Production and optical characterisation of PET and PEN scintillator samples

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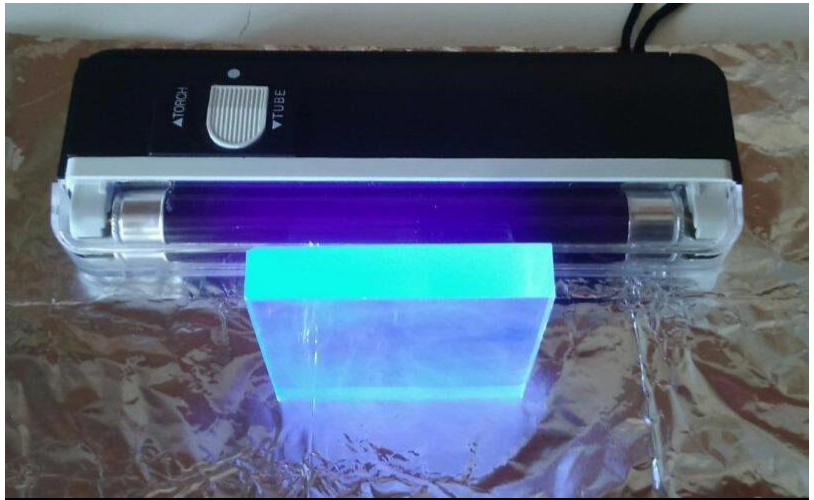
INTRODUCTION

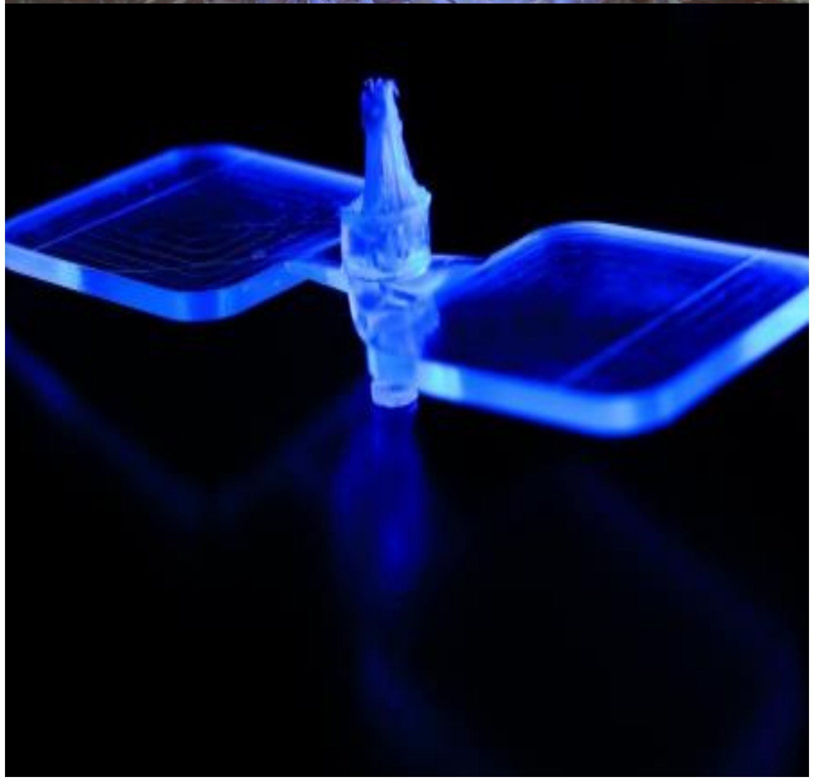
Organic Plastic Scintillators

- Widely used in Particle and Nuclear Physics research and related applications.
- Scintillating Plastic has low cost/weight and is malleable

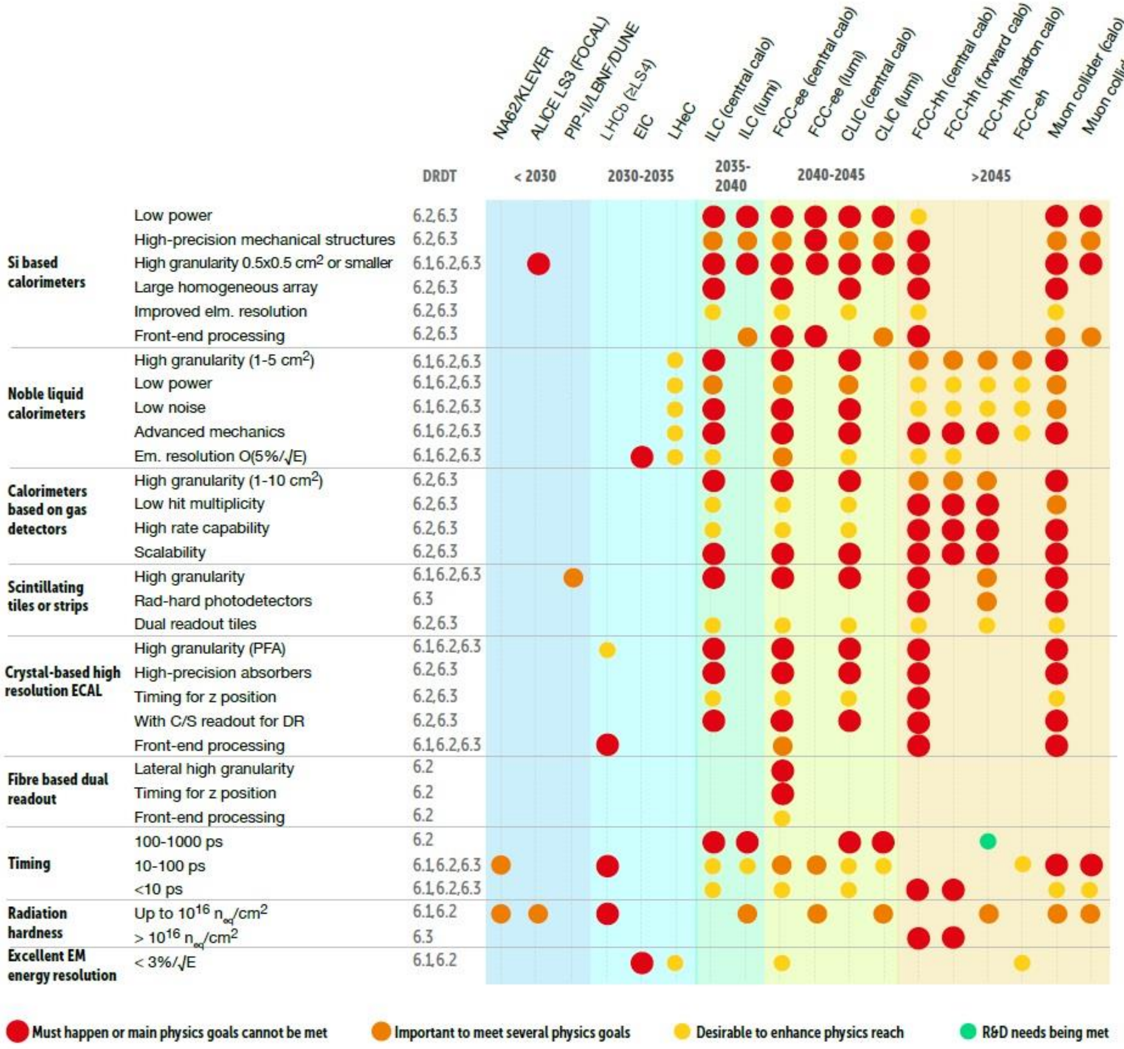
- Typical organic polymer bases:
  - Polystyrene and Polyvinyltoluene

- These materials are doped with wavelength shifters (WLS) in residual concentrations to:
  - Bypass the low transmission efficiency of UV light emitted by the base materials
  - Increase the effective scintillation light response.





Challenges for future scintillator-based detectors in High-Energy Physics



cds.cern.ch/record/2784893

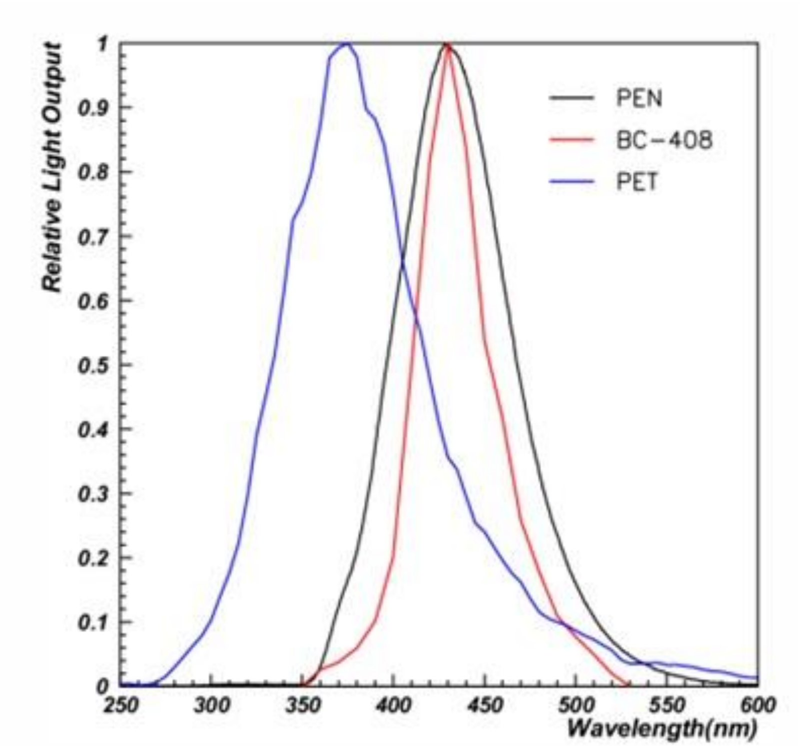
- Future precision/high energy colliders will impose stringent requirements on next generation detectors
- R&D starting now to ensure that key technologies are ready at the time of construction

Scintillator Requirements [1]:
- Large light response;
- Fast signals;
- High radiation hardness

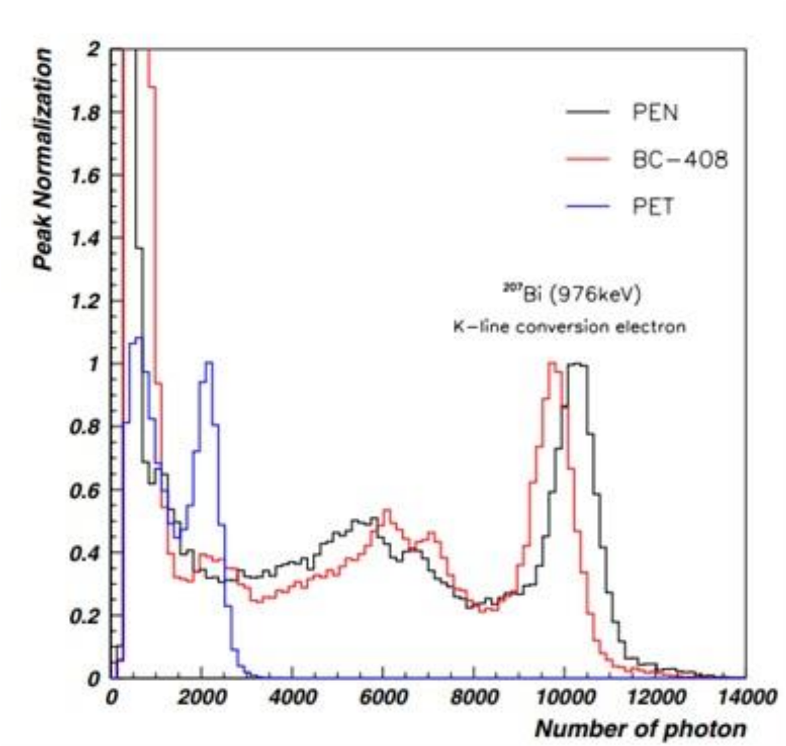
For FCC-hh [2] [3] [4]:
- Doses of up to 5 GGy are expected in the forward calorimeters.

Scintillation Properties of PEN (Polyethylene Naphthalate) and PET (Polyethylene Terephthalate)

- PEN is a good option for new scintillators [5];
  - Competitive light response;
  - Emits light ≈ in the same λ as some commercial scintillators (BC-408);
  - Adequate emission spectrum



(a) Emission Spectra [5]



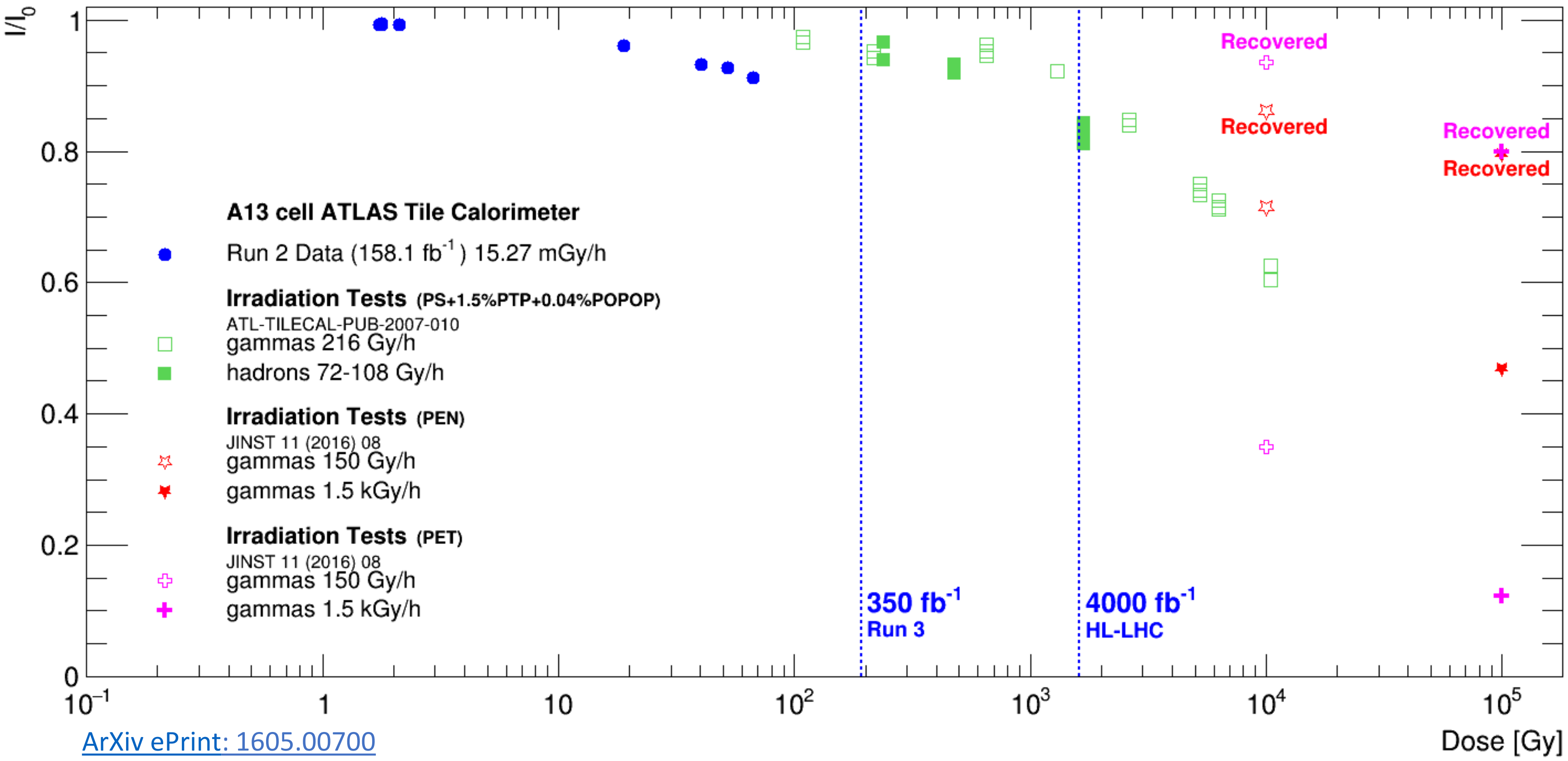
(b) Light Response Spectrum [5]

- PET has a faster light pulse [6], [7], [8]:
  - PEN: ~ 35 ns
  - PET: ~ 7ns

	PEN	BC-408	PET
Light Output photons/MeV	~ 10500	~ 10000	~ 2200
Max WL emission (nm)	425	425	370

(c) Emission & Light Response [5]

Radiation Hardness of PEN and PET [9]



ArXiv ePrint: 1605.00700

2401.16034 (arxiv.org)

Atlas Tile Calorimeter uses:

- plastic scintillator tiles (Polystyrene+1.5% PTP+ 0.044% POPOP) as the active material
- steel as absorber material

- PET/PEN have a good recovery when exposed to radiation
- PEN degrades less
- PEN recovers faster
  - PEN: 5 days
  - PET: 60 days
- PET has a larger total recovery
  - PET: 93.5%
  - PEN: 85.9%

Objectives

Research new plastic scintillating materials, PEN and PET, with a specific focus on their optical and scintillation properties.

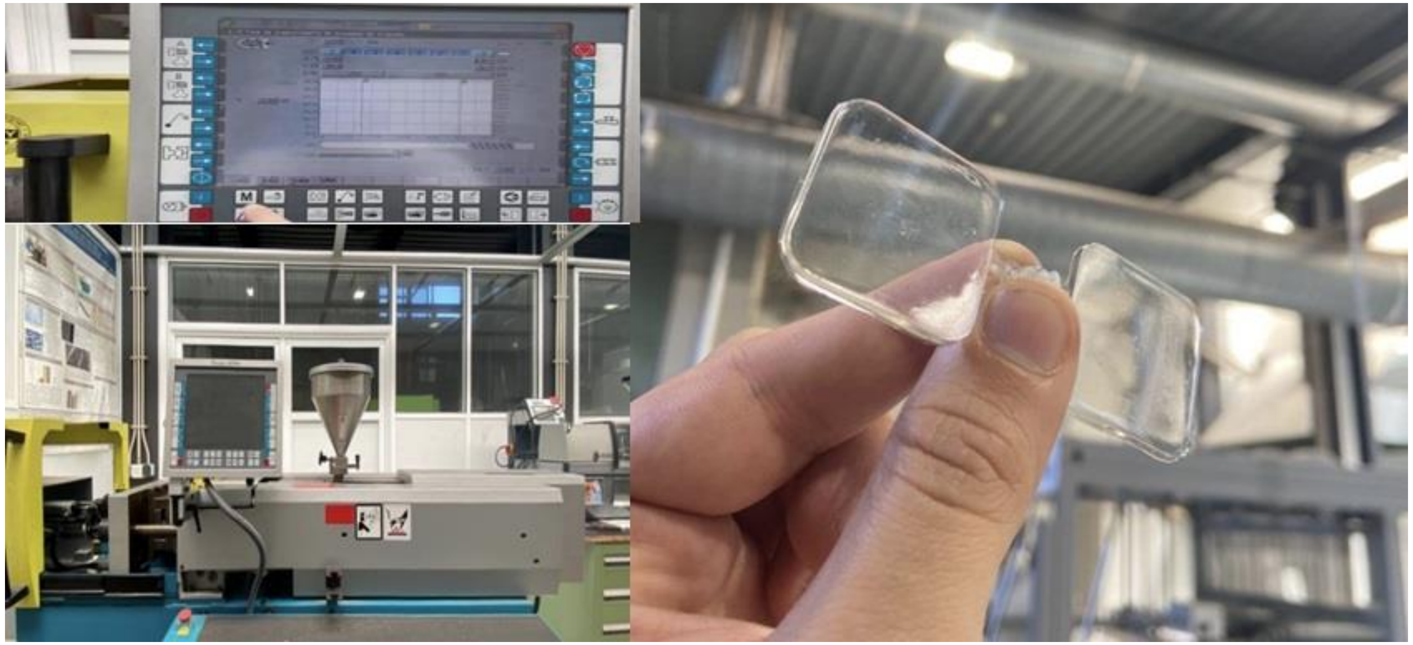
- *Do PET and PEN blend with synergy?*
  - *PEN (high light response, radiation hardness)*
  - *PET (damage recovery, faster timing)*

Outline:

- Production of Scintillator Samples: pure PET/PEN, PET:PEN blends and PET+Dopants
- Characterization of samples:
  - Emission and Transmittance Spectra
  - Measurement of Light Response
- Summary and Future work

Sample Production

Granulated raw materials (PET/PEN) are used



- The samples were produced in collaboration with the Institute of Polymers and Composites (IPC) of the University of Minho
- Manufacturing Processes: Injection molding.
- Samples measure 30 x 30 x 2 mm^3
- Scintillator properties depend on production parameters:
  - Material flow
  - Injection speed
  - Pressure
  - Cooling time
  - Melting temperature

Sample Production

Samples produced:

- Pure PET and PEN

- PET:PEN blends with different mass proportions (10:90, 25:75, 50:50, 25:75 and 10:90)

- PET + dopants (BBOT and POPOP in 0.22% concentration)

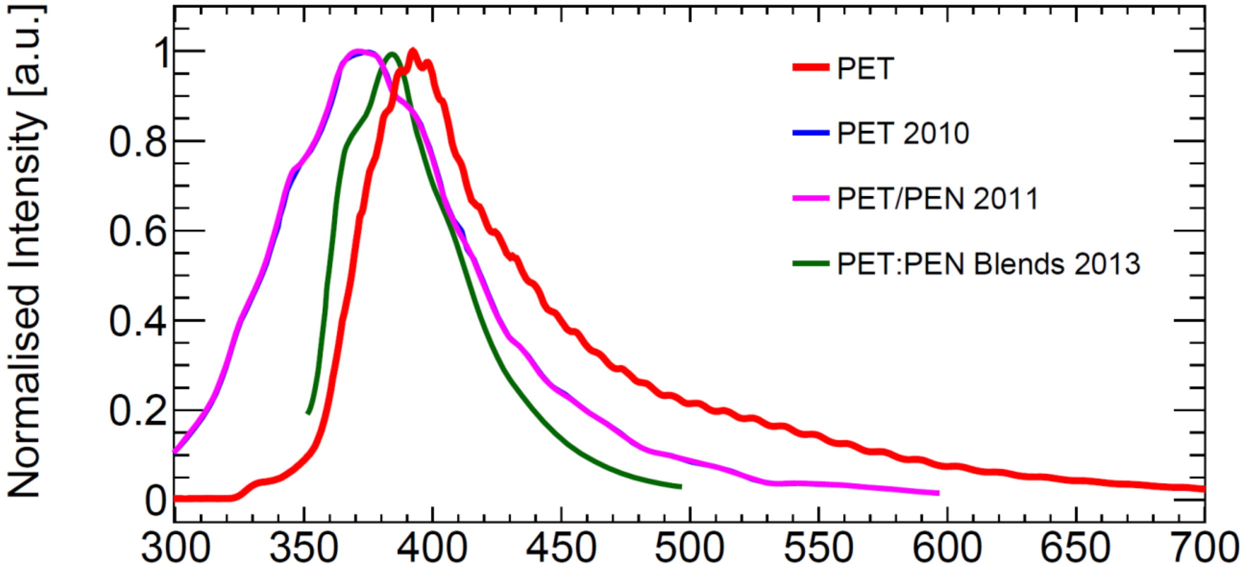
Light response of PEN samples to UV source
Picture by Agostinho Gomes

Emission and Transmittance Spectra

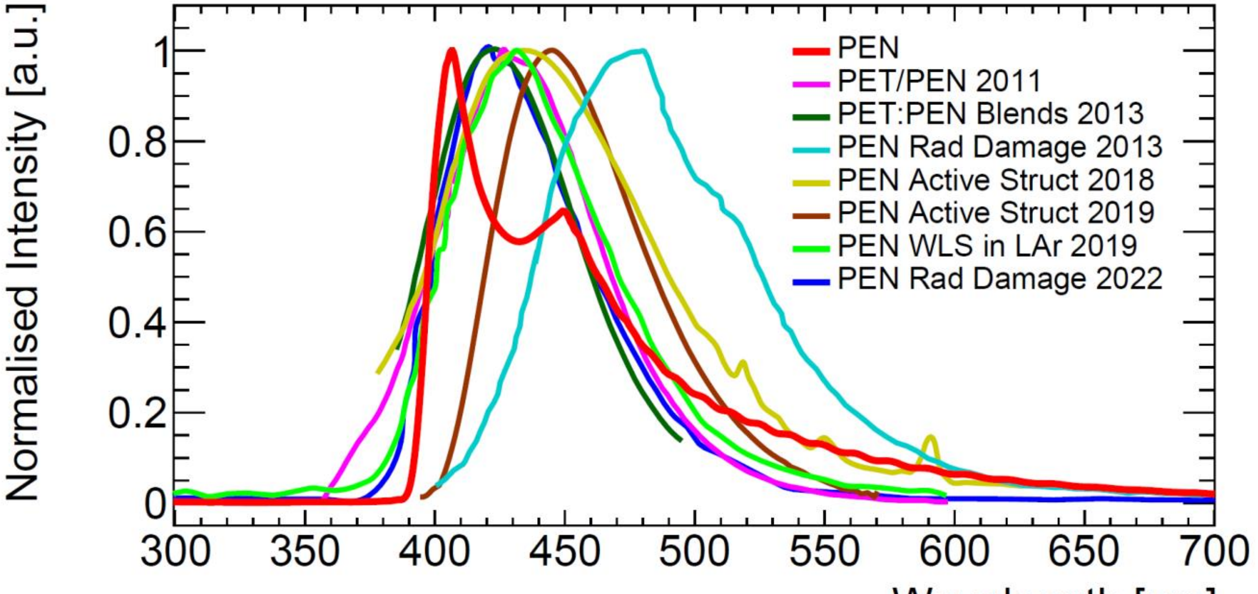
Emission Spectra

- PET sample:
  - Peak ~ 395 nm
  - Shape and peak are similar with Literature

- PEN sample:
  - In the literature, the spectra vary a lot from each other
  - Main peak ~ 405 nm, slightly below the Literature
  - 2nd peak ~ 450 nm, could be attributed to differences in the source material composition



a) PET



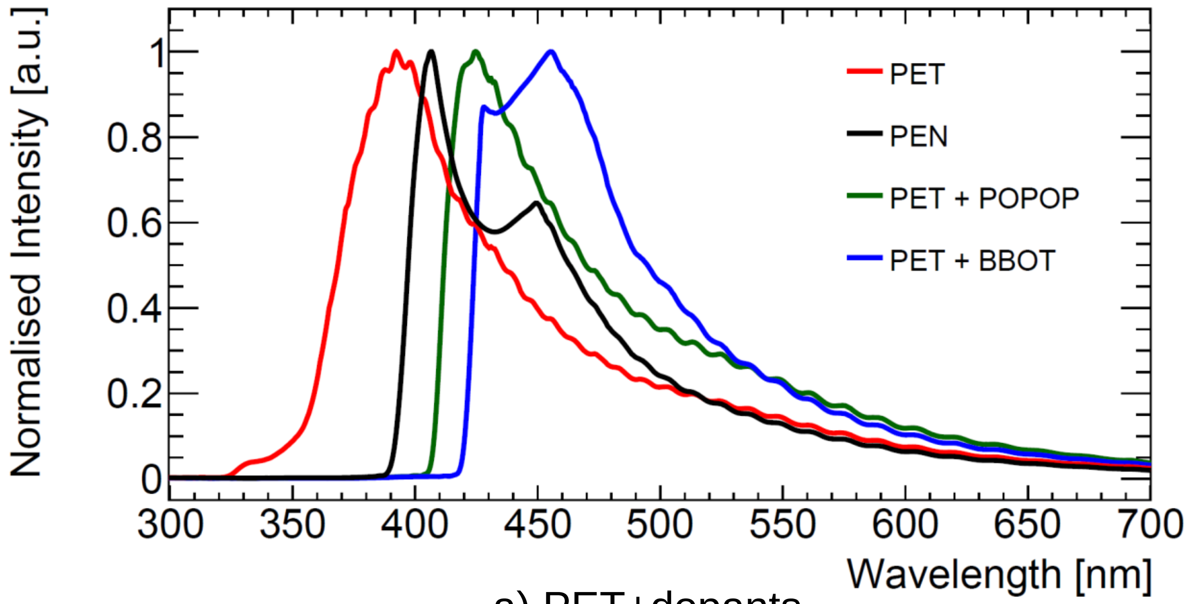
b) PEN

PET 2010 [10], PET/PEN 2011 [11], PET:PEN Blends 2013 [12], PEN Rad Damage 2013 [13], PEN active struct 2019 [14], PEN Rad Damage 2022 [6]

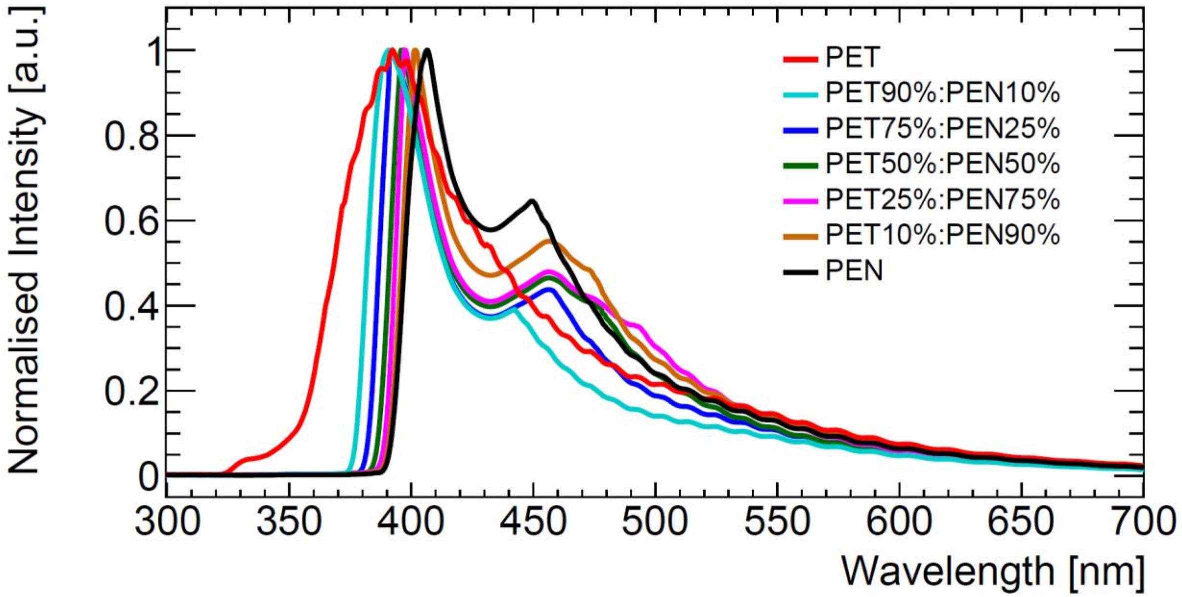
Emission Spectra

- As expected, adding POPOP and BBOT to PET causes the WLS of the original scintillation light
- Resulting peaks:
  - PET+POPOP ~ 425 nm
  - PET+BBOT ~ 455 nm

- PET:PEN mixtures:
  - Spectra are similar to the PEN spectrum
  - Peak gradually shifts 390 nm → 410 nm with increasing PEN proportion



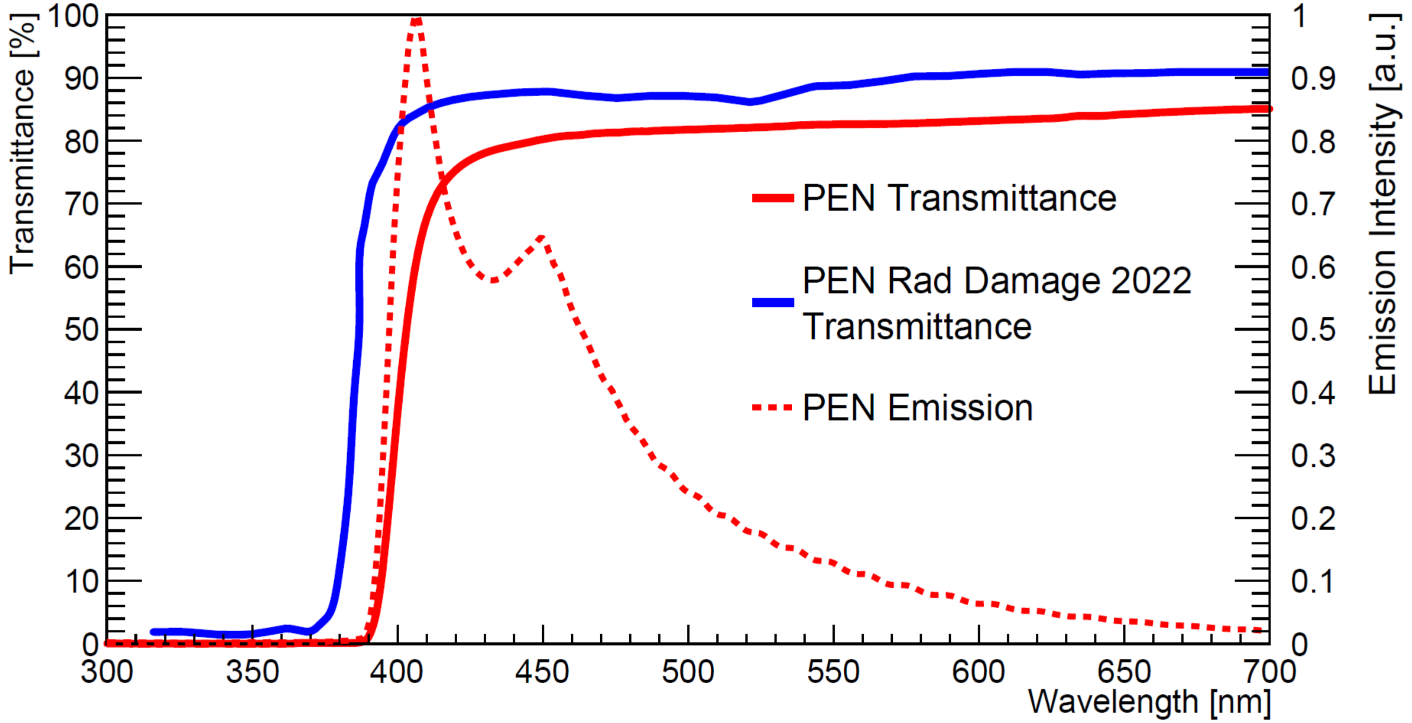
a) PET+dopants



b) PET:PEN blends

PEN Transmittance

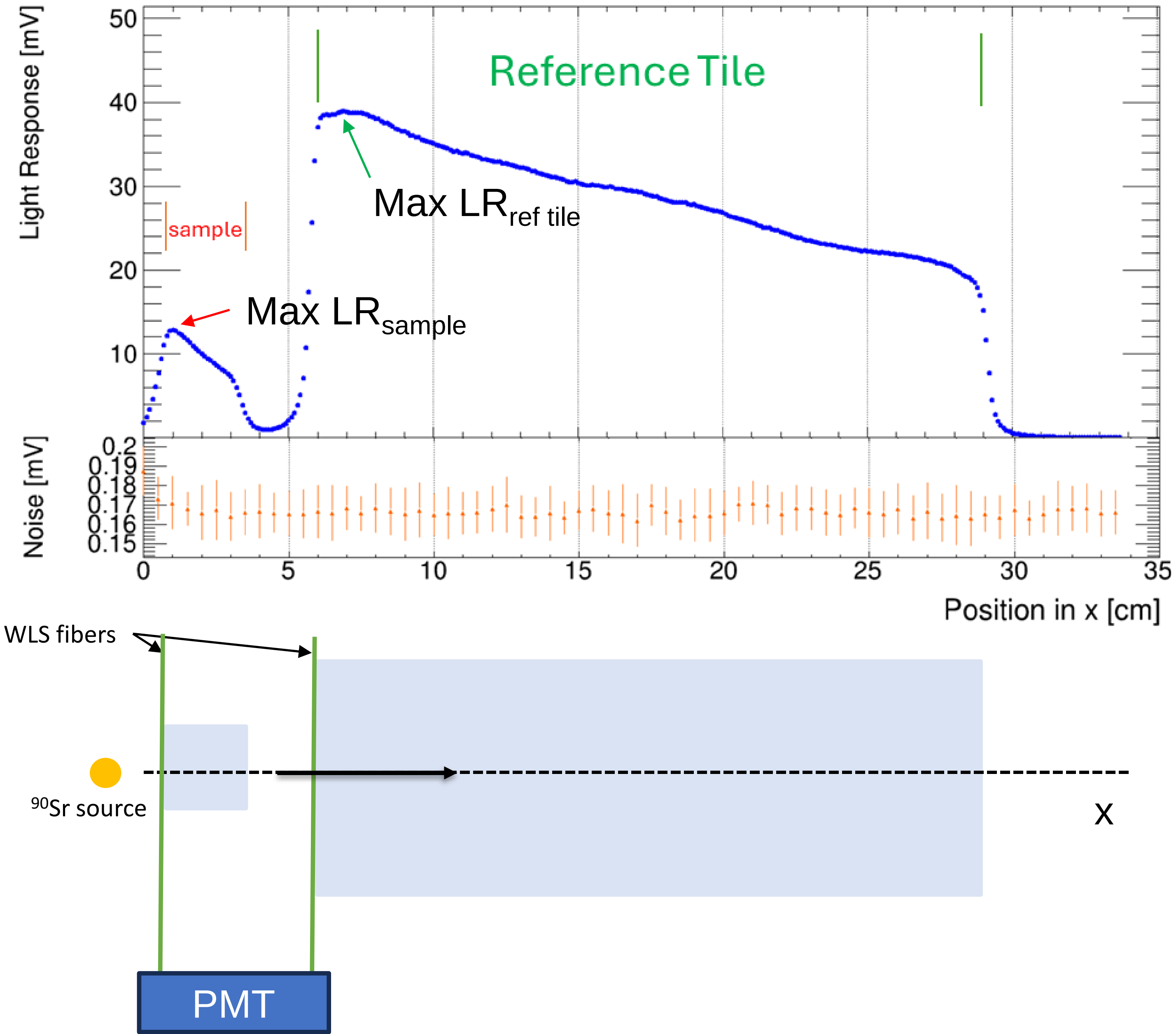
- Results show good agreement
  - PEN: ~ 80 %
  - PEN Literature: ~ 90 %
- Difference (our and Literature PEN) in transmittance is probably due to the different thicknesses
  - PEN sample: 2 mm
  - Literature: 0.1 mm
- PEN exhibits transparency above 400 nm
  - Scintillation below 400 nm is attenuated by the transmission characteristics
  - PEN's Light yield might improve by adding an adequate WLS



PEN Rad Damage 2022 [6]

Light Response

^{90}Sr scan Measurements

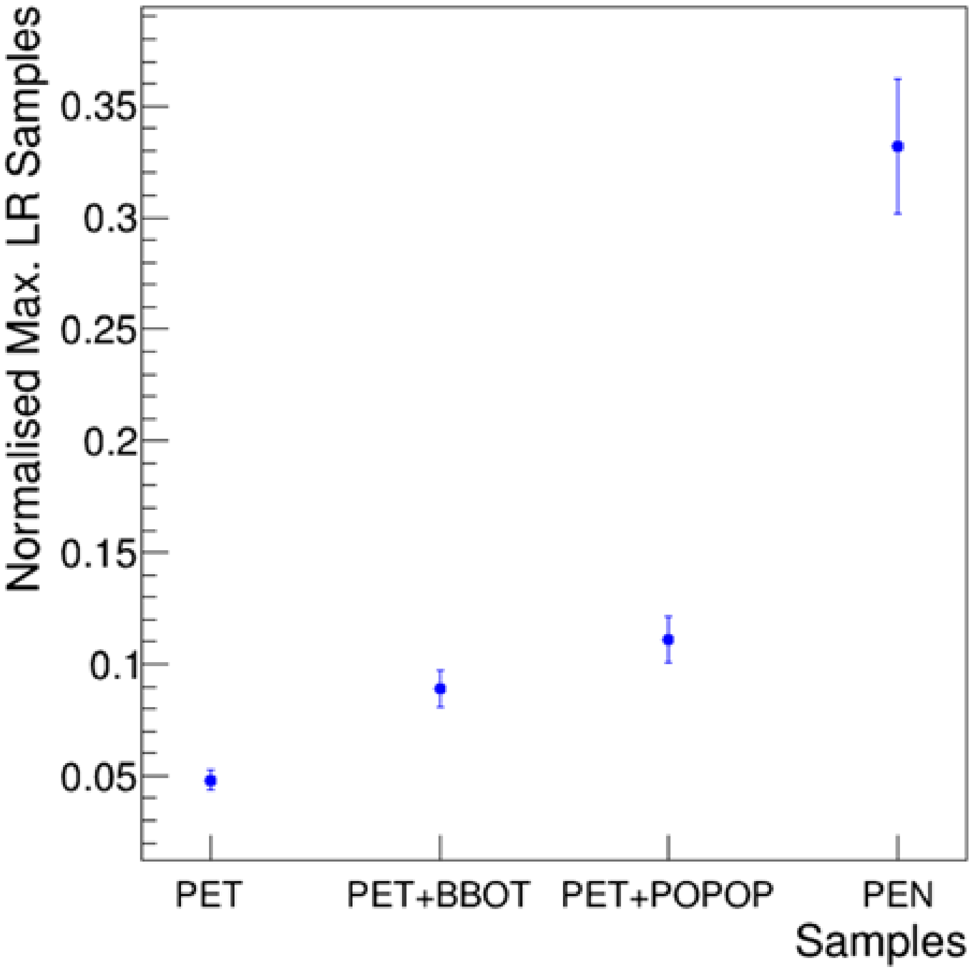


- Light response (LR in mV) as a function of ^{90}Sr source position
- Two scintillators are measured:
  - Reference Tile: 3 mm thick scintillator (ATLAS/LHC Tile Calorimeter - tile #4)
  - Sample: Manufactured scintillator (2 mm thick)
- Two values are extracted from the scan
  1. Maximum LR in the sample
  2. Maximum LR on the reference tile
- Max normalized LR is $\frac{Max\ LR_{sample}}{Max\ LR_{ref\ tile}}$
  - is the main metric for evaluating performance of different composition samples

Normalised LR Samples to PEN/PET and PET+dopants

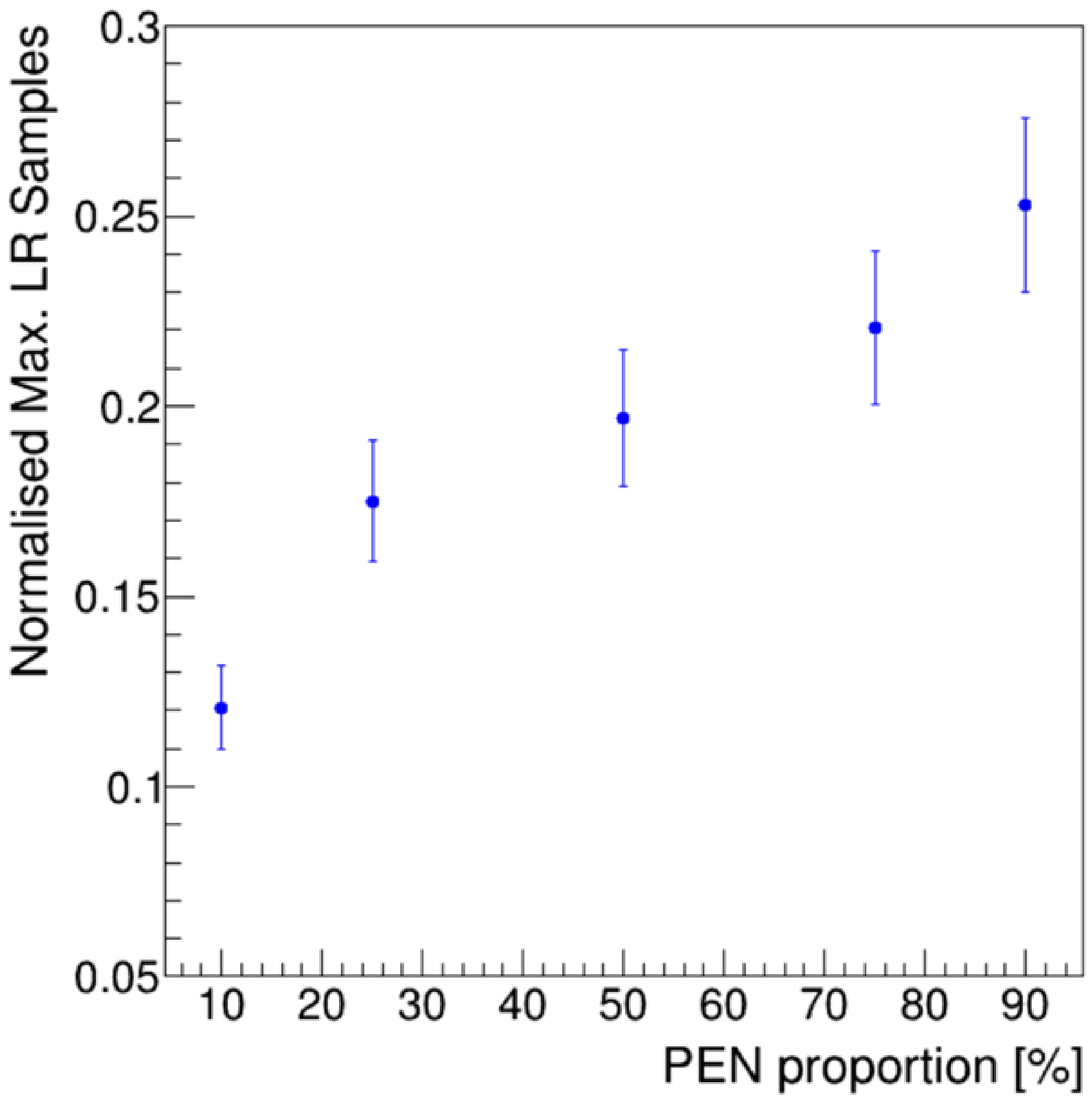
- PEN has 7 times higher light response than PET

- Addition of dopants to the PET-base material potentiates the light emission:
  - Dopants in 0.22% mass concentration
  - BBOT: increase in the maximum LR by 80%
  - POPOP: increase in the maximum LR by 120%



Normalised LR Samples for Mixtures

- Different PET:PEN mixtures as a function of the PEN proportion;
- Increase in light response with the proportion of PEN, expected given the higher light response of PEN compared to PET;



Summary and Future Work

- Future HEP experiments with scintillator detectors will need cheap materials with high scintillation efficiency and radiation hardness.

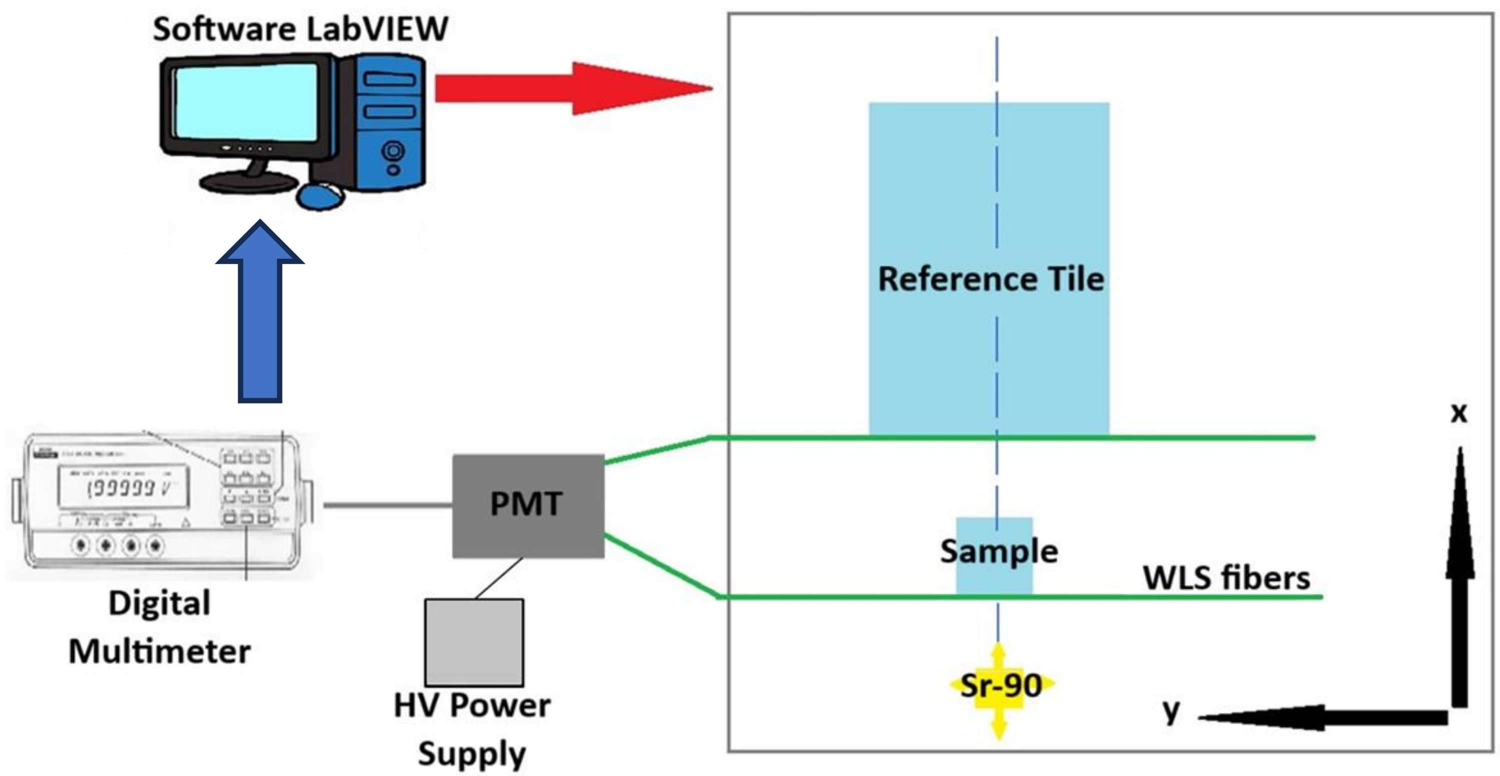
- R&D of pure PEN and PET samples , PET+dopants, and PET:PEN mixtures in different proportions:
  - Light response of PEN is about 7 times higher than PET
  - Addition of dopants to PET doubles its light response
  - PET with dopants exhibits wavelength shifting (WLS) in light emission
  - For PEN/PET blends, light response increases with the PEN proportion
  - For blends, PEN has predominant spectrum

Future work:

- Measurement of the signal time properties of the existing samples
- R&D for the production of larger samples
- Study of the radiation hardness of PEN/PET and PET:PEN blends

BACKUP

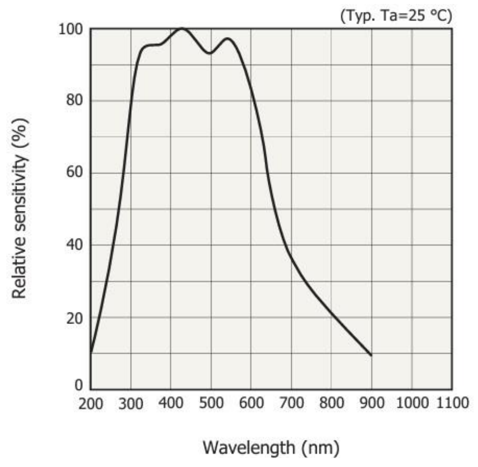
Setup for Measuring the Light Response (LR)



* ^{90}Sr source scans the scintillators
* PMT
* Multimeter
* Control and data acquisition software (LabVIEW)
* WLS fibers
* HV Power Supply

- Scintillator signal: each point is the average of 30 measurements.
  - a measurement is the PMT signal integrated over 400 ms;
- Noise value is updated at each 5 scan points
  - source outside the scintillator area;
- Light response (LR) is defined as measured signal after noise subtraction

Experimental Setup for the Emission Spectrum measurement

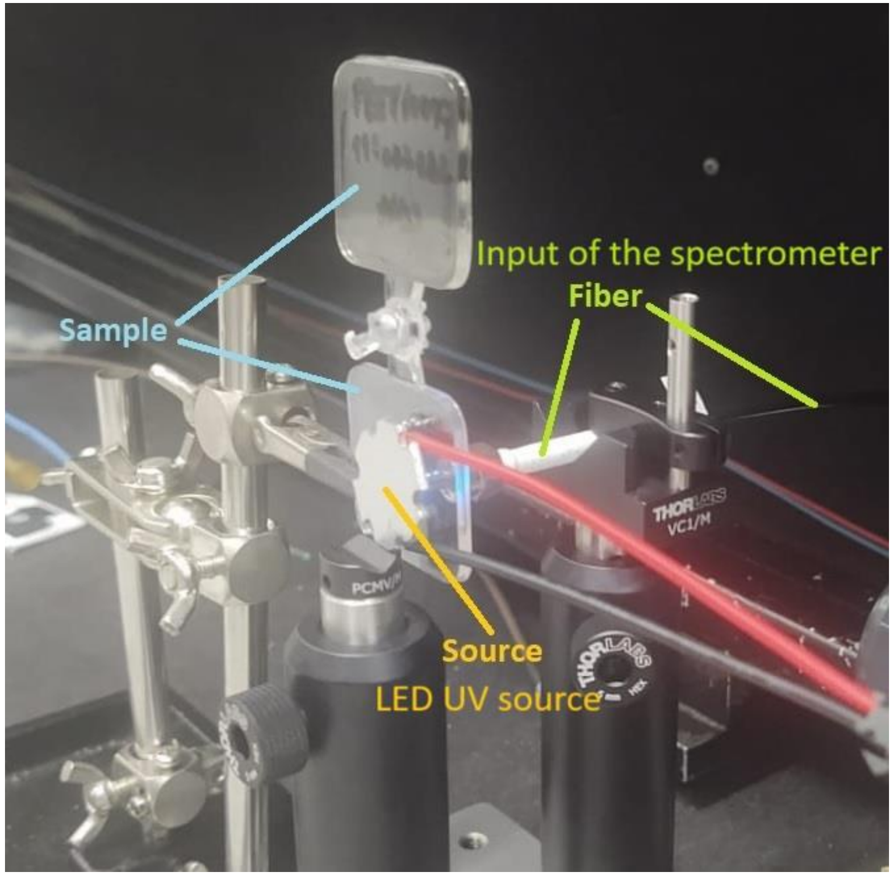


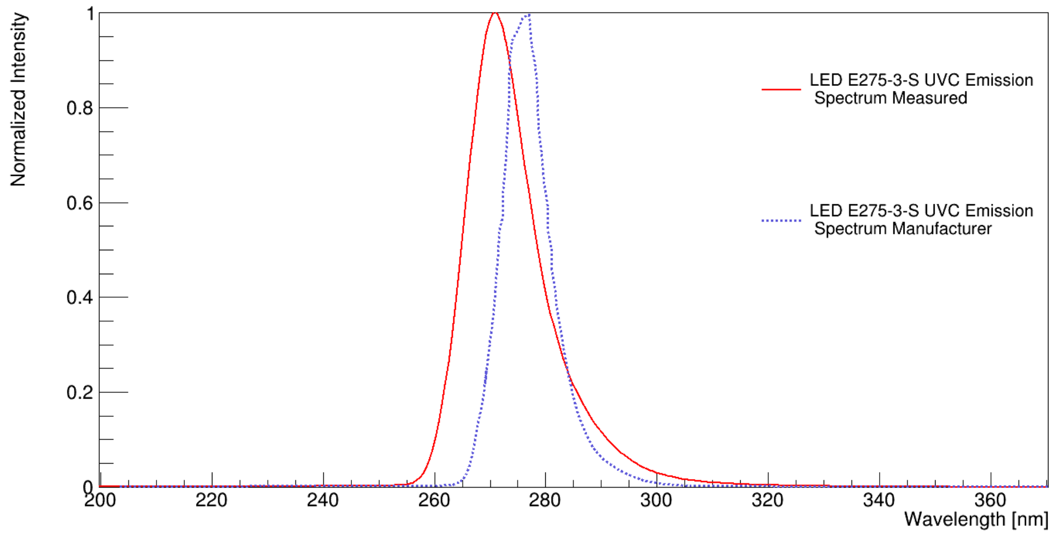
Spectrometer

C10082MD, for UV to near IR (200 to 800 nm)

Measured with the spectrometer

- LED source: E275-3-S UVC LED
- Manufacturer information: peak between 270-280 nm
- Our measured Peak ≈ 271 nm





Sample Production Parameters

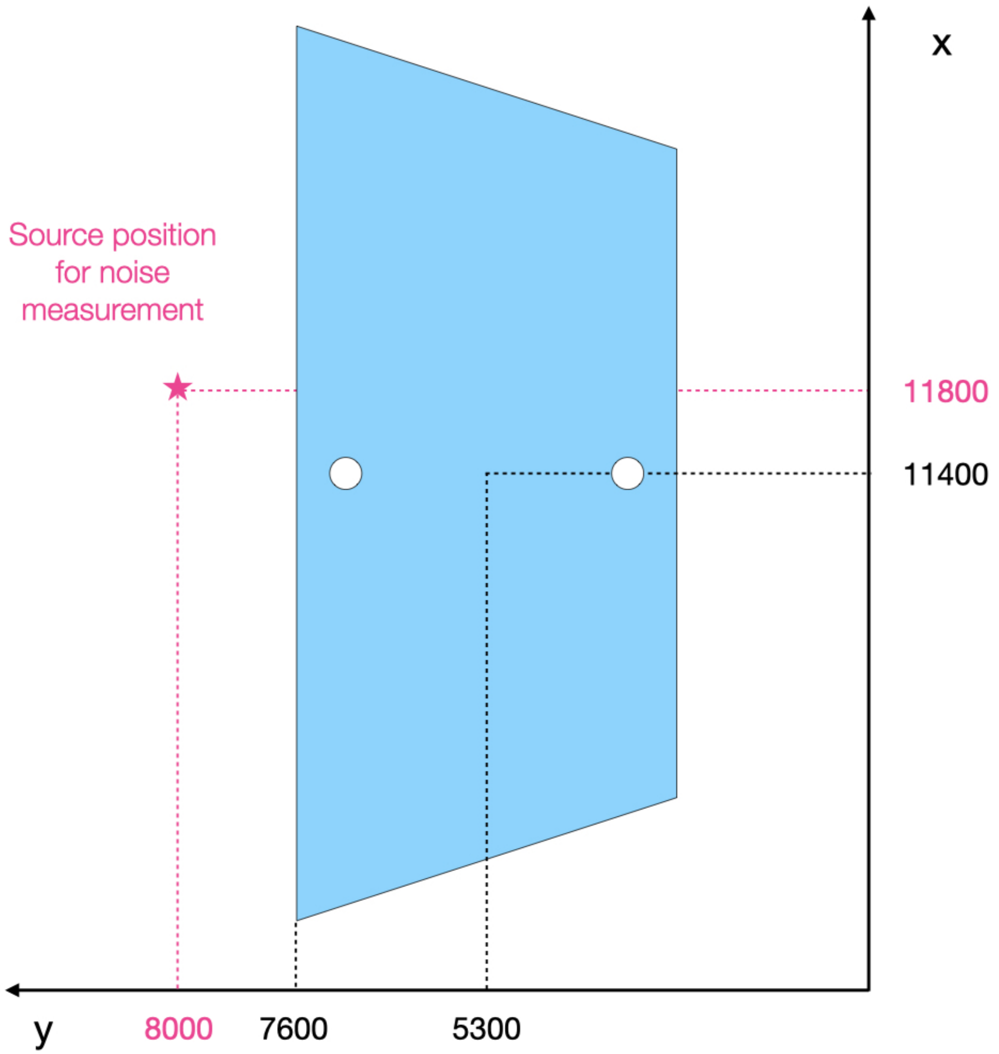
					Injection				2nd Injection				Dosing							
Samples	Period	Process	Model	Dried material	Dosing cm^3	Comutation cm^3	Speed cm^3/s	Pressure bar	Pressure time (s)	Comutation cm^3	Speed cm^3/s	Pressure bar	Dosing mm^3	Comutation mm^3	Speed mm/s	Pressure bar	Temperature Set Nozle/T5/T4/T3/T2/T1 (°C)	Cycle Time (s)	Cooling time (s)	Residence time (min)
PET + BBOT	September-23	Injection	Boy 22A	4h, 60°C	8.5	2.7	30	1500	4	2.7	2.5	400	8.5	2.7 cm^3	150	30	*/265/260/250/250/245	50.73	20	Not needed
PET + POPOP	September-23	Injection	Boy 22A	4h, 60°C	8.5	2.7	30	1500	4	2.7	2.5	400	8.5	2.7 cm^3	150	30	*/265/260/250/250/245	47.05	20	Not needed
PET75PEN25	12-Oct-23	Injection	Boy 22A	PET: 4h, 60°C; PEN: 4h, 110°C	8.5	2.7	30	1500	3	5 mm^3	10 mm/s 2.5 cm^3/s	300	8.5	2.7 cm^3	150	10	*/295/290/280/260/250	52.1	20	5
PET:10/PEN:90	13-Oct-23	Injection	Boy 22A	PET: 4h, 60°C; PEN: 4h, 120°C	8.5	2.7	30	1500	4	5 mm^3	10 mm/s 2.5 cm^3/s	300	8.5	2.7 cm^3	150	30	*/300/285/280/275/255	51.6	20	5
PEN	6-Nov-23	Injection	Boy 22A	PEN: 6h, 110°C	8.5	2.7	30	1500	4	2.7	2.5 ccm/s	600	8.5	2.7	150	20	*/295/290/285/280/250	52.85	20	5
PET	7-Nov-23	Injection	Boy 22A	6h, 70°C	8.5	2.7	30	1500	4	2.7	2.5	600	8.5	2.7	150	20	*/275/270/265/260/250	47.05	20	Not needed

Manufacturing PET/PEN

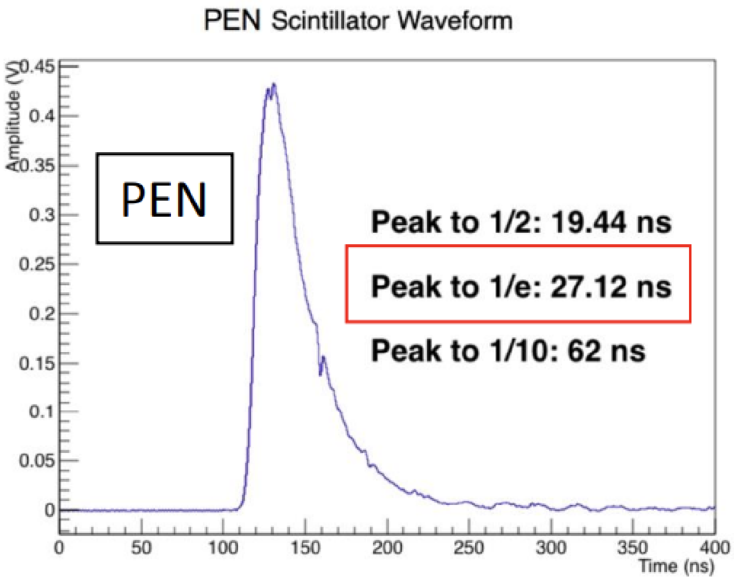
PET			
Samples/Articles	**Brand/Type**	**Material Form**	**Sample Size**
Our PET Sample, doi:10.1016/j.nima.2024.169627	Selenis Selekt™ BD 110	granulate	30 x 30 x 2 mm3
doi:10.1098/rspa.2010.0118 (PET 2010)	Mitsui Chemicals Inc., Japan	lump of PET bottles	110×50×5mm3
doi:10.1209/0295-5075/95/22001 (PET/PEN 2012)	Teijin Chemicals Ltd.	plate	35 × 35 × 5 mm3
doi:10.1016/j.radmeas.2013.06.006 (PET:PEN blends2013)	--	plate	31 x 31 x 5 mm3

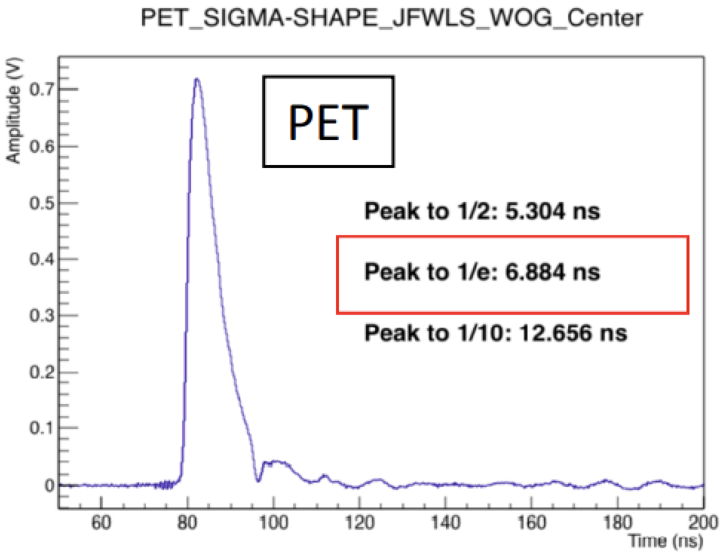
PEN			
Samples/Articles	**Brand/Type**	**Material Form**	**Sample Size**
Our PEN Sample, doi:10.1016/j.nima.2024.169627	GoodFellow Cambridge Ltd.	granulate	30 x 30 x 2 mm3
doi:10.1016/j.radmeas.2013.06.006 (PET:PEN blends2013)	--	plate	31 x 31 x 5 mm3
doi:10.1016/j.nimb.2013.03.027 (PEN Rad Damage 2013)	Teonex®, Teijin DuPont, Japan	film	9 µm thick
doi:10.1063/1.5019011 (PEN Active struct 2018)	Tejin-DuPont:TN-8065S and TN-8050SC (Teonex®)	pellets	30 x 30 x 3 mm3
doi:10.1088/1748-0221/14/07/P07006 (PEN Active struct 2019)	Tejin-DuPont:TN-8065S and TN-8050SC (Teonex®)	pellet or granulate	30 x 30 x 3 mm3
doi:10.1140/epjc/s10052-019-6810-8 (PEN WLS in Lar 2019)	Teijin DuPont:(Teonex® Q83)	film	125 µm thick
doi:10.3390/ma15196530 (PEN Rad Damage 2022)	Teonex® (Mod. Q65HA)	flexible film	40 x 30 x 0.1 mm3

Coordinates in the scan for noise acquisition

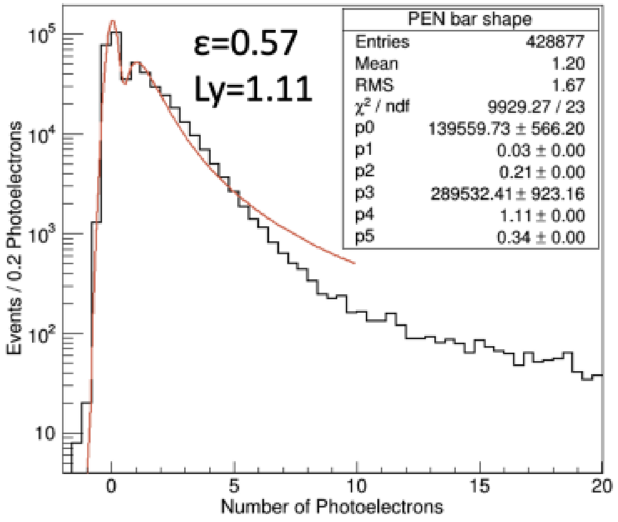


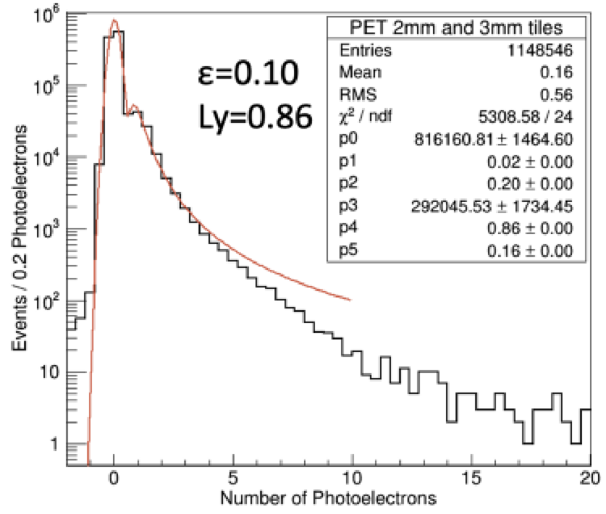
Timing and Efficiency





The signal timing of PEN and PET in response to the pulsed nitrogen laser.





[8]

The detection efficiency and light response of PEN and PET in response to 150 GeV muons of CERN test beam

- PET has a faster light response than PEN, but a lower light response.
- PEN has an detection efficiency of approximately 60 % and PET has an efficiency of 10 %