Space-Borne Accelerators

Quinn Marksteiner\textsuperscript{1}, Bruce Carlsten\textsuperscript{1}, Patrick Colestock\textsuperscript{2}, Gian Luca Delzanno\textsuperscript{1}, Seth Dorfman\textsuperscript{2}, Leanne Duffy\textsuperscript{1}, Michael Holloway\textsuperscript{1}, John W. Lewellen\textsuperscript{3}, Dinh Nguyen\textsuperscript{3}, Geoffrey D. Reeves\textsuperscript{1}, Vadim Roytershteyn\textsuperscript{2}, Nikolai Yampolsky\textsuperscript{1}, Haoran Xu\textsuperscript{1}

1. Los Alamos National Laboratory
2. Space Science Institute
3. SLAC National Accelerator Laboratory

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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)

Measured and Calculated energy gain/cavity (keV) vs. Cavity Power (W).
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.

![Graph showing S/C Potential & Plasma Potential during 33mA Transient Testing]

- “Beam” emitted, “Beam” emission off
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

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.
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.
“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.
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.
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.
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.
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.
A Simple Electron Beam for Plasma Diagnostics in Space
Detector in sunlight is blinded by photoelectrons

Detector Count: what the detector sees

In simulations we can separate both species

Material: Aluminum (in space)
\( J_{\text{ph}} = 100 \, \mu\text{A/m}^2 \) (40 \( \mu\text{A/m}^2 \) in the lab)
\( T_{\text{ph}} = 1 \, \text{eV} \)

Density = 13 cm\(^{-3}\)
\( T_e = 0.5 \, \text{eV} \)
Debye Length \( \sim 1.4 \, \text{m} \)
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.

Material: Aluminum (in space)

- $J_{ph} = 100 \mu A/m^2$ (40 $\mu A/m^2$ 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

Material: Aluminum (clean)

\[ J_{ph} = 40 \mu A/m^2 (\sim 100 \mu A/m^2 \text{ aged}) \]

\[ T_{ph} = 2 \text{ eV} \]

Density = 13 cm\(^{-3}\)

\[ T_e = 0.5 \text{ eV} \]

Debye Length \(~\sim 1.4 \text{ m}~\)
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.