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

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

ARA Vpol antenna
150-850 MHz

Vpol antenna
Hpol antenna
LNA + filter (230-430 MHz)
Ice target
Antenna tower
Extendable: 2-12m

40 MeV electron beam line

TA LINAC

ARA Vpol antenna
40 MeV electron bunch train

~2ns

Ice block
electron excess

coherent radio wave from electron shower

40 m cables
Trigger + beam probe

Oscilloscope Rohde Schwarz
10GS/s

K. Mase
TA LINAC

- 40 MeV electron beam
- Typical electron number per bunch train: $2 \times 10^8 \rightarrow 30$ 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%)

Measurements show:

- 2 ns
- ~10 bunches

Correlation → Electron number monitoring

2 $\times 10^8$ electrons → Enough signal strength

Cover wide range → Coherence
Ice target and the configurations

- 100 x 30 x 30 cm³
- 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

Thermometer

Dry ice (on side)

Ice target

1 m

40 MeV electron beam line

Cherenkov angle in ice (56°)

antenna height [m]

Index of Tower Height

- 17 m
- 14 m
- 10 m

Antenna

Angle Relative to Beam (deg.)

Ice inclination angle (α)

Observation angle

Emission angle

α = 60°

α = 30°
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)

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

\[
E = -\nabla \phi - \frac{\partial A}{\partial t}
\]
Simulation

Electron beam (Geant4)
Including accelerator configurations

E-field calculation

Ray trace

tables made

E-field

Detector response

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

**Middle point**

**Endpoints**
Sudden beam appearance signal

1. AirRadar

2. ARAcalTA

3. IceRadar

4. Konan

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

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

<table>
<thead>
<tr>
<th>Item</th>
<th>Data</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical error</td>
<td>±8%</td>
<td>±10%</td>
</tr>
<tr>
<td>Stability</td>
<td>±19%</td>
<td>-</td>
</tr>
<tr>
<td>Bunch width</td>
<td>-</td>
<td>-14% +17%</td>
</tr>
<tr>
<td>Sum</td>
<td>±21%</td>
<td>-17% + 20%</td>
</tr>
</tbody>
</table>
Signals with an ice target

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

All signals show relatively high vertical polarization

Reasonable coherence

Similar values for all the configurations

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

Slope index: 1.86 ± 0.01

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

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

Observed radio energy @ 1m [J]

Preliminary

Solid: Data
Dashed: Simulation

θ_c(30° )
θ_c(45° )
θ_c(60° )

Observed observation elevation angle [deg.]
Each component

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

- Small $\lambda$ add destructively
- Large $\lambda$ add coherently
- Shower size $\ll \lambda$ to be coherent
- Dense material better

Cerenkov emission (Frank-Tumm result)

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

in case $N$ electrons,

- $z=1$ (not coherent) → $W \propto N$
- $z=N$ (coherent) → $W \propto N^2$

Power $\propto \Delta q^2 \propto E^2$, thus prominent at ultra-high energy ($>\sim 100$ 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**
- Obs. angle 0°
- Data
- Simulation

**Ice target (30°)**
- Obs. angle 0°
- Data
- Simulation

Reasonable agreements without scaling!
Detector simulation

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)

TA LINAC

Counting house

Found out the TA short cable attenuate signal significantly

The emission power is proportional to the charge square → correction of \(x^{2.1} (1.46^2)\)
Ray trace for emissions in ice

- Refracted at top
- Refracted at side
- Refracted at side
- Reflected at bottom + refracted at side

Ice 30 deg.

- Complicated...
- Need a full simulation (with lookup tables)
- Relatively large signal observed
- Less Hpol signal → high polarization
- Relatively flat frequency spectrum → Indicating something else from Askaryan radiation

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

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

**Measured waveform and the frequency spectrum**
Ray traces

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

More signals for 30 deg. and 45 deg.
Properties of the signals

- **Polarization**
  - With ice target: $0.92 \pm 0.03$
  - No target: $0.82 \pm 0.0$

- **Polarization angle**

- **Coherence**
  - Slope index: $1.86 \pm 0.01$

- All signals show high vertical polarization
- No target data shows slightly less polarization
- High coherence, but not full

Configuration:
Ice angle $30^\circ$, obs. angle: $0^\circ$
**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**
- 2 ns

**Lateral distribution**
- 4.5 cm

**Obs. angle 0° (θ = 60°) at 1 m**

**Emission in ice**

**Emission in air**

**Beam pipe**
- 20 cm hole
- 40 MeV electrons

**Electron Light Source facility**
- Metal
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%
Signals observed!

~500 mV
**Polarization**

Data Simulation (Askaryan)
Simulation with sys. uncertainty
No target

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

All signals show high vertical polarization
Data is off from simulation

Configuration: Ice 30°, obs. angle 0°, \( V_{pol} \)}
Coherence

Slope index: $1.86 \pm 0.01$

High coherence, but not full

High coherence over the main waveform

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

Data

Simulation

x6 for simulation
- 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
The ARA system

- DAQ at surface
- in-ice
- optical fiber (~200 m)
- ~40 dB
- DAQ box

- LNA
- band-pass filter
- ~40 dB
- 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

Antenna

V-pol

H-pol

band-pass filter

~40 dB

LNA

in-ice

optical fiber signal transfer system

DTM

FOAM

optical fiber (200m)

DAQ at surface

DAQ box

K. Mase
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