Observation of radio signals from an electron beam using an ice target

K. Mase, D. Ikeda, A. Ishihara, H. Sagawa, T. Shibata, M. Fukushima, T. Yamamoto, S. Yoshida, R. Gaior, K. Hanson, J. N. Matthews, T. Meures, B. K. Shin and G. B. Thomson, K. De Vries

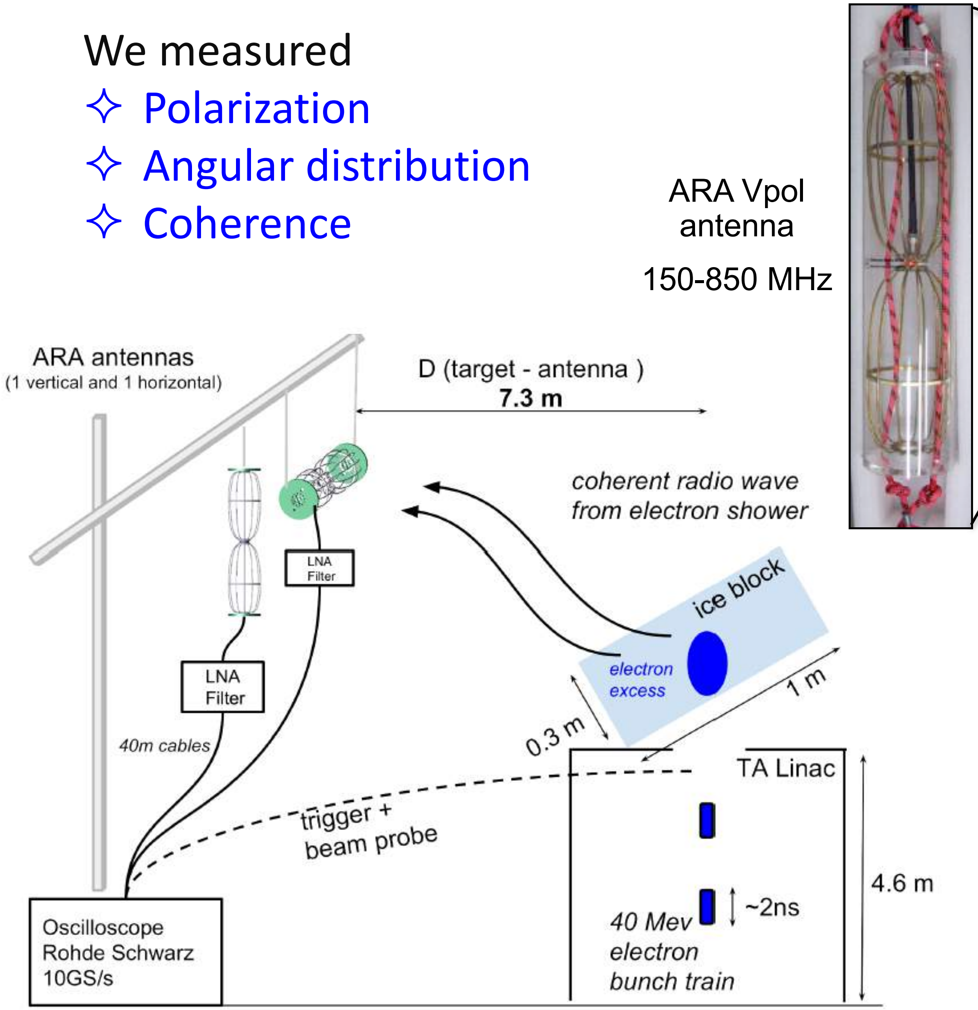
The ARA calibration with the TA-ELS (ARAcalTA)

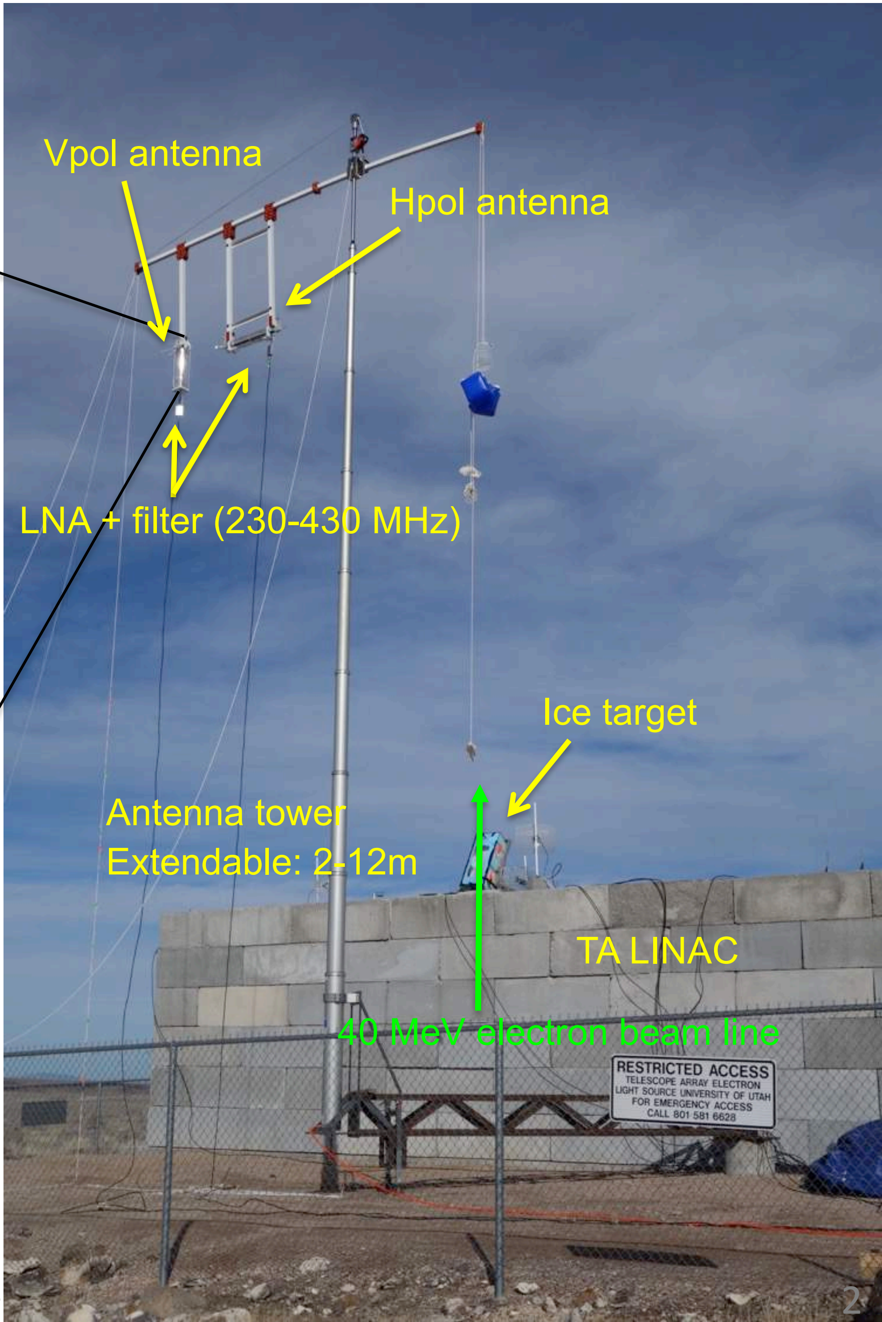
Performed in January, 2015 at TA site, Utah

Purpose: Better understanding of the radio emissions and our detector

We measured

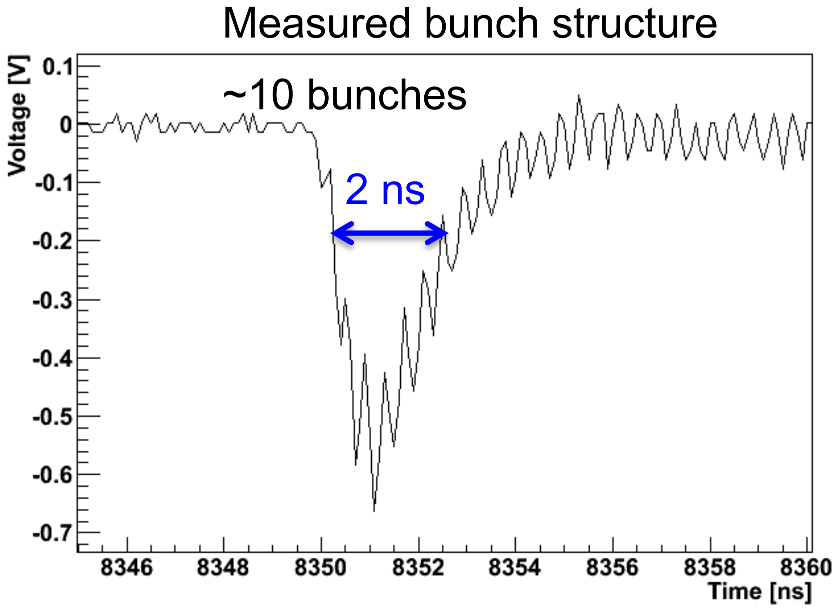
- ✧ Polarization
- ✧ Angular distribution
- ✧ Coherence





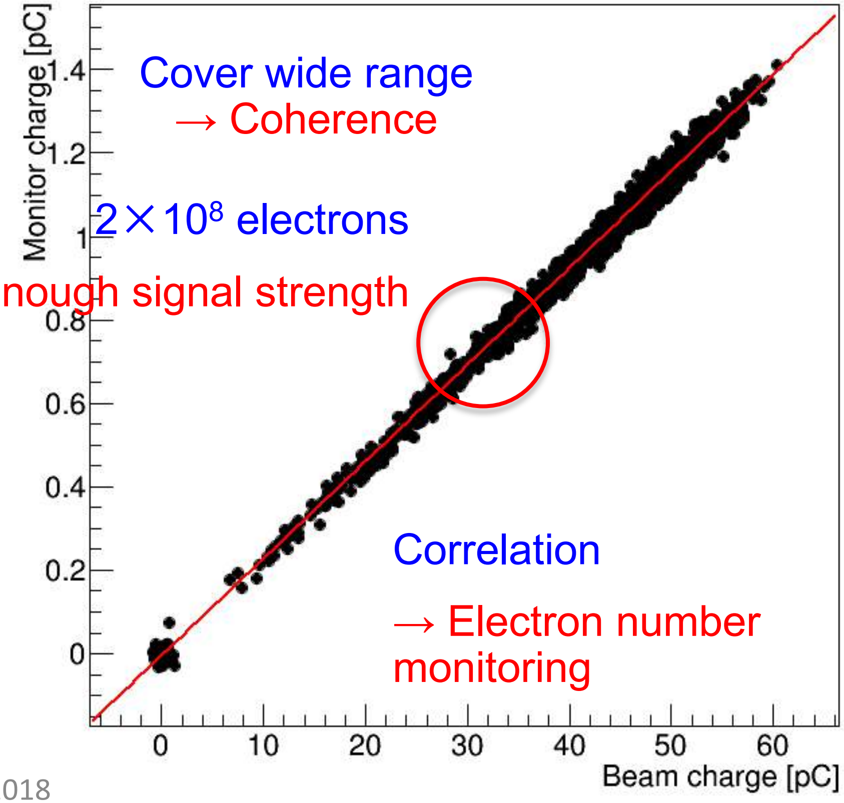
TA LINAC

- ✓ 40 MeV electron beam
- ✓ Typical electron number per bunch train: 2×10^8 → 30 PeV EM shower (shower length ~20 cm)
- ✓ 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 (~3%)


Measured bunch structure

~10 bunches

2 ns

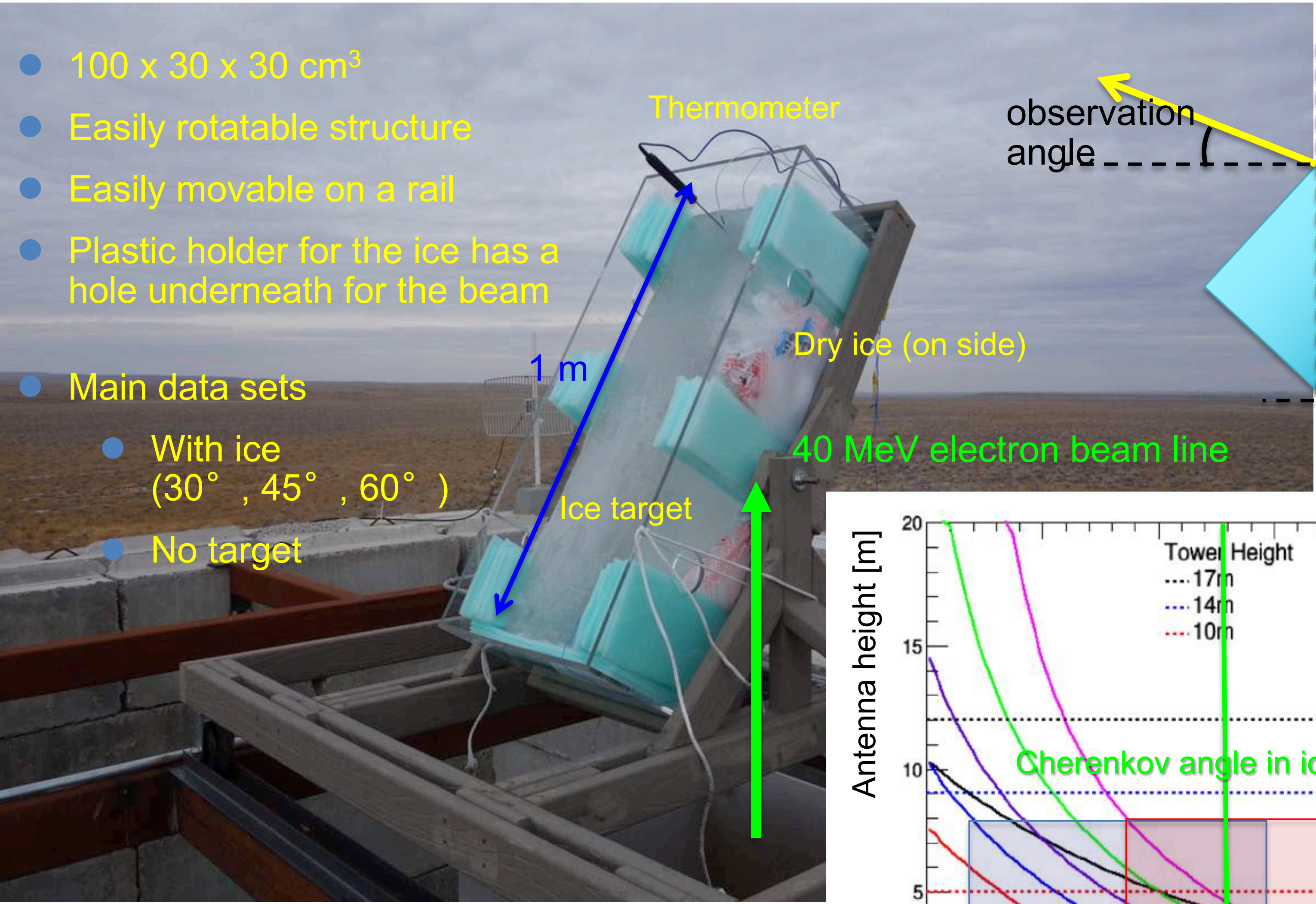

Cover wide range
→ Coherence

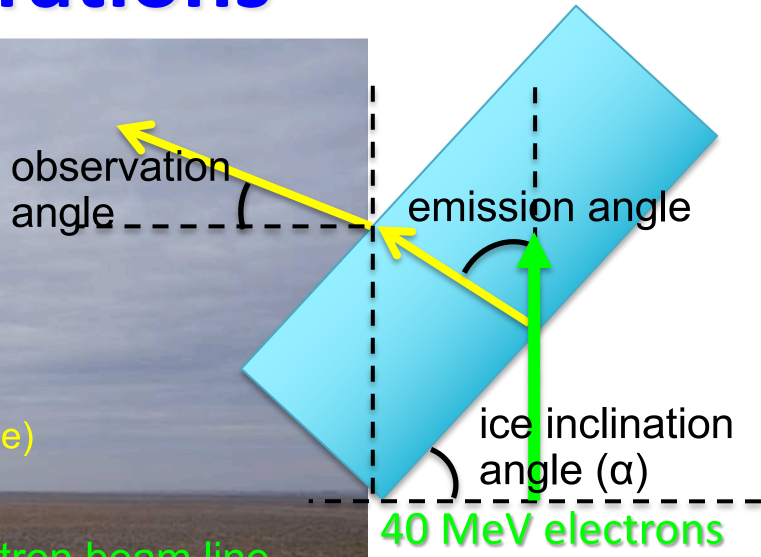
2×10^8 electrons
→ Enough signal strength

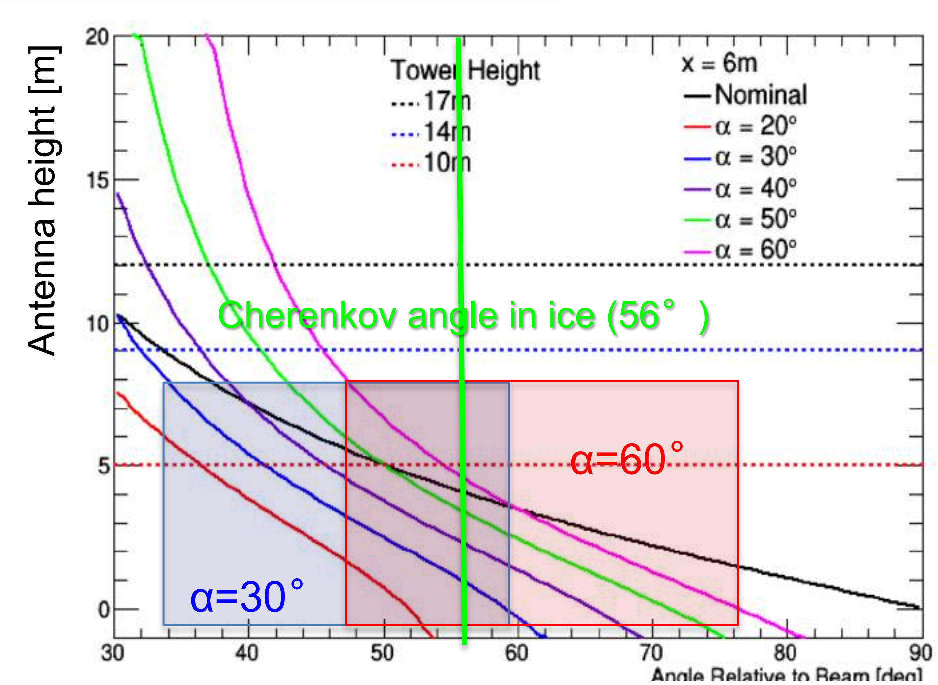
Correlation
→ Electron number monitoring

Ice target and the configurations

- $100 \times 30 \times 30\ \mathrm{cm}^3$
- 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







emission angle [deg.]

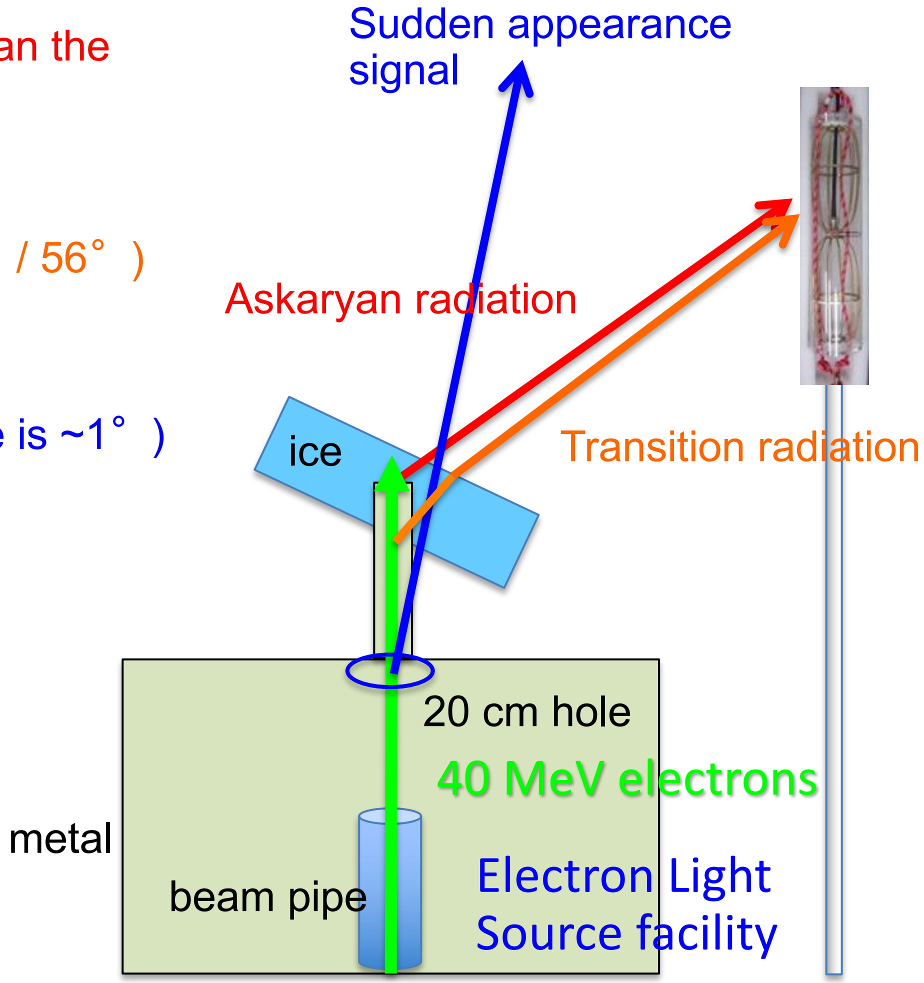
Expected radio emissions

- Several radio emissions are expected
  - Askaryan radiation
    - In ice
    - Wide angular distribution due to the short tracks
    - Peak at more horizontal direction than the Cherenkov angle (56°)
  - Transition radiation
    - At air/ice boundary
    - Peak at two Cherenkov angles (~1° / 56°)
  - Sudden beam appearance radiation
    - When beam appears
    - Forward emission (Cherenkov angle is ~1°)

- Originated from the same mechanism: Lienard-Wiechert potential (for the moving particle)

$$\Phi(\vec{x},t) = \left[\frac{e}{(1 - n\vec{\beta}\cdot\hat{r})R}\right]_{\text{ret}}, \quad \vec{A}(\vec{x},t) = \left[\frac{e\vec{\beta}}{(1 - n\vec{\beta}\cdot\hat{r})}\right]_{\text{ret}},$$

$$\boldsymbol{E} = -\nabla\phi - \frac{\partial \boldsymbol{A}}{\partial t}$$



Sudden appearance signal

Askaryan radiation

Transition radiation

ice

20 cm hole

40 MeV electrons

metal

beam pipe

Electron Light Source facility

Simulation

Electron beam (Geant4)

Including accelerator configurations

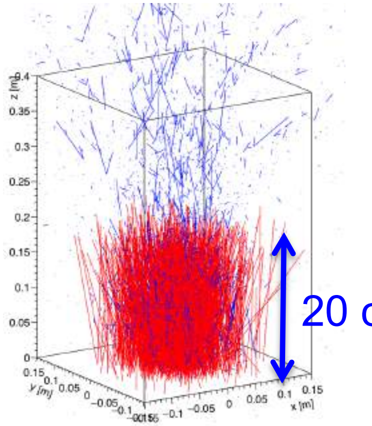
E-field calculation

Ray trace

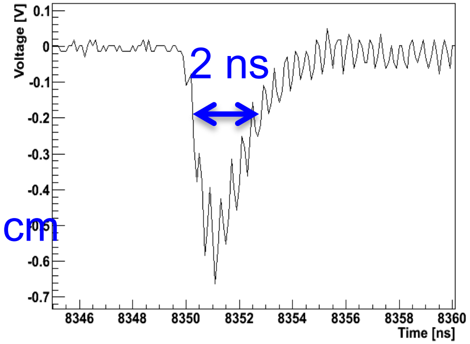
tables made

E-field

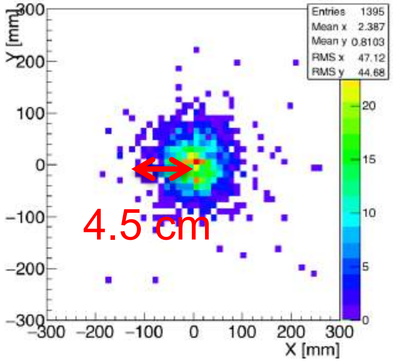
Detector response



Bunch structure



Lateral distribution



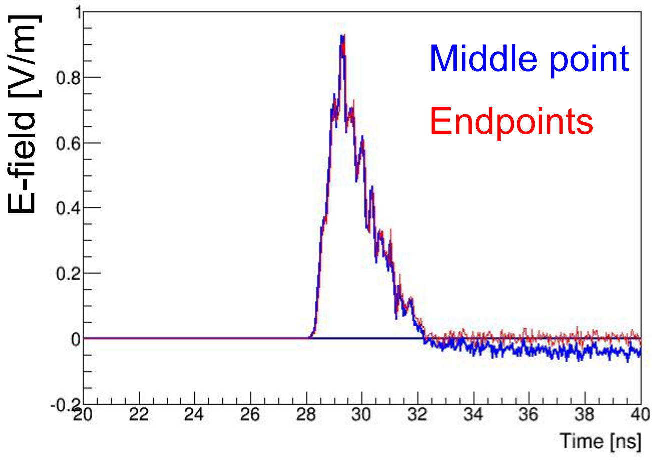
Based on the classical EM theory (Lienard-Wiechert potentials)

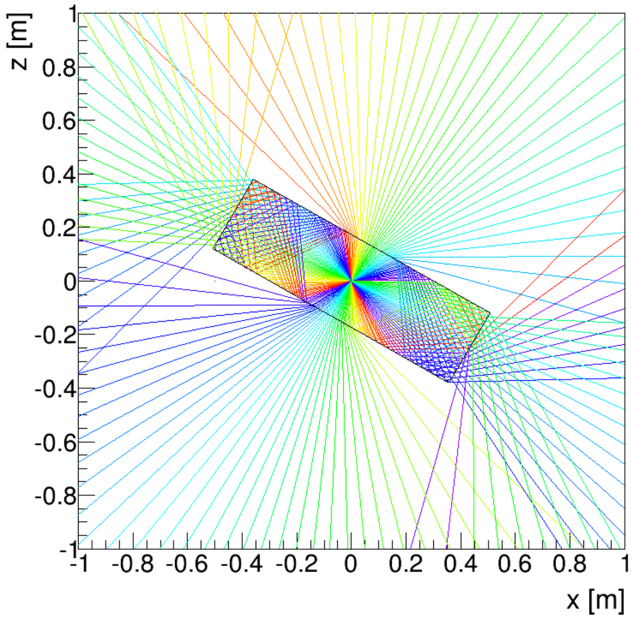
Middle point method (PRD 81, 123009 (2010))

Thanks to Anne Zilles for sharing her code for the implementation

Endpoints method (PRE84, 056602 (2011))

Obs. angle 0° (no target) at 1 m

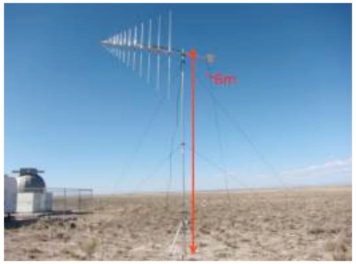


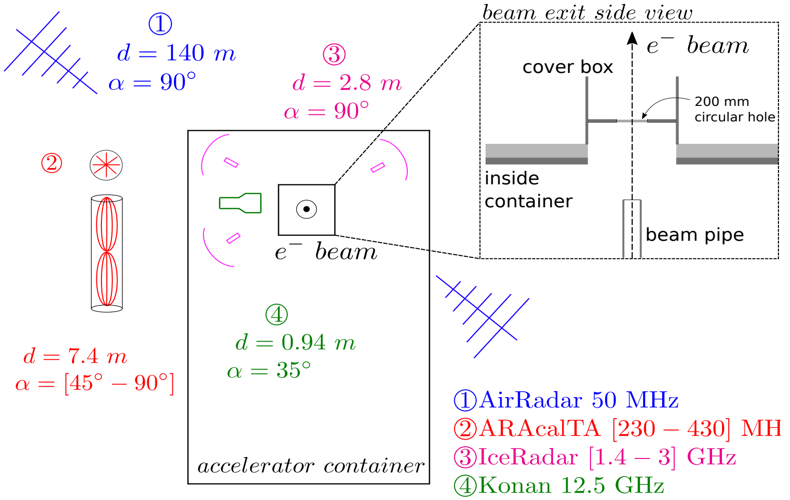


Sudden beam appearance signal

- ✓ Four independent experiments performed at the TA site
- ✓ All experiments clearly observed strong signals when beams appear

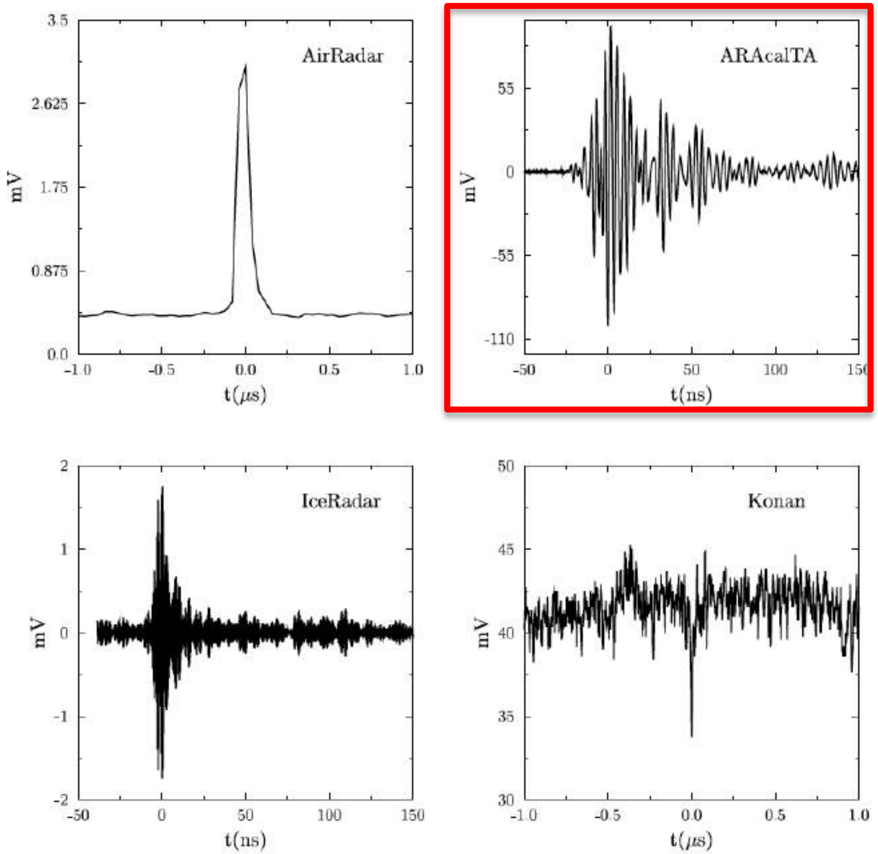
1. AirRadar



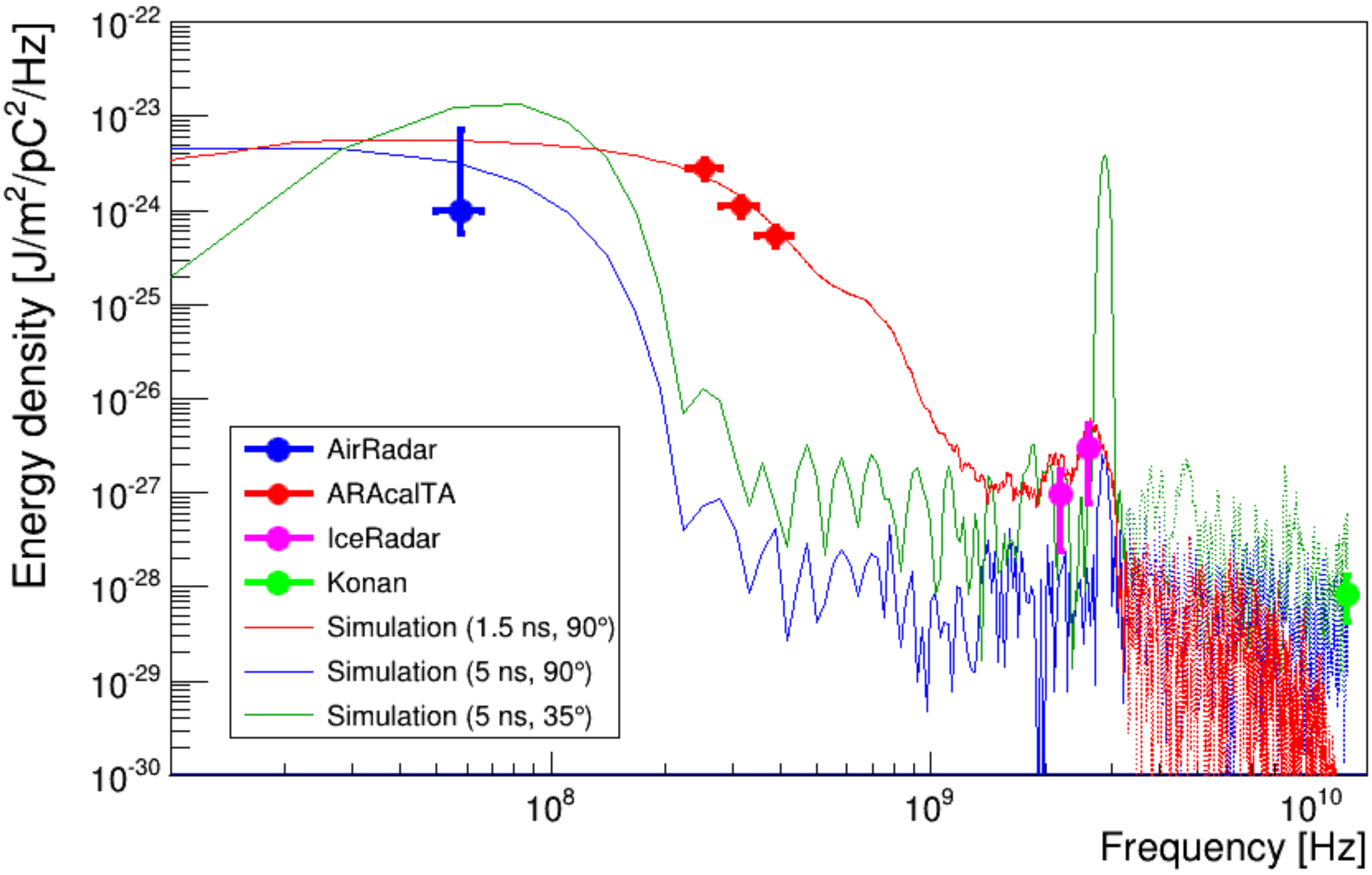


2. ARAcalTA

4. Konan

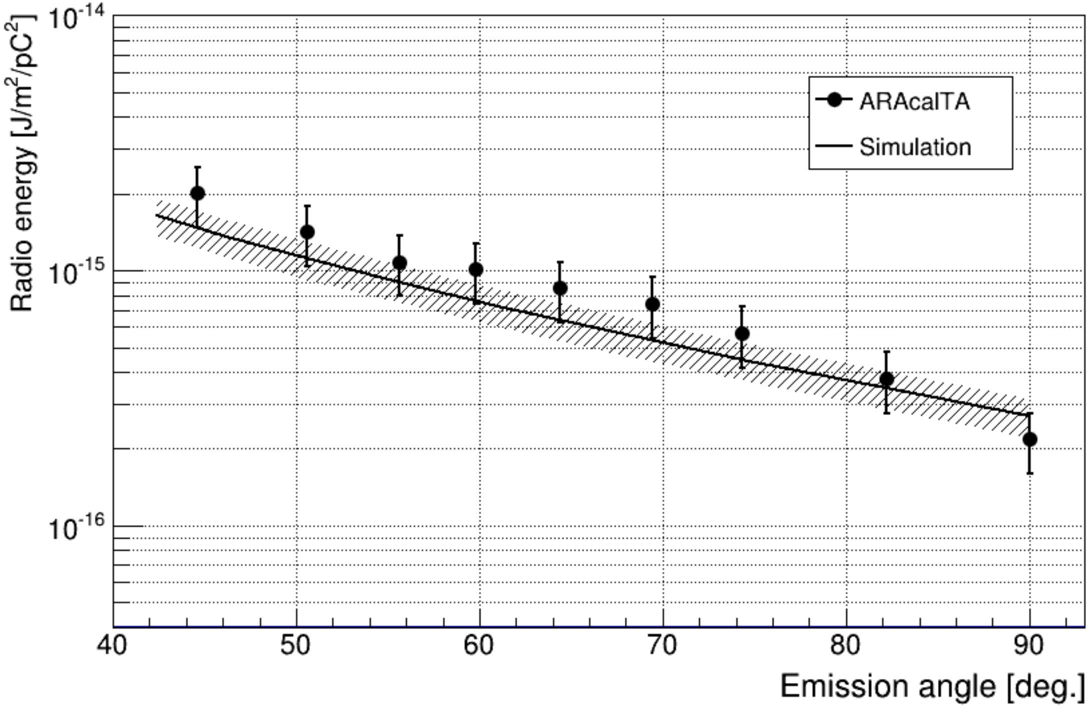


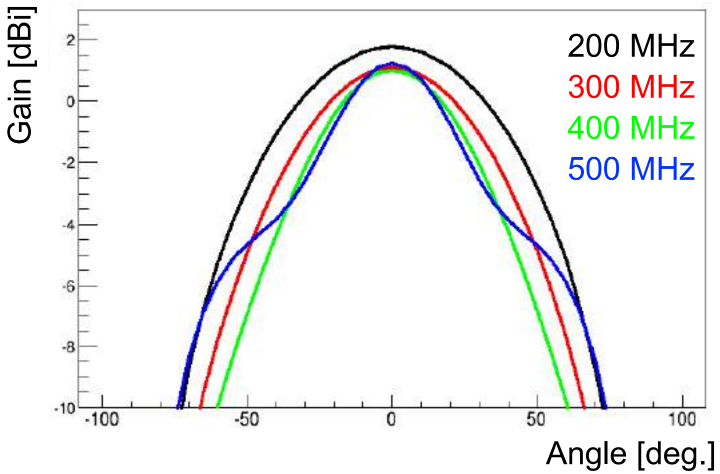
Frequency spectrum of the sudden beam appearance signals



- ✓ First result to show the consistency with the expectation for the wide frequency range
- ✓ Radiation well understood
- ✓ Applicable for the UHECR detection

Angular distribution of the sudden beam appearance signals

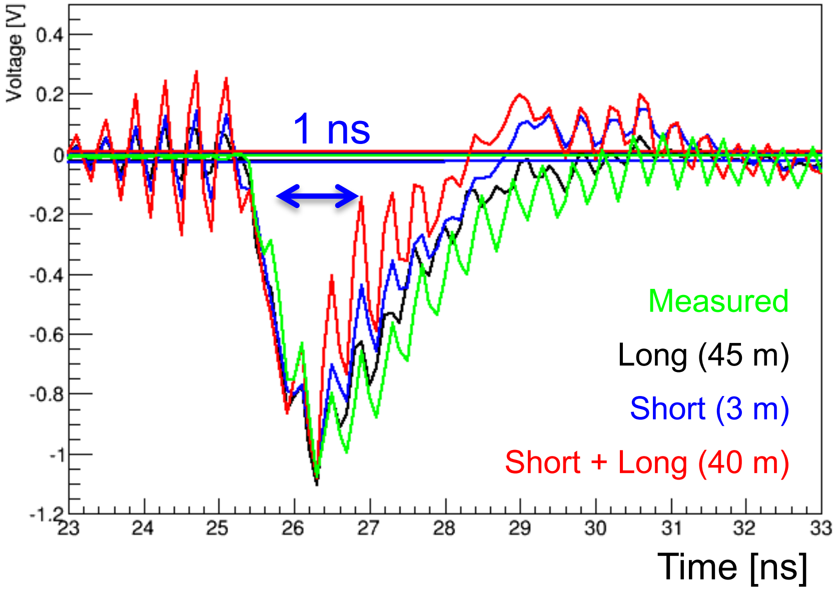

Chi2 / ndof = 2.49 / 9

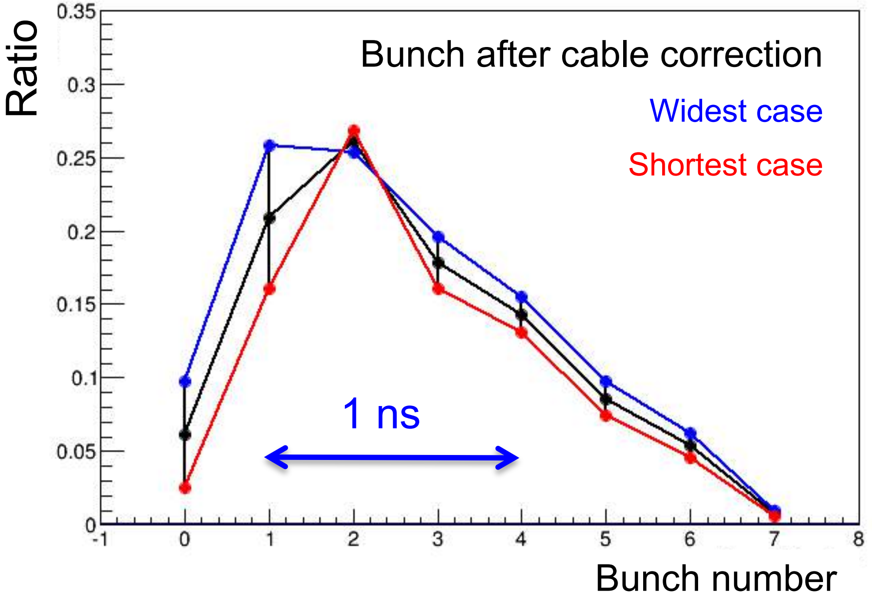

Antenna gain of XFDTD simulation

- ✓ Reasonable agreement between data and simulation (XFDTD)
- ✓ Radiation and our detector are well understood (level of 30%)

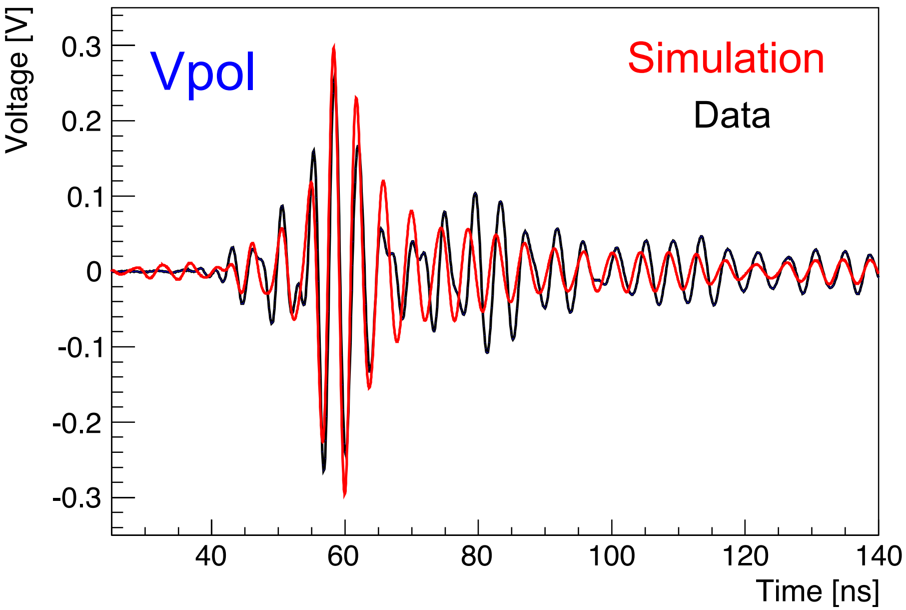
Systematic uncertainties

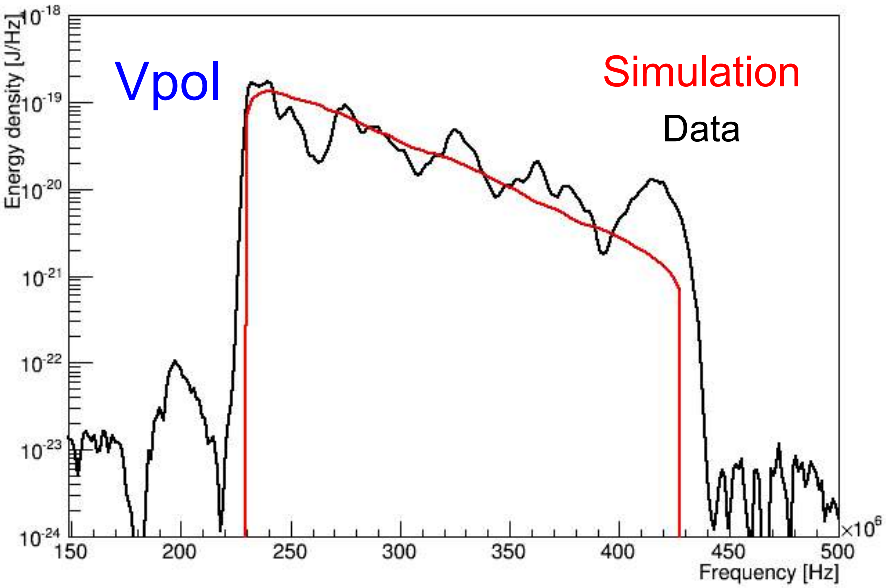
Item	Data	Simulation
Statistical error	±8%	±10%
Stability	±19%	-
Bunch width	-	-14% +17%
Sum	±21%	-17% + 20%

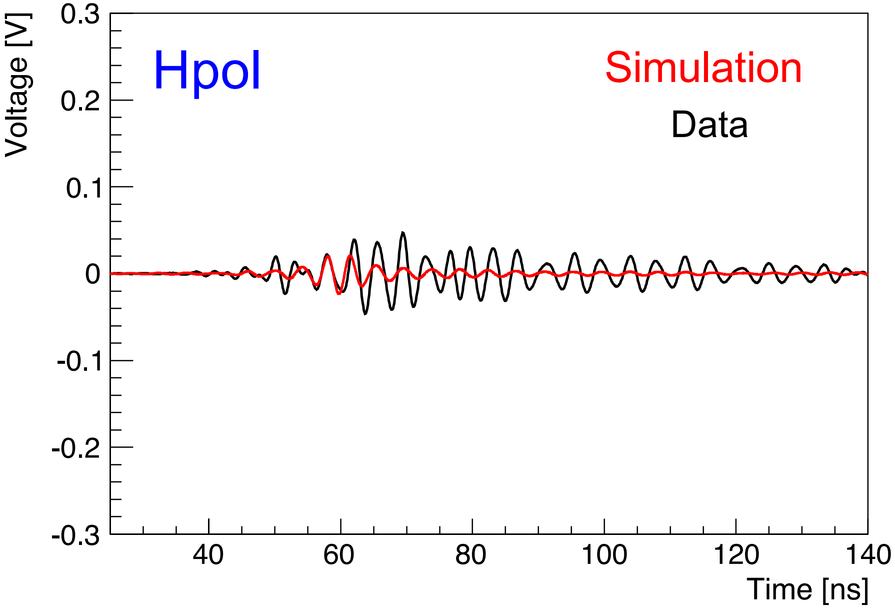




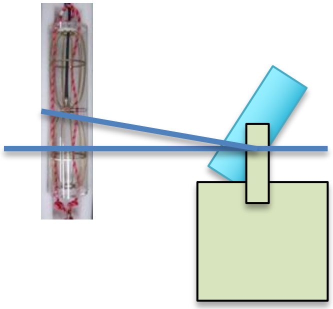
Signals with an ice target







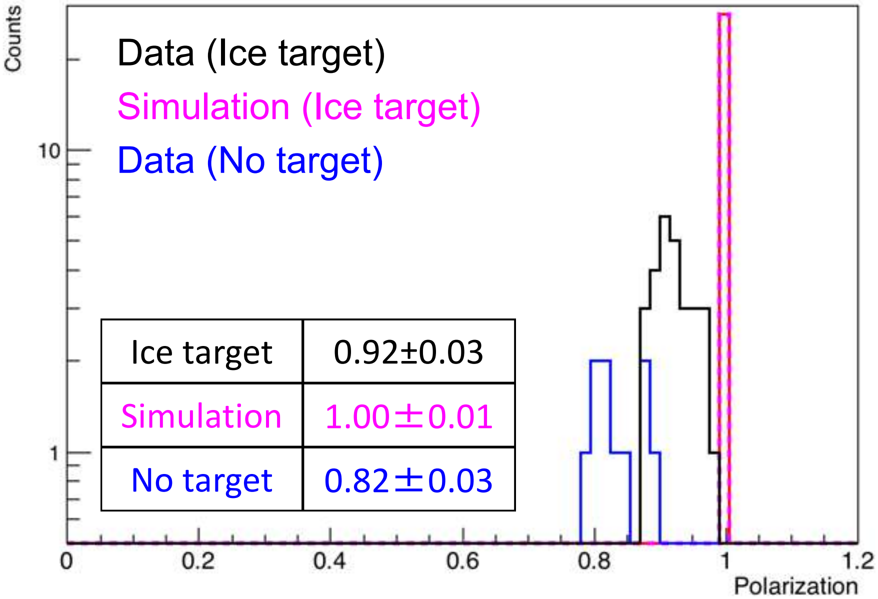
Configuration:
Ice 60° , obs. angle: 15°



- ✓ Reasonable agreements between data and simulation
- ✓ Less Hpol signal → high polarization

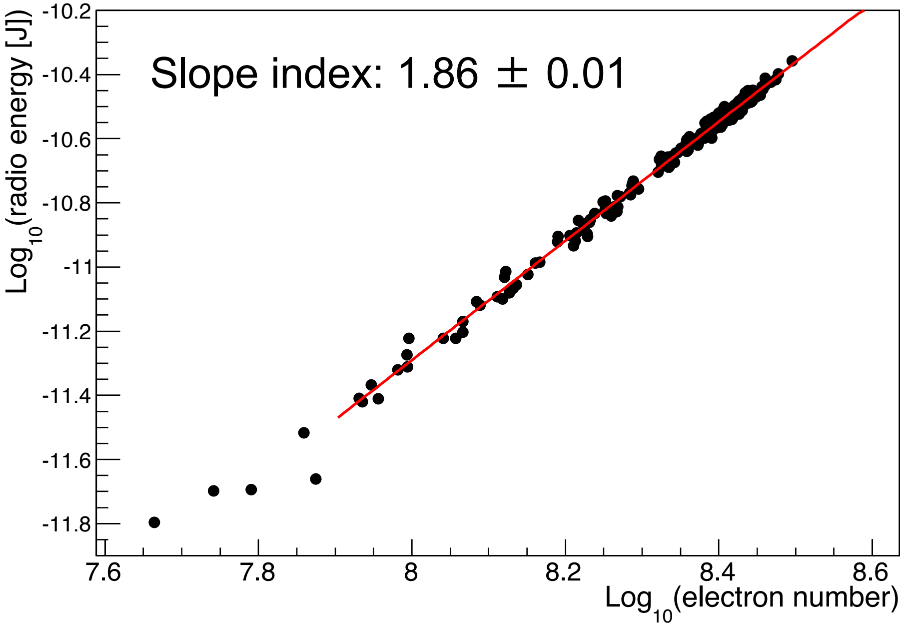
Polarization and coherence

Polarization



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

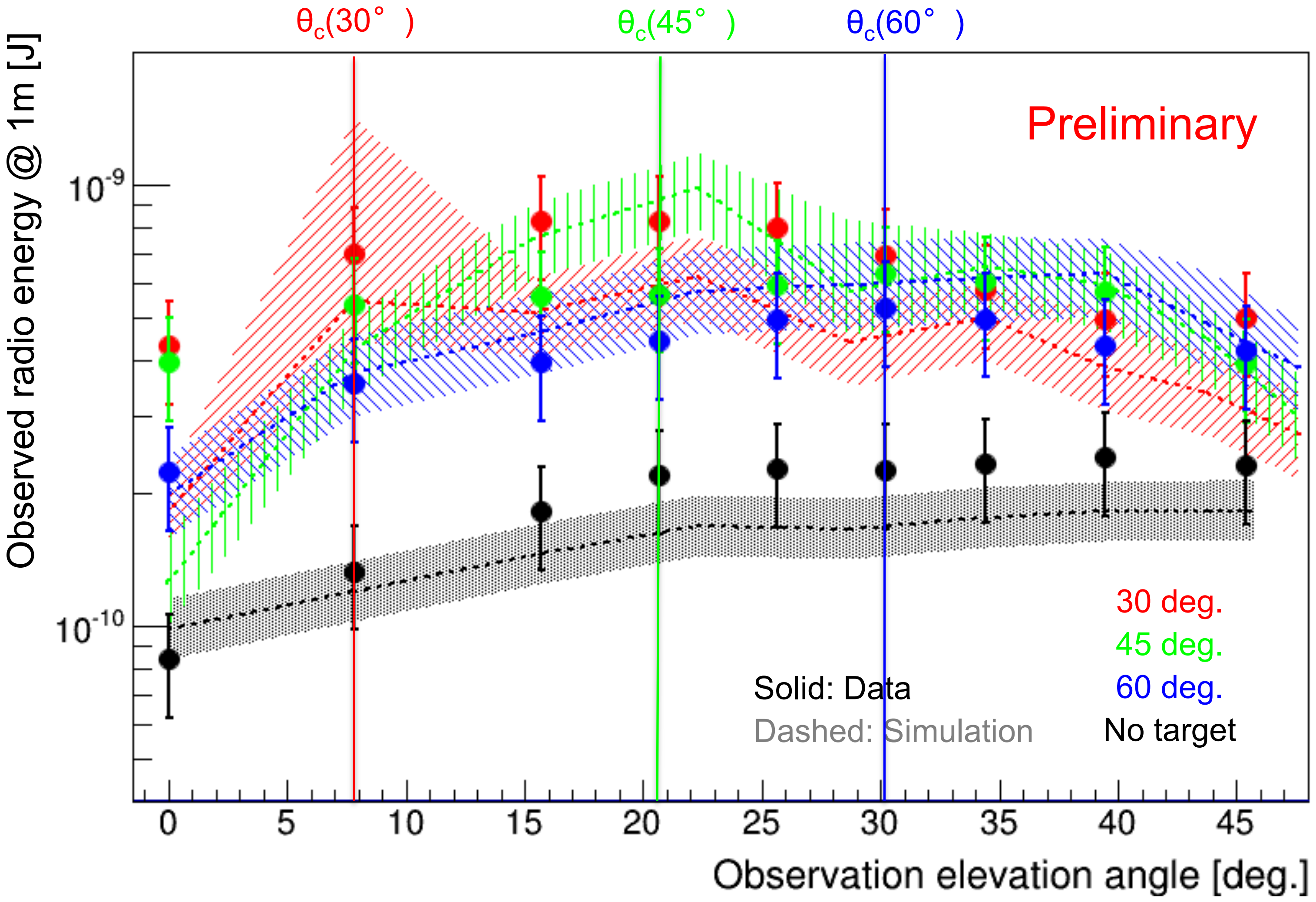
Configuration: Ice 30°, obs. angle 0°, Vpol



- ✓ All signals shows relatively high vertical polarization

- ✓ Reasonable coherence
- ✓ Similar values for all the configurations

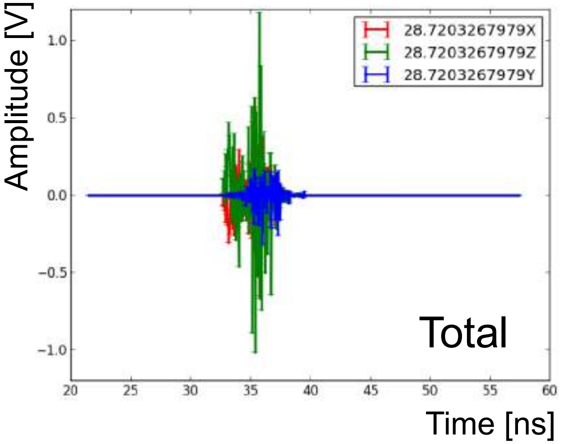
Angular distribution



- Reasonable agreements
- Detector effects included in simulation
- Need to be changed to radio energy vs emission angle

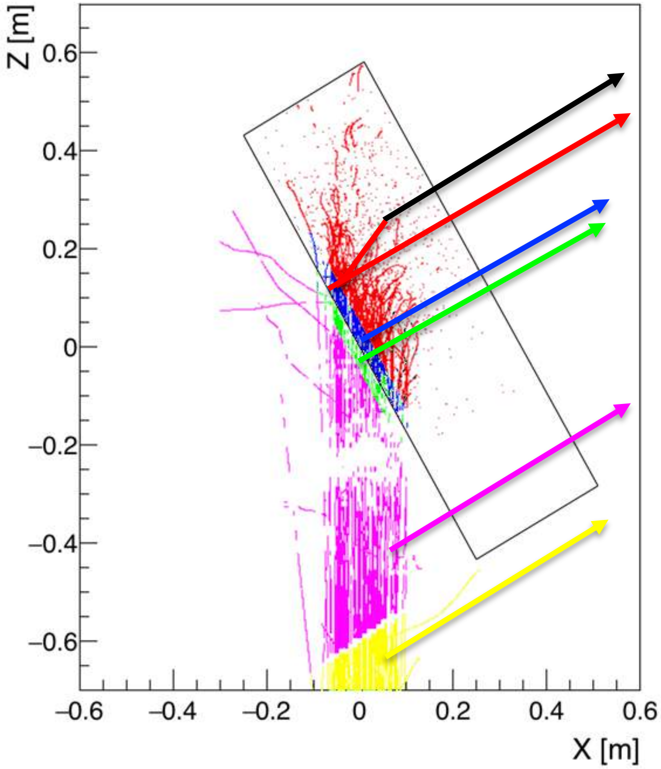
Each component

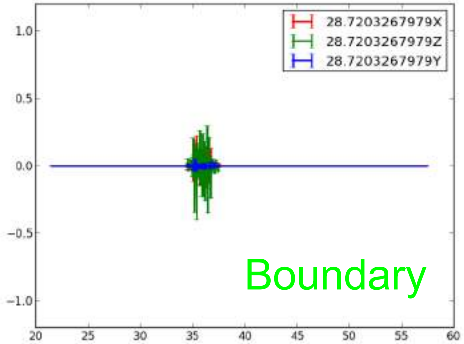
Preliminary



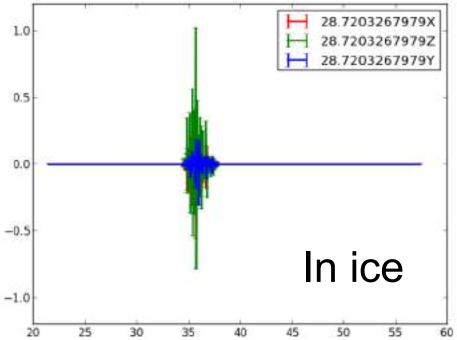
Total

Configuration:
Ice 60° , obs. angle: 29°

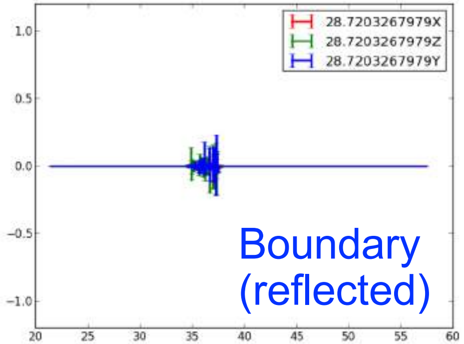




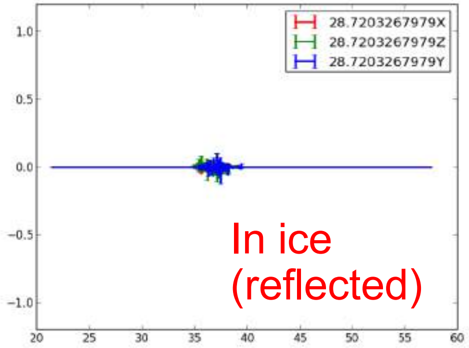
Boundary



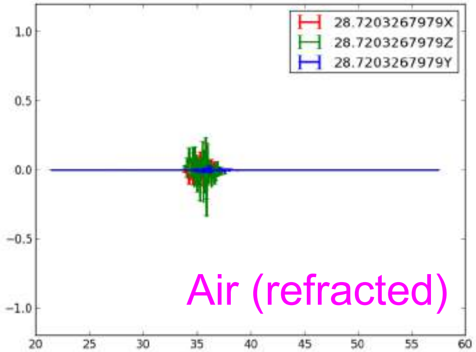
In ice



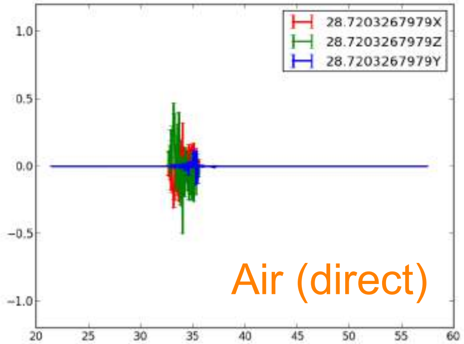
Boundary
(reflected)



In ice
(reflected)



Air (refracted)



Air (direct)

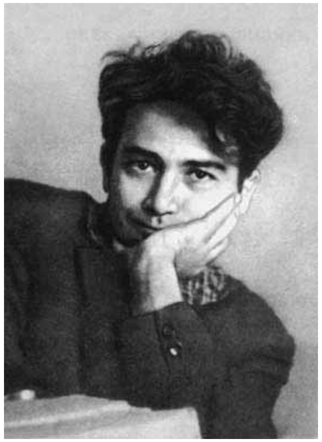
■ Summary

- ✓ Performed experiments using an accelerator to verify the understanding of the radio signals as well as our detectors
- ✓ Clearly polarized and coherent signals observed
- ✓ Observed signals are consistent with the expectation within the uncertainty level of 30%
- ✓ Understanding the emission further by checking each component
- ✓ Would be important for sudden deaths of air showers

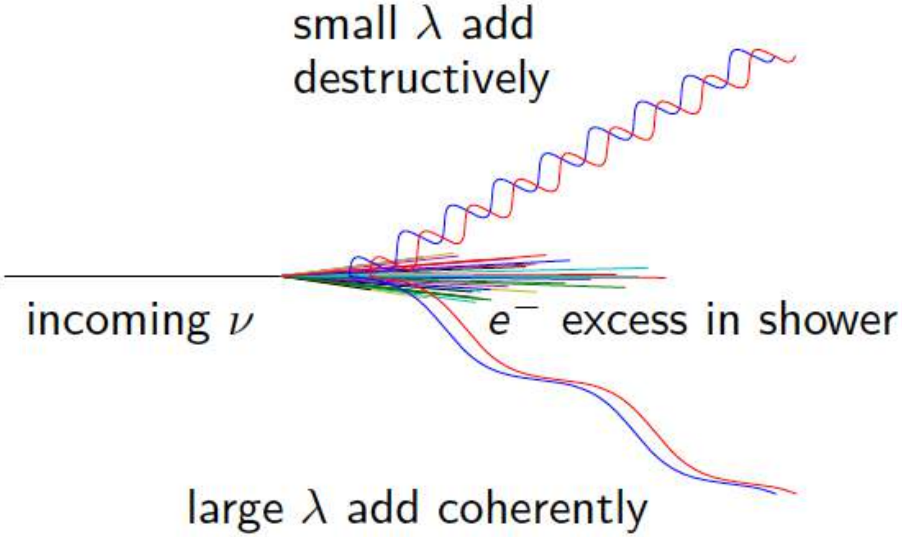
Backups

Askaryan effect

- 1962: Askaryan predicted coherent radio emission from excess negative charge in an EM shower
  → **Askaryan effect**



G. Askaryan



Shower size << λ to be coherent

→ Dense material better

Cherenkov emission (Frank-Tumm result)

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

in case N electrons,

z=1 (not coherent) → W ∝ N

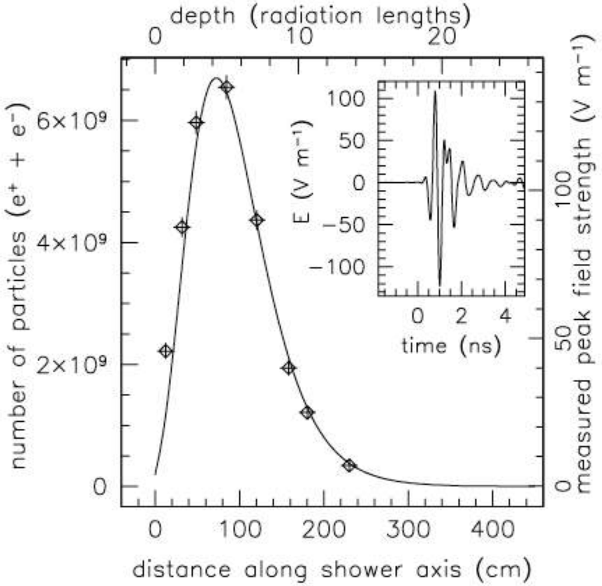
z=N (coherent) → W ∝ N^2

Power ∝ Δq^2 ∝E^2, thus prominent at ultra-high energy (>~ 100 PeV)

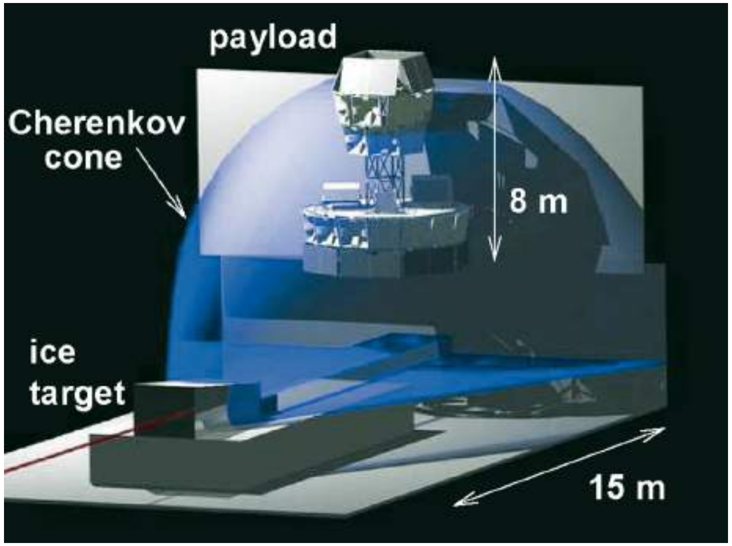
Verification of the Askaryan effect

- Askaryan effect has been verified using an accelerator
  - 2001: firstly confirmed at SLAC with Silica sand (D. Saltzberg et al.)
  - 2005: confirmed with salt (P. Gorham et al.)
  - 2007: confirmed with ice (P. Gorham et al.)

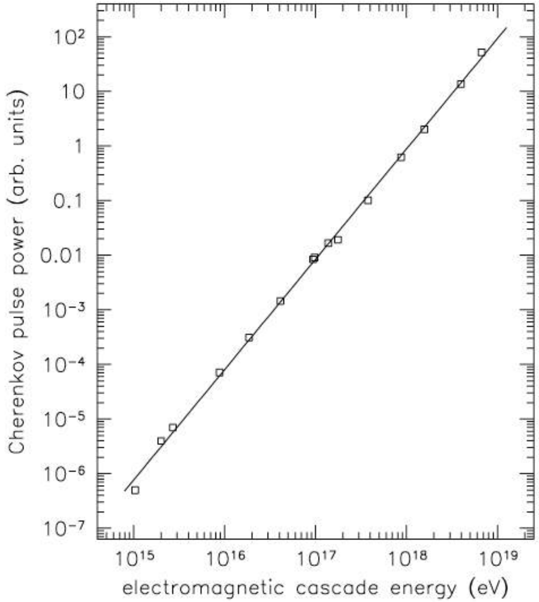
Saltzberg et al. PRL 2001



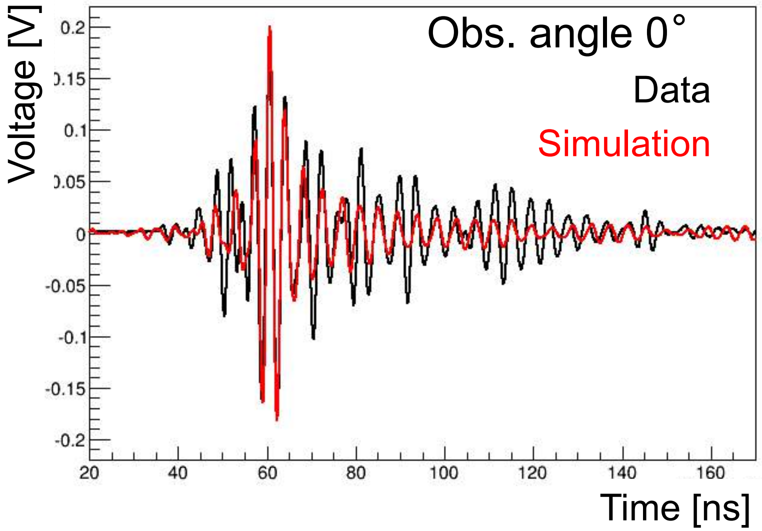
Gorham et al. PRL 2007



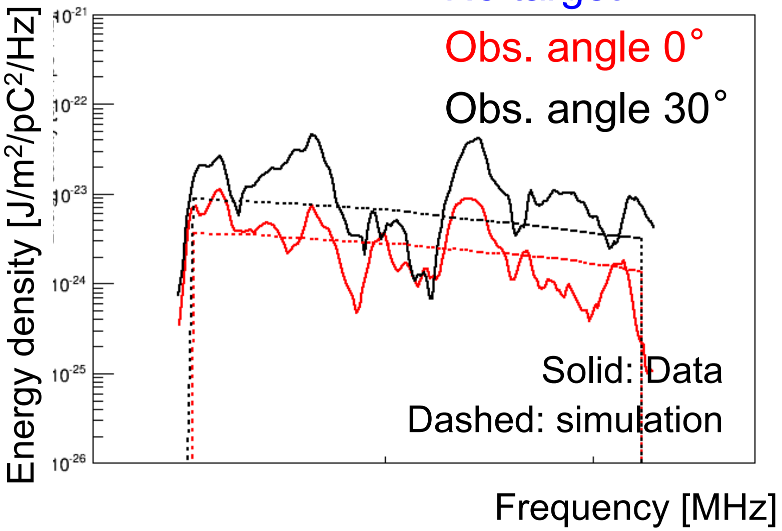
Gorham et al. PRD 2005



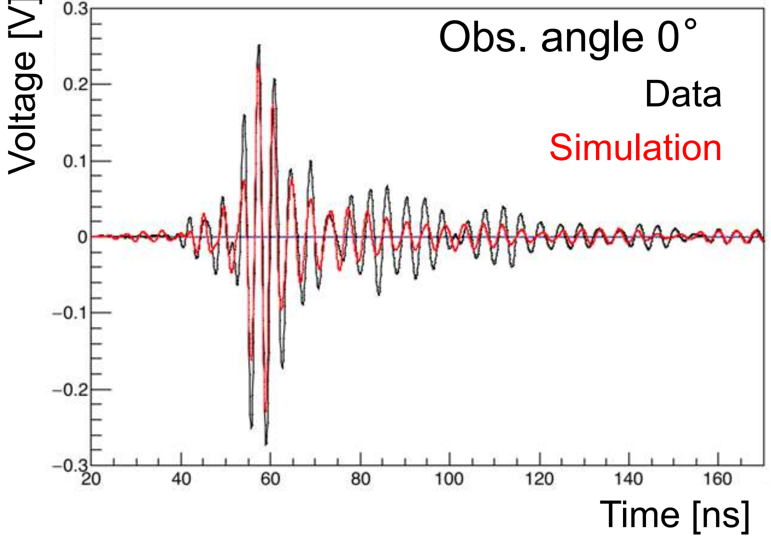
Comparison of waveforms and frequency spectrum



No target



No target

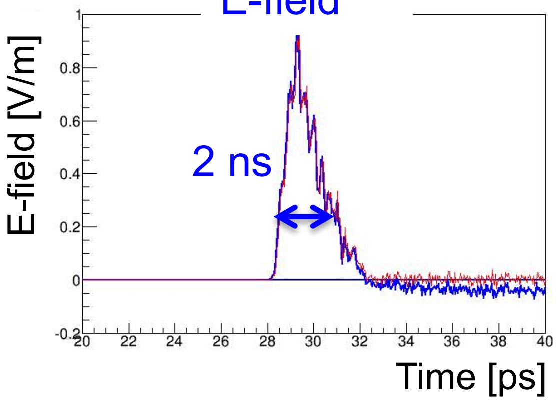


Ice target (30°)

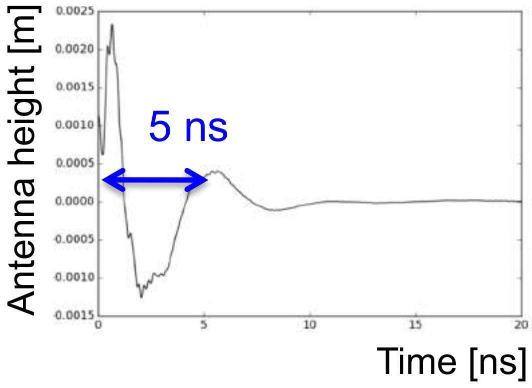
Reasonable agreements without scaling!

R. Gaior, 1135, ICRC2015

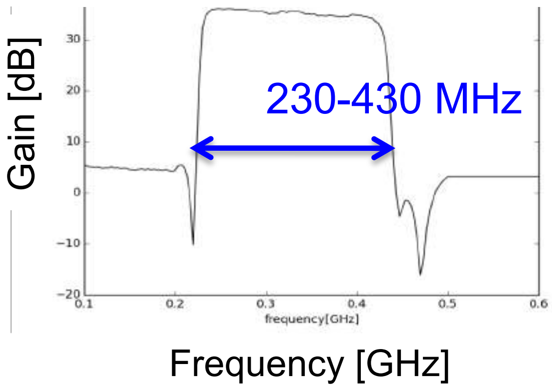
Detector simulation


E-field

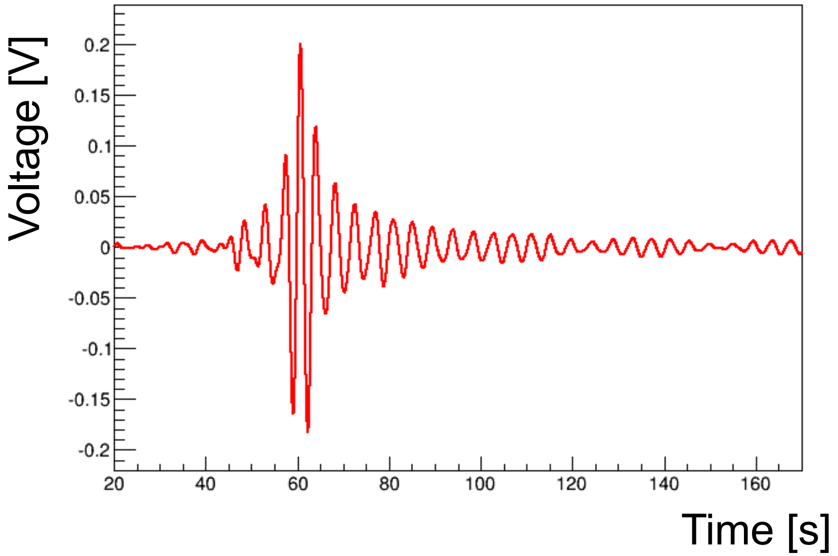
+


Antenna response (T-domain)

+

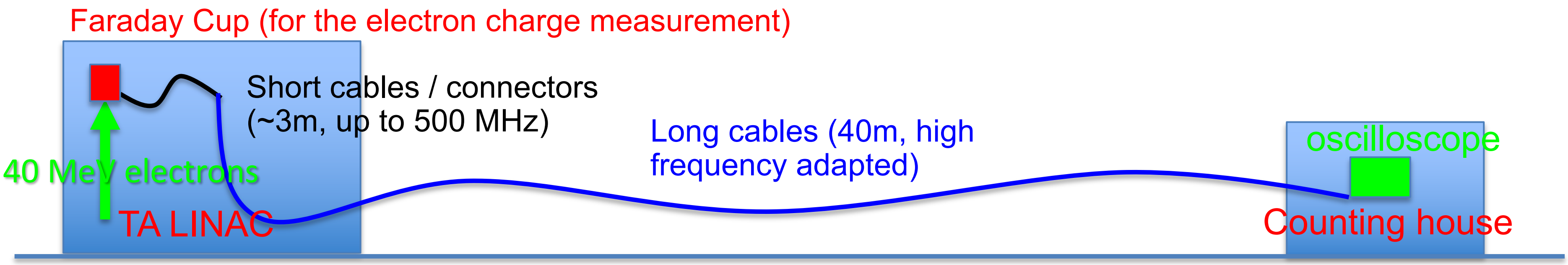

filter + LNA response

=



Verify the understanding the emission mechanisms and detector responses, comparing with data

Cable / connector attenuation correction


Faraday Cup (for the electron charge measurement)

Short cables / connectors
(~3m, up to 500 MHz)

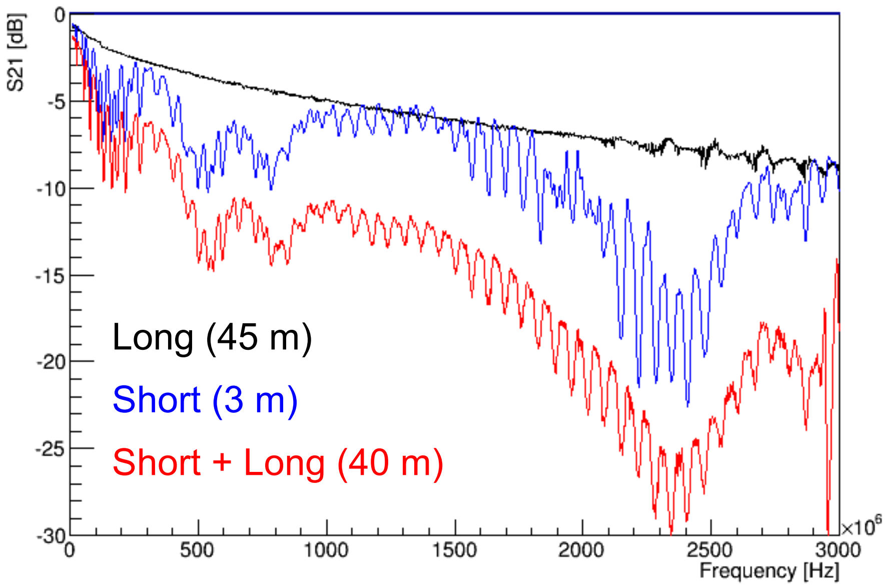
Long cables (40m, high
frequency adapted)

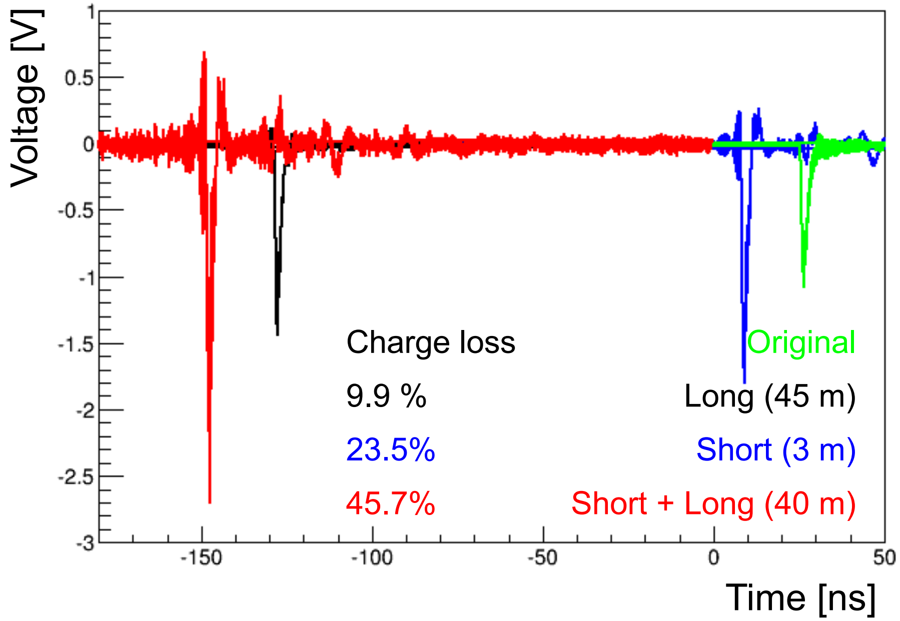
oscilloscope

40 MeV electrons

TA LINAC

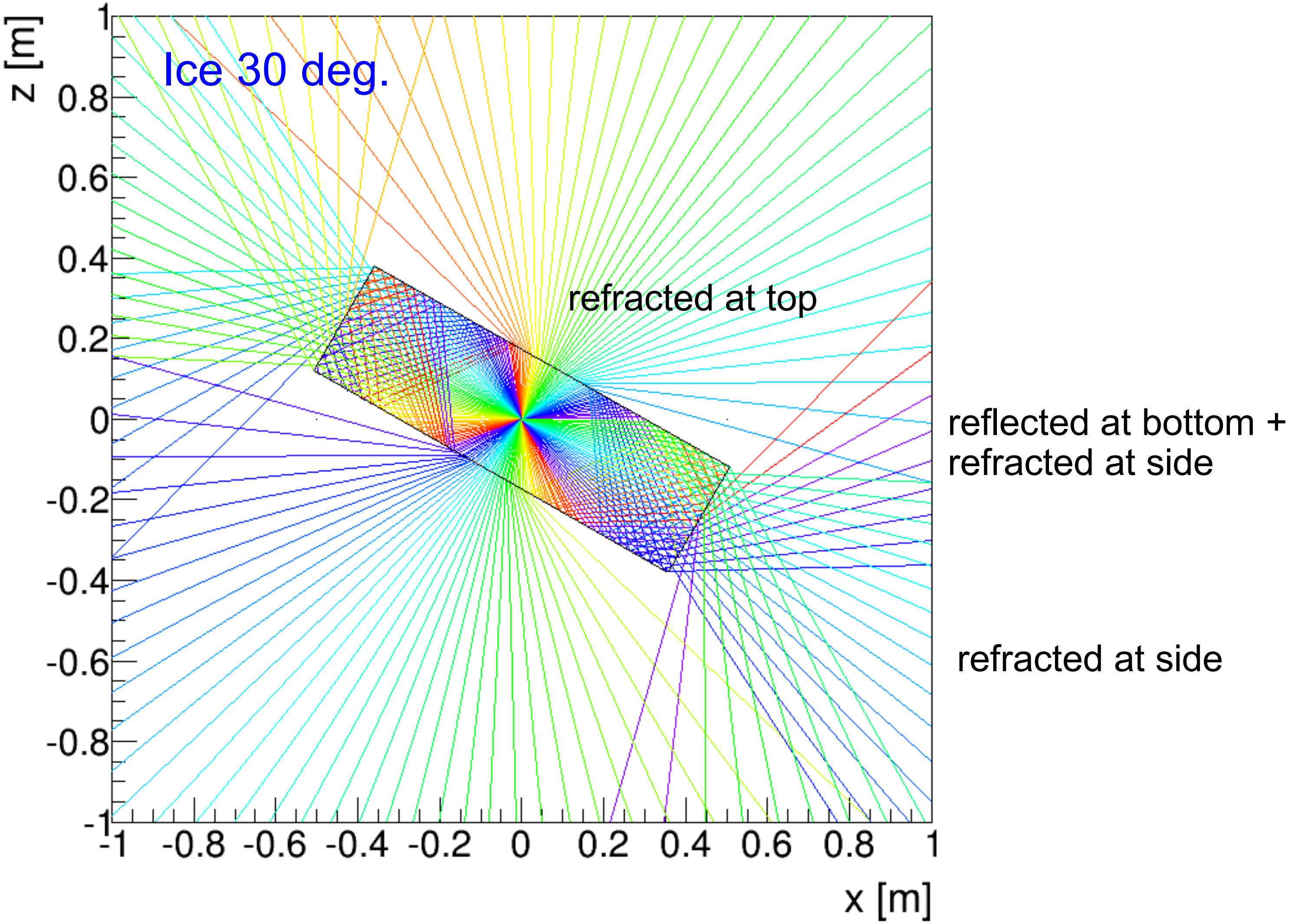
Counting house





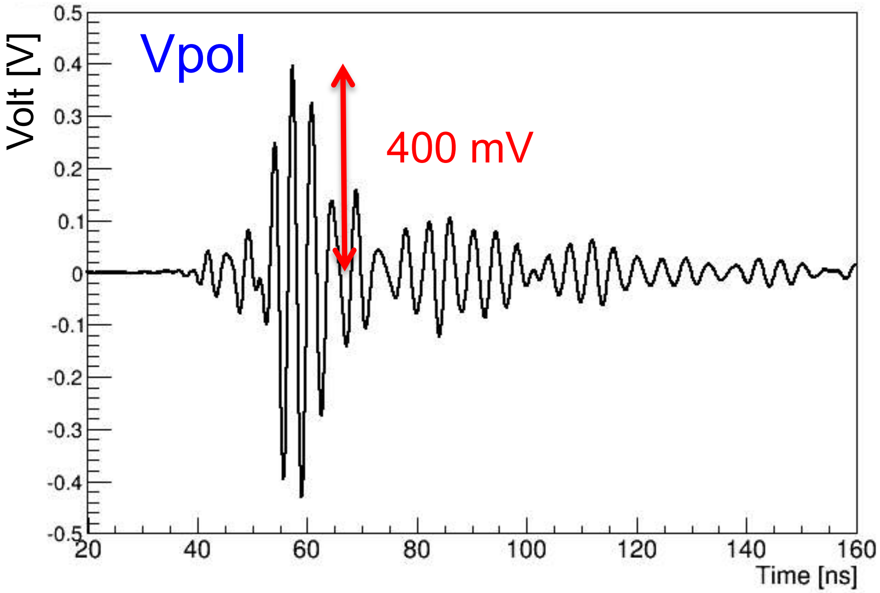
- ✧ Found out the TA short cable attenuate signal significantly
- ✧ The emission power is proportional to the charge square → correction of x2.1 (1.46^2)

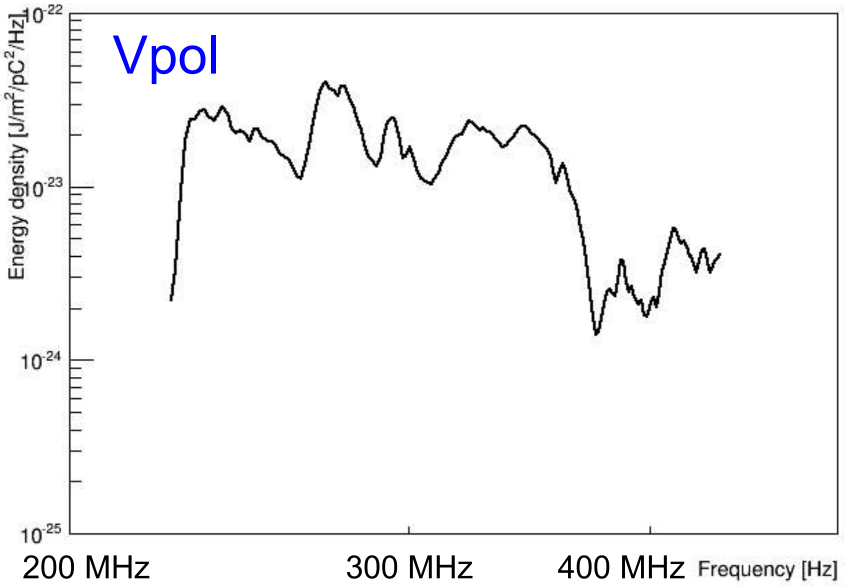
Ray trace for emissions in ice

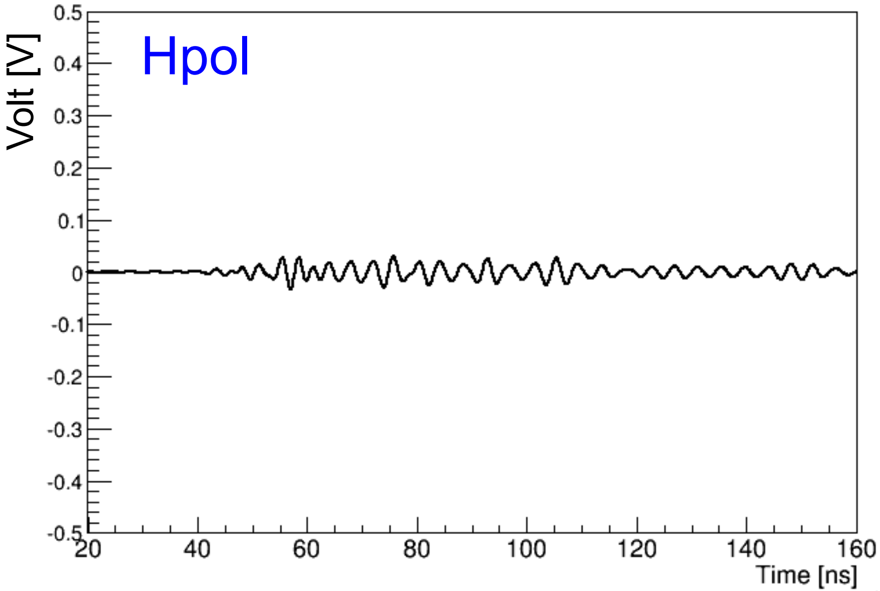


- Complicated...
- Need a full simulation (with lookup tables)

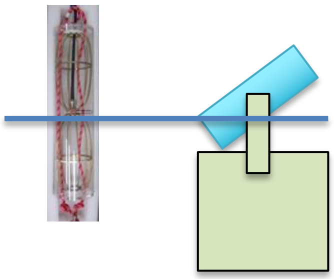
Measured waveform and the frequency spectrum







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

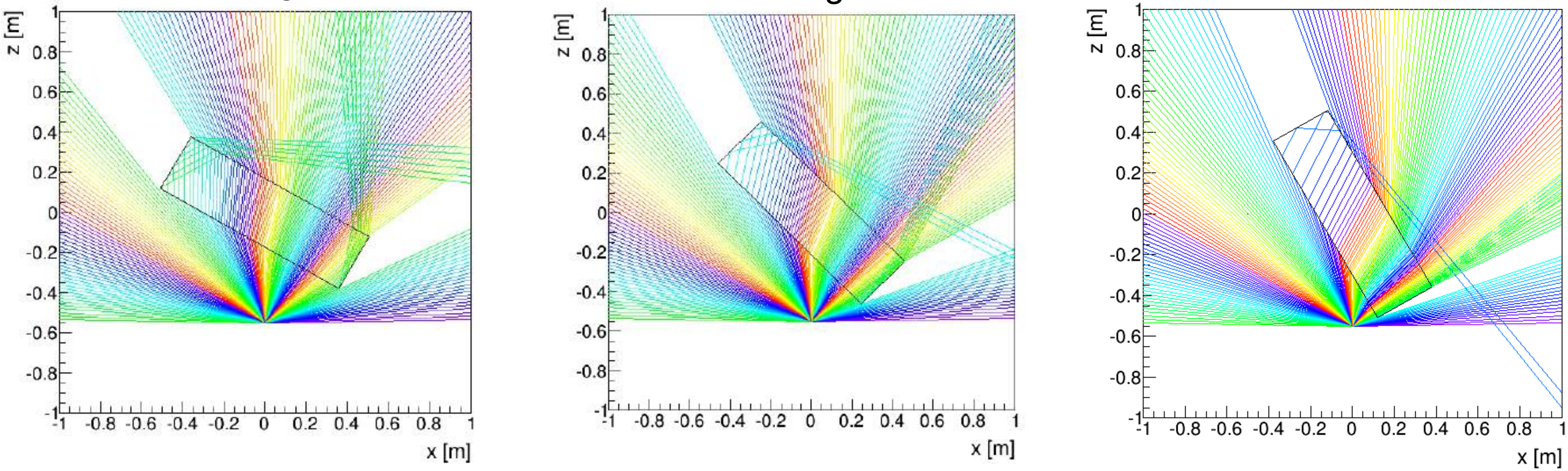


- ✓ Relatively large signal observed
- ✓ Less Hpol signal → high polarization
- ✓ Relatively flat frequency spectrum

→ Indicating something else from Askaryan radiation

Ray traces

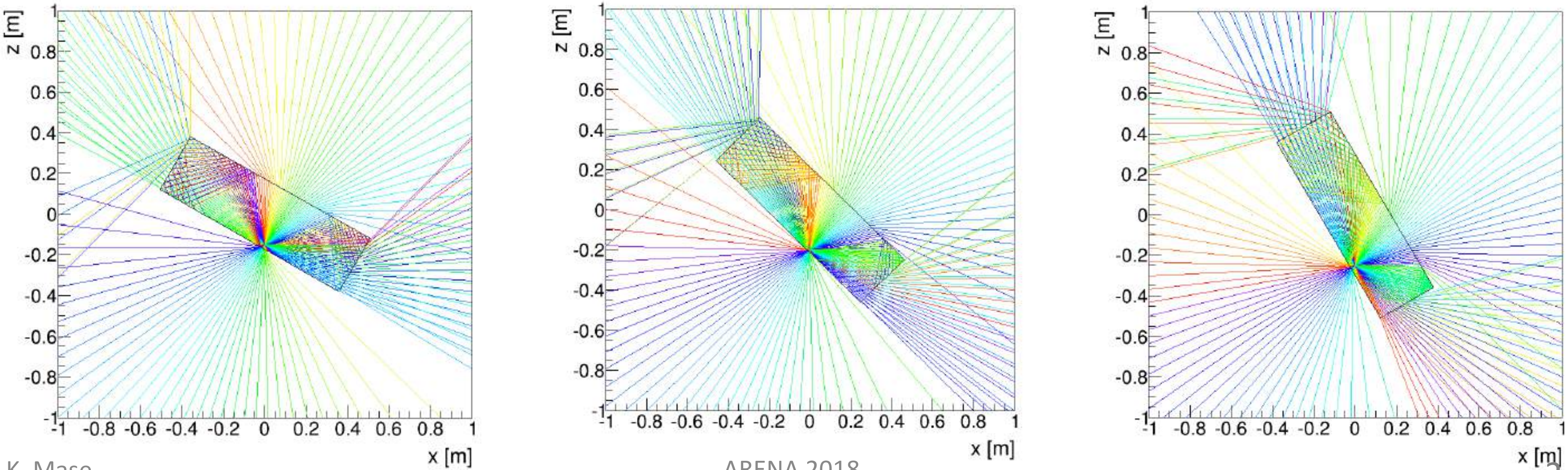
More shadowing effect for 30 deg. and 45 deg.
above observation angle of 30 deg.


30 deg.

45 deg.

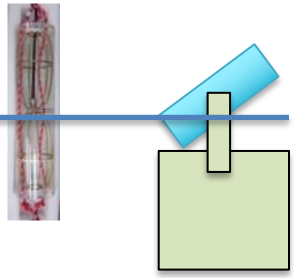
60 deg.

More signals for 30 deg. and 45 deg.

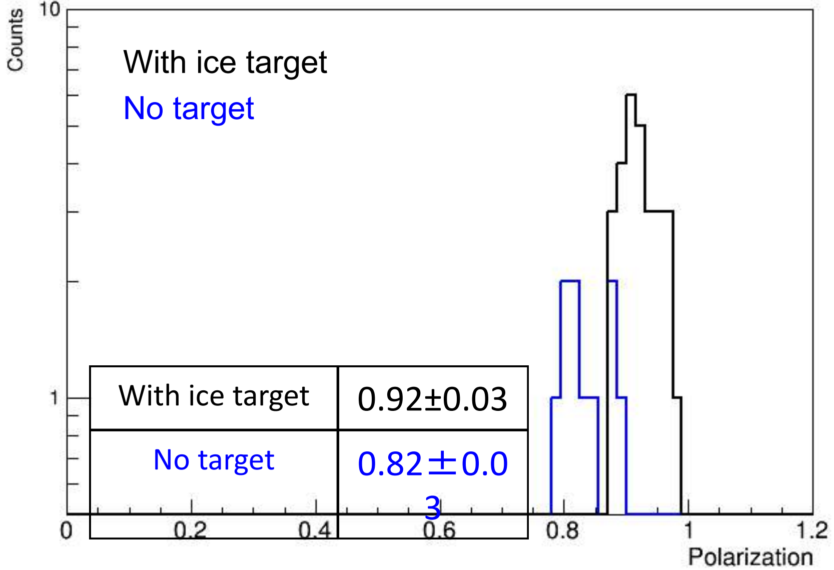


Properties of the signals

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

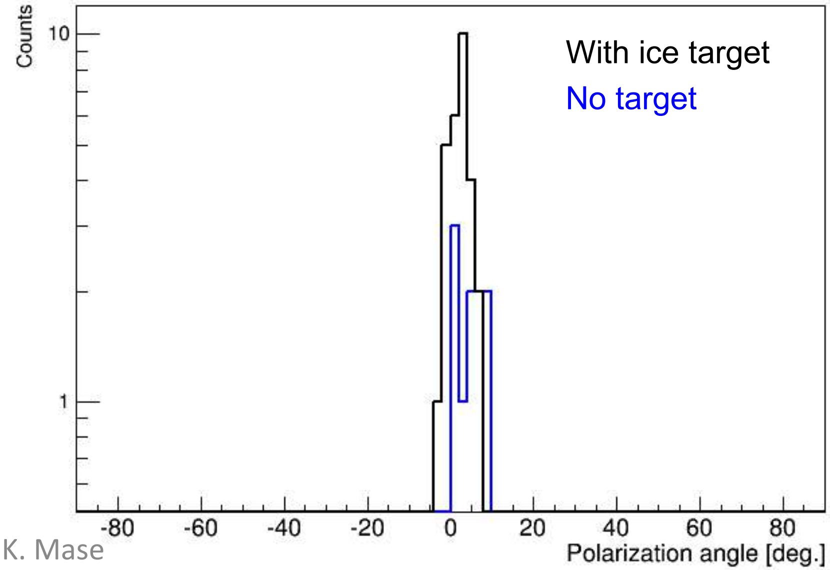


- Polarization

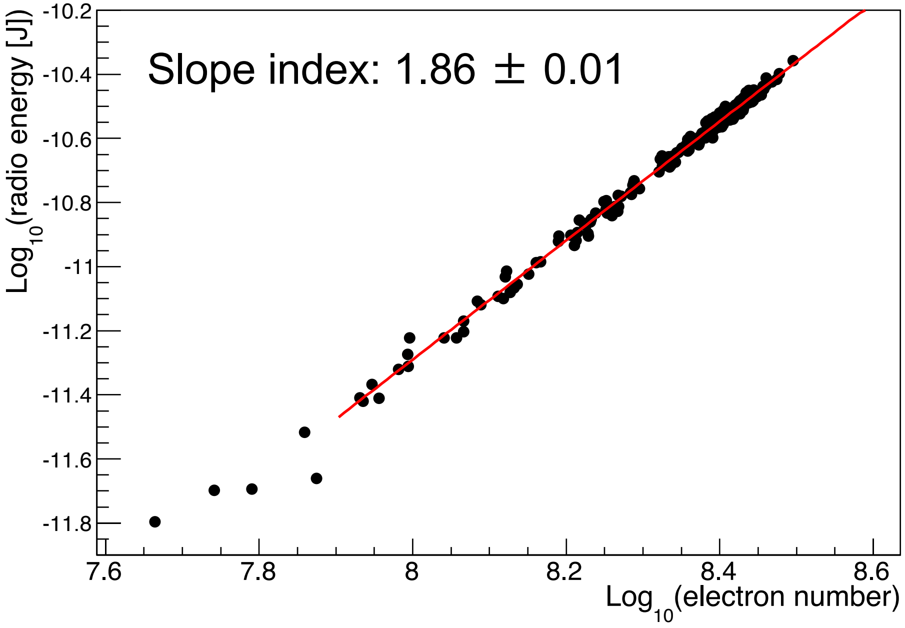


With ice target	0.92±0.03
No target	0.82±0.03

- Polarization angle



- Coherence



✓ All signals shows high vertical polarization

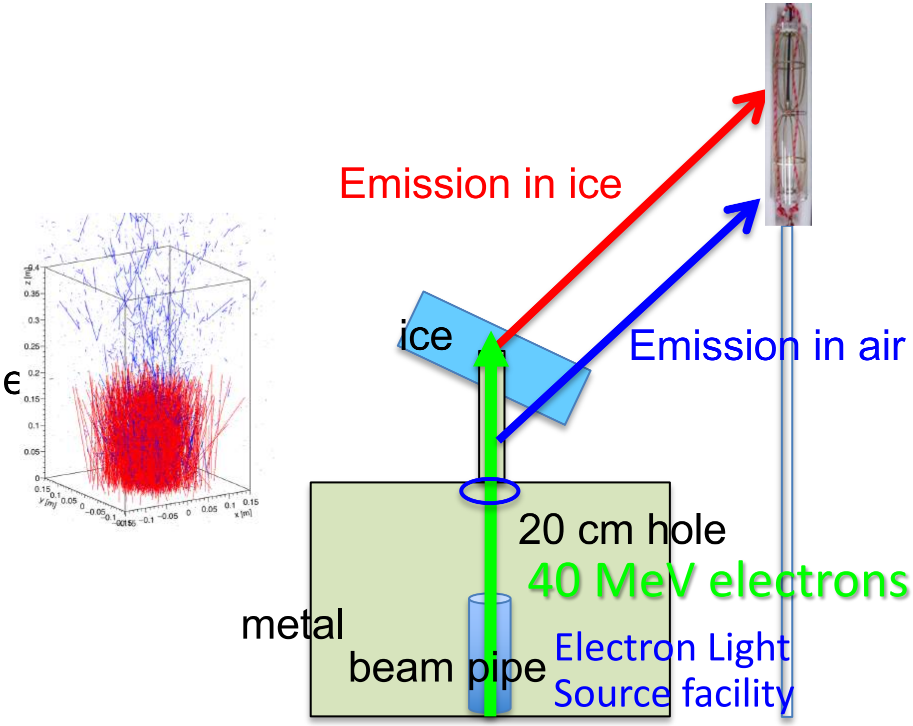
✓ No target data shows slightly less polarization

✓ High coherence, but not full

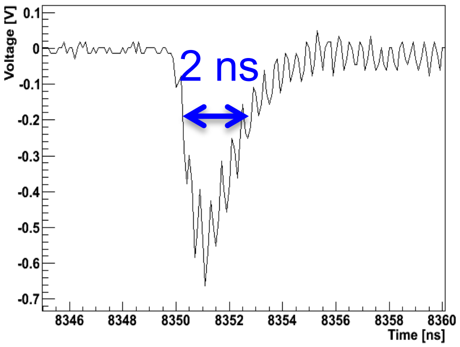
Simulation

- ✓ Electron beams simulated by Geant4
- ✓ Accelerator configurations included
- ✓ E-field calculated by the middle point method (ZHS method, PRD 81, 123009 (2010)) and the endpoints method (PRE84, 056602 (2011))

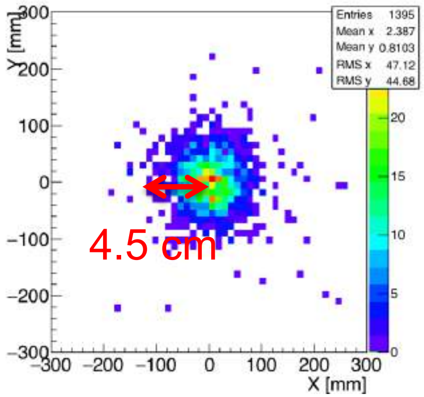
→ Both methods give the same results

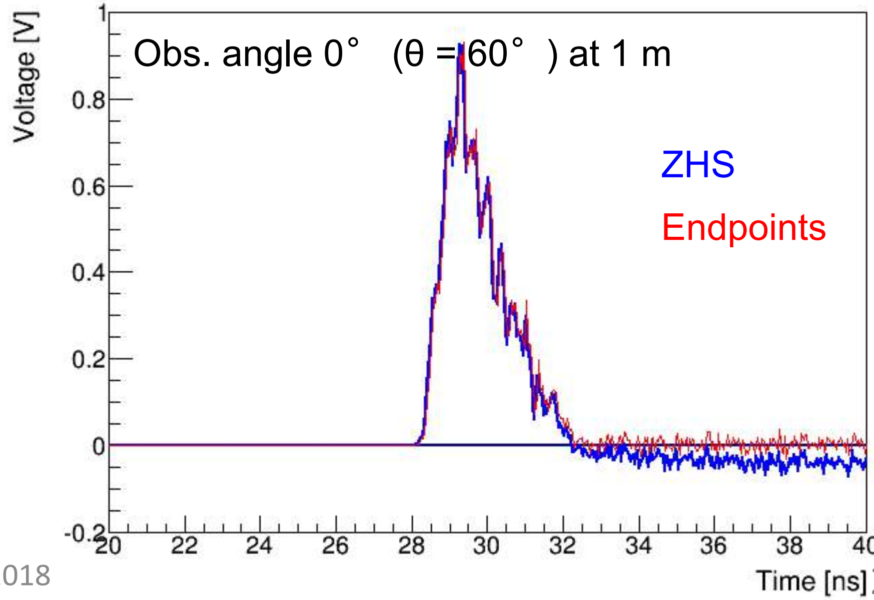


Bunch structure



Lateral distribution



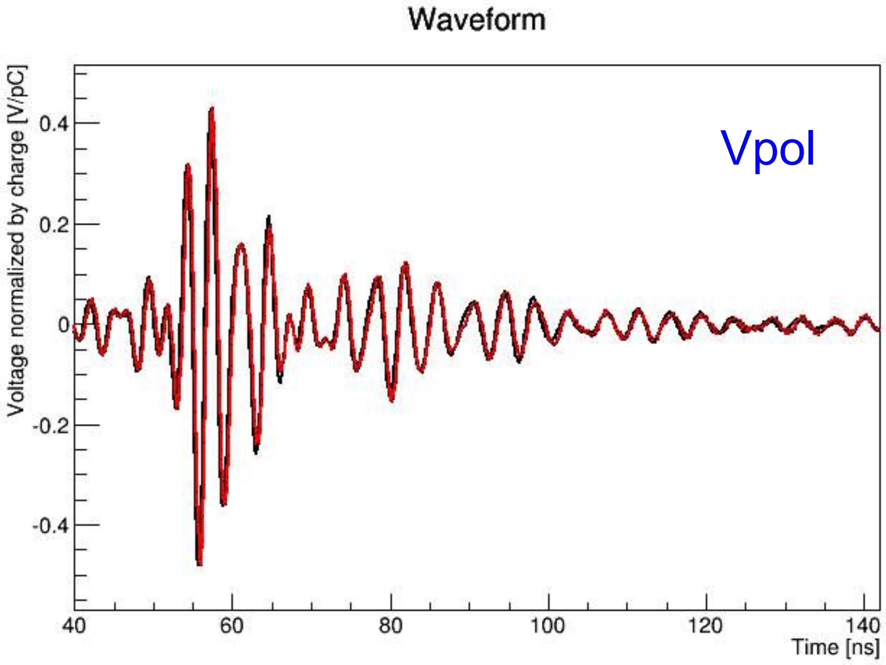


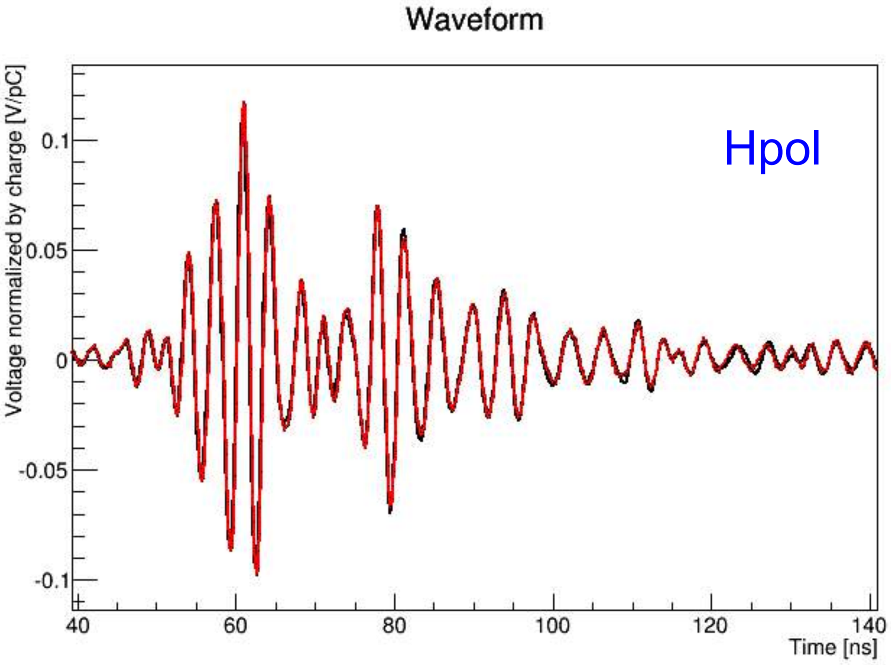
Reproducibility

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)

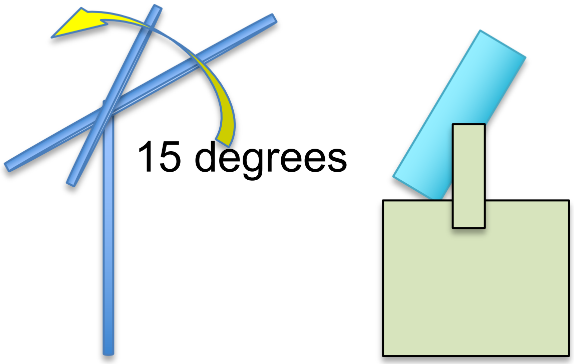


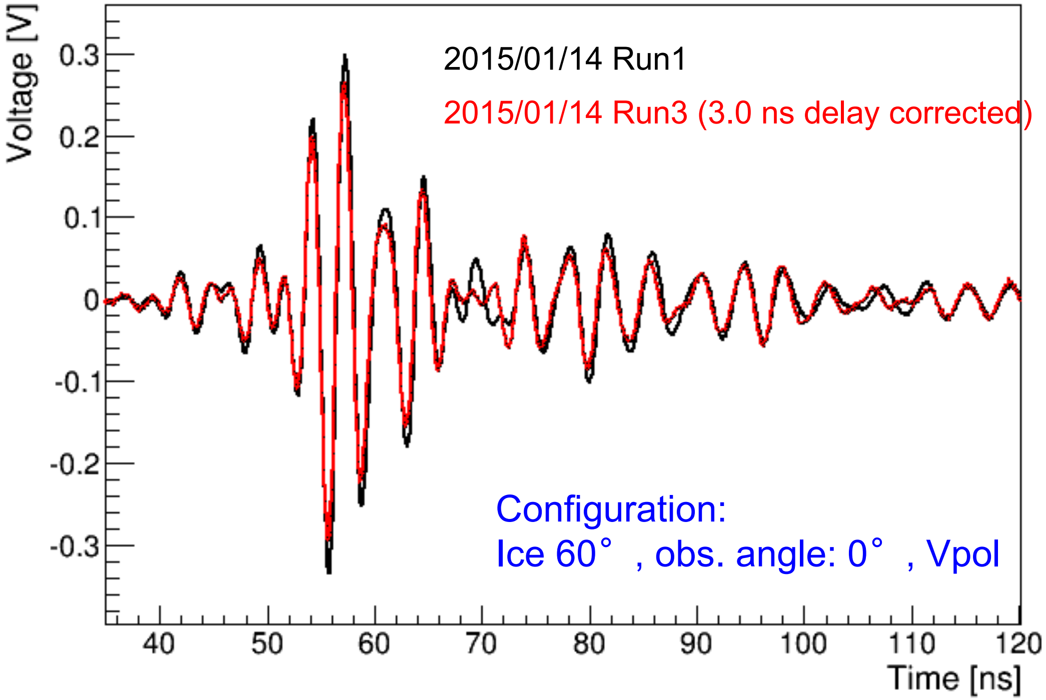


The difference in the amplitude is 5% → 10% in power (Vol)

Stability and far field confirmation

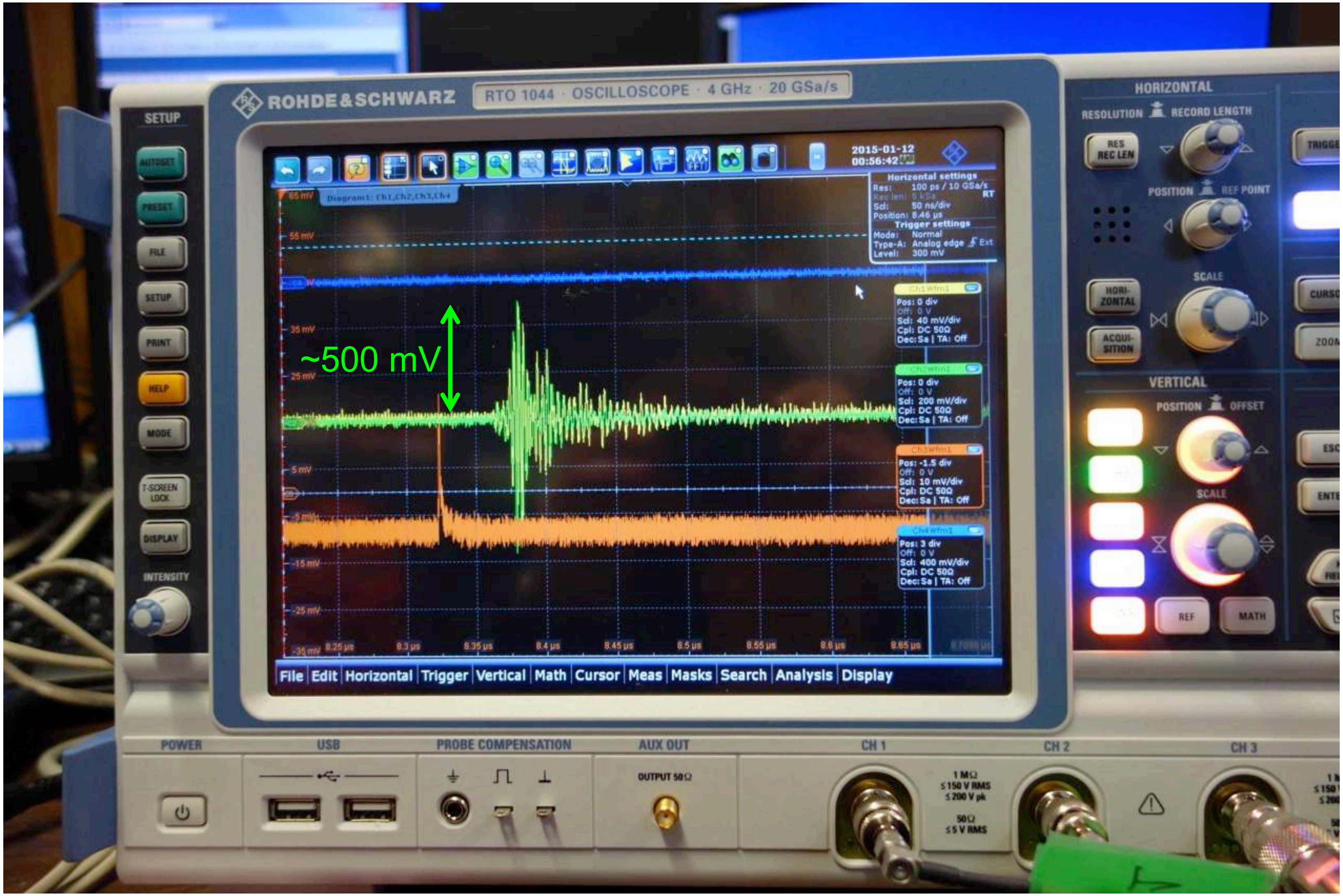
- The stability with the same configuration: 5% in amplitude
- The antenna mast was intentionally rotated by ~15 deg.
- The signal amplitude decreased proportionally with the distance change. → Far field confirmation
  (3.0 ns time delay → 12% distant → 12% amplitude decrease)
- Time difference from the expectation was checked for each configuration.
- The spread is 1.9 ns → 9° rotation → 8% in amplitude
- The overall systematic uncertainty in power: 19%



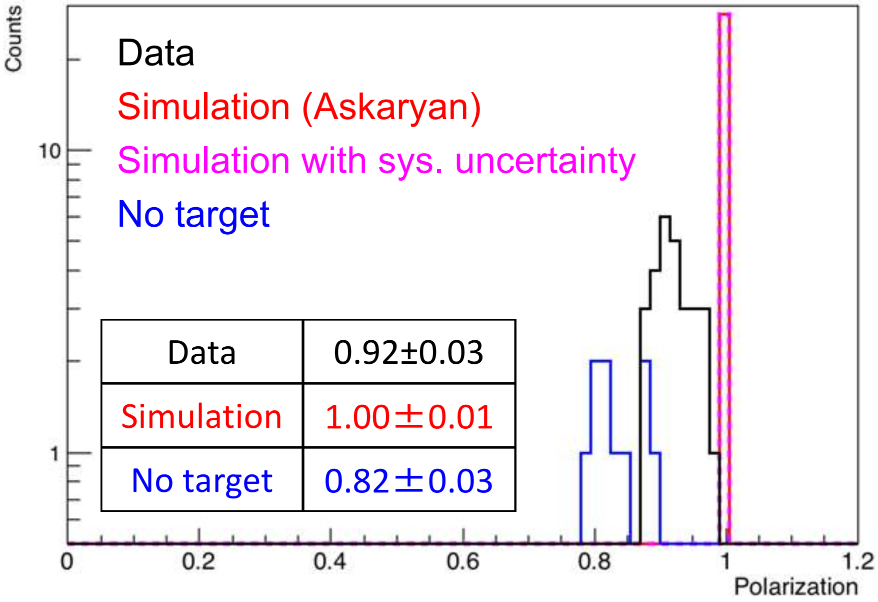


Configuration:
Ice 60°, obs. angle: 0°, Vpol

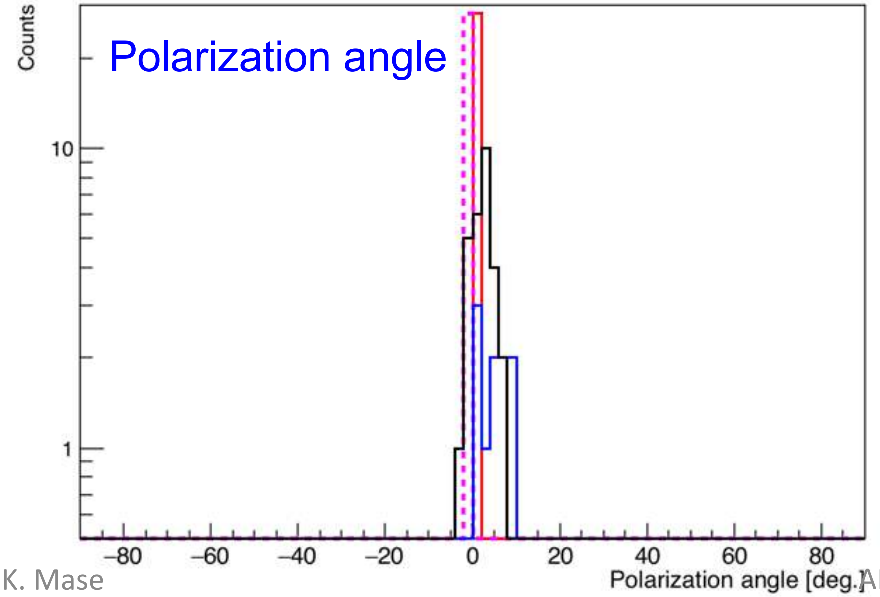
Signals observed!



Polarization

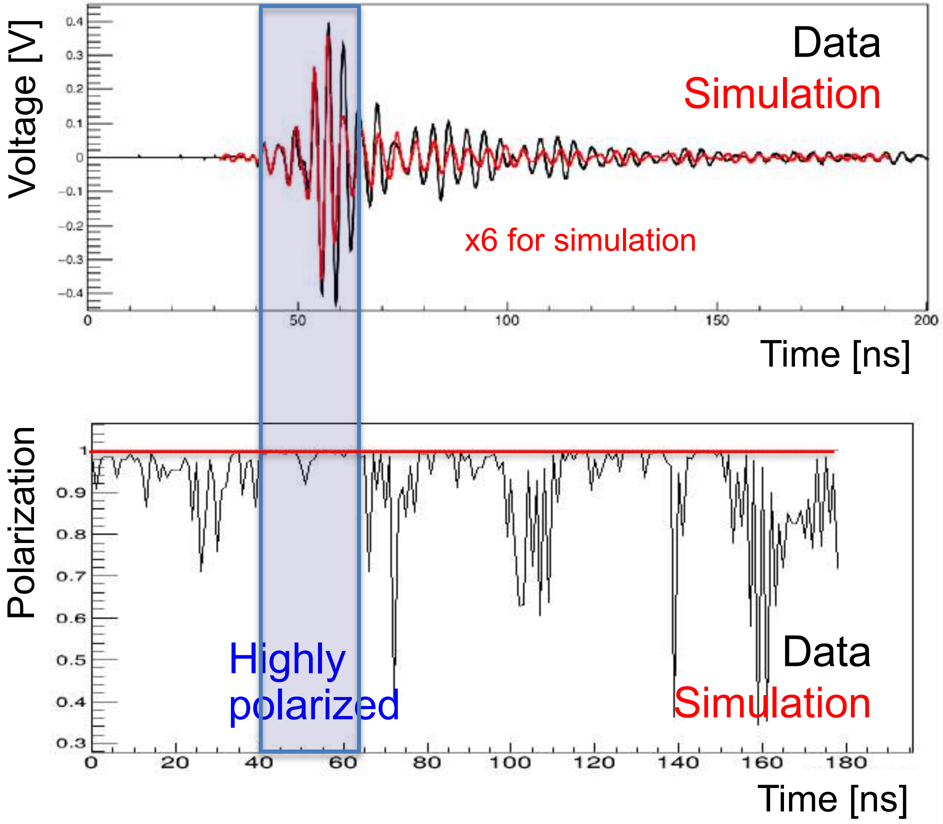


Data	0.92±0.03
Simulation	1.00±0.01
No target	0.82±0.03



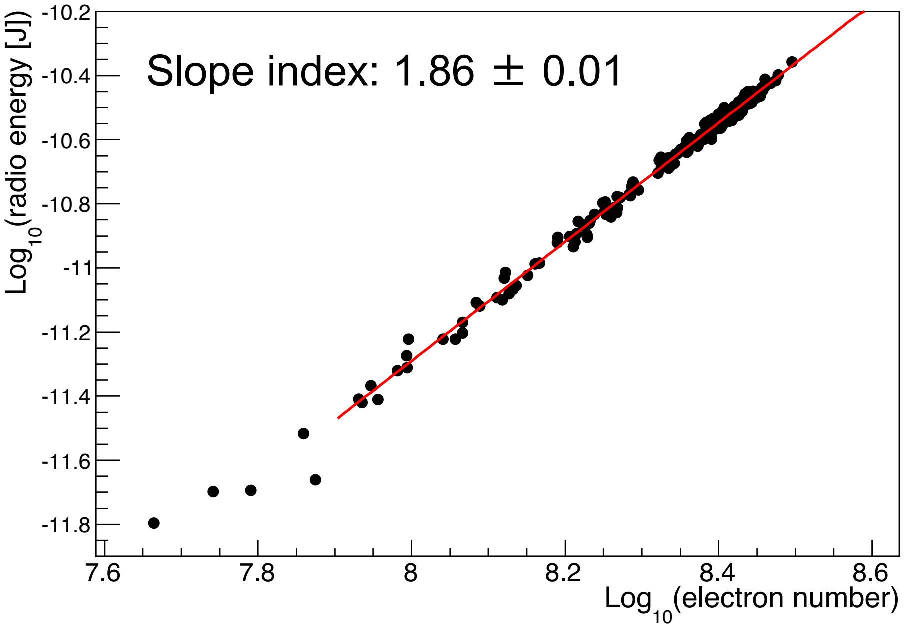
Time development of polarization

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



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

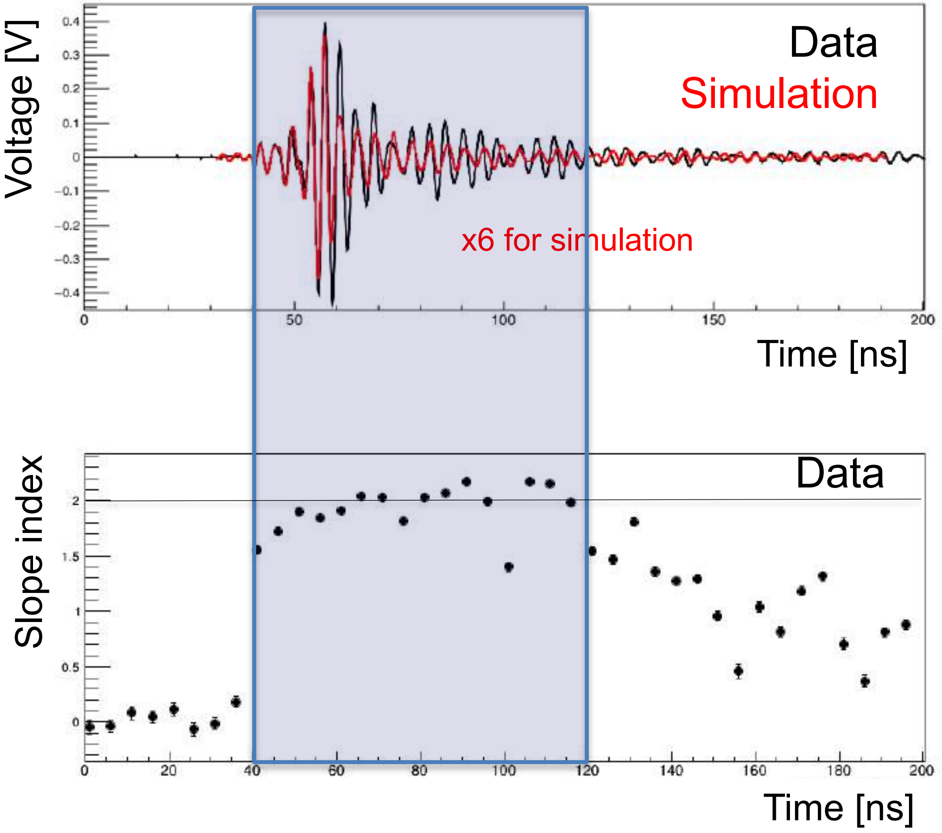
Coherence



High coherence, but not full

Time development of coherence

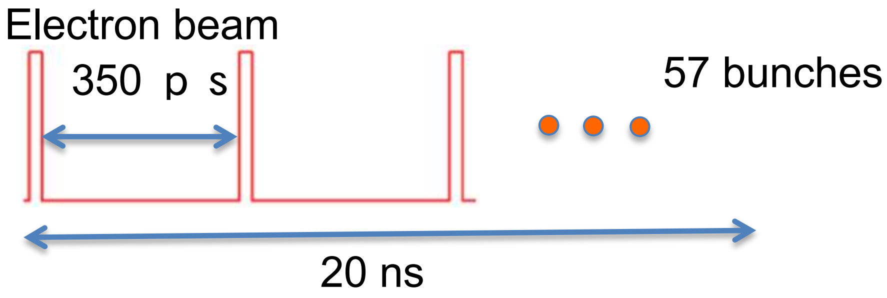
Configuration: Ice 30° , obs. angle 0° , Vpol



High coherence over the main waveform

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



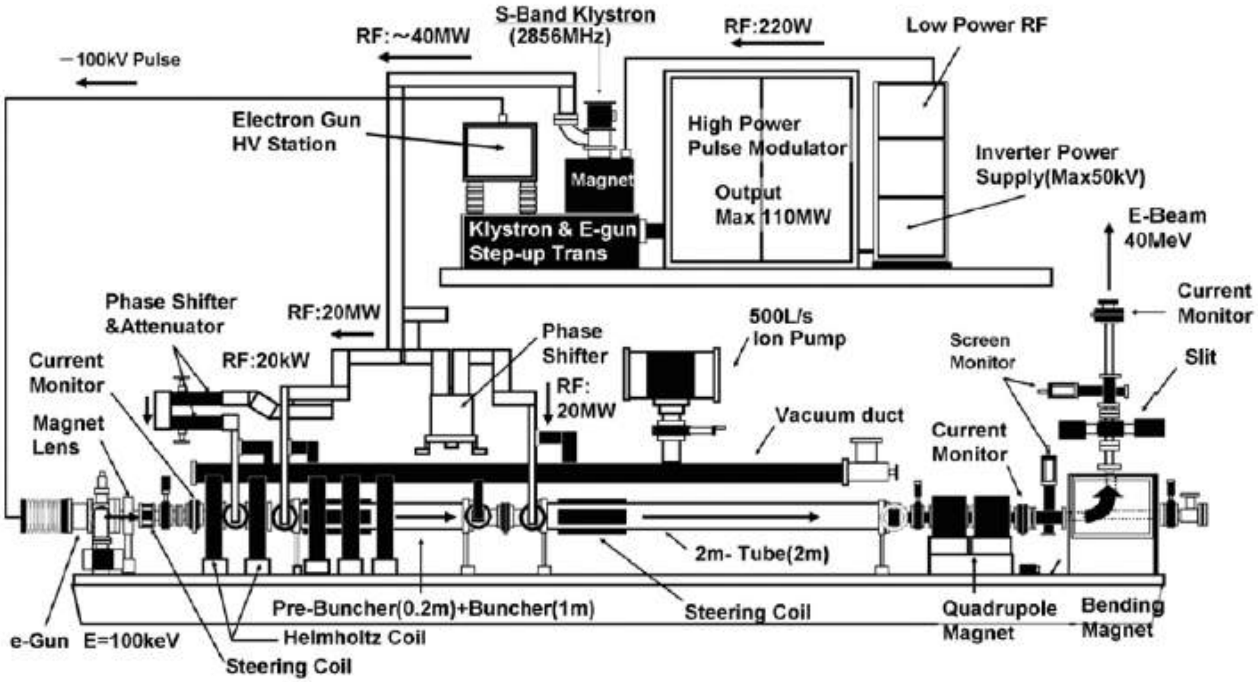
Electron beam

350 p s

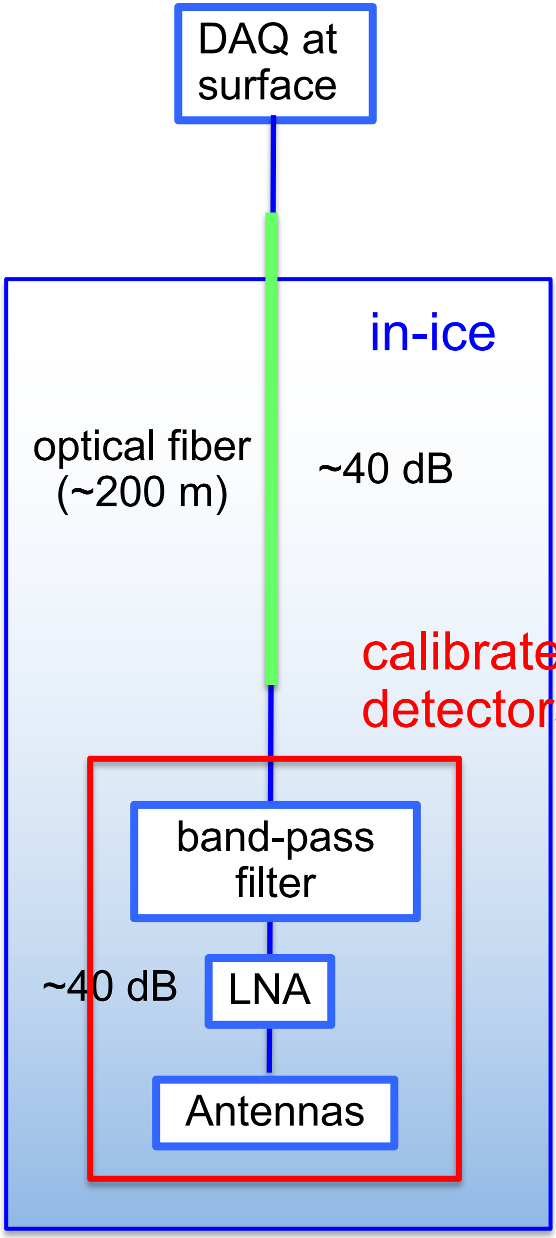
57 bunches

20 ns

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



The ARA system



DAQ at surface

in-ice

optical fiber (~200 m)

~40 dB

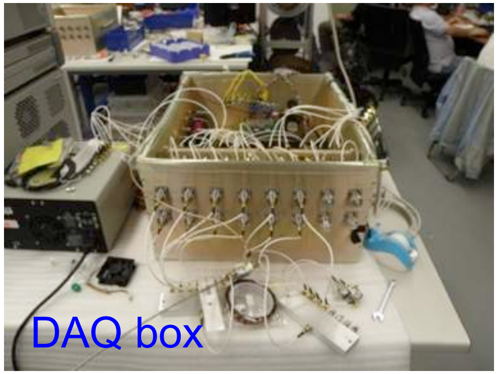
calibrate these detectors

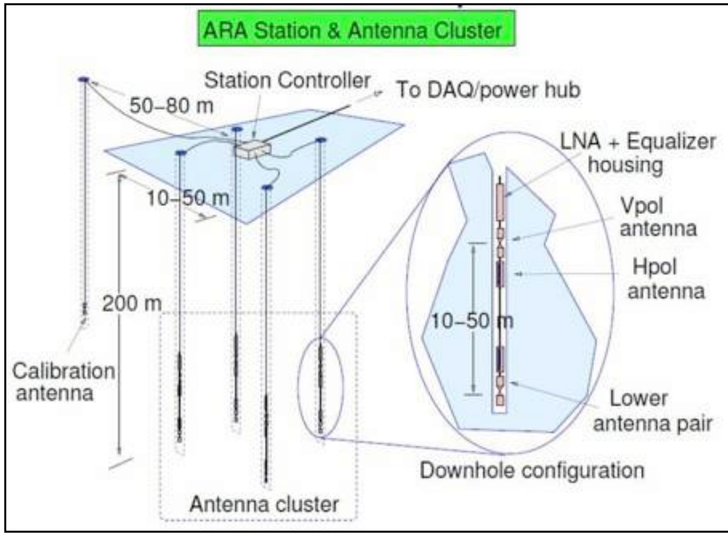
band-pass filter

~40 dB

LNA

Antennas





V-pol antenna

Bicone

150-850 MHz

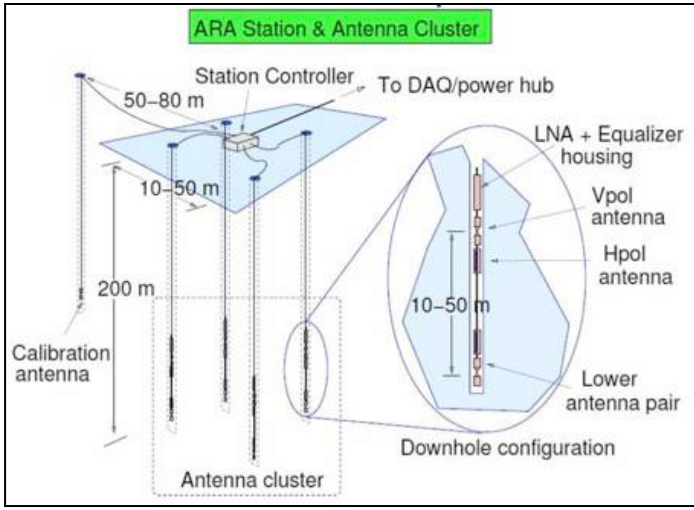
H-pol antenna

Quad-slot cylinder

200-850 MHz

Gain similar to dipole (+2 dBi)

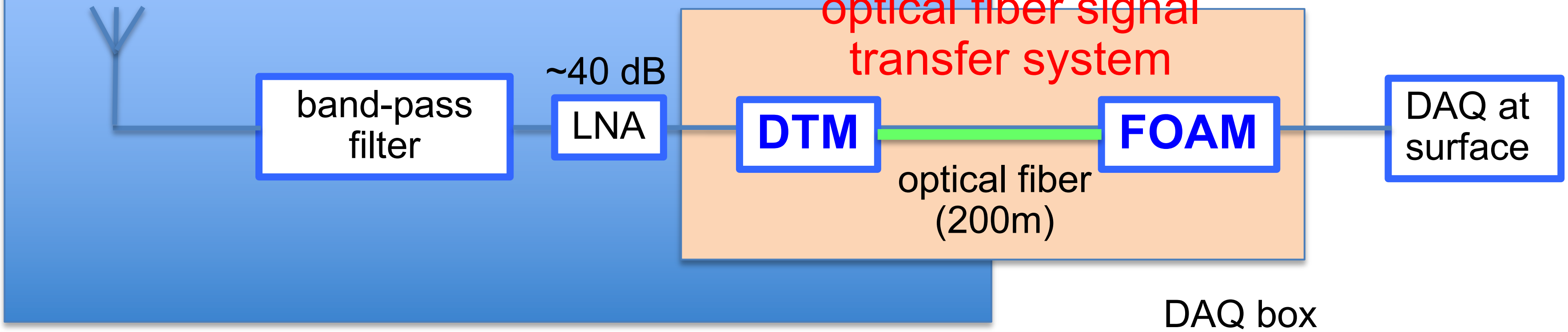
Schematic of the ARA system



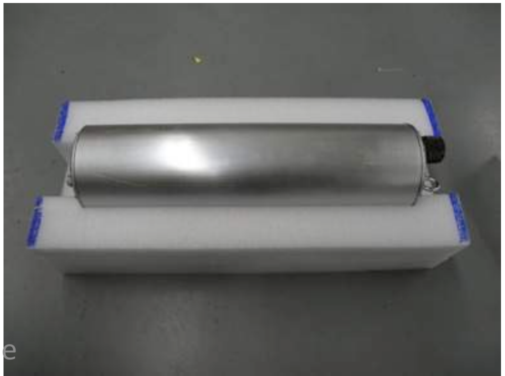
V-pol **H-pol**

in-ice

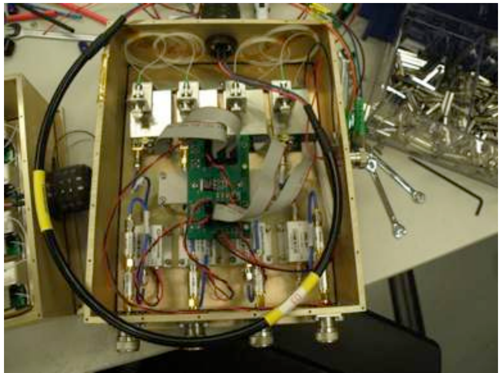
Antenna



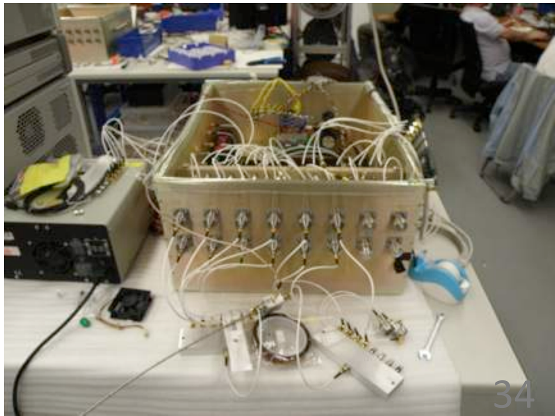
DTM



FOAM



DAQ box

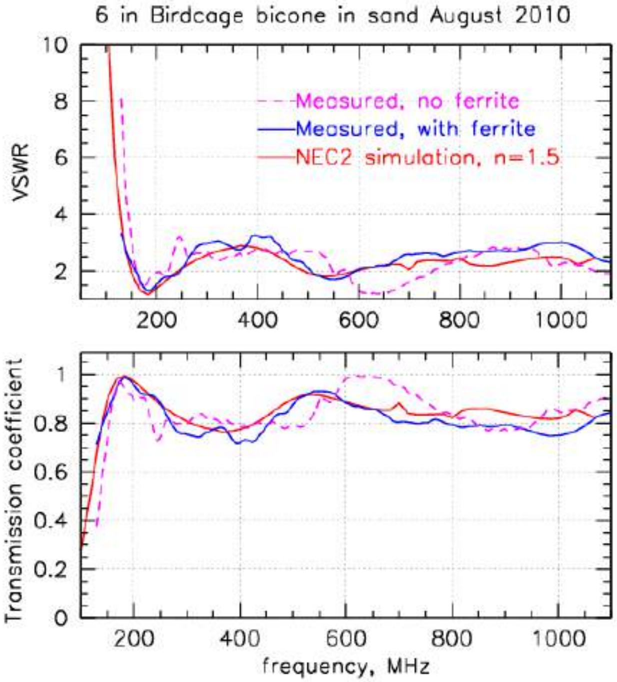


Antennas

V-pol antenna

Bicone

150-850 MHz

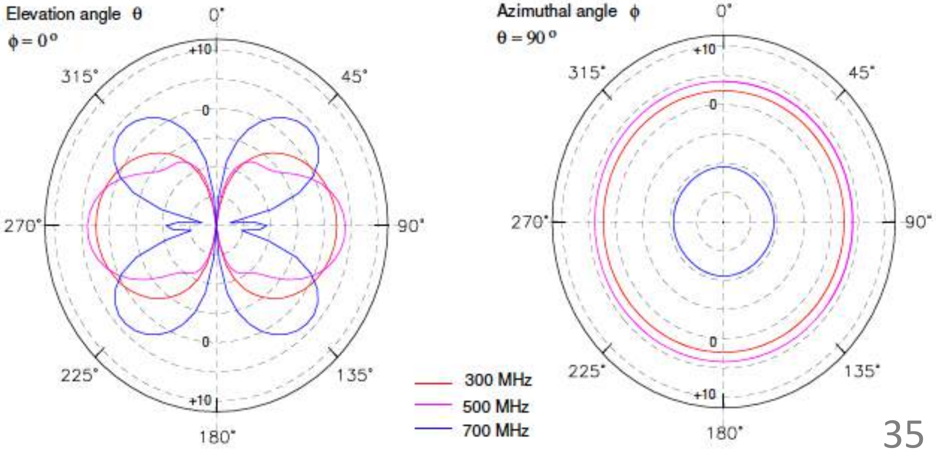


H-pol antenna

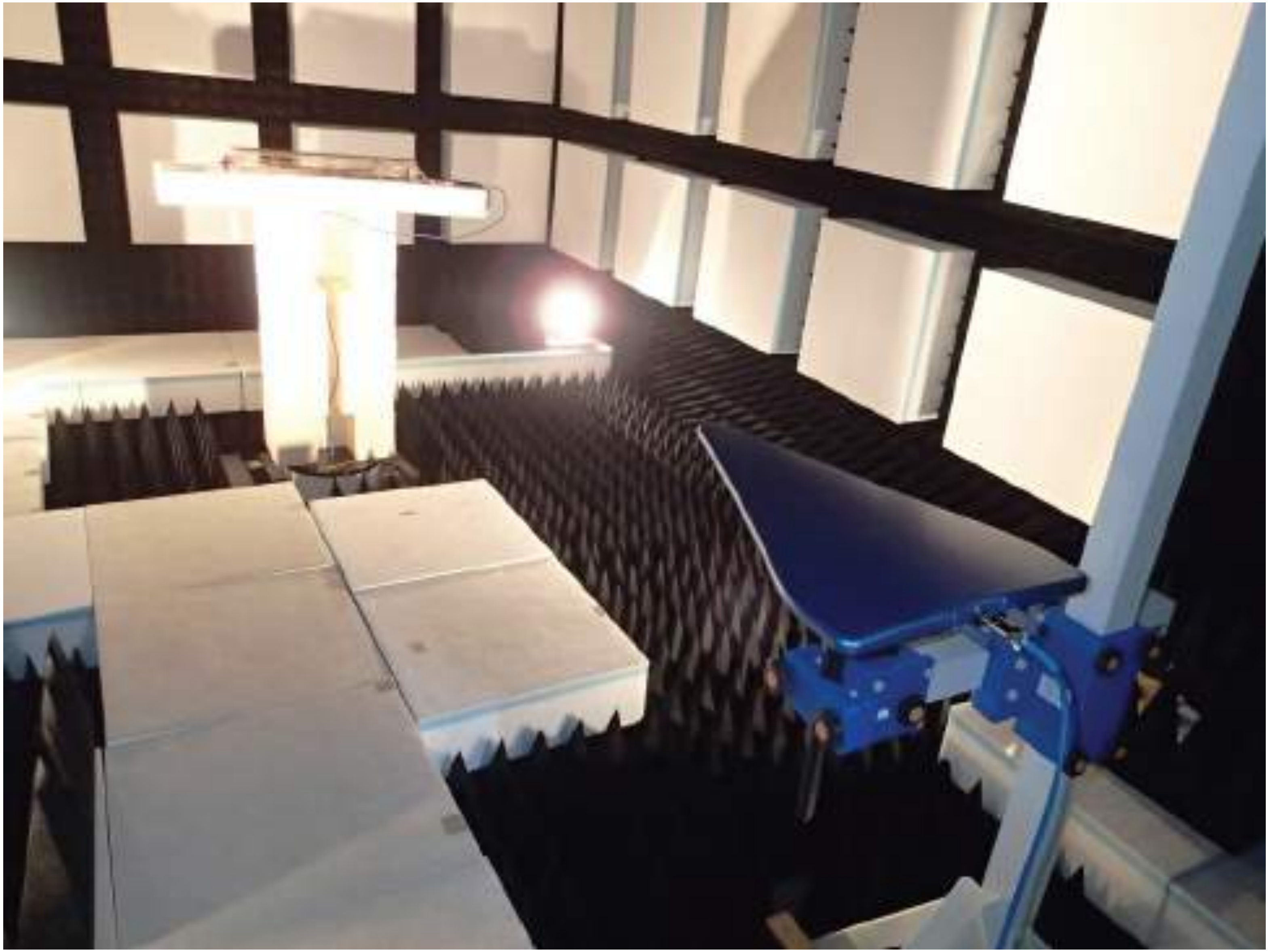
Quad-slot cylinder

200-850 MHz

Gain similar to dipole (+2 dBi)

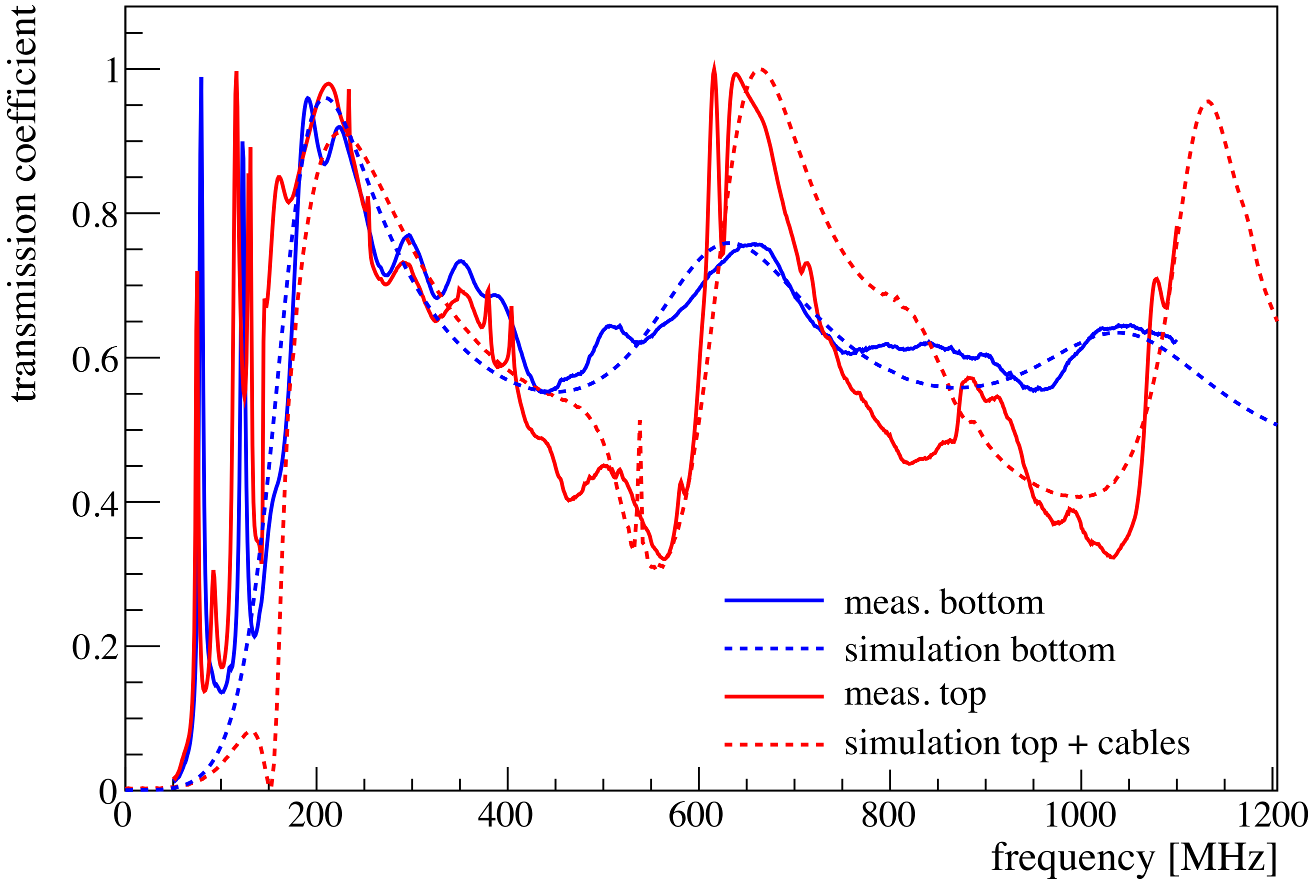


Antenna calibration



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