Pulsed Neutron Source calibration system

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Calibration workshop
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Outline

- Motivation
- Pulsed Neutron Source
- PNS system location
- Simulation efforts
- R&D activities
- Summary

DUNE Far Detector Calibration Needs

- Neutrino **oscillations** is a **L/E dependent** process → DUNE **needs to understand the energy scale and resolution within 2% level**
- **The detector response of a liquid argon TPC is not always uniform** → need calibration at different locations
- **DUNE far detector calibration is challenging**
  - **Deep underground** → only 30 stopping muons and 20 Michel electrons /day/10 kt
  - **Large Volume** → spatial coverage of traditional calibration methods is limited

- **Could use an external Pulsed Neutron Source (PNS) system**
  - A technique under development (similar method used by SNO and Super-K)
  - One of the main TDR strategies

Why neutrons?

- **Wide coverage: neutrons can scatter to the entire volume of TPC**
  - Scattering length is long: 1.5 km in 40-Ar, 30 m in natural argon
  - Mean fractional energy loss per scatter is 4.8%

- **Multi-gamma output: neutron capture emits 6.1 MeV gamma cascade**
  - Fixed energy deposition as a “standard candle” for energy deposition calibration

- **External deployment: neutrons mostly ignore the stainless steel cryostat**
  - External deployment
  - No contamination to argon purity

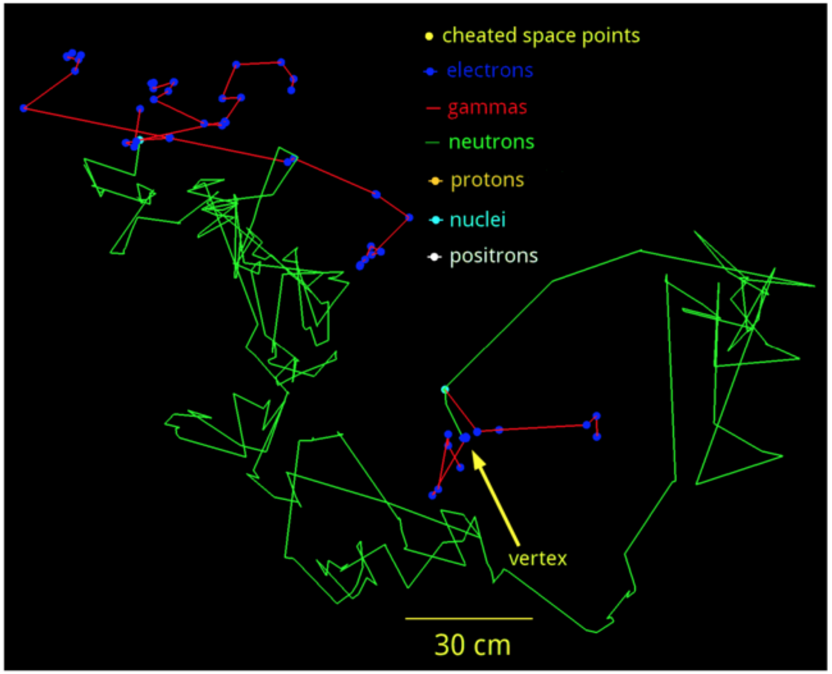
- **Pulsed trigger: neutrons can be created with a DD generator:**
  - Triggered source
  - High neutron yield (~10^6 neutrons per pulse)

Physics Impact

- Pulsed Neutron Source provide low energy calibration relevant to supernova and solar neutrino physics
  - Calibration of absolute energy scale and its position dependence
  - 6.1 MeV “standard candles” provide a method to assess if the detector model is incomplete or insufficient

- Neutrons are part of the supernova neutrino signal in DUNE.
  - Study of neutron capture tagging could help to constrain the uncertainty in energy reconstruction
- Neutrons are key components in DUNE energy reconstruction for beam neutrinos
  - Important to understand the neutron production and transport

Particle trajectories from a simulated SN event in DUNE



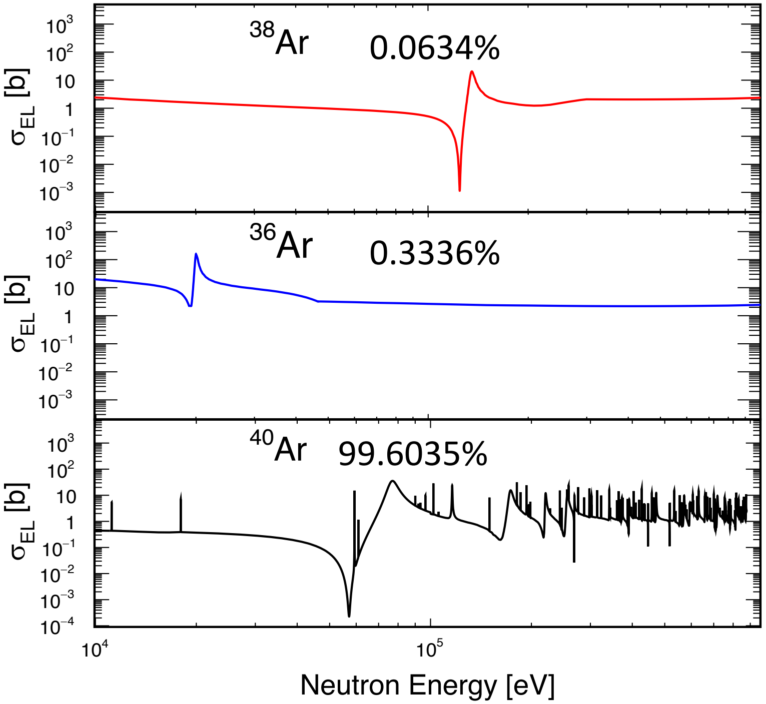
How does it work?

- 40-Ar is near transparent to 57 keV neutrons at the anti-resonance “dip”
- 38-Ar and 36-Ar have different resonance structures that keep the natural argon from being totally transparent
- **The effective scattering length is ~30 m in natural argon (to be verified with a TOF neutron beam)**

38-Ar, λ = 47 cm @ 57 keV

36-Ar, λ = 16 cm @ 57 keV

40-Ar, λ = 1.4 km @ 57 keV



Make anti-resonance neutrons with a DD Generator

- DD Generators are commercial devices that could provide a source of low energy (2.5 MeV) neutrons.
- Costs are low (~$125k) and they can be operated in pulse mode to give a trigger signal.
- No tritium used – makes import/export and compliance with local rules much less difficult than DT or TT generators
- 2.5 MeV is well below the neutron and proton separation energy of most elements – little activation expected.
- Monoenergetic spectrum will simplify neutron moderator design and shielding
- Neutron moderator is designed in Geant4 using NeutronHP neutron transport physics

Candidate DD Generator

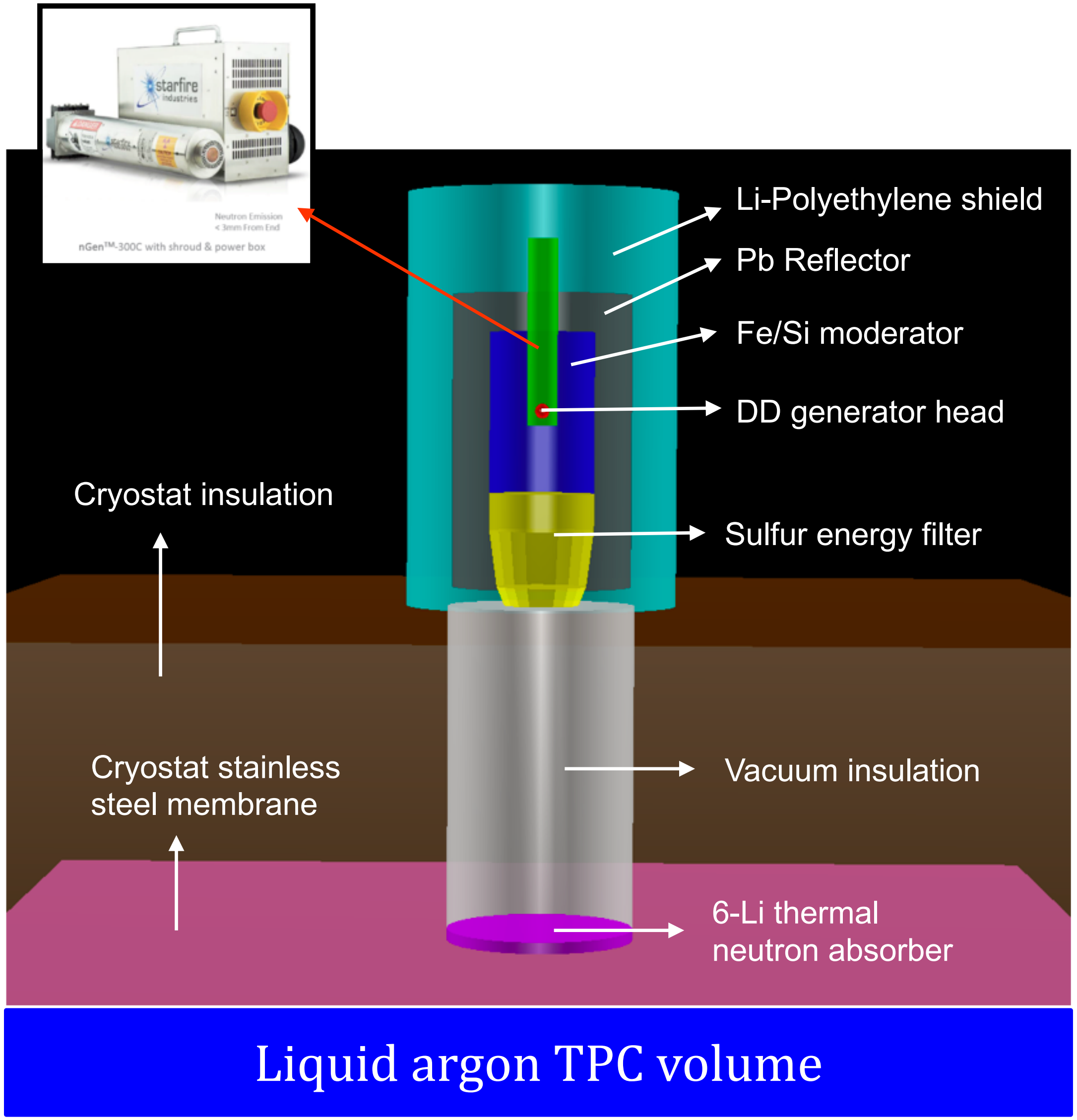
Neutron Emission
< 3mm From End

nGen™-300C with shroud & power box

SPECIFICATIONS

Neutron Output	
Time-averaged Yield	10^7 n/s
Pulsed DD Neutron Energy	2.5MeV
Ion Source Type	ECR-coupled plasma
Pulse Rate	Single shot to 200 kHz
Pulse Width	5-1000µs
Pulse Rise/Fall Time	< 5µs
Nominal Duty Factor	4-10%
Dark Current between Pulses	None
Max Neutron Flux	> 2×10^7 n/cm^2•s during pulse
Power and Operation	
Operating Voltage	150kV
Power Requirements	400W
System Information	
Neutron Source Dimensions	3" OD x 19.6" L (7.6 cm OD x 46 cm L); without shroud
Neutron Source Weight	11 lbs, 9 oz.
Supporting Hardware Dimensions	6.25" W x 10" H x 15.75" L (31 cm W x 31 cm H x 31 cm L)
Supporting Hardware Weight	29 lbs, 6 oz. + 5.5lb battery
Integrated cooling w/cowling Dimensions	3.5" OD x 22" long
Battery Operation Time	45 min (at 4% duty factor); 30 min (at 10% duty factor)

Neutron Moderator Design

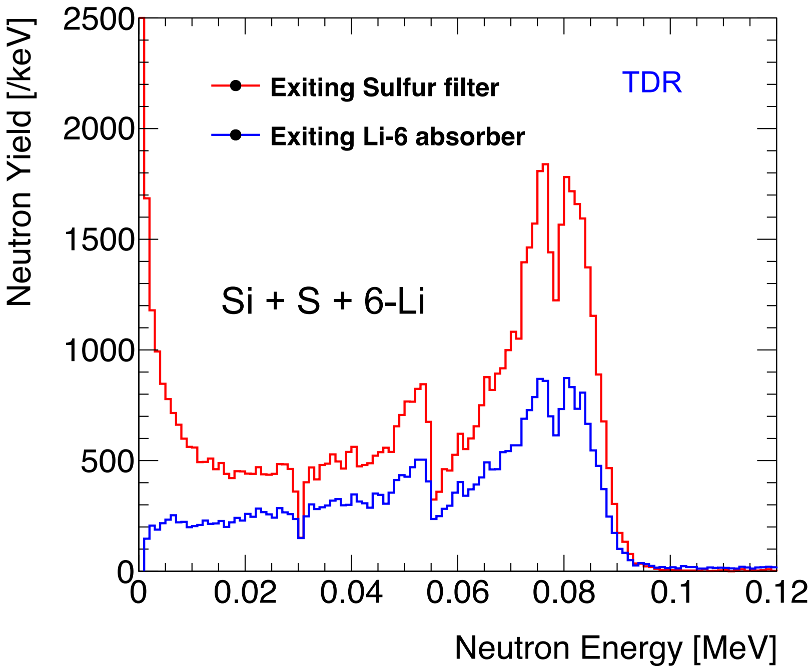


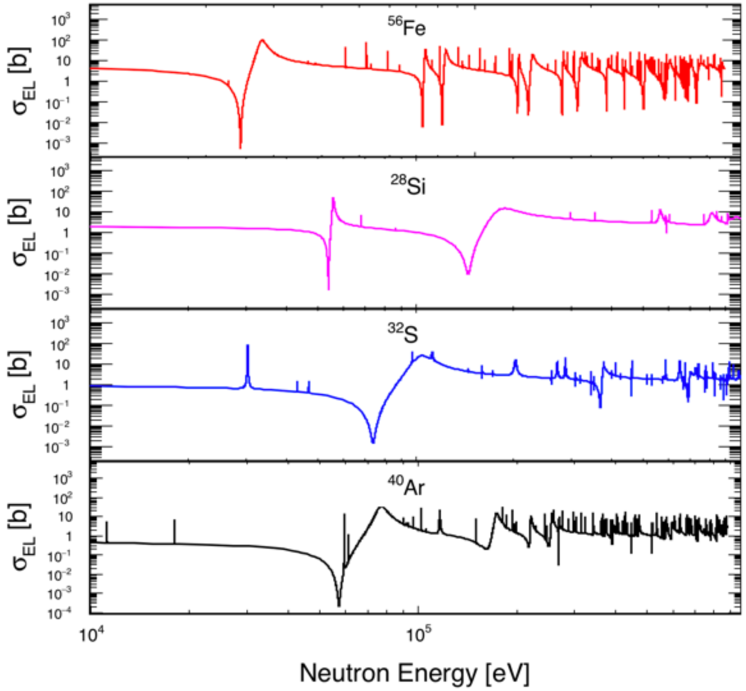
PNS Base Design:

- **DD generator** → 2.5 MeV neutrons
- **Fe/Si moderator** → efficiently reduce energy down to below 1 MeV
- **Sulfur filter** → select 73 keV neutrons
- **Pb/Bi reflector** → Increase neutron yield
- **6-Li absorber** → suppress thermal neutron fraction
- **Li-Polyethylene shield** → radiation protection

Moderator Performance

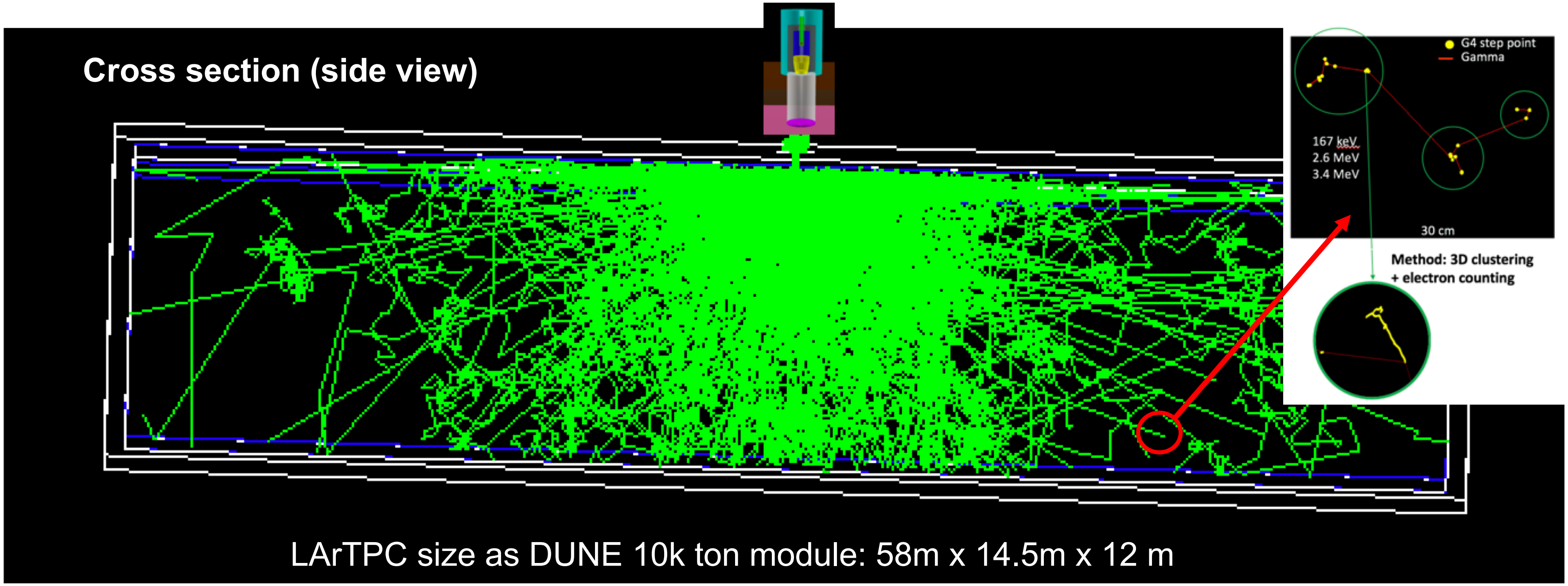
- Fe/Si-S-Li moderator can make 73 keV neutrons
  - Reach 57 keV after a few scatters, and then travel long distance in argon
  - Moderated neutron yield: **4.5% (fraction of surviving neutrons)**
- The spectrum of the moderated neutrons is used as an input to save simulation time





Neutron Transport in DUNE-size TPC

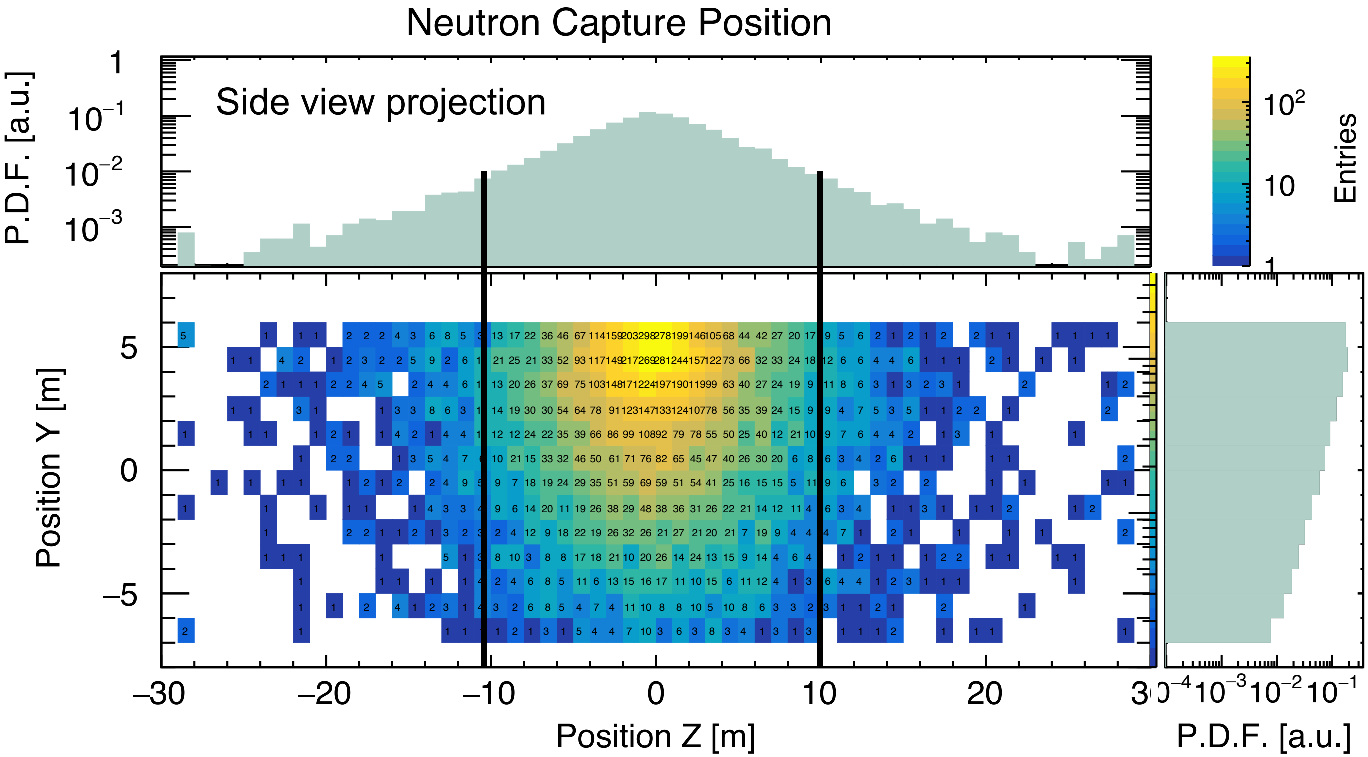
- **One source covers about 1/3 the DUNE-TPC.** Having **several** sources **is sufficient to cover the entire detector volume**
- Measurement of the **energy response at low energy (6.1 MeV)**
  - Provide energy scale and resolution at (x, y, z)
  - Access various detector response parameters: electron lifetime…
  - Test supernova trigger efficiency



LArTPC size as DUNE 10k ton module: 58m x 14.5m x 12 m

Neutron Capture Position

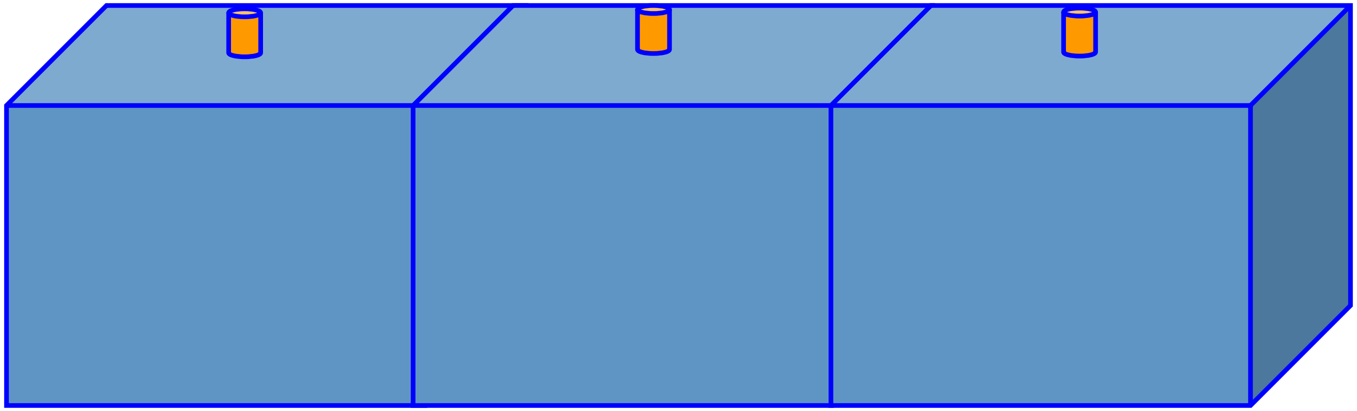
- Realistically, moderated neutrons around 73 keV are injected from the top of the cryostat through a port
- The neutron capture distribution depends on the scattering length that will be measured by the proposed ARTIE experiment at LANL.
- Need three neutron sources to cover the whole volume



- DD generator yield: 1e5 per pulse (100 μs)
- DAQ Rate: 0.5 Hz
- Run time: 3 minutes
- DD Pulses: 90
- DD neutrons: 9e6
- Neutron capture yield: ~0.13%
- Neutron captures: 12576

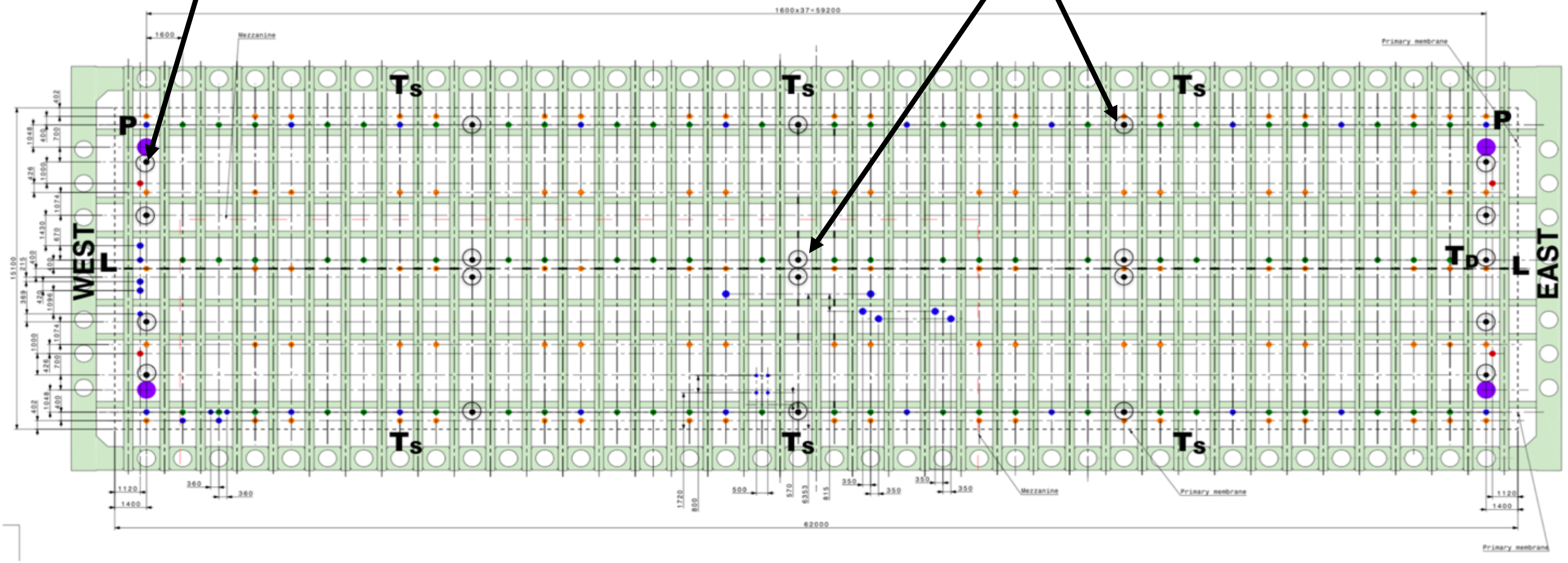
Nominal Design

- Ideally, we need three DD generators to cover the whole detector
- The neutron source can be permanently deployed on top of the cryostat
- We need less than one day for complete calibration



Existing Calibration Ports

- 25 cm feedthrough ports and 80 cm manholes are available for the PNS neutron source deployment.
- Two different types of penetration ports require different PNS designs

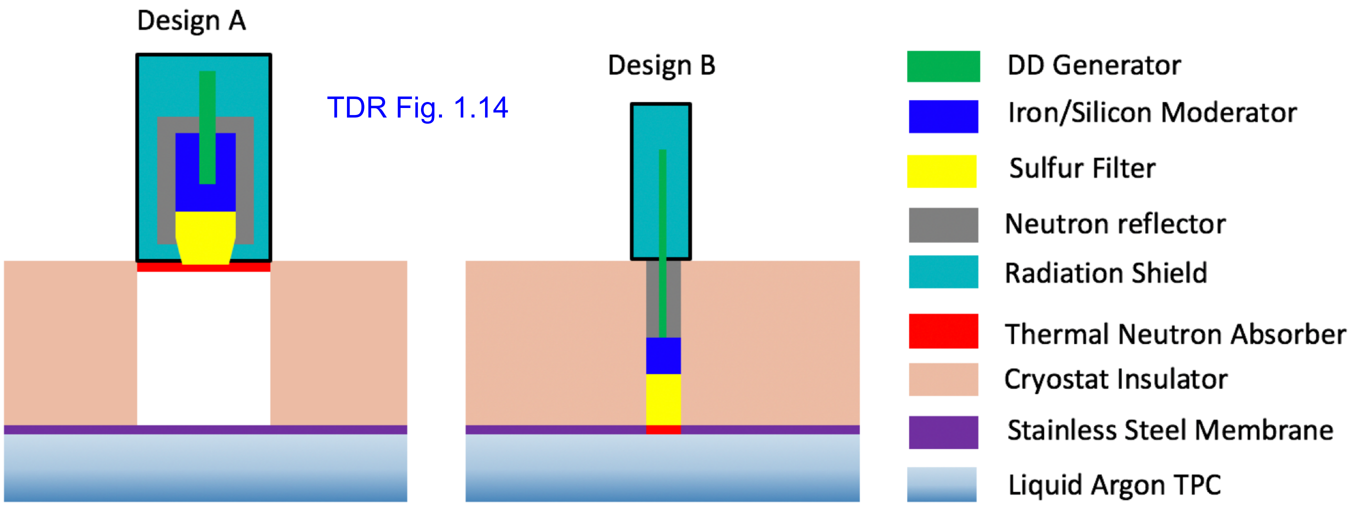


Purple circles: human access ports (manhole)

Multi-purpose calibration feedthrough

PNS Design and Location

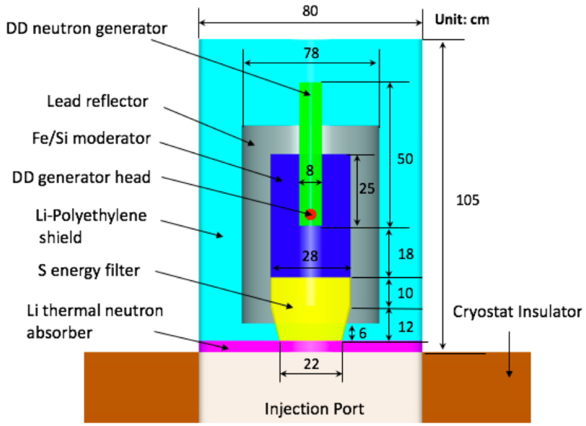
- Two basic designs currently in TDR
  - **Design A**: Large format PNS fully shielded; require large injection ports (e.g. manhole); can be placed inside the port
  - **Design B**: Small format PNS to be placed inside the 25 cm feedthrough ports; need extra shielding
- Current plan is to deploy two large sources at the human access ports (manhole), and one small movable source on top at the center of the cryostat using the feedthrough ports



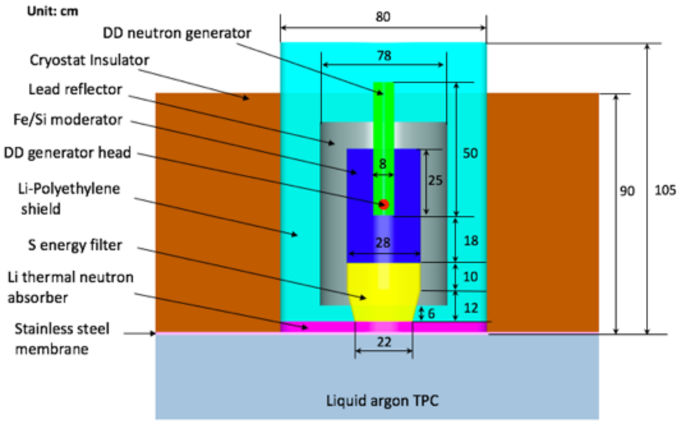
TDR Fig. 1.14

Design Options

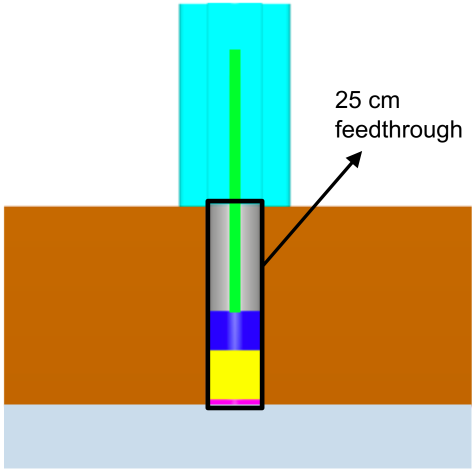
Design A-1: Above Manhole (base design)



Design A-2: Inside Manhole (alternative option)



Design B: inside feedthrough Base design)

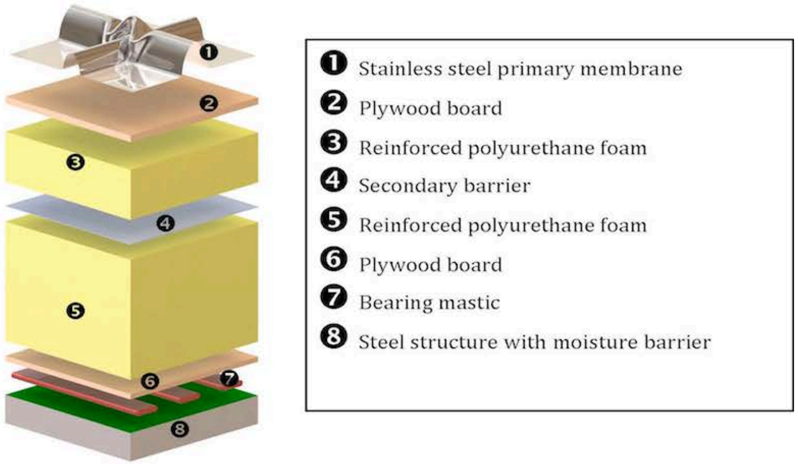


	Location	PNS Size [cm]	Weight [kg]	Neutron Capture Yield	Extra Shield
Design A-1	Above manhole	80 OD × 105 H	1600	0.13%	No
Design A-2	Inside manhole	80 OD × 105 H	1600	0.65%	No
Design B	Inside feedthrough	20 OD × 160 H	140	0.13%	Yes

Human Access Port Interface

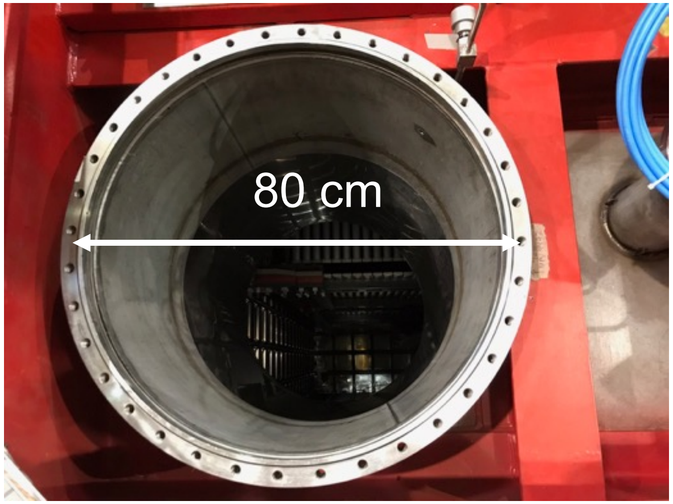
- Placing the PNS inside the manhole can gain a factor of 5 increase of the neutron yield.
- The modification of the current interface flange should be easy (confirmed by CERN engineer), but we need to evaluate the effect to heat insulation.

Cryostat insulation material

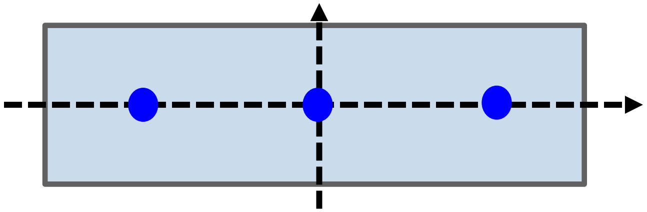


❶ Stainless steel primary membrane
❷ Plywood board
❸ Reinforced polyurethane foam
❹ Secondary barrier
❺ Reinforced polyurethane foam
❻ Plywood board
❼ Bearing mastic
❽ Steel structure with moisture barrier

ProtoDUNE manhole interface

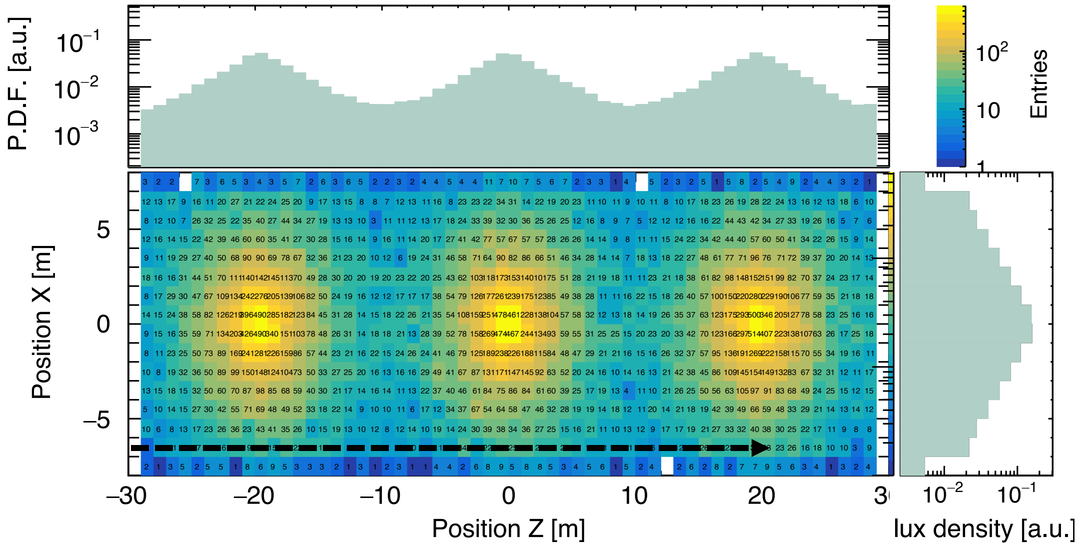


Ideal locations has good coverage

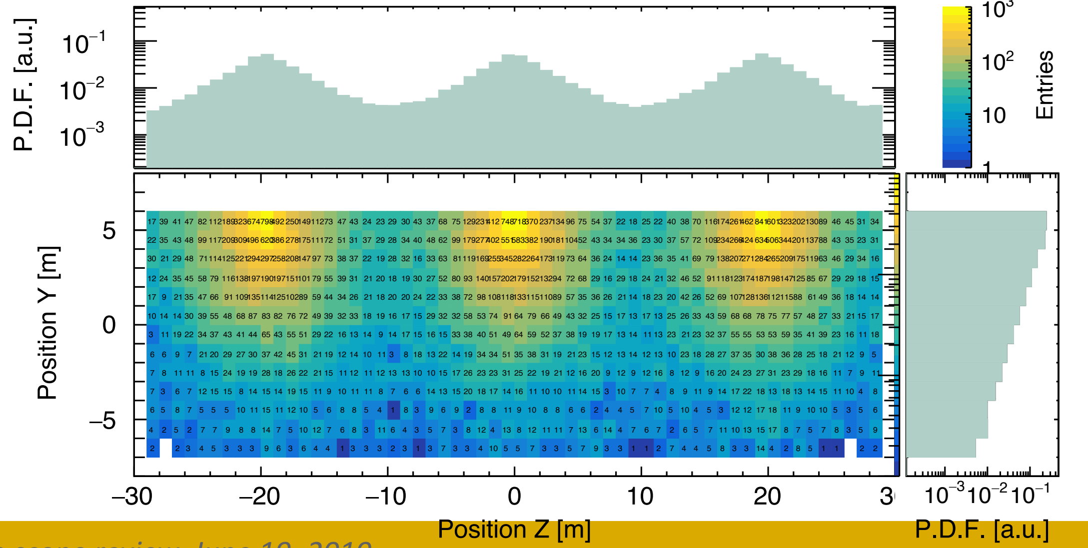


- Three large format PNS sources (Design A-1) at ideal locations can cover most of the TPC volume
- However, Locations are unavailable in the current cryostat design.

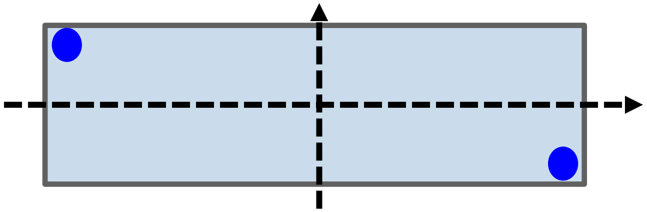
Neutron Capture: Top view projection



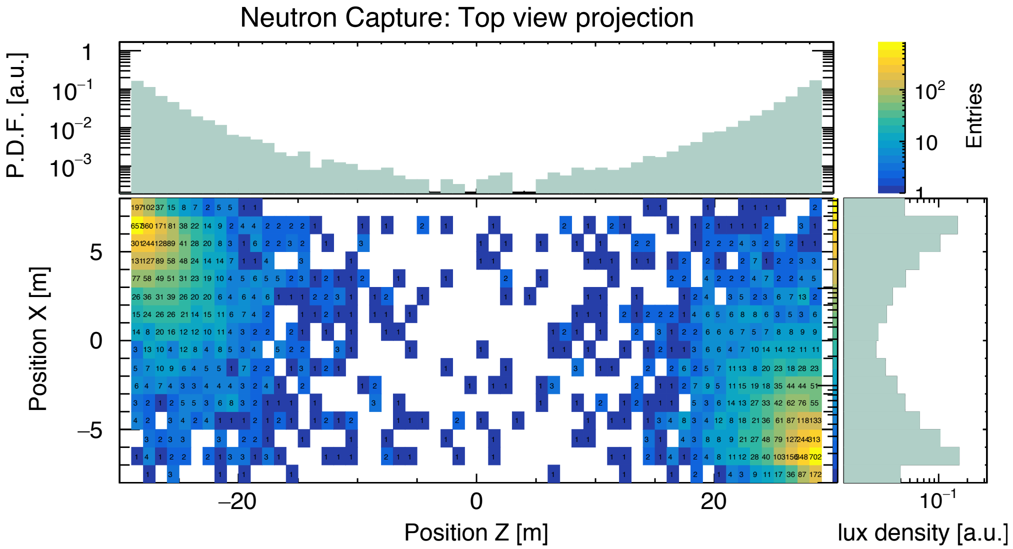
Neutron Capture: Side view projection



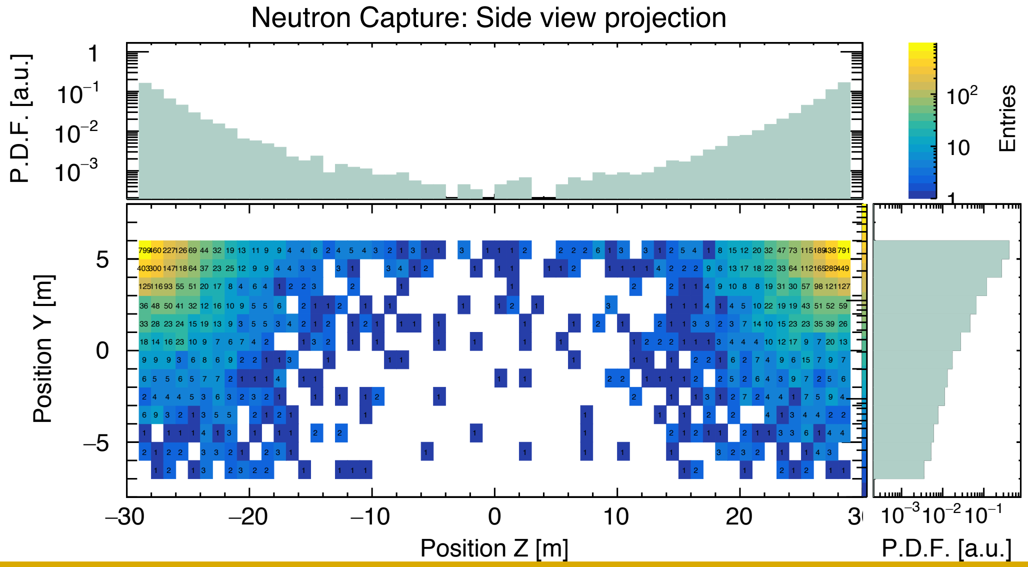
Two corner manholes are not sufficient



- In the current cryostat design, the corner manholes are available to deploy the large format PNS (Design A-1)
- Two PNS sources at manhole locations cannot cover the central volume of the detector
- Need additional neutron sources for the central volume→ small format PNS (Design B)

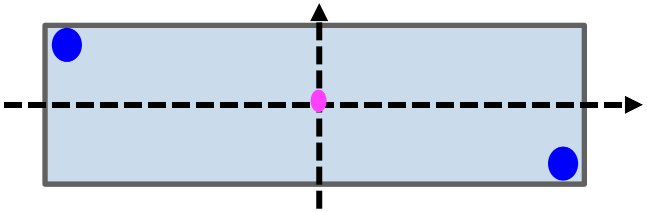


Neutron Capture: Top view projection

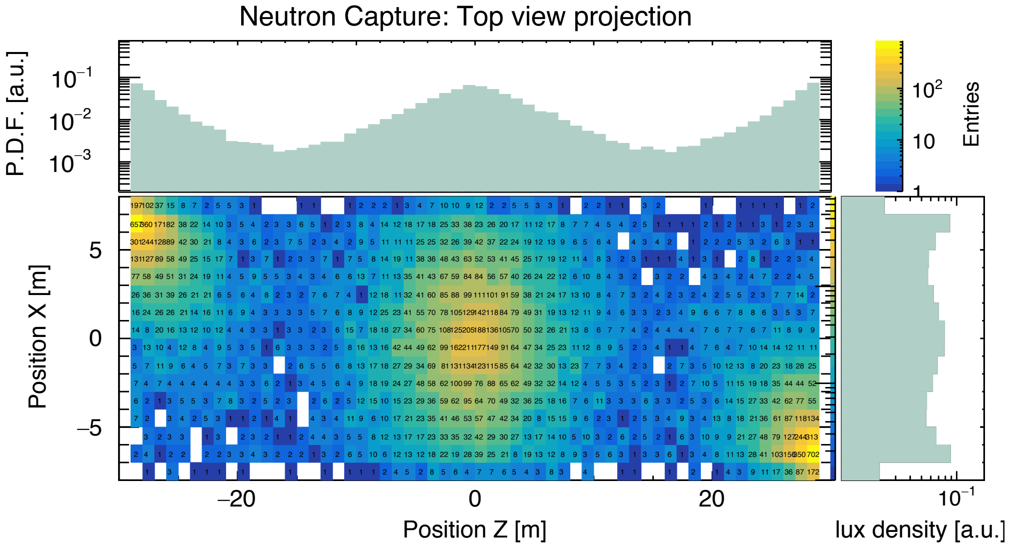


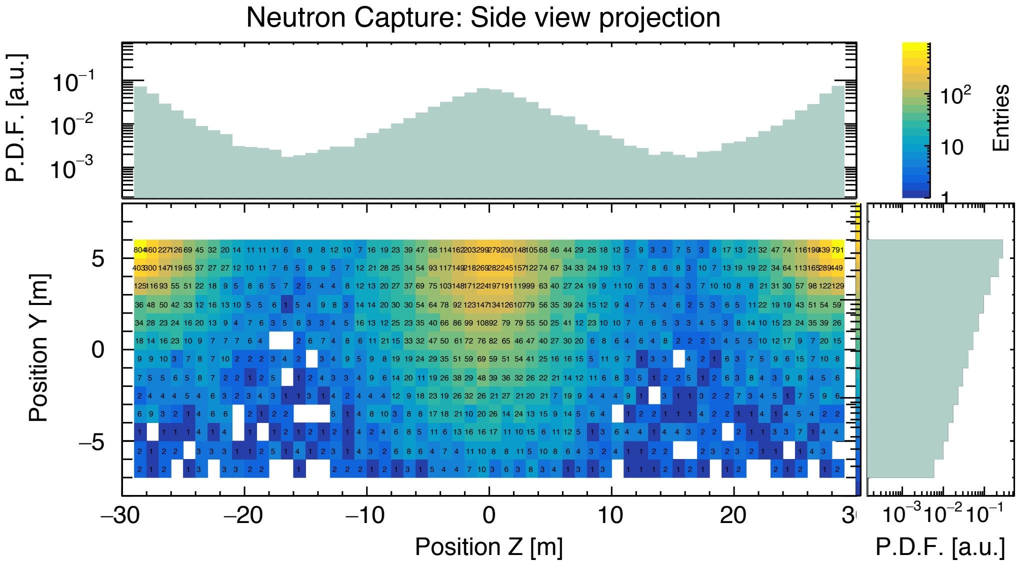
Neutron Capture: Side view projection

Additional small format PNS



- In the current cryostat design, the corner manholes are available to deploy the large format PNS (Design A)
- Two PNS sources at manhole locations cannot cover the central part of the detector
- Need to use the feedthrough to inject neutrons → movable small format PNS (Design B)





Data Volume Estimate

- The DAQ will be triggered by the DD generator pulses. The data size is simply **6.22 GB times the total number trigger pulses**
- Typically, a commercial DD neutron generator produces 10^5 neutrons/pulse (100 μs)
- Assumptions for evaluation of the data size:
  1) Assume that neutron capture positions are uniform inside the TPC
  2) Need more than 100 neutron captures **for every m^3** → 6×10^5 neutron captures in total for a 10 kt TPC
  3) About **0.13%** initial DD neutrons are captured in liquid argon → need 4.6×10^8 initial DD neutrons → 4600 pulses are needed
  4) Number of triggers = 4600 pulses / 3 DD generators = 1540 triggers
  5) Calibration time: 1540/0.5Hz = 50 minutes (to be updated for non-uniform distribution, expect a factor of 10 increase of calibration time)

1540 triggers x 6.22 GB = 9.5 TB /run

- If we run the PNS system twice a year, the total data size is 19 TB /year (Note: number not same as TDR)

Radiation Shielding

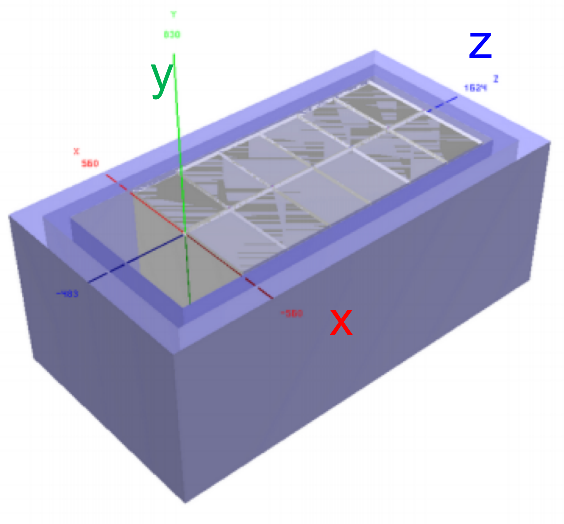
- The goal of the shield is to block both scattered neutrons and gammas which are produced in the source
- Lithium-Polyethylene (7.5 %) is chosen to be the material for the neutron shield because it’s very effective in blocking neutrons and reducing gammas
- The main 2.2MeV gammas are a characteristic signature for neutron captures on hydrogen. The dose of radiation is calculated for
- For Design A large format neutron source, simulation indicates that 12 cm of Lithium-Polyethylene shield satisfies basic safety requirements
- For Design B small format neutron source, as there is no sufficient space inside the feedthrough port for the shielding materials to fit in, the neutrons would be shielded by the cryostat insulation materials.
- Need to study the shielding capability of the insulation materials

PNS Simulation Needs

- **Neutron source design**
  - Neutron moderator optimization in Geant4 (done)
  - Radiation shield design (done, need cross-check)
- **Neutron transport simulation with real TPC materials (ongoing)**
  - Single Phase TPC: APA, CPA, Photodetector, Field cage, Foam insulation…
  - Dual Phase TPC: CRP, Field cage, Photodetector, Foam insulation…
- **Neutron capture tagging in TPC**
  - Neutron capture tagging (ongoing)
  - Photodetector sim & reco for t0 determination(not done yet)
- **Analysis**
  - Validation of calibration capabilities: energy deposition, electro life time, field non-uniformity… (ongoing)

Realistic Neutron Transport in LArSoft

- Validation of neutron transport in LArSoft
  - Use real TPC materials
  - Shoot ideal 57 keV neutrons along z direction
- Neutrons travel through argon; captures may be concentrated in TPC components
- Next: Confirm materials in simulation; inject neutrons with realistic energy spectrum



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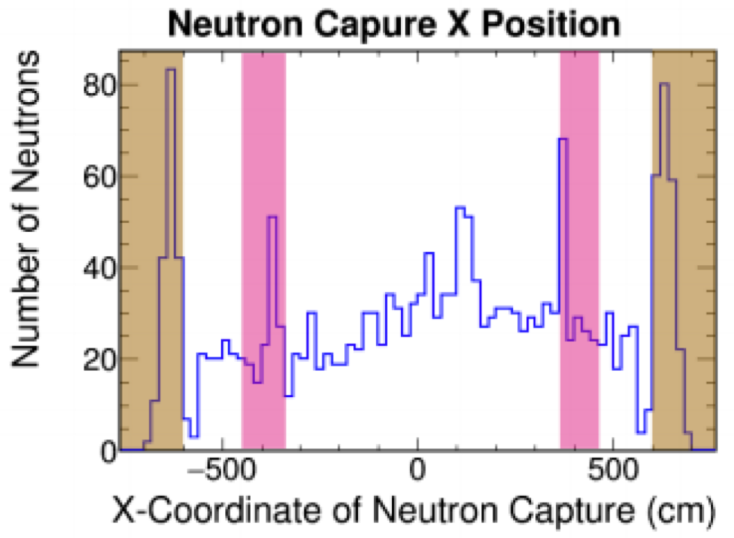
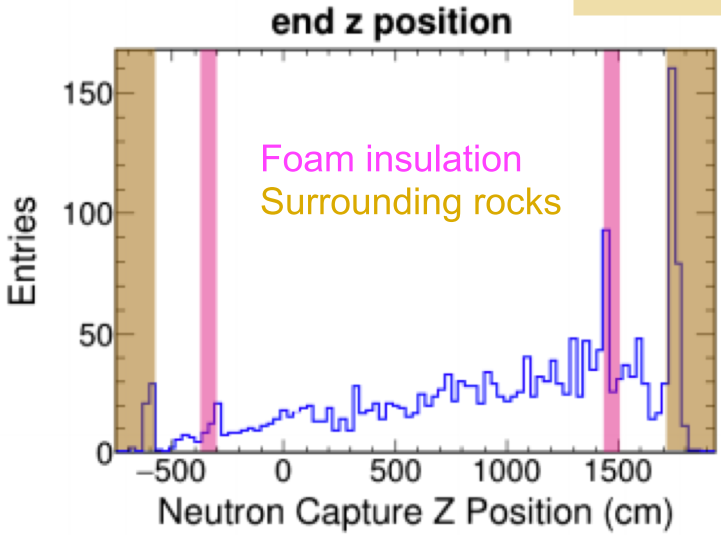
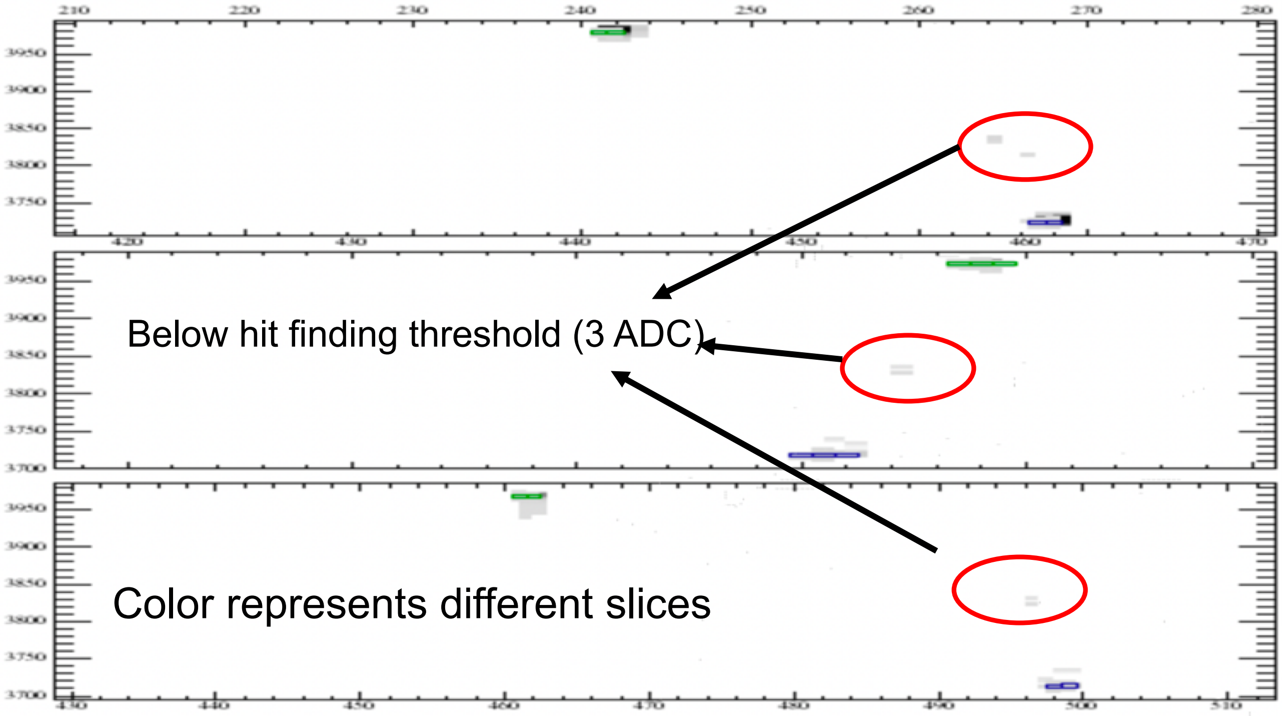




Neutron Capture Reconstruction

- Default neutron capture gammas in LArSoft is wrong (same issue for Gd).
- Current simulation use correct gamma cascade input from text file
- Challenge to reconstruct such events, but initial studies show charge of collected hits is sensitive to detector response parameters

Event display



Below hit finding threshold (3 ADC)

Color represents different slices

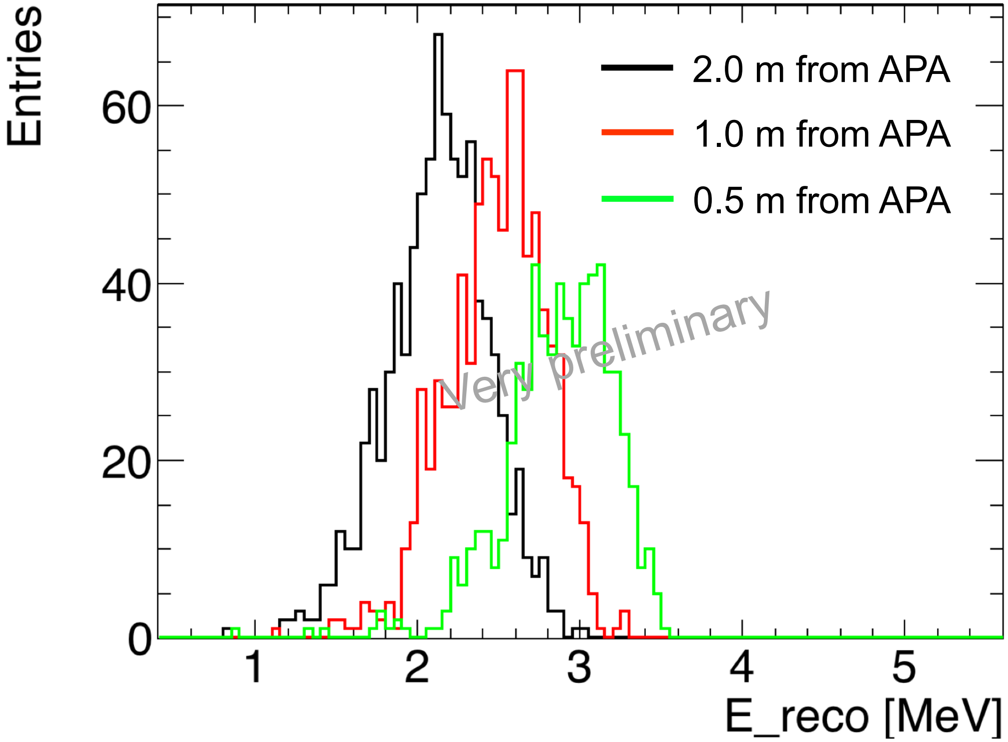
collection

induction

induction

Neutron Capture Energy Reco

- Measured charge spectrum at three different positions (Simulation running)
  - Point source of gamma cascade: 0.5m, 1m, 2m from APA
  - 6ms electron lifetime
  - Without lifetime or recombination correction



Risks of PNS

Dedicated experiment @ LANL

Test @ Berkeley
Test @ ProtoDUNE

High intensity DD generator,
Wider pulse width

Design B neutron source using feedthroughs

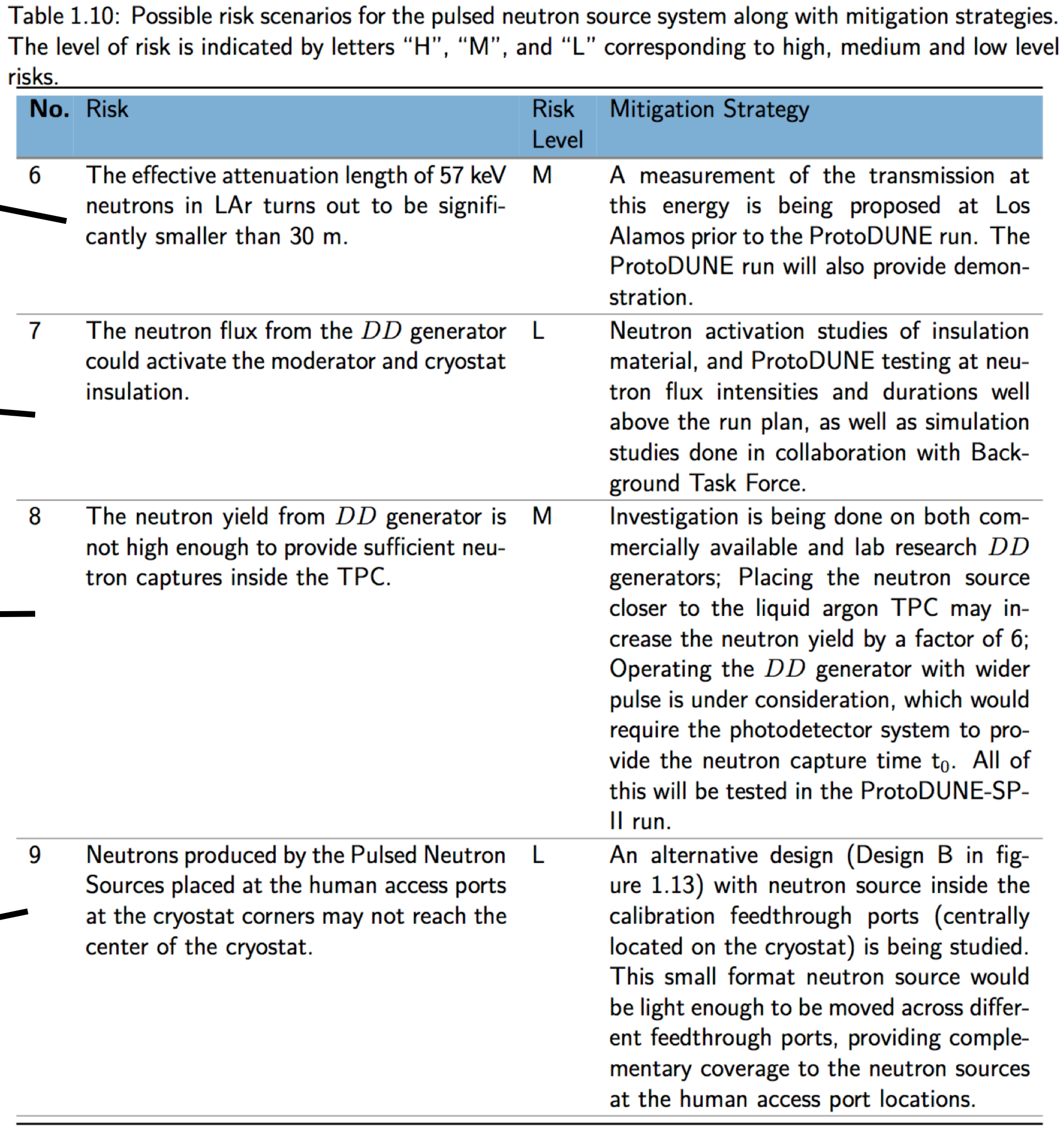
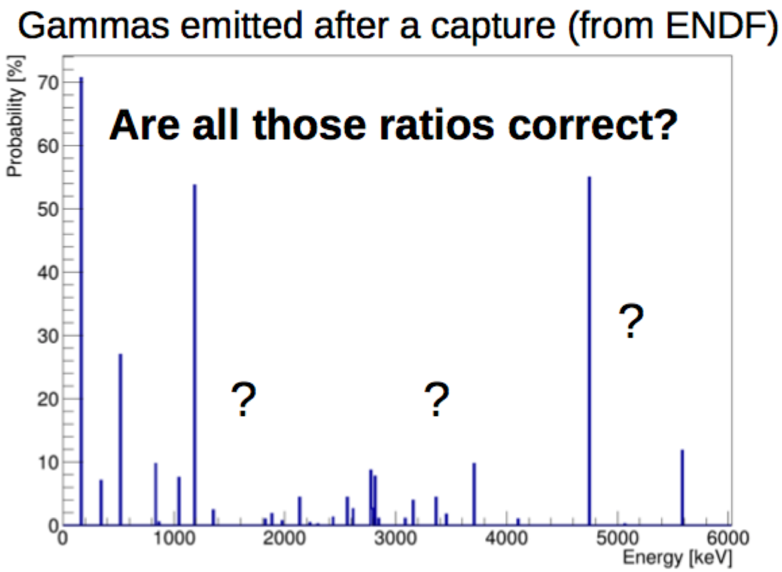


Table 1.10: Possible risk scenarios for the pulsed neutron source system along with mitigation strategies. The level of risk is indicated by letters "H", "M", and "L" corresponding to high, medium and low level risks.

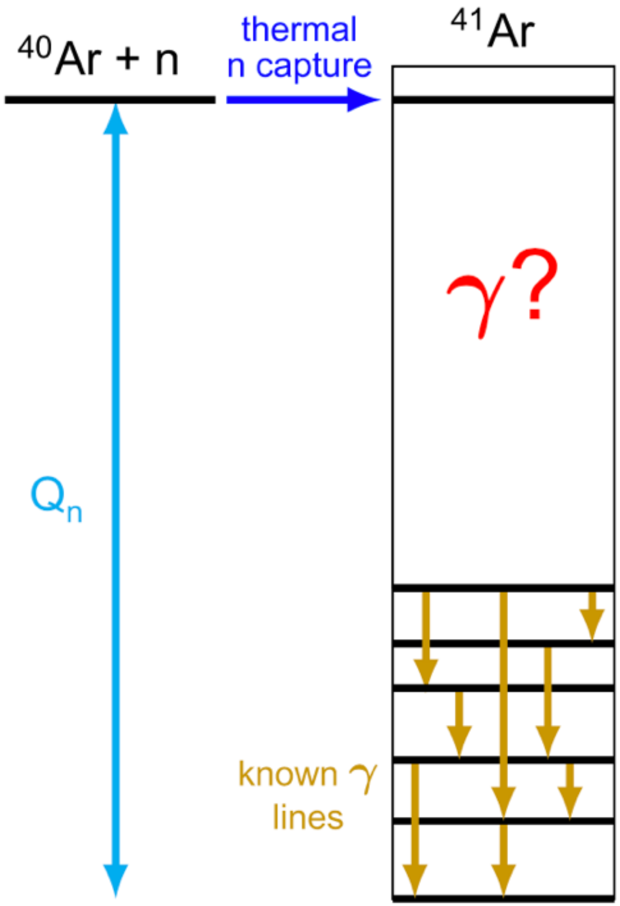
No.	Risk	Risk Level	Mitigation Strategy
6	The effective attenuation length of 57 keV neutrons in LAr turns out to be significantly smaller than 30 m.	M	A measurement of the transmission at this energy is being proposed at Los Alamos prior to the ProtoDUNE run. The ProtoDUNE run will also provide demonstration.
7	The neutron flux from the DD generator could activate the moderator and cryostat insulation.	L	Neutron activation studies of insulation material, and ProtoDUNE testing at neutron flux intensities and durations well above the run plan, as well as simulation studies done in collaboration with Background Task Force.
8	The neutron yield from DD generator is not high enough to provide sufficient neutron captures inside the TPC.	M	Investigation is being done on both commercially available and lab research DD generators; Placing the neutron source closer to the liquid argon TPC may increase the neutron yield by a factor of 6; Operating the DD generator with wider pulse is under consideration, which would require the photodetector system to provide the neutron capture time t_0. All of this will be tested in the ProtoDUNE-SP-II run.
9	Neutrons produced by the Pulsed Neutron Sources placed at the human access ports at the cryostat corners may not reach the center of the cryostat.	L	An alternative design (Design B in figure 1.13) with neutron source inside the calibration feedthrough ports (centrally located on the cryostat) is being studied. This small format neutron source would be light enough to be moved across different feedthrough ports, providing complementary coverage to the neutron sources at the human access port locations.

How well do we understand the gamma cascade?

- The spectrum of correlated gamma cascade is not well understood
- Some well-known low-lying levels were measured in activation experiment, but many high-lying levels are unknown, and are difficult to be determined theoretically

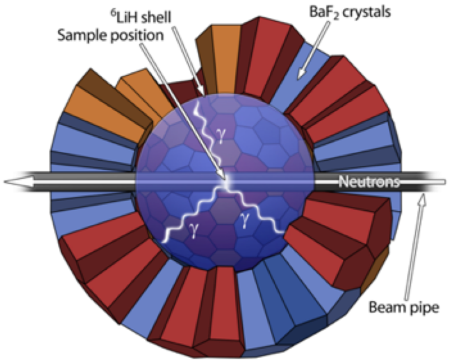

Gammas emitted after a capture (from ENDF)

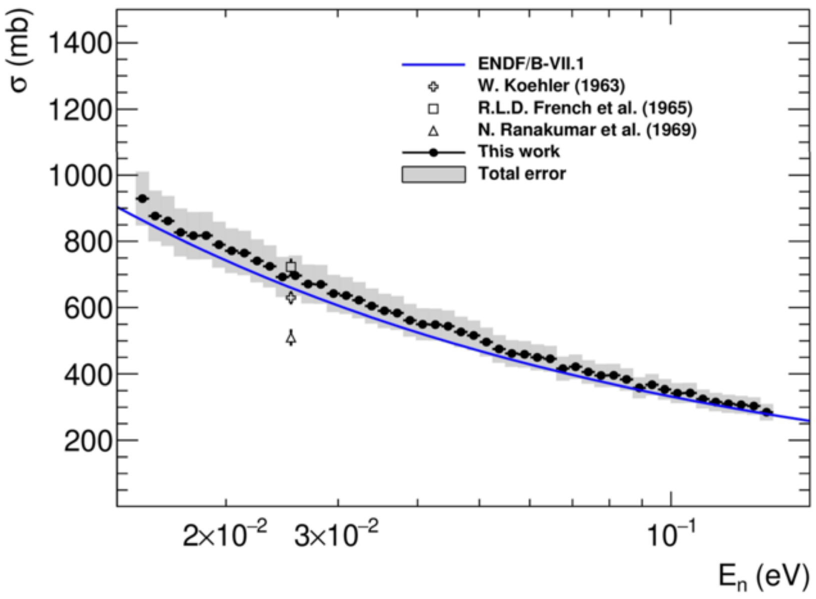
Are all those ratios correct?

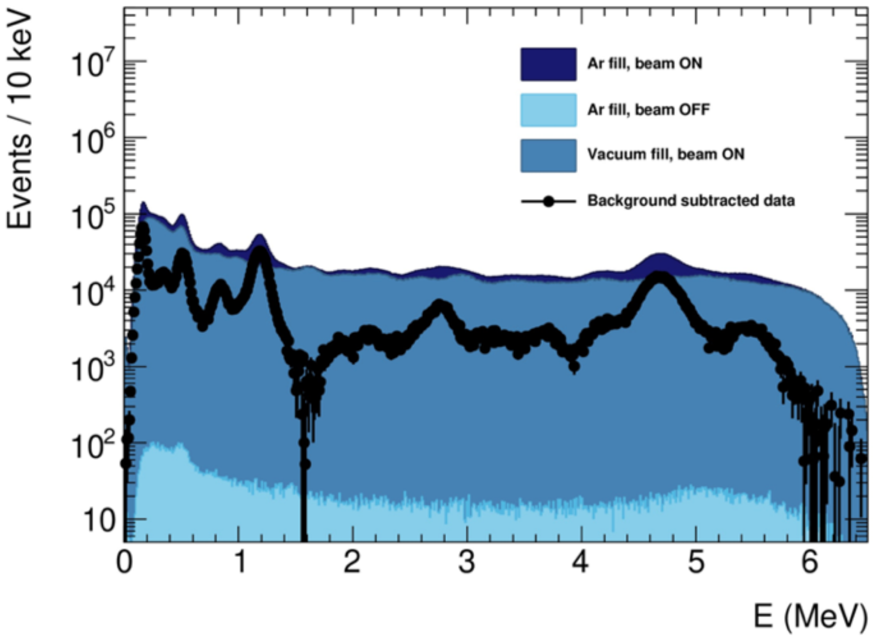


R&D: Understanding neutron captures

- Argon Capture Experiment at DANCE (ACED)
  - Measure the radiative neutron capture cross section in argon at thermal energies
  - Measure the branching ratios of the correlated gamma cascade on event-by-event basis



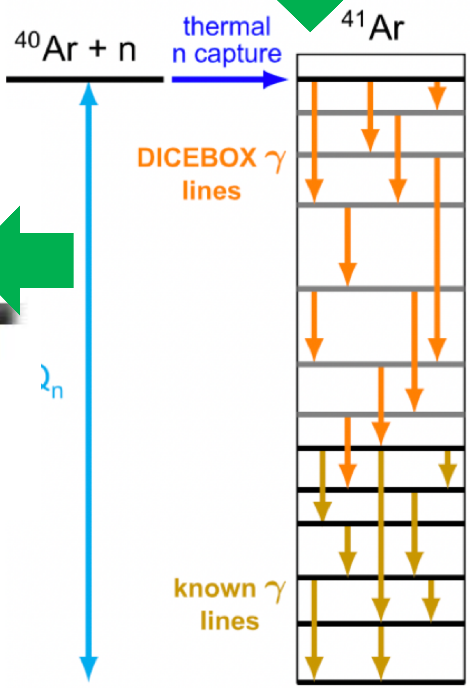




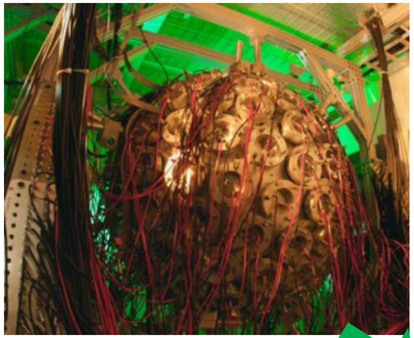
R&D: Analyzing Correlated Gamma Cascade

- Use a code called DICEBOX to generate realistic decay schemes for ^{41}Ar as a function of well-known lines and nuclear theory
- Simulate those decays in well-tuned DANCE simulation
- Compare those simulations to our data and find the most compatible solution

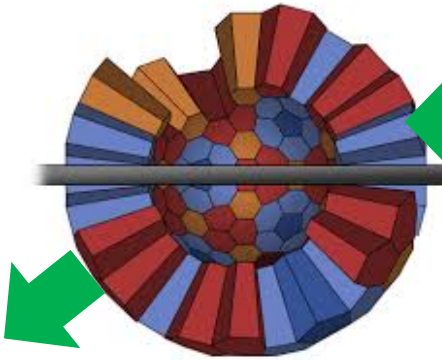
DICEBOX

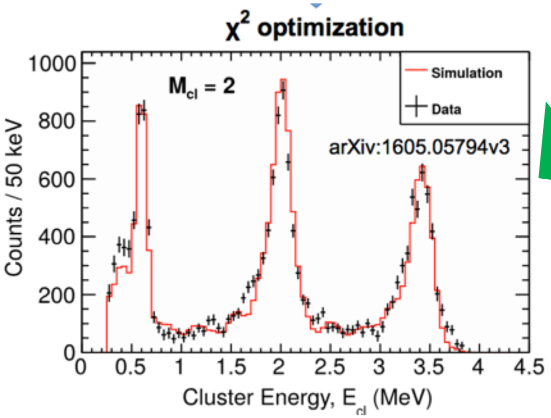


ACED Measurement



Data analysis underway





R&D: Verifying the 57 keV anti-resonance

Argon **R**esonant **T**ransport **I**nteraction **E**xperiment

ARTIE

Proposed measurement of 57 keV neutron anti-resonance in 40-Ar at LANSCE.
Important for calibration, reconstruction, and simulations in liquid argon

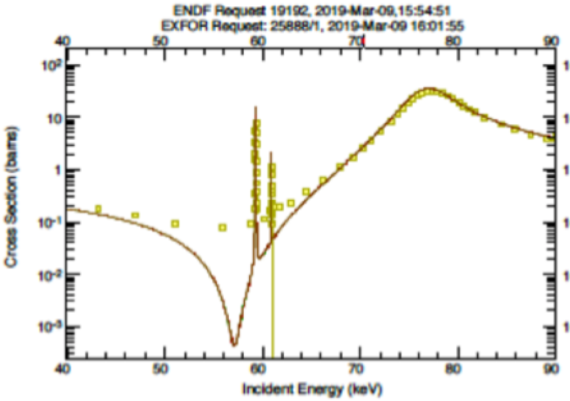
Isotope	abundance (%)	σ at 57 keV (b)	contribution to σ (b)	scattering length (m)
^{40}Ar	99.6035	1×10^{-3}	0.996×10^{-3}	343
^{38}Ar	0.0629	1.0	6.29×10^{-4}	542
^{36}Ar	0.3336	3.0	1.00×10^{-2}	34
Total			1.16×10^{-2}	29

Table 1: Argon isotopes and contributions to scattering length at 57 keV.

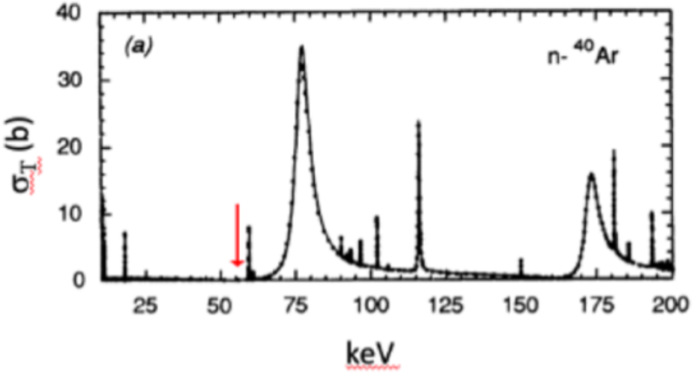
According to ENDF neutron transport in the resonance region is dominated by 36-Ar

Curve is ENDF (used by GEANT)

Points are data



One previous experiment did not see the anti-resonance, but may not have been sensitive…



R.R. Winters, R.F. Carlton, C.H. Johnson, N.W. Hill, and M.R. Lacerna, Phys. Rev. C 43 492 (1991)

Beyond TDR: Tests & Analysis

- Relevant tests:
  - Possible moderator test at UC Berkley High Flux Neutron Source
  - ARTIE experiment at Los Alamos (proposal submitted, possibly to be done in early fall)
- Physics studies:
  - Update the neutron cross-section library and fixed the gamma cascade generator in LArSoft
  - Develop neutron capture tagging and reconstruction algorithms
  - Study the impact on supernova neutrino measurement
- Get a DD generator and build a prototype
  - Possibly through Small Business Innovation Research (**SBIR**)
- First operation at ProtoDUNE-SP detector at CERN

PNS Working Group

- **UC Davis**: Robert Svoboda, Mike Mulhearn, Jingbo Wang, Grace Meeker, Junying Huang, Yashwanth Sai Bezawada
- **Boston University**: Chris Grant
- **University of Pittsburgh**: Donna Naples, Emily Harris, Logan Rice
- **Michigan State University** : Kendall Mahn
- **University of Iowa:** Paul Debbins, Jane Nachtman, Yasar Onel
- **LIP (Portugal)**: Jose Maneira, Sofia Andringa

Summary

- Pulsed Neutron Source system provides a method to calibrate the energy scale, resolution, and other detector response parameters and their position dependence.
- Current design requires two large format neutron sources at the human access hole locations, and one small format neutron source at the central feedthrough
- Full LArSoft simulation with real TPC materials has started. Need to confirm the far detector geometry and materials
- Neutron capture reconstruction has shown sensitivity to relevant physics
- Aiming at building a prototype to be tested in ProtoDUNE at CERN

Backup

Charge Questions

- The baseline design uses two human access ports to cover full detector. Are other options being considered and what are the benefits and risks of these alternative options?
  - Two-manhole design is not optimal. The central part of the TPC volume is uncovered.
  - Need a movable small format source inside the calibration feedthrough to compensate the coverage in the center volume. The space inside the feedthrough is not sufficient for full radiation shielding, so extra shielding on top of the cryostat around the feedthrough is needed.
- Please comment on outstanding issues as well as plans for R&D and the implementation of a prototype system for ProtoDUNE-II?
  - ACED gamma cascade analysis
  - ARTIE measurement verifying the scattering length
  - Neutron capture tagging from cosmic and radiological backgrounds

Technical/integration questions

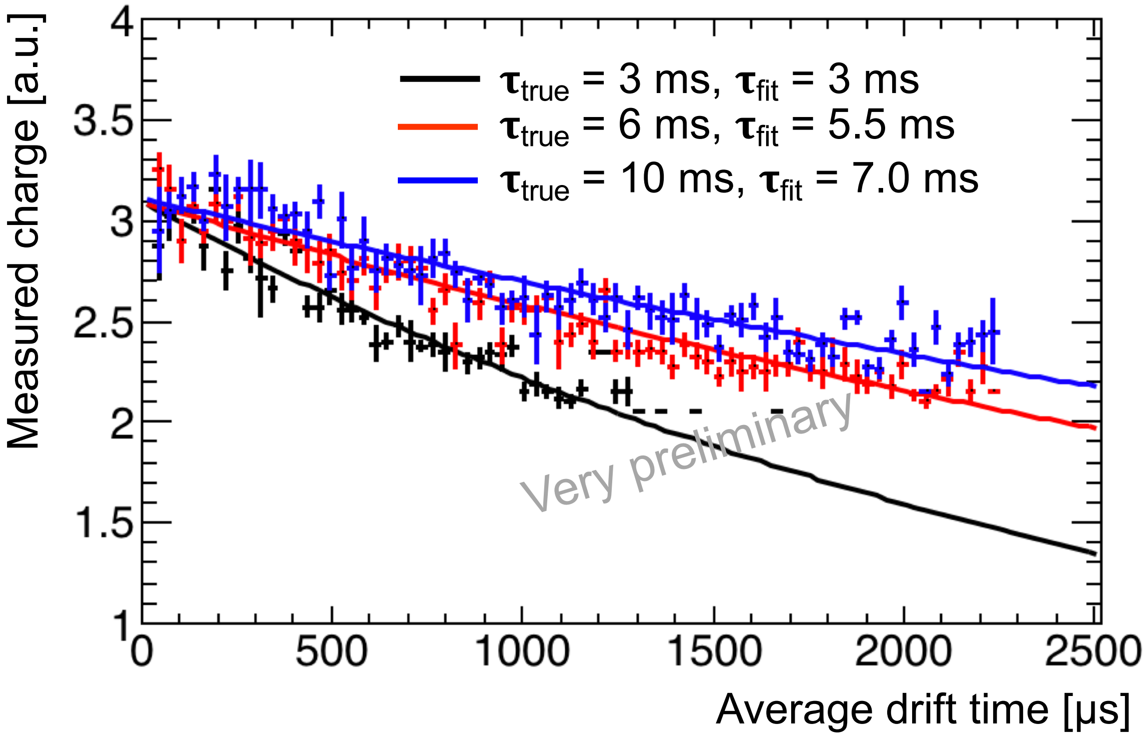
- Are the human access ports (manholes) sufficient or not? If not, we need a strong and clear justification based around size of voxels in the detector or run time. (Sowjanya, Kendall)
  - Not sufficient.
  - Voxelization in case of non-uniform neutron capture is under study. Current run time in TDR assumes uniform neutron capture distribution. Better uniformity can be achieved by adding more neutron sources.
- We need to show the sources give us sensitivity to energy and detector resolution at the relevant energies. Are you each preparing a simple set of plots of "detected charge" or "detected energy", and event displays of events (Kendall)
  - Done with ProtoDUNE-SP geometry (no cosmic or radiological background)
- Give very clear numbers how long (in hours/days) does a calibration campaign take, how many per year and the justification (Jose)
  - Determined by the DD generator neutron yield and the neutron transport.

Many Others

- The following list is the example of directory/file structure that will have to sit in EDMS for each consortium (suggestion from TC):
  1) 3D models
  2) Part drawings
  3) Production documents
  4) Grounding diagram
  5) System Level block diagrams
  6) Wiring diagrams
  7) Printed Circuit boards
  8) Cable and Wire documentation
  9) Interface documents
  10) Engineering notes

Sensitive to electron lifetime

- Using textfilegen module, generate 1000 correlated gamma cascades that are evenly distributed within the ProtoDUNE-SP Detector.
- Run full reconstruction and calculate the total charge from all hits.
- Define the drift time of a neutron capture as the averaged drift time weight by charge of individual hit, assuming true t0 is known.

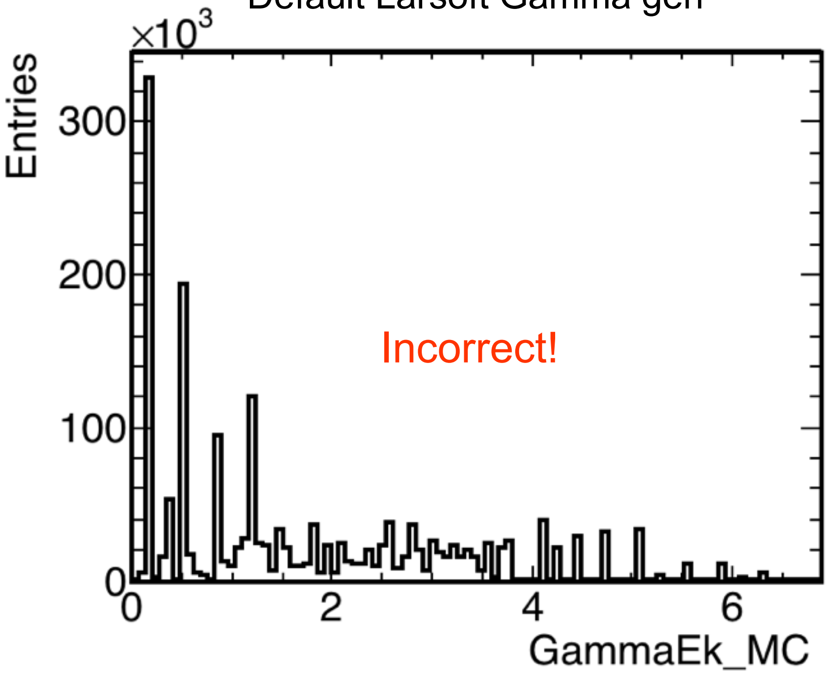


How many neutrons are needed per m^3

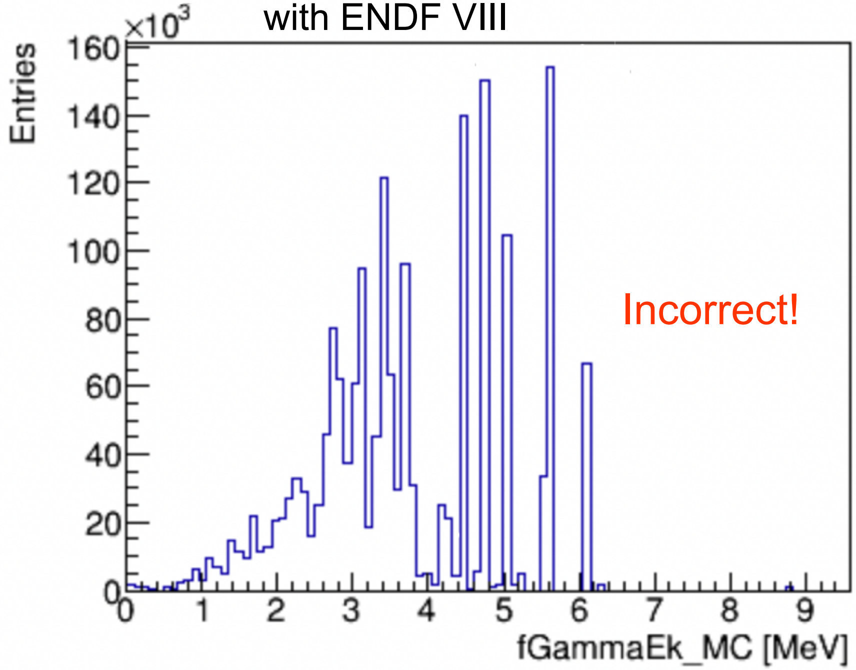
- Need 100 captures per m^3
- Event scale size is 20 cm. resolution on detector effects.
- 100 captures with reasonable run time

Neutron gamma spectrum in LArSoft is wrong

- The default gamma cascade generator is incorrect in LArSoft
- Even after the installation of the latest ENDF library, the gamma cascade generator is still incorrect.
- We developed code to generate the right spectrum. Need to adapt it to LArSoft

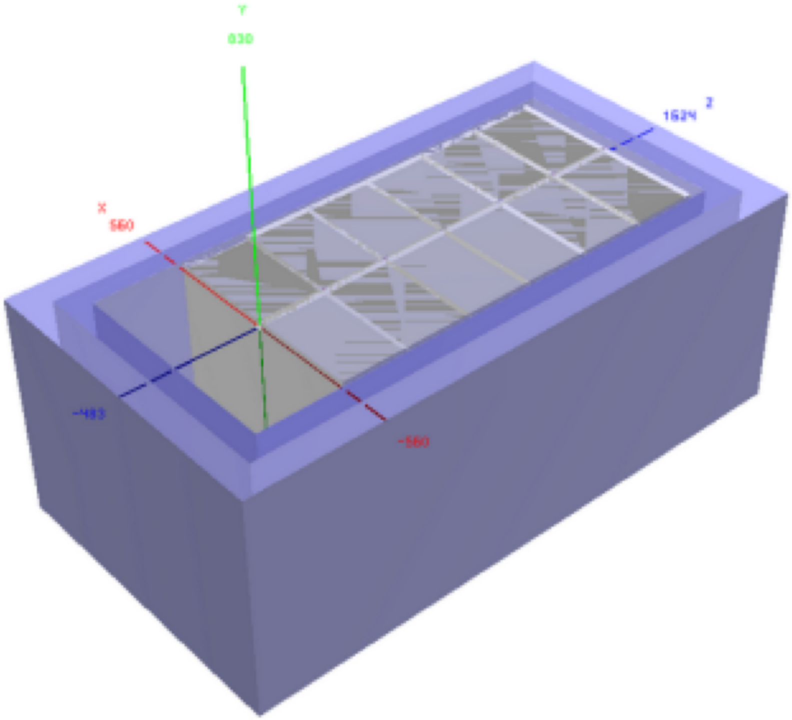

Default Larsoft Gamma gen

Incorrect!


Default Larsoft Gamma gen with ENDF VIII

Incorrect!

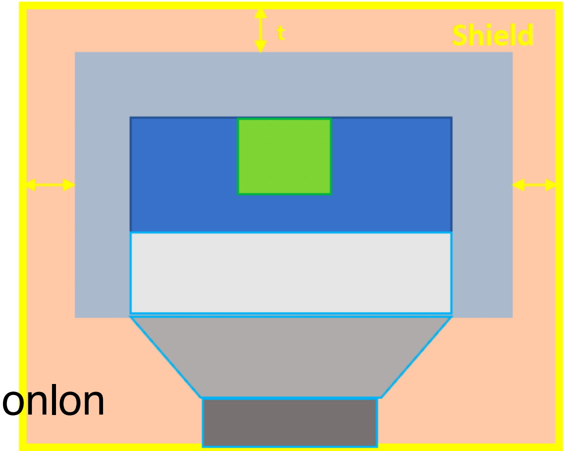
1x2x6 Geometry



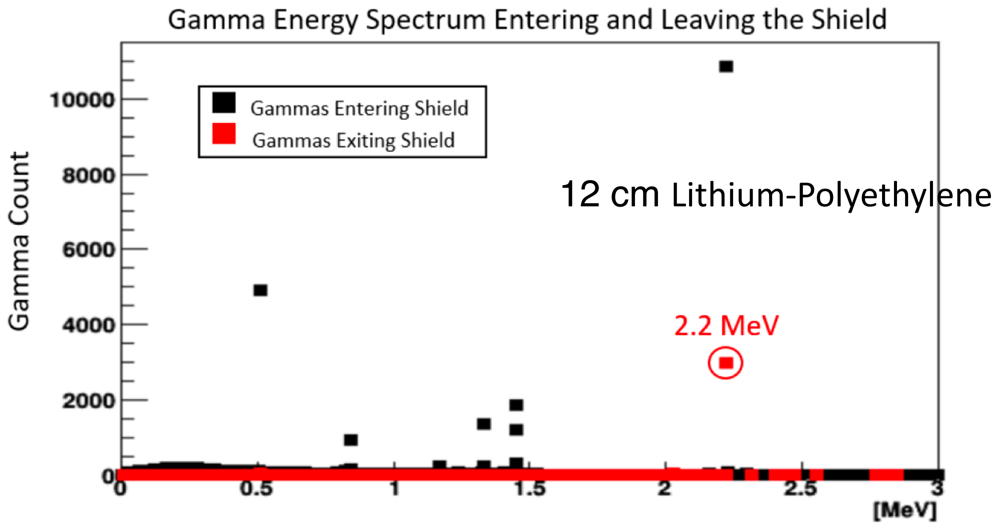
- Defined in the /dune /Geometry/ gdml/dune10kt_v4_1x2x6*.gdml files.
  - 1 row of APAs, 2 APAs high, 6 APAs deep.
  - Around the APAs are the field cage and the CPAs.
  - Around the field cage and CPAs is insulating foam.
  - Around the foam is a steel support box.
  - Around the support box is the detector enclosure (cavern).
  - Everything is surrounded by rock.

Preliminary Shielding study

- Lithium-Polyethylene is used as the shielding material
- Shield is to block both neutrons and gammas from neutron capture
- 2.2 MeV gamma peak is from neutron capture on hydrogen
- Shield can effectively block the lower energy gammas peaks but is only able to degrade 2.2 MeV gammas
- The dose of radiation form 2.2 MeV gammas is 1.8×10^{-7} mrem per pulse (10^6 neutrons) for a person standing 1 meter away from the source
- The source could run 7.7×10^7 shots per day being compliant with the limit (5 merm annual radiation dose) set by Nuclear Regulation Commission (NRC)



S.Conlon


Gamma Energy Spectrum Entering and Leaving the Shield

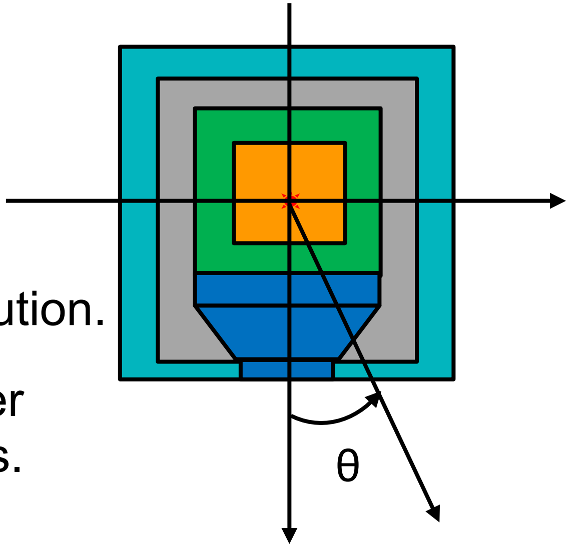
12 cm Lithium-Polyethylene

Measurement Program

- The neutron capture location along drift direction is determined by the electron drift time:
  - Rough t_0 provided by the DD generator: smeared by the DD neutron pulse width (can be tuned down to 10 μs level) and the neutron capture time (150 μs)
  - Precise t_0 provided by the photodetector system: the neutron source has to be operated at low intensity to avoid photodetector pileup.
- 39-Ar background strongly suppressed by opening a short window of ~100 μs after the DD pulse
- **Ideally, measure the neutron capture gammas for every m^3 volume.**

DD generator modeling

- The neutron initial direction is modeled with a the experimental measurement in Ref [1].
- The angular distribution in Ref [1] is adapted to the coordinates in the simulation.
- Forward neutrons follow the measured angular distribution.
- Set a flat distribution for backward neutrons. The paper shows no measurement for backward emission angles.



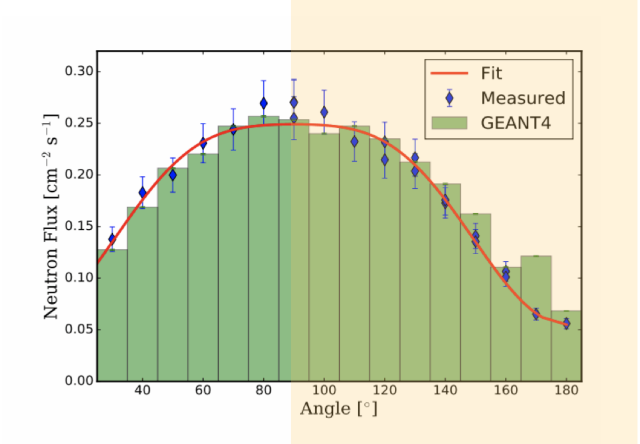
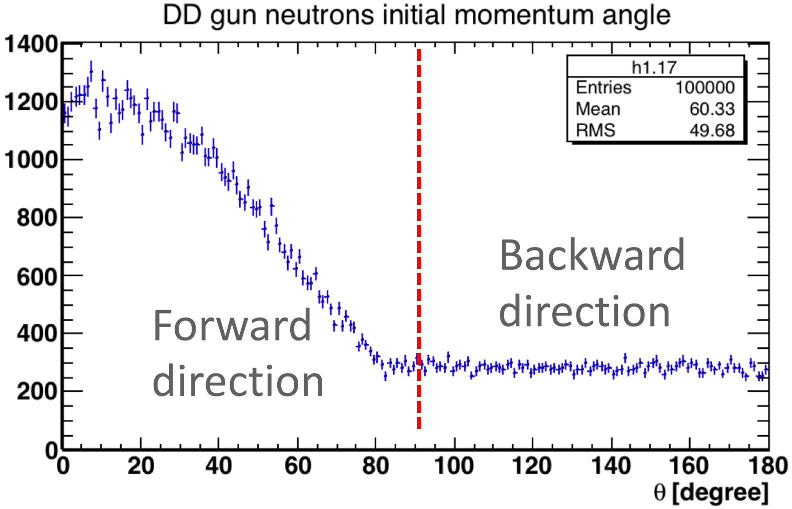


Figure 9: Measured neutron flux as function of polar angle. Data taken with the the Long Counter is shown (blue diamonds) together with the angular neutron flux dependence predicted by a detailed GEANT4 simulation of the neutron generator (green bars). A fourth order polynomial fit to the data is shown as well (red line), parametrizing the measured dependence.



[1] R.F. Lang, et. al., Nucl. Instrum. Methods, 879 (2018), P. 31-