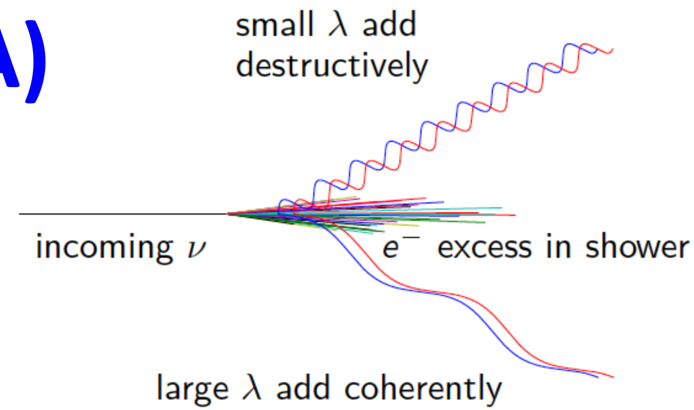
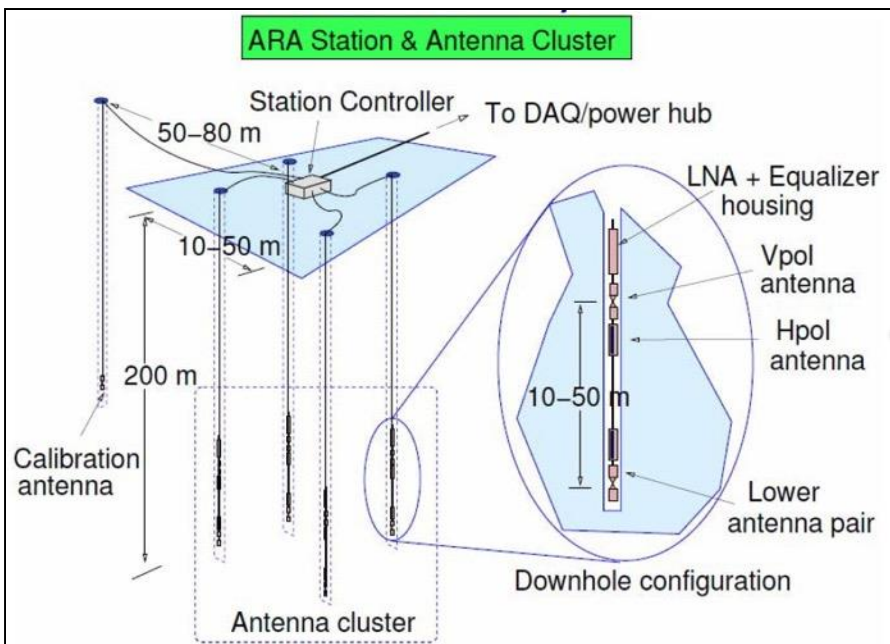
Experimental calibration of the ARA radio neutrino telescope with an electron beam in ice

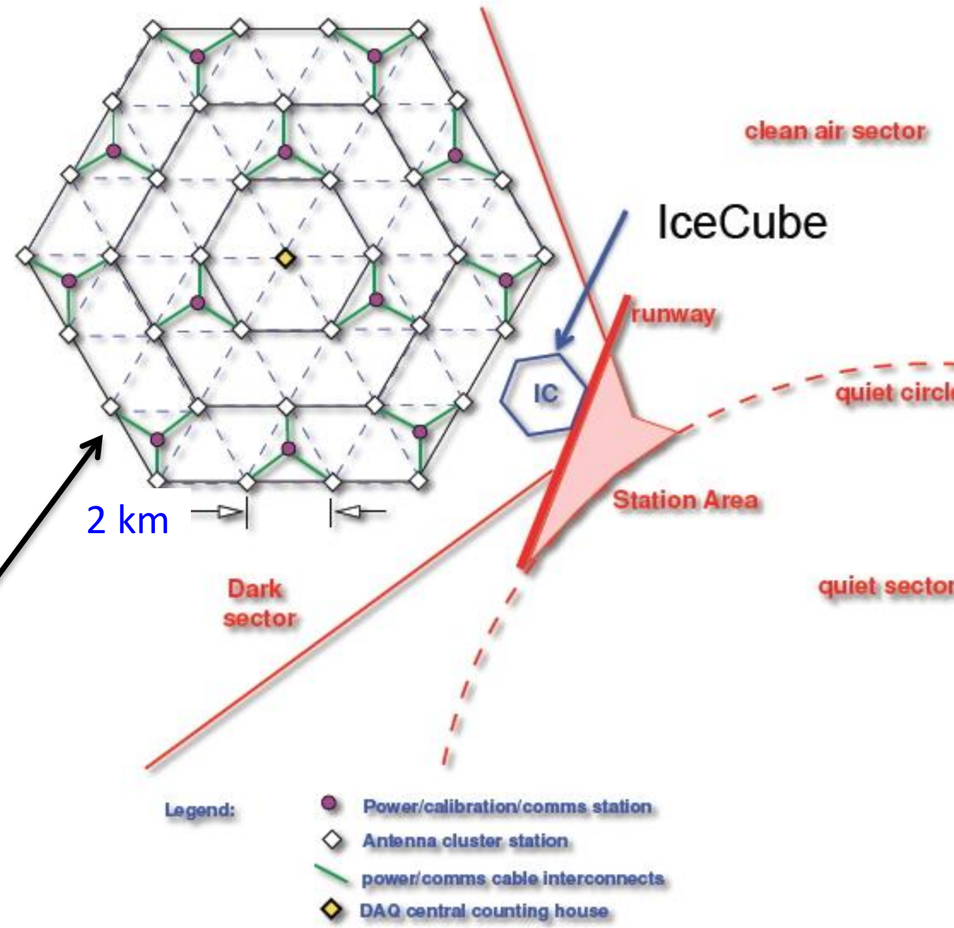
R. Gaior, A. Ishihara, T. Kuwabara, **K. Mase**, M. Relich, S. Ueyama, S. Yoshida
for the ARA collaboration,
M. Fukushima, D. Ikeda, J. N. Matthews, H. Sagawa, T. Shibata, B. K. Shin and G. B. Thomson

Askaryan Radio Array (ARA)

- Designed to observes high energy neutrinos above 10 PeV using Askaryan radiation
- 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





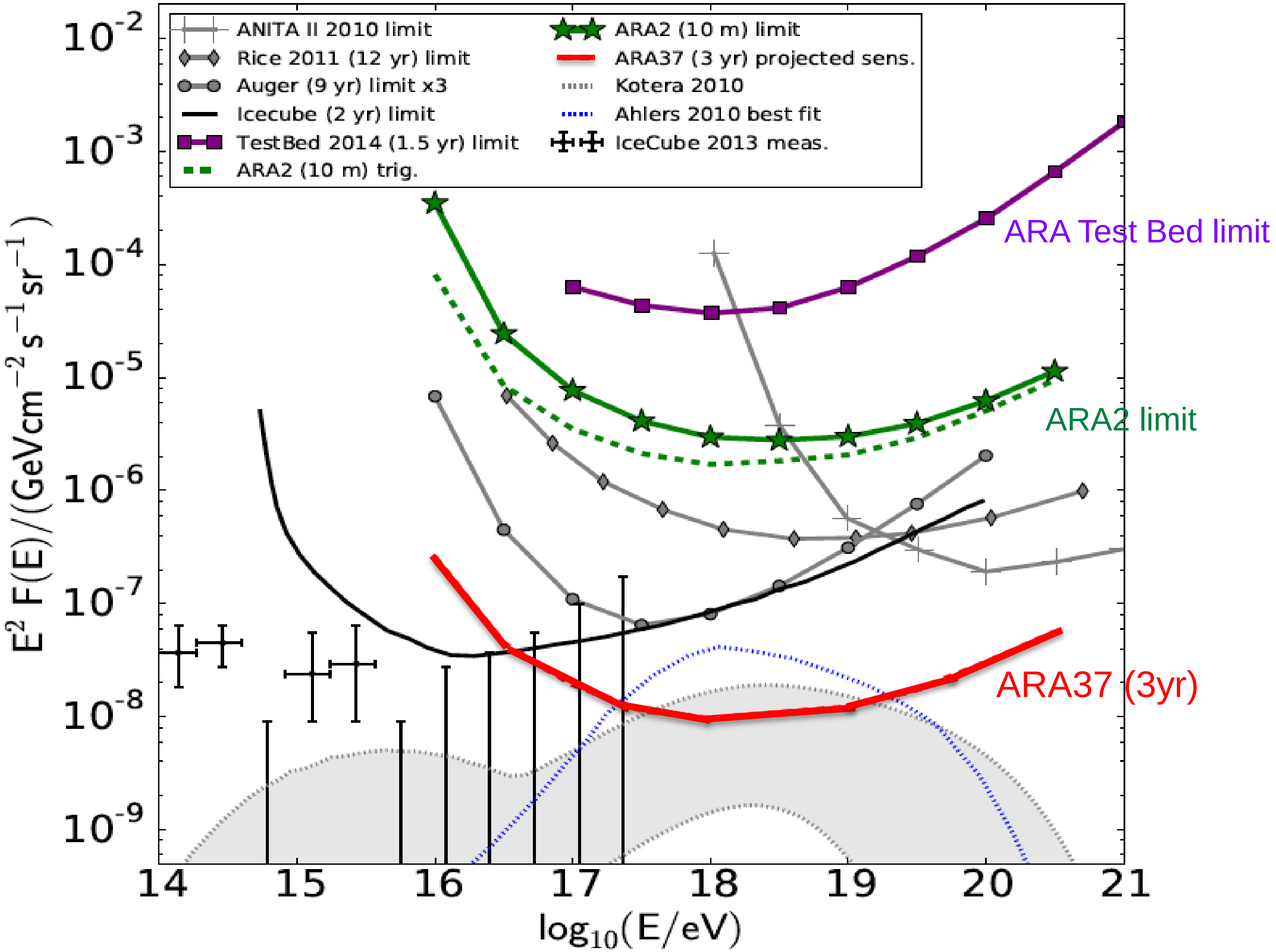


Astroparticle Physics **35** (2012) 457–477

The ARA sensitivity

Test Bed (Tue.): C. Pfendner, 1 1 05, ICRC 2015

ARA2 (Mon.): T. Meures and A. O Murchadha, 1 1 15, ICRC 2015



■ The ARA calibration with the TA-ELS (ARAcalTA)

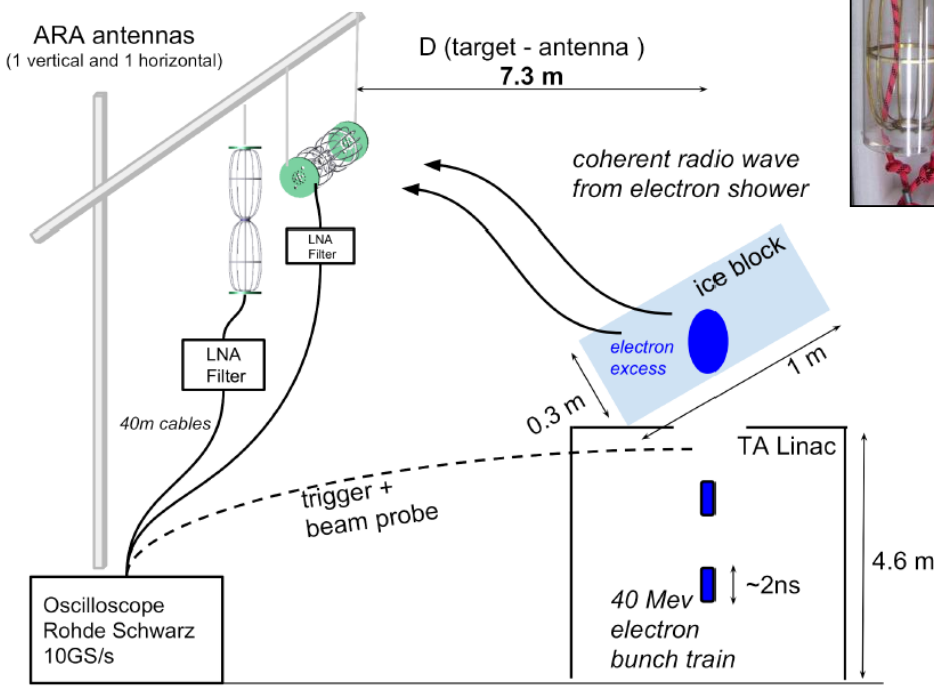
Performed in January, 2015 at TA site, Utah

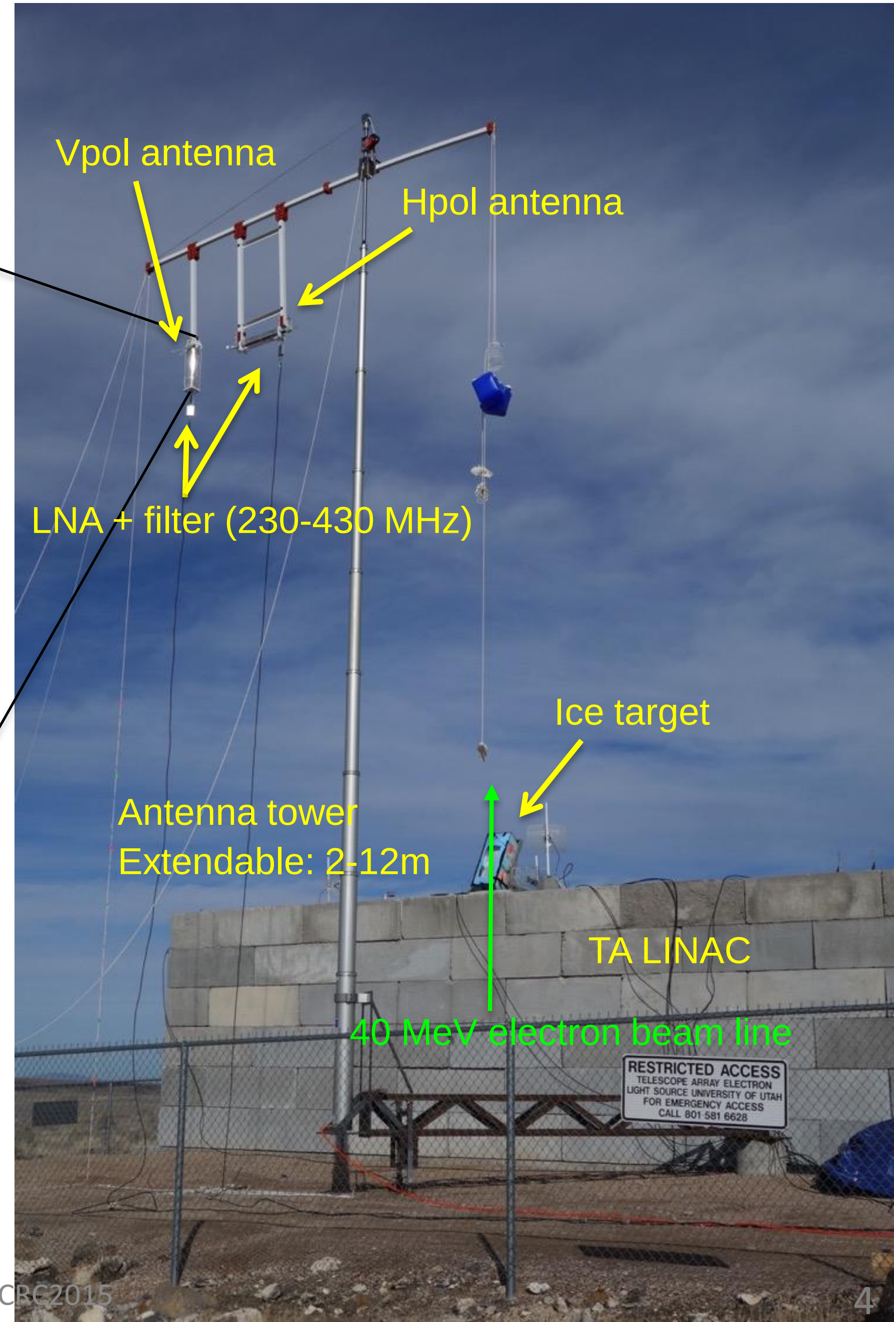
Purpose: Better understanding of the Askaryan signals and the detector calibration

We measured
- ✧ Polarization
- ✧ Angular distribution
- ✧ Coherence

Bicone ARA antenna

150-850 MHz

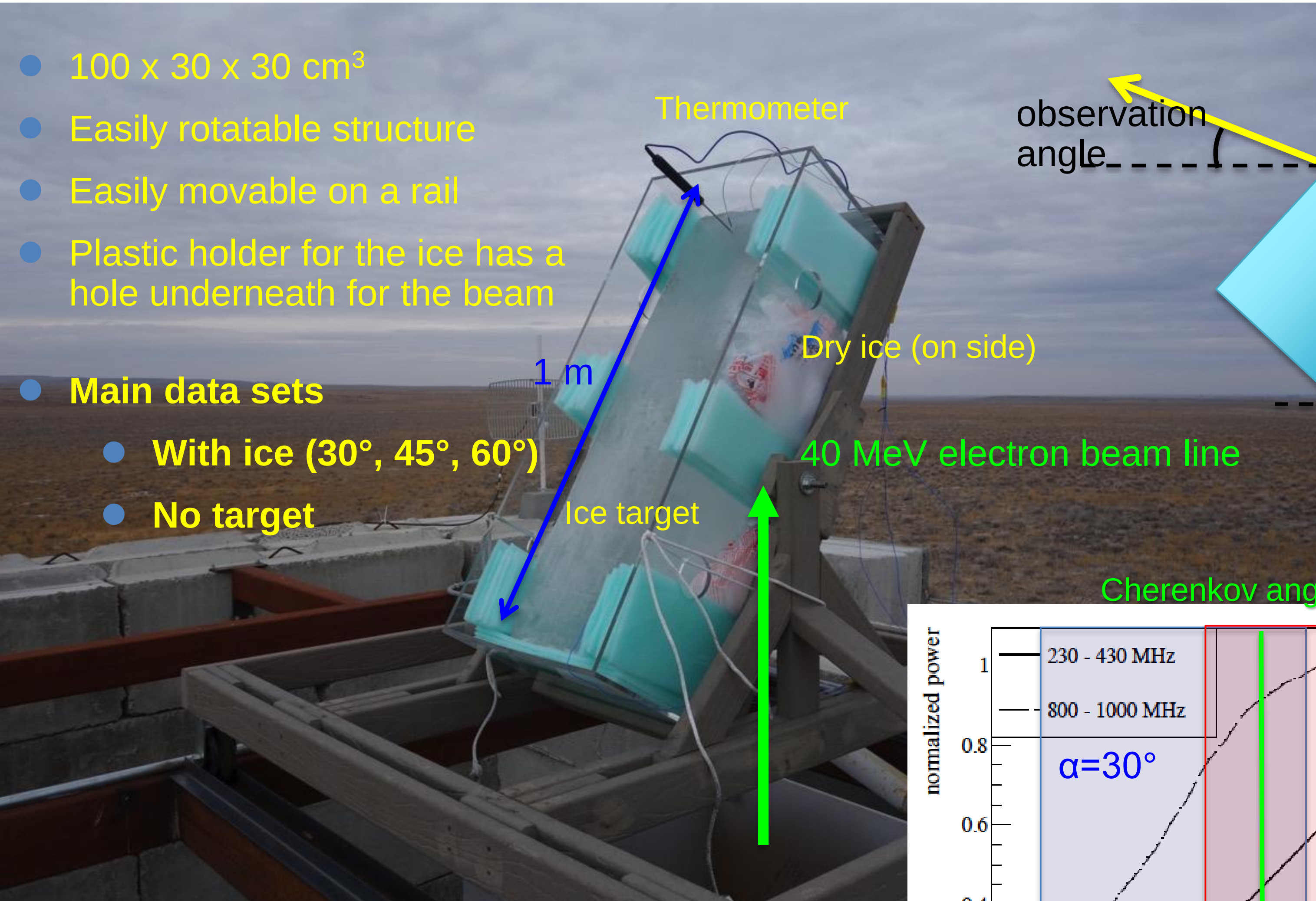


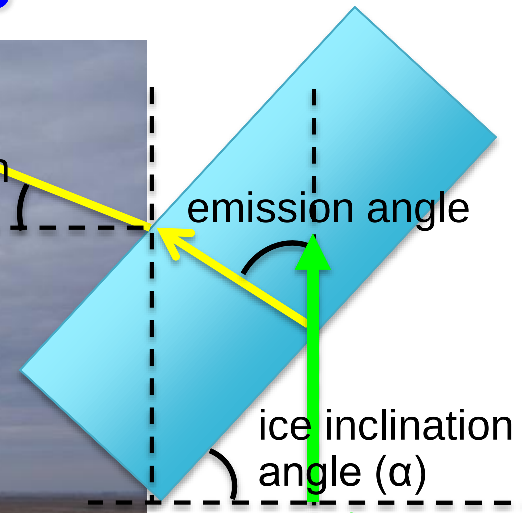


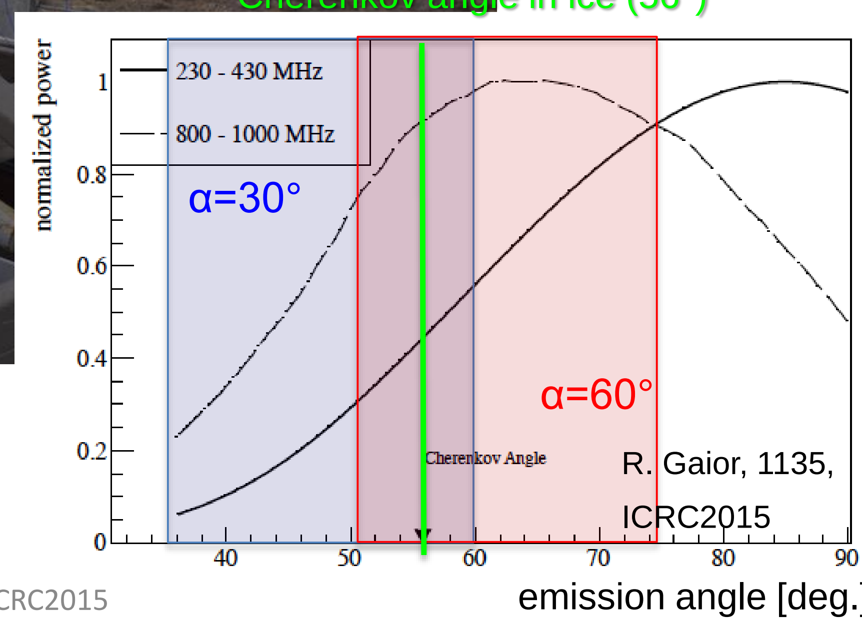
■ Ice target and the configurations

- 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 data sets**
  - **With ice (30°, 45°, 60°)**
  - **No target**



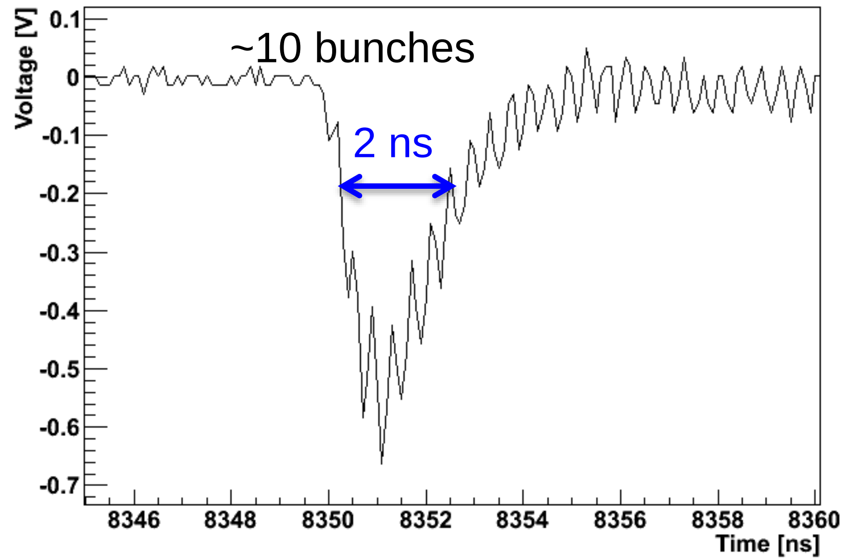


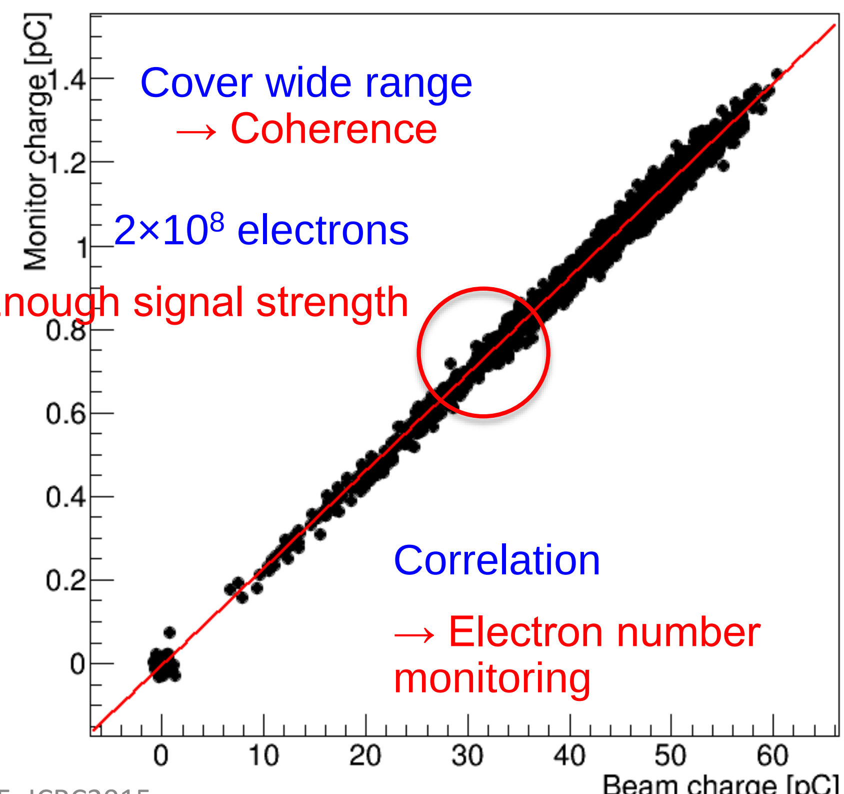


■ TA LINAC

- ✓ **40 MeV electron beam**
- ✓ Typical electron number per bunch train: **2×10^8**
  → 30 PeV EM shower
- ✓ Pulse frequency: 2.86 GHz →
  pulse interval: 350 ps
- ✓ Bunch train width was optimized to ~2 ns
- ✓ Beam lateral spread: ~4.5 cm
- ✓ Trigger signal available
- ✓ Electron number can be monitored (<1%)

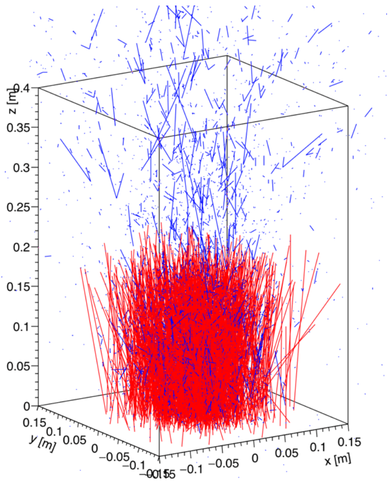
Measured bunch structure

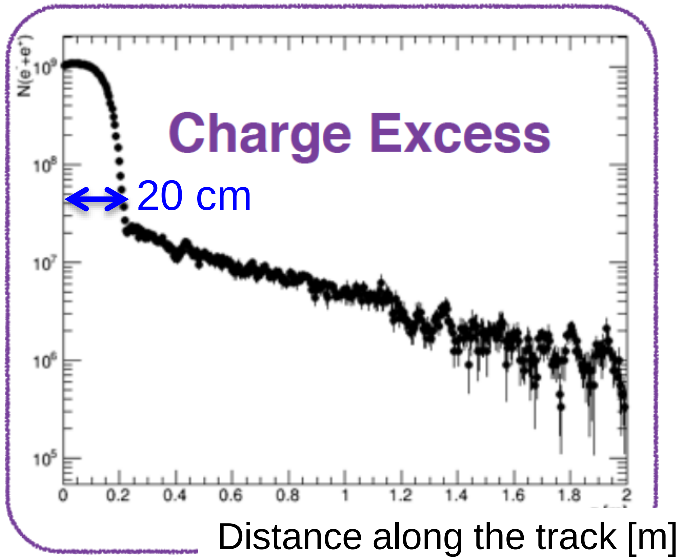




Expected electric field

GEANT4





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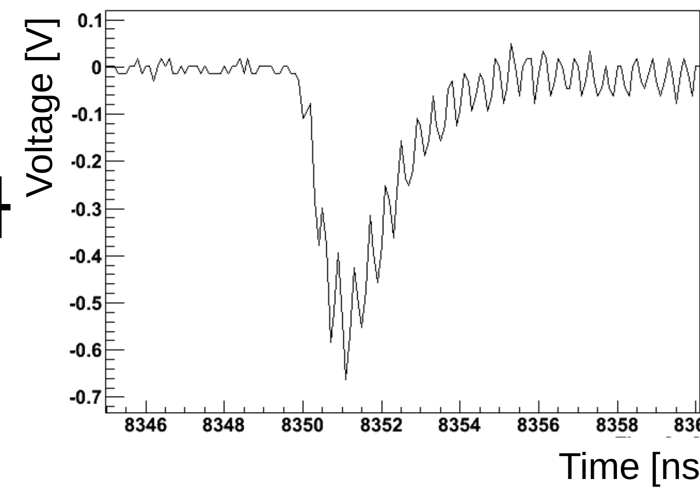
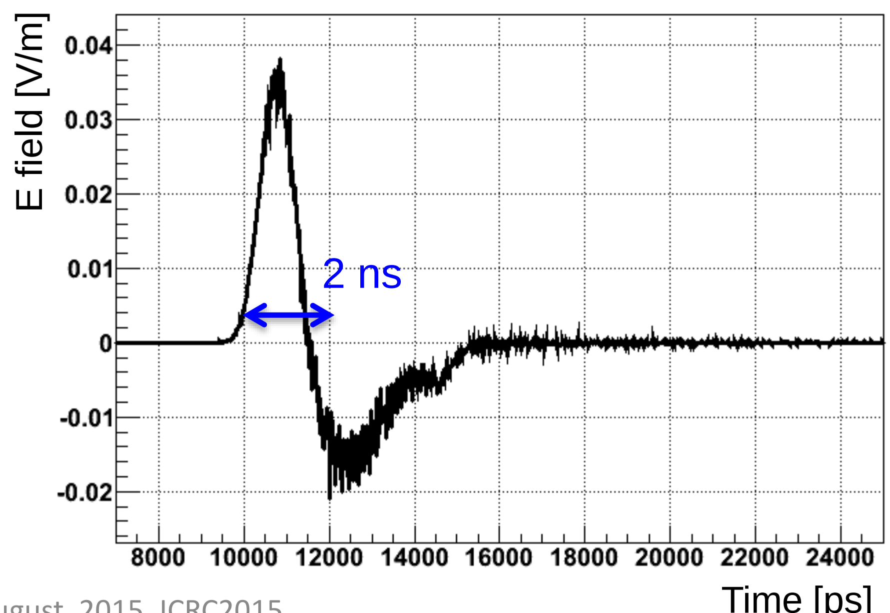


+ E-filed calculation =

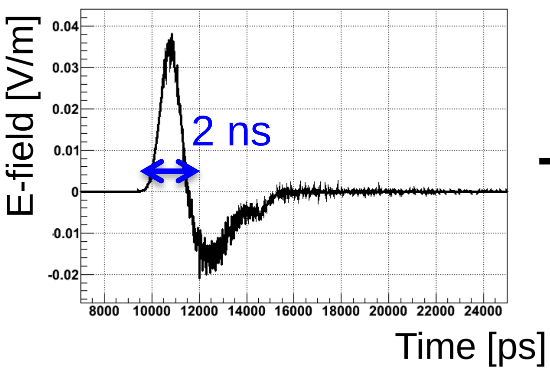
(ZHS method)

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



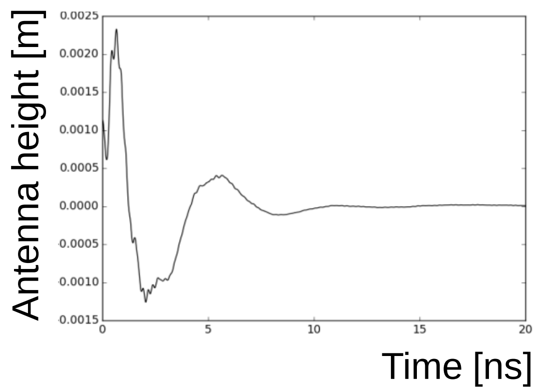
Expected waveform

E-field



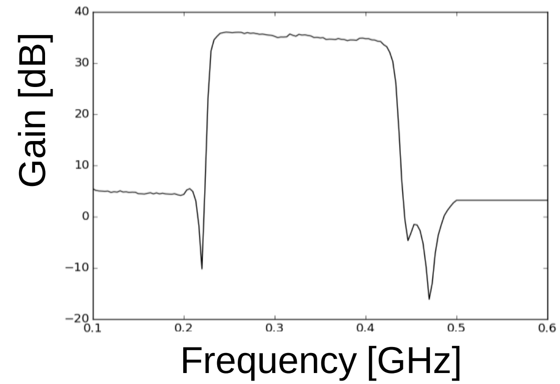
+

Antenna response (T-domain)



+

filter + LNA response



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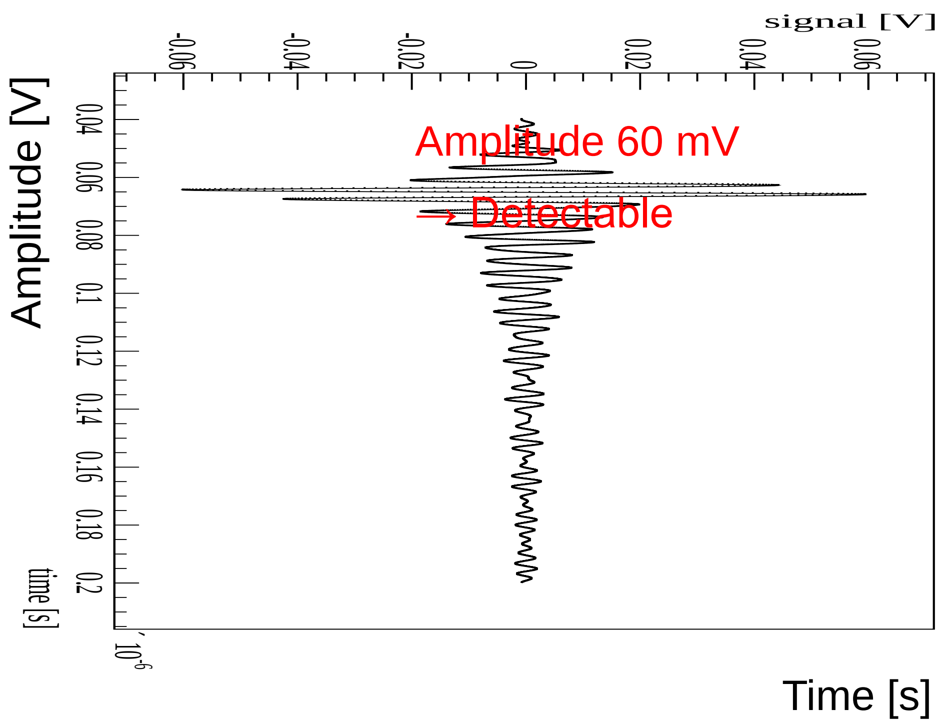
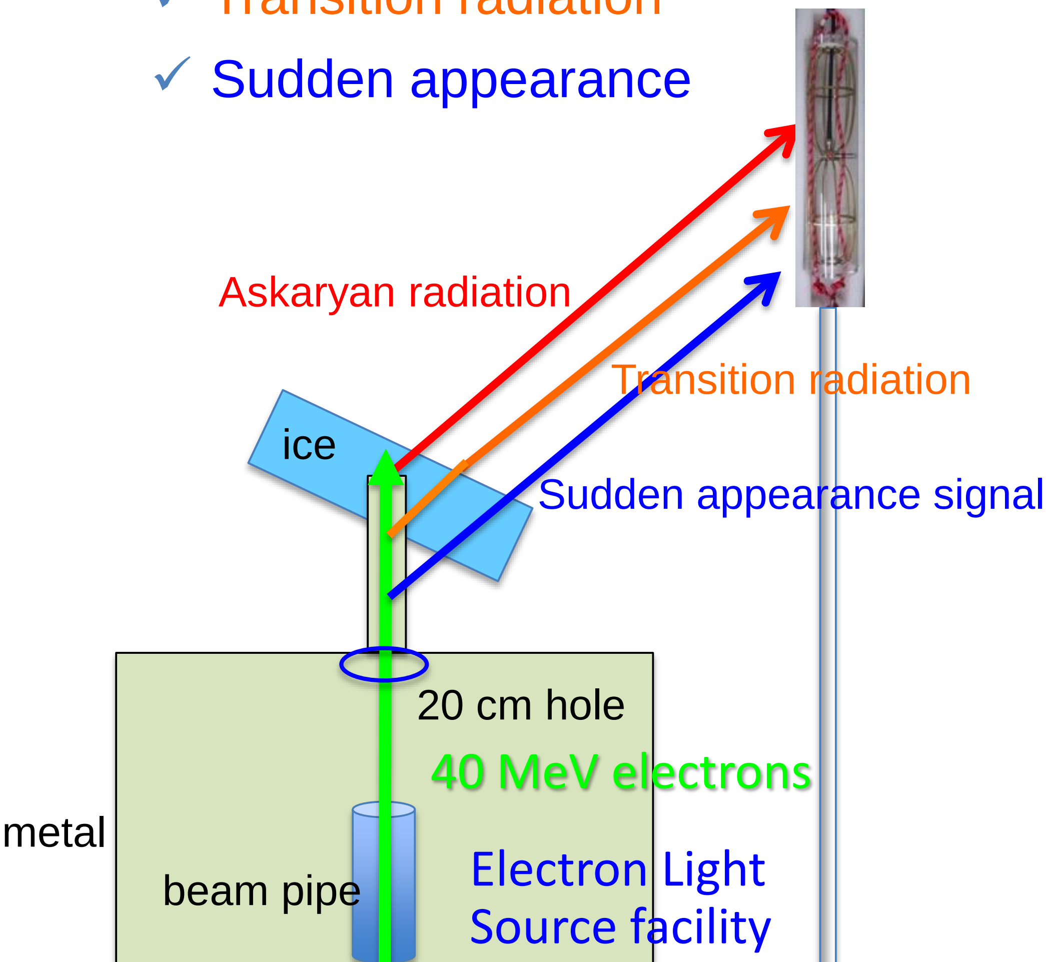
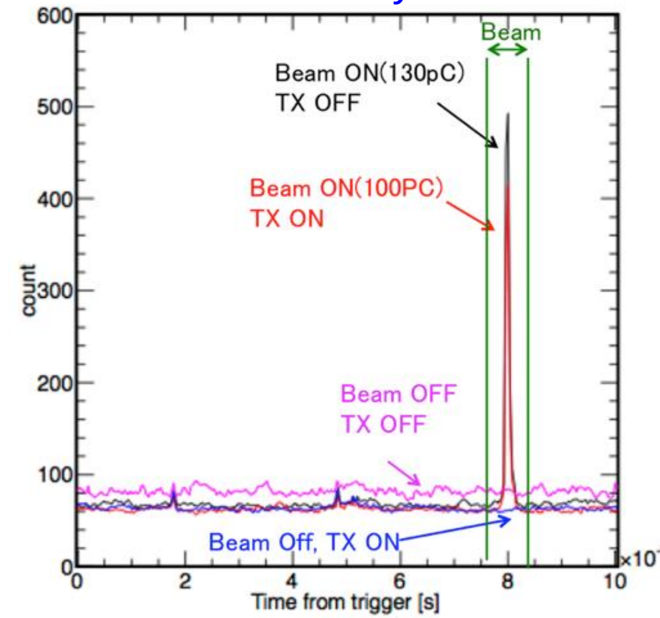


■ Backgrounds

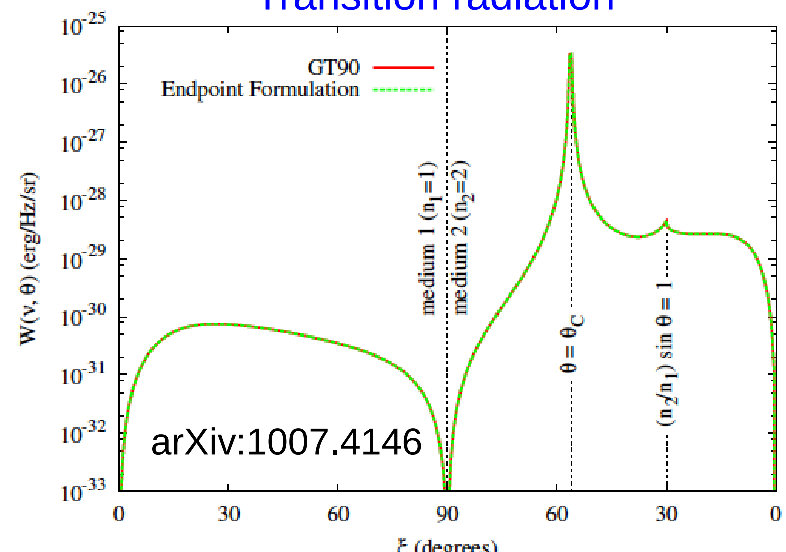
- ✓ Several backgrounds are expected
  - ✓ Transition radiation
  - ✓ Sudden appearance



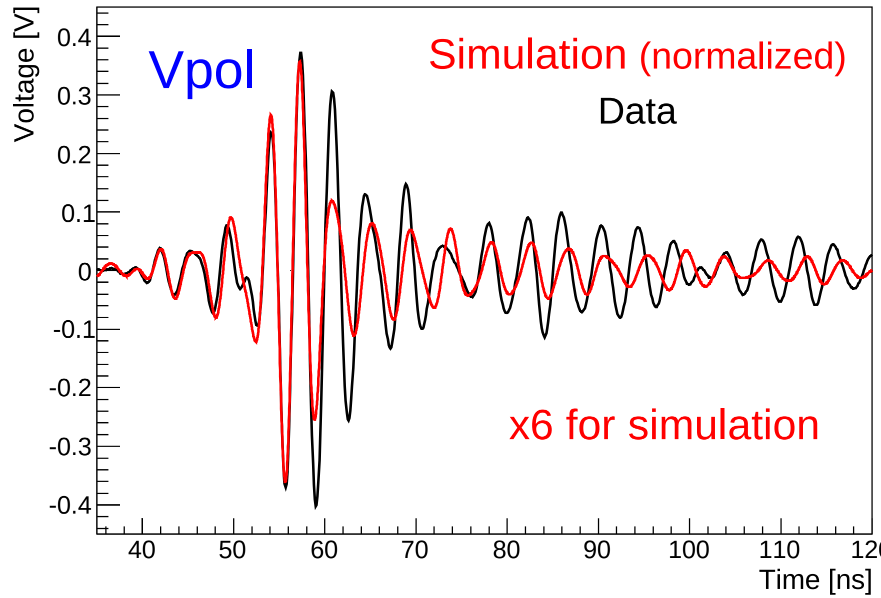
Sudden appearance signal observed by D. Ikeda

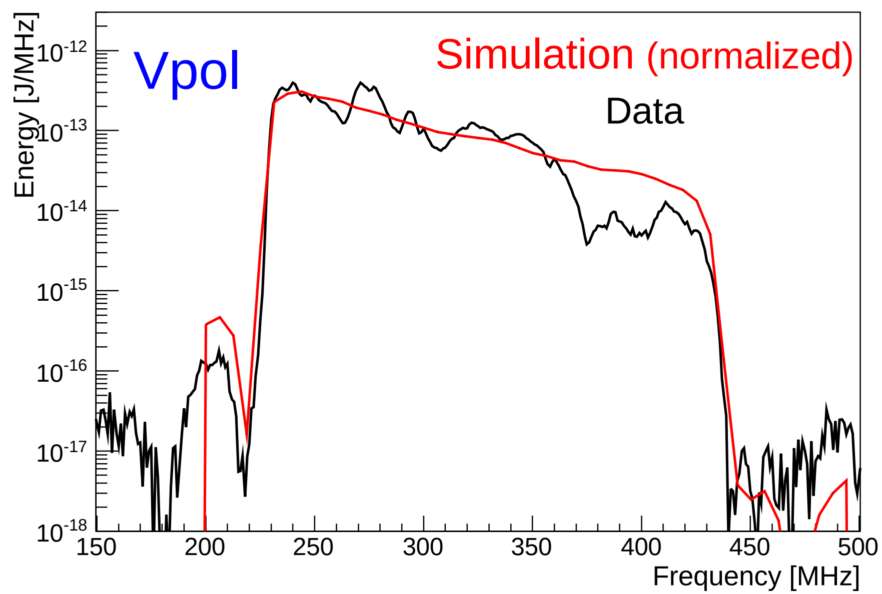


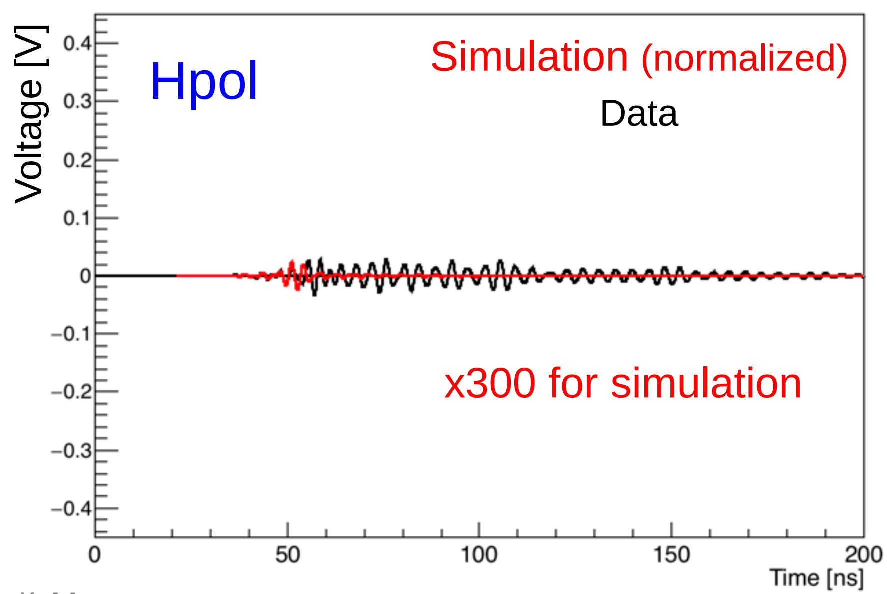
Transition radiation



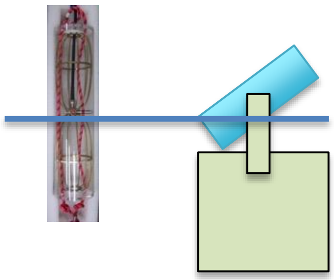
■ Comparisons of waveform and the frequency spectrum







Configuration:
Ice 30°, obs. angle: 0°

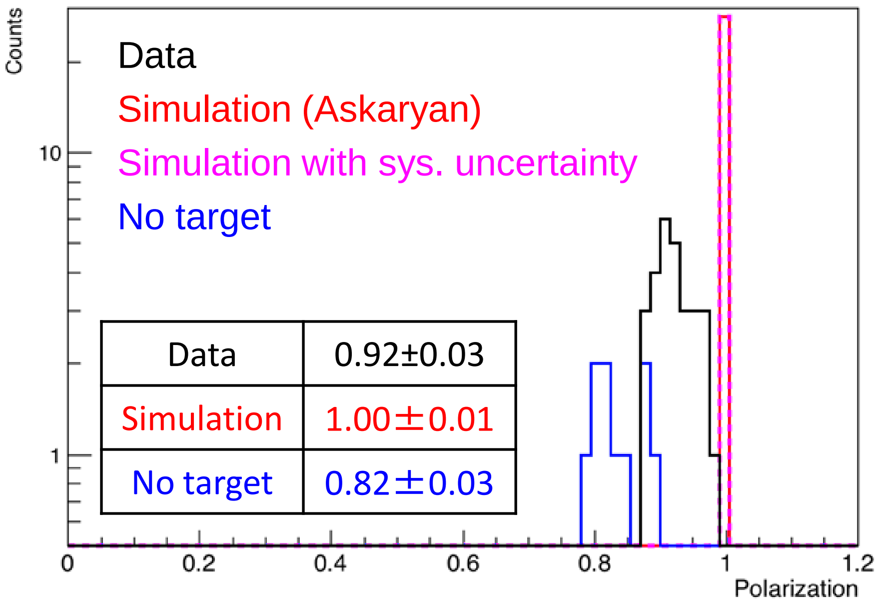


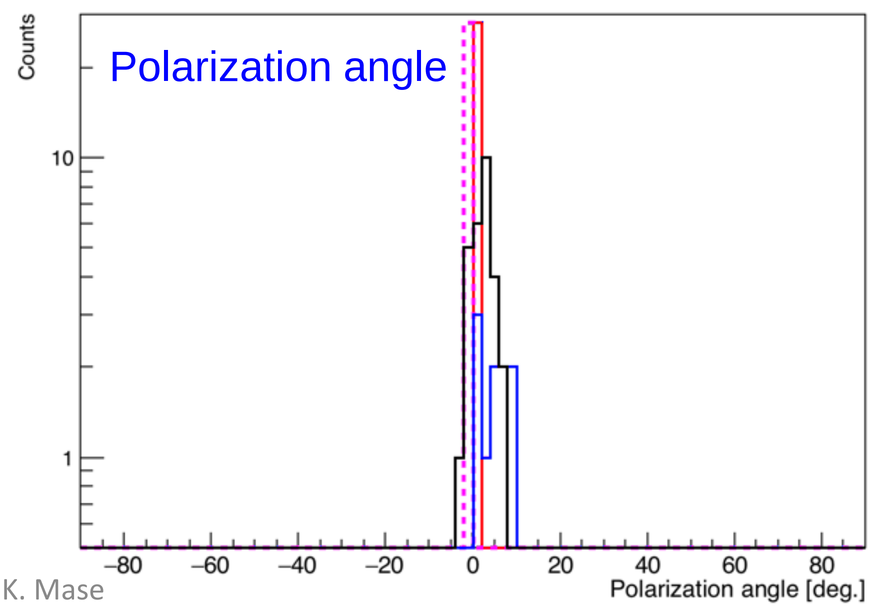
- ✓ The absolute waveform amplitudes are different by 6 times for Vpol
- ✓ The early part of the waveforms relatively match. There is a difference for the later part

→ Other components than Askaryan radiation

Polarization

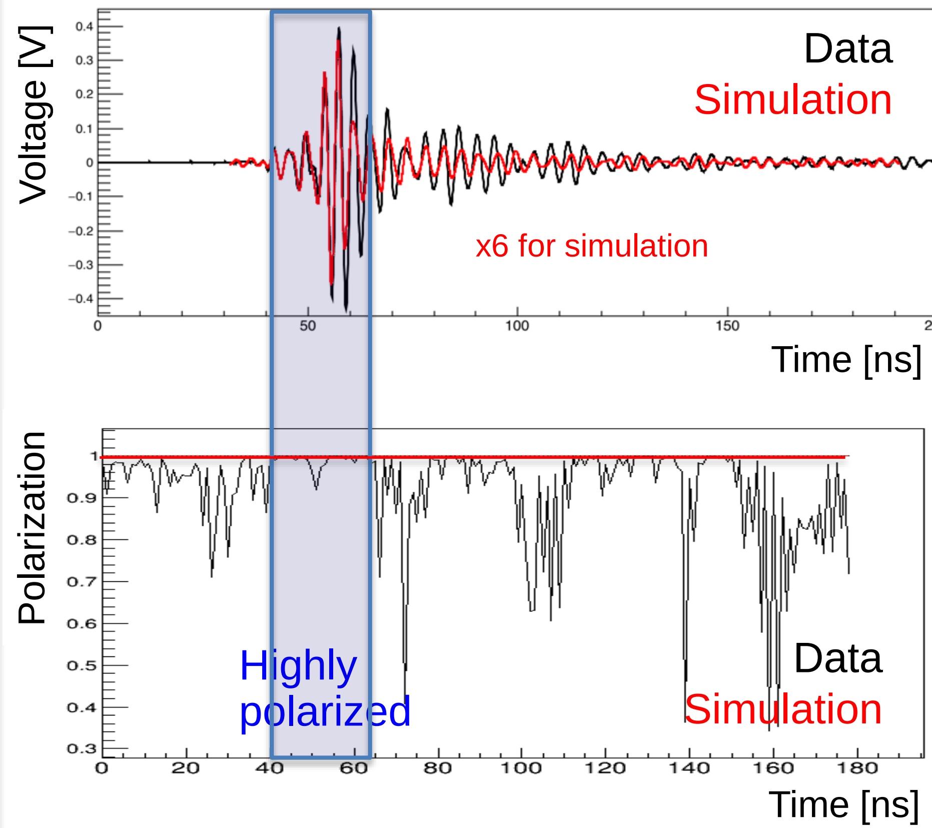
Polarization





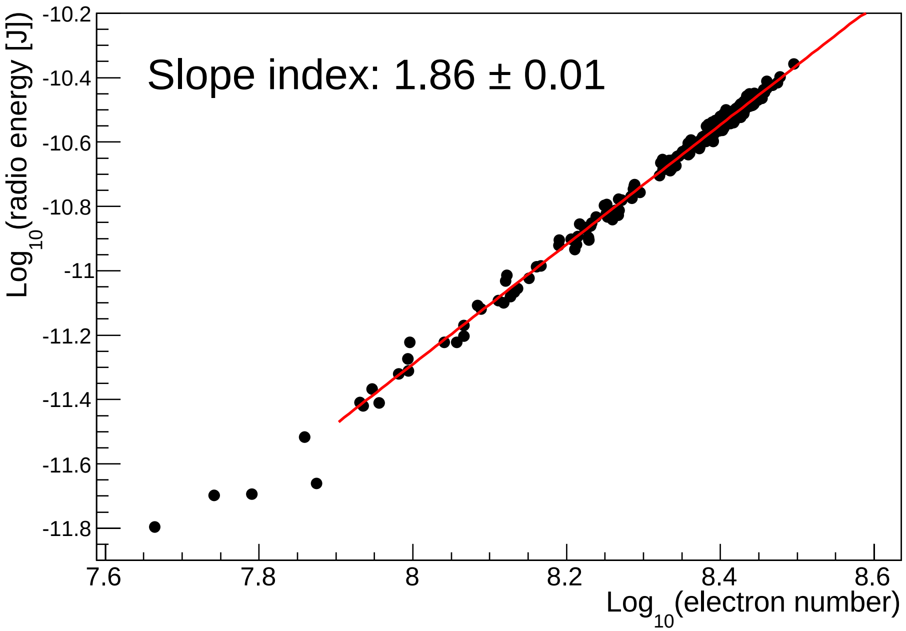
Time development of polarization

Configuration: Ice 30°, obs. angle 0°, Vpol



- ✓ All signals shows high vertical polarization
- ✓ Data is off from simulation

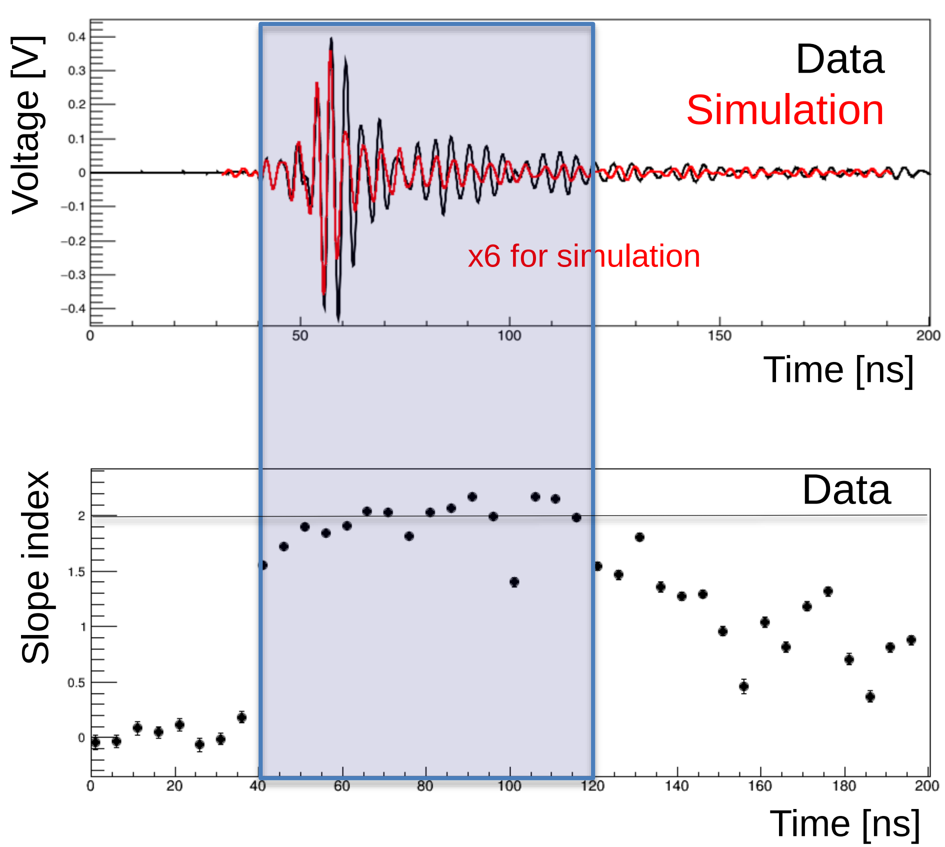
Coherence



High coherence, but not full

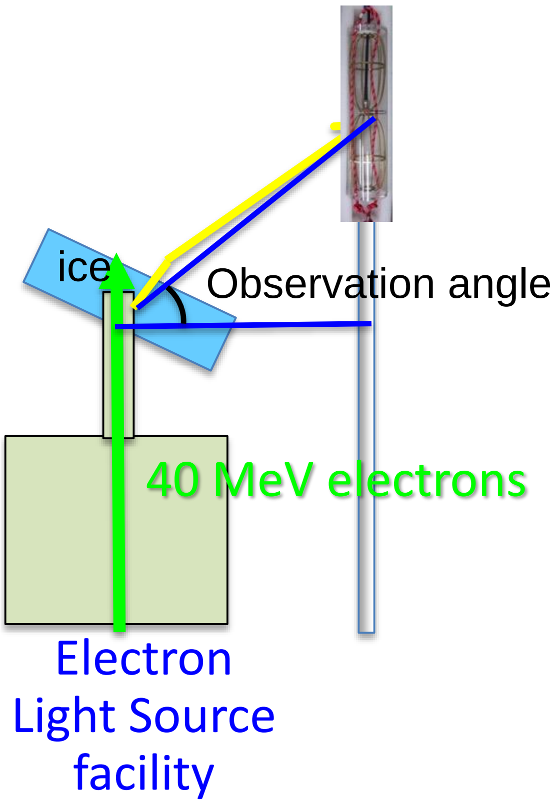
Time development of coherence

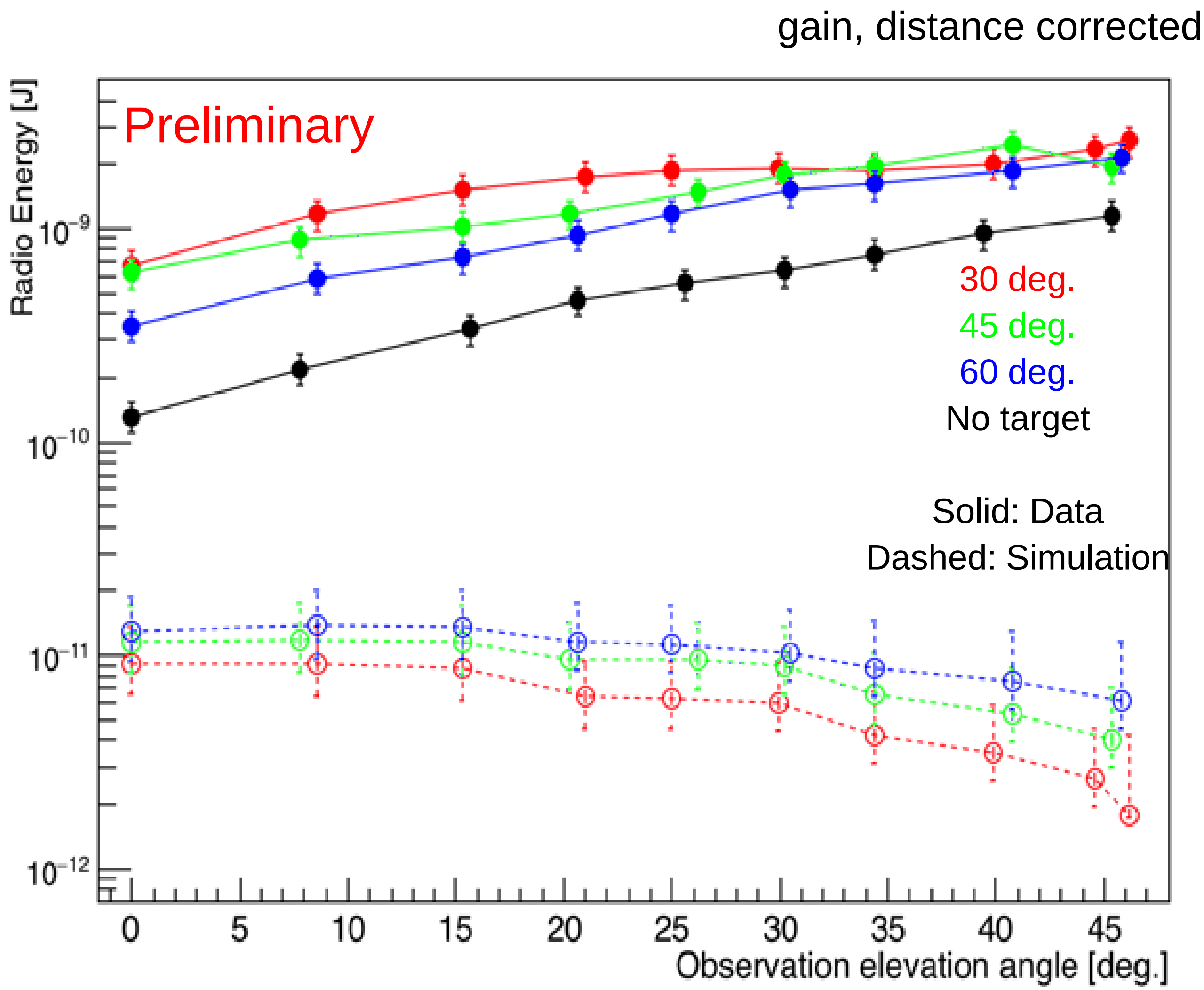
Configuration: Ice 30°, obs. angle 0°, Vpol



High coherence over the main waveform

Angular distribution





Observed signals are larger than the expected Askaryan radiation

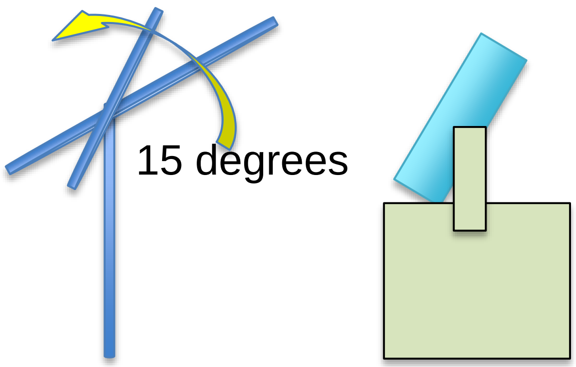
■ Summary

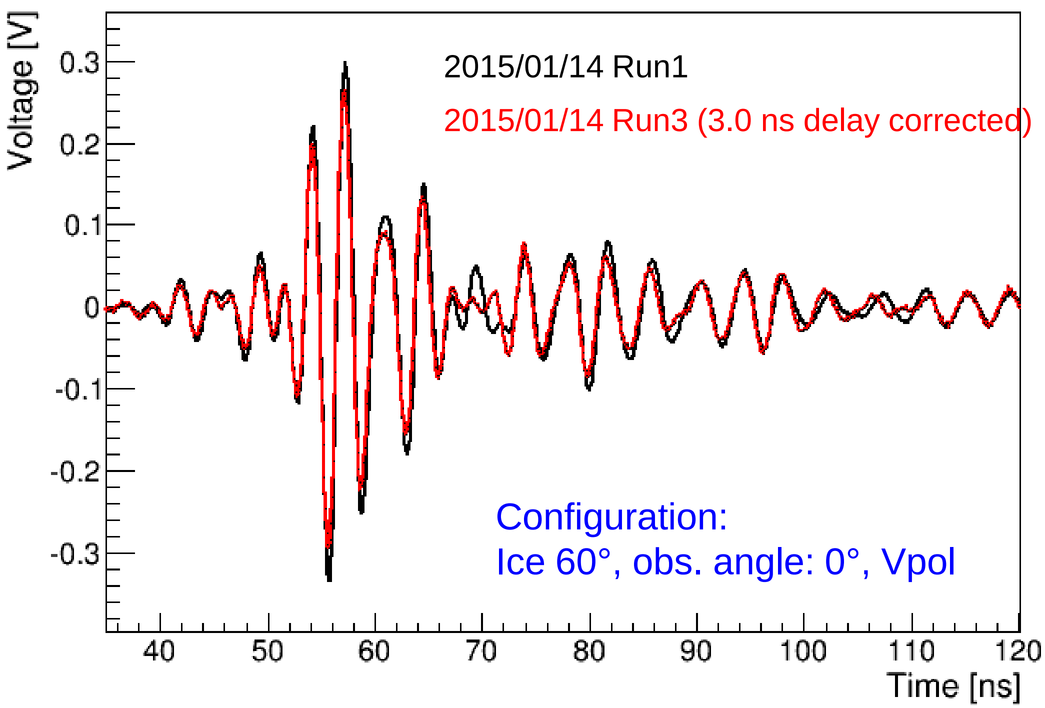
- We have performed an experiment at Utah using the TA-ELS for the better understanding of Askaryan radiation and the calibration of the ARA detectors
- Highly polarized and coherent signals were observed
- Observed signals are larger than the expected Askaryan radiation
- We are going to simulate the background contributions (transition radiation and sudden birth) to explain the difference between data and simulation

Backups

Stability and far field confirmation

- ✓ The stability with the same configuration: 5% in amplitude
- ✓ The antenna mast was intentionally rotated by ~15 deg.
- ✓ The signal amplitude decreased proportionally with the distance change. → Far field confirmation (3.0 ns time delay → 11% distant → 12% amplitude decrease)
- ✓ Time difference from the expectation was checked for each configuration.
- ✓ The spread is 1.9 ns → 9° rotation → 6% in amplitude
- ✓ The overall systematic uncertainty in power: 16%

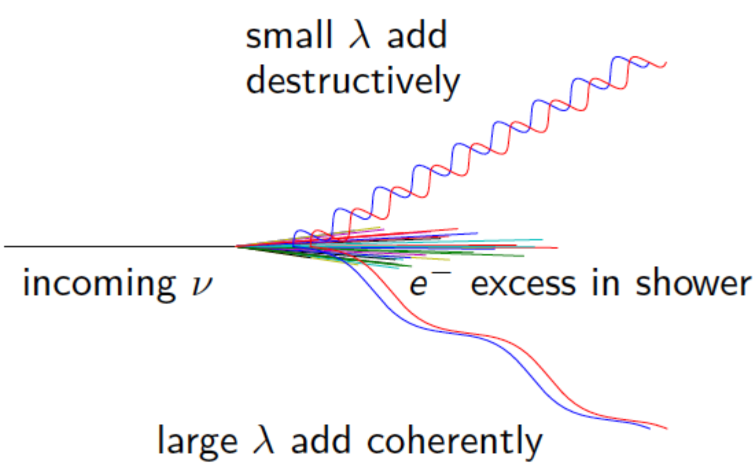




Purpose

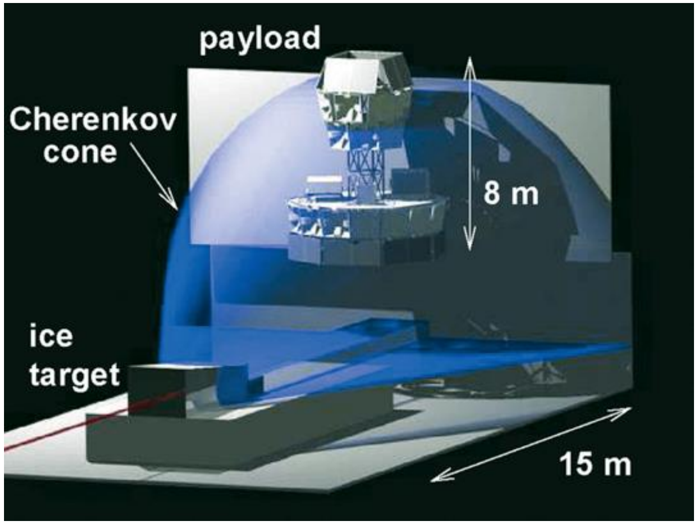
- 1962: Askaryan predicted coherent radio radiation from excess negative charge in an EM shower (~20% due to mainly Compton scattering and positron annihilation)

  → **Askaryan effect**



Shower size << λ to be coherent

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

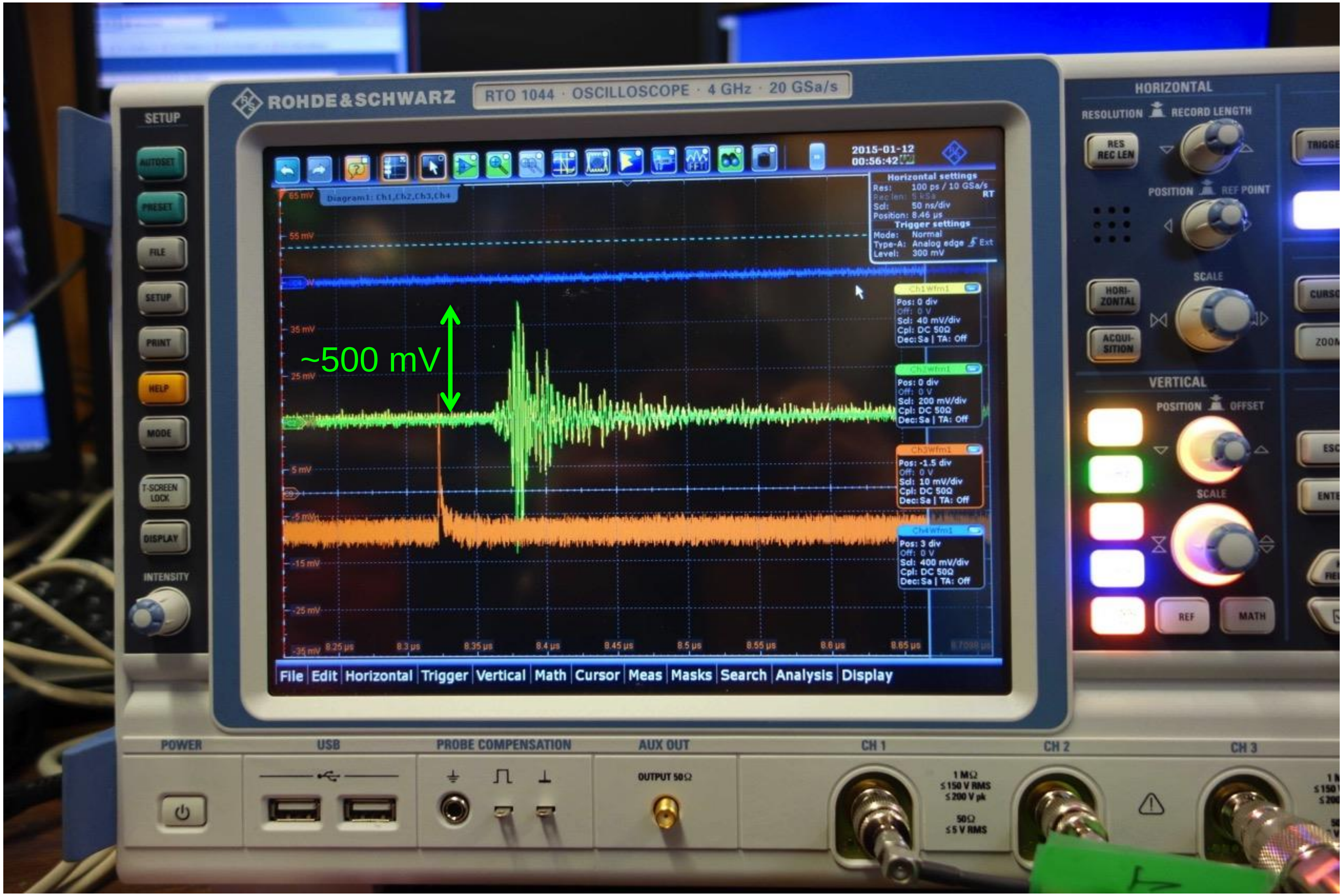


P. W. Gorham et al., PRL 99, 171101(2007)

Purpose: Understanding of the Askaryan signals

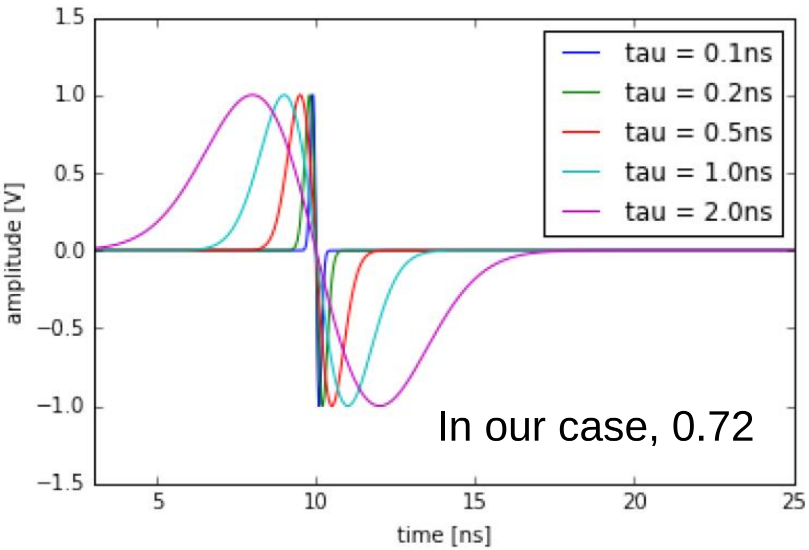
Detector calibration

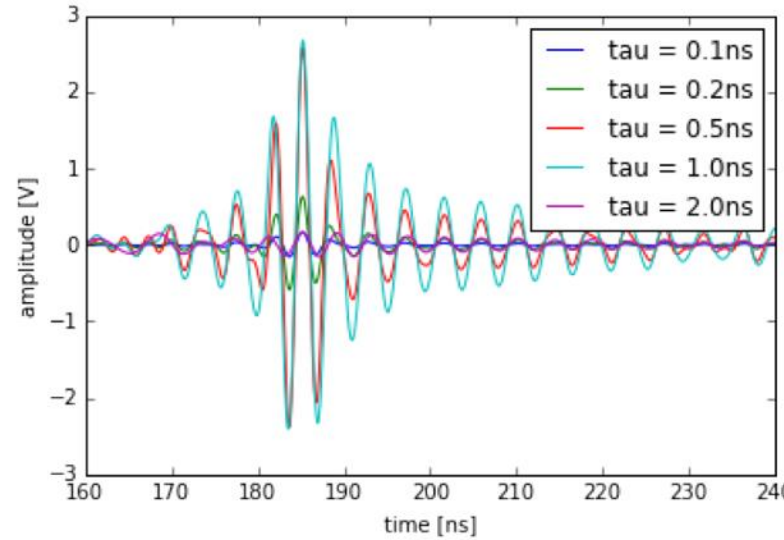
■ Signals observed

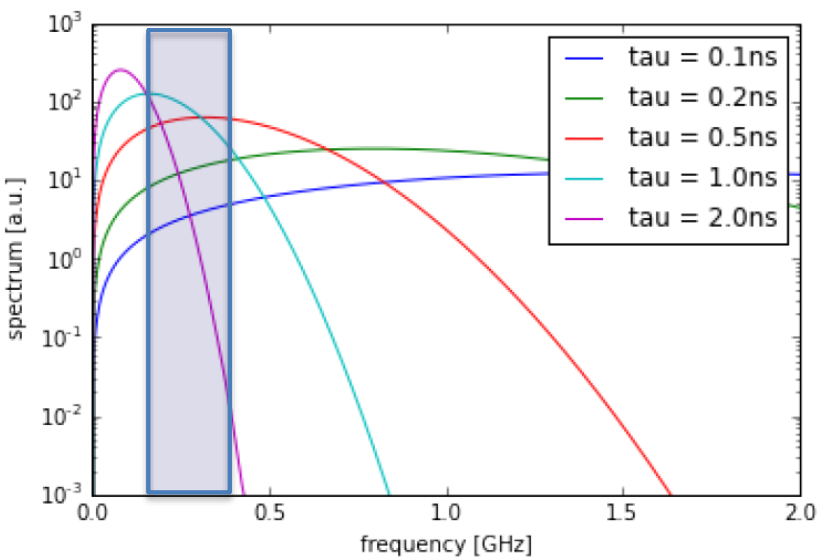


Dependence of the input E-field

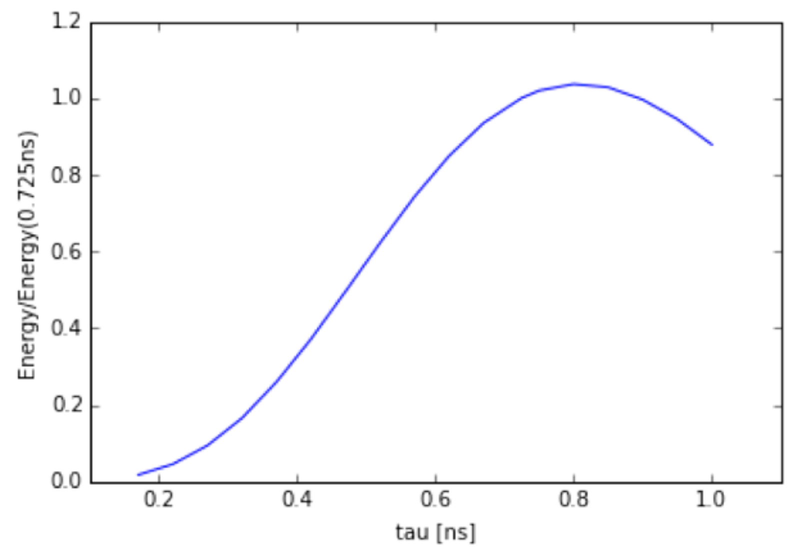
R. Gaior







Sensitive to 0.5-1.0 ns input



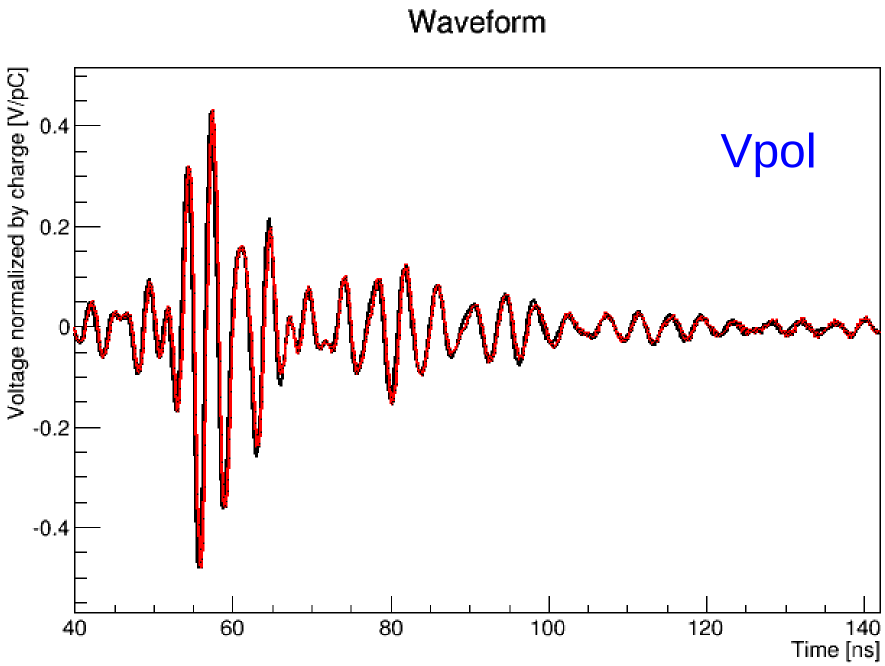
Upper limit exists

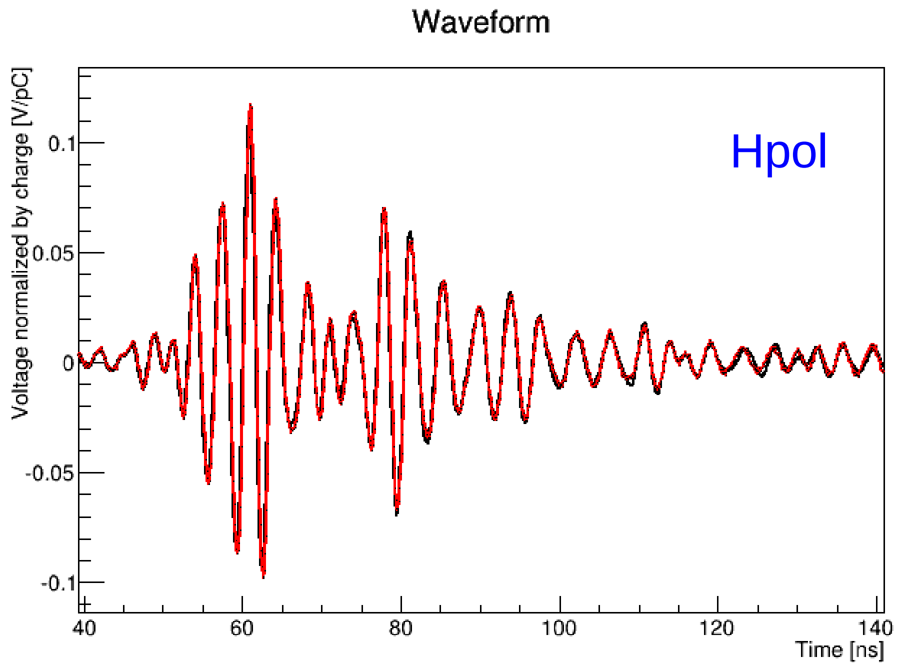
Reproducibility

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)

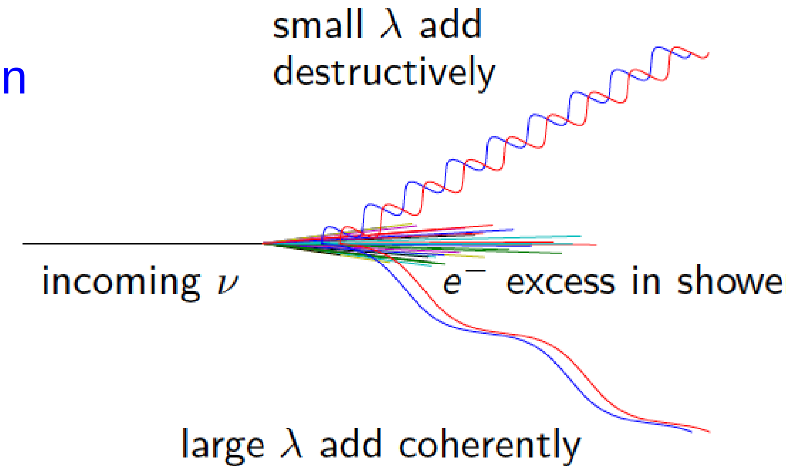


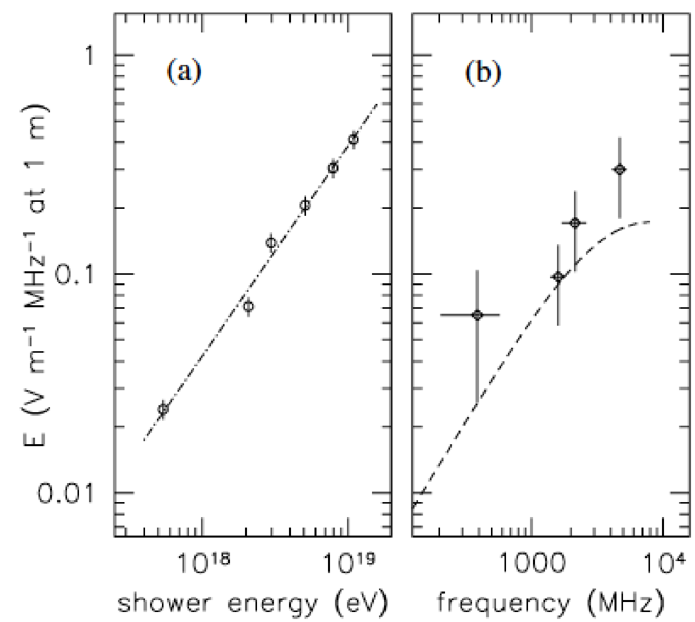


The difference in the amplitude is 5% → 10% in power (Vol)

Radio wave through Askaryan effect

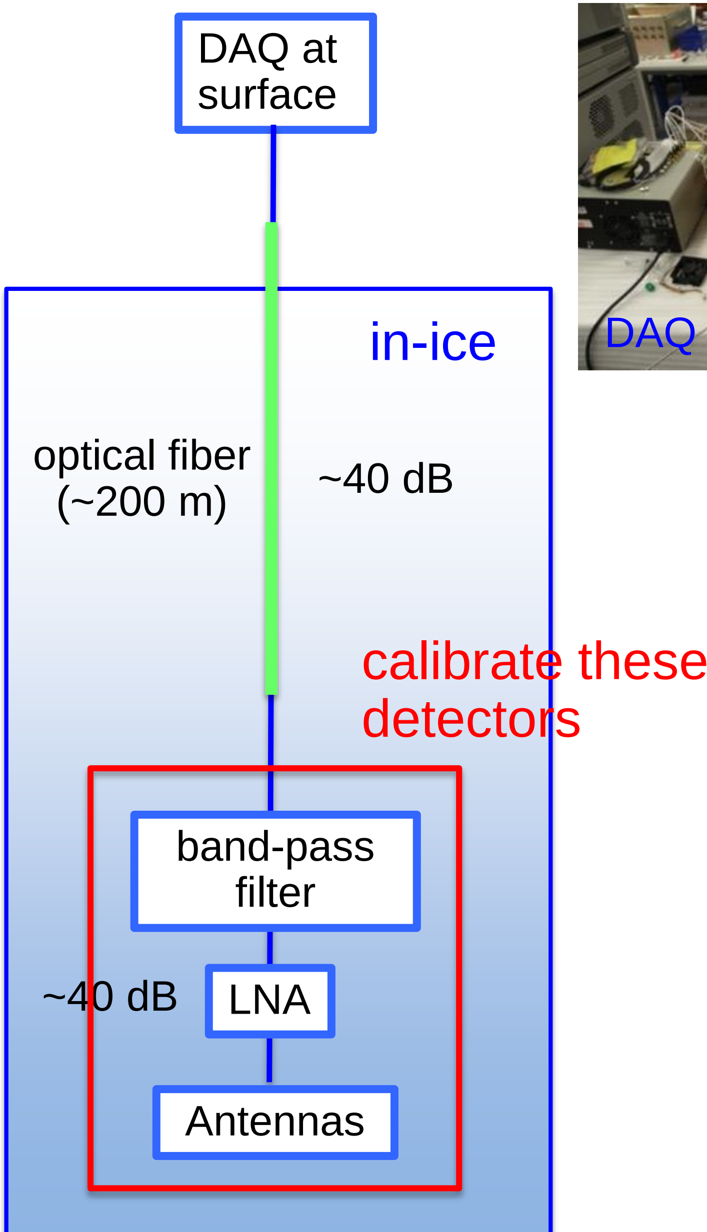
- ✓ 1962: Askaryan predicted coherent radio emission from excess negative charge in an EM shower (~20% due to mainly Compton scattering and positron annihilation) → **Askaryan effect**
- ✓ 2000: Attempt to measure Askaryan effect with Argonne Wakefield Accelerator (AWA) (P. W. Gorham et al., PRE 62, 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

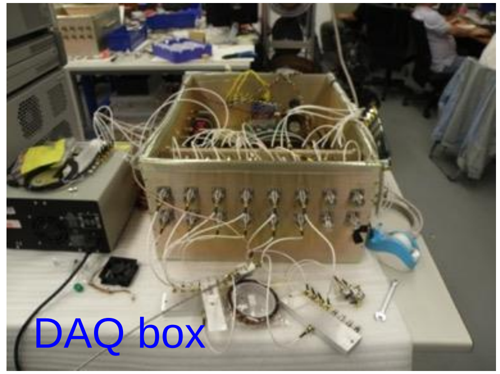


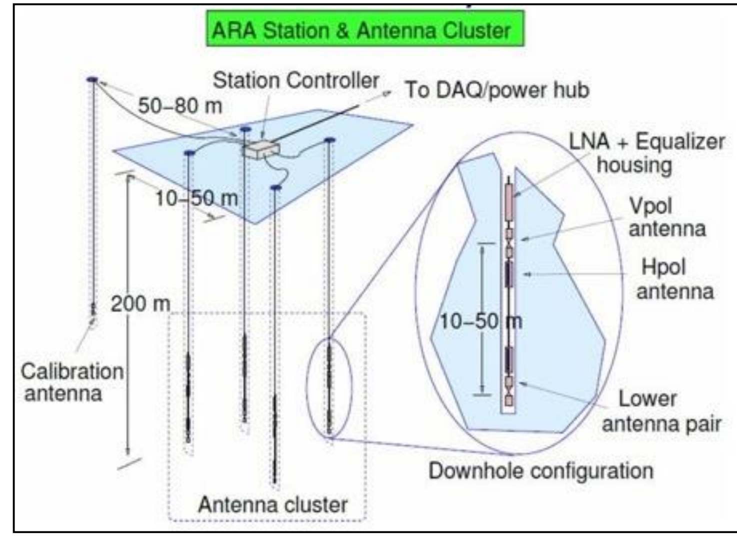


D. Saltzberg et al., PRL 86, 13 (2001)

The ARA system



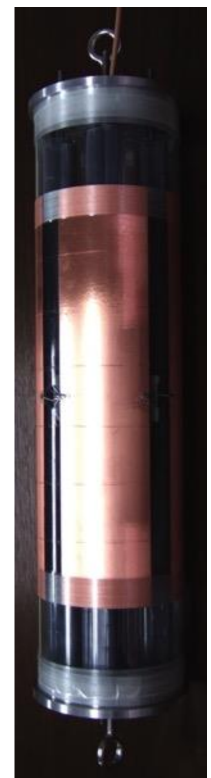




V-pol antenna

Bicone

150-850 MHz



H-pol antenna

Quad-slot cylinder

200-850 MHz

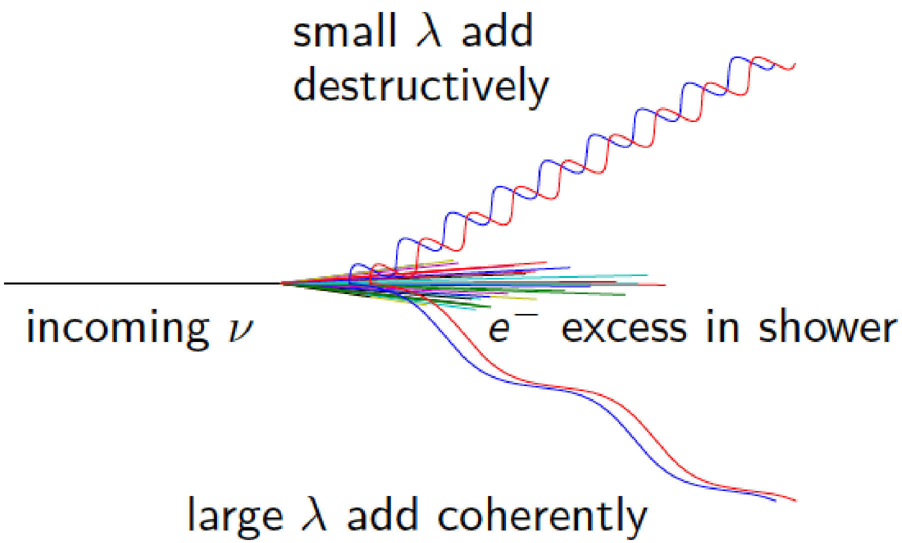
Gain similar to dipole (+2 dBi)

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

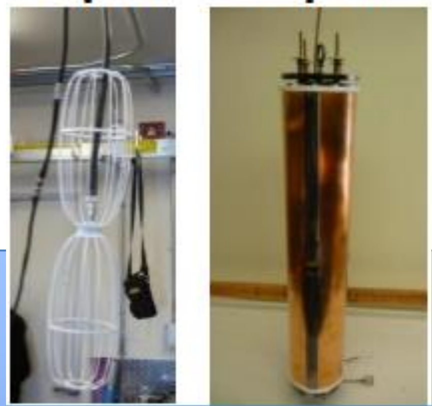
z=N (coherent) → W ∝ N^2

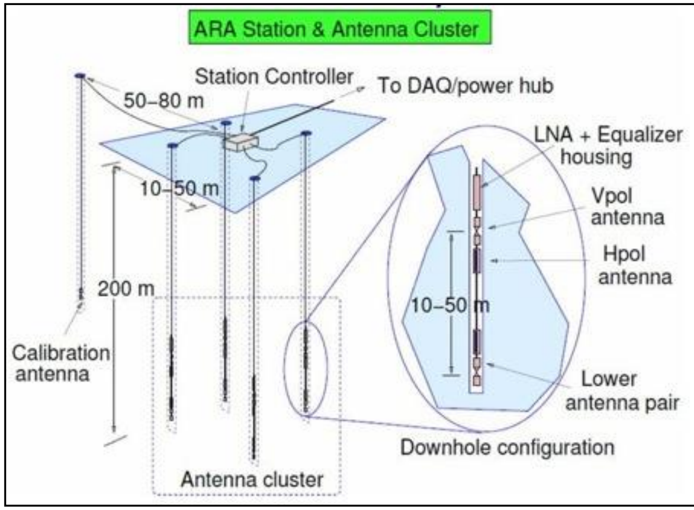
Power ∝ Δq^2, thus prominent at EHE (>~ 10 PeV)

Attenuation length in ice ~ 1 km

Schematic of the ARA system

V-pol H-pol





in-ice

Antenna

band-pass filter

~40 dB

LNA

optical fiber signal transfer system

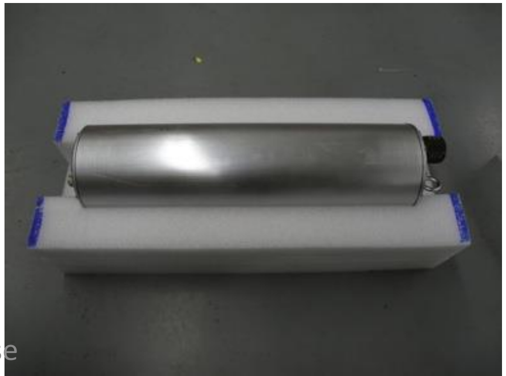
DTM

FOAM

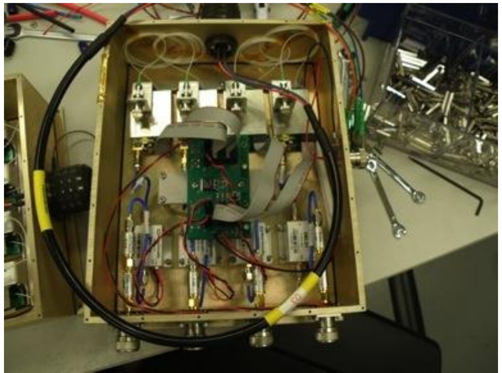
optical fiber (200m)

DAQ at surface

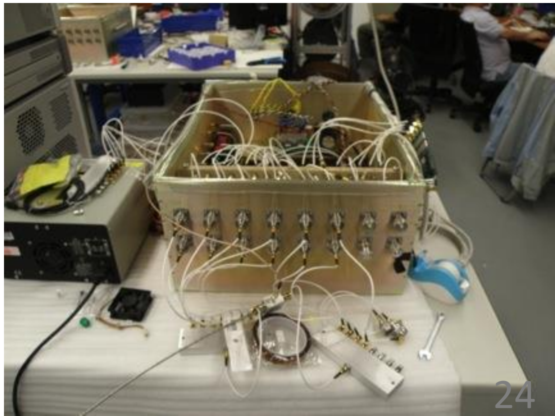
DTM



FOAM



DAQ box

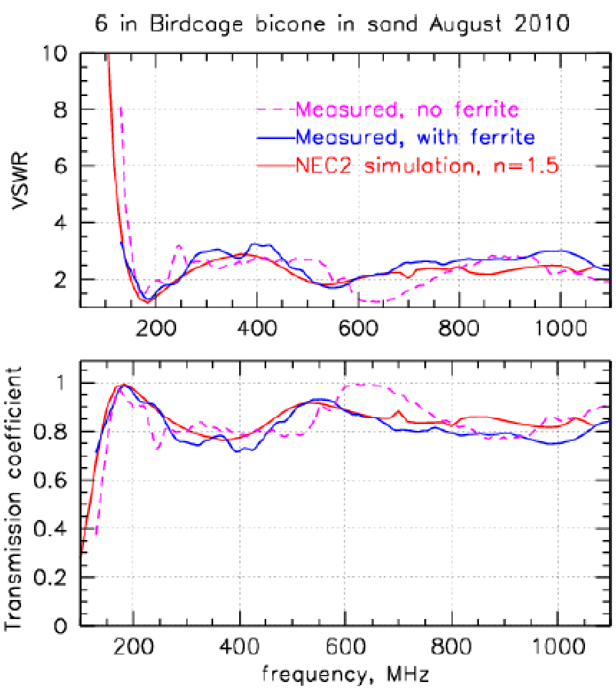


Antennas

V-pol antenna

Bicone

150-850 MHz



H-pol antenna

Quad-slot cylinder

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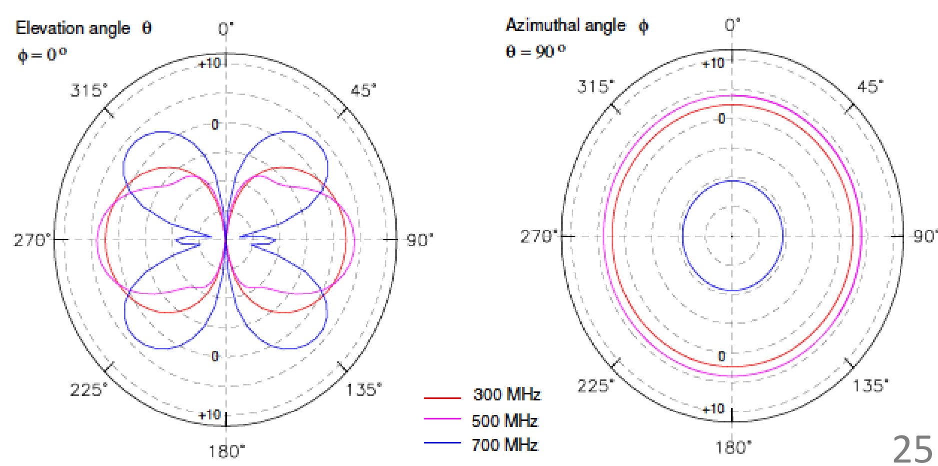
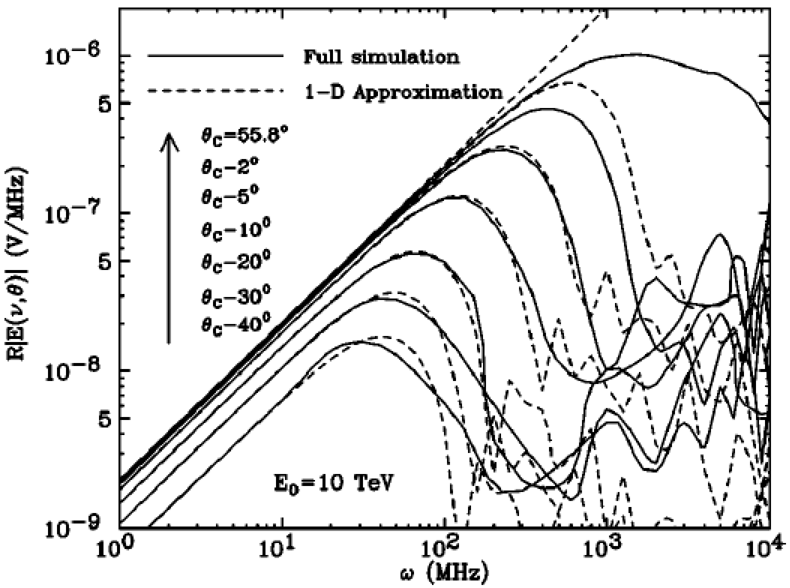
Gain similar to dipole (+2 dBi)



Parameterization of Askaryan radio wave



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

Signal amplitude

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

$$n_0 = 1.15\,GHz$$

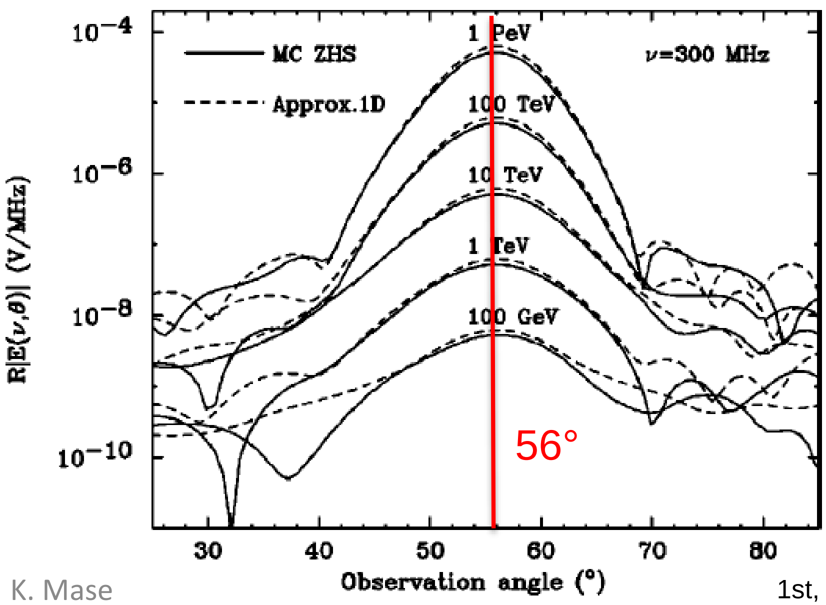
J. Alvarez Muniz et al., Physics Lett. B, 411 (1997) 218

Signal spread

$$E(w,R,q) = E(w,R,q)e^{-\ln 2\left(\frac{q-q_c}{Dq}\right)^2}$$

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

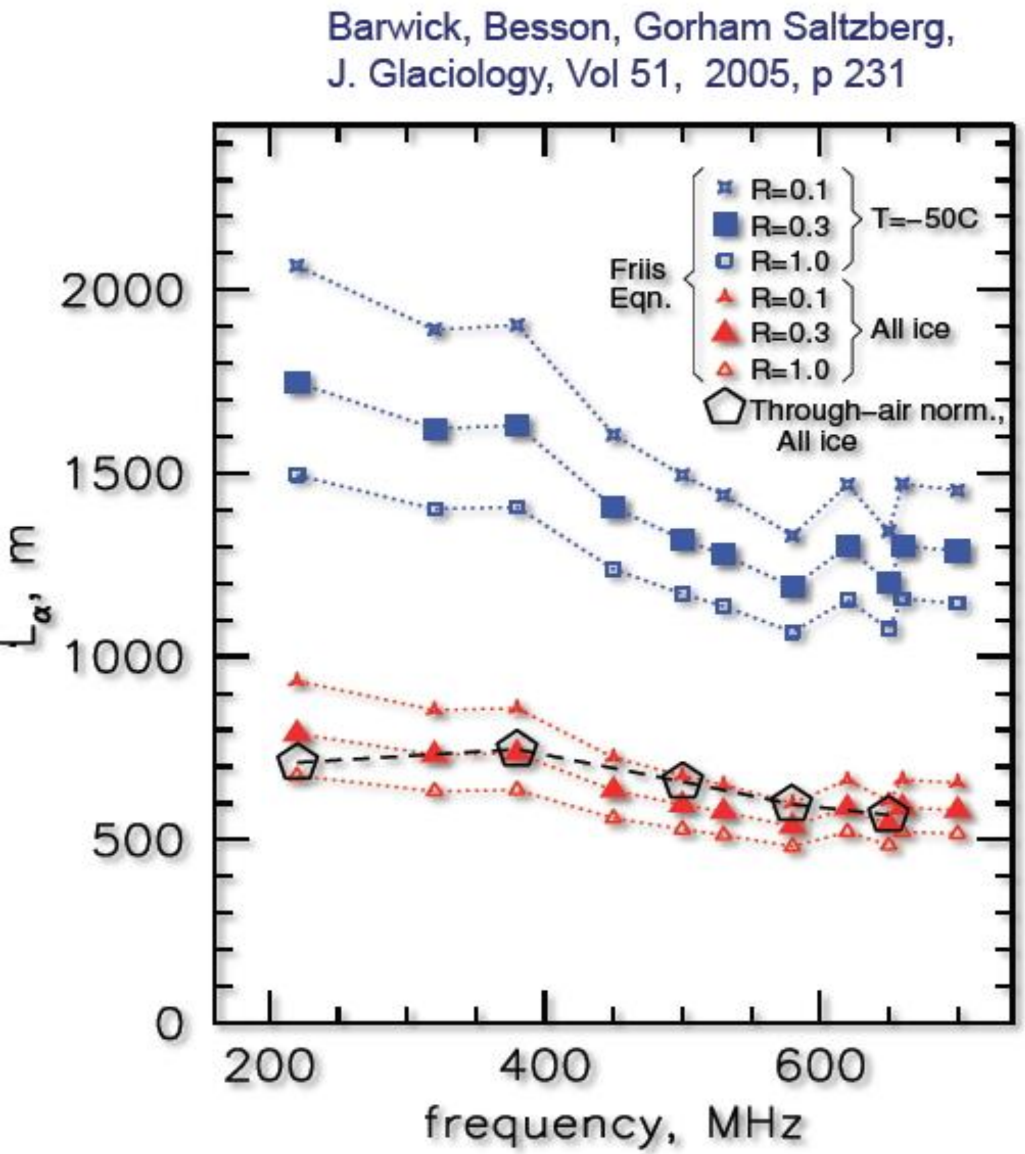
$$n_0 = 500\,MHz$$

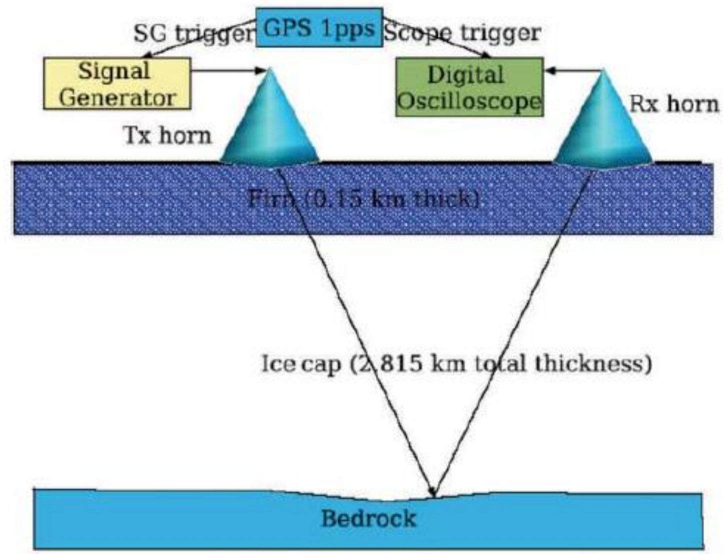


Incident particle energy → signal characteristics

Note: confirmed at SLAC

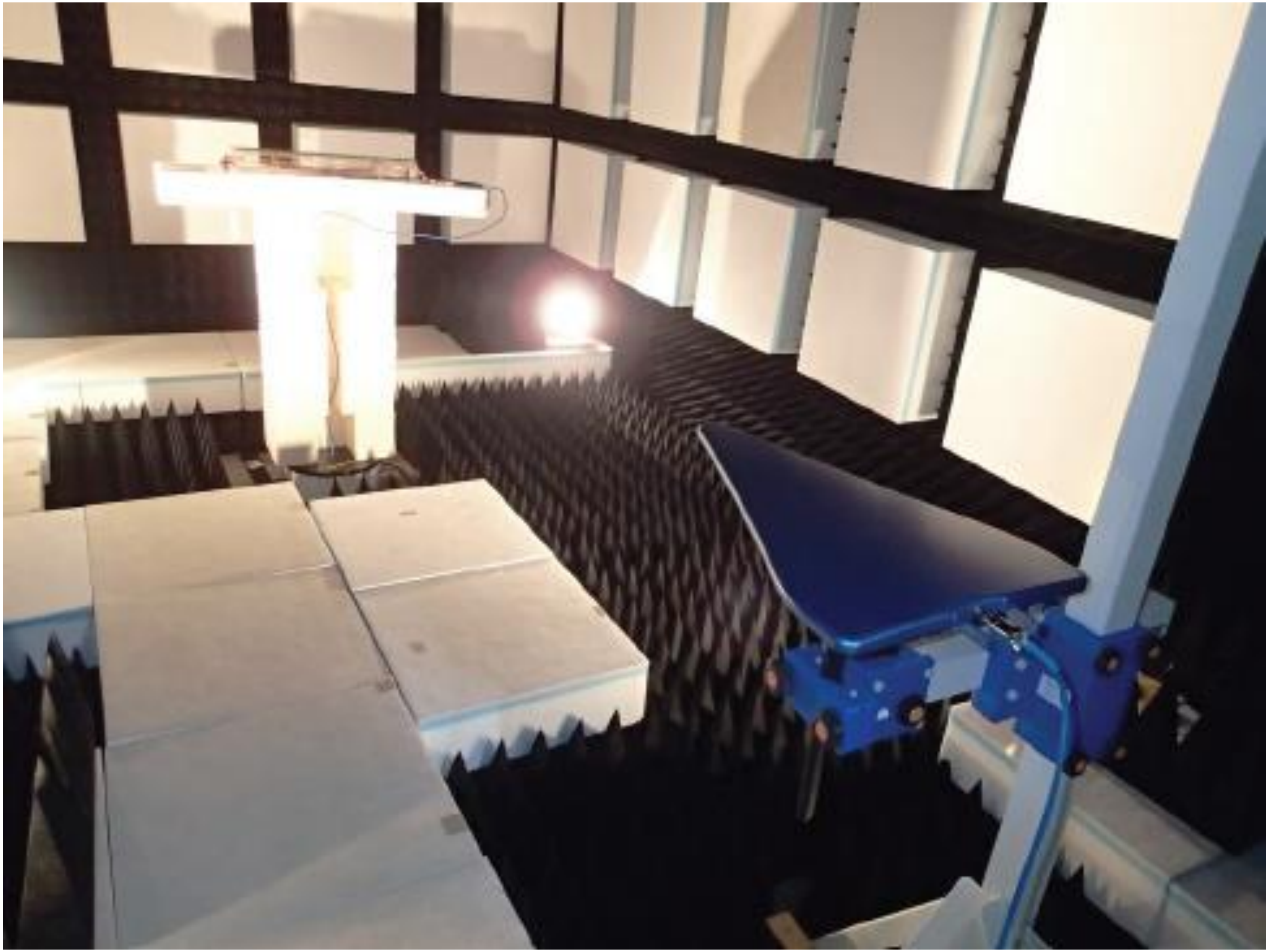
Why radio wave?





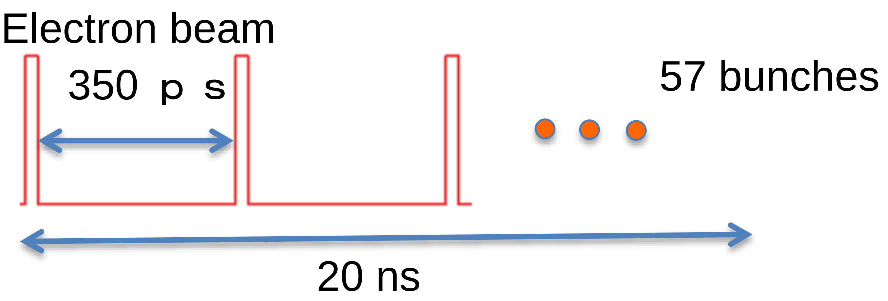
- Attenuation length of the south pole ice
  - Optical: ~100m
  - **Radio: ~1km**
- Easier to make a bigger detector in an economical way

■ Antenna calibration

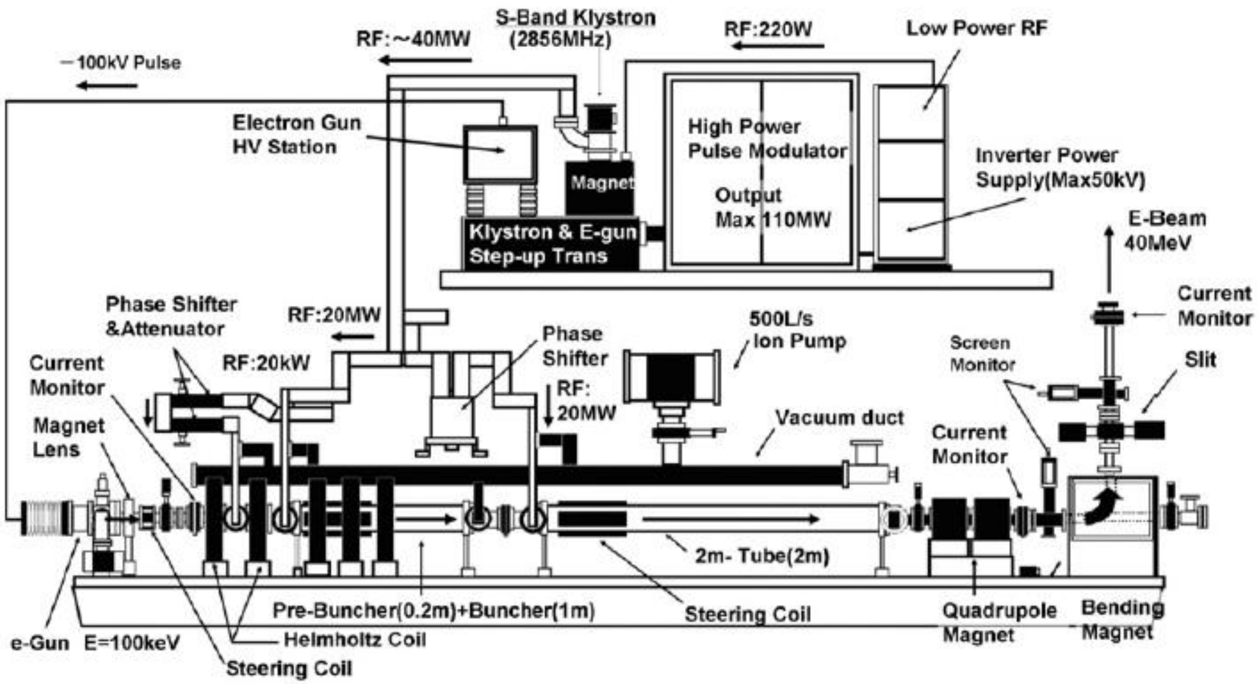


TA LINAC

- ✓ 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

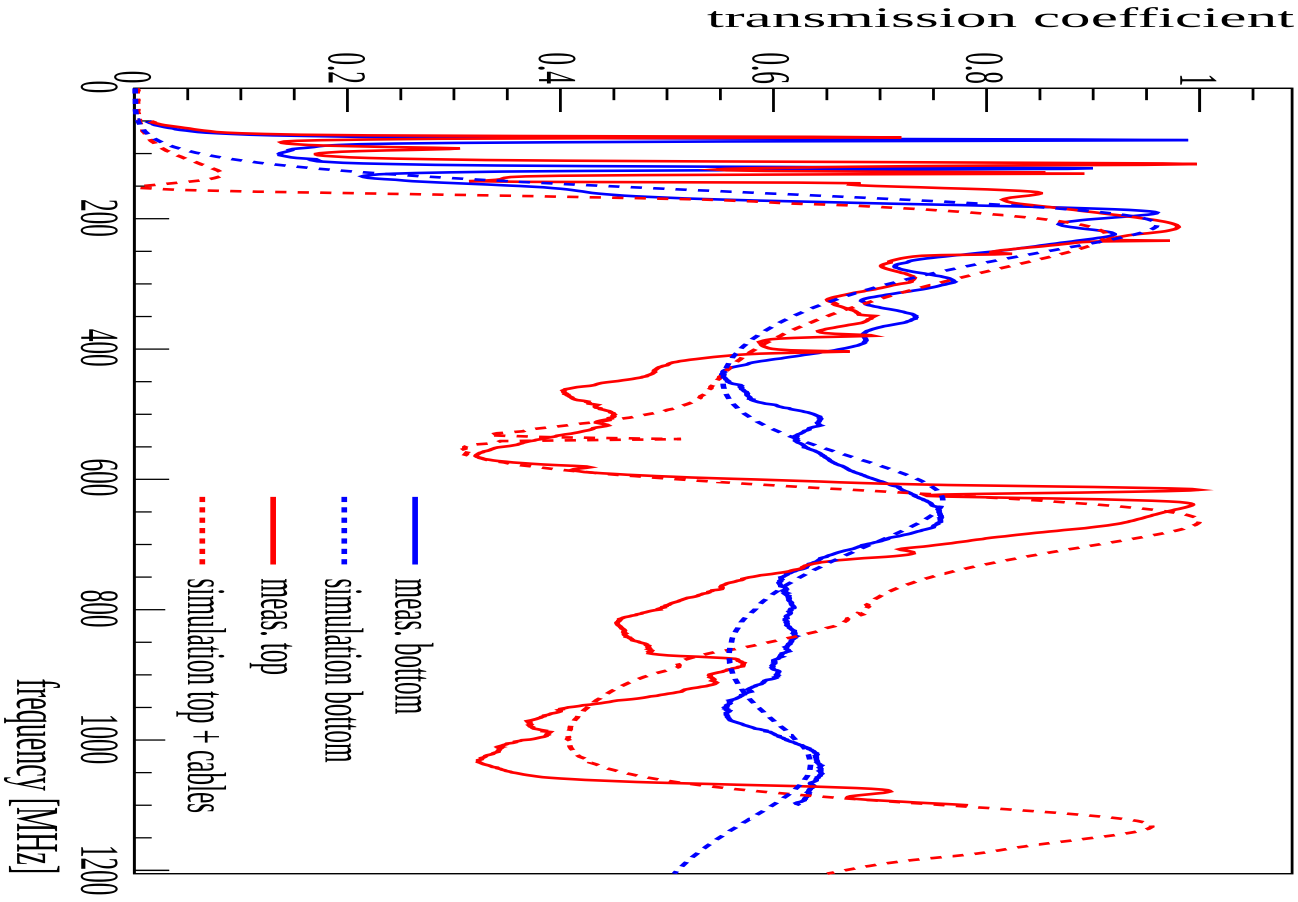


T. Shibata et al., NIMA 597 (2008) 61

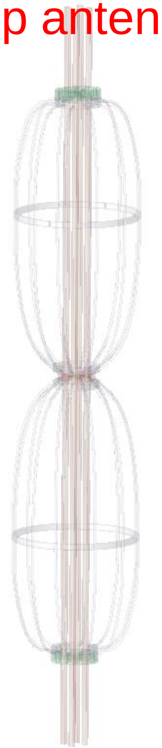


Antenna transmission coefficient

- ✓ 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