5D Picosecond Timing Layers for Future Calorimeters

Updates from the Askaryan Calorimeter Experiment (ACE)

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INTRODUCTION
As part of the Askaryan Calorimeter Experiment (ACE), we have developed and beam-tested a new 5D calorimeter technology utilizing coherent microwave Cherenkov emission generated via the Askaryan effect that could provide:

1. Picosecond to sub-picosecond timing of high-energy showers.
2. Sub-millimeter to millimeter spatial resolution in all three coordinates.
3. Calorimetric energy measurement.

while simultaneously being mostly commercial-off-the-shelf (COTS), relatively low-cost, and extremely rad-hard, capable of withstanding FCC radiation fluences in the forward region. In this presentation, we show:

1. Brief review of the results of the T-530 beam tests at SLAC.
2. New simulations on deploying ACE layers at FCC and EIC relevant energies.
ASKARYAN EFFECT
In dense media, EM showers develop a 10-20% compact negative charge excess on the shower front ($e^-$ preferentially upscattered into shower, $e^+$ annihilated). Typically mm-thick.

At wavelengths larger than the size of the charge excess, the Cherenkov from individual particles cannot be resolved and is observed as a single charge with $Q \sim N_{\text{excess}}e \sim 0.2N_{\text{shower}}e$.

The emission from all the particles in the shower is adding constructively; for typical media, this coherence extends up to >10 GHz.

This is coherent microwave Cherenkov!
Experimental Validation of the Askaryan Effect

First theorized by G. Askaryan in 1962, and first detected in 2001 by Gorham & Saltzberg [1], Askaryan radiation since been directly measured in ice [2], salt [3], air [4], and alumina [5] up to $E \sim 3 \times 10^{19} \text{ eV}$ with both $e^-$ and $\gamma$ using SLAC’s ESA (T460, T464, T486, T530).
Askaryan emission is the primary method for detecting UHE neutrinos ($E_\nu > 10^{18}$ eV) via radio-Cherenkov (Askaryan) from neutrino-induced showers in the Antarctic ice with ARA [6], ARIANNA [7], and ANITA [8].

This allows these neutrino experiments to instrument up to $\sim 3\text{M km}^3$. 
T-530: Askaryan Calorimeter Experiment
Askaryan Cherenkov Elements

- We use standard WR51 (12.6mm x 6.3mm) copper waveguides loaded with alumina bars (Al₂O₃).
- Askaryan (microwave Cherenkov) from a shower moving through the waveguide is coupled into the TE₁₀ mode (5-8 GHz) and propagates to each end.
- We amplify the ns-scale pulse with low-noise amplifiers (LNAs) and sample with high-bandwidth digitizers.
- The measured waveform is a direct measurement of the shower energy via the coupled Askaryan emission and provides a precise time of arrival!
- **Figure:** Three ACEv3 elements in their test frame along with three COTS LNAs.
Alumina is a perfect material for this application:

- Extremely low loss dielectric ($\tan \delta \lesssim 3 \times 10^{-5}$ for commercial products).
- High microwave refractive index; $n \sim 3.15$ => low threshold for Cherenkov production.
- Extremely rad-hard - has been tested up to $\sim 10^{25} \text{n}_{\text{eq}}/\text{cm}^2$ and $>10^7 \text{Gy/s}$ (for potential use in fusion reactors [9] - no permanent change in dielectric properties after irradiation under FCC-hh forward calorimeter conditions.
- Annual production $> 120$ M tonnes with a diverse array of commercial uses - supply will not be an issue and keeps costs low.
- Very low thermal emissivity ($\epsilon \sim 0.02$) so not a significant contributor to thermal noise.

Only (available) material better than alumina is sapphire (which has cost and production complications).
To validate this concept, we have performed three extensive beam-tests at SLAC’s ESTBA as part of the T-530 experiment:

  - First generation waveguide designed (COTS) w/ LN$_2$ cooling.
  - $\sim 20$ K noise-figure (NF) cryo-LNAs and standard RF oscilloscopes.
  - First measurement of Askaryan effect in bounded dielectrics w/ detailed studies using a commercial calorimeter.
  - Achieved $\sim 3$ ps timing resolution.
- **ACEv2 (2016)**
  - Second generation waveguide design to explore smaller form factors.
- **ACEv3 (2018)**
  - New third-generation waveguide design w/ timing studies in LHe.
  - $\sim 4$ K NF cryo-LNAs.
  - Experimental focus on lowering energy threshold.
  - Achieved $\lesssim 1.2$ ps timing resolution.
ACE3 Elements outside Dewar
In radio & microwave, thermal noise a major challenge -> all EM modes are “pre-loaded” with thermal photons. ACE elements must be operated in cryo to be most effective.

Due to the low emissivity of alumina, the primary contributor to the system temperature is the first-stage low-noise amplifier (LNA). The best COTS LNAs (today) achieve ~30 K of noise at room temperature, ~10 K in LN$_2$/LAr, and ~2 K in LHe.

For our ACEv3 prototype in LHe, the single-element (waveguide) energy threshold was $90 \pm 18$ GeV but this scales as $1/\sqrt{N} \implies 51 \pm 11$ GeV for a 3-waveguide ($2.5 \text{ cm} = 0.7 \times 0$) layer.

For a single prototype ACE waveguide in T-530, the shower energy resolution:

$$\sigma_{E,\text{single}} \sim 15\% \left( \frac{90 \pm 18 \text{ GeV}}{E} \right) \sqrt{\frac{1}{N_{\text{det}}}}$$
Extracting Timing Information

- This is not a traditional photon counter - ACE elements record the full time-domain electric field as the shower transits the waveguide.
- Cross-correlating separate ACE elements, or individual elements with the waveguide impulse response, gives an exceptional time of arrival measurement for the shower front.
- The high-bandwidth (>4 GHz) and high center frequency (6 GHz) compared to other HEP technologies both contribute to the exceptional timing precision.
For our ACEv3 prototypes, we measured $\sim 1.2$ ps per-element timing resolution for showers significantly above threshold.

The timing resolution scales with $1/\sqrt{N}$ so the 3-waveguide (2.5 cm = 0.7 $X_0$) layer in ACEv3 achieved better than 3 ps resolution for showers with total energy $\sim 50$ GeV.
Spatial Resolution

- The relative timing of the waveforms at each end measures the location of the shower centroid along the long axis \( \Rightarrow \) position measurement much finer than the size of a waveguide.

- For a nominal 1 m long ACE waveguide, \( \Delta y \sim 300 \, \mu \text{m} \) at 90 GeV. This improves to \( 100 \, \mu \text{m} \) for \( E \gtrsim 3 \times E_{\text{thr}} \).

- With multiple elements, the transverse waveguide response gives a measurement smaller than the waveguide width \( \Delta x \sim 3 - 5 \, \text{mm} \).

A transverse scan of an ACE element across the beam showing the expected \( \text{TE}_{10} \) response function.
**Dynamic Range & Linearity => Multiple Shower Resolution**

### Dynamic Range

- ACE elements are **streaming detectors w/ 100% duty cycle** - no separate readout period/dead time.
- The dynamic range of ACE elements is limited only by the RF electronics (primarily, the LNA's IP3 & P1dB).
- $\gtrsim 10,000$ with current COTS electronics => will cover threshold to $> 100$ TeV without saturation.

### Reconstructing Multiple Showers

- With high-dynamic range & high-linearity, ACE elements can reconstruct **multiple simultaneous showers** (as long as they transit the waveguide in different locations) => they act as calorimeter with much **finer segmentation than their physical size** => **reduced channel count & cost!**
5D Askaryan Calorimeters for Future Colliders
Significant Improvements to ACE Elements

Since the ACEv3 beamtests in 2018, we have undergone an intense period of R&D on improving the individual ACE waveguides. Since then, we have designed:

1. New double-stacked waveguide design with waveguide couplers to lower the energy threshold by ~2x.
2. A completely new waveguide-coax coupler with double the bandwidth of existing designs; a ~30% improvement in timing and energy threshold.
3. Improved LNAs with ~40% lower noise figure (← not included in this presentation)

These improvements have been demonstrated in the lab as well as in our electromagnetic simulations and potentially make ACE suitable for other experiments outside of the FCC.

We have recently started several more years of DOE funding (including more beam tests in the future).
An ACE Timing/Calorimeter Layer

- A baseline ACE timing layer is nominally 3-6 waveguides thick.
- Total thickness is \( \sim 50 \text{ mm} = 1.4 \times X_0 \) (few % of FCC-hh baseline ECal depth)
- Using our latest waveguide design in LN\(_2\) with LHe cold-taps for the LNAs, a single Askaryan timing layer would provide:
  
  \[
  E_{\text{thr}} \sim 20 \text{ GeV}
  \]
  
  \[
  \sigma_t \sim 1.8 \text{ ps} \left( \frac{E_{\text{thr}}}{E} \right)
  \]
  
  \[
  \frac{\sigma_E}{E} \sim 10\% \left( \frac{E_{\text{thr}}}{E} \right)
  \]
  
  \(\Delta x \sim 100-300 \mu\text{m}, \Delta y \sim 1-3 \text{ mm}, \Delta z \sim 8 \text{ mm}\)

For showers from particles above \( \sim 20 \text{ GeV} \), these are 5D detectors!
Due to their high threshold and relatively coarse energy resolution, ACE layers are not practical as a standalone calorimeter technology for most applications. However, at a future high CoM colliders (i.e. HE-LHC, FCC-ee/hh) or even in the far-forward direction at the EIC, many showers will be above threshold ($\mathcal{O}(20 \text{ GeV})$).

Several Askaryan layers could therefore be embedded inside another ECAL or HCAL technology (LAr, dual-readout, etc.) at several depths to provide exceptional timing and spatial measurement(s) as well as an additional energy measurement to be used in particle flow algorithms (PFA) and pile-up reduction.

ACE elements could also be used as standalone detectors in far-forward regions, especially in regions where other detectors may struggle with radiation fluence.
Askaryan detectors (shown in red) could be integrated directly into barrel, endcap, or forward calorimeters.

At $1.4X_0$, several layers could be placed inside an HCal (or fewer in an ECal) depending upon the desired detection efficiency; each layer individually would provide sub-picosecond timing.
A single ACE layer could provide sub-picosecond timing, or extreme angular measurements \( \sim 10 \mu \text{rad} \), for far-forward or off-momentum hadrons/photons from eA collisions at the EIC for diffractive studies or precision measurement of the collision location; \( \geq \)order of magnitude better than current proposals.
At the energies found at the (proposed) FCC-ee/FCC-hh, single ACE layers can provide sub-picosecond timing for most showers in the barrel, endcap, and forward detectors.

Multiple layers at different depths inside another ECAL/HCAL could further boost the detection efficiency.
### Timing Measurement

- $\sigma_t < 1$ ps for almost all events. For the best events, $\sigma_t \lesssim 300$ fs.
- For this configuration, these timing constraints provide a position measurement along the long waveguide axis to $\sim 150 \mu$m.
- At 0.7-1.4 $X_0$, an Askaryan layer adds minimal absorption to the calorimeter.

### Angular Measurement

- At 2m in the barrel region, polar angular resolution, $\Delta \theta \simeq 0.0043^\circ \Rightarrow \Delta \eta \simeq 7 \times 10^{-5}$. $\sim 50-100x$ better $\eta$-resolution than FCC baseline designs if the vertex is otherwise known.
- The $\sim 3$ mm transverse position resolution corresponds to $\Delta \phi \simeq 0.1^\circ$.
- If the vertex is not known, a standalone Askaryan layer can provide strong sub-mm constraints on the vertex location.
We performed a preliminary simulation of FCC-hh pileup reduction using a single Askaryan layer in the barrel region - we assume each vertex produces an event that traverses an ACE element.

With the resolution achieved by T-530, the mean rate per picosecond is $O(1)$ - massively reducing pileup.

This requires that the as-built detector geometry be known to sub-mm precision and a sub-ps zero-timing reference for the interaction be provided.
Extremely interested in feedback/thoughts/ideas/collaboration from the community. In particular,

- How ACE could integrate and enhance performance of existing ECal/HCal designs? We are open to collaboration with calorimeter groups to study the performance of these combined calorimeters.
- Does sub-picosecond timing, and extreme $\eta$-resolution, on some fraction of ECal/HCal events significantly enhance particular searches for new physics?
- …and anything else!

Feel free to email me (prechelt@hawaii.edu) or send me a Zoom link; I’ll gladly chat about the possibilities of ACE.
BACKUP
Askaryan emission is directly proportional to shower energy i.e. a calorimeter!

Validated across >8 orders of magnitude in shower energy - extreme dynamic range.

The field tracks the shower evolution and produces an extremely broadband (impulsive) signal [10, 11].
Askaryan (ACE)
Barrel Calorimeter
Concept

~20,000 channels
~7000 channels

Observation of the askaryan effect: Coherent microwave cherenkov emission from charge asymmetry in high energy particle cascades.


Observations of the askaryan effect in ice.


Picosecond timing of microwave Cherenkov impulses from high-energy particle showers using dielectric-loaded waveguides.


Development toward a ground-based interferometric phased array for radio detection of high energy neutrinos.


**White paper: Arianna-200 high energy neutrino telescope.**

2020.
The antarctic impulsive transient antenna ultra-high energy neutrino detector design, performance, and sensitivity for 2006-2007 balloon flight.

Investigation of radiation induced electrical degradation in alumina under iter-relevant conditions.