NEW RADIATION-HARD SCINTILLATORS FOR FCC DETECTORS

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FCC WEEK 2017
MAY 29 – JUNE 2, 2017
BERLIN, GERMANY

OUTLINE

1. Introduction
2. Radiation Resistant Scintillators
3. Beam Tests
4. Irradiation Tests and LED Stimulated Recovery
5. Summary & Conclusions

Motivation for Particle Detector Development

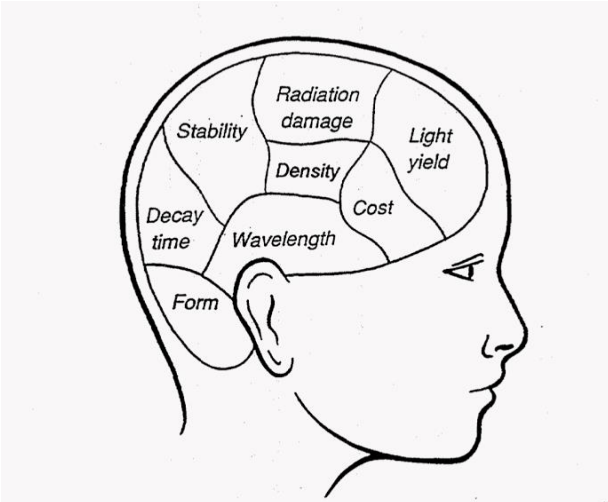


Figure 2. Properties of scintillators to be considered when selecting materials.

What are we looking for?

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

Our goal is:

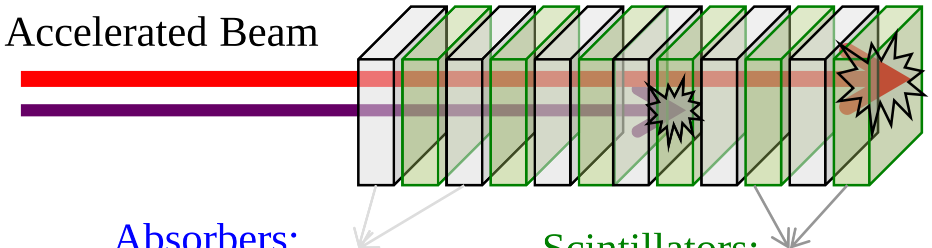
- to provide the best solution for the CMS Calorimeter Phase II Upgrade and future collider experiments.
- to find/improve the high-performance, radiation-hard: active media and readout components

For any particle experiments in general

Calorimeter Design

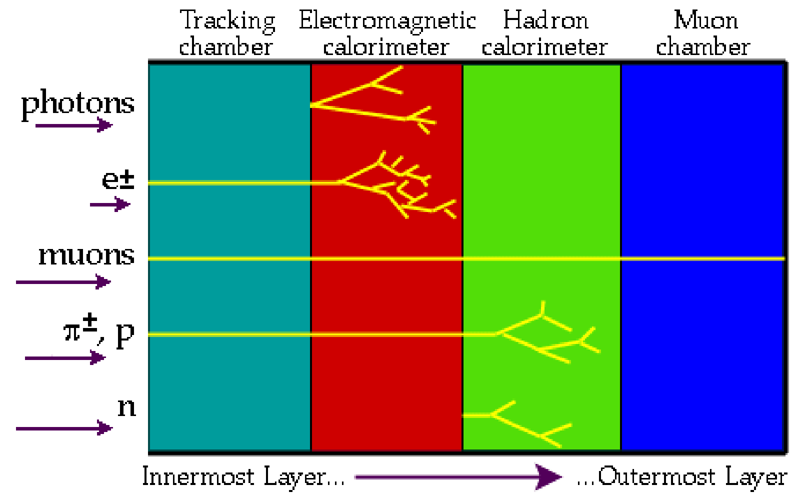
Calorimeters;

- stop particles to measure the energy of them ($p^{+/-}$, p^{o})
- are too large to absorb as much particle energy as possible

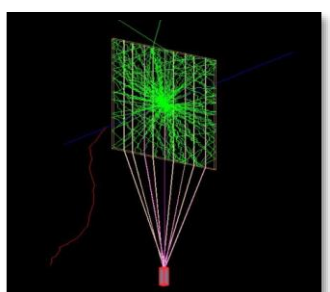


Absorbers:
lead, tungsten, etc.
(slow down particles)

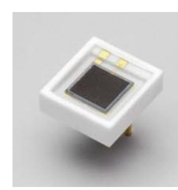
Scintillators:
plastic, quartz, etc.
(produce photons called scintillation)

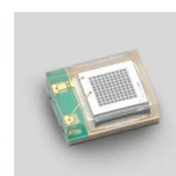


- different geometries:



- different photodetectors:





SiPM

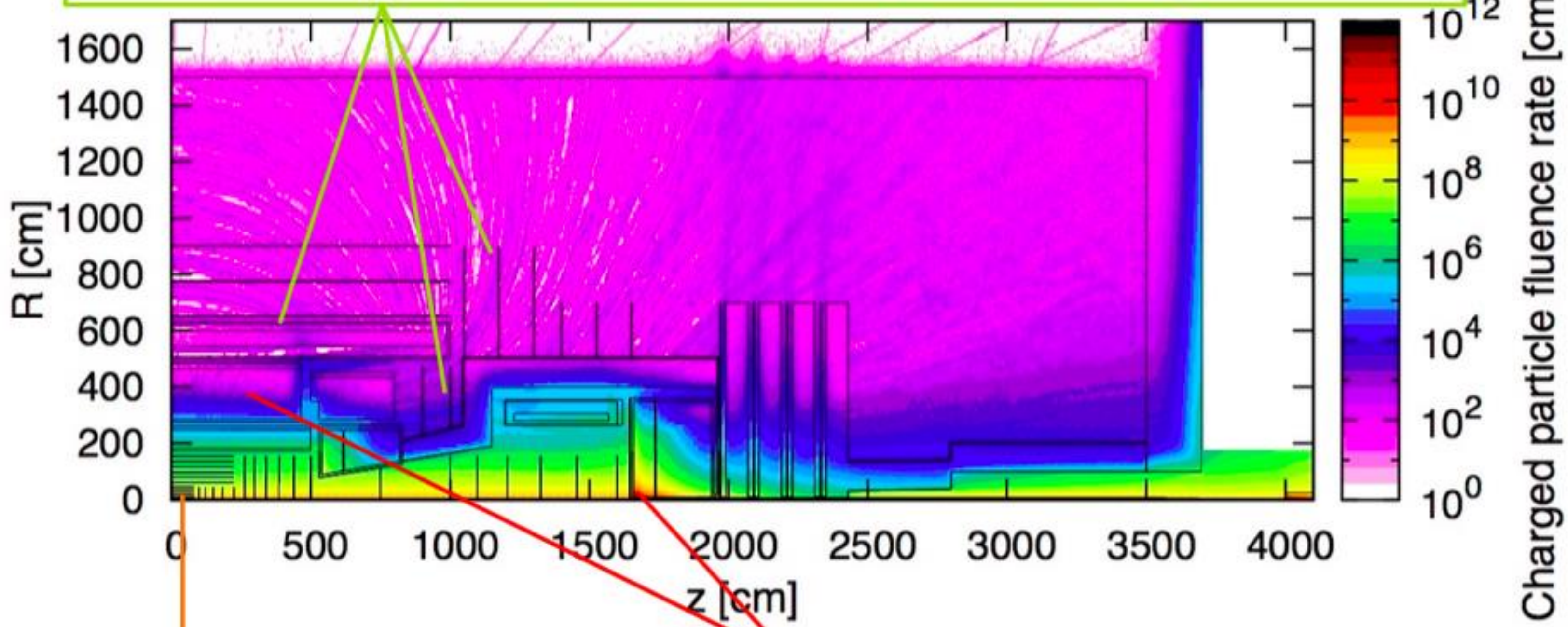
PMT

Charged Particle Fluence in FCC

All Charged Particles Fluence Rate

Fluence rates in the muon chambers:

- barrel: ~300 $cm^{-2}s^{-1}$
- end-cap chambers for z > 10 m: ~500 $cm^{-2}s^{-1}$, but for the two chambers at z < 10 m: 10^4 $cm^{-2}s^{-1}$
- max previous layout: < 100 $cm^{-2}s^{-1}$, but with an hermetic detector



Fluence rates in the tracker:

- first IB layer (2.5 cm): ~ 1.2 10^{10} $cm^{-2}s^{-1}$
- external part: 3 10^{6} $cm^{-2}s^{-1}$

Fluence rates in the calorimeters:

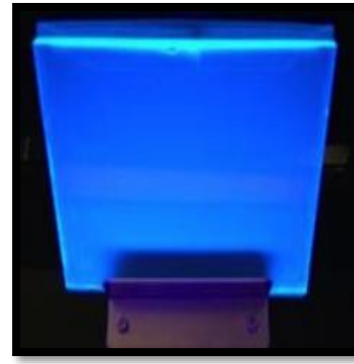
- minimum in the barrel HAD-calo: ~ 100 $cm^{-2}s^{-1}$
- max in the forward calorimeters: 10^{11} $cm^{-2}s^{-1}$

Radiation Resistance Key

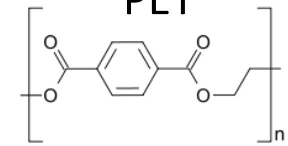
Collision energy and luminosity (# of particles/sec.) are increasing so total radiation level is increasing.

Scintillating Materials: we look at different materials

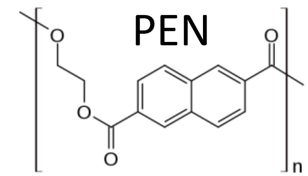
- Polyethylene Naphthalate (PEN)
- Polyethylene Terephthalate (PET)



PET

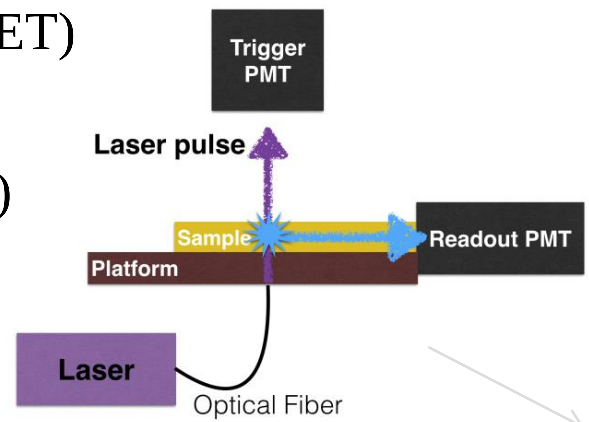


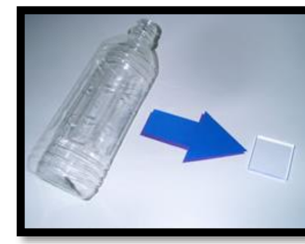
PEN

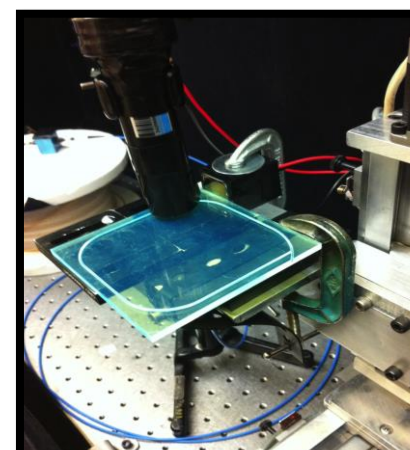


PEN:

- ✓ Intrinsic blue scintillation (425 nm)
- ✓ Short decay time







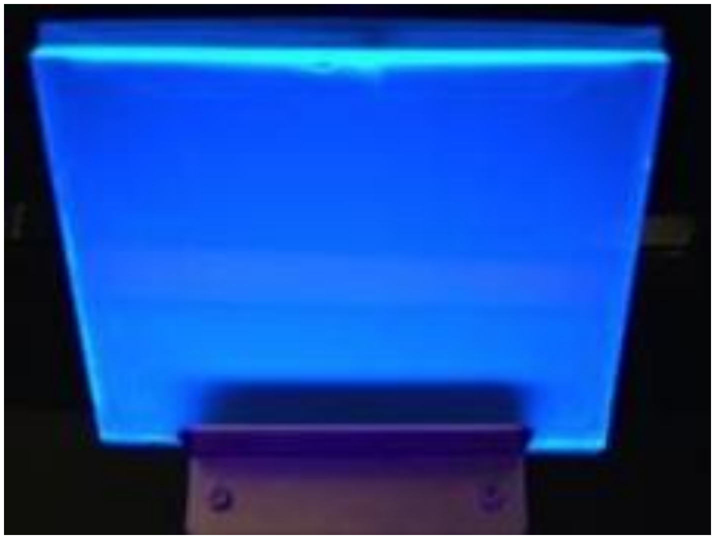
PET:

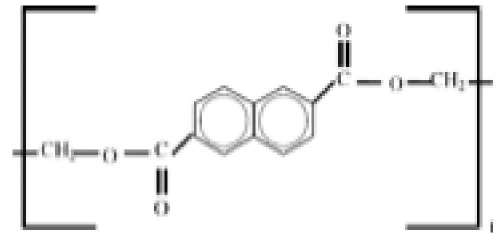
- ✓ A common type polymer
- ✓ Plastic bottles and as a substrate in thin film solar cells.
- ✓ Emission spectrum of PET peaks at 385 nm [Nakamura, 2013]

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; short decay time….





Pure PEN Tile used in Fukishima Survey Meter

Fig. 1 The inside of a survey meter. From the left, a) light-shielding curtain of thin aluminum foil, b) PEN sheet, c) acrylic sheet support, d) reflection section of white celluloid, and e) photomultiplier tube.

Intrinsically Rad-Hard Scintillators - PEN

Poly(Ethylene-2,6-Naphthalate)/PEN: ***intrinsic blue scintillation!***

425 nm; 10,500 photons/MeV; short decay time….

epl A LETTERS JOURNAL EXPLORING THE FRONTIERS OF PHYSICS

July 2011

EPL, 95 (2011) 22001
doi: 10.1209/0295-5075/95/22001

www.epljournal.org

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

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

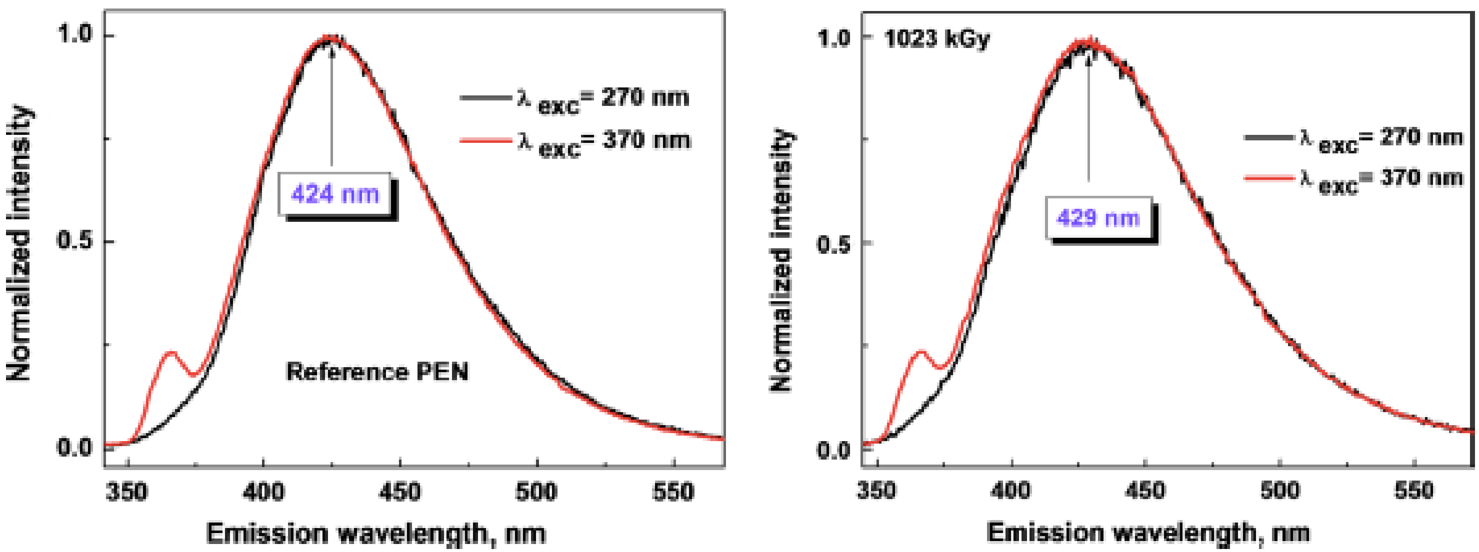
Material	Polyethylene naphthalate	Organic scintillator (ref. [14])	Plastic bottle (ref. [13])
Supplier	Teijin Chemicals	Saint-Gobain	Teijin Chemicals
Base	$(C_{14}H_{10}O_4)_n$	$(C_9H_{10})_n$	$(C_{10}H_8O_4)_n$
Density	$1.33\,g/cm^3$	$1.03\,g/cm^3$	$1.33\,g/cm^3$
Refractive index	1.65	1.58	1.64
Light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

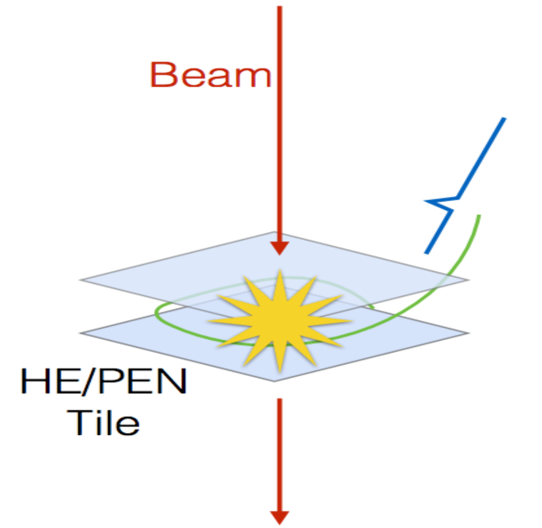
Abstract: *Polyethylene naphthalate (PEN) thin films were subjected to gamma rays at different doses and changes in both the dielectric and photophysical properties were investigated. Samples were irradiated in air at room temperature by means of a 60Co gamma source at a dose rate of ~31 Gy/min. Total 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

Beam Tests



Where?

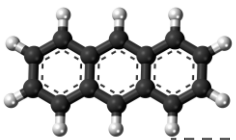
- CERN Test Beam Area
- Fermilab Test Beam Facility

What beam?

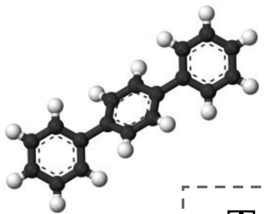
- Shower particles: electrons, pions, etc.
- Minimum Ionizing particles: muons, protons, etc.

What materials?

- Quartz plates coated with various organic materials
  - p-Terphenyl (pTp),
  - Gallium-doped Zinc Oxide (ZnO:Ga)
  - Anthracene (An)
- PEN, PET and HEM



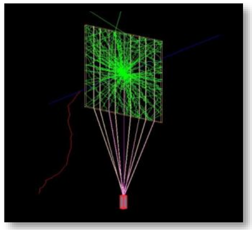
An

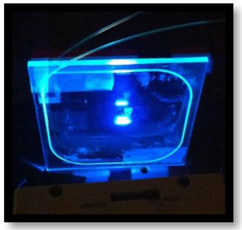


pTp

What geometry and readout?

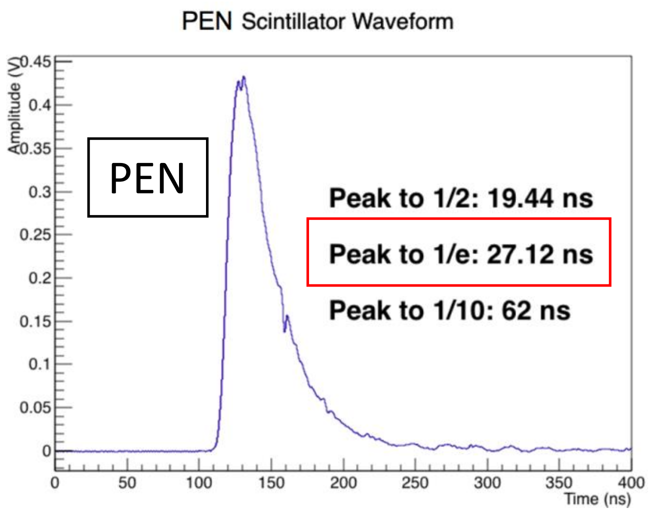
- Sigma & Bar shape
- SiPM, PMT

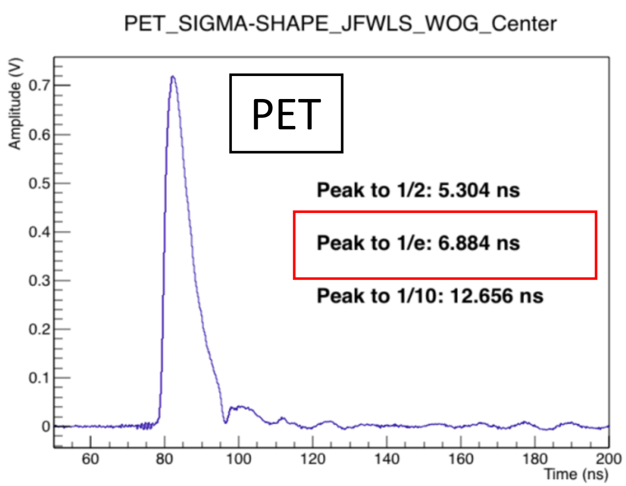




Beam Test Results

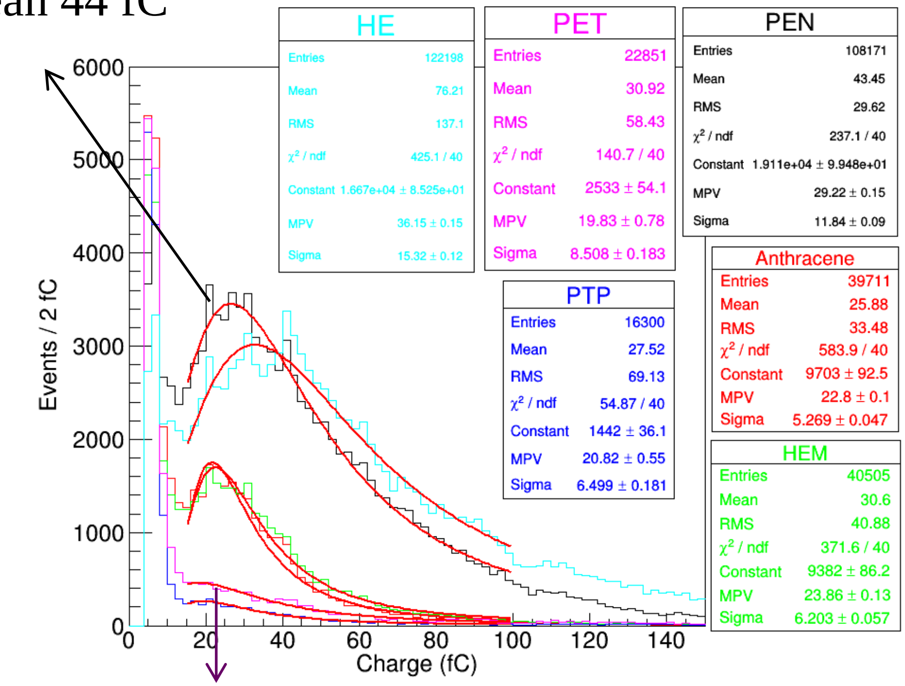
Timing





Light Yield

PEN → Light yield mean 44 fC

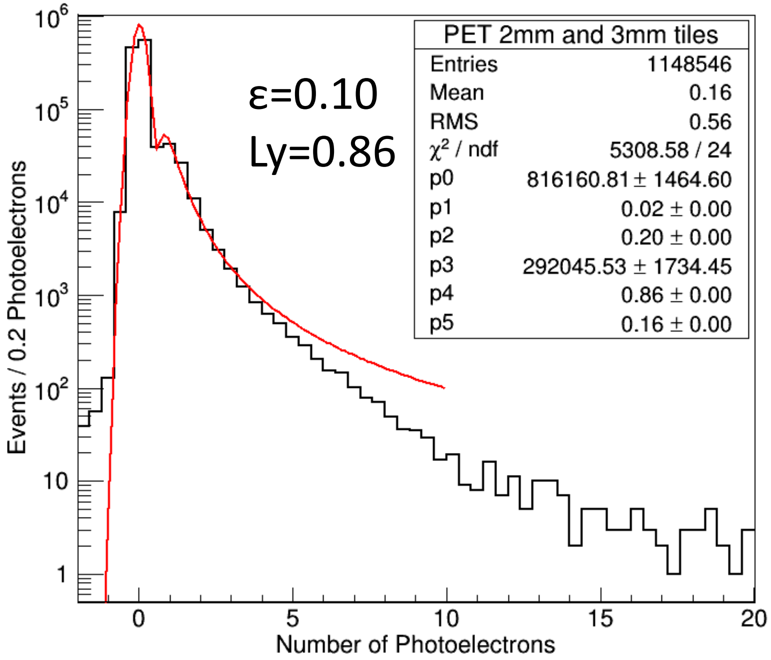


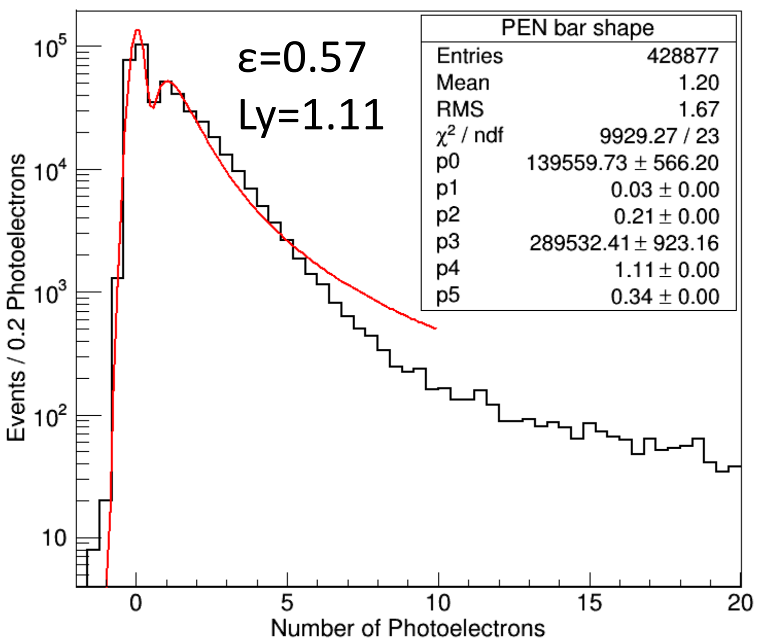
PET → Light yield mean 31 fC

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

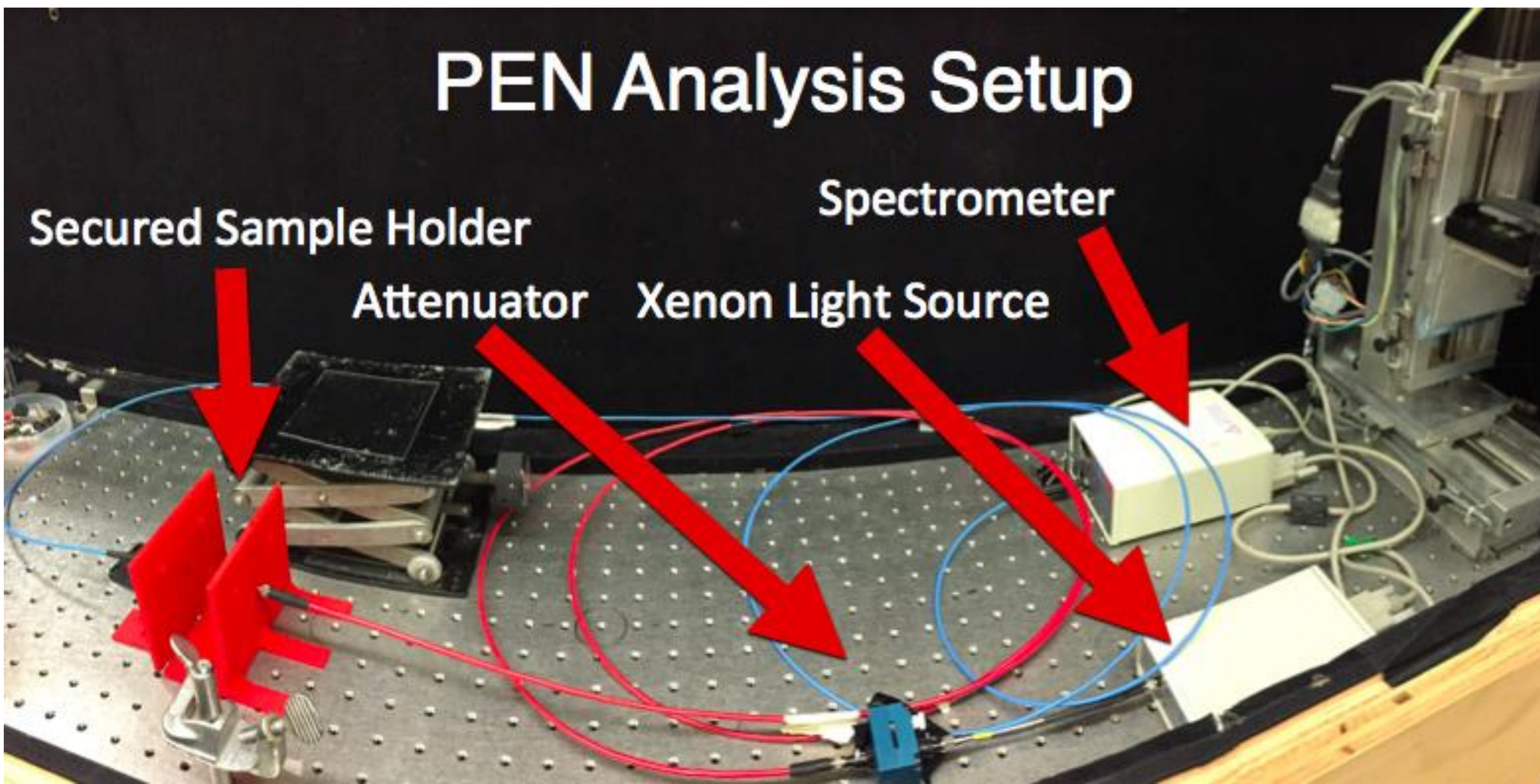




PEN Radiation Damage Studies (MSU)

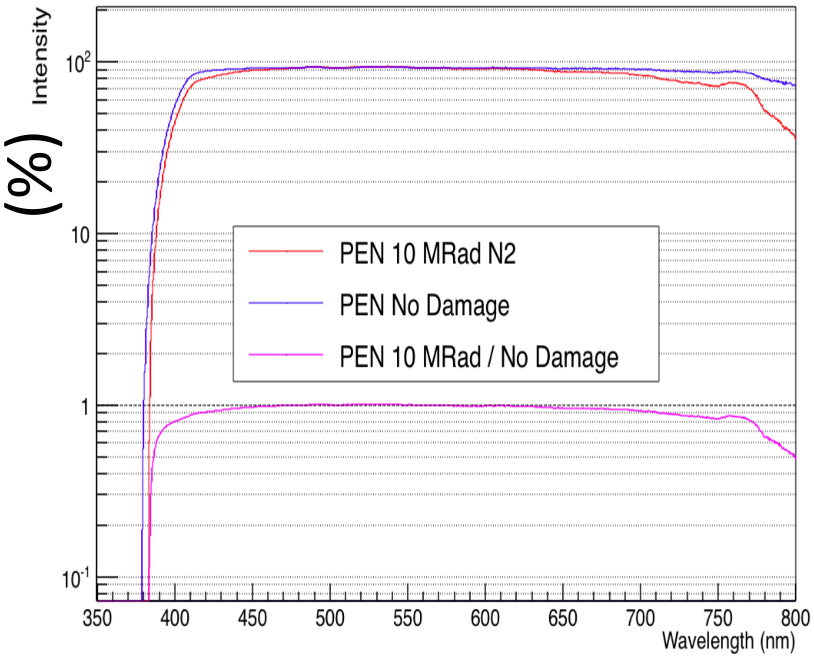
Facilities:
- National Superconducting Cyclotron Laboratory
- Used ^{60}Co, 1.33 MeV Gammas

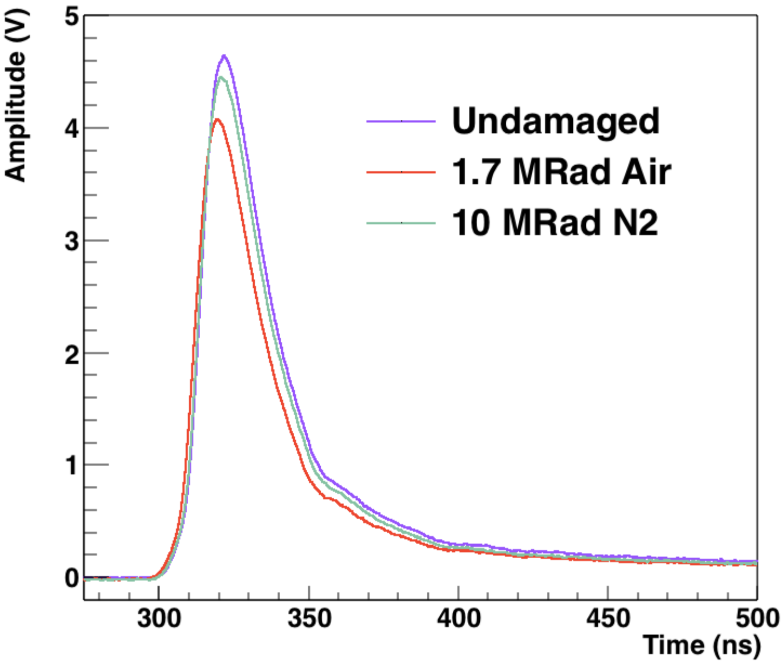
Two Samples:
- 1.7 MRad in Air
- 10 MRad in N_2



PEN Radiation Damage Studies (MSU)

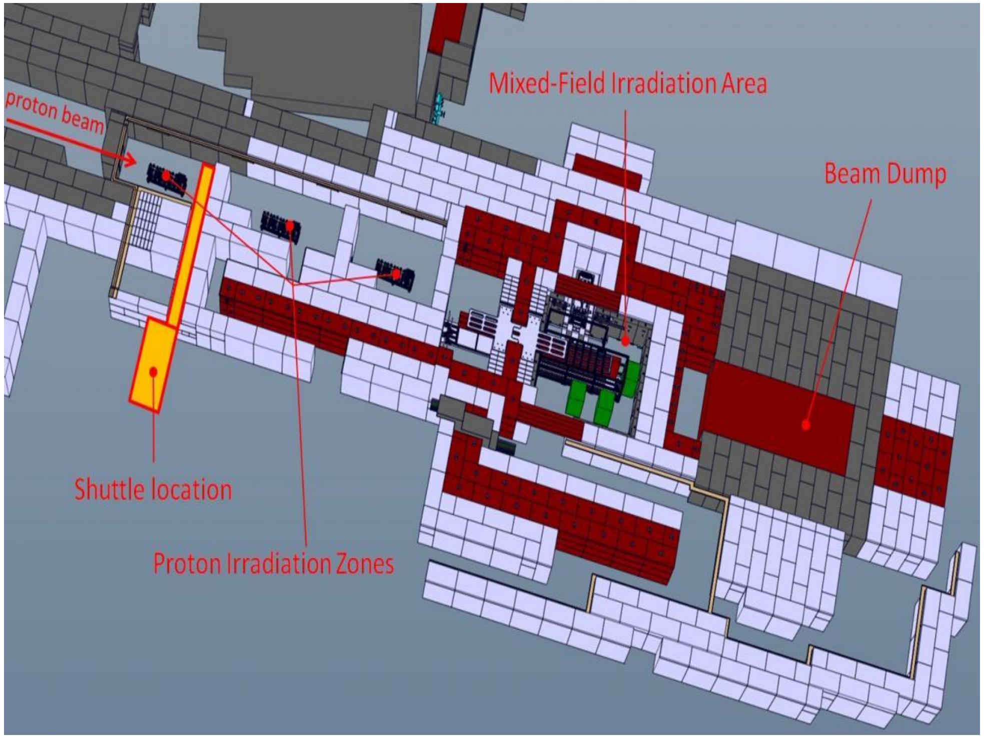
Transmission





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

IRRAD facility at CERN PS

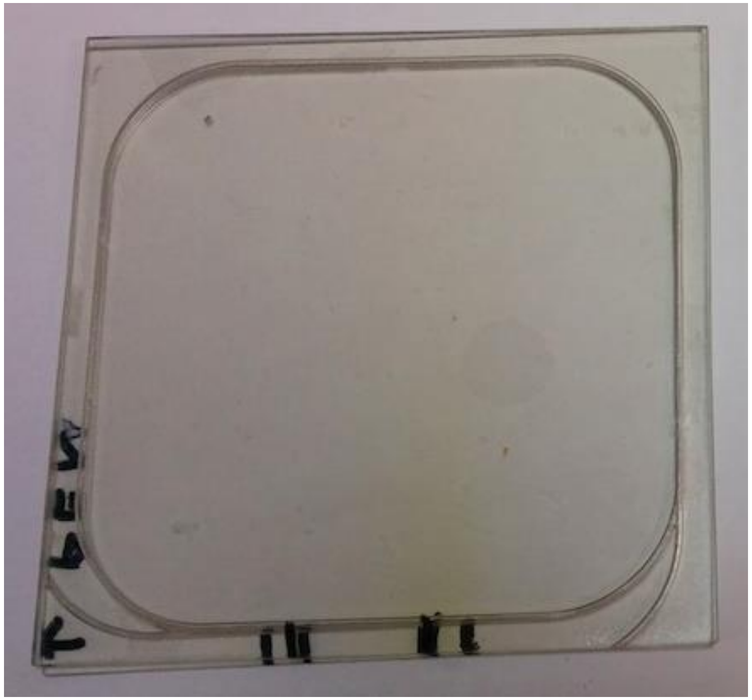


24 GeV protons ,
beam spot (FWHM) 15x15 mm^2
proton flux - ~$6x10^9$ p cm^{-2} s^{-1}

- The IRRAD proton facility is located on the T8 beam-line at the CERN PS East Hall where the primary proton beam with a momentum of 24GeV/c is extracted from the PS ring. As shown in the figure, the space allocated for irradiation tests in the East Hall is shared between two irradiation facilities: the IRRAD proton facility is located upstream, while the CHARM mixed-field facilities implemented downstream

PEN Radiation Damage Studies (CERN)

- 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. In average 30 Mrad was absorbed per spot



PEN Radiation Damage Studies (CERN)

Measurement procedure

- 370 mBq St^{90} β source was used to generate light in scintillating tiles
- Before and after irradiation Source was spaced on top of center of tile
- Light produced was collected with WLS fiber inserted in a σ shaped groove on tile and was coupled with clear fiber.
- Using clear fiber light was delivered to Hamamatsu R7600 single anode PMT
- Pico Ampere Meter was used to measure current produced
- Each measured value for the current corresponds to 15 to 20 minute integrated current measurements

PEN Radiation Damage Studies (CERN)

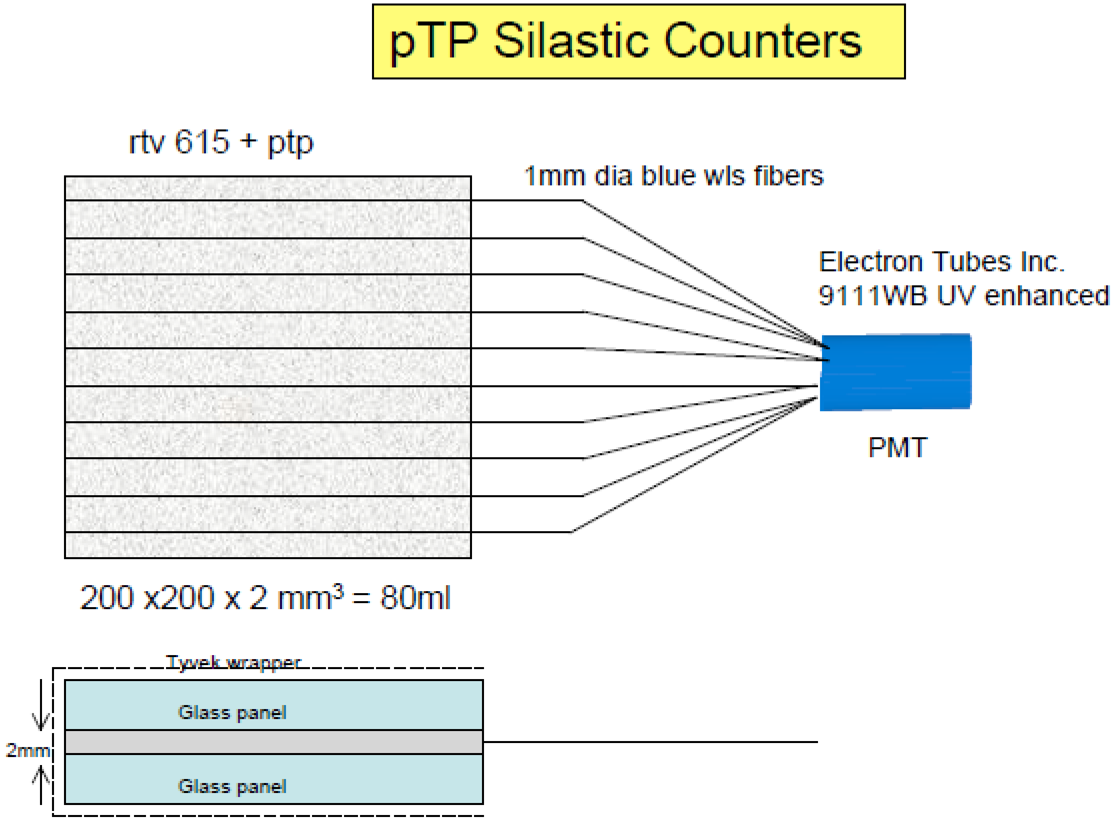
- Average of 125 nA , with lowest 123 nA and highest 128 nA were produced by radioactive source on not irradiated PEN tile

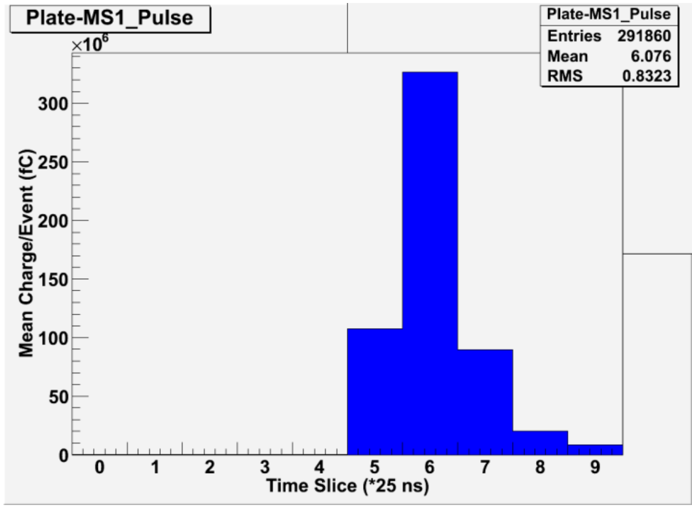
- Average of 30 nA, with lowest 27 nA and highest 35 nA were produced by radioactive source on irradiated PEN tile

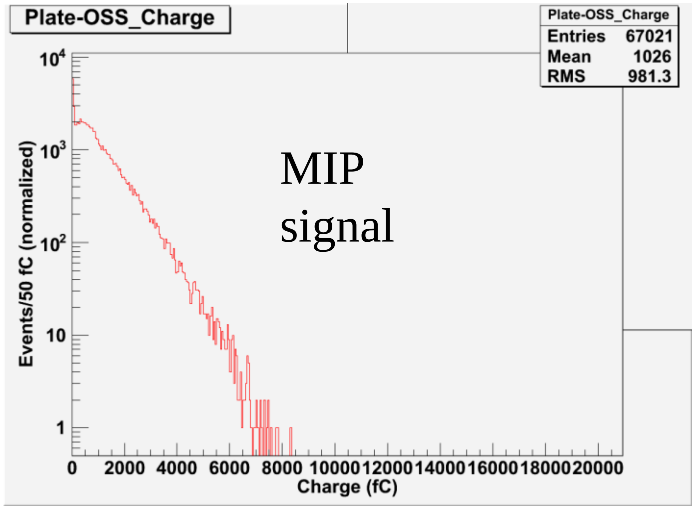
➔ 75% loss at 40 Mrad.

The pTerphenyl Silastic Tiles

The Silastic material was prepared in University of Iowa and University of Mississippi. Green WLS fibers were used to carry light out to PMTs. All are standalone units.





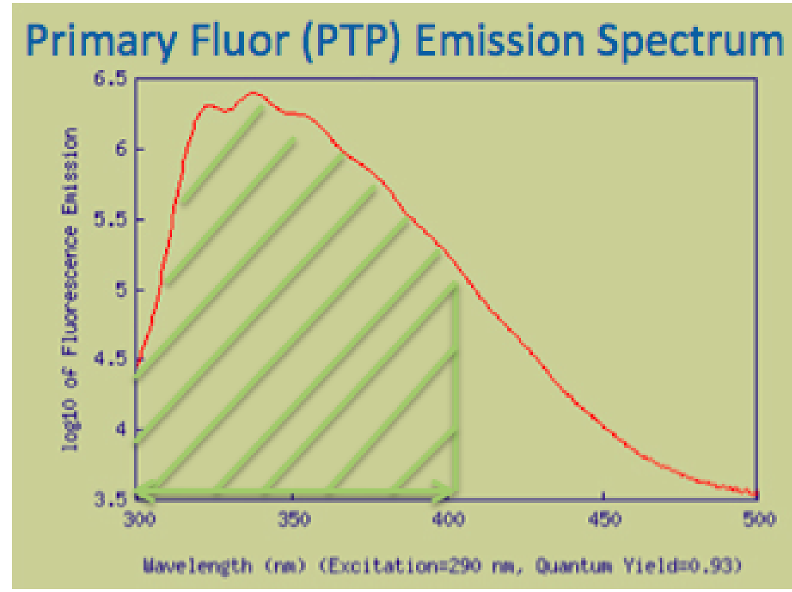


New SiX Scintillators

- 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.



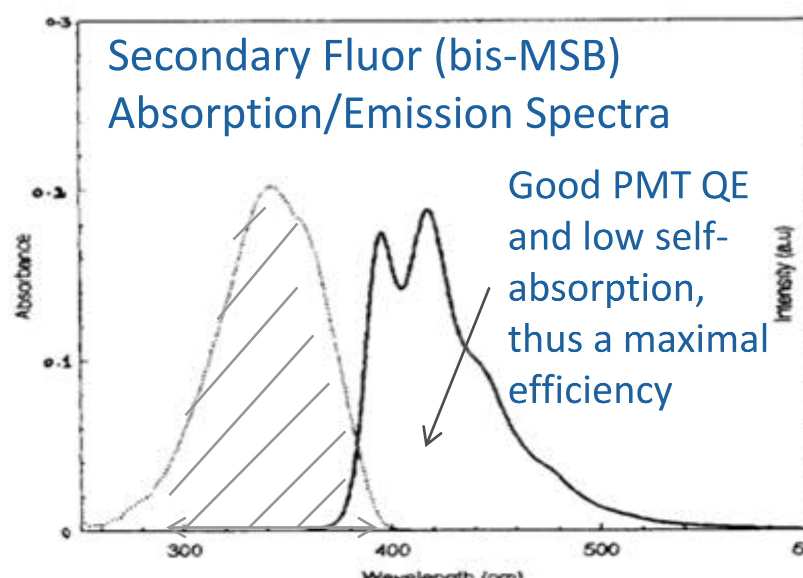


Fig. 1. Absorption (· · ·) and emission (——)

New SiX Scintillators

Lose only 7 % transmission after 40 Mrad proton radiation

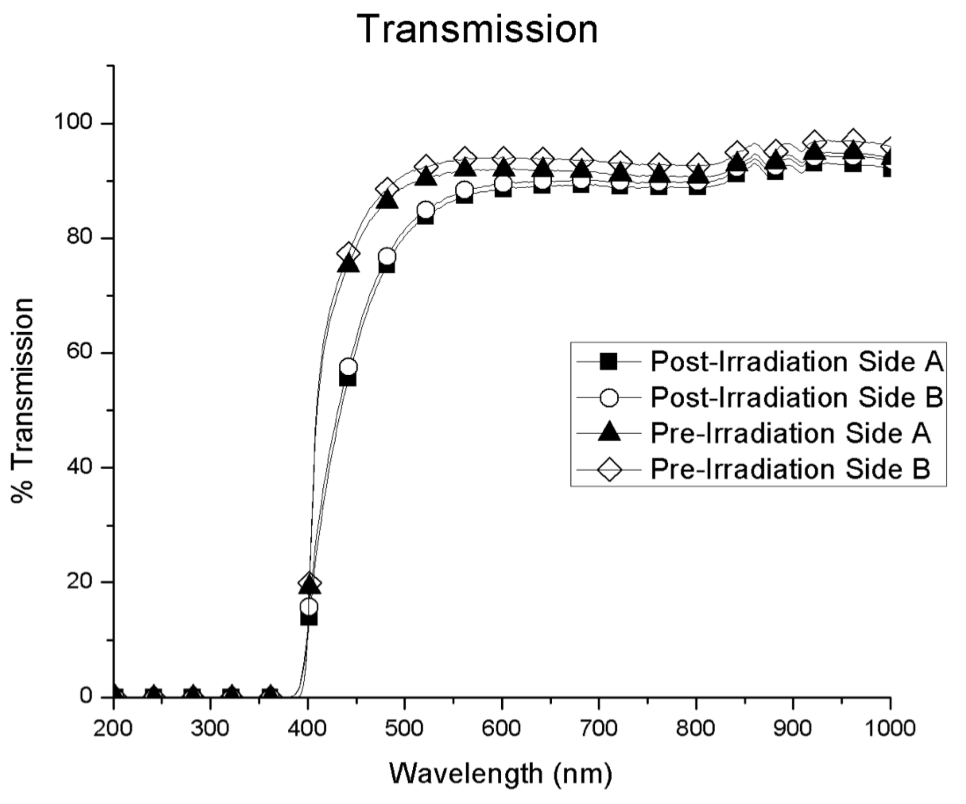


Figure 3: The transmission before and after irradiation;

New “P-S” Scintillators

Almost no change on emission and absorption after irradiation

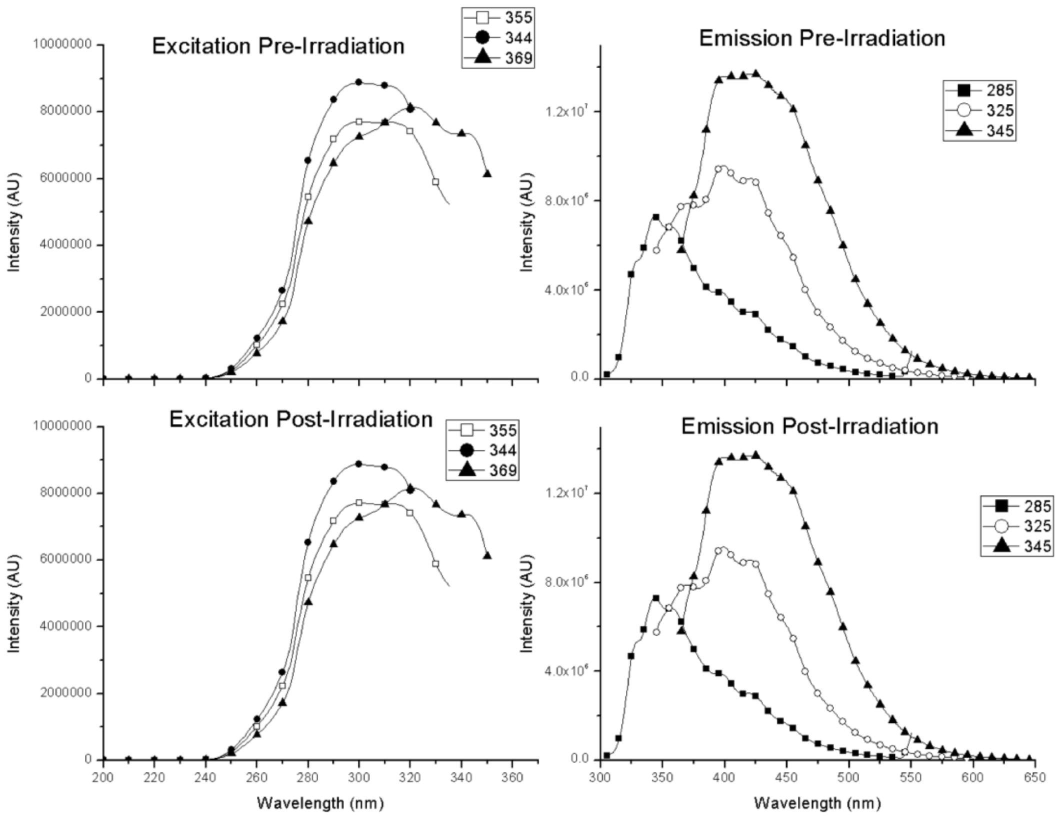
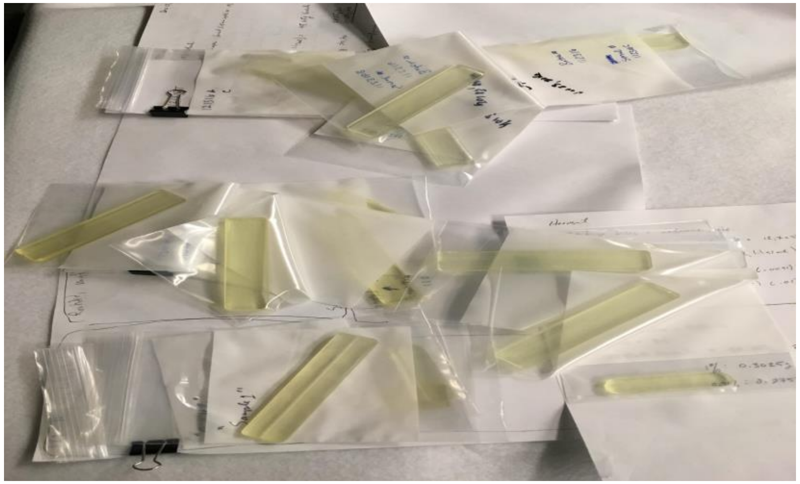


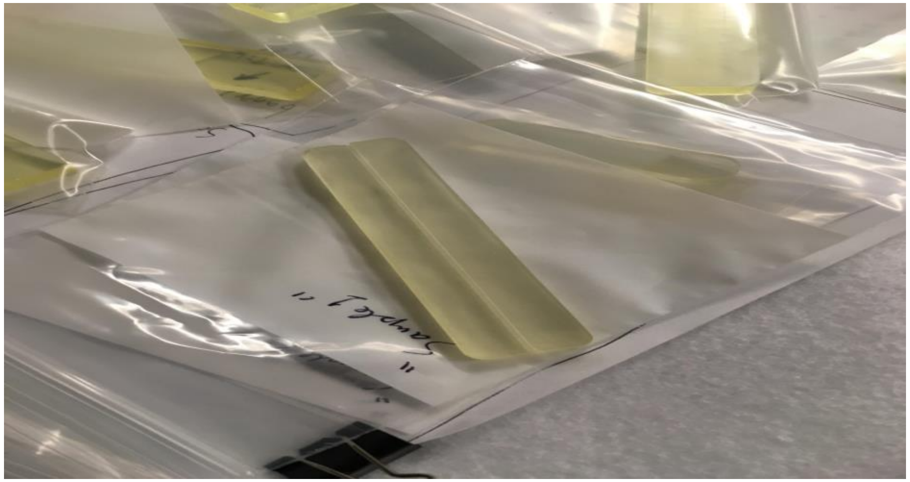
Figure 3: The excitation/emission taken before and after irradiation

SiX Production

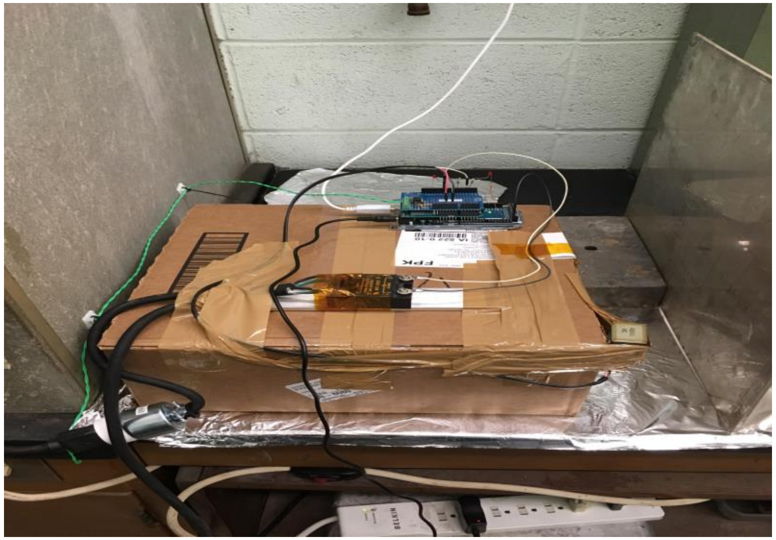
Finger Tiles



Grooved Tiles



Control Circuits



Modified Owen

Radiation Damage Studies (Iowa)

We tested samples of PEN and PET using laser stimulated emission on separate tiles exposed to 1.4 Mrad and 14 Mrad gamma rays with a ^{137}Cs source.

- PEN exposed to 1.4 Mrad and 14 Mrad emit 71.4% and 46.7% of the light of an undamaged tile, respectively, and maximally recover to 85.9% and 79.5% after 5 and 9 days, respectively.

- PET exposed to 1.4 Mrad and 14 Mrad emit 35.0% and 12.2% light, respectively, and maximally recover to 93.5% and 80.0% after 22 and 60 days, respectively.

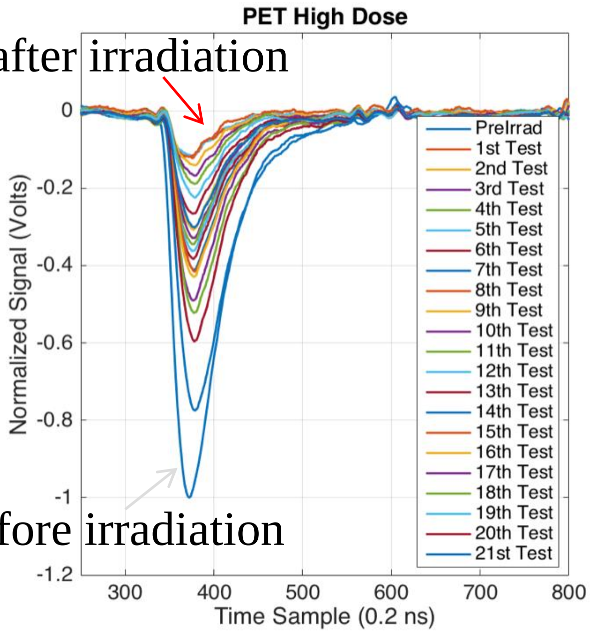
Irradiation of Scintillators

We irradiated our samples with using ^{137}Cs gamma source at Iowa Rad Core
1.4 Mrad and 14 Mrad

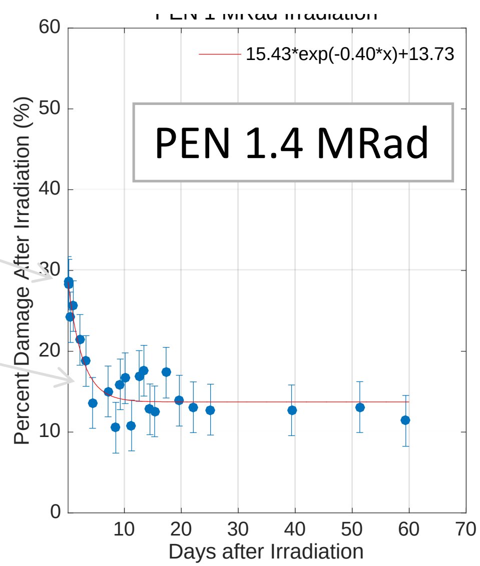
Initial damage

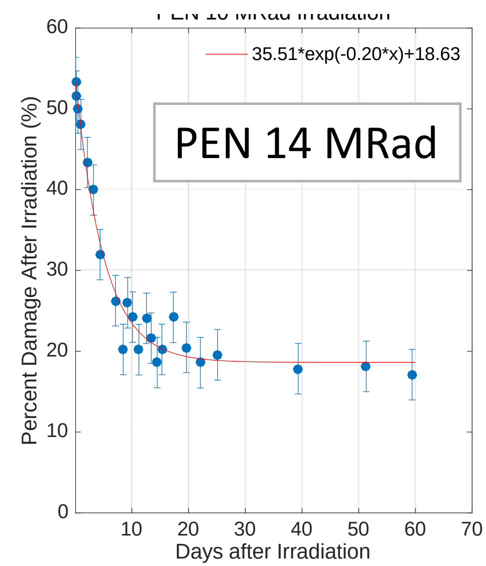
Permanent damage - plateau

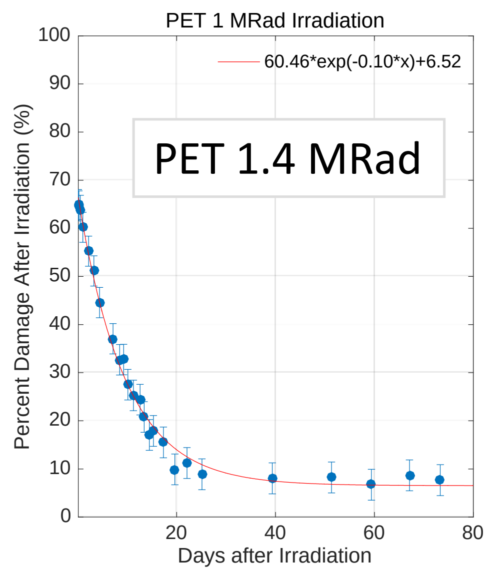
Right after irradiation

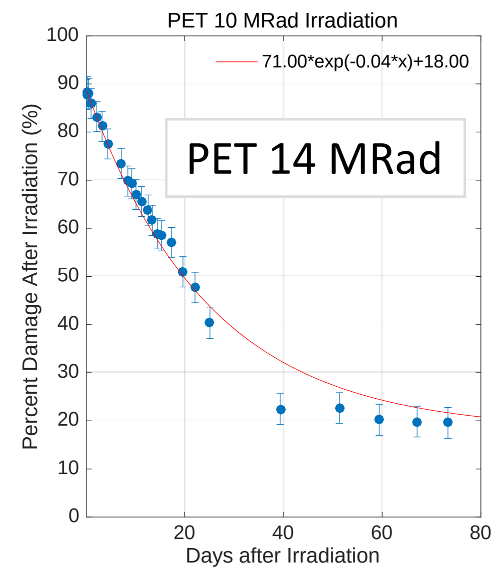


Before irradiation





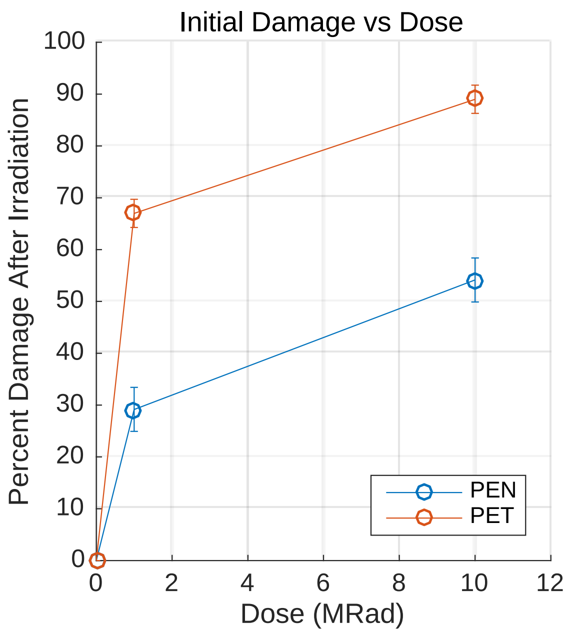




- Damage was calculated in terms of light yield

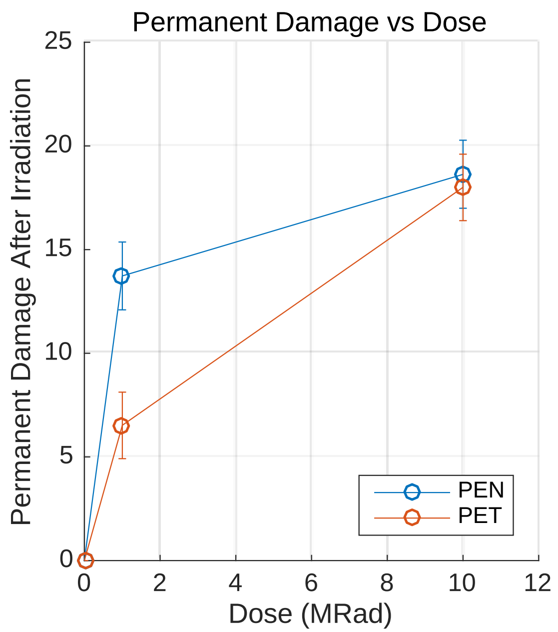
Summary of irradiation results

Initial damage



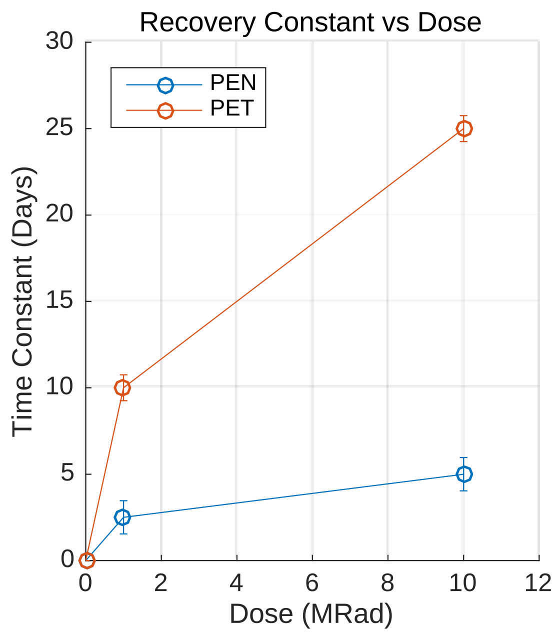
- PET was damaged more than PEN initially

Permanent damage



- Permanent damage was same at 14 MRad

Time for Recovery

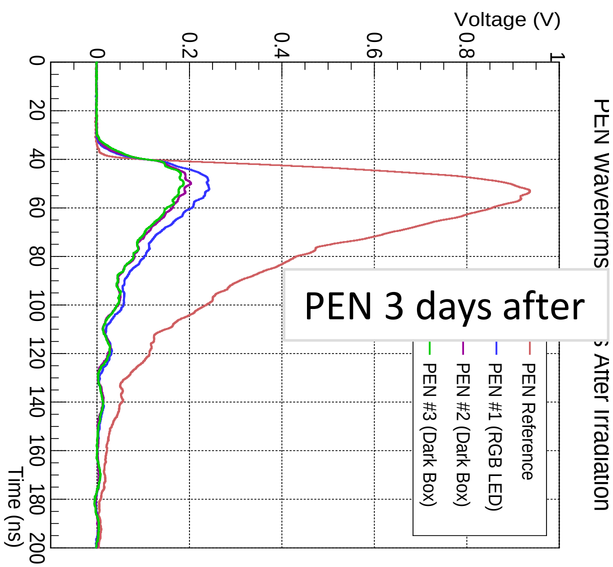


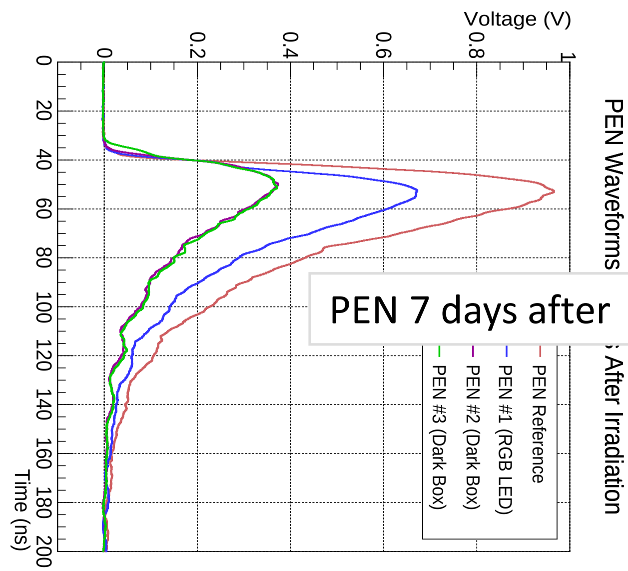
- PEN was recovered in 5 days only and PET in 25 days – so slow

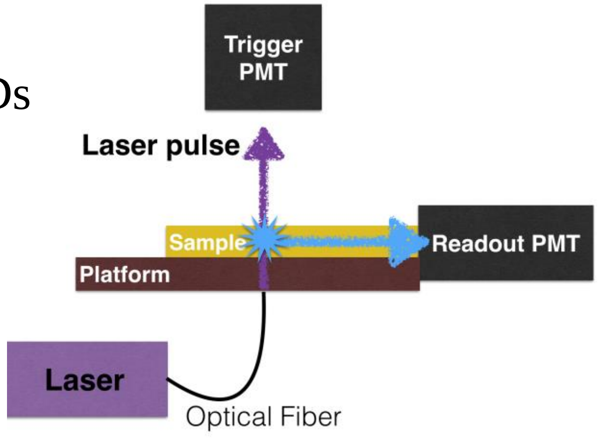
LED Stimulated Recovery

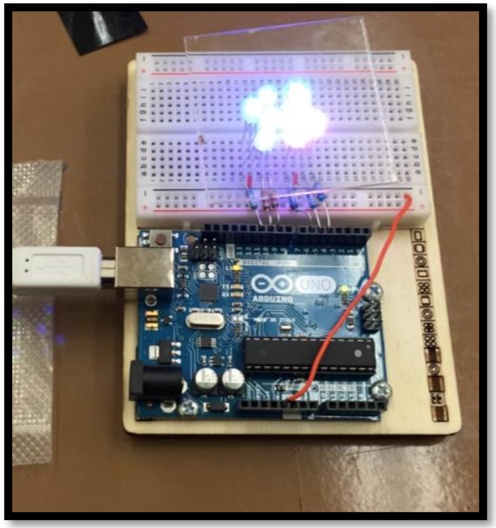
Can we stimulate the recovery of scintillators damaged from radiation?

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





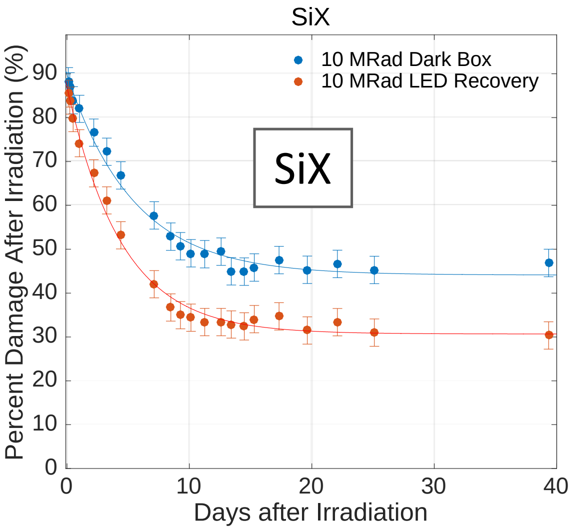




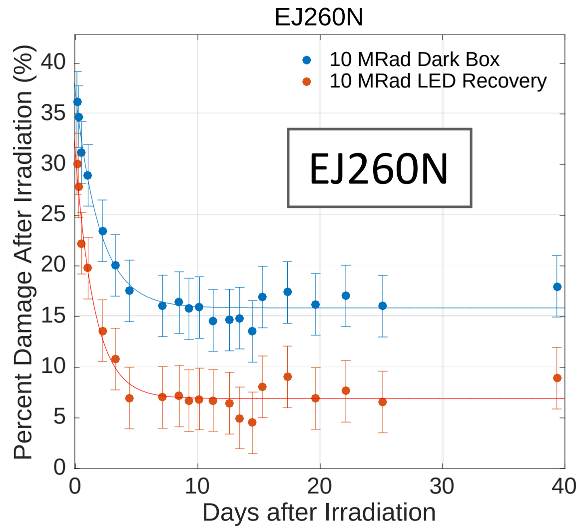
Different Materials:

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

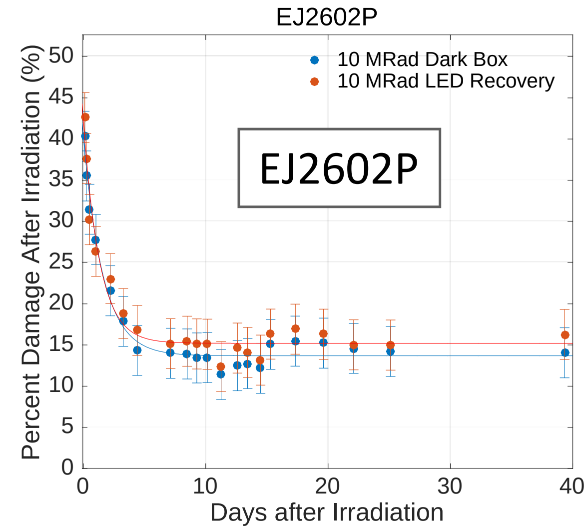
LED Stimulated Recovery



Blue emission



Green emission



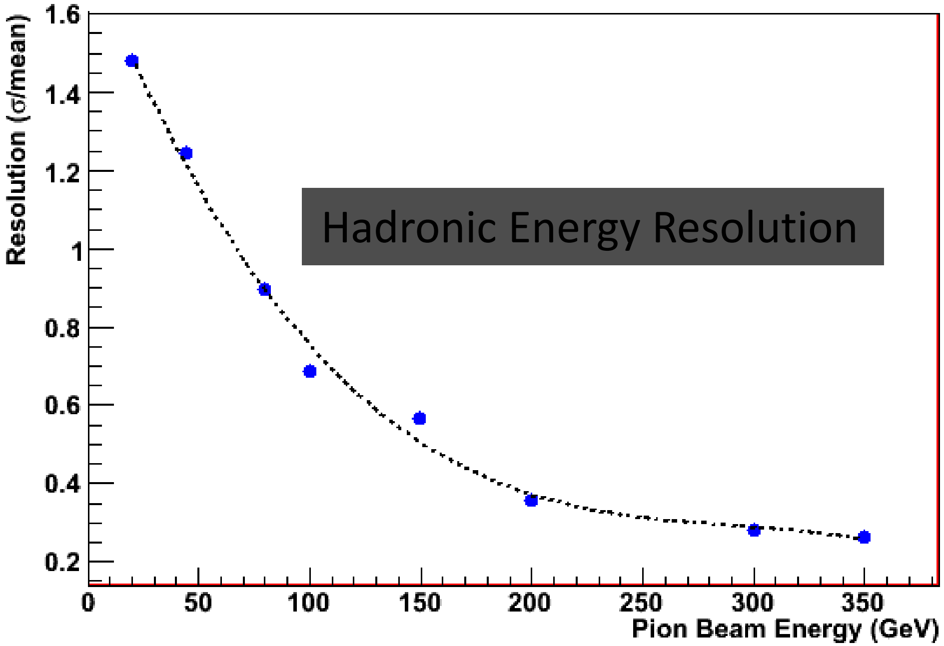
Green emission

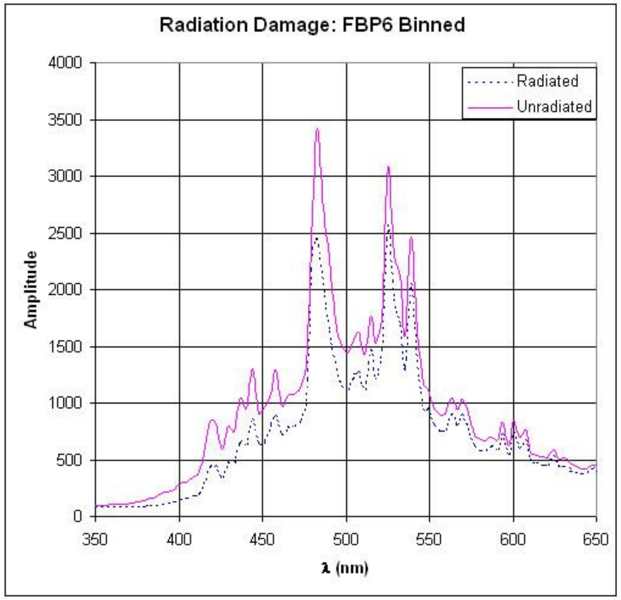
Tile	'a', Total Recovery	'c', Permanent Damage
SiX RGB	56.3 ± 2.4%	30.7 ± 1.6%
SiX dark box	45.7 ± 2.5%	44.1 ± 1.9%
EJN RGB	24.0 ± 2.2%	6.92 ± 0.7%
EJN dark box	21.1 ± 1.8%	15.9 ± 0.6%
EJ2P RGB	26.9 ± 3.1%	15.2 ± 0.9%
EJ2P dark box	26.5 ± 2.2%	13.7 ± 0.7%

- 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.

Quartz Radiation Damage Studies

WLS Fiber Embedded Quartz Plate Calorimeter Module





20 Mrad of neutron
75 Mrad of gamma
At ANL

➔ Quartz plates coated with organic/inorganic scintillators/wavelength shifters

Quartz Tiles with WLS

This technique utilizes quartz plates with Wavelength Shifting (WLS) fibers running in grooves of different geometries, read out with photo-detectors as the active medium.

A. Scintillator/WLS Films on Quartz Tiles

- **Ptp, anthracene**
- **ZnO:Ga; CsI; CeBr3 – emissions 375-450 nm; T<17ns**
- **CsI and CeBr3 will be protected with an over-deposited quartz film ≥50 nm thick.**

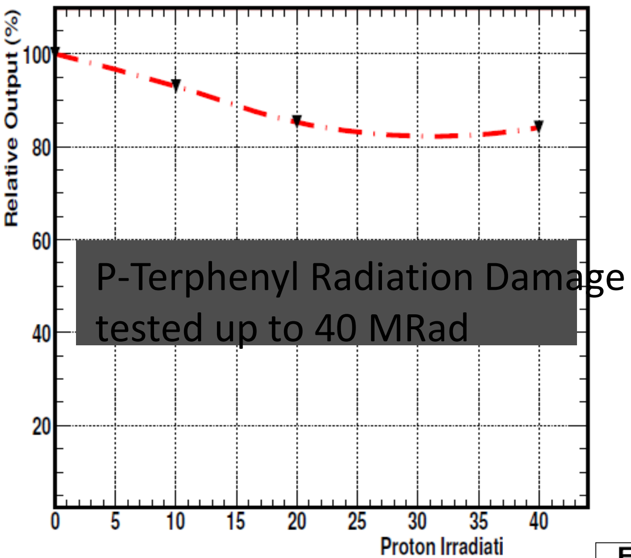
1. Double-sided Single Plate: coated 300 µm ≤ 3 mm thick tiles (thickness & optical finish chosen for the lowest cost, up to 3mm thick), 10 x 10cm; coating thickness up to ~10 µm. Minimum 2 Tiles each of 2 downselected materials. Readout: WLS fibers.

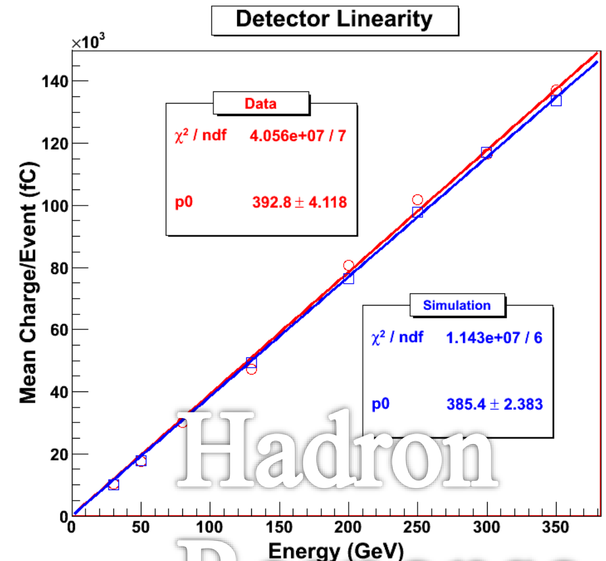
2. Sandwich: ≥300µm thick quartz tiles as above, 10 x 10 cm, single-sided coating, but assembled in stacks up to ≤3 mm thick. Film thickness: 5-10 µm. Preferred deposition: e-beam evaporation. Minimum 2 sandwiches each of 2 downselected materials. Readout: WLS fibers, one per edge

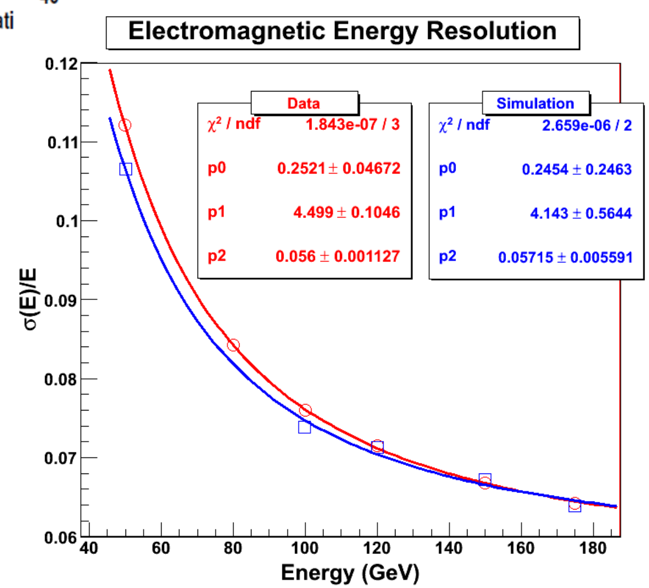
Fermilab's THIN FILM Facility Coating Systems at Lab 7

- **2 Bell Jar sputtering systems**
  - **Al, Ag, Au, Cr, Cu, Ir, Ni, PtIr, Ti, ZnO_2-Ga**
- **2 tube sputtering systems-dedicated to 99.999% pure aluminum sputtering**
  - **Optical fiber mirroring**
- **1 Bell Jar system for resistive evaporation**
  - **Al, Ag, Au, Cr, Cu, Al & MgF_2 surface mirrors, Ni, NiCr, TiN**
- **1 Pyrex Bell Jar system for resistive evaporation-dedicated to Scintillator and WLS materials**
  - **pTp, TPB, POPOP, Cesium Iodide, Anthracene, Bis-MSB, Cerium(III) bromide**
- **1 Tall Bell Jar system (17"dia x 70"tall) designed for resistive evaporation with rotating motor at 45° and 6 rpm speeds**
  - **NiCr "electroding" of MCPs**
  - **Distance from boat to substrate is 34"**
- **1 Large Bell Jar (34.5" ID x 50.5" tall)**
  - **Resistive setup currently**

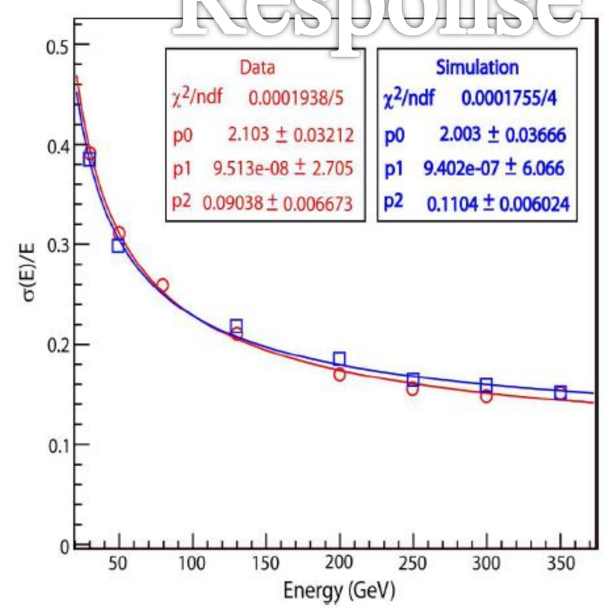
Calorimetry with pTerphenyl (pTp)-Coated Quartz Plates





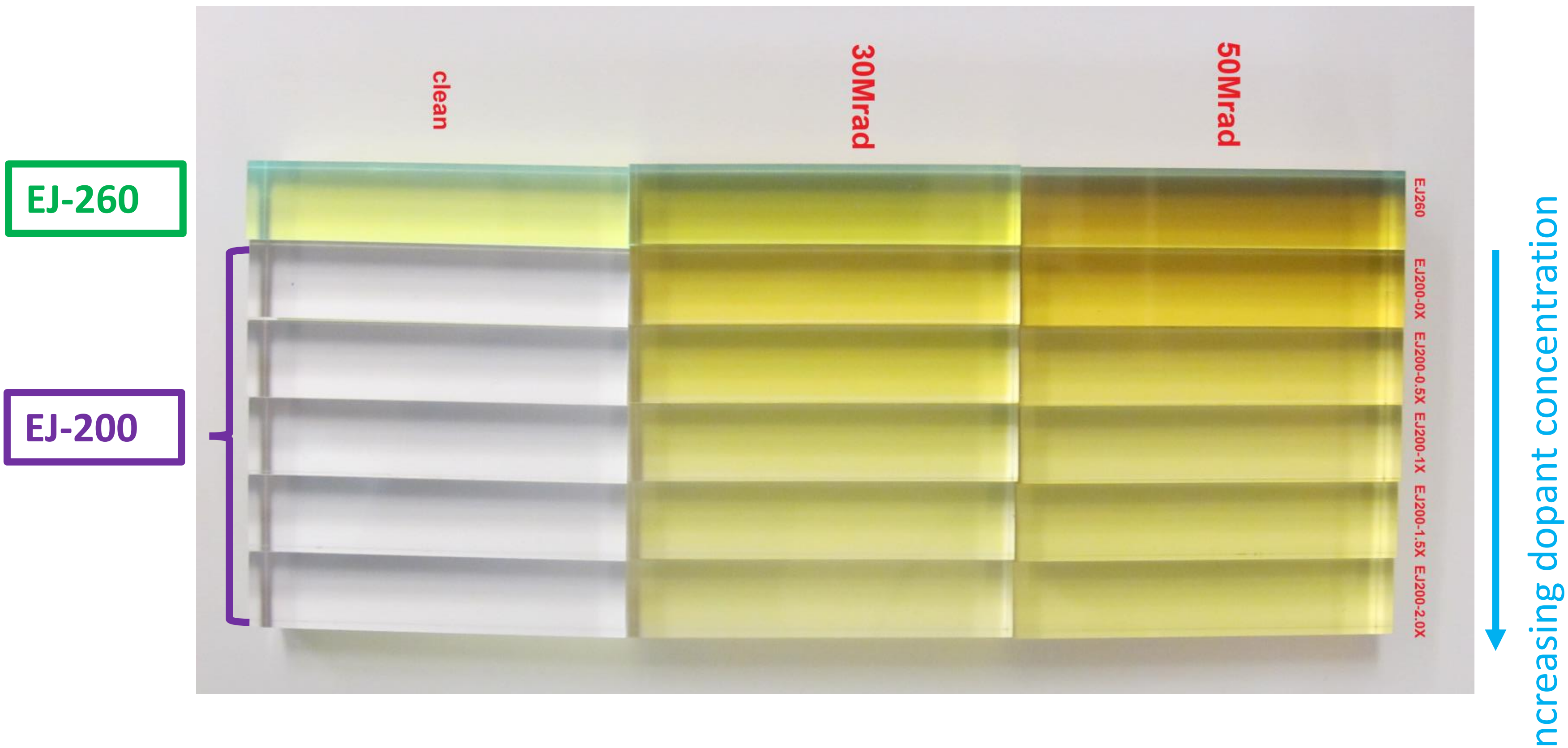


Hadron Response



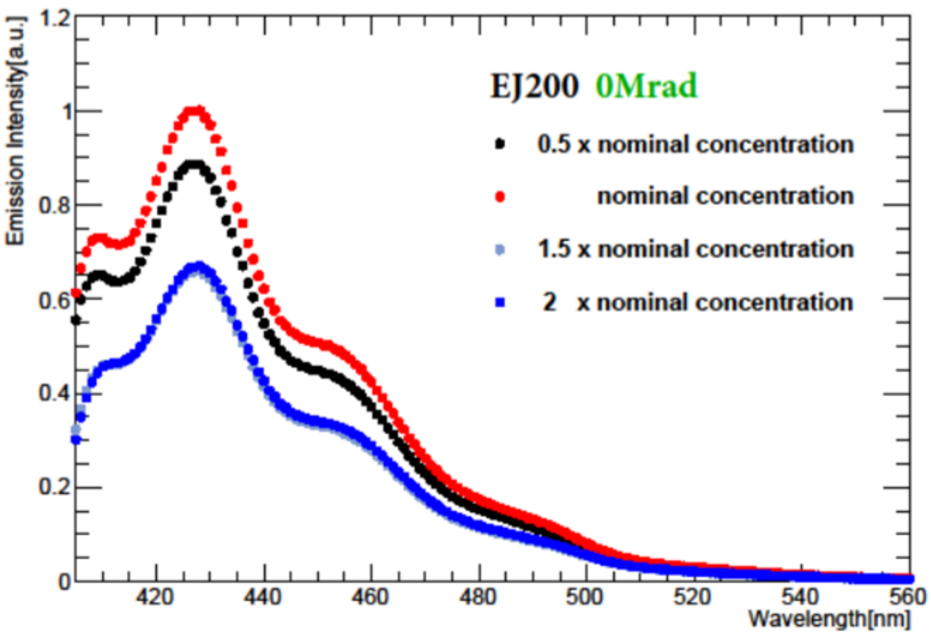
Over-doped Scintillators

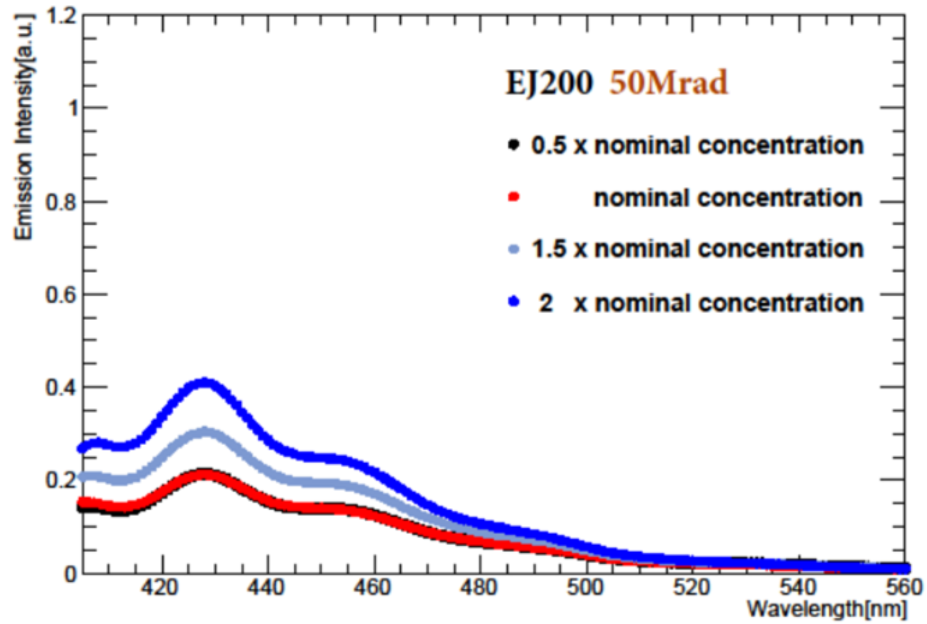
- A set of PVT rods with different concentrations of primary dopant were produced by Eljen and irradiated at UMD
  - Increasing the dopant concentration is suggested to be a way of improving radiation tolerance: radiation damages the dopant thus decreasing both the light yield and self-absorption



Over-doped Scintillators - Emission Spectra

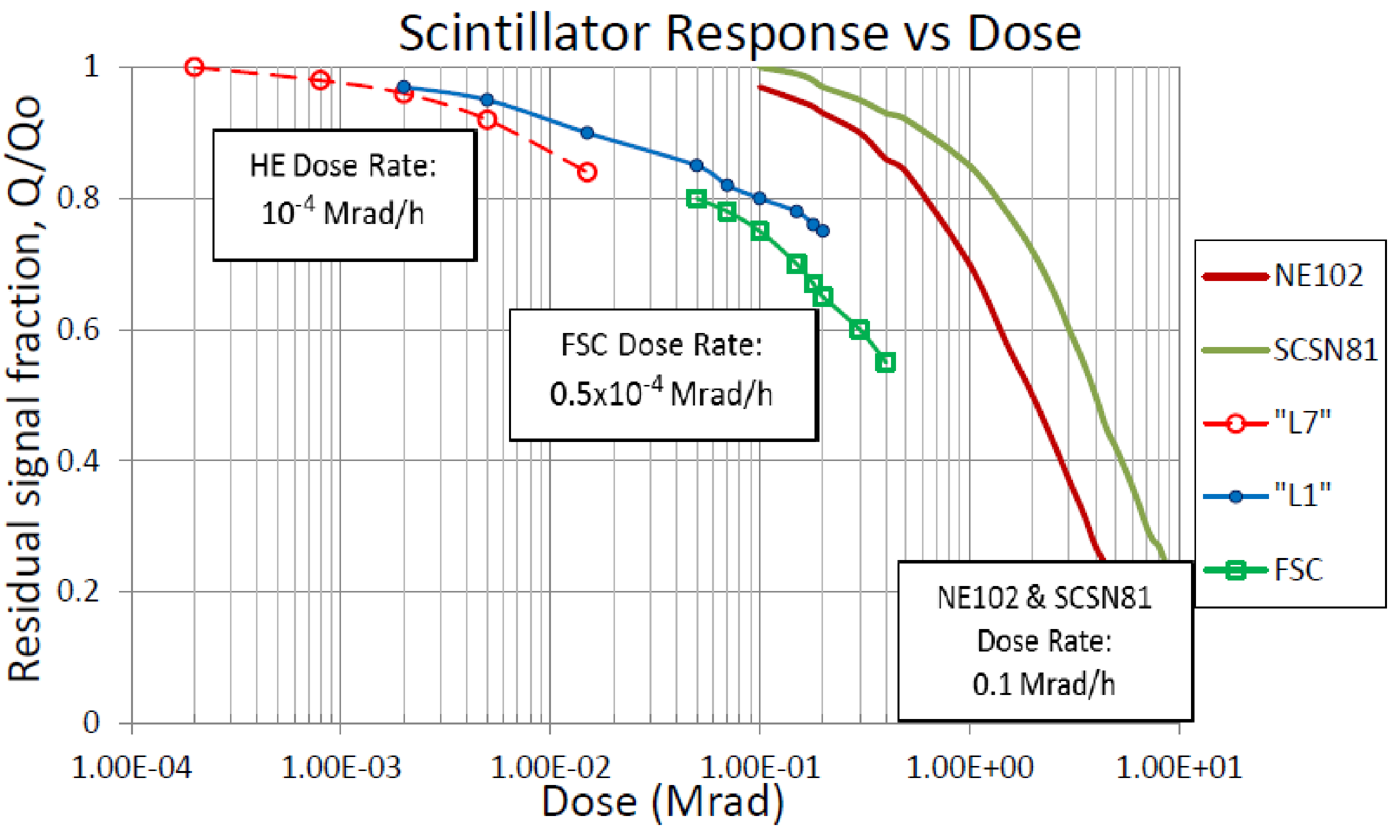
- The comparison among emission spectra shows that increasing the doping helps increasing the resiliency to radiation damage
  - The 2x sample starts with a smaller light yield w.r.t. the 1x sample (the nominal EJ-200 concentration), but after 50Mrad emits twice as much light with respect to it, after losing about 30% of its light emission (commercial EJ-200, instead, reduces its emission by 80%)





Measurements performed right after irradiation

Scintillator (EJ212) radiation damage in Run1 (2011-2013)



Scintillator radiation damage (and recovery) depend on "Dose Rate" and presence of O_2

[HE Data from Pawel de Barbaro: HE Rebuild Update, EC Review, 24Mar2015; see also CMS AN--2014/226]

Over-doped Scintillators - Coating Tests

- Tile Fiber Gamma Source response
- Blue tile green fiber 288.8
- Blue tile 50 Mrad green fiber 4.6 4.6/289=1.6% dead
- --
- Blue tile Orange fiber 105.9
- Blue tile 50Mrad Orange fiber 12.0 12/106 =11.3% ***
- ** Done with Tyvek wrapping – expect better results with black paper
- --
- Blue – 1 green coat Orange fiber 138.4
- Blue tile -50Mrad)
- 1 green coat Orange fiber 19.9 10/138=14.5%
- --
- Blue – 2 green coats Orange fiber 114.9
- Blue tile - (50Mrad)

2 green coats Orange fiber 17.8 17.8/115=15.5%

A. Bodek – J. Han

Conclusions

- The options of intrinsically radiation-hard scintillators is being expanded with the addition of Scintillator-X. Different combinations e.g. PEN+PET and different variants of Scintillator-X can be probed.

- Quartz is extremely radiation-hard. With the correct combination of coating and readout, it can be the optimal option for forward region in all collider experiments. Coating is a relatively easy process nowadays. We need to probe different types of coatings and also their mixtures.