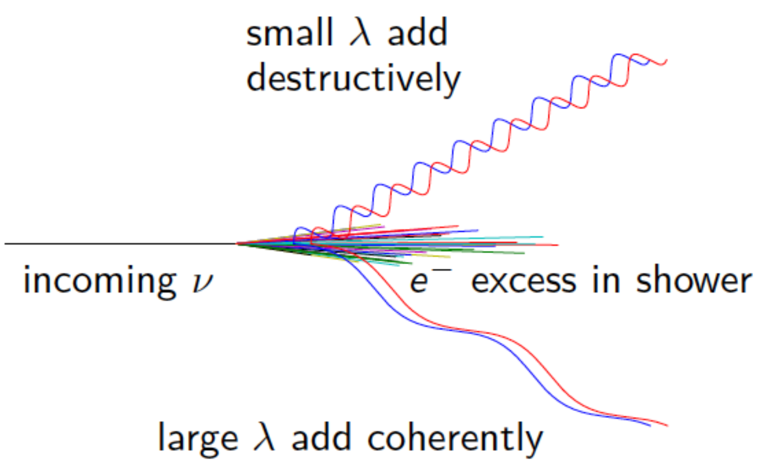
The calibration of the ARA detector using TA Electron Light Source

K. Mase
for the ARA collaboration

Purpose

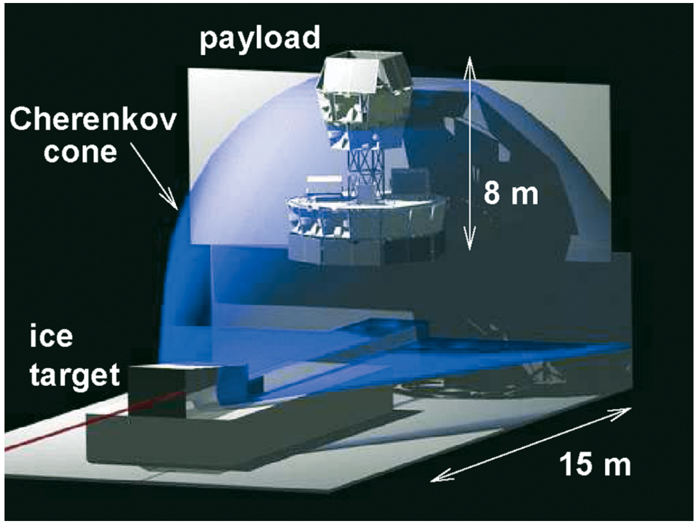
- 1962: Askaryan predicted coherent radio radiation from excess negative charge in an EM shower (~20% due to mainly Compton scattering and positron annihilation)

  → **Askaryan effect**



Shower size << λ to be coherent

- 2000: Saltzberg et al. confirmed the Askaryan radiation experimentally with the SLAC accelerator



P. W. Gorham et al., PRL 99, 171101(2007)

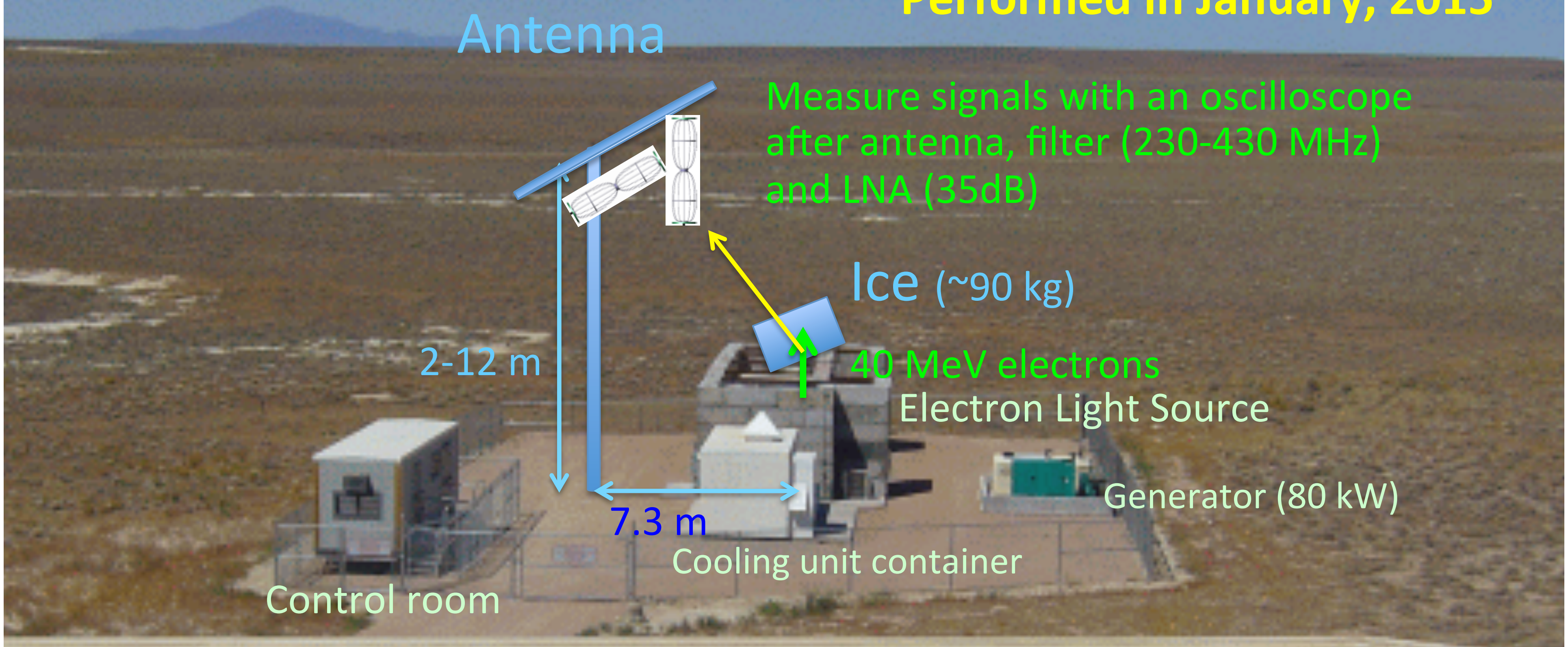
Purpose: Understanding of the Askaryan signals

Detector calibration

■ End to end calibration with the TA LINAC

LINAC at Telescope Array (TA) site @Utah

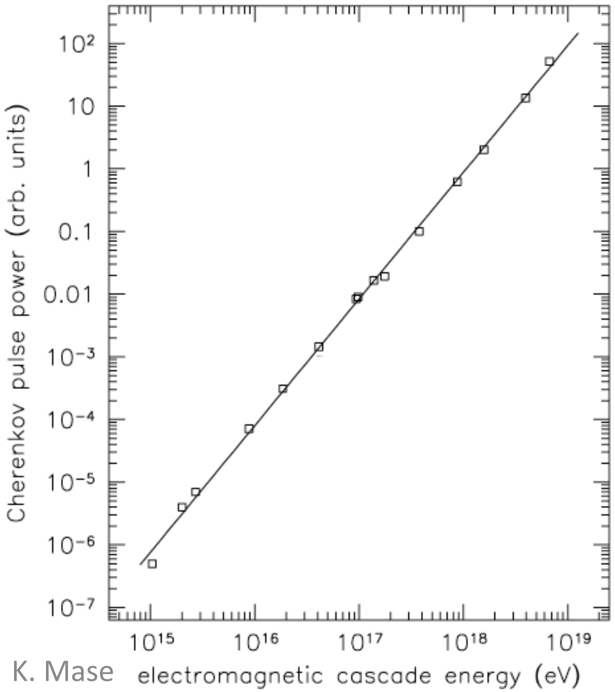
Performed in January, 2015

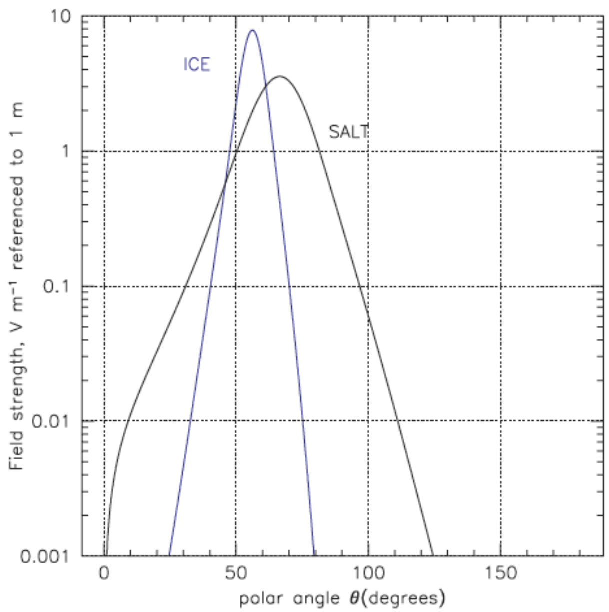


Characteristics of Askaryan radiation

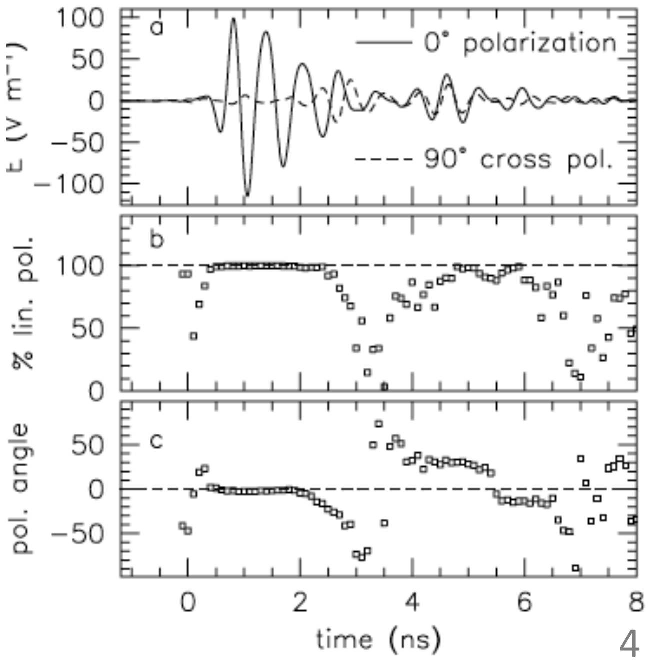
- ✓ Coherence (signal power Vs. electron number)
- ✓ Angular distribution
- ✓ Polarization

P. W. Gorham et al., PRD 72, 023002 (2005)





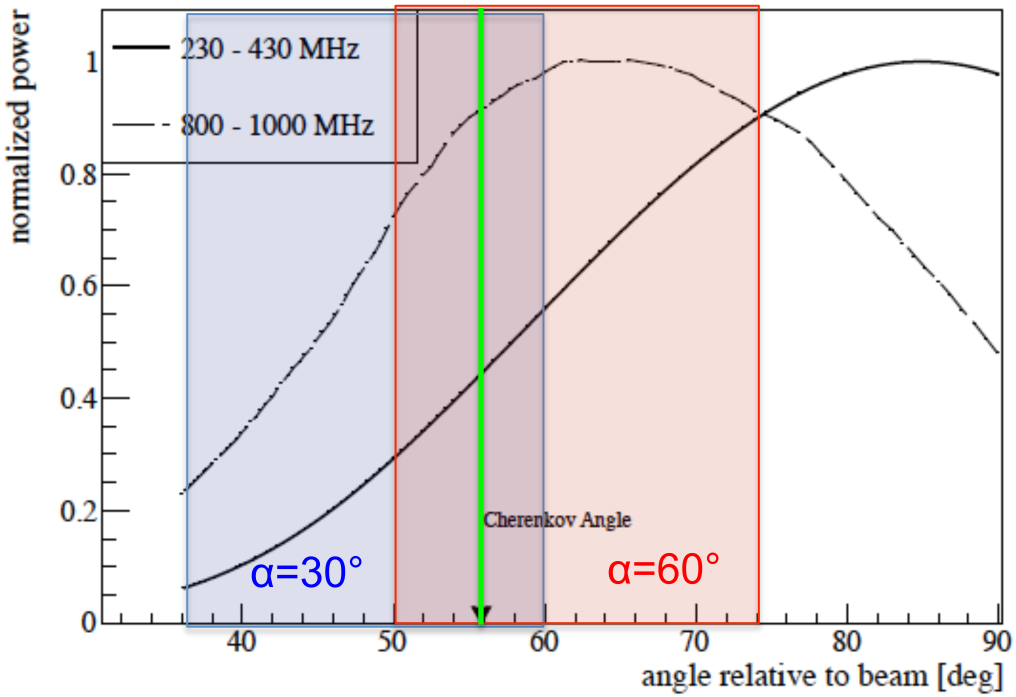
D. Saltzberg et al., PRL 86, 13 (2001)



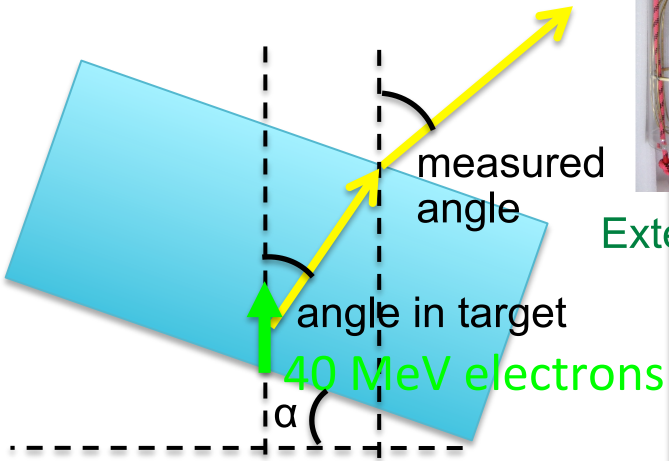
Expected angular distribution and the target structure

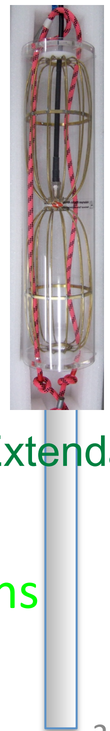
R. Gaior

Cherenkov angle in ice (56°)



- ✓ Angular distribution is wide due to short electron charge excess distribution
- ✓ Peak is not Cherenkov angle (56°), but shifted due to the effective shower length



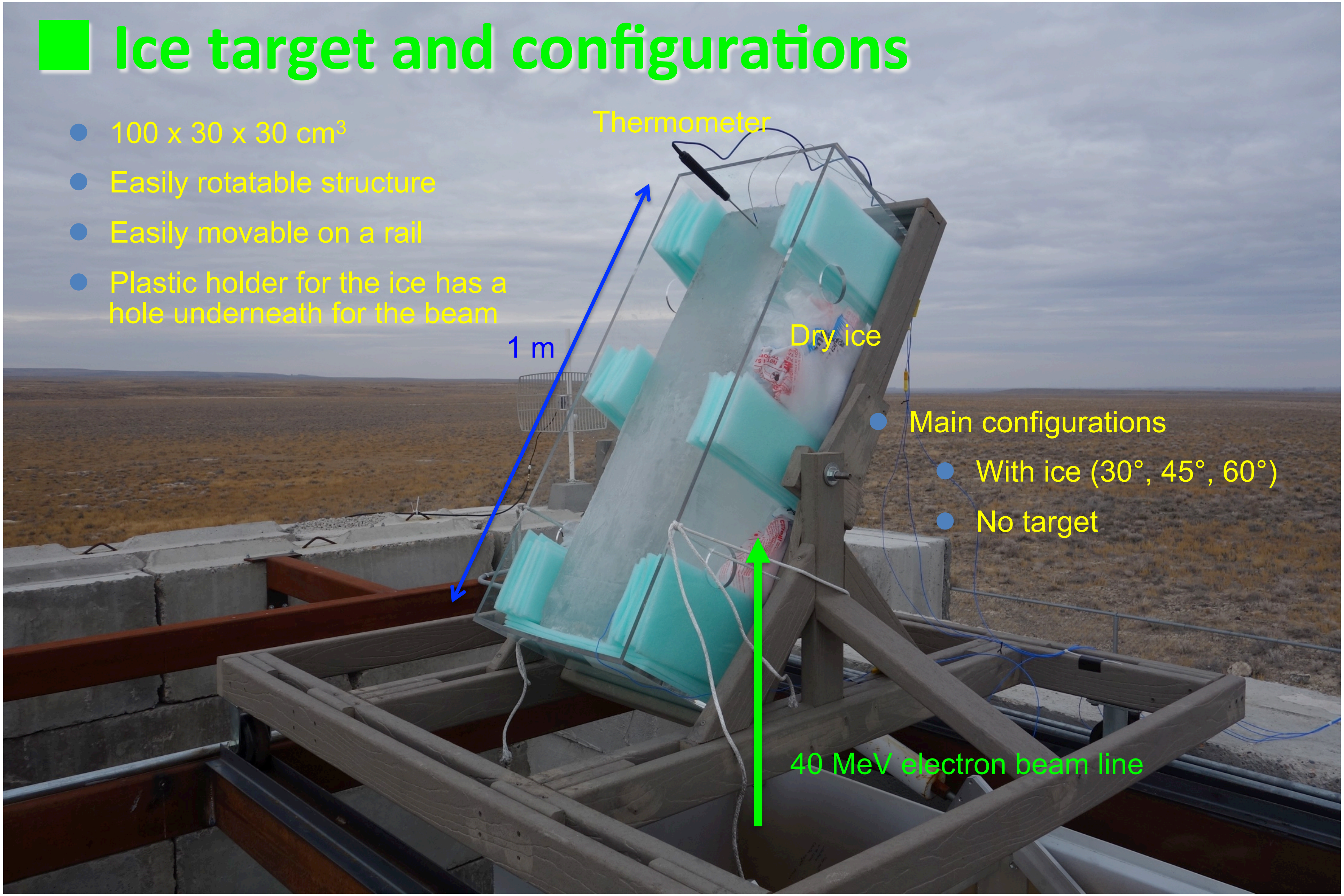


Extendable: 2-12m

The ice target has to be inclined for light to get out and to observe more easily

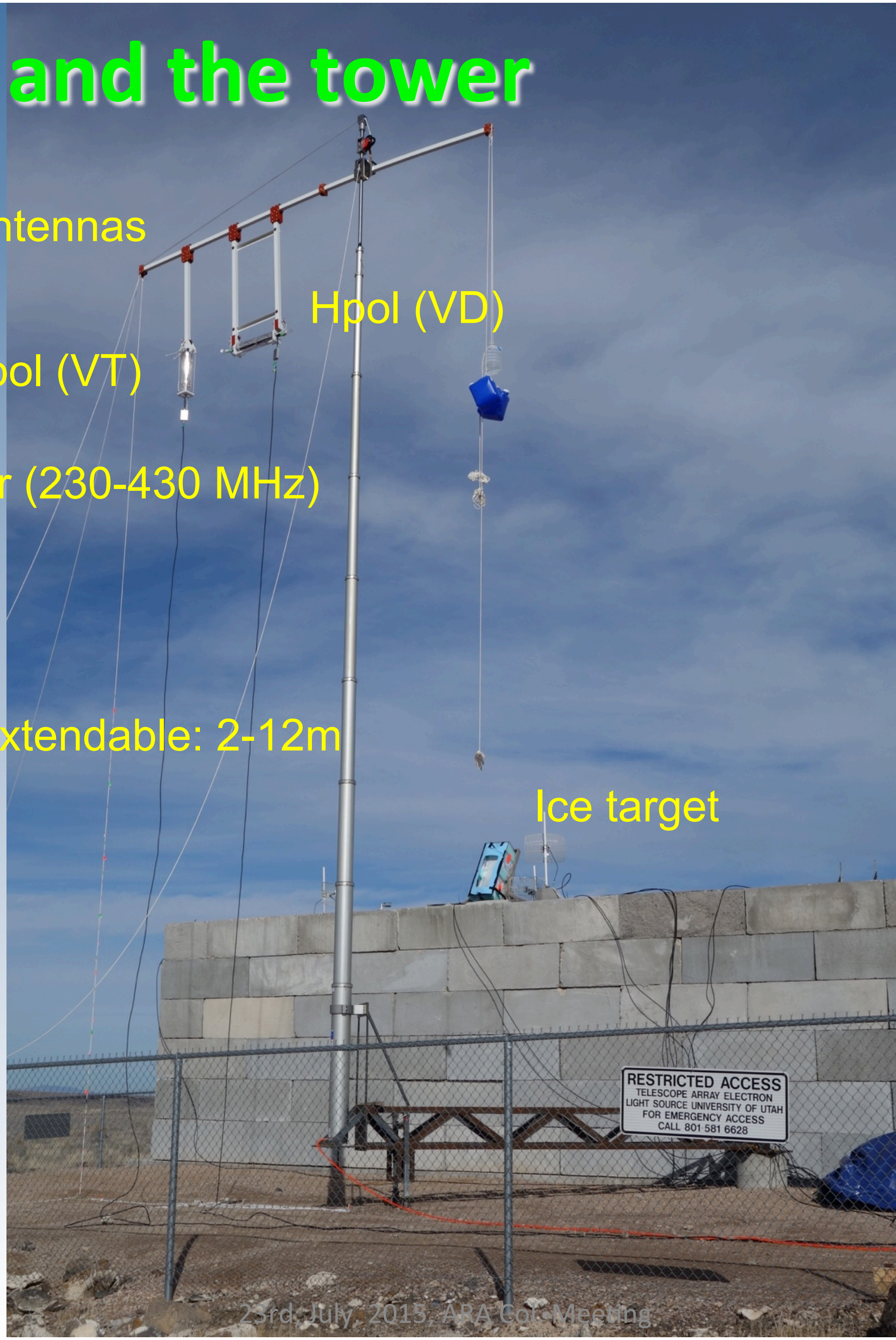
Ice target and configurations

- 100 x 30 x 30 cm^3
- Easily rotatable structure
- Easily movable on a rail
- Plastic holder for the ice has a hole underneath for the beam



- Main configurations
  - With ice (30°, 45°, 60°)
  - No target

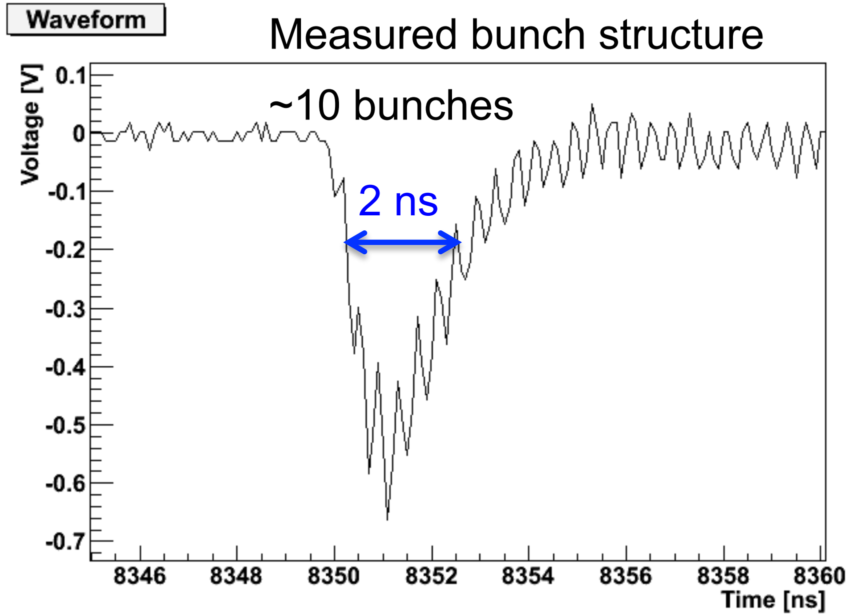
Antenna and the tower



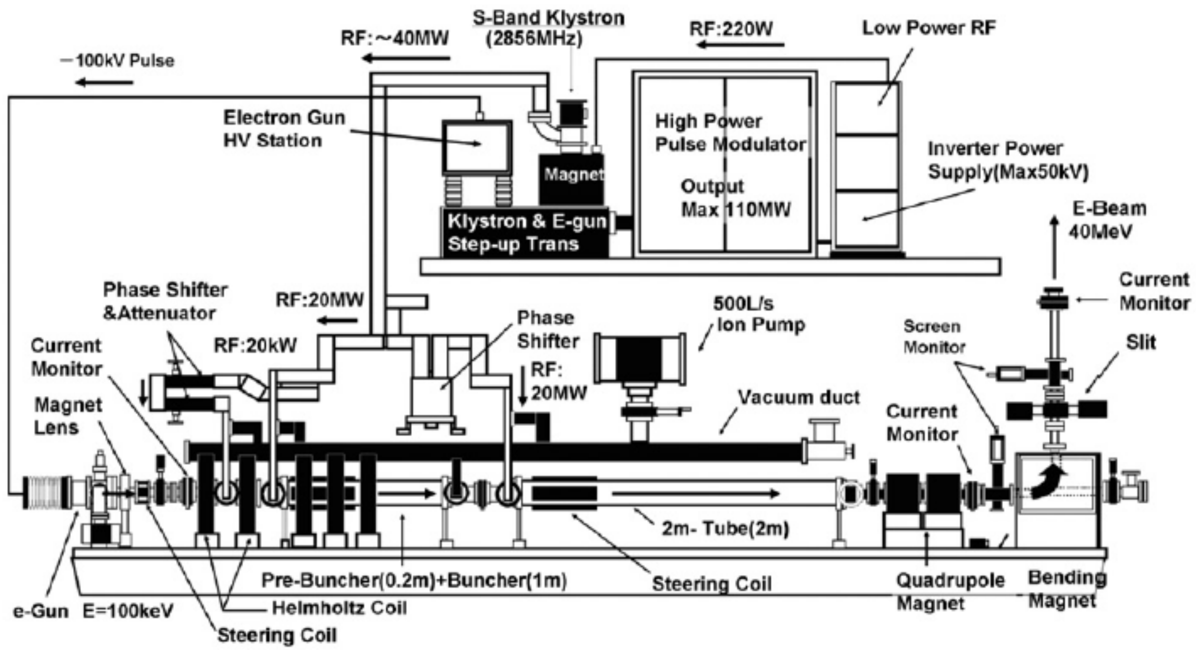
- Extendable: 2-12m

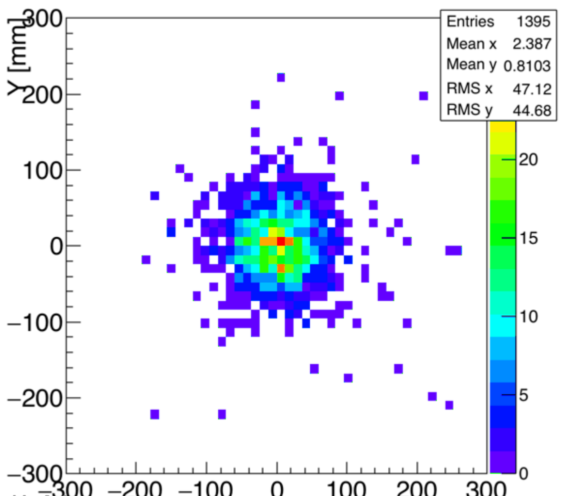
TA LINAC

- ✓ **40 MeV electron beam**
- ✓ Maximum electron number per bunch: **10^9** → 160 PeV EM shower
- ✓ Pulse frequency: 2.86 GHz
  → pulse interval: 350 ps
- ✓ Bunch train width was optimized to ~2 ns
- ✓ Beam spread: ~4.5 cm
- ✓ Trigger signal available



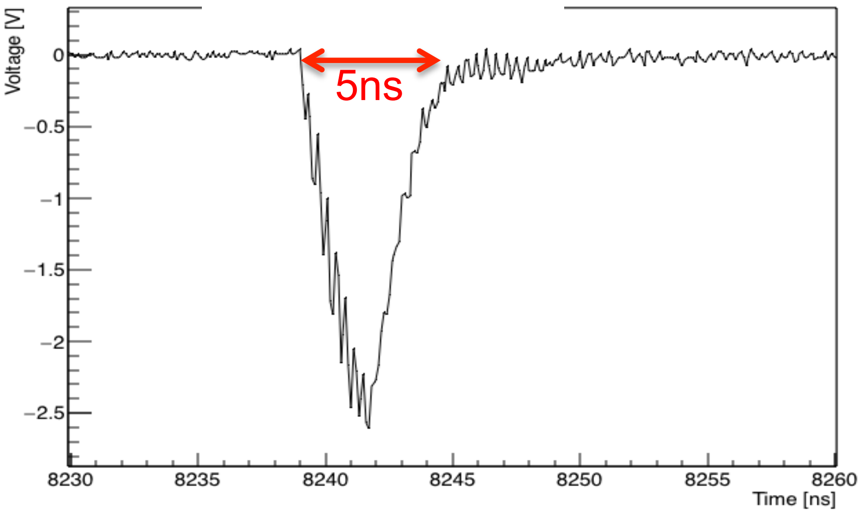
T. Shibata et al., NIMA 597 (2008) 61



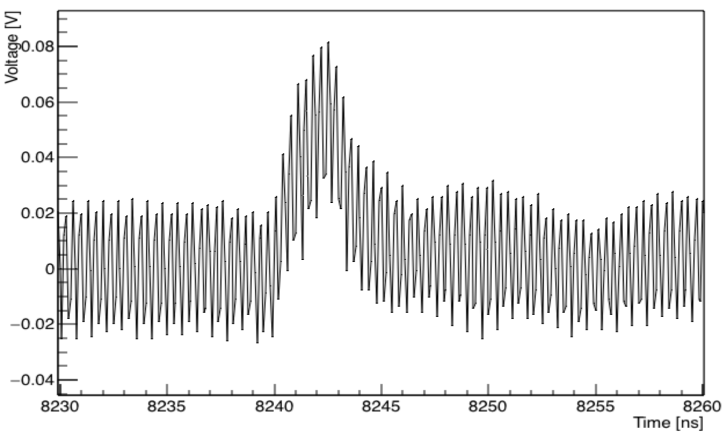


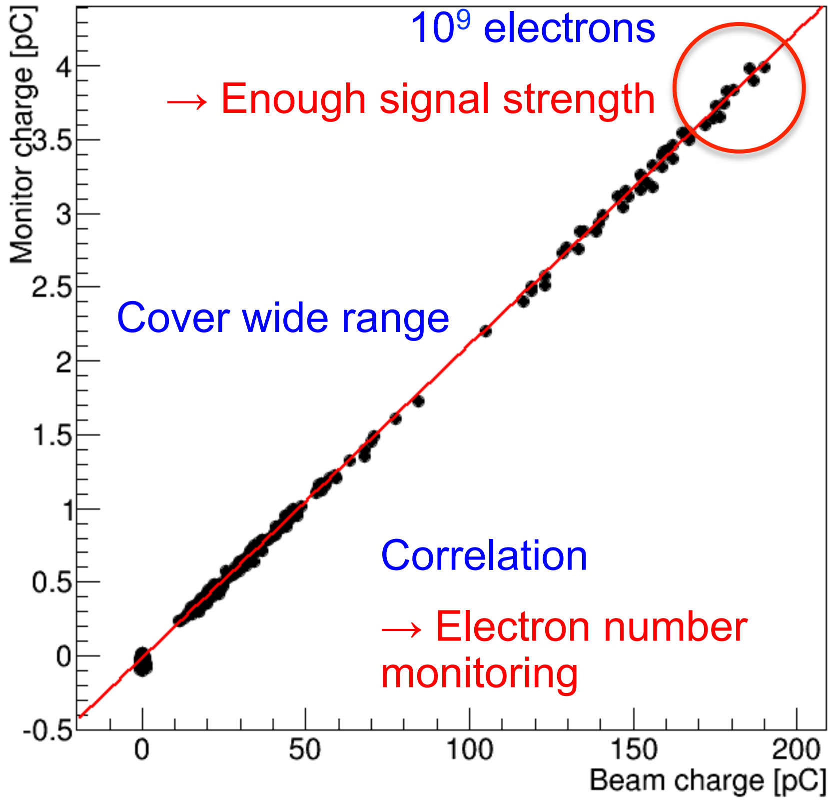
TA accelerator configurations

Beam waveform



Monitor waveform

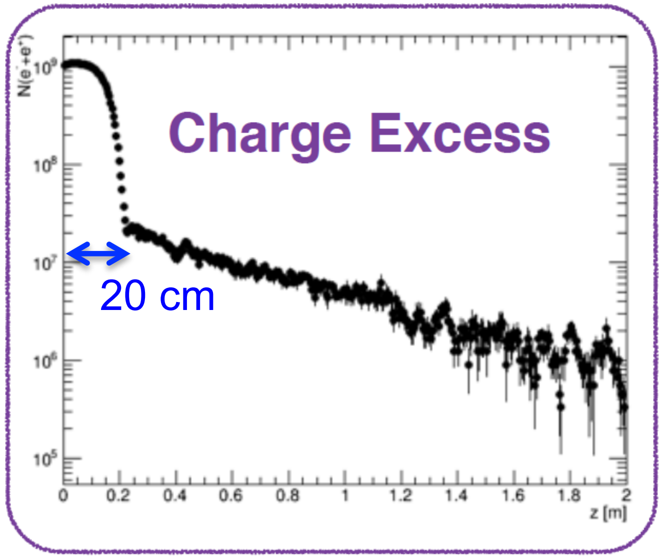




Expected electric field

M. Relich

GEANT4



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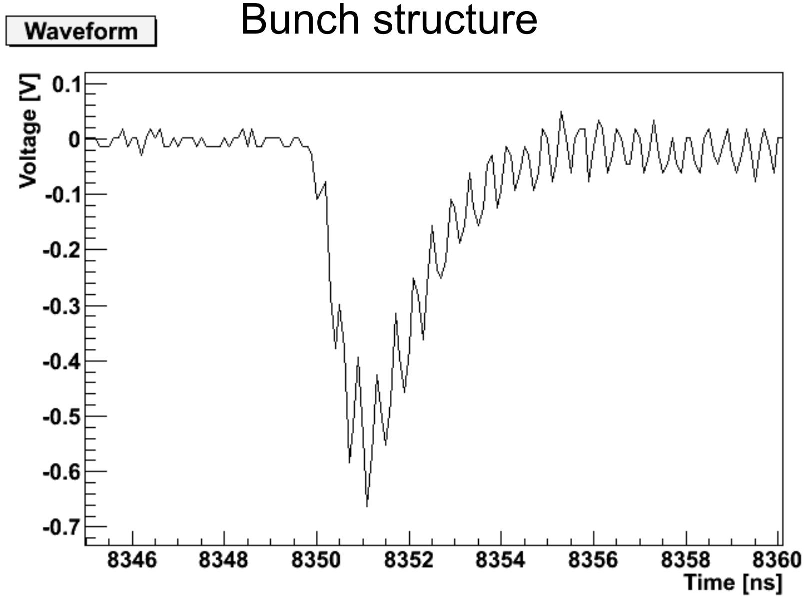
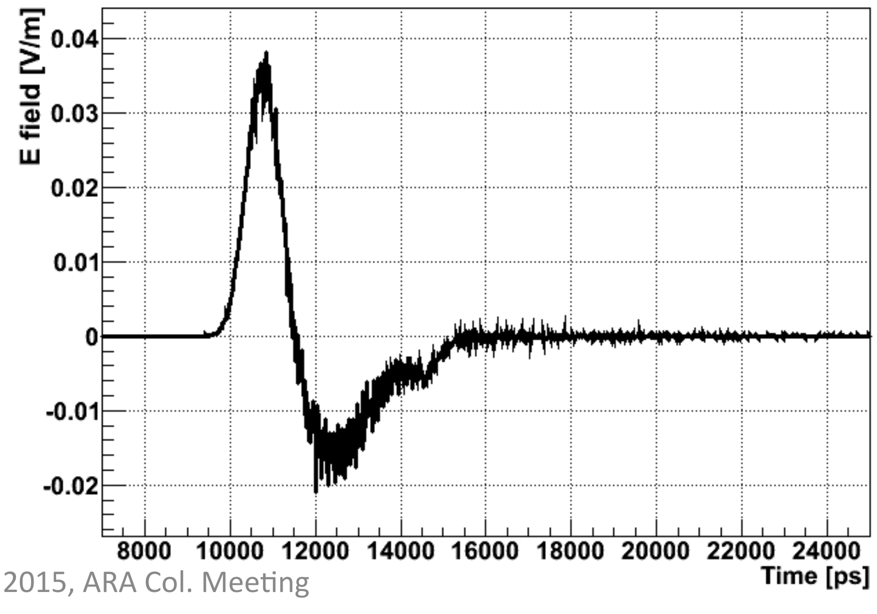


Bunch structure

+ E-filed calculation =

(ZHS method)

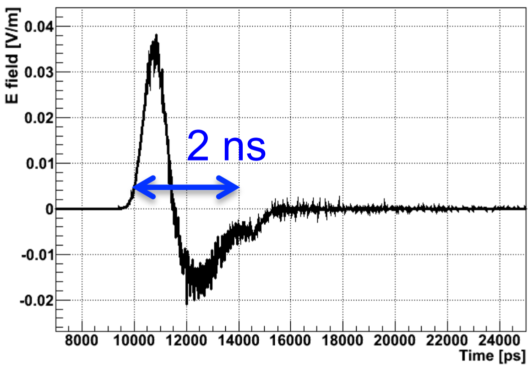
Zas, Halzen, Stanev, PRD 45, 362 (1992)



Expected waveform

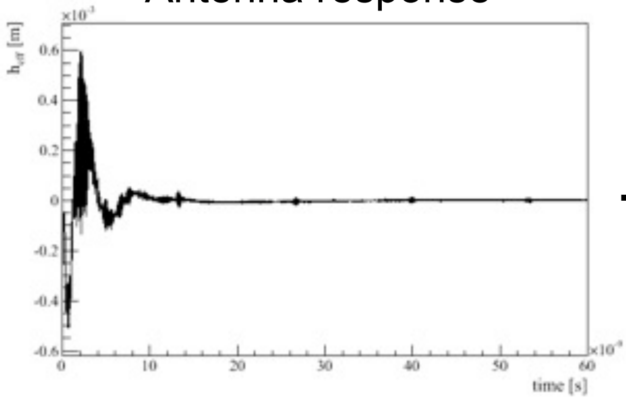
R. Gaior

E-field



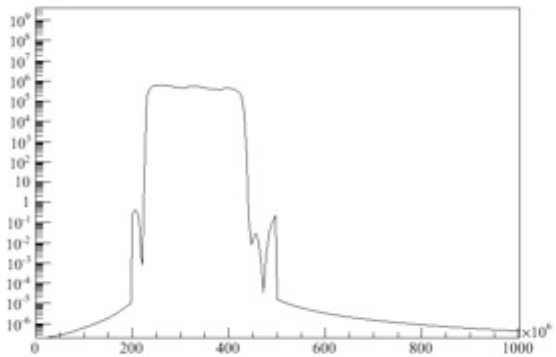
+

Antenna response



+

filter + LNA response



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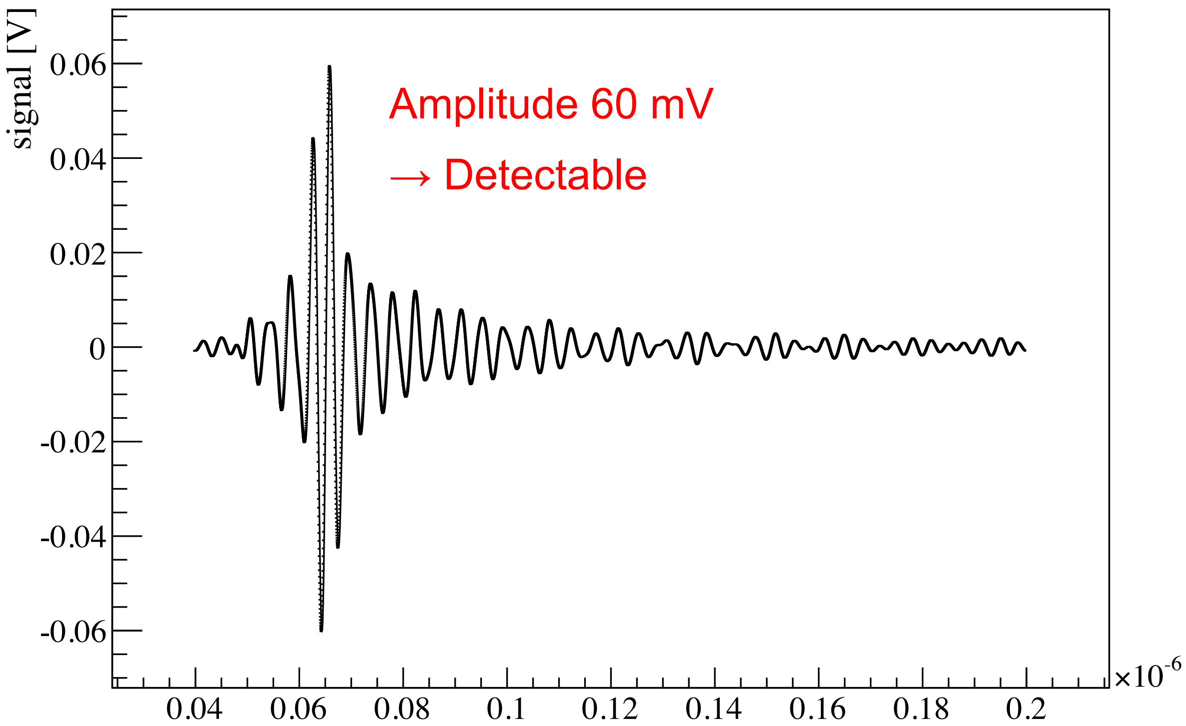
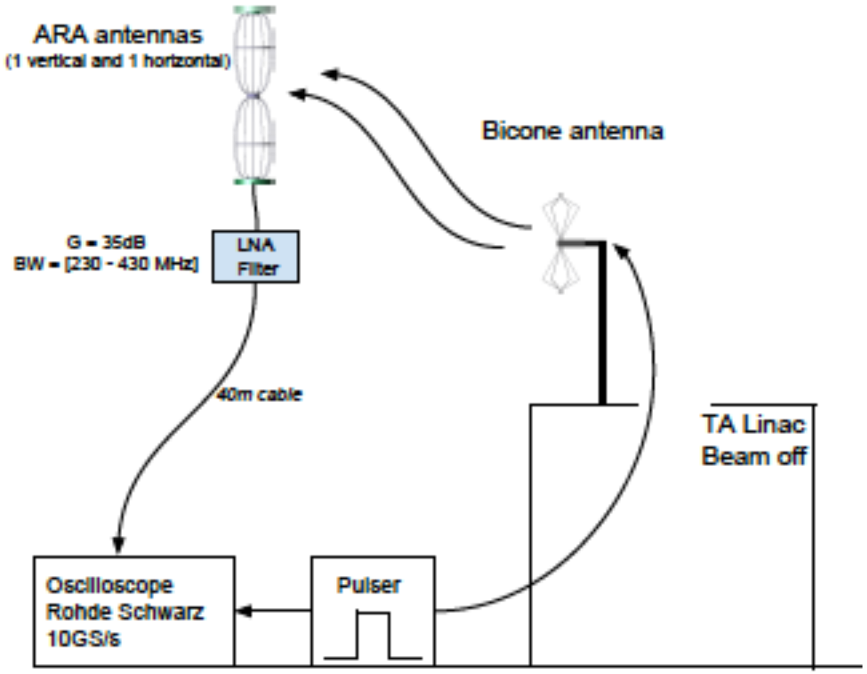
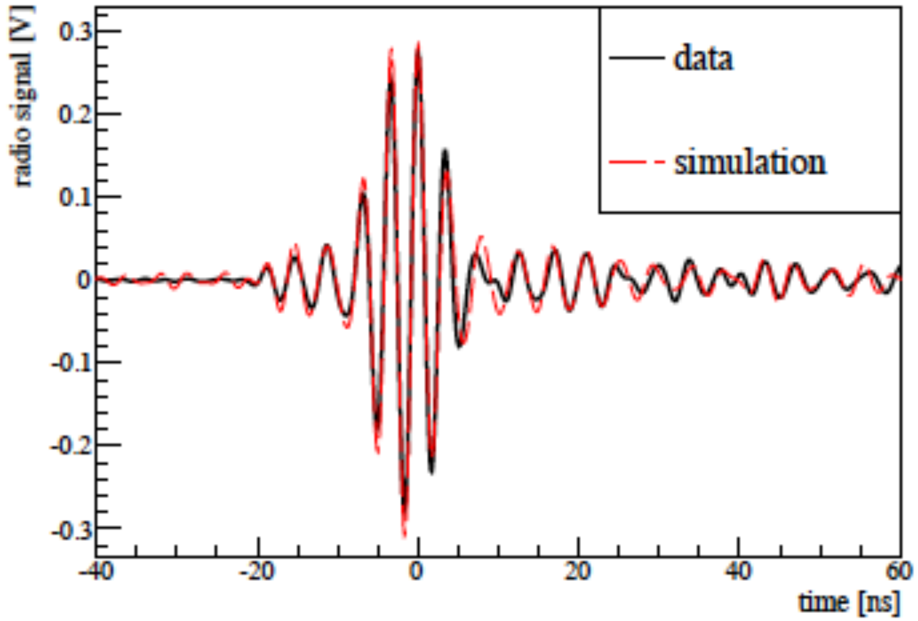


Confirmation of the detector simulation

R. Gaior

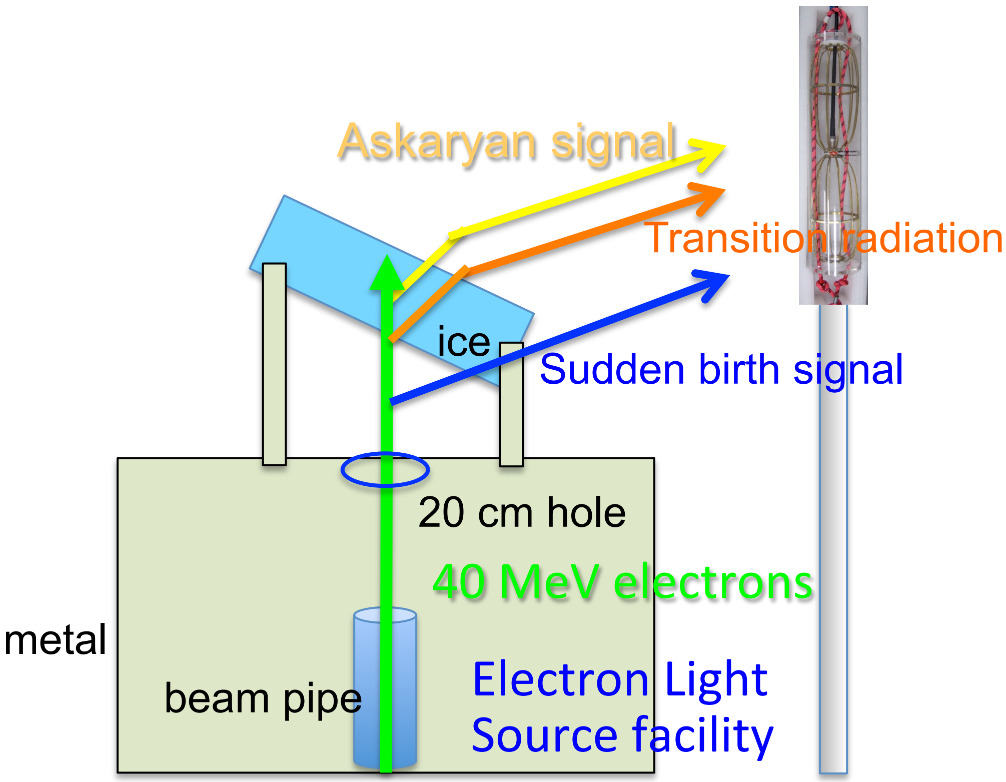




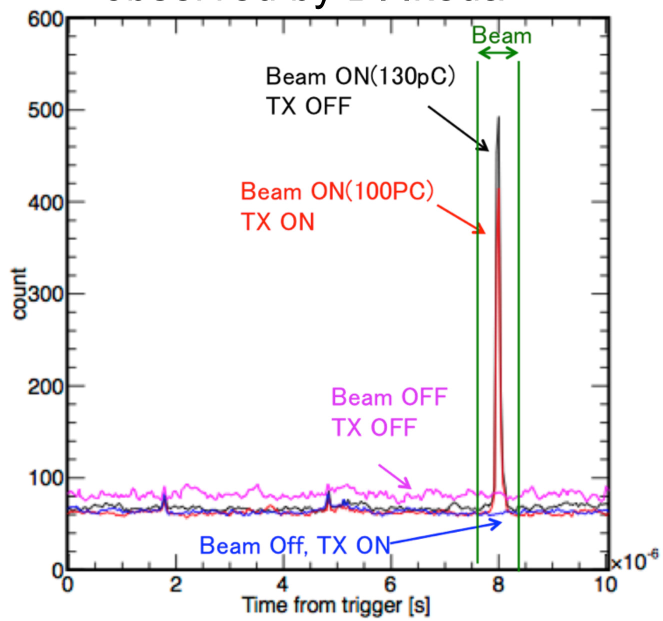
15% difference

Backgrounds

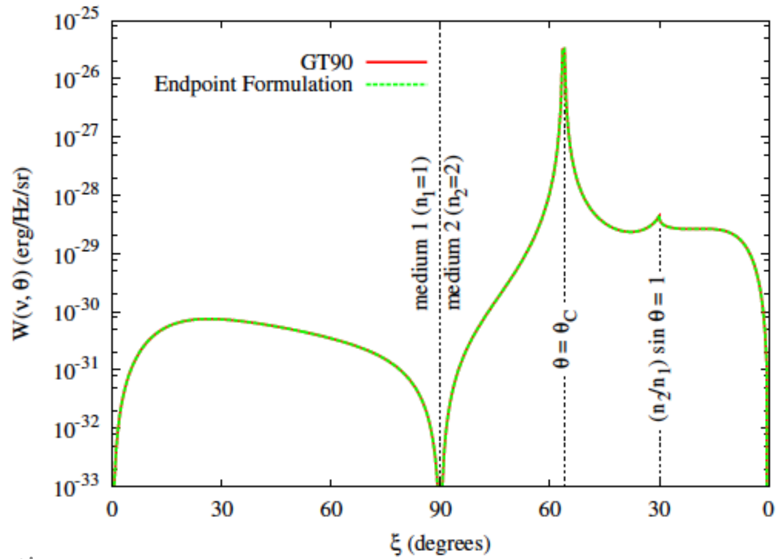
- ✓ Several backgrounds are expected
  - ✓ Transition radiation
  - ✓ Sudden birth



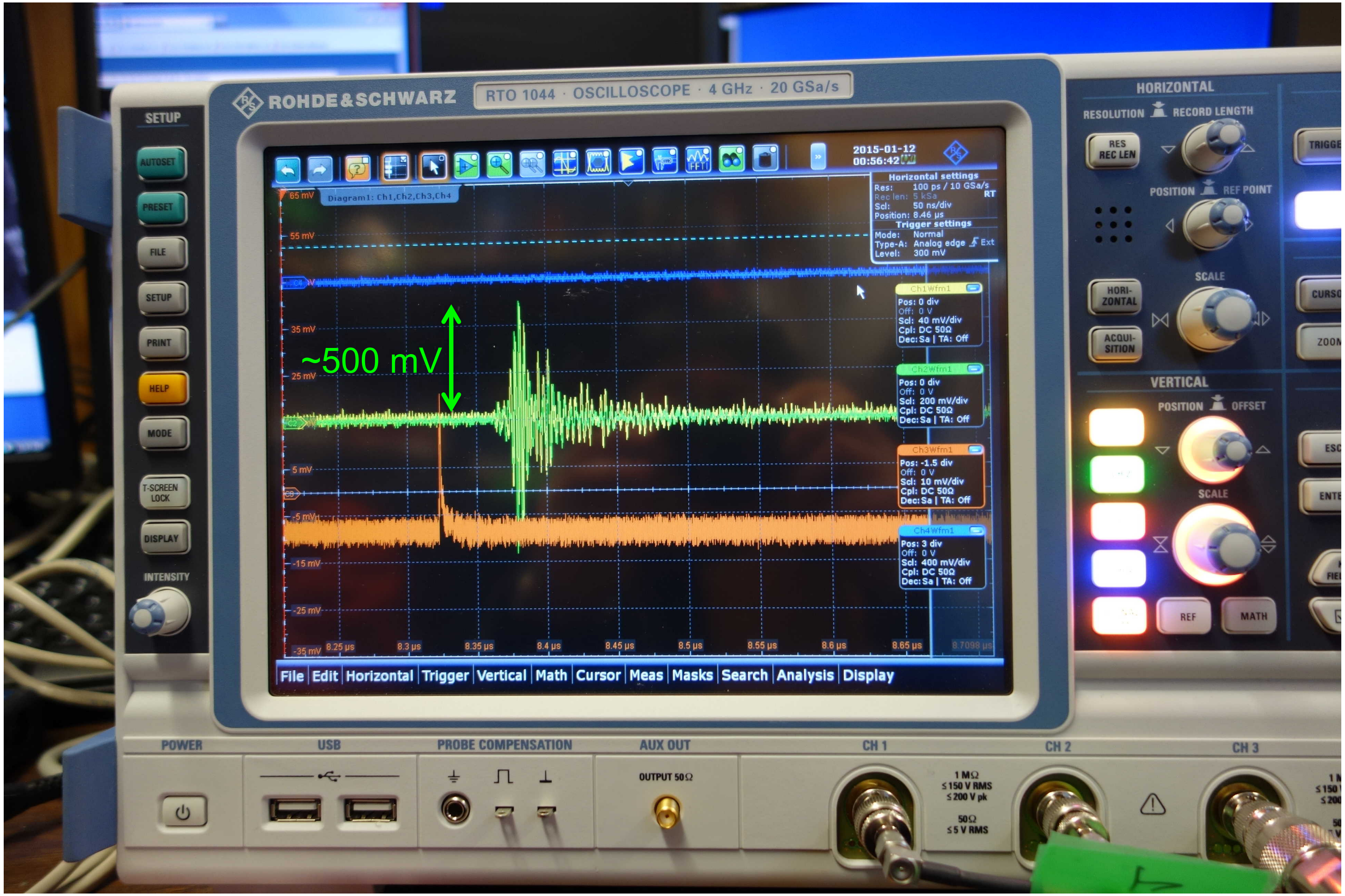
Sudden birth signal observed by D. Ikeda



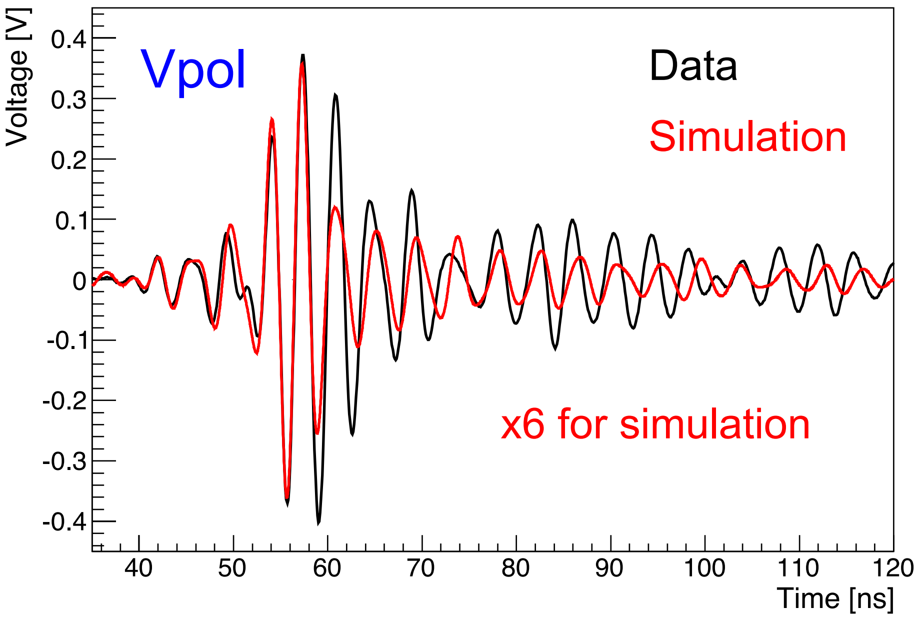
arXiv:1007.4146

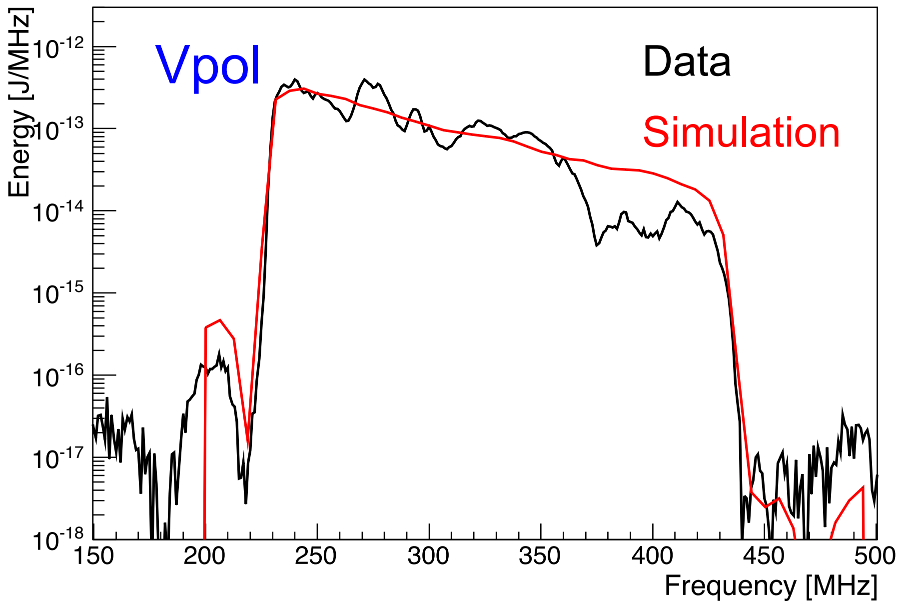


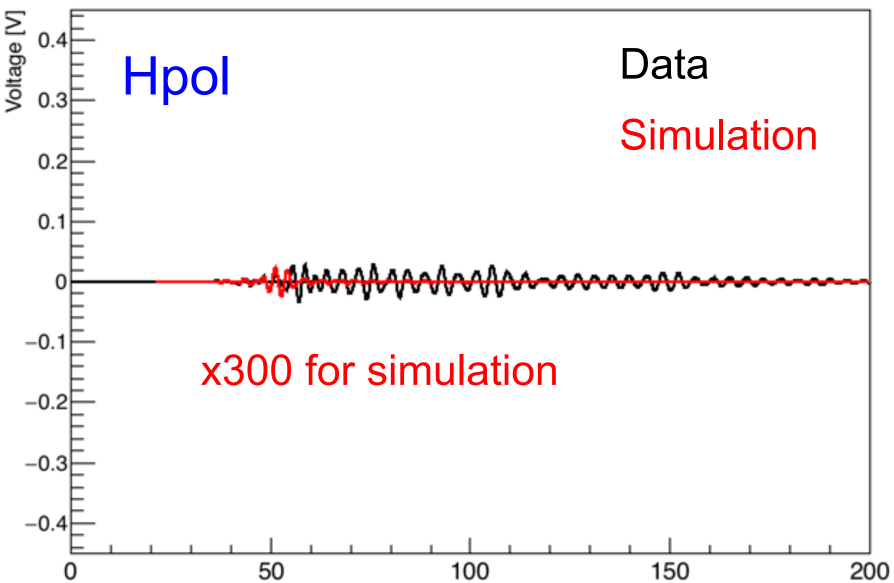
Signals observed



Comparisons of waveform and the frequency spectrum







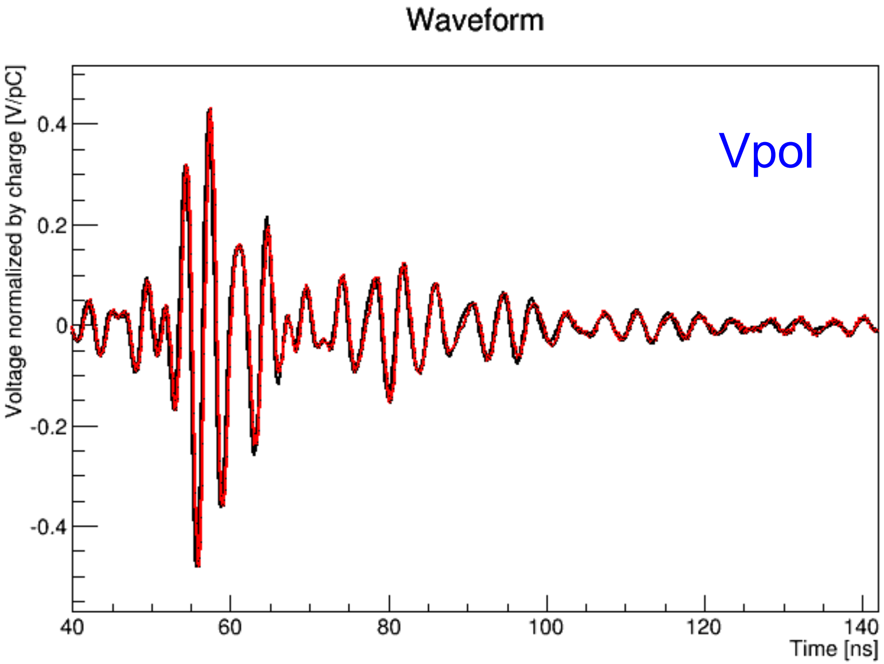
- ✓ The absolute values are different by 6 times (Vpol)
- ✓ The earlier part matches relatively well, but there is a difference for the later part
- ✓ Less Hpol signals → high polarization

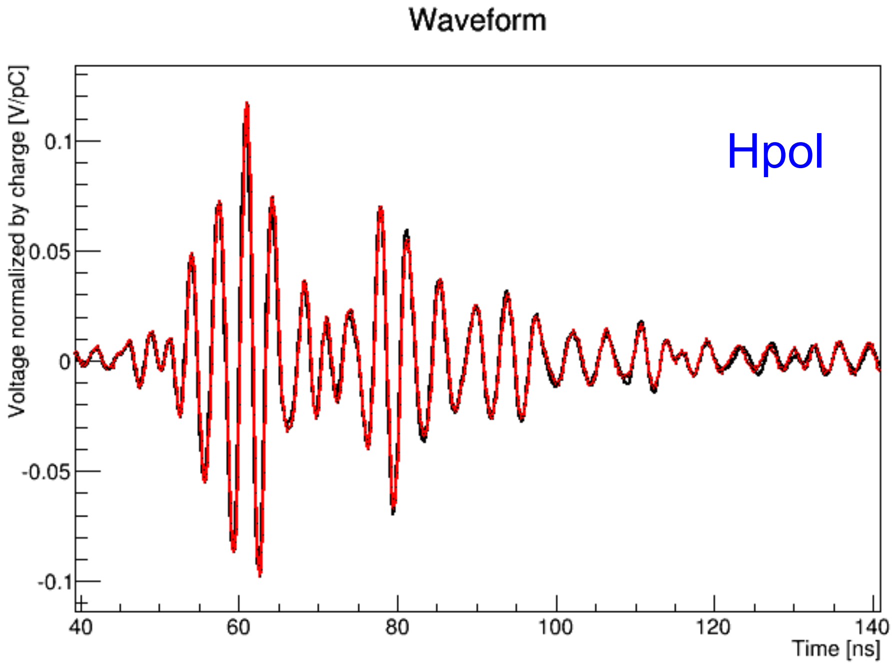
Reproducibility

The reproducibility was checked with data with the same configuration

2015/01/14 Run1 (ice 60 deg., 0m)

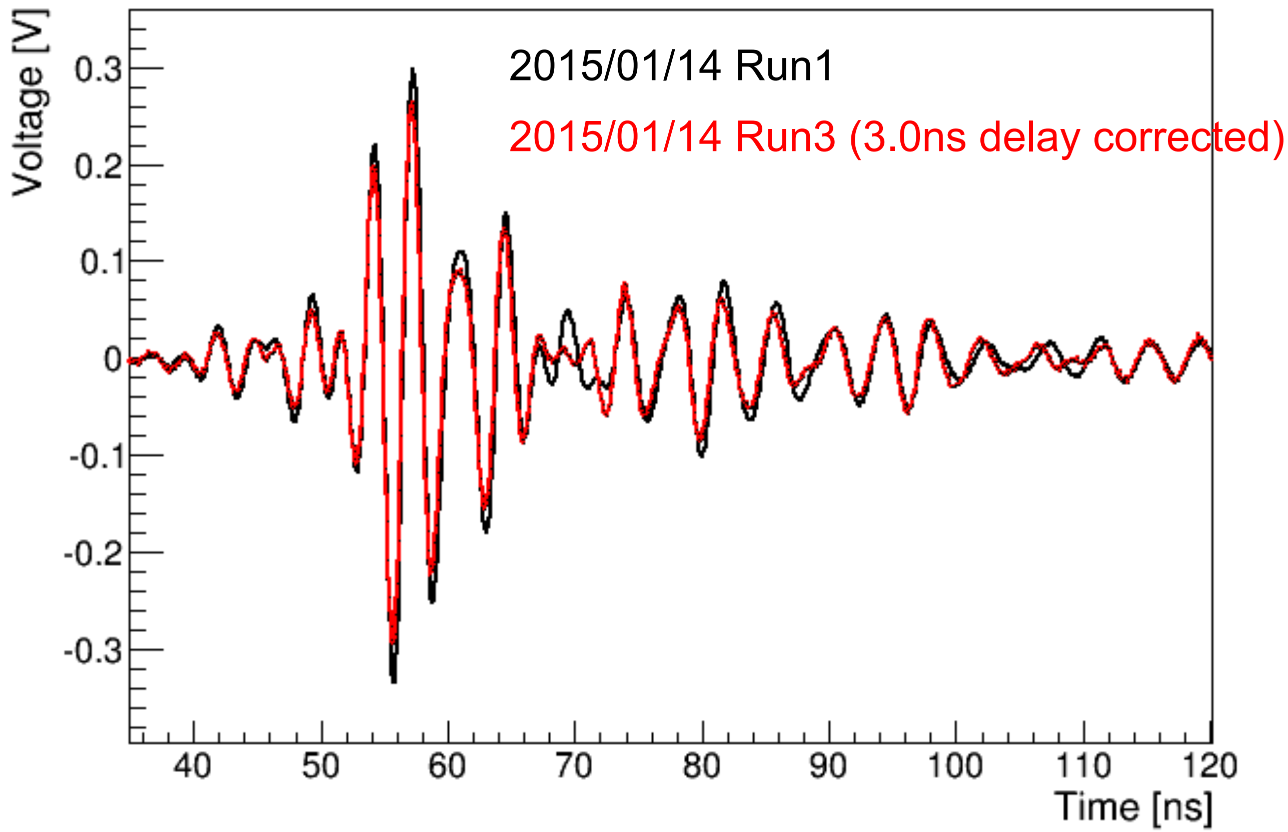
2015/01/14 Run4 (ice 60 deg., 0m)

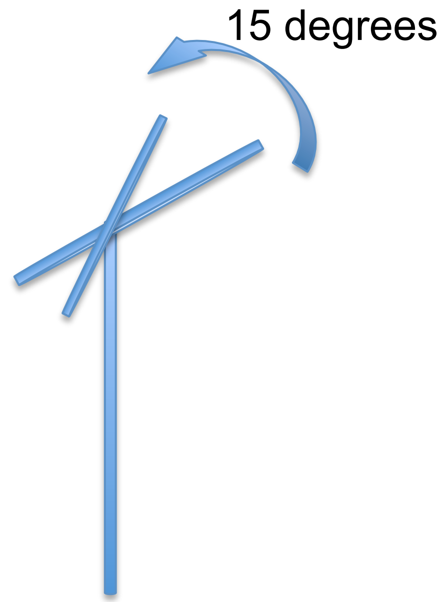




The difference in the amplitude is 5% → 10% in power (Vol)

Far field confirmation





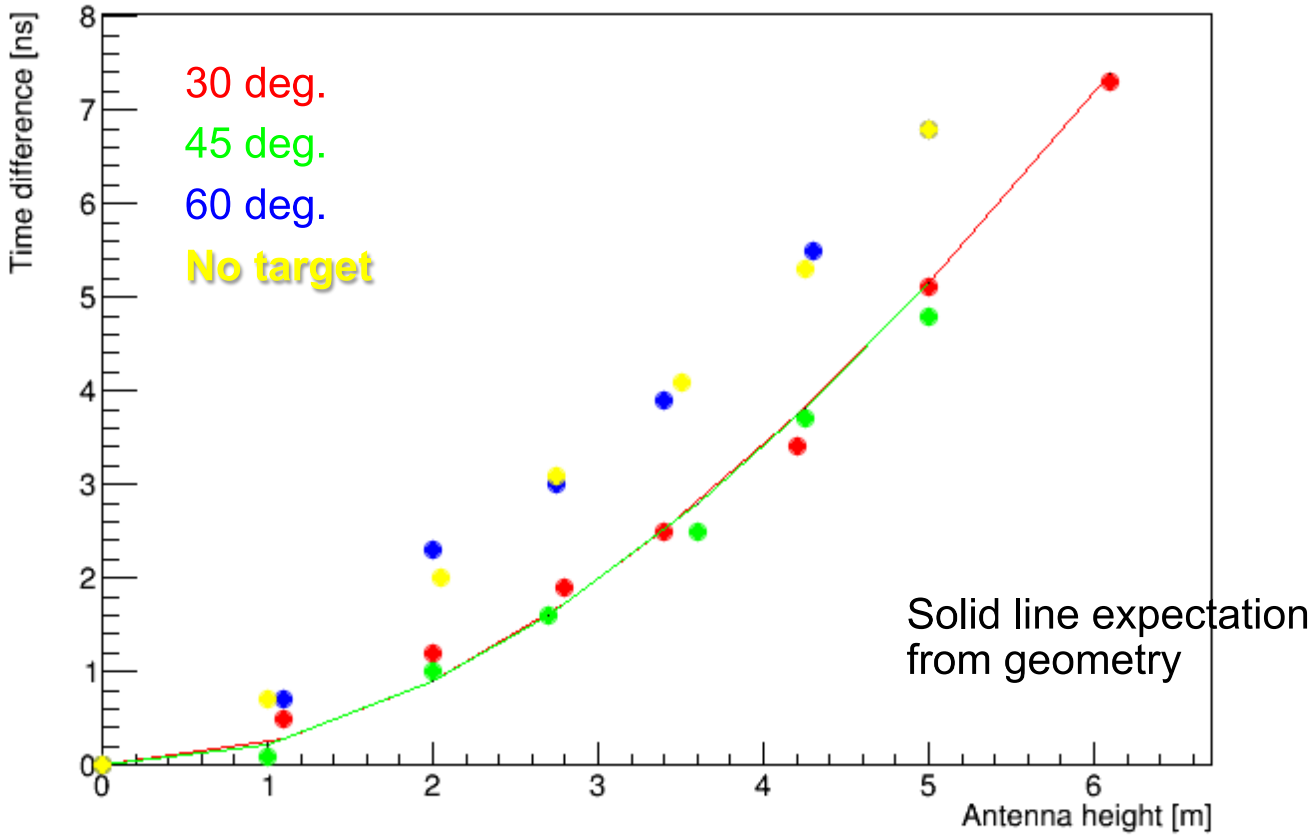
The antenna mast was intentionally rotated by ~15 deg. for Run3.

Time delay of 3.0 ns -> 0.90 m. The distance changed from 7.3 m to 8.2 m (7.3/8.2 = 0.89)

Signal also reduced by 0.88 times. (from 297 mV to 262 mV) as expected.

Confirmation of the far field condition

Time delay Vs. antenna height (Vpol)

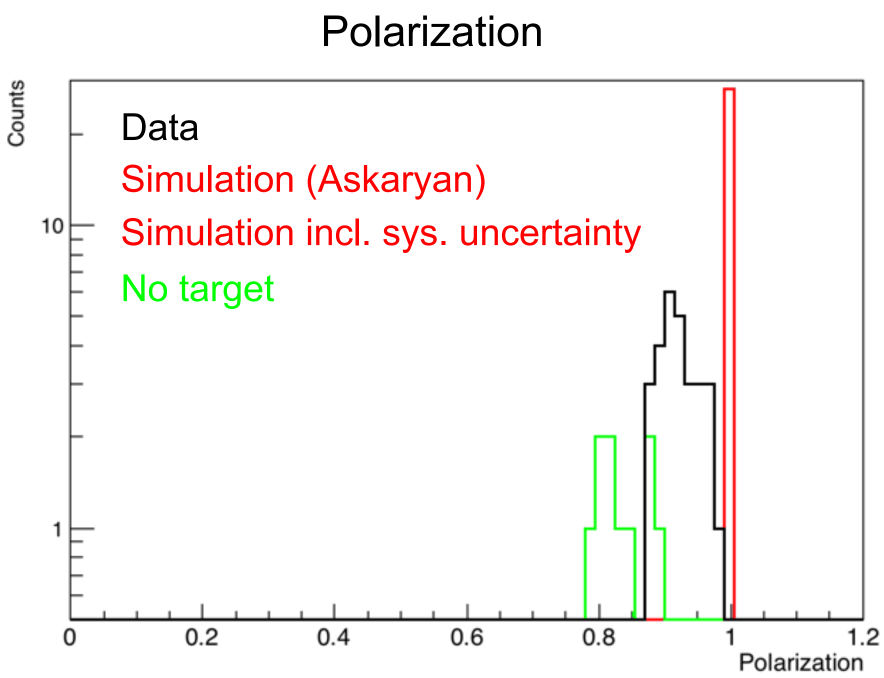


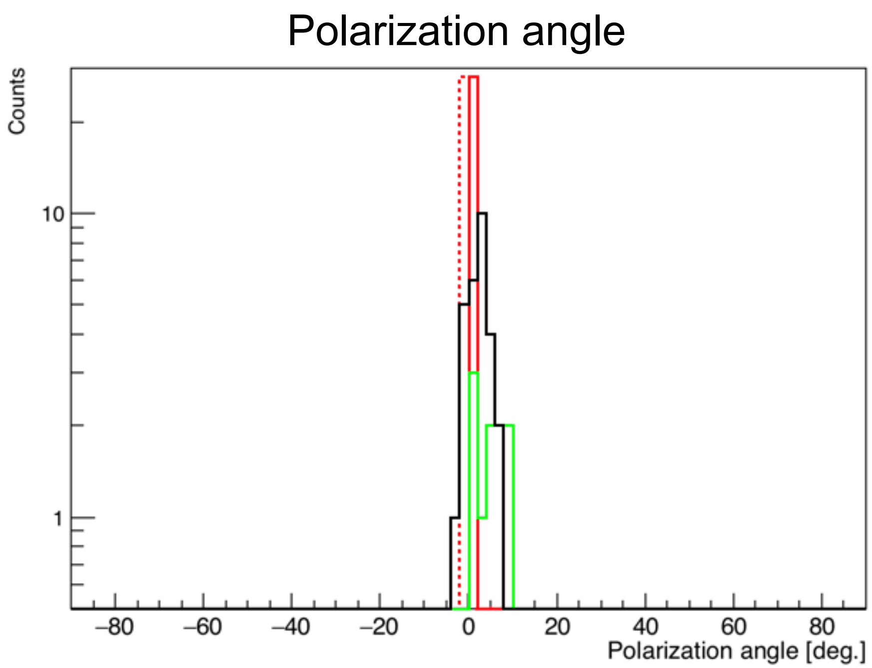
The rotation angles checked by the time delay

Constant time delay of ~1.5 ns for 60 deg. and no target case.

This corresponds to ~7 deg. in the rotation angle.

Polarization



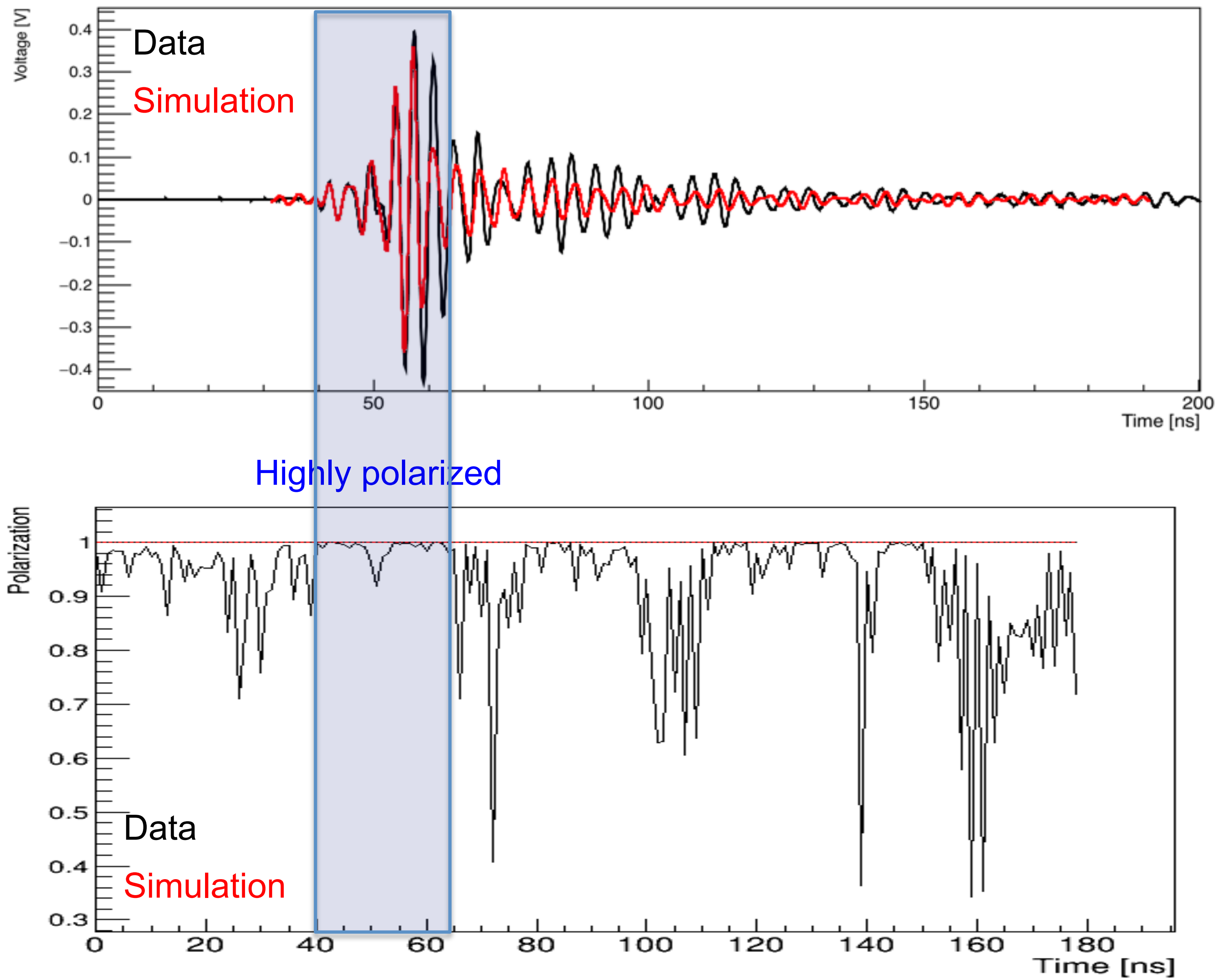


Data	0.92±0.03
Simulation	1.00±0.01
No target	0.82±0.03

All signals shows high vertical polarization

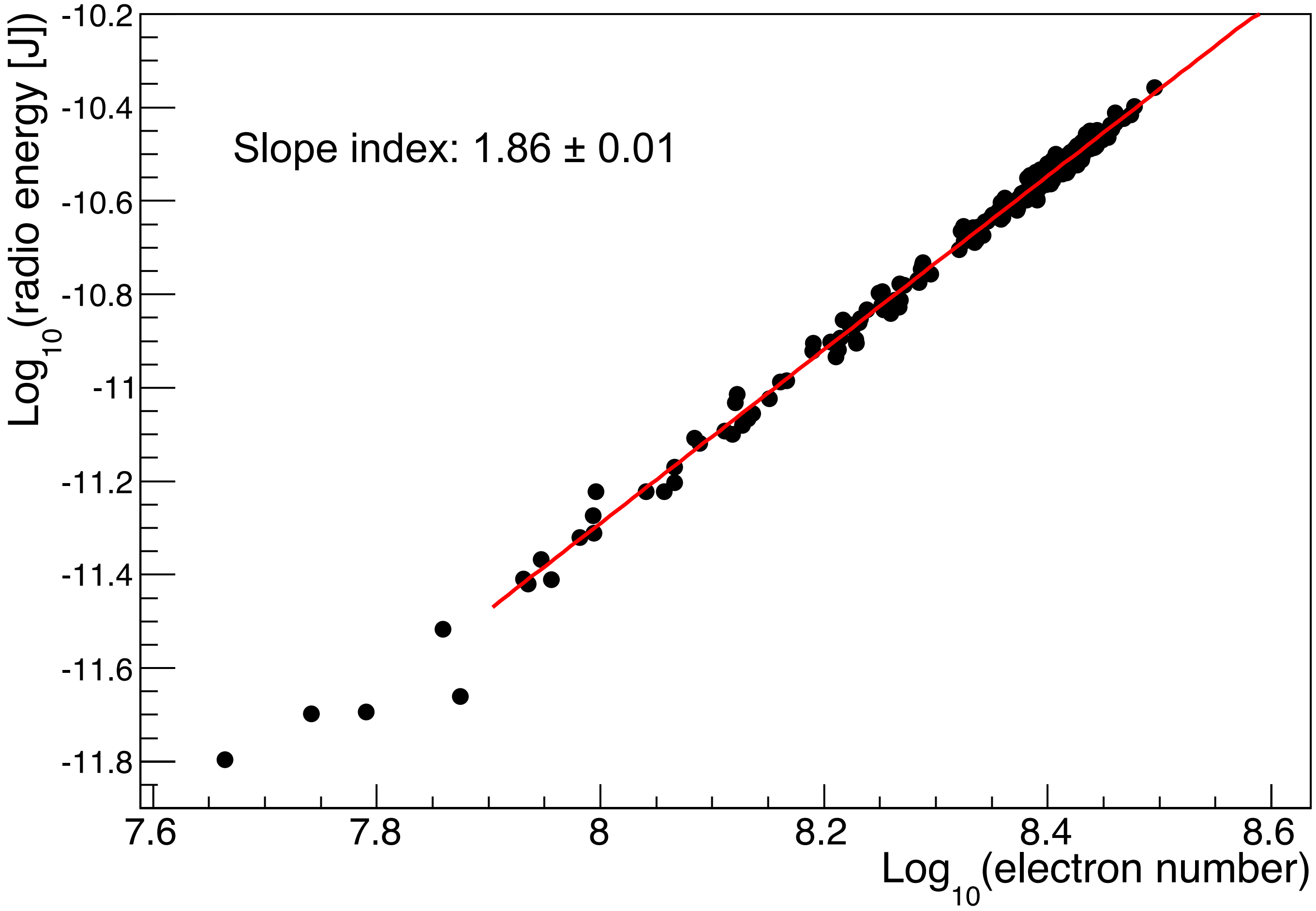
Data is off from simulation

Time development of polarization



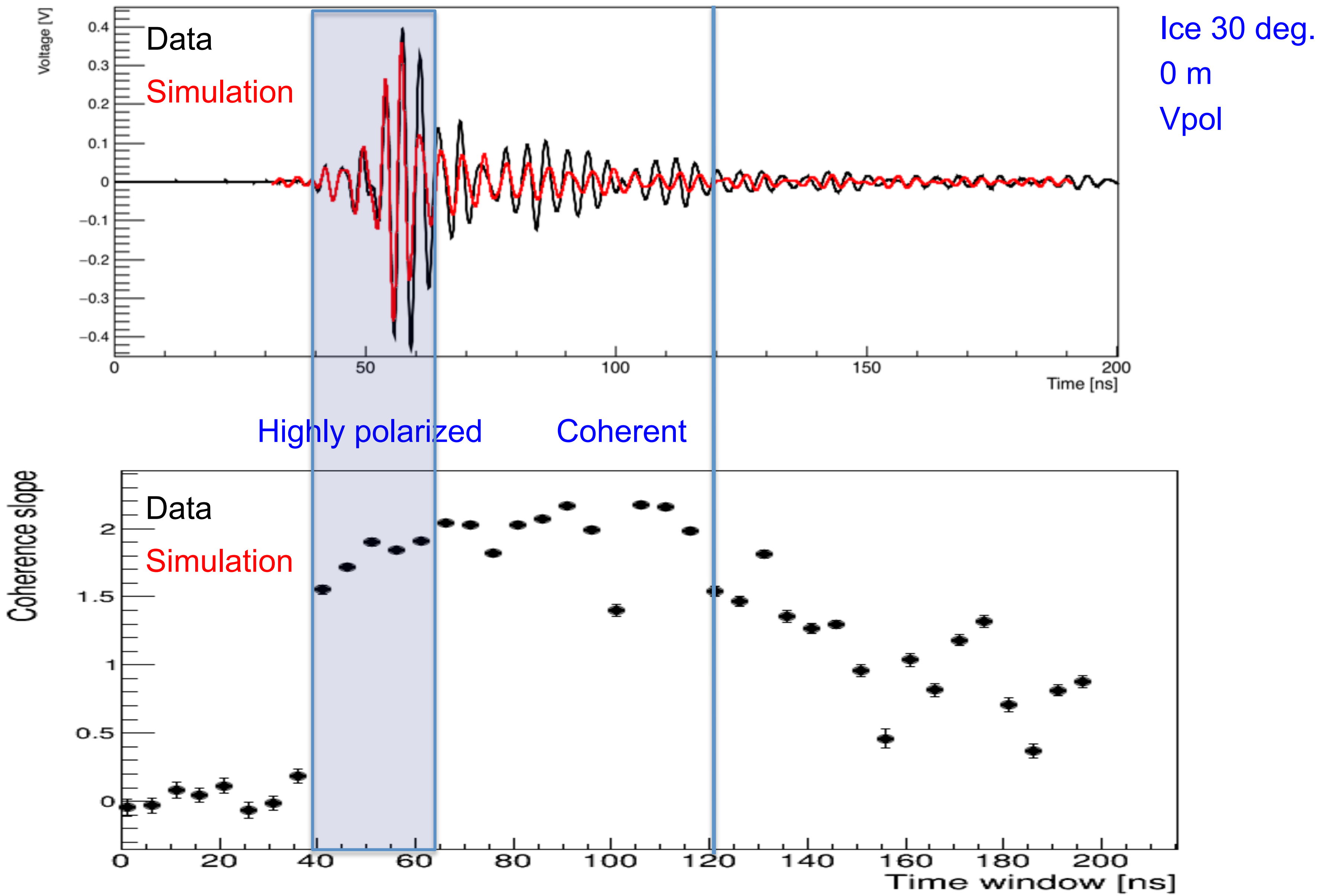
Ice 30 deg.
0 m
Vpol

Coherence

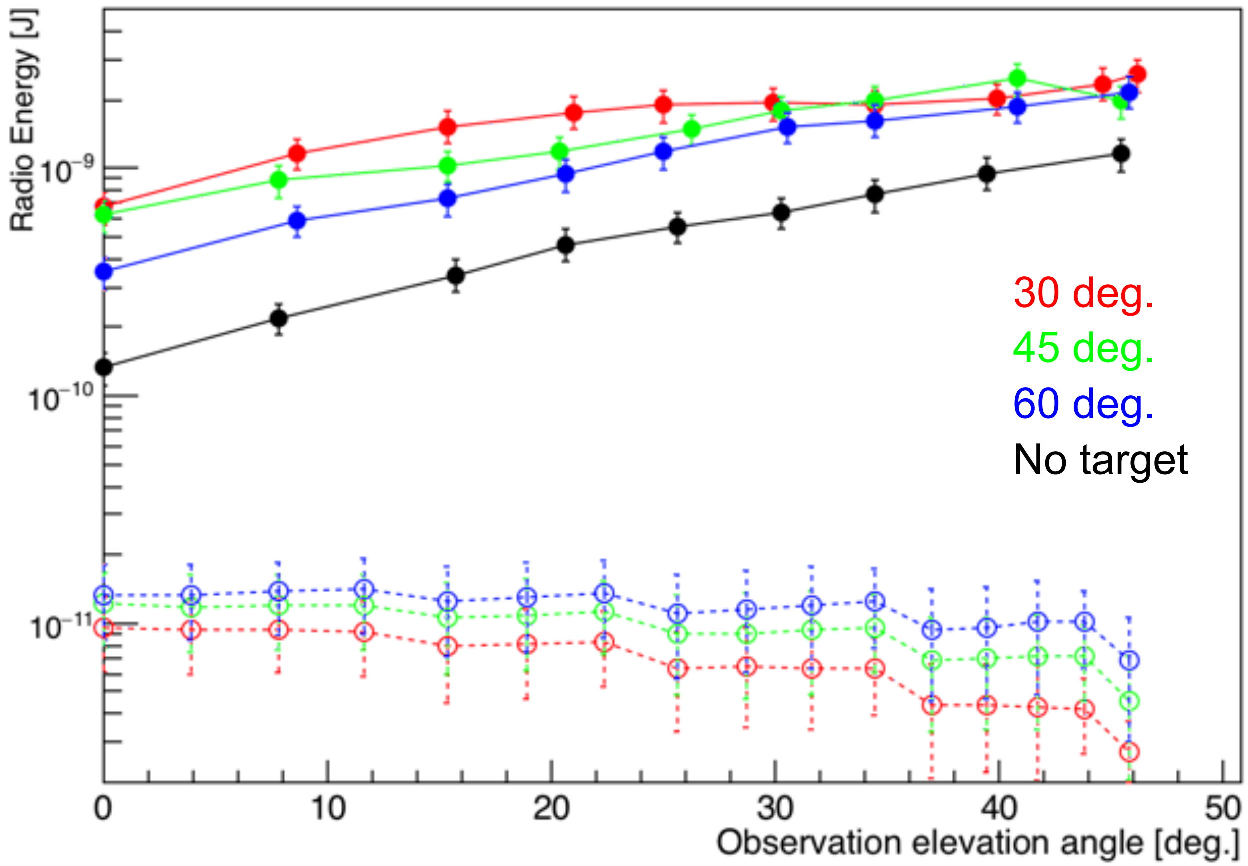


High coherence, but not 2

Time development of coherence



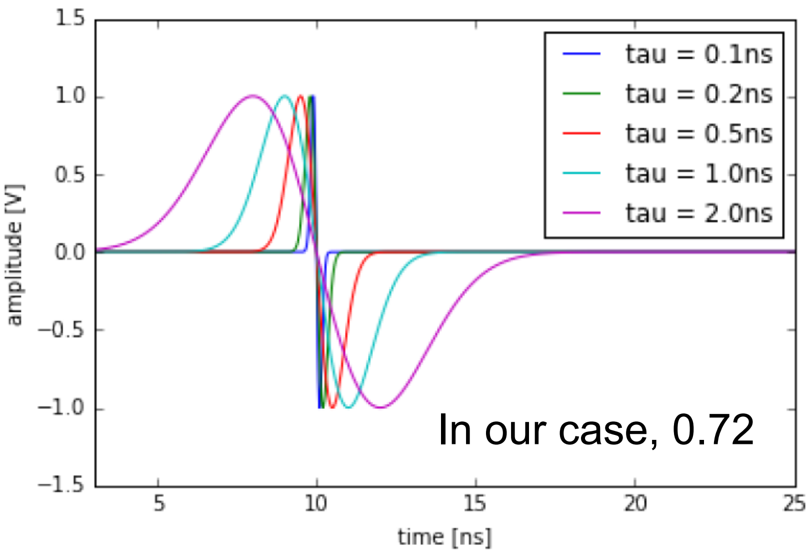
Angular distribution

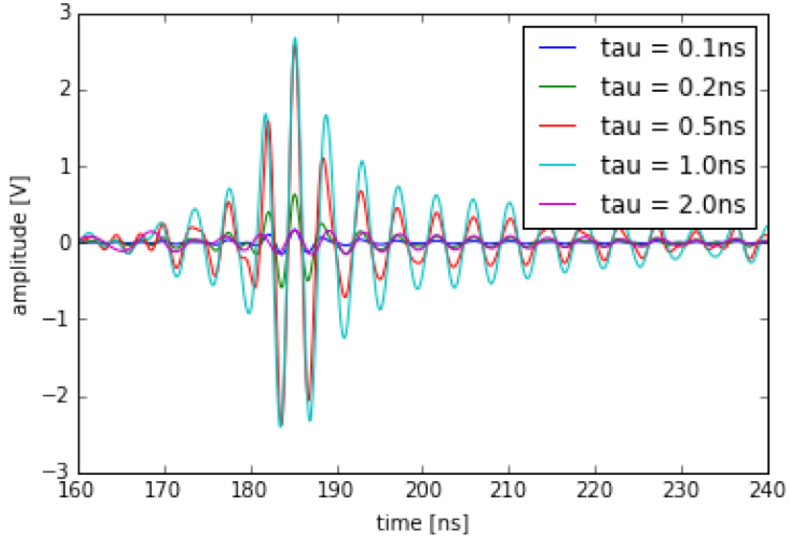


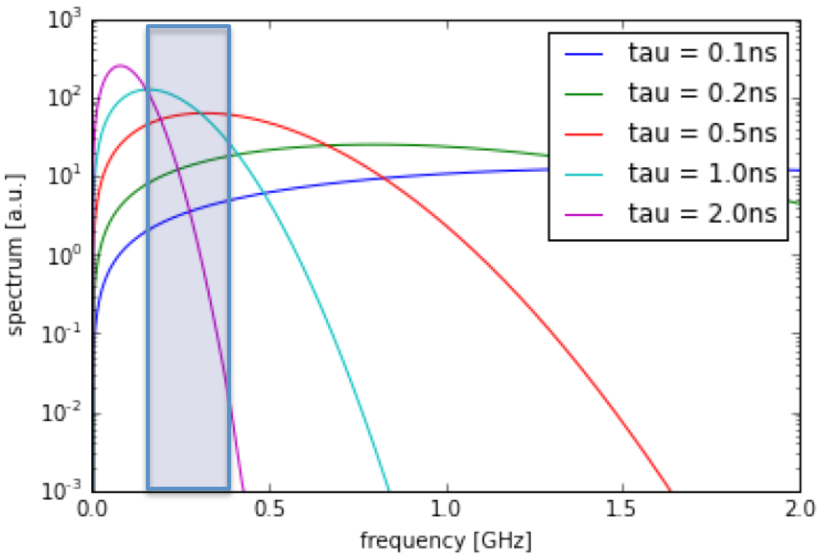
Observed signals are above the expected Askaryan radiation

Dependence of the input E-field

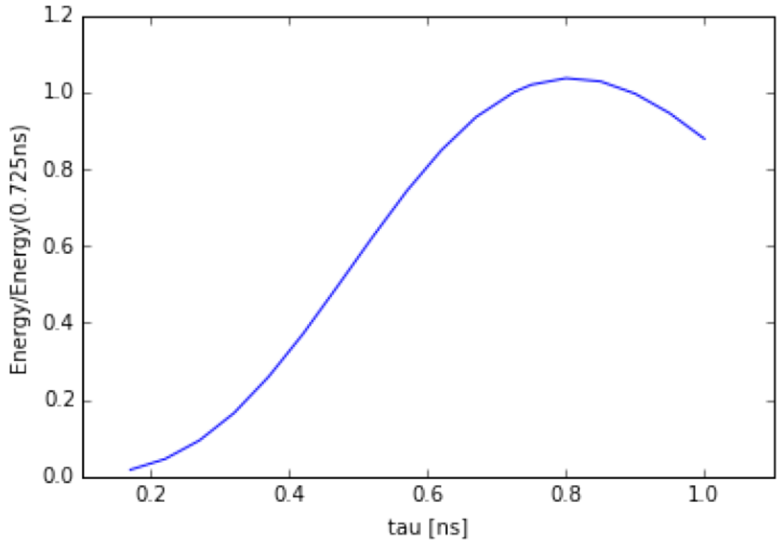
R. Gaior







Sensitive to 0.5-1.0 ns input



Upper limit exists

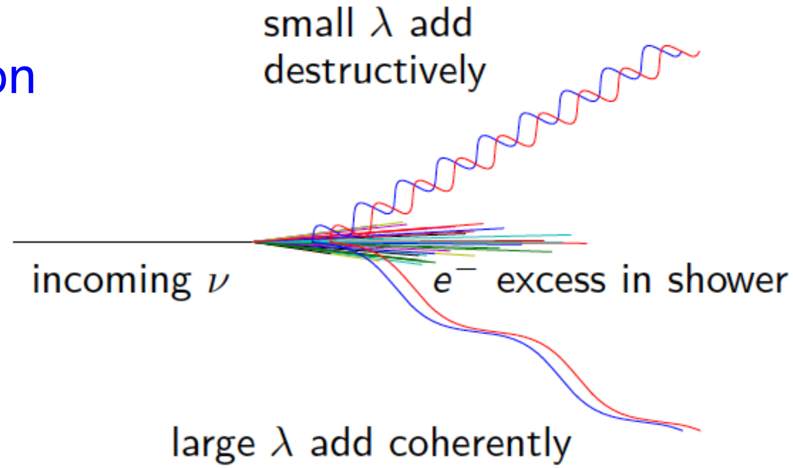
Summary

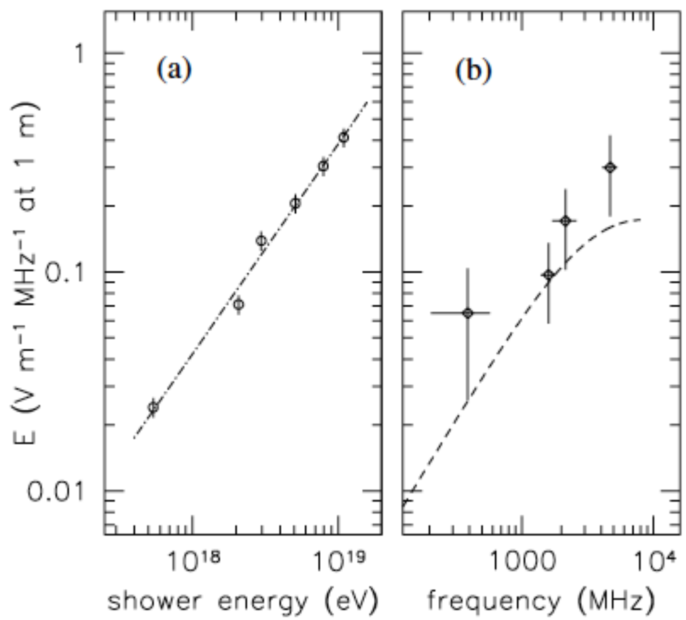
- We have performed an experiment for the better understanding of Askaryan radiation and the calibration of the ARA detectors using TA-ELS
- Highly polarized and coherent signals were observed
- Observed signals are more than the expected Askaryan radiation
- We are going to understand our data in more detail using more detailed simulation which includes the background contribution

Backups

Radio wave through Askaryan effect

- ✓ 1962: Askaryan predicted coherent radio emission from excess negative charge in an EM shower (~20% due to mainly Compton scattering and positron annihilation) → **Askaryan effect**
- ✓ 2000: Attempt to measure Askaryan effect with Argonne Wakefield Accelerator (AWA) (P. W. Gorham et al., PRE 62, 6 (2000))
- ✓ 2001: **First experimental detection of Askaryan effect** at SLAC with silica sand (D. Saltzberg et al., PRL 86, 13 (2001))
- ✓ 2005: Observation of Askaryan effect in rock salt at SLAC (P. W. Gorham et al., PRD 72, 023002 (2005))
- ✓ 2007: Observation of Askaryan effect in ice at SLAC (P. W. Gorham et al., PRL 99, 171101 (2007))
- ✓ We intended to measure the Askaryan radio wave using the Telescope Array (TA) LINAC and use it for end-to-end calibration of the ARA detector

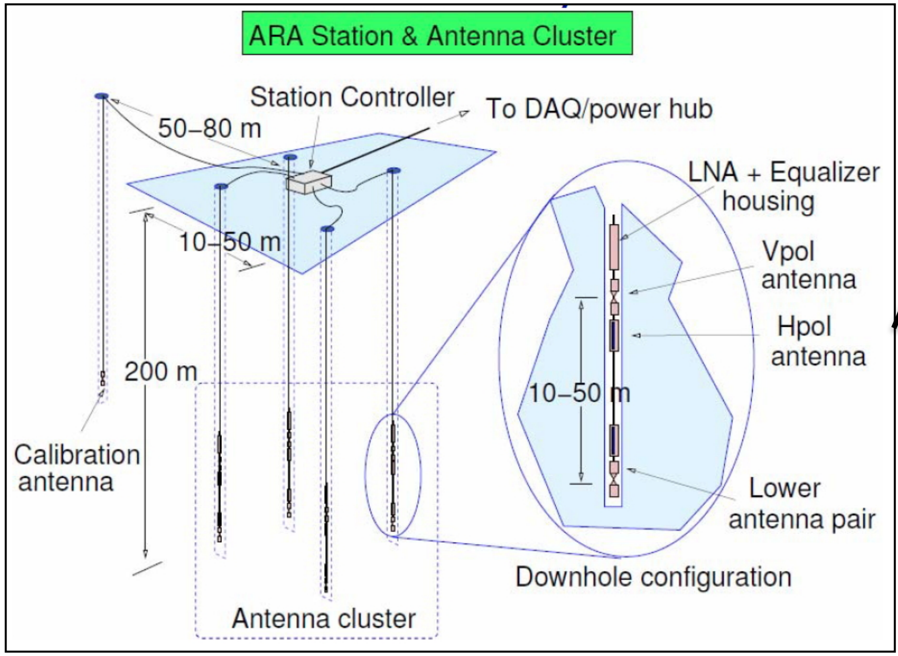


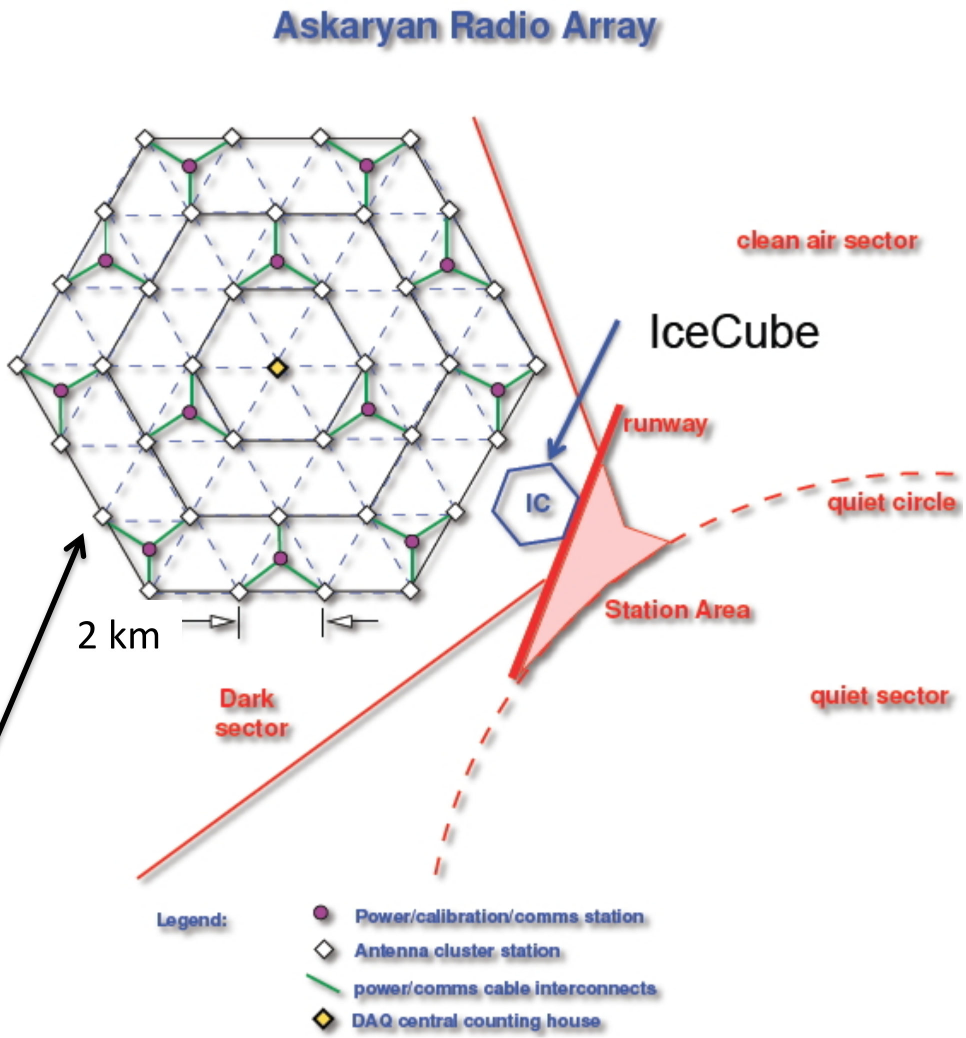


D. Saltzberg et al., PRL 86, 13 (2001)

Askaryan Radio Array (ARA)

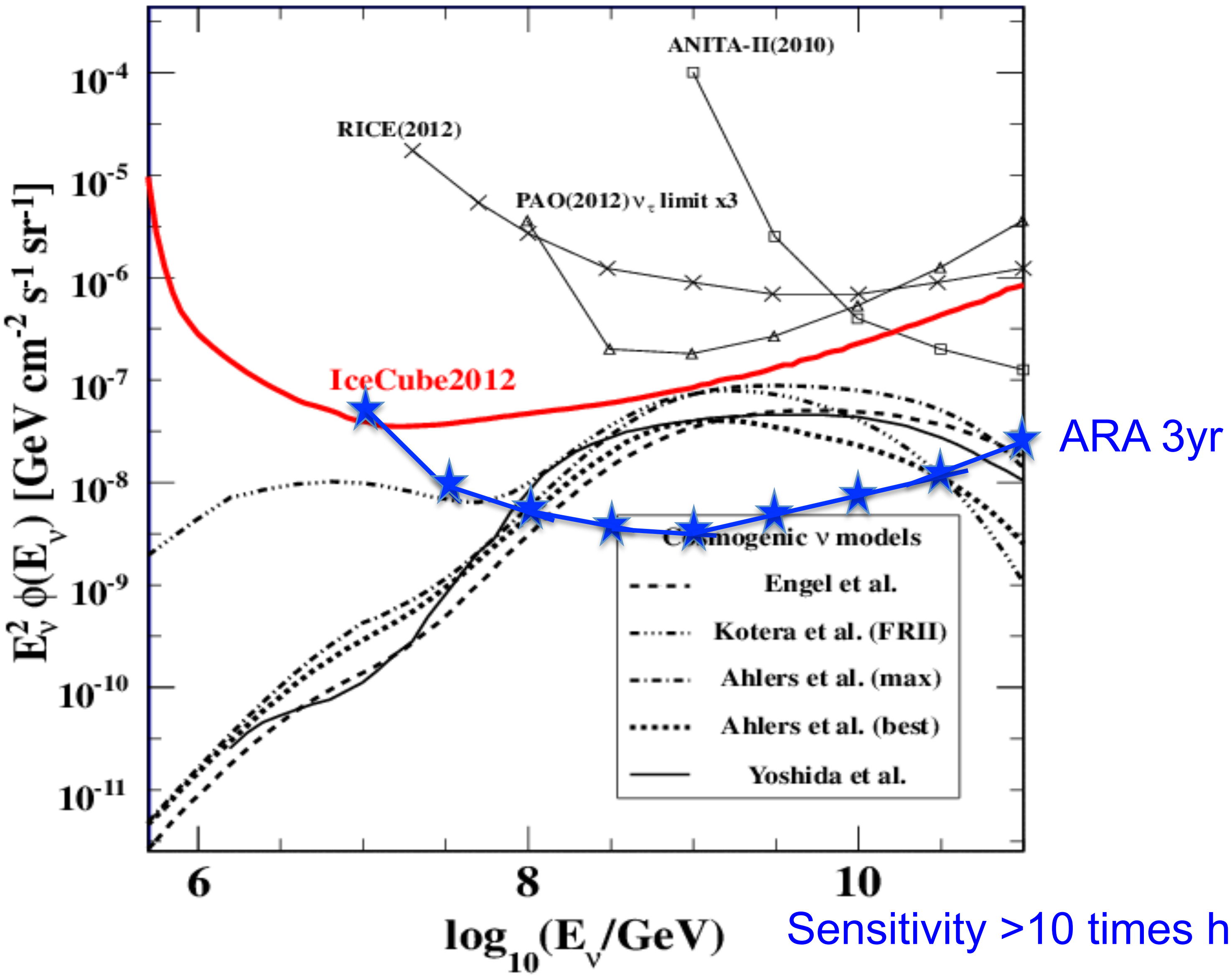
- Designed to observes high energy neutrinos above 100 PeV
- 37 stations (3 stations deployed so far)
- Each station has 4 strings of 200m depth
- Each string has 2 Vpol + 2Hpol broadband antennas (~200–800 MHz)
- Total surface area ~100 km^2





Astroparticle Physics **35** (2012) 457–477

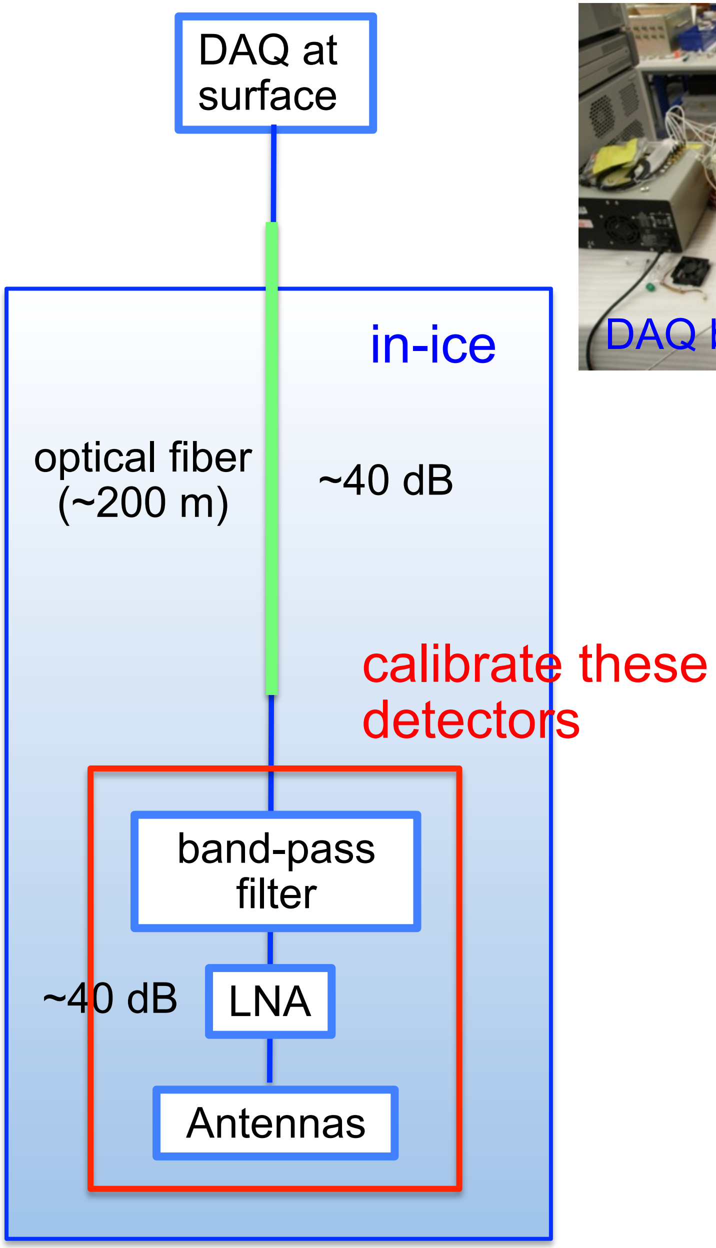
The ARA sensitivity

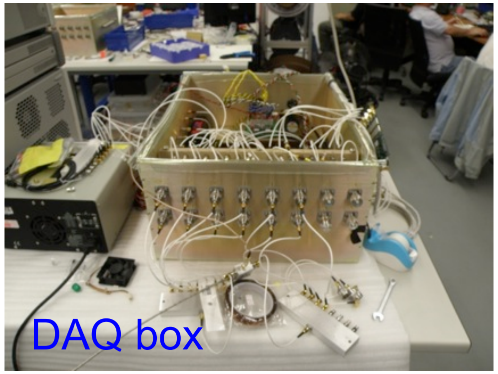


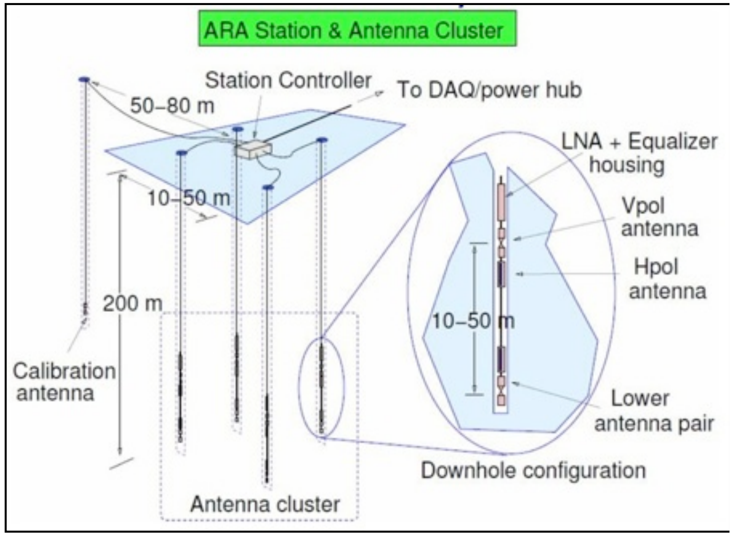
Sensitivity >10 times higher

>~10 events/yr

The ARA system



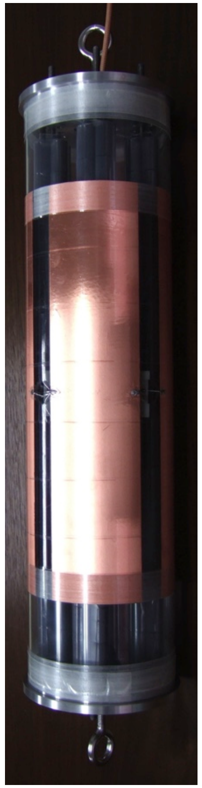




V-pol antenna

Bicone

150-850 MHz



H-pol antenna

Quad-slot cylinder

200-850 MHz

Gain similar to dipole (+2 dBi)

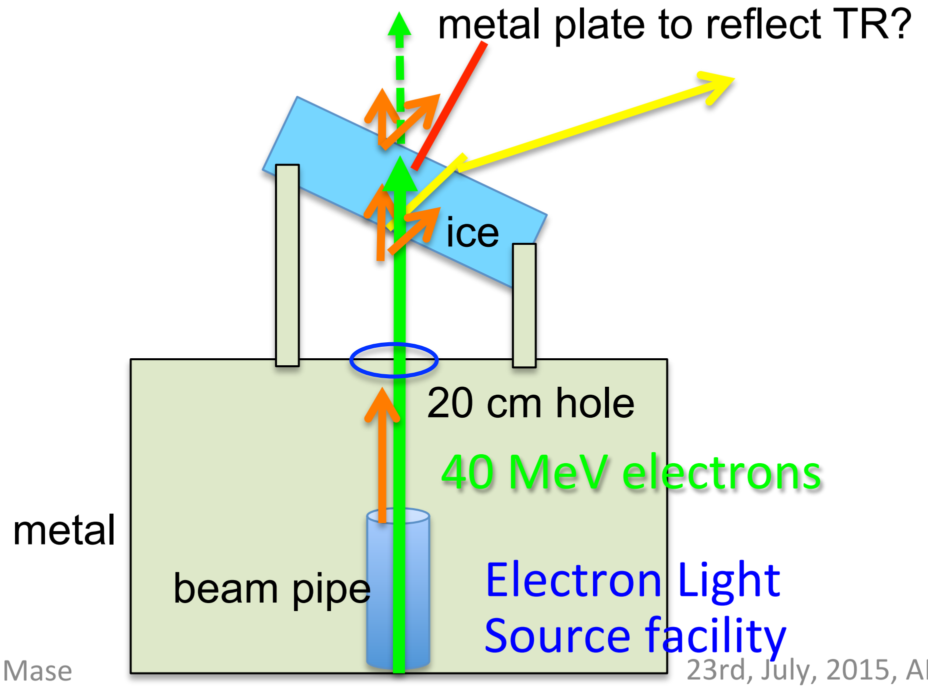
Transition radiation

- Transition Radiation (TR) was a severe background for the experiment performed by AWA
- Several places where TR is expected
- At the beam end cap (metal → air): only vertical direction
- Air → ice: TR suppressed because electrons terminated before the formation zone. The angle closed to the Cherenkov angle
- Ice → air: less electrons. The angle is close to the Cherenkov angle → metal plate to reflect TR?
- Evaluate more precisely with simulation

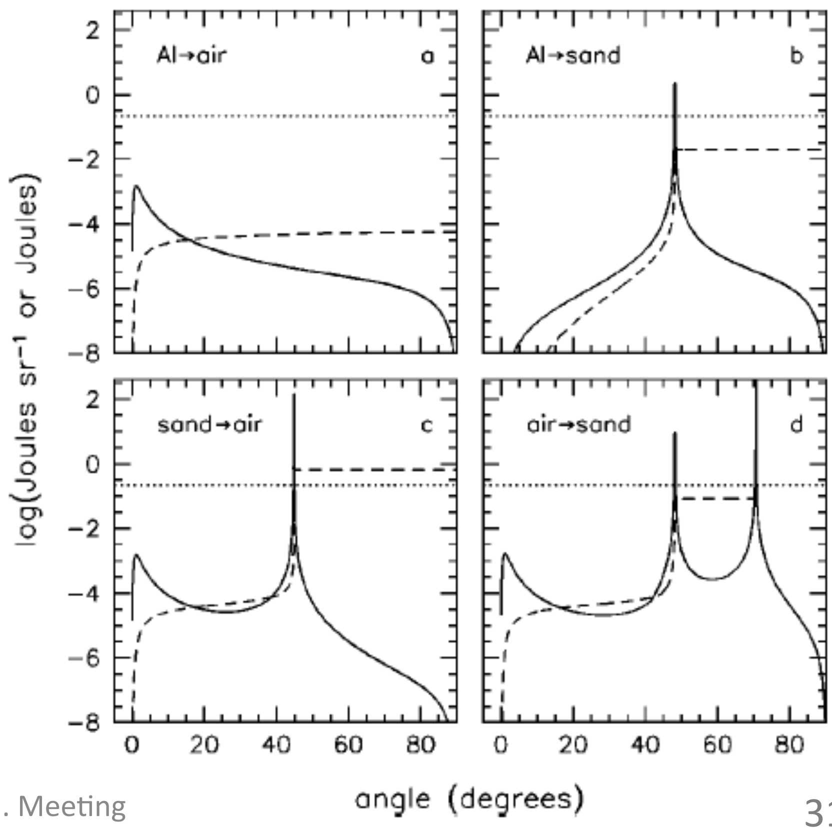
Formation zone

$$L_f = \frac{2\pi\beta c}{|\omega(1-n_2\beta\cos\theta)|}$$

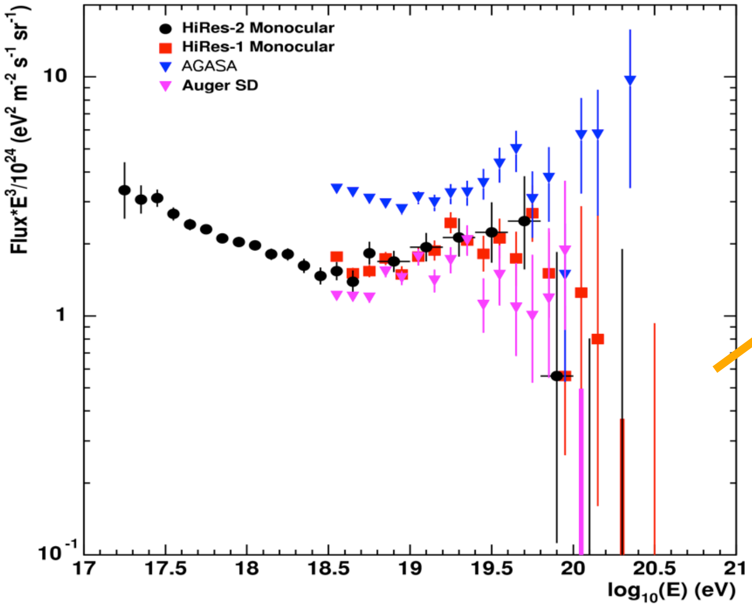
$$\approx \lambda$$



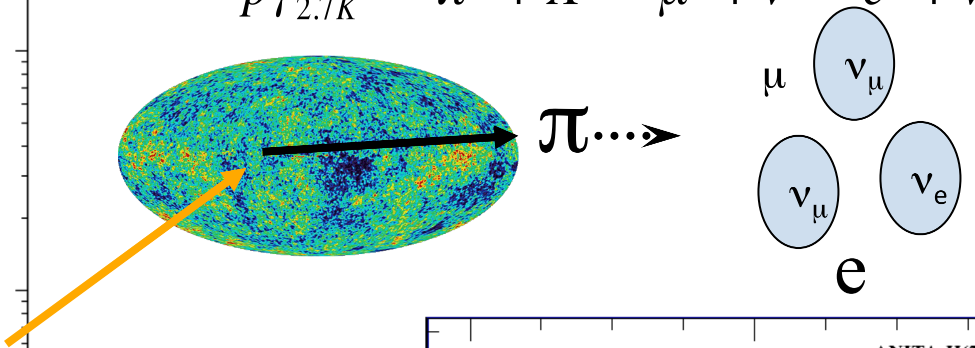
P. W. Gorham et al., PRE 62, 6 (2000)

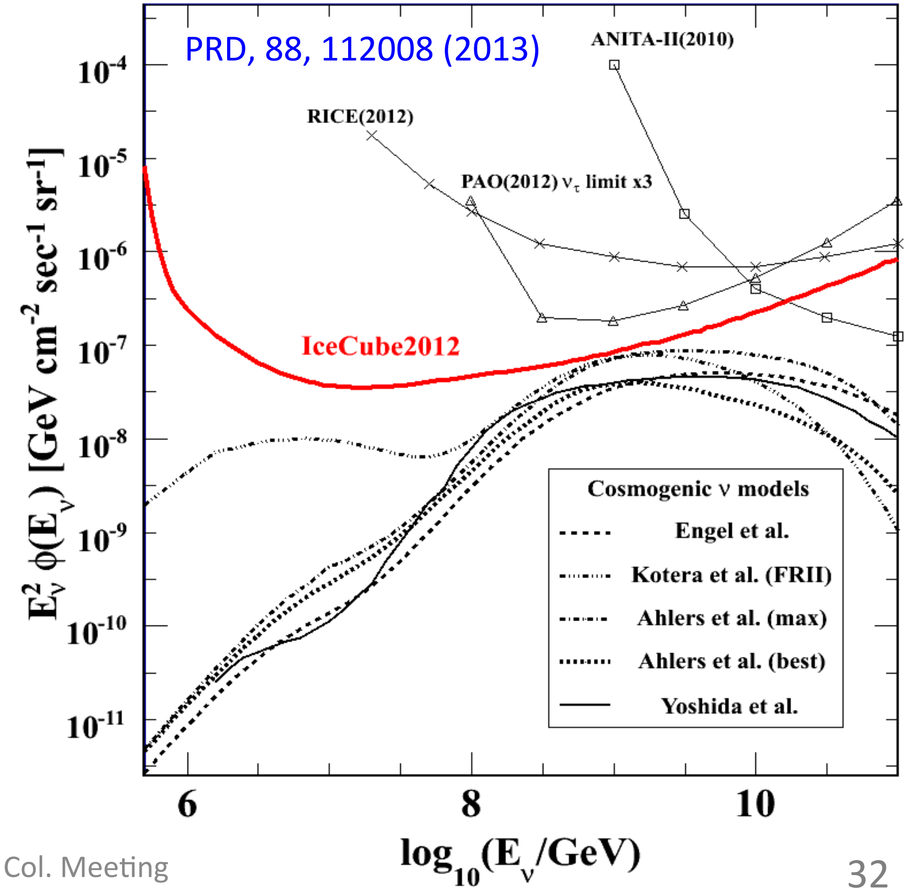


The origin of Ultra High Energy Cosmic Rays



$$p\gamma_{2.7K} \rightarrow \pi^{\pm} + X \rightarrow \mu^{\pm} + \nu \rightarrow e^{\pm} + \nu's$$





Shed light on the UHECR origin

- ✧ Source evolution
- ✧ Composition (proton/iron)?
- ✧ Source position

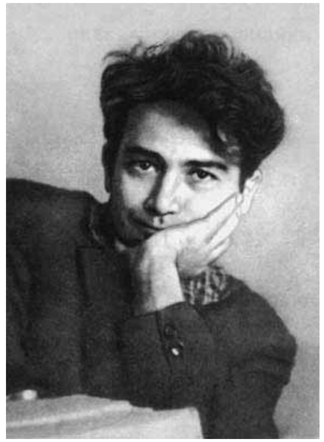
IceCube: ~1 event/year expected

-> want MORE!

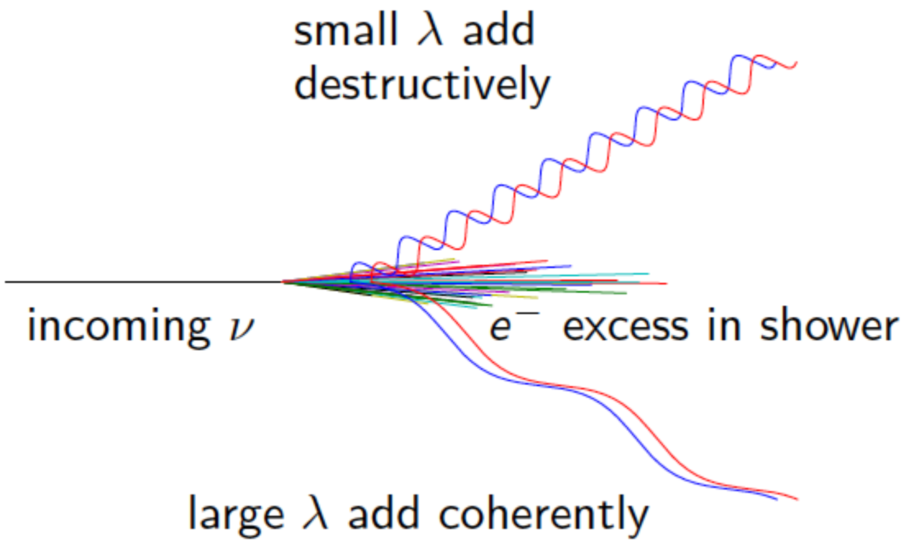
Askaryan effect

- 1962: Askaryan predicted coherent radio emission from excess negative charge in an EM shower (~20% due to mainly Compton scattering and positron annihilation)

  → **Askaryan effect**



G. Askaryan



Shower size << λ to be coherent

Cherenkov emission (Frank-Tumm result)

$$\frac{d^2W}{d\nu dl} = \frac{4\pi^2\hbar}{c}\alpha z^2\nu\left(1-\frac{1}{\beta^2 n^2}\right)$$

in case N electrons,

z=1 (not coherent) → W ∝ N

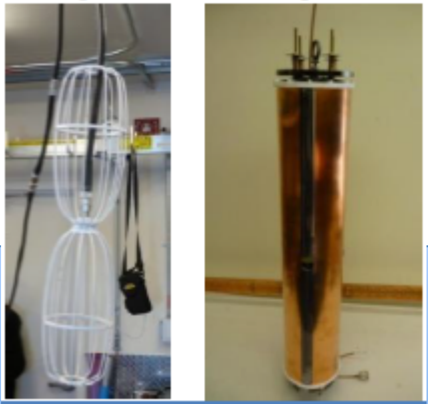
z=N (coherent) → W ∝ N^2

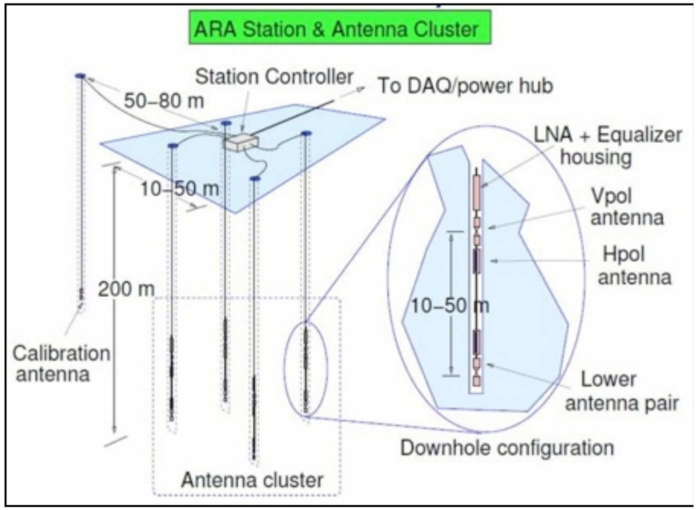
Power ∝ Δq^2, thus prominent at EHE (>~ 10 PeV)

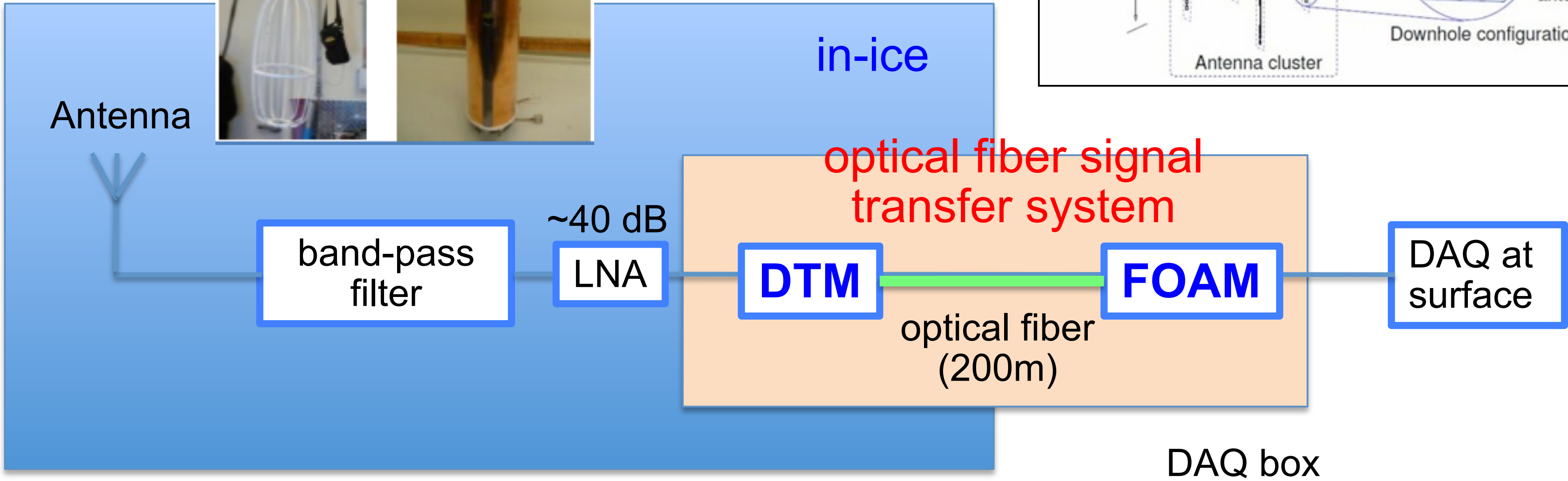
Attenuation length in ice ~ 1 km

Schematic of the ARA system

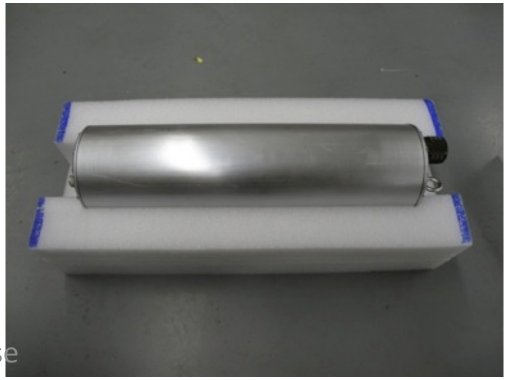
V-pol H-pol



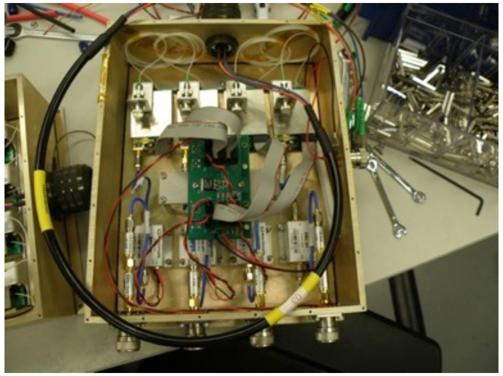




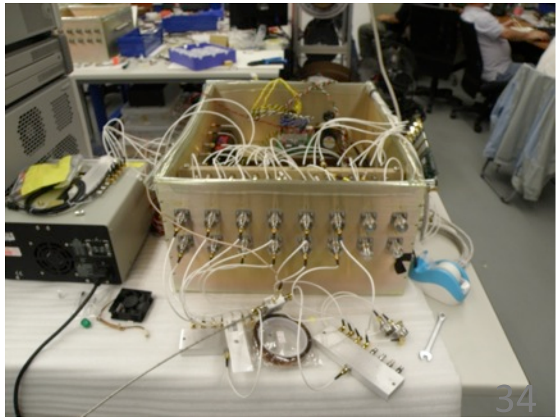
DTM



FOAM



DAQ box

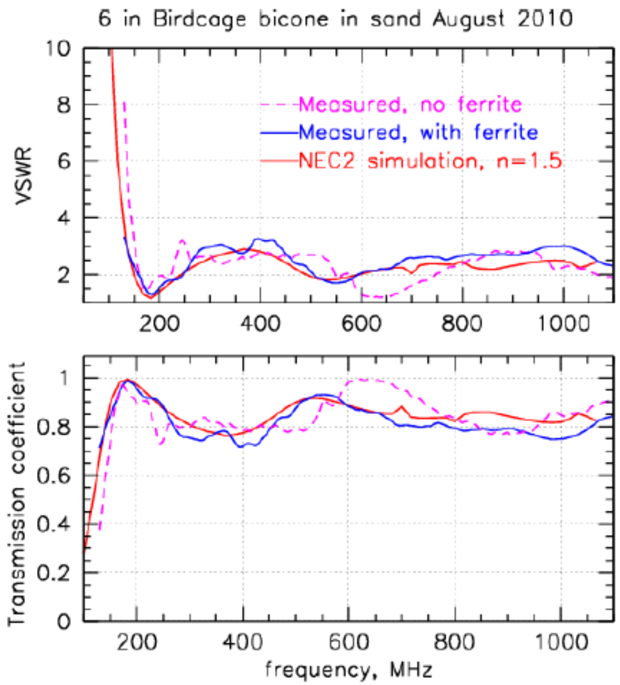


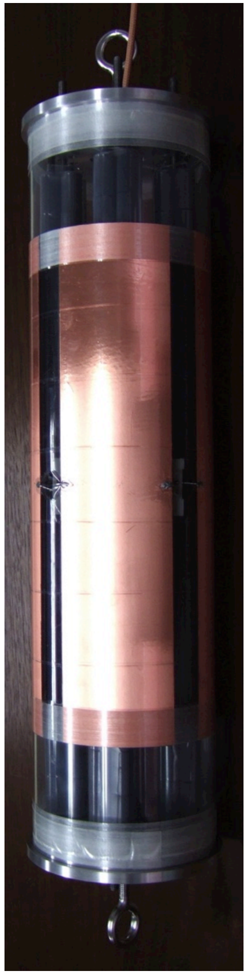
Antennas

V-pol antenna

Bicone

150-850 MHz



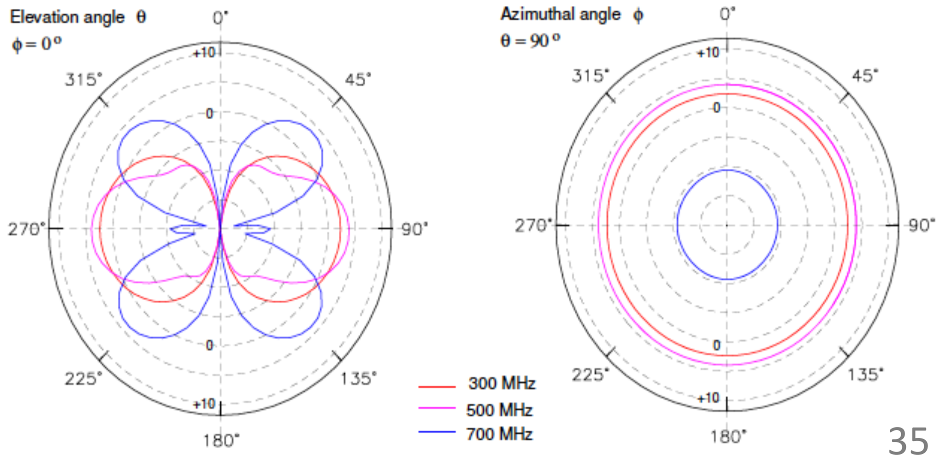


H-pol antenna

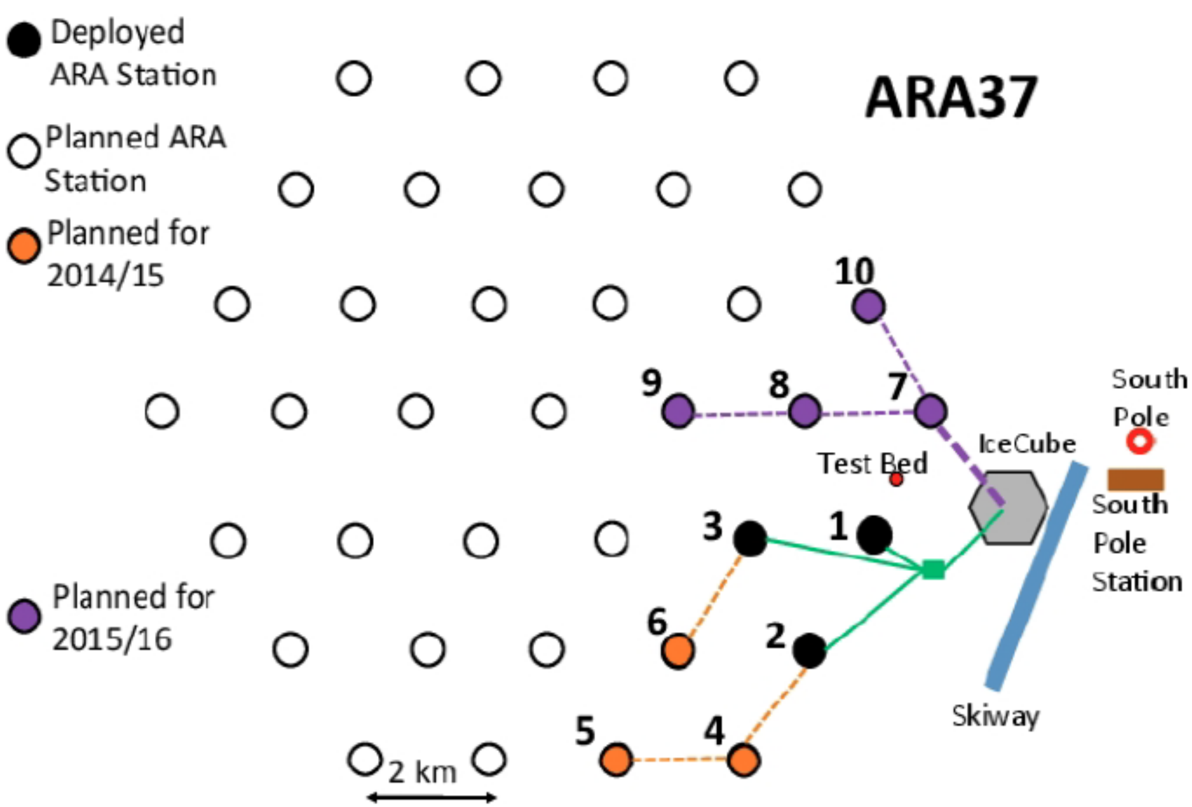
Quad-slot cylinder

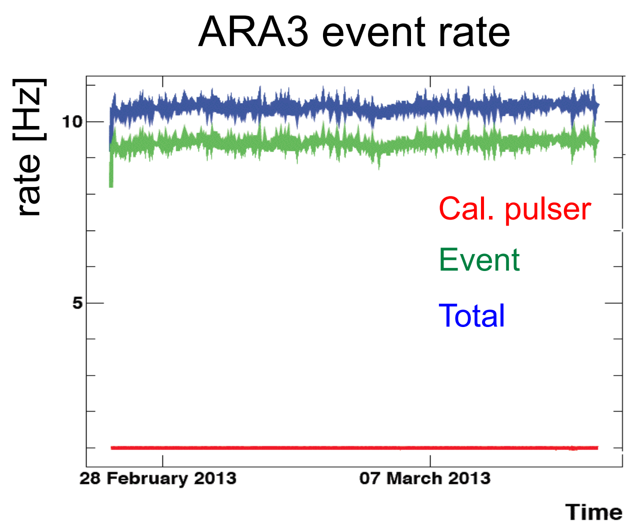
200-850 MHz

Gain similar to dipole
(+2 dBi)



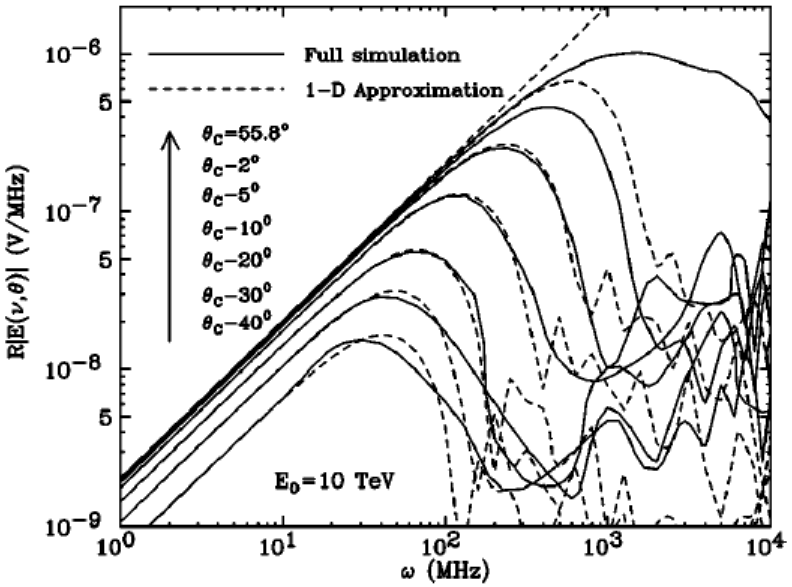
Current status and further plan





- 3 stations operational
- 3 planned for 2014/2015
- More to come

Parameterization of Askaryan radio wave



J. Alvarez Muniz et al., PRD 62, 063001 (2000)

Signal amplitude

$$R\left|\vec{E}(\omega,R,\theta_c)\right| \cong 2.53\times10^{-7}\left[\frac{E_{em}}{1\,TeV}\right]\left[\frac{\nu}{\nu_0}\right]\left[\frac{1}{1+(\nu/\nu_0)^{1.44}}\right] VMHz^{-1}$$

$$\nu_0 = 1.15\,GHz$$

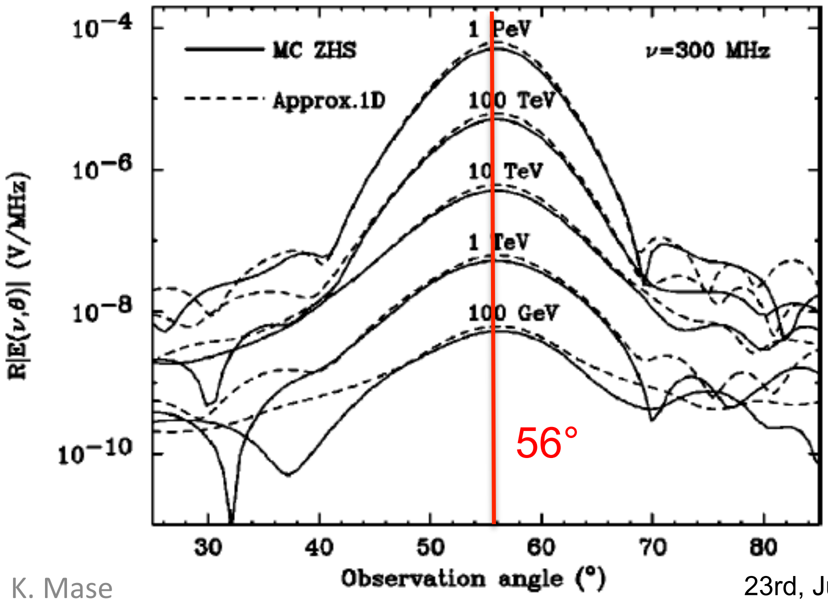
J. Alvarez Muniz et al., Physics Lett. B, 411 (1997) 218

Signal spread

$$E(\omega,R,\theta) = E(\omega,R,\theta)e^{-\ln 2\left(\frac{\theta-\theta_c}{\Delta\theta}\right)^2}$$

$$\Delta\theta = \begin{cases} 2.7^\circ \dfrac{\nu_0}{\nu}\left(\dfrac{E_0}{1\,PeV}\right)^{-0.03} & for\ E_0 < 1\,PeV \\ 2.7^\circ \dfrac{\nu_0}{\nu}\left(\dfrac{E_{LPM}}{0.14E_0+E_{LPM}}\right)^{0.3} & for\ E_0 > 1\,PeV \end{cases}$$

$$\nu_0 = 500\ MHz$$

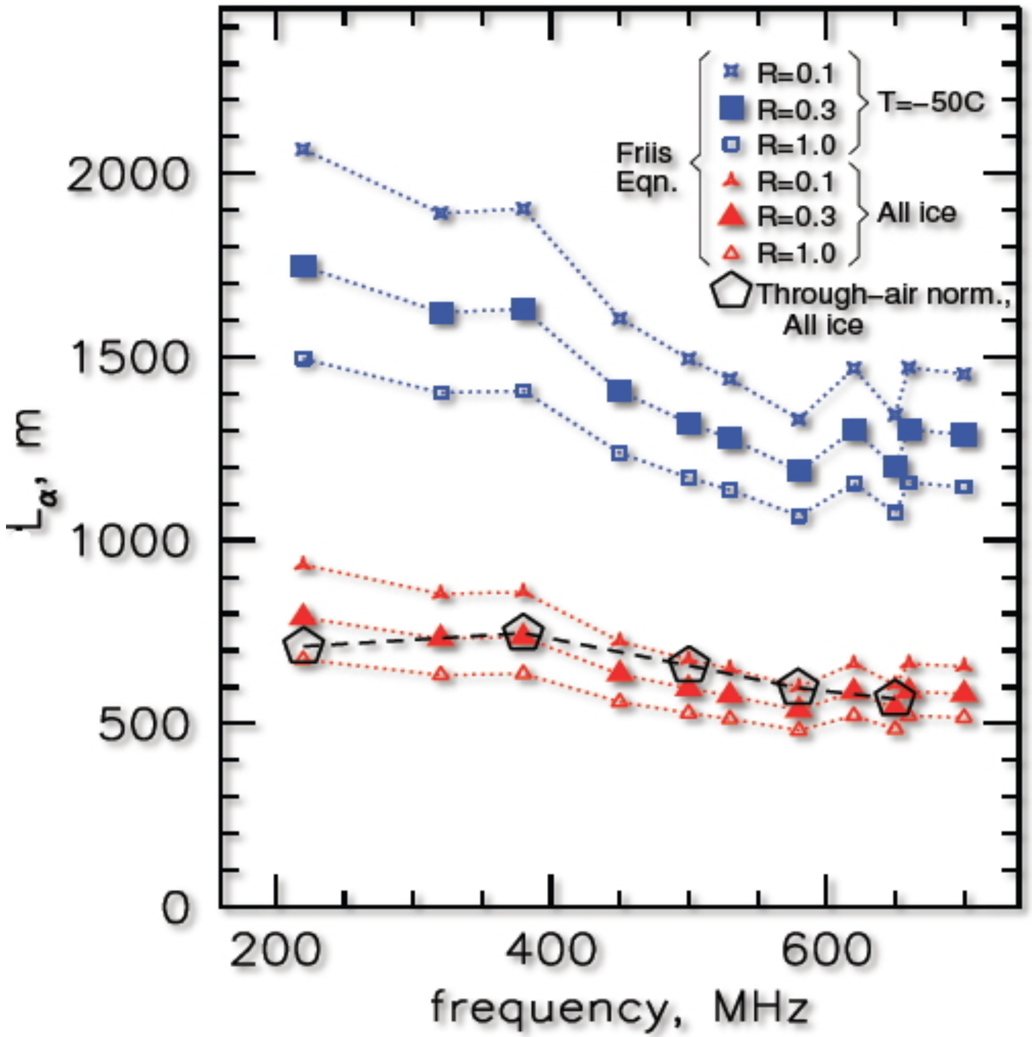


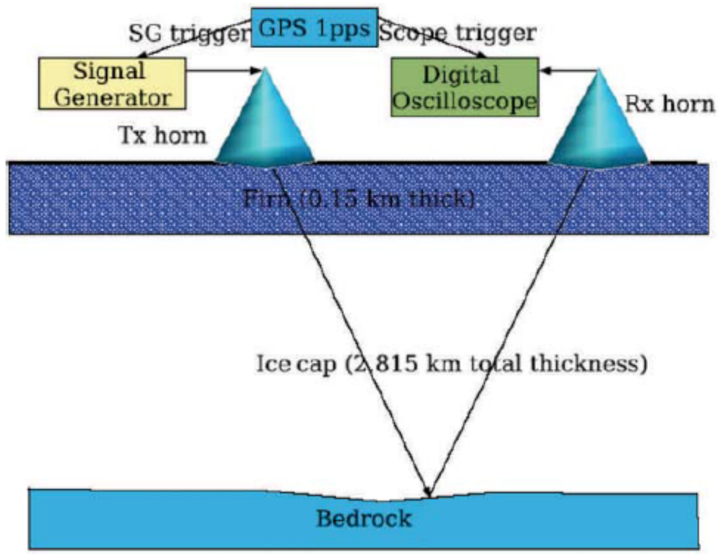
Incident particle energy → signal characteristics

Note: confirmed at SLAC

Why radio wave?

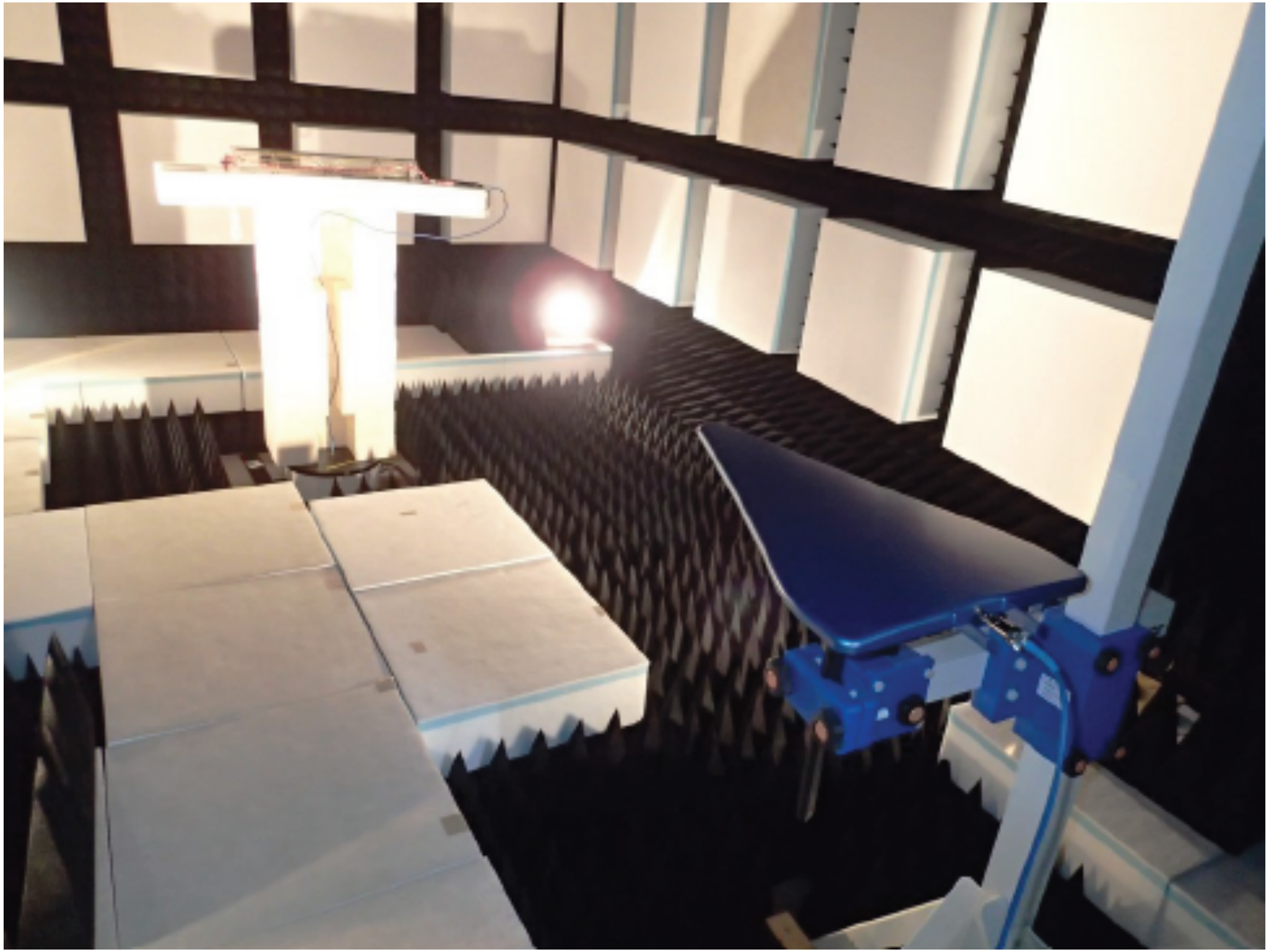
Barwick, Besson, Gorham Saltzberg,
J. Glaciology, Vol 51, 2005, p 231





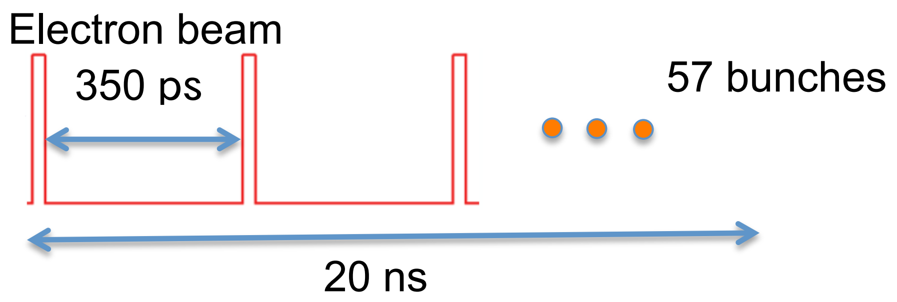
- Attenuation length of the south pole ice
  - Optical: ~100m
  - **Radio: ~1km**
- Easier to make a bigger detector in an economical way

Antenna calibration

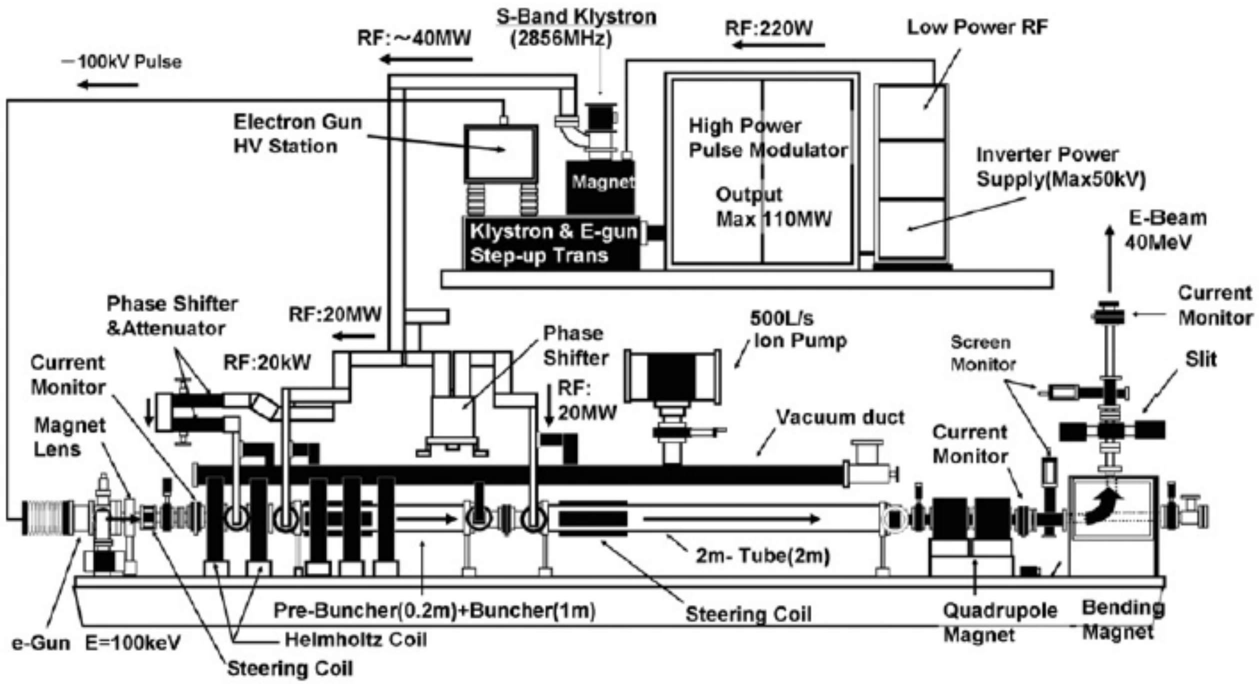


TA LINAC

- ✓ 40 MeV electron beam
- ✓ Maximum electron number per bunch: 10^9
- ✓ Pulse frequency: 2.86 GHz → pulse interval: 350 ps
- ✓ Bunch duration is 20 ns
- ✓ Output beam width: 7 mm
- ✓ Trigger signal available

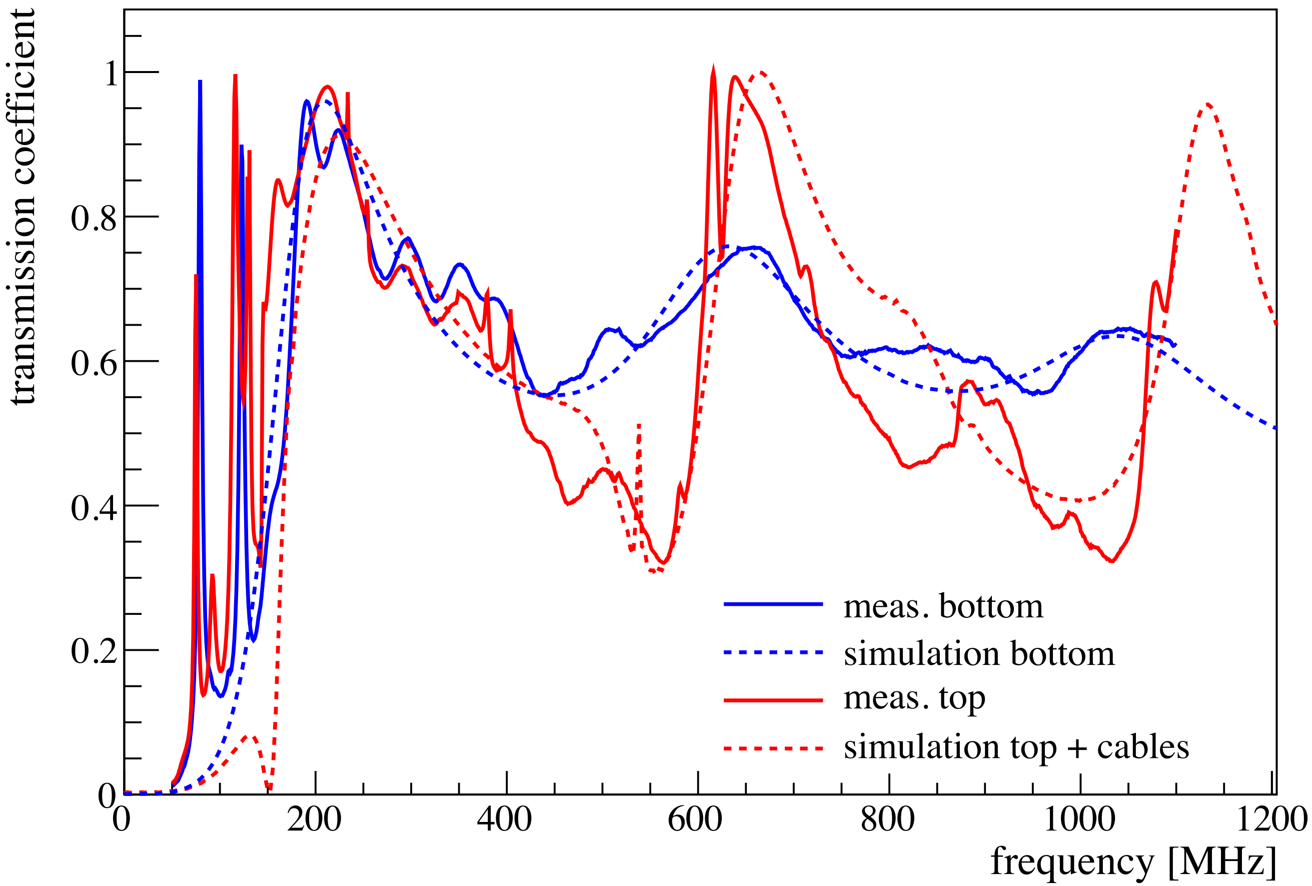


T. Shibata et al., NIMA 597 (2008) 61

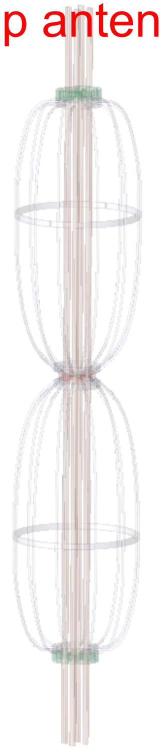


Antenna transmission coefficient

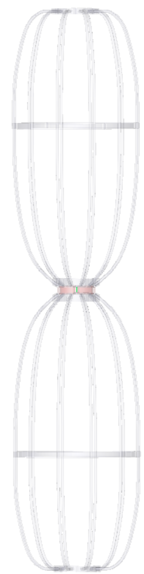
- ✓ Measured by network analyzer
- ✓ Simulation with XFdtd
- ✓ Measurement consistent with simulation
- ✓ The difference of top and bottom antenna due to pass-through cables



Top antenna



Bottom antenna

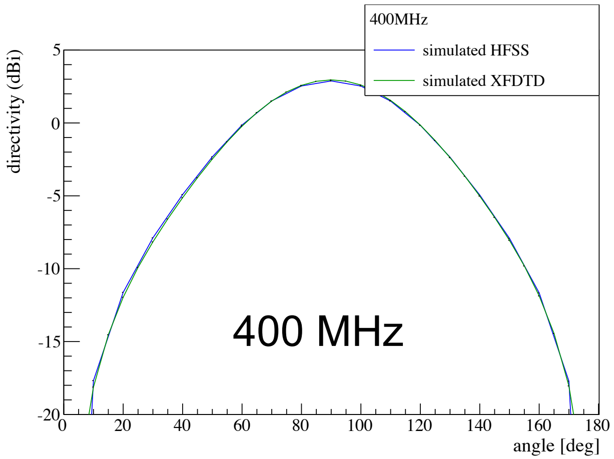


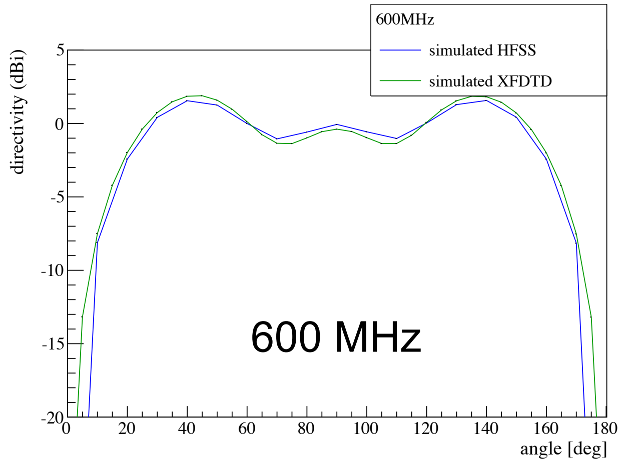
Antenna pattern

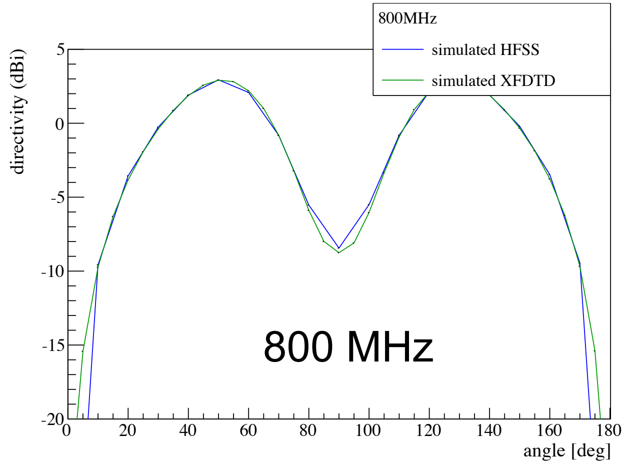
- ✓ Same results from two simulations (HFSS and XFdtd)
- ✓ Measurements are on-going

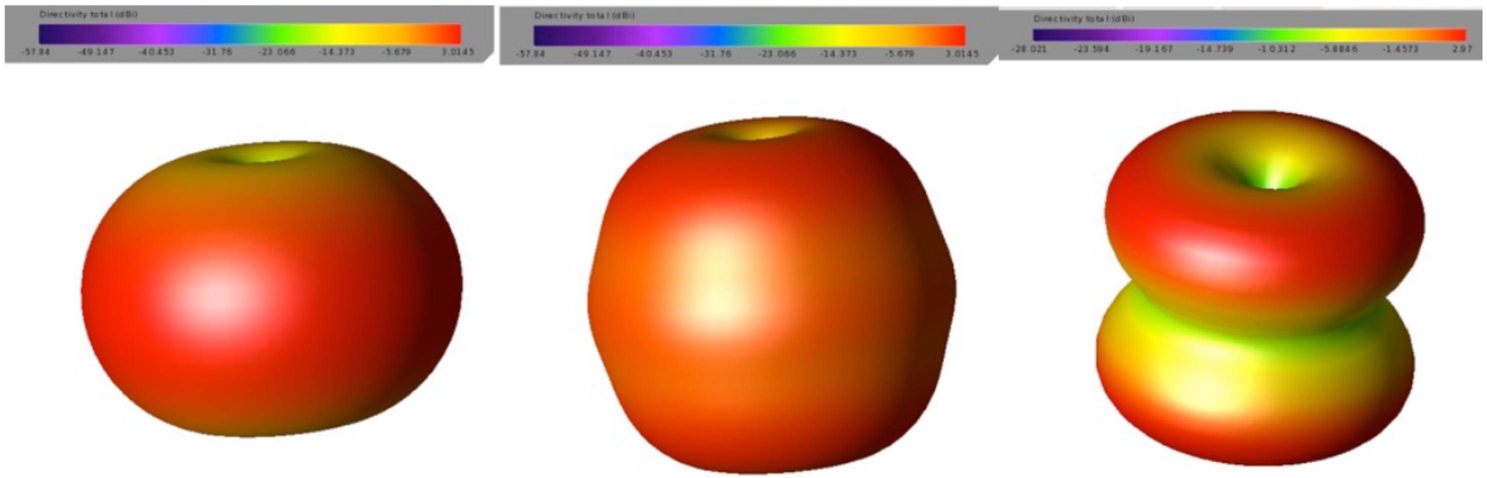
HFSS

XFdtd









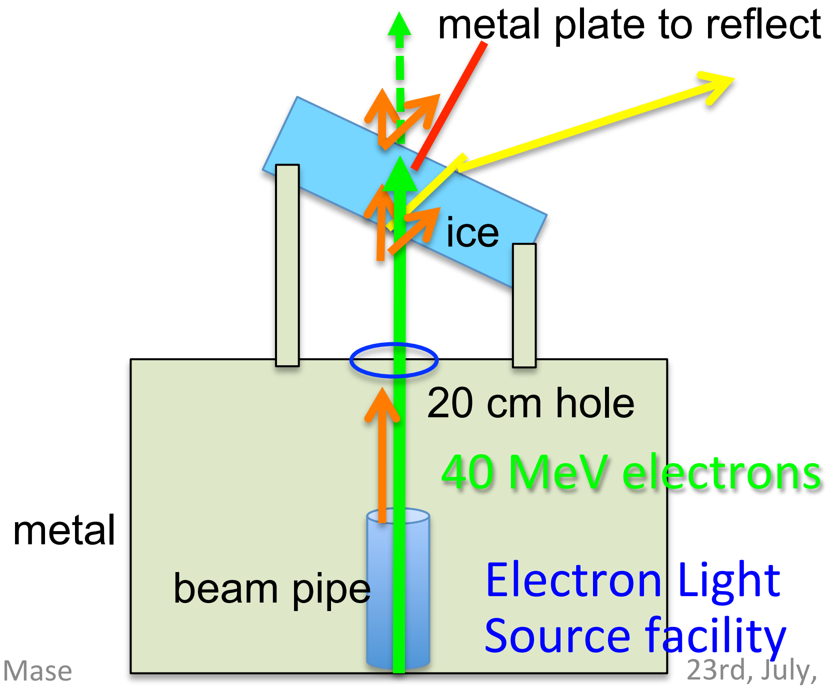
Transition radiation

- ✓ Transition Radiation (TR) was a severe background for the experiment performed by AWA
- ✓ Several places where TR is expected
- ✓ At the beam end cap (metal → air): only vertical direction
- ✓ Air → ice: TR suppressed because electrons terminated before the formation zone. The angle closed to the Cherenkov angle
- ✓ Ice → air: less electrons. The angle is close to the Cherenkov angle → metal plate to reflect TR?
- ✓ Evaluate more precisely with simulation

Formation zone

$$L_f = \frac{2\pi\beta c}{|\omega(1 - n_2\beta\cos\theta)|}$$

$$\approx \lambda$$



P. W. Gorham et al., PRE 62, 6 (2000)