Askaryan Calorimeter Experiment (ACE)

Picosecond Timing of High-Energy Particle Showers using Microwave Cherenkov Impulses in Dielectric-loaded Waveguides

Peter Gorham [1] Remy Prechelt* [1] Christian Miki [1] Gary Varner [1] David Saltzberg [2] Stephanie Wissel [3] Carsten Harst [4] Keith Jobe [4]

[1]Univ. of Hawai'i at Mānoa [2]UCLA [3]CalPoly [4]SLAC

CPAD 2019

Instrumentation for New Physics

Jim Hirschauer's plenary[1] this morning laid out a very clear set of instrumentation requirements for a future 100 TeV-scale collider to potentially discover new physics:

1. 5 ps particle timing.
2. 10 mrad (4') angular resolution.
3. Psuedorapidity coverage of $|\eta < 6|$.
4. High radiation tolerance ($\geq 10^{18}$ neutrons/cm^2).

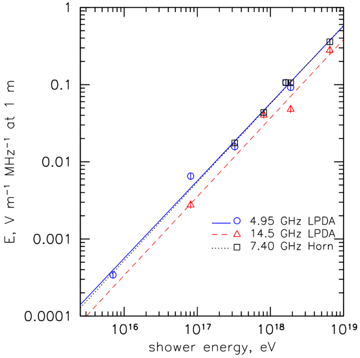
Precise timing has been a recurrring theme.

ACE has the potential to satisfy all of these requirements!

[1] Hirschauer, *Higgs as a tool for discovery (CPAD 2019)*

Askaryan Radiation

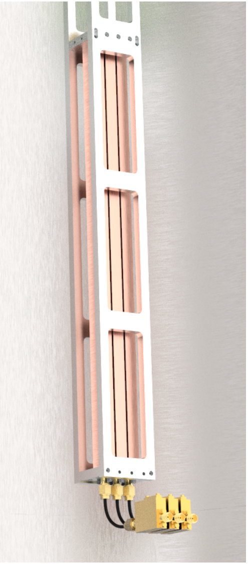
1. High-energy particle showers in dielectrics emit broadband **Askaryan** radiation (coherent microwave Cherenkov from the charge excess in the shower) with many-GHz of bandwidth.
2. Experimentally measured in sand, salt, ice, and now alumina.
3. The basis for a number of UHE neutrino experiments (ANITA, ARA, ARIANNA).

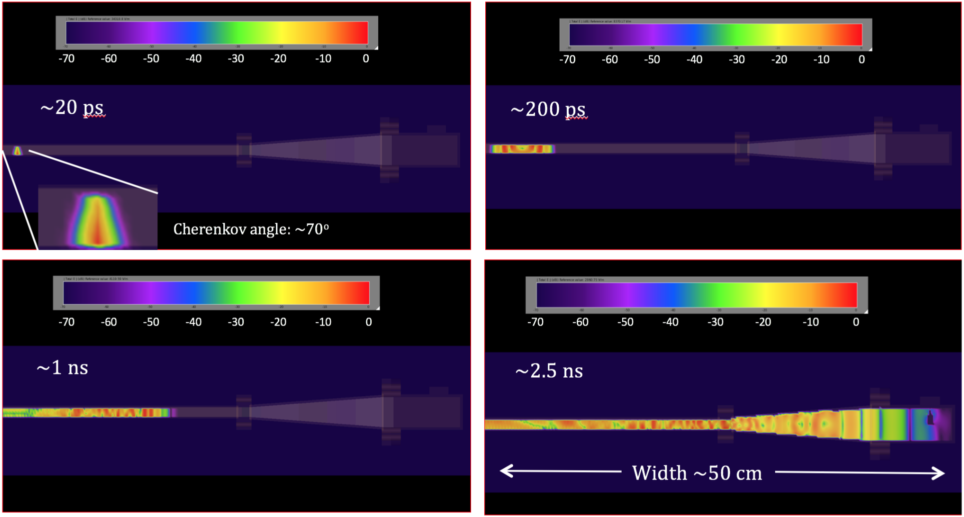


Field strength is linear in shower energy across many orders of magnitude!

The ACE Concept

1. We use standard WR51 copper waveguides loaded with alumina (Al_2O_3).
2. The Askaryan radiation emitted in the alumina is coupled into the TE_{10} mode (5-8 GHz).
3. We amplify and readout the nanosecond-scale pulse at each end with COTS amplifiers and oscilloscopes.
4. **Alumina** is a fantastic low-loss dielectric and one of the most radiation hard materials known.




-70 -60 -50 -40 -30 -20 -10 0
~20 ps
Cherenkov angle: ~70°
-70 -60 -50 -40 -30 -20 -10 0
~200 ps
-70 -60 -50 -40 -30 -20 -10 0
~1 ns
-70 -60 -50 -40 -30 -20 -10 0
~2.5 ns
Width ~50 cm

Experimental Validation (SLAC T530)

Two experiments at SLAC (ESTB A) to explore the ACE concept:

1. ACEv1 (2015)[2]

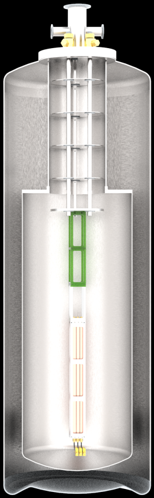
   First generation waveguide design
   Performed in LN_2.
   $\sim$20K NF cryo-LNAs.

2. ACEv3 (2018)

   Third-generation waveguide design.
   Performed in LHe.
   New 2K NF cryo-LNAs.
   Improved lower-threshold trigger system.

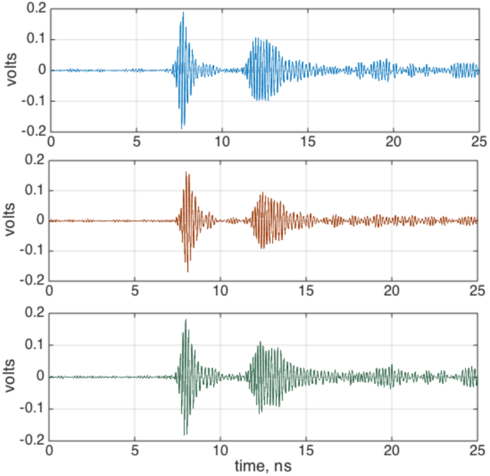
ACEv4 already in development and is the best ACE yet!

[3] ArXiV:1708.01798



Waveforms

1. For both SLAC tests, one end of the waveguide was shorted so we see both the direct and reflected Askaryan pulse.



Timing Resolution

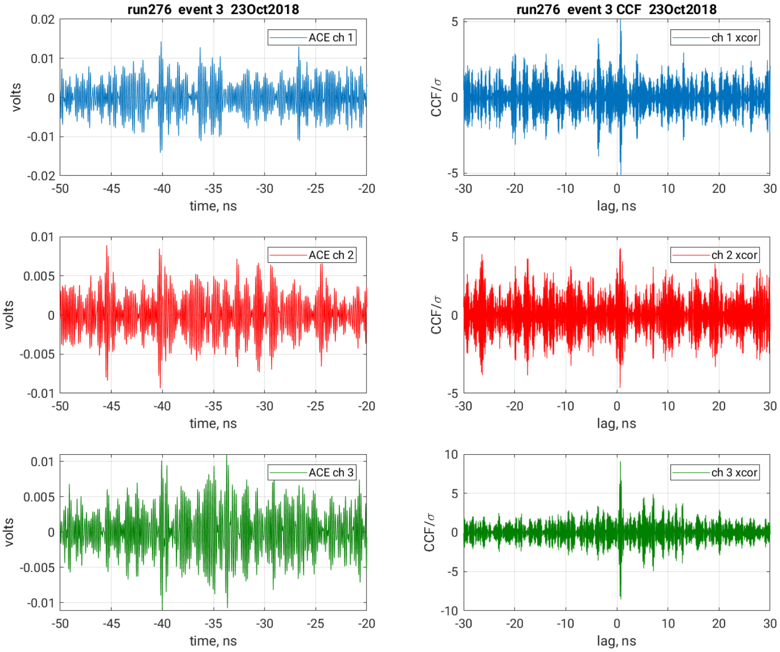
1. Signals measured by successive waveguides can be used to measure time-of-flight to picosecond precision.
2. The relative phase of the waveforms at each end of a waveguide can also give great spatial resolution along the long axis of the waveguide.
3. Measured time resolution for a single ACEv3 element was $\sim 2 - 3$ ps depending on SNR.
4. Time-of-flight resolution scales with $(\sqrt{N_{\text{det}}})^{-1}$ so a four-element ACE layer approaches 1ps resolution.

Dynamic Range

1. Askaryan emission is linear across <u>many</u> orders of magnitude!
2. Practical dynamic range is limited by the dynamic range of the chosen microwave LNAs.
3. For an ACEv3-like system, with $\sim$30-40dB of gain on a thermal background of $\approx$ -96dBm, the dynamic range would be $\geq$1000 in shower energy. (100 TeV for a turn-on energy of 100 GeV).
4. Multiple (different) gain stages can be used to further increase dynamic range.

Turn-on Shower Energy

1. The minimum detectable shower energy is primarily determined by the system temperature, T_{sys}
2. For the three-element ACEv3 with 2K cryo-LNAs, the minimum shower energy ~ 200 GeV.
3. The minimum shower energy scales with $\sqrt{T_{\mathrm{sys}}/N_{\mathrm{det}}}$ so systems with more elements, better LNAs, and different waveguide designs, could lead to turn-on energies ≤ 100 GeV.

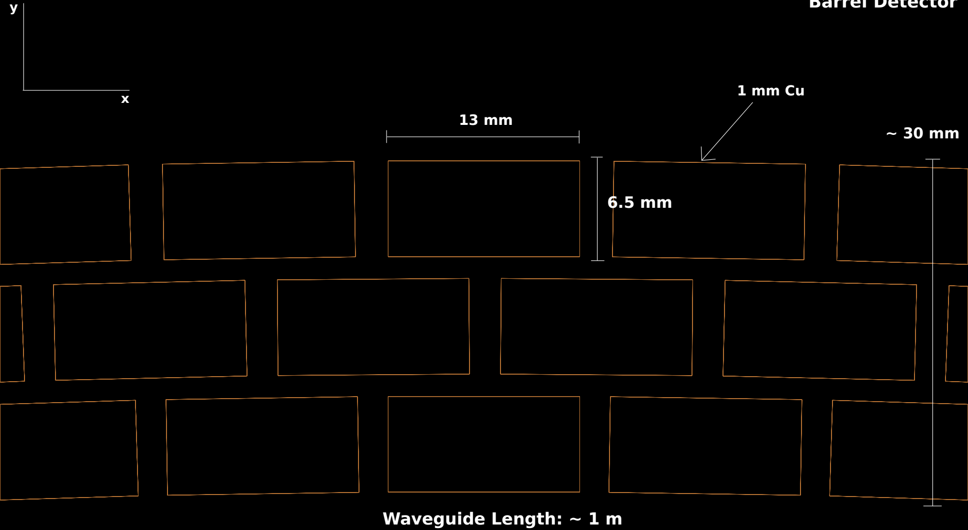


run276 event 3 23Oct2018
ACE ch 1
ACE ch 2
ACE ch 3
volts
time, ns
run276 event 3 CCF 23Oct2018
ch 1 xcor
ch 2 xcor
ch 3 xcor
CCF/σ
lag, ns

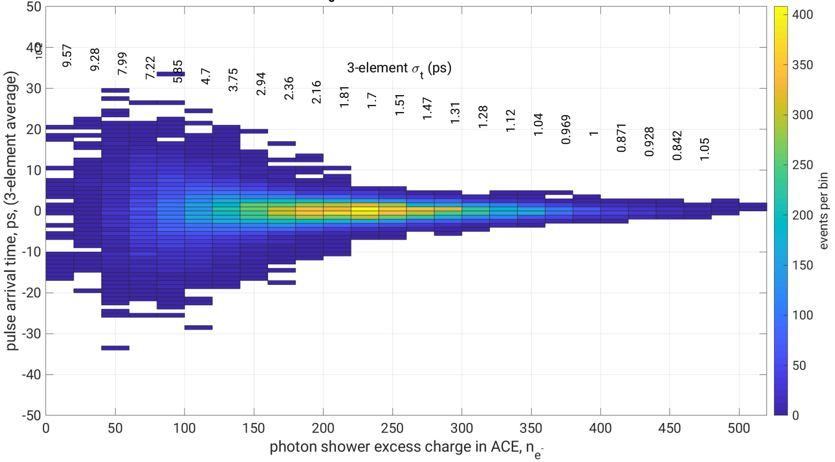
What might this look like for the FCC-hh?

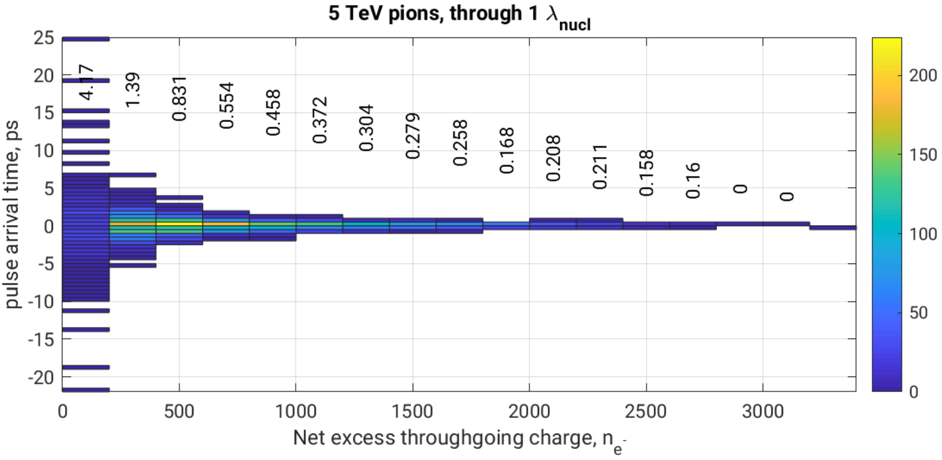
[2]When in doubt, Monte Carlo!

Barrel Detector



1 TeV photons, through 10 X_0, 3 ACE elements, SNR>3, 81% detection efficiency



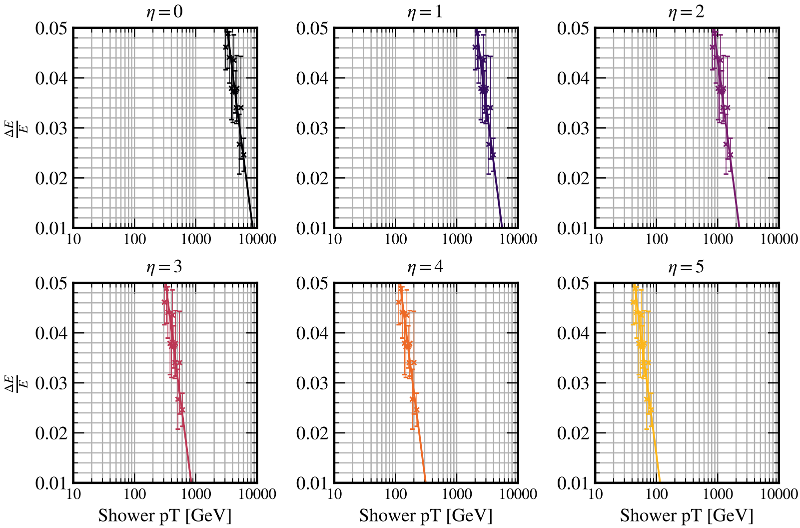

5 TeV pions, through 1 λ_{nucl}
pulse arrival time, ps
Net excess throughgoing charge, n_{e^-}
4.17
1.39
0.831
0.554
0.458
0.372
0.304
0.279
0.258
0.168
0.208
0.211
0.158
0.16
0
0
25
20
15
10
5
0
-5
-10
-15
-20
0
500
1000
1500
2000
2500
3000
200
150
100
50
0

Angular Resolution

1. A resolution of ~ 1ps in alumina corresponds to a spatial resolution of $\sim 100\mu$m along the long-axis of the waveguide.
2. In the perpendicular direction, our spatial resolution is limited by the 6mm width of the waveguide.
3. Assuming an ACE layer at 2m radius from the interaction point, this corresponds to an angular resolution of 10 arcseconds in θ and 6 arcminutes in ϕ in the barrel.
4. This is improved in the forward region where d$\theta \approx$ 100 arcseconds and d$\phi \approx$ 10 arcseconds at $\eta = 3$.

This easily exceeds the 34 arcminute requirement set by Jim this morning!

Calorimetry



Summary

1. ACE elements are extremely simple in design, low-cost, extremely rad-hard, with extreme dynamic range ($\geq$ three orders of magnitude).
2. Realistic turn-on energy of $\sim (100 - 200)$ GeV for 4 elements (or a pT of $\sim (3 - 8)$ GeV/c at $\eta = 4$).
3. Timing resolution is at most a few picoseconds for almost all events, pushing down to sub-picosecond in the forward region and for several-TeV events in the barrel.
4. Angular resolution for typical collider geometries is $\mathcal{O}(10)$ ($\mathcal{O}(100)$) arcseconds in θ and $\mathcal{O}(60)$ ($\mathcal{O}(10)$) arcseconds in ϕ in the barrel (forward) region.
5. Can also provide decent calorimetry for high-energy or high-η events.
6. Potentially a transformative $\sim$5D vertexing technology?

Questions?