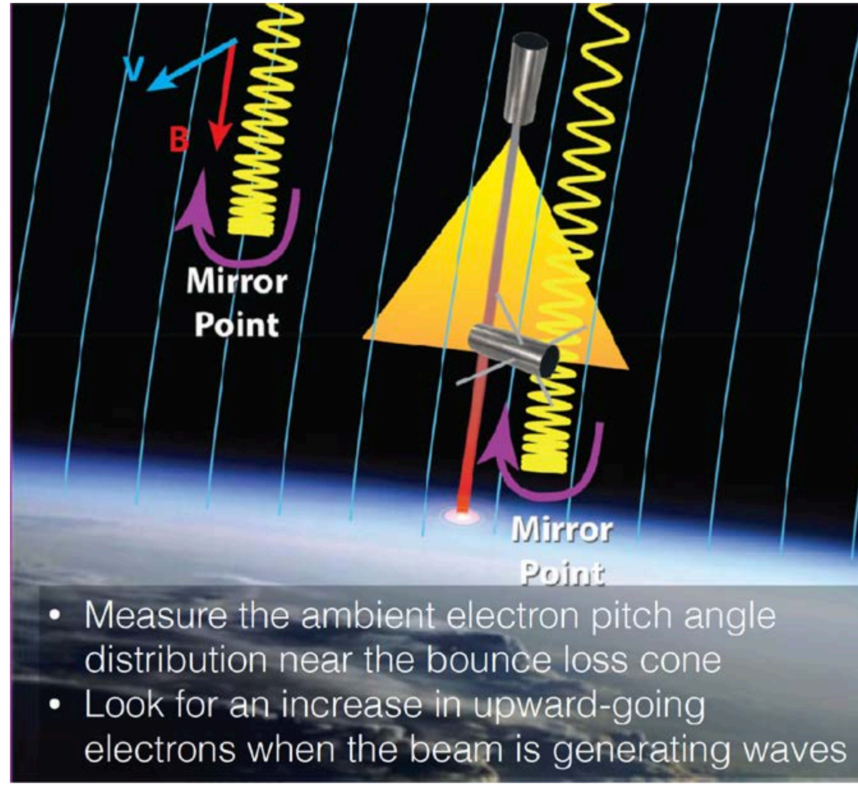




With these parameters, 20% of the particles experience a change in PA greater than 3 deg in the right direction

Beam Plasma-Interaction Experiment (Beam PIE)



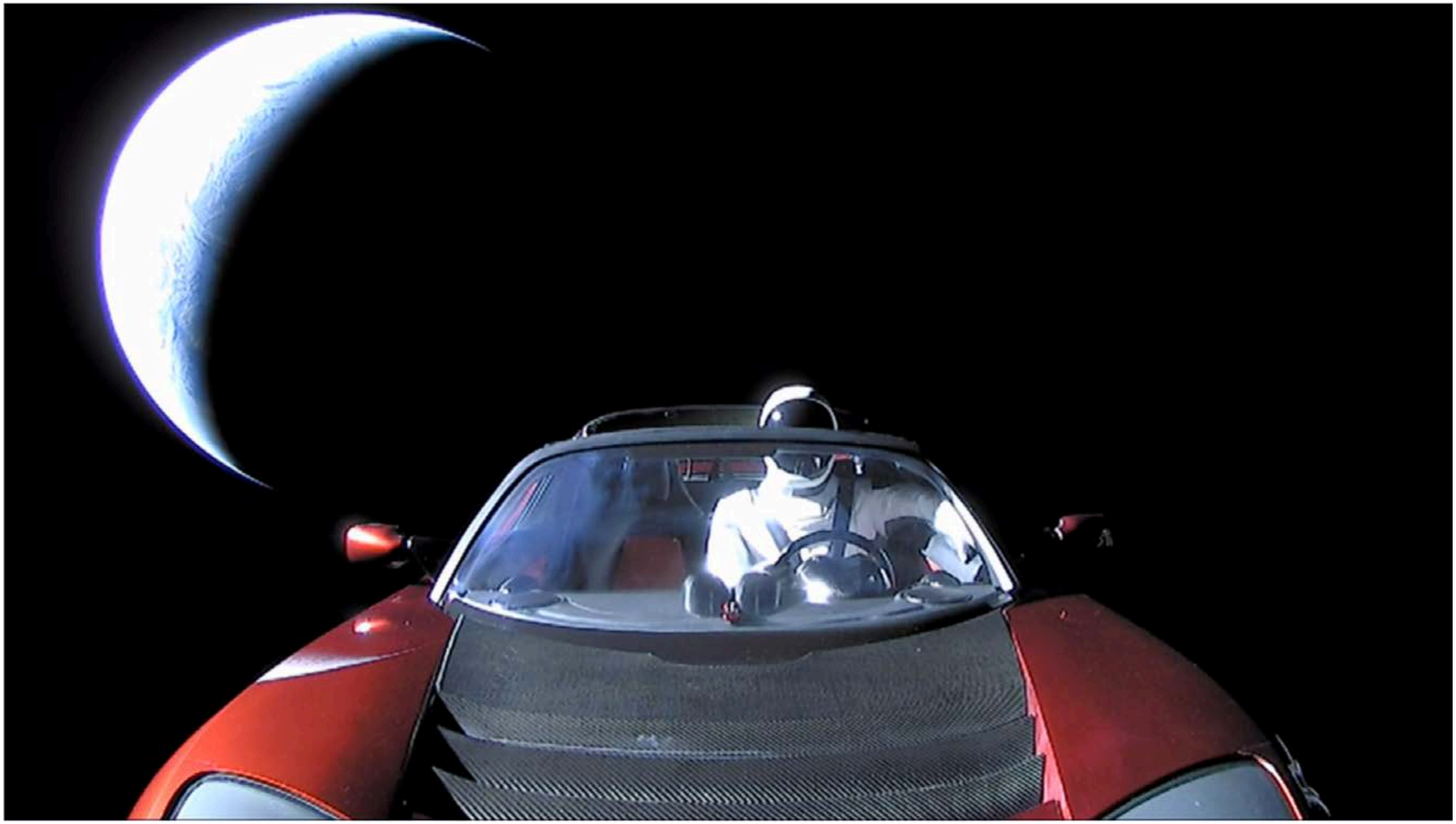


+ Raise TRL on accelerator

LCAS proposal selected last week!

V. Conclusions

It's a very exciting time for space research!



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