Status of the MAD Project and Construction Details of the PSD Plastic Antineutrino Subdetector

LL22-ML-Mobile Anti-neutrino-PD3Ta

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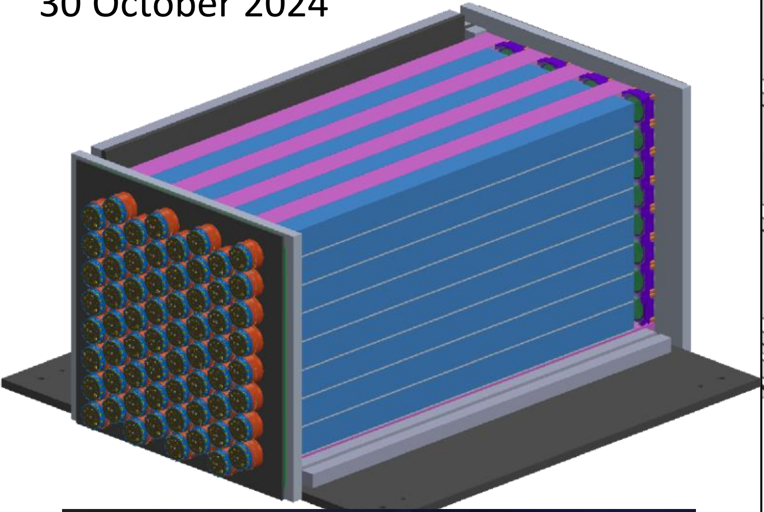
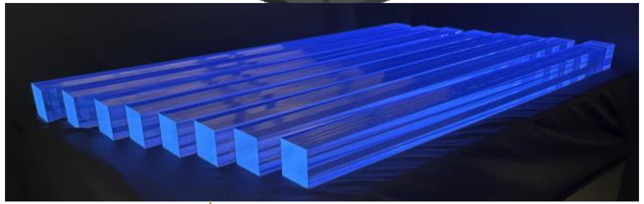
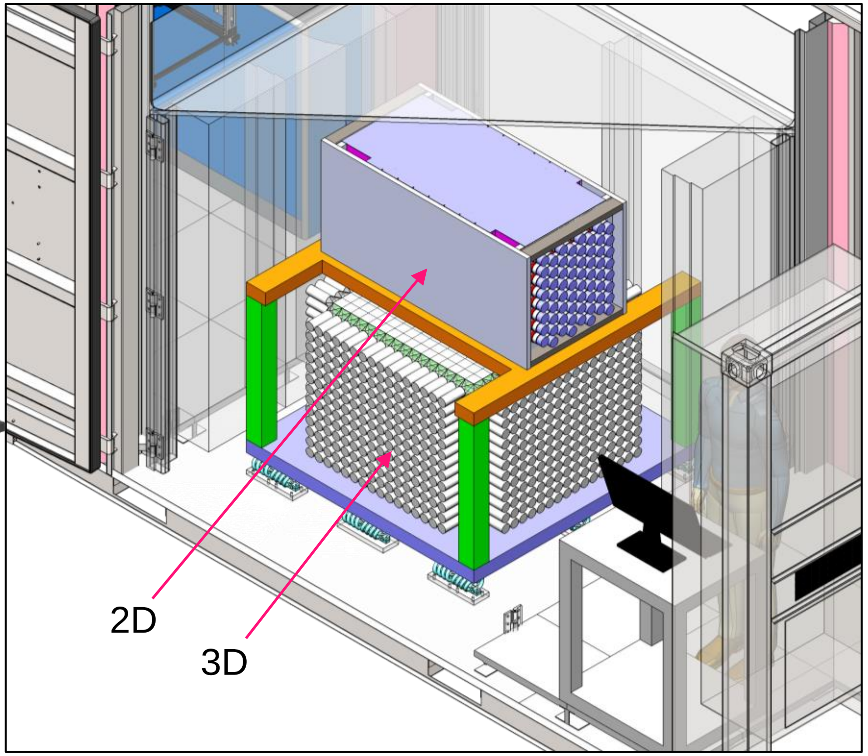
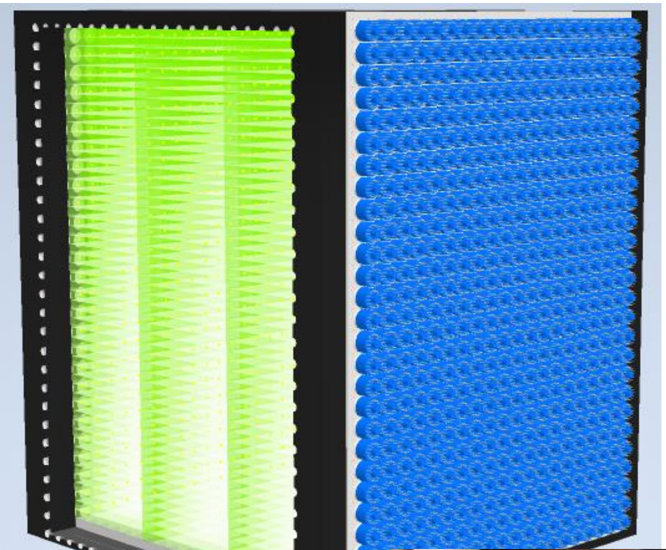
Lawrence Livermore National Laboratory

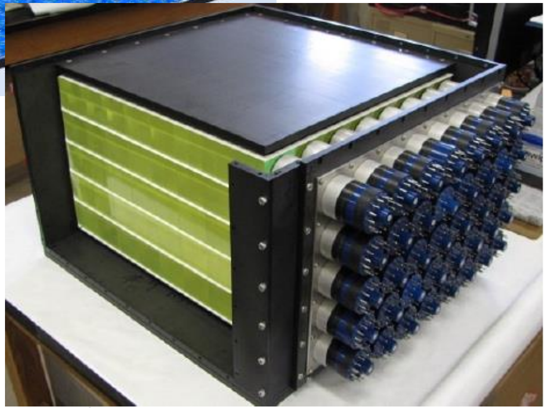
30 October 2024











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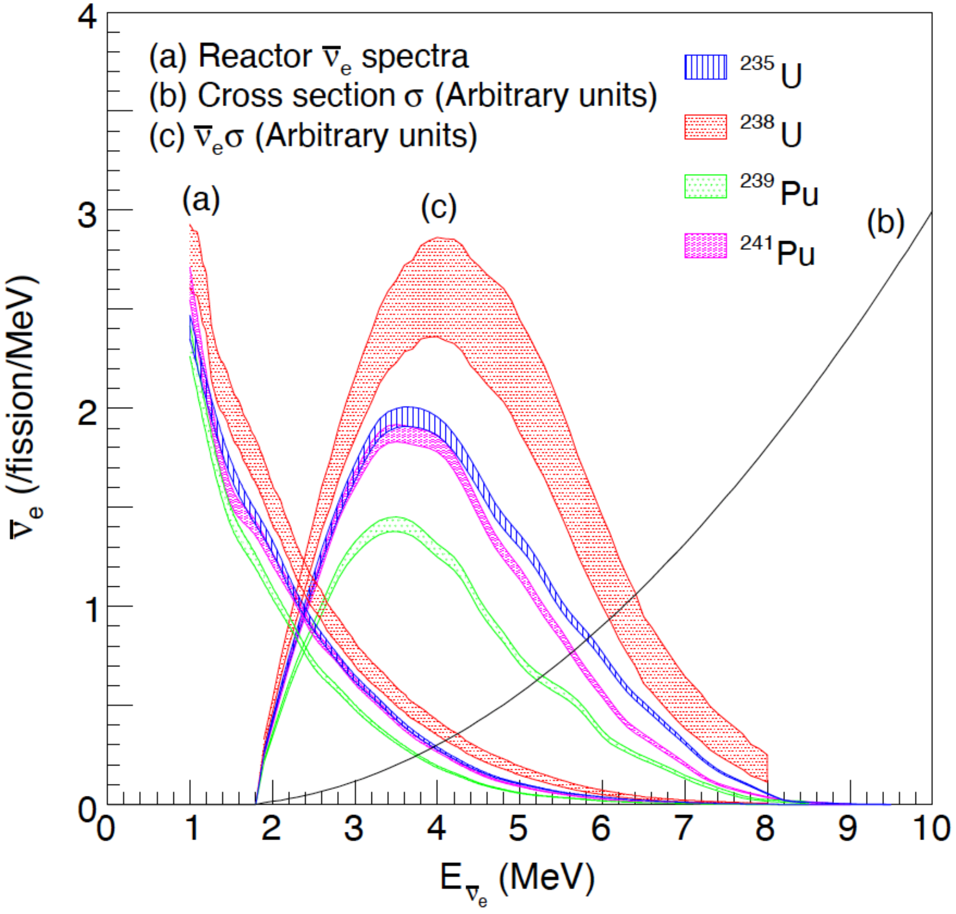
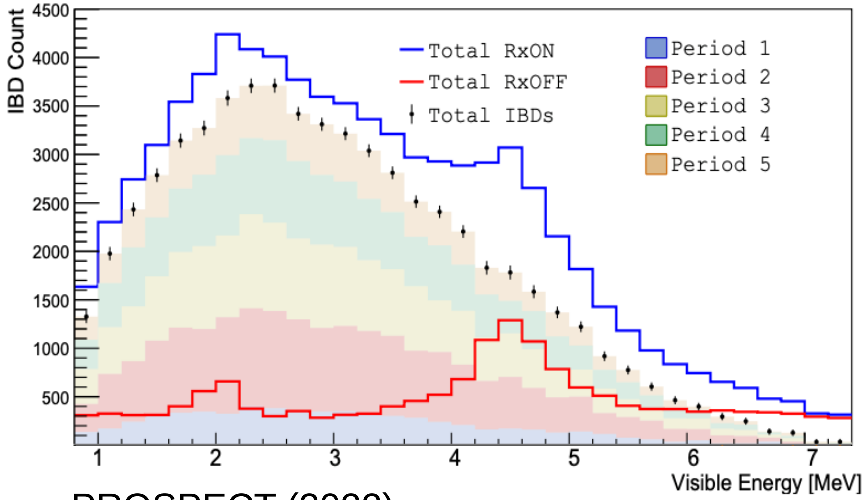
Near-field Reactor Antineutrino Monitoring

Non-intrusive detection of reactor power and Pu production

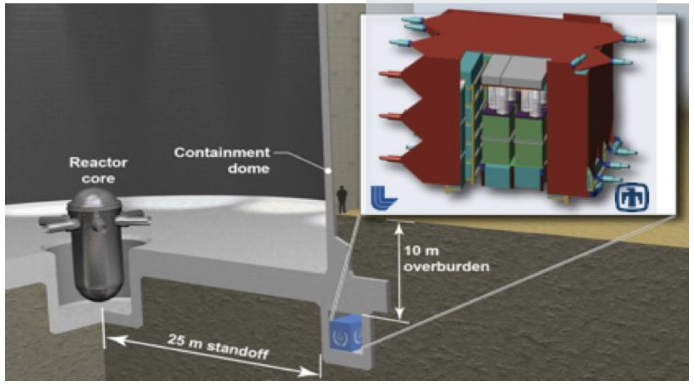


K. Nakajima *et al.* (2006)

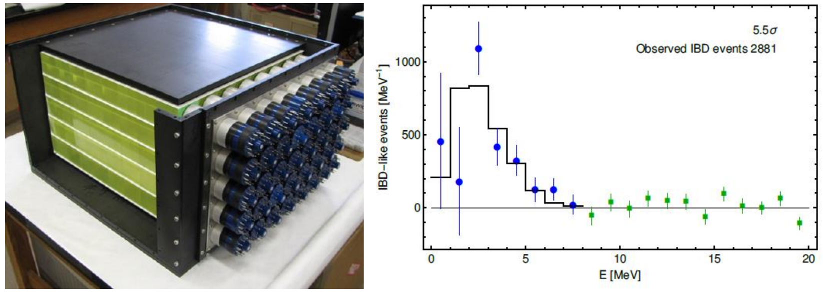
- ~6 neutrinos per fission
- Rate & spectrum vary with fuel mix
- Proposed (1970's) & first demonstrated (1980s) in USSR
- … and several other countries
- Recently observed *above ground*



PROSPECT (2022)



SONGS1 detector at the San Onofre Nuclear Generating Station (2003-2007)



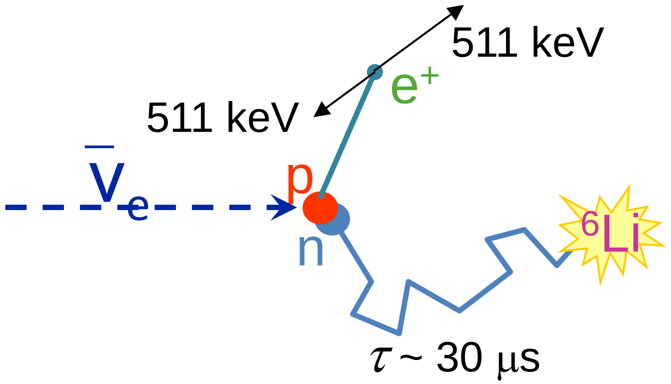
MiniCHANDLER (2020)

MAD – Mobile Antineutrino Demonstrator

Goals and constraints

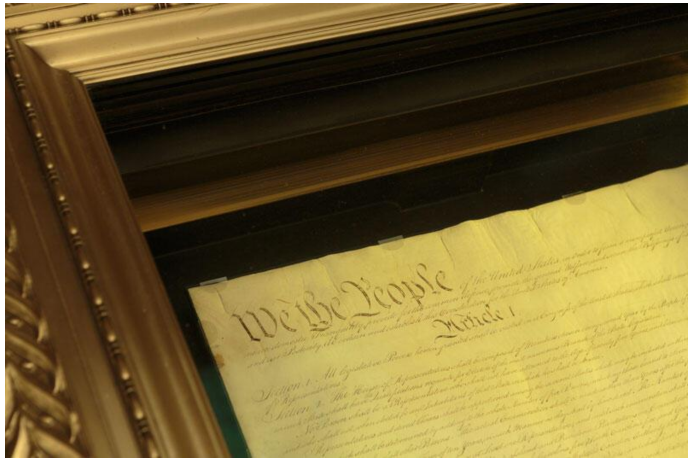
- Detector requires minimal external inputs: Only power, internet, and (at deployment) water.
- Detector will operate autonomously for months to years at a time.
- Detector does not present complications due to safety, environmental, or customs regulations. → Plastic scintillator.
- Detector is easily moved through standard transportation infrastructure.
- Detector can be repositioned and resume operation quickly with the assistance of a small staff.
- Detector is durable against insults of outdoor operation and transportation.

Inverse beta decay



prompt e^+ signal + n capture on ^{6}Li

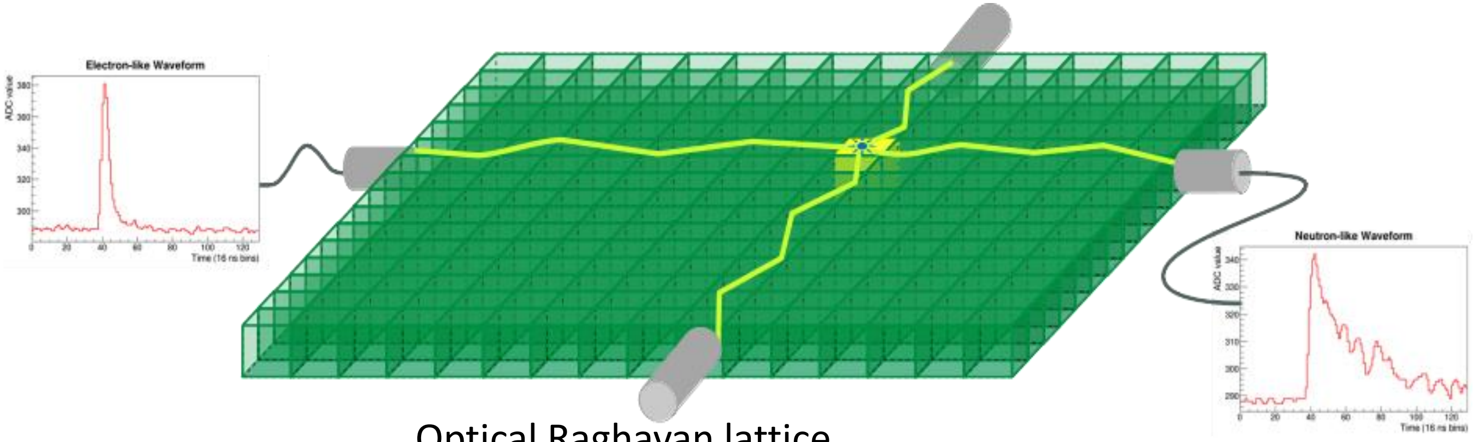
This is a packaging problem.
Protect the detector during transport while allowing data aquisition.



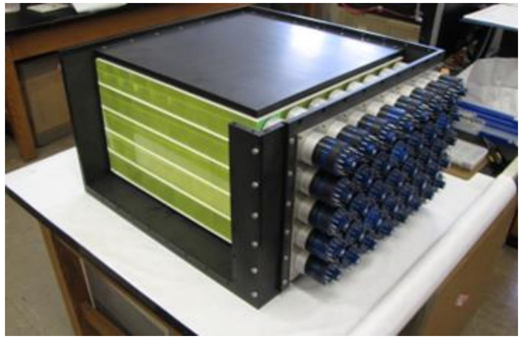
US constitution in protective case

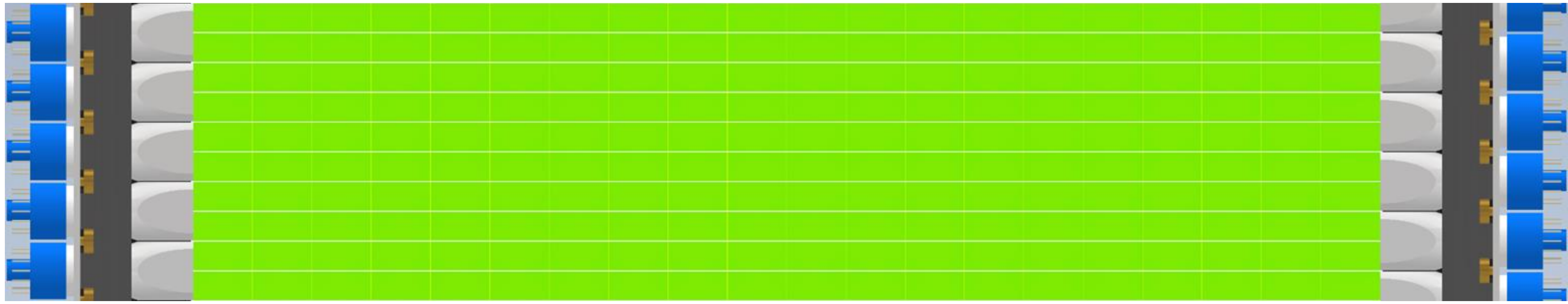
Approaches with Solid Plastic Scintillators – 3D Raghavan Lattice

- Light is transported via total internal reflection along rows and columns to PMTs through a lattice of plastic scintillator cubes (EJ-260). 600 kg size.
- ^{6}Li loaded ZnS sheets (EJ-426) between the layers absorb thermal neutrons and emit slow-decaying (200 ns) light into adjacent layers.
- The large difference in scintillation decay time between the bulk plastic and the ZnS sheets identifies neutron captures.
- 3D topology of positron and gamma energy identifies the IDB reaction site.



Optical Raghavan lattice



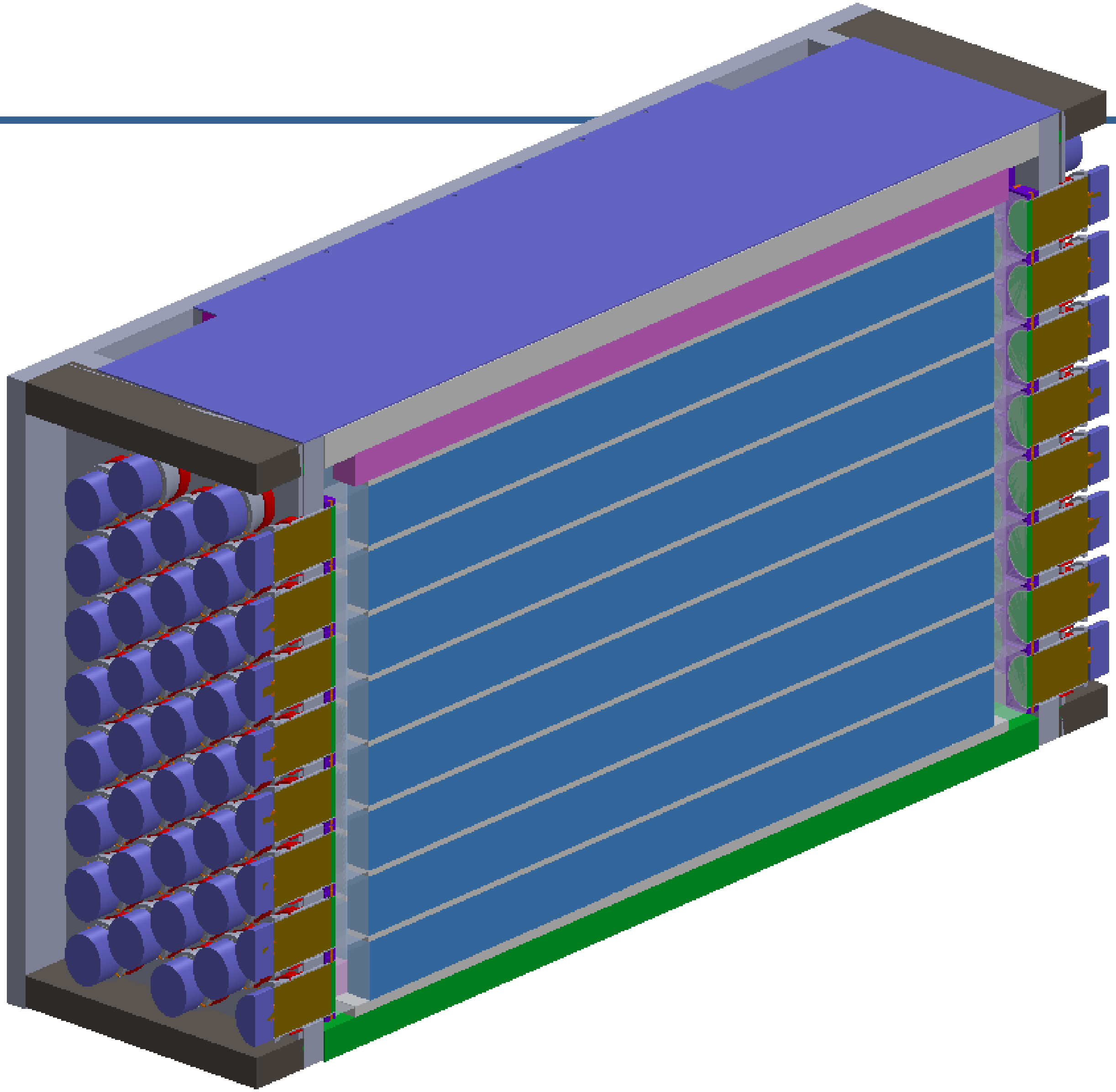


PMT vertical staggering allows higher Z resolution

MiniCHANDLER prototype successfully observed neutrinos at a power reactor : A. Haghighat *et al*. Phys. Rev. App. **13**, 034028 (2020)

Approaches with Solid Plastic Scintillators – 2D Scintillator Bar Array

- ^{6}Li (0.1 %) loaded pulse-shape discriminating plastic scintillator captures thermal neutrons.
- PSD distinguishes fast neutron backgrounds from IBD positron and gamma signals.
- Reflectors channel light to PMTs at bar ends.
- Relative light intensity and time of flight indicates interaction position along the bar.



Pulse Shape Discrimination Capable Plastic Scintillators

- 2012 – Discovery that PPO in plastic scintillator leads to PSD

  N. Zaitseva et al. Nucl. Inst. Meth. A, V668, P88 (2012)

- 2013 – First ^{6}Li doped PSD plastic scintillator

  N. Zaitseva et al. Nucl. Inst. Meth. A, V729, P747 (2013)

- Commercial PSD plastics developed by Eljen (EJ-299-33) became available soon afterward

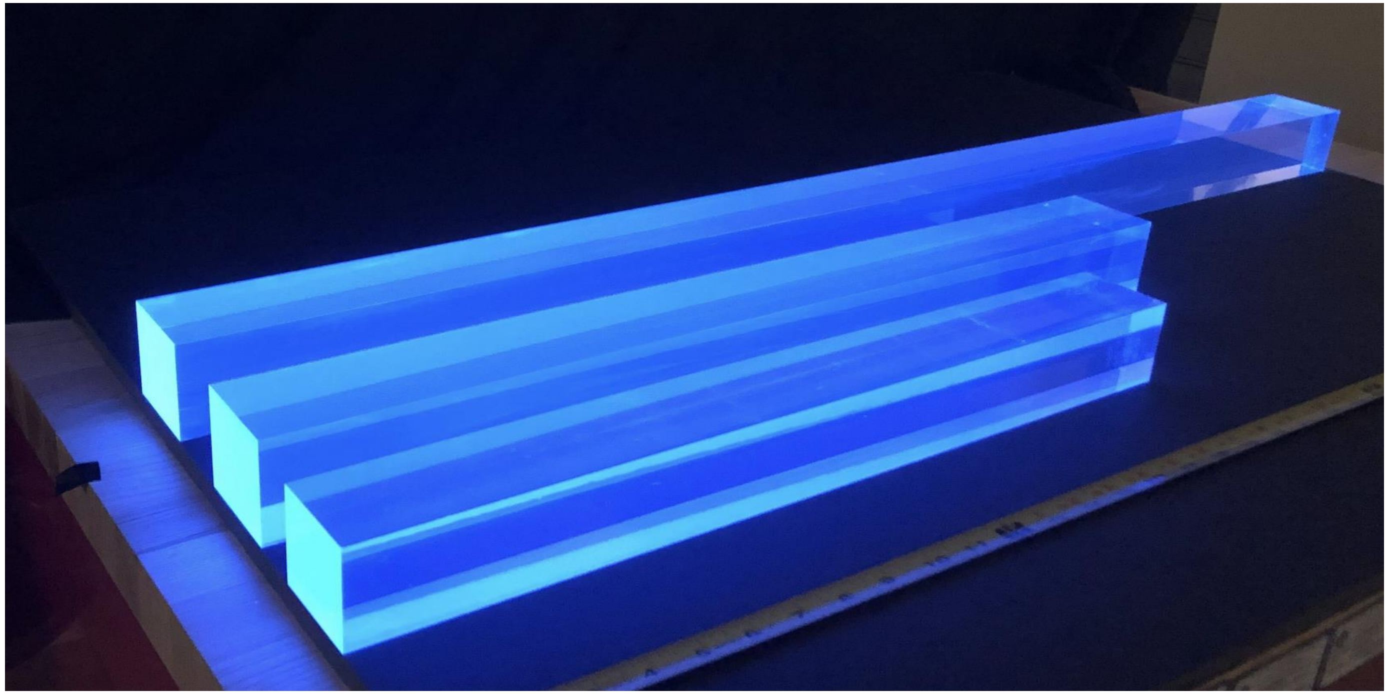
- 2017 – Development of large ^{6}Li-doped plastics began under LLNL LDRD projects and continues under MAD (Mobile Antineutrino Demonstrator) project

  A. Mabe et al., proceedings of AAP 2018, arXiv:1911.06834

  F. Sutanto et al. Nucl. Inst. Meth. A, V1006, 165409 (2021)

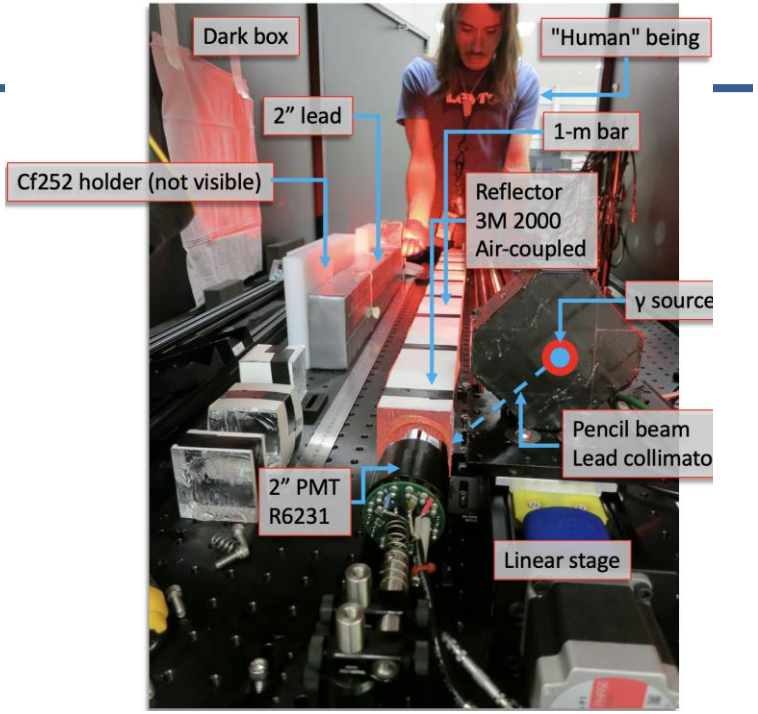
  C. Roca et al. Nucl. Inst. Meth. A, in press, 169916 (2024)

High PPO fraction → triplet-triplet energy transfer → slow component scintillation

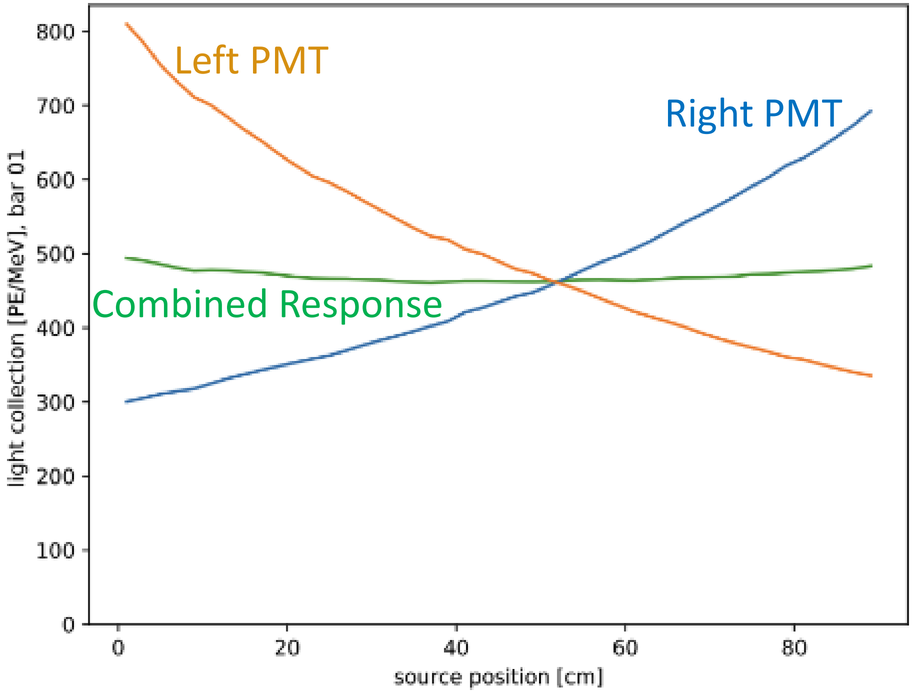


Eljen Technology has recently produced meter-scale ^{6}Li-doped bars (EJ-299-50)

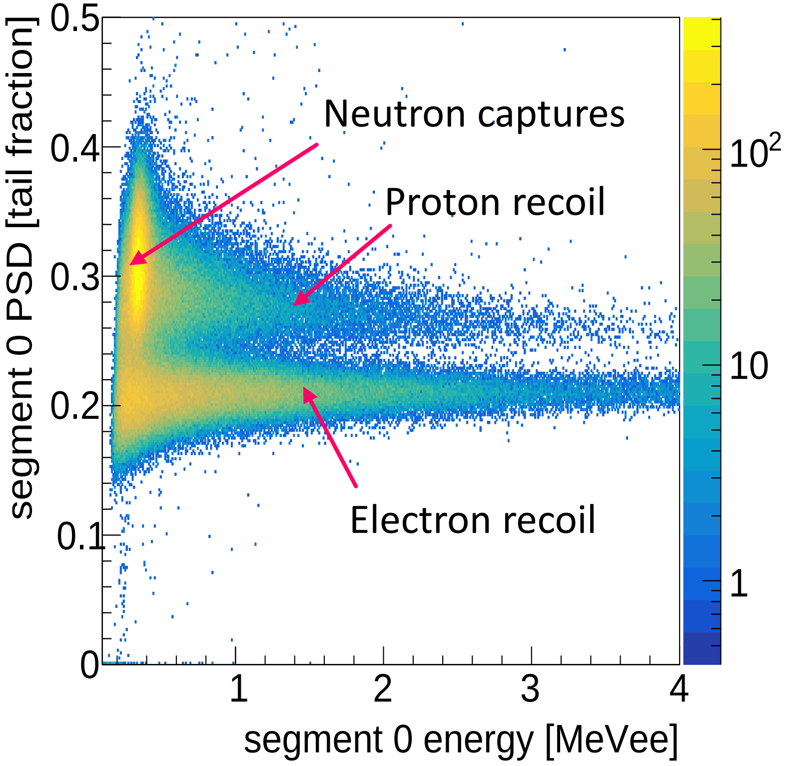
1 Meter EJ-299-50 Bar Performance



Attenuation length test apparatus



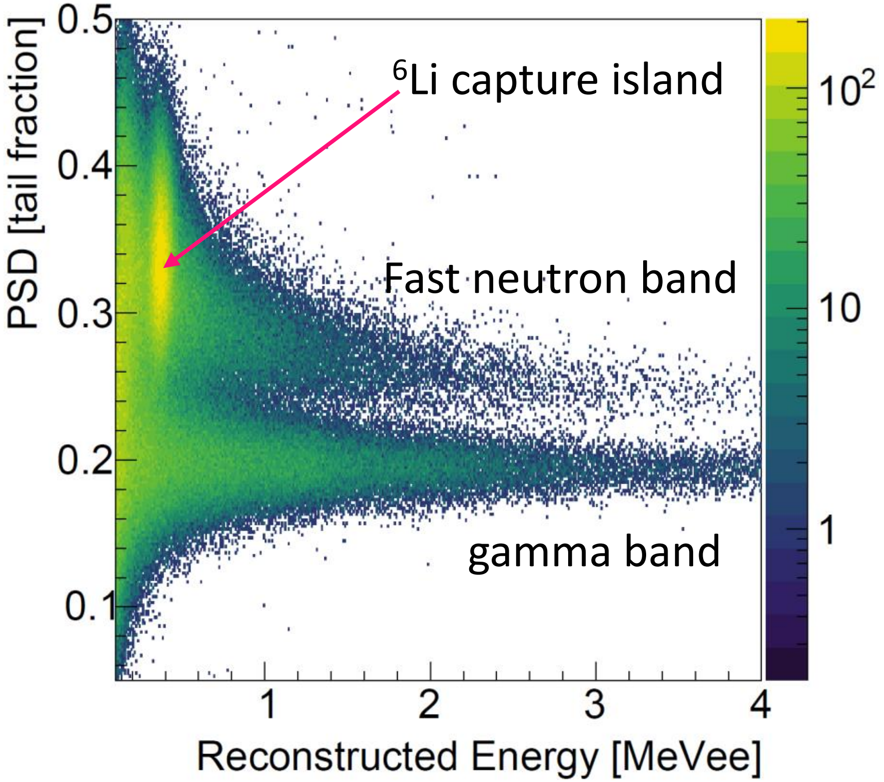
Light output and attenuation performance
1m long bar



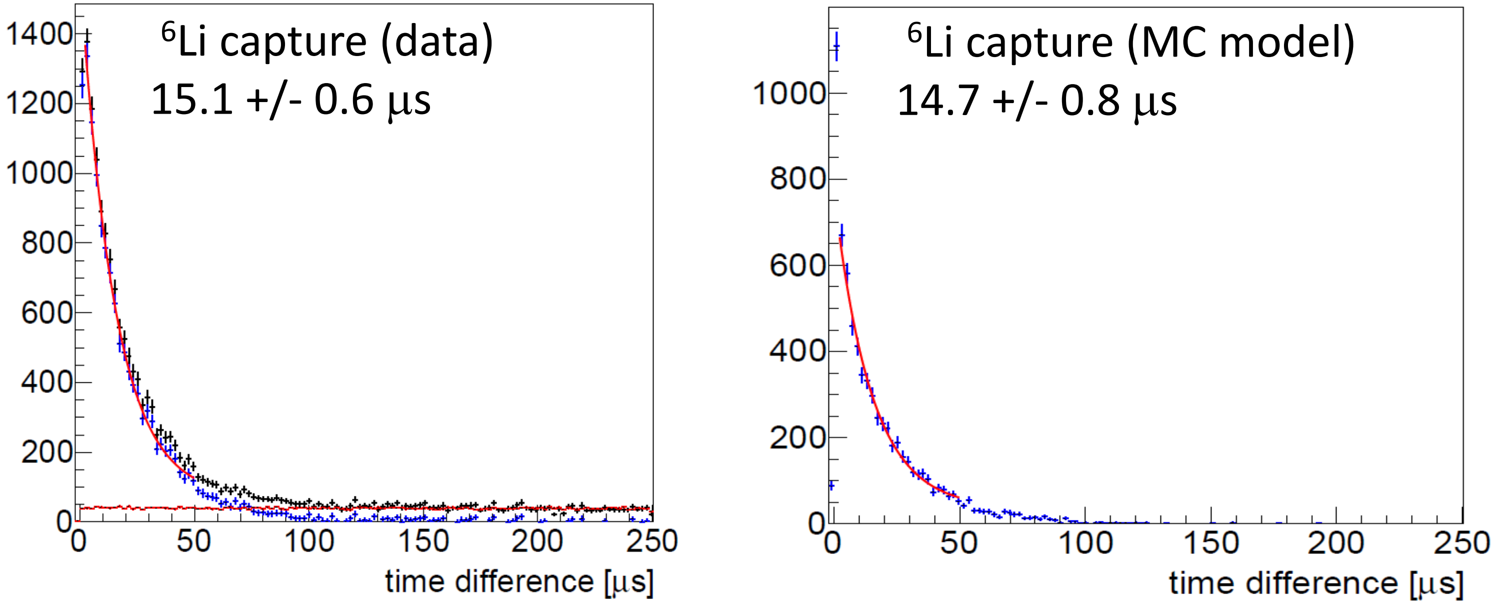
PSD for 1 m bar

- Performance of 1 meter casting consistent with measured properties from smaller bars – collect ~ 500 PE/MeV
- Light output is generally ~65% of EJ-200 (standard non-PSD plastic)
- Good ‘triple’ PSD performance
- No apparent degradation over 6-12 month time-scales operated in air
- Light output, light transport, and PSD all suitable for cubic meter scale systems

Liter-Scale Eljen “EJ-299-50” Bar Neutron Capture Modeling



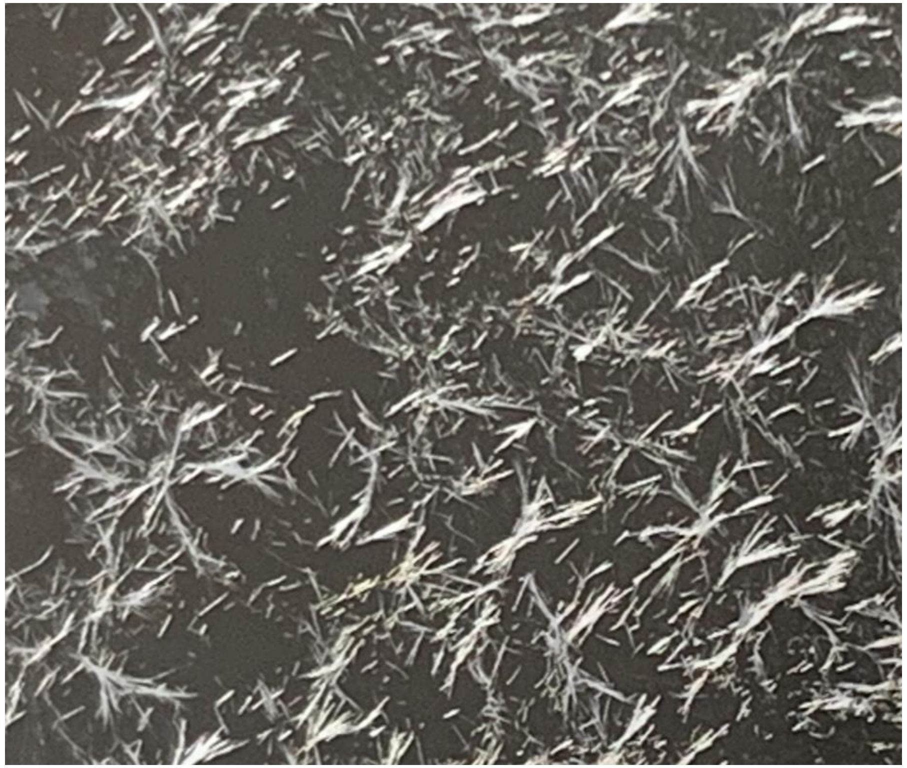
- This material is applicable to the selection of any process producing a fast neutron

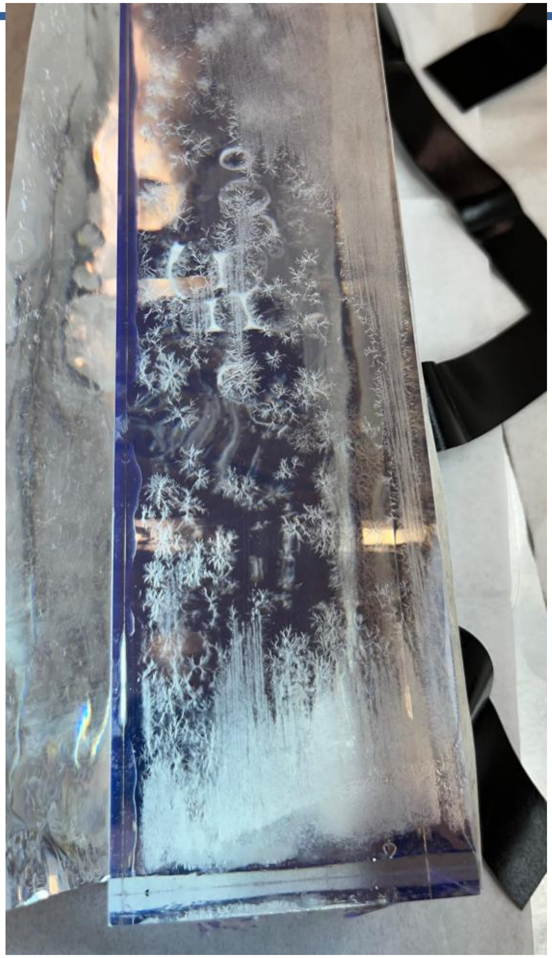


- ^{6}Li capture modeling closely matches data for a 50 mm square bar.
- Modeling of capture of a thermal neutron centered within a 1m sphere gives a 37 μs capture time and a thermalization distance of 42 mm
- 85% of captures occur on ^{6}Li, 15% on ^{1}H, and 2% on C, N

Final Implementation Problem: PPO Outgassing & Crystallization

- Two step process:
  - Outgassing of PPO from the polymer
  - Trapping of gaseous PPO near the scintillator surface
- If gaseous PPO cannot escape, crystals can form on the surface
- Unrelated to intrinsic degradation, a longer-term effect reduces optical collection
- Easily removed by cleaning - does not affect intrinsic scintillator performance but must be prevented for long-term stable operation
- Mitigations under investigation:
  - Age / bake out – effect is strongest in ‘fresh’ castings (surface layer)
  - Barrier layers
  - Surface treatments – Ethanol Cleaning

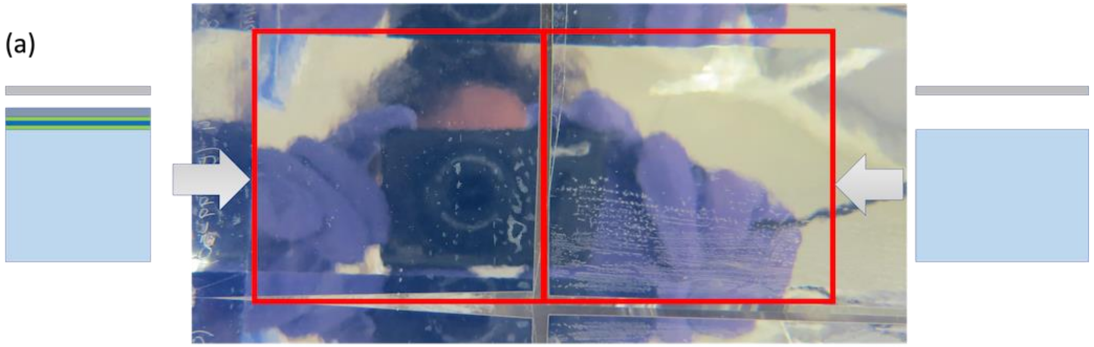




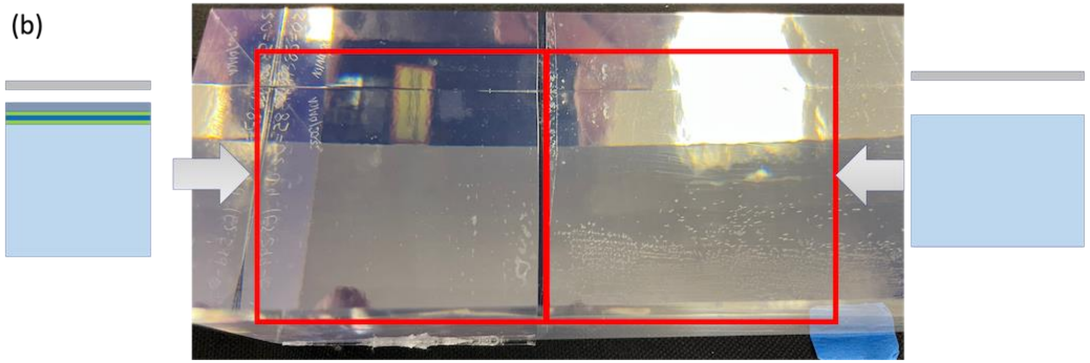
PPO crystals on 50 cm long (ROADSTR) bar after 6 months operation

PPO Outgassing & Crystallization Mitigation

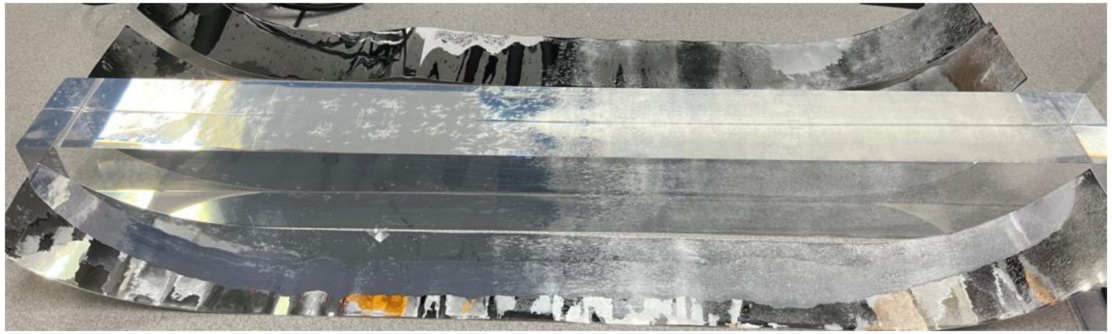
4 weeks (a)



7 weeks (b)

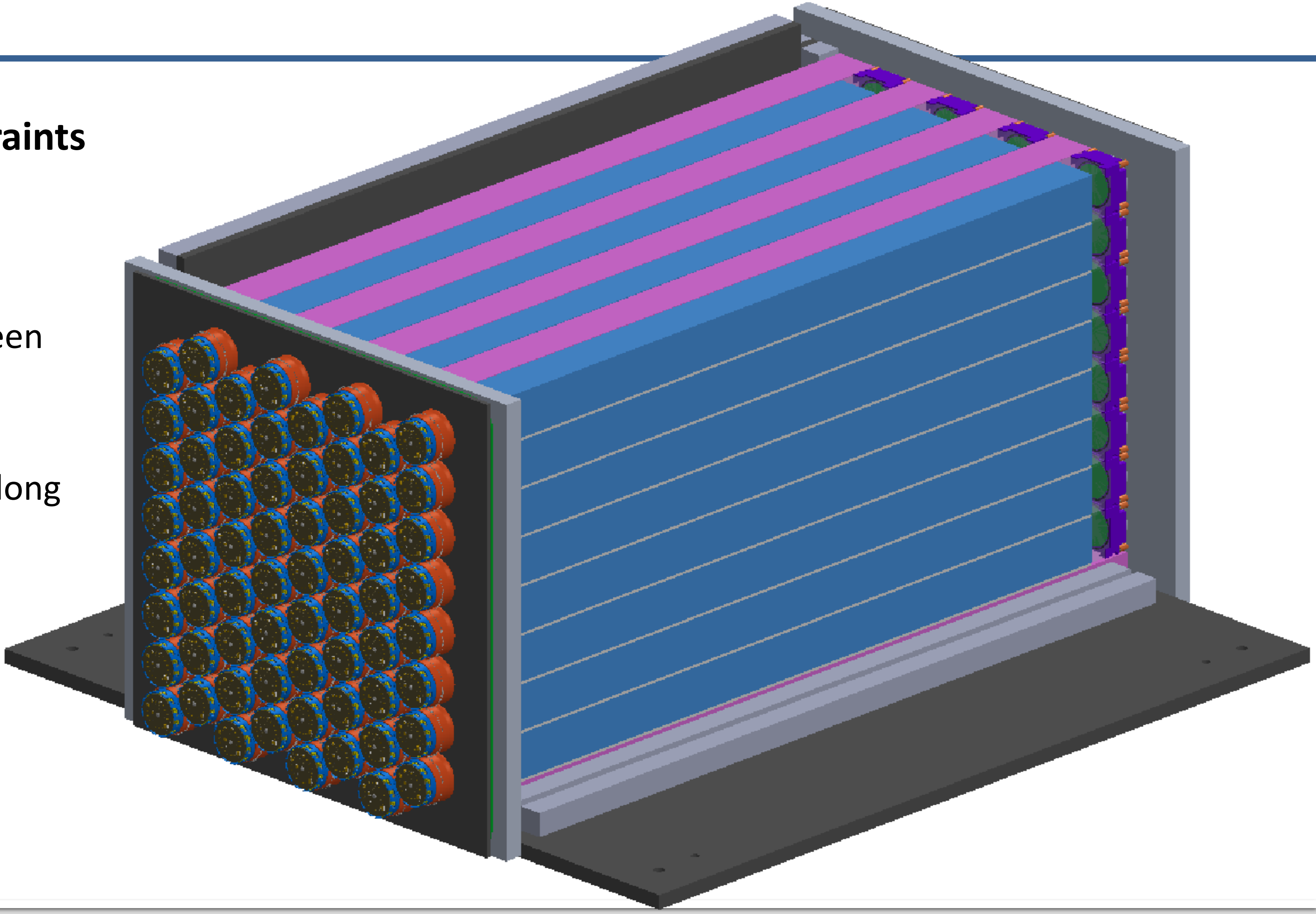


- No change observed after (now) 12 weeks
- While not entirely conclusive, this test qualitatively supports the use of the bonded barrier approach for the 2D concept



- Left side: Ethanol thoroughly cleaned prior to wrapping
- Right side: No ethanol cleaning
- Bar was left wrapped for 17 months prior to opening

Mechanical Integration of the MAD2D Subdetector



Mechanical Design Goals and Constraints

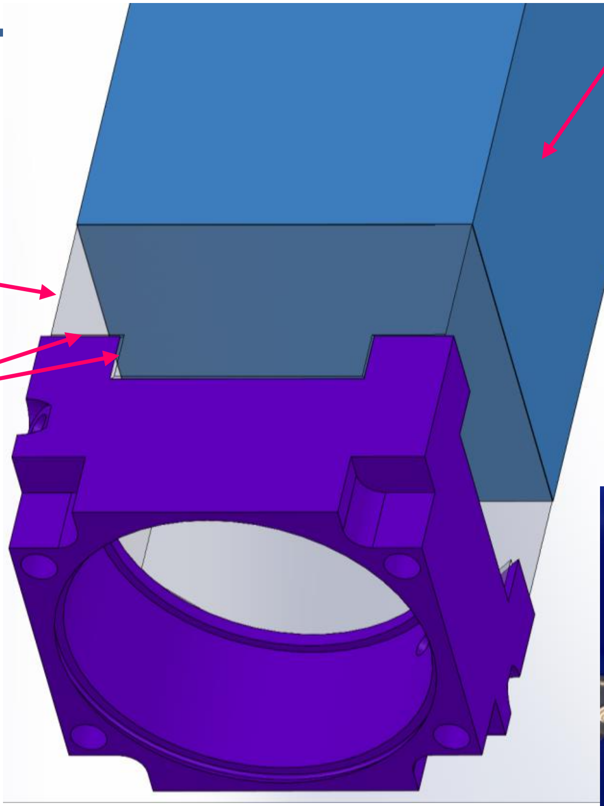
- Dense packing
- Minimal uninstrumented material between scintillator bars
- Mechanical support of scintillator bars along their full length
- Nitrogen purge around scintillator bars
- PMT exchange without disassembly

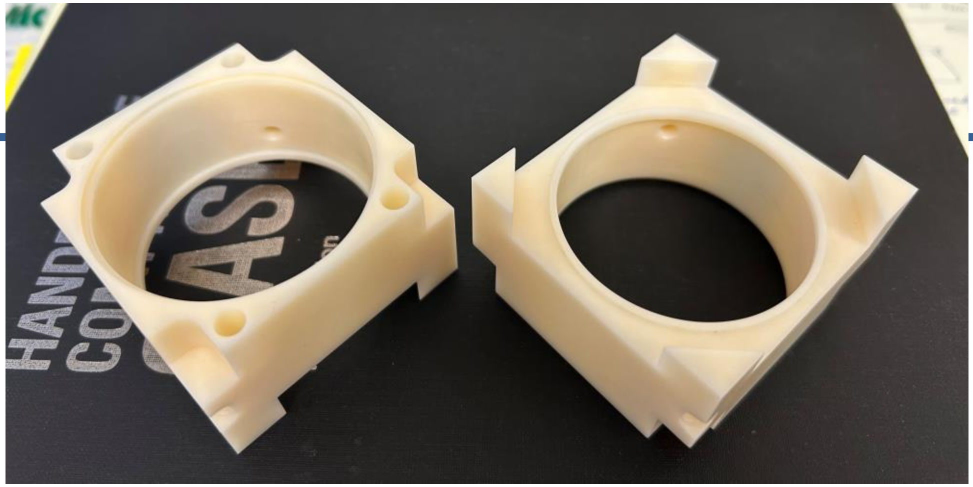
Scintillator Bar Preparation

Scintillator bars are wrapped in reflector

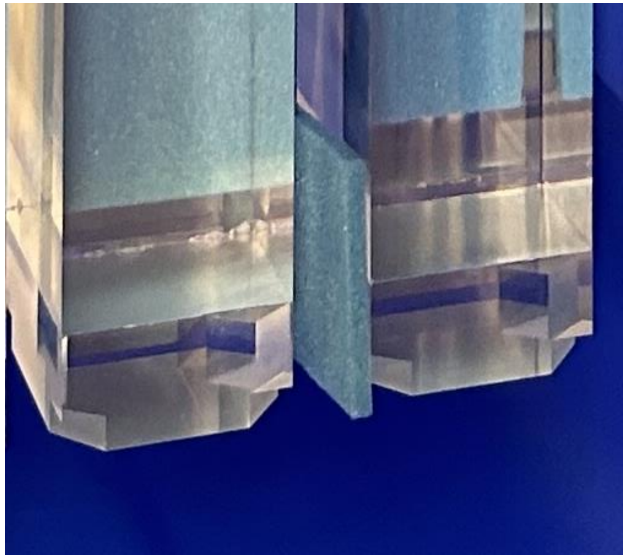
Acrylic light guides are glued to scintillator bars

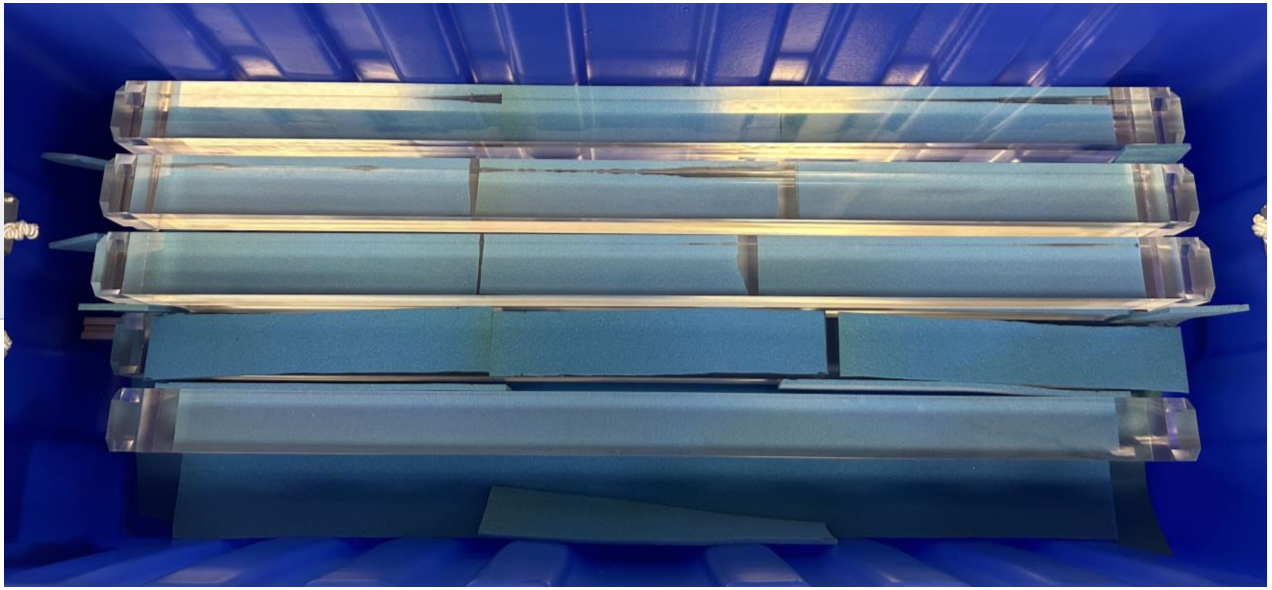
Locating collar captures corners of acrylic and is glued on these faces



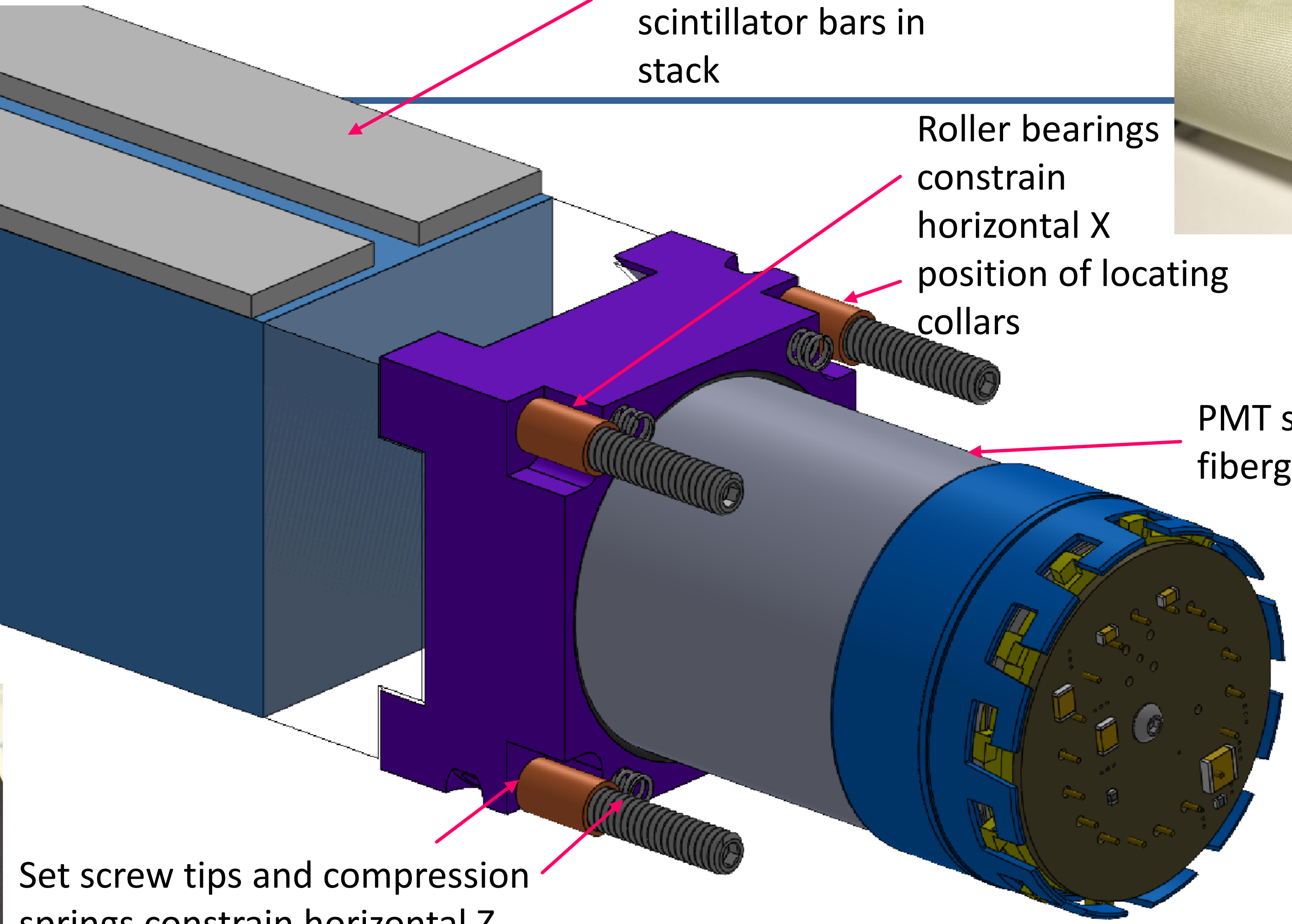


Locating collars



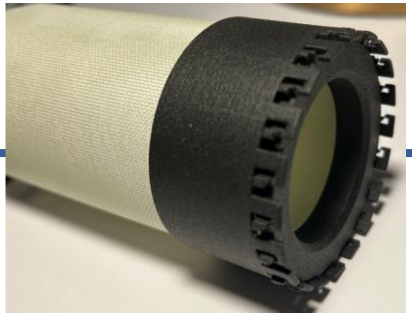


Scintillator Bar Mechanical Constraints



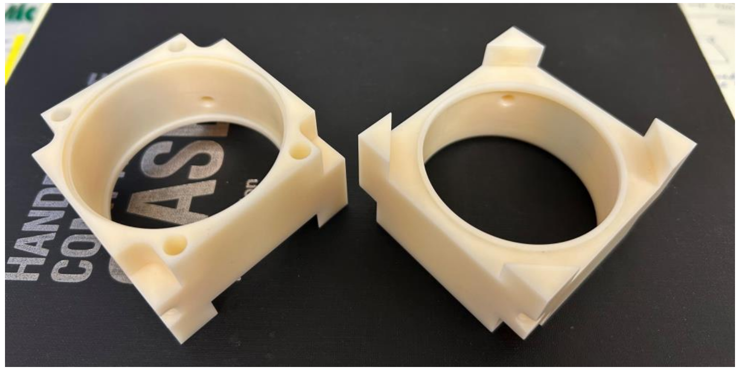
Polystyrene foam strips support higher scintillator bars in stack

Roller bearings constrain horizontal X position of locating collars



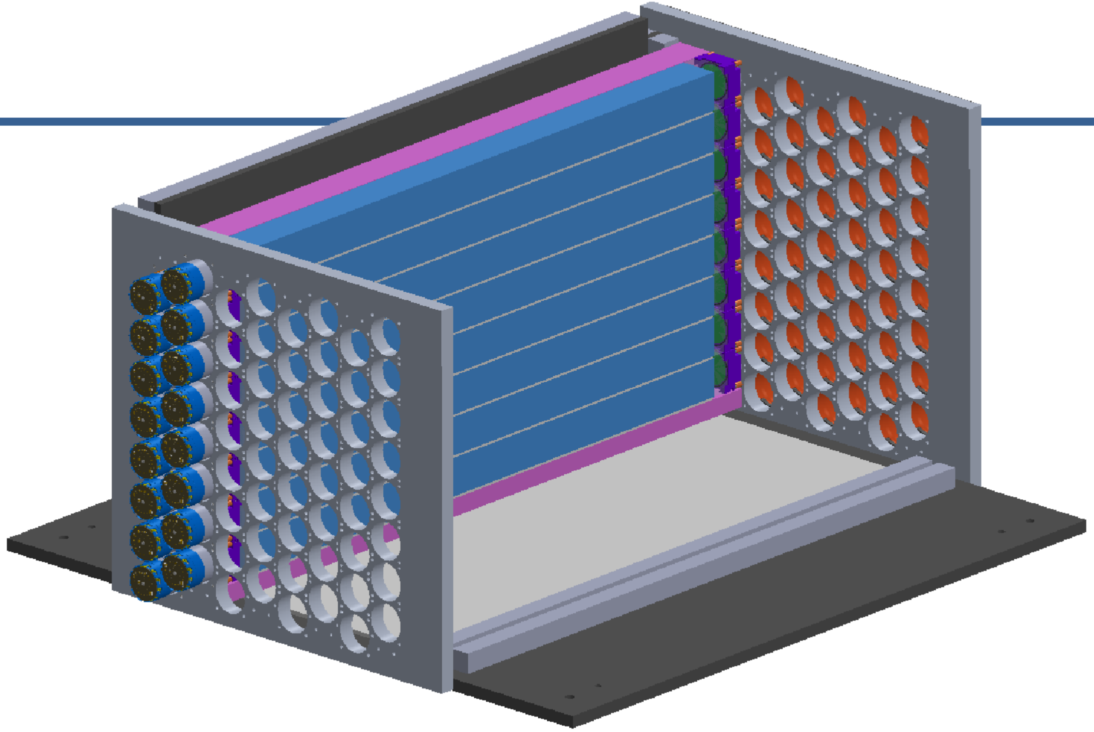
PMT sits inside of fiberglass tube

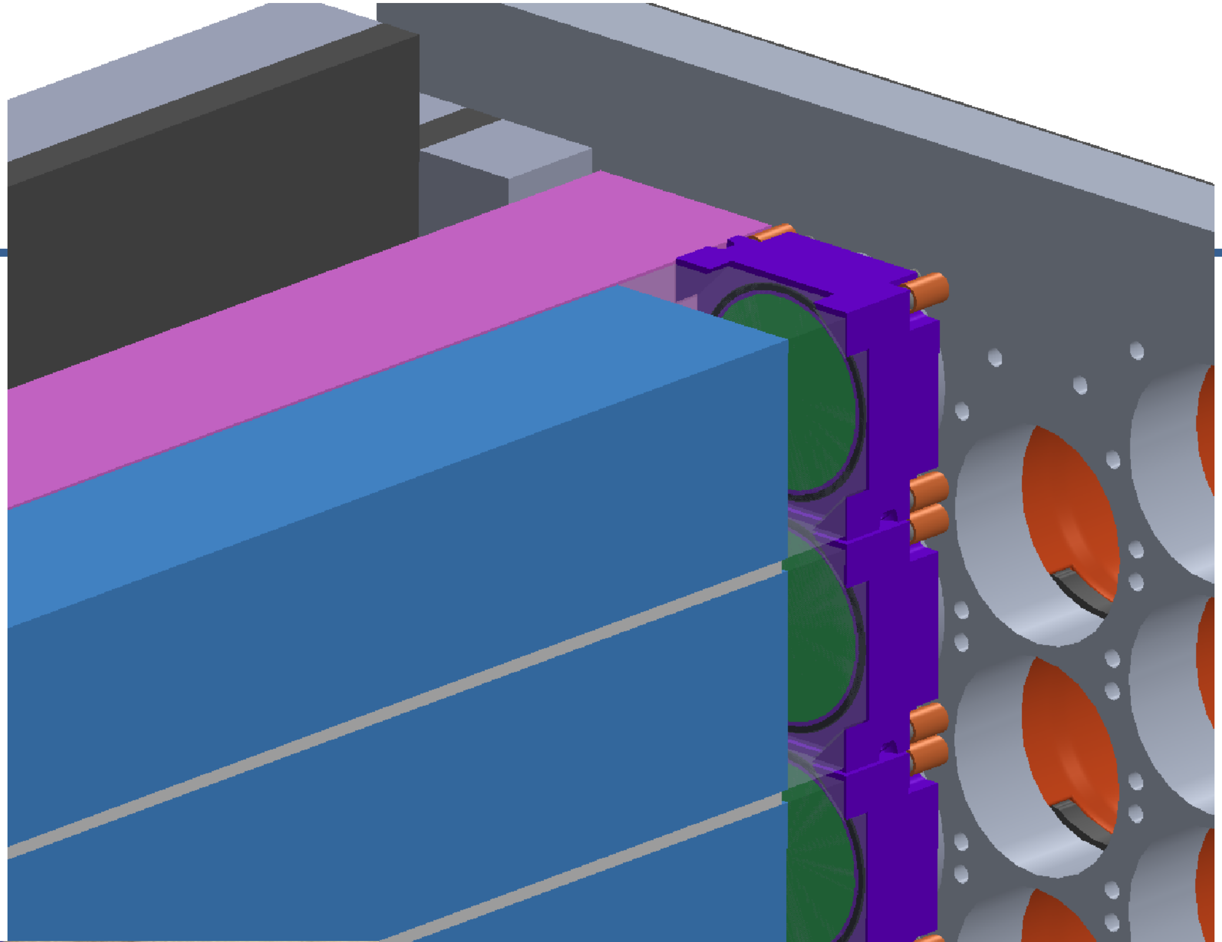
Scintillator bar is supported from below



Set screw tips and compression springs constrain horizontal Z position of locating collars

Scintillator Bar Support

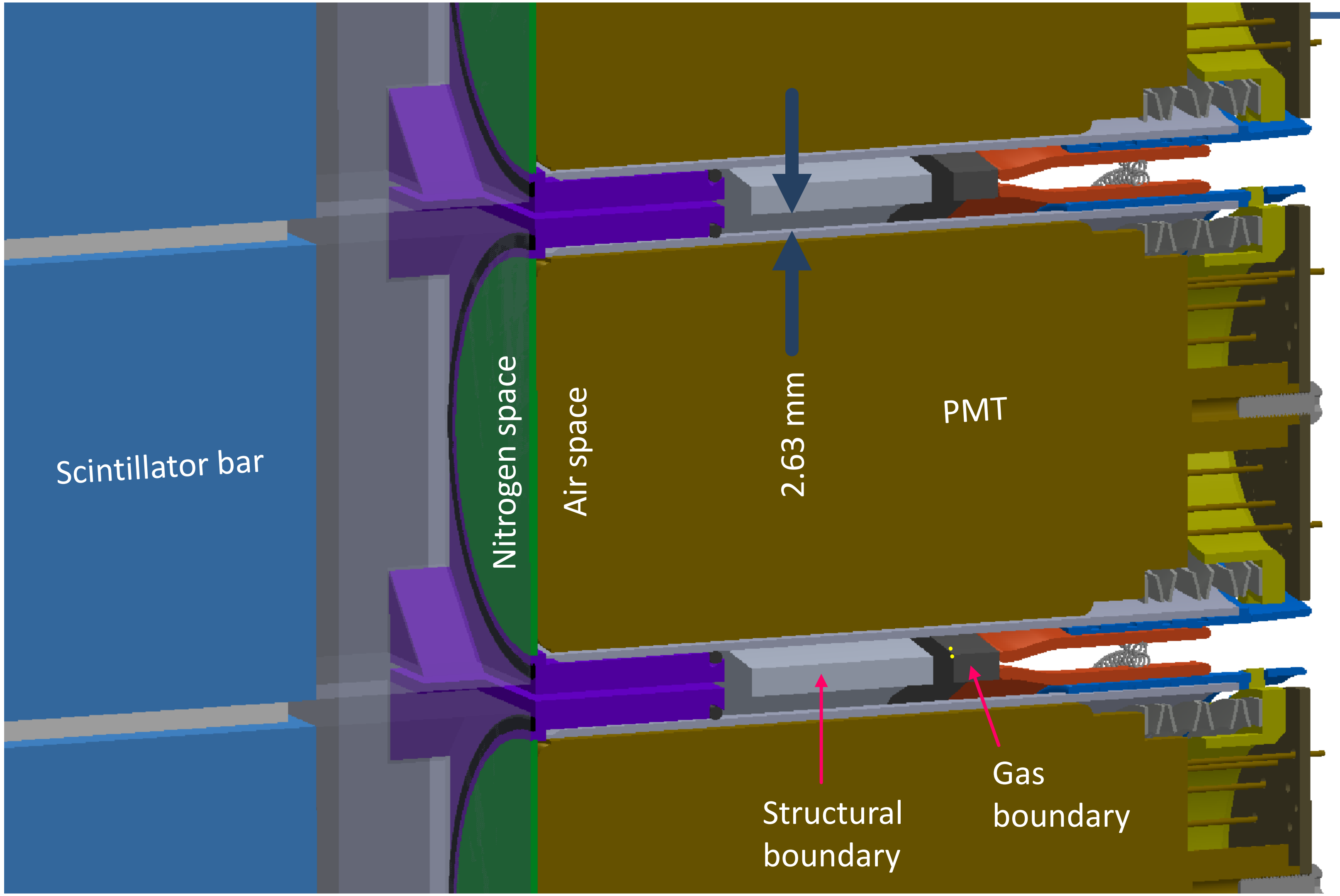




- Bars are stacked 8 high in columns
- Columns staggered in height to allow close packing
- Each bar is supported from below by strips of polystyrene foam

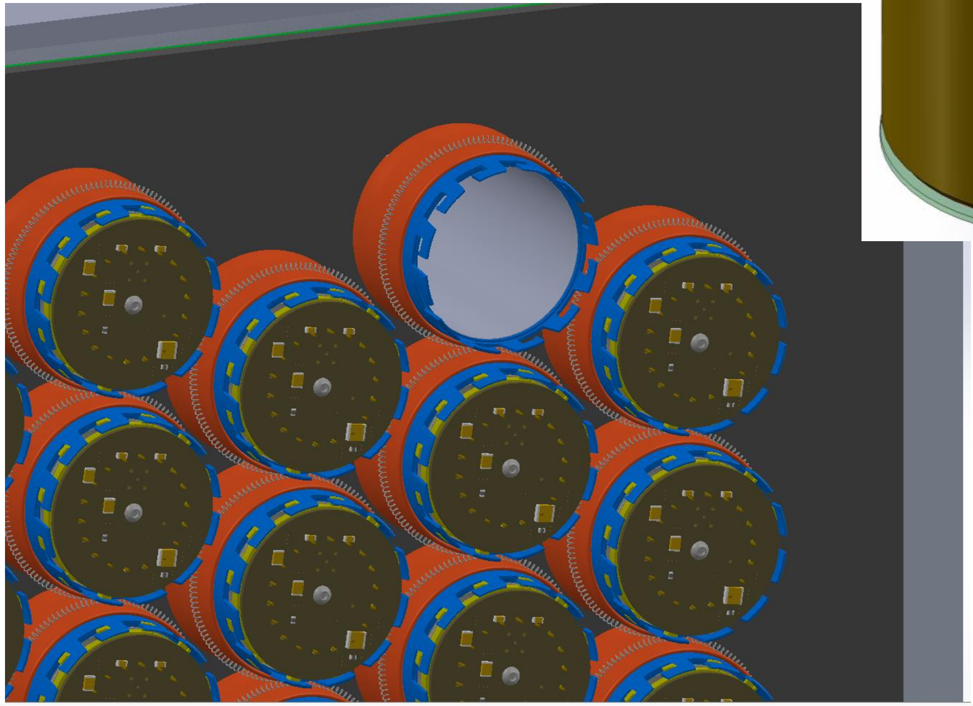
Structural and Gas Boundaries

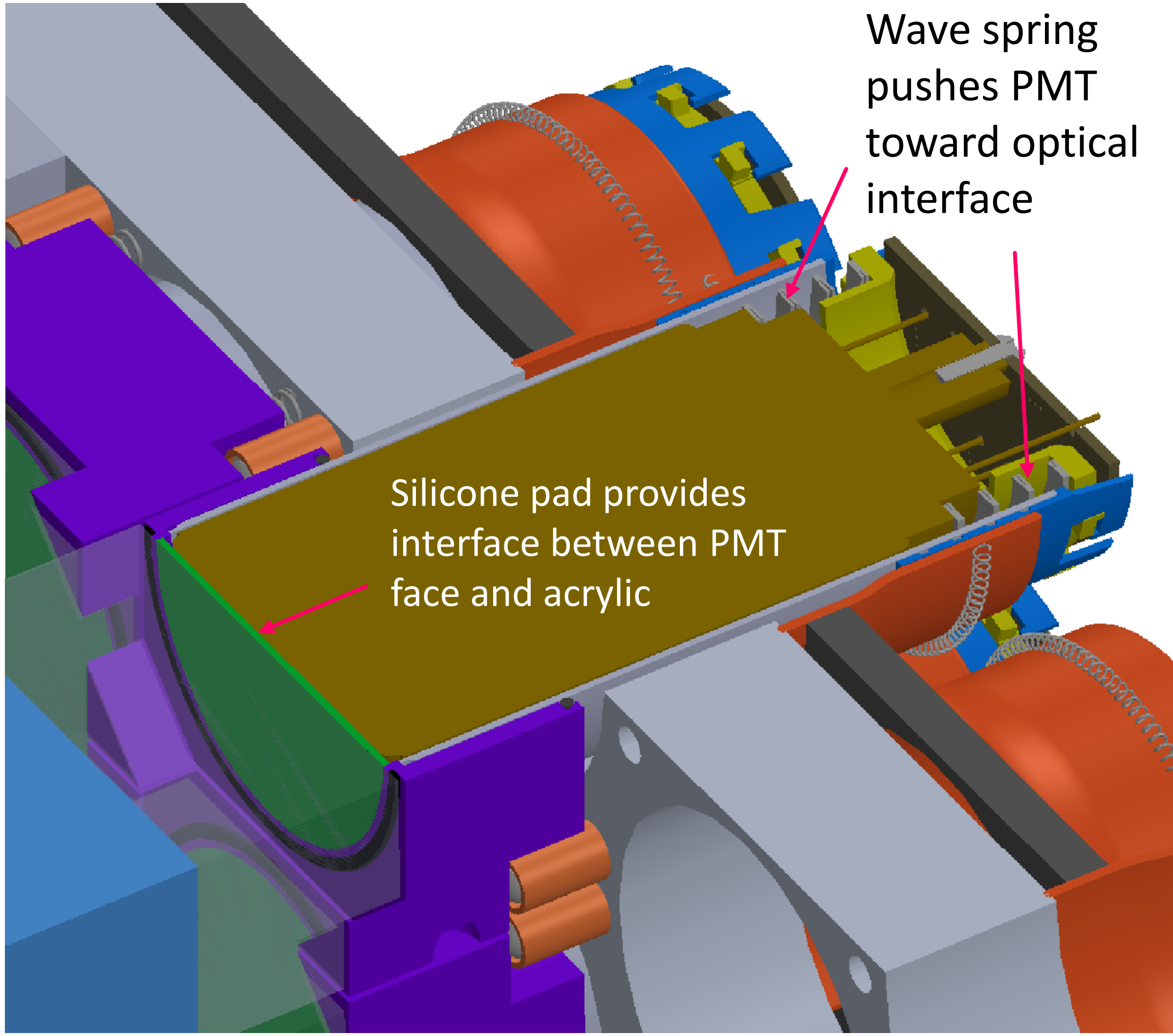
- PMTs pass through oversize holes in the container. This prevents over constraint of the bars and minimizes force on the PMTs.
- Structural boundary provides forces to constrain the horizontal positions of the columns.
- Nitrogen purged space around scintillator bars is isolated from air.
    - Locating collar seals to the light guide with glue
    - PMT support tube seals to the light guide with an O-ring
    - PMT support tube seals to the gas boundary with a flexible rubber cuff.



PMT Optical Coupling

- PMTs load through support tubes
- Bayonet mechanism and wave spring provides compression of optical interface
- Allows easy exchange in the field without interrupting the nitrogen purge



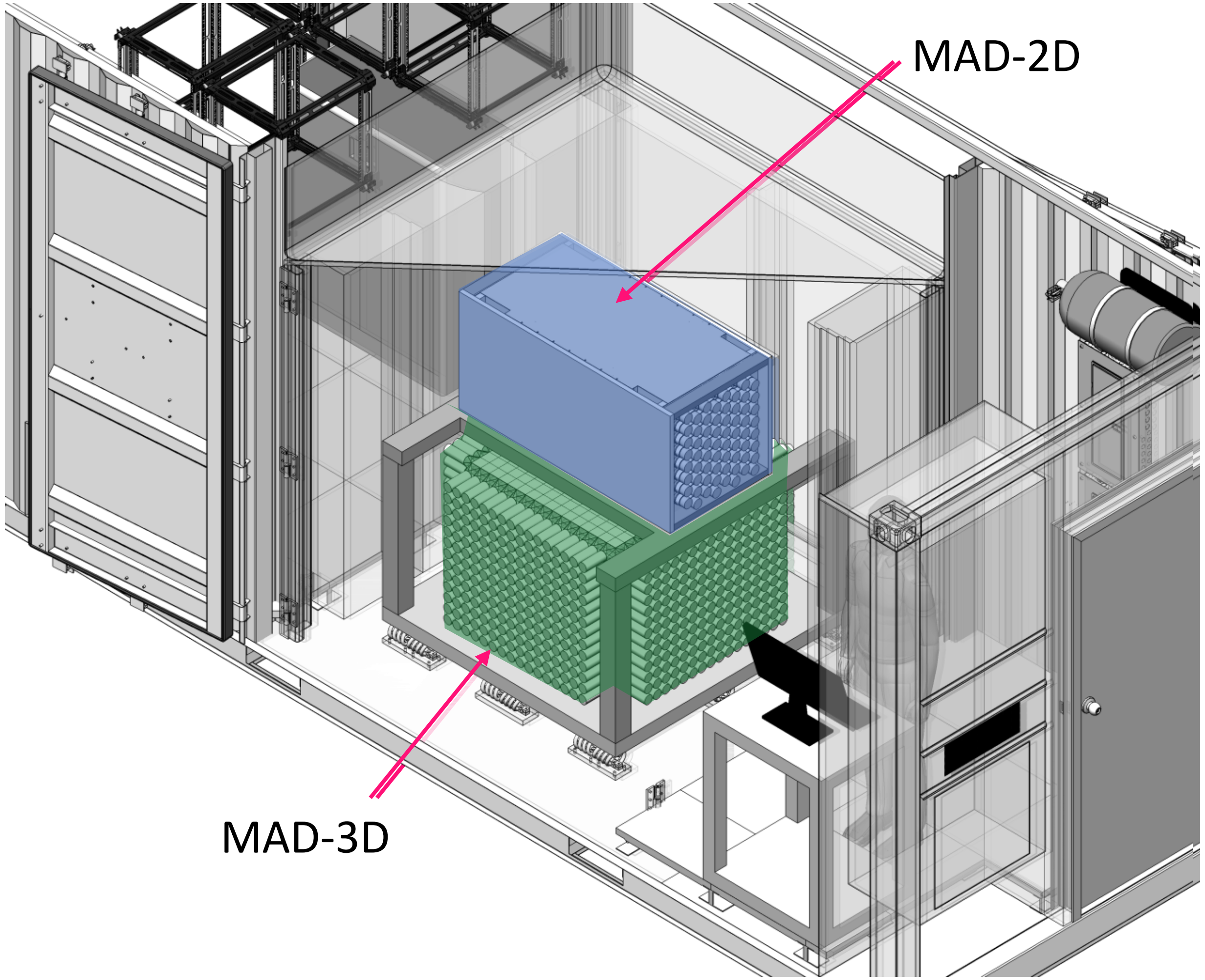


Wave spring pushes PMT toward optical interface

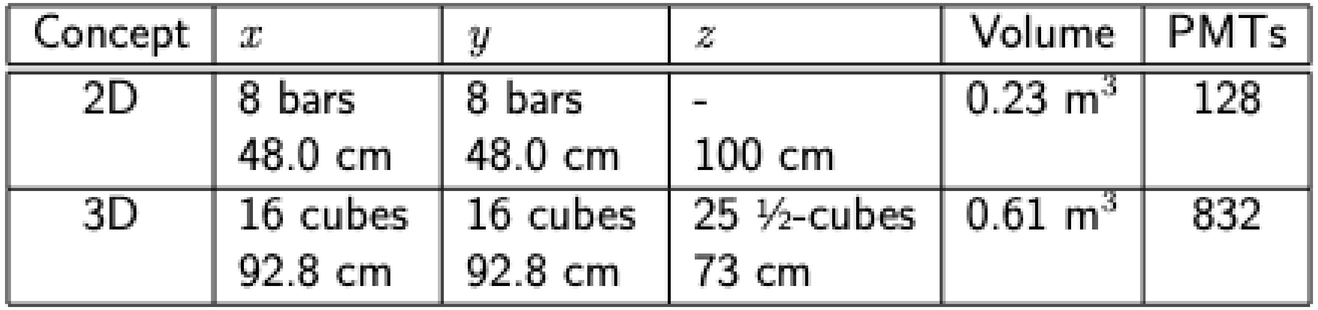
Silicone pad provides interface between PMT face and acrylic

MAD-2D (Mobile Antineutrino Demonstrator - 2D Detector)

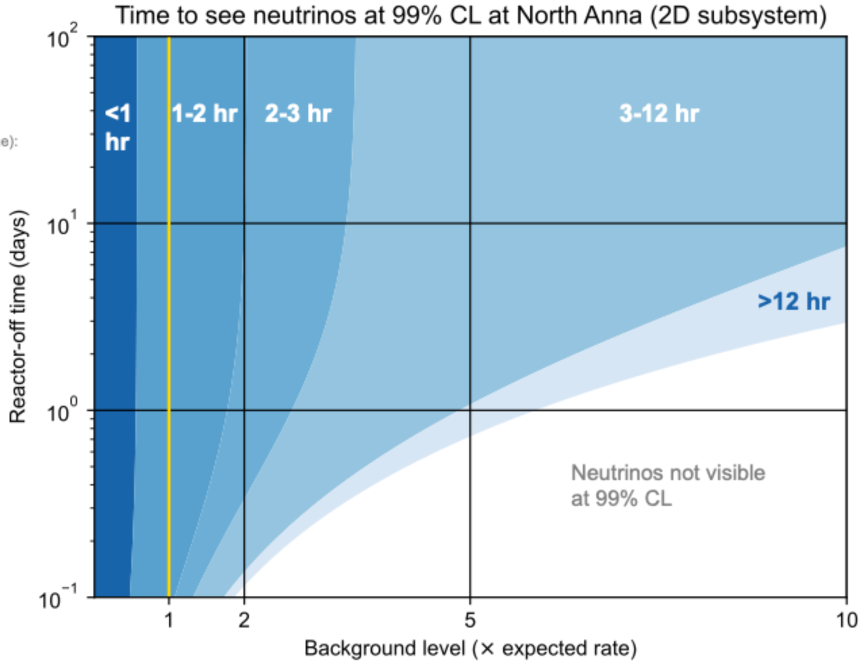
- Prototype detector built into a 20-foot intermodal shipping container for easy transport to reactors
- Bars closely packed in an 8x8 module with minimal intervening material
- Bar size: 60mm x 60mm x 1000mm
- 250 kg active mass
- Now under construction

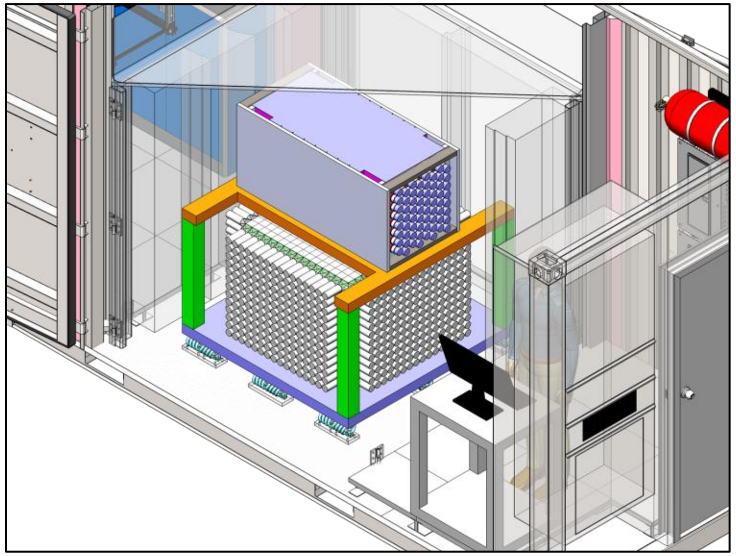


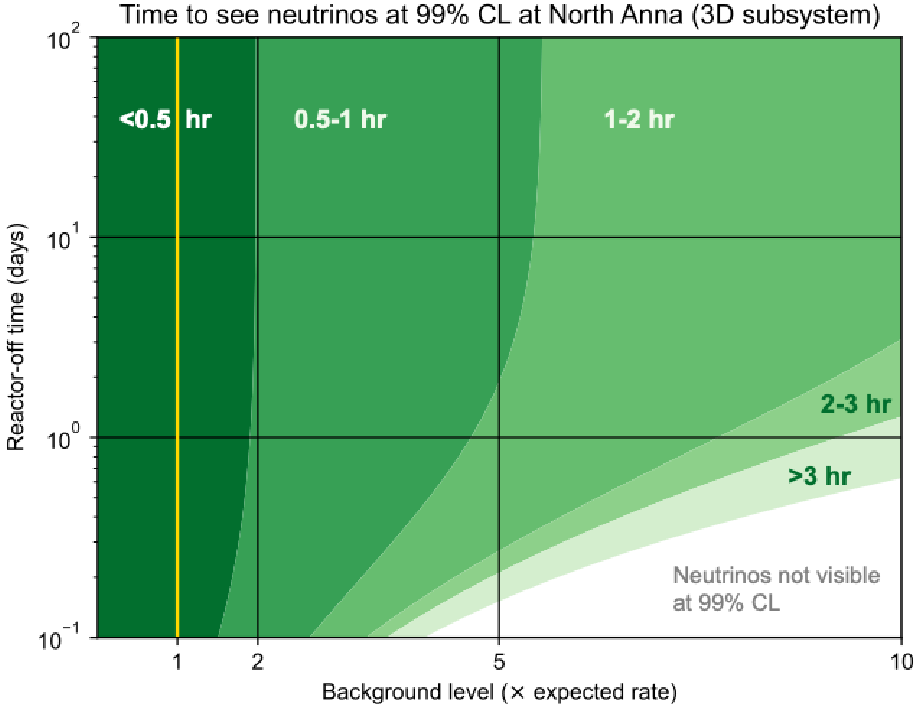
MAD Will Proceed With Two Detector Subsystems



Concept	x	y	z	Volume	PMTs
2D	8 bars 48.0 cm	8 bars 48.0 cm	- 100 cm	0.23 m^3	128
3D	16 cubes 92.8 cm	16 cubes 92.8 cm	25 ½-cubes 73 cm	0.61 m^3	832

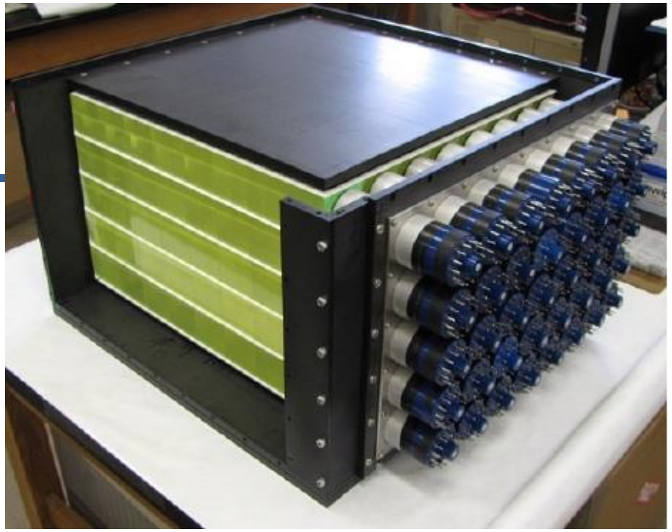






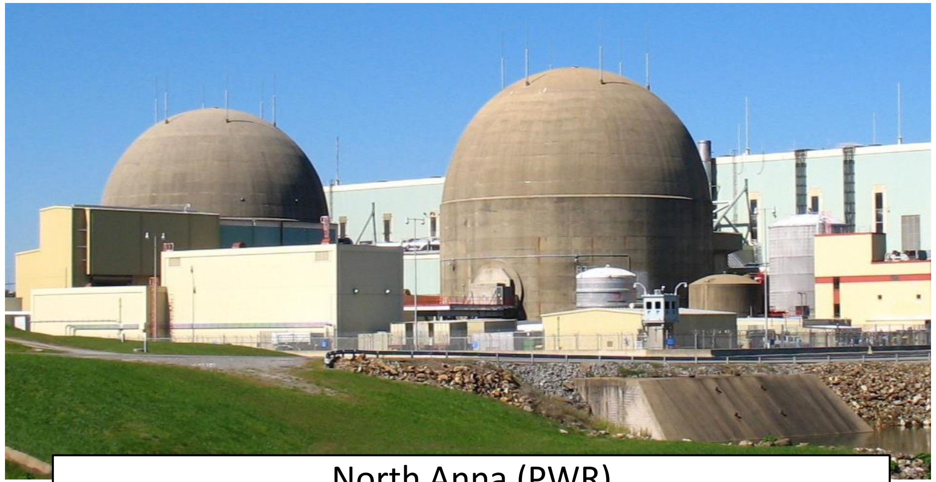
Demonstrator with two subsystems will perform capability demonstrations and advance both technology concepts

Demonstration and Measurement Options



- The MAD Testbed can support identified use cases via demonstrations and measurements:
  - Validate detection performance
  - Validate reliable unattended operation in relevant use-case environments
  - Validate durability against the stresses of transport
  - Validate background prediction in relevant use-case environments

- Potential Measurement Sequence:
  - Reactor demonstration in 2025-2026
  - Background measurements in varied environments with 2D & 3D prototypes and/or full MAD system 2025-2027



North Anna (PWR)

MAD will perform capability demonstrations, validate technologies at scale, and provide supporting measurements