Usage of PEN as self-vetoing structural material in low background experiments

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On behalf of the ***PEN working group***

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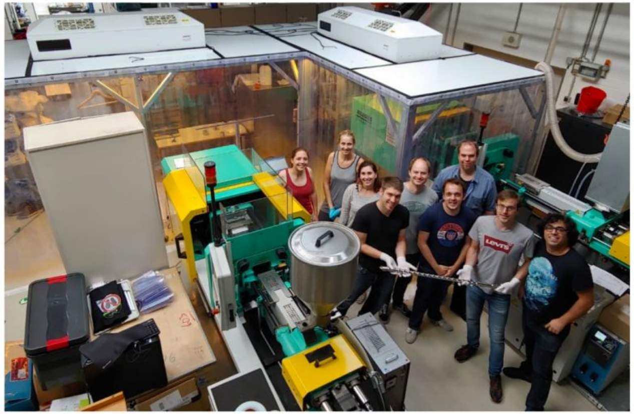
PEN working group

- **Oak Ridge National Laboratory** - Synthesis
  - M. Febbraro, D. Radford, B. Dial, M. Kidder
- **Max-Planck Institute for Physics** – Characterization & Simulations
  - B. Majorovits, O. Schultz, I. Abt, F. Fischer, M. Guitart, L. Manzanillas
- **TUM** - WLS & test in LAr
  - S. Schoenert, M. Schwarz, P. Krause, K. Gusev, N. Rumyantseva
- **Lancaster University** – Surface Treatment & Simulations
  - D. Muenstermann, C. Hayward
- **Technical University Dortmund** – Machining & Characterization
  - M. Stommel, M. Pohl, R. Rouhana, J. Weingarten, I. Schilling
- **Czech Technical University** – Radio-purity measurements & characterization
  - I. Stekl, R. Hodak, L. Fajt, E. Rukhadze
- **University of Tennessee** – Synthesis & Radio-purity measurements
  - Y. Efremenko, B. Hackett
- **Nuvia A.S.** Czech Republic - Synthesis
  - R. Pjatkan
- **AstroCeNT:** Particle Astrophysics Science & Technology Centre - WLS
  - Marcin Kuźniak



Oak Ridge National Laboratory

Lancaster University

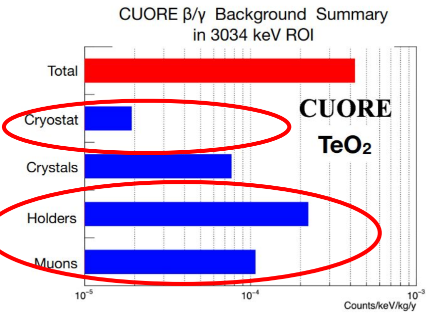
Max-Planck-Institut für Physik

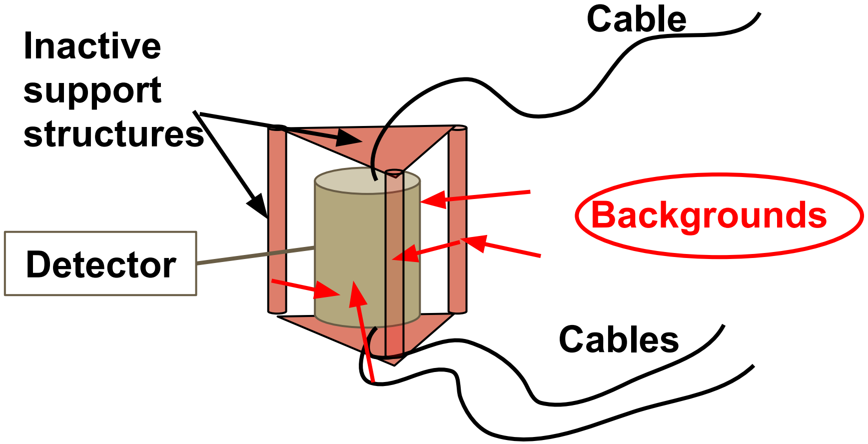
CTU Czech Technical University in Prague

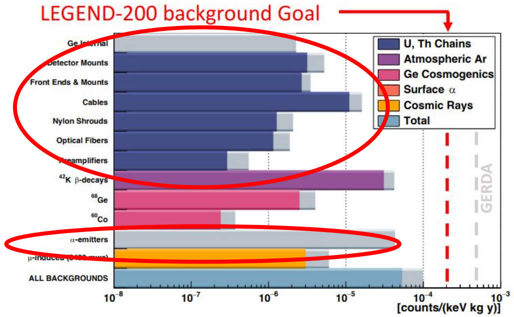
The University of Tennessee Knoxville

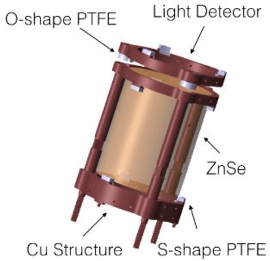
technische universität dortmund

Motivation: Low background experiments

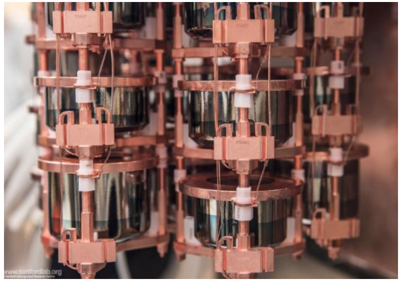






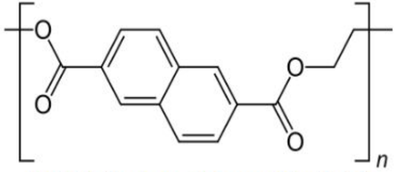


- Rare event **physics experiments** **demand** **ultra low backgrounds**
  - Ultrapure materials required
  - **Inactive materials need to be minimized**
    - **Important source of backgrounds**
    - **Absorb light that can be used to veto external backgrounds**
- Can we do better? → **replace inactive** materials with self-vetoed **active materials** ⇒ **PEN**

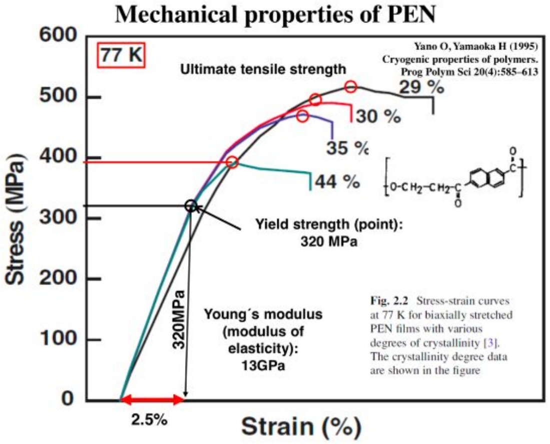


PEN: Poly(ethylene 2,6-naphthalate)

- PEN is a **commercially available polyester**
- PEN has **yield strength higher than copper** at cryogenic temperatures
    - Ideal for experiments using cryogenic liquids
- **Fluorescence** reported in 2011
- **WLS** capabilities (1806.04020)
    - Deployed in Proto-DUNE DP
- Good candidate to use as a **structural self-vetoing material**
    - “Use of poly(ethylene naphthalate) as a self-vetoing structural material”, JINST 14 (2019) 07, P07006 (1901.03579)

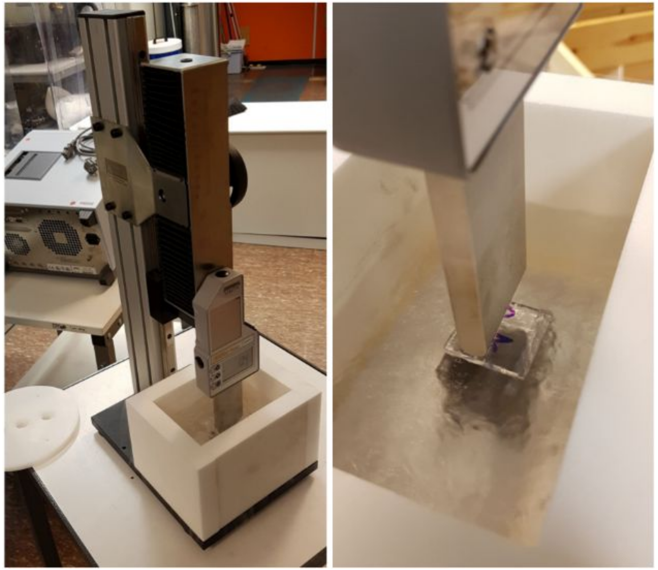


Poly(ethylene 2,6-naphthalate) (PEN)



PEN mechanical properties

- 3-point bending test of material at room and LN_2 temperatures at MPI
  - **High structural stability at room and cryogenic temperatures**
- Very chemically resistant to most acids and organic solvents
  - **Can be aggressively cleaned**



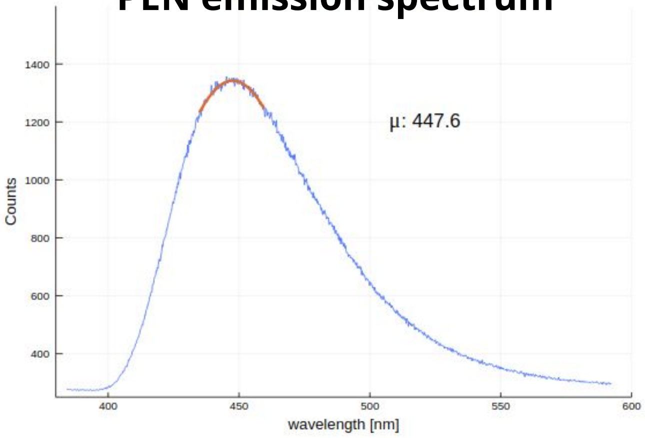
	PTFE[1]	Cu[2]	Electroformed Cu[5]	PEN	PEN at 77 K
Tensile Strength σ_{el} [MPa]	< 45.0	100	85.8 ± 7.8	108.6 ± 2.6	209 ± 2.8
Young's Modulus E [Gpa]	< 2.25	128	77.8 ± 15.6	1.86 ± 0.01	3.71 ± 0.08

1. https://www.treborintl.com/content/properties-molded-ptfe
2. http://www.memsnet.org/material/coppercubulk/
3. https://www.pnnl.gov/main/publications/external/technicalreports/PNNL−21315.pdf

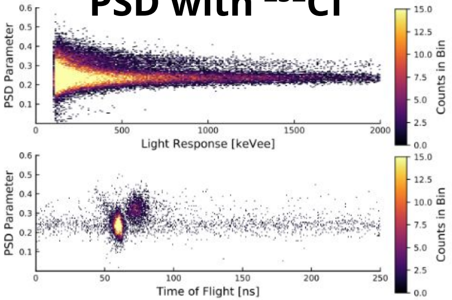
PEN scintillation properties

- PEN **scintillates** in the **blue regime**
  - Peaks around 445 nm
    - **Ideal for most of photosensors**
  - Scintillation yield around ⅓ of standard plastic scintillators
    - > 3500 photons / MeV
- **Shifts light from VUV to visible light**
  - Can be used to shift light of LAr (128 nm) or LXe (175 nm)
  - Efficiency **about 40% of TPB**
- **Pulse Shape Discrimination** (PSD) possible with PEN
  - Alpha decay identification
- Attenuation length of few cm

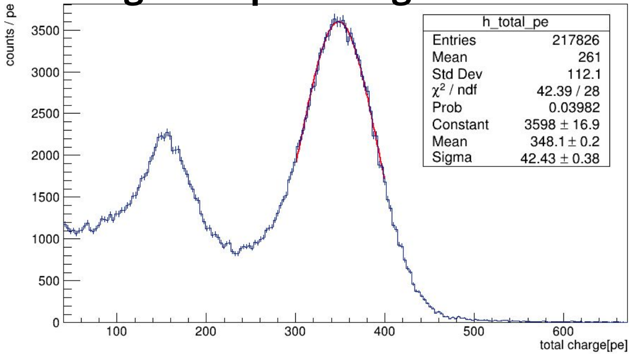
PEN emission spectrum



PSD with ^{252}Cf

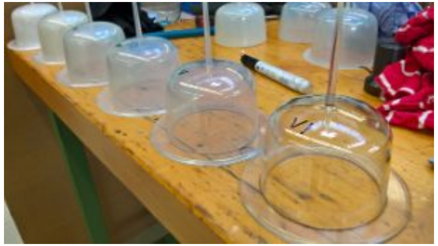


PEN light output using ^{207}Bi source



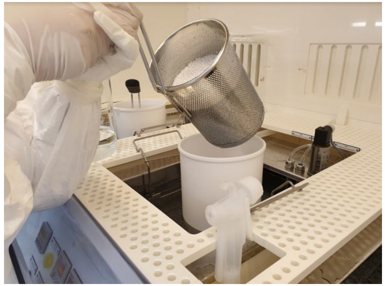
Production of moulded arbitrary shapes

- PEN is a **semi-crystalline polymer**
- Crystallization leads to polymer appearing opaque
- PEN must be cooled from ~300ºC to 220ºC in <10 seconds to remain amorphous
    - **Parts can be made by injection moulding**
- Progress on producing **arbitrary shapes**
    - *Holding plates*
    - *Containers*
    - *Capsules*
    - *Fibers*
- Current efforts to **synthesize PEN** ongoing **at ORNL** *(publication coming soon)*



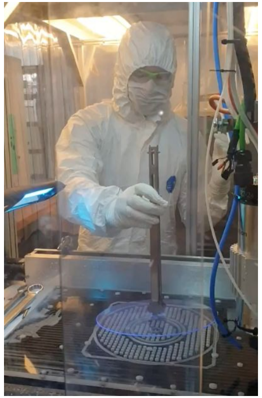
Radio-Clean production method of PEN parts

Cleaning raw material



Clean injection moulding technology developed

Production of PEN tiles



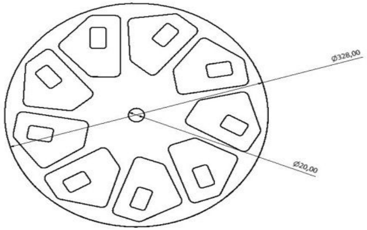
- In 2019: **radio-clean PEN plates** were **produced** by injection compression moulding using commercially available PEN pellets
  - PEN pellets were washed to remove surface impurities
  - Inner components of injection moulding machine were replaced and cleaned
  - **Entire process from granulate to finished plates was completed in < 4 min in a Class-1000 clean room**
- **Radio-clean production protocol defined** *(publication coming soon)*

PEN radiopurity of moulded parts

- About **20 kg of PEN samples measured** at LNGS and LSM
  - 112 tiles at OBELIX
  - 130 at GeMPI4
- For a **5 g detector** mount base **plate**
  - ~ 0.5 µBq/plate ^{228}Ra ✓
  - ~ 0.3 µBq/plate ^{226}Ra ✓
  - ~ 0.2 µBq/plate ^{228}Th ✓

Isotope	Radiopurity GeMPI4 at LNGS	Radiopurity OBELIX at LSM
	14.315 kg	5.231 kg
	t = 5851612 s	t = 6825600 s
^{228}Ra	$92 \pm 25\,\mu$Bq/kg	$107 \pm 38\,\mu$Bq/kg
^{228}Th	$32 \pm 16\,\mu$Bq/kg	$67 \pm 18\,\mu$Bq/kg
^{226}Ra	$60 \pm 15\,\mu$Bq/kg	$76 \pm 22\,\mu$Bq/kg
^{234}Th	< 1.9 mBq/kg 90 %C.L.	-
^{234}Pa	< 1.7 mBq/kg 90 %C.L.	-
^{235}U	$< 56\,\mu$Bq/kg 90 %C.L.	-
^{40}K	< 0.24 mBq/kg 90 %C.L.	0.567 ± 0.014 mBq/kg 90 %C.L.
^{137}Cs	$< 0.15\,\mu$Bq/kg 90 %C.L.	-

9 Legend plates machined from 180 grams PEN plate.

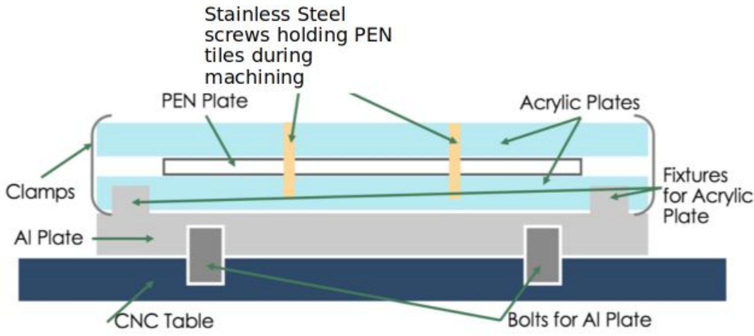


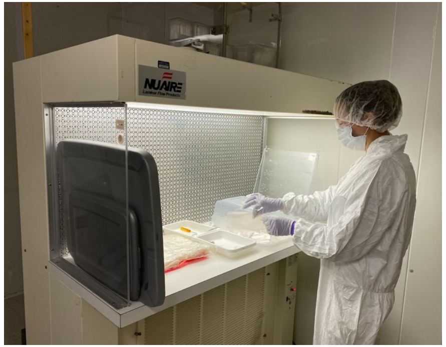
M. Laubenstein (LNGS)

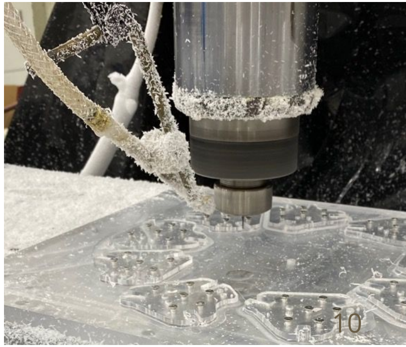
E. Rukhadze (CTU)

Machining procedure for PEN plates

- PEN plates were **CNC machined** at UT Physics machine shop
  - **Machine** was **cleaned** with ethanol and machine cleaner
  - **Nitrogen gas boil-off blowing during machining**
- **Jig designed** to **minimize PEN** plate **exposure** in machine shop by creating a ”sandwich”
  - Jig was assembled and disassembled inside a laminar flow hood inside a clean room
- **Cleaning** procedure for **tools** (except end mills):
  - 2% sol. Micro-90, 18 MOhm water (24 hrs)
  - Rinse with 18 MOhm water
  - Rinse water conductivity measured

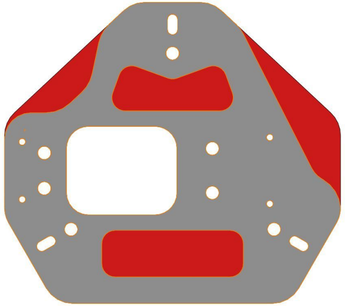


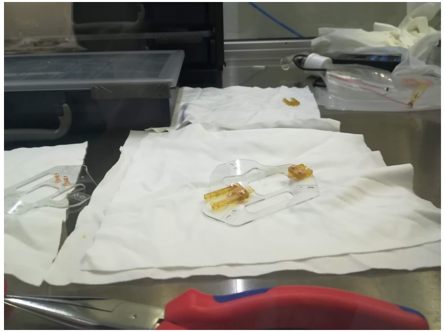


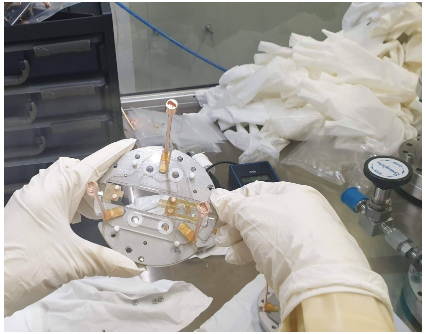


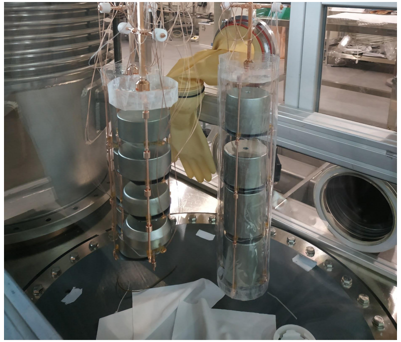
Deployment of PEN during post-GERDA test at LNGS

- **Design of PEN** holders **optimized** to reduce mass
  - Deployed at TUM cryogenic facility
- **PEN plates cleaned and mounted at LNGS**
  - 3% nitric acid solution used
  - Successful integration
- PEN plates used in about 40% of detectors
  - Allows for direct comparisons with Si plates
  - Data with PEN holders from PGT being analyzed
    - Preliminary results showed that detector response is not affected by PEN
- Production and characterization of LEGEND-200 plates ongoing
- **R&D** for further application in **LEGEND-1000** ongoing





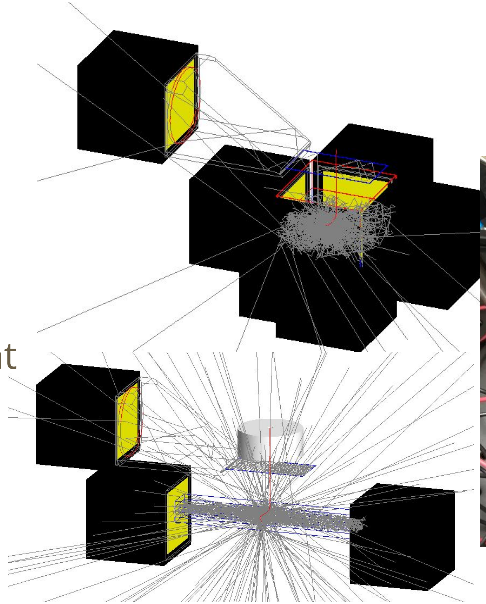


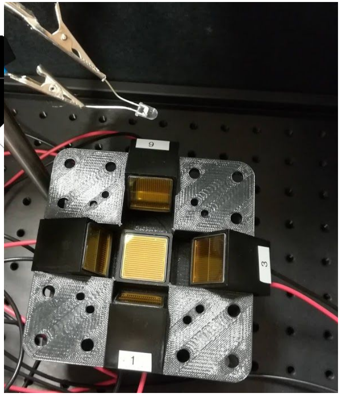


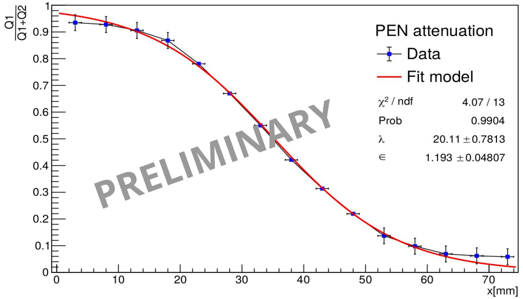
__Special thanks:__ Konstantin G. et al (detector mounting) + Michael W. et al (electronics) + LNGS + TUM + MPIK+ MPP + many others

Optical characterization

- Several **setups mounted** to fully characterize first production run
  - **Light yield:** ⅓ of standard plastic scintillators
  - **Emission spectrum:** peaks at ~445 nm
  - **Attenuation:** of the order of cm and wl dependent
  - **Surfaces:** Being studied
- **Geant4 developed** to extract absolute optical parameters
  - Light yield: > 3500 photons/MeV
  - Absorption as function of wavelength: Ongoing
  - Surface effects: Ongoing
- **Results will be used as input** for detailed studies/optimization of PEN **effect/improvements** in LEGEND







Summary and outlook

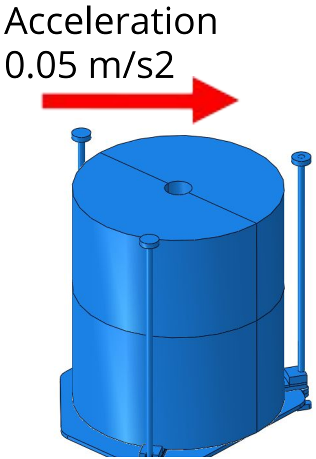
- **PEN is an attractive scintillator to be used as active structural material**
  - **Successful production of low background PEN holders**
  - Design optimized with reduced mass for LEGEND-200
  - Protocol for production under clean conditions defined
- **PEN holders deployed in detector mount prototypes in LEGEND-200 prototyping tests at LNGS**
- Optical characterization ongoing
  - Preliminary **light yield: > 3500 photons / MeV**
  - Preliminary **attenuation length: Of the order of cm and wl dependent**
  - Detailed Geant4 simulations of setups ongoing
- **Papers on production run and synthesis in preparation**
  - *Stay tuned*
- Next steps:
  - **Production of holders for LEGEND-200**
  - Extract absolute values for optical parameters: light yield, attenuation(wl). surface effects, etc
  - Complete characterization of WLS capabilities
  - Continue R&D for LEGEND-1000

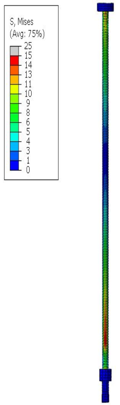
Thanks for your attention!

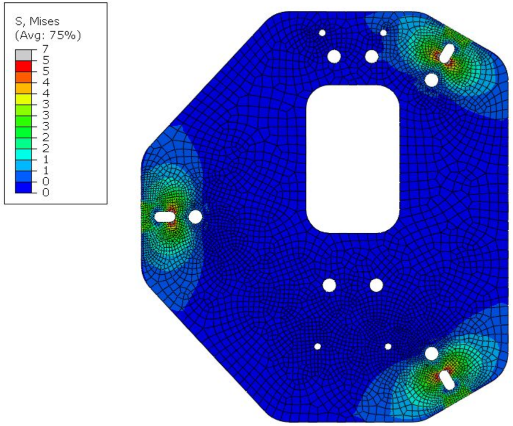
Backup

Mass optimization for PEN detector holder

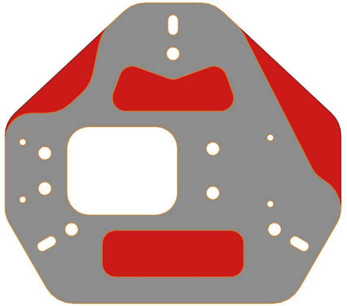
- **Design of PEN** holders **optimized** to reduce mass
  - **3** different **models**
  - Geometry can be adjusted if needed
- Mechanical simulations using PEN rods instead of copper also performed
- **Some areas thinned** to fit thickness of Si plates
  - No problem for mounting front-end electronics board







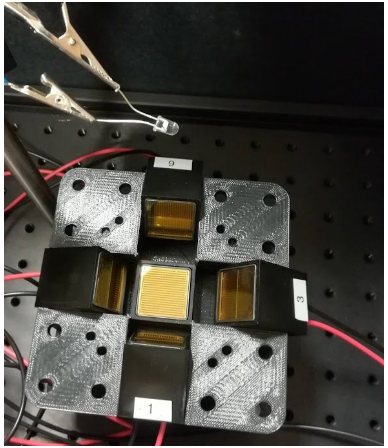
019375-PEN
7.3 g →5.3 g

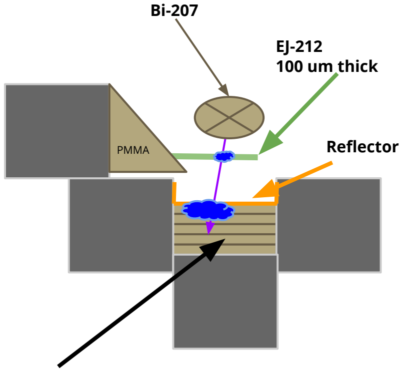


018695-PEN
8.25 g →6.25 g

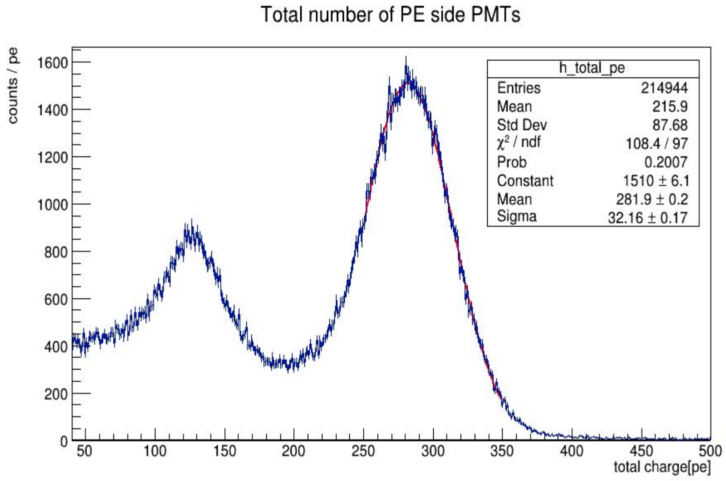
Light output

- PEN samples (**L200 production**) placed in PMT setup
  - Excite PEN with ^{207}Bi source
  - Select electrons (~1 MeV and ~400 keV)
- **Compare with PS samples** of same dimensions





Samples of 1.5x30x30 mm^3

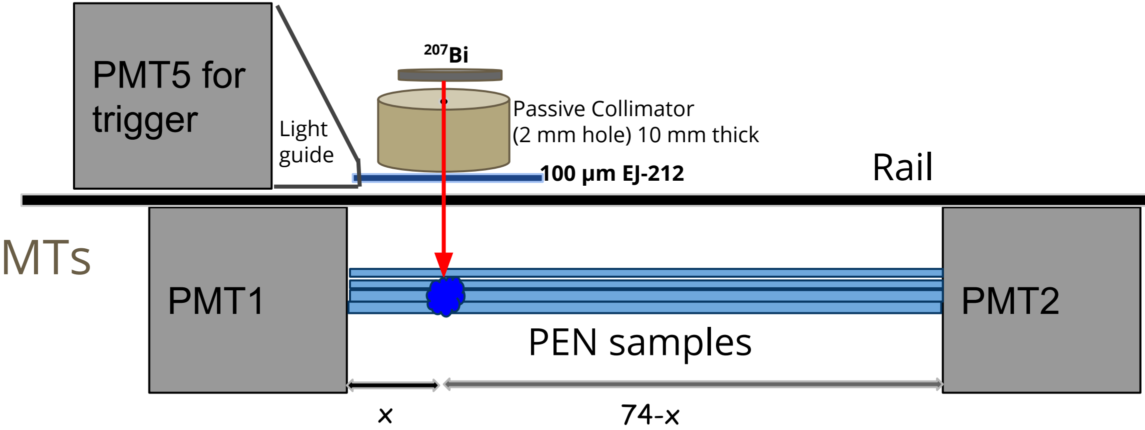


- PEN (? ph/MeV):
  - 282 pe/MeV
  - σ ~11% at 1 MeV

- PS (~10000 ph/MeV):
  - 853 pe/MeV
  - σ ~7% at 1 MeV

- **Light yield of PEN larger than 3500 ph/MeV**
  - Attenuation length much more important for PEN

Light attenuation



- PEN samples (**LEGEND-200 production**) coupled to two PMTs
- **Active + passive collimation**
- Steps of 5 mm
  - 15 positions in total
- Use $f(x) = Q_1/(Q_1+Q_2)$
  - Q_i = detected charge in PMT_i
  - A = Emitted light at position of interaction
  - $Q_1 = A\eta_1 e^{-(x/\lambda)}$ $Q_2 = A\eta_2 e^{-(74-x/\lambda)}$
  - $f(x) = 1/(1+\varepsilon e^{-(74/\lambda)}e^{(2x/\lambda)})$
  - $\varepsilon=\eta_2/\eta_1$
- Two data sets
  - **λ ~ order of cm and wl dependent**
- More data expected soon