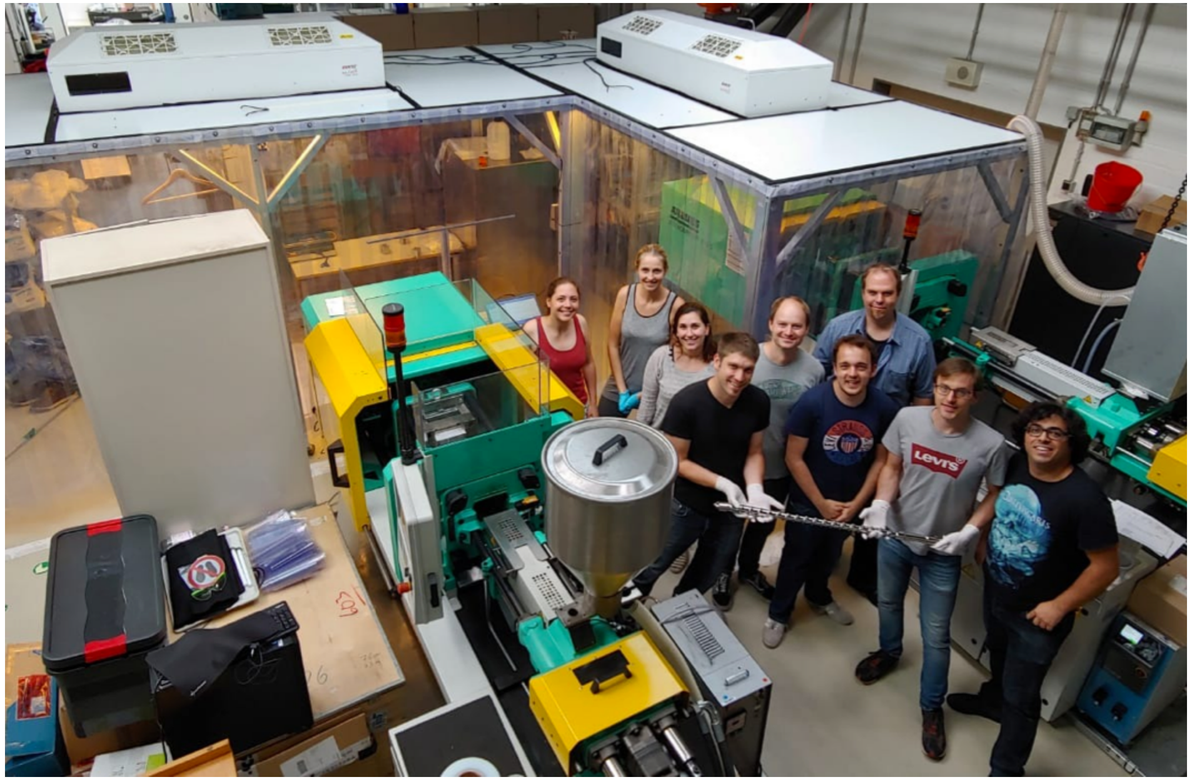
Scintillation and Optical Properties of the Low-Background Scintillator, PEN

Brennan Hackett

PEN Working Group

- 9 institutions
- 30+ Active members



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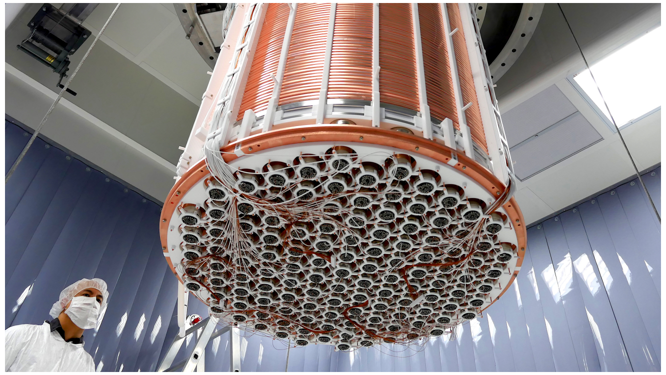
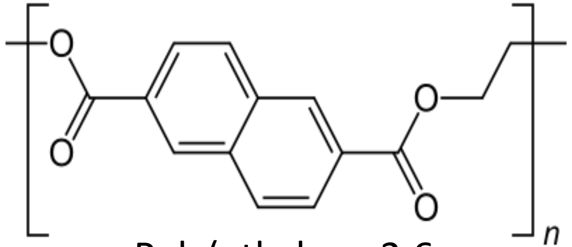
Max-Planck-Institut für Physik

Motivation – Low Background Physics

- Large scale low background physics experiments demand ultra low levels of radioactivity
  - Ultra radio-pure materials
  - Minimized inactive components
- Inactive components:
  - Cables, connectors, electronics
  - Structural components, etc.
- Active veto components could replace structural components, improving background levels
  - One possible material for structural active veto components is poly(ethylene 2,6-naphthalate) (**PEN**)



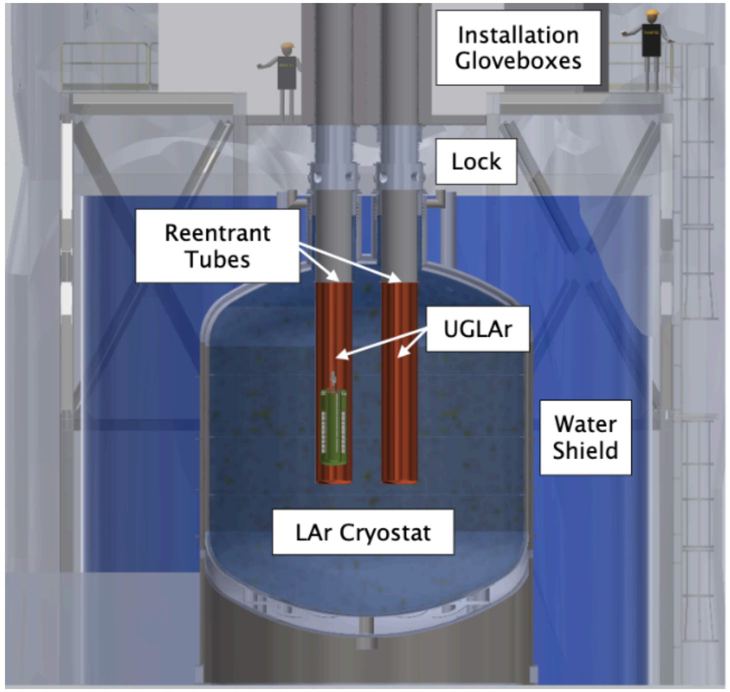
Above: XENON1T
Below: LUX



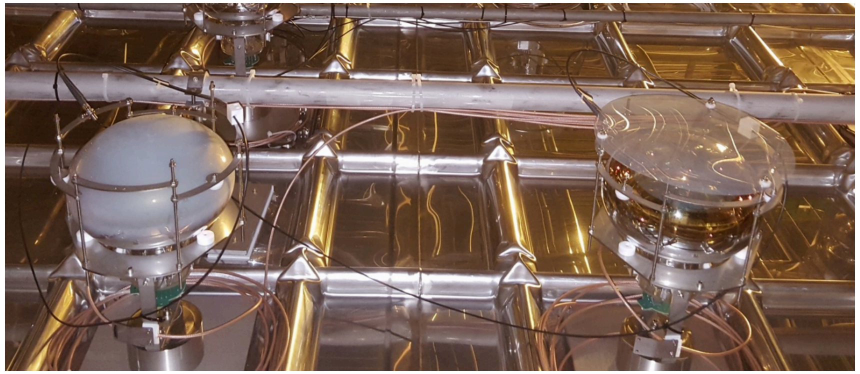
Poly(ethylene 2,6-naphthalate)

Motivation – LAr Detectors

- Next generation of multi-ton liquid argon (LAr) detectors calls for improved light collection technology
- LAr scintillation light is difficult to detect directly, so it is common to use a wavelength shifter (WLS)
- 1,1,4,4-Tetra-phenyl 1,3-butadiene (TPB) is commonly is used as a WLS by evaporating it onto surfaces
  - Peak emission at 430 nm
- PEN is also a WLS for LAr light
  - Commercially available in films
  - Structural stability
  - Peak emission at 450 nm



LEGEND-1000 Design [1]



Cryogenic PMTs coated with TPB (left) and PEN film (right) [2]

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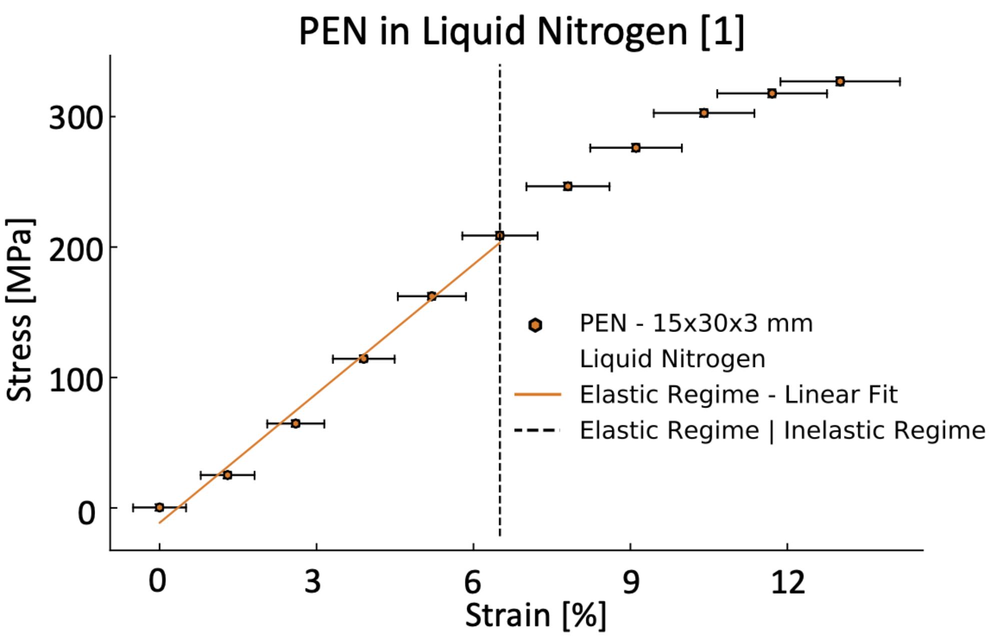
[1] http://legend-exp.org/
[2] https://indico.fnal.gov/event/43249/contributions/185711/attachments/128654/155768/DPPD_PENTPB_20200526.pdf

PEN Chemical and Structural Properties

- Bending flexural test of PEN completed 295 K and 77 K
  - High structural stability at room and cryogenic temperatures
  - Yield strength higher than copper at 77 K
- PEN is chemically resistant
  - Can be aggressively cleaned by acids
  - Hydrolysis resistant
  - Low levels of outgassing (compared to PET) [2]

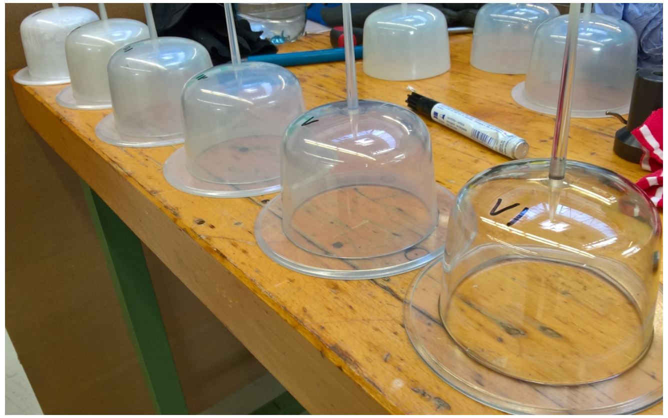


	Cu [3]	Electroformed Cu [4]	PEN	PEN at 77K
Tensile Strength (Mpa)	100	85.8±7.8	108.6±2.6	209±2.8
Youngs Modulus	120	77.8±15.6	1.86±0.01	3.71±0.08

[1] F. Fischer Master's Thesis, Munich, Germany. 2019.
[2] http://www.technolox.com/pdf/SVC2005.PDF
[3] http://www.memsnet.org/material/coppercubulk/
[4] ://www.pnnl.gov/main/publications/external/technicalreports/PNNL–21315.pdf

PEN Components with Optical Clarity

- Some PEN materials have poor optical transparency because PEN is a semi-crystalline polymer
  - Crystalline structures create grain boundaries, causing light to scatter
  - Teonex Q53, a biaxially orientated film, appears hazy
- Optical properties can be improved by rapid cooling
  - PEN heated to 300 °C for injection molding
  - PEN's glass transition temperature, T_g=120 °C [1]
  - Cool from 300°C to 220°C in <6 seconds, increase crystallization half life, τ_c



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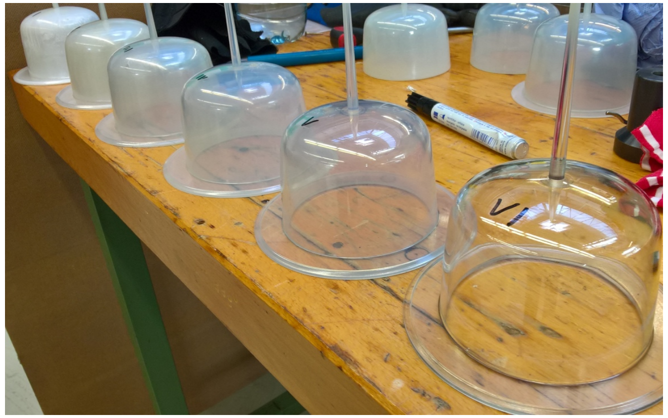
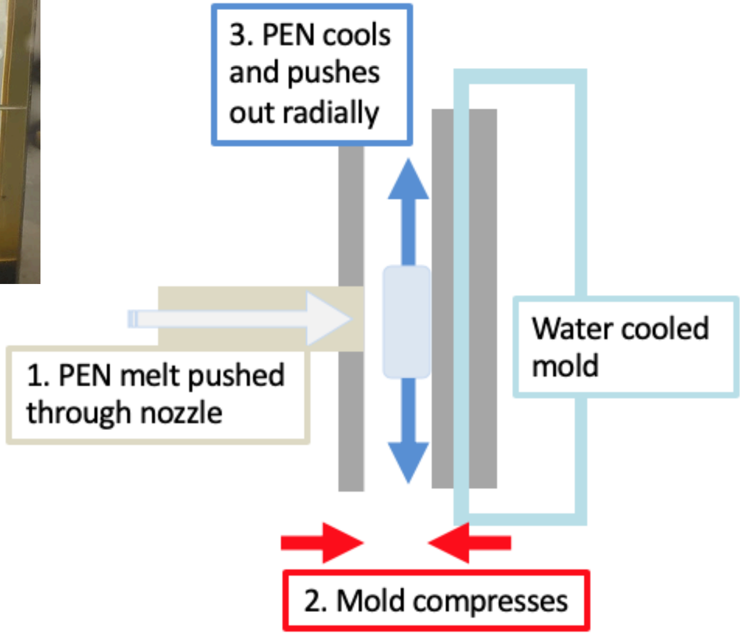
[1] U.S. Patent 5,744,578. April 28, 1998

PEN Components with Optical Clarity

- Injection molding allows rapid cooling and production of unique shapes
  - Water cooled mold controls cooling rate
  - Different molds allow for new geometries
- Injection compression molding specifically used for low background structural material
  - Large disks with uniform thickness
  - Minimal contact with molds to minimize contamination
  - Optical finish on disks with electropolished stainless steel





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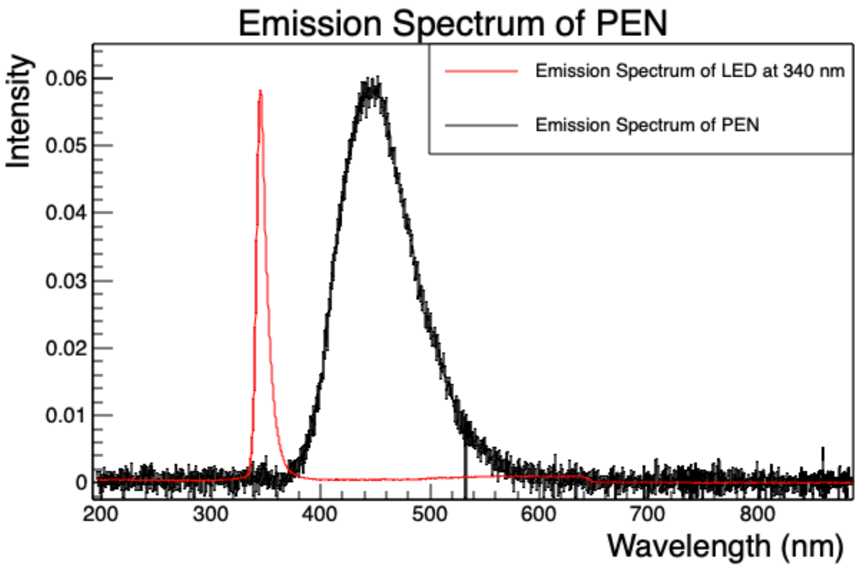
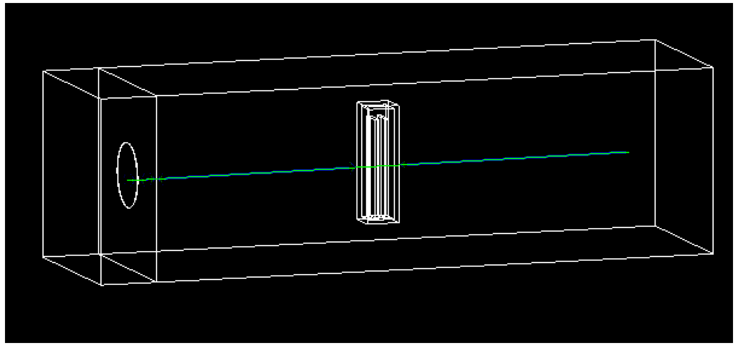
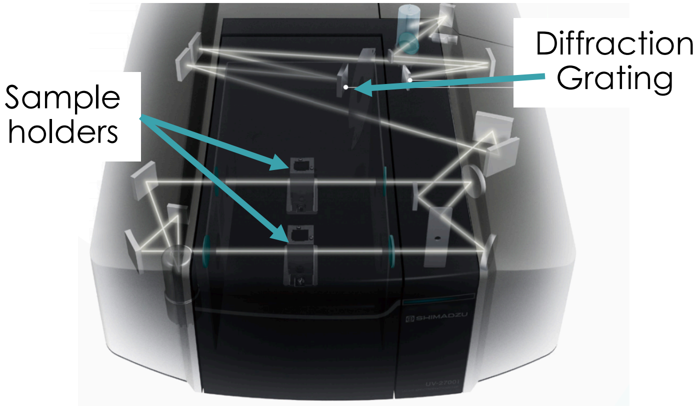
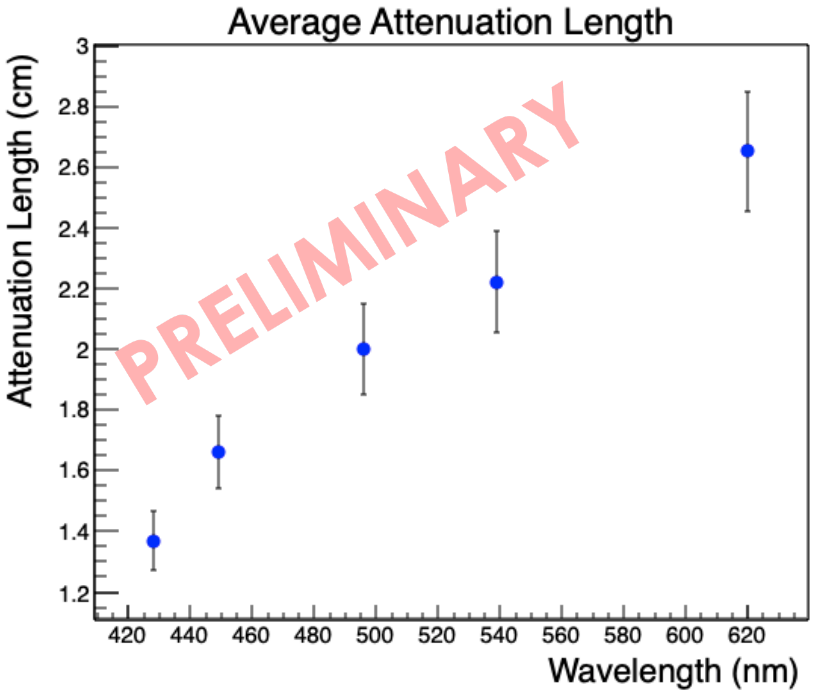
Optical Properties of Injected Molded PEN

- Light yield was measured to be 3500 ph/MeV
  - Approx. ~30% conventional plastic scintillators
- Peak Scintillation is at ~ 450 nm
- Attenuation length measured for 1.5 mm thick tiles
  - Shimadzu UV-Vis 2700 dual beam spectrophotometer
  - Submerged material in reference liquid
  - Optical simulations predict loss of light due to changing refractive index









Measuring Luminescent Properties with Neutrons

- PEN can distinguish electron and proton recoils using pulse shape discrimination (PSD)
- At the University of Notre Dame, $^{13}C(\alpha,n)$ reaction used as a source of neutrons for a range of energies
  - E_n : 1.2 – 7.3 MeV
- The neutron source was used to measure PSD and determine:
  - Figure of Merit (FOM) - Describes the separation of the electron and proton recoil bands
  - Quenching factor
  - Birk's constant

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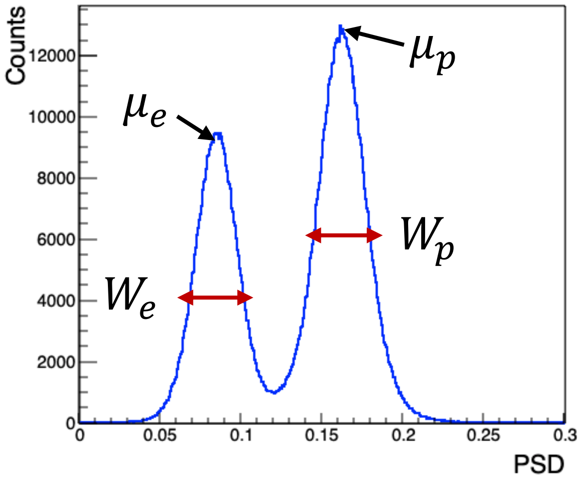
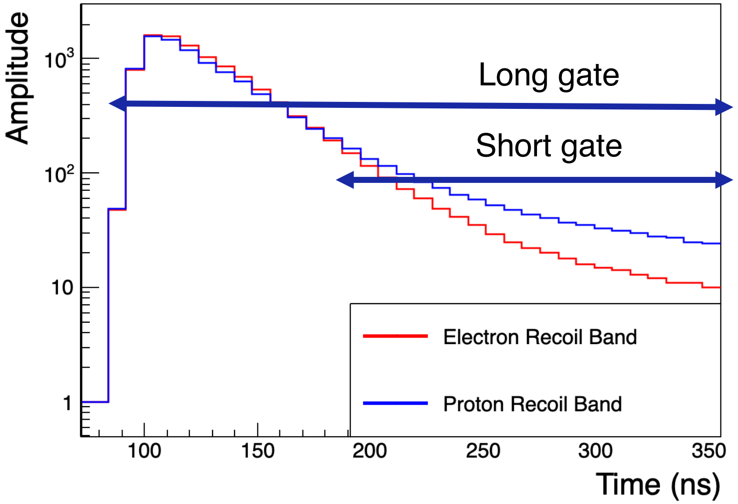
$$FOM = \frac{\mu_p - \mu_e}{W_p + W_e}$$

$$PSD = \frac{\int_{tail:start}^{tail:end} Q dt}{\int_{full\ signal} Q dt}$$





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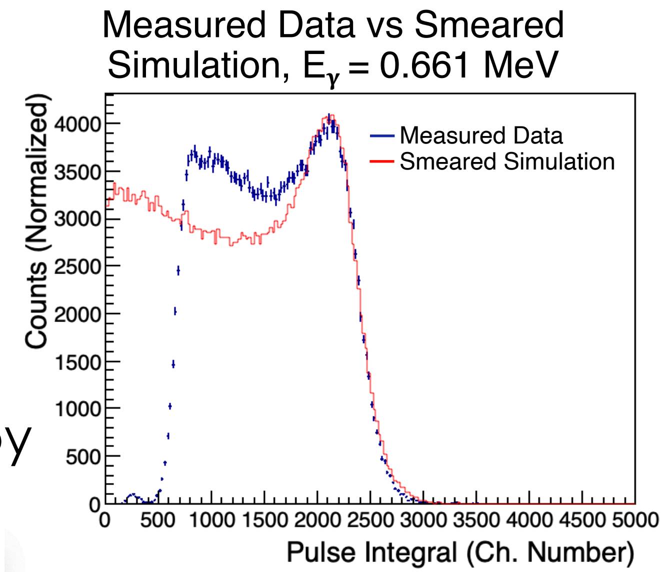
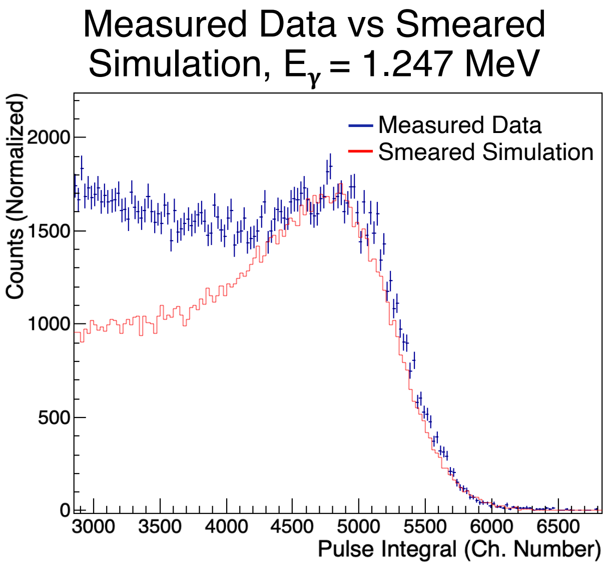
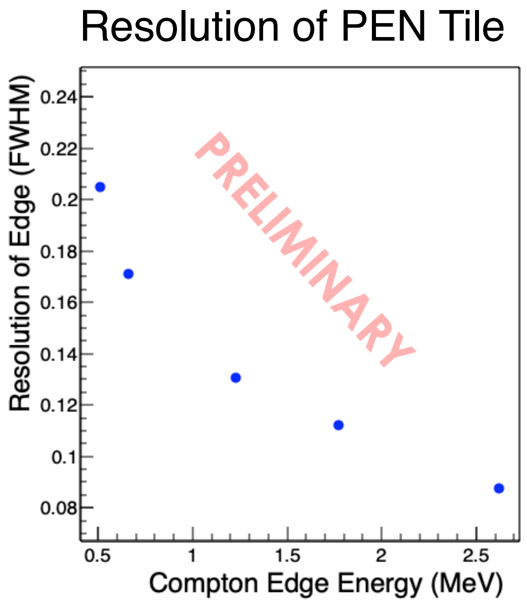
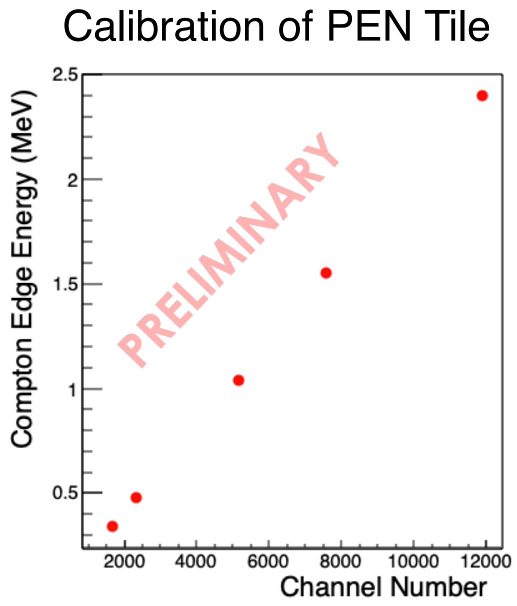
Calibration of Neutron Measurements

- PEN detector dimensions:
  - 0.5 cm thick, 5 cm wide
- Simulations were conducted in geant4 of gamma interactions in the tile
  - Simulations record energy deposited by electronic recoils in the tile
- Simulations are gaussian smeared using error functions to fit to the calibration data
- Parameters derived to fit simulations describing the resolution function
  - $FWHM = E\sqrt{\alpha^2 + \beta^2/E}$
  - $\alpha = 0.020$; $\beta = 0.14$







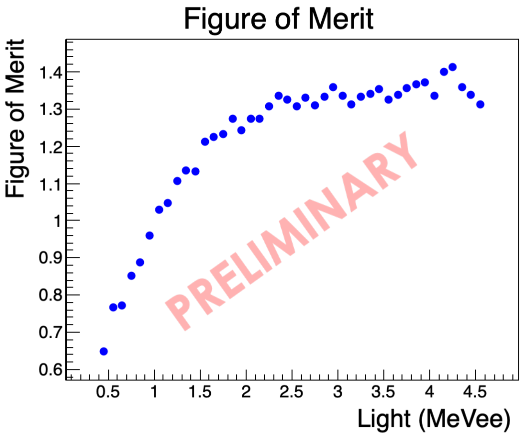


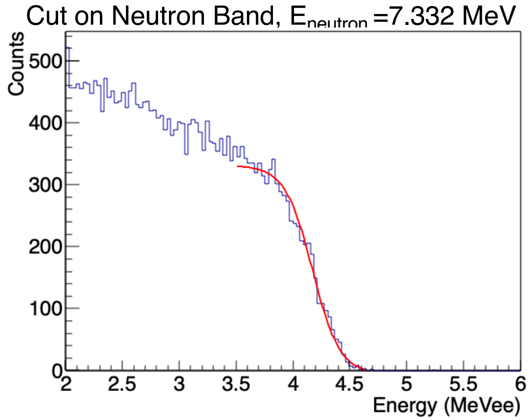
Pulse Shape Discrimination and Quenching Factor

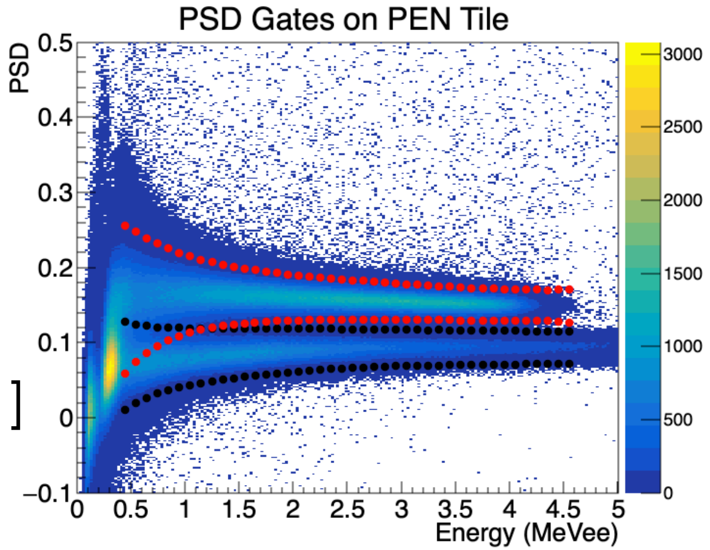
- PSD gates were fitted to the electron and proton recoil bands at 2.5$\boldsymbol{\sigma}$, giving 99.4% C.L.
- FOM defines separation of proton and electron recoil bands
  - FOM >1 at L > 1 MeVee
- Proton recoil edge fit with a sigmoid function
- Preliminary Birk's parameter found to be:
  - kB_{PEN} = 0.124 ± 0.019 mm MeV^{-1}
  - $kB_{BC\text{-}408}$ = 0.154 ± 0.017 mm MeV^{-1} [1]

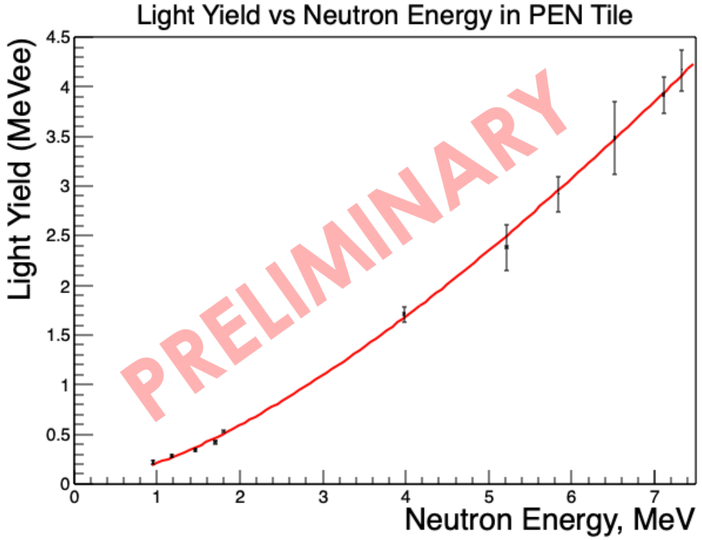
$$FOM = \frac{\mu_p - \mu_e}{W_p + W_e}$$

$$PSD = \frac{\int_{tail:start}^{tail:end} Qdt}{\int_{full\,signal} Qdt}$$







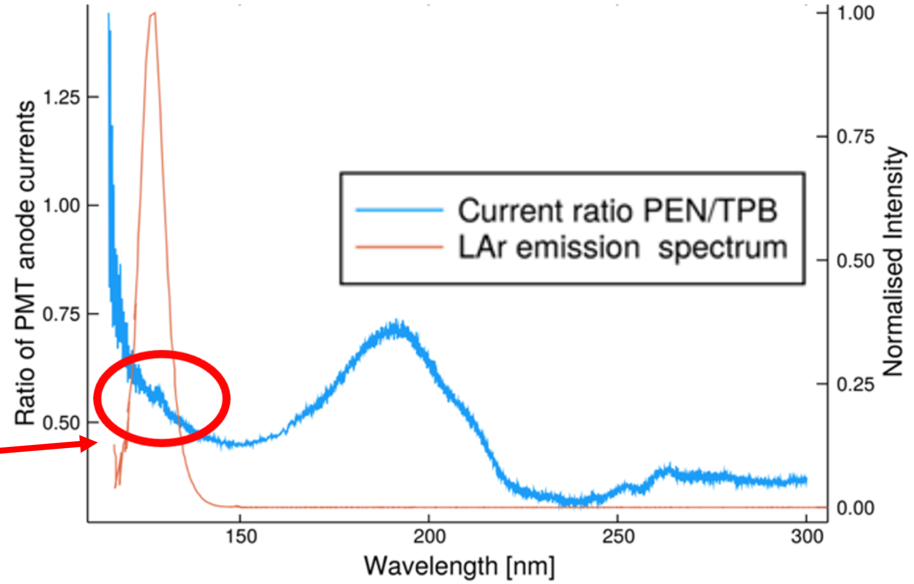


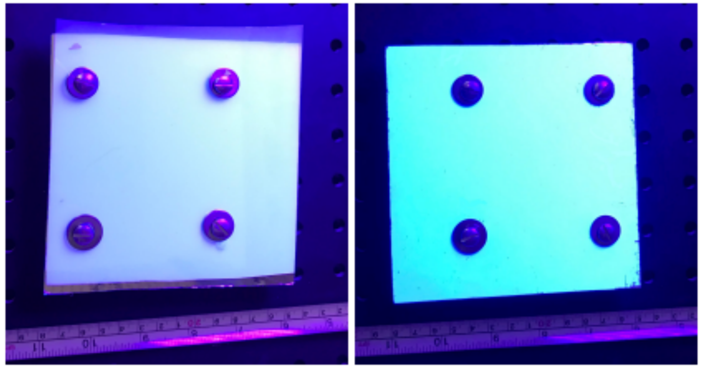
[1] https://aapm.onlinelibrary.wiley.com/doi/pdf/10.1002/acm2.12143

Wavelength Shifting Properties of PEN

- PEN working group measured wavelength shifted light of PEN and compared it to 200 µg/cm^2 TPB evaporated onto a piece of acrylic
- This measurement looked at transmission of WLS light through the sample
- PEN's WLS efficiency compared to TPB is approx. ~ 50%
- Similar measurements have been taken by Ryan Dorill, see next talk for more information:
  - "Wavelength-Shifting Performance of Polyethylene Naphthalate Films in a Liquid Argon Environment"

Wavelength Shifting Efficiency of LAr light
arXiv 1901.03579





PEN film (left) and TPB sample (right) under UV light
arXiv 2103.3232

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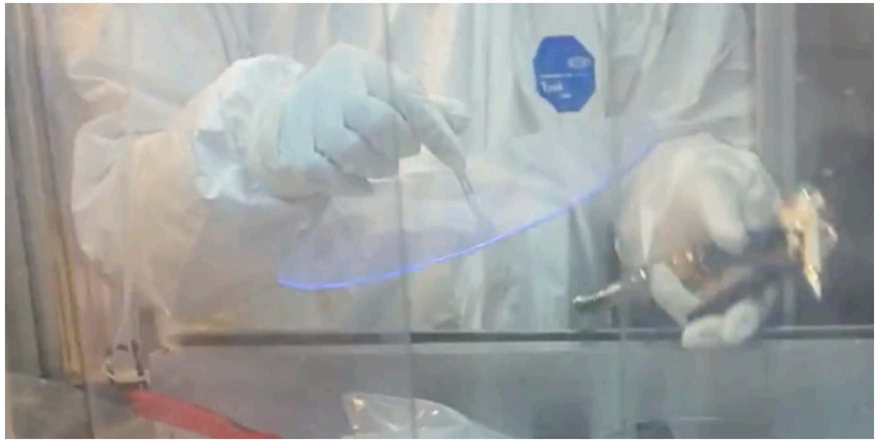
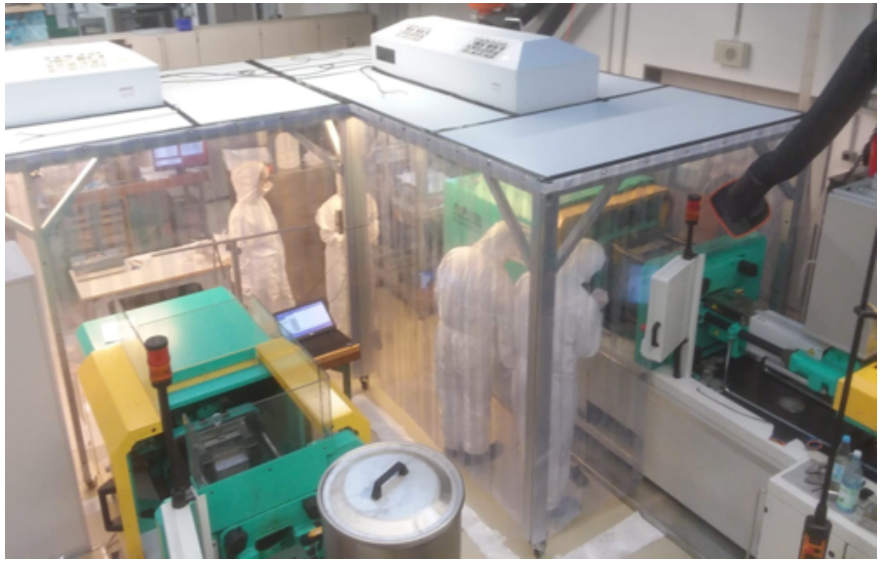
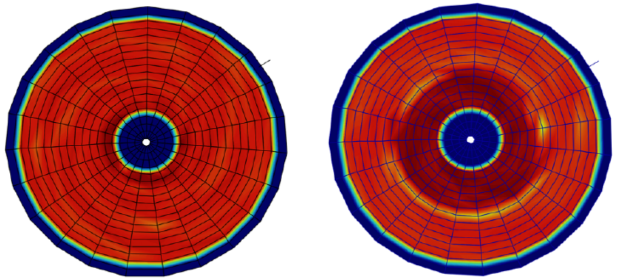
PEN Tiles Produced from Commercial Material in Radioclean Environment

- In July 2019, commercially available PEN pellets (TN-8065S) were processed into 1.5 mm thick plastic disks and radio assayed
- The cleaning procedure included:
  - Pellets washed to remove surface impurities
  - Inner components of injection machine replaced and cleaned
  - Process completed in a Class-1000 clean room
- Each tile was optically scanned identifying optical defects





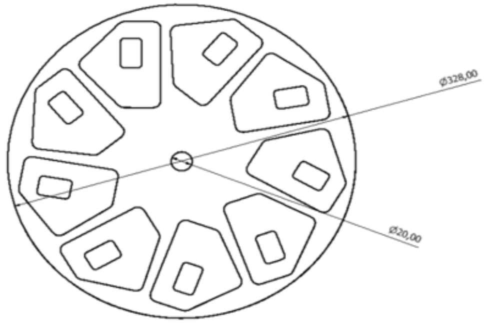


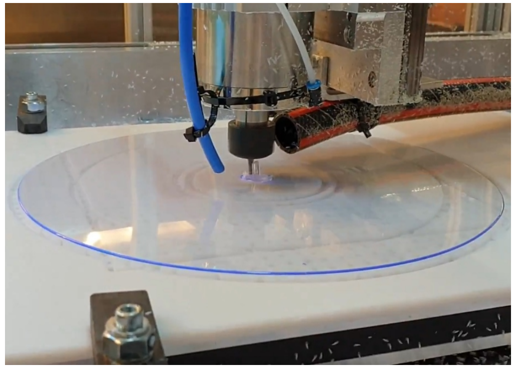
Optical scan of accepted and defective tile

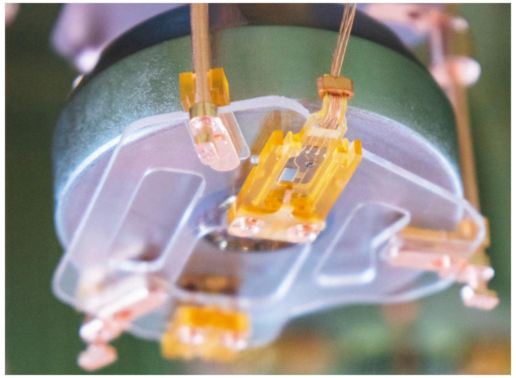
Radioassay of PEN Plates

- A total of 242 tiles were sent out for radioassay
- The activity was measured using HPGe detectors at underground laboratories
  - OBELIX at LSM (E. Rukhadze)
  - GeMPI at LNGS (M. Laubenstein)
- Radiopurity of PEN improved from pellets to plates
  - Washing pellets removed impurities
  - Minimal contamination as a result of injection molding
- Evaluating possible contamination from machining plates and have sent samples to PNNL for ICP-MS for radioassay

Isotope	TN-8065S pellets (µBq/kg)	PEN Plates (µBq/kg)	
		GeMPI (14.3 kg)	OBELIX (5.23 kg)
^{228}Ra	<150	92 ± 25	107 ± 38
^{228}Th	230 ± 5	32 ± 16	67 ± 18
^{226}Ra	250 ± 5	60 ± 15	76 ± 22
^{40}K	2e5± 4e4	<24	57 ± 1

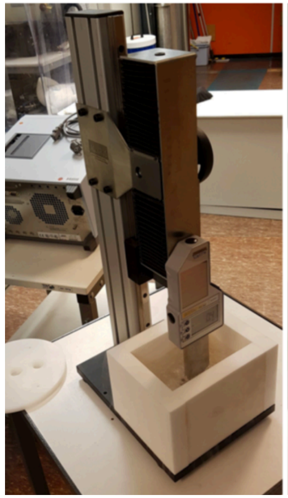


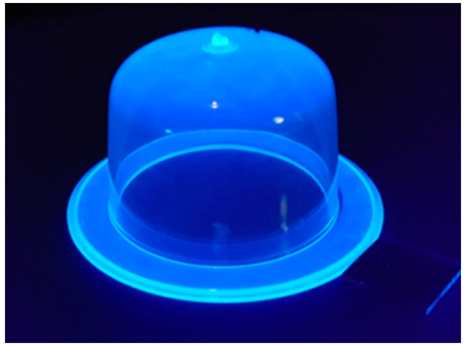


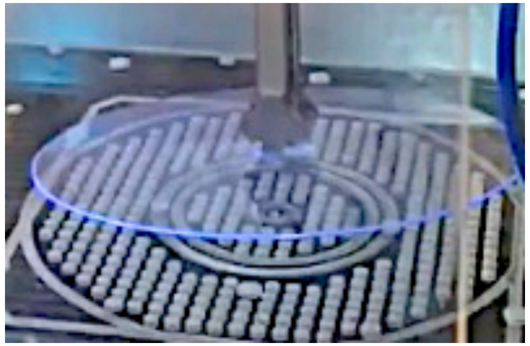


Conclusion

- PEN is a novel scintillating material
- It has potential applications in both noble detectors and low background experiments
- PEN has a demonstrated structural stability
  - Yield strength higher than copper at cryogenic temperatures
- Injection molding can prevent crystalline structures forming in PEN
  - Improved optical clarity
  - Alternative geometries other than commercially available films

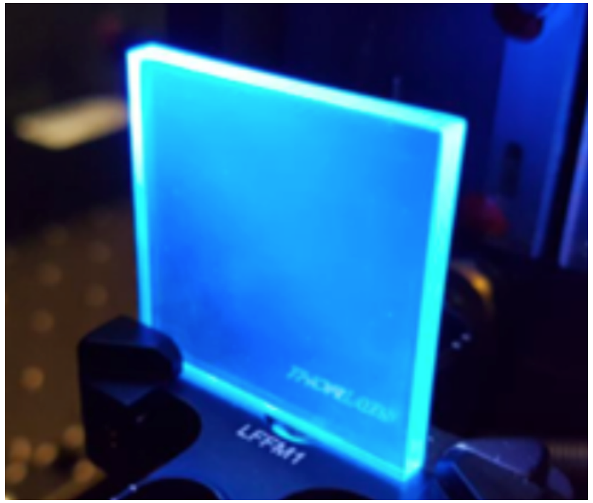


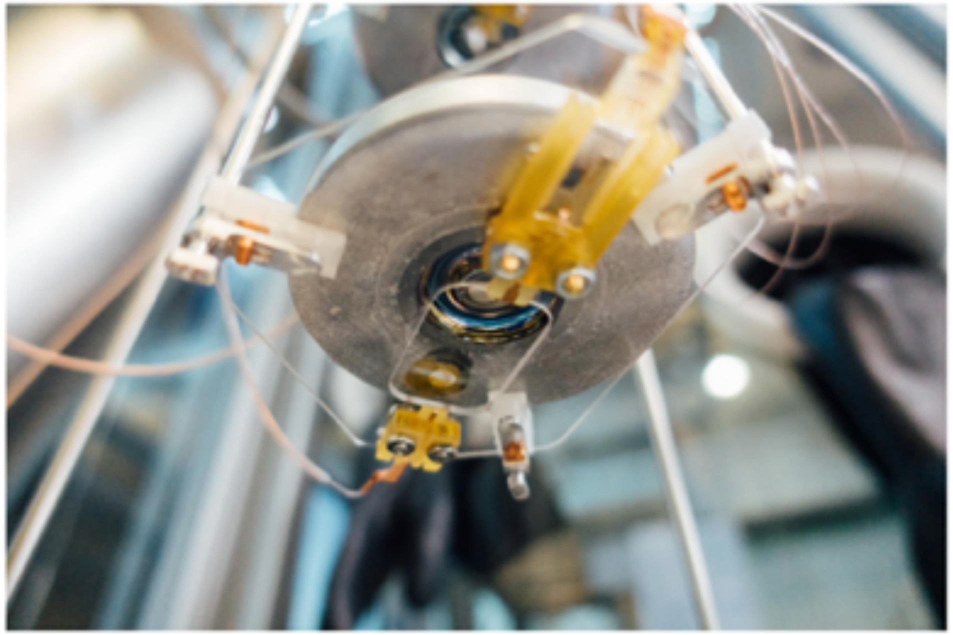




Conclusion

- Optical properties have been characterized
  - PSD Figure of Merit
  - Quenching Factor
  - Birks parameter
  - Wavelength shifting efficiency of LAr light
- Radioclean production run successful
  - Produced 290+ plates
  - Radioassay showed no evidence of contamination from the injection compression molding process
  - Possible contamination from machining is under investigation
- PEN plates are being used by the LEGEND collaboration for low background R&D





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