DEVELOPMENT OF RADIATION-HARD SCINTILLATORS AND WAVELENGTH-SHIFTING FIBERS

B. Bilki, Y. Onel, E. Tiras, J. Wetzel, D. Winn

Calorimetry for the High Energy Frontier
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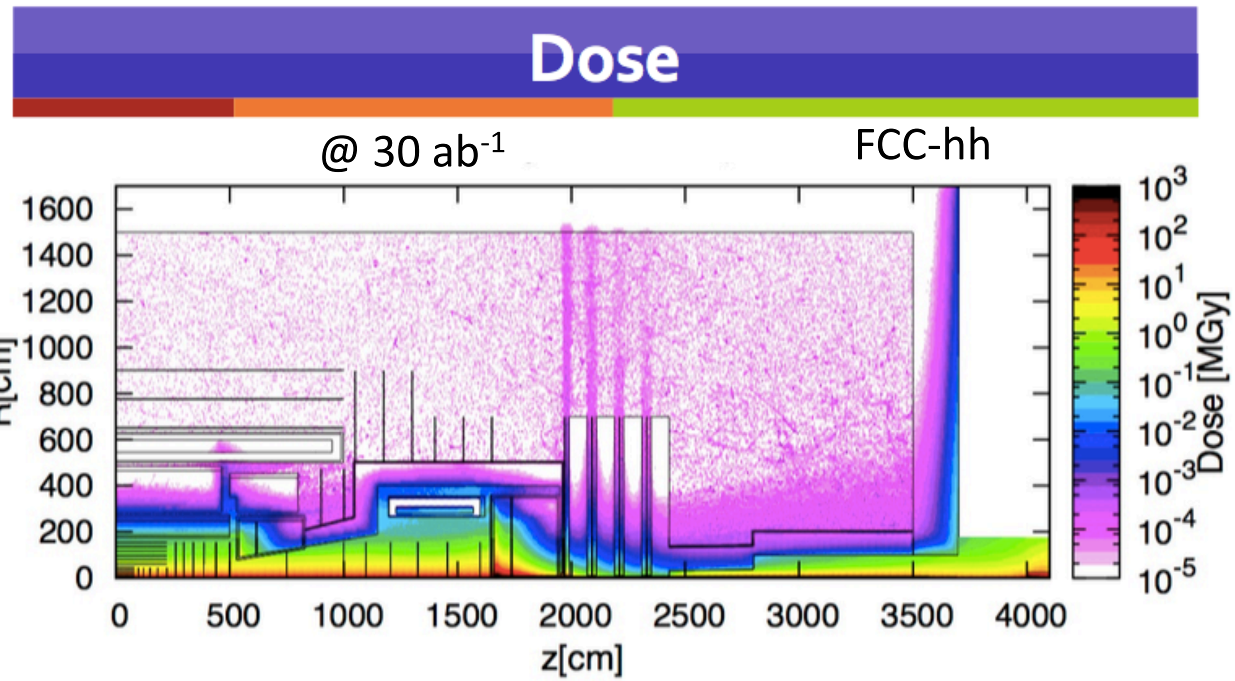
Motivation for Radiation-Hard Scintillator and WLS Fiber Development

Future and upgrade colliders impose unprecedented challenges on the radiation-hardness of the active media of the calorimeters. Scintillators play a central role as the active medium of calorimeters.

What are we looking for?

- ✓ Compact
- ✓ High light yield
- ✓ High resolution
- ✓ Radiation resistant
- ✓ Fast
- ✓ Cost effective scintillators.

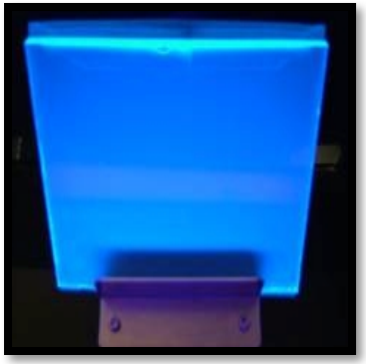


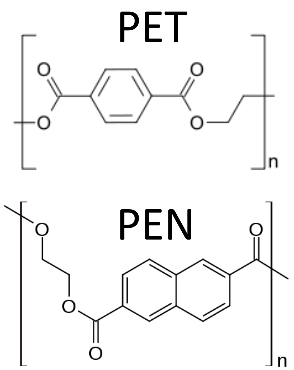
500 Grad

	Dose [MGy]
first layer of the IB (R =2.5 cm)	~400
max in forward calorimeters	5 10³

05/04/16 M.I. Besana, FCC hadron detector meeting 17

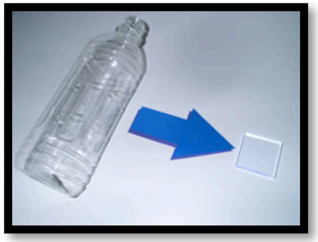
Intrinsically Rad-Hard Scintillators





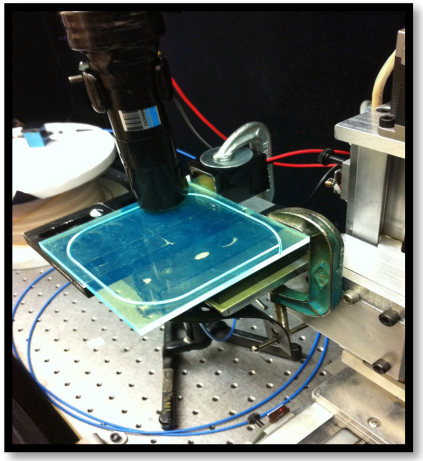
Commercially Available Scintillating Materials:

- Polyethylene Naphthalate (PEN)
- Polyethylene Terephthalate (PET)



PEN:

✓ Intrinsic blue scintillation (425 nm)



PET:

✓ A common type polymer
✓ Plastic bottles and as a substrate in thin film solar cells.
✓ Emission spectrum of PET peaks at 385 nm [Nakamura, 2013]

Intrinsically Rad-Hard Scintillators

HEM/ESR: sub-µm film stack of Poly(Ethylene-2,6-Naphthalate)/PEN, polyester, polyethylene terephthalate (PET): ***intrinsic blue scintillation!***

425 nm; 10,500 photons/MeV; ….

epl A LETTERS JOURNAL EXPLORING THE FRONTIERS OF PHYSICS

July 2011

EPL, 95 (2011) 22001 www.epljournal.org
doi: 10.1209/0295-5075/95/22001

Evidence of deep-blue photon emission at high efficiency by common plastic

H. NAKAMURA[1,2(a)], Y. SHIRAKAWA[2], S. TAKAHASHI[1] and H. SHIMIZU[3]

Table 1: Properties of the three samples used in the present study.

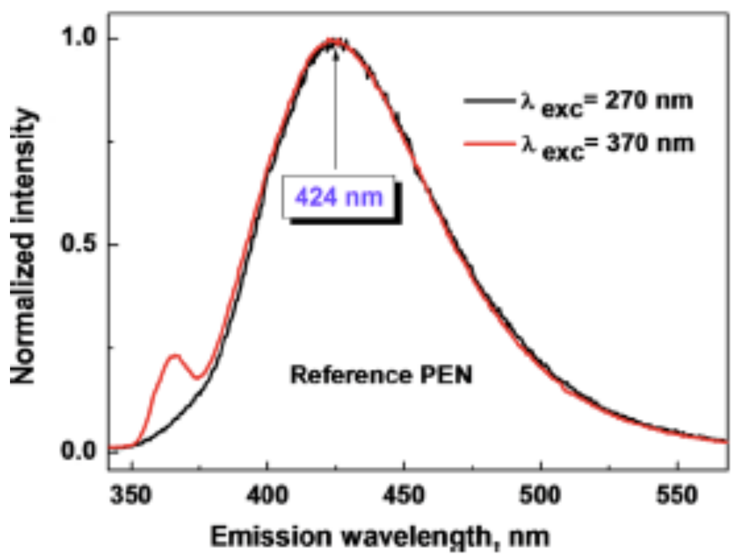
Material	Polyethylene naphthalate	Organic scintillator (ref. [14])	Plastic bottle (ref. [13])
Supplier	Teijin Chemicals	Saint-Gobain	Teijin Chemicals
Base	$(C_{14}H_{10}O_4)_n$	$(C_9H_{10})_n$	$(C_{10}H_8O_4)_n$
Density	$1.33\,g/cm^3$	$1.03\,g/cm^3$	$1.33\,g/cm^3$
Refractive index	1.65	1.58	1.64
Light output	~10500 photon/MeV	10000 photon/MeV	~2200 photon/MeV
Wavelength max. emission	425 nm	425 nm	380 nm

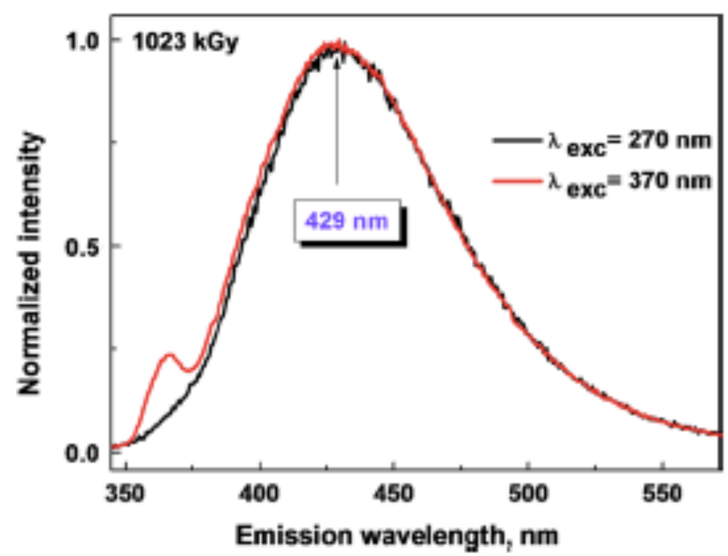
Intrinsically Rad-Hard Scintillators - PEN

100 MRad (1 MGy) Radiation Resistance!

N. Belkahlaa et al., *Space charge, conduction and photoluminescence measurements in gamma irradiated poly (ethylene-2,6-naphthalate)* Rad. Physics & Chem, V101, August 2014

Abstract: *Polyethylene naphthalate (PEN) thin films were subjected to gamma rays at different doses and changes in both the dielectric and photophysical properties were investigated. Samples were irradiated in air at room temperature by means of a 60Co gamma source at a dose rate of ~31 Gy/min. Total doses of 650 kGy(344 h) & 1023 kGy(550 h) were adopted. The high radiation resistance of PEN film is highlighted.*



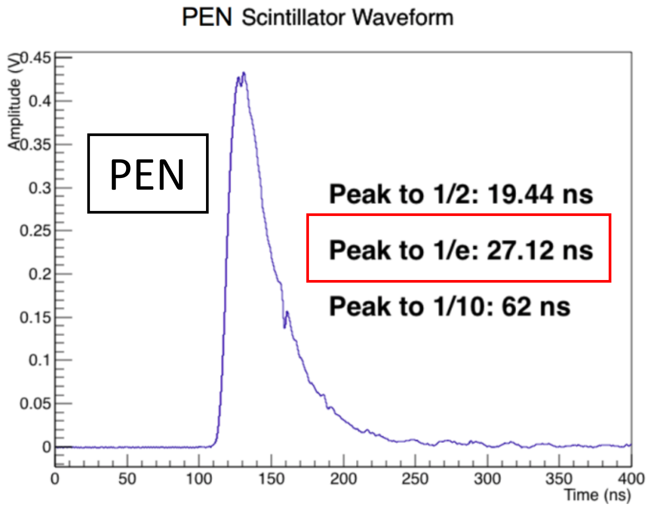


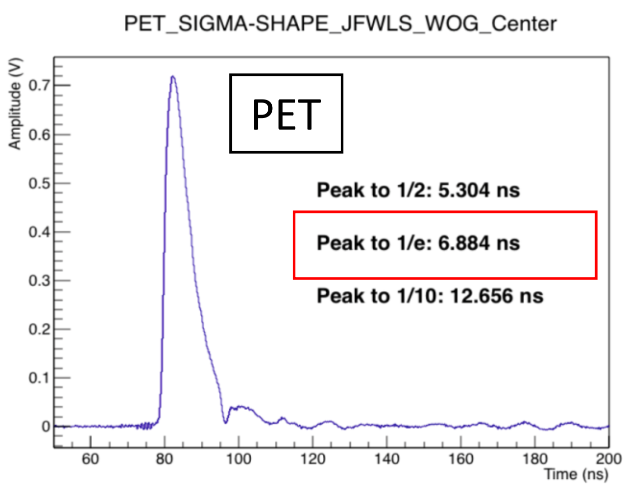
PL intensity at peak maximum (relative units) versus irradiation dose.

Excitation wavelength	Reference-PEN	650 kGy	1023 kGy
$\lambda_e = 270$ nm	1	0.98	0.95
$\lambda_e = 370$ nm	1	0.98	0.96

Laboratory Measurements

Timing



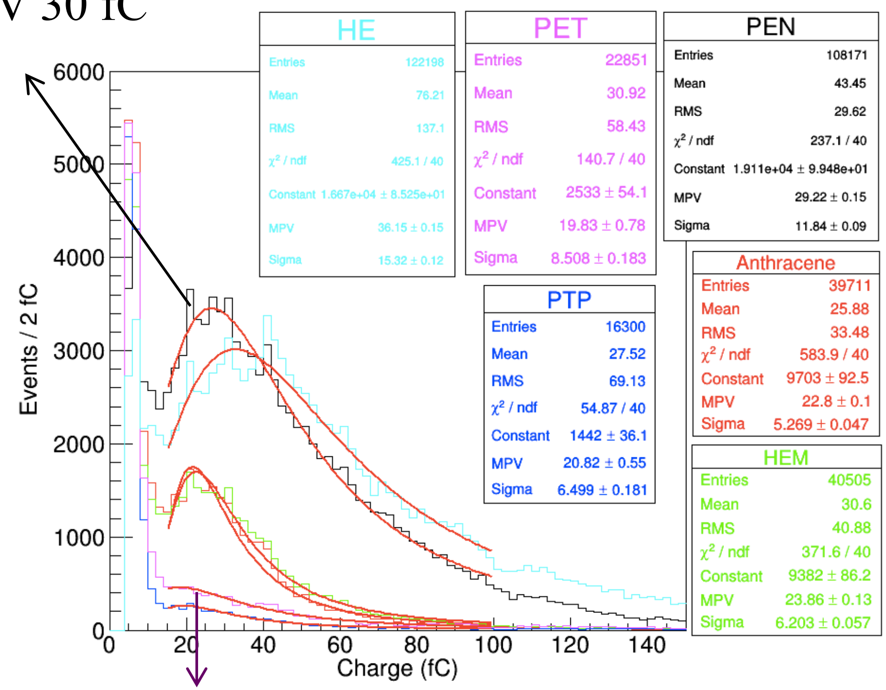


Beam Test Results

Light Yield

150 GeV muons @ CERN

PEN → Light yield MPV 30 fC

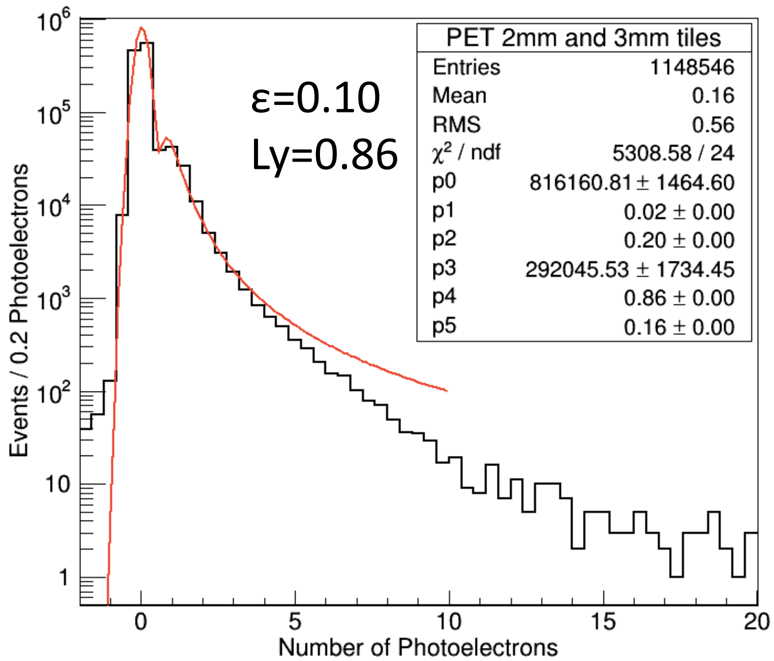


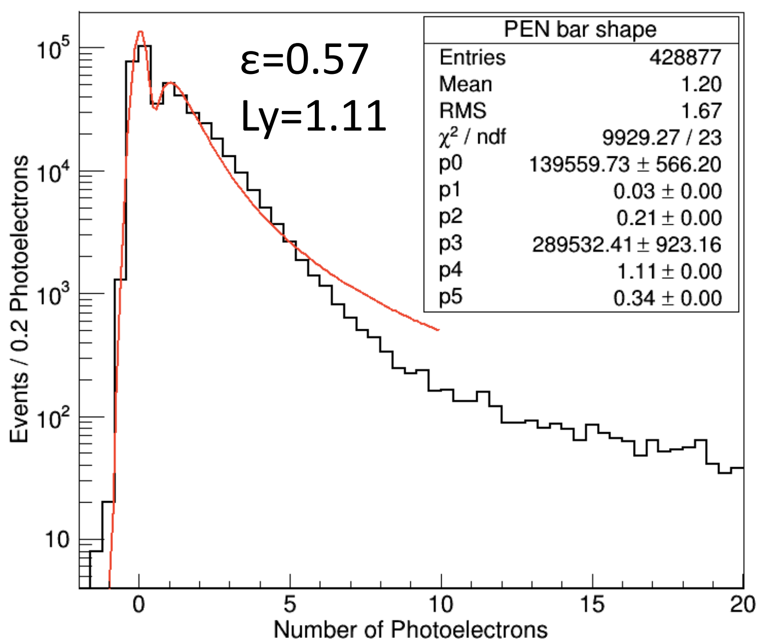
PET → Light yield MPV 20 fC

- PET is faster but emits less light. PEN is radiation resistant up to 10 Mrad and it has a significant light yield but it is too slow.

PEN Performance in Beam Measurements

We tested 2 - 4 mm thick PEN and PET tiles read out with green wavelength shifting fibers with 150 GeV muons.



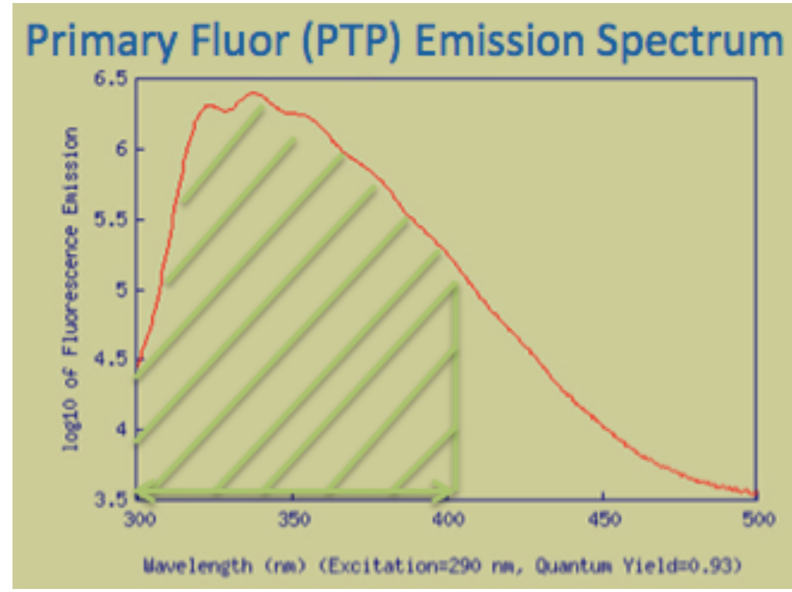


New SiX Scintillators

- The scintillators have a base material, primary fluor, and secondary fluor.

- The main scintillation comes from the primary fluor.

- The secondary fluor, or waveshifter, absorbs the primary's emissions and re-emits to a wavelength that is desirable for optimum efficiency.



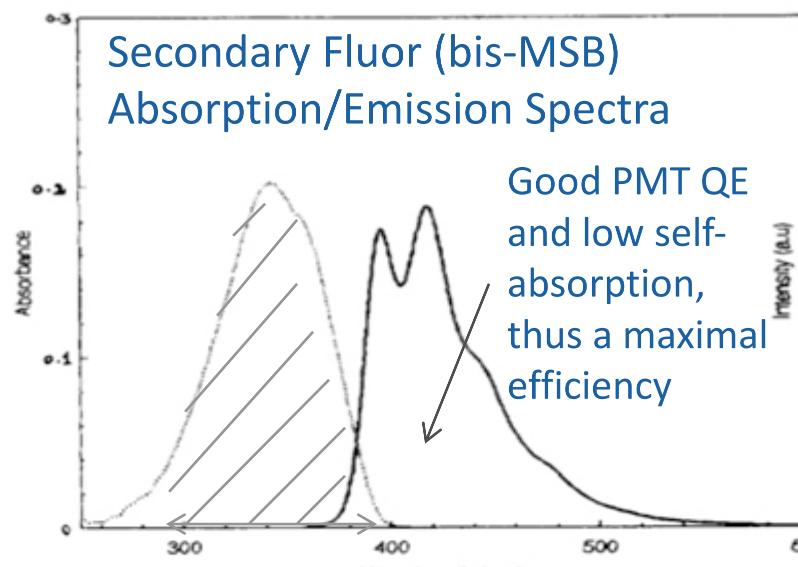
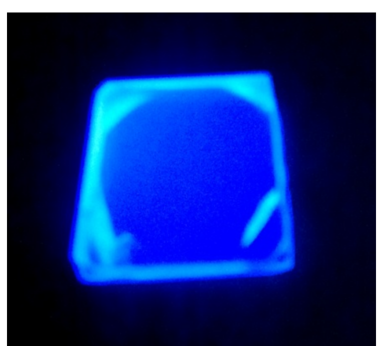
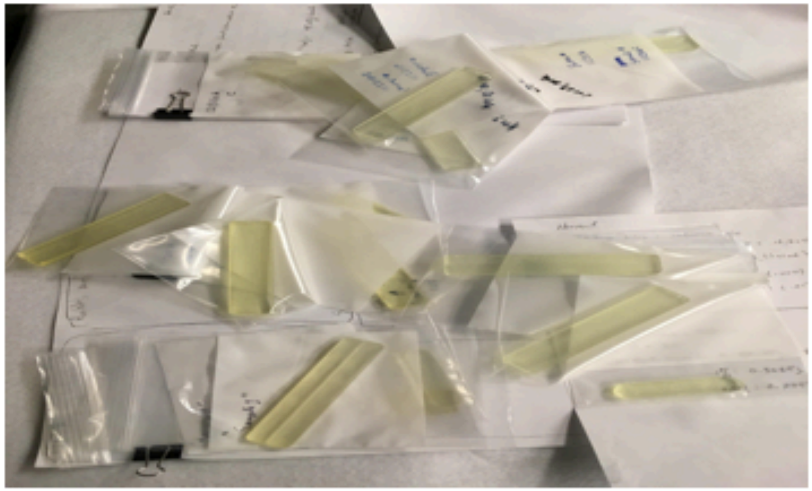


Fig. 1. Absorption (· · ·) and emission (——)

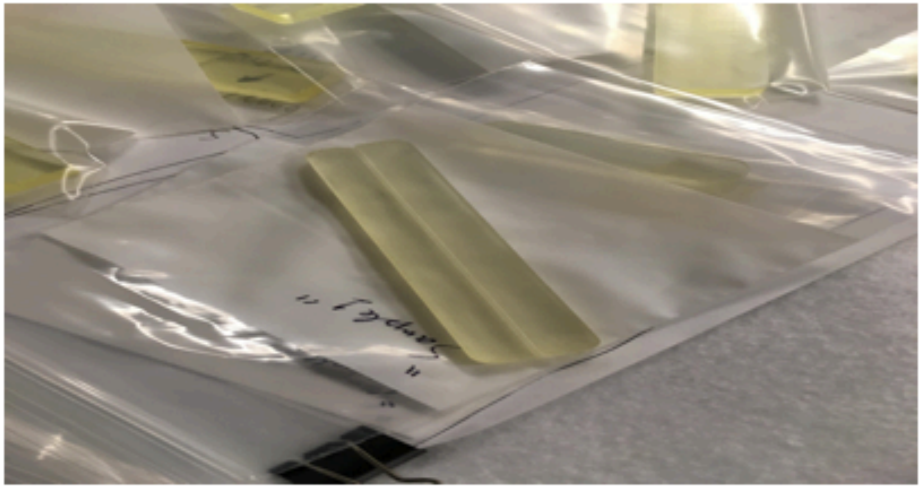


SiX Production

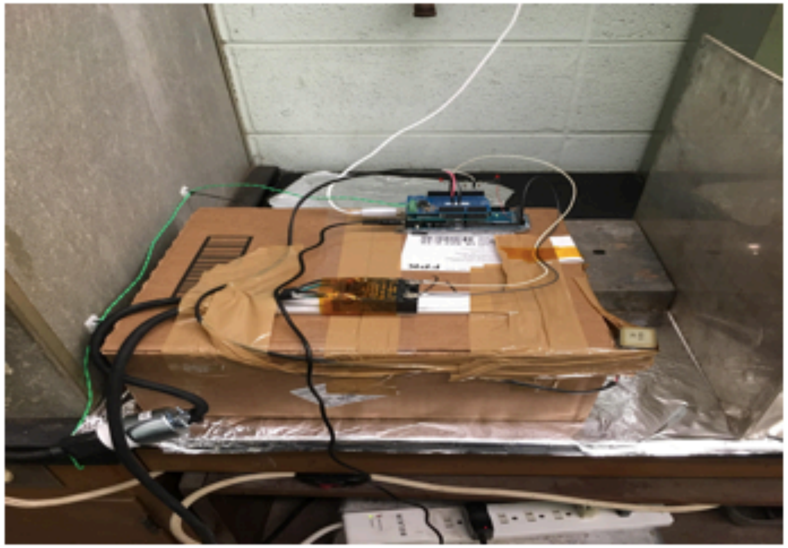
Finger Tiles



Grooved Tiles



Control Circuits



Modified Owen

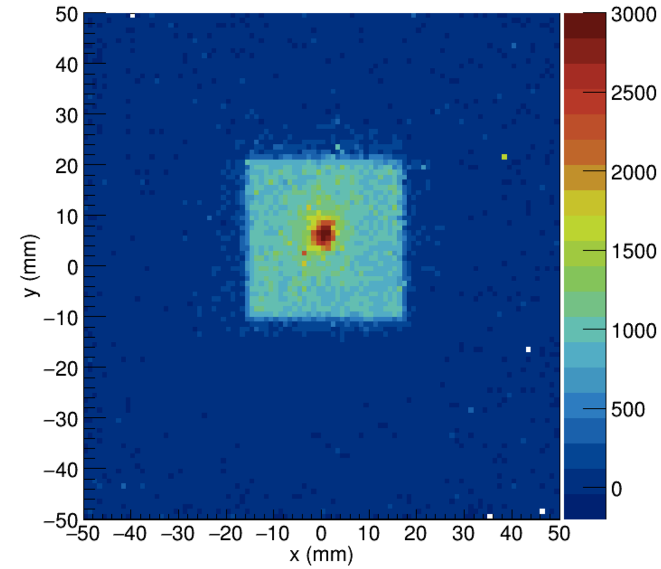
SiX in Test Beam

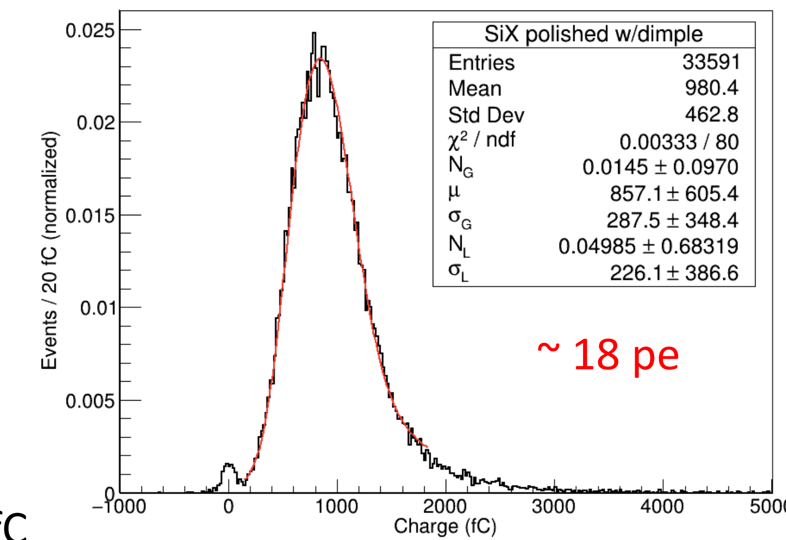
Scintillator-X response to 150 GeV muons

SiPM directly coupled to dimple (Hamamatsu S12572-010)

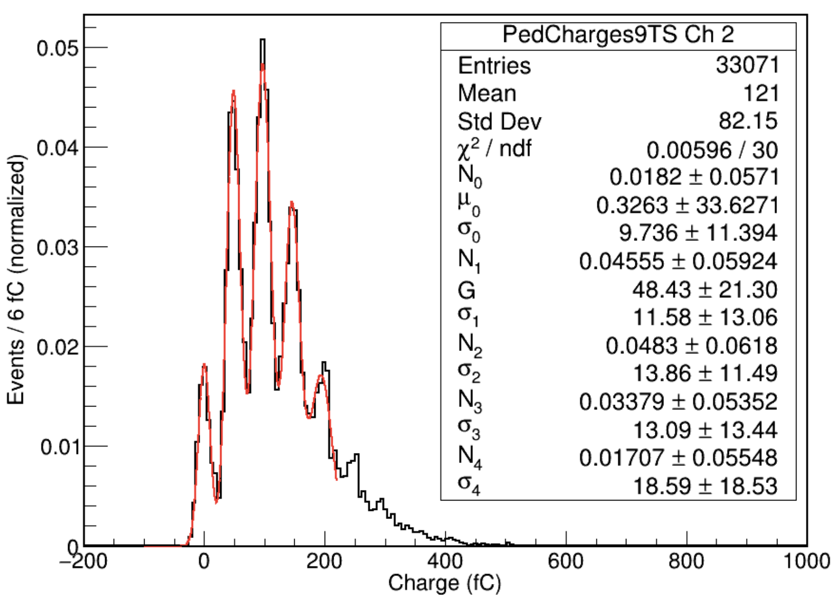
Tile size 3 cm x 3 cm

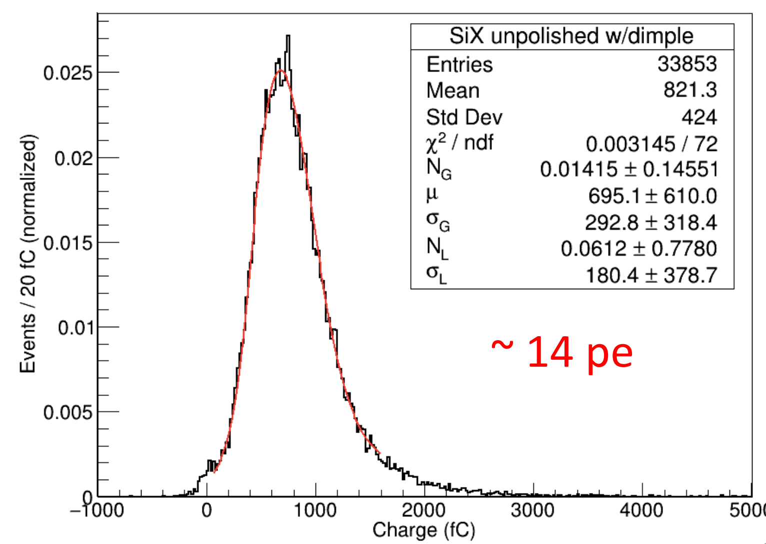
Select the muons passing through the tile and 1 mm away from the SiPM





Gain ~ 50 fC





Fit to a Gaussian + Landau

Radiation Tests

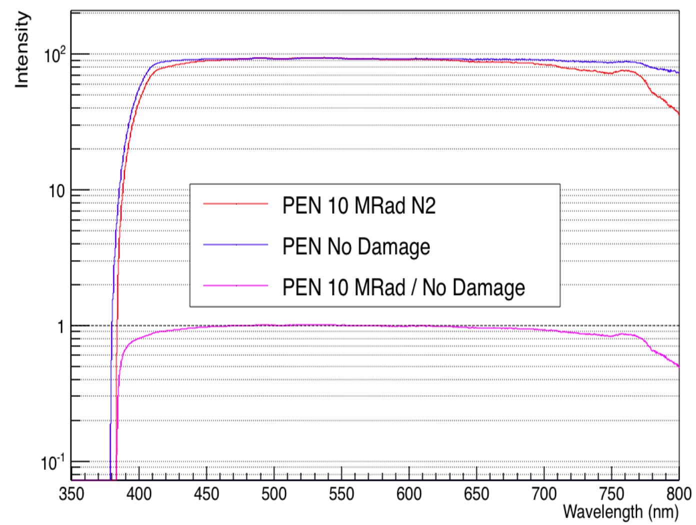
PEN Radiation Damage Studies (MSU)

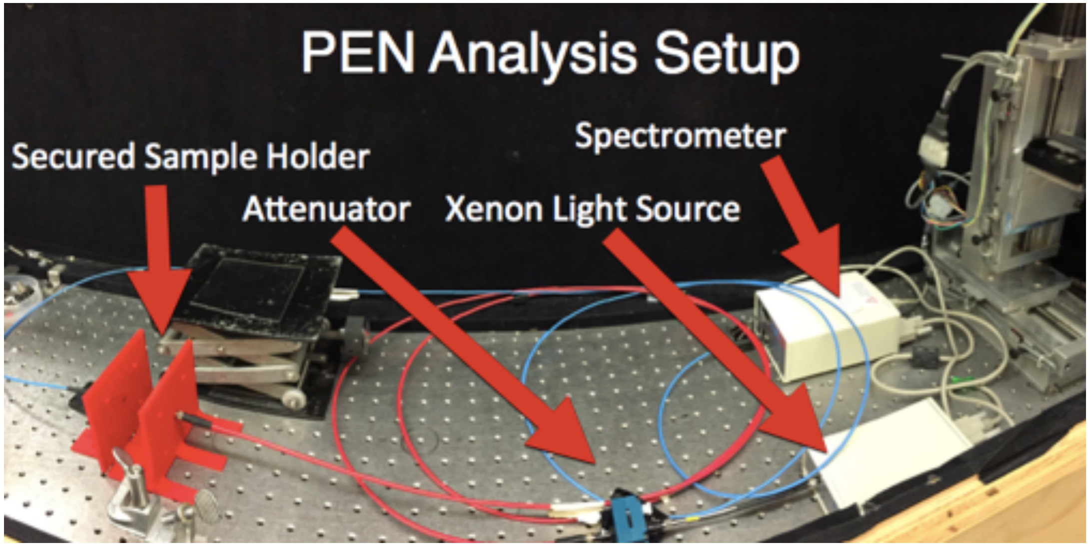
Facilities:
- National Superconducting Cyclotron Laboratory
- Used ^{60}Co, 1.33 MeV Gammas

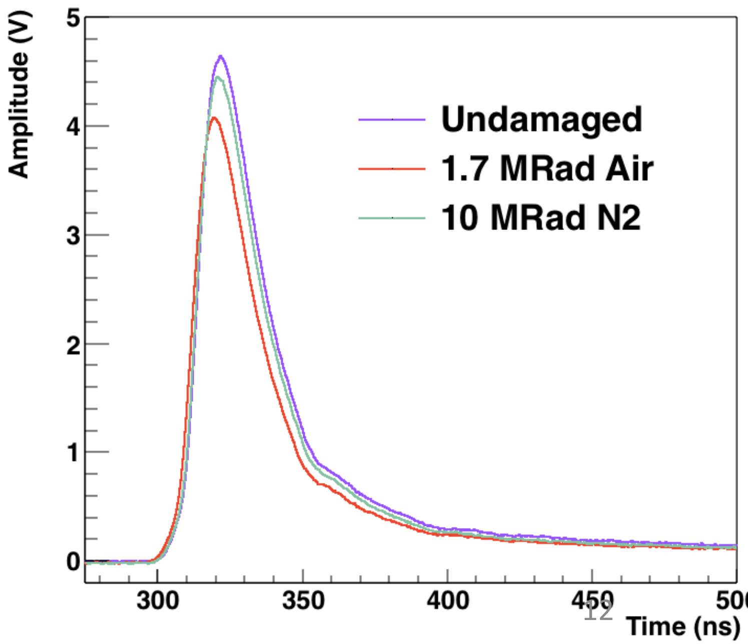
Two Samples:
- 1.7 MRad in Air
- 10 MRad in N_2

	Undamaged	10 MRad N2	1.7 MRad Air
Integral (300-450 ns)	20208	19012	17311
Relative % (damaged / Undamaged)	100%	94.1%	85.7%

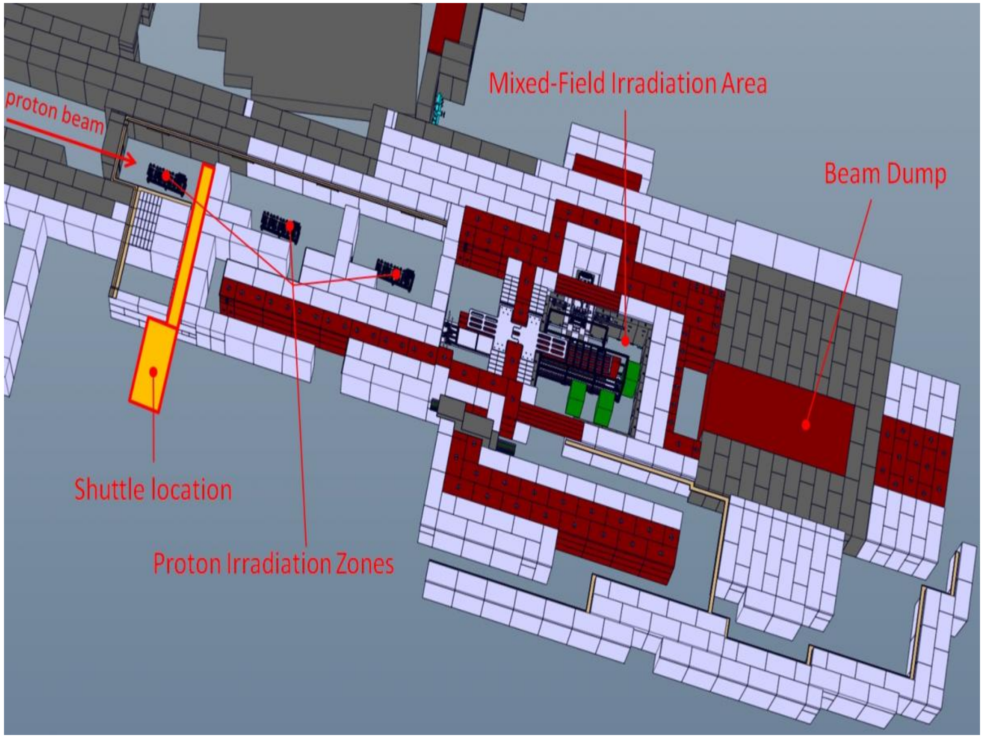
Transmission







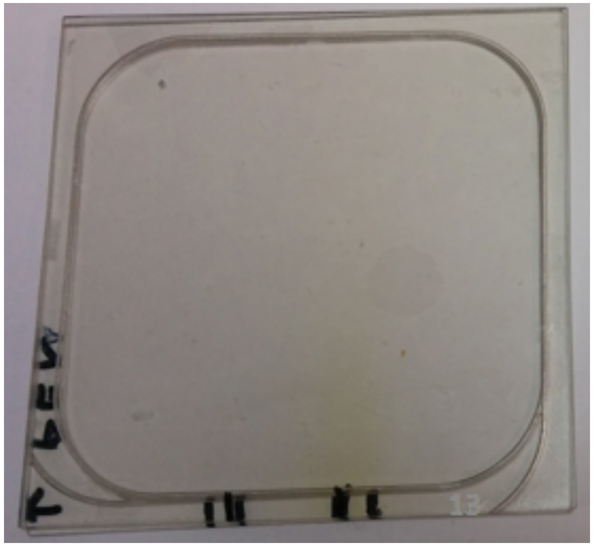
IRRAD facility at CERN PS



- 10 x 10 cm PEN tile was placed in the PS accelerator IRRAD area .
- First batch – perpendicular to the beam direction. Three different positions were selected to expose to protons
- Second batch – tilted ~30 degrees to beam direction – three different position were exposed to the proton beam
- Samples were irradiated during one week.

24 GeV protons ,
beam spot (FWHM) 15 x 15 mm^2
proton flux - ~$6x10^9$ p cm^{-2} s^{-1}

➔ 75% loss at 40 Mrad.



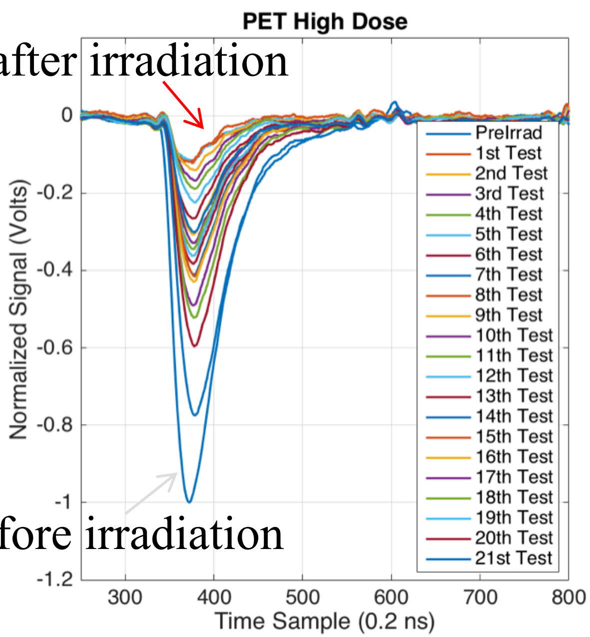
Radiation Damage Studies (Iowa)

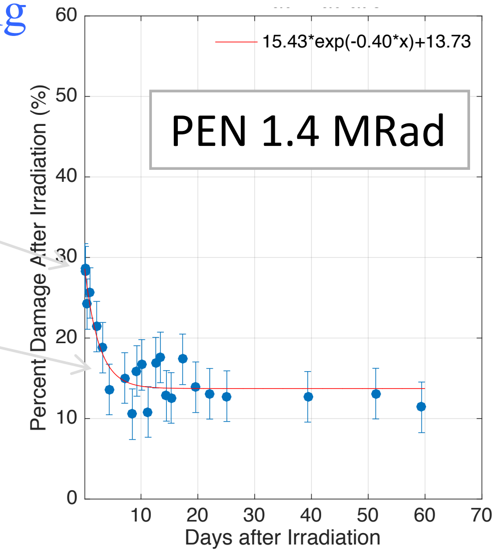
We irradiated scintillator samples with using ^{137}Cs gamma source at Iowa Rad Core

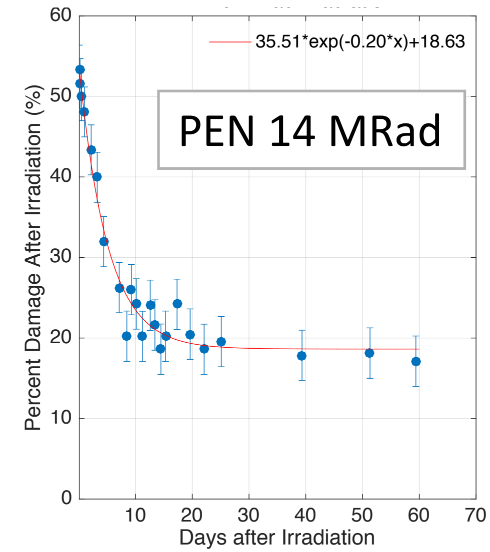
1.4 Mrad and 14 Mrad

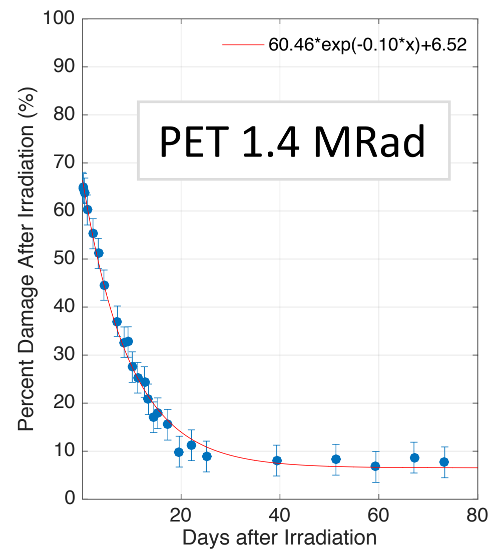
Initial damage

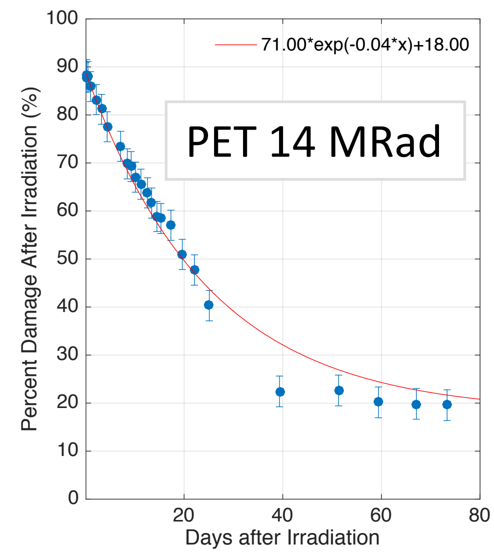
Permanent damage - plateau









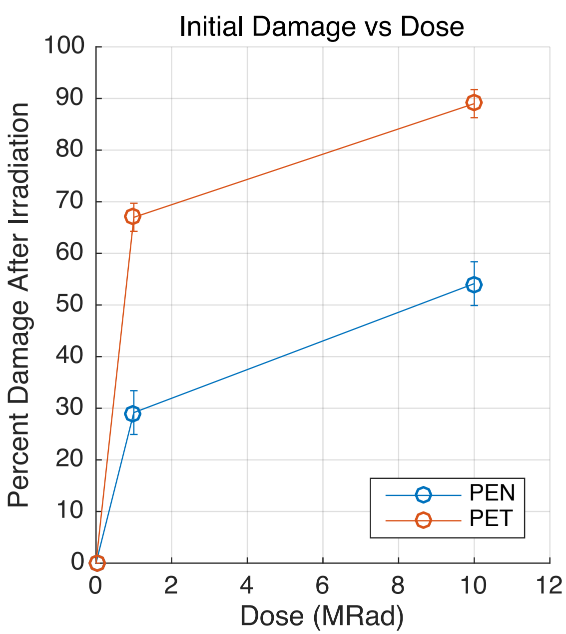


- Damage was calculated in terms of light yield

JINST 11, P08023, 2016

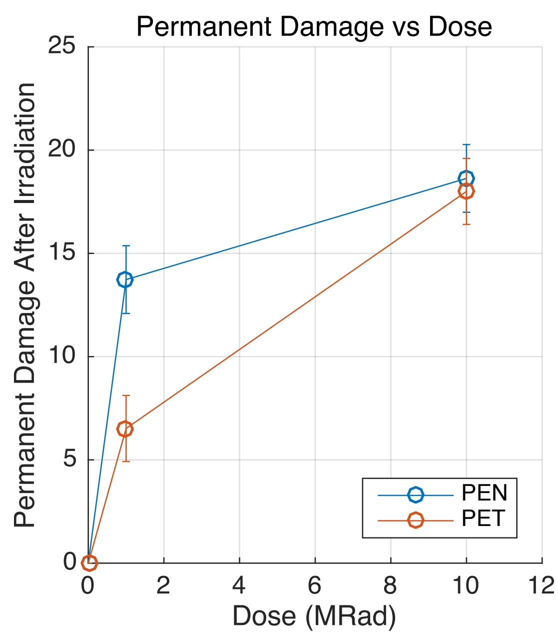
Summary of irradiation results

Initial damage



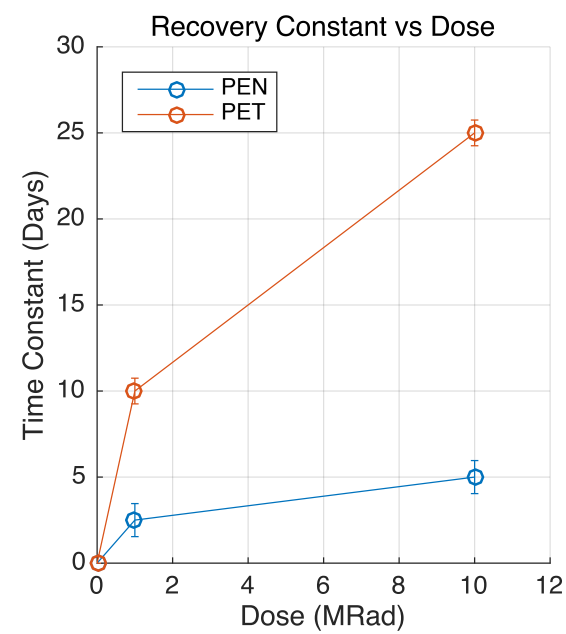
- PET was damaged more than PEN initially

Permanent damage



- Permanent damage was same at 14 MRad

Time for Recovery



- PEN was recovered in 5 days only and PET in 25 days – so slow

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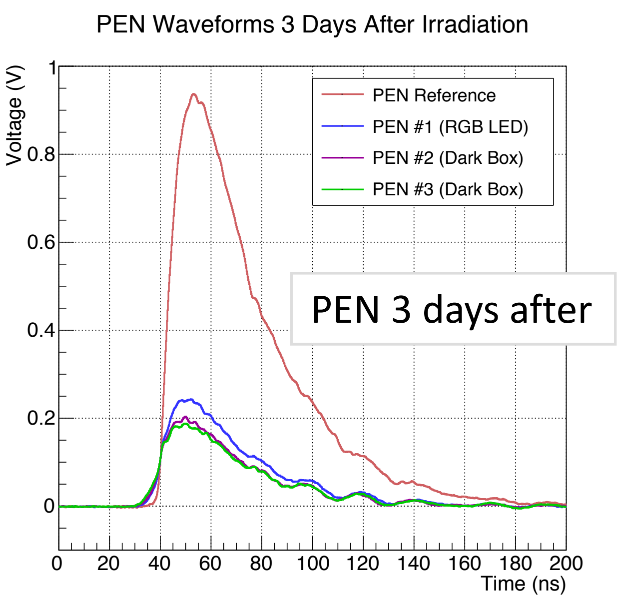
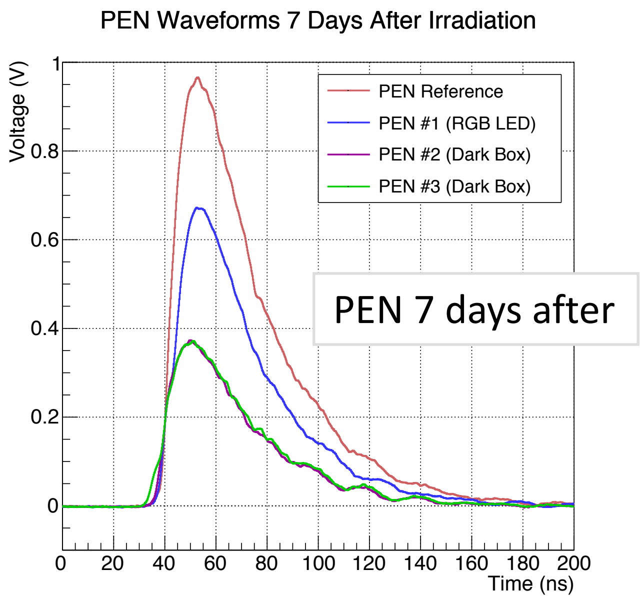
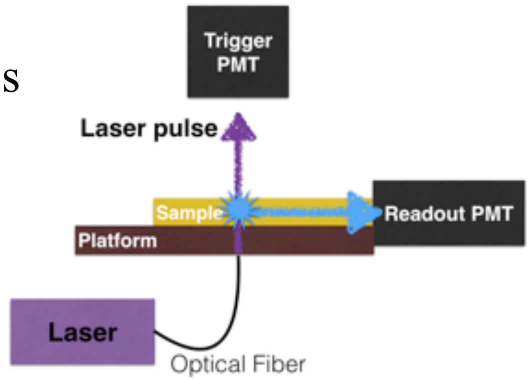
LED Stimulated Recovery

Can we stimulate the recovery of scintillators damaged from radiation?

✓ By using an array of tri-color red, blue, green (RGB) LEDs





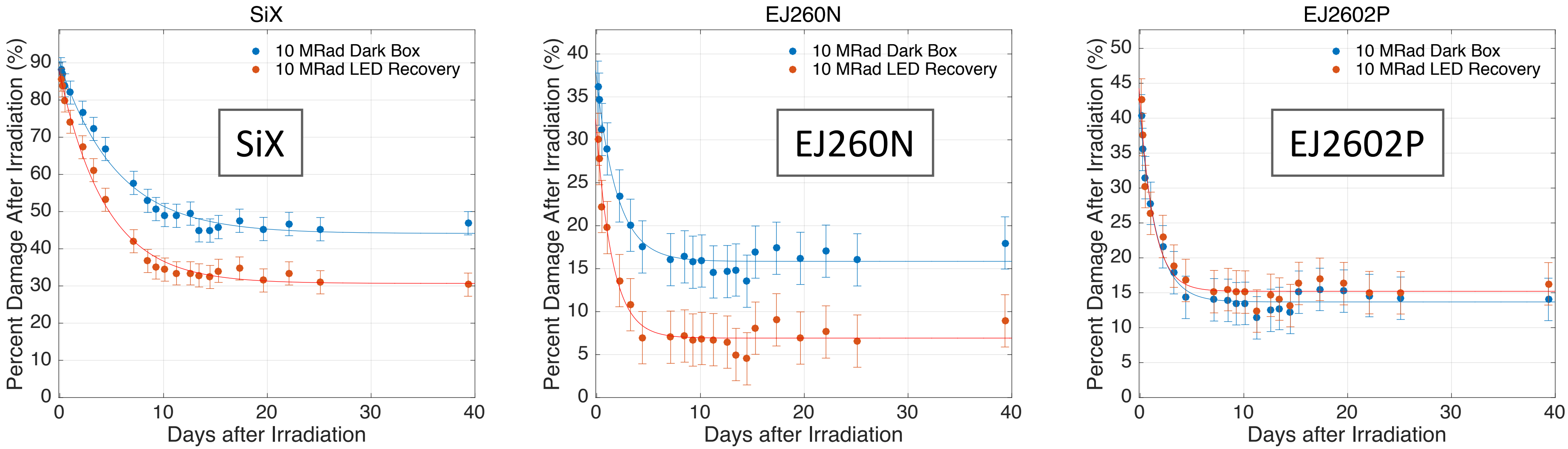


Different Materials:

- Eljen brand EJ-260 (N) and overdoped version EJ2P.
- Lab produced plastic scintillator (SiX)

NIM B395, 13, 2017

LED Stimulated Recovery



Blue emission | Green emission | Green emission

Tile	'a', Total Recovery	'c', Permanent Damage
SiX RGB	56.3 ± 2.4%	30.7 ± 1.6%
SiX dark box	45.7 ± 2.5%	44.1 ± 1.9%
EJN RGB	24.0 ± 2.2%	6.92 ± 0.7%
EJN dark box	21.1 ± 1.8%	15.9 ± 0.6%
EJ2P RGB	26.9 ± 3.1%	15.2 ± 0.9%
EJ2P dark box	26.5 ± 2.2%	13.7 ± 0.7%

- SiX showed significant effect, the sample on RGB LED recovering 10% more and faster (4.5 vs 5.5 days)
- Neither EJN and EJ2P showed significant effect.
- 'Blue' scintillators respond to color spectrum but 'green' scintillators are affected very little.

Very useful to implement on the on-detector electronics!

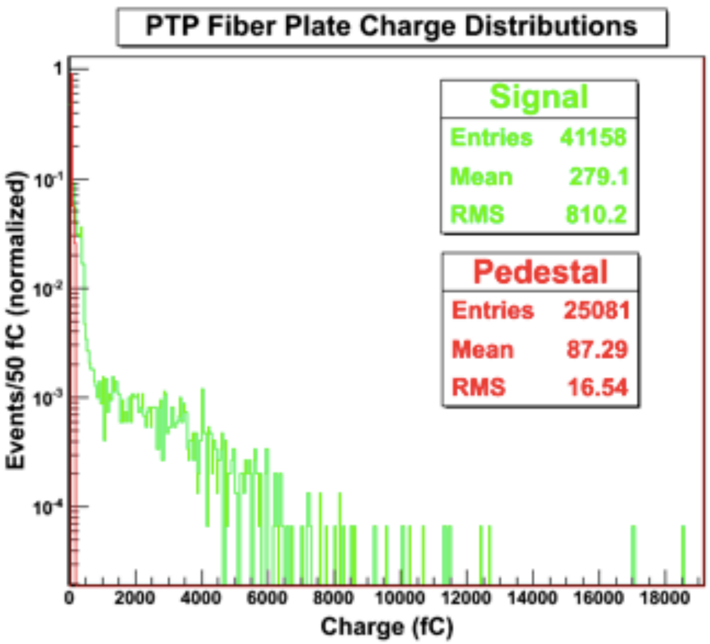
NIM B395, 13, 2017

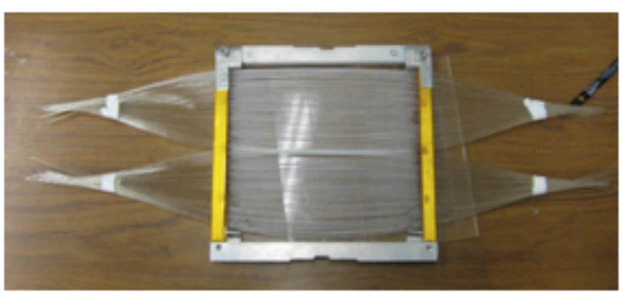
Wavelength Shifting Fibers

Radiation-Hard WLS Fibers

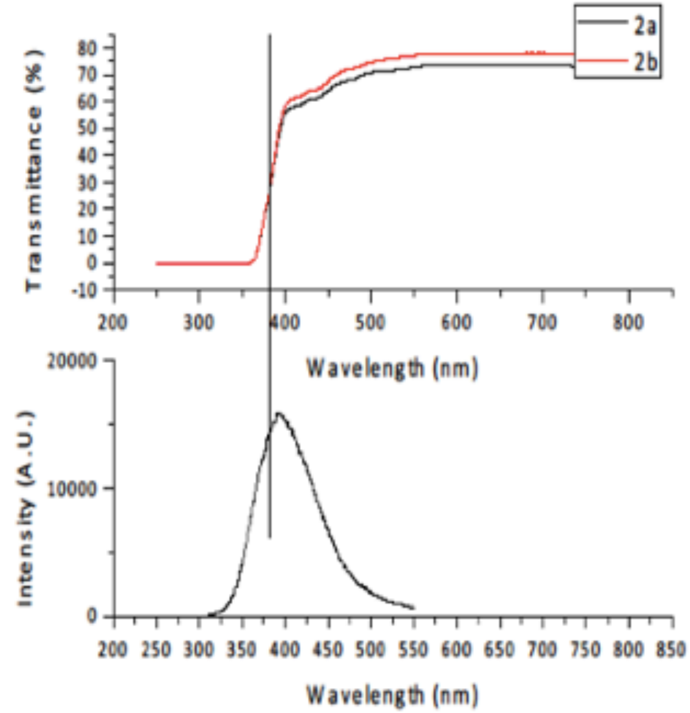
[1] Quartz rods with surface coating
[2] Capillaries
[3] Doped quartz rods

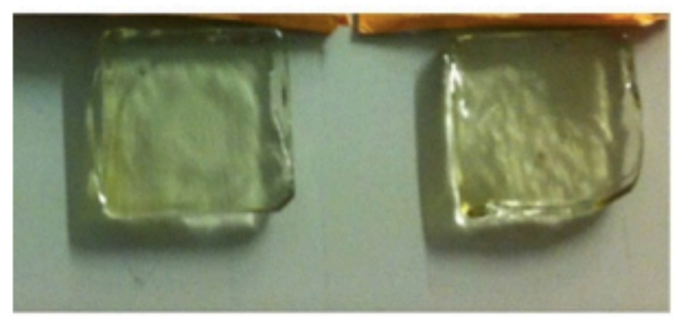
[1] Quartz Fibers with pTp Coating





[3] Cerium-doped Scintillating Glasses

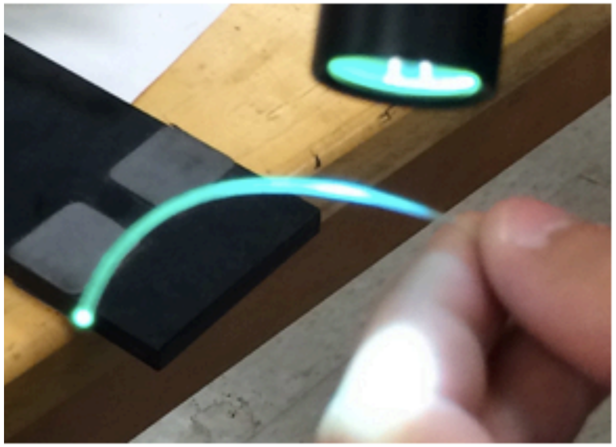


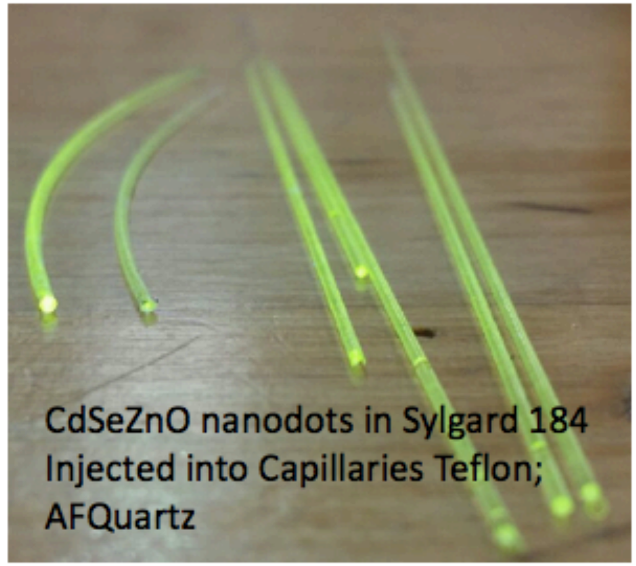


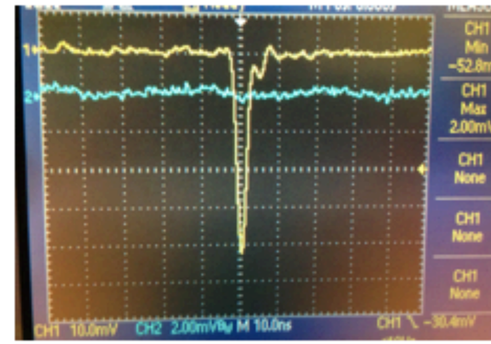
Radiation-Hard WLS Fibers

1. Quartz rods with surface coating
2. Capillaries
3. Doped quartz rods

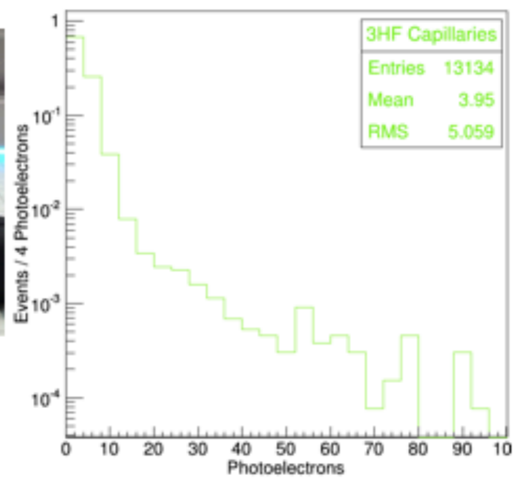
3HF+Meltmount injected TeflonAF 800µm ID







3HF Core Quartz WLS Capillaries



Expected Anthracene Fiber Pulse:

~200 KeV/mm x 0.25mm x 40 photons/KeV x 2% transmission x 20% QE ~ 8 p.e.

Typical Observed Pulse:

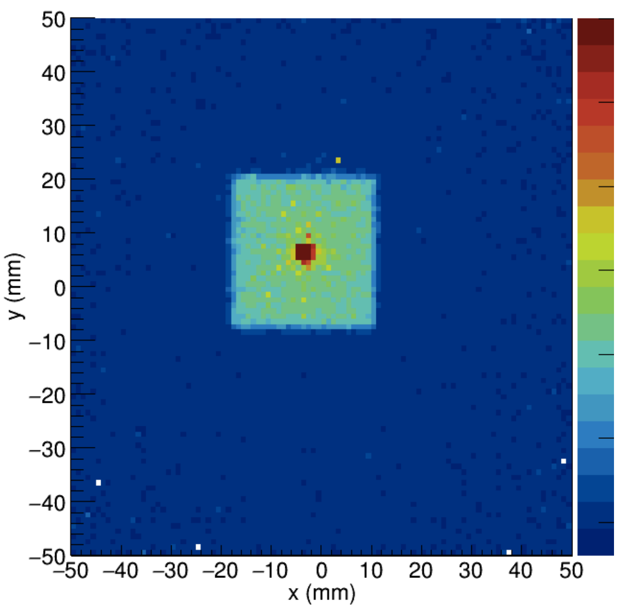
~ 8-9 p.e.

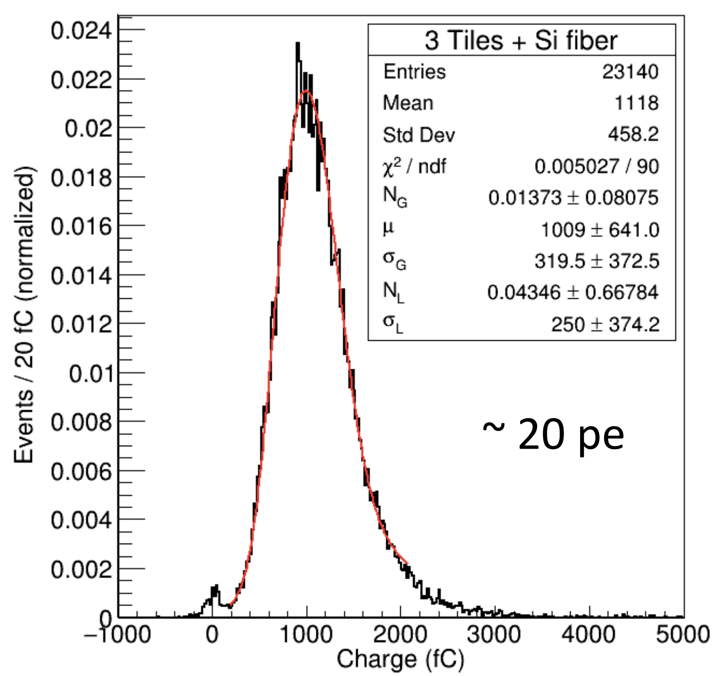
WLS Capillary Fiber with RadHard Components - Response to 150 GeV muons

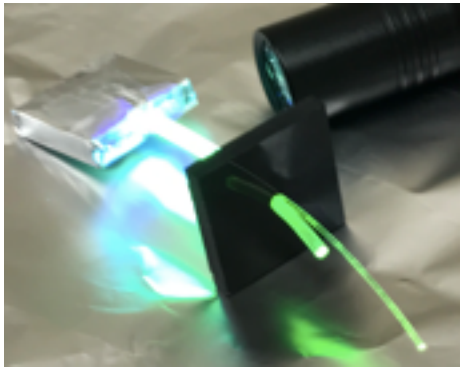
Three 5mm thick blue scintillator tiles (2.5 cm x 2.5 cm) with a silicone-based WLS fiber going through the center, coupled to a SiPM.

The WLS fiber is a Pt-cured silicone capillary (2.3 mm OD, 1 mm ID), certified for gamma sterilization, with a silcone gel conveying 3HF (3HF tested to 100 Mrad at FNAL).

Histogram: Wire Chamber selected muons passing through the tile, 1 mm away from the Fiber and SiPM







Capillary WLS fibers:
Silcone gel core doped w/3HF
Larger: Silicone Capillary
Smaller: Teflon AF capillary

Conclusions

- The options of intrinsically radiation-hard scintillators are being expanded with the addition of Scintillator-X. Different variants of Scintillator-X should be probed.

- Radiation-hard wavelength shifting fibers need to be studied in further detail. Realistically sized samples produce promising results. More samples with complementing scintillators should be prepared.