Pulsed Neutron Source (PNS) Calibration System

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DUNE CALCI Scope Review
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Outline

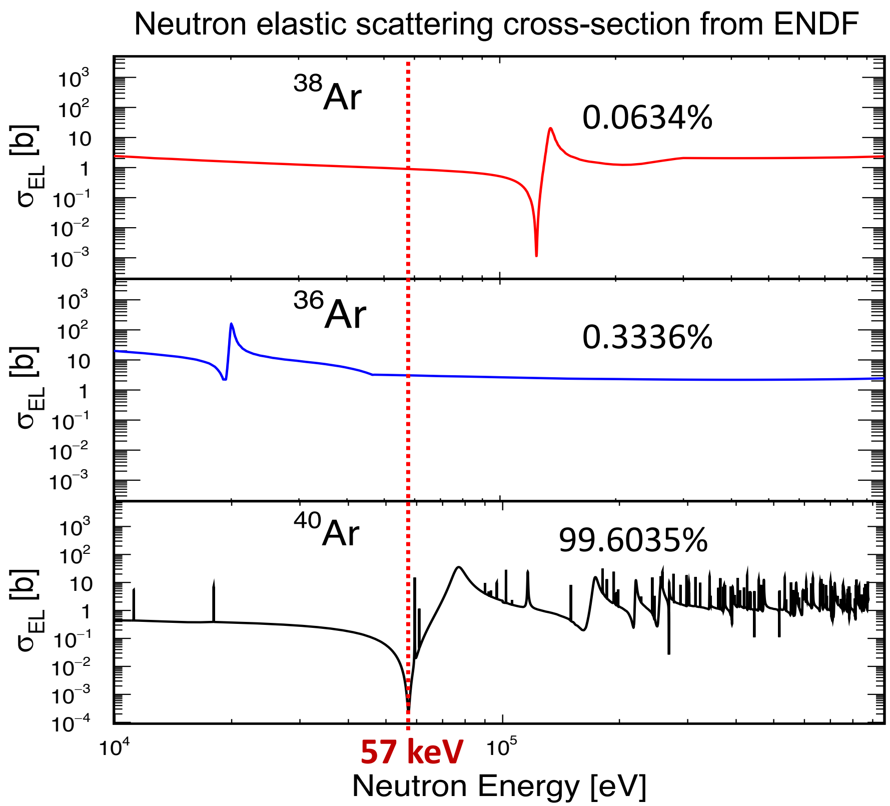
- **Introduction to Pulsed Neutron Source**
  - Motivation
  - Conceptual design
- **Plan of Activities**
- **Recent Progress**
  - Simulation update
  - ARTIE analysis
  - CERN DD generator test
- **Conclusion**
- **Charge Questions**

Motivation

- **Energy scale and resolution are one of the dominant systematic uncertainties in DUNE physics** See Jose's and Bob's talks
  - Oscillation physics: energy scale and resolution must be known to 2%
  - Supernova physics: energy scale known to <5%, energy resolution known to 10%
  - Need calibration sources to measure space/time variations of the detector response
- **Traditional calibration sources are limited in far detector modules**
  - **1.5 km underground** → 177 stopping muons and 146 Michel electrons /day/10 kt
  - **10 kt large volume** → spatial coverage is limited by the source deployment locations
- **Pulsed Neutron Source (PNS) system is one of the main calibration strategies**
  - Neutron generators were used by SNO and Super-K
  - Neutron capture provides a fixed energy deposition to calibrate the energy scale, energy resolution spatially and temporally across the enormous DUNE volume
  - Expect to calibrate a full far detector module within one day.

How can neutrons help?

- Neutrons can travel long distance through scattering. Average fractional energy loss per elastic scatter is only 4.8%.
- Neutrons falling into the 57 keV “anti-resonance “dip” can travel ~30 m in liquid natural argon

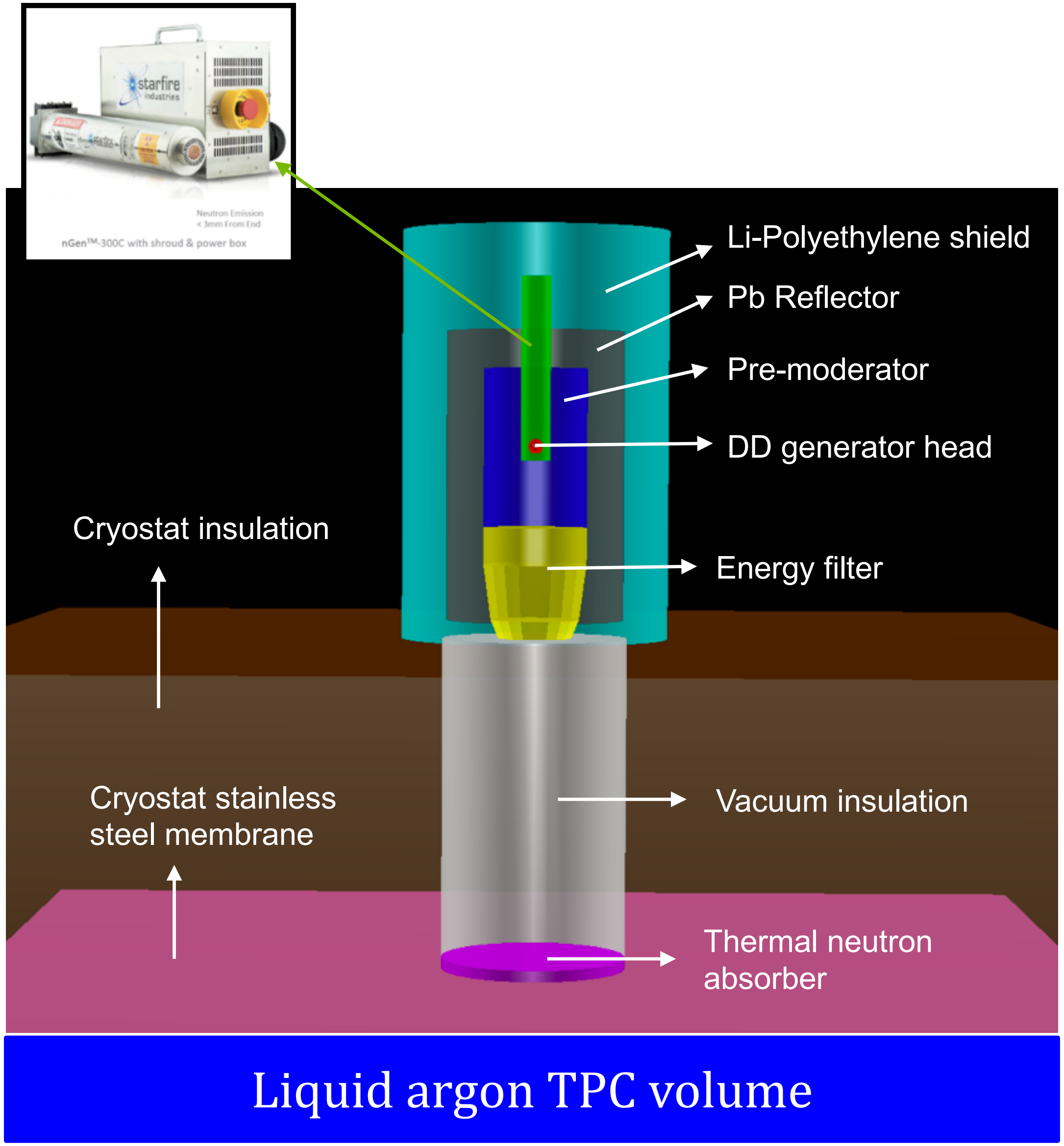


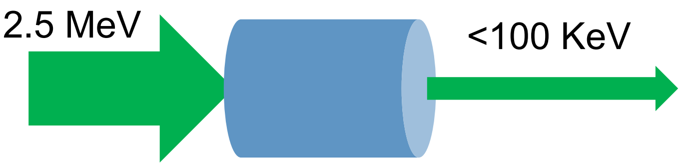
Neutrons above the anti-resonance will lose **4.8%** of energy per scatter until they “fall in the dip” – most neutrons will fall into the dip.

$n + {}^{40}Ar = {}^{41}Ar + 6.1$ MeV

Low-threshold photon detection can reveal the signature of neutron capture (~307 µs in infinite volume, ~ 240 µs in DUNE far detector)

What is the Pulsed Neutron Source?





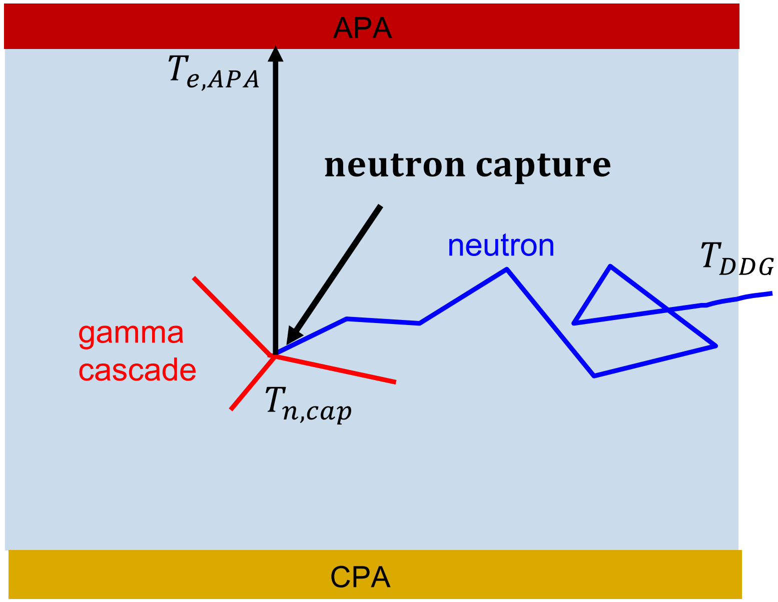
Conceptual Moderator

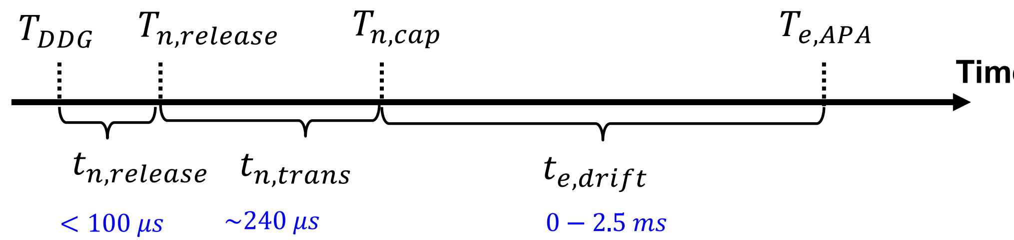
- **DD generator** → 2.5 MeV neutrons
- **Pre-moderator** → efficiently reduce energy down to below 1 MeV
- **Energy filter** → reduce neutron energy down to sub-hundred keV level
- **Pb reflector** → Increase neutron yield
- **Thermal absorber** → suppress thermal neutrons
- **Li-Polyethylene shield** → radiation protection

PNS Benefits

- **External deployment: neutrons mostly ignore the stainless steel membrane of the cryostat**
  - Easy setup. No contamination to argon purity, no field distortion
- **External pulsed trigger: use a pulsed DD generator to produce neutrons:**
  - Pulsed trigger allows reconstruction of neutron capture location
- **Adjustable neutron pulse/yield/rate**
  - Adjustable pulse width from 0-1000 μs. Maximum neutron yield of 10^6-10^8 /s
  - Adjustable pulse rate from 0-200 kHz
- **Wide coverage: neutrons can travel long distance**
  - Fractional energy loss per elastic scatter is 4.8%
  - Antiresonance at 57 keV
- **Multi-gamma output: neutron capture emits 6.1 MeV gamma cascade**
  - Fixed energy deposition as a “standard candle”

What Can We do with the PNS?



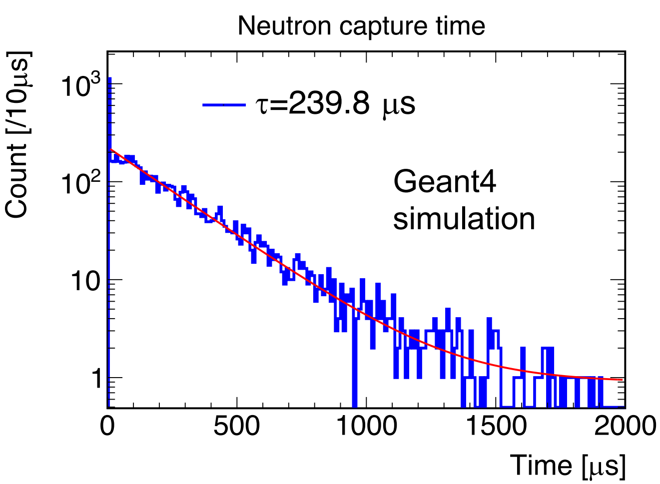


Scenario1: Rough t_0 provided by DDG. Position bias due to neutron transport

$$t_{meas} = T_{e,APA} - T_{DDG} = t_{n,release} + t_{n,trans} + t_{e,drift}$$

Scenario2: Precise t_0 provided by PDS. No position bias

$$t_{meas} = T_{e,APA} - T_{n,cap} = t_{e,drift}$$



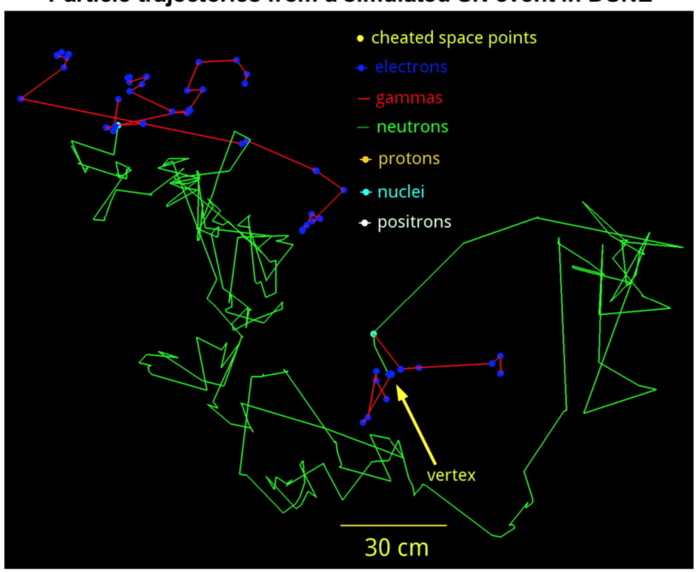
Neutron capture time never measured

1. **Energy scale and resolution**
   - 6.1 MeV fixed energy as "standard candle'
   - Wide-spread neutrons for uniformity scan in space and time
2. **Electron lifetime in active TPC**
   - Extracted from the fit to $Q_{meas} = Q_{true}e^{-\frac{t_{meas}}{\tau}}$
3. **Supernova trigger efficiency**
   - Wide-spread gamma cascades mimic SN events

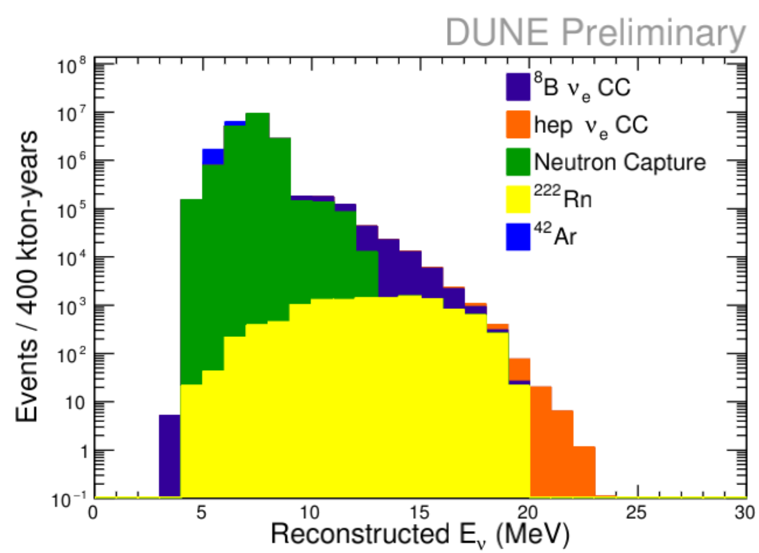
Better Understanding of Low-E Physics

- Neutrons are part of the signal components of supernova event
  - The MARLEY generator suggests that 15-30% of supernova events involve neutron emission. Missing the neutrons could result in large uncertainty in energy reconstruction.
- Neutrons are the dominant background for solar neutrino measurement.
  - Neutron captures look like solar neutrino events
- PNS provides neutron capture data to help understand the neutron transport and capture in liquid argon

Particle trajectories from a simulated SN event in DUNE

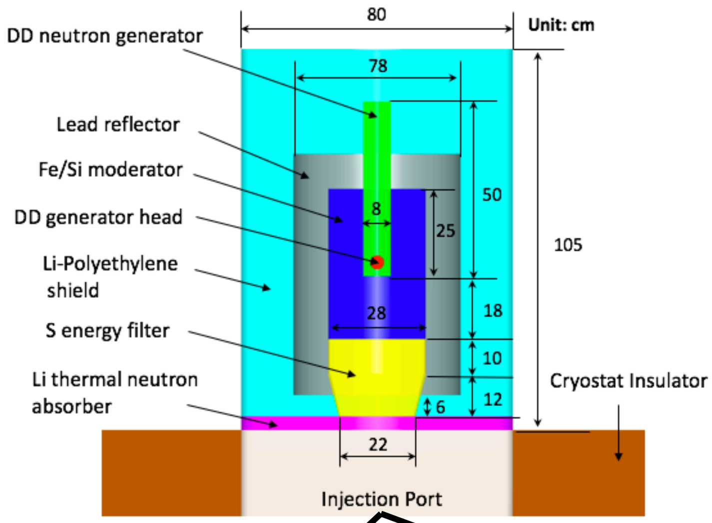


Solar neutrino signal and background

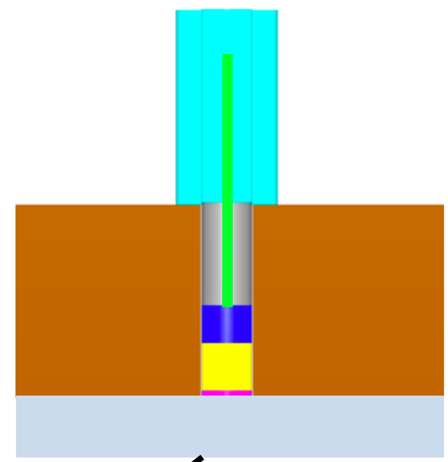


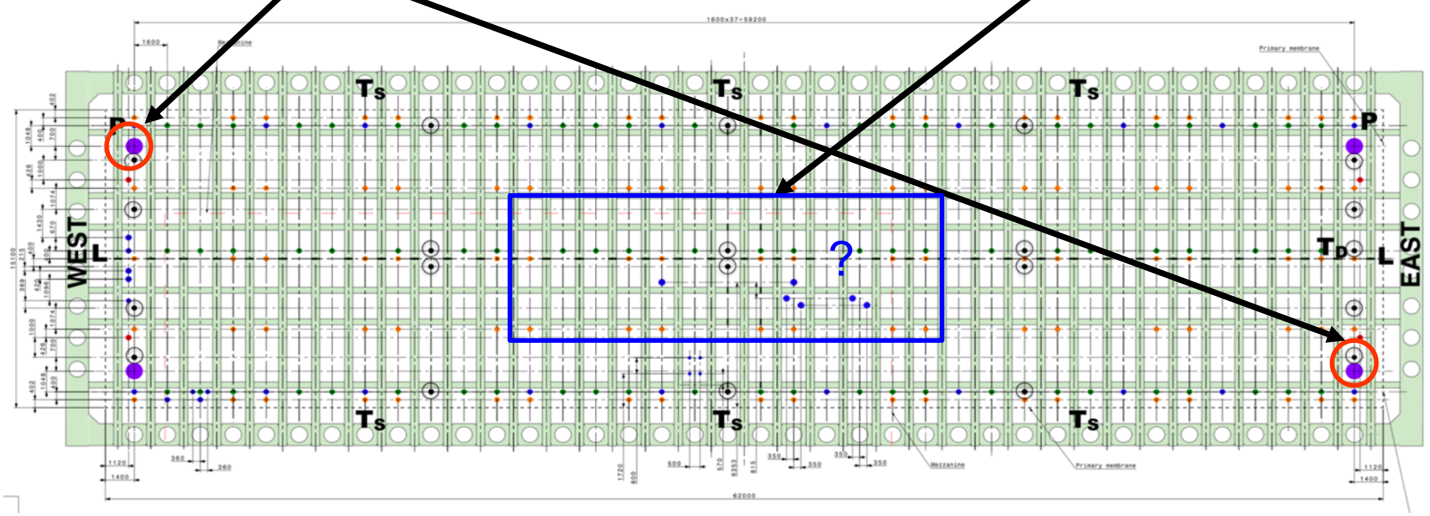
Two PNS Designs in TDR

Baseline Design: Above/inside Manhole



Alternative Design: using one of the central cryogenic ports





Recommendation from last review

1. Continue with the program of measurements and simulations to finalize the source design. (ARTIE done. Need new simulation)
2. Understand radiation safety issues. (Understood in simulation. To be tested at CERN with a real DD generator)
3. Demonstrate the capability of reconstructing the 6.1 MeV shower in simulation. (LArsoft Simulation in progress)
4. Develop a plan for deploying a pulsed neutron source for the 2nd run of ProtoDUNEs (Done)
5. Work with the LBNF facility and TC to understand mechanical constraints, under the assumption that two sources will be installed in the manholes at the two ends of the detector. (Will start during the phase of mechanical design)
6. Work with the LBNF facility and TC to understand where to install the third source (Under discussion).

Recent Activities

▪ ARTIE experiment at LANL	10/08/2019 – 10/20/19
▪ Prepare DD generator test at CERN	12/10/19 – 04/30/20
▪ LANL DD generator arrived at CERN	04/15/20
▪ Preliminary ARTIE data analysis	04/01/20 – 05/30/20
▪ Finalize PNS conceptual design	04/01/20 – 06/30/20
▪ **Calibration Review Workshop**	05/11/20 – 05/28/20

Planning for ProtoDUNE RUN-II

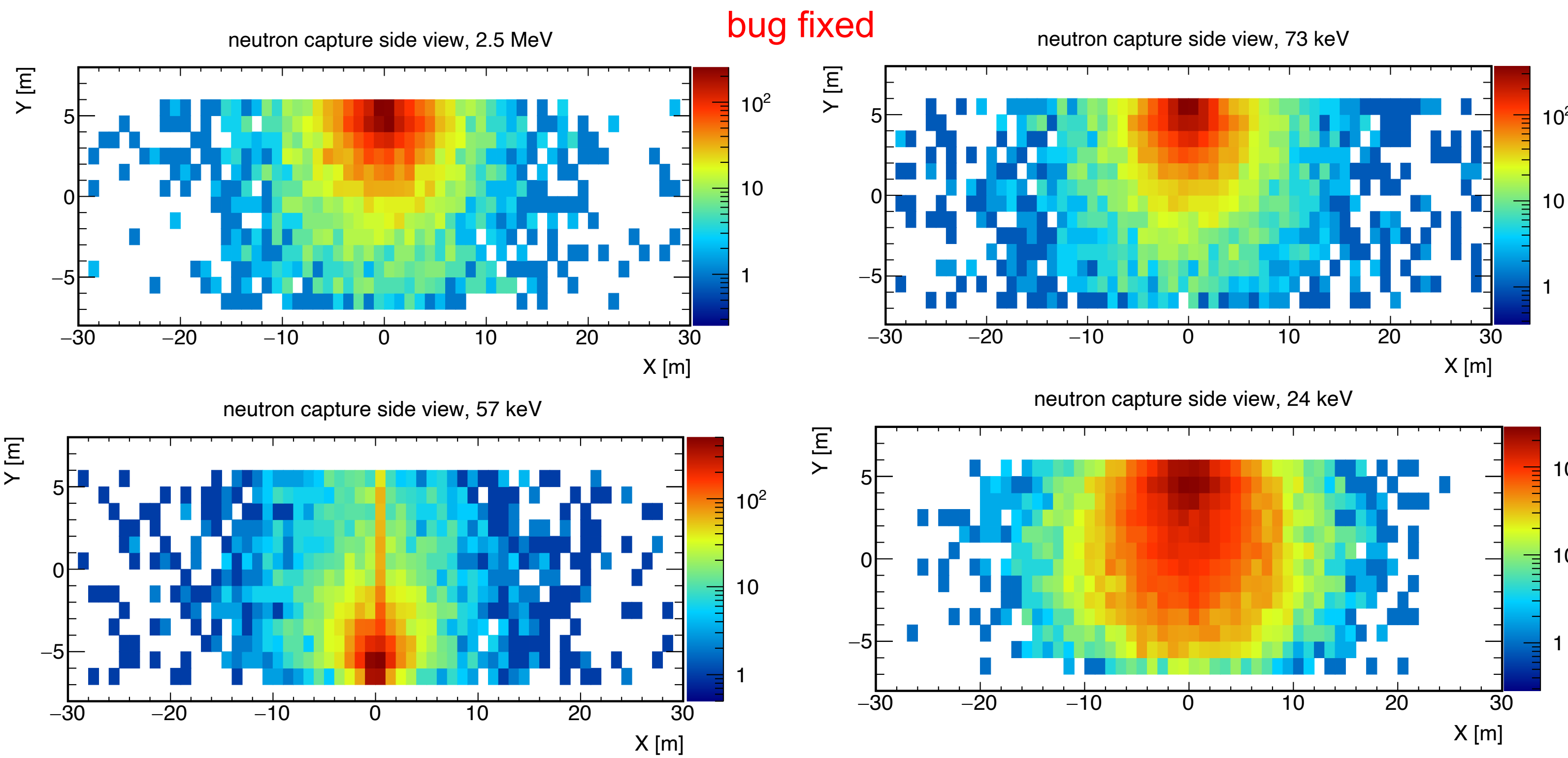
▪ DD generator test at CERN	06/01/2020 – 06/30/20
▪ Analyze the DD generator test data	06/01/2020 – 12/31/2020
▪ Ship the DD generator back to US	07/01/2020 – 07/31/2020
▪ PNS CAD first design	07/01/20 – 07/30/20
▪ Set up a PNS test lab	08/01/20 – 11/30/20
▪ Assemble small-format moderator	08/01/20 – 12/31/20
▪ Test for small-format moderator (may be skipped)	08/01/2020 – 11/31/2020
▪ Identify a DD generator	11/01/20 – 02/28/21
▪ Set up full-size PNS system	12/01/20 – 03/31/21
▪ PNS system arrives at CERN	08/31/21
▪ Install PNS system at ProtoDUNE-SP	09/01/2021 – 11/15/2021
▪ ProtoDUNE Run-II	01/01/2022

Bug fix in Simulation

- There existed a bug in the previous simulations: the neutron was simulated twice per step. This bug is not a huge problem, but it affects the moderator design and the neutron transport
- With the bug fixed, the neutron capture time increases from 150 μs to 240 μs, but neutrons also spread out more in space.
- We will repeat all the previous studies with new simulations. And we need to decide if a neutron moderator is really needed.

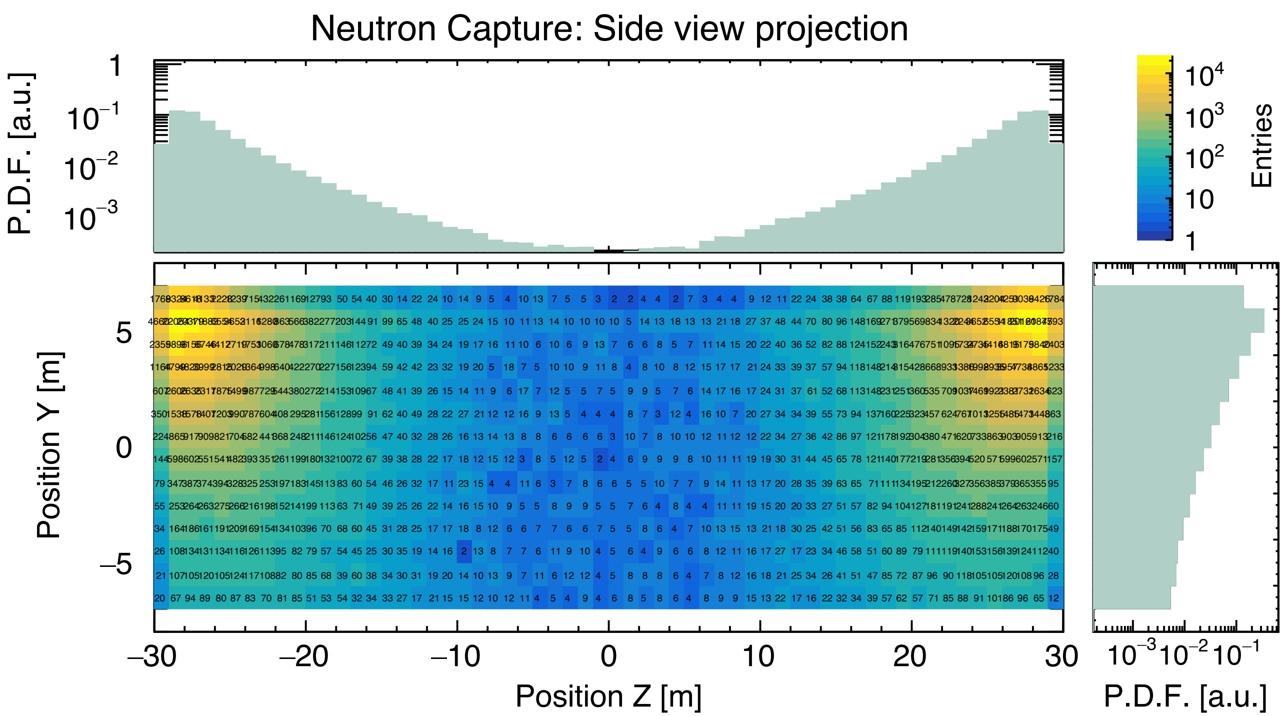
New Simulation of Neutron Spread

- Neutron transport in DUNE-size liquid argon volume was simulated for downward neutron beams with different energies
- Compared to the old studies, the neutrons spread more in the new simulation
- keV neutrons are preferred, but it's hard to make an adequate moderator. We are investigating the use of DD generator without moderator.



Simulation without moderator

- Without a moderator, the DD generator could be placed inside the manholes to get the maximum primary neutron flux (x5 increase), which leads to a much higher neutron capture yield inside liquid argon.
- The coverage of the middle region needs to be compensated by the 3rd PNS.



- DD generator yield: 10^5 per pulse (100 μs)
- DAQ Rate: 0.5 Hz
- Run time: 3.3 minutes
- DD Pulses: 100
- DD neutrons: 2×10^7
- Neutron capture yield: ~4.4% (X34 higher than TDR result)
- Neutron captures: 440618

PNS Simulation Status

- **Neutron source design with new simulations**
  - Neutron moderator design in Geant4 (To be reviewed after simulation bug fix)
  - Radiation shield design (Done. To be tested with a DD generator)
- **Neutron transport simulation with real TPC materials** (Done)
  - Studied for both Single Phase and Dual Phase TPC materials
  - TPC material effects are on the order of 5% for SP detector
- **Neutron capture tagging in TPC**
  - Correlated gamma cascade implementation (Done)
  - Neutron capture tagging (In progress).
  - Photodetector sim & reco for t_0 determination (No effort yet)
- **Analysis validation**
  - Validation with full simulation: field non-uniformity, electron lifetime, recombination, space charge… (In progress)

Update on Risks Mitigation

Dedicated experiment @ LANL (done. Less dependent on ARTIE)

Test @ Berkeley
Test @ ProtoDUNE

High intensity DD generator,
Wider pulse width (not a risk if use DD neutrons without moderator)

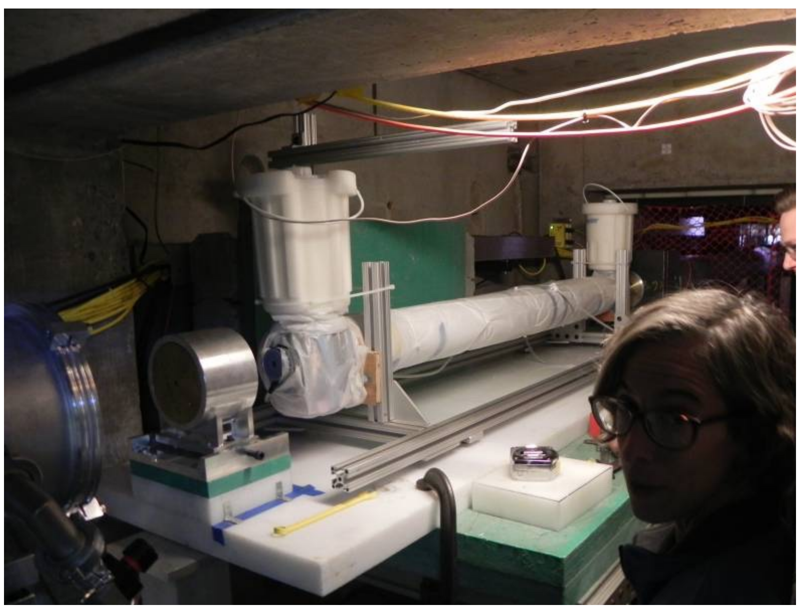
3rd PNS system in the middle (under discussion)

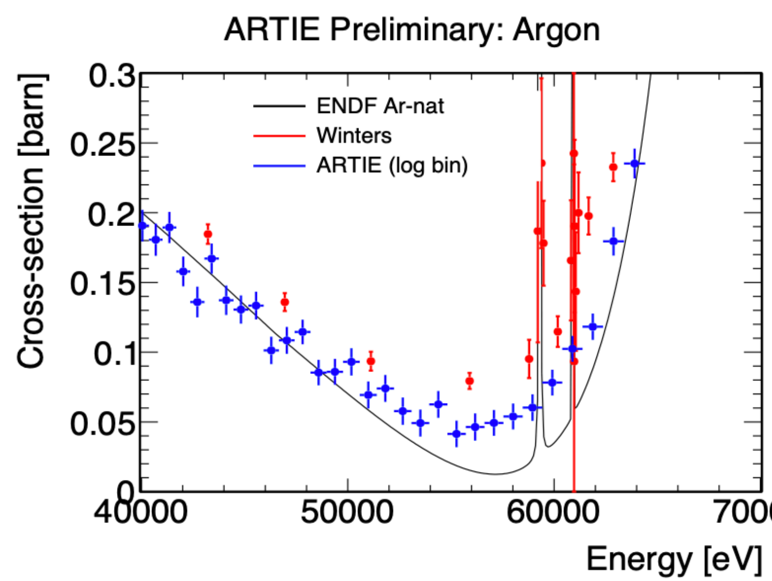
Table 1.10: Possible risk scenarios for the pulsed neutron source system along with mitigation strategies. The level of risk is indicated by letters "H", "M", and "L" corresponding to high, medium and low level risks.

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.

Argon Resonant Transport Interaction Experiment (ARTIE)

- There is a large discrepancy between ENDF library and Winters' data (1991).
- ARTIE measured the neutron **total cross-section** in argon around **57 keV,** with much higher precision than Winters' measurement.
- Result affects the neutron spatial spread in liquid argon, and is also of particular interest to supernova and solar neutrino physics.

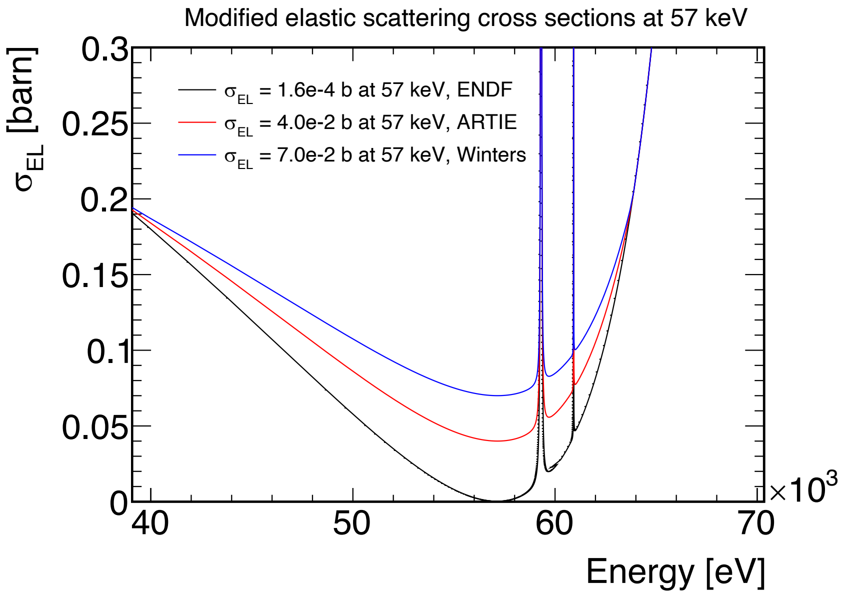




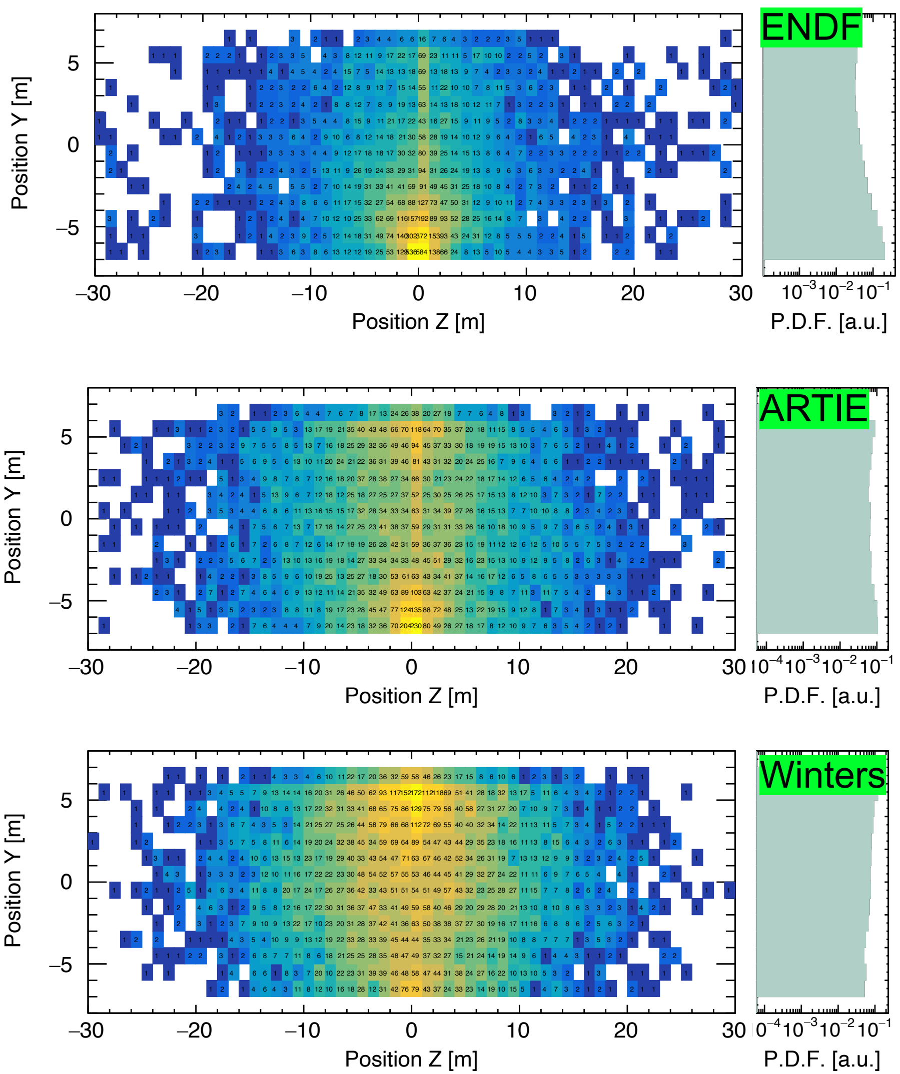
No background subtraction applied. Error is statistical.

Ideal Moderator: 57 keV Neutrons

- Prepared dummy cross-section data sets to mimic Winters and ARTIE measurements.
- Performed neutron transport simulation for 57 keV neutrons using different cross-section sets.
- Right plots: Assuming perfect moderator making 57 keV neutrons

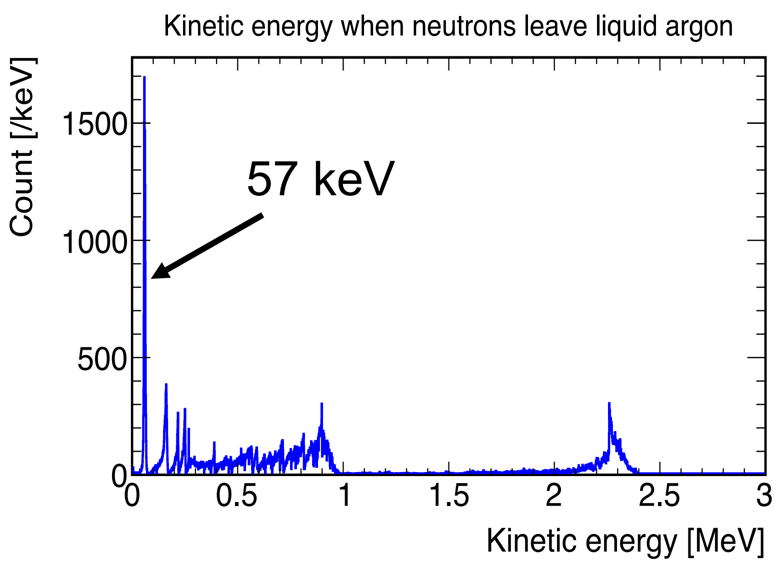


Capture position side view for **57 keV** neutrons

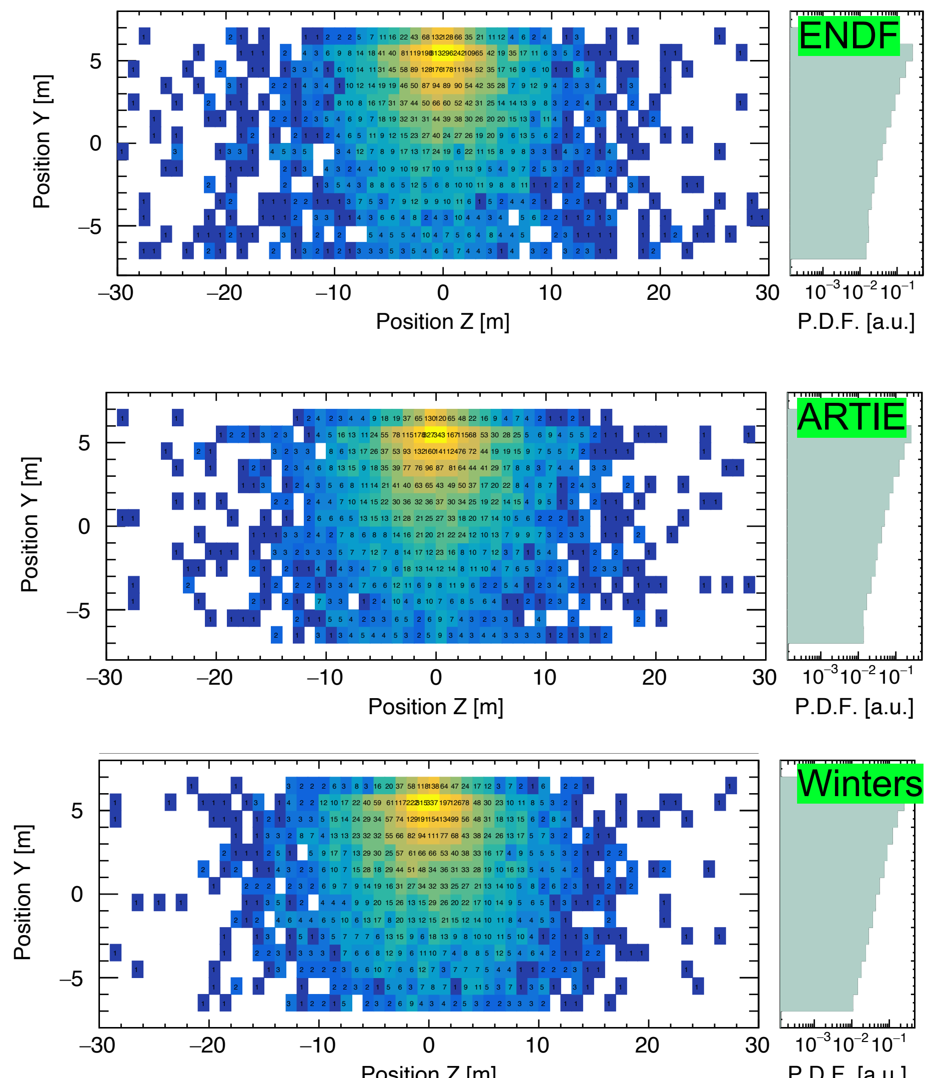


Without Moderator: 2.5 MeV Neutrons

- If LAr volume is infinite, almost all the 2.5 MeV neutrons can fall into the 57keV antiresonance dip.
- However, the DUNE detector is not big enough to contain the 2.5 MeV neutrons. About 85% of the escaping neutrons have an energy above 57 keV
- The 57 keV antiresonance effect to 2.5 MeV neutrons is insignificant.



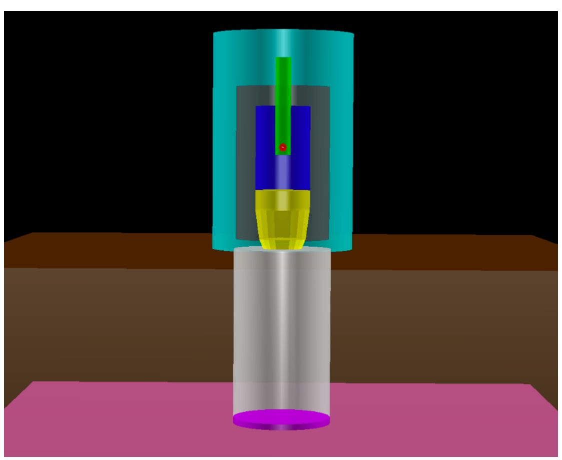
Capture position side view for **2.5 MeV** neutrons

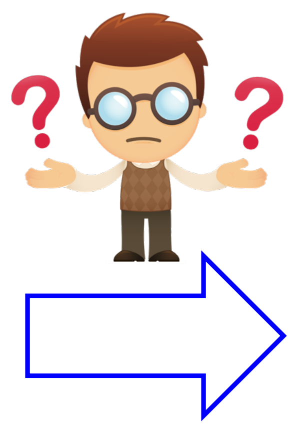


Do we need a moderator?

DD generator + moderator

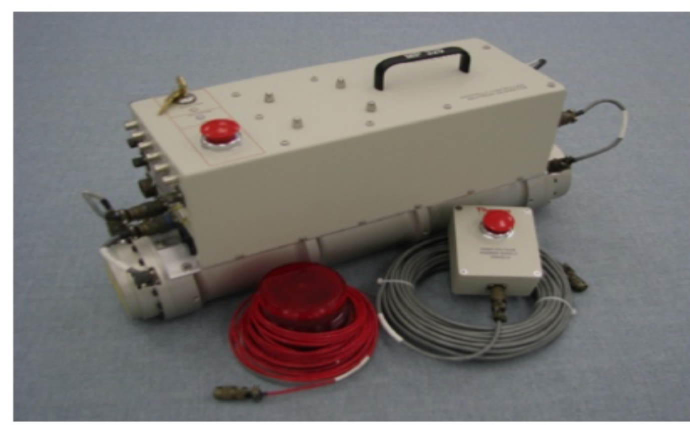
- Sub-100keV neutrons can spread more, but the moderator design is not easy. Need more moderating materials to obtain similar spectrum as that in TDR
- Neutron flux is significantly reduced by moderator: neutron captured yield inside TPC is ~0.1%
- Total weight and volume are high. Need more shielding materials





DD generator only

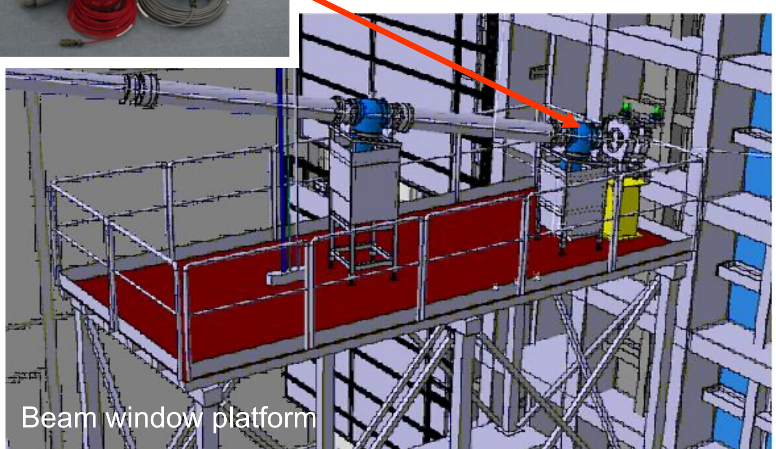
- Neutron capture yield in TPC is high: ~4.4% of the DD neutrons are captured.
- Neutron shielding is easier.
- Total weight and volume are small. Mechanical design and installation procedures are easier. Source is movable.
- Can be tested at CERN in summer 2020.



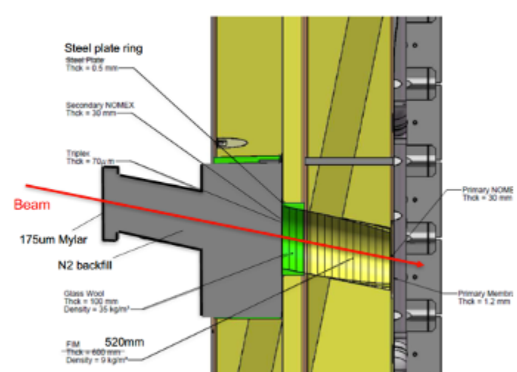
DD Generator Test at ProtoDUNE

- We are planning a DD generator test at ProtoDUNE-SP in summer 2020.
  - Take neutron capture data to test our neutron transport model and help develop neutron capture reconstruction algorithms.
  - Gain experience on DD generator operation and shielding.
- The idea is to inject 2.5 MeV DD neutrons into active of ProtoDUNE-SP detector volume through the existing beam plug.

LANL DD generator arrived at CERN!

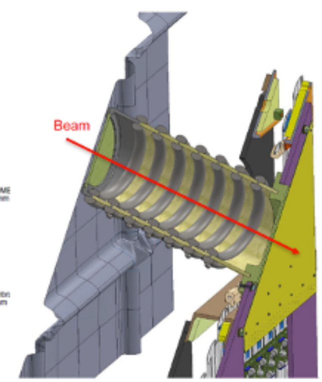


cryostat penetration



52 cm foam

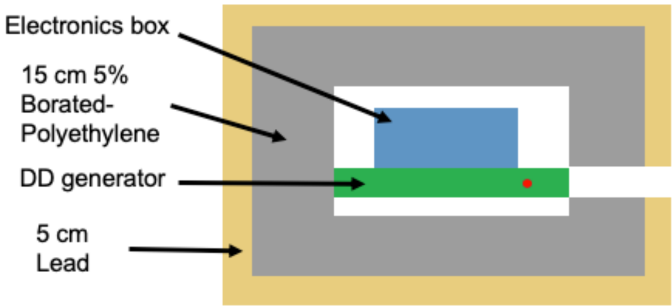
Beam plug



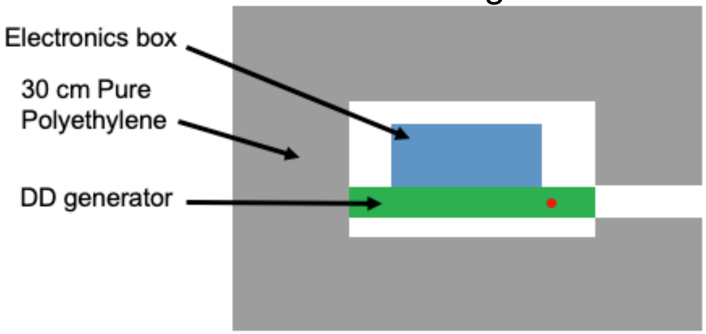
DD Generator Shield Design

- Proposed two shield designs to shield the LANL DD generator.
- Shield designs were simulated using a near-exact ProtoDUNE-SP cryostat geometry. The neutron and gamma dose rates are evaluated for six planes defining different locations from the DD generator.
- Results to be submitted to CERN for safety review (see backup slide)

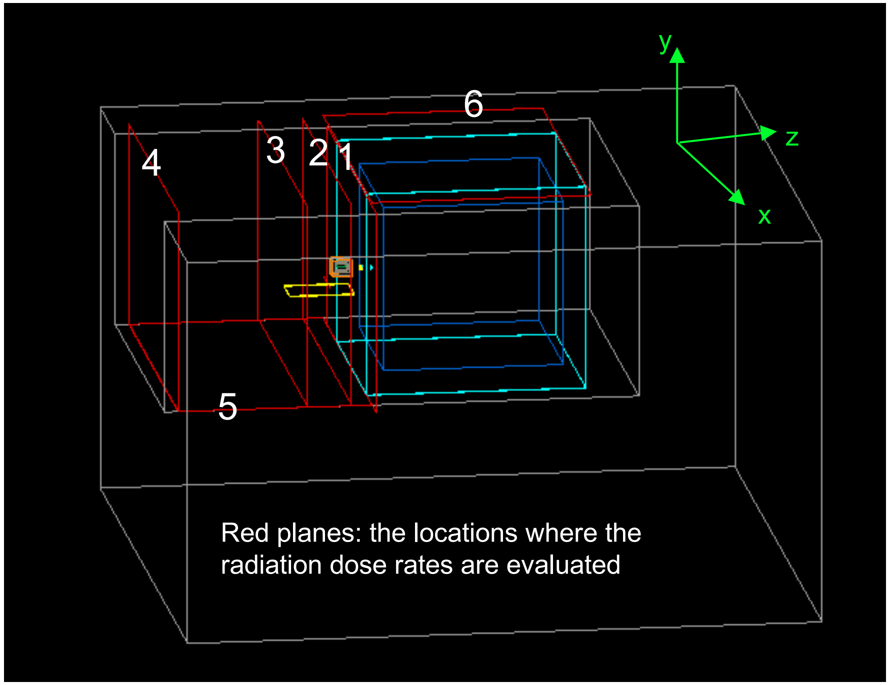
Shield design #1



Shield design #2



Simplified ProtoDUNE geometry



Conclusion

- Pulsed Neutron Source system provides a method to calibrate the energy scale, resolution, electron lifetime, and space/time variations
- Made a plan for PNS development aiming at ProtoDUNE Run-II.
- Studying the PNS performance with new simulation after bug fix.
- Considering using DD generator directly: less dependent on ARTIE and moderator, but gain high neutron capture yield. To be tested at CERN using LANL DD generator

Review Charge Questions

1. Does the system have a well-justified role in facilitating the analysis of far detector data, and if so, what is the minimum amount of system scope required to fulfill this role?
2. Have all technical issues related to the feasibility of the system (including those raised in the previous workshops) been resolved?
3. Are there any risks to overall detector performance associated with the implementation of the system, and if so, is there a plan in place for mitigating these risks?
4. Is there a credible plan in place for demonstrating system performance in ProtoDUNE-II?
5. Does the functionality of the system justify its overall cost?

Review Charge Question

1.1 Does the system have a well-justified role in facilitating the analysis of far detector data, and if so, what is the minimum amount of system scope required to fulfill this role?

See slide 7 and slide 9

Role of PNS

- Measure the electron lifetime, energy scale, energy resolution and detection threshold spatially and temporally across the whole DUNE volume.
- Check the detector response uniformity across the whole volume. Spatial and temporal dependences can be measured.
- Test the supernova trigger efficiency, as wide-spread neutron captures can mimic the low energy supernova events
- Provide real TPC data to study the neutron transport and capture in DUNE.

Minimum amount of systems

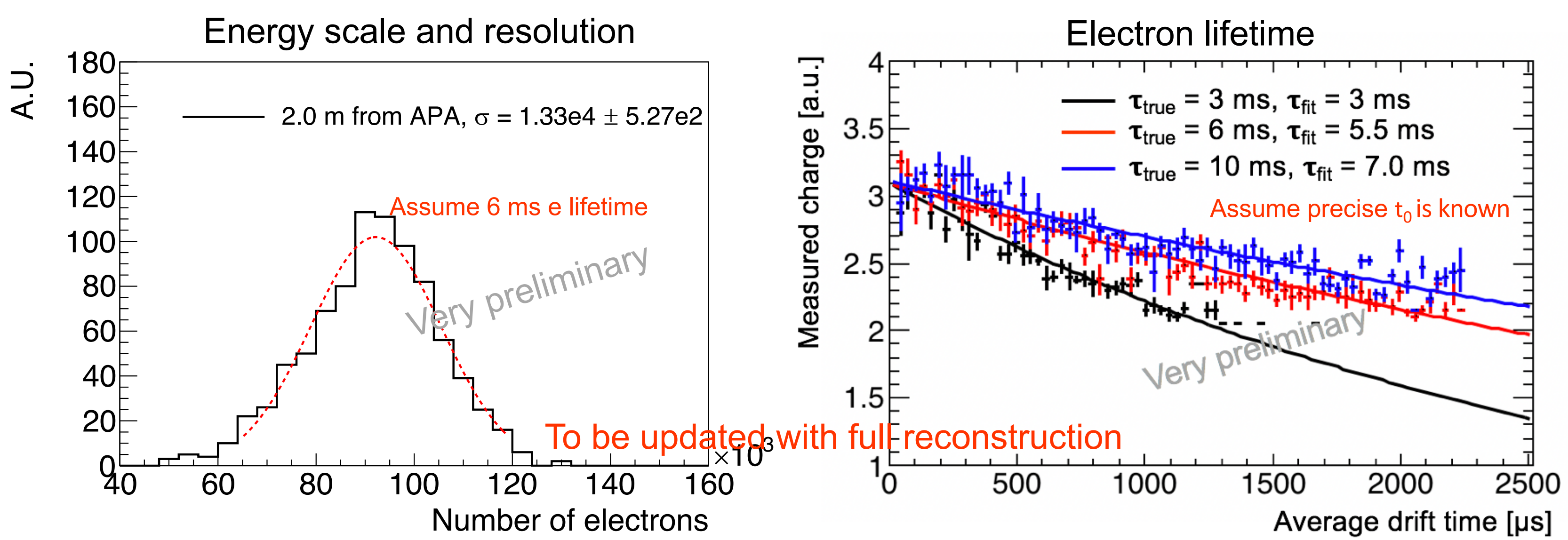
- Two PNS at the corner manhole locations plus the 3^{rd} PNS in the middle at one of the cryostat ports

Simulation Studies

To be updated with full reconstruction

- Left plot: reconstructed charge for 6.1 MeV neutron capture gammas
- Right plot: Lifetime fit from uniform neutron capture distribution, assuming exact t_0 is known

Idealized simulation with no corrections for recombination or argon purity



Review Charge Question

1.2 Have all technical issues related to the feasibility of the system (including those raised in the previous workshops) been resolved?

- The conceptual design is near-finalized. Simulations confirmed that the technique is feasible. Test measurement will be done at CERN with a DD generator
- The CAD design of PNS will start after the workshop. During this phase, we will work with the LBNF facility and TC to understand mechanical constraint about the details of the source deployment.
- The assembly and installation procedures will be tested before the entire system is shipped to CERN.
- Other technical issues, including the PNS installation, cabling and wiring, triggering, will be tested during the DD generator test at CERN.

Review Charge Question

1.3 Are there any risks to overall detector performance associated with the implementation of the system, and if so, is there a plan in place for mitigating these risks?

- To our knowledge, there are minor risks to other systems, because the PNS system is external.
- Radiation protection could be an issue for people present in the experimental area. The radiation dose rate is studied in simulation. Radiation shield will be tested at CERN using the LANL DD generator.
- If the PNS system is deployed inside the manhole, we need to design a special interface to maintain Liquid argon temperature. This is a common issue for all calibration systems. Thermal conduction will be investigated during ProtoDUNE Run-II.
- Electrical noise from the DD generator will be investigated during ProtoDUNE Run-II.

Review Charge Question

1.4 Is there a credible plan in place for demonstrating system performance in ProtoDUNE-II?

- We made a development plan aiming at the operation in ProtoDUNE-II
- Before ProtoDUNE-II, we will test the DD generator performance at ProtoDUNE-SP at CERN
- In ProtoDUNE-II, a full size PNS system will be deployed at the manhole
  - Installation and operational procedures will be tested.
  - Neutron transport will be compared between data and MC simulation
  - Neutron capture data will be used to test the calibration performance for essential detector parameters.

Review Charge Question

1.5 Does the functionality of the system justify its overall cost?

Scenario1: with moderator

Description	Items	Total Price ($)
DD generator		170,000
Neutron moderator	Silicon	10,990
	Sulphur	672
	Pb reflector	7,274
	B-10 neutron absorber	28,600
Radiation Shield	7.5% Li-poly shield	33,000
Neutron Monitor	He-3 tube	10,000
Shipping Costs	From US to CERN	5000
Total Tax (7.25%)		18,889
Total Cost		284,425

Scenario 2: without moderator

Description	Items	Total Price ($)
DD generator		170,000
Neutron reflector	Pb reflector	3,637
Radiation Shield	7.5% Li-poly shield	33,000
Neutron Monitor	He-3 tube	10,000
Shipping Costs	From US to CERN	5000
Total Tax (7.25%)		15,969
Total Cost		237,343

Without moderator, the cost can be reduced by 16% for a single PNS system. Cost can be further reduced if the DDG is moved across TPC modules

PNS Working Group

- **UC Davis**: Robert Svoboda, Mike Mulhearn, Jingbo Wang, Junying Huang, Yashwanth Sai Bezawada
- **SDSM&T:** Juergen Reichenbacher
- **LANL**: Sowjanya Gollapinni
- **University of Pittsburgh**: Donna Naples, Logan Rice
- **LIP (Portugal)**: Jose Maneira, Sofia Andringa
- **Michigan State University** : Kendall Mahn
- **Boston University**: Chris Grant
- **University of Iowa:** Paul Debbins, Jane Nachtman, Yasar Onel

Backup

Other Question

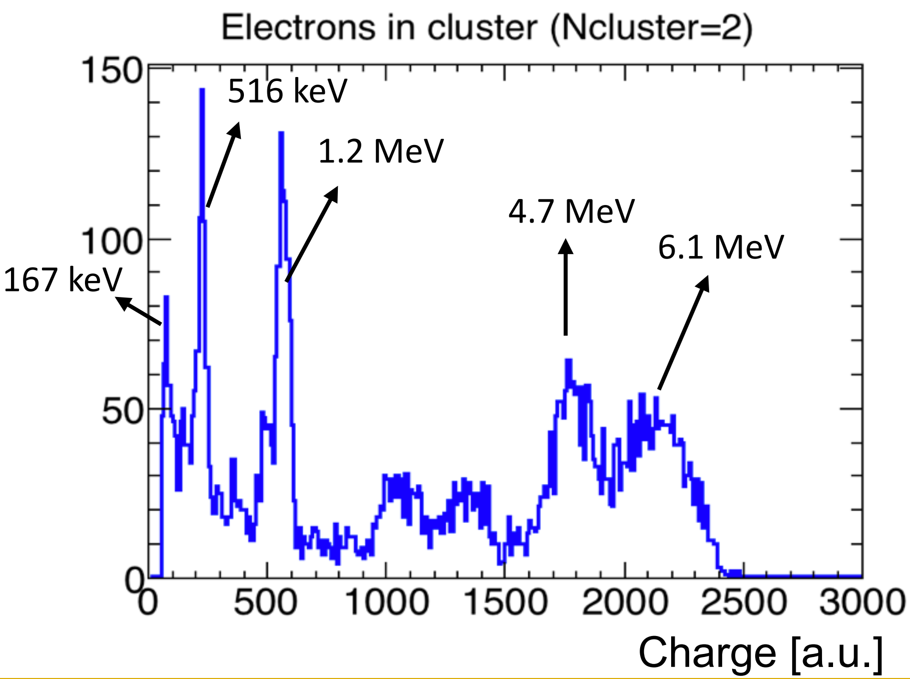
How many wires will a neutron capture cloud hit? How much above noise (~1000 ENC) will the smaller hits be? Does the analysis need clustering algorithms to reduce noise?

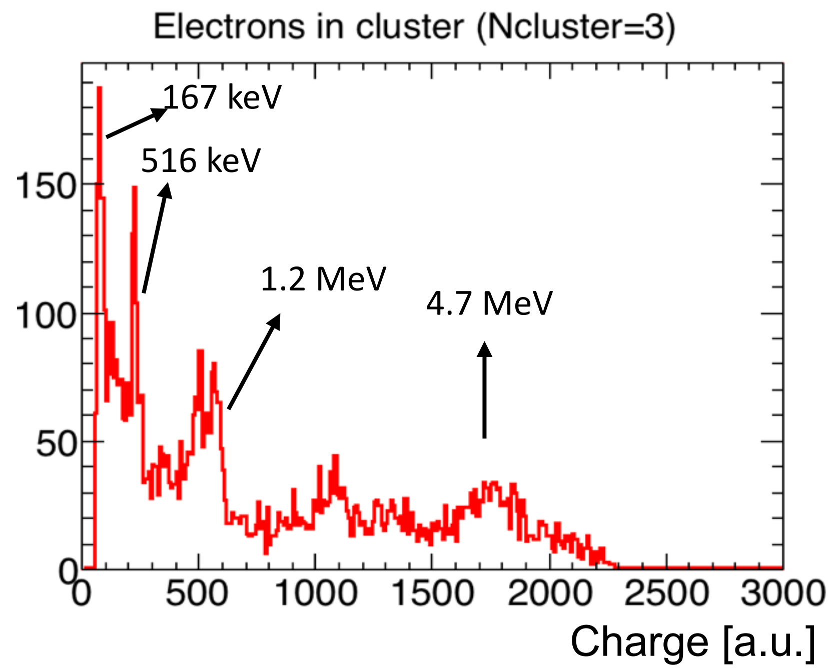
- The neutron capture is identified as a cascade of gammas. Each gamma fires only a few wires.
- The energy-electron conversion factor is 4.237e7 electrons/GeV. 1 MeV gamma can release 4.237e4 electrons, which is well above the ENC~500. In ProtoDUNE-SP, the signal-to-noise ratio is very high after noise mitigation (~40 for collection plane, 15-20 for induction plane). ProtoDUNE-SP has demonstrated few hundred keV level threshold level.

Other Question

Questions: How many wires will a neutron capture cloud hit? How much above noise (~1000 ENC) will the smaller hits be? Does the analysis need clustering algorithms to reduce noise?

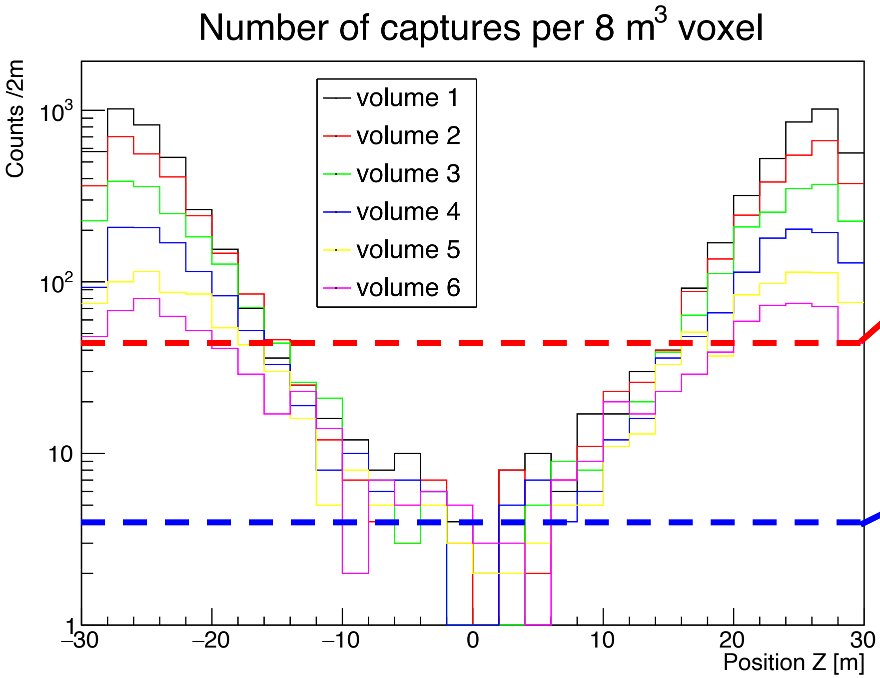
- Clustering algorithms are needed to identify a gamma from neutron capture. Geant4 simulation was done using the low energy Livermore model, and clustering with truth information worked well. LArSoft clustering is being investigated. Noise and background should be added.





Other Question

What is the fraction of detector volume that can be "illuminated" (more than 100 n/m³) with a 1hr run of a single source in a corner human access port



100 capture/m³ in one hour. 40% of the m³ voxels have more100 captures

100 capture/m³ in ten hours. 80% of the m³ voxels have more than 100 captures

2x2x2 meter box along z axis for 3-minute dual run of corner PNS

The detector along vertical direction is sliced into 6 volumes

For 100 captures/m³ at the center we would need to run both PNS systems for more than 10 hours.

Other Question

Is there a realistic design for a moderator? Does it obey radiation safety rules? Does it need weight support from cryostat I-beams?

- We have two types conceptual designs: 1) baseline design with large-format PNS systems and 2) alternative design with small-format PNS systems
- Radiation dose for both neutrons and gammas were calculated. The radiation level is well below the safety rules. Now we are working with CERN safety officers to implement a design for the DD generator test at ProtoDUNE-SP. Having this experience, we will go back to review the design proposed for the full size PNS systems.
- The baseline PNS design has a weight of about 1-1.5 ton, including all components. The support from the I-beams is definitely needed. If we use the DD generator without a moderator, the weight support may not be needed.

Other Question

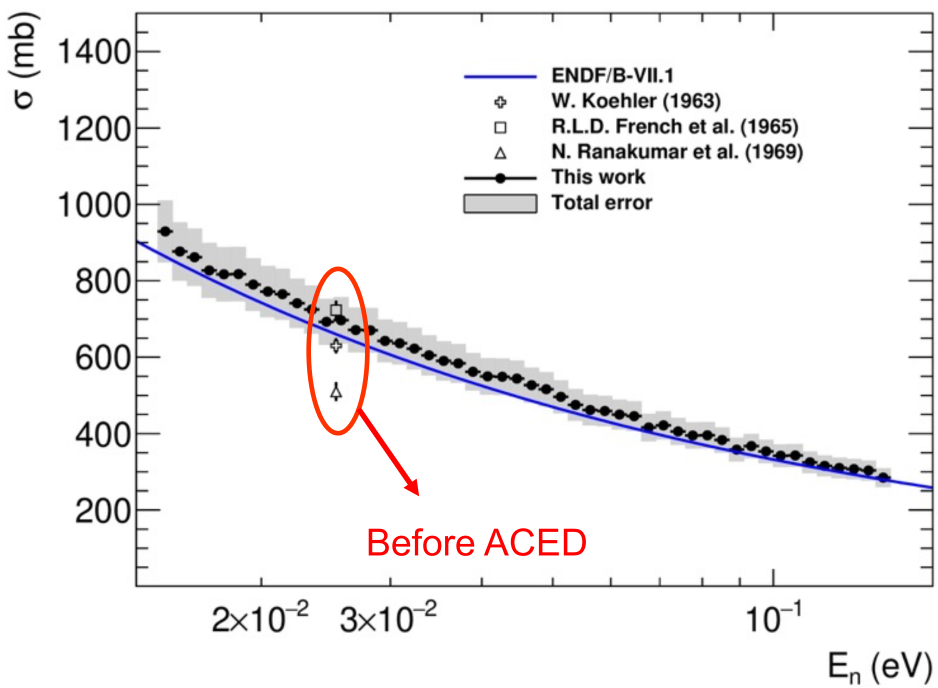
What is the ratio between close/far capture rates? What is the DD generator rate and total calibration time needed to calibrate the farthest volumes?

- The close capture rate is expected to be satisfactory, but the far capturer rate would be very low. The two baseline PNS systems at manhole locations cannot reach the middle of the far detector. Running the source for longer time (>10 hours) would help, but is not ideal.
- The lifetime of a DD generator is 1000 hours. Recharge the depletion target may cost a lot. Instead of running for longer time, it is significantly beneficial to deploy a small-format PNS system in the middle of the detector using one of the multi-purpose calibration port. This is an alternative plan for DUNE, which is being considered and discussed.

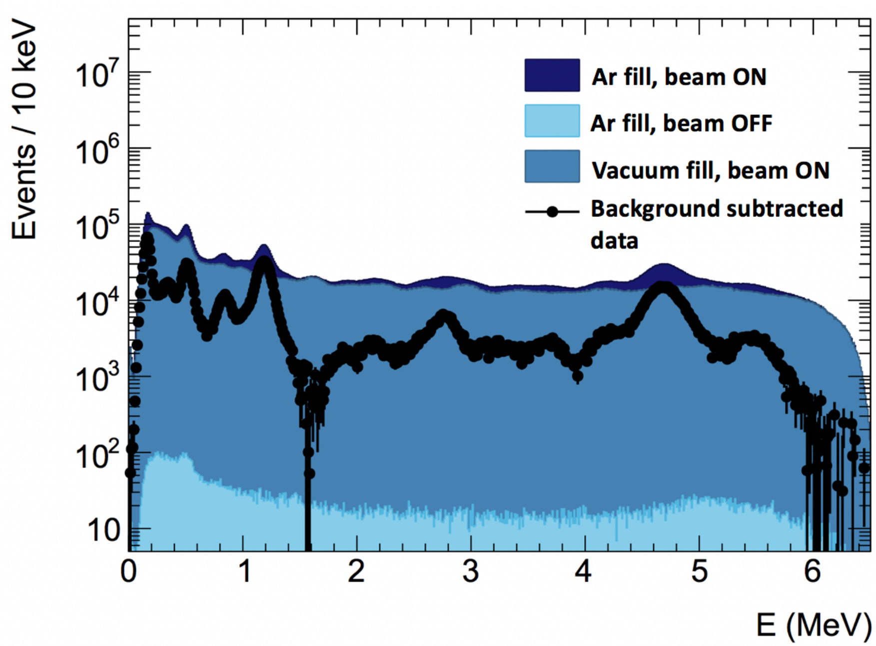
Argon Capture Experiment at DANCE (ACED)

- ACED collaboration measured the **thermal neutron capture cross-section** and the **correlated-gamma cascade** (never measured before)
- **Two papers published:**
  - **Neutron capture cross section:** *arXiv:1902.00596* (**PRD**)
  - **Thermal neutron beam calibration** using sodium: *arXiv:1902.01347* (**NIM A**)

Neutron capture cross-section



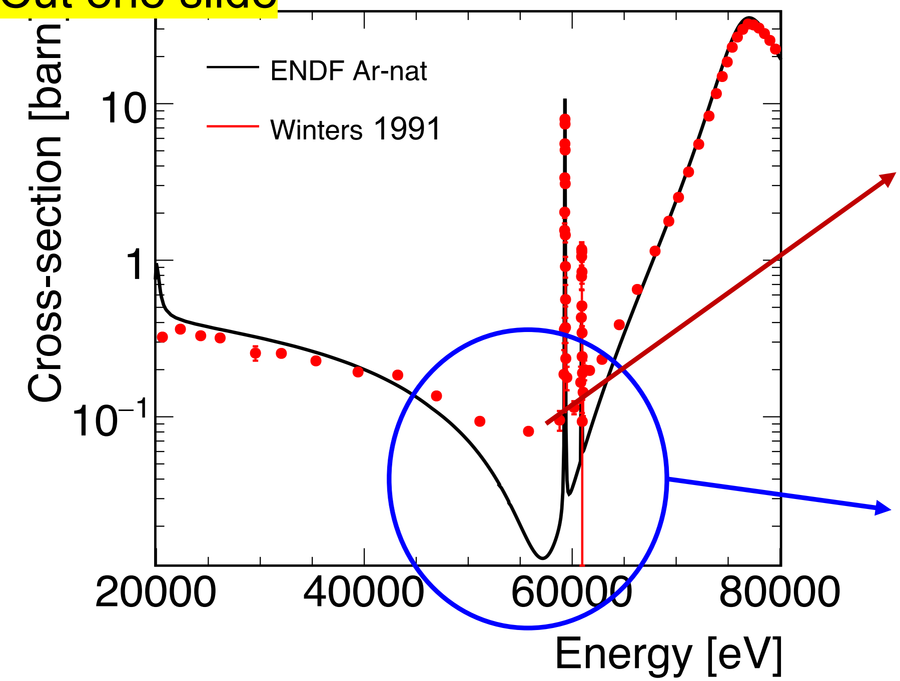
Neutron capture gammas



Argon Resonant Transport Interaction Experiment (ARTIE)

- There is a large between ENDF prediction and Winters' data (1991).
- ARTIE measured the neutron **total cross-section** in argon around **57 keV,** with much higher precision than Winters' measurement.

Cut one slide



Winters' measurement:

- 2.216 meter long gas target with **0.211 atoms/barn** density: sensitive to high cross-section, but not sensitive to low cross-sections

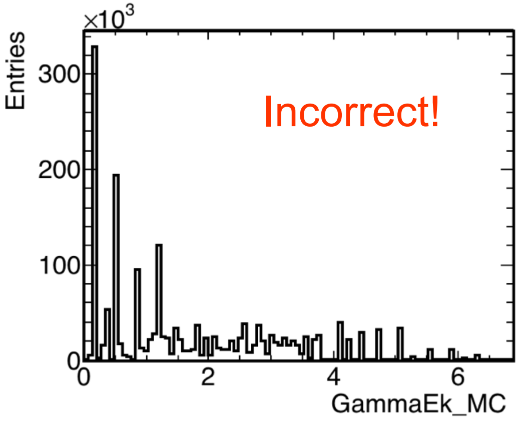
ARTIE measurement:

- 168 cm long liquid argon target with **3.5 atoms/barn** density: blind to high cross-section but very sensitive to low-cross sections

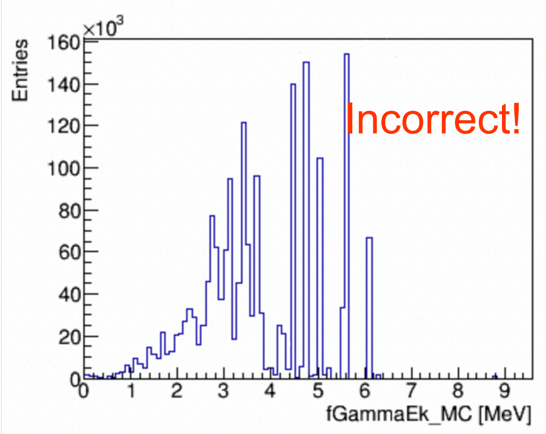
Neutron Capture Gamma Generator

- The default gamma cascade generator is incorrect in LArSoft (photon evaporation model)
- The gamma cascade generator with ENDF library is also incorrect (Final state model).
- We wrote a new physics process in Geant4 to generate the NNDC gamma cascade (https://www.nndc.bnl.gov/capgam/index.html). This is a critical step toward the full simulation.

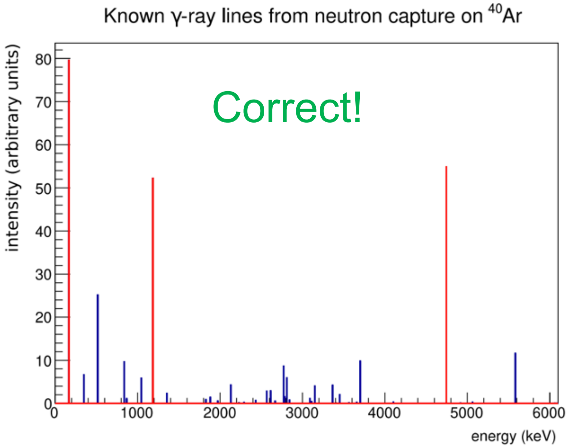
LArsoft Cap-Gamma with photon evaporation model



LArsoft Cap-Gamma with ENDF-VIII Final State model

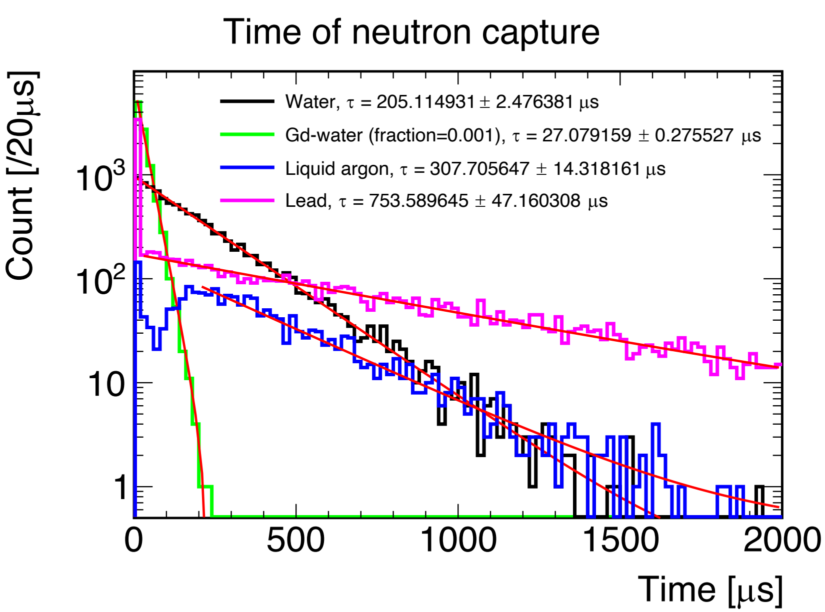


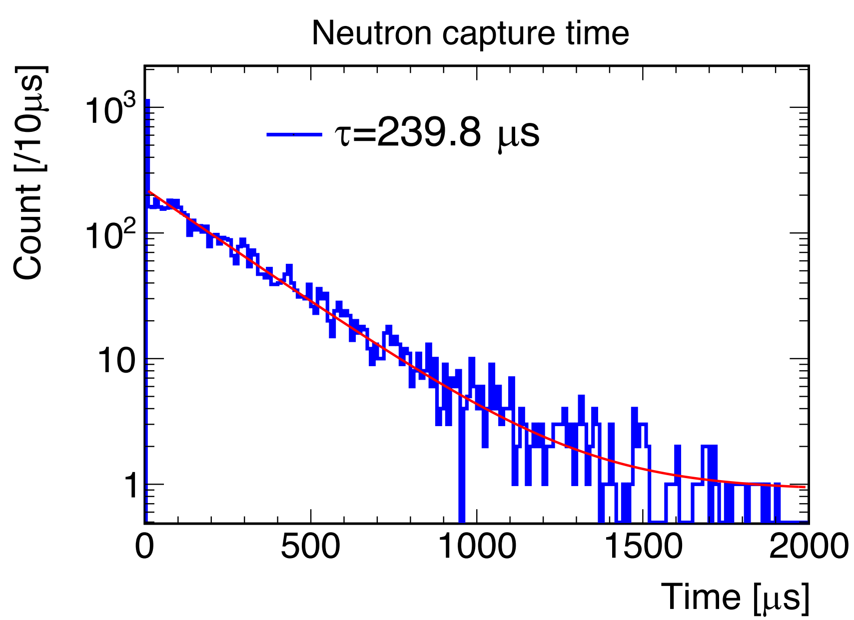
New Cap-Gamma generator being implemented in LArSoft



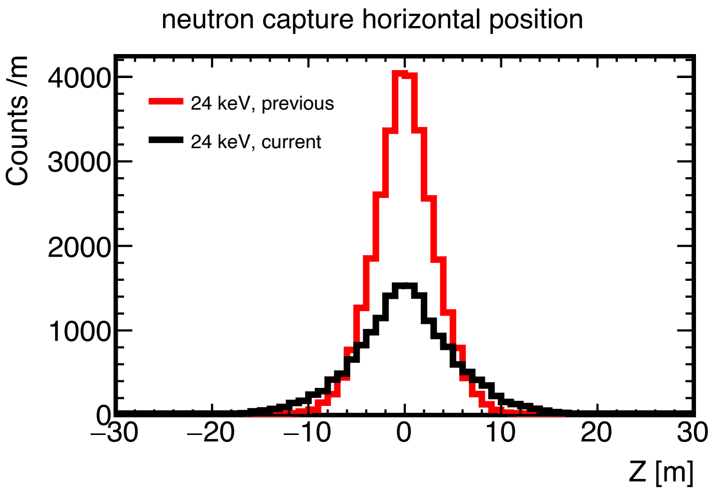
Neutron Capture Time in New Simulation

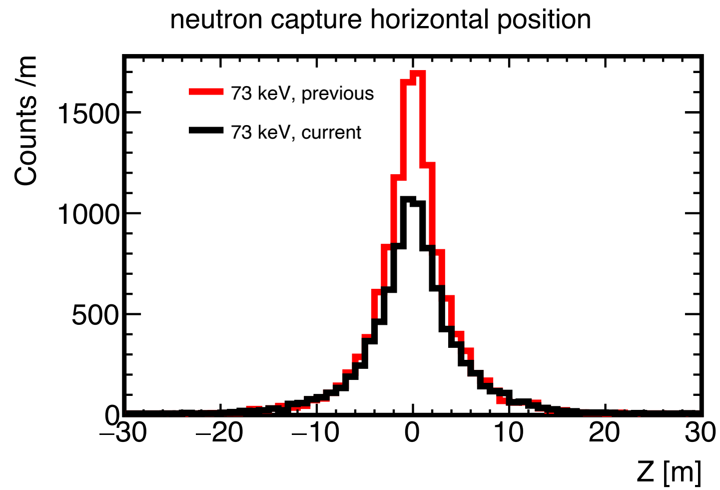
- Left: Effectively infinite liquid argon volume. 2.5 MeV neutrons generated in the middle. The neutron capture time constant is 307 μs
- Right: DUNE-size liquid argon volume. 2.5 MeV neutrons injected from the top. The neutron capture time constant is 240 μs. There is a bias coming from the selection of neutron capture inside the liquid argon volume. Neutrons with longer slowing-down time tend to escape the detector.

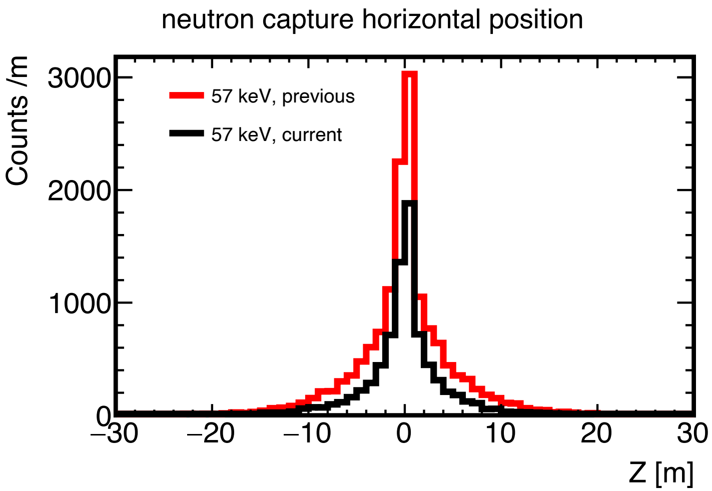


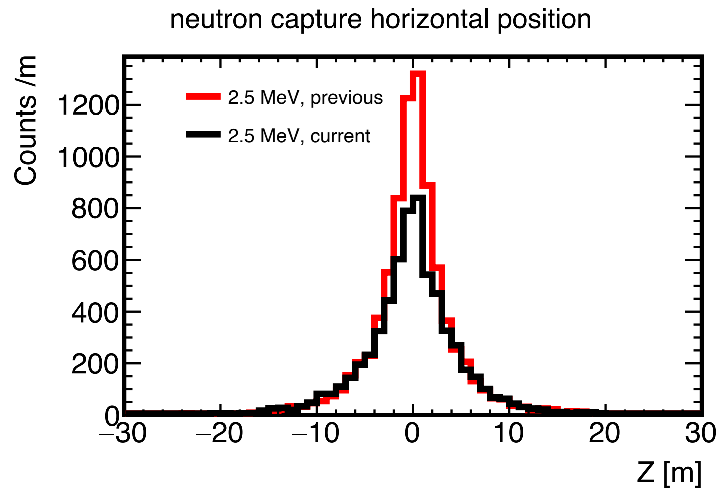


Horizontal Spread Comparison

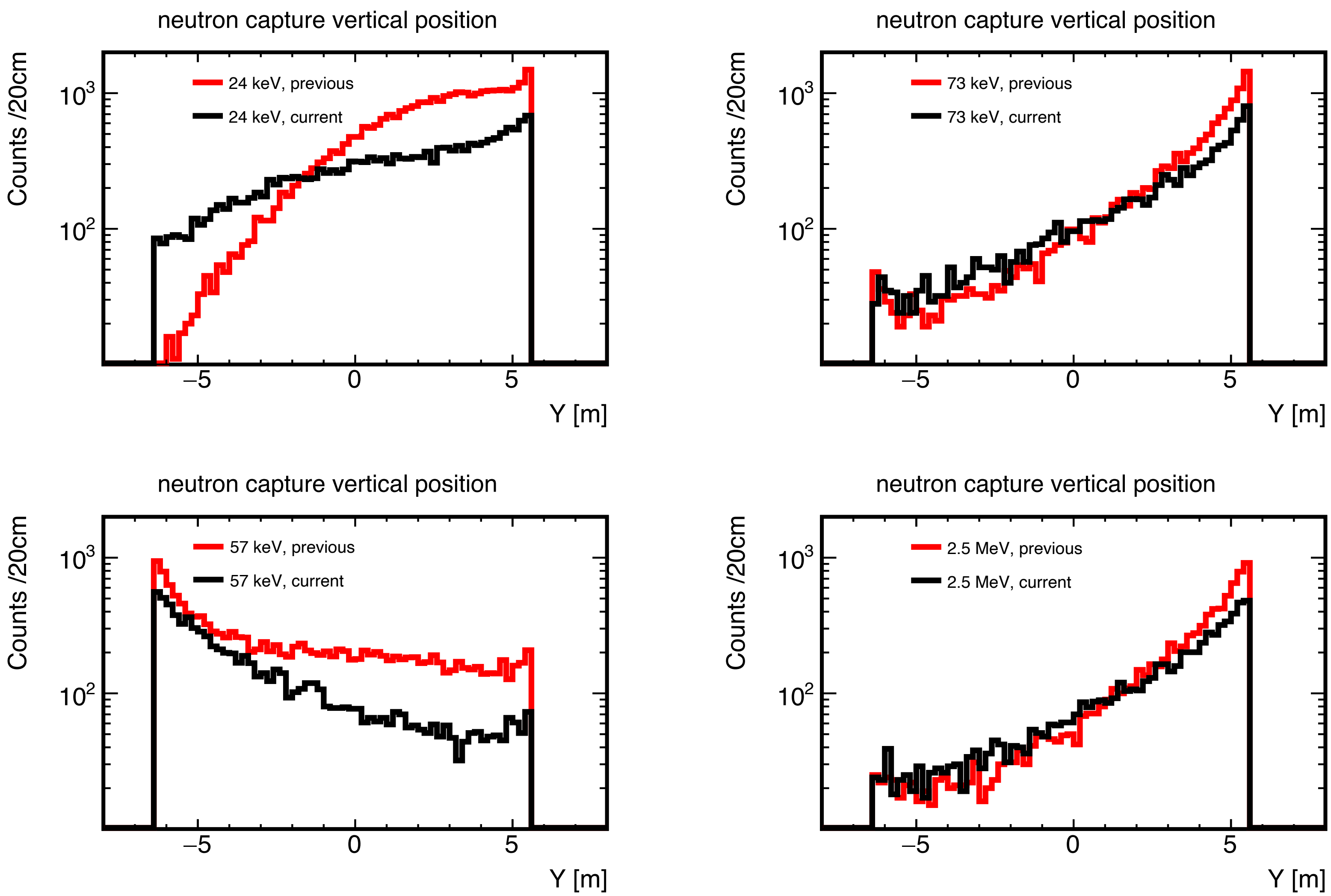








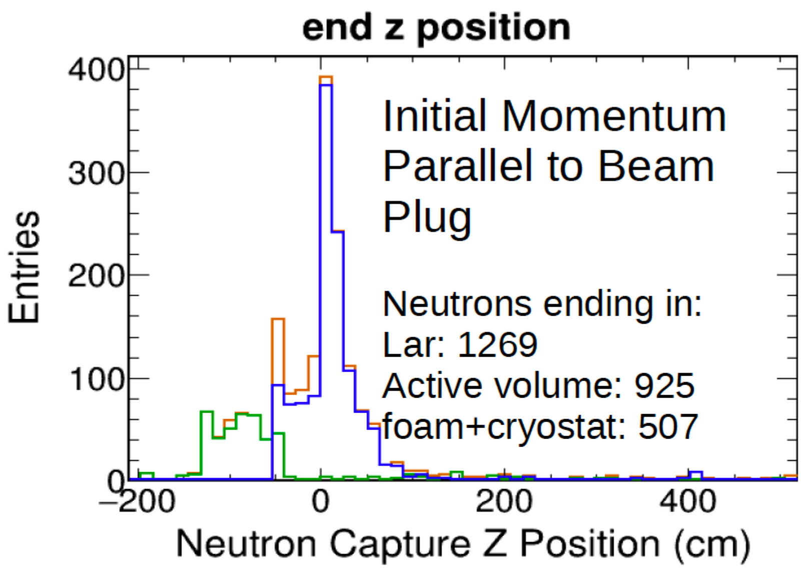
Vertical Spread Comparison

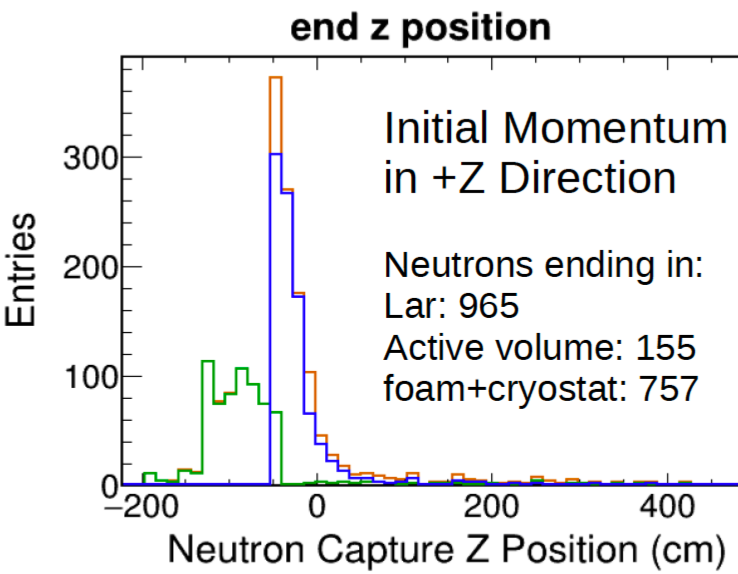


DD Generator Test at ProtoDUNE

- **Neutron transport simulation in LArsoft**

L. C. J. Rice, University of pittsburgh





How far do the neutrons go in the beam direction?

Neutron's whose end process is inelastic scattering (or capture) in foam insulation or cryostat steel
Neutron's whose end process is capture (or inelastic scattering in liquid argon)
All neutron's ending position for all processes in all materials.

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Dose Rate Calculation

- The neutron dose rate is determined using the following relation:

$$D = \phi B$$

where D is the equivalent radiation dose, and ϕ is the particle (neutron) flux in unit of counts/cm^2/s. B = 420 $pSv\ cm^2$ is the conversion factor valid for neutrons in the energy range from 1 - 10 MeV (CERN document)

- The gamma dose rate is given by the relation:

$$D = \phi \frac{\mu_{en}}{\rho} E$$

where ϕ is the particle (gamma) flux in unit of counts/cm^2/s. $\mu_{en}/\rho = 0.014\ cm^2/g$ is the Mass Energy-Absorption Coefficient. $\rho = 1\mathrm{g/cm^3}$ is the approximate density of human flesh. E is equal the 2.2 MeV gamma energy.

https://physics.nist.gov/PhysRefData/XrayMassCoef/ComTab/water.html

DD Generator Shield Simulation

- CERN requirement for shield: The radiation level for Supervised Radiation Area where the DDG is located must stay below 15 μSv/h. Non-designated Areas where the DDG will be operated, must have radiation levels below 2.5 μSv/h for low occupancy and otherwise 0.5 μSv/h.

Description		Shield Design#1		Shield Design#2	
		Maximum Neutron Dose rate (μsV/h)	Maximum Gamma Dose rate (μsV/h)	Maximum Neutron Dose rate (μsV/h)	Maximum Gamma Dose rate (μsV/h)
Plane#1	Vertical, at neutron exit window	129.6	0.254	16.9	0.31
Plane#2	Vertical, right behind the neutron shield	2.838	2.06e-3	6.05e-2	7.97e-2
Plane#3	Vertical, 3m from cryostat	0.174	6.75e-4	3.03e-2	1.09e-2
Plane#4	Vertical, 9m from cryostat	4.3e-2	2.49e-4	3.03e-2	1.78e-3
Plane#5	Horizontal, on the floor below platform	9.8e-2	4.80e-4	3.03e-2	3.02e-3
Plane#6	Horizontal, on top of cryostat	1.9e-2	1.78e-4	3.03e-2	1.42e-3