Proton Radiation Belt Remediation (PRBR)

Presentation to Review Committee

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Removing Energetic Protons

- Removal is accomplished in the same way as HANE electron remediation: increase the pitch angle diffusion rate so that protons precipitate into the atmosphere
- Pitch angle diffusion rate is increased by producing waves with the proper wavelength to resonate with energetic protons
  - ULF waves in the 1 – 10 Hz band
- Unlike HANE electrons, inner belt protons are produced by very slow processes so remediation can be done periodically (e.g. for 1-2 years every 10 years) as well as monitored
- Remediation of natural inner belt protons would have an immediate operational impact
- Environmental concerns

Proton Effects on Commercial Electronics

- Higher LEO Orbits: commercial electronics are regularly affected by proton upsets
- Lower LEO Orbits: affected during SAA transits and at high latitudes
- Example: IBM PowerPC 603 in Iridium (0.5 micron CMOS) – cache had to be disabled because of upsets caused by SAA

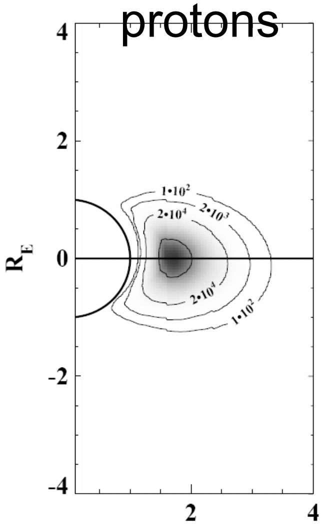
Proton Effects Scaling with Feature Size

- As commercial feature sizes scale down, proton upsets will become much more frequent
- Critical charge for upset scales as (feature size)^2
- For large feature sizes, protons cause upsets by hitting nuclei and releasing secondary particles that deposit charge
- At 65 nm and smaller, a proton deposits enough charge in silicon to cause an upset directly
- This can increase the proton SEU cross section by 2-3 orders of magnitude for deep submicron devices
- Major issue for micro-satellites

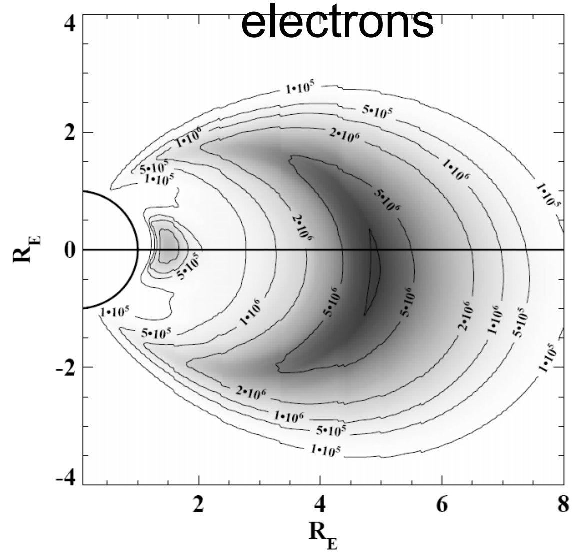
IS PRBR A SOLUTION – ARE THERE ENVIRONMENTAL EFFECTS

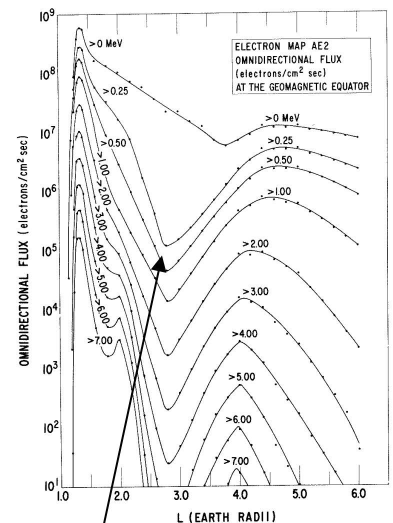
Electrons (RBR) vs. Protons (PRBR)

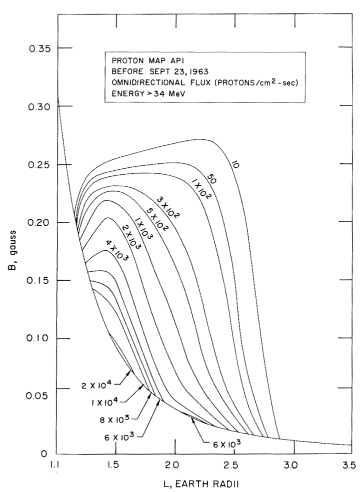
protons



electrons



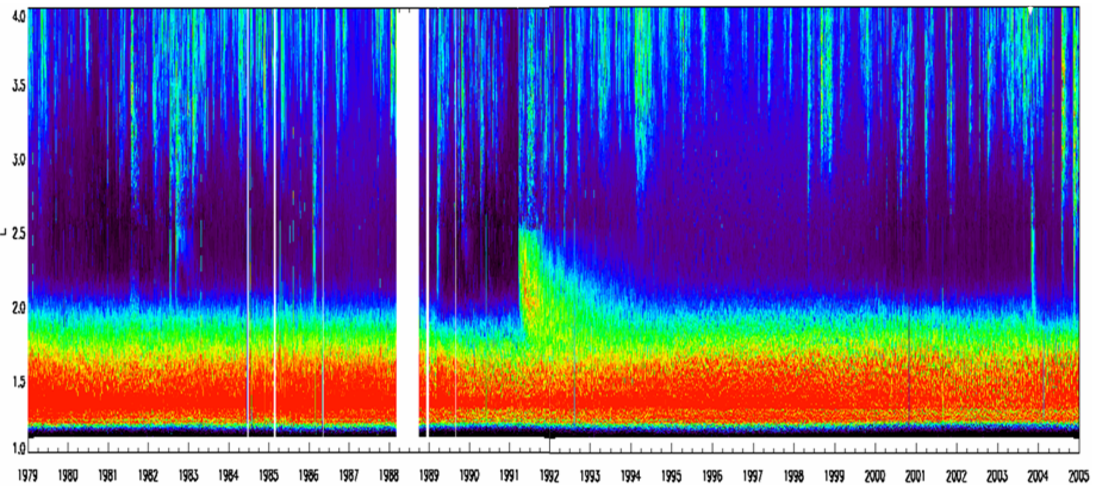




- Only one proton belt – many MeV
    - Peak near L ≈ 1.8
    - Relatively stable
    - **Sharp flux grad after L≈2**
    - **PRBR focus on L=1.5-2.0**
    - **Time scale of year(s)**

- Two electron belts with a slot region in between
    - For E>1 MeV, peaks near L ≈ 1.6 and L≈4
    - RBR focuses on slot
    - Time scale few days

Proton Lifetime in the Inner RB



26 years

Steady State → Source = Loss

Loss → Slowing down by exciting and ionizing electrons in the thermosphere

$$T \approx 2 \times 10^4 (E / MeV)^{1.3} (\# cm^3 / < \rho >) \text{ years}$$

55 MeV

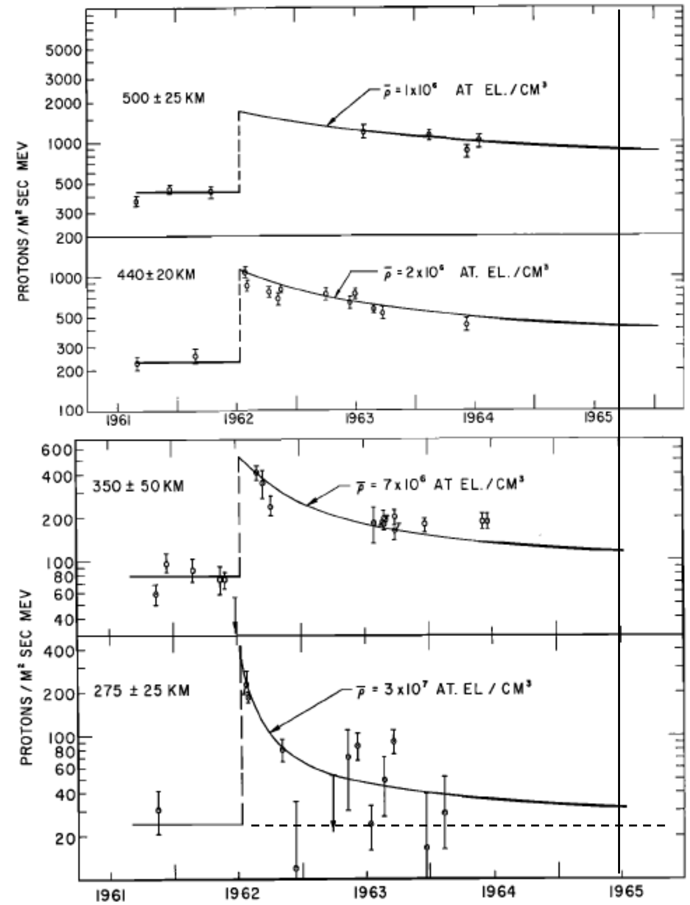


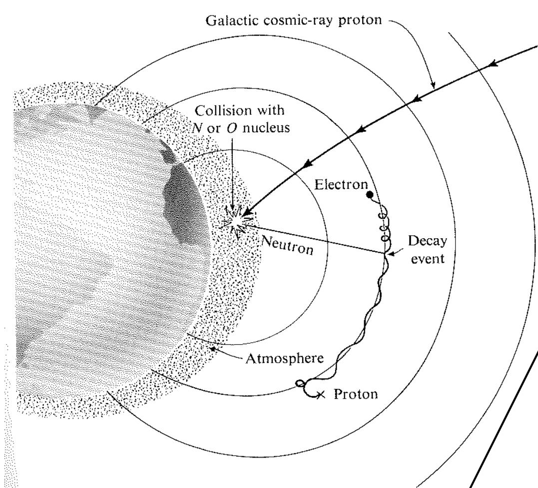
Fig. 10. Time variation of the 55-Mev proton flux for altitudes of H_e = 275, 350, 440, and 500 km from August 1961 to July 1964. The solid curves drawn for the period after July 1962 are the theoretical decay curves based on the first data point following July 1962.

Proton RB Steady State Flux

$$\frac{dN(E)}{dt} = S(E) + \frac{d}{dE}\left(N(E)\frac{dE}{dt}\right)$$

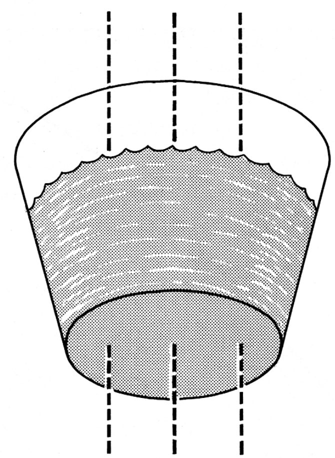
$$\frac{dE}{dt} = v\frac{dE}{dx} : <\rho>$$

Slowing down by exciting and ionizing electrons of Oxygen atoms in the thermosphere

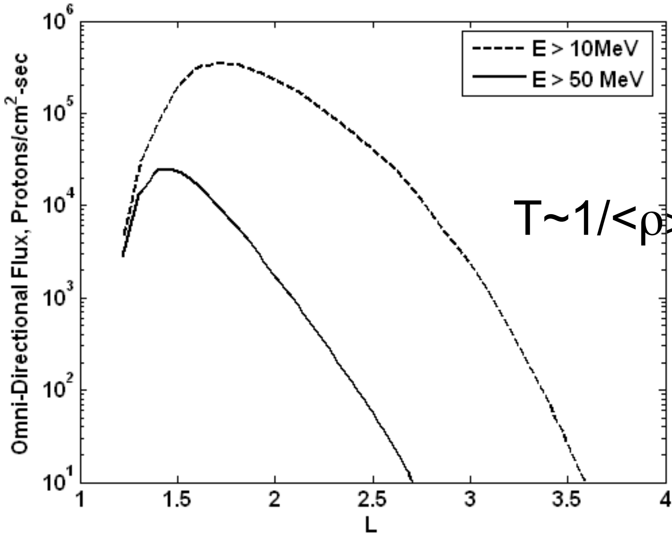


$$S(E) = -\frac{d}{dE}\left(N(E)\frac{dE}{dt}\right)$$

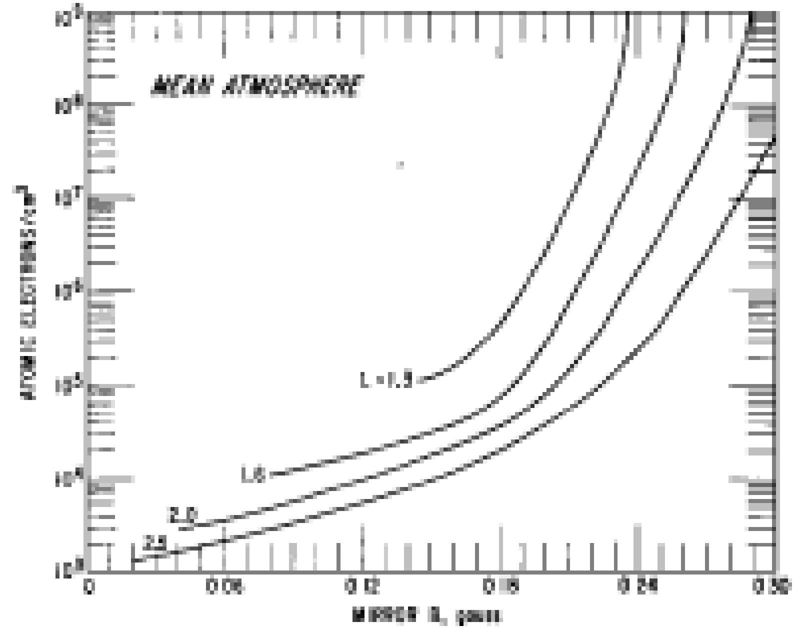
Cosmic Ray Albedo Neutron Decay (CRAND)



Proton Lifetime vs. L



$T \sim 1/\langle\rho\rangle$



$$S(E) + \frac{d}{dE}\left(N(E)\frac{dE}{dt}\right) - \frac{N(E)}{T_L} = 0$$

$$\frac{d}{dE}\left(N(E)\frac{dE}{dt}\right) \ll \frac{N(E)}{T_L} \text{ if } L>2$$

$$\frac{d}{dE}\left(N(E)\frac{dE}{dt}\right) \gg \frac{N(E)}{T_L} \text{ if } L<2$$

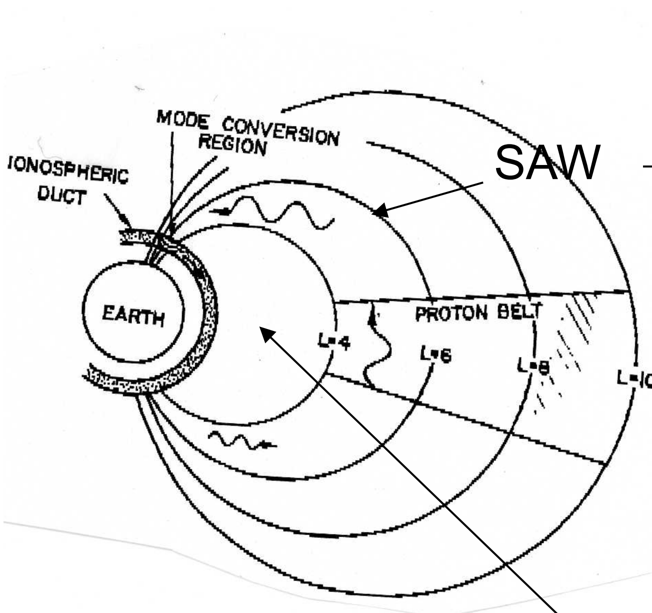
If lifetime at L=1.5 is 20-50 years

Lifetime at L=2.5-3 should be days

Need new loss mechanism

Pitch angle scattering into loss cone by SAW (A.Dragt) driven by Ion Cyclotron Instabilities

Pitch Angle Diffusion (PAD) at high L



$$\omega - k_z v_z = \pm\Omega$$

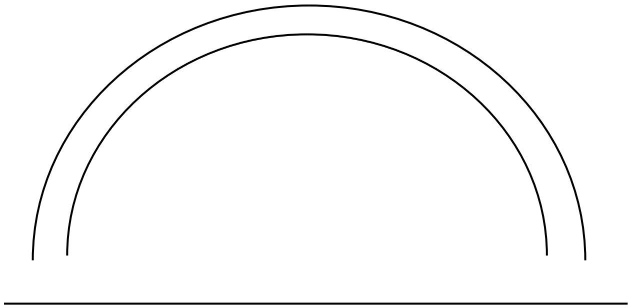
$$k_z v_z \approx \Omega$$

Enhance proton loss rate in the inner RB by PAD on artificially generated and injected SAW

Inner RB Proton Removal Requirements

Example for L=1.5

Fill tube with SAW

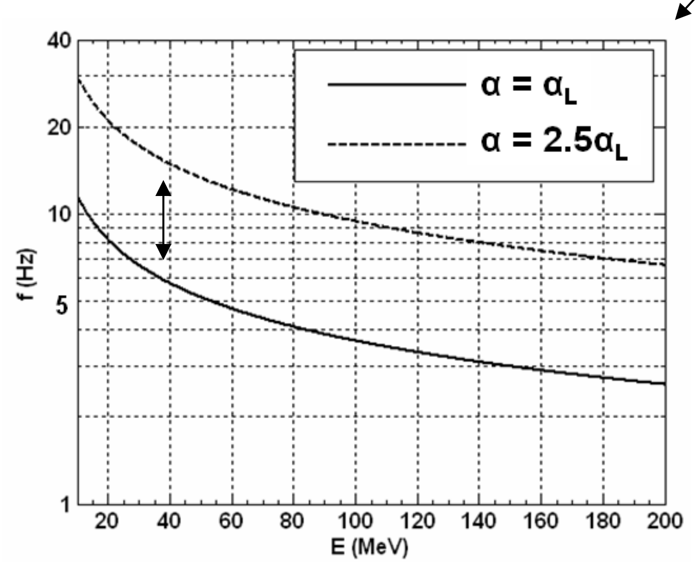


Frequency Selection for Resonance of Protons with SAW

$$\omega \approx k_z V_p$$

$$\omega = k_z V_A$$

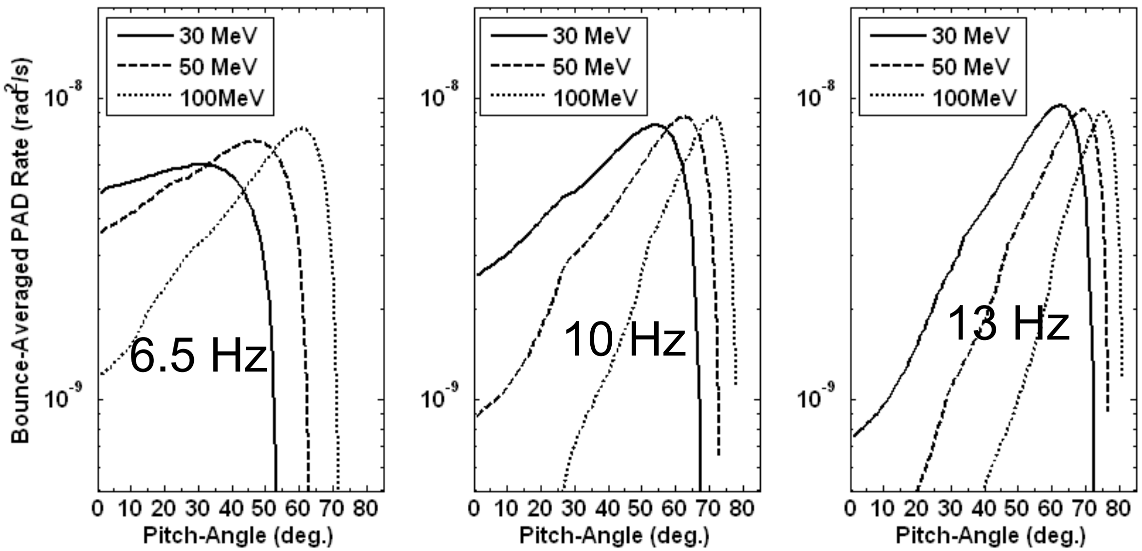
$$\omega(E,\alpha) \approx \frac{\Omega}{\cos\alpha}\sqrt{\frac{MV_A^2}{2E}}$$



Frequency requirement for equatorial resonance with SAW at L=1.5

Frequency range 5-15 Hz

PAD Rate and Lifetime



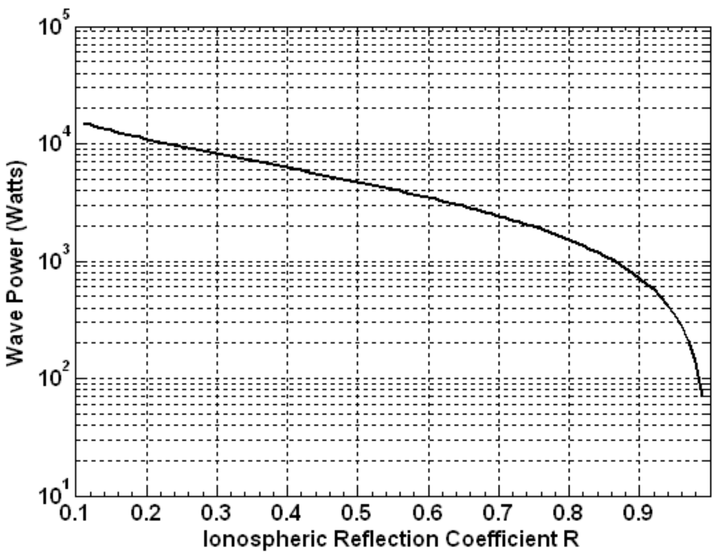
$\Delta f/f$ [illegible] 1/2 , <B> [illegible] 25 pT

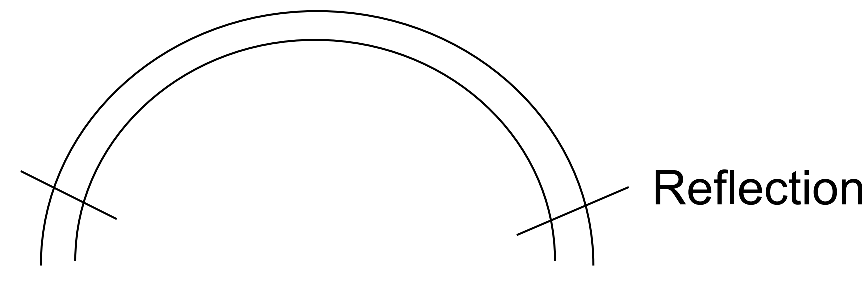
	f_1= 6.5 Hz	f_2= 10 Hz	f_3= 13 Hz
E = 30 MeV	1688 days	880 days	595 days
E = 50 MeV	900 days	586 days	920 days
E = 100 MeV	580 days	1032 days	1600 days

Energy stored in SAW at L=1.5 and ΔL=.1 with <B> =25 pt is

W= 75 kJ

Injection Power Requirement





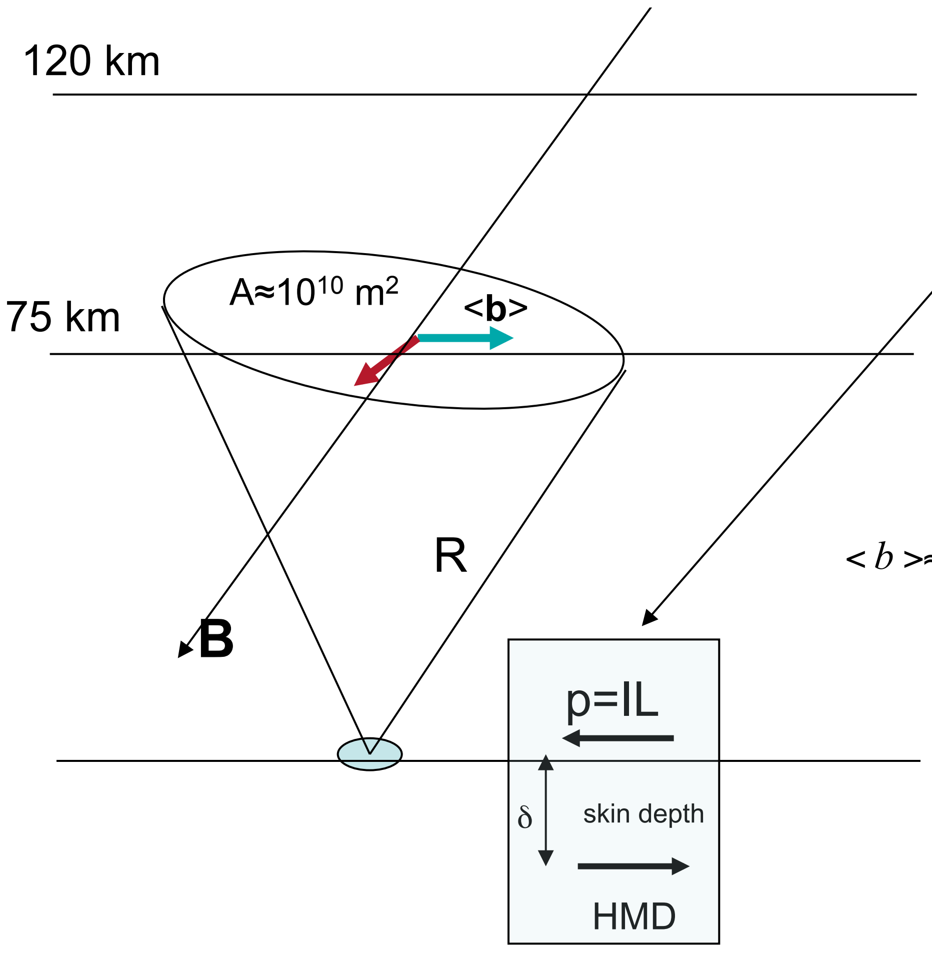
Injection power required to maintain
75 kJ at L=1.5 per .1 L width

How to Get these Waves - Ground-based Transmitter Options

- Initial estimates indicate that less than kWatt level of ULF injected into the L = 1.5-1.8 region is required to get interesting removal lifetime
- What does it take to get it
- There are a number of potential options:
  - Conventional ULF/ELF transmitters (grounded dipoles)
  - Rotating electromagnets (conventional and low and high temperature superconducting)
  - Space based rotating magnets or neutral gas injection
  - Electrojet-free F-region ionospheric heating
- Present estimates for the first two

Ground-based Conventional Transmitter - HED

To inject 1 kW we require <b>≈30 pT at 75 km, the bottom of the magnetized ionosphere.

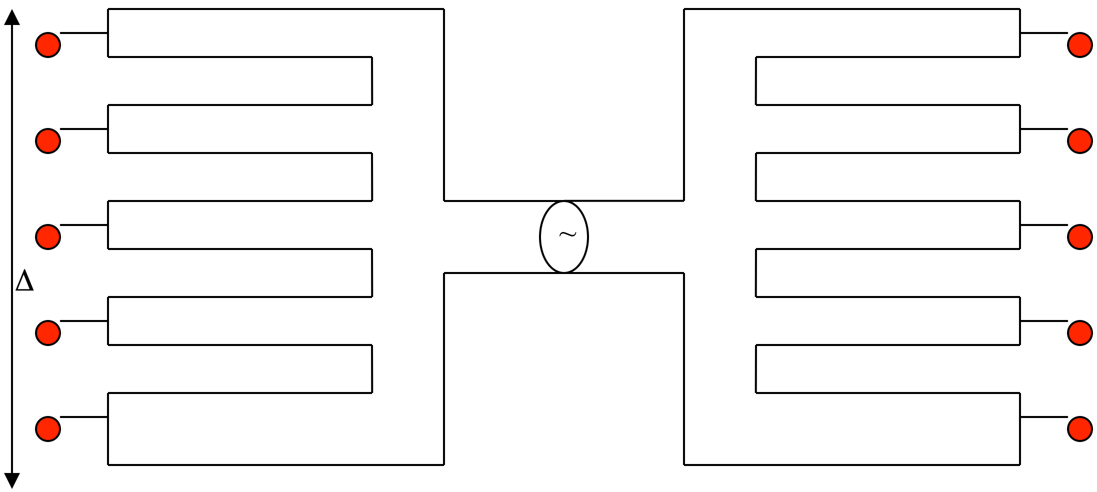


Conventional ULF/ELF sources (like Sanguine/Seafarer) are grounded wires – HED (Jason Study by Perkins et al.)

$$< b > \approx 60(IL^2 / 2\times 10^{10})[\frac{\delta}{2(L+\delta)}]pT \approx 30(IL^2 / 2\times 10^{10})pT$$

Need M[illegible]IL² [illegible] 2x10¹⁰ A-m²

Traditional HED Sources



Plane view of HED antenna

$$M_{eff} = \frac{Il^2\delta}{2(l+\delta)}$$

$$B \approx \mu \frac{M_{eff}}{h^3} \approx \frac{\mu I l \delta}{2h^3} \frac{1}{(1+\delta/l)}$$

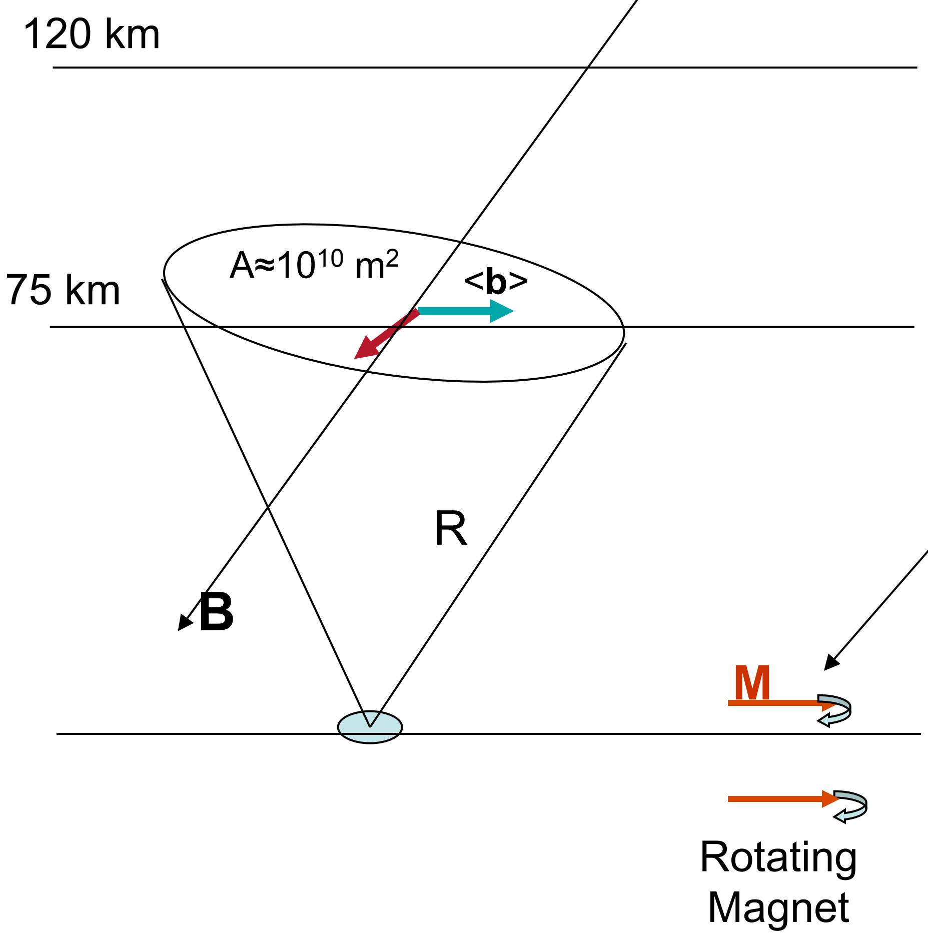
$$I = 3.3(P/MW)^{1/2}(\sigma/10^{-2})^{1/2}(L/km)^{1/2} \text{ kA}$$

$$\mathrm{IL}^2 = 2\times 10^{10}(P/MW)^{1/2}(\sigma/10^{-2})^{1/2}(L/2km)^{5/2} A-m^2$$

Jason study Perkins et al.

Ground-based Rotating Magnet Array (RMA)

To inject 1 kW we require <b>≈30 pT at 75 km, the bottom of the magnetized ionosphere.



A superconducting magnet rotating at a ULF frequency has a reflected image in phase with primary

$$< b > \approx 30(M / 5\times10^{9})\,pT$$

Need RMA with M [illegible] 5x10^9 A-m^2

Innovative Sources: Rotating Magnets

- Rotating superconducting magnets are useful for frequencies of up to 10 Hz
- They are compact sources of large moments and can be used in arrays
- Example design:
  - Superconducting coil 5 m high x 5 m wide x 5 m long
  - 25 m^2 area
  - 100 Amps DC current
  - 4×10^4 turns
  - M = 10^8 A-m^2 per coil, meaning 50 coils are needed
- Cost estimate: ~$1M/coil
  - LTS wire at $2/kA-m: $160k/coil
  - Dewar and refrigeration: $500k/coil (assuming LHe large plant shared across dozens of coils)
  - Mechanical rotation: $300k/coil (depends strongly on maximum frequency)

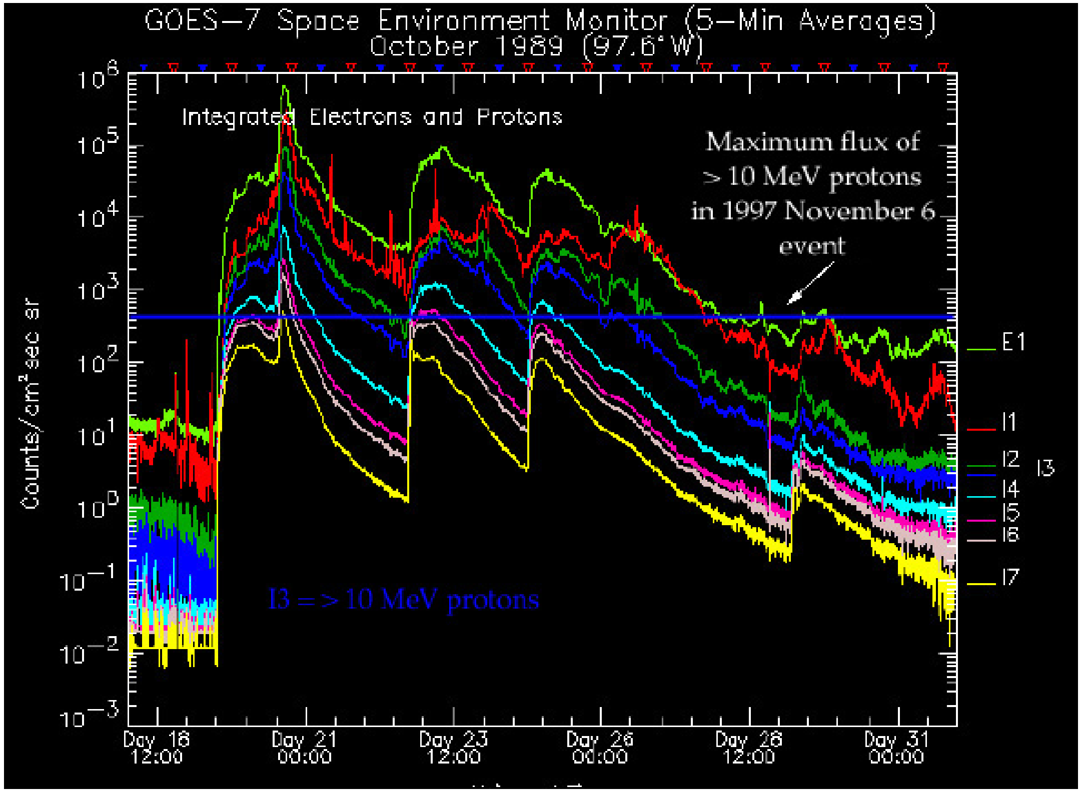
Removing Energetic Protons

- Removal is accomplished in the same way as HANE electron remediation: increase the pitch angle diffusion rate so that protons precipitate into the atmosphere
- Pitch angle diffusion rate is increased by producing waves with the proper wavelength to resonate with energetic protons
  - ULF waves in the 1 – 10 Hz band
- Unlike HANE electrons, inner belt protons are produced by very slow processes so remediation can be done periodically (e.g. for 1-2 years every 10 years) as well as monitored
- Remediation of natural inner belt protons would have an immediate operational impact
- Similar ULF system could potentially be used for MeV electrons

Environmental Effects of Energetic Proton Precipitation in Middle Atmosphere

Solar Proton (SPE) Events associated with CMEs

Flux of > 10 MeV protons
>10^4 #/cm^2 sec
Leads to 20% variation of Ozone in middle atmosphere (40-50 km) with recovery time of week



Noise for E>10 MeV   10 #/cm^{2}sec

Verronen et al JGR, 2005

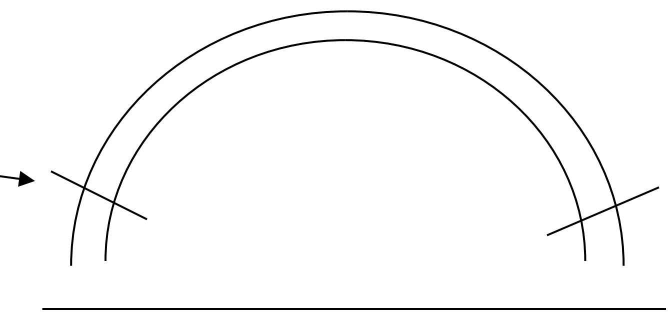
Jackman et al. JGR,1995

Environmental Issues – Effects in the Stratosphere – Ozone Loss

PRBR precipitation flux

L=1.5-2

Precipitation area 10^{17} cm^2



Proton inventory 10^{23}-10^{24}

Assume all particles precipitate over one year

Proton flux in atmosphere

<1 #/cm^2 sec

Smaller than noise

Environmental Effects - Magnetic

- Diamagnetic current due to Inner Belt protons << Ring Current
- Magnetic Moment of Ring Current <<Magnetic Moment of Earth (7×10^{21} A-m^2)
- Magnetic effect from PRBR nrgligible