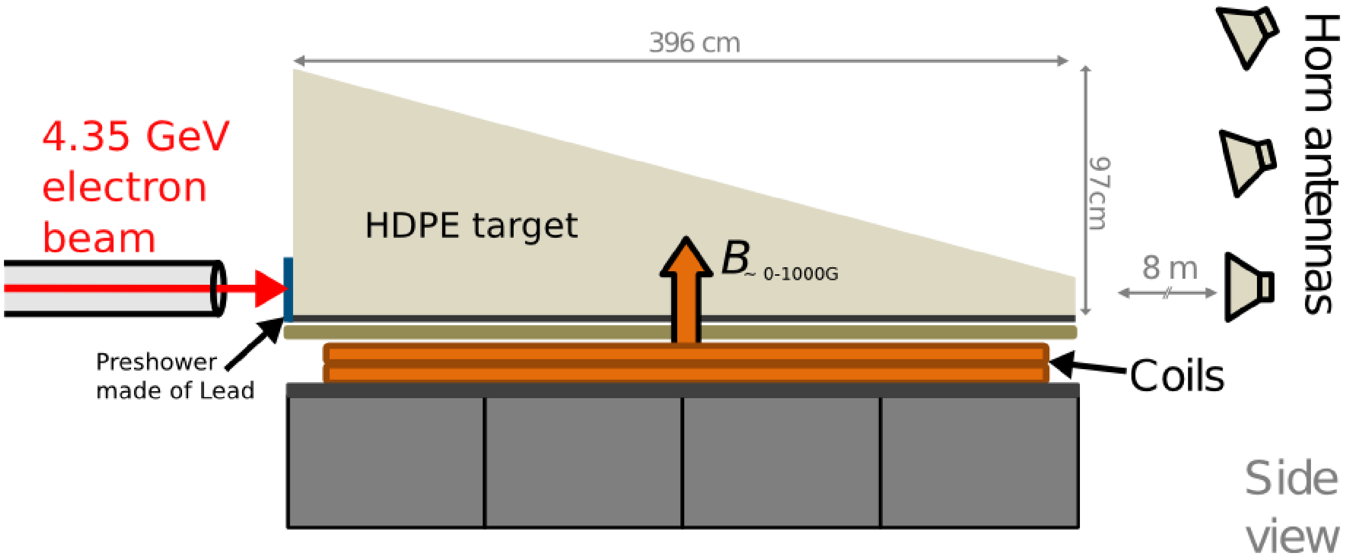
Geant4 simulations of radio signals from particle showers for the SLAC T-510 experiment

Anne Zilles for the SLAC T-510 Collaboration
ARENA 2014, June 9th

Institut für Experimentelle Kernphysik (IEKP), KIT

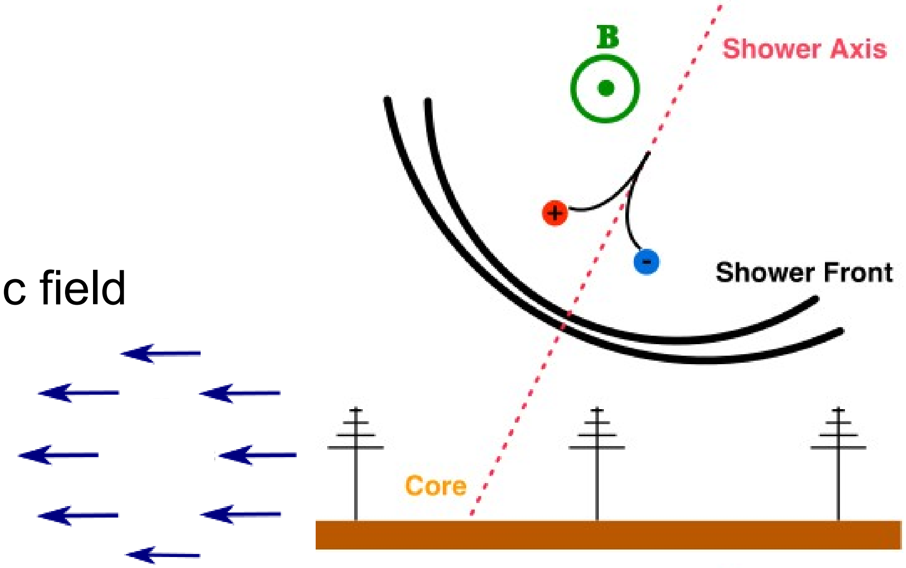


Emission of radio signals from air showers

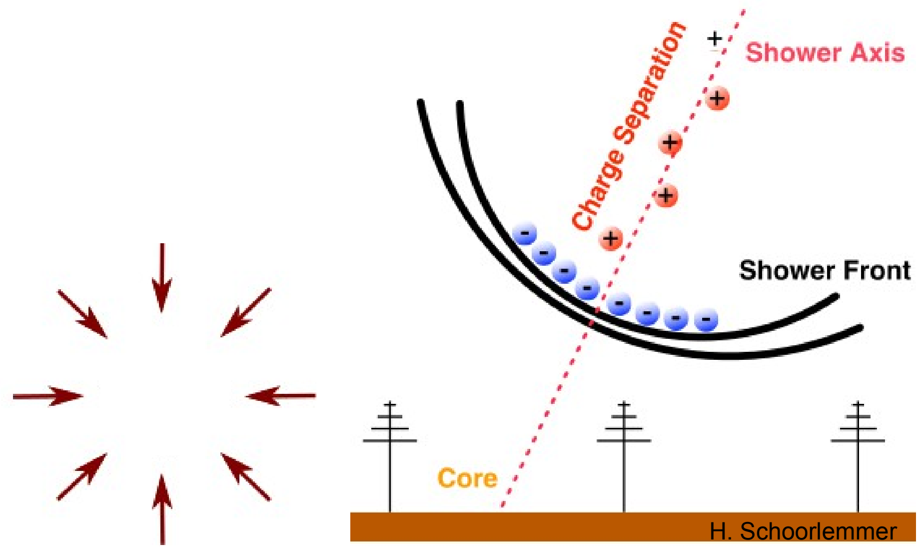
Karlsruhe Institute of Technology

- Coherent at MHz frequency
- two main emission mechanisms:

1. Geomagnetic emission
Deflection of e^- and e^+ in Earth´s magnetic field
→ time dependent transverse current,
linearly polarised $\vec{E} \propto \vec{v} \times \vec{B}$



2. Askaryan effect
Time variation of net charge excess
→ linearly polarised,
$\vec{E}$ radial oriented around shower axis



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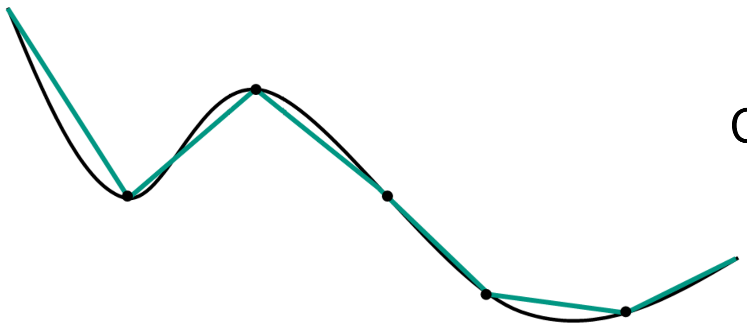
Simulation scheme

- Comparison of measured data and simulation results of air showers
  → How well can we describe the physics with our models

- Used programs for simulation of extensive air showers
  → **AIRES** (AIR-shower Extended Simulations) [arXiv:astro-ph/9911331v1]
  → **CORSIKA** (COsmic Ray SImulations for KAscade) [https://web.ikp.kit.edu/corsika/]



Continuous trajectories of particles
→ split into subtracks

Basis for calculation of radio emission by particle showers:

ZHS (ZHAireS) [arXiv:1107.1189]
Endpoint (CoREAS) [arXiv:1301.2132v1]

Test formalisms under controlled lab conditions
→ Goal: Do these formalisms reproduce the measured data?

See: Contributions of Konstantin Belov and Clancy James, ARENA 2012

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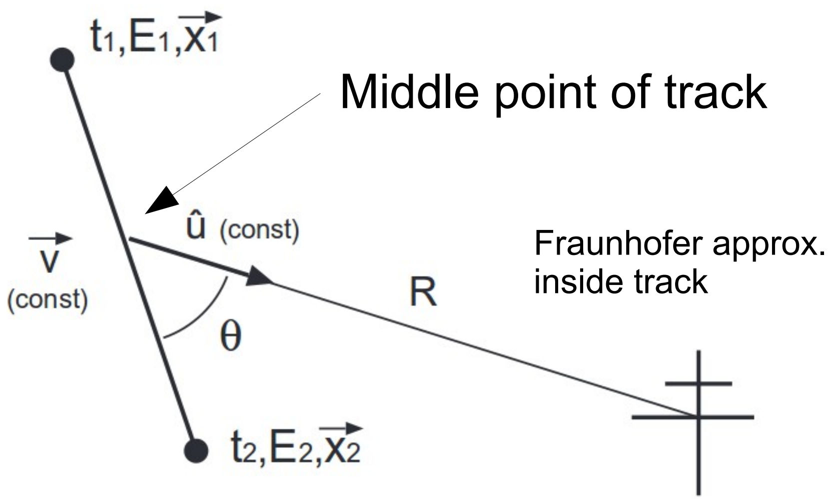
ZHS formalism (ZHAireS)



$$\vec{A}(t,\hat{u}) = \frac{\mu e}{4\pi R c}\vec{\beta}_{\perp}\frac{\Theta(t-t_1^{det})-\Theta(t-t_2^{det})}{1-n\vec{\beta}\cdot\hat{u}}$$

$$\vec{\beta} = \vec{v}/c, \quad \vec{\beta}_{\perp} = -\left[\hat{u}\times(\hat{u}\times\vec{\beta})\right]$$

$$t_{1,2}^{det} = t_{1,2} + nR/c - n\vec{\beta}\cdot\hat{u}(t_{1,2}-t_0)$$

Time derivative: $$\vec{E}(t,\hat{u}) = -\frac{\mu e}{4\pi R c}\vec{\beta}_{\perp}\frac{\delta(t-t_1^{det})-\delta(t-t_2^{det})}{1-n\vec{\beta}\cdot\hat{u}}$$

[see: Astroparticle Physics 35 (2012) 325–341]

Radiation from the 'particle track'

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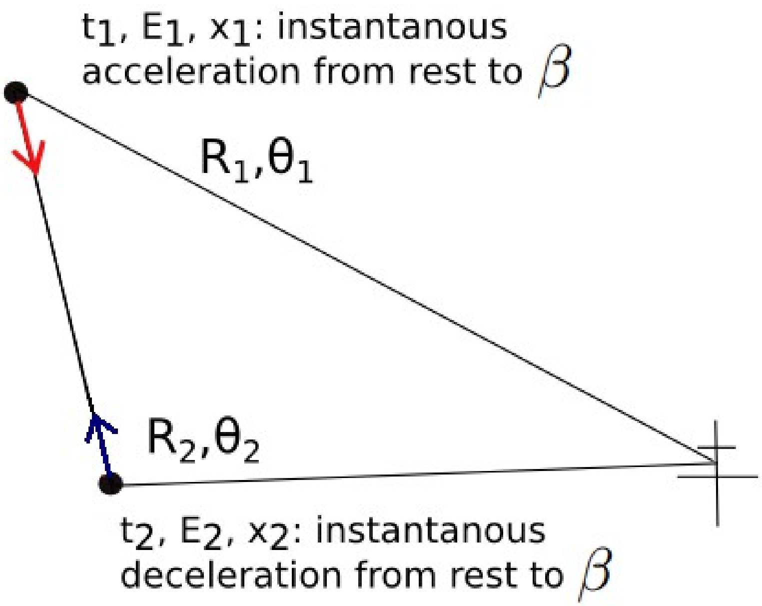
Endpoint formalism (CoREAS)



Instantaneous @ Endpoints:

- acceleration from rest to β
- deceleration from β to rest

(Production and annihilation taken into account)

$$\int \vec{E} dt = \frac{e}{cR_2}\left(\frac{\vec{r_2}\times(\vec{r_2}\times\vec{\beta})}{(1-n\vec{\beta}\vec{r_2})}\right) - \frac{e}{cR_1}\left(\frac{\vec{r_1}\times(\vec{r_1}\times\vec{\beta})}{(1-n\vec{\beta}\vec{r_1})}\right)$$

with $\delta t \ll \frac{1}{\nu_{\text{observed}}}$

[see: arxiv:1007.4146]

Radiation from the 'implied' acceleration at the 'endpoints' of a track

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Experiment T510 @ SLAC

Goal: Testing the MC-Simulations under controlled lab conditions

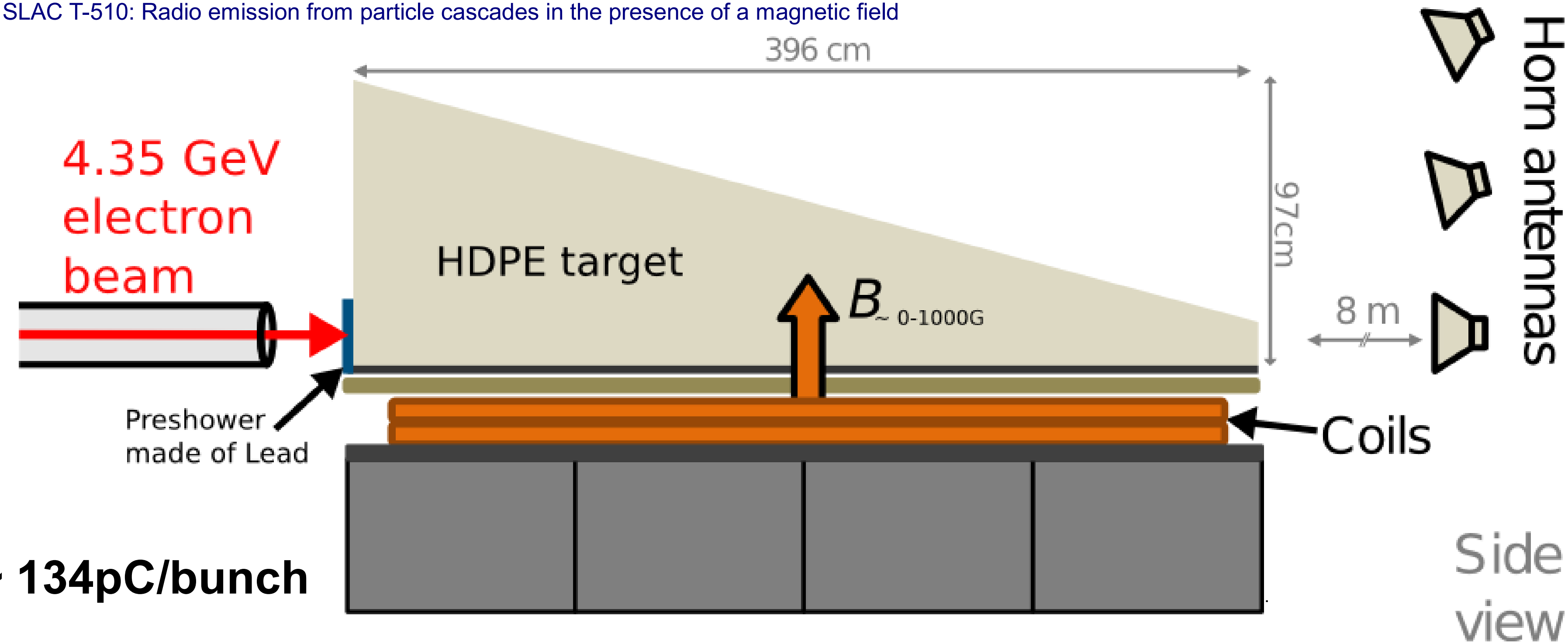
→ produce an extensive shower by a primary particle of known energy, in controllable magnetic field

→ Comparison of measured data with predictions of MC-Simulations

→ Verify and calibrate MC-Simulations

Data taken: Jan./Feb. 2014

s. Talk: Katie Mulrey
SLAC T-510: Radio emission from particle cascades in the presence of a magnetic field



~ 134pC/bunch

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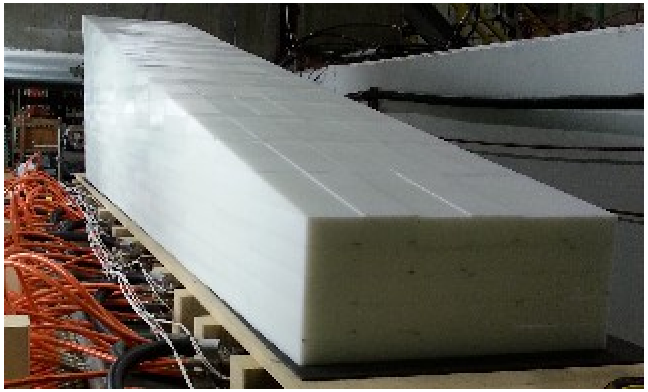
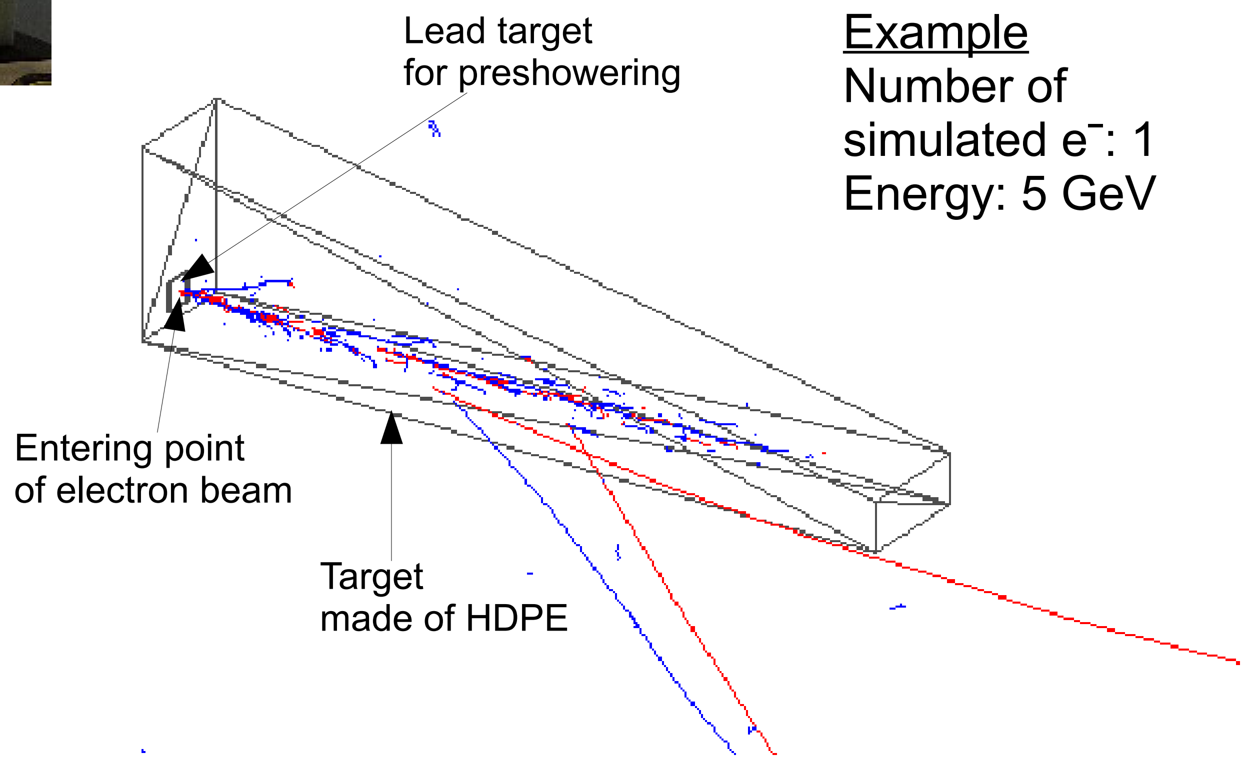
Simulation with Geant4



a toolkit for the simulation of the passage of particles through matter
→ propagation and interaction

→ Calculation of produced radio emission added, both formalisms parallel in one shower simulation

<u>Example</u>
Number of simulated e⁻: 1
Energy: 5 GeV



Blue: negatively charged particles
Red: positively charged particles

More about Geant4: http://geant4.web.cern.ch/geant4/

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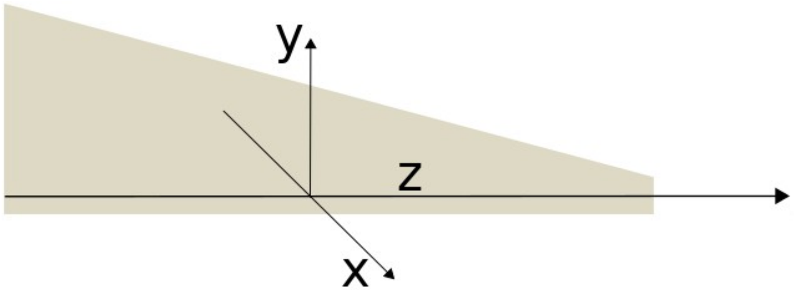
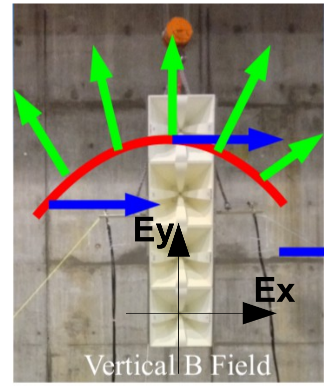
Simulation results





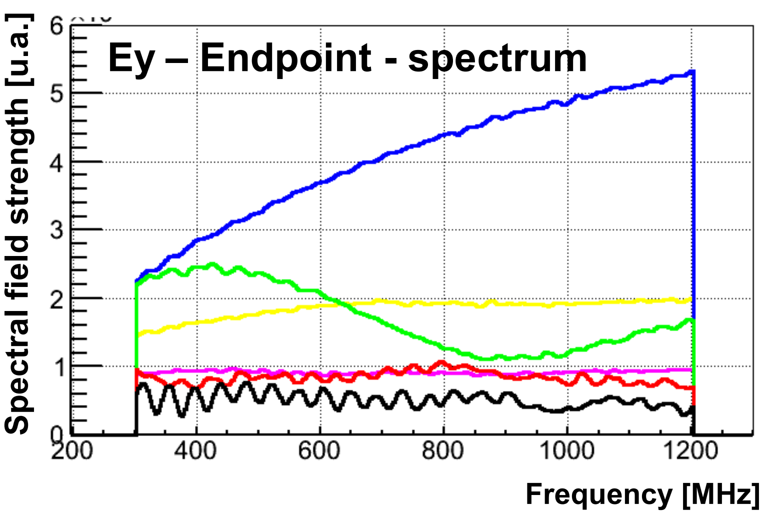
Cherenkov Cone
Askaryan
“Geo” Magnetic

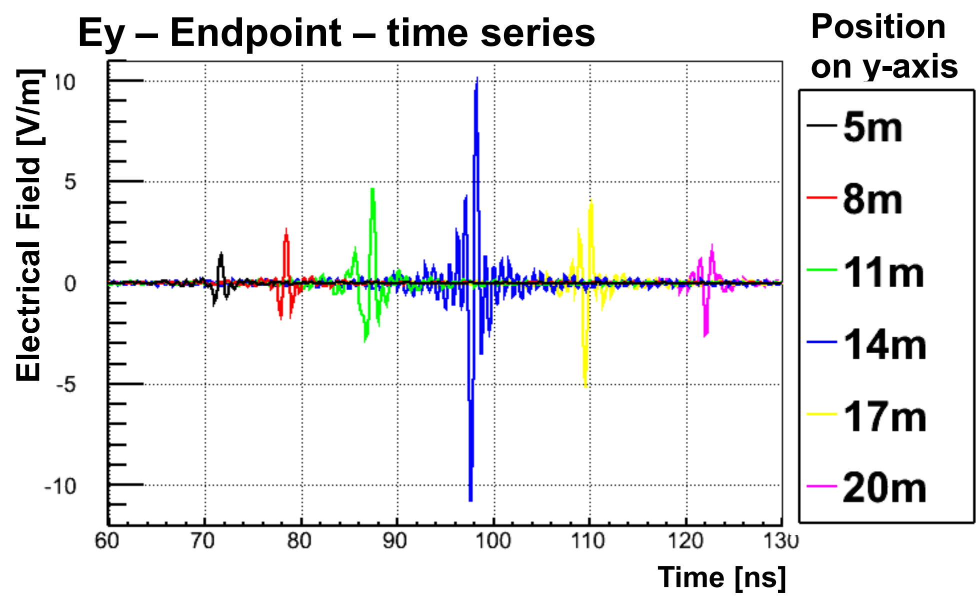
Rectangle filter:
300-1200MHz

No refraction at boundary of target taken into account

4.35GeV, 134pC, 0G ← No magnetic field

Antenna @ (0m, y*m, 11m)





→ **Strong signal visible on Cherenkov angle (Askaryan effect)**
→ **in agreement with expectations**

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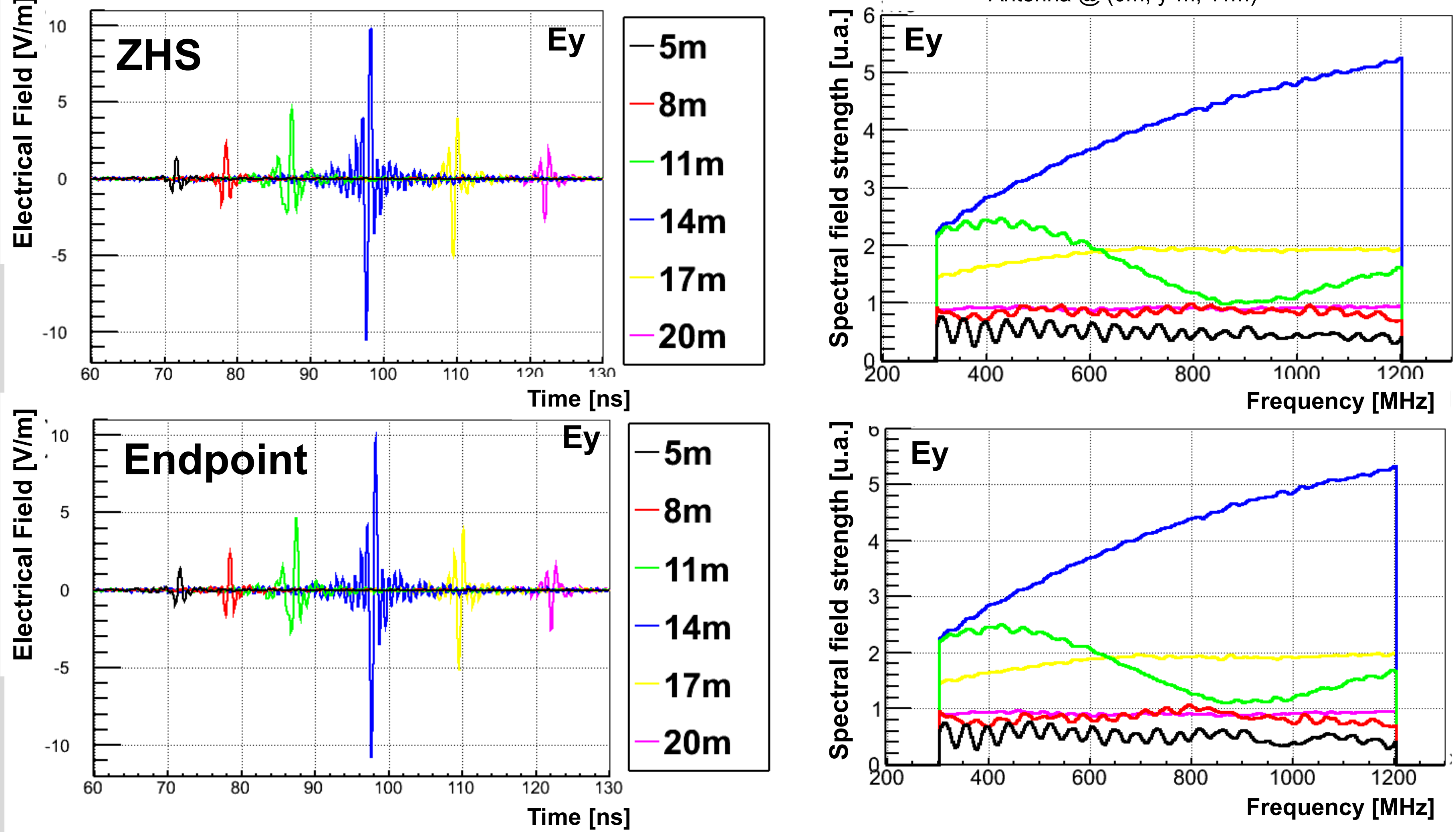
Comparison of formalisms to calculate radio emission

No refraction taken into account **Position on y-axis**

4.35GeV, 134pC, 0G
Antenna @ (0m, y*m, 11m)



Parallel implemented in simulation → 1to1 comparison possible!

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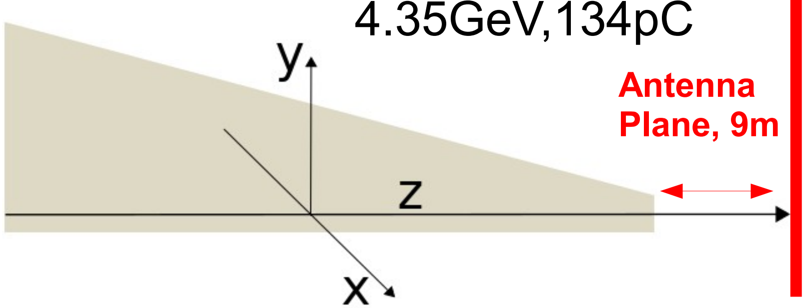
Comparison of time integrated Signal

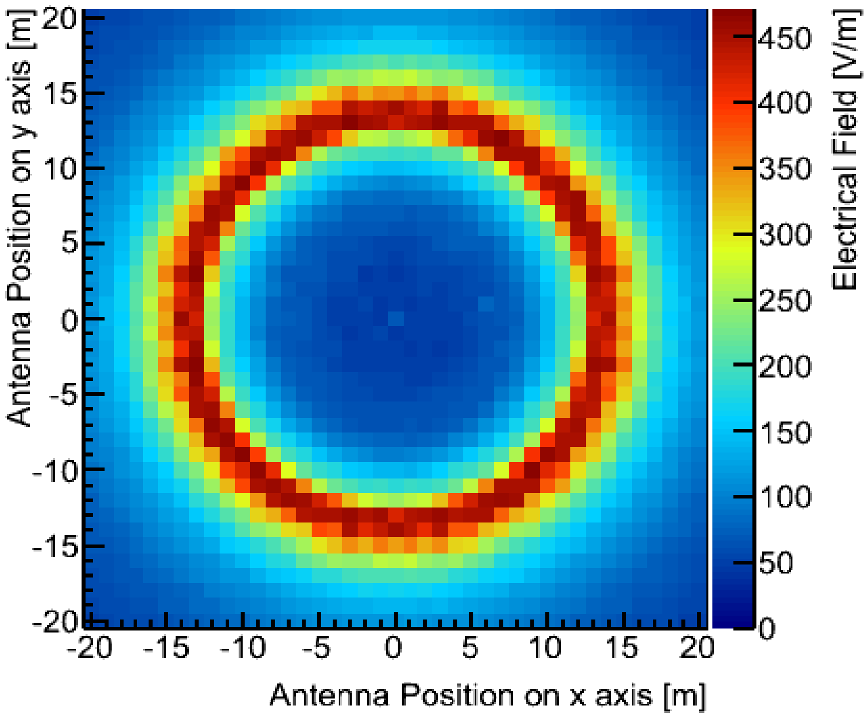
B = 0G
→ clearly visible Cherenkov ring
→ just Askaryan effect (linear pol.)

For both Formalisms!

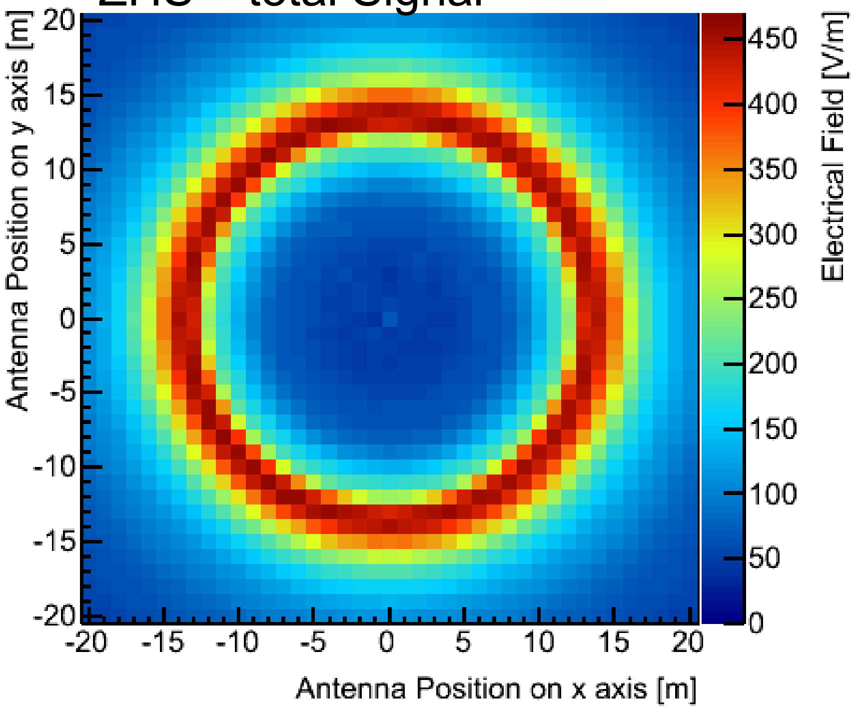
No refraction at the boundary of the target taken into account



Endpoint – total Signal



ZHS – total Signal



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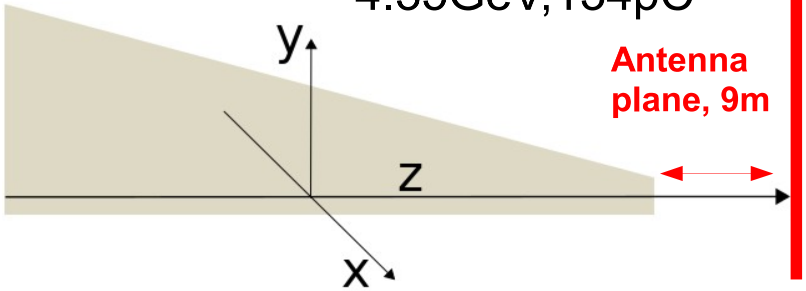
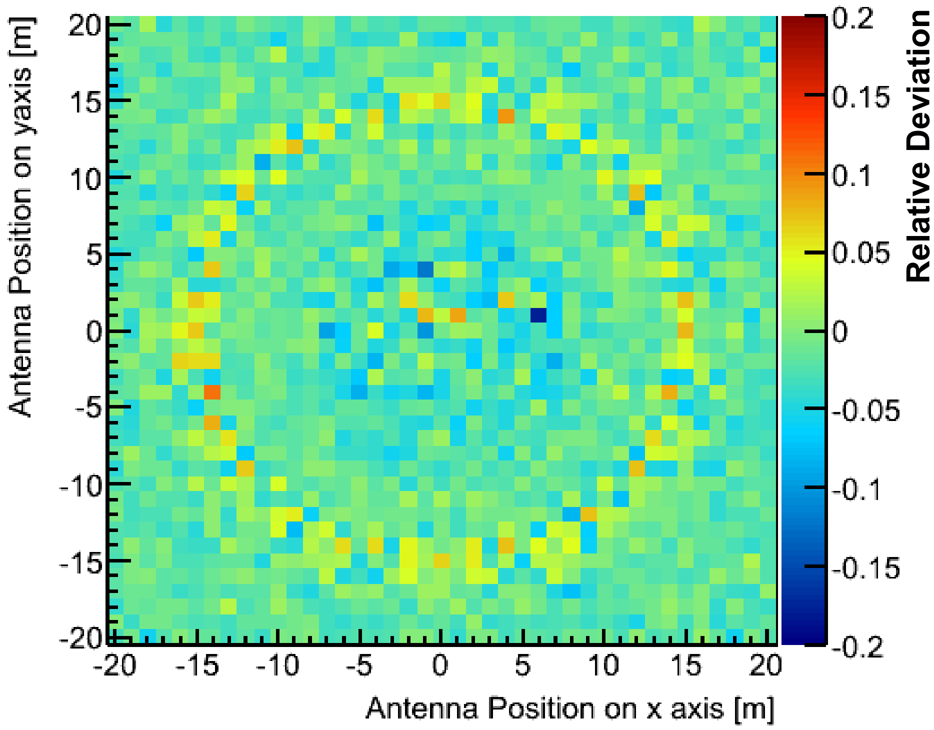
Difference of time integrated Signal

No refraction taken into account

4.35GeV,134pC



Substract: Endpoint - ZHS



Deviation in both directions

→ **ZHS and Endpoint are consistent in simulation results for electrical field Deviations ≤ 5%**

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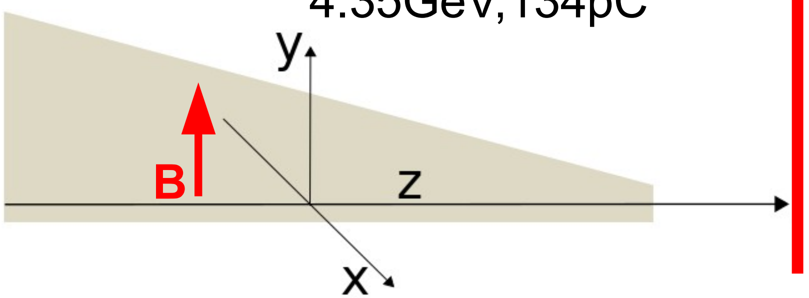
Influence of a magnetic field – time integrated Signal

No refraction taken into account

4.35GeV,134pC



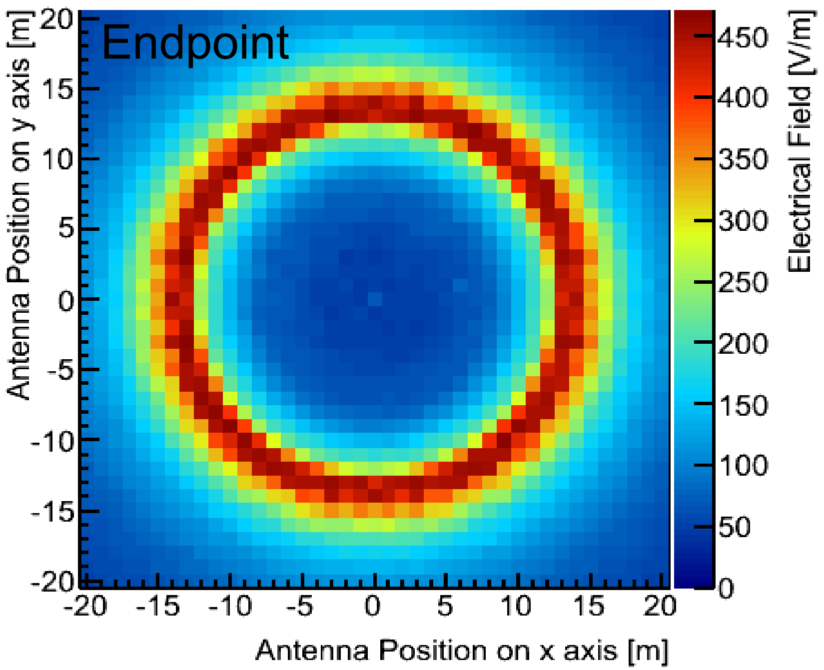
B = 0G

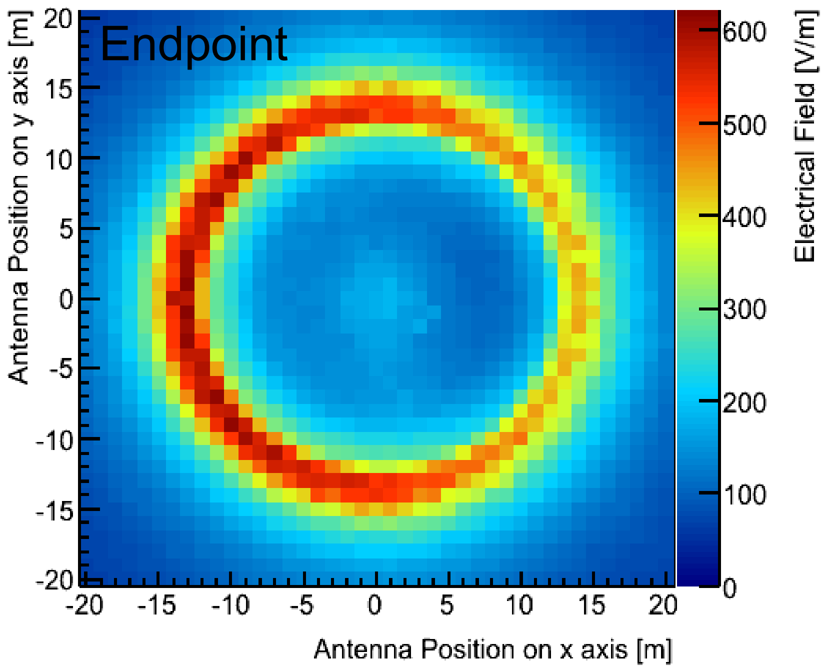
→ clearly visible Cherenkov ring

→ just Askaryan effect (linear pol.)

B = 1000G (s. Talk by K. Mulrey)

→ Superposition of "geo"magnetic Emission (radial pol.) and Askaryan effect





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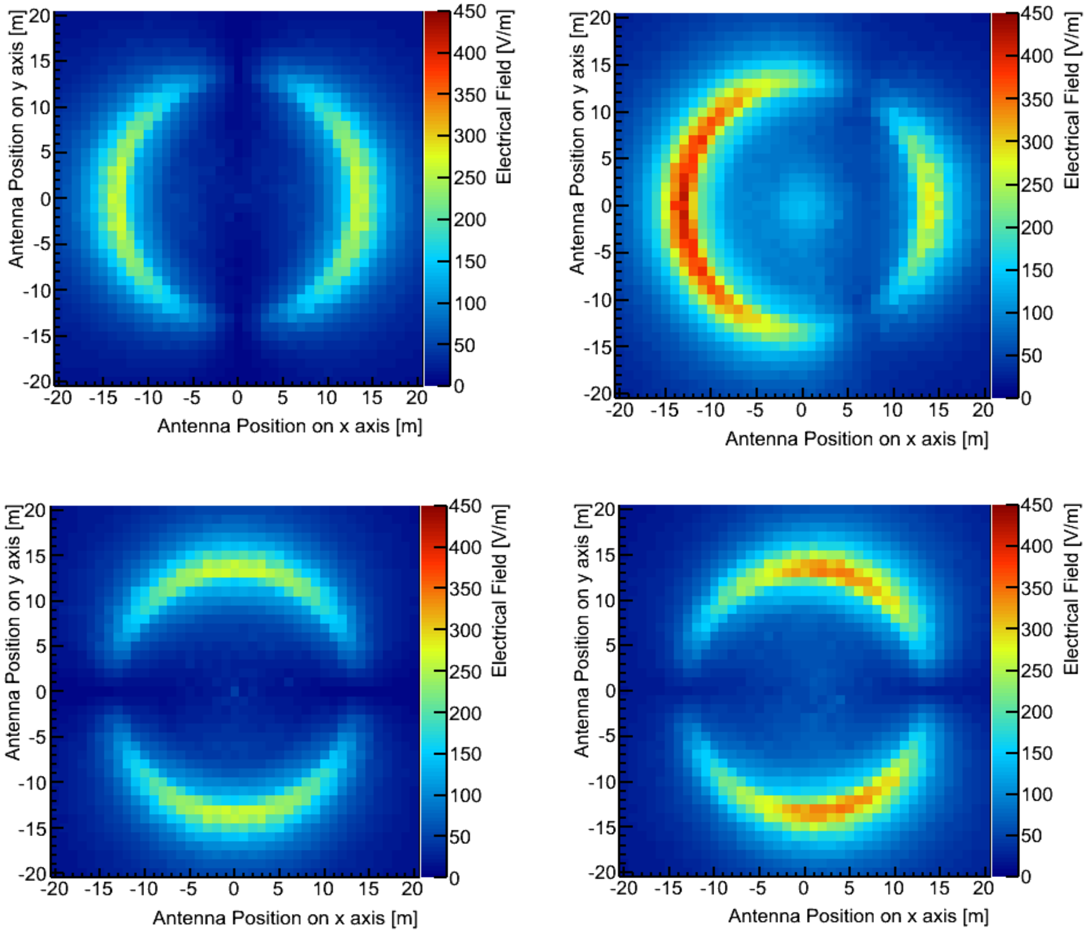
Influence of a magnetic field - Endpoint

0G

1000G

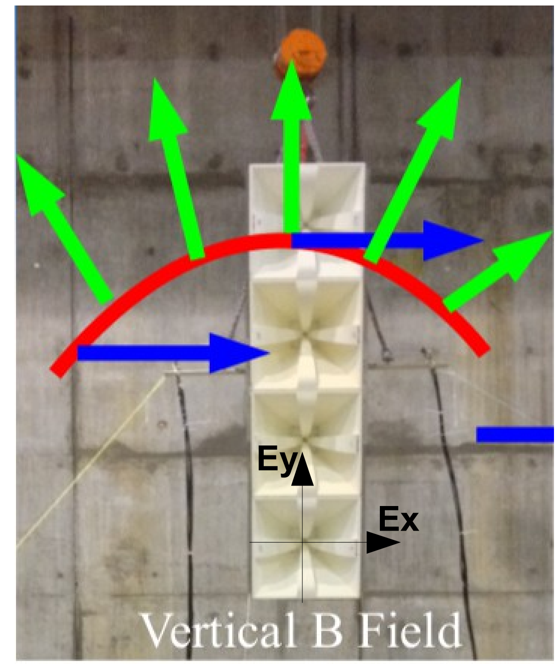
Ex

Ey



Askaryan

Askaryan +"Geo"Magnetic



Cherenkov Cone

Askaryan

“Geo” Magnetic

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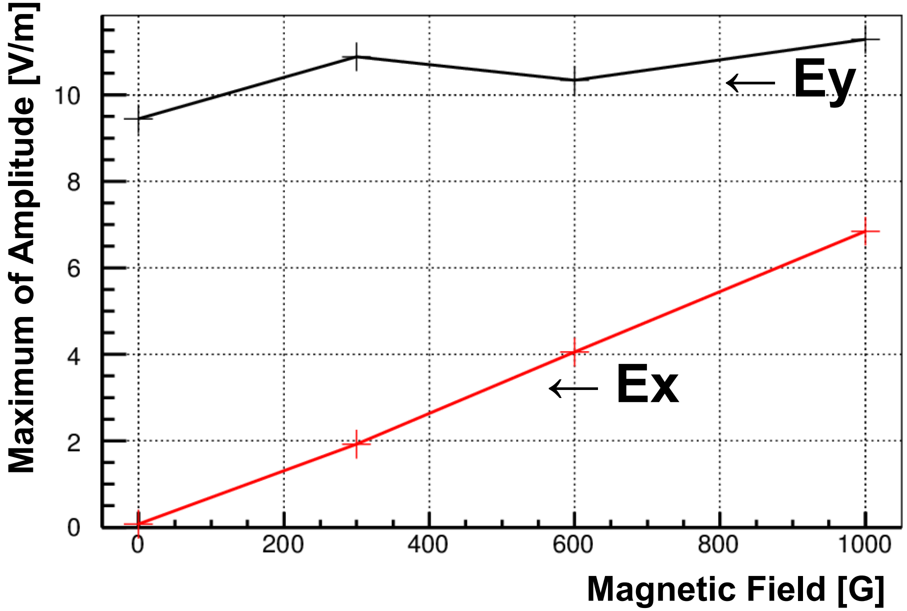
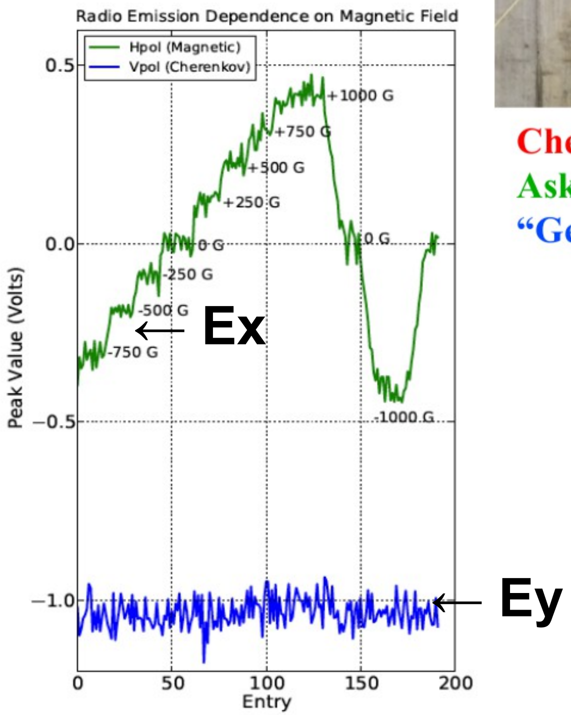
Electrical field strength in dependence of magnetic field strength

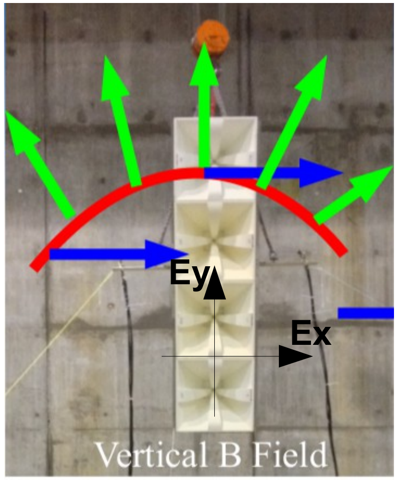
For measurements/simulation:

- Rising signal in horizontal component ("geo"magnetic effect) proportional to magnetic field strength!
- Signal in vertical component ≈ constant

On antenna on Cherenkov ring:







Cherenkov Cone
Askaryan
"Geo" Magnetic

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Summary and Outlook

- ✓ Testing formalisms by SLAC-T510
- ✓ Preparation of simulation studies using Geant4
  - → Clearly visible Cherenkov ring as expected
  - → Consistent simulation results for both used formalisms
  - → Strong signal dependency on magnetic field visible

➔ Refraction at the boundary of the target to be implemented
➔ Comparison of measured and simulated ablsolute amplitude of electrical field strength

Thank you for your attention!

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Appendix

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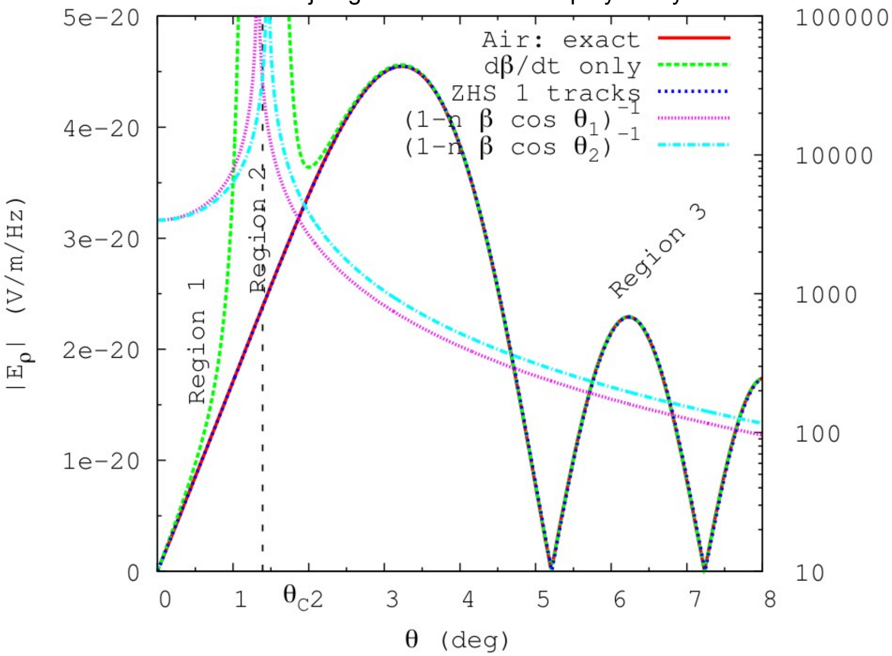
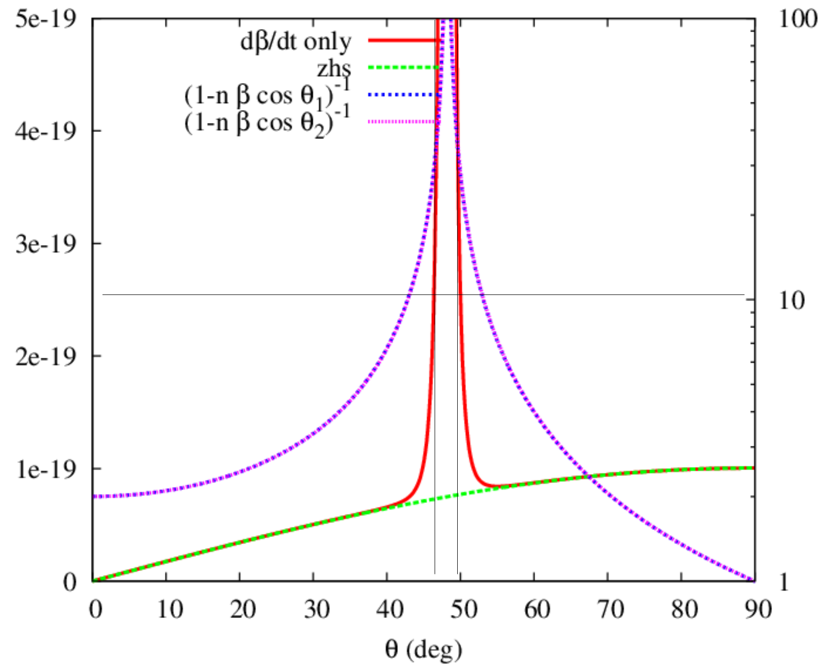
Divergence at Cherenkov angle for Endpoints

Presented at Nijmegen LOFAR workshop by Clany James





Plots made by Clancy James

For air shower close to Cherenkov angle:
Doppler factor > 1000
→ Fallback to ZHS-like calculation

Track length: 780m
Distance to Observer: 8km
Frequency: 100MHz
Refractive Index: 1.0003

For HDPE, close to Cherenkov angle:
Doppler factor > 10
→ Fallback to ZHS-like calculation
~ 4-5° around Cherenkovring

Track length: 1cm
Distance to Observer: 10m
Frequency: 1GHz
Refractive Index: 1.5

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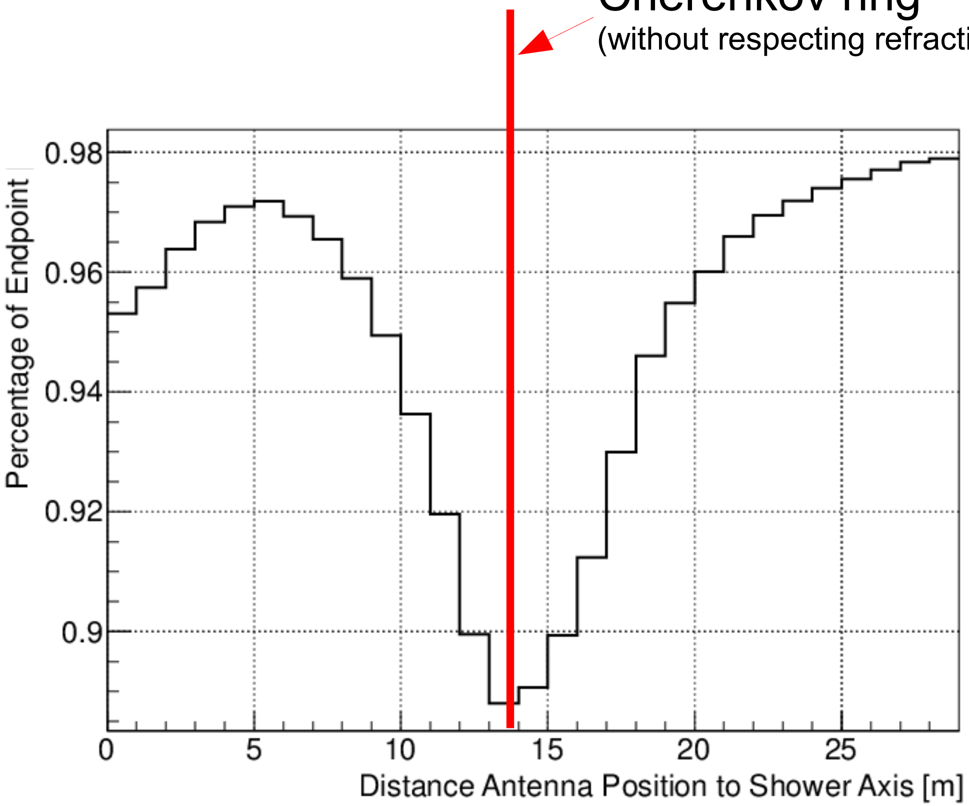
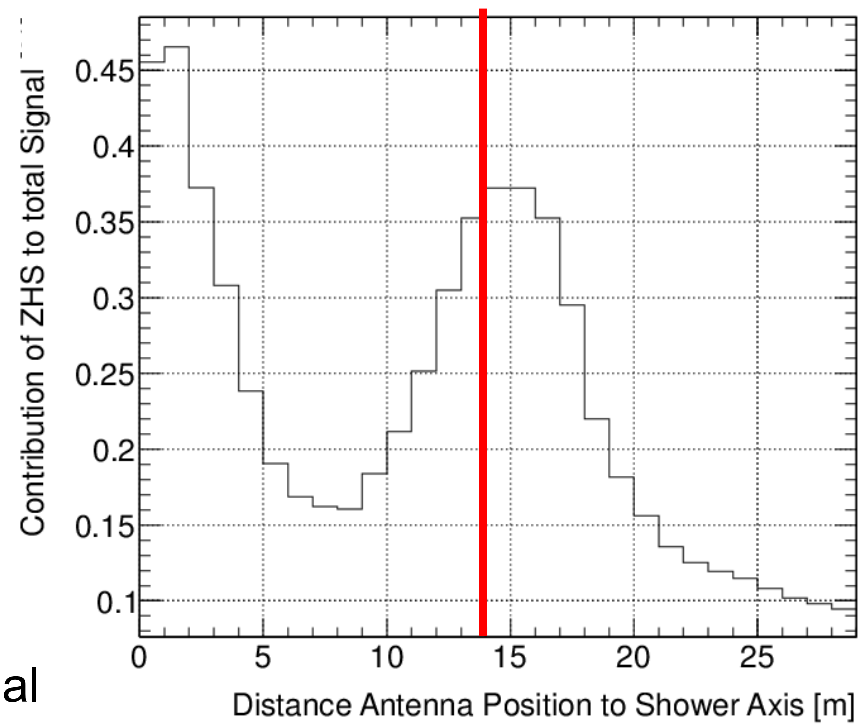
Contribution of fallback to signal

Estimated position of
Cherenkov ring
(without respecting refractive index)



Contribution of
ZHS Fallback to total Signal



Close to Cherenkov angle:
→ in ~90%: **Endpoint** used!
→ still more than 60% contribution to signal

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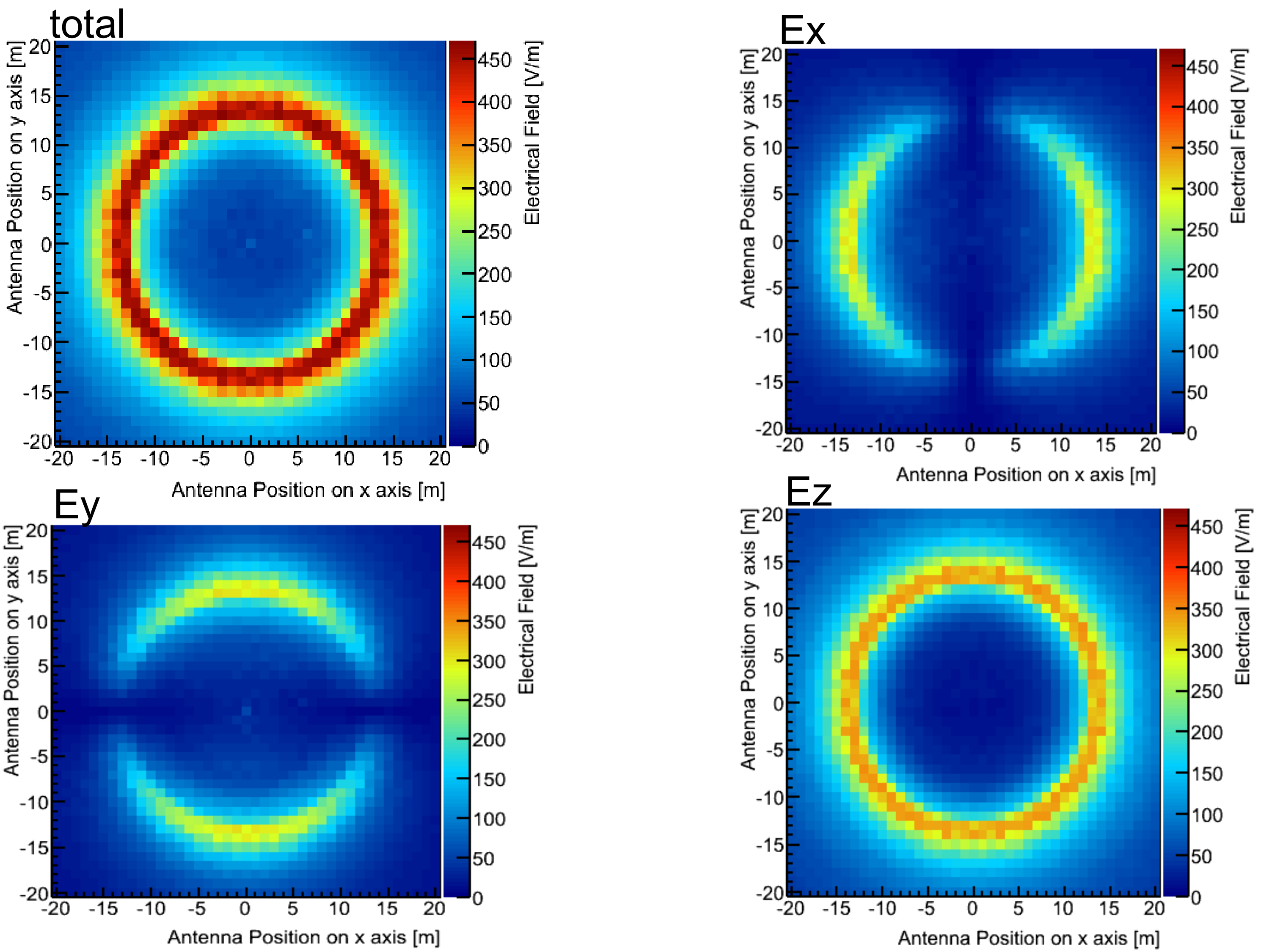
Endpoint - 0G



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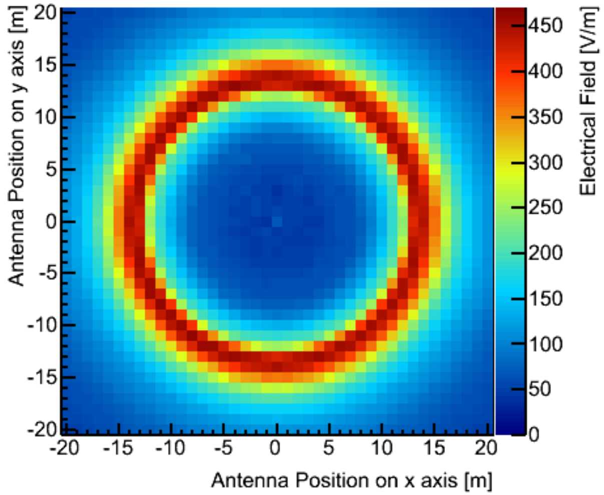
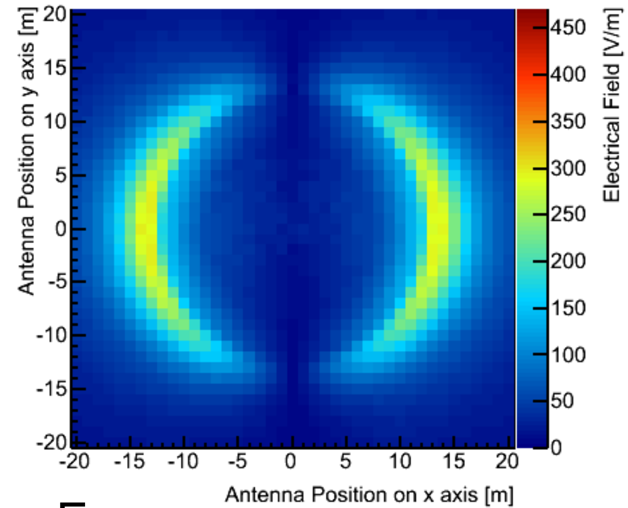
ZHS - 0G

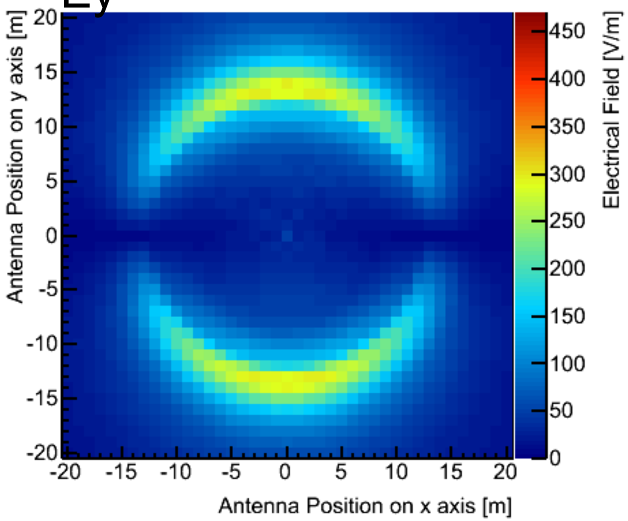
total



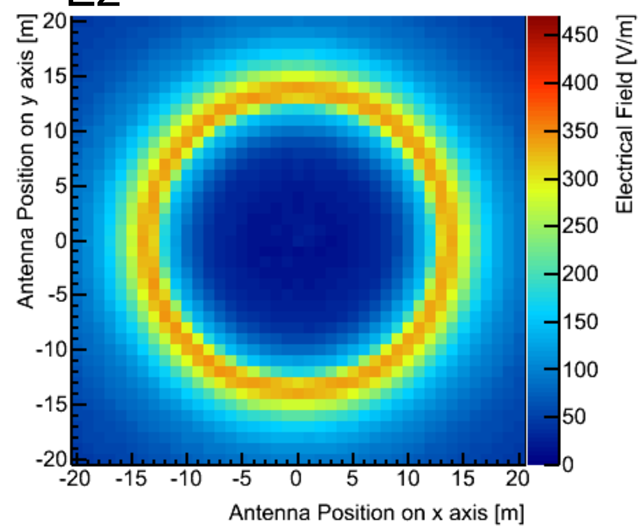
Ex



Ey



Ez



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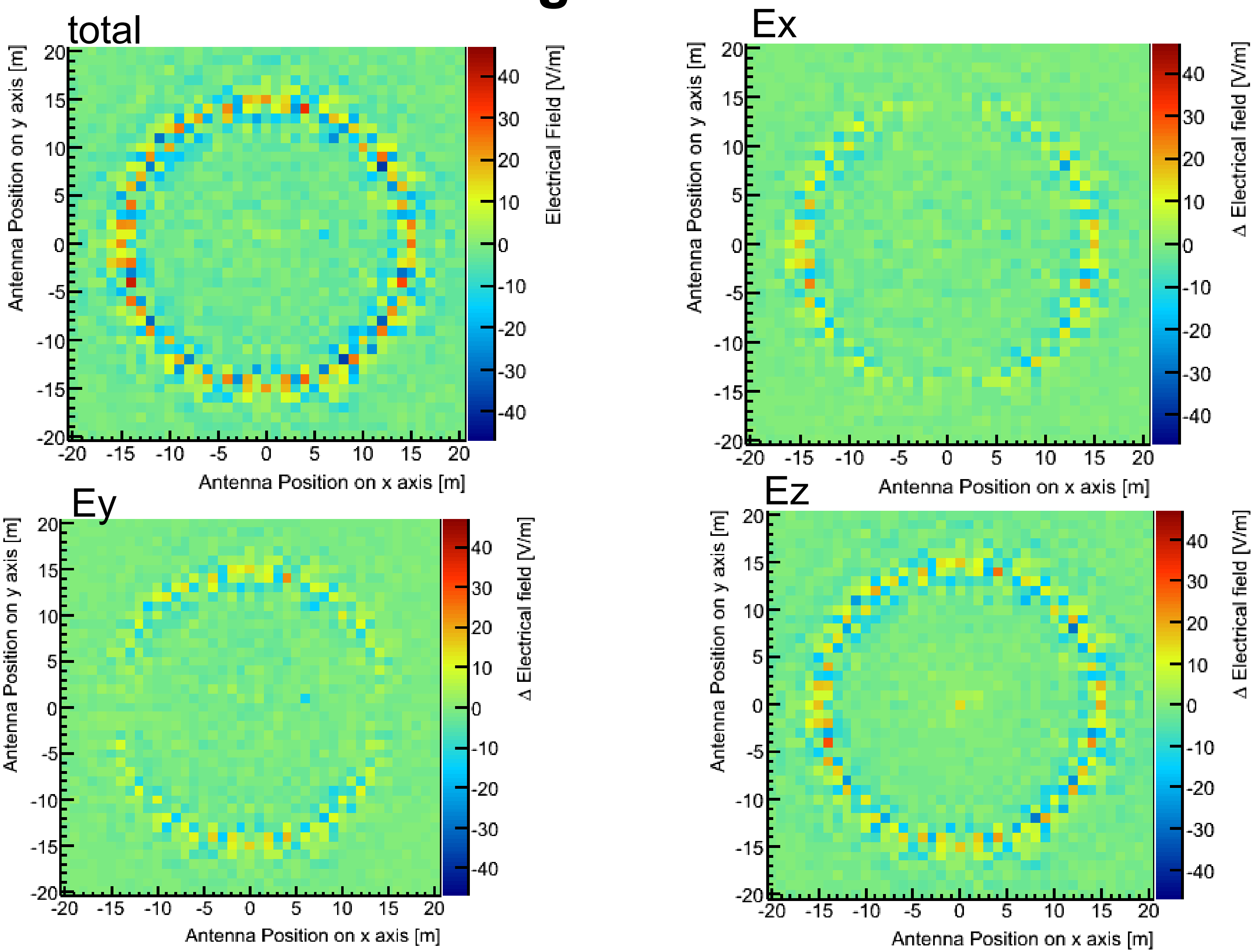
Difference in Int. Signal - 0G



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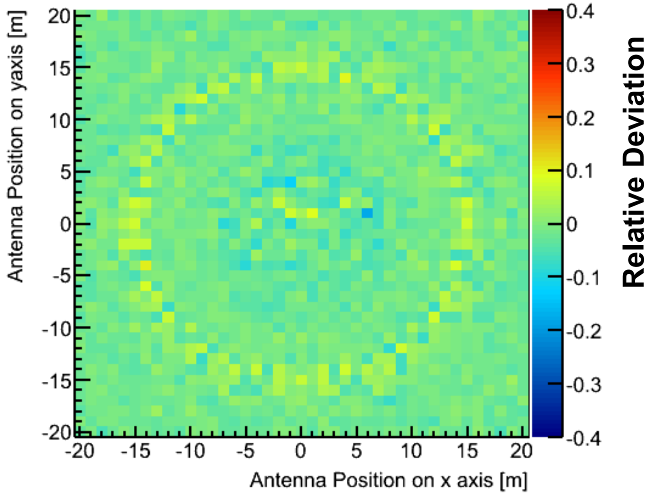
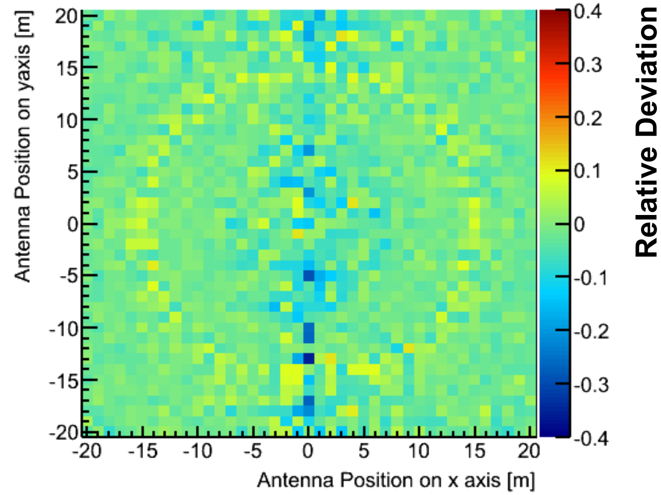
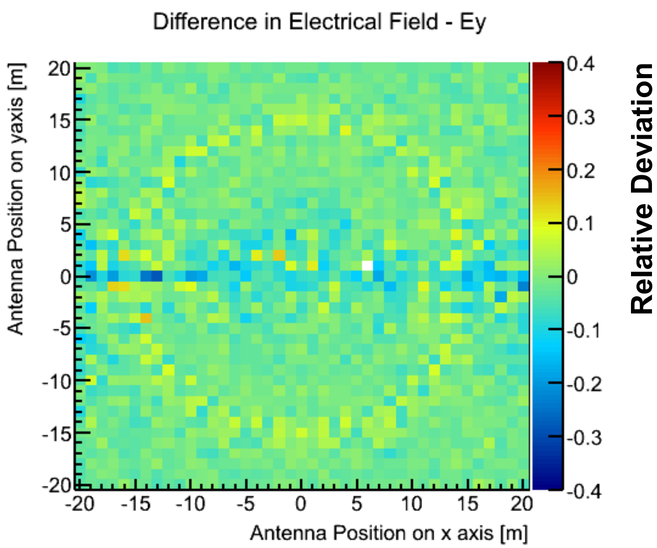
Difference in Int. Signal - 0G

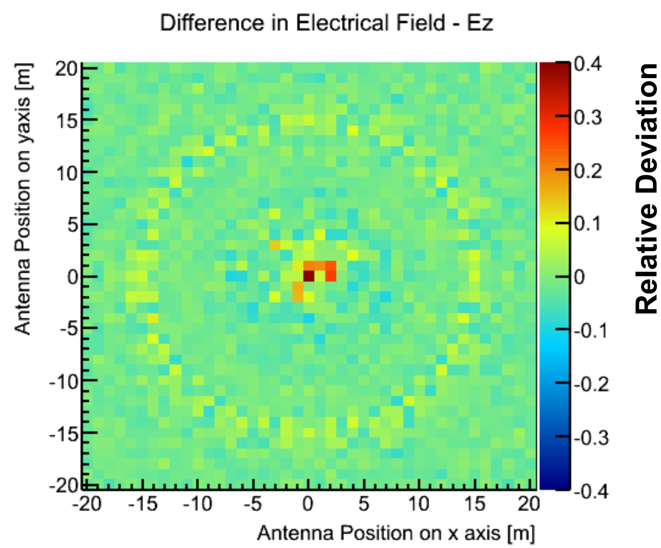
total



Ex







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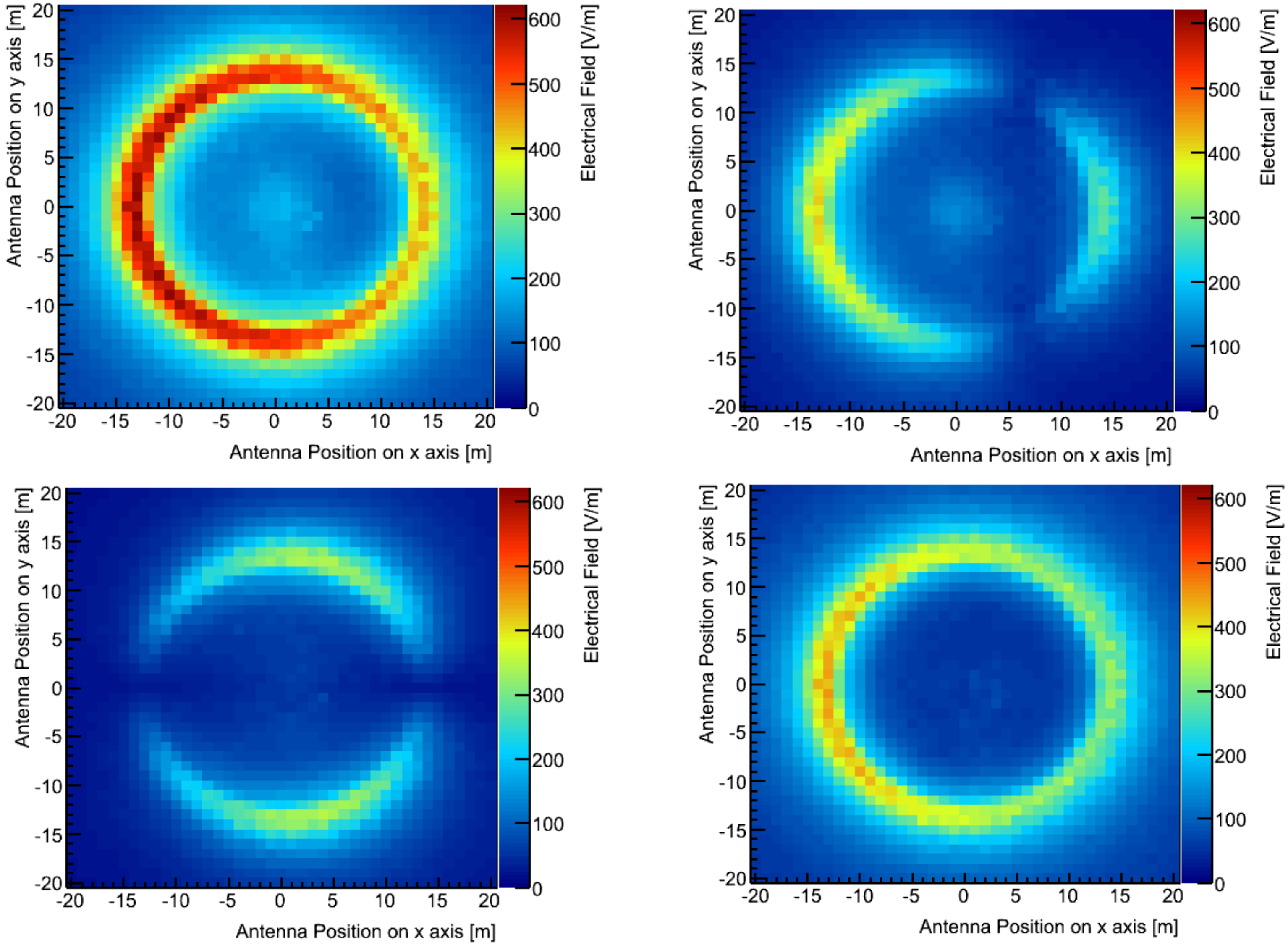
Endpoint - 1000G



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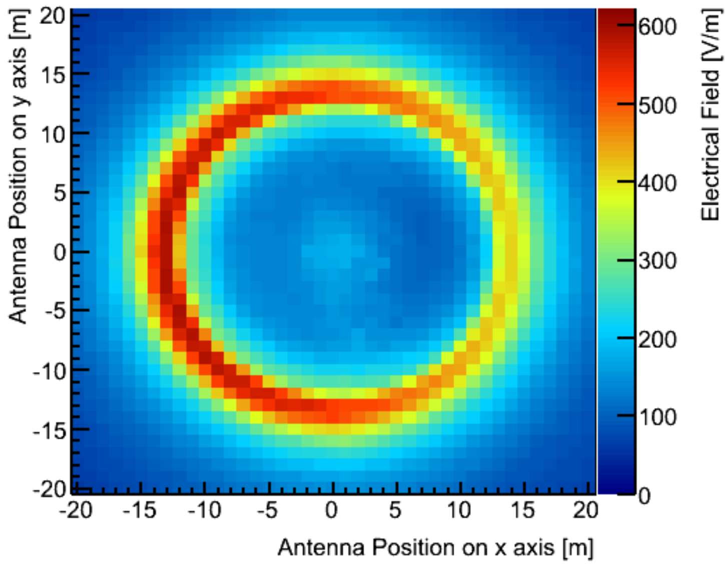
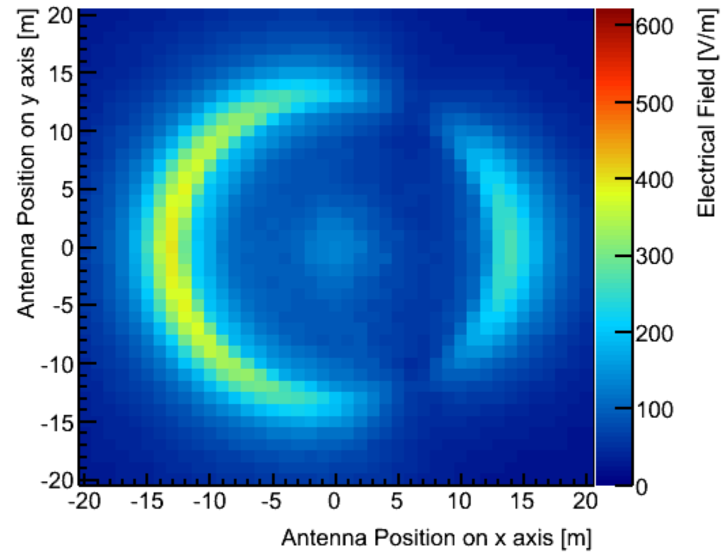
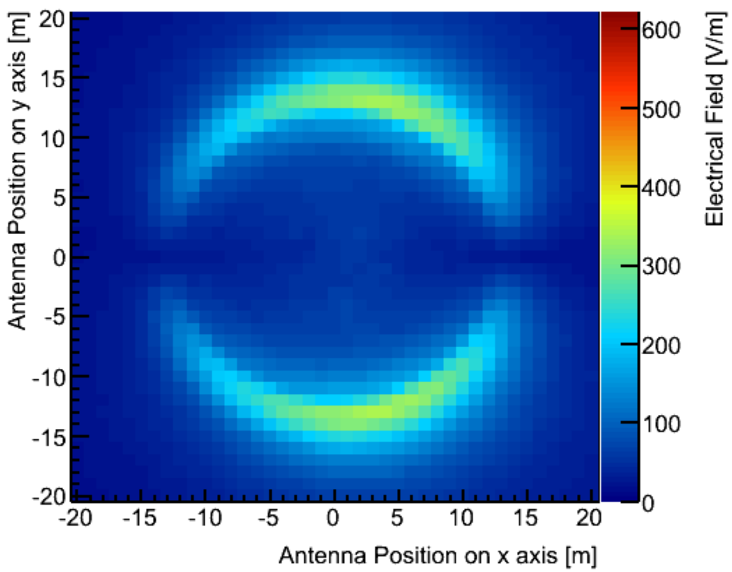
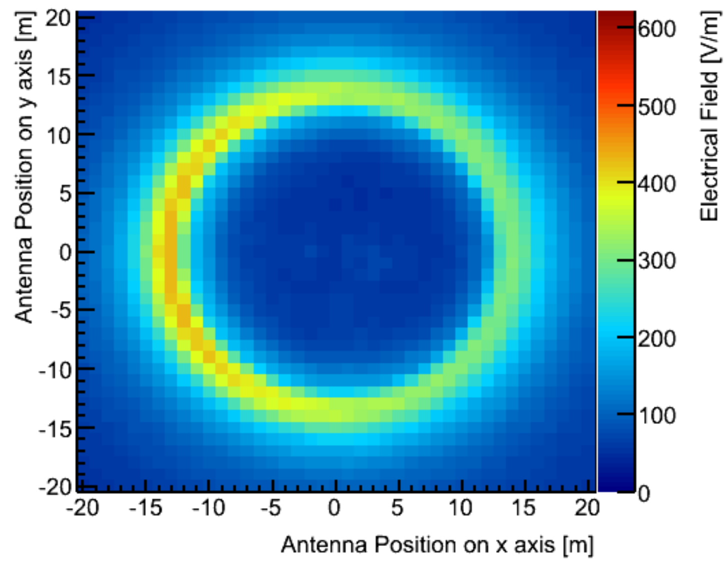
ZHS - 1000G









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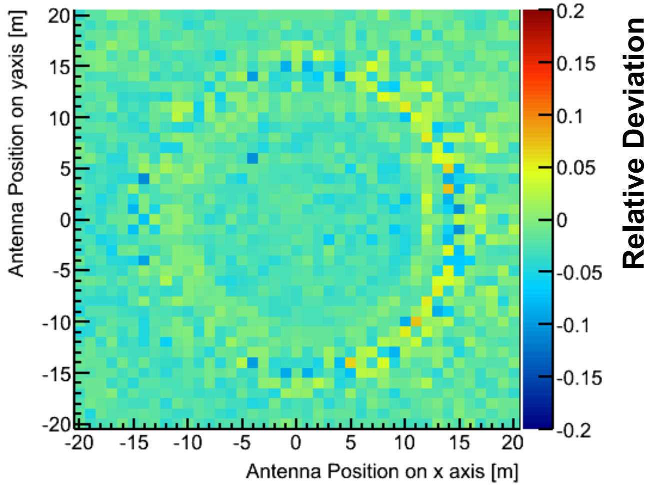
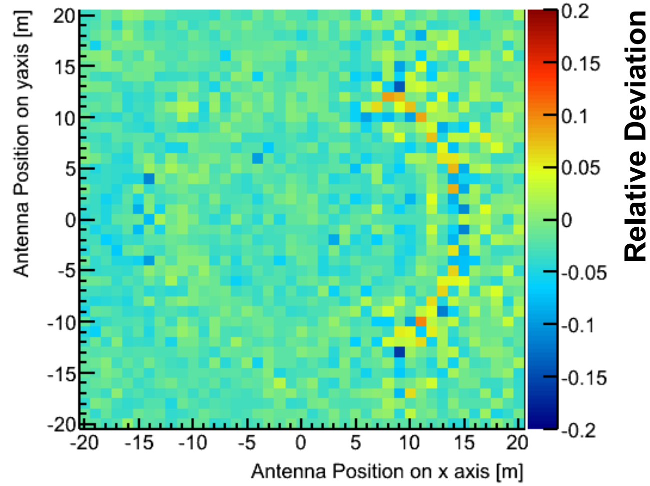
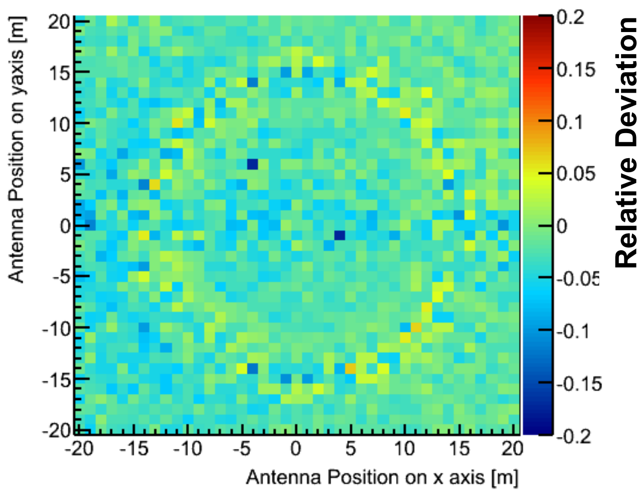
ZHS (1000G) – Endpoint (1000G)



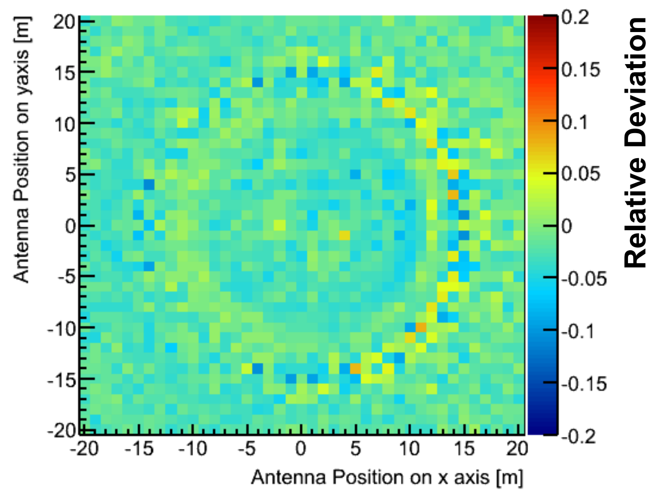
Difference in Electrical Field - Ex



Difference in Electrical Field - Ey



Difference in Electrical Field - Ez



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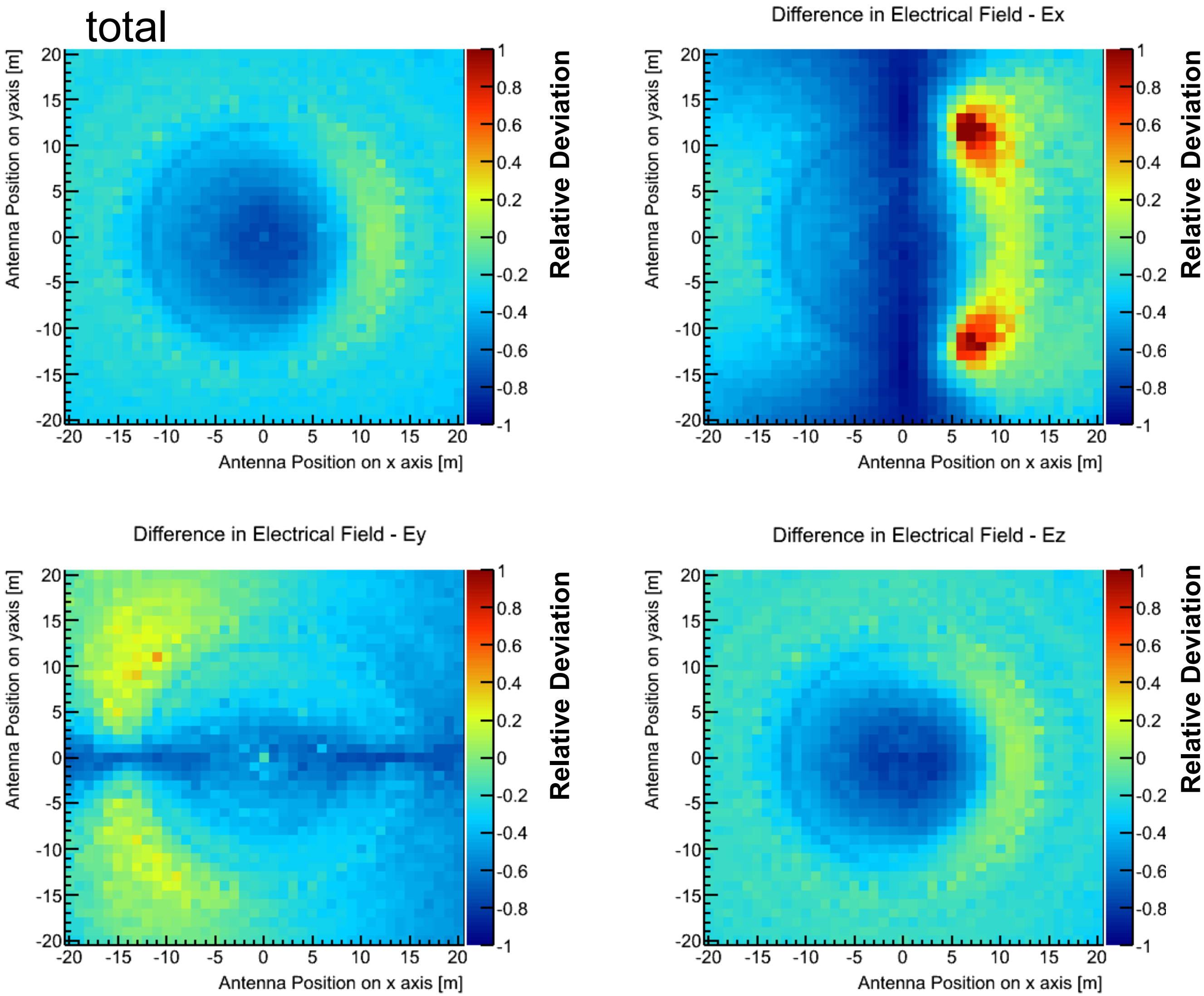
Endpoint: 1000G – 0G



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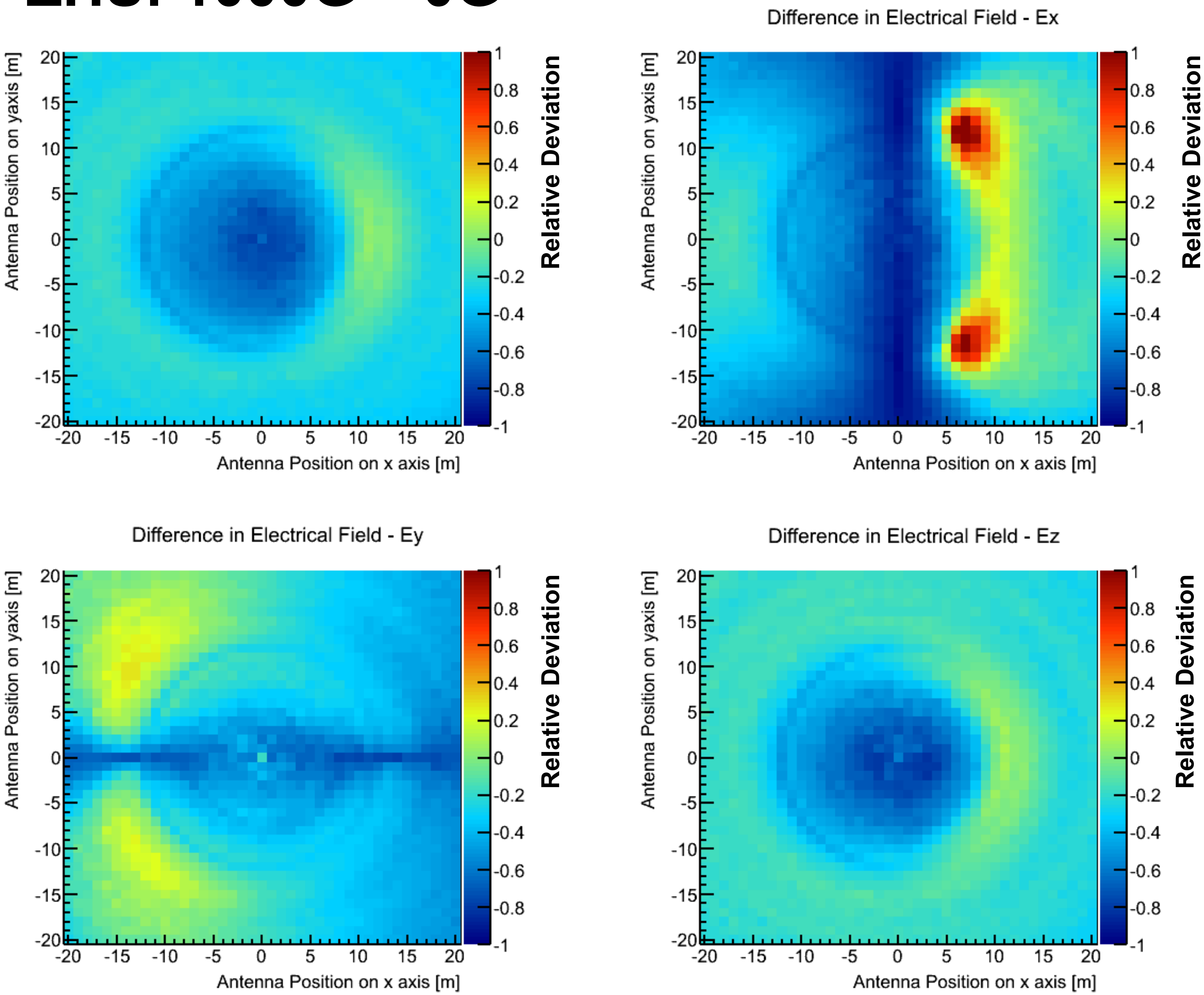
ZHS: 1000G – 0G



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More about T510:
http://t-510.physics.ucla.edu/

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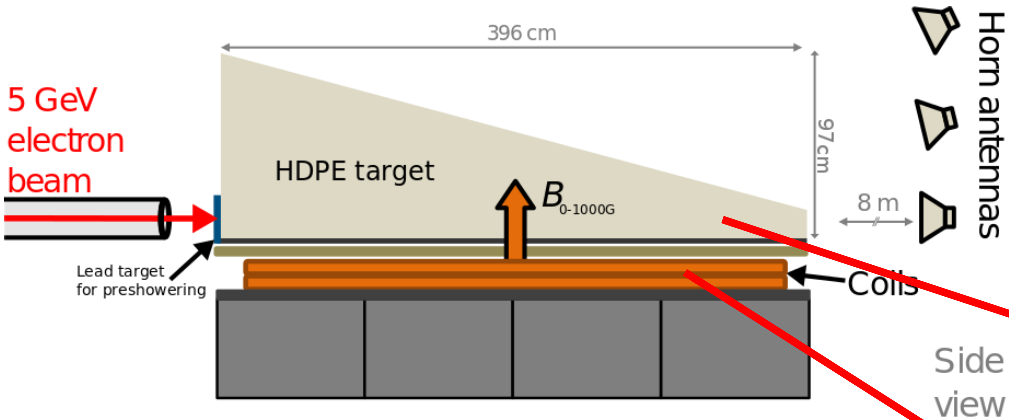
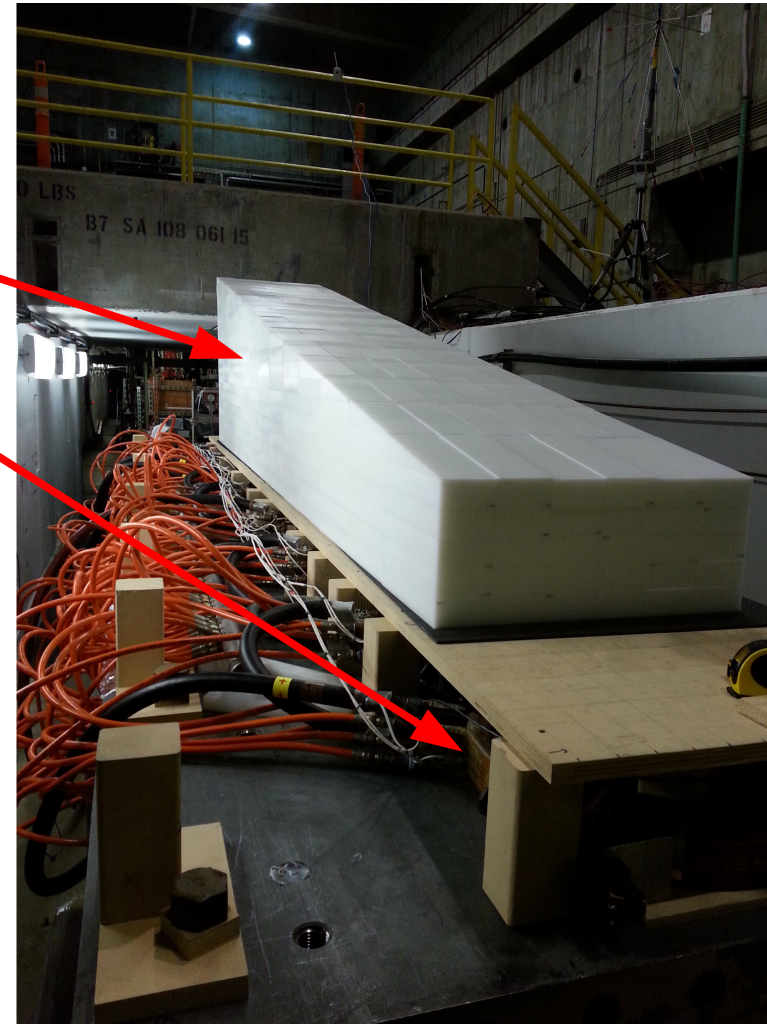
Experiment T510 @ SLAC

KIT Karlsruhe Institute of Technology





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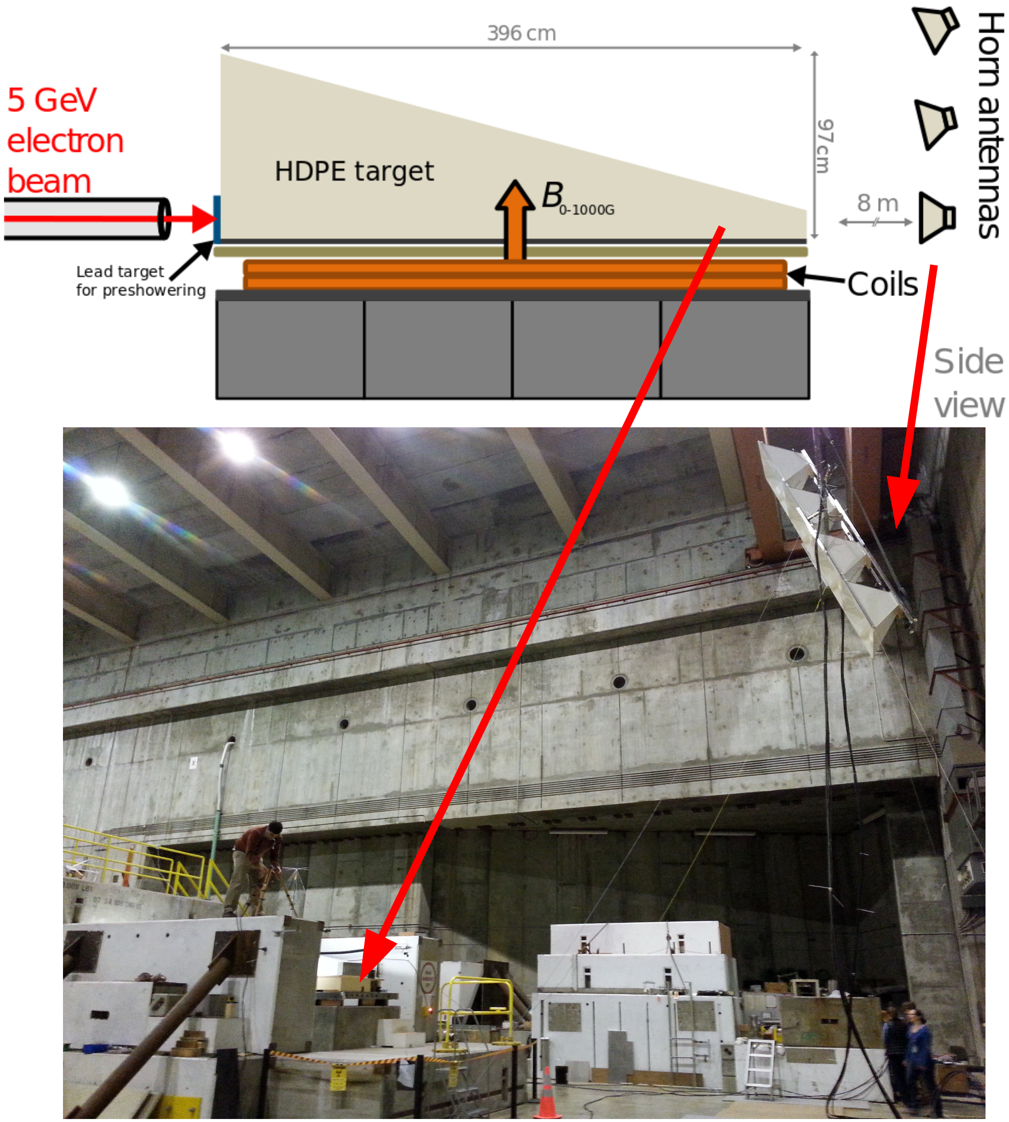

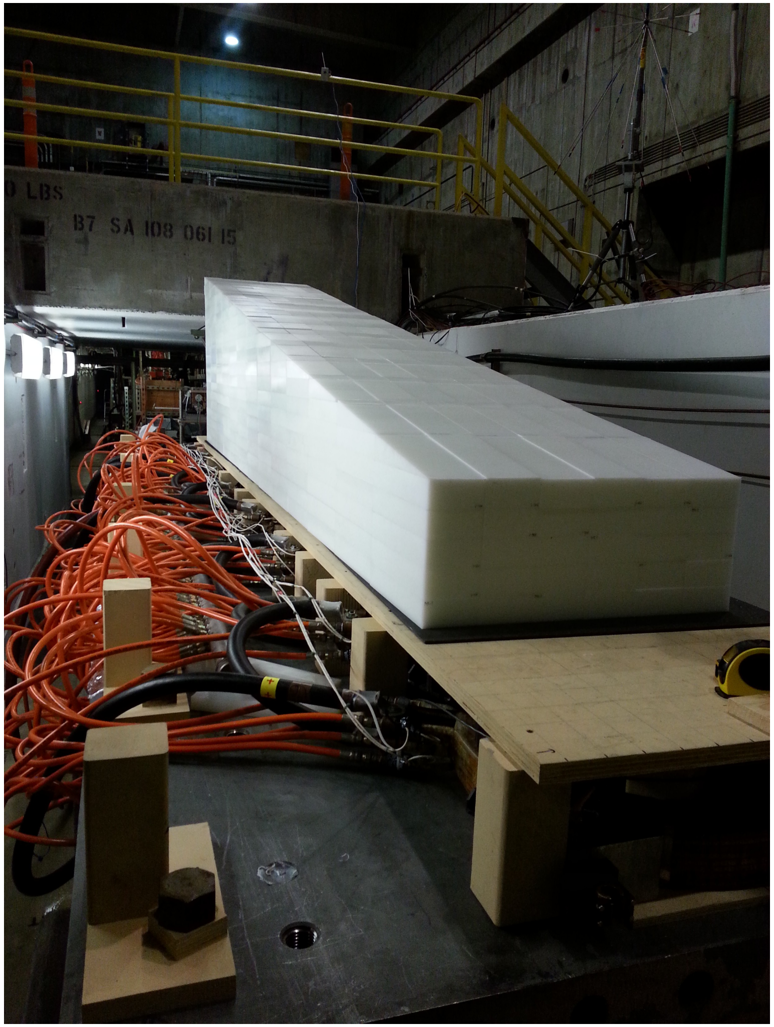

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