CHANDLER: 3D segmented surface-level plastic antineutrino detector

In association with the MAD collaboration

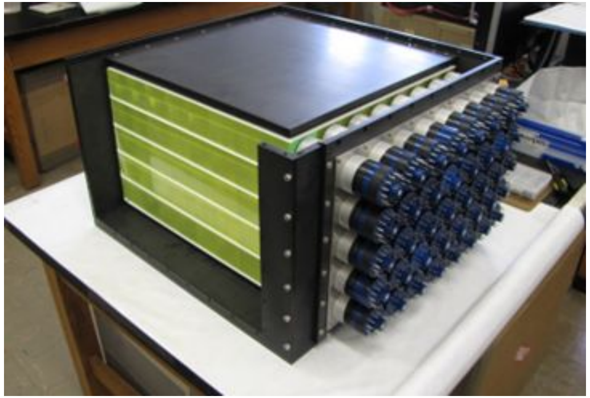
For the Applied Antineutrino Physics Workshop

Keegan Walkup (September 18th 2023)

VIRGINIA TECH

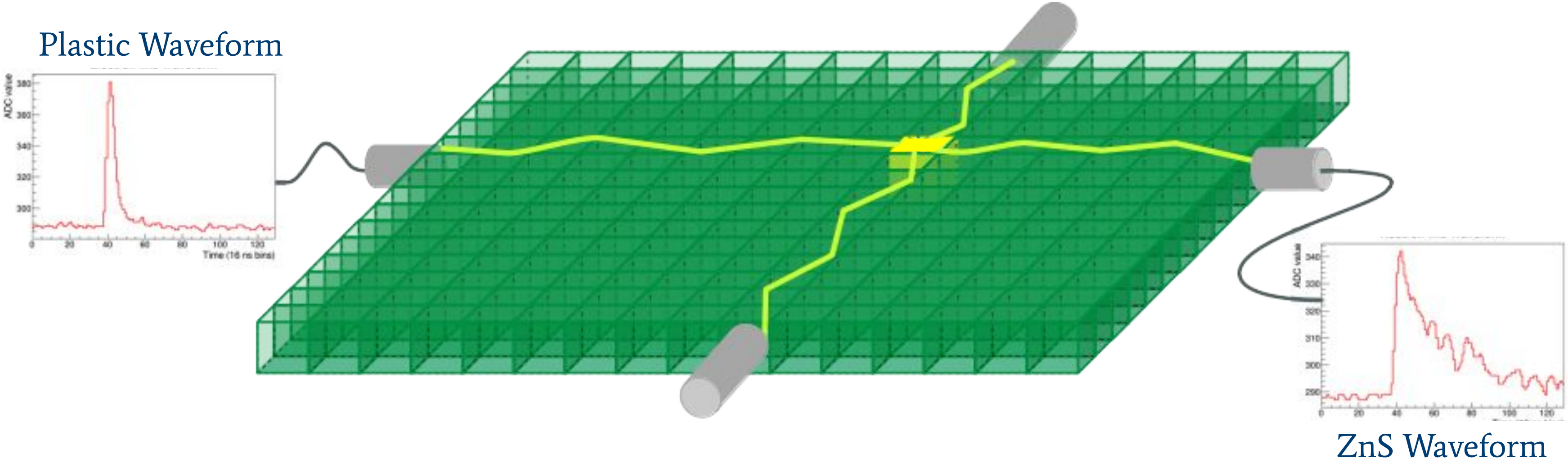
What is CHANDLER*?

- CHANDLER is an antineutrino detector technology designed with robustness, mobility and active IBD identification in mind.
- The neutrino target volume consists of a highly segmented array of plastic scintillating cubes called a Raghavan Optical Lattice to tag the positron.
- Between layers, there is a thin sheet of ZnS scintillator doped with Lithium-6 to tag neutron captures.



*Carbon Hydrogen Anti-Neutrino Detector with a Lithium Enhanced Raghavan optical lattice

How does the Raghavan Optical Lattice work?

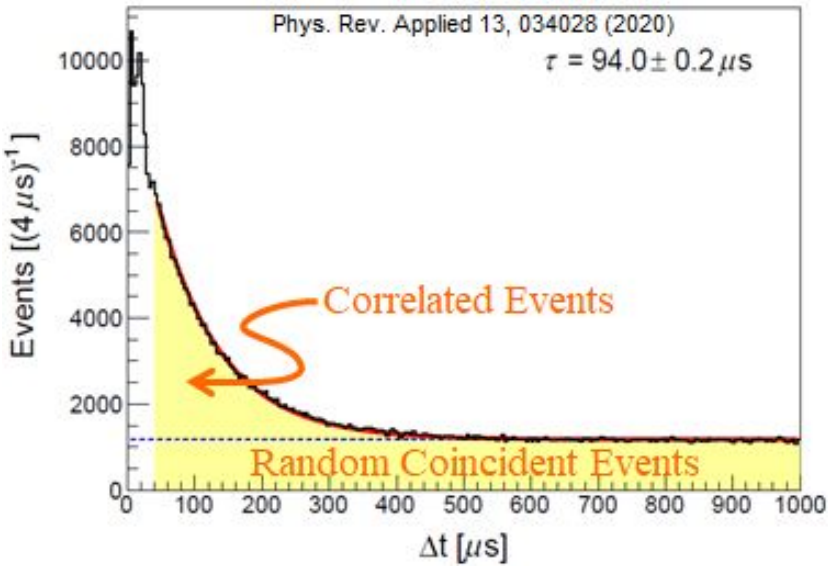


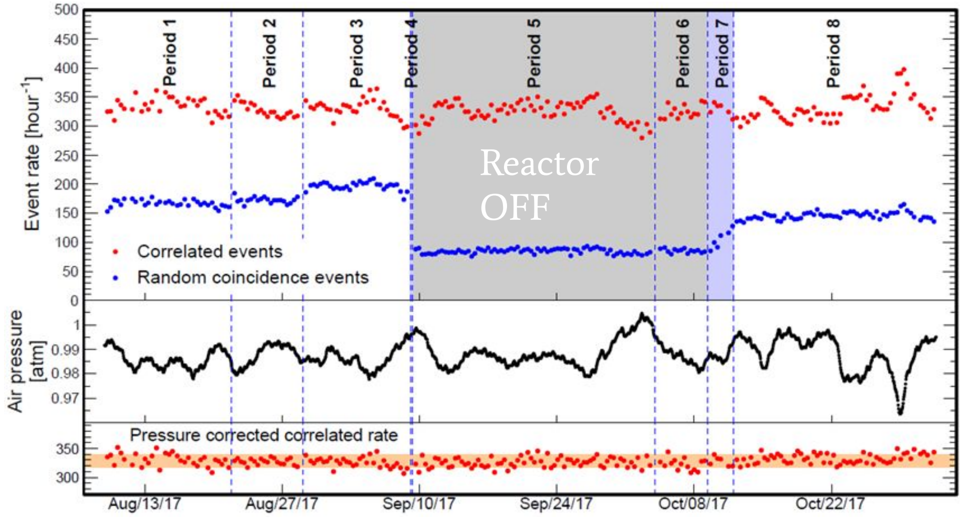
- Light is transported via total internal reflection along rows and columns to PMTs
- The plastic has a wavelength shifter which absorbs blue light from the sheet's scintillation
- This light is retransmitted isotropically, including angles permitting total internal reflection.
- The large difference in scintillation decay time between the plastic and the ZnS sheets allows us to identify neutron captures with ease.

Deployment of the MiniCHANDLER prototype

We developed an 80kg prototype detector, MiniCHANDLER which was installed in the Mobile Neutrino Lab and deployed to North Anna Nuclear Generating Station.

MiniCHANDLER analysis



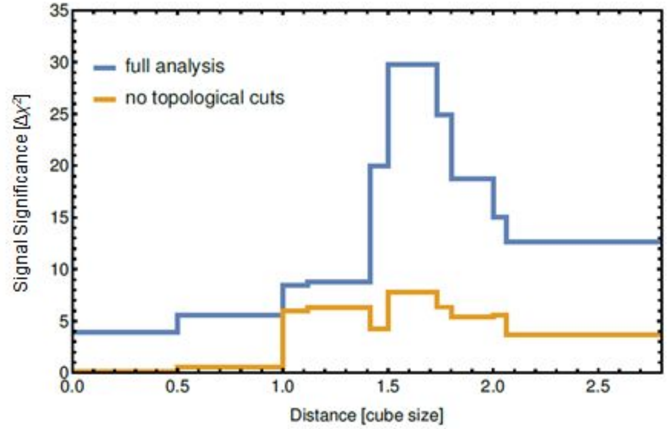


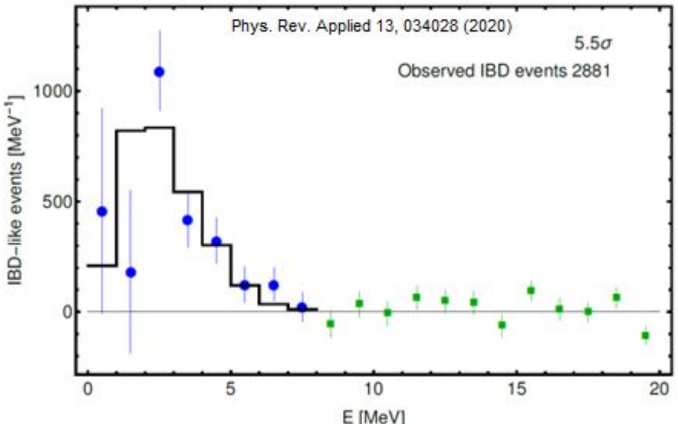
We split the IBD candidates into correlated (IBD and fast neutron) and random coincident events and plotted the rates over time to get a picture of the stability

The reactor ON periods have about 4 more events per hour than the reactor OFF periods, this is what we expect for the IBD rate once inefficiencies are accounted for.

MiniCHANDLER sees antineutrinos

- After applying topological cuts and performing a reactor OFF subtraction, we isolated the IBD signal.
- The residue was fit to an IBD spectrum (black) generated from Monte Carlo and we found reactor antineutrinos at 5.5σ
- MiniCHANDLER is an 80kg prototype that was deployed on the surface 25m from a 2.9GW_{th} PWR reactor for 4 months





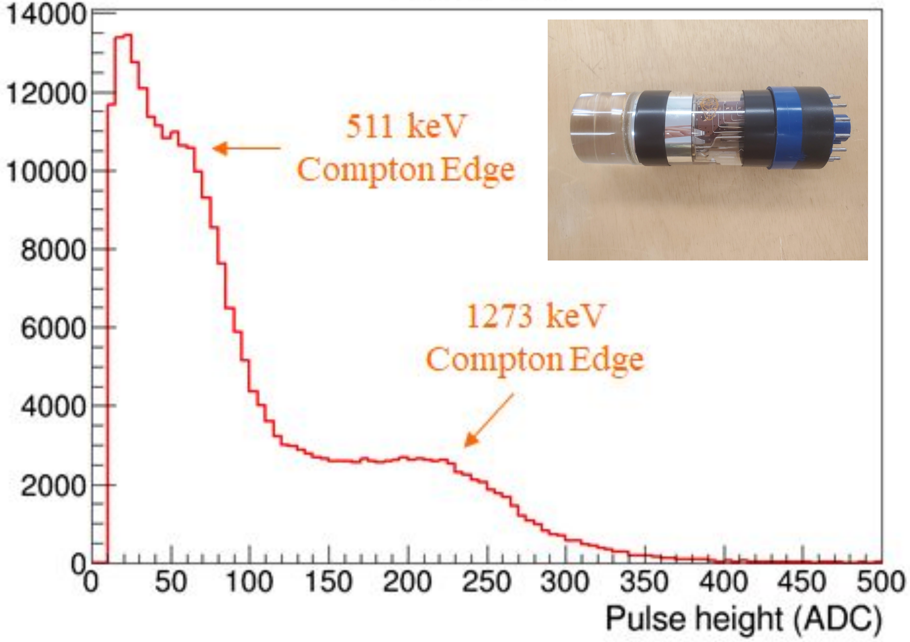
CHANDLER further details

We have made a number of updates and improvements going from the prototype to the full detector design which I will discuss in greater detail.

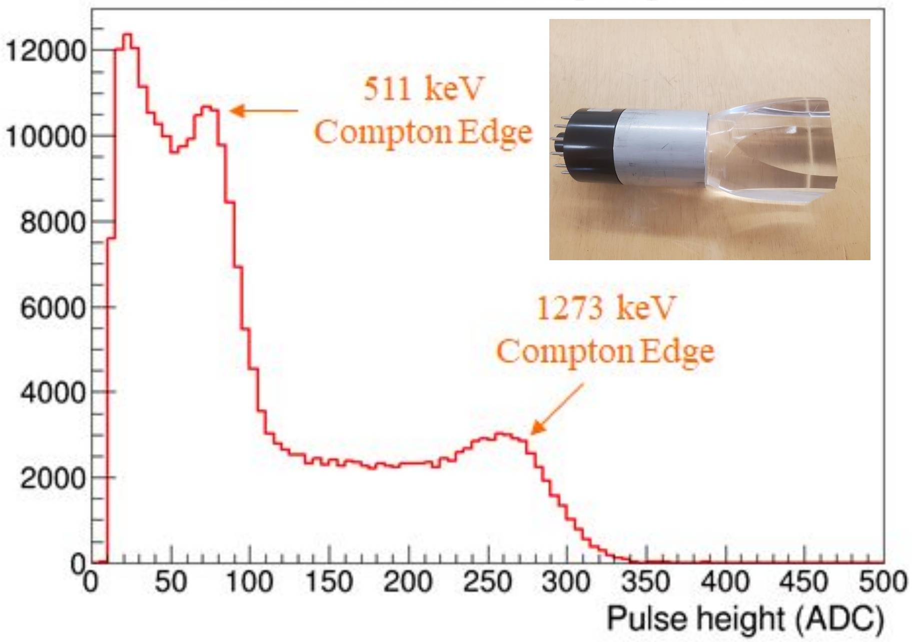
1. Optics
2. Topology
3. Sensitivity
4. Hit Reconstruction
5. Engineering

Optics: New PMTs and lightguides with ^{22}Na source

Old PMT

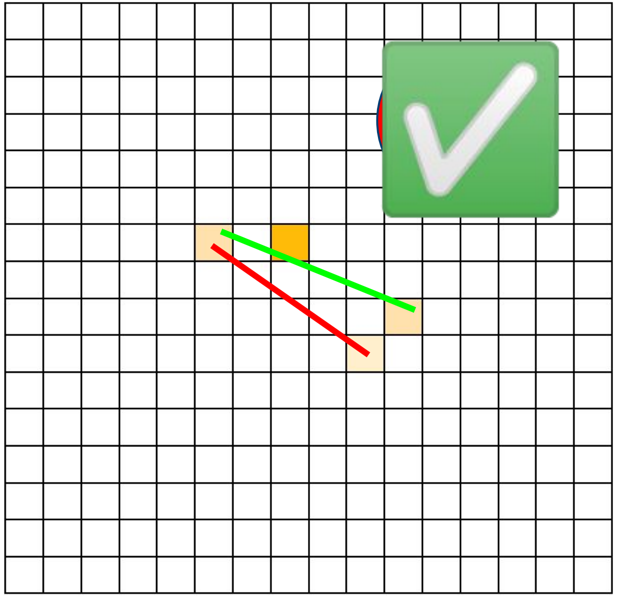


New PMT with lightguide



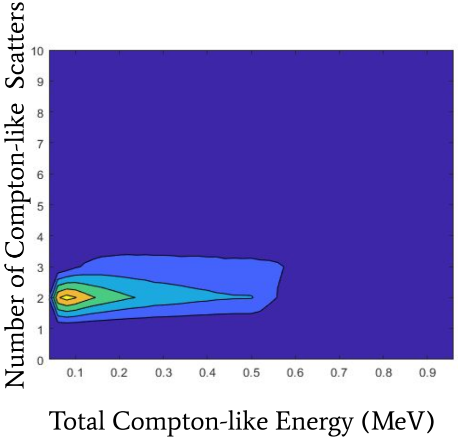
New PMTs and lightguides have improved resolution by over a factor of 2.

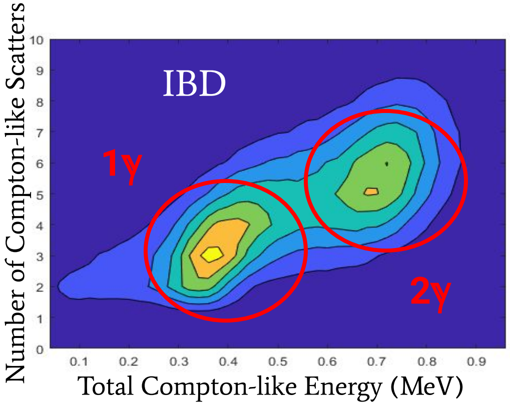
Topology with a larger detector

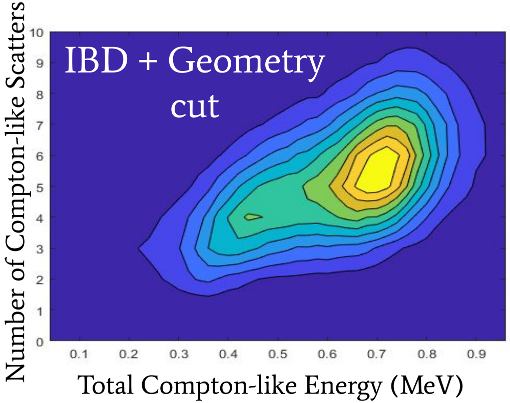


- The mean free path of an annihilation gamma is 10 cm.
- This means in MiniCHANDLER 87% of the detector volume is one mean free path away from a surface
- A $1m^3$ detector would have 48% of the detector volume one mean free path away from a surface, 50x the fiducial volume.
- This leads to a natural division of into “two gamma” events where both annihilation gammas are contained and “one gamma” events where the second annihilation gamma escapes through the surface
- For example, we can use a simple geometric cut that checks for back-to-back gammas with a line drawn through Compton scatters including the positron cube.
- A larger detector is more efficient at finding IBDs, has less fast neutron hits per unit volume and has a better cost performance per unit volume.

Topology geometry cut example





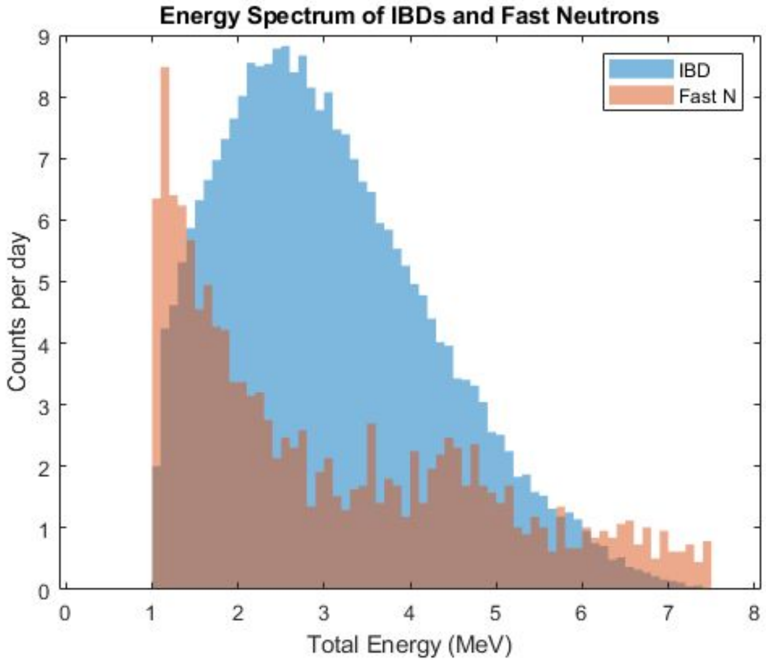


- If we look at total Compton energy and number of Compton hits, we can see 1 gamma and 2 gamma islands.
- With the geometry cut, we select for 2 gamma events.
- It is difficult to mimic two small hits sandwiching a large hit.

Monte Carlo Data

Sensitivity measurements

- In general, an analysis must trade off between efficiency and purity.
- One of the use cases considered is power monitoring, where a high signal efficiency is preferred.
- For spectral measurement based use cases, a high signal-to-noise ratio is preferred.



Monte Carlo Data

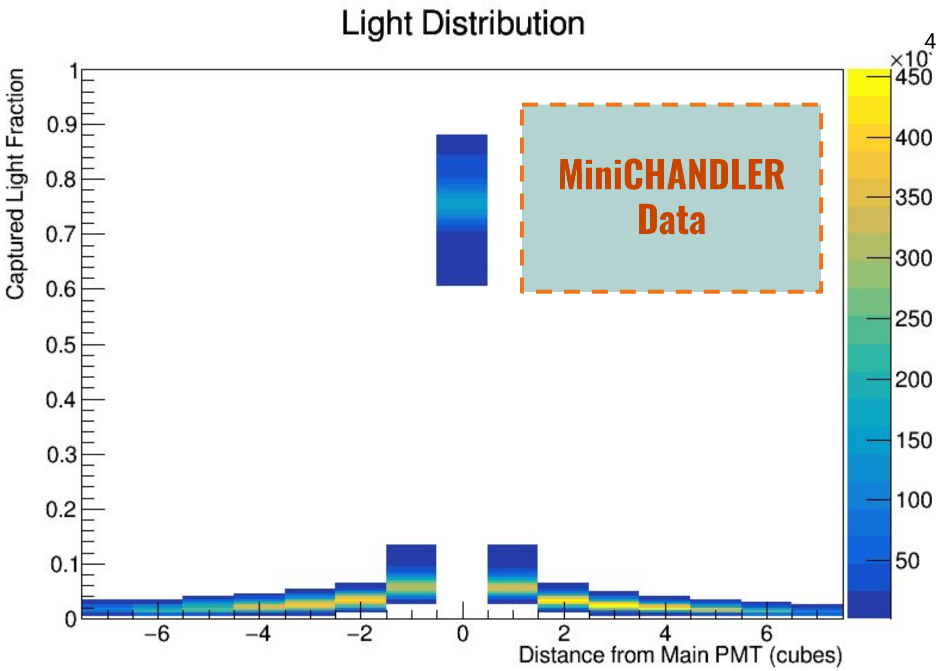
Sensitivity Example

Scenario		IBD per day	BG per day	S/B	Eff. Counts (/day)
0.65 ton	1 gamma	131	739	0.18	10.6
	2 gamma	190	207	0.92	59.7
1 ton	1 gamma	197	506	0.39	31.9
	2 gamma	196	63	3.09	118.9
2.5 ton	1 gamma	440	2247	0.20	39.3
	2 gamma	712	355	2.01	356.7

- For an easy illustration of detector sensitivity, we used a simple metric of determining whether a reactor was ON or OFF given one day of reactor OFF measurement at 40 meters from a 3 GWth reactor.
- Mathematically this is $\sigma^2 = S^2/(S+2B)$

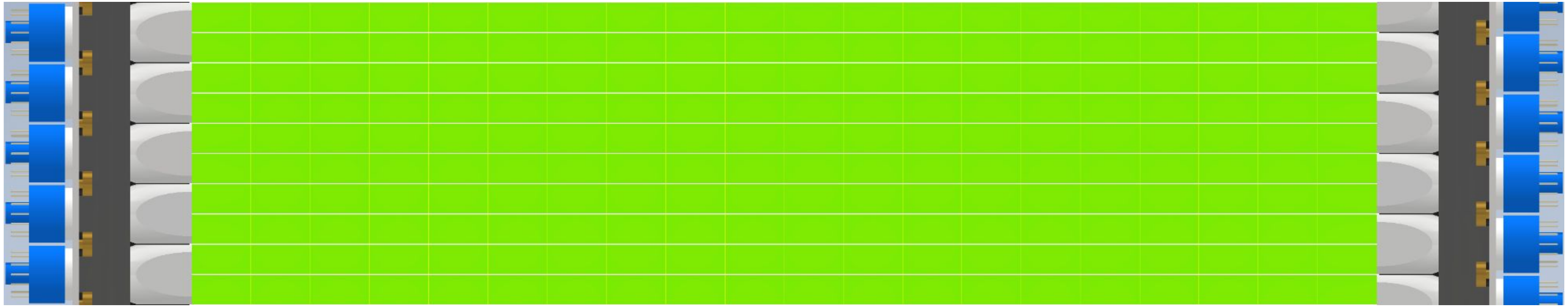
Monte Carlo Data

Reconstruction



- When there is a hit in the Raghavan Optical Lattice, about 75% of observed light is captured in the same row and column.
- The remainder is spread out to other PMTs in the same layer with a fairly consistent pattern.
- Minimum ionizing vertical muons deposit a consistent 11 MeV per layer, which allows us to build profiles for each hit location.

Half Cubes

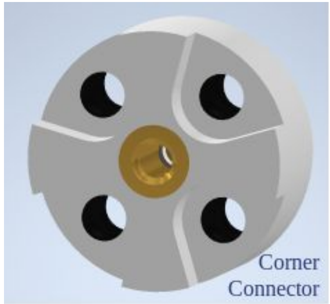


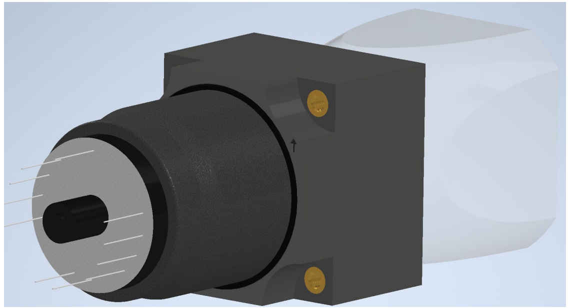
We split each cube in half and offset opposing PMTs, which lets us double the amount of ^{6}Li

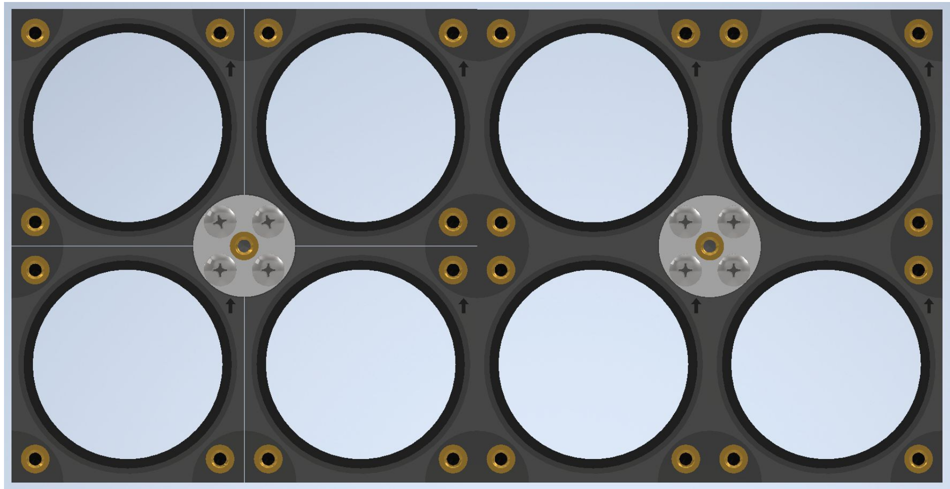
Configuration	^{6}Li Capture	Time to 90% Capture
Full Cubes	51%	229 μs
Half Cubes	69%	120 μs

Doubling ^{6}Li loaded sheets increases costs by 12%, but increase capture efficiency by 35% as well as reducing capture time and capture distance and adding more segmentation for topology.

Engineering



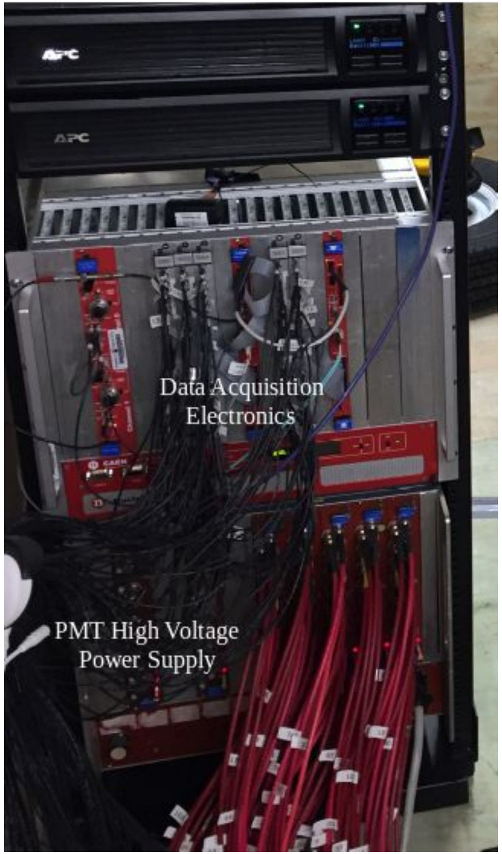


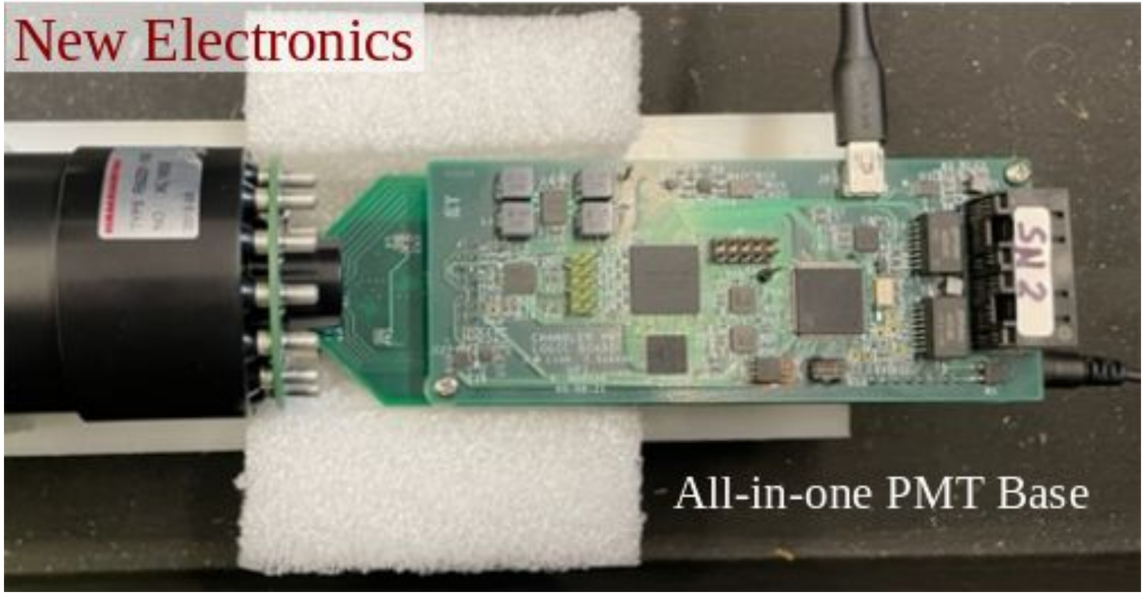


- A PMT support structure will provide a light tight seal and alignment to individual PMTs
- Built in assembly tolerances allow for small variations in cube face positions and PMT dimensions.
- The structure makes in-field repair more feasible

Electronics

Old Electronics





This new all-in-one base provides high voltage, 14 bit ADC and FPGA based trigger at the PMT.

- Uses power over Ethernet
- Eliminates crosstalk and attenuation
- Can identify neutrons/gammas on board
- Costs about half as much as using external high voltage and ADC

Conclusion

- CHANDLER uses technology based on a 3D optical lattice that *actively identifies* IBDs, with positrons identified through topology and neutrons identified through a scintillator with a long decay time.
- The technology has been experimentally *proven to work*.
- Moving from the prototype stage to a full-size detector presents opportunities to *develop* better optics, engineering, electronics and analysis tools.
- We will be deploying a CHANDLER detector as part of the *Mobile Antineutrino Demonstrator*.

Questions?

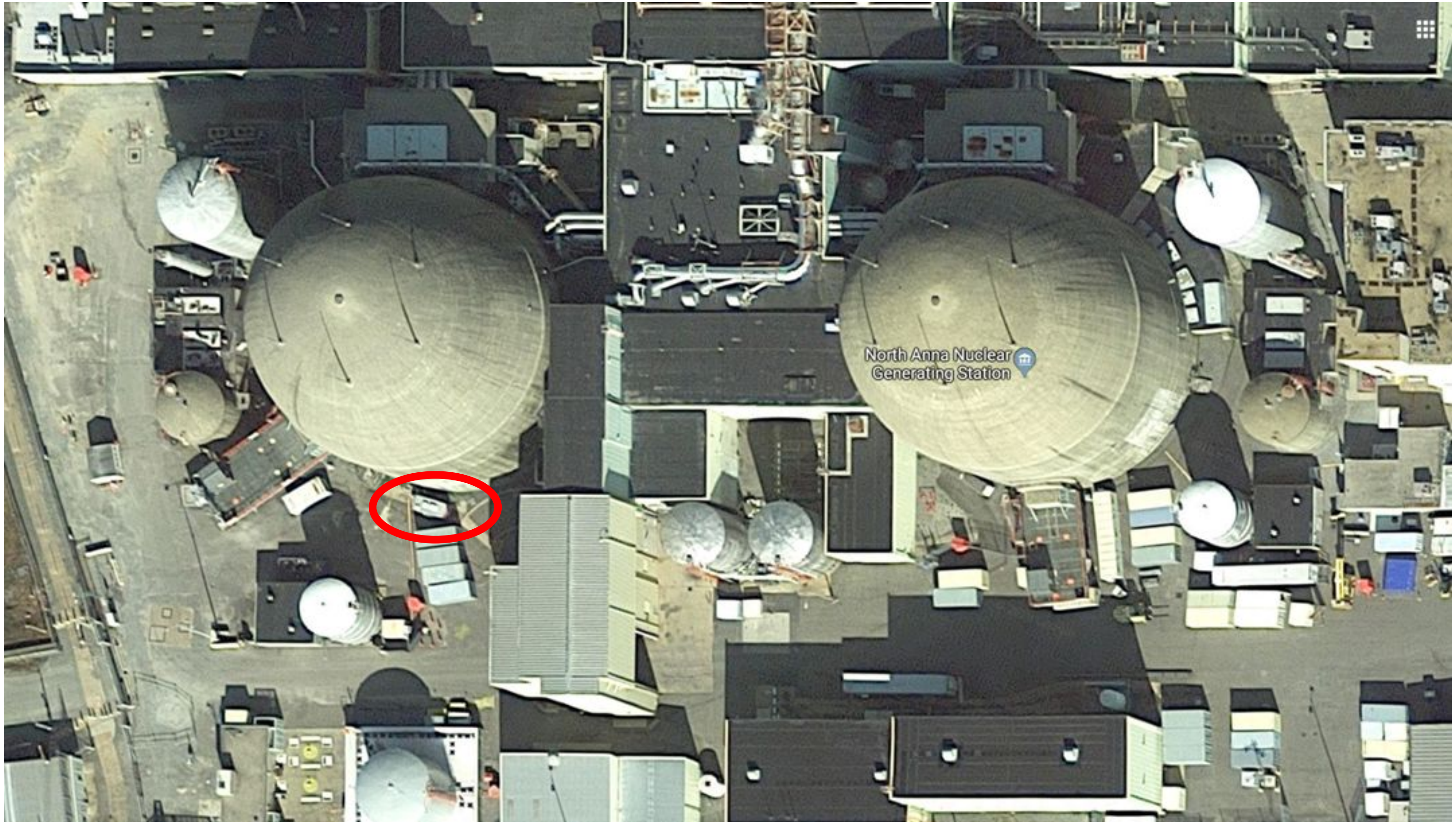
How does CHANDLER identify IBDs?

- Our goal it not to reject backgrounds, but to actively identify IBDs.
- We identify the neutron through its distinct waveform
- We identify the positron through the distinct back-to-back annihilation gammas using the high segmentation of the Raghavan optical lattice

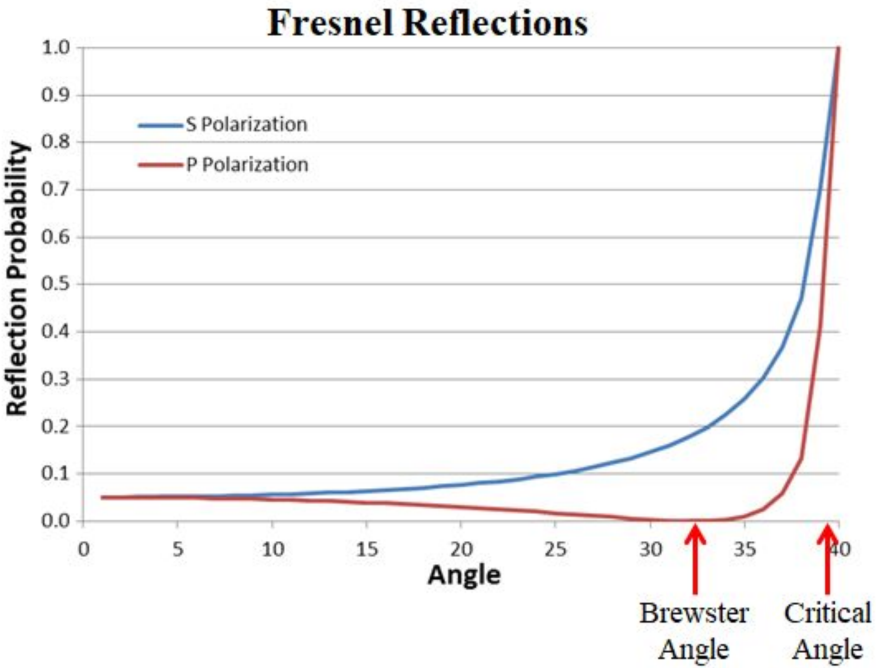
$$\bar{\nu}_e + p \rightarrow n + e^+$$

Deployment of the MiniCHANDLER prototype

MiniCHANDLER was deployed to this commercial 2.9 GW_{th} PWR at a standoff of 25 m for 4 months in 2017



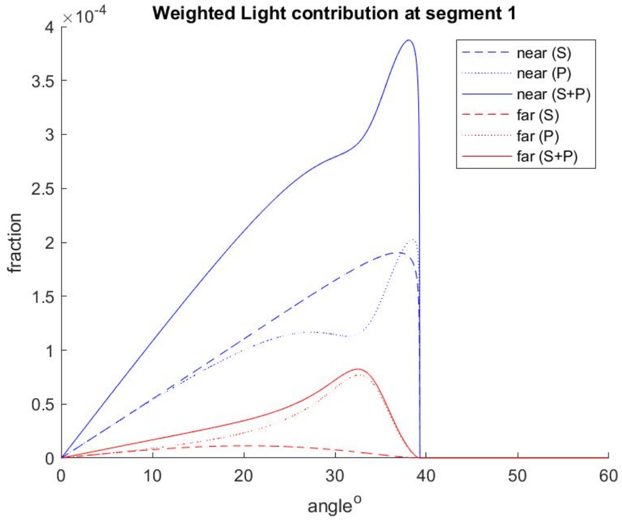
Optics: Total Internal Reflection

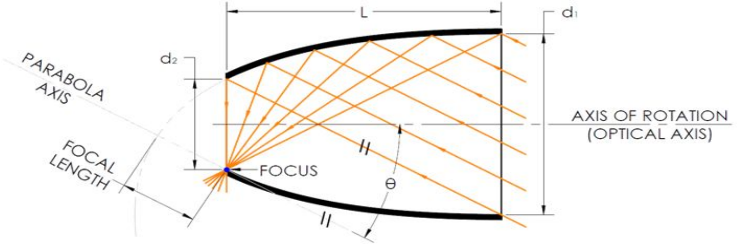


- The optics of the Raghavan optical lattice are determined by the PVT (n=1.58) and air interface.
- This makes the critical angle 39° and the Brewster angle 32°
- All light capable of transmitting along a channel will be in a total internal reflection mode.
- 45% of light is produced at a total internal reflection capable angle

Optics: Lightguides

- Since total internal reflection cuts off at 39º the angular penalty for using a compound parabolic lightguide does not apply to CHANDLER.
- When the PMT is nearby, the combination of a larger solid angle and back reflection effects means high angle light is the major contributor to light collection efficiency.
- In testing, the lightguide has improved collection efficiency by about 35%.



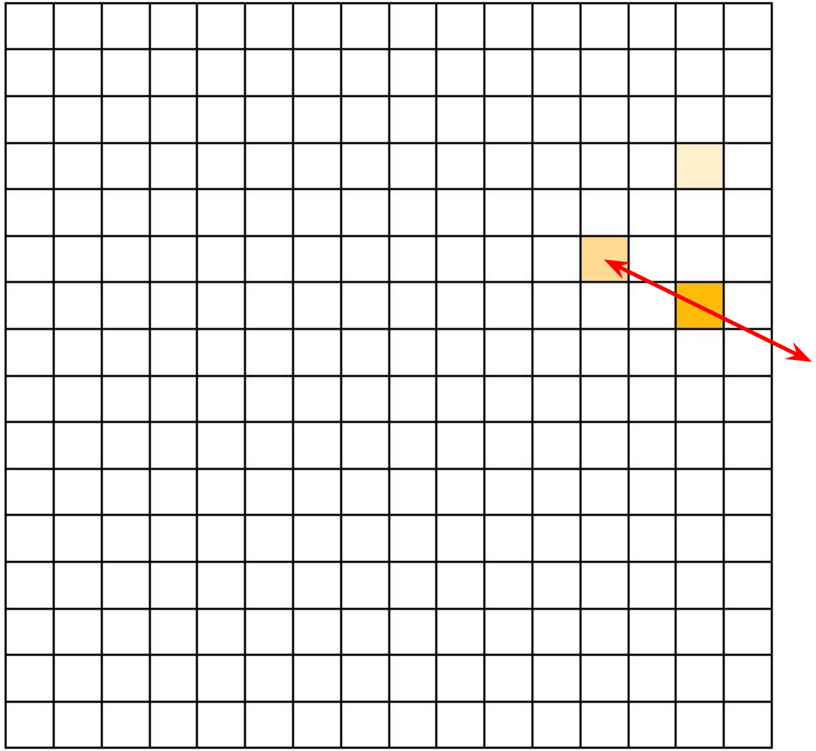


$$d_1 = \frac{d_2}{sin(\theta_c)} \qquad L = \frac{d_2}{2} cot(\theta_c)[1 + csc(\theta_c)]$$

Topological cuts in MiniCHANDLER

- The goal of our topological cuts is to find patterns consistent with the Compton scattering of one or both of the annihilation gammas.
- We consider all positron-like events in 1000 μs preceding a neutron capture.
- A spatial separation cut between the positron and neutron is applied.
- The largest hit segment and any large hits in adjacent segments are assumed to be the positron track.
- Other segments are assumed to be Compton scatters and we demand:
  - The total Compton energy is <1.022 MeV
  - Each hit is <511 keV
- This method is not tailored to reject fast neutron backgrounds like PSD, but is capable of rejecting key non-PSD backgrounds such as carbon de-excitation gammas

Topology “one gamma” metric example



- We can also create metrics for “one gamma” events
- By looking at the contained gamma’s Compton scatter we can estimate the distance the other annihilation gamma must have travelled to escape, giving us an “escape probability”

Energy Reconstruction Math

- For a detector of size N there are 4N PMTs pointing at N^2 segments on each segment layer
- We can represent what will be seen in the PMTs for a given deposition pattern with a matrix equation: $\mathbf{p} = \mathbf{M}\mathbf{e}$
- With **p** accounting for the 4N channels and **e** accounting for the N^2 energy profiles
- The transfer matrix M is a 4N by N^2 matrix, therefore its rank is <=4N
- Then the solution space of: $\mathbf{M}^{+}\mathbf{p} = \mathbf{e}$ has very high dimension in general ~= N^2-2N

How does the reconstruction process work?

- In general, well known transforms like fourier transforms and spherical harmonic transforms use an orthonormal basis to pick out components in the transformation space $\langle f_i|f_j\rangle = \delta_{ij}$
- The hit profiles are nearly orthogonal on each axis, which means we can select likely hit locations by taking the inner product of the measured PMT space against the profile space.
- For each selection we can minimize error using a Poisson distribution against the measured PMT values.
- We repeat this process until a statistics driven halting condition is met

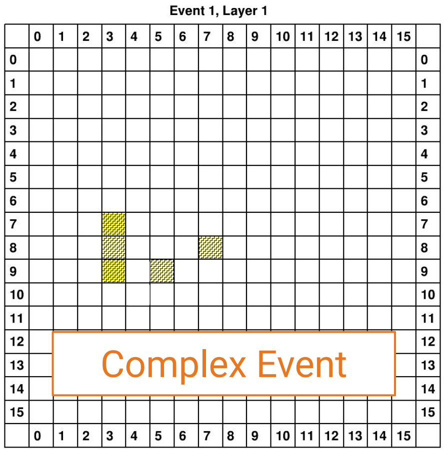
Selection *Minimization*

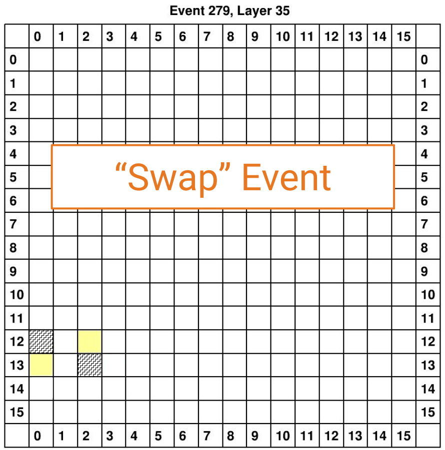
$$\langle p - Me_i|M_j\rangle = C_j \longleftrightarrow \sigma_j = min(|p - Me_{i+1}|)$$

Reconstruction Success Rate

- Position reconstruction is about 95% efficient on Monte Carlo data in testing.
- Common error mode is “swapping” when hits of similar energy are diagonal from each other
- Fortunately, swapping errors maintains high fidelity to aggregate variables such as total energy

Layer Multiplicity	Reconstruction Efficiency	Frequency
1	99.8%	72.9%
2	96.2%	20.5%
3	84.9%	5.0%
4	66.7%	1.2%
5	34.3%	.2%
6	61.5%	.06%





			per day	S/B	Significance