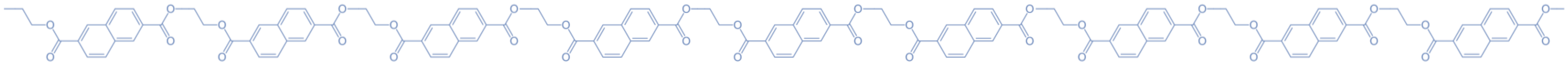
Polyethylene Naphthalate in LEGEND-1000



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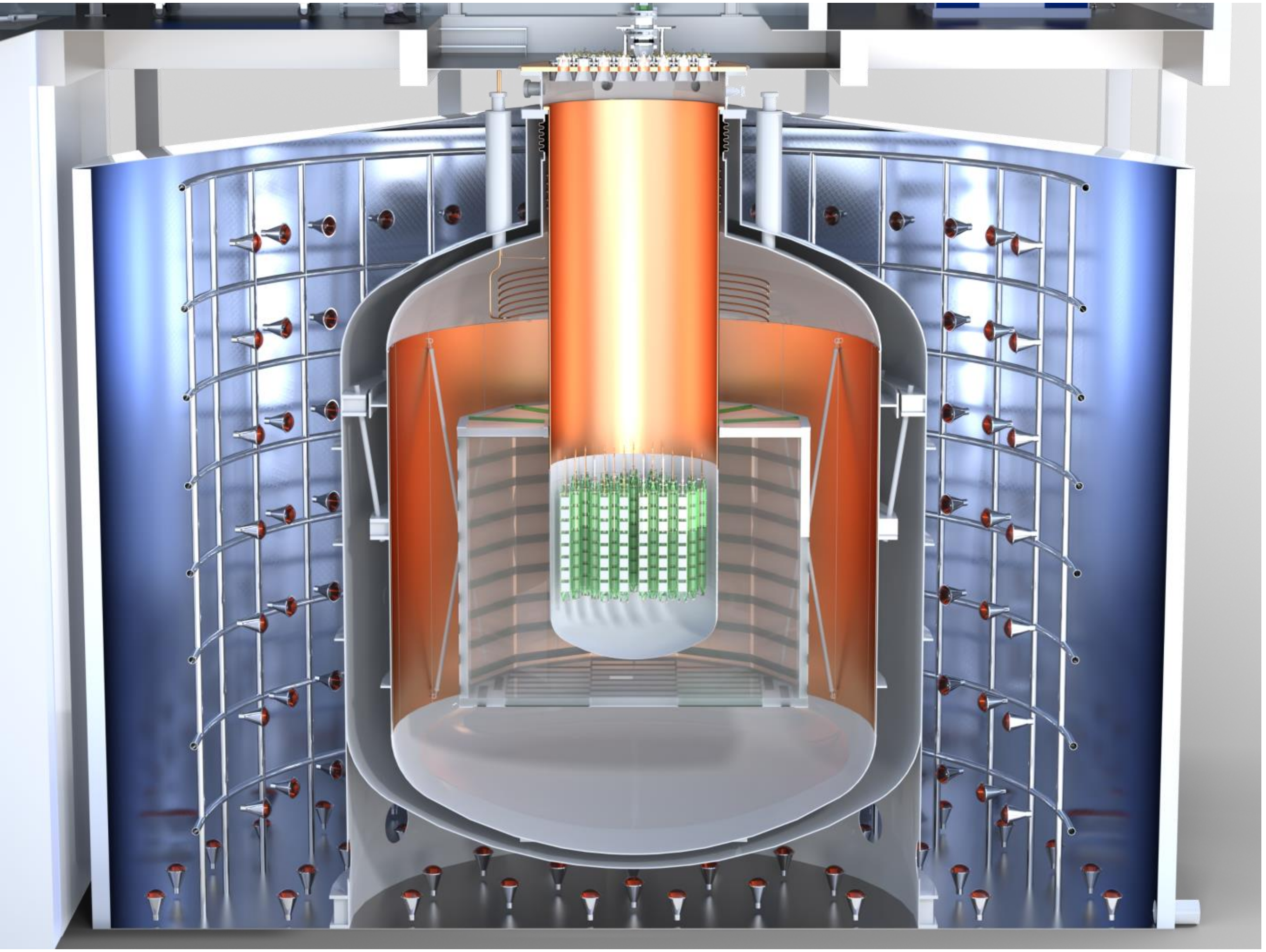
LEGEND-1000 aims to detect neutrinoless double-beta decay (0νββ) in ^{76}Ge



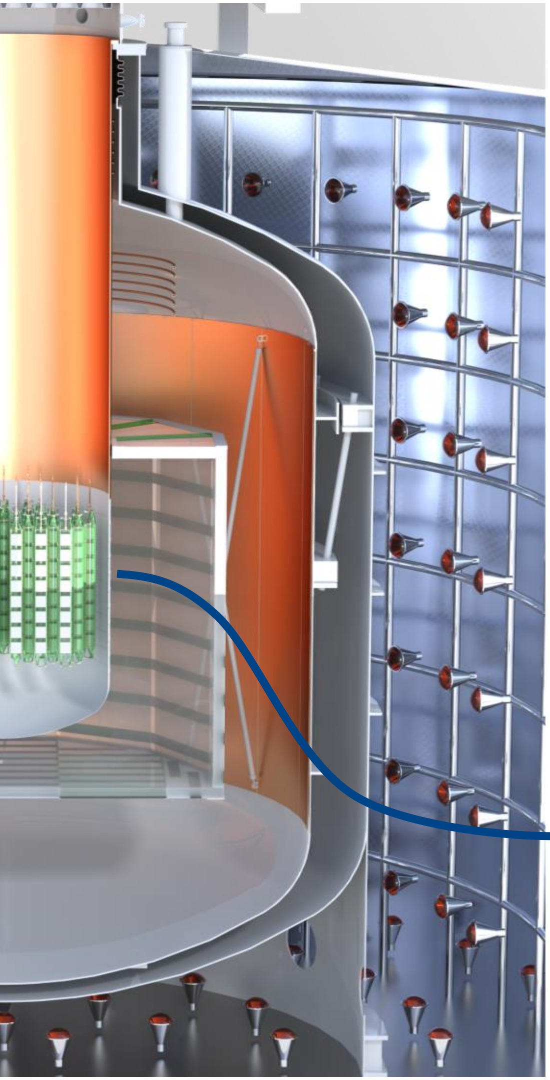
LEGEND-1000 is designed for a discovery potential of 0νββ at a half-life **beyond 10^{28} years.**

Deployment of 1000 kg of high-purity Ge detectors enriched in ^{76}Ge, which act as source and detector.

The first phase, LEGEND-2000, is taking physics data since spring of 2023.

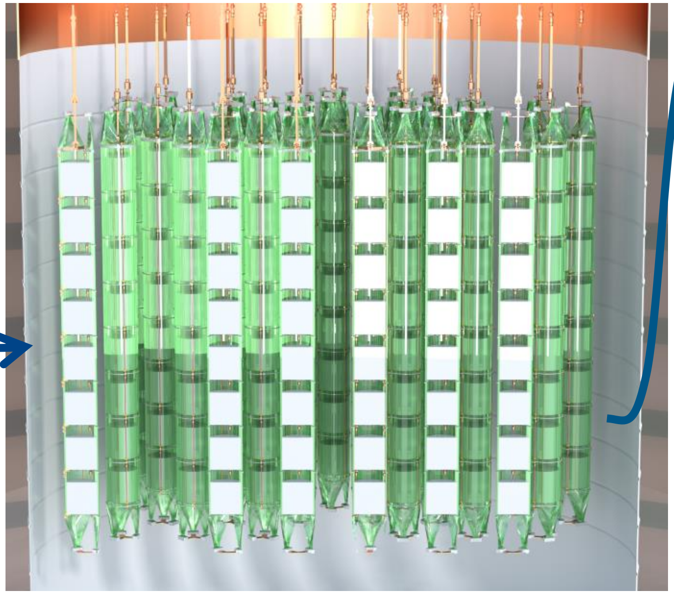
Operation of instrumented Liquid Argon (LAr) volume as coolant and for background rejection.

HPGe detectors are deployed in an instrumented underground argon volume



Underground argon (UGLAr) in copper tube

Lined with wavelength shifting reflector (WLSR) to increase LAr detector efficiency



Detectors in strings covered by wavelength-shifting fiber shroud

Coupled to SiPMs for detection of LAr scintillation signal

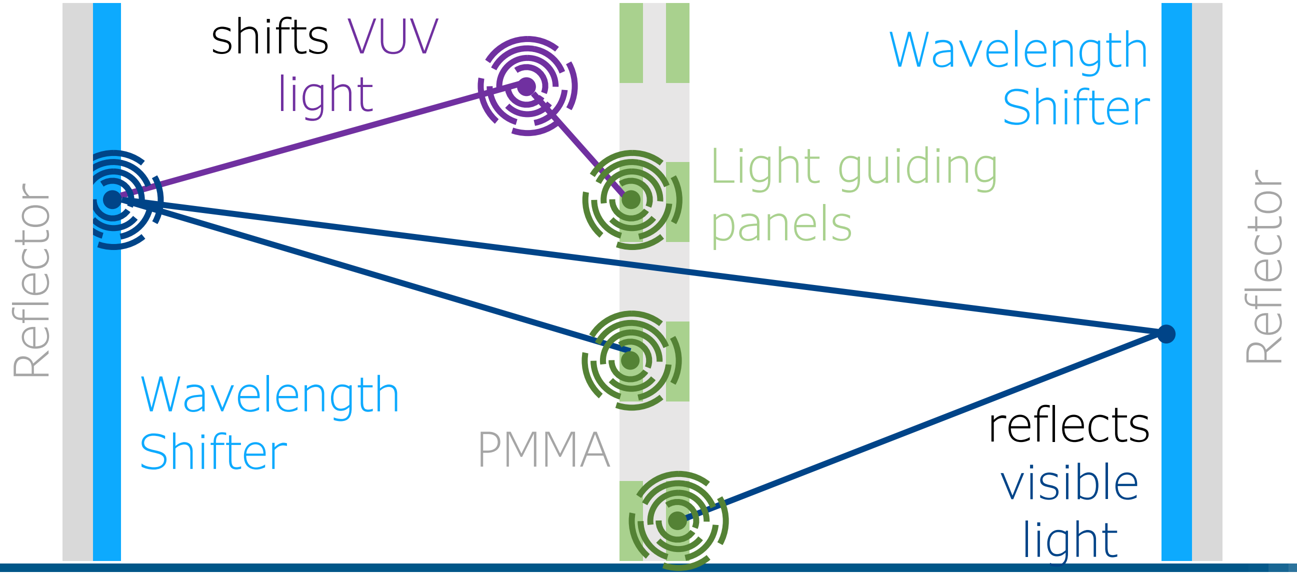
HPGe detectors mounted on holder plates and read out individually

The instrumented atmospheric argon volume is used to detect cosmogenically activated neutrons

Atmospheric liquid argon (ALAr) volume in outer cryostat

PMMA neutron moderator instrumented by SiPMs coupled to wavelength shifting & and guiding panels

Large-scale WLSR on inner cryostat wall & outer copper tube surface



Polyethylene naphthalate (PEN) is a scintillating and wavelength shifting polymer

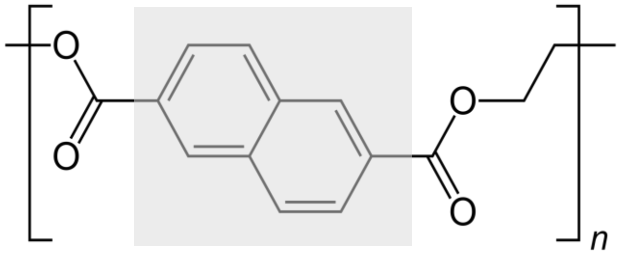
Polyethylene naphthalate (PEN) is a thermoplastic polyester

Scintillating and wavelength-shifting naphthalene-dicarboxylate units

Can be acquired commercially as granulate for injection molding

Higher yield strength than copper at LAr temperature

Replace or cover optically inactive materials (Copper, PTFE, etc.) with PEN to increase background rejection efficiency



PEN granulate illuminated by UV light

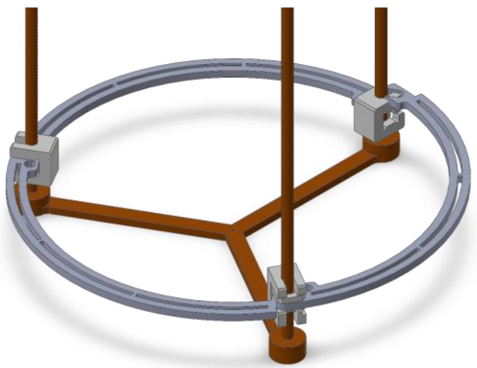
Optical Properties:

- Wavelength Shifting Efficiency of ≥ 49% [1]
- Emission time scale ~ 30 ns
- Emission in visible blue (peaks at 430 nm)

[1] G. R. Araujo, et al., Eur. Phys. J. C, 82(5):442, 2022, arXiv:2112.06675.

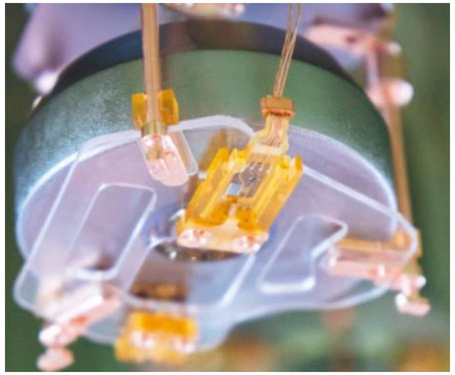
PEN will be featured throughout LEGEND-1000 to replace or cover optically inactive materials

Wavelength Shifting fibers need to be guided and supported



Preliminary Design for L1000 Fiber Holders

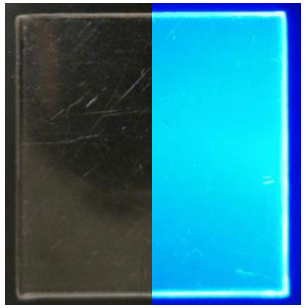
L200 PEN Holders



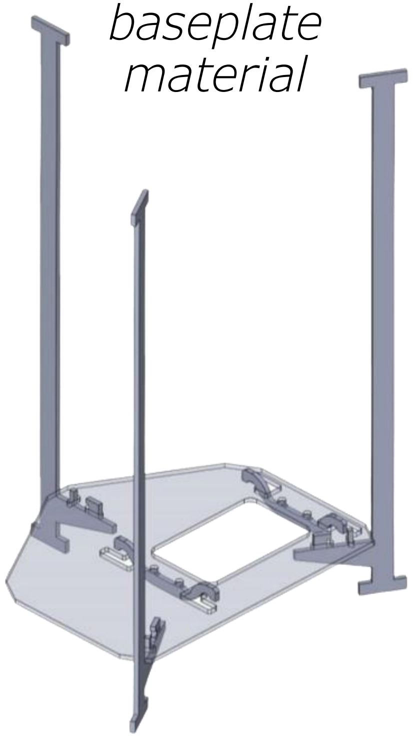
PEN can be used for structural detector holders & and holding rods

Increase background detection efficiency in vicinity of detectors

Successful implementation in LEGEND-200, molded from commercial Teonex granulate



L200 PEN baseplate material



Preliminary Design for L1000 PEN Holders + Rods

PEN enclosures around Ge detectors for mitigation of $^{42}Ar/^{42}K$ background

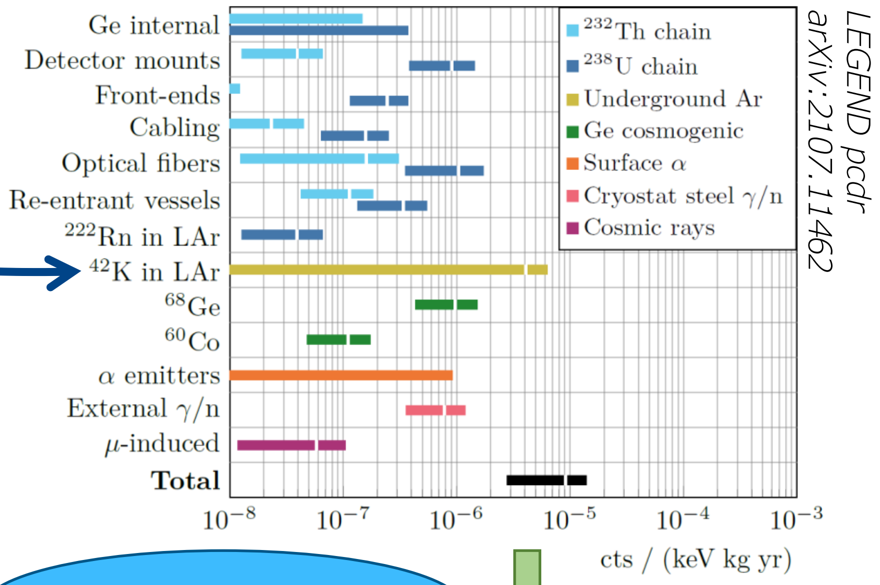
$^{42}Ar/^{42}K$ cosmogenically produced in ALAr

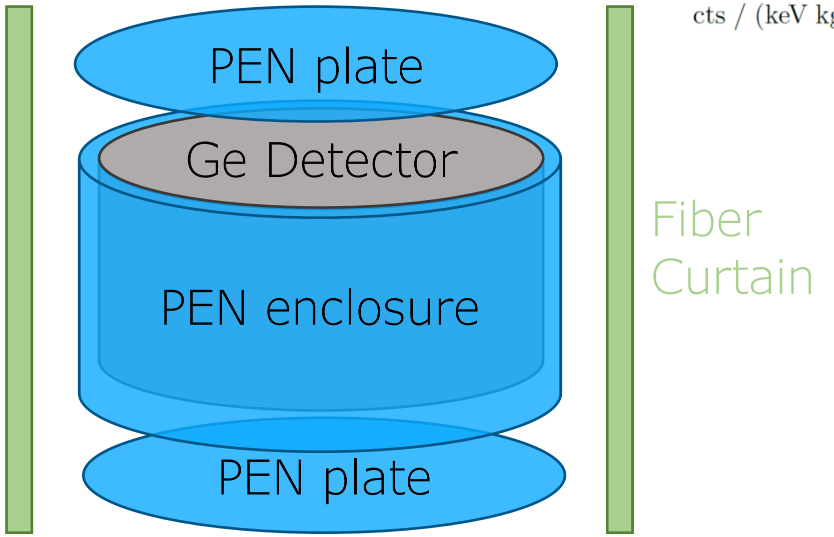
Beta decay of ^{42}K (Q_β = 3525 keV) background in 0νββ ROI ($Q_{\beta\beta}$ = 2039 keV)

UGLAr expected to be depleted in $^{42}Ar/^{42}K$

Alternative: PEN enclosure for Ge detectors

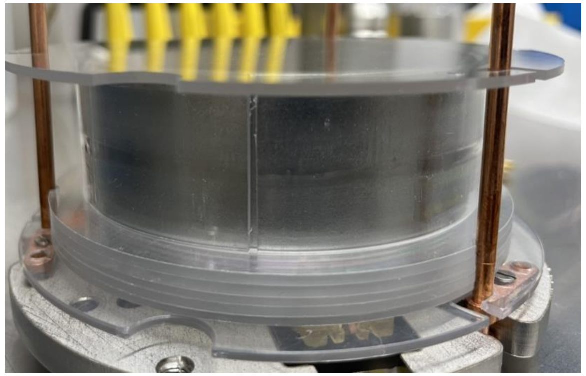
passive	Limits amount of ^{42}K on Ge detector surface	Lower energy of beta particle below $Q_{\beta\beta}$
active	Generate scintillation signal to increase veto efficiency	

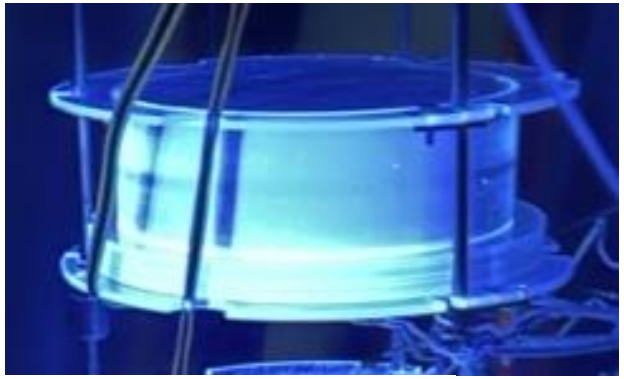




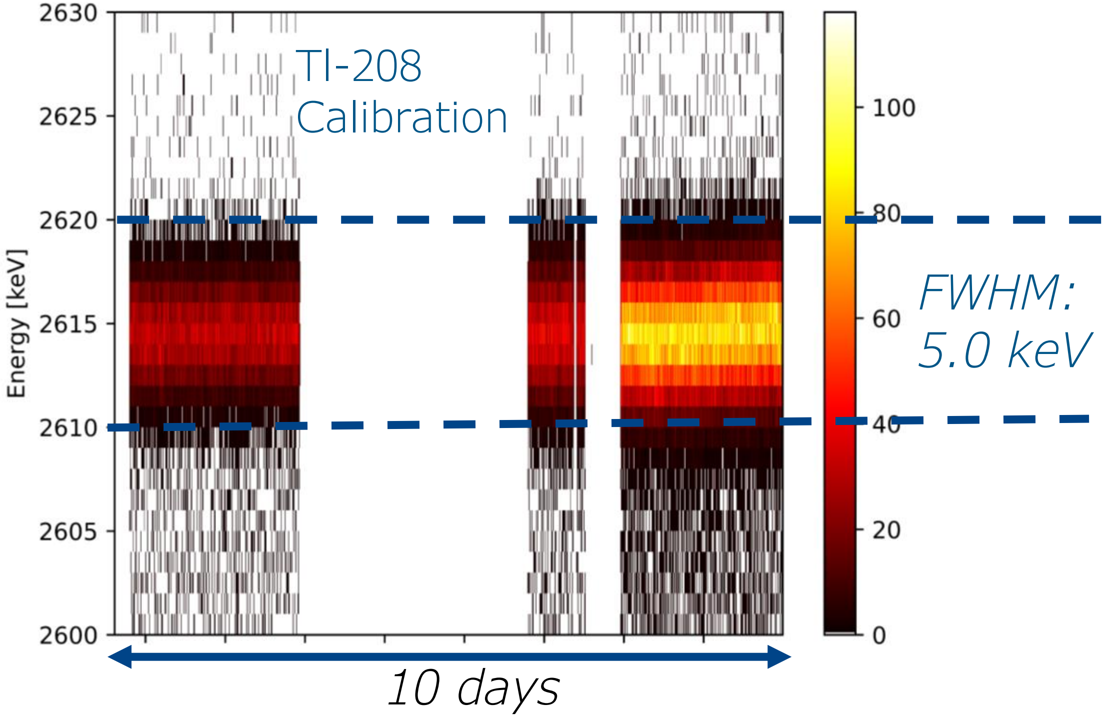
First implementation of PEN enclosure indicates no decreased Ge detector performance

Tightly fitting PEN enclosure for Ge detector created by re-shaping heated PEN holder plate material





Successful operation of Ge detector in LAr cryostat with PEN enclosure

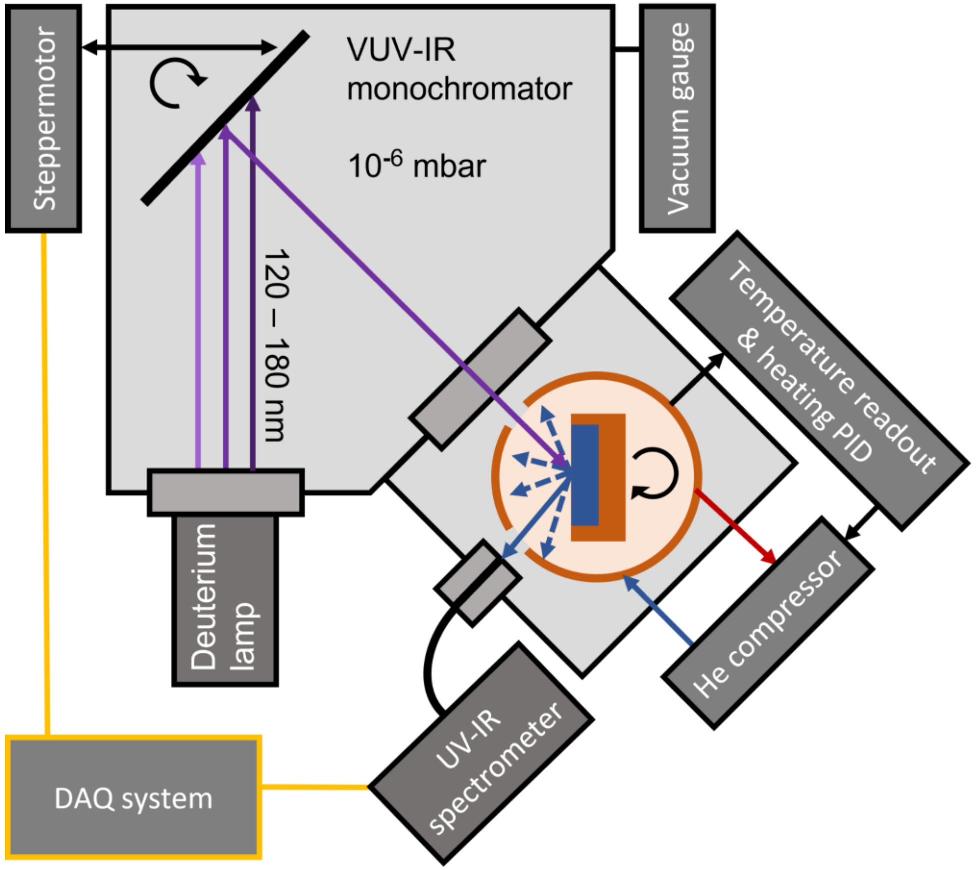


Upcoming:
Operation of Ge detector in ^{42}Ar-spoiled LAr to test PEN performance on ^{42}Ar/ ^{42}K mitigation

More information on ^{42}Ar/ ^{42}K mitigation in the GERDA experiment:

Lubashevskiy et al., Eur. Phys. J. C 78, 15 (2018)

Characterization of wavelength shifters with VUV excitation at cryogenic temperatures



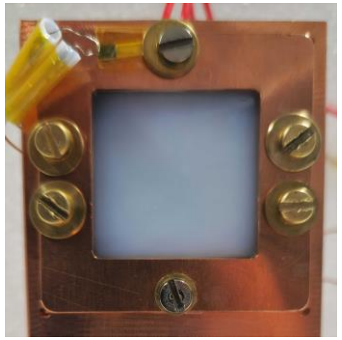
Stable temperature between 300 – 35 K within 3 K

Relative wavelength shifting yield and emission spectrum

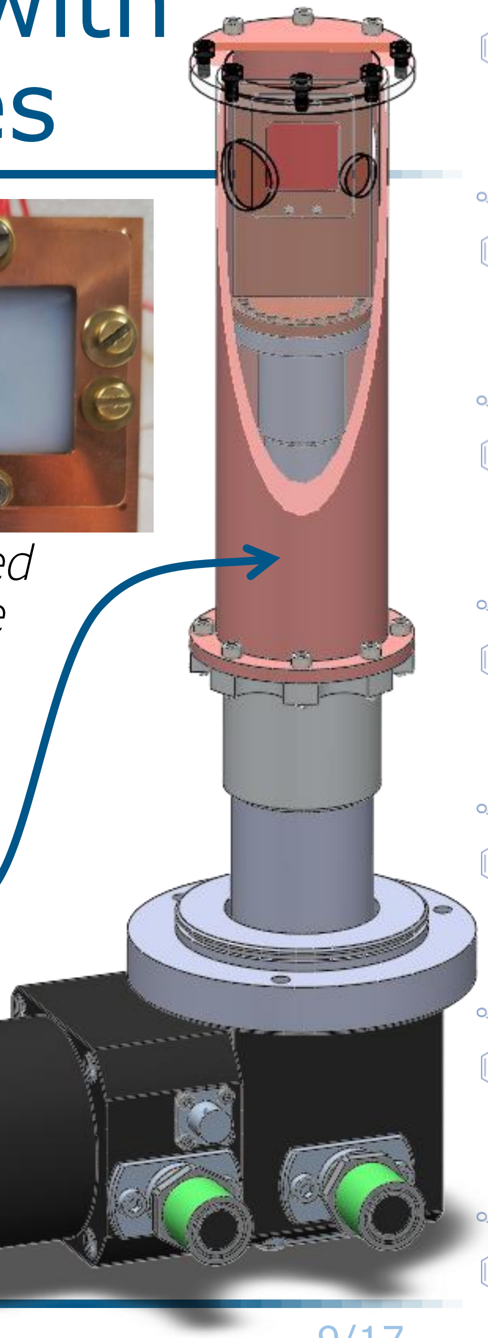
High-intensity deuterium lamp (128 nm) and UV LED (300 nm) for excitation

Copper cold shield to prevent VUV-blocking fogging on sample

More on fogging: Neumeier et al. Eur. Phys. J. C 72, 2190 (2012)



Mounted Sample

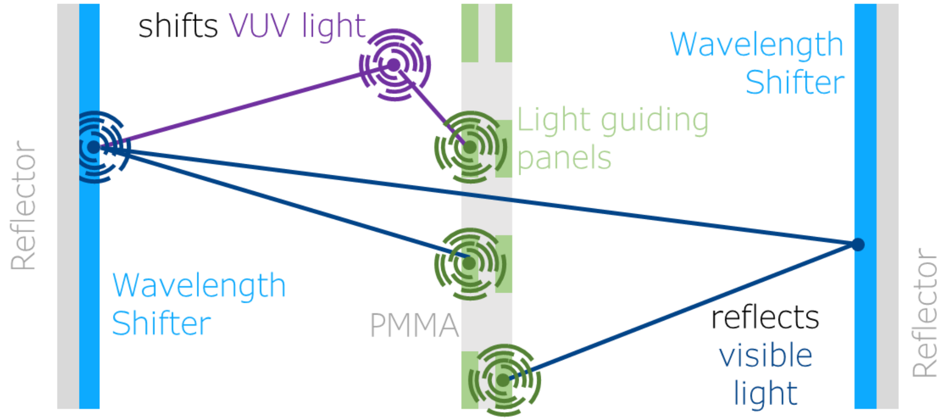


PEN can be extruded in thin films to cover large-scale surfaces in liquid argon volume

~ 100 m² of WLSR needed to cover LEGEND-1000 cryostat walls in ALAr volume

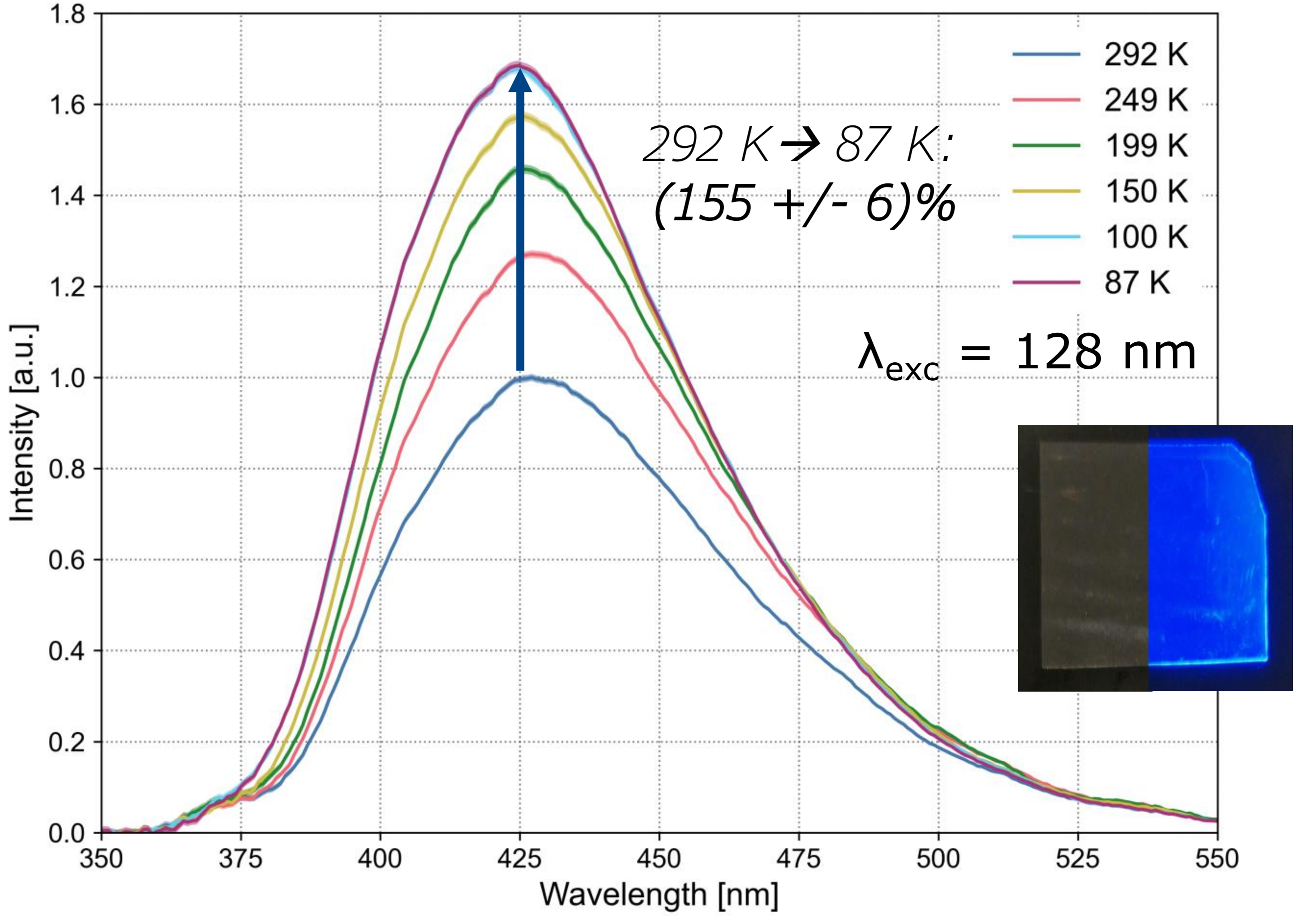
Application of tetraphenyl butadiene (TPB) wavelength shifter challenging

PEN can be extruded in large-scale thin films and coupled to a reflector

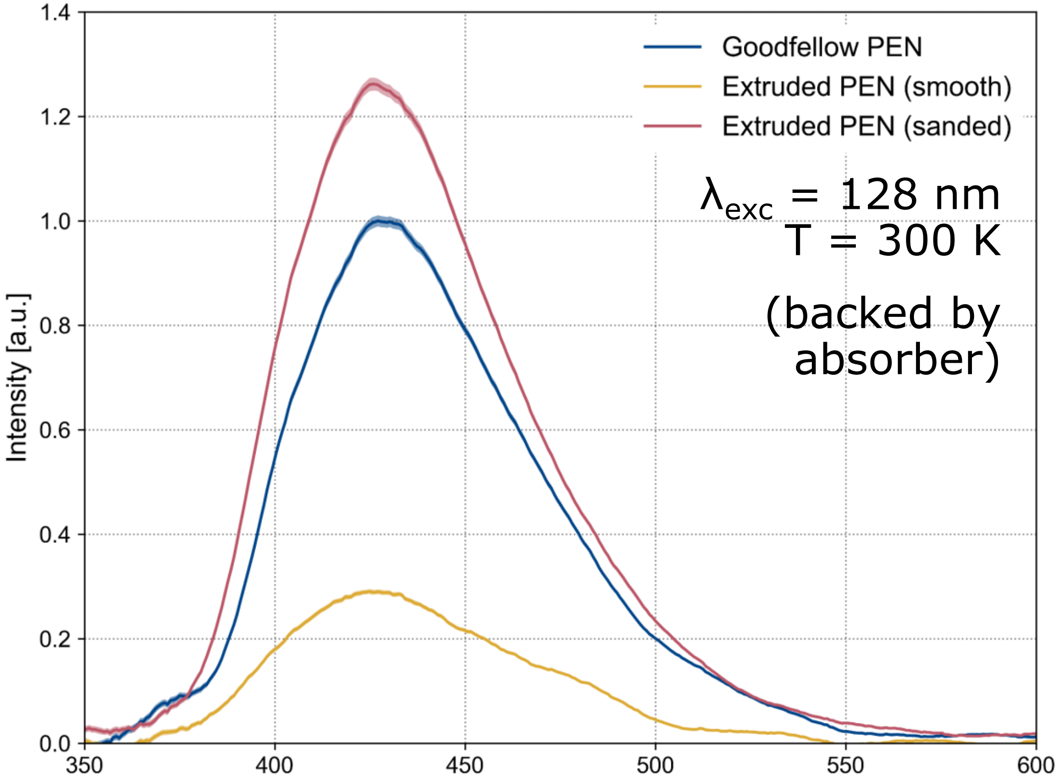


Extruded PEN film from Teonex commercial granulate (L200 PEN)

ipf Leibniz-Institut für Polymerforschung Dresden



Self-extruded PEN films exceed commercially available ones in terms of light yield



Commercially available thin films not optimized for optical properties

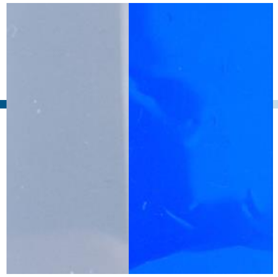
Extrusion of PEN films from Teonex granulate yields amorphous PEN film

Roughening is needed to enable shifted light to leave PEN film surface

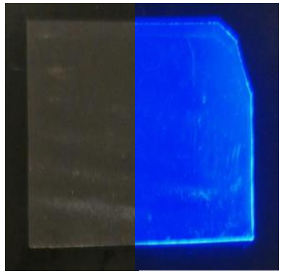
Small-scale film extruder at ipf Dresden

Leibniz-Institut für Polymerforschung Dresden

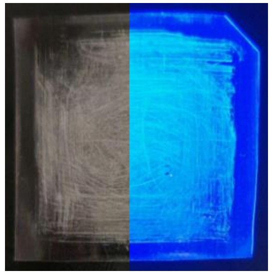
PEN film *preliminary*	Relative Light Yield
Goodfellow	100 %
smooth	28 ± 2 %
sanded	125 ± 4 %



Teonex Q53 125 µm



Extruded PEN ~ 70 µm

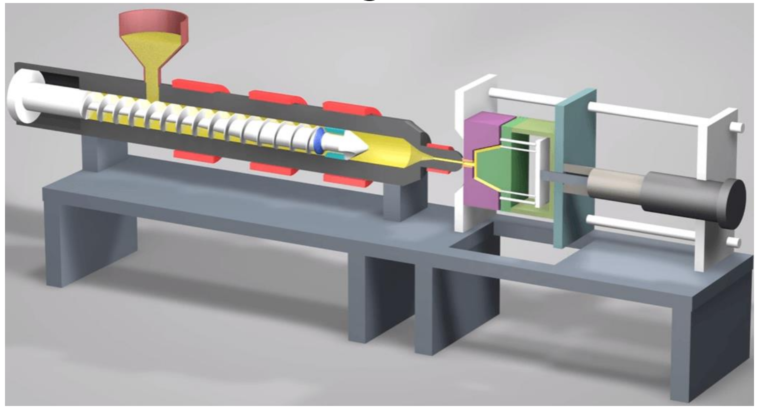


Extruded PEN ~ 70 µm sanded

For LEGEND-200 commercial PEN granulate was molded into baseplate material for PEN holders

Teijin-DuPont TN-8065 SC granulate

Plastic injection molding machine



PEN baseplate material

final PEN component

Additives in granulate might be harmful for usage in LEGEND-1000 (radio-impure) or optical properties (UV blocking)

Radiopurity not considered by the supplier during synthesis of PEN granulate

Extensive cleaning procedure needed to clean PEN granulate before molding

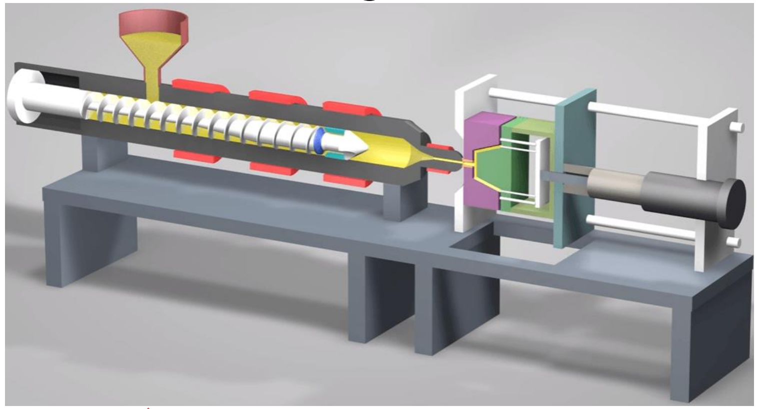
	Raw TN-8065S GeMPI4 at LNGS	Discs GeMPI4 at LNGS
	-	14.315 kg 68 days
^{228}Ra	< 0.15 mBq/kg	(92 ± 25) μBq/kg
^{228}Th	(0.23 ± 0.05) mBq/kg	(32 ± 16) μBq/kg
^{226}Ra	(0.25 ± 0.05) mBq/kg	(60 ± 15) μBq/kg
^{234}Th	< 11 mBq/kg	< 1.9 mBq/kg
^{234}Pa	< 3.4 mBq/kg	< 1.7 mBq/kg
^{235}U	< 0.066 mBq/kg	< 56 μBq/kg
^{40}K	(1600 ± 400) mBq/kg	< 0.24 mBq/kg
^{137}Cs	< 0.057 mBq/kg	< 0.15 μBq/kg

From: Y. Efremenko et al 2022 JINST 17 P01010

PEN Synthesis is pursued to achieve higher radiopurity and optical performance

Teijin-DuPont TN-8065 SC granulate

Plastic injection molding machine



PEN baseplate material

final PEN component

Semi-industrial Production of PEN in kilogram batches

… with

TITK DIVERSITY IN POLYMERS — synthesis

ipf Leibniz-Institut für Polymerforschung Dresden — molding

Successful Synthesis of 2-kg batch of PEN granulate

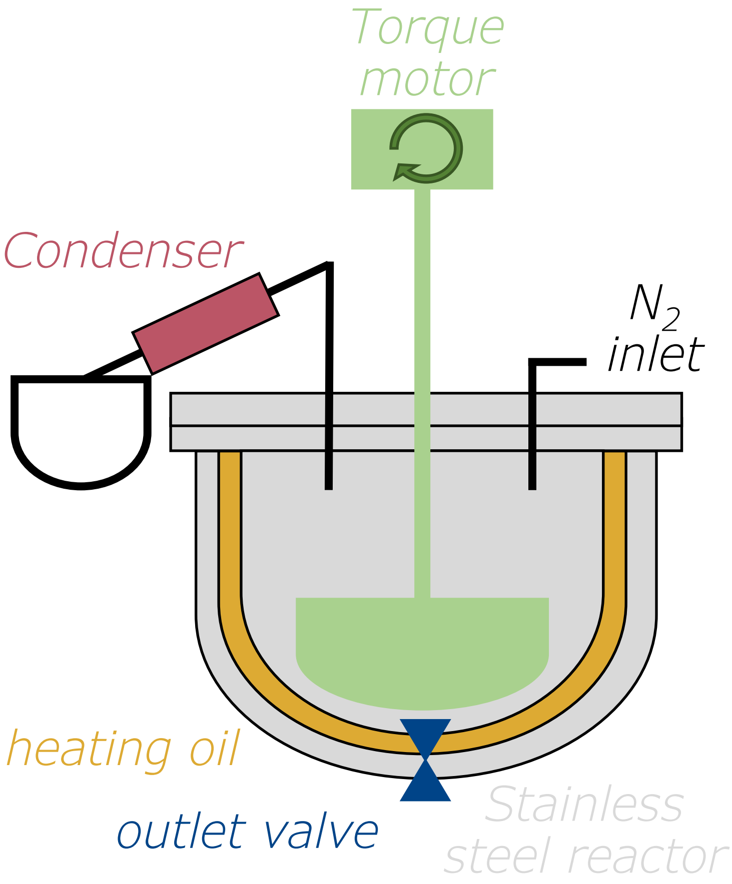
Two-step synthesis: Transesterification & Polycondensation

Performed in a stainless-steal, nitrogen-flushed, 10-liter autoclave reactor

Synthesis reagents can be obtained with low impurities (e.g., GeO_2 from detector production)

Synthesis process can be easily adapted to clean environment

First successful synthesis of two-kilogram batch of PEN

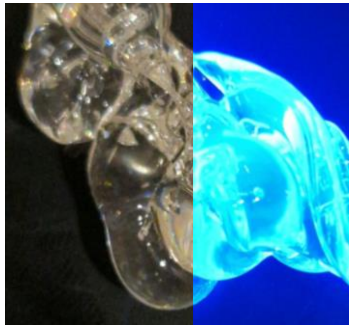


TITK DIVERSITY IN POLYMERS

10-liter autoclave reactor at TITK

Fine-tuning of synthesis and molding procedure needed to optimize optical properties

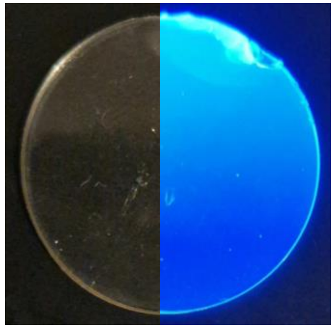
Temperature during molding was too high (yellowing)



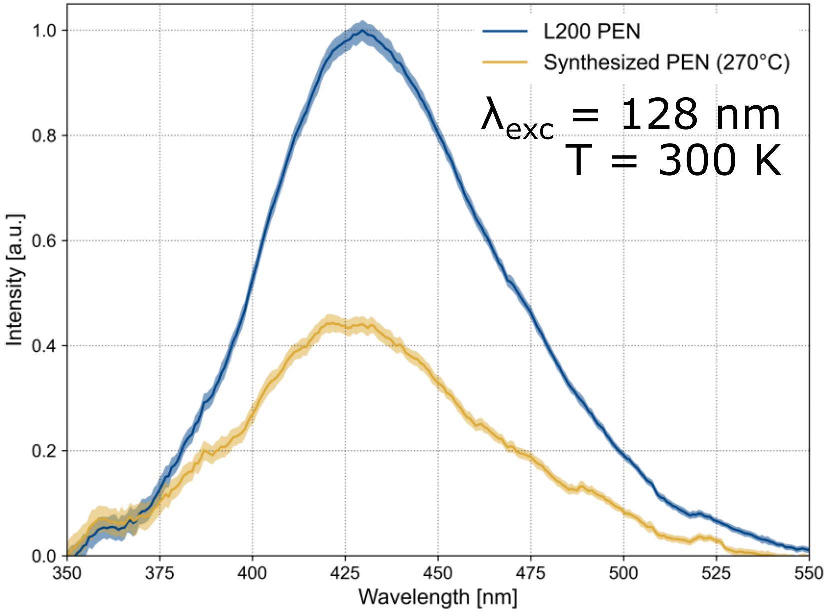
Synthesized PEN piece before cutting

Synthesized PEN pellets

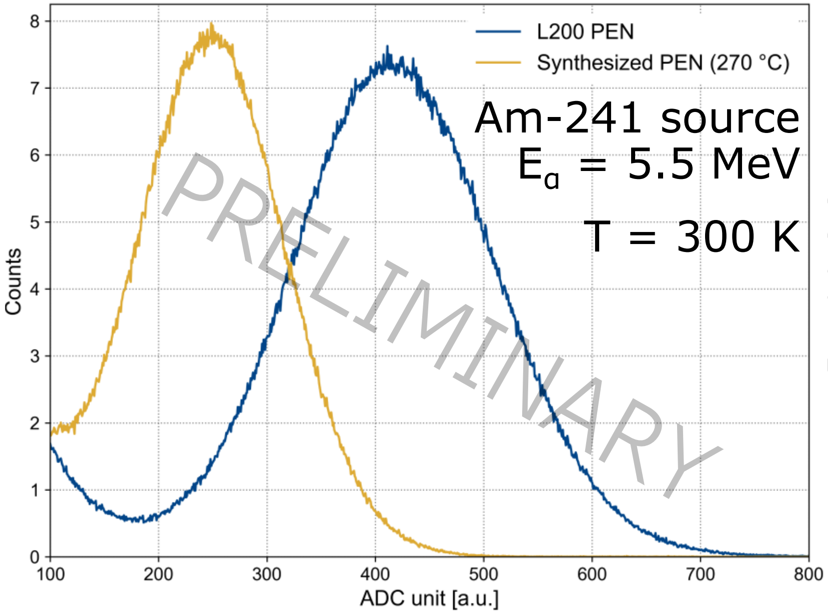
molded PEN 1-inch disk



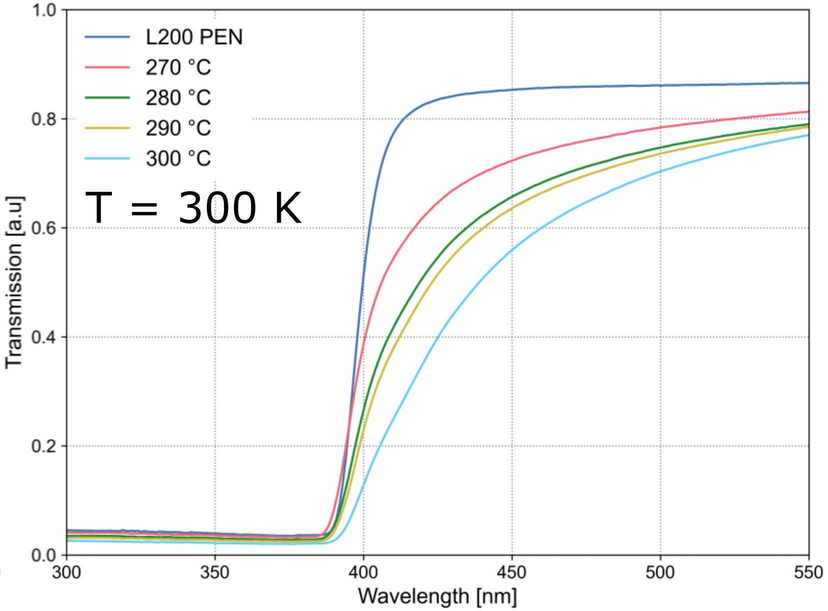
Wavelength Shifting Efficiency (47 +/- 6)& of L200 PEN



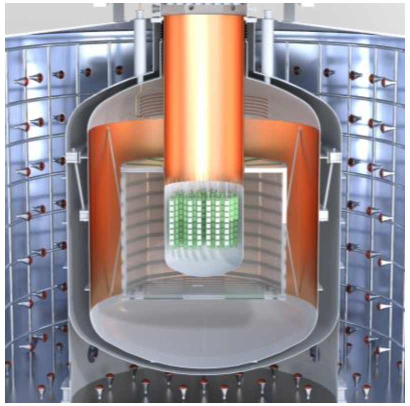
Scintillation Light Yield is ~ 60% of L200 PEN



Transmissivity is ~ 80% of L200 PEN in 450 nm range

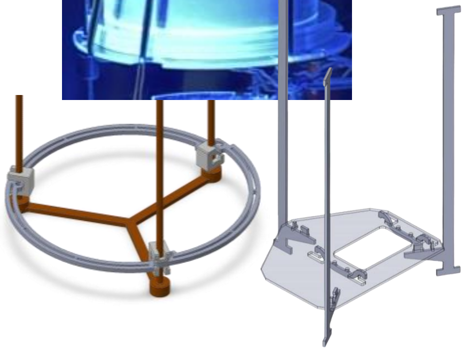


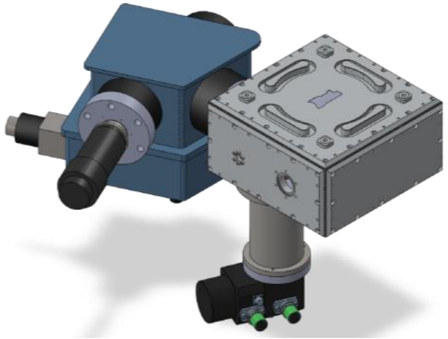
PEN in LEGEND-1000



LEGEND-1000 uses LAr for background suppression

PEN will be used as structural material & for WLSR

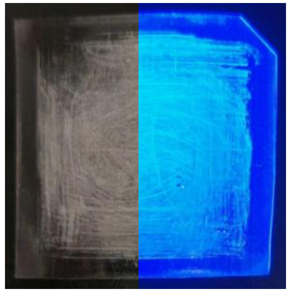


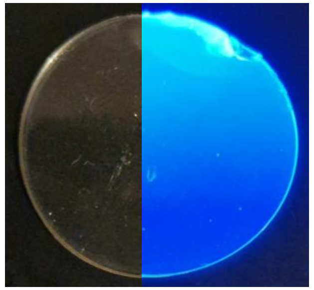


Cryogenic VUV Spectro-fluorometer

300 K – 35 K
128 nm excitation

Self-extruded PEN films exceed commercial PEN films in LY by **(25 +/- 4)%**



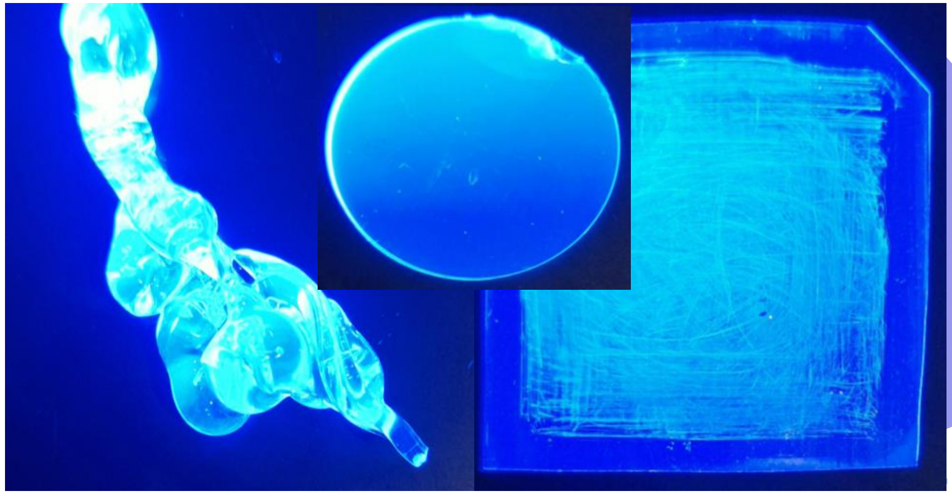


Successful 2-kg synthesis of PEN

Fine-tuning of synthesis/ molding parameters for improved optical performance

„Buckle up, Babe! TPB-land is now PENland“ – Ken, 2023 (or similar)

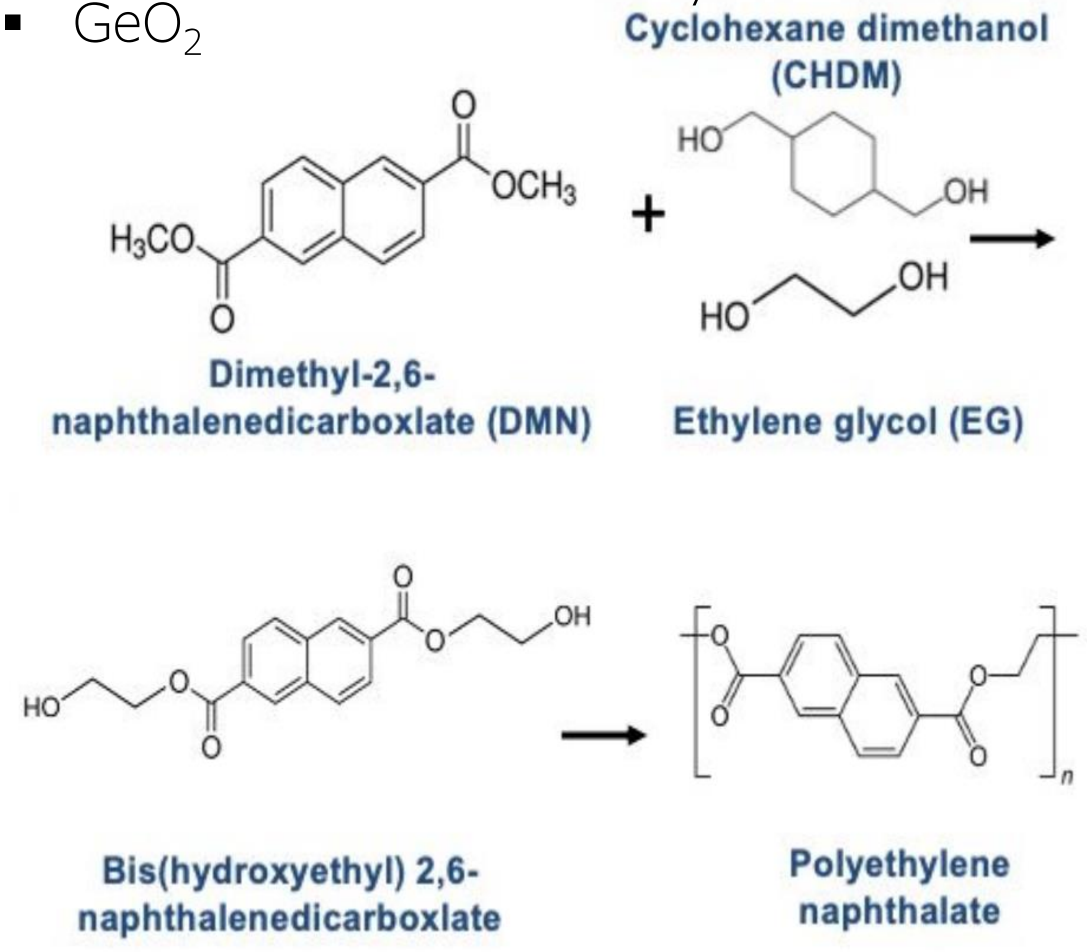
I always carry my PEN around so speak to me if you want to see some



Backup: Synthesis

Catalysts:
- magnesium acetate
- GeO_2

Replace some EG by CHDM to prevent crystallization



Extensive Information on Synthesis of PEN:

Brennan Hackett's PhD Thesis:
Improving Sensitivities in 0νββ Decay Searches by Utilizing PEN as a Structural Scintillating Material

Intrinsic viscosity = molecular weight
„how long are the PEN chains"

Sample	Intrinsic viscosity
Commercial PEN	0.47 g/dL
V1001	0.52 g/dL
Standard PET	~0.6 g/dL
V1002	0.6 g/dL