Applications of Compact Accelerators in Space for National Security

Bruce Carlsten
Los Alamos National Laboratory

May 4, 2018

LA-UR-17-28782

Acknowledgements

- **I learned about the space science material in this talk largely from:**
  - Geoff Reeves, Gian-Luca Delzanno, Eric Dors, Greg Cunningham, Mike Henderson, Patrick Colestock, Chris Jeffery

- **Accelerator-in-space technology development team:**
  - Dinh Nguyen, John Lewellen, Mike Holloway (LANL)
  - Emilio Nanni, Jeff Neilson, Sami Tantawi (SLAC)

- **Slides were borrowed from:**
  - Gian-Luca Delzanno, Eric Dors, Geoff Reeves, Dinh Nguyen, and John Lewellen

Accelerators May Also Have Important Applications In Space

- **Accelerators are important tools for discovery science**
  - High-energy and nuclear physics
  - Light sources for materials research
- **Accelerators have important medical applications**
  - Cancer treatment
  - Isotope production
- **Accelerators have important industrial applications**
  - Food sterilization, waste processing
  - Industrial processing
- **Accelerators might have important applications in space**
  - We will talk about one specific application (radiation belt remediation)

Outline

- **What is Radiation Belt Remediation (RBR)?**
  - Enhanced electron flux in the radiation belts can happen ***naturally*** or be induced by a ***high-altitude nuclear detonation***
- **Why do we care about RBR?**
  - Enhanced electron flux can lead to a rapid degradation/loss of satellites in low-Earth orbit (LEO)
- **How do we fix this?**
  - Driving VLF waves in the ionosphere can drive electrons out of the radiation belt (VLF=Very Low Frequency, 3-30 kHz)
  - VLF waves can be generated by antennas and electron beams

Radiation Belt Remediation is a "no-kidding" national security mission

The Threat Has Been Well Known For Decades

2001 DTRA study "High Altitude Nuclear Detonations (HAND) Against Low Earth Orbit Satellites (HALEOS)"

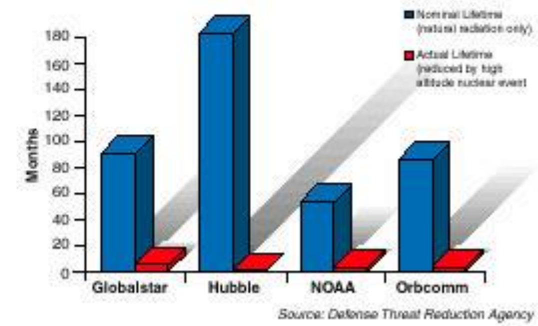
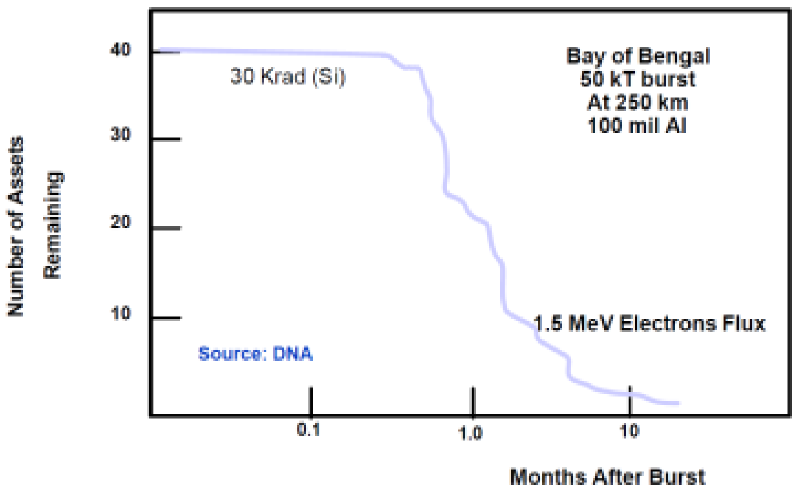


Figure 13: Impact of a nuclear detonation on the lifetime of satellities

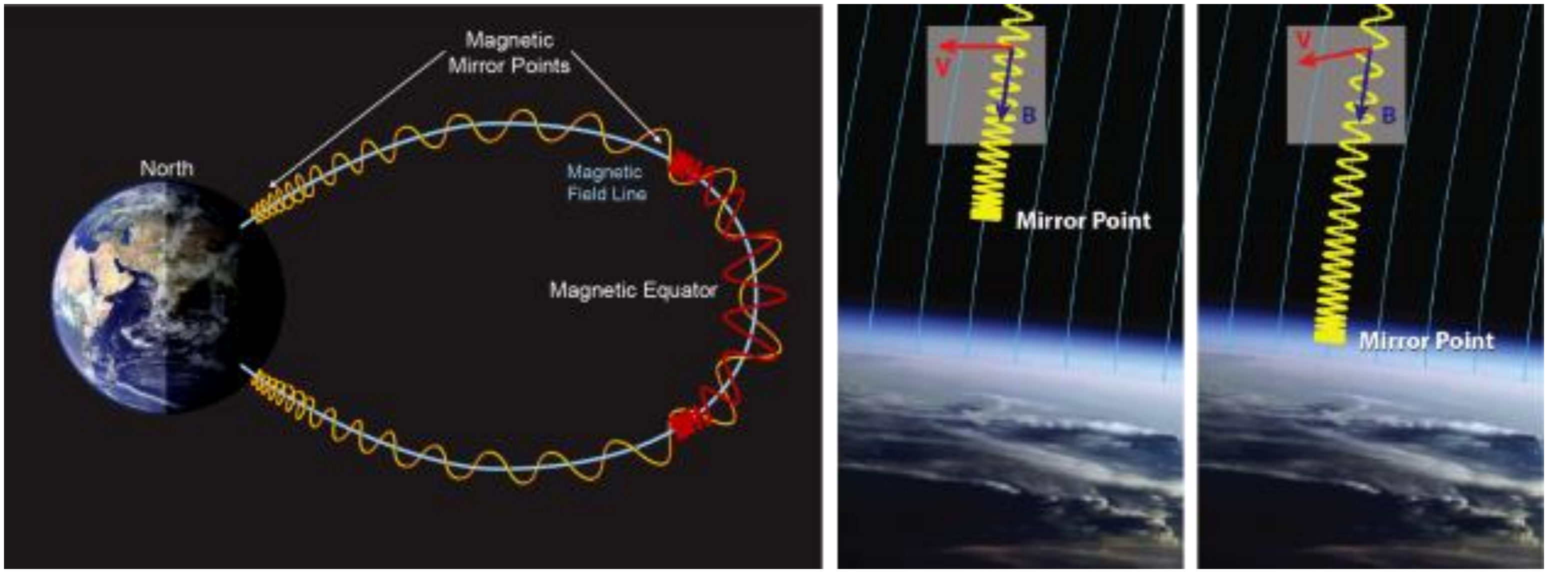
2001 Rumsfeld Space Commission Report



2002 Tether Panel HAARP Study (recommendation: *reduce MeV electron lifetime to a few days)*

Although this problem has been recognized for a long time, a solution has yet to be implemented

The Radiation Belts Trap Charged Particles



Energetic electrons are trapped in the radiation belts by the Earth's magnetic field lines and are mostly mirrored above the atmosphere due to the electrons' transverse energy because the magnetic field intensifies near the Earth; the red trajectory corresponds to a larger electron transverse energy than the gold trajectory.

Co-propagating VLF waves can modify the electrons' transverse energy by stochastic multiple scatterings; these scatterings sometimes reduces the transverse energy until the electrons are mirrored low enough they interact with the Earth's atmosphere and can precipitate as aurora.

Space Weather From The Sun Can Enhance The Radiation Belt Flux

- **One of the biggest geomagnetic storms occurred in Sept 1859**
  - Known as Carrington event
  - Solar coronal mass ejection hit the Earth's magnetosphere (17 hours to reach the Earth)
  - A similar sized CME occurred in 2012 but missed the Earth
- **There were significant effects from the Carrington event**
  - Aurora was seen in the Caribbean and as close to the equator as Colombia
  - Telegraph systems failed and some caught on fire
- **A CME will load the radiation belts with electrons**
  - Estimates of damage from a Carrington-sized CME today are $1T to $2T
  - NASA estimates $30B-$70B of satellite damage from a Carrington-sized event

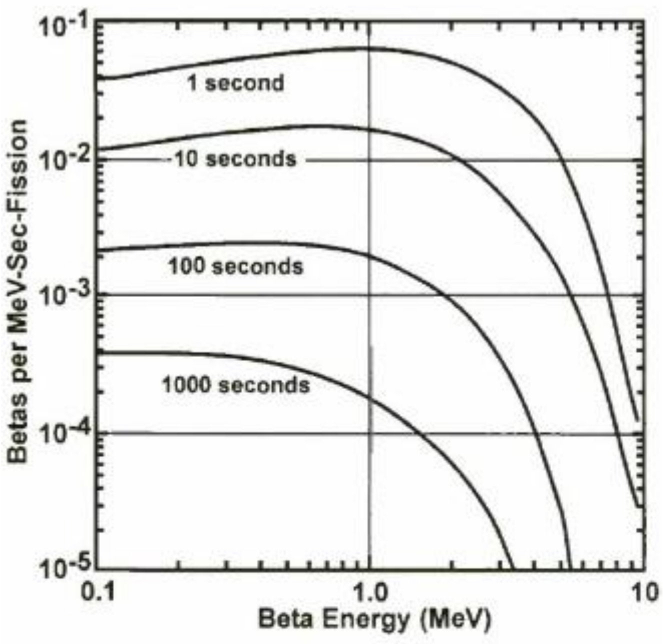
Delayed Beta Decay Radiation From A Nuclear Explosion Also Enhances The Radiation Belt Flux

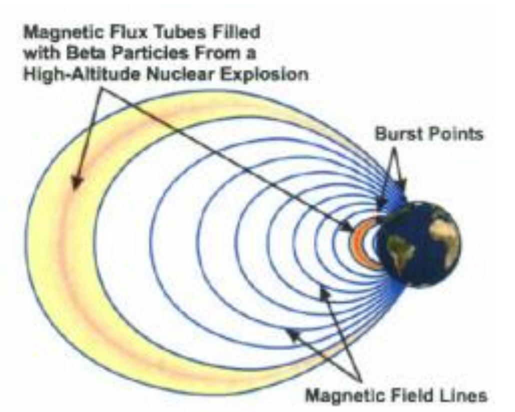
Electrons are mostly emitted well after a nuclear detonation

Fission debris emits approximately 6 e^- per fission event from beta decay (1 kT yields about 9×10^{23} e^- total).

Electrons with small enough pitch angles relative to the ambient B field and emitted downward collide and ionize the air below 100 km; air fluorescence forms aurora ("beta tube")

The higher the detonation, the greater the trapped electron fraction. A detonation at a lower latitude will produce more trapped electrons than at a higher latitude.





Text and figures from DTRA Technical Report 201001029076 (Aug 2010) (Approved for unlimited distribution)

Trapped MeV Electrons Can Damage LEO satellites

Electrons can cause ionization effects in electronics (i.e., forms electron-hole pairs in transistors' gate insulation layers, gate biasing, etc)

Electrons also cause internal charging of dielectric surfaces

Types of single-event effects (SEE):

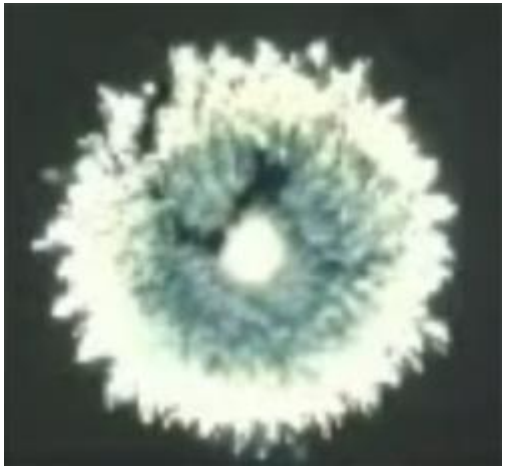
- **Single-event transient**
- **Single-event upset (as many as the rest put together)**
- **Single-event latchup**
- **Single-event snapback**
- **Single-event induced burnout**
- **Singe-event gate rupture**

~ 1 US satellite lost/year from natural flux enhancement to 10^8 $e^-/cm^2/sec$

Damage from energetic particles is a very active research area, including mitigation techniques

LEO Satellites Were Damaged By Early Atmospheric Tests

Starfish Prime (part of Operation Fishbowl) - July 8, 1962, 400-km altitude, launched from Johnston Island 1200 miles SW of Hawaii



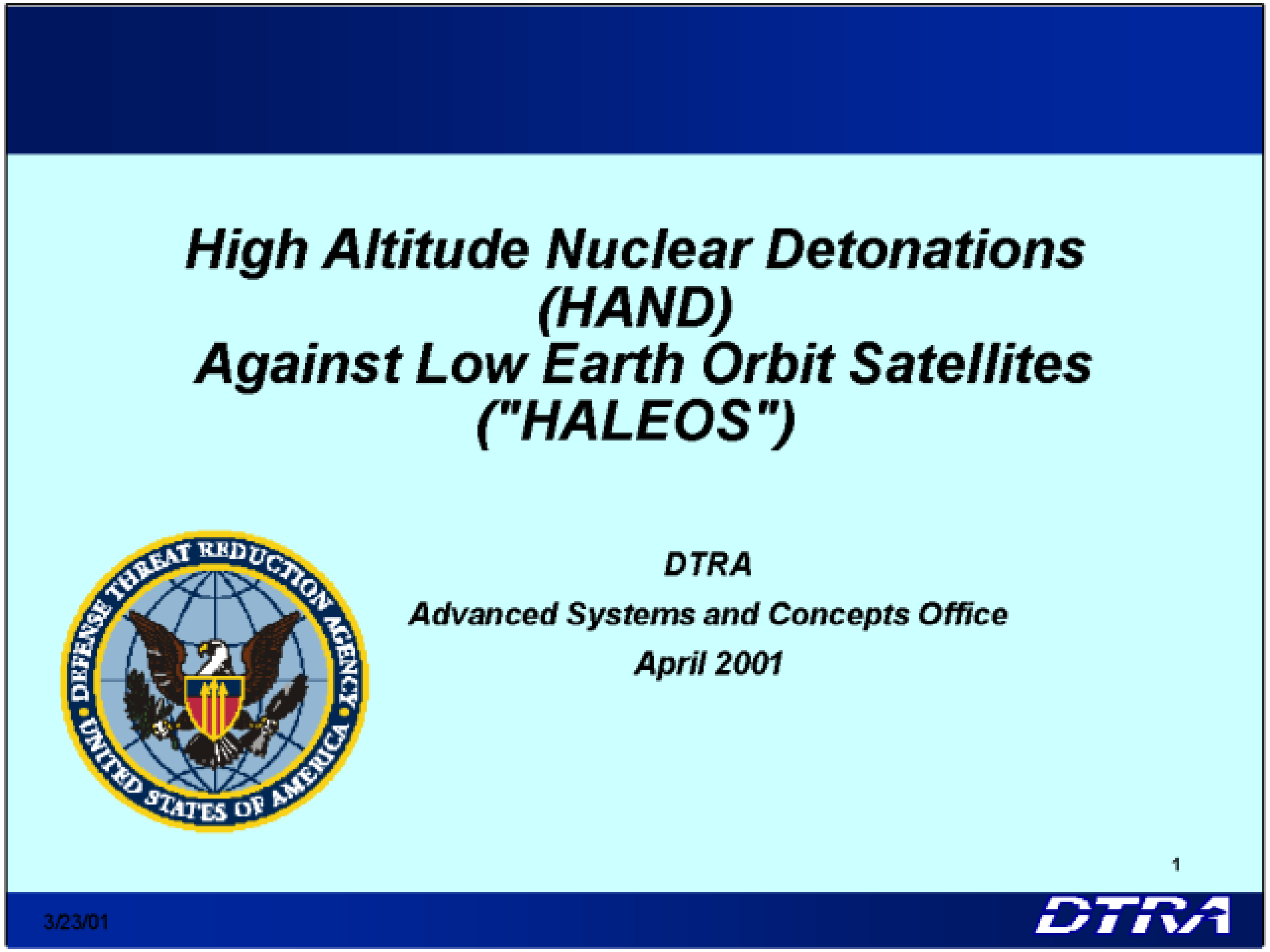
Expanding fireball

Debris fireball plus aurora as electron along field lines enter atmosphere

Starfish detonation created a belt of ~ MeV electrons that lasted for >5 years (~60 rad/day for 4 months)

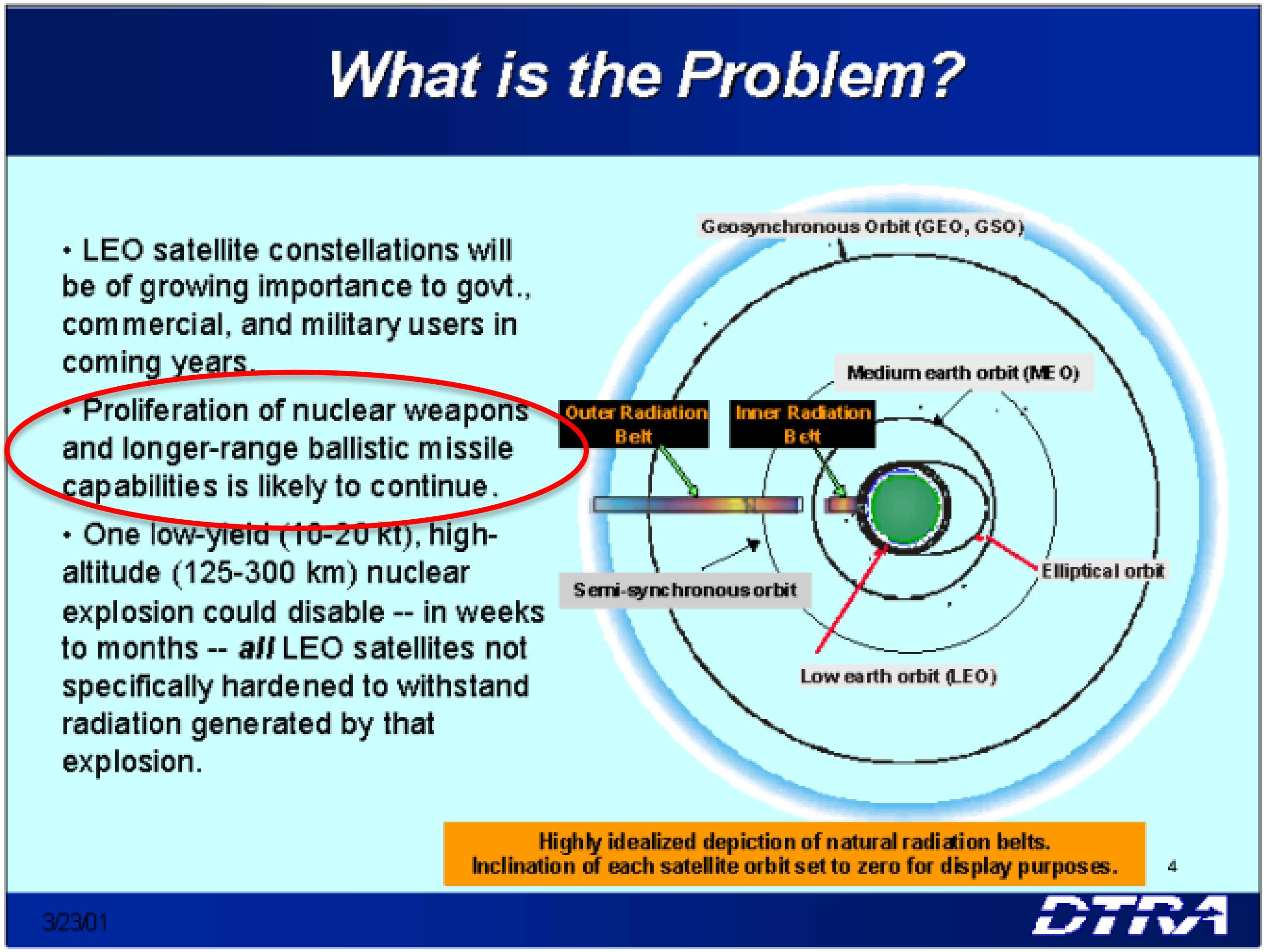
Starfish detonation damaged or destroyed 7 satellites within 7 months (1/3 of all satellites in LEO), including Telstar (first commercial communications satellite), Ariel-1 (the UK's first satellite), and a Soviet satellite (Transit 4B, Traac, Ariel damaged by solar cell degradation, Telstar by command decoder failure by Nov, 1962)

DTRA's HELEOS Study (2001) Quantifies Threat



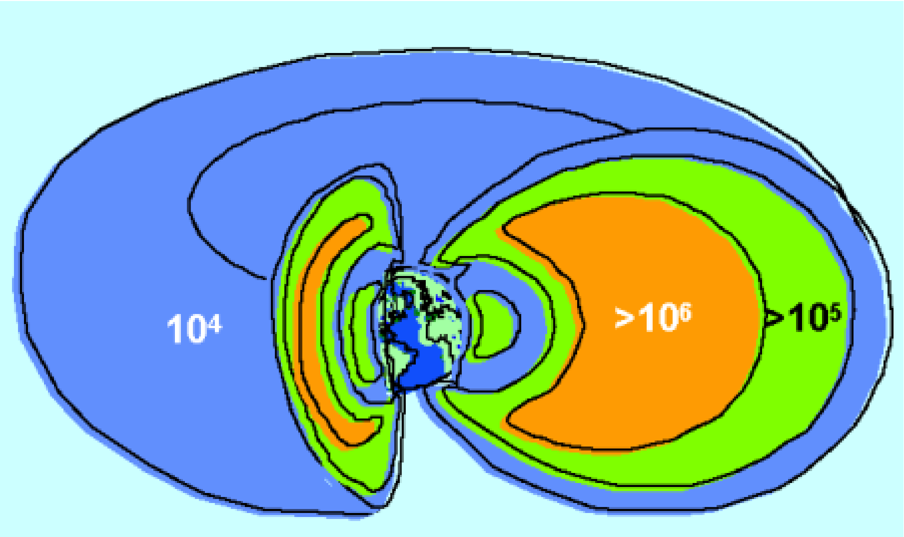
Slides from DTRA HELEOS Program Summary (April 2001)
(Approved for unlimited distribution)

Satellites In LEO Are Vulnerable To Enhanced Electron Flux In The Inner Radiation Belt

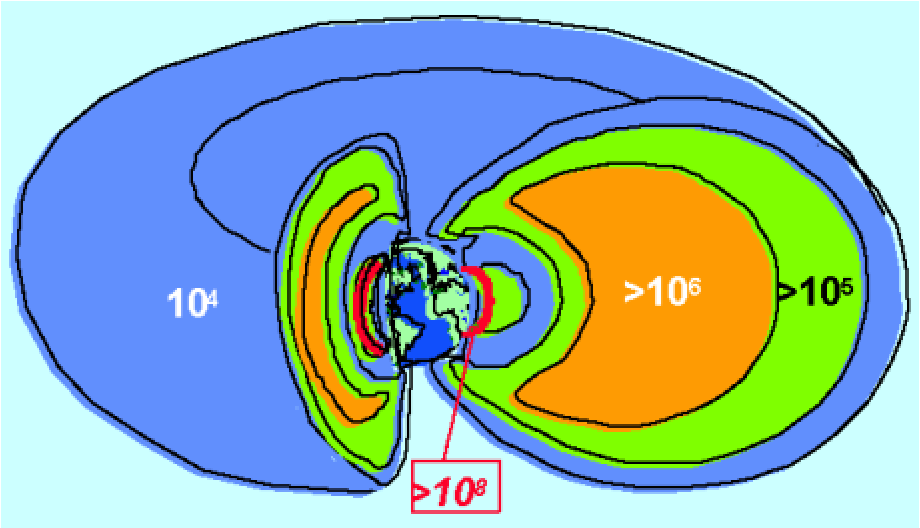


Radiation belts also called Van Allen belts. Inner belt can affect LEO (150-1500 km) satellites. The "slot" region is between the inner and outer belts and is normally empty.

The > 1 MeV Electron Flux Level Will Drastically Increase At LEO Altitudes After A Nuclear Detonation



Typical background radiation flux levels ($e^-/cm^2/sec$)



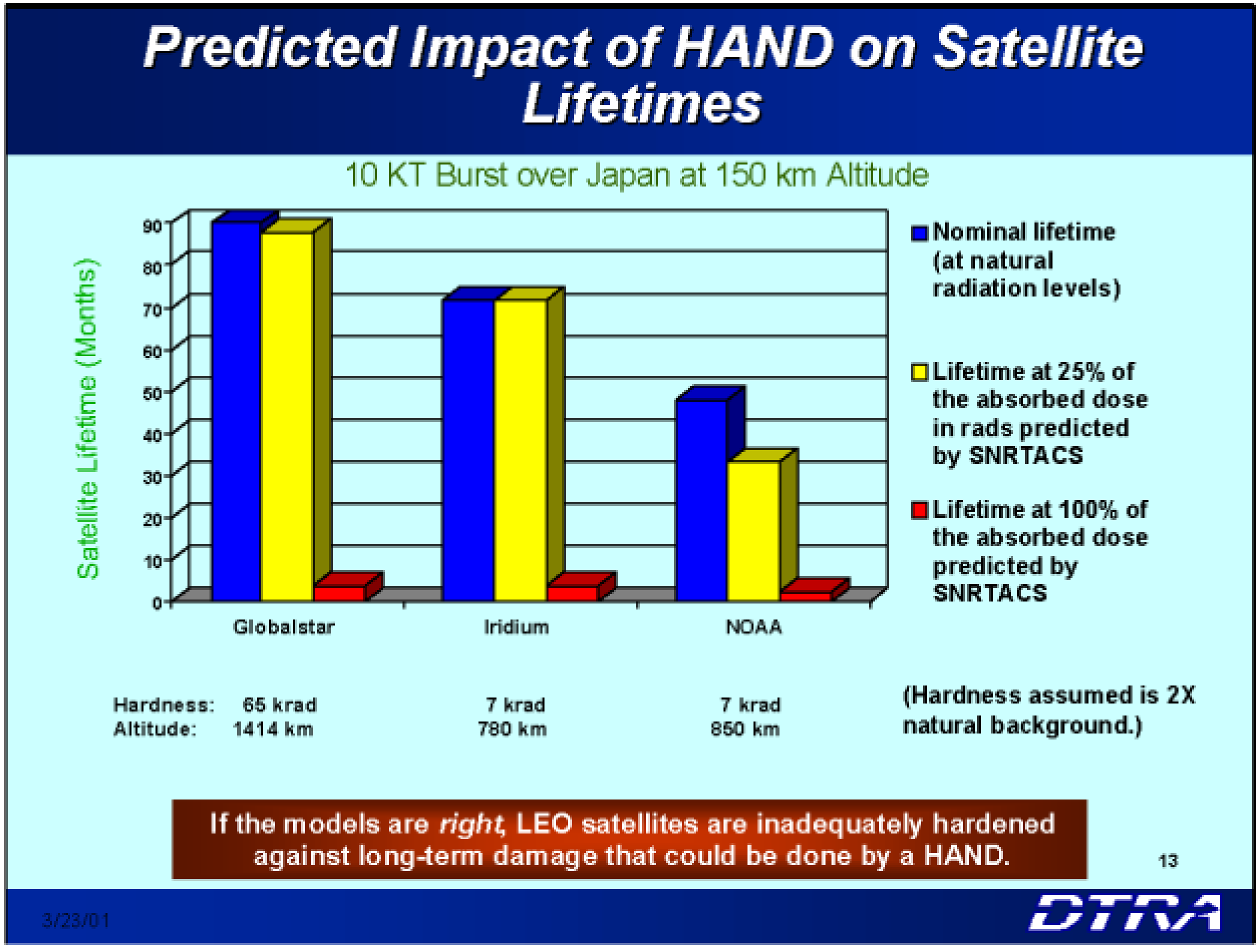
Expected flux levels one day after burst over Korea

Primary source of natural total dose is from protons and electrons trapped in the belts.

HAND raises peak radiation levels in LEO by 3-4 orders of magnitude. Peak flux will remain for 6 months to 2 years at lower latitudes and higher orbital altitudes.

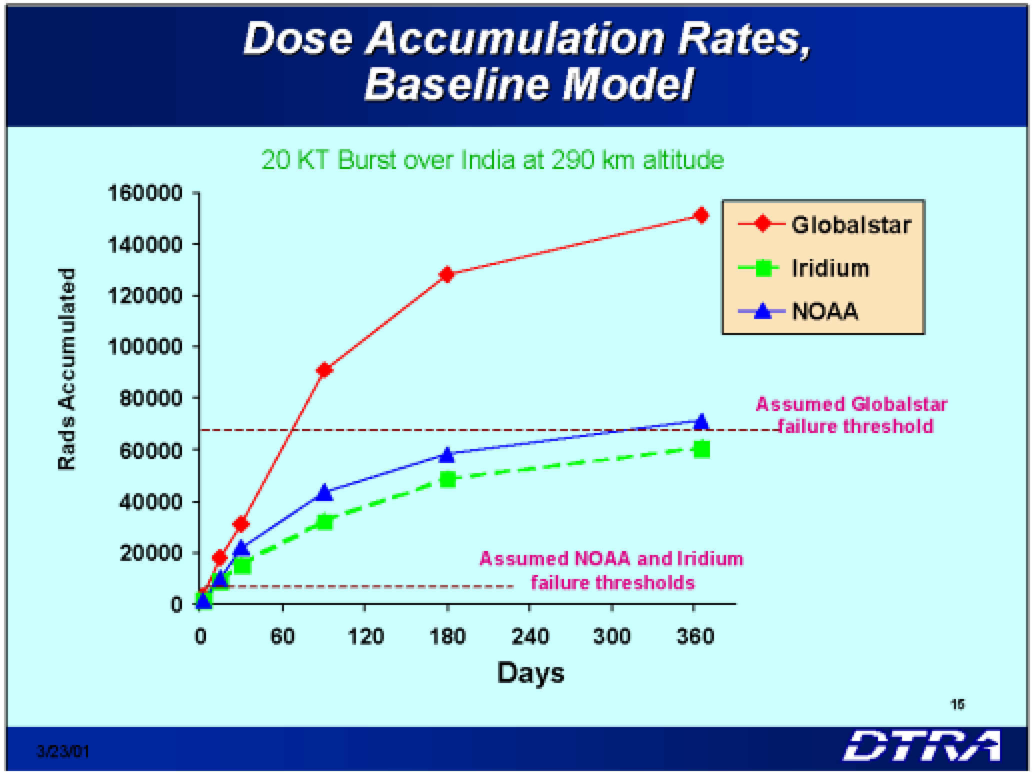
Slot area will also fill in (e.g., high solar activity fills in for weeks to months)

A 10-kT Detonation At 150 km And Above Will Greatly Decrease Satellite Lifetimes



Typical low LEO satellites (~800 km) are designed to tolerate ~ 5 krads and high LEO satellites (~ 1400 km) are designed to tolerate ~ 50 krads. For 10 kT at 150 km, enhanced flux leads to about 2.3 krad/month at 800 km.

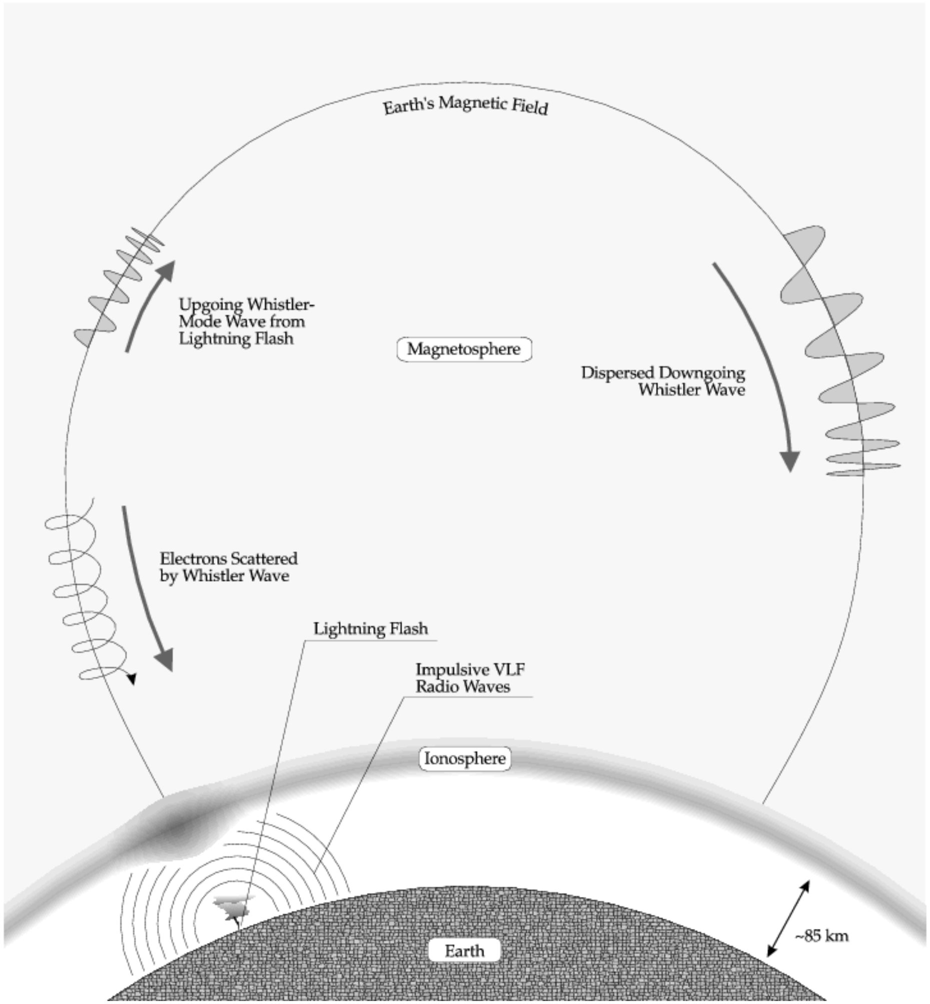
Satellites In Low LEO Will Fail Within A Month And Cannot Be Replaced For Over One Year



Replacement satellites at low LEO would see enhanced fluxes for at least a year after detonation. Would need to wait 18 to 24 months.

Example: Telstar 1 was launched a day after Starfish Prime

What Is A VLF Wave And How Does It Help?



There are several types of VLF modes (whistlers, low-hybrid waves, Bernstein modes, etc).

These are specific solutions to the wave equation in a plasma with a magnetic field (*anisotropic media*)

Whistler modes have the most resonant interaction with reflecting electrons

Whistler modes can be generated by lightning strikes and have a characteristic pitch change (from slower velocity of lower frequencies in the ionosphere)

How Much VLF Power Is Needed?

- **All three steps in the process have inefficiencies:**
  - Wave generation efficiency (complicated near-field effects and losses)
  - Wave propagation efficiency (complicated medium leads to mode conversion and reflections)
  - Wave-particle interaction efficiency (not all interactions help, whistler versus X mode)
- **Total power depends on efficiency of wave-particle interaction**
  - Estimates lead to needing B~30 pT within belt, determines power/number of satellites
- **Need ~ MW of total VLF power to reduce accelerated degradation of LEO satellites to an acceptable level**
- **Probably need ~ 10 MW of power generating VLF waves**

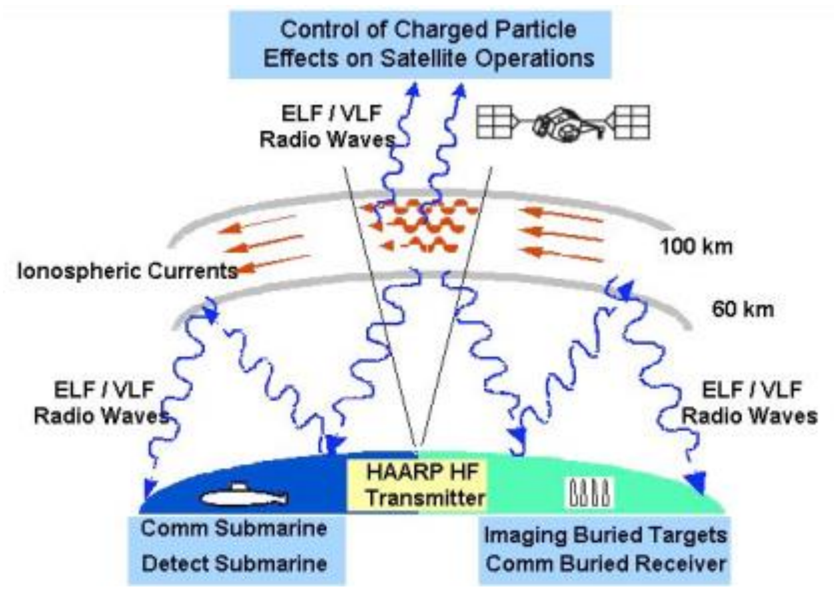
How Do We Generate VLF Modes?

Three approaches to generating VLF waves have been considered:

- **Antenna on Earth**
- **Antenna in space**
- **Electron beam in space**

Antenna On Ground - HAARP

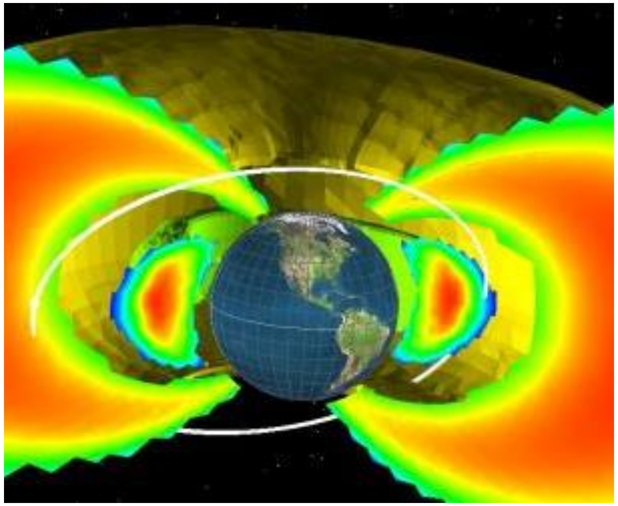
- **HAARP (High Frequency Active Auroral Research Program) is a large ionospheric research facility in central Alaska**
- **Was joint project of AFRL and ONR, now University of Alaska**
- **Powerful, flexible source of ELF/VLF signals over a very wide frequency range (0.1 Hz – 40 kHz)**
- **Up to 3.6 MW at 2.8-10 MHz, generated VLF by modulating the ionosphere with the HF**
- **Limited by coupling efficiency plus about 20 dB loss from whistler mode to lower hybrid mode**



Antenna In Space - DSX

- **DSX (Demonstrations and Science Experiment) satellite has an 80-m long dipole antenna**
- **Air Force mission launching this summer**
- **Orbit is 6000 km by 12000 km**
- **Three experiments including a wave-particle interaction experiment:**
  - Determine efficiency of injecting VLF into space plasmas *in situ*
  - Determine distribution of natural & man-made ELF-VLF waves
  - Characterize and quantify wave-particle interactions

  DSX will conduct both generation and propagation measurements with seven possible collaboration satellites to receive VLF waves

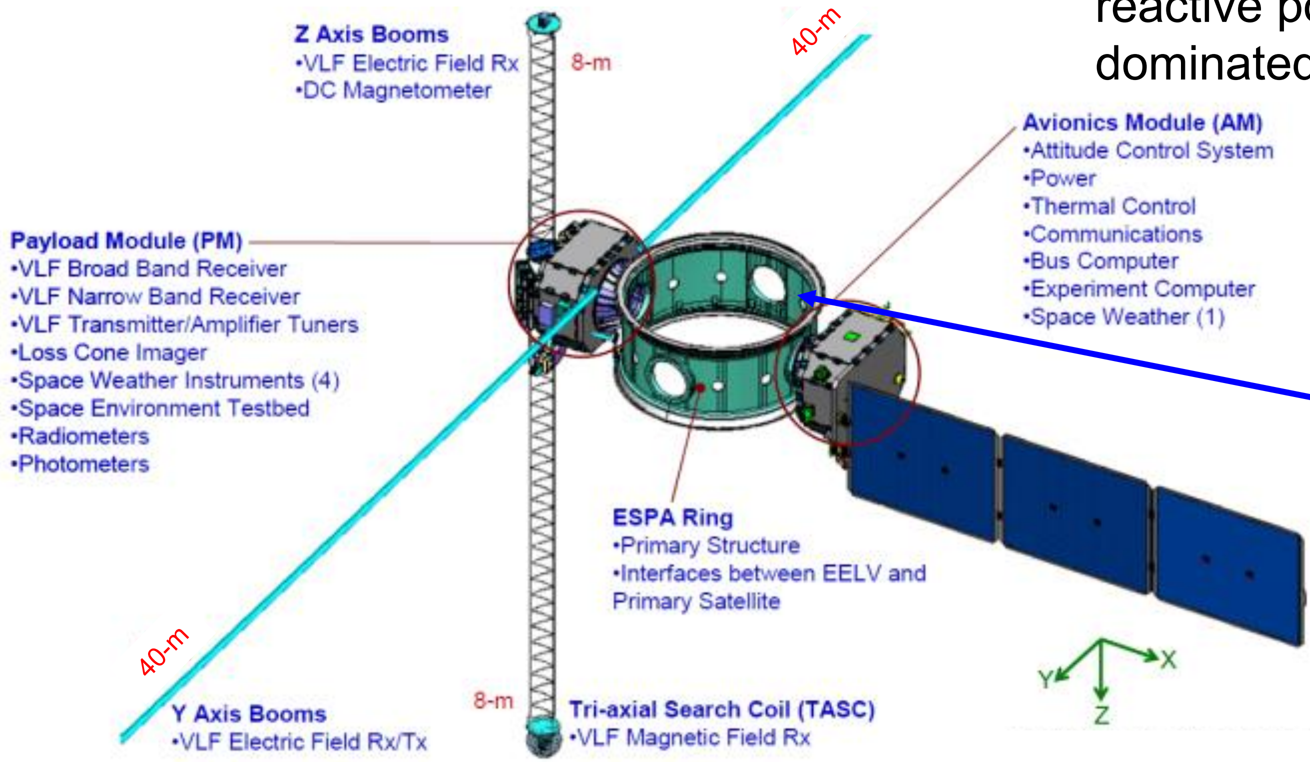


DSX orbit with radiation belts

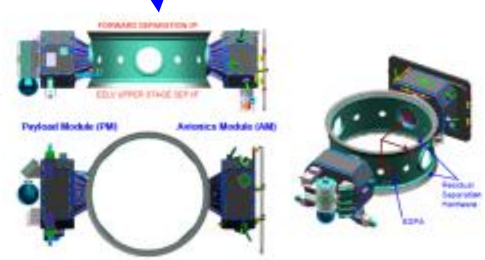
- **LANL is funded to partner with AFRL to predict antenna performance**

Antenna In Space - DSX

Antenna emission is complicated
– electrically very small, lots of reactive power, losses, and dominated by electrostatic modes



ESPA Ring
- Interfaces between EELV & satellite



Stowed configuration

Electron Beam In Space

Modeling and theory indicates there may be highly efficient coupling between an electron beam and the X-mode

- ***How well does the X-mode interact with the energetic electrons?***

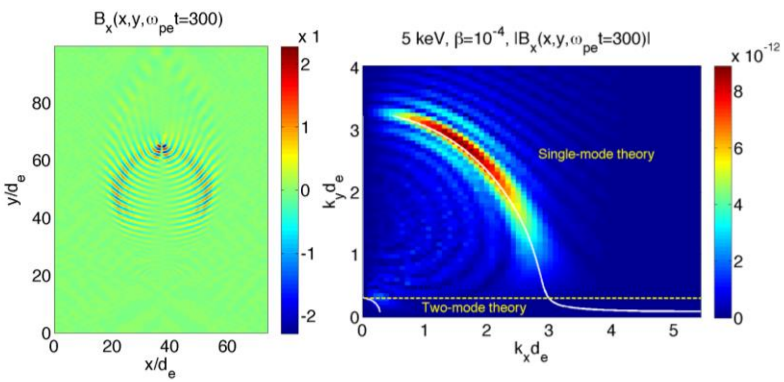
Funded e-beam/plasma interaction experiments will close science/technology gaps:

- **NSF - MeV beam at UCLA Large Area Plasma Device (2018 through 2020)**
- **NASA – BeamPIE (Low Cost Ascent to Space, launch in 2020)**

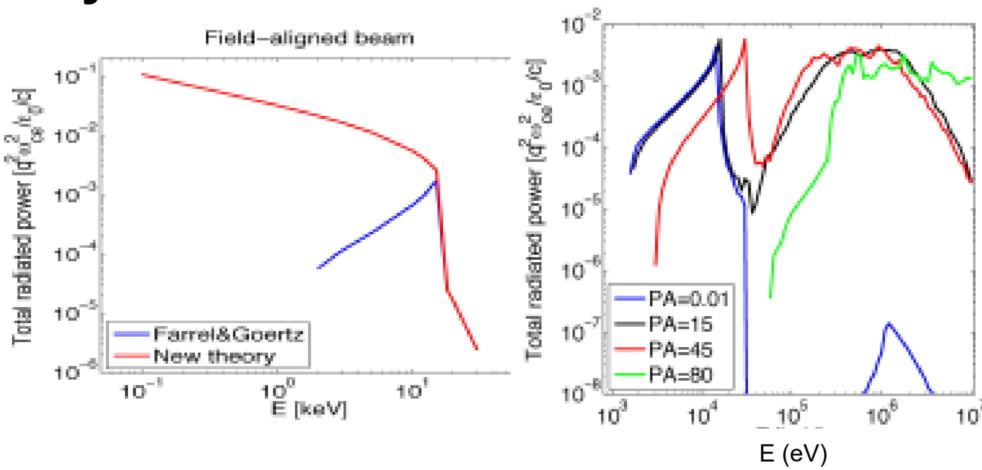
Proposed CONNEX MidEx NASA experiment will further advance accelerator-in-space technology

Electron Beam In Space - Theory

- **An electron beam may be able to efficiently drive VLF modes, contrary to conventional theory**

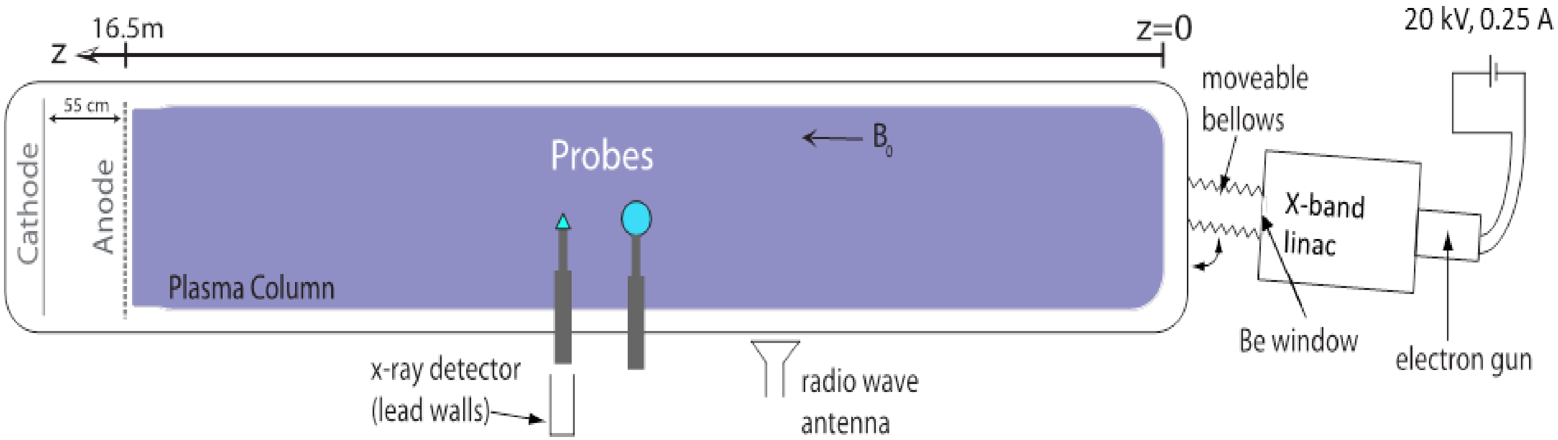


SPS simulations: Snapshot of the magnetic field due to a bunch of charge traveling in the *y* direction (5 keV); the bunch is at leading edge of the radiated field. Corresponding wavenumber plot with theoretical mode solutions shown by the white lines. The radiated power largely corresponds with a single X mode



The analytic efficiency of generated VLF power for the conventional theory (blue line) and new theory (red line) for a zero pitch angle; and the analytic efficiency of generated VLF power for the conventional theory as a function of pitch angle (PA). Additional coupling in the single-mode regime is orders of magnitude higher below 10 keV. Relativistic electron beams do well at large pitch angles –is if there is an equivalent increase in efficiency due to a single-mode interaction for relativistic beams also.

Electron Beam In Space – NSF Experiment



7 degree injection angle translates to ~ 40 degree pitch angle in LAPD (due to conservation of first adiabatic invariant)

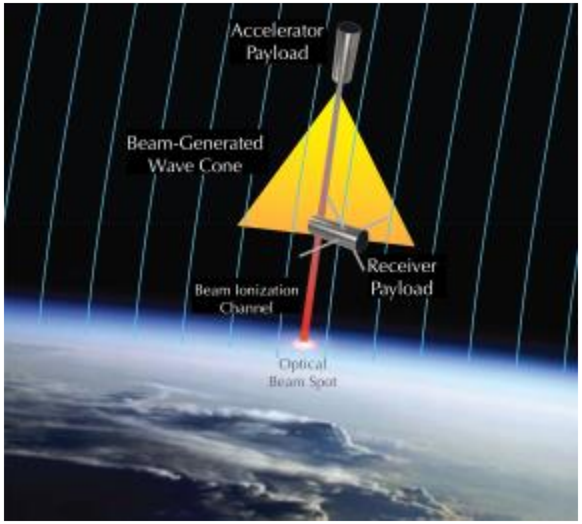
We are grateful for loan of a 1-MeV X-band linac from our Lancaster University and STFC collaborators

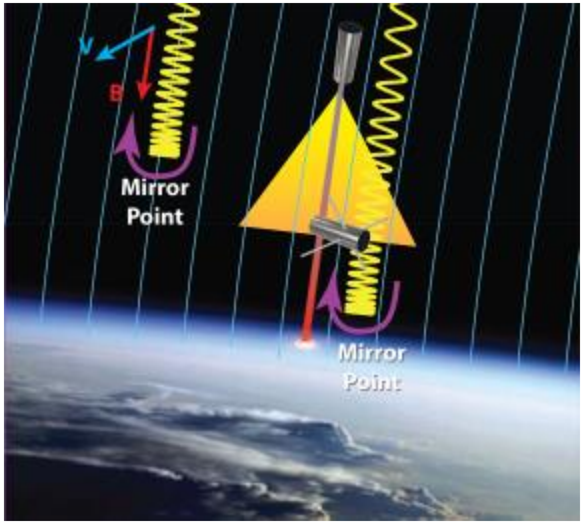
Fully diagnosed with scaled (plasma) physics

Can vary plasma density (10^{12}/cm^3 and 5 eV are typical)

Experiment will illuminate how modulated, finite-sized electron beams propagate through a plasma and what kind of modes are excited (especially whistler and X- modes)

Electron Beam In Space – NASA Experiment (BeamPIE)

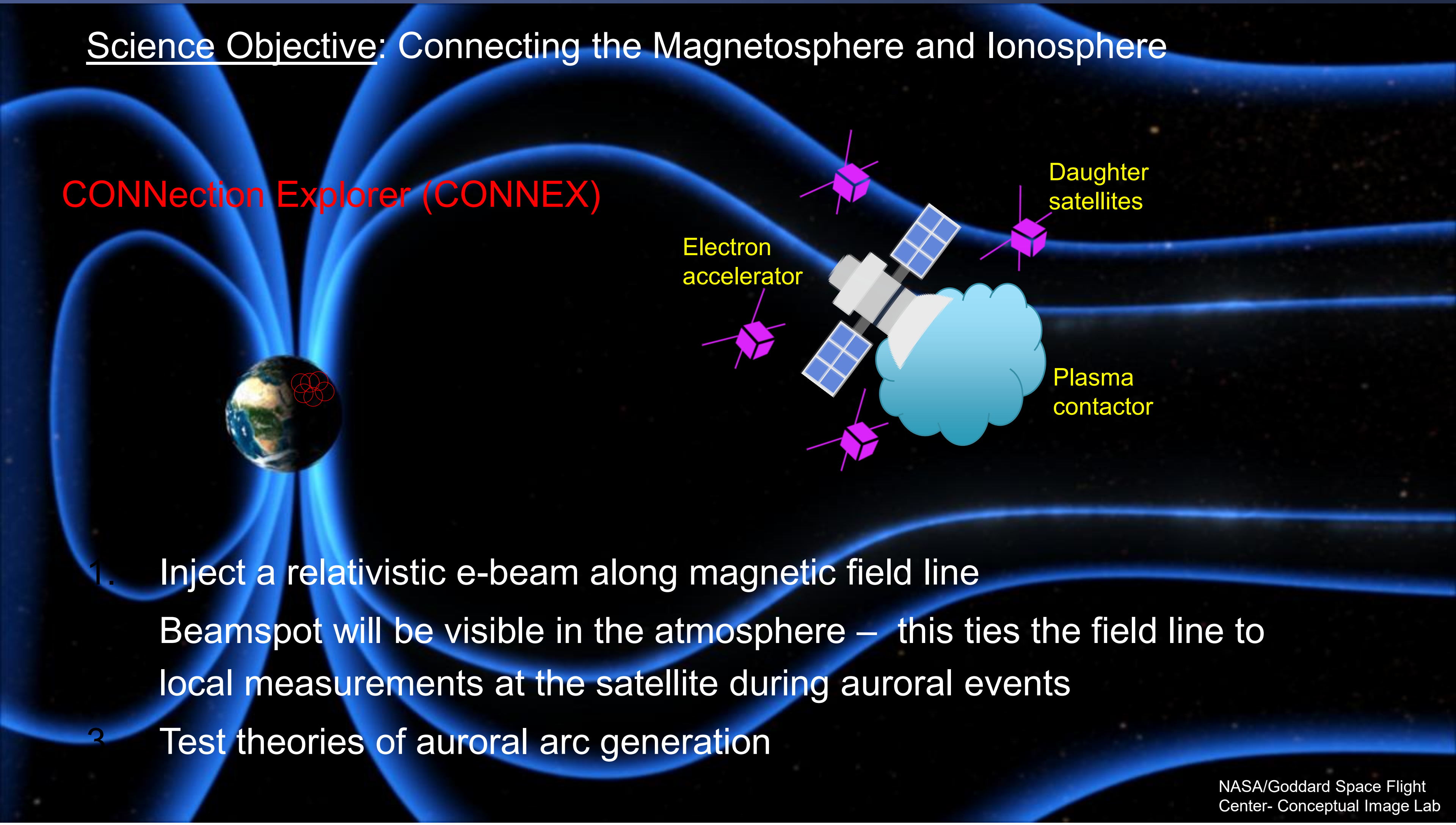




The Accelerator Payload directs the electron beam down the magnetic field line. The beam-generated waves spread out in a cone of wave power. The waves are detected and characterized by the Receiver Payload flying at a somewhat lower altitude. In the region where waves are present they resonantly pitch angle scatter ambient ionospheric electrons which lowers their magnetic mirror points and increases the flux of upward going electrons detected at the Receiver Payload.

Funded and will launch in 2020; nominally 60 keV C-band RF accelerator

Electron Beam In Space – Proposed NASA Experiment



Science Objective: Connecting the Magnetosphere and Ionosphere

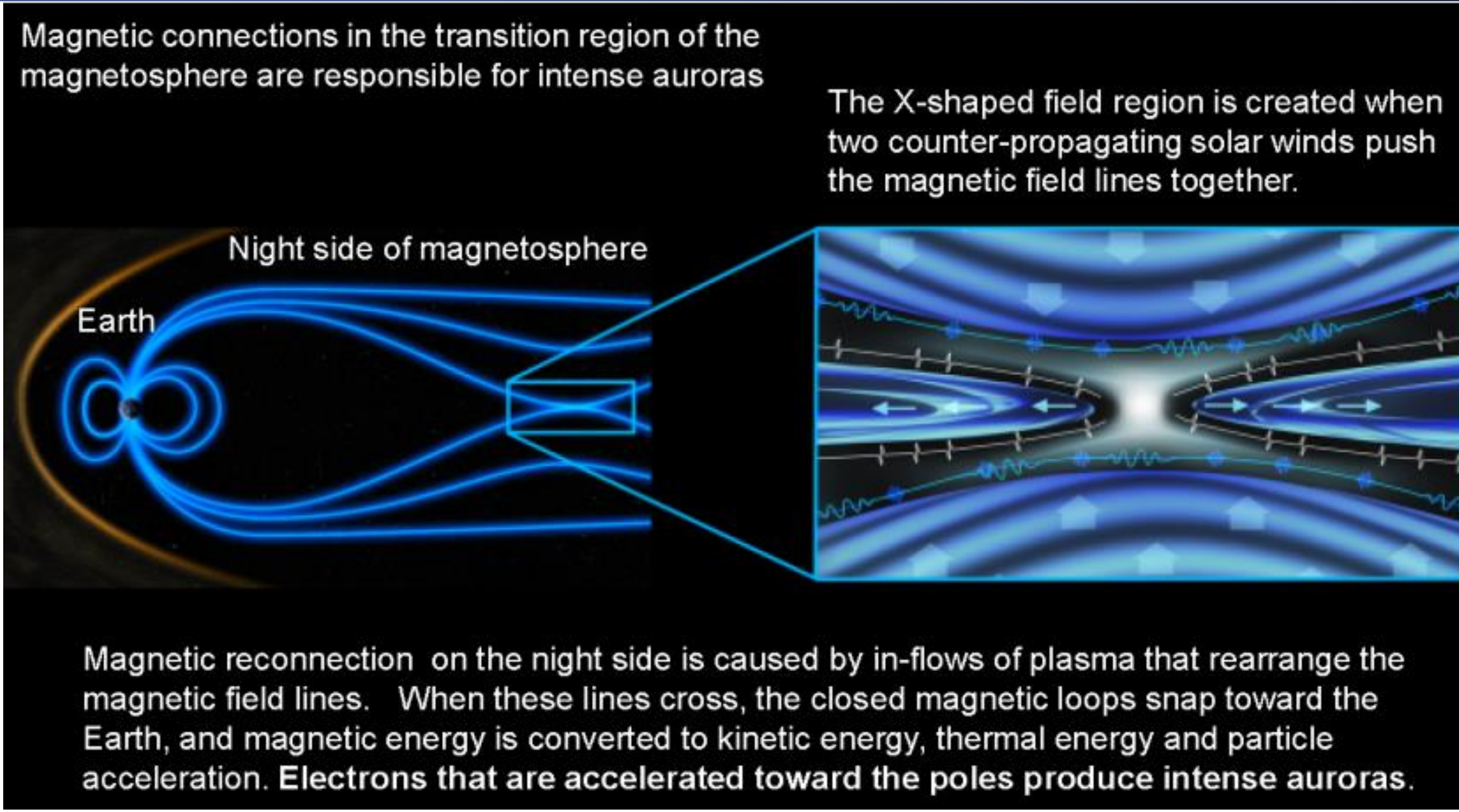
1. Inject a relativistic e-beam along magnetic field line

   Beamspot will be visible in the atmosphere – this ties the field line to local measurements at the satellite during auroral events

3. Test theories of auroral arc generation

Science experiment supports the technology development needed for the RBR mission

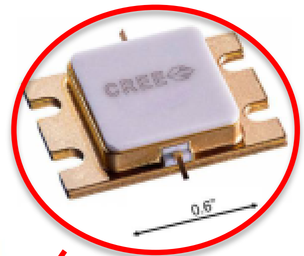
Electron Beam In Space – Proposed NASA Experiment



CONNEX questions: Why do auroras occur? How do the solar wind-magnetic field interact in the MS? How accurately can ionospheric and aurora observations predict the state of the MS?

We Believe 5-GHz Cavities Driven By Solid-State HEMTs Are A Practical Accelerator Technology For Space

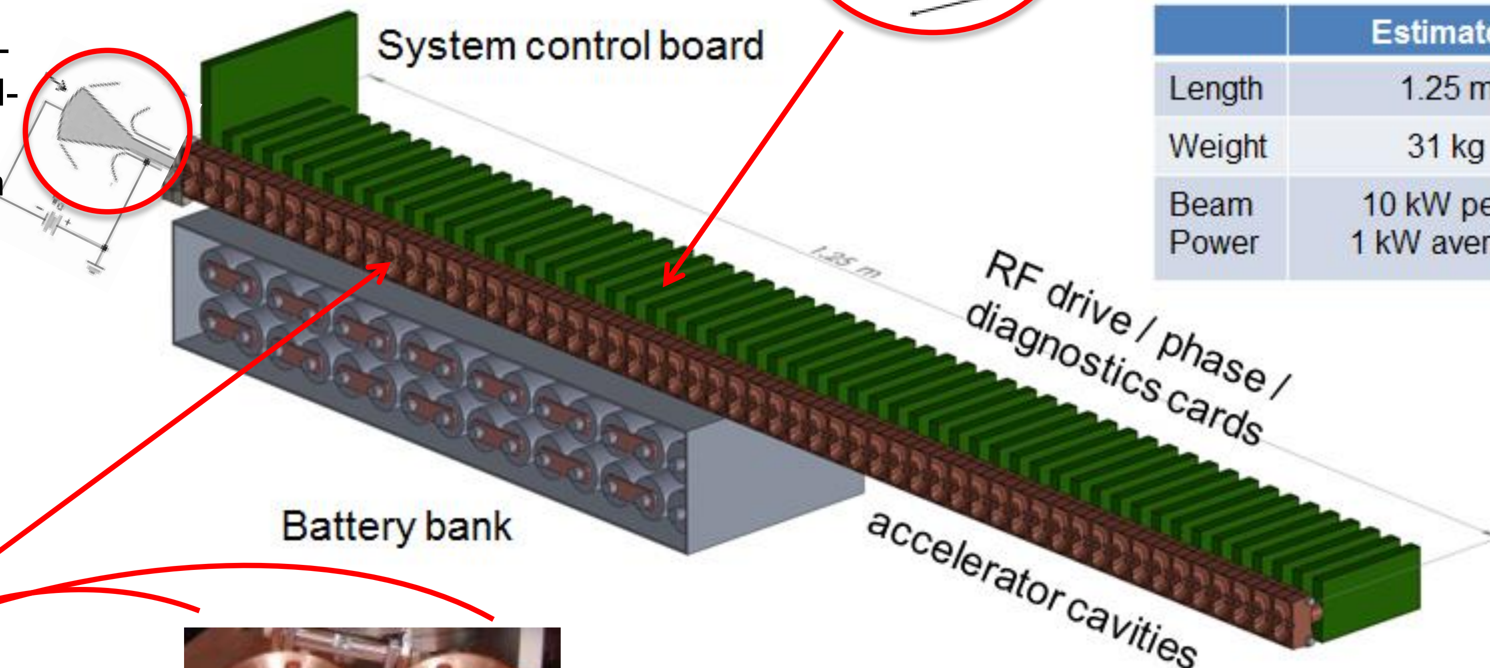
SLAC/LANL partnership developing accelerator-in-space technology (leads: Nguyen, Lewellen, Neilson)



50-V, 500-W, 50%-efficient HEMTs currently under radiation testing by LANL/Goddard

	Estimates
Length	1.25 m
Weight	31 kg
Beam Power	10 kW peak 1 kW average

Standard space-qualified technol-ogy for 10-kV DC electron gun



Summary

We are actively taking steps to develop an optimized RBR strategy

1. **Understand VLF wave generation**
   - Antenna and electron beam generation (ongoing)
2. **Understand VLF wave propagation/conversion**
   - Non-ideal effects will stimulate loss of power in desired VLF modes (ongoing)
3. **Understand wave-particle interactions**
   - This understanding may be already mature enough
4. **Advance the technology components**
   - Antenna will be in space this summer and we will be flying the first HEMT-driven accelerator in 2 years