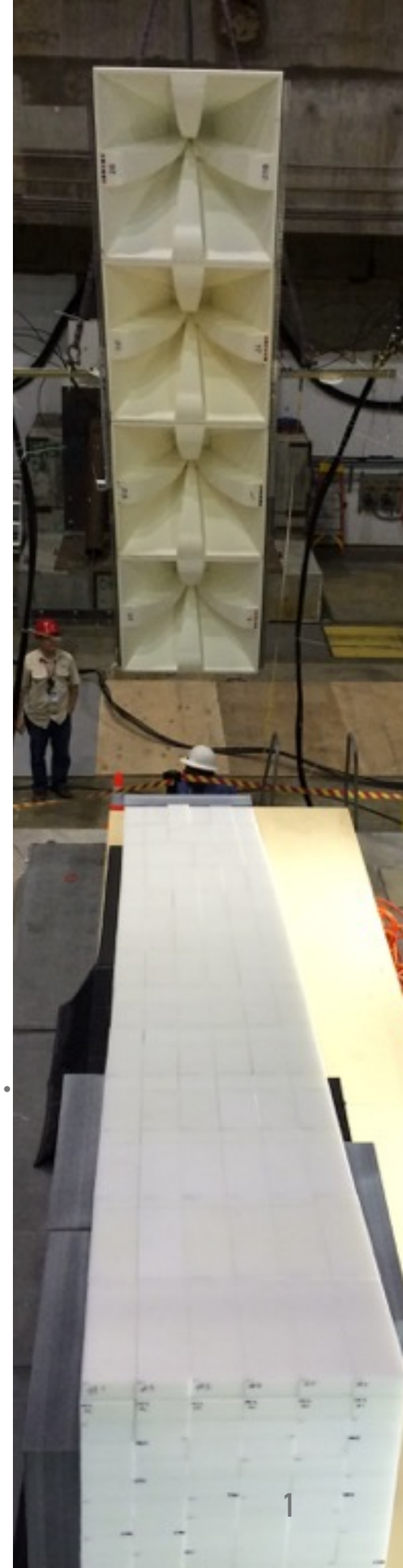
Implications for the Radio Detection of Cosmic Rays

–from–

Accelerator Measurements of Particle Showers in a Magnetic Field



CAL POLY

Stephanie Wissel

1 March 2016

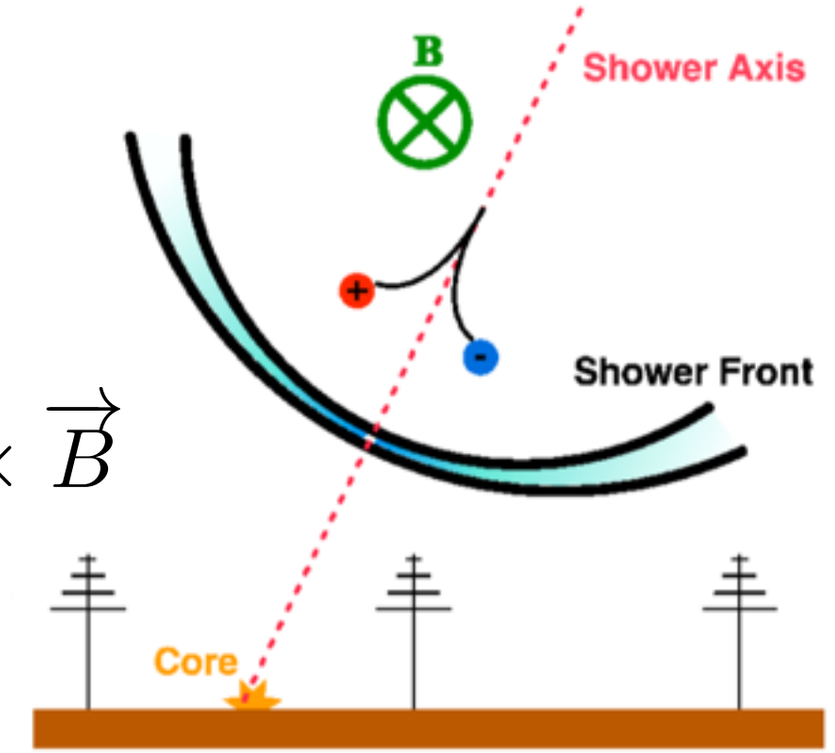
T-510

T-510 Collaboration, PRL, in press, 2016, arXiv:1507.07296

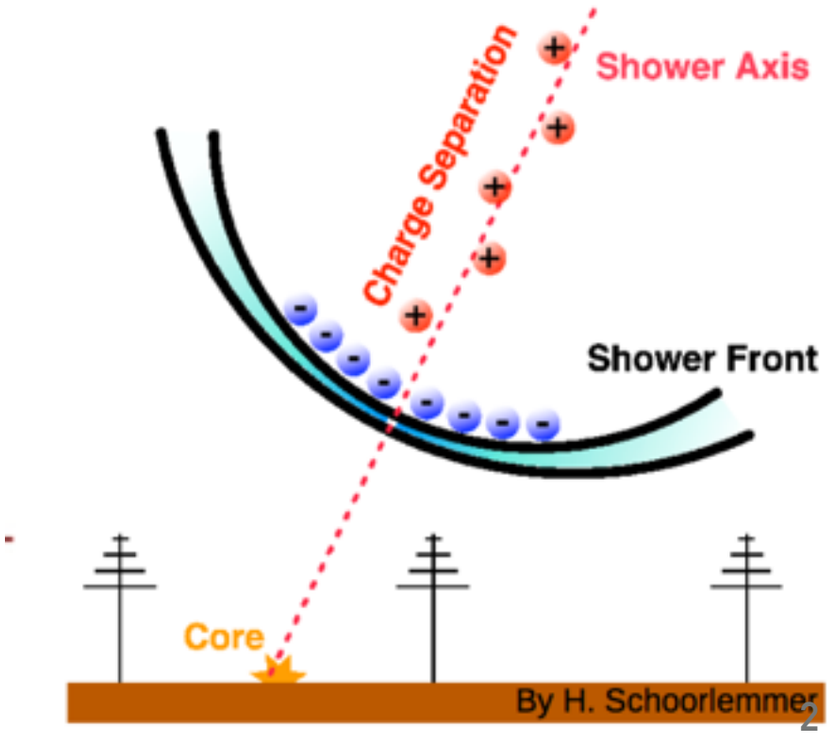
Radio Emission of Cosmic Ray Air showers

- Two main emission mechanisms:
- **Geomagnetic emission:** separation of positive and negative charges in shower due to Lorentz force:

$$\vec{E} \propto \vec{v} \times \vec{B}$$



- **Askaryan emission**: radiation from net negative charge excess in shower



- Broadband (MHz – GHz)
- Cherenkov-like emission pattern
  - Coherent up to cutoff frequency

The RF Technique: A Maturing one

- Dominated by Geomagnetic, but some Askaryan

  PAO Collab. Phys Rev. D. 2014

- Electromagnetic models + hadronic shower codes predict magnitude of E-field
  - Recently shown to be consistent with LOPES measurements at 16% level

    Apel et al. Astropart. Phys. 2016

- Beam pattern depends on shower geometry, observation frequencies, atmosphere index of refraction *n*

  Nelles et al. Astropart. Phys. 2015

  de Vries, et al. PRL 2011

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  PAO Collab. Phys Rev. D. 2014

- Electroma[illegible] predict magnitude[illegible]
  - Recentl[illegible] *part. Phys. 2016* measur[illegible]

Beam test calibrates RF models in a different system

- Beam pattern depends on shower geometry, observation frequencies, atmosphere index of refraction *n*

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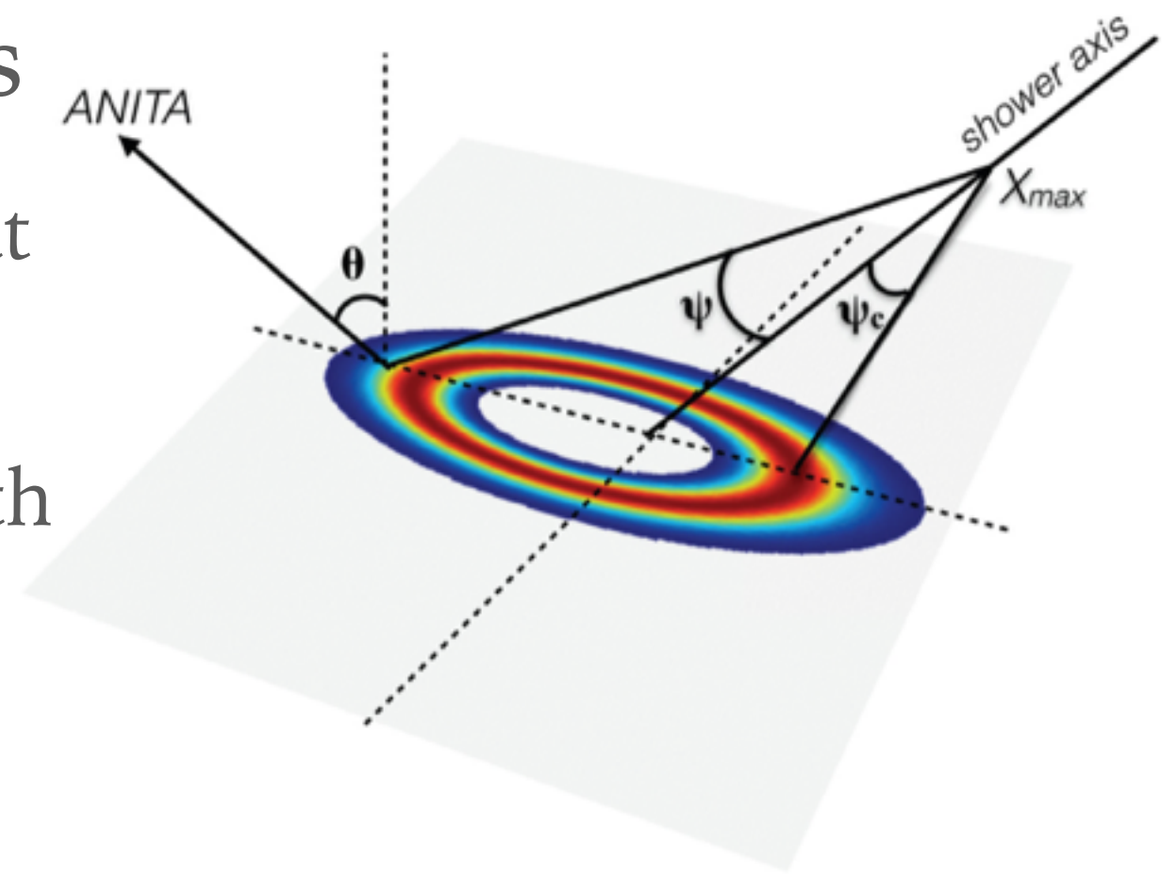
Important for e.g. ANITA

- UHECRs observed by ANITA at high frequencies *2006/2007*
  - Inconsistent with models at the time *PRL 105, 2010*
    - Predicted no observable power in the ANITA band
  - Current models allow for this **if** include realistic *n*
- Energy of ANITA UHECRs
  - ANITA samples RF emission at a single point
  - RF beam width degenerate with CR energy



Schoorlemmer et al, 2016

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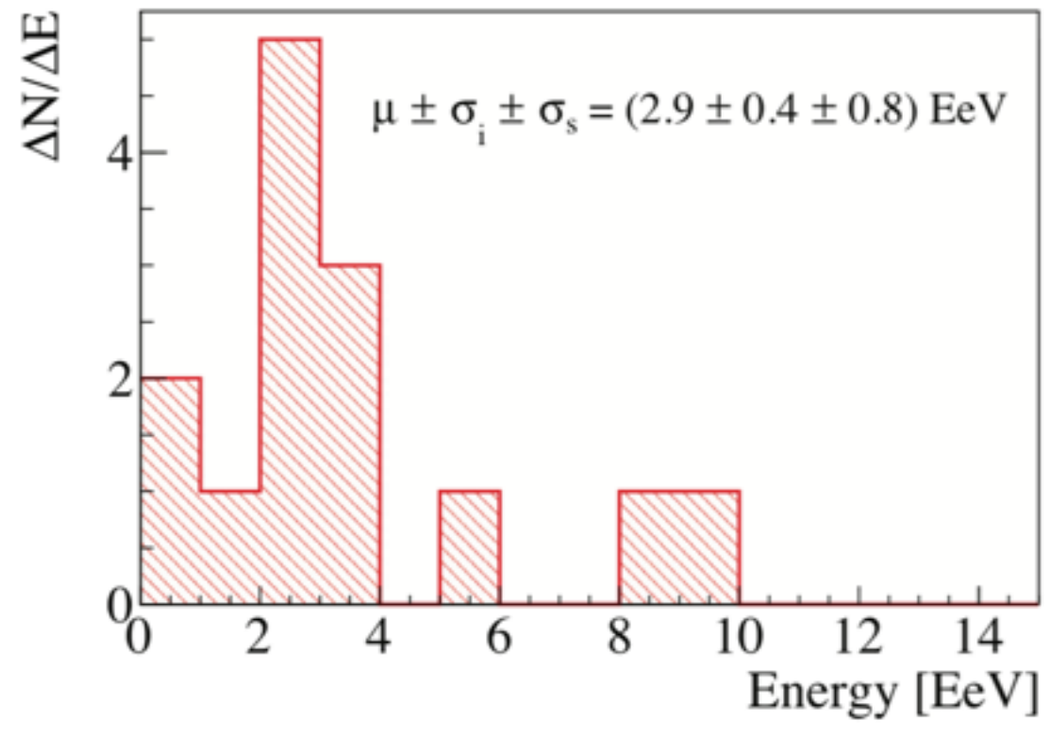

Schoorlemmer et al, 2016

The Need to go to an Accelerator

- Test emission mechanism in a controlled laboratory environment:
  - Relative strength of Askaryan to Geomagnetic
  - Do the RF models accurately predict the absolute magnitude of E-field?
  - Does coherence depend on the index of refraction?

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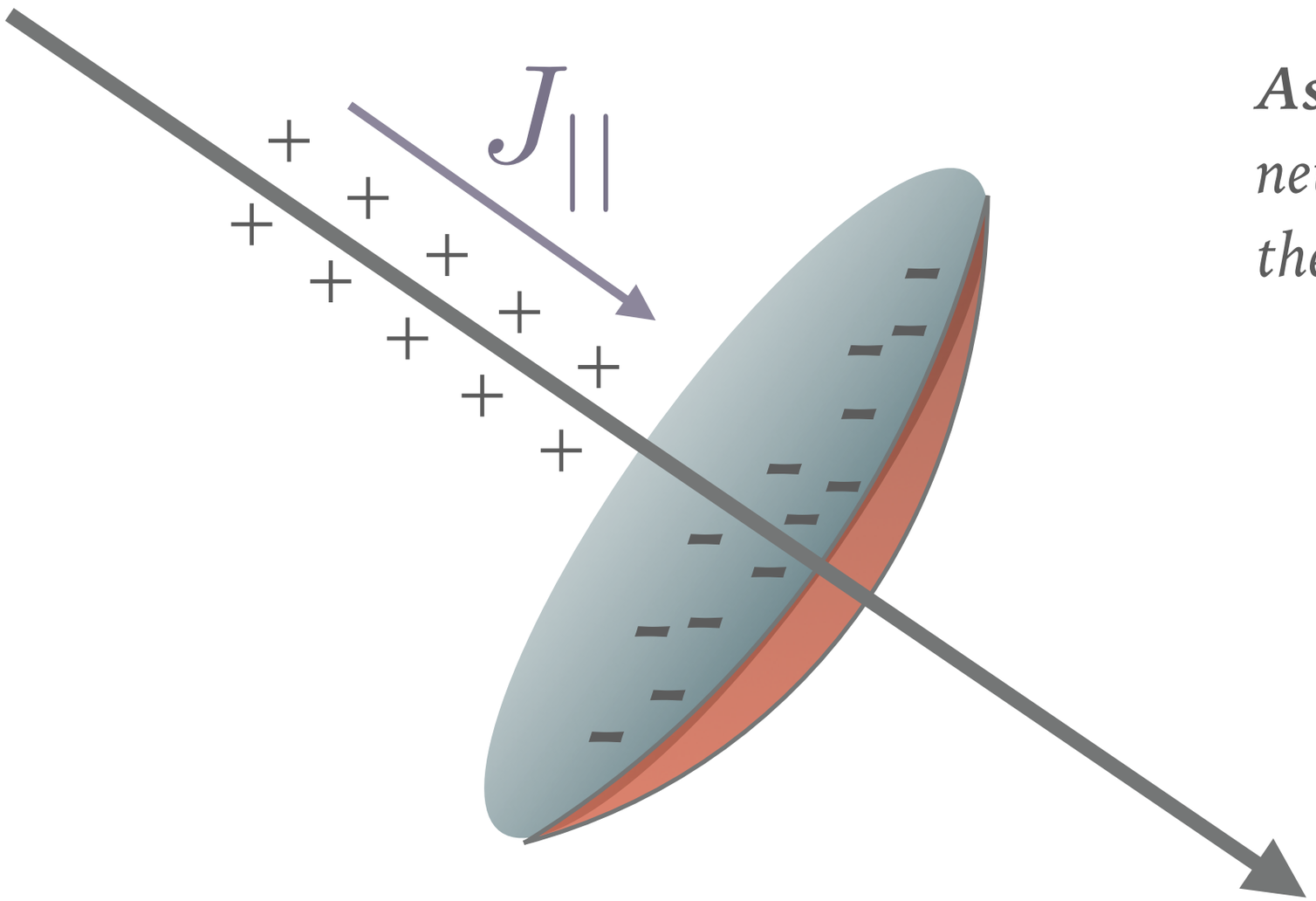
Challenge: Build a laboratory scale model of a km-scale air shower

Currents Paradigm

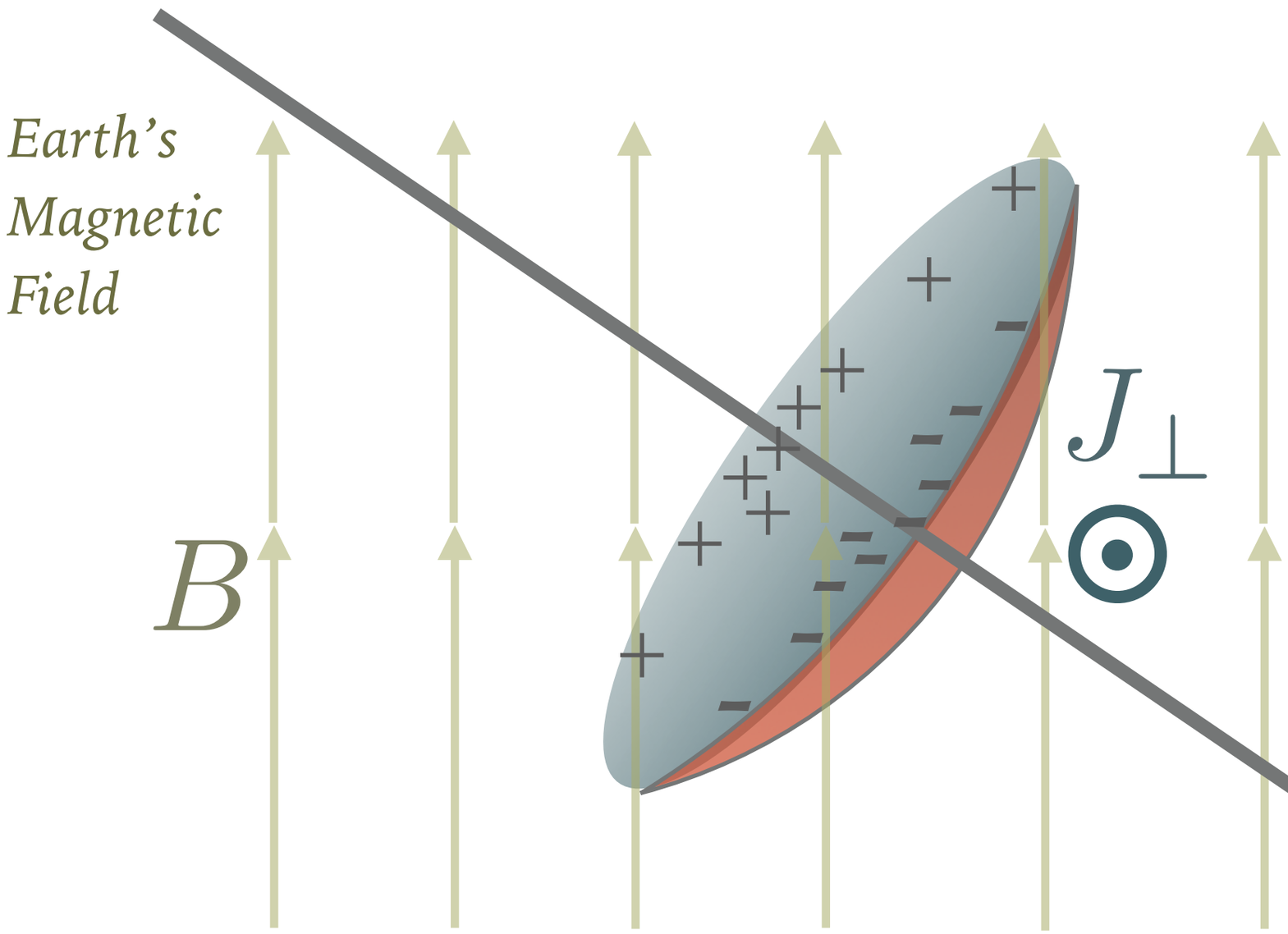


Askaryan Radiation:
net (negative) charge excess in the shower

$$A_{Askaryan} \sim J_{||}$$

Askaryan 1962

Currents Paradigm



Askaryan Radiation:
net (negative) charge excess in the shower

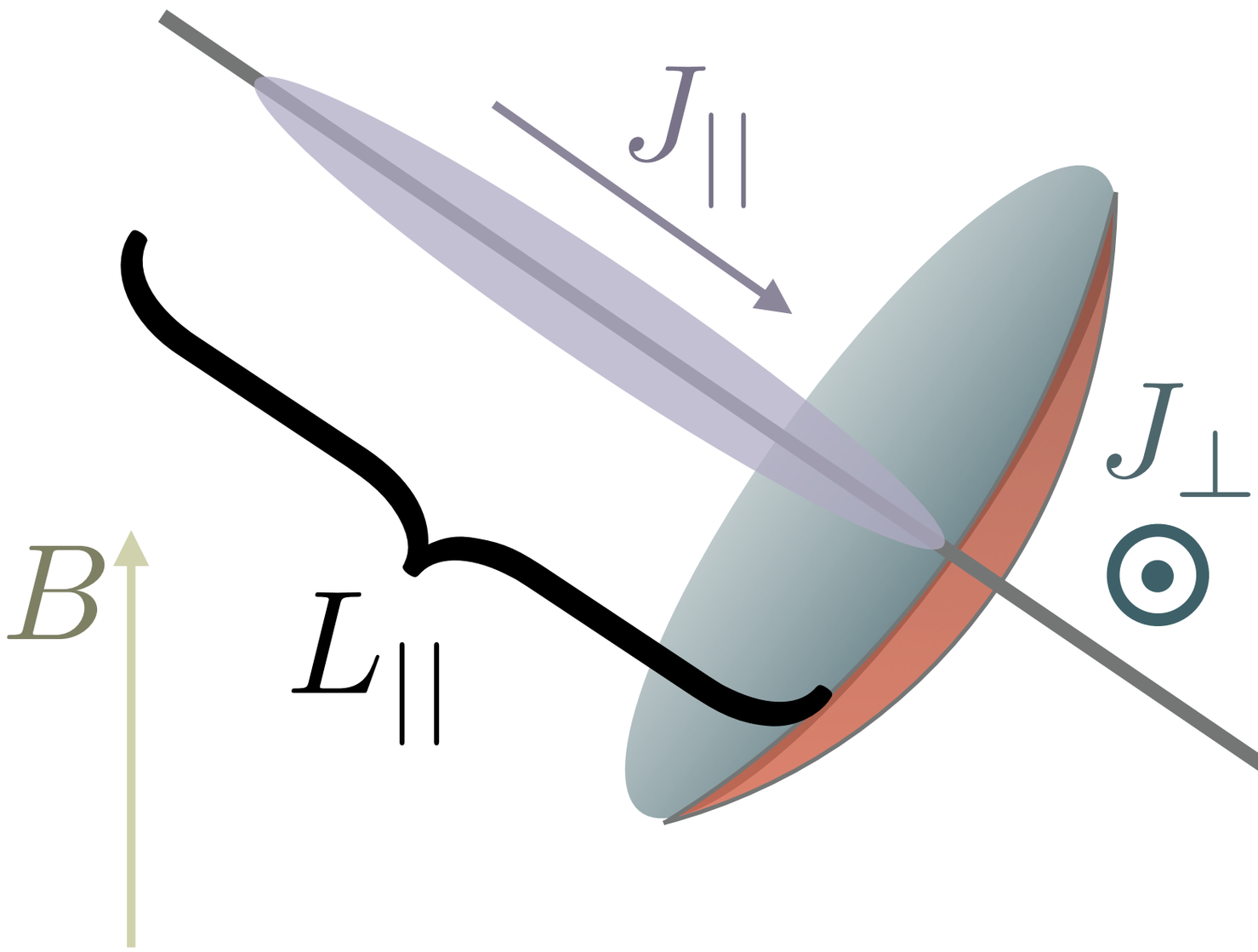
$$A_{Askaryan} \sim J_{||}$$

Geomagnetic Radiation:
charge separation in the presence of a magnetic field

$$A_{Geomagnetic} \sim J_\perp$$

Kahn, Lerche, 1976
Scholten, Werner, Rushydi, 2008

Scaling to the Lab



Both *currents scale with the total track length, L, of the shower.*

Shower length shorter in dense media, so: $L_{||} \sim \frac{1}{\rho}$

Instantaneous Transverse current *scales with transverse drift velocity:* $v_d \sim a_{\perp} t \sim \frac{B}{\rho}$

Geomagnetic : Askarayn $$\frac{J_{\perp}}{J_{||}} \sim \frac{B}{\rho}$$

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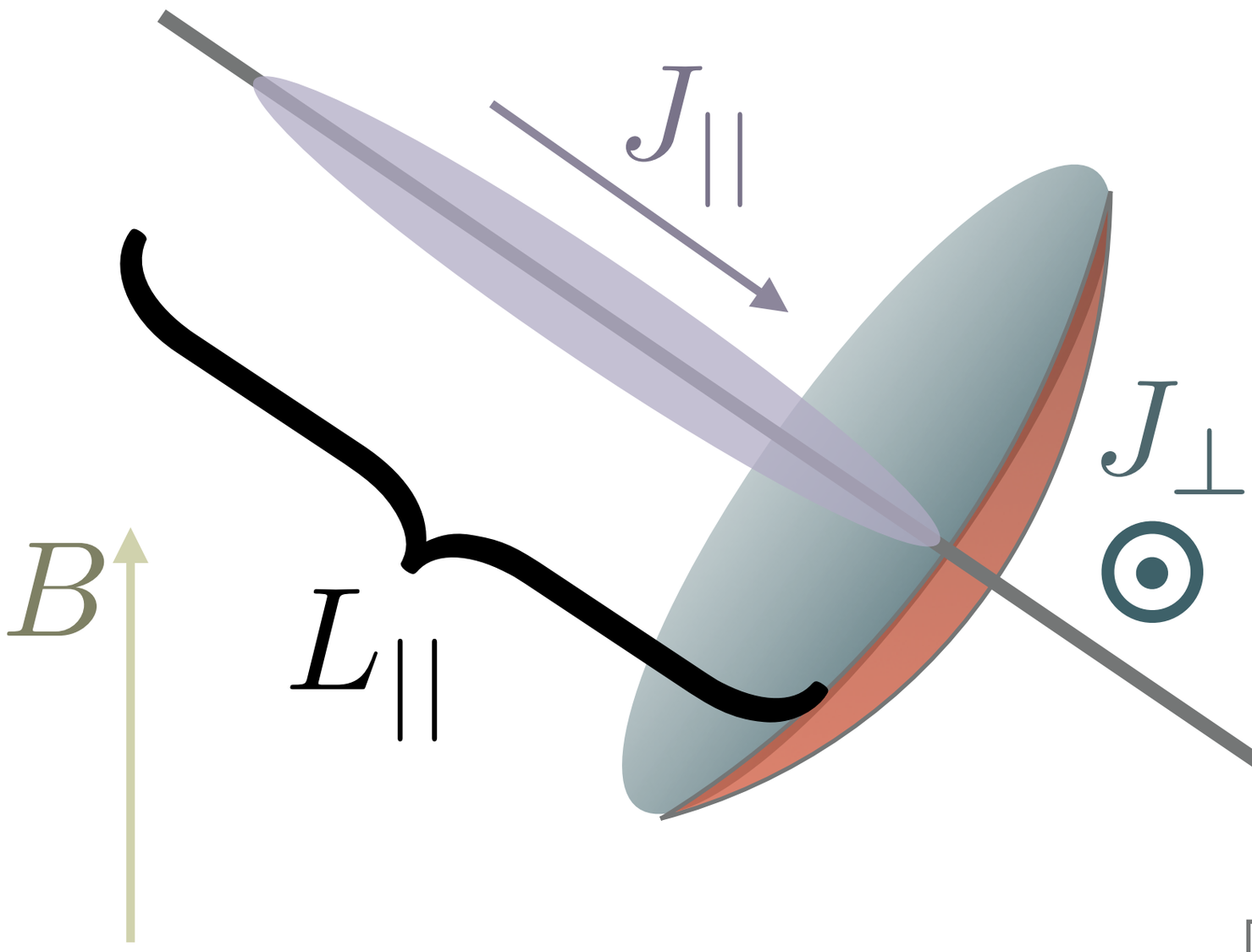

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Scaling shower length down by a factor of 1000, requires O(1 kG) magnetic field in the lab!

SLAC T-510 Objectives

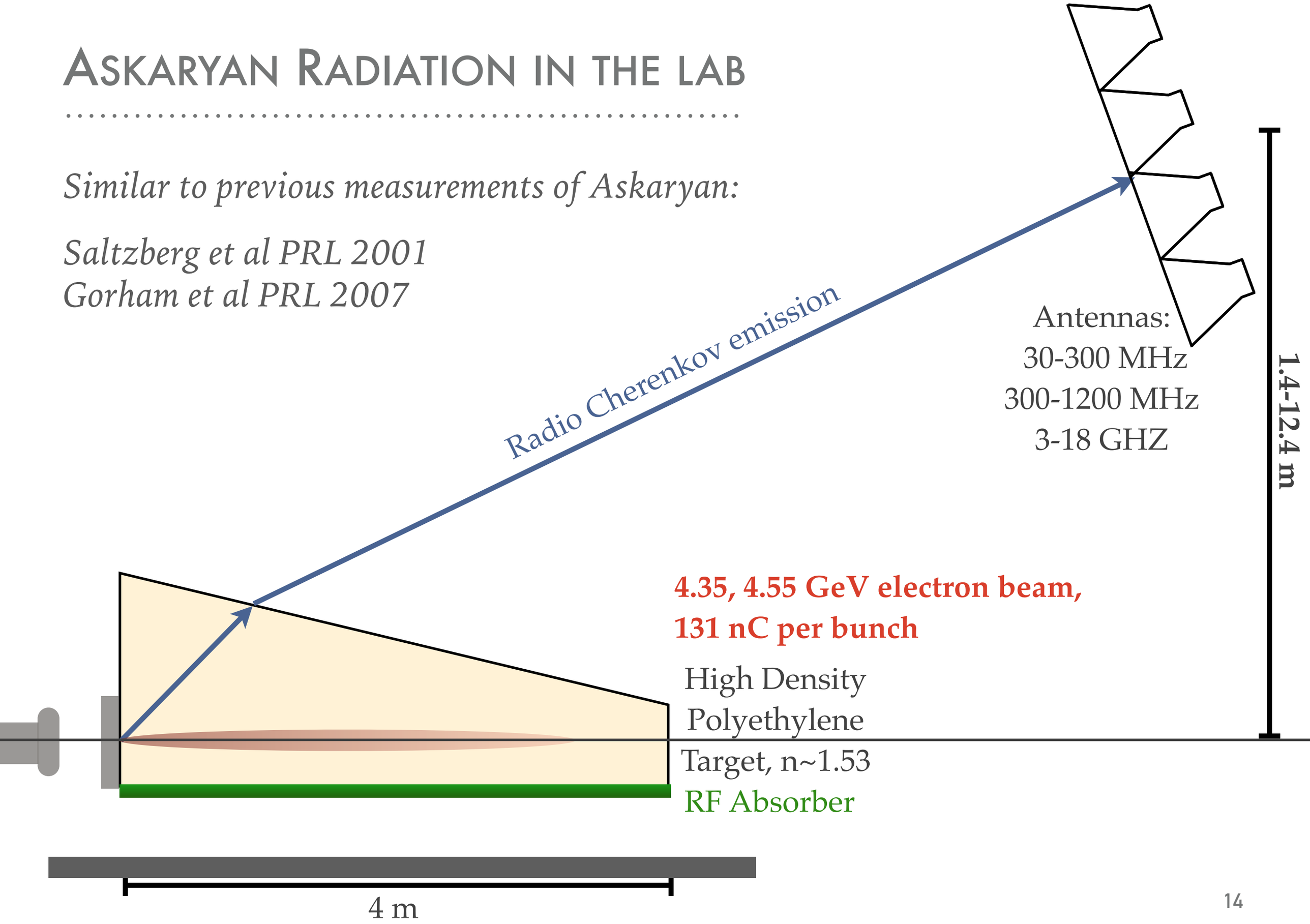
- **Design Principles**
  - Scale magnetic field & bandwidth to the lab
  - Isolate electromagnetic emission from hadronic physics
  - Separate Askarayan emission from Magnetic Emission

- **Complement Air Shower Measurements with Lab Exp.**
  - Controlled electromagnetic showers with precise geometry
  - Controllable magnetic field → Controllable Magnetic Emission
  - Map out beam patterns → Test of Cherenkov cone, importance of n

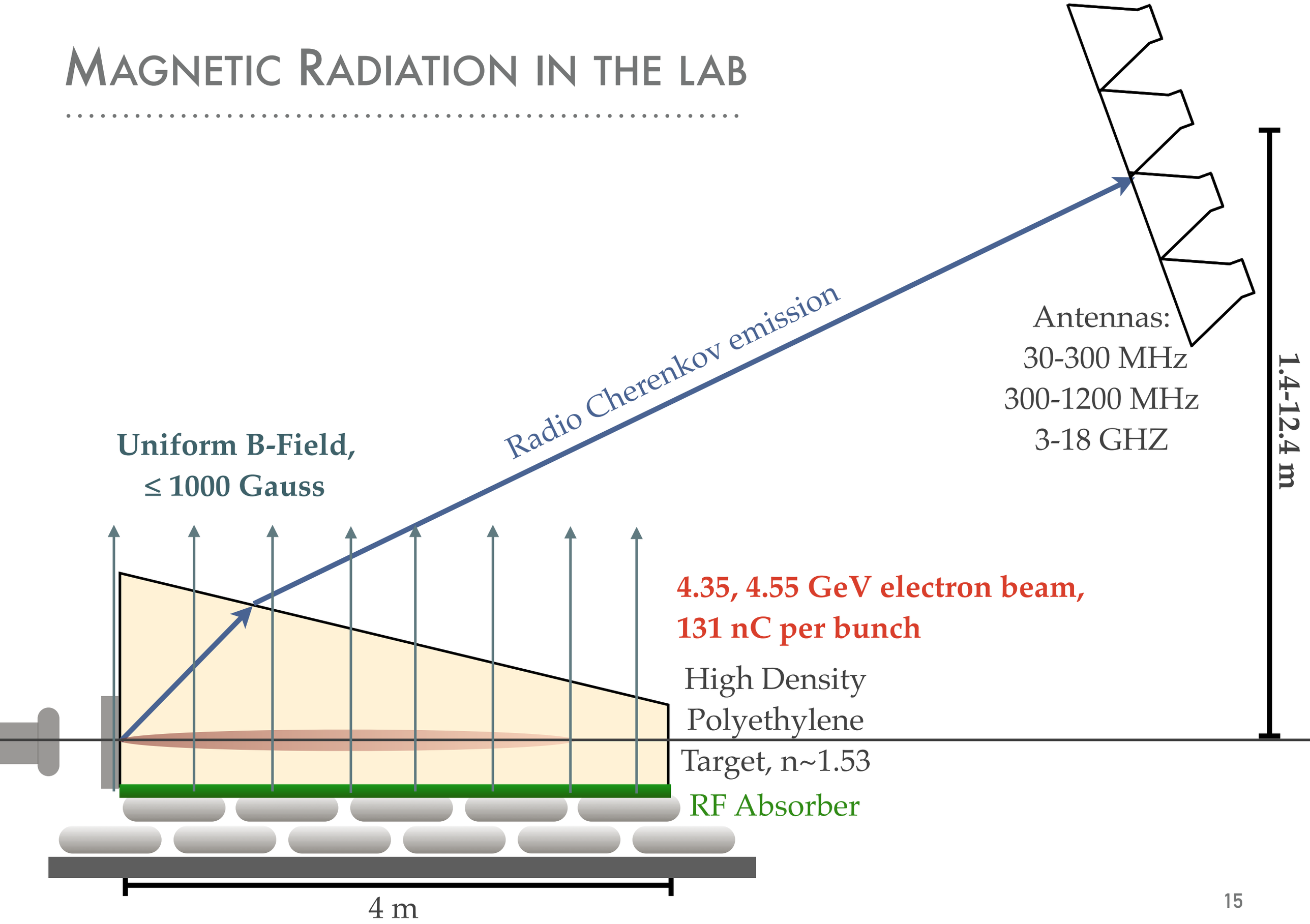
Askaryan Radiation in the lab

Similar to previous measurements of Askaryan:

Saltzberg et al PRL 2001
Gorham et al PRL 2007

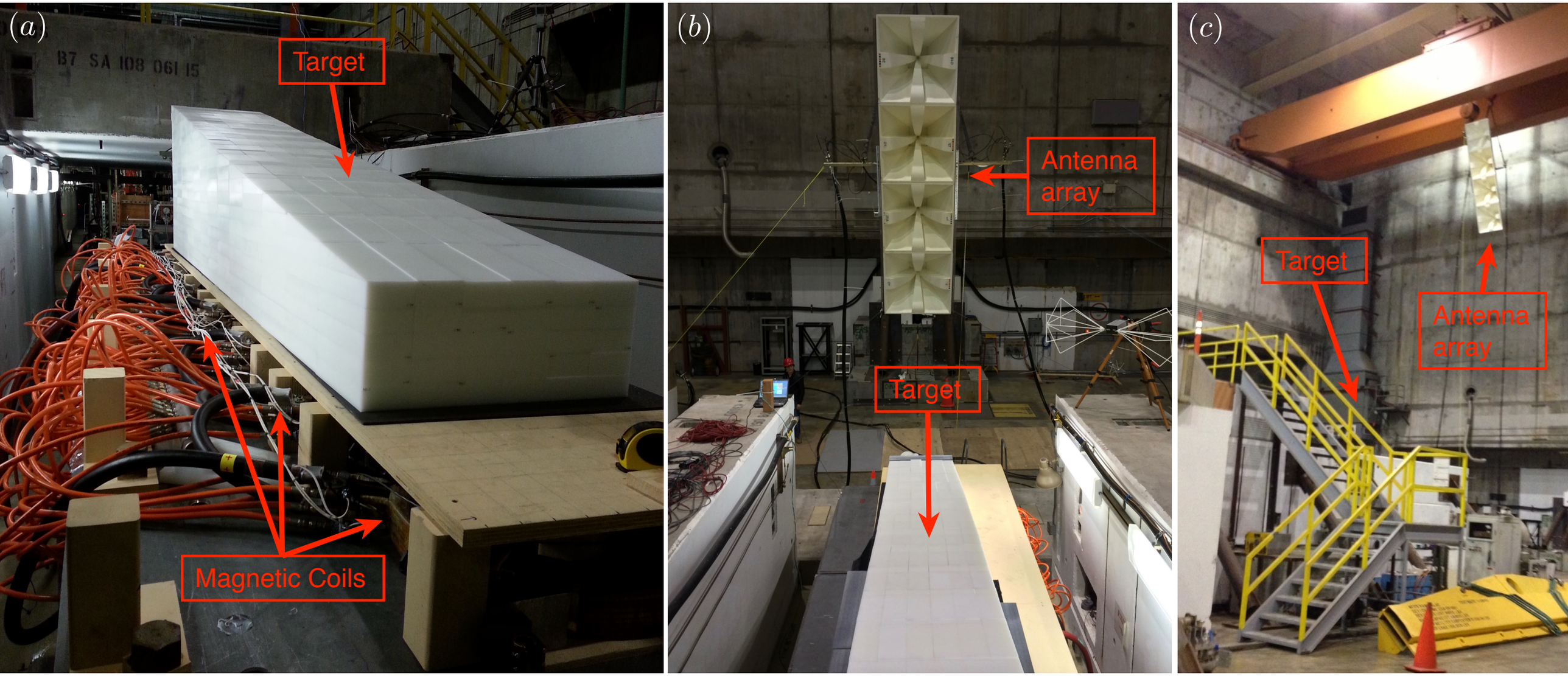


Magnetic Radiation in the lab



In Practice: Laboratory Setup

- End Station A in End Station Test Beam at SLAC

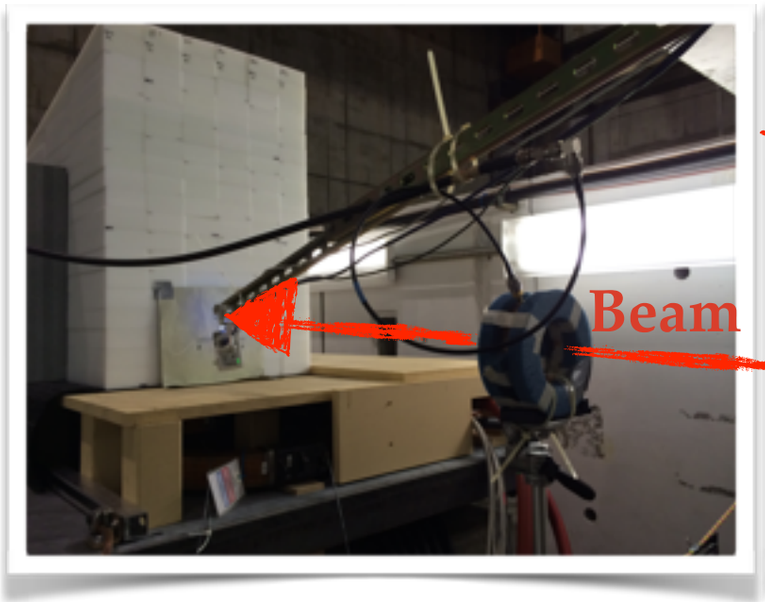


300-1200 MHz antennas

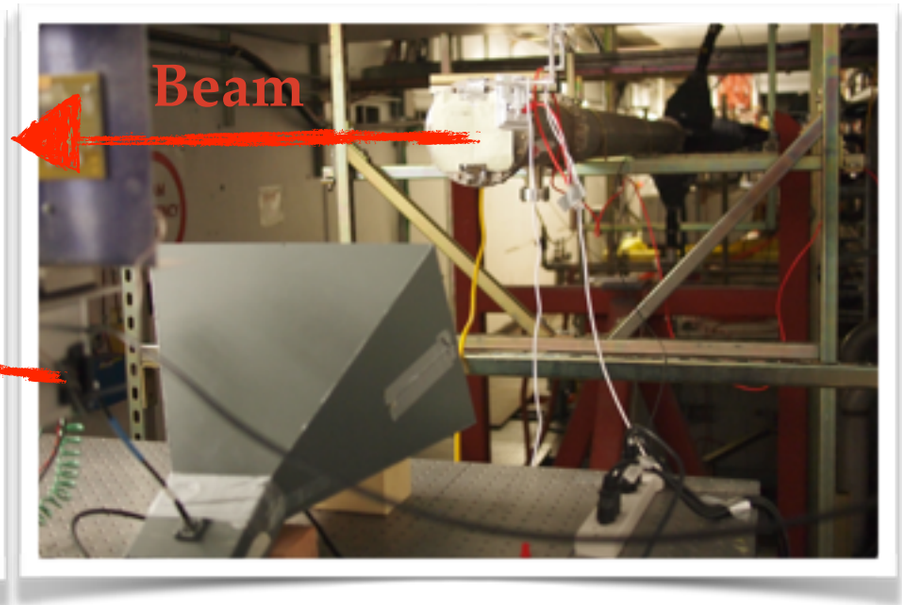
scales to 10-60 MHz in air showers

Beam Characteristics

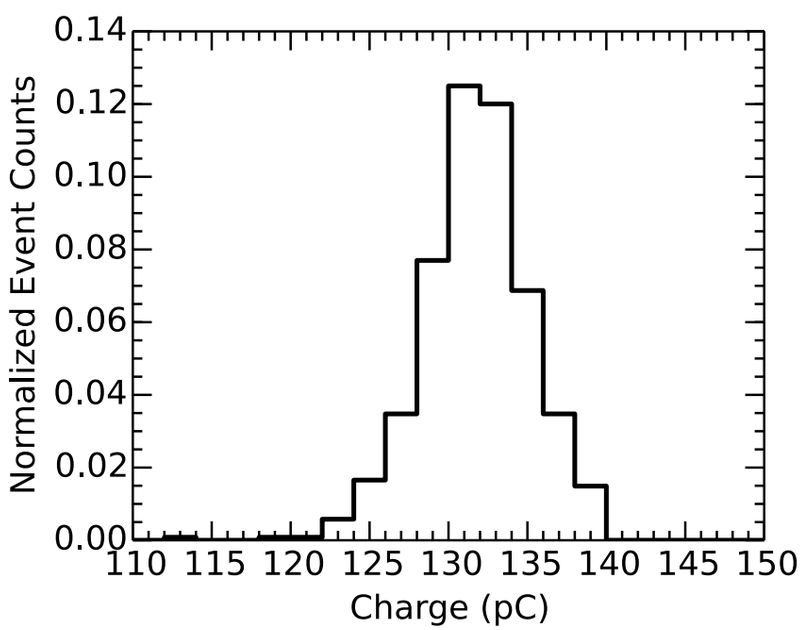
- 4.35, 4.55 GeV electron beam
- 131±3 pC average bunch charge
- equivalent to 4 x 10^{18} eV cosmic ray primary

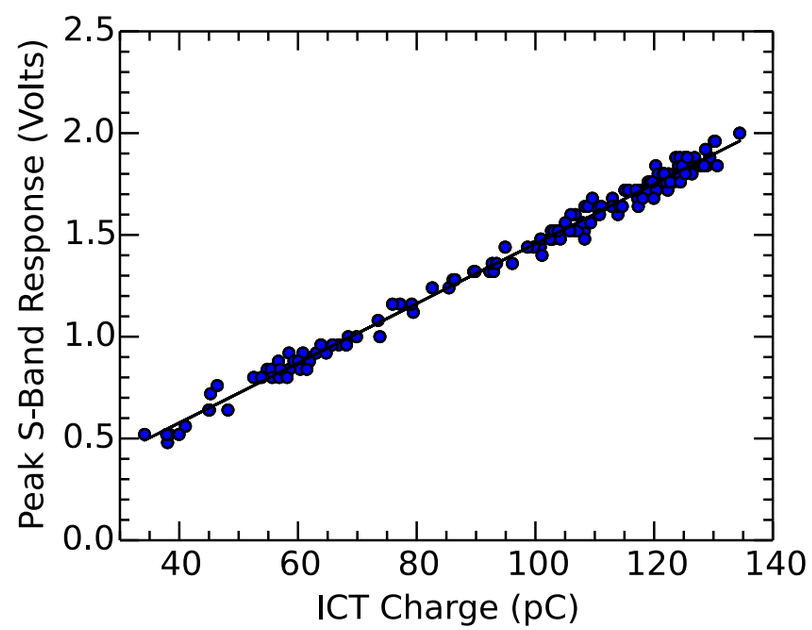


Bergoz Integrating Charge Transformer



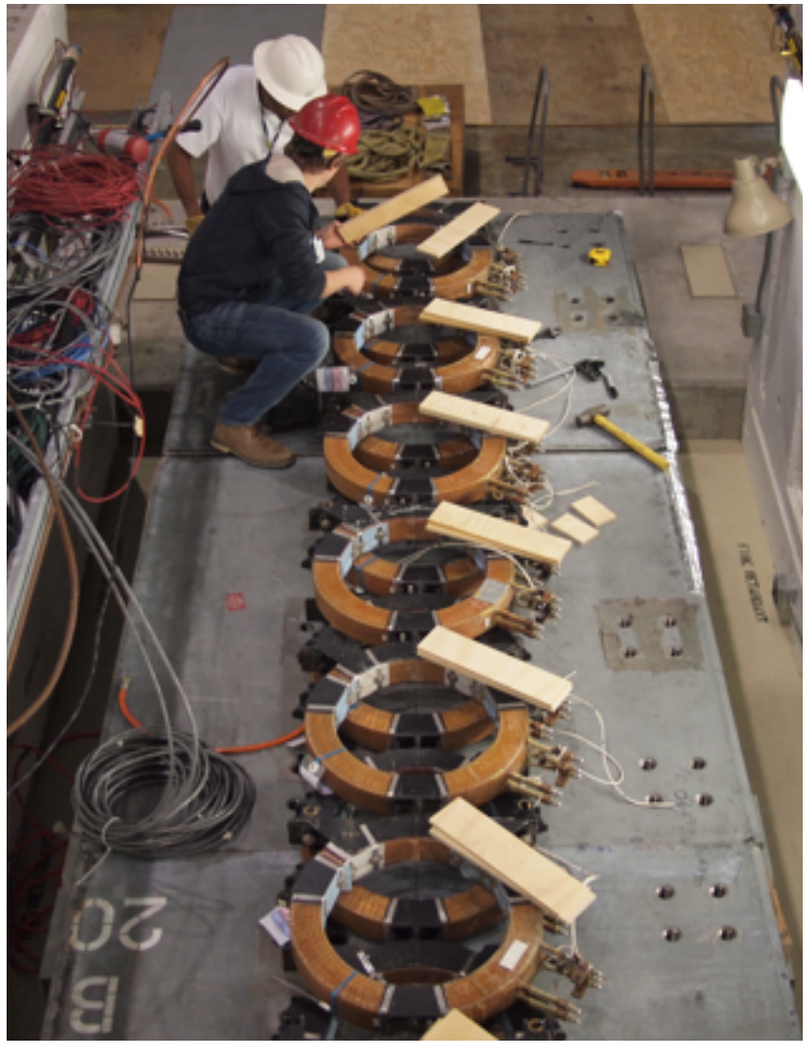
2-4 GHz Transition Radiation Antenna

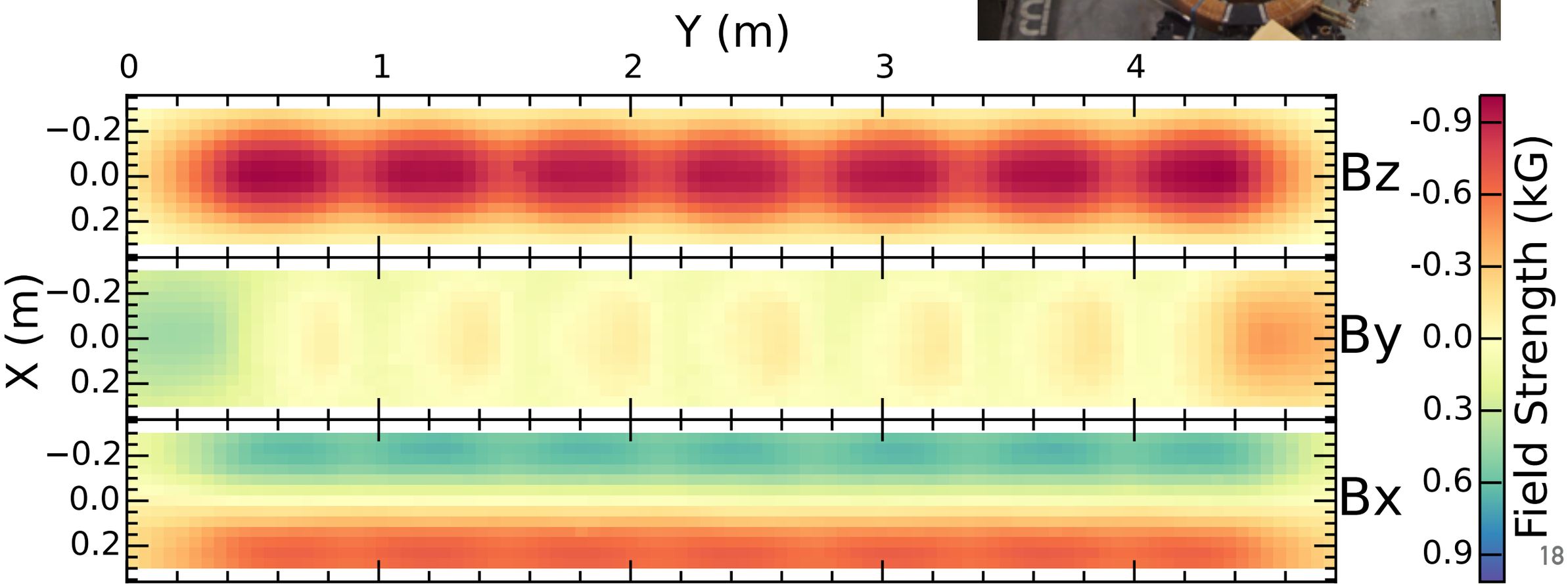




Magnetic Field

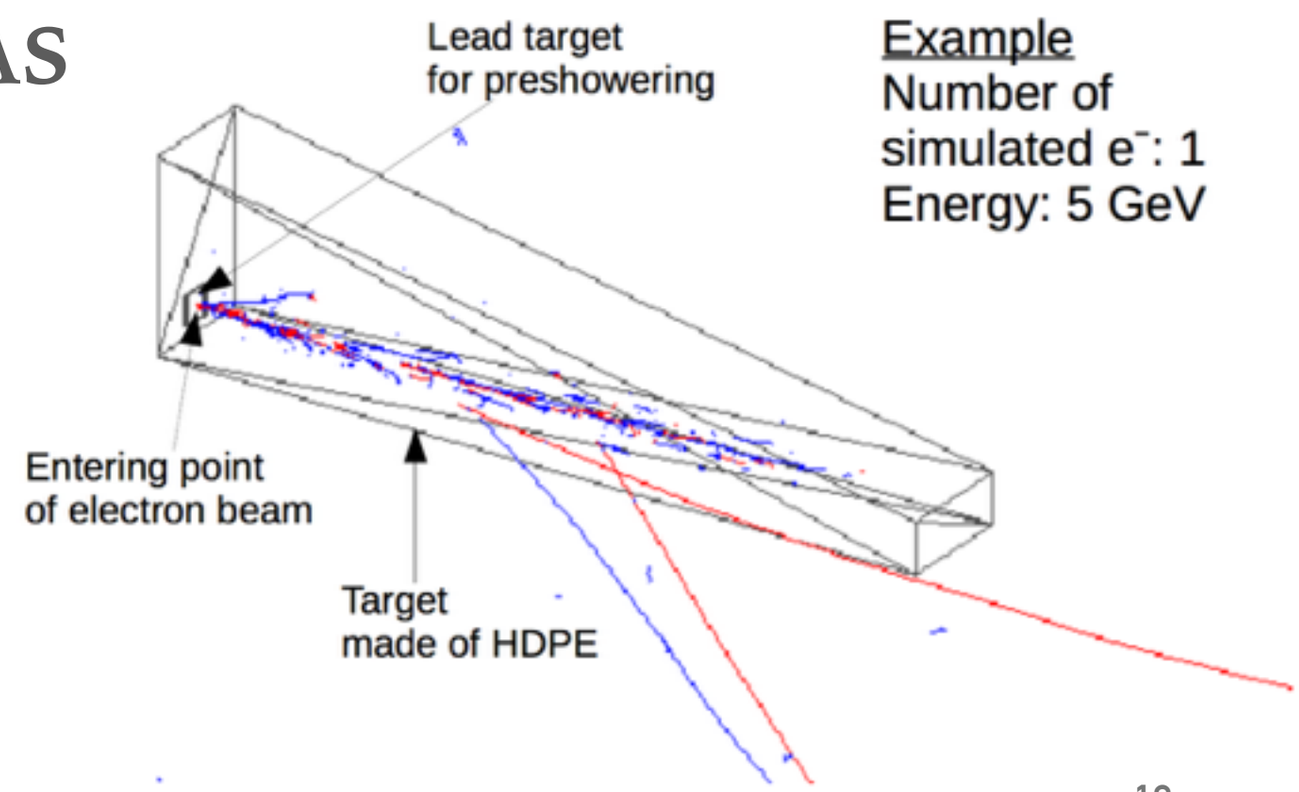
- 15 water-cooled stacked solenoids
- Vertical magnetic field ≤ 970 G





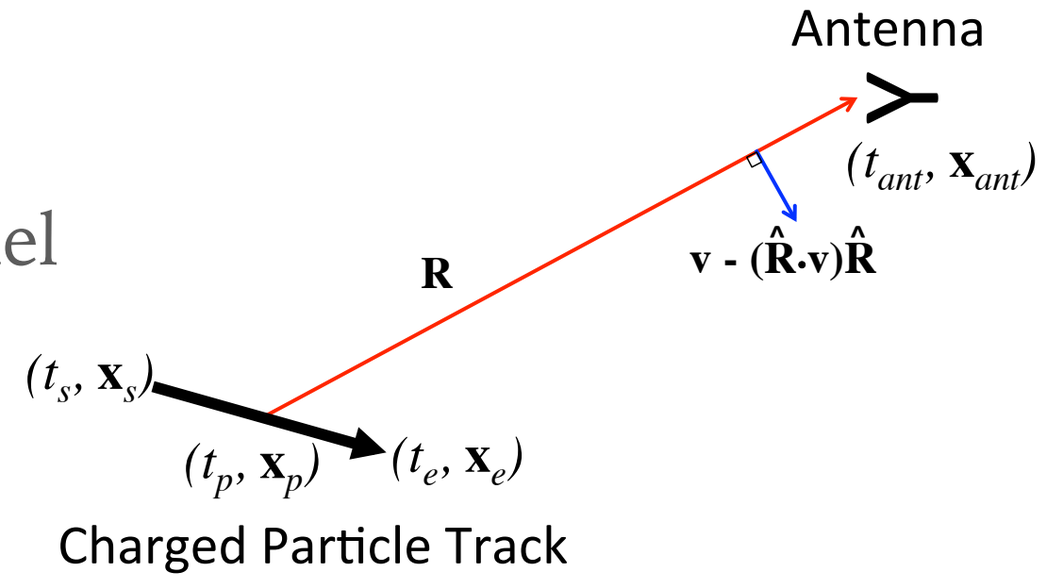
Air Shower Simulations adapted for T-510

- Radio-frequency emission codes based on track-level calculations of RF emission used in extensive air shower simulations.
- **Formalisms**:
  - **ZHS** used in **ZHSAires**
  - **Endpoints** used in **CoREAS**
- Particle showers simulated with GEANT4

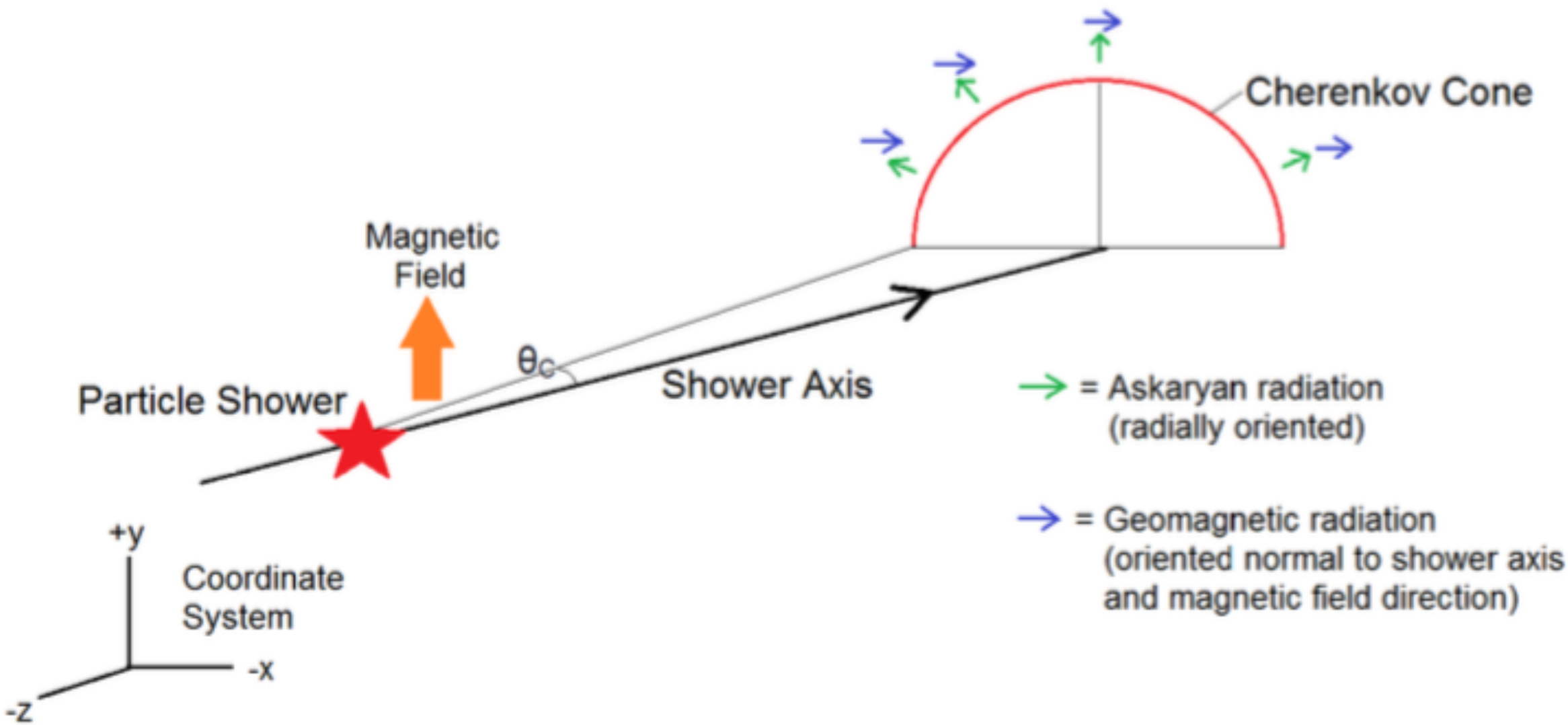


Track-Level Model Details

- Divide particle trajectories up into tracks, sum the radiation for all tracks
- RF emission calculated from first principles, with no free parameters
- Includes:
  - Full measured magnetic field model
  - Refraction
  - Fresnel tranmission
  - De-magnification effects
  - Transition Radiation estimated with Endpoints → 1% percent

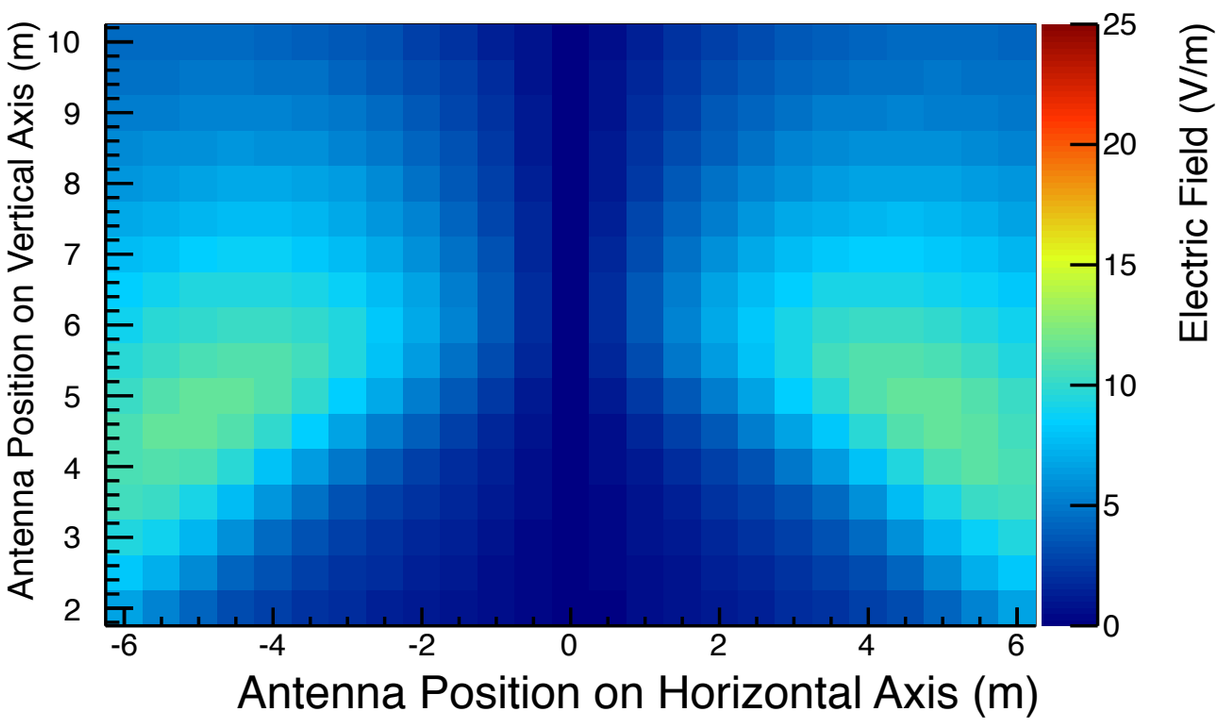


Signal Polarization

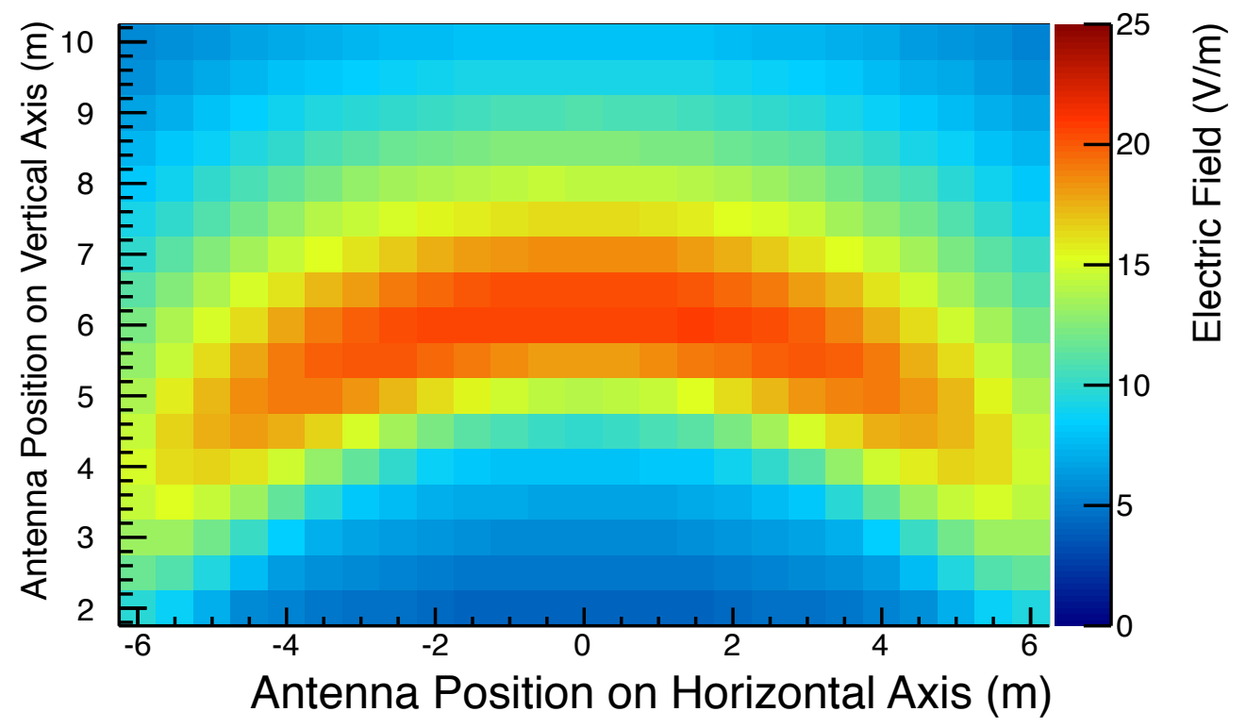


Simulated Emission: No Magnetic Field

Hpol

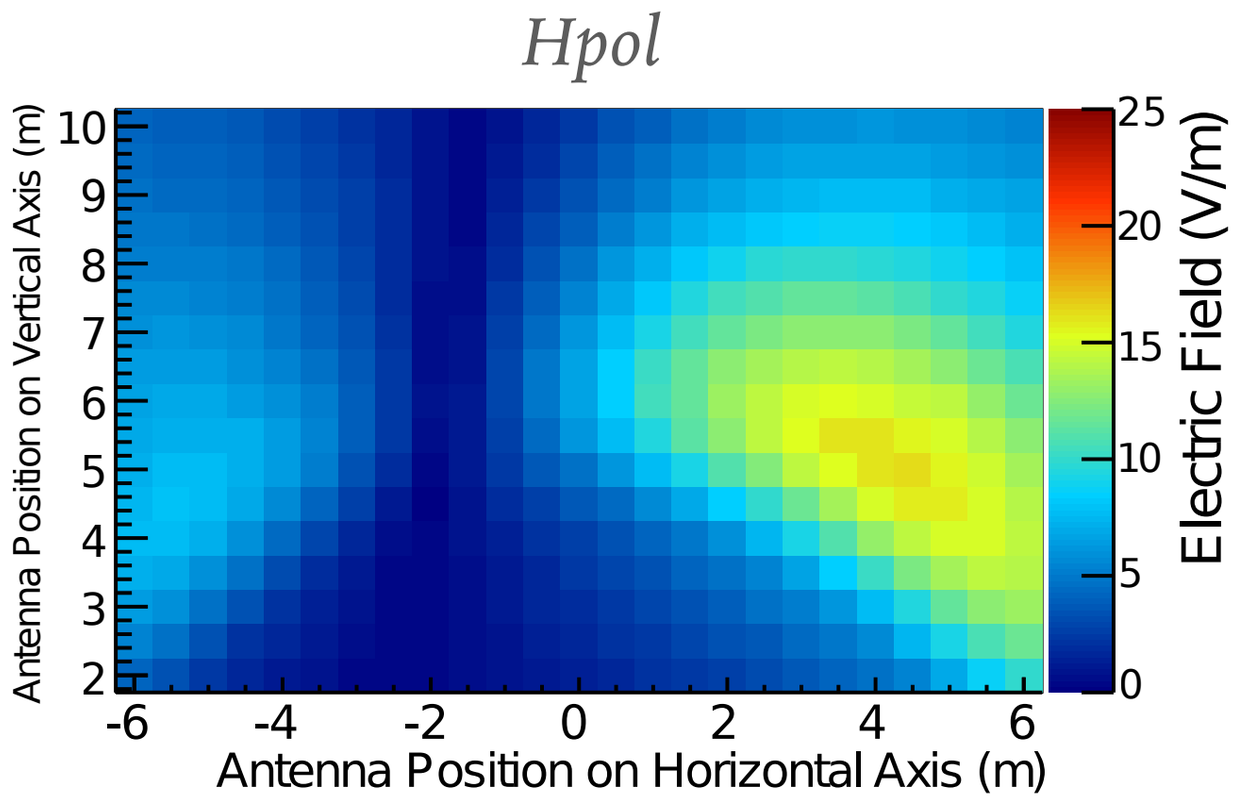


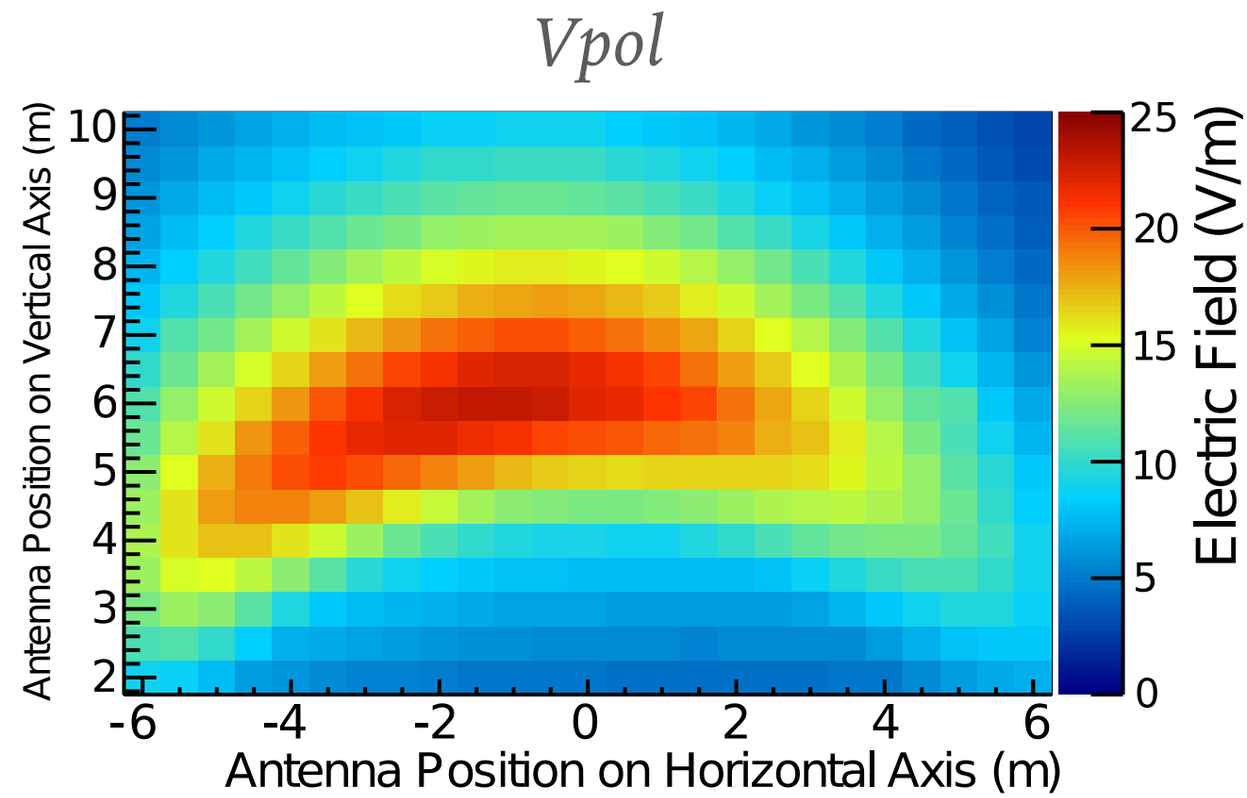
Vpol



T-510 Collab. in prep, 2016, A. Zilles, ICRC 2015

Simulated Emission: Full B-Field





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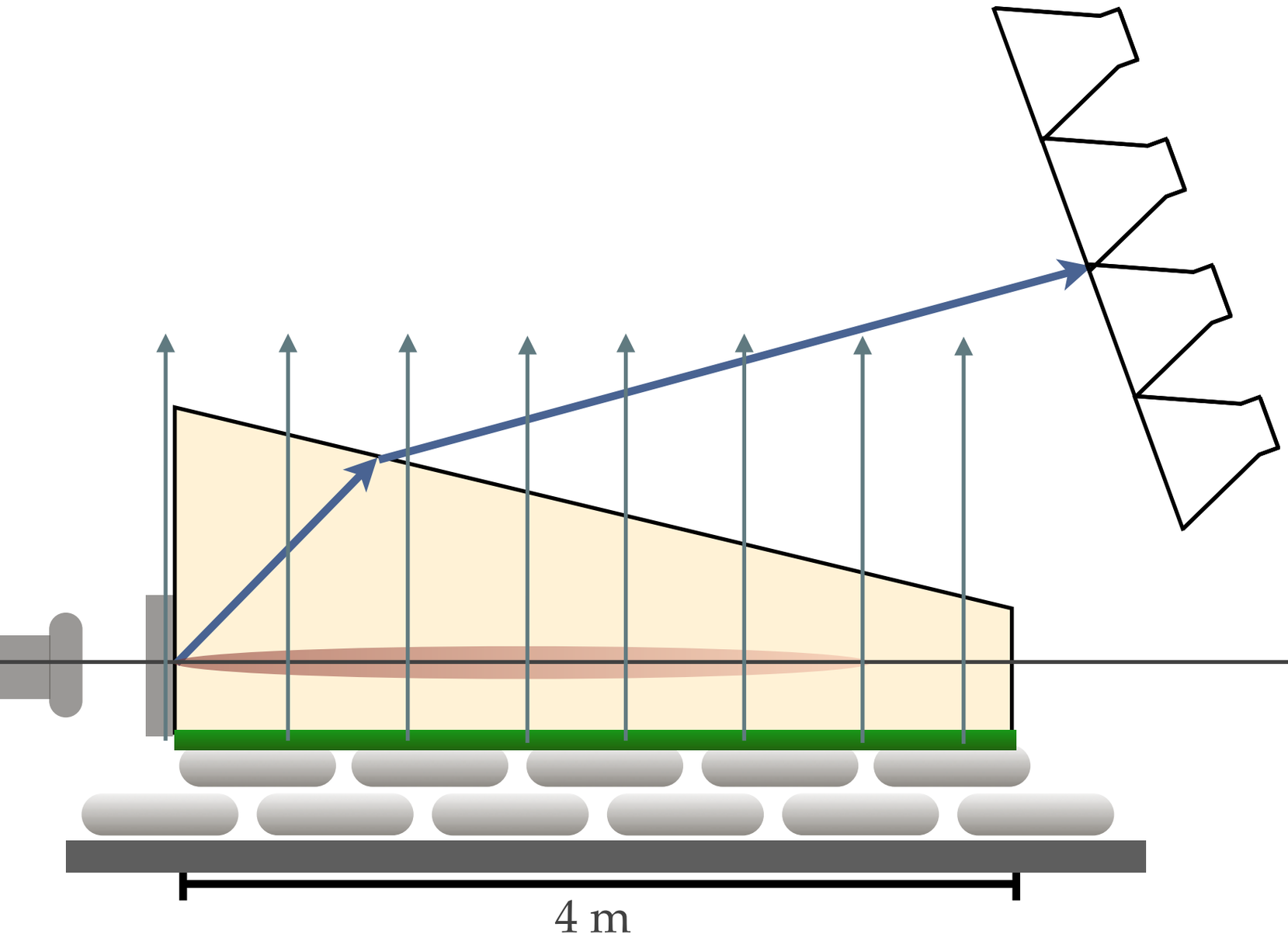
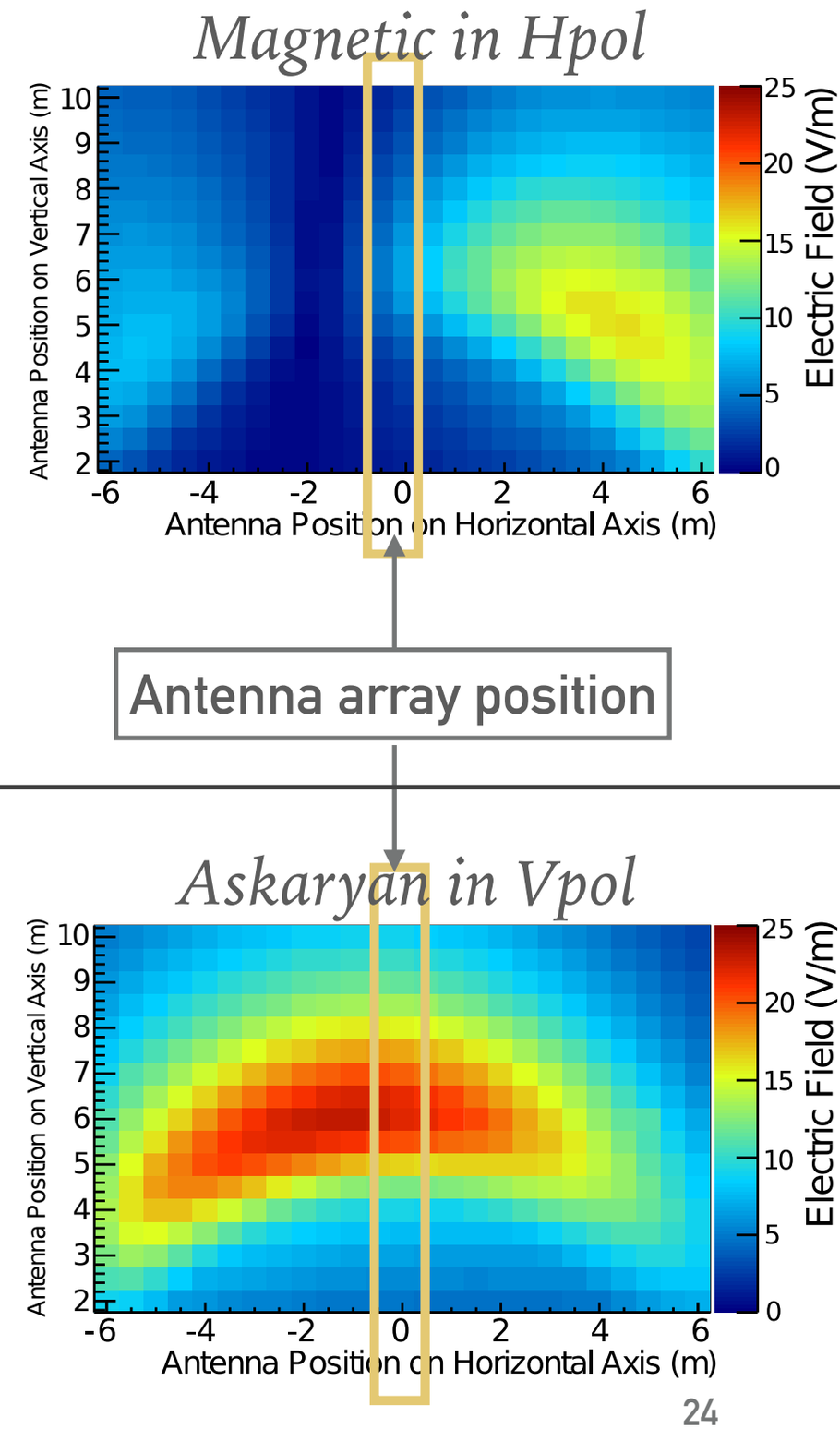
SEPARATING COMPONENTS* BY DESIGN

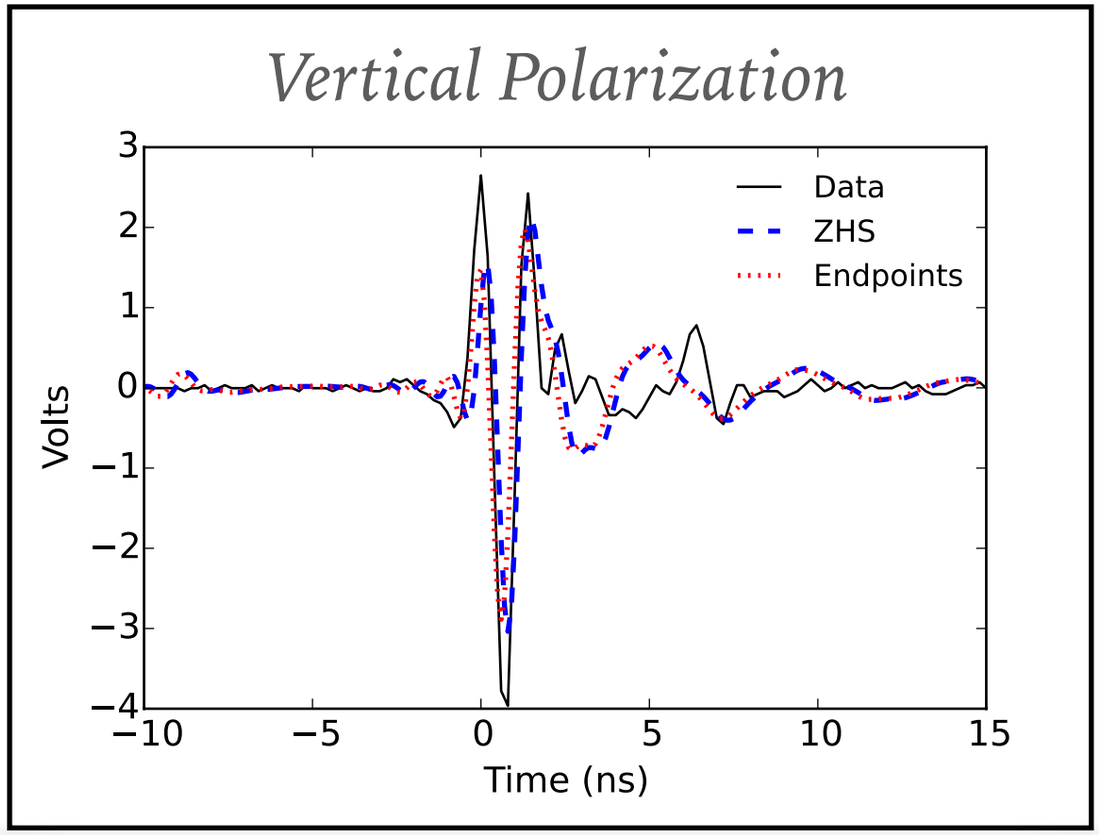


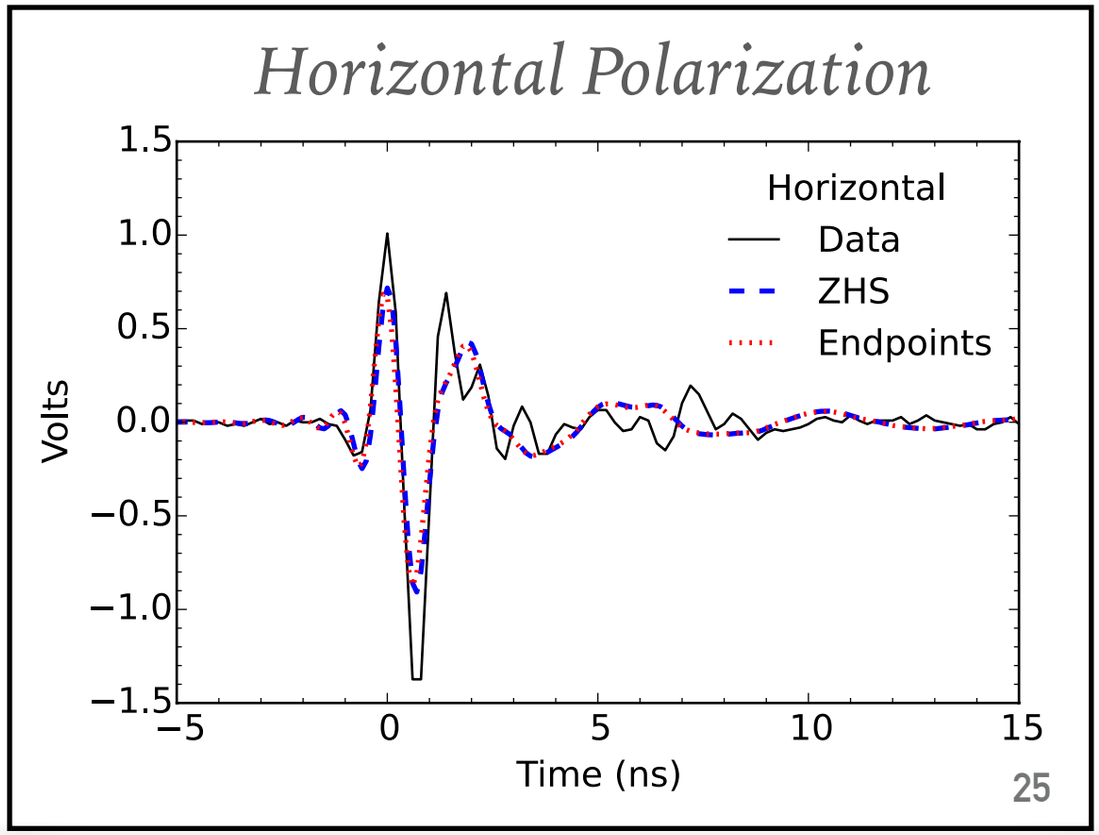


** In practice: compare full simulations to measurements*

On the Cherenkov Cone

- ZHS & Endpoints agree within 7% over 300-1200 MHz spectral band
- Reflections (~1ns, 6ns) evident in measured spectra and and waveforms → 40% systematic uncertainty
- Disagreement in peak amplitude between data and simulations is 35%

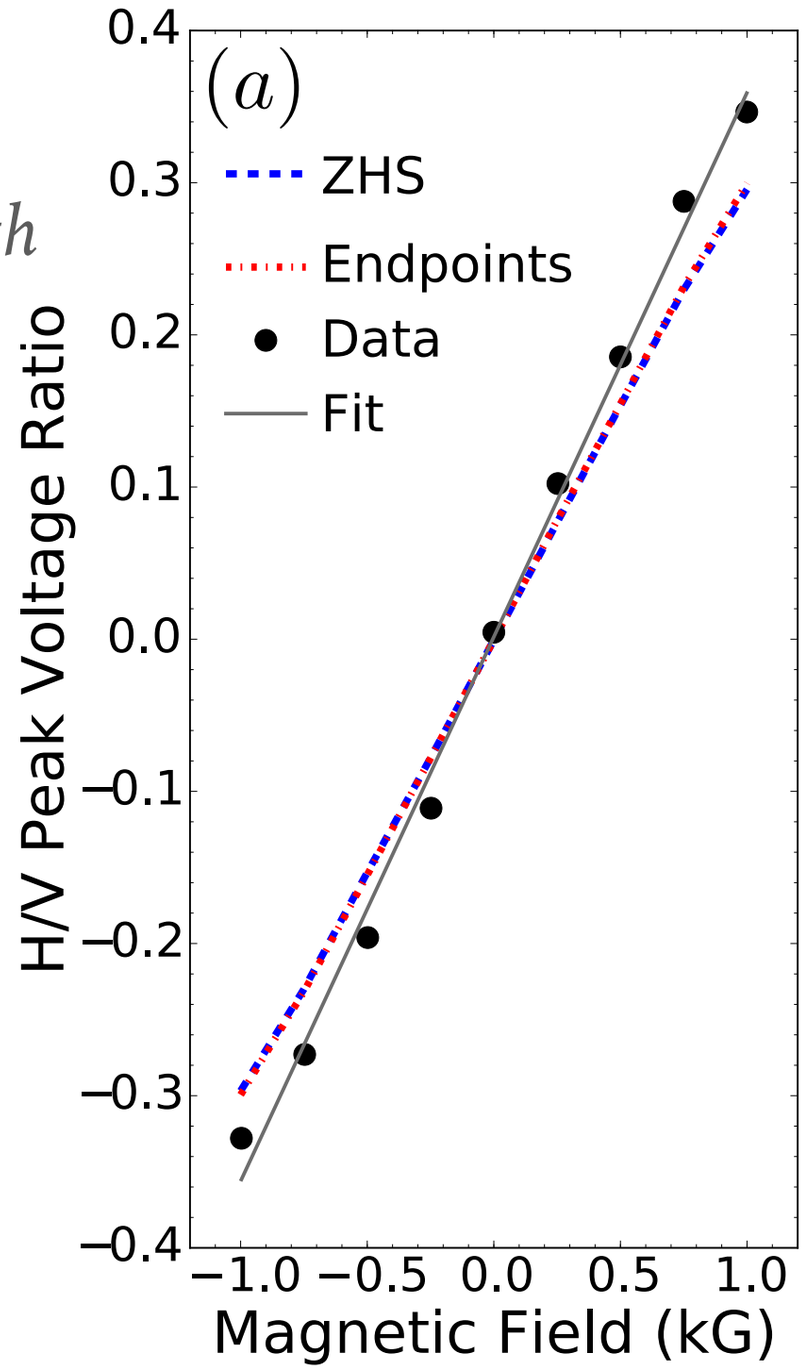


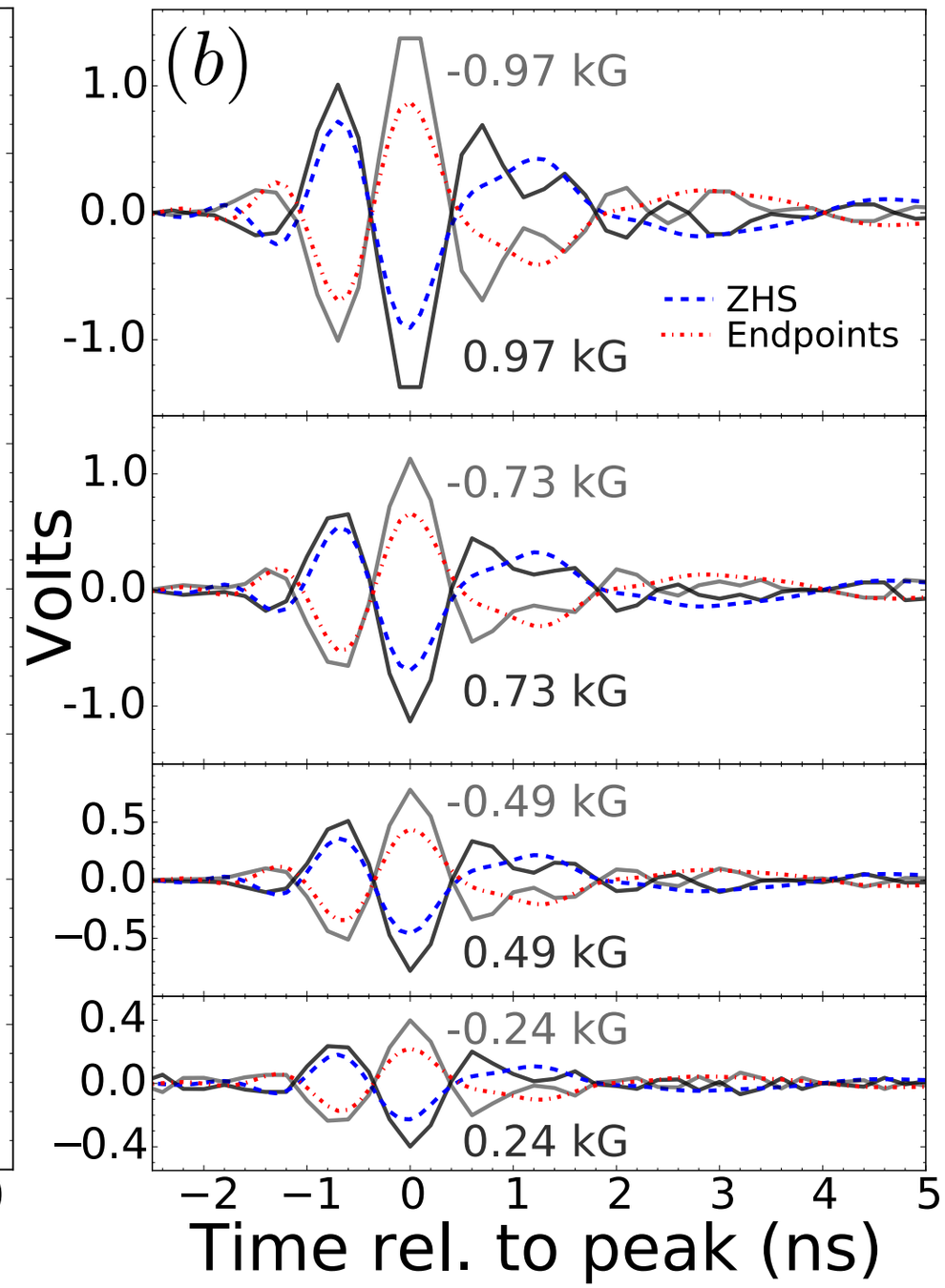


Scaling with Magnetic Field Strength

Vpol constant with increased B

H/V scales linearly with B

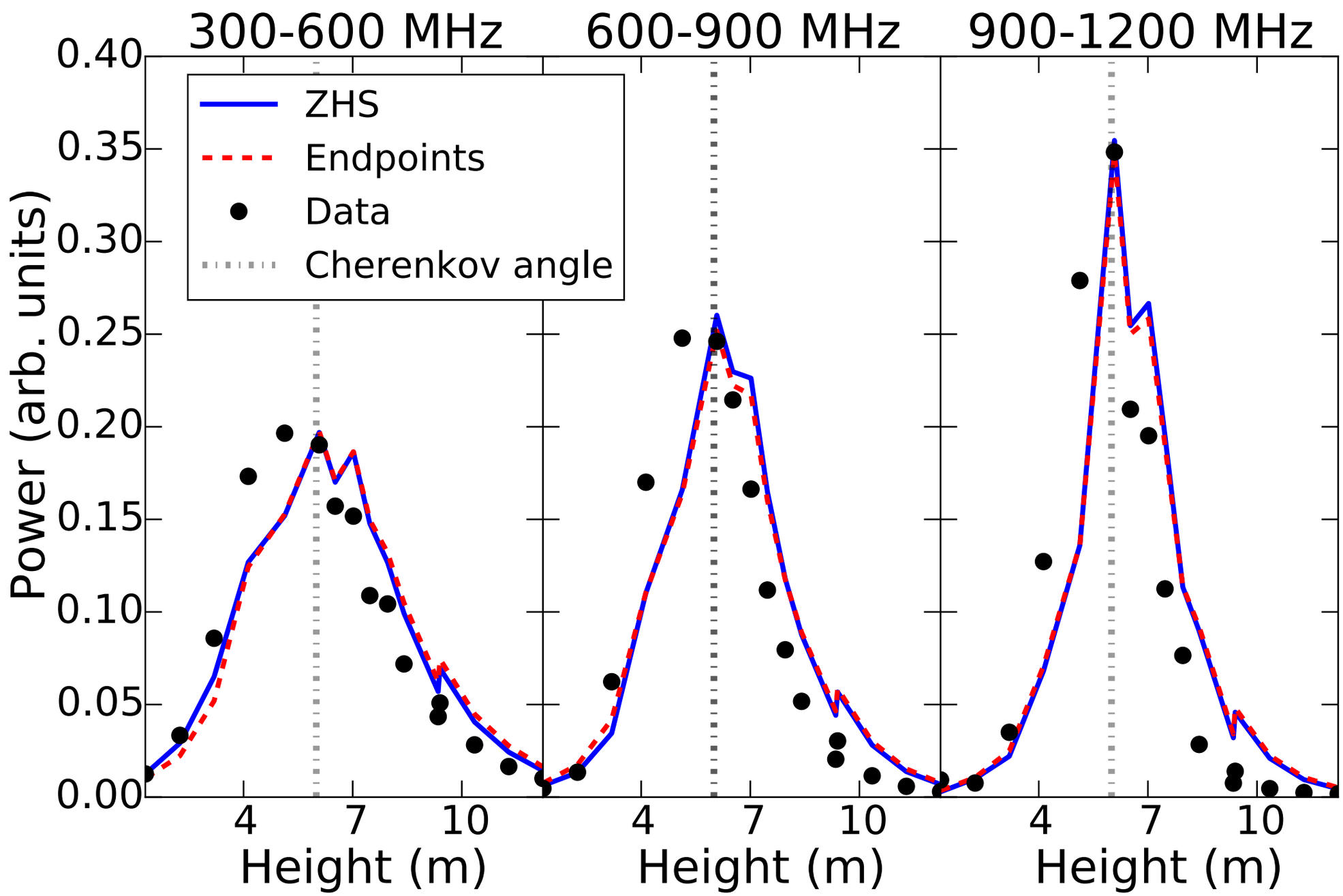




Sign reversal when flipping direction of magnetic field

Linearity confirms currents paradigm!

Magnetic Radiation Beam Pattern



Magnetic emission forms a Cherenkov cone!

Comparison to Air Shower Experiments

Experiment	δf (MHz)	θ_C	δθ
LOPES	43-74	1°	2°
LOFAR	110-190	1°	<1°
ANITA	200-1200	1°	<1°
T-510	300-1200 / 10-60	49°	5°

$\delta\theta > \theta_C$

→ *Filled in Cherenkov cone*

$\delta\theta < \theta_C$

→ *Cherenkov annulus*

Conclusions about the T-510 Experiment

- **First laboratory experiment** of RF emission from particle showers in magnetic field
- **Complements** cosmic-ray air showers observations:
  - Different systematics
  - Insensitive to hadronic physics & uncertain shower geometries
- **Agreement** between first principles RF models and accelerator data to **within systematic uncertainty**
- Hpol Scaling with magnetic field + RF Component separation confirms current paradigm
- Observed Cherenkov cone emphasizes importance of certain details (*e.g.*, index of refraction)