Space-Borne Accelerators

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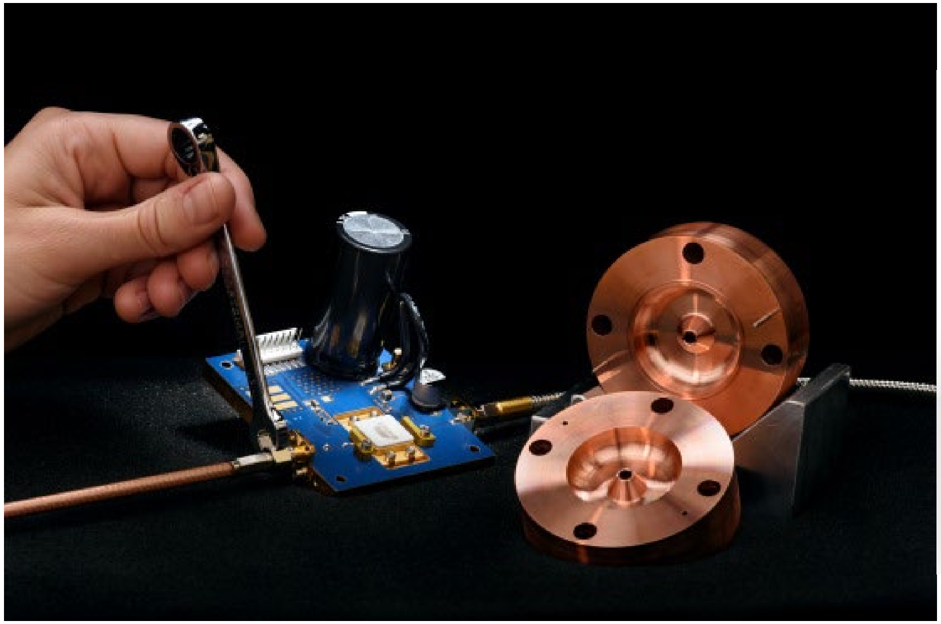
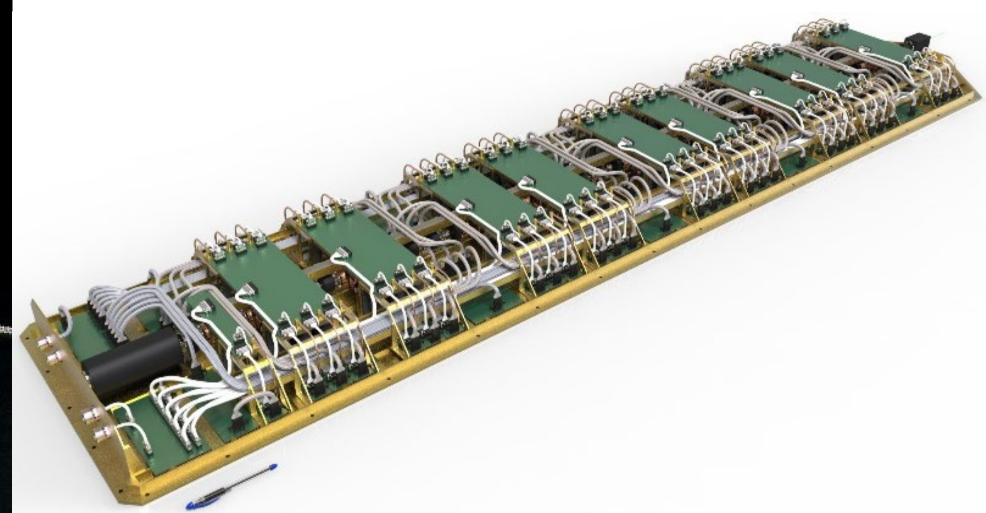
Compact Accelerators in Space Using HEMTs

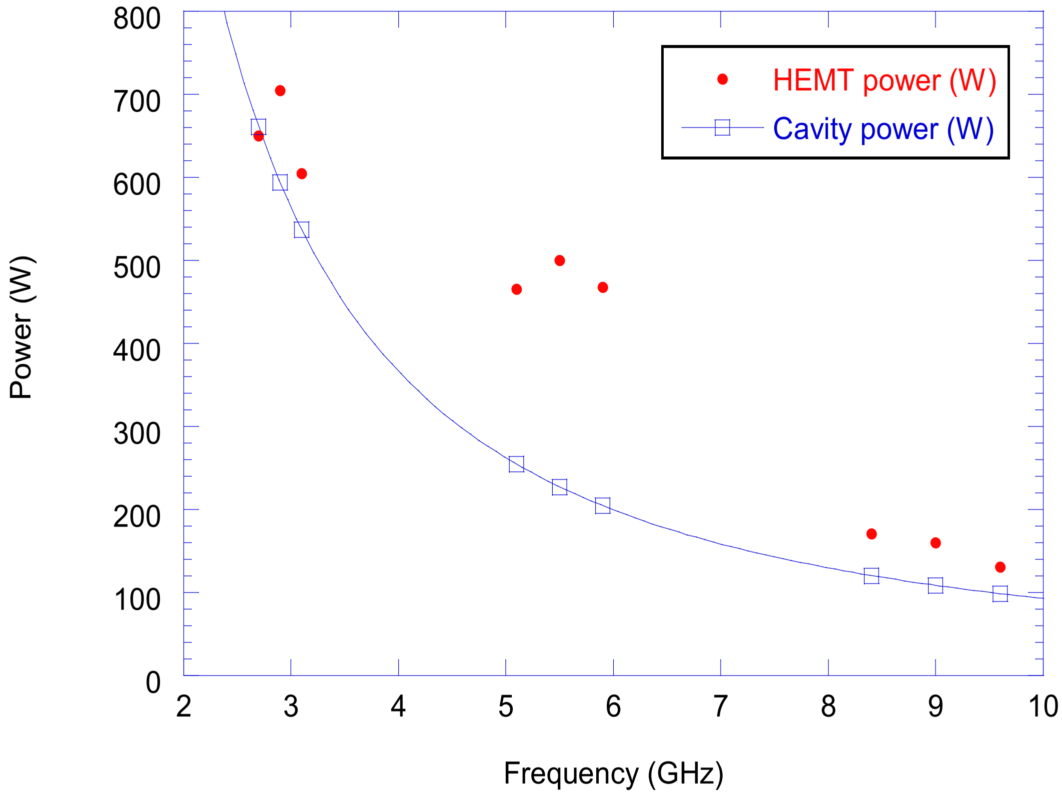
HEMT RF Sources for Compact Acceleration





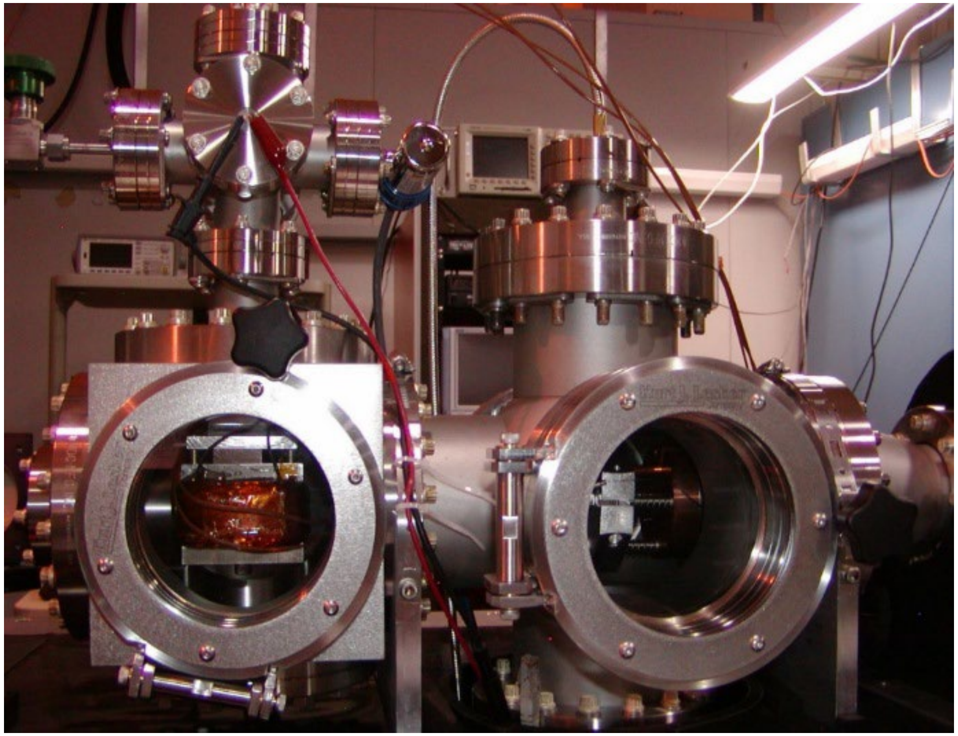
- High Electron Mobility Transistors (HEMTs) used to drive small C-band (5 GHz) cavities.
- The HEMTs are compact, solid state devices that can generate up to 500 W of RF power.
- These allow for compact acceleration of electrons without relying on bulky devices such as Klystrons.

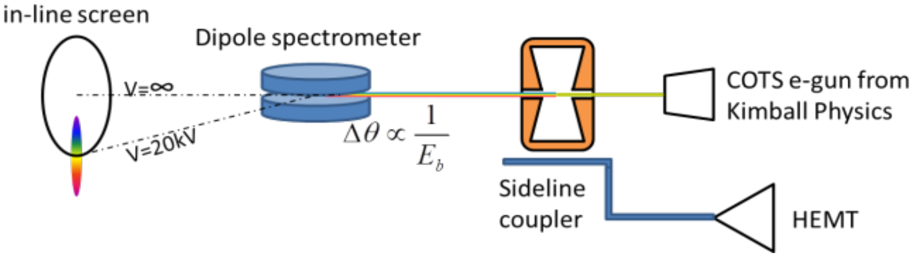
Frequency Chosen to Optimize Available Power



- At low frequencies, HEMTs produce high power, but cavity resistive loss is high so there is not much power left.
- At high frequencies, cavity loss is low but HEMT power is also low.
- Around 5 GHz, HEMT power is higher than cavity loss, leaving a large amount of power to accelerate beam.

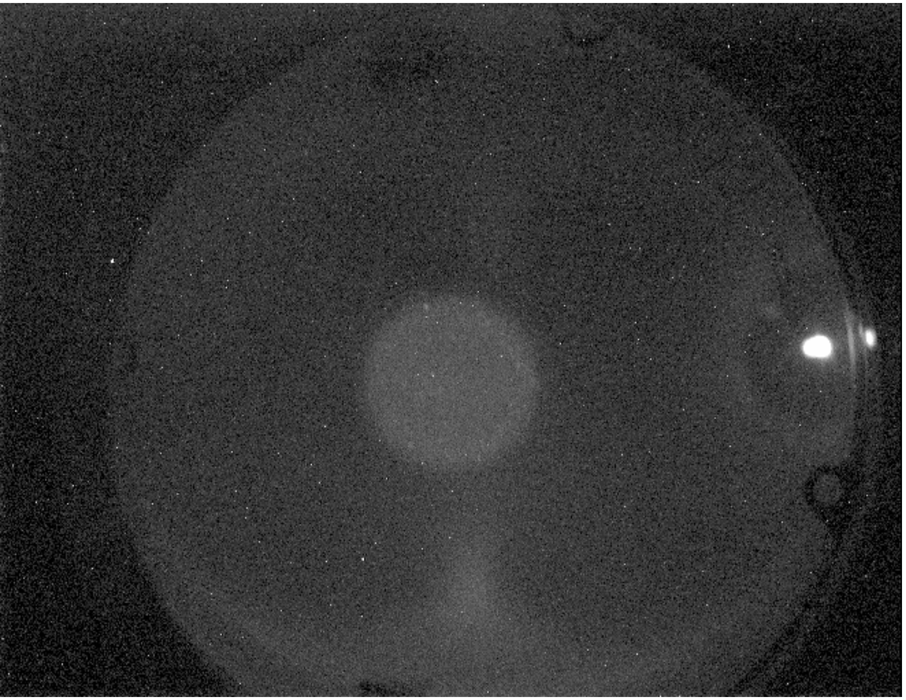
Experimental Demonstration of HEMT Acceleration

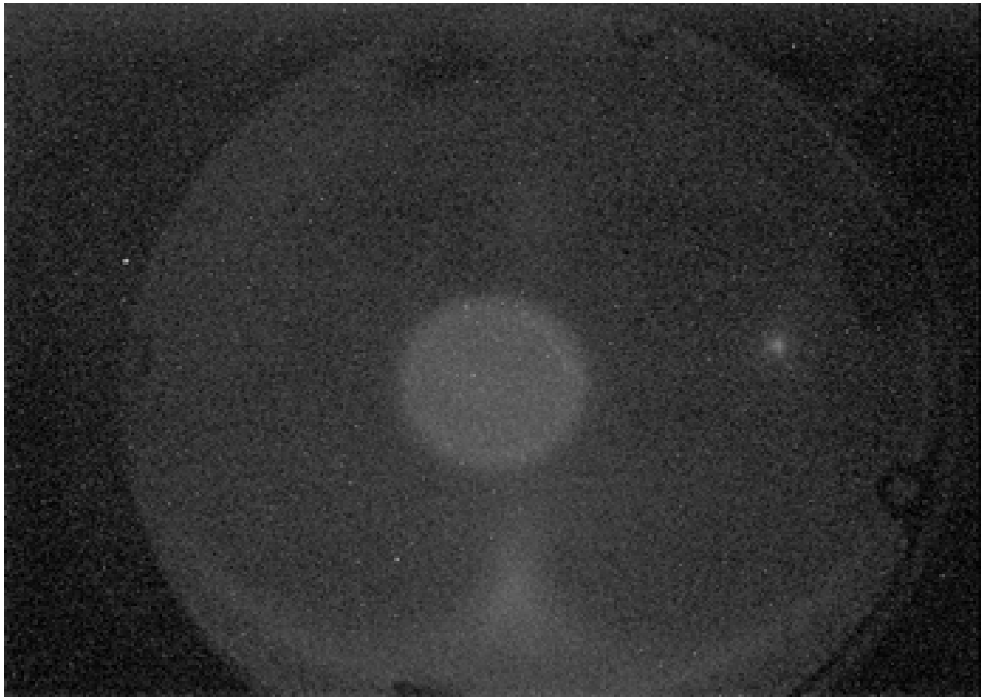




- Use a dipole spectrometer to measure energy gain from a single cavity driven by a HEMT.

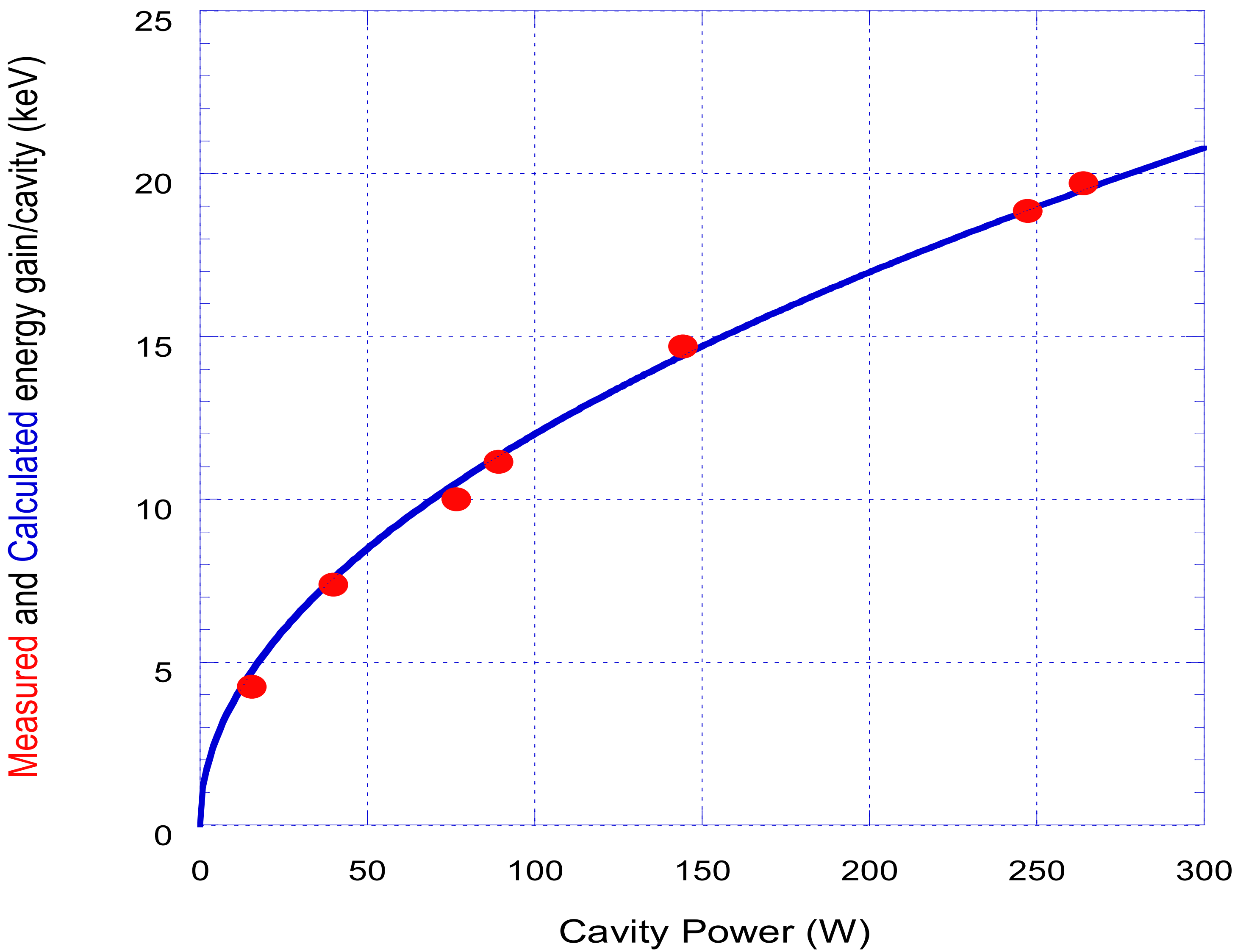
Experimental Demonstration of HEMT Acceleration (2)





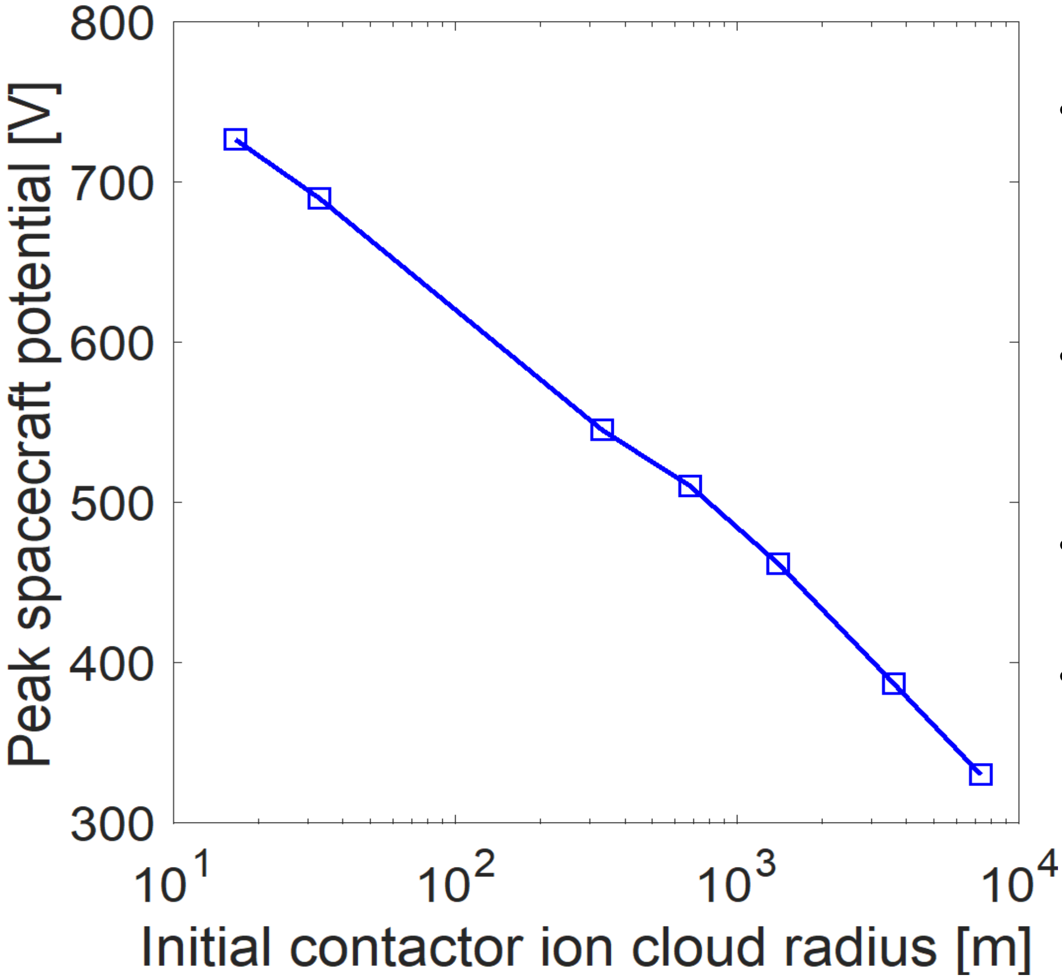
- Left is without cavity RF power, right is with. Change in location can be used to measure energy gain.

Experimental Demonstration of HEMT Acceleration (3)



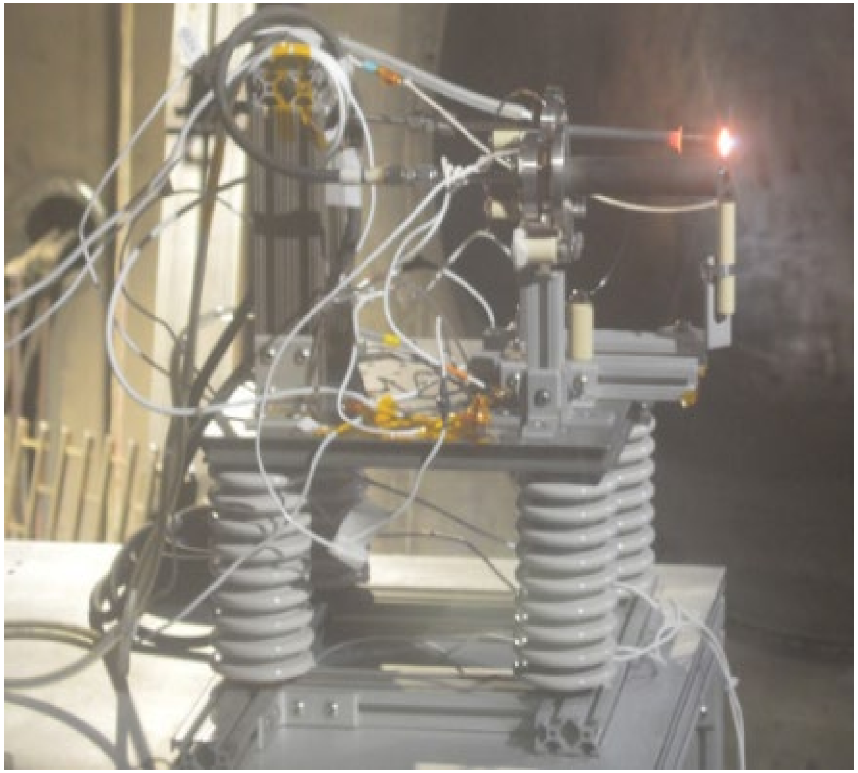
Plasma Contactor

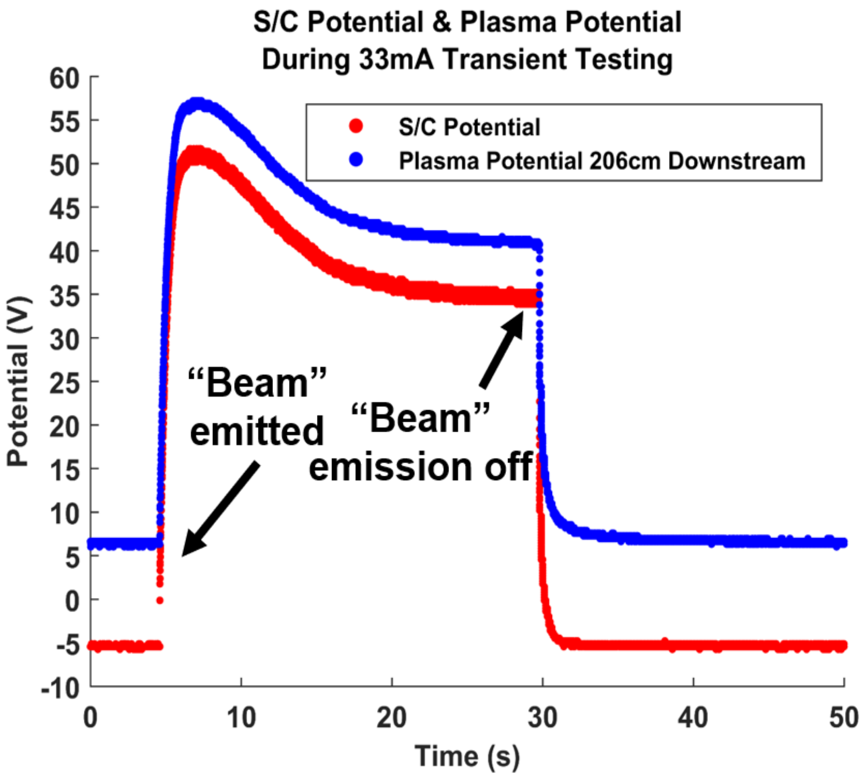
Plasma Contactor to Mitigate Spacecraft Charging



- In the magnetosphere, the plasma is too low density to recharge spacecraft after electrons (or ions) are emitted away.
- A 1 mA beam could charge up spacecraft to 100 kV, which could damage the spacecraft.
- Use a plasma contactor to eliminate this problem.
- Simulations show this can reduce spacecraft charging to below 1 kV.

Validation of Spacecraft Charging Model

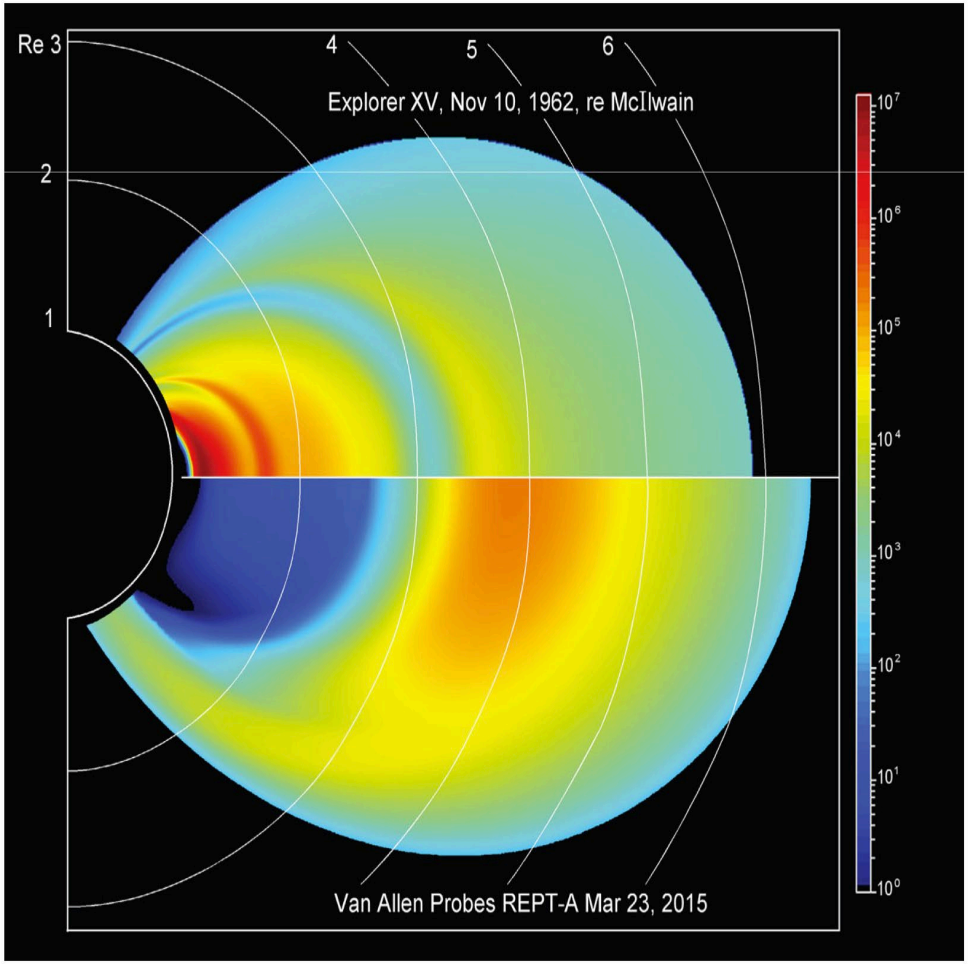




- Experiments at U. Mich's Large Vacuum Test Facility validate models of spacecraft charging.

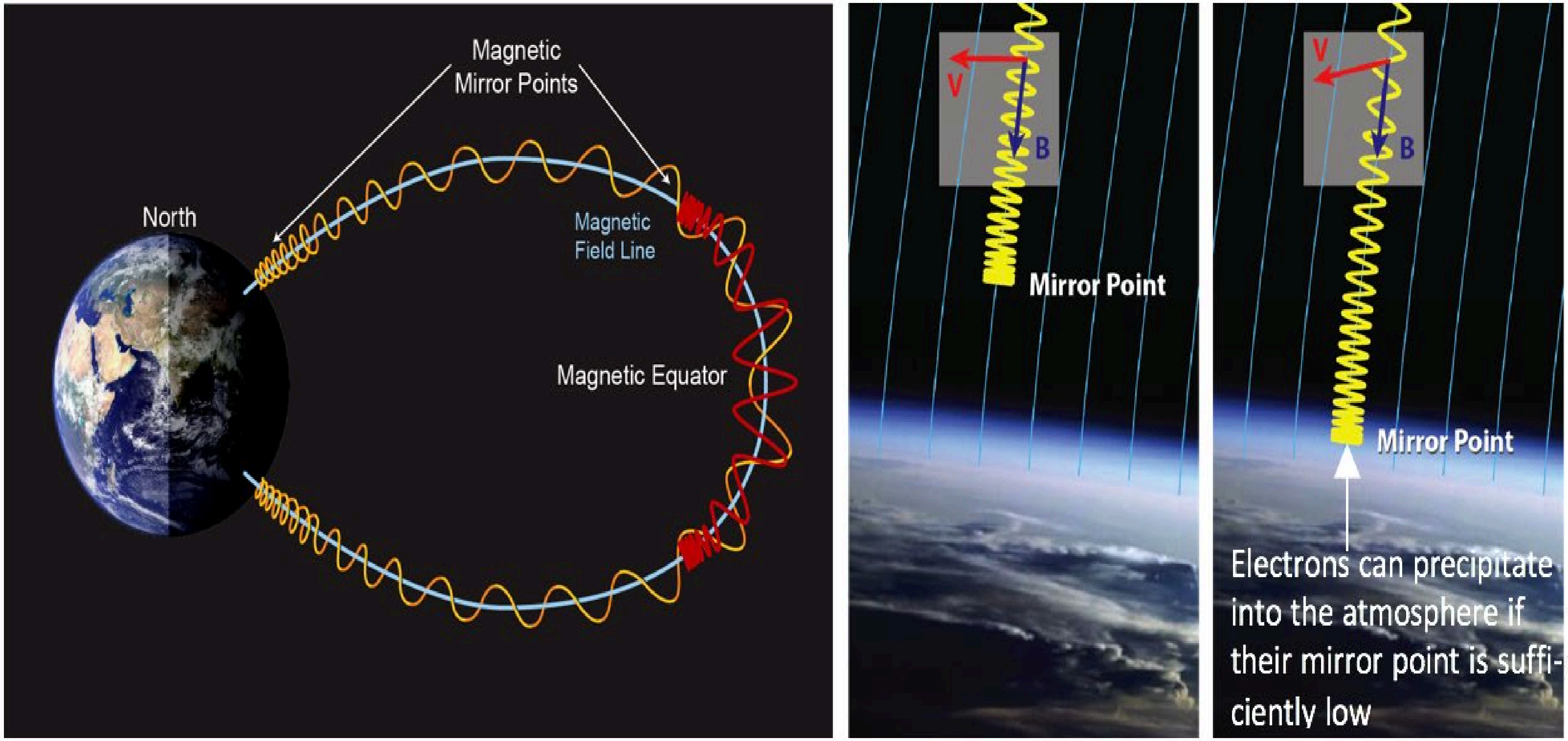
Radiation Belt Remediation

A HANE could destroy most LEO satellites



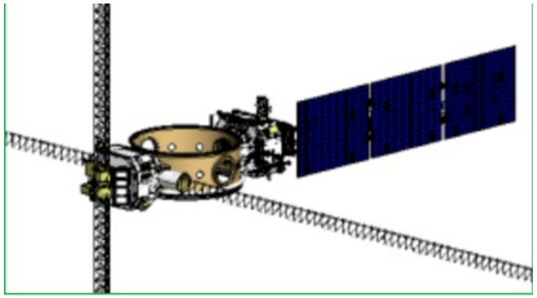
- In 1962, the Starfish Prime high altitude nuclear test produced an artificial HANE belt of high energy electrons.
- These “killer electrons” destroyed a third of all LEO satellites deployed at the time.
- In modern times, we have many more LEO satellites, which would be threatened by a rogue nation performing a HANE test.
- A method is needed to quickly reduce the number of energetic electrons trapped in the artificial belt.

Use Artificial Waves to Precipitate Electrons into the Atmosphere

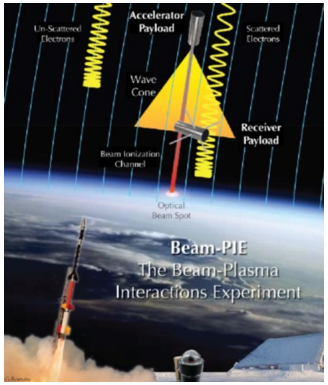


- Directly inject whistler waves into HANE belt using either an antenna or an electron beam.
- These waves cause diffusion in the trapped electrons' trajectories, which causes them to align with the loss cone and travel into the atmosphere.

Exploring 3 different methods of wave generation



Shown with optional tripod mount



Dipole Antenna

- Most studied, both theoretically and experimentally
- Likely not very efficient at generating whistler waves.

Loop Antenna

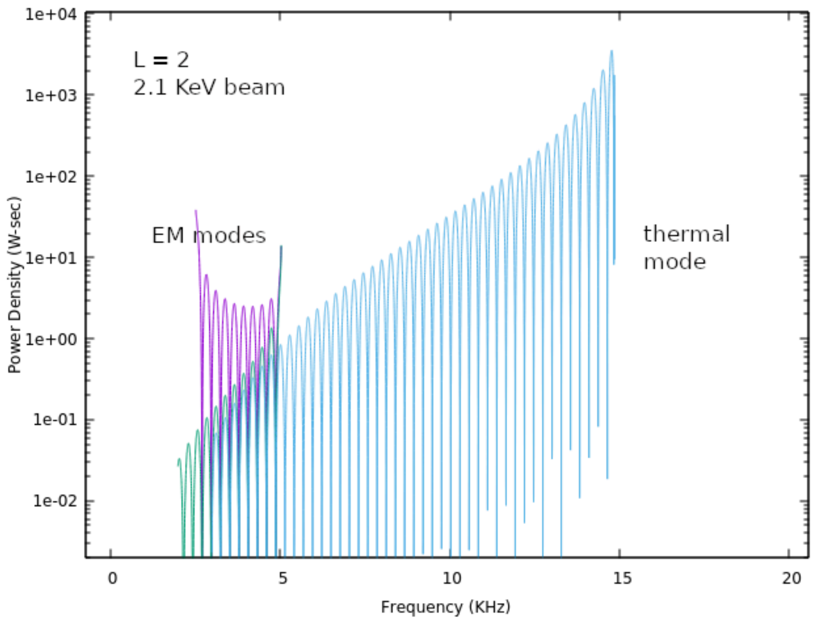
- Not very well studied – some theory and lab experiments, no space experiment.
- Much more efficient than dipole.

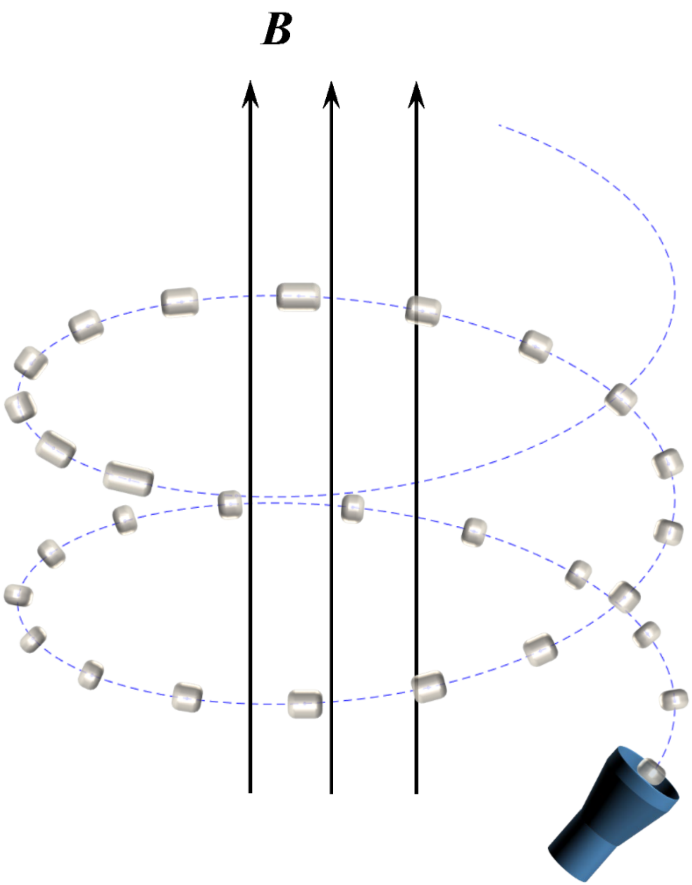
Modulated electron Beam

- Planned BeamPIE experiment 1st for wave gen.
- LANL studies show promise.

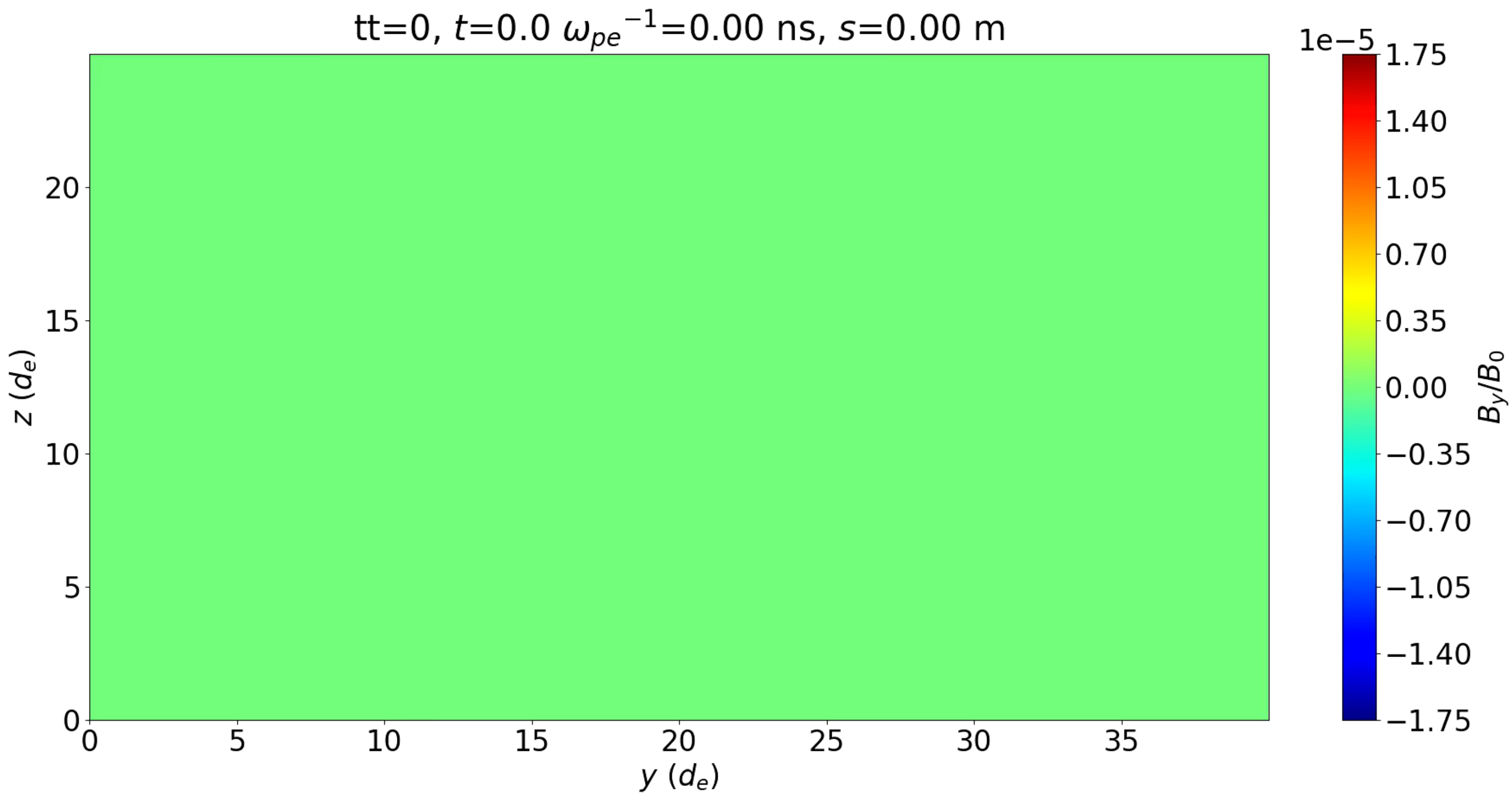
Linear Theory Calculates Wave Generation for Beams

- Can model finite beam length and beams that are not aligned with B-field.
- Find lots of power in complicated thermal mode, showing need for SPS simulations.





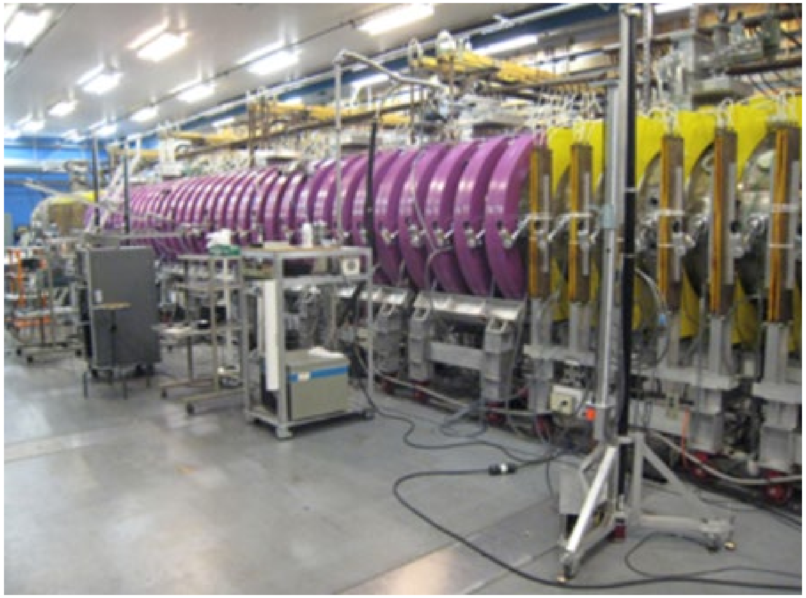
LANL (T-5) developed code SPS used to model an ideal electron pulse

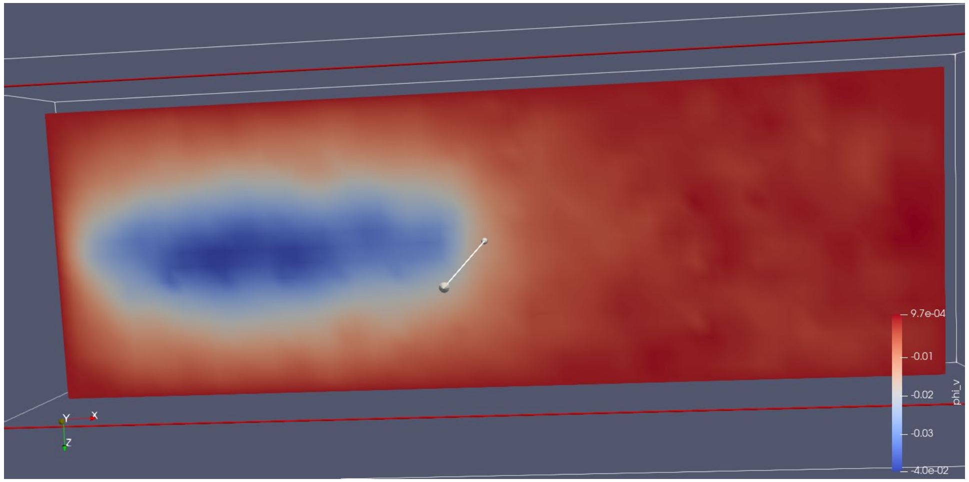


- SPS used to model waves generated from ideal electron beam.
- Currently comparing these results to linear theory predictions.

Lab validation experiment at LAPD

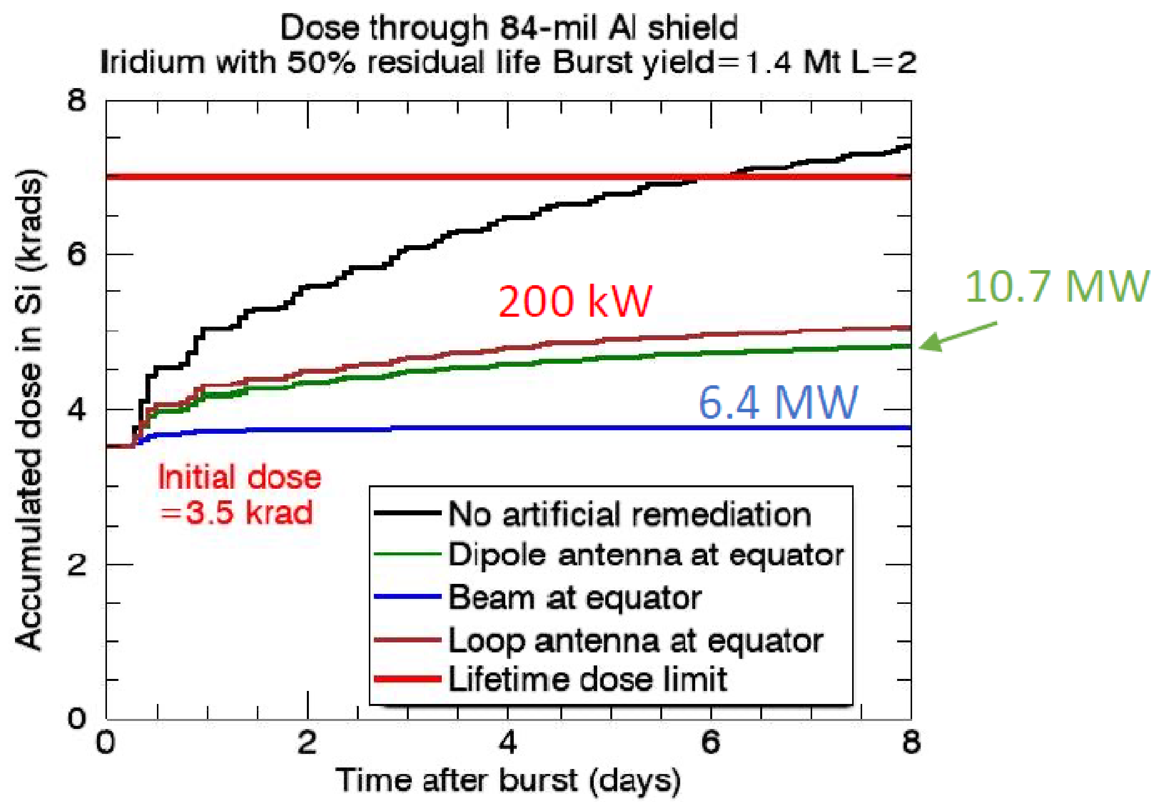
- A validation experiment is taking place at the Large Area Plasma Device (LAPD) at UCLA (Gekelman 2016).
- For this experiment, a 20 keV electron beam was injected into the plasma, and the resulting plasma waves were measured.
- These results are being compared to analytical theory and first principles modeling based on the CPIC code.





Our model suggests RBR concept is feasible

- We have done S2E models, including the generation and propagation of waves, as well as the interaction of the waves with MeV electrons.
- Our models suggest that an electron beam can remediate the belt fast enough to save most satellites.
- Have compared the beam with a dipole and loop antenna.



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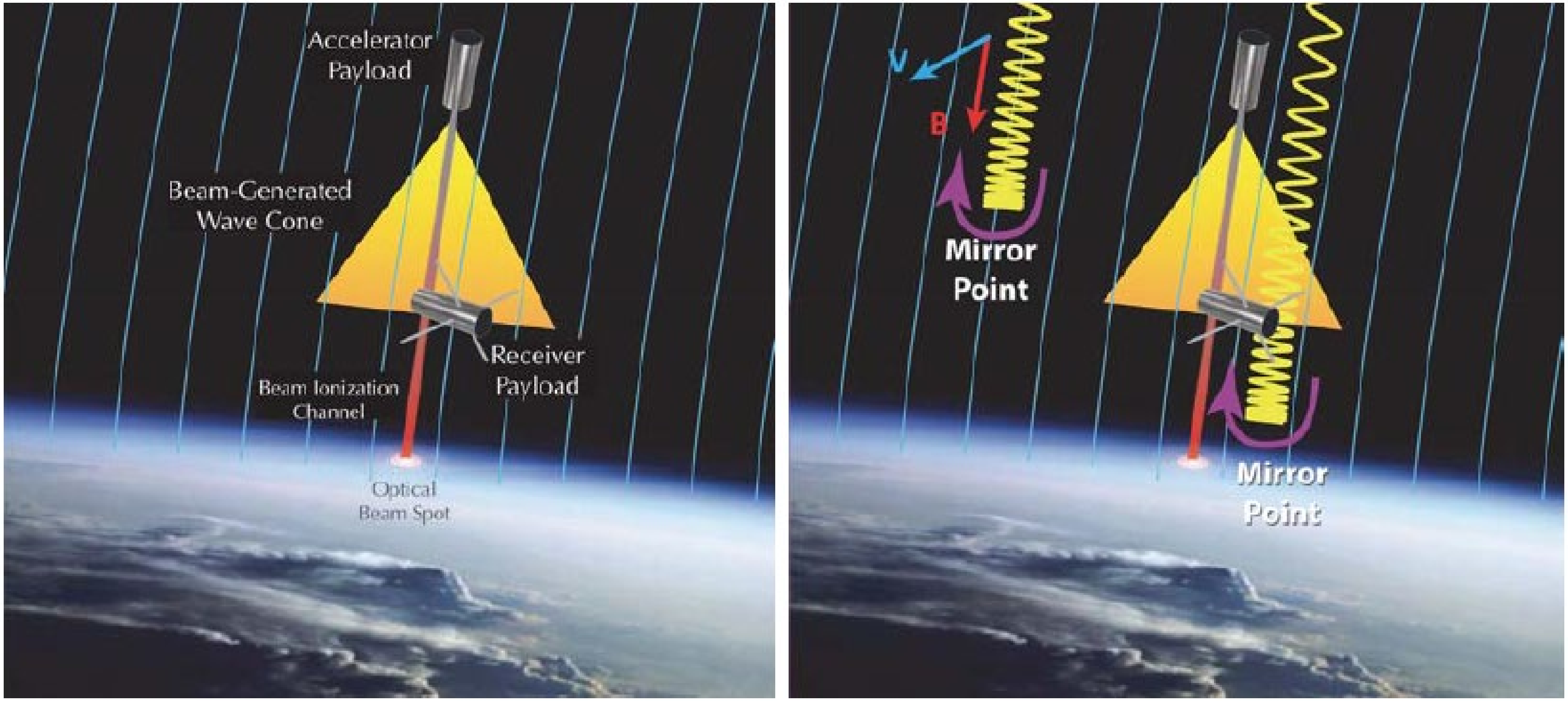
The Beam Plasma Interactions Experiment: BEAM PIE

BEAM-PIE will test the models of radiation from a beam



- BEAM-PIE will field a 6 mA, 10-50 keV electron beam aboard a sounding rocket.
- Uses a HEMT cavities to accelerate electron beam.

BEAM-PIE Diagnostics

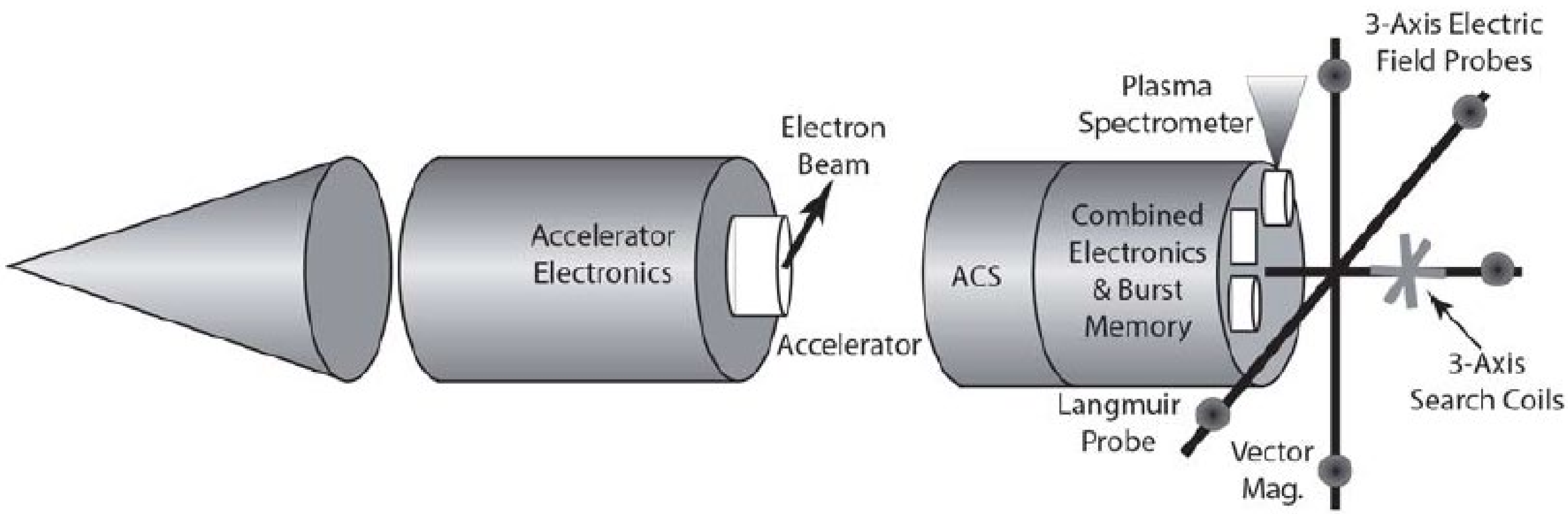
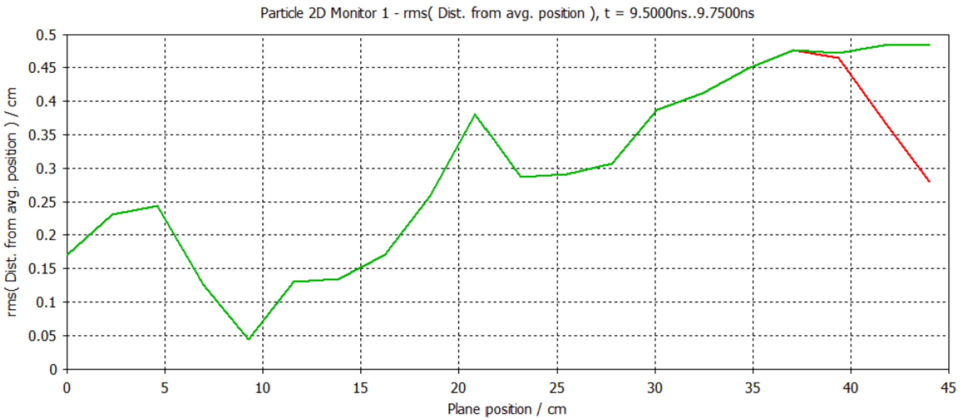


Figure 9. Schematic of the Beam-PIE payload and instrument locations.

- “Mother-Daughter” rocket configuration allows a diagnostic section to split off from electron beam.
- Measurement of plasma waves will be used to validate the models.

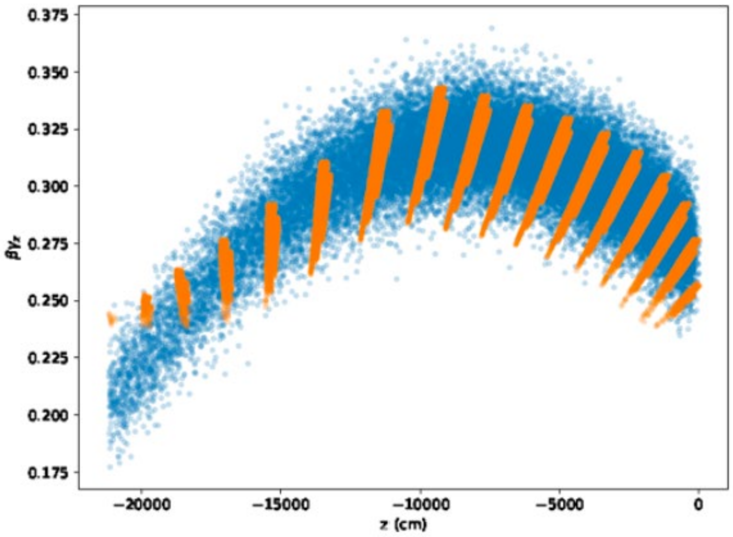
BEAM-PIE accelerator designed, being built in lab

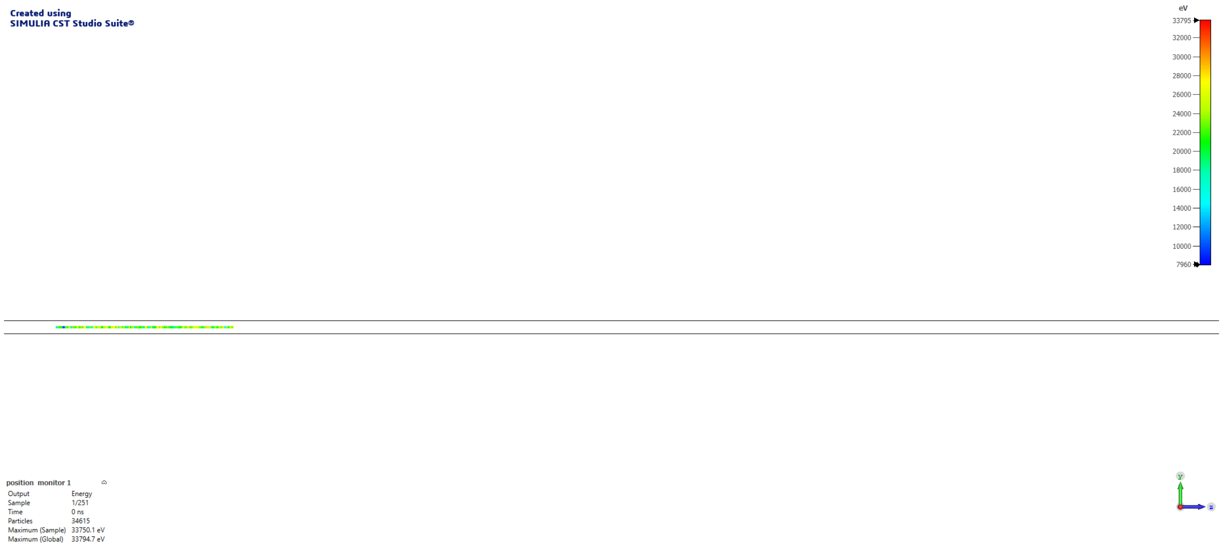


- The BEAM-PIE accelerator has been designed and modeled using microwave studio.
- Being assembled in lab to verify that it works, then will be put in rocket body.

Model propagation of BEAM-PIE beam into space

- Take outputs of many microwave studio simulations to make one distribution of a single BEAM-PIE bunch.
- Use a new microwave studio simulation to model the beam propagating into space.
- Beam debunches more quickly than ideal beam because of energy spread.





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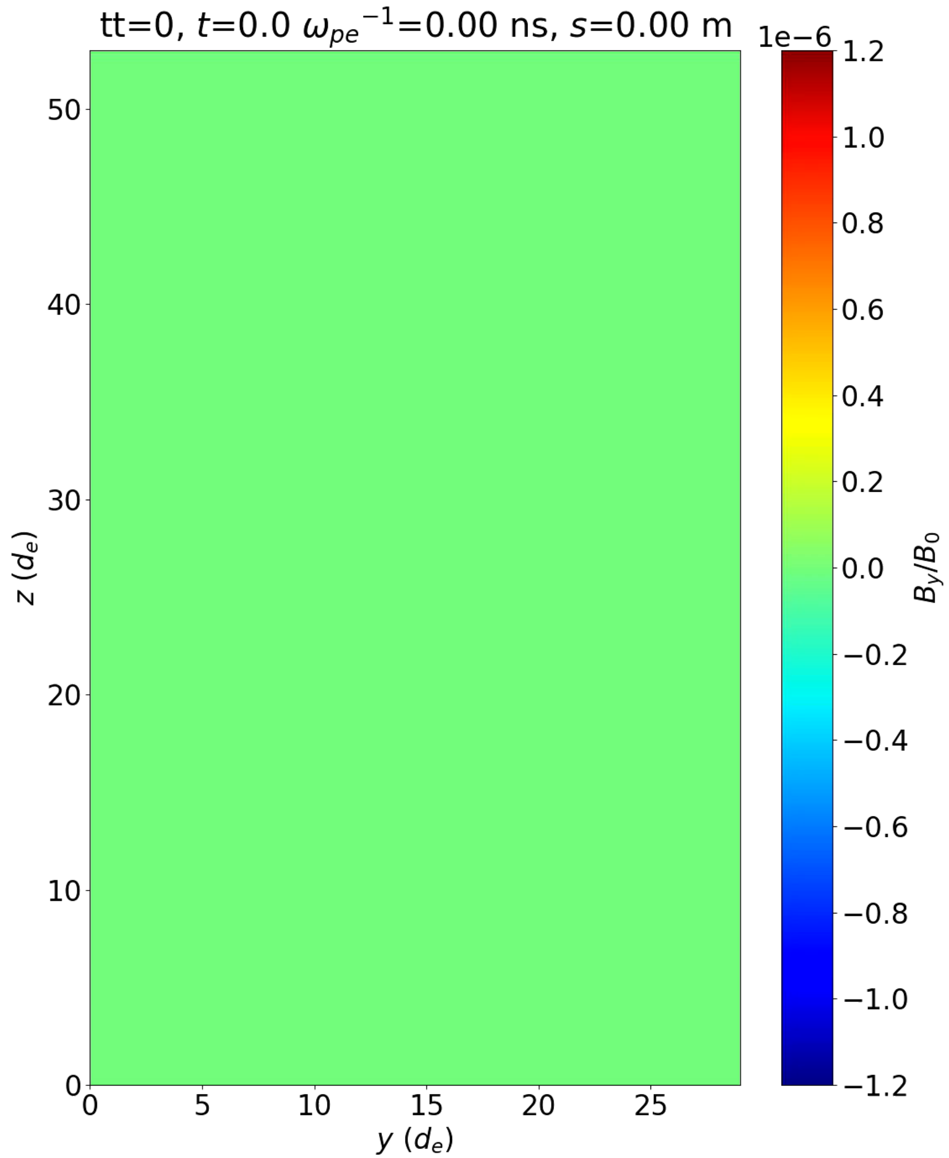
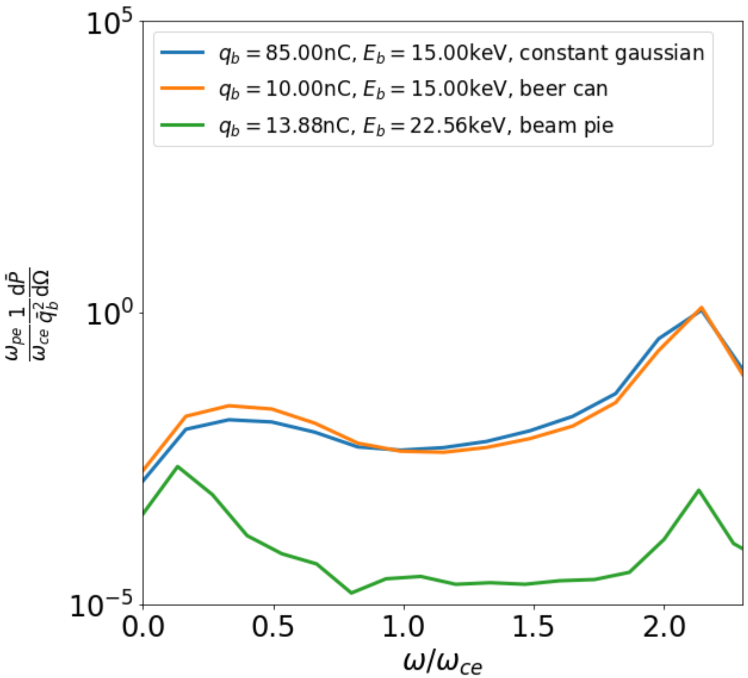
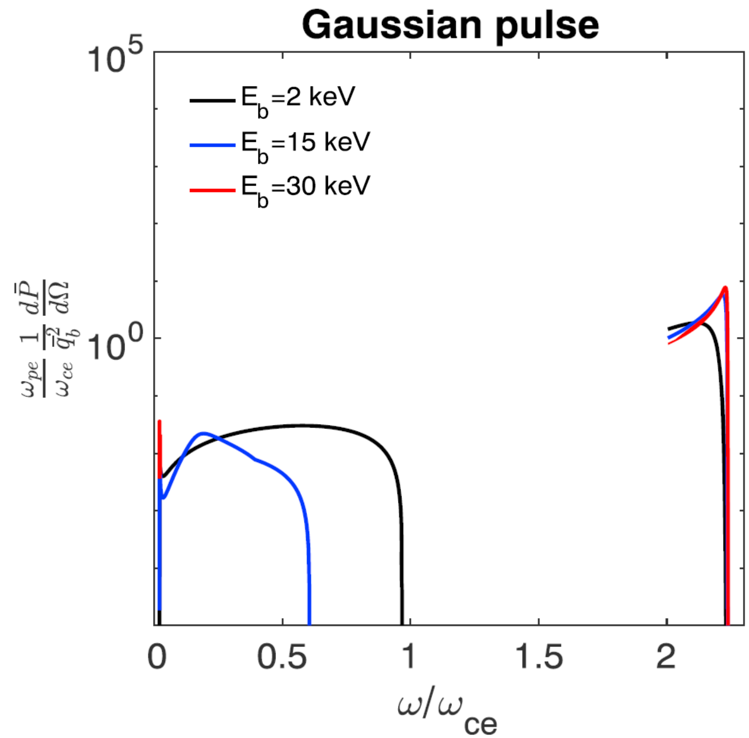
Model BEAM-PIE beam with SPS to predict waves generated from experiment

- Beam spreads out because of energy spread.
- This reduces the high frequency oscillations (x-mode) significantly (scale of colorbar is different here).
- Low frequency waves (whistler) are only slightly reduced.
- Can compare these results to experiment.



Comparison of SPS to linear theory





- Compare total wave power from BEAM-PIE and ideal beam in SPS to analytical theory (for an ideal beam).
- Find reasonable agreement between ideal beam and analytical theory for ideal beam, BEAM-PIE significantly lower at high frequencies.
- Allows for quantitative comparison of SPS results.

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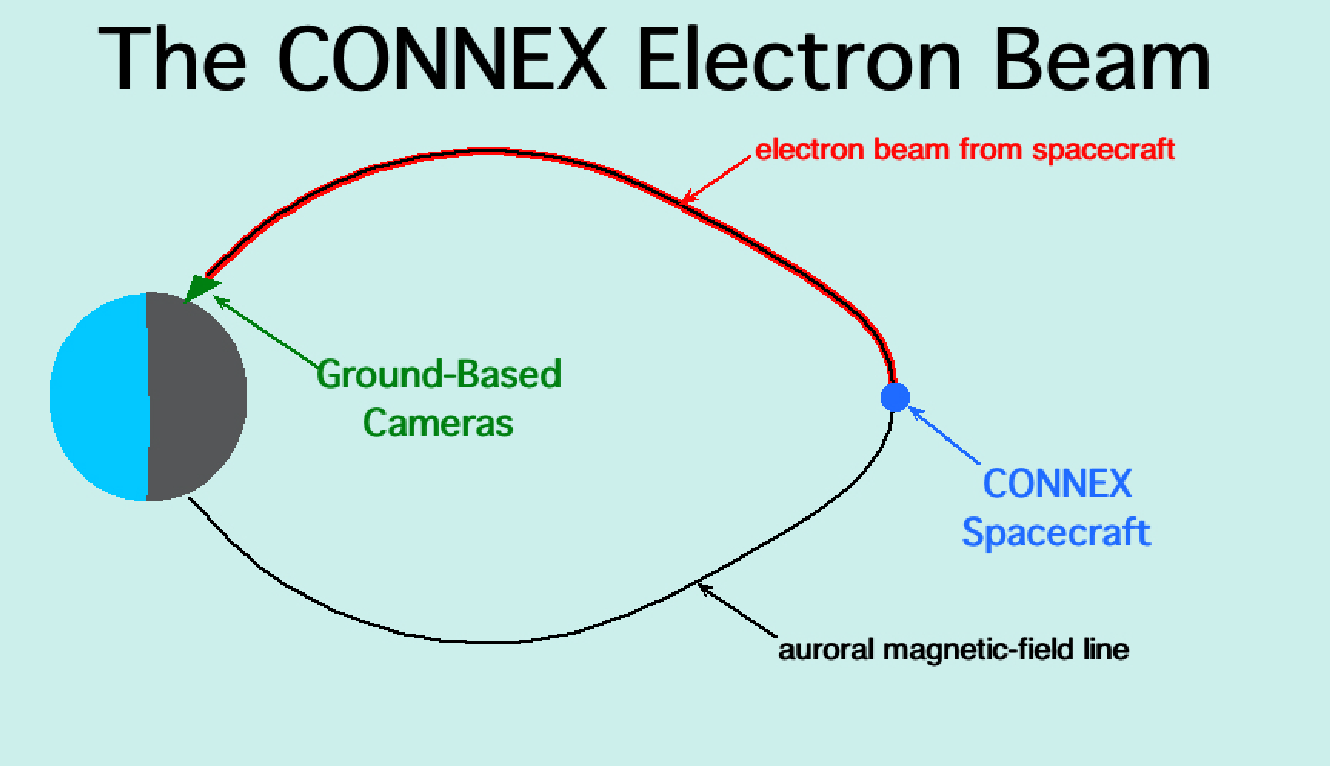
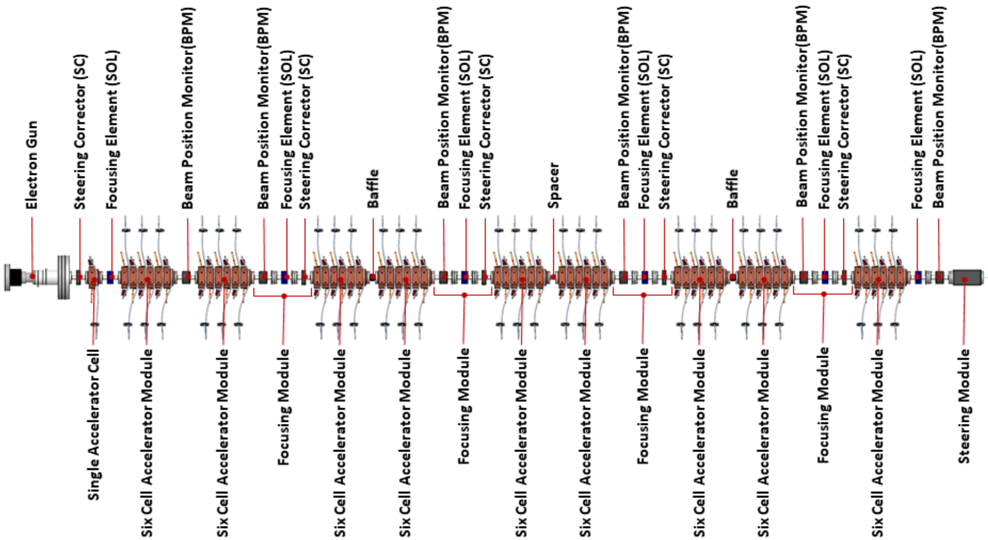
The CONNEX Experiment

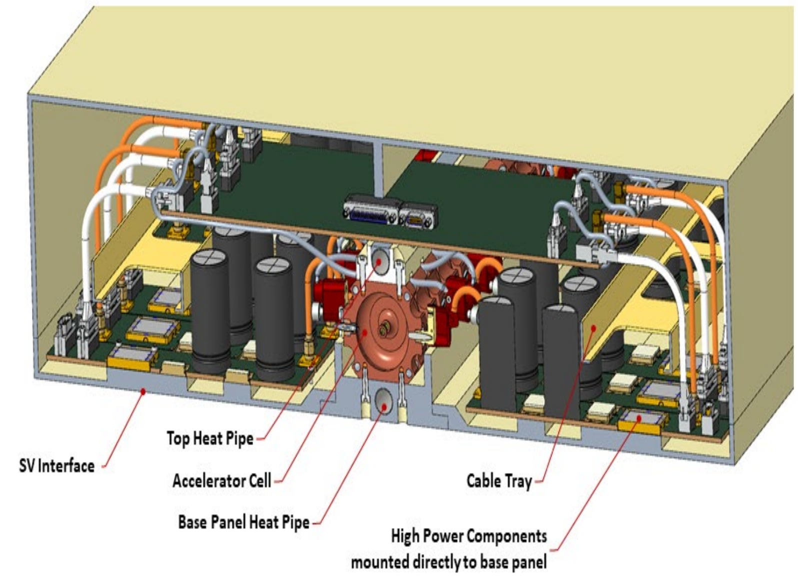
The CONNEX experiment: map out magnetic field



- Experimentally map magnetic field between the magnetosphere and the ionosphere using a 1 MeV electron beam.
- Image the electron beam hitting the atmosphere by using ground based cameras.
- Answers important questions about the auroras.

Experimental design of CONNEX

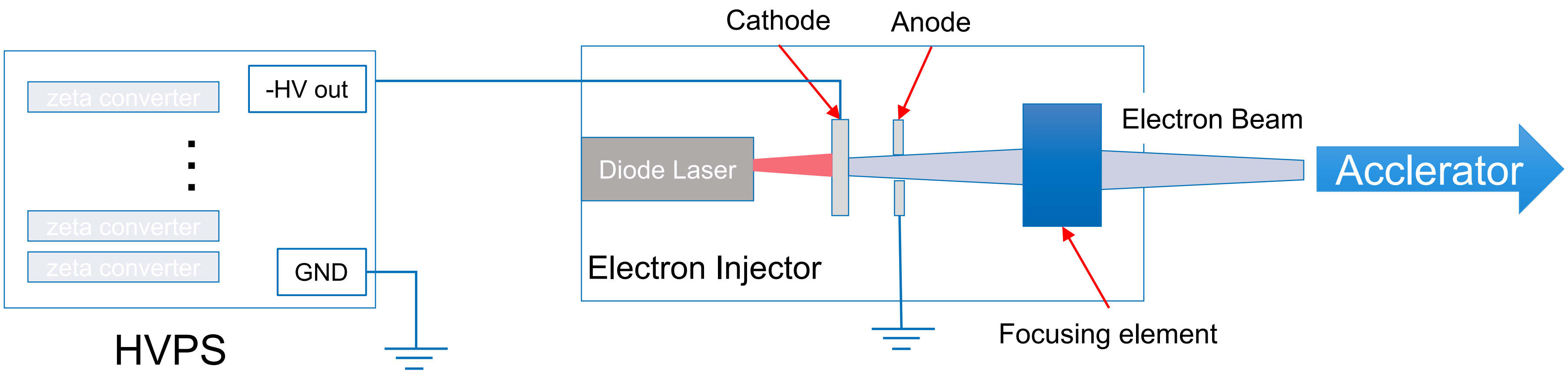




- The CONNEX experiment will be driven with a 1 MeV, 1 mA electron beam.
- Modular design simplifies things and allows for easy adjustment of total energy of beam.

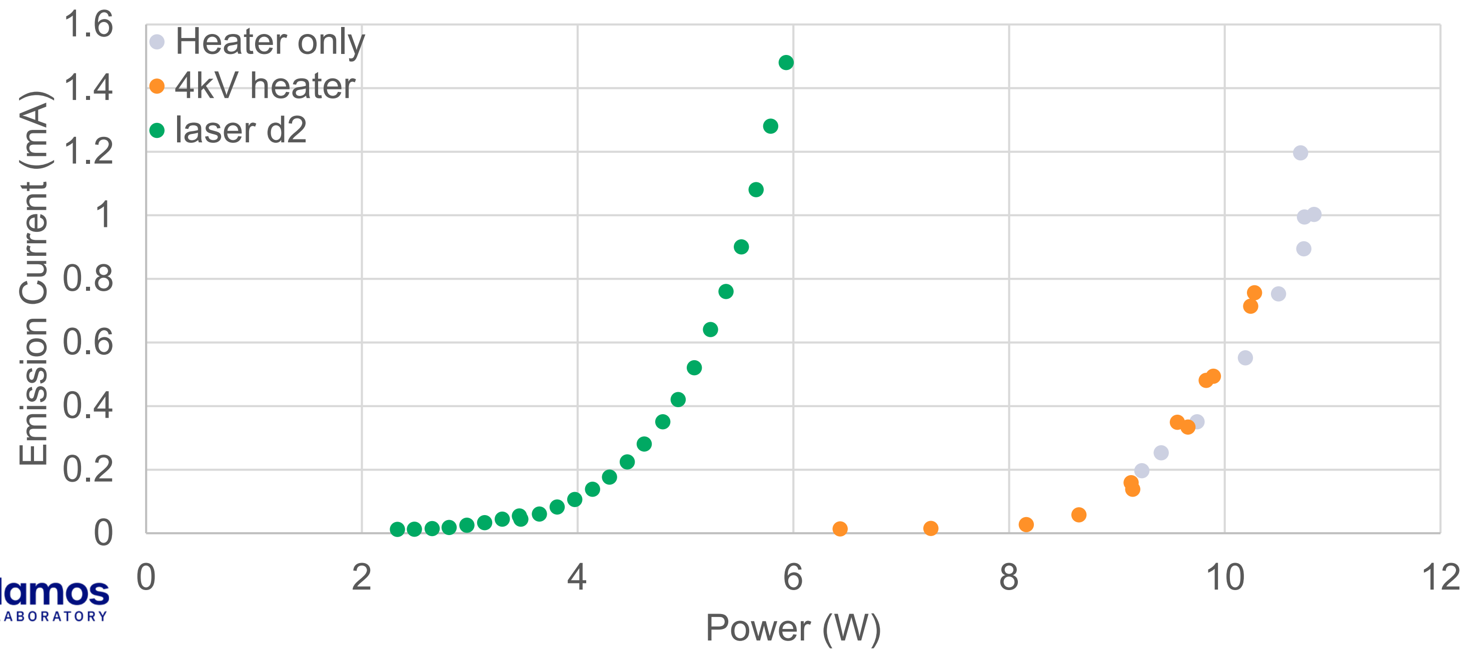
Low Power Electron Injector for Space Applications

Low power electron injector for space applications



- Use a diode laser to heat the cathode. This electrically decouples the heating from the high voltage power supply.
- Design a high voltage power supply specifically qualified for space that is modular and scalable.

Experimental results show laser heating is highly efficient



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A Simple Electron Beam for Plasma Diagnostics in Space

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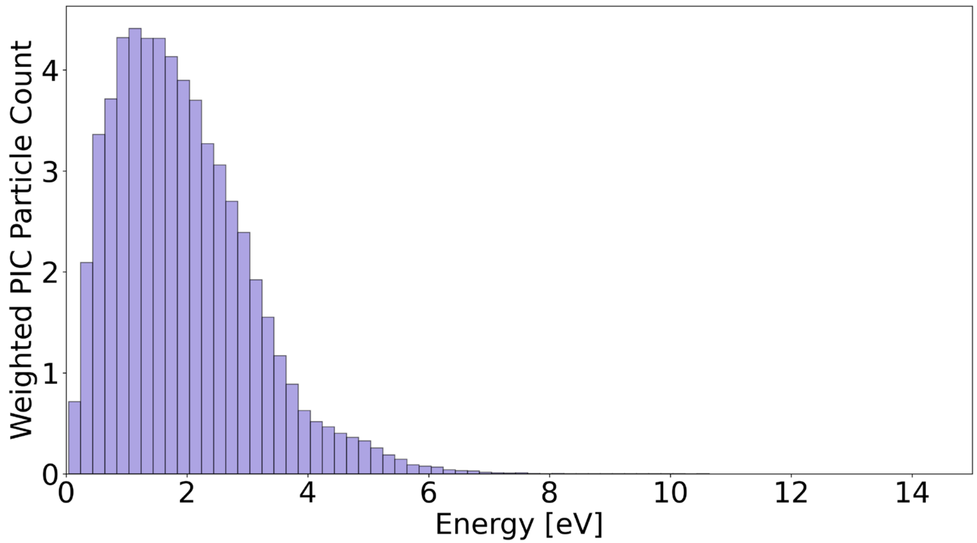
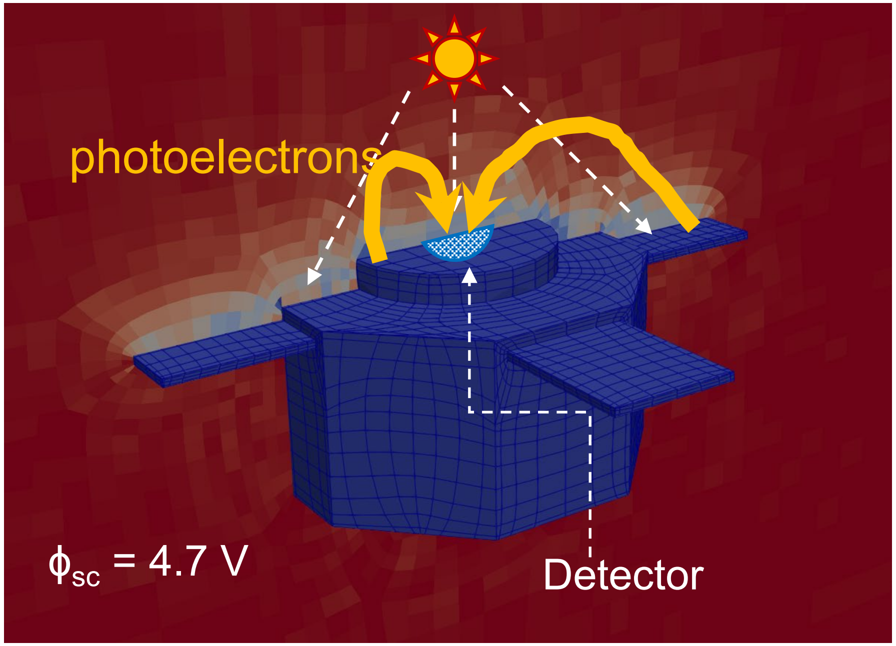
Detector in sunlight is blinded by photoelectrons

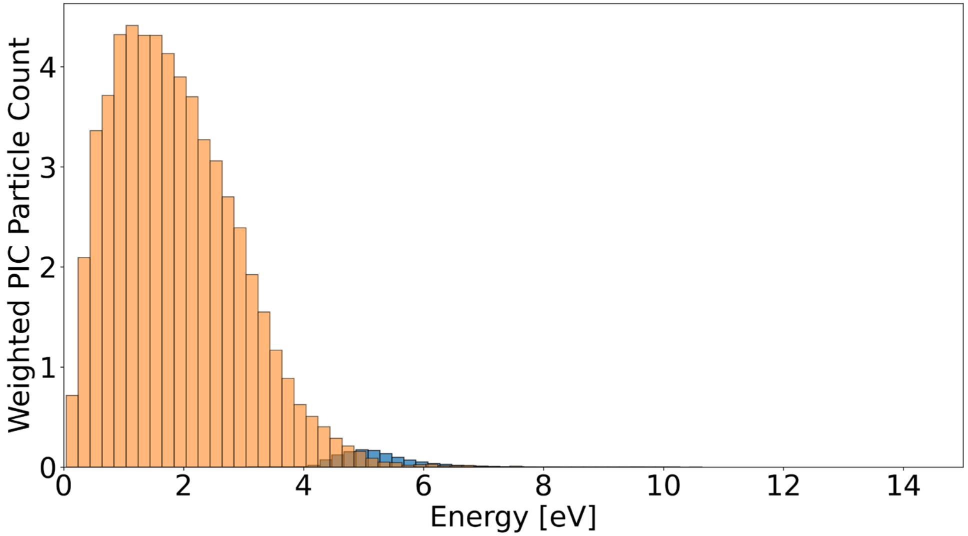
Detector Count: what the detector sees



CPIC Simulation



In simulations we can separate both species



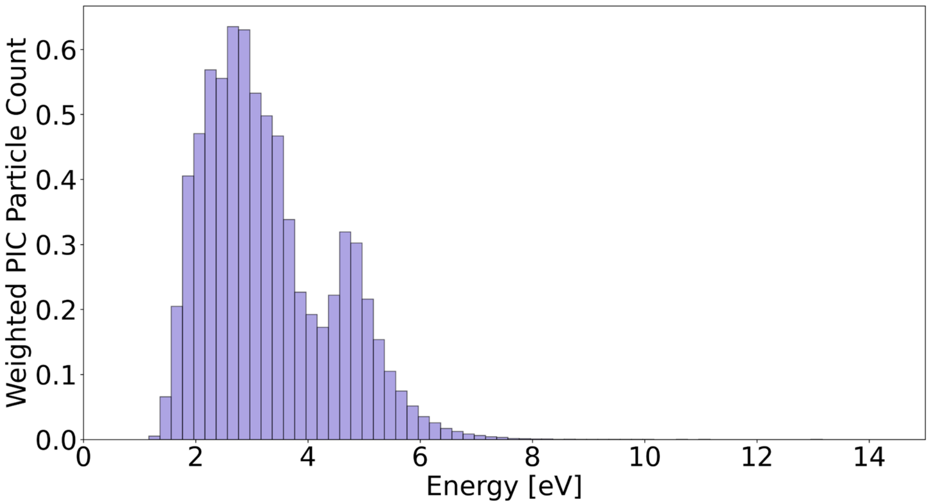
Material: Aluminum (in space)
J_{ph} = 100 μA/m^2 (40 μA/m^2 in the lab)
T_{ph} = 1 eV

Density = 13 cm^{-3}
Te = 0.5 eV
Debye Length ~ 1.4 m

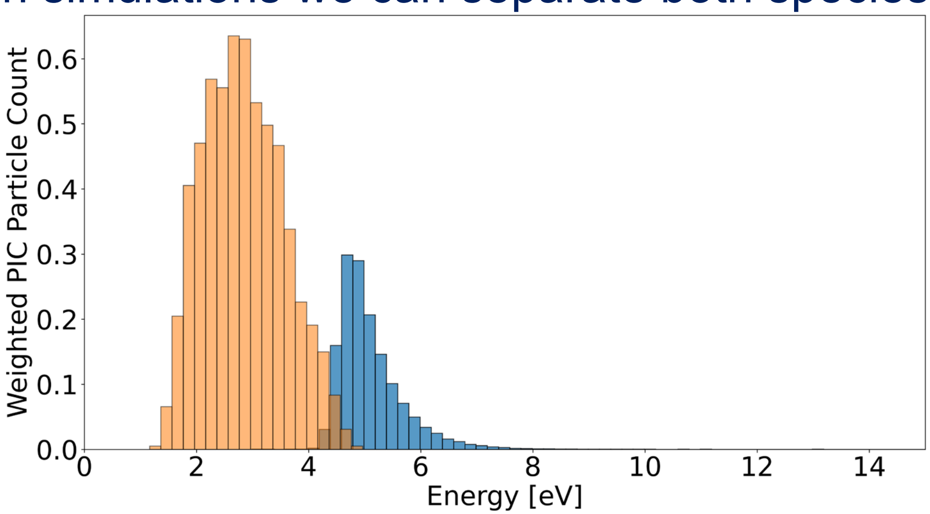
Having the detector in the shade helps, but in a real case it would still be hard to distinguish the two signals

Note: this is idealized, uncertainties in photoelectron spectrum could still mask the signal!

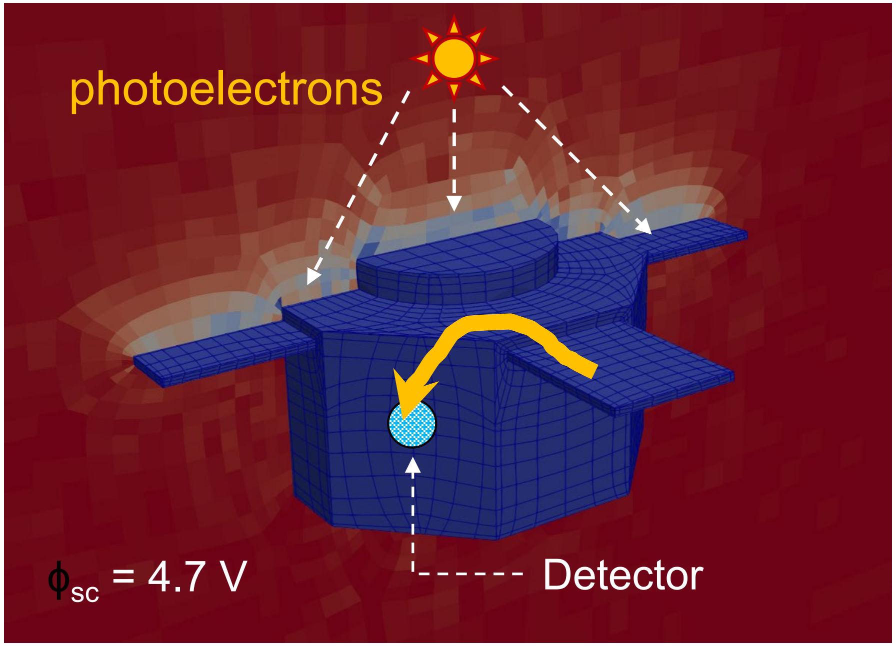
Detector Count: what the detector sees



In simulations we can separate both species



CPIC Simulation

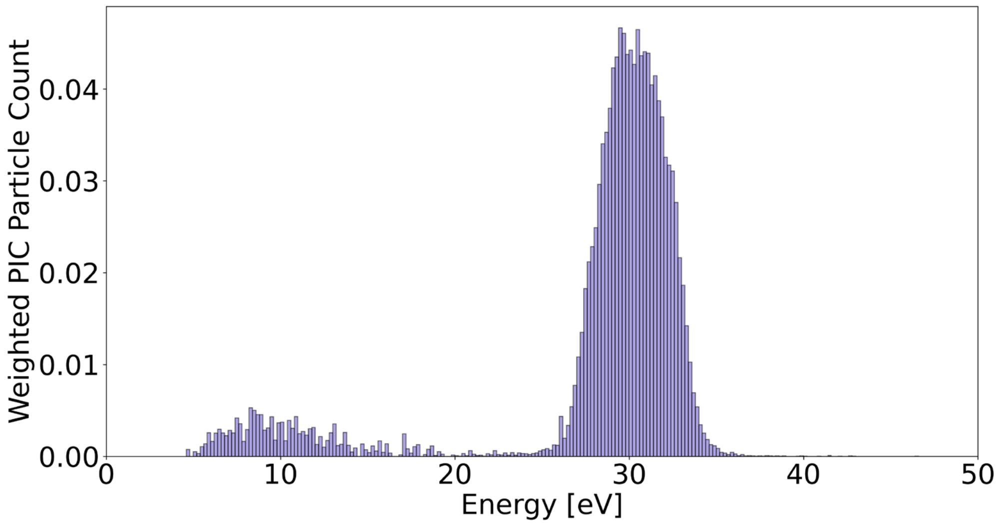


Material: Aluminum (in space)
J_{ph} = 100 μA/m^2 (40 μA/m^2 in the lab)
T_{ph} = 1 eV

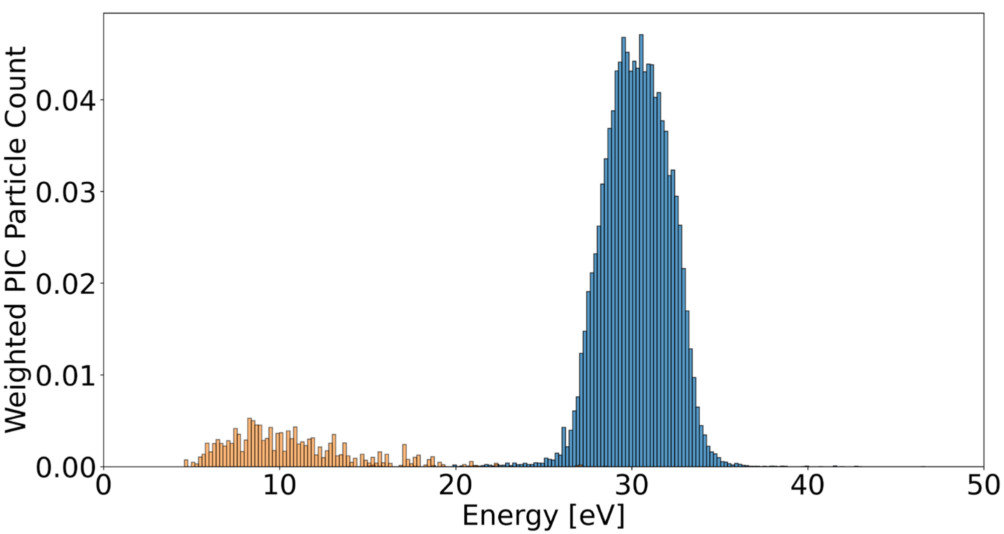
Density = 13 cm^{-3}
Te = 0.5 eV
Debye Length ~ 1.4 m

Here we study a case where we bias the whole spacecraft to +30 V. It works, we can separate the two signals!!!

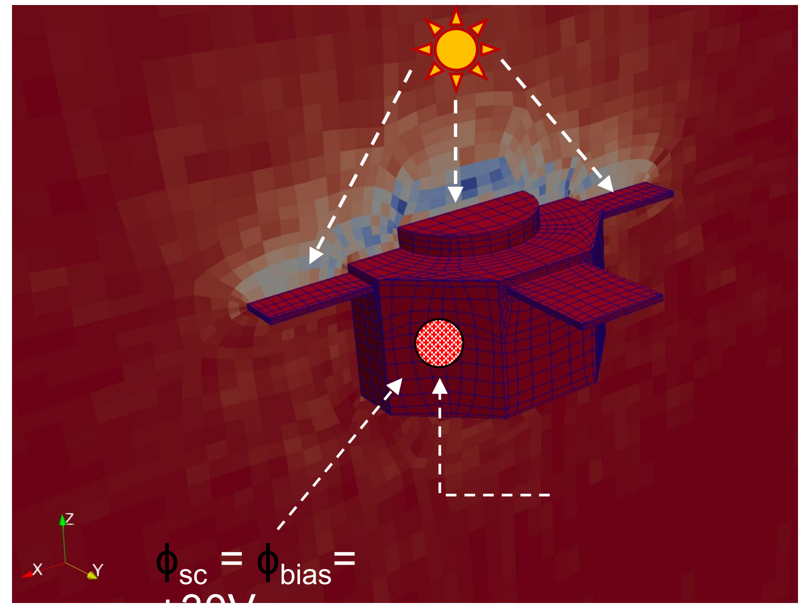
Detector Count: what the detector sees



In simulations we can separate both species



CPIC Simulation



Material: Aluminum (clean)
J_{ph} = 40 μA/m^2 (~100 μA/m^2 aged)
T_{ph} = 2 eV

Density = 13 cm^{-3}
Te = 0.5 eV
Debye Length ~ 1.4 m

Conclusion

- A novel method is being developed and tested at LANL for using HEMTs to power cavities. This allows for a compact electron accelerator that is well suited for space applications.
- In order to mitigate spacecraft charging, a plasma contactor scheme is being developed.
- An electron beam can be used to generate whistler waves in the magnetosphere, which can then mitigate a radiation belt.
- This concept is being tested with the BEAM-PIE experiment.
- Several other important concepts related to accelerators in space are currently being developed at LANL.