NEW RADIATION-HARD MATERIALS

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Outline

1. The necessity of new radiation-hard materials in high energy physics experiments

2. Intrinsically radiation-hard scintillators

3. Microprocessing for radiation-hard detectors

4. Radiation-hard wavelength shifting fibers

5. Conclusions

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1. The necessity of new radiation-hard materials in high energy physics experiments

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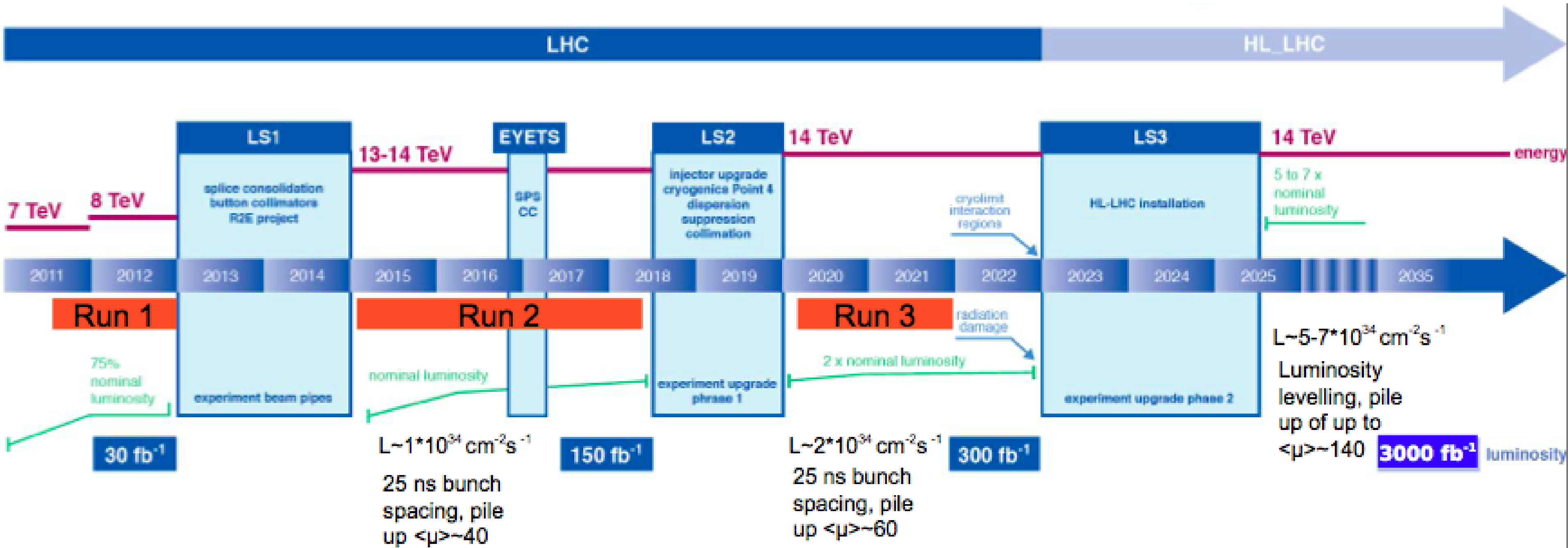
High Luminosity LHC



From LHC to HL-LHC

Instantaneous luminosity x5 (for ATLAS, CMS, LHCb) → Particle densities x5-10

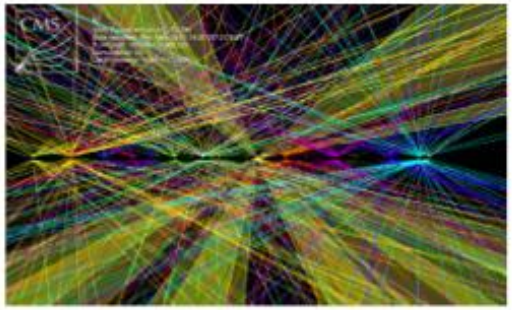
Integrated luminosity x10 (for ATLAS, CMS, LHCb) → Radiation damage x10

Increase of overlap of pp events (pile up x3-5)

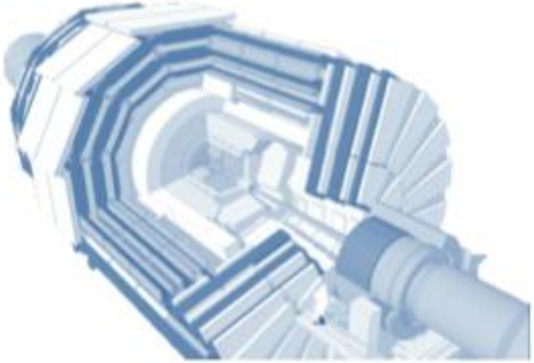
High Luminosity LHC

Phase II Upgrades

- from LHC design to ultimate performance
  - **luminosity** **1×10^{34}**$\text{cm}^{-2}\text{s}^{-1}$ → **5×10^{34}**$\text{cm}^{-2}\text{s}^{-1}$ leveled (**ATLAS + CMS**),
    4×10^{32} $\text{cm}^{-2}\text{s}^{-1}$ → **2×10^{33}**$\text{cm}^{-2}\text{s}^{-1}$ (**LHCb**) **x5**
  - **integrated luminosity 300**/fb → **3000**/fb (**ATLAS + CMS**), **5**/fb → **50**/fb (**LHCb**) **x10**
  - → **new and more precise measurements, extended reach for discoveries**
    IF detector performance can be preserved / improved



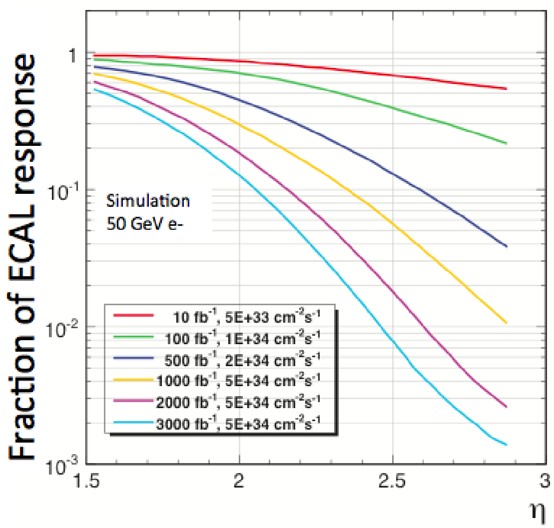
- the price to pay:
  - pile-up 20 → 140-200 (ATLAS+CMS), 2 → 5 (LHCb)
  - particle densities x5-10
  - radiation damage x10
- the casualties (radiation damage and/or performance loss)
  - pixel
  - tracker
  - trigger
  - end-cap calorimetry, electronics
  - end-cap muon system, electronics



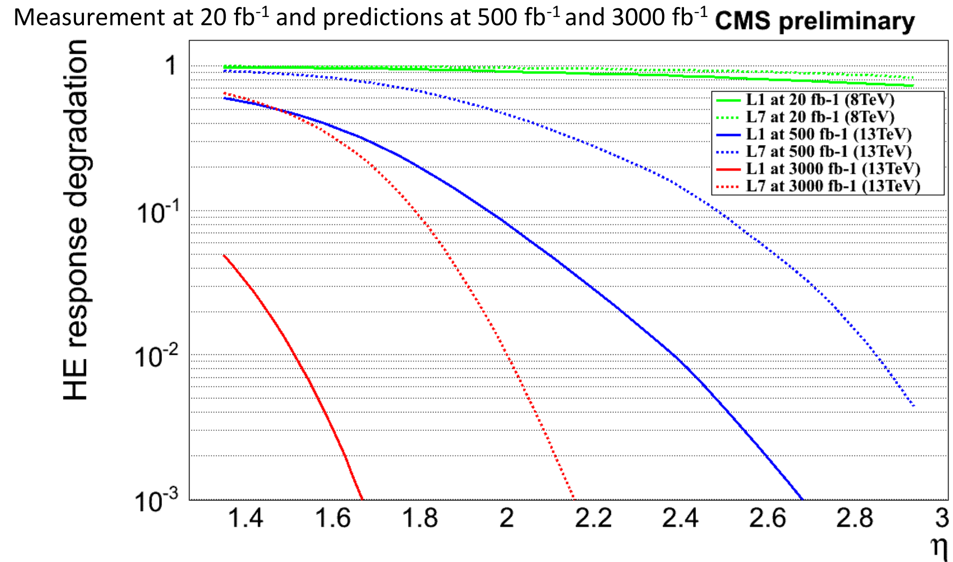
- the brave (in general)
  - calorimetry
  - muon system
- when?
  - installation mainly in 'long shut down 3' currently foreseen 2022-2023 (ATLAS+CMS)
    partly already in 'long shutdown 2' currently foreseen 2018 (LHCb)

Example: CMS Forward Region (1-100 Mrad at 500 fb^{-1})

ECAL Endcap



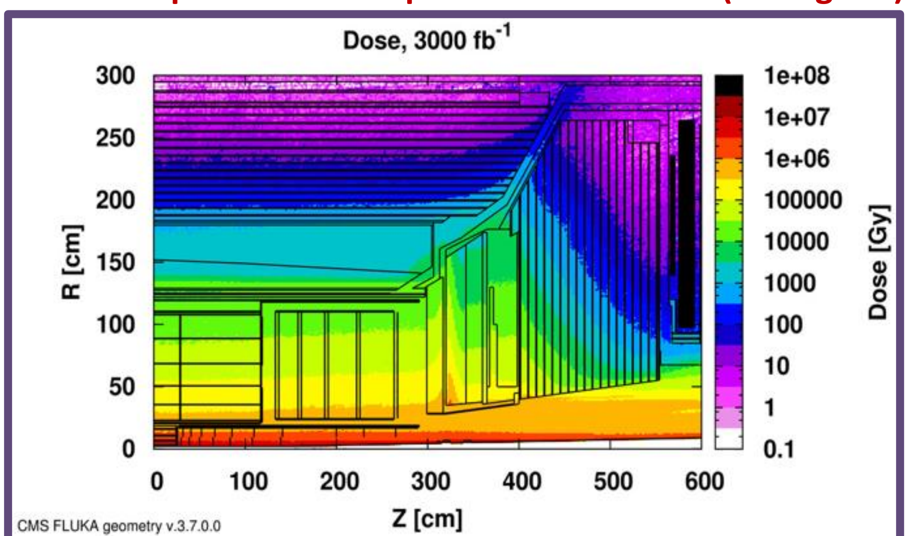
HCAL Endcap



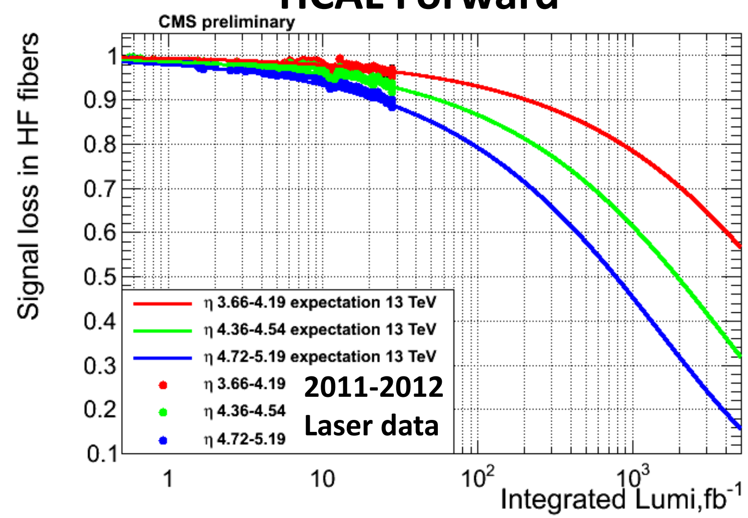
Progressive deterioration of energy resolution and trigger efficiency, with strong η dependence

HCAL endcaps should be upgraded/replaced during LS3

ECAL endcaps should be replaced after 500 fb^{-1} (during LS3)

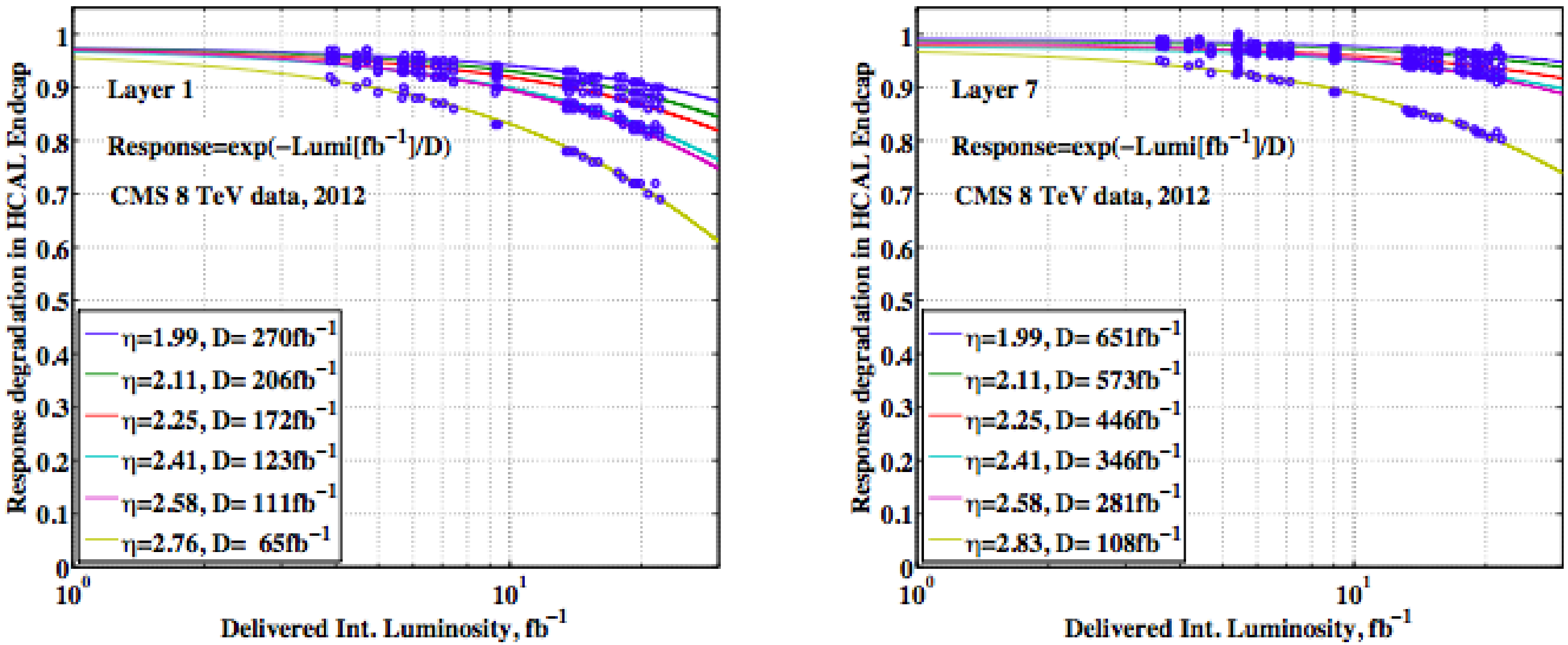


HCAL Forward



HCAL forwards require no/minimal upgrade

CMS Endcap Region Dose Rate Dependence of Radiation Damage



(a) Layer 1 (b) Layer 7

Figure 3. Ratio of light output to initial light output for tiles as a function of integrated luminosity, with extracted dose constant, for CMS hadron endcap calorimeter scintillators in Layer 1 (a) and in Layer 7 (b).

V. Khachatryan, et.al., accepted for publication JINST

CMS Endcap Region Dose Rate Dependence of Radiation Damage

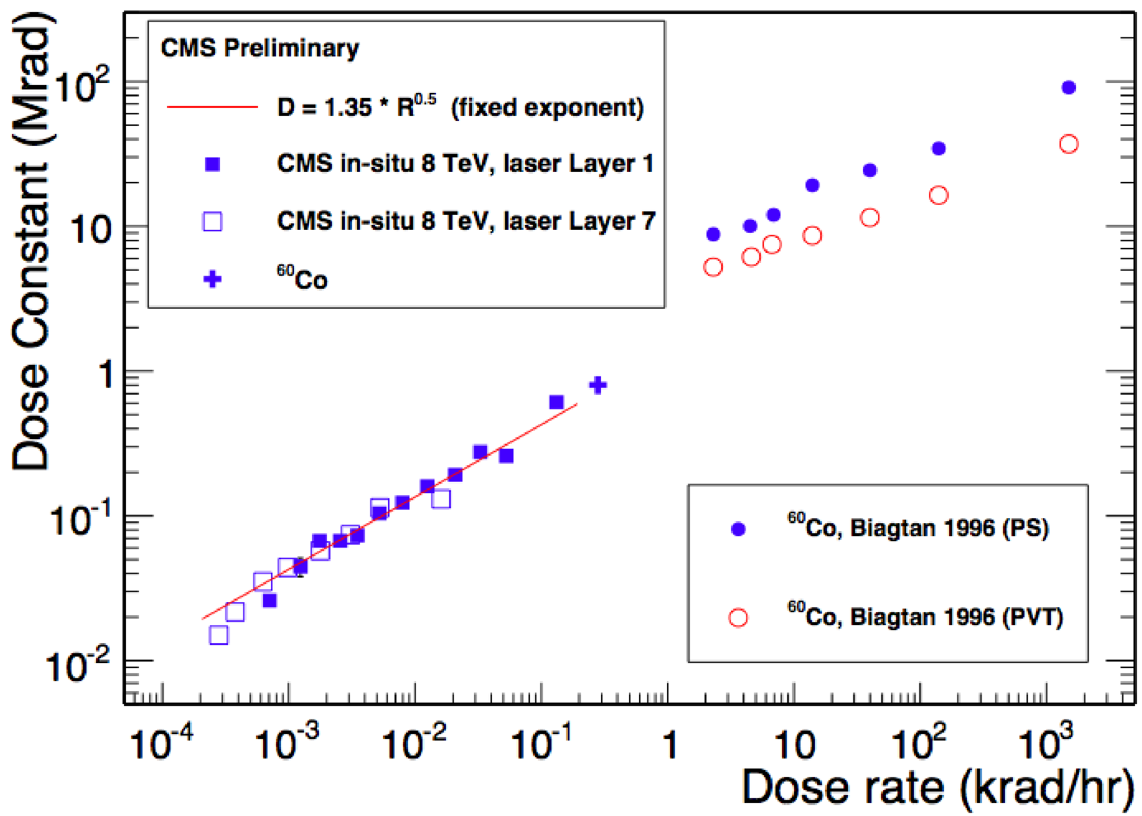


Figure 4. Exponential constant as a function of dose rate. Results from scintillators based on PS are shown in blue, while those based on PVT are shown in red. Results from Layer 1 (7) of the CMS HE scintillator are indicated by filled squares (open squares). Each point corresponds to a different tile pseudorapidity. Results from the ^{60}Co irradiations discussed in Biagtan [2] are indicated with circles. The label "^{60}Co, CMS" (cross) refers to the measurement first presented in this paper, which was taken using irradiation from a gamma source. A fit to the in situ data to a power law is shown, where the power is set to 0.5.

V. Khachatryan, et.al., accepted for publication JINST

Future Hadron Collider Experiments

FCC-hh

Baseline
- Promise
- Goal 250 fb^{-1} per year
    - 2 fb^{-1} per day
- focus on 25 ns spacing

Ultimate
- reasonable hope
- goal 1000 fb^{-1} per year
- more emphasis on 5 ns

Assume 5 year operation cycles
- 3.5 year run
- 0.75-1.0 year for stops, MDs etc.
- 70% efficiency
- 625-700 effective days per year

	Baseline	Ultimate
Luminosity [$10^{34}cm^{-2}s^{-1}$]	5	20
Bunch distance [ns]	25 (5)	
Background events/bx	170 (34)	680 (136)
Bunch charge [10^{11}]	1 (0.2)	
Norm. emitt. [μm]	2.2(0.44)	
RMS bunch length [cm]	8	
IP beta-function [m]	1.1	0.3
IP beam size [μm]	6.8 (3)	3.5 (1.6)
Max ξ for 2 IPs	0.01 (0.02)	0.03
Crossing angle [σ□]	12	Crab. Cav.
Turn-around time [h]	5	4

10 Mrad – 5 Grad / 5 years (estimate)

Daniel Schulte, FCC Week, Washington DC, March 2015

Future Lepton Collider Experiments

CLIC

~ 500 fb^{-1} / year

~ 20 Mrad / year in the forward region

Parameter	Units	$\sqrt{s} = 500$ GeV	$\sqrt{s} = 3$ TeV
θ_c	mrad	18.6	20
f_{rep}	Hz	50	50
n_{b}		354	312
Δt	ns	0.5	0.5
N		$6.8 \cdot 10^9$	$3.72 \cdot 10^9$
σ_x	nm	≈ 200	≈ 45
σ_y	nm	≈ 2.3	≈ 1
σ_z	µm	72	44
β_x	mm	8	4
β_y	mm	0.1	0.07
L* [a]	m	3.5	3.5
$\mathscr{L}$	cm^{-2}s^{-1}	$2.3 \cdot 10^{34}$	$5.9 \cdot 10^{34}$
$\mathscr{L}_{0.01}$	cm^{-2}s^{-1}	$1.4 \cdot 10^{34}$	$2.0 \cdot 10^{34}$
n_γ		1.3	2.1
$\Delta E/E$		0.07	0.28
N_{coh}		$2 \cdot 10^2$	$6.8 \cdot 10^8$
E_{coh}	TeV	$1.5 \cdot 10^1$	$2.1 \cdot 10^8$
N_{incoh}		$8 \cdot 10^4$	$3 \cdot 10^5$
E_{incoh}	TeV	$3.6 \cdot 10^2$	$2.3 \cdot 10^4$
n_{Had} ($W_{\gamma\gamma}$ >2 GeV)		0.3	3.2

[a] This value holds for CLIC_SiD, and has been used throughout the accelerator studies for this CDR. For CLIC_ILD, the corresponding value is 4.3 m.

CLIC CDR

Future Lepton Collider Experiments

parameter	FCC-ee	LEP2
energy/beam	45 – 175 GeV	105 GeV
bunches/beam	**50 – 60000**	4
beam current	**6.6 – 1450 mA**	3 mA
hor. emittance	**~2 nm**	~22 nm
emittance ratio $\varepsilon_y/\varepsilon_y$	**0.1%**	1%
vert. IP beta function β_y^*	**1 mm**	50 mm
luminosity/IP	**1.5-280** x 10^{34} $cm^{-2}s^{-1}$	0.0012 x 10^{34} $cm^{-2}s^{-1}$
energy loss/turn	0.03-7.55 GeV	3.34 GeV
synchrotron radiation power	**100 MW**	23 MW
RF voltage	0.3 – **11 GV**	3.5 GV

20 Mrad / year in the forward region (estimate)

Frank Zimmermann, FCC Week, Washington DC, March 2015

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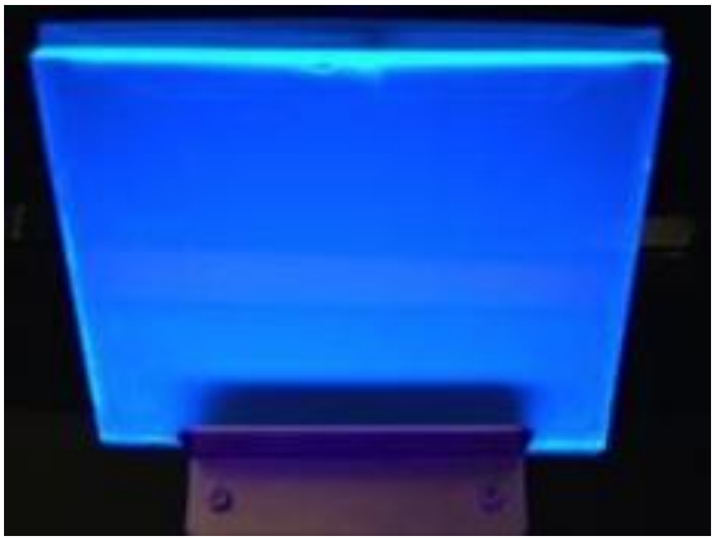
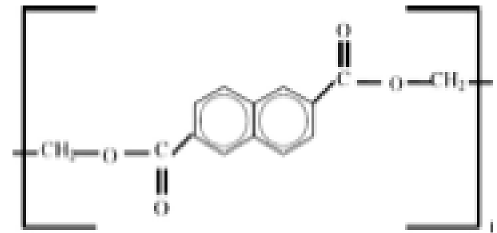
Intrinsically Rad-Hard Scintillators

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

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.

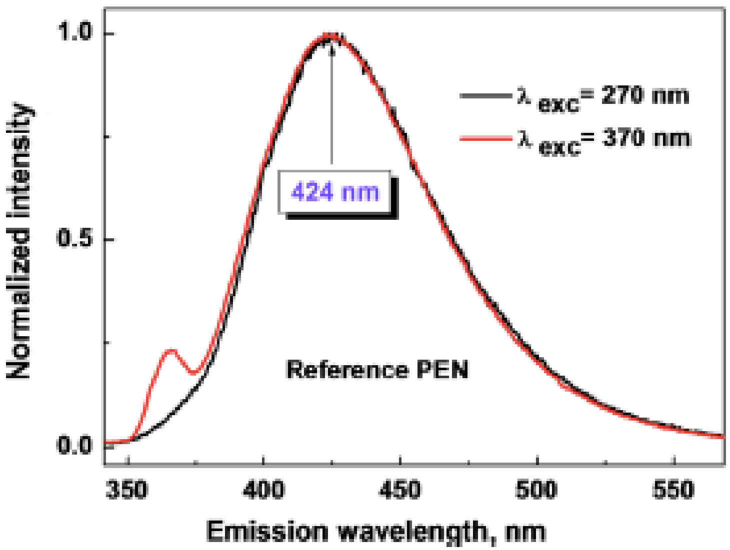
Material	Polyethylene naphthalate	Organic scintillator (ref. [14])	Plastic bottle (ref. [13])
Supplier	Teijin Chemicals	Saint-Gobain	Teijin Chemicals
Base	$(C_{14}H_{10}O_4)_n$	$(C_9H_{10})_n$	$(C_{10}H_8O_4)_n$
Density	$1.33\,g/cm^3$	$1.03\,g/cm^3$	$1.33\,g/cm^3$
Refractive index	1.65	1.58	1.64
Light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

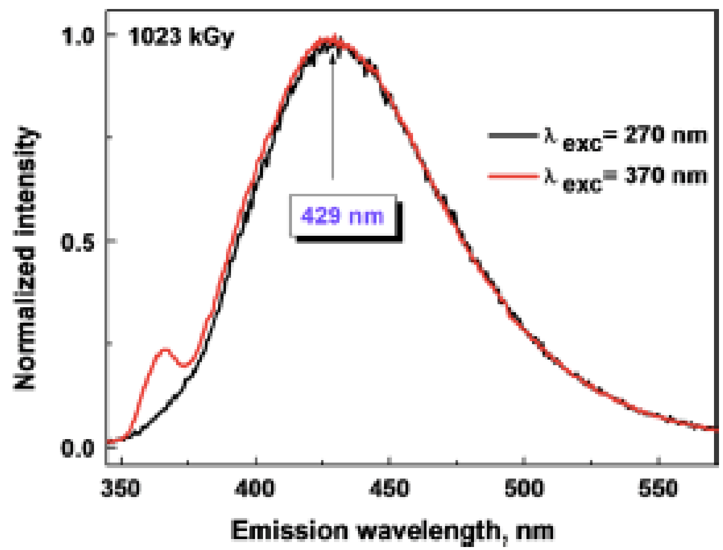
Intrinsically Rad-Hard Scintillators - PEN

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.

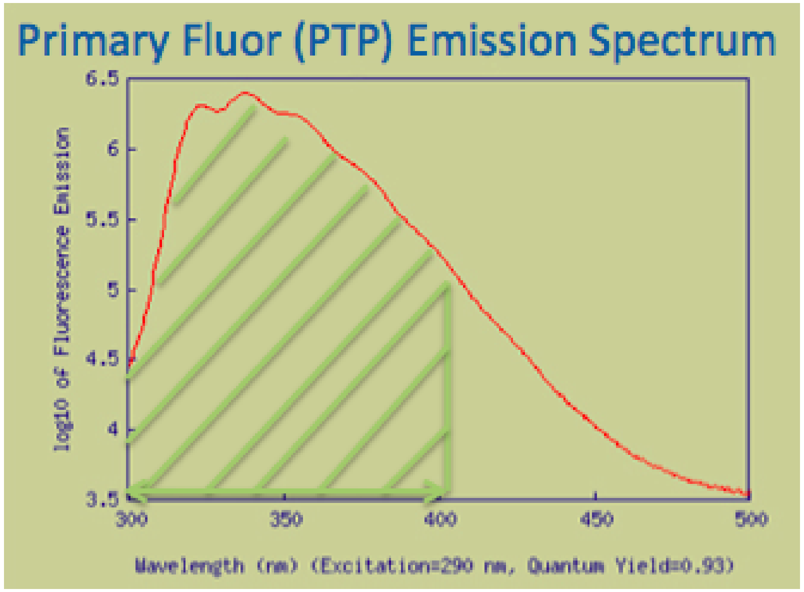
Excitation wavelength	Reference-PEN	650 kGy	1023 kGy
$\lambda_e = 270$ nm	1	0.98	0.95
$\lambda_e = 370$ nm	1	0.98	0.96

New “SX” 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.



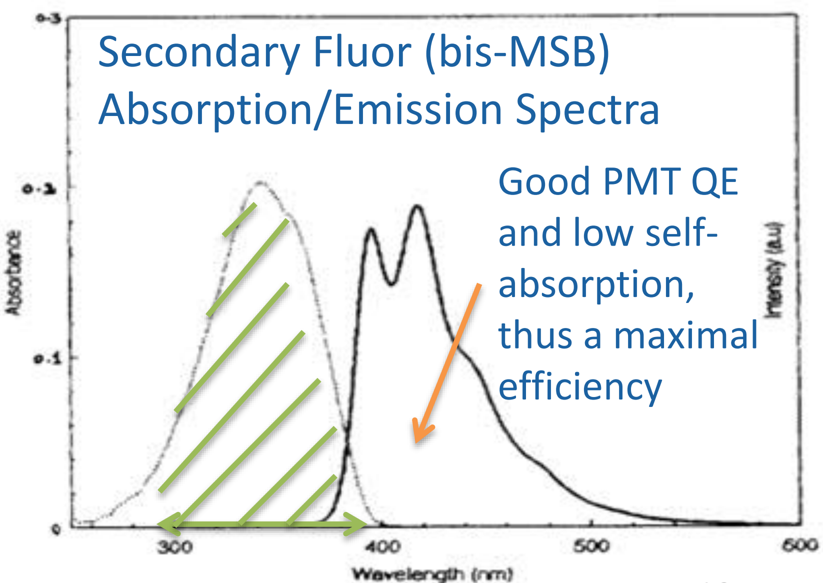
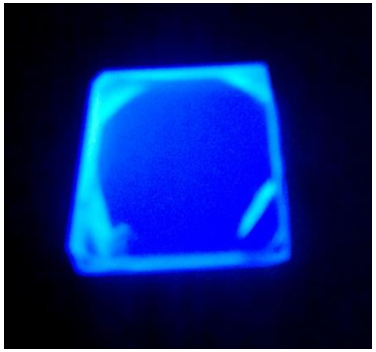
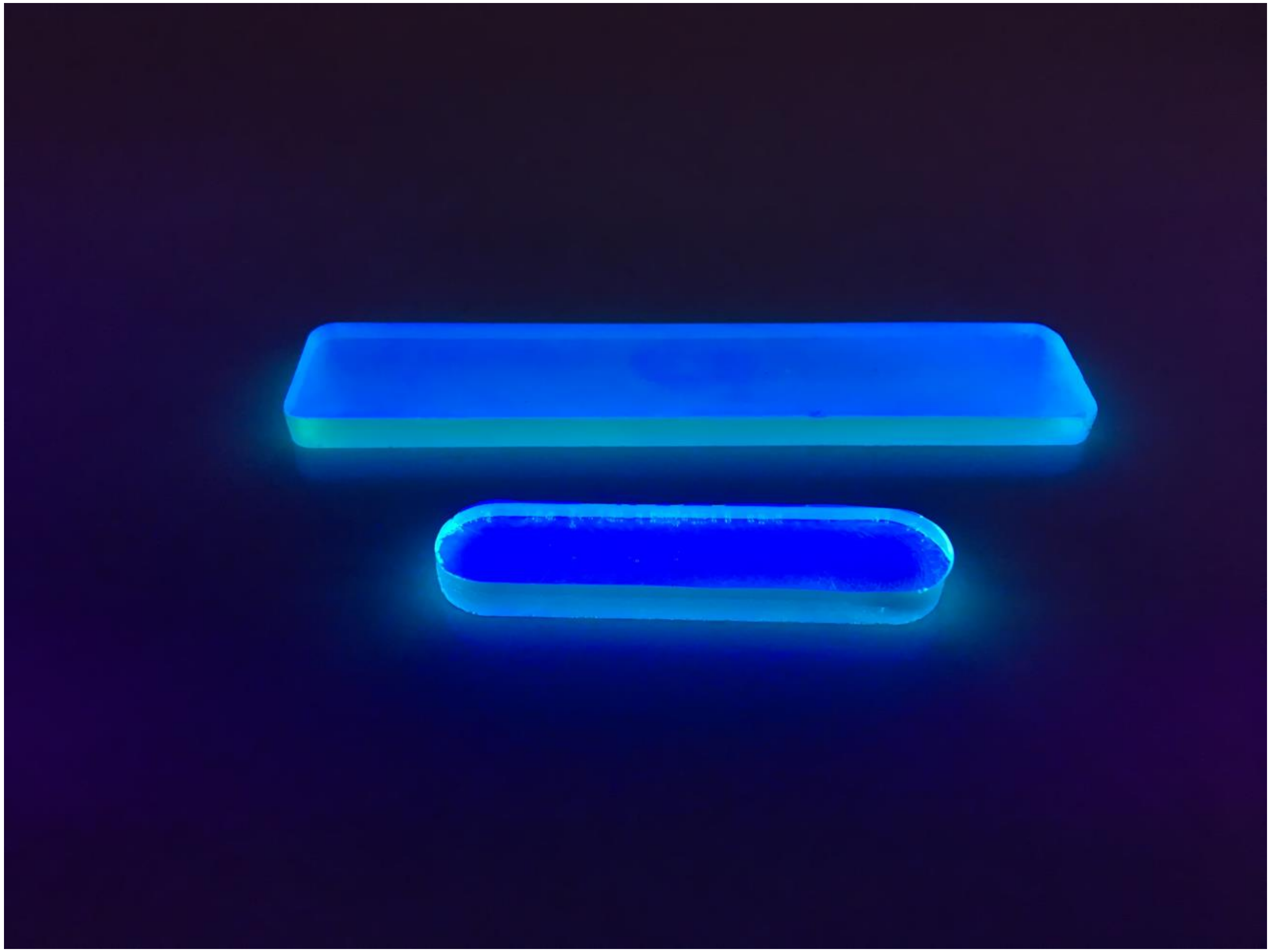
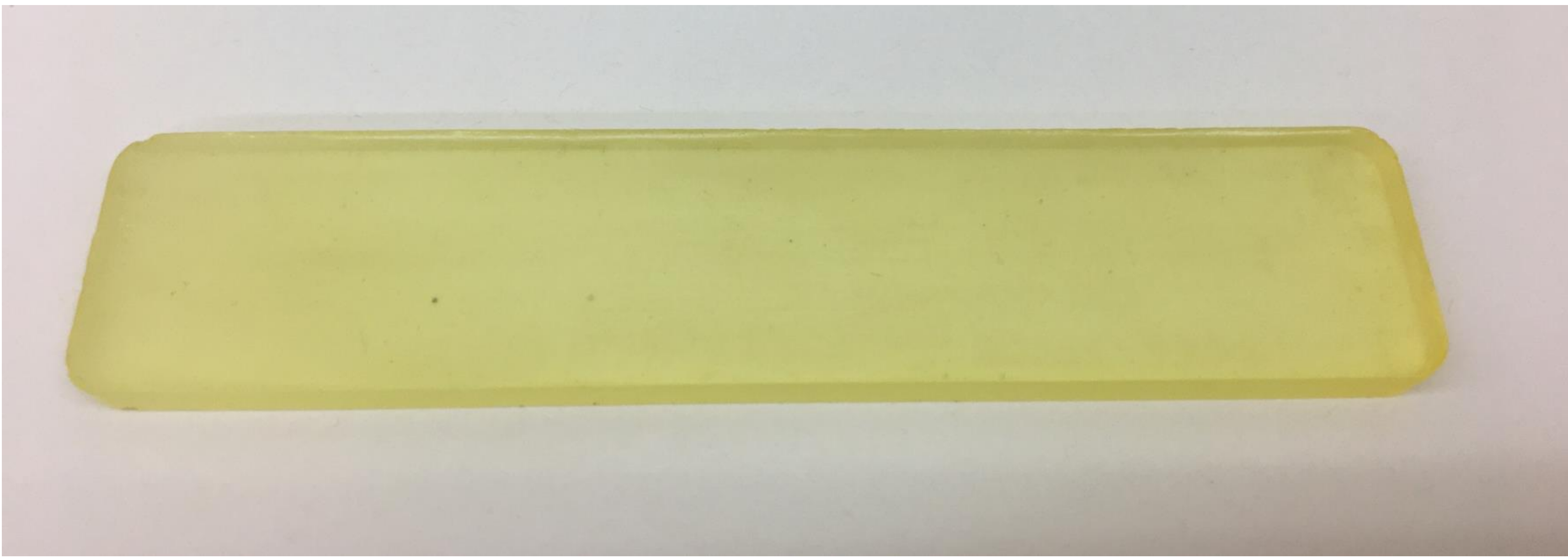


Fig. 1. Absorption (· · ·) and emission (———)



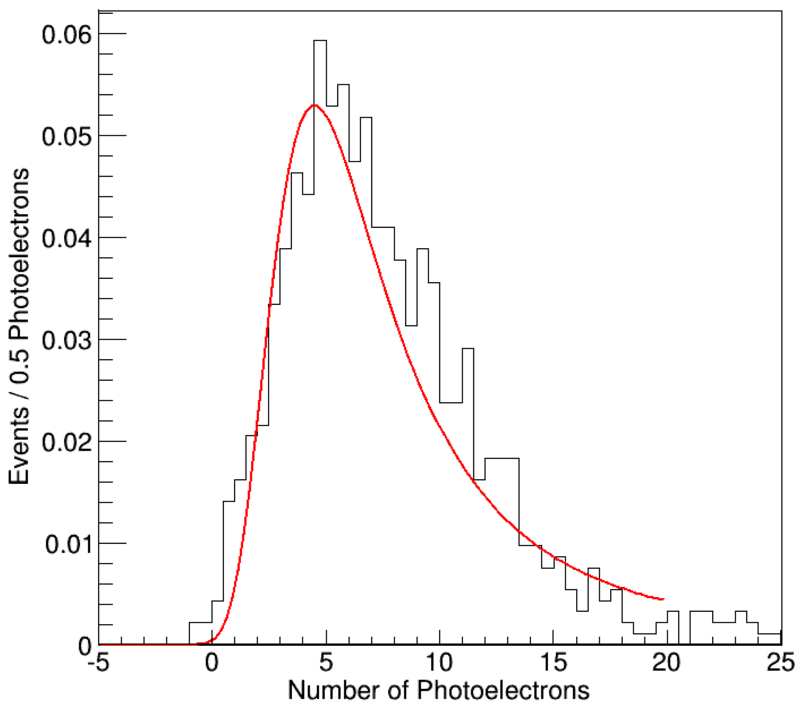




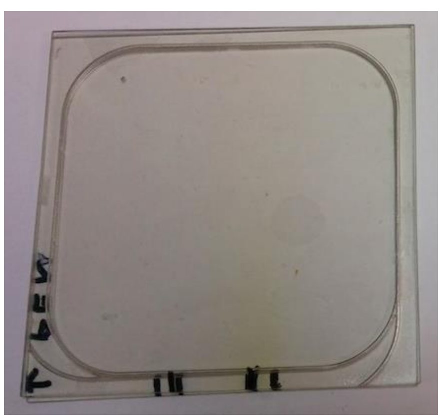
Tests with Direct PMT Coupling

- Tiles tested: clean quartz, PEN and SX-1
- Beam: Fermilab 120 GeV proton beam
- Readout: Hamamatsu R7600U-200 directly coupled to the edge → Scope

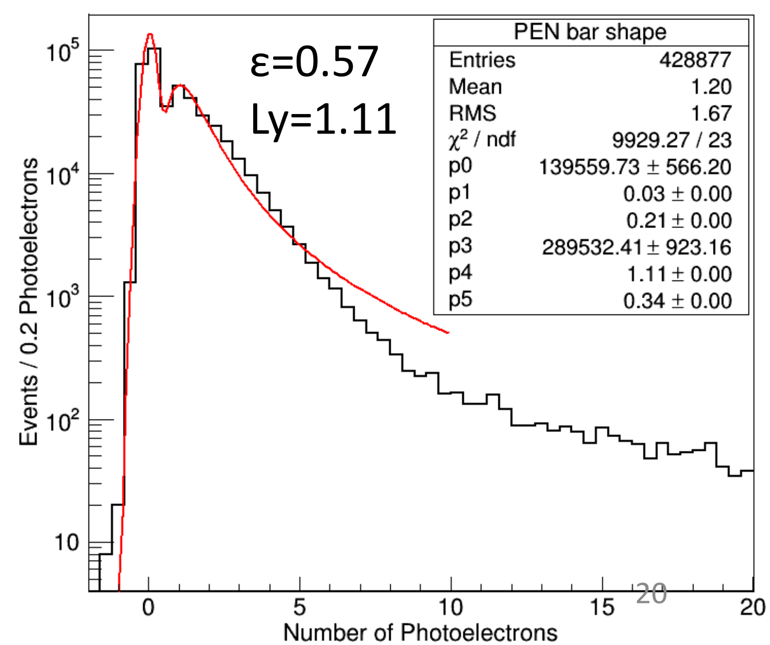
PEN



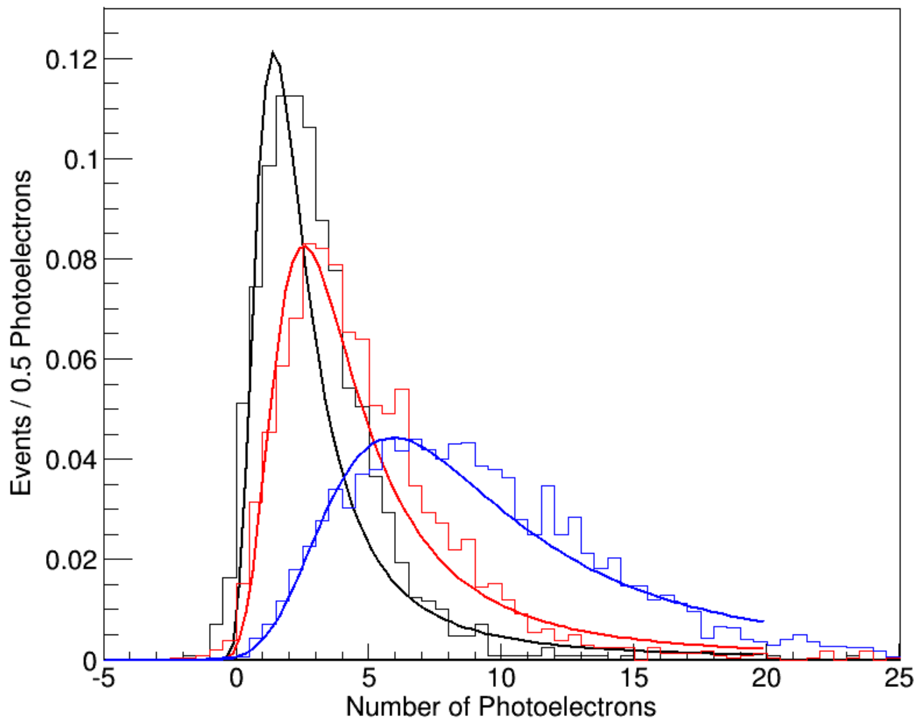
4 1-mm PEN tiles



CERN TB14 2 mm PEN tile with green fiber



Clean Quartz

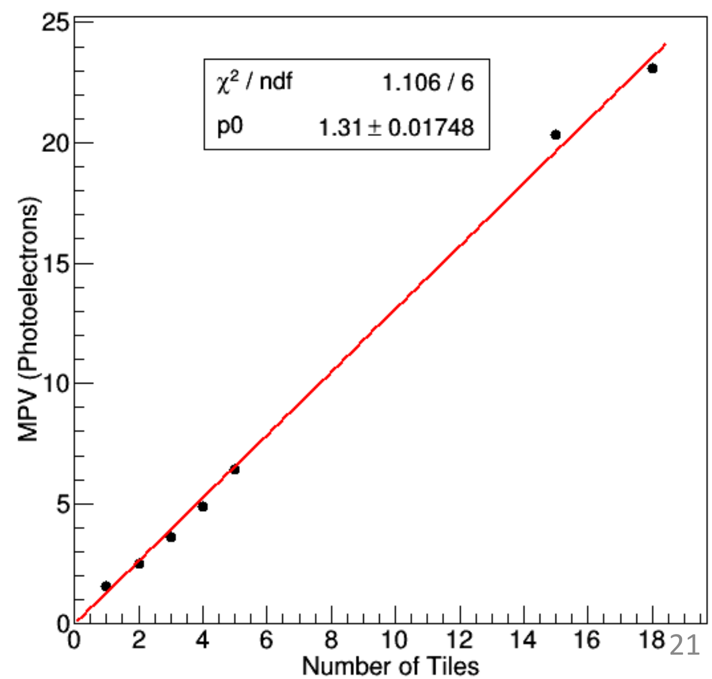


Single tile with reflective wrapping

5 tiles with no wrapping

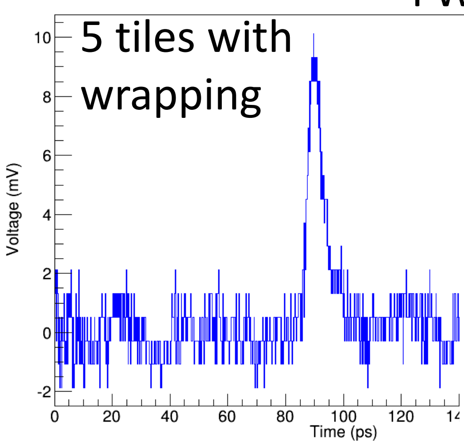
5 tiles with individual reflective wrappings

1 mm clean quartz tiles

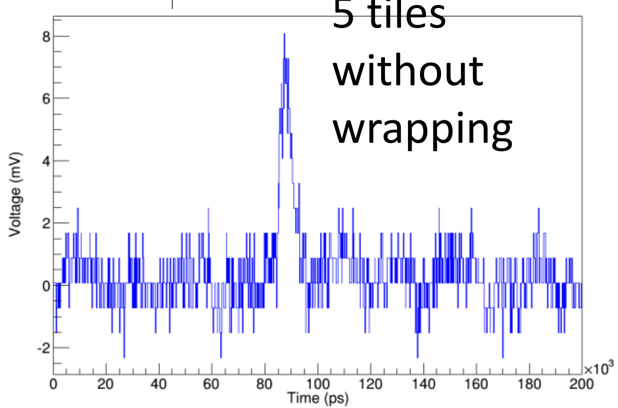


FW @ 1/10 ~ 10 ns

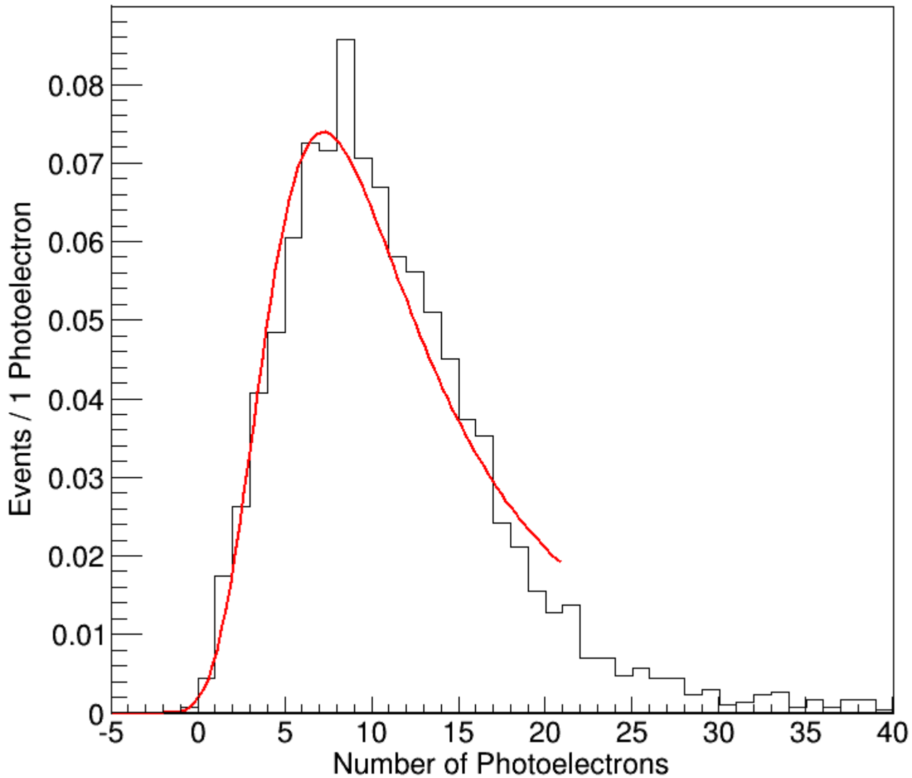
5 tiles with wrapping



5 tiles without wrapping



SX-1



Small sample: 2 cm x 3 cm x 6 mm

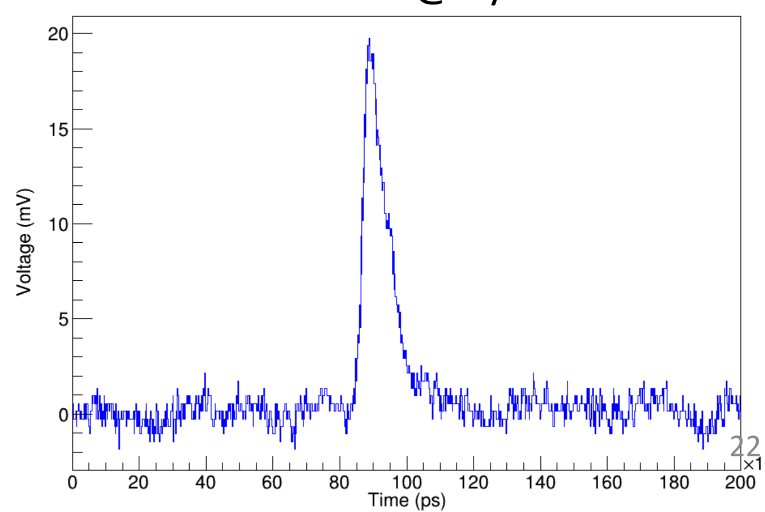
The edge coupling the PMT is polished.

No reflective wrapping.

Tile

PMT

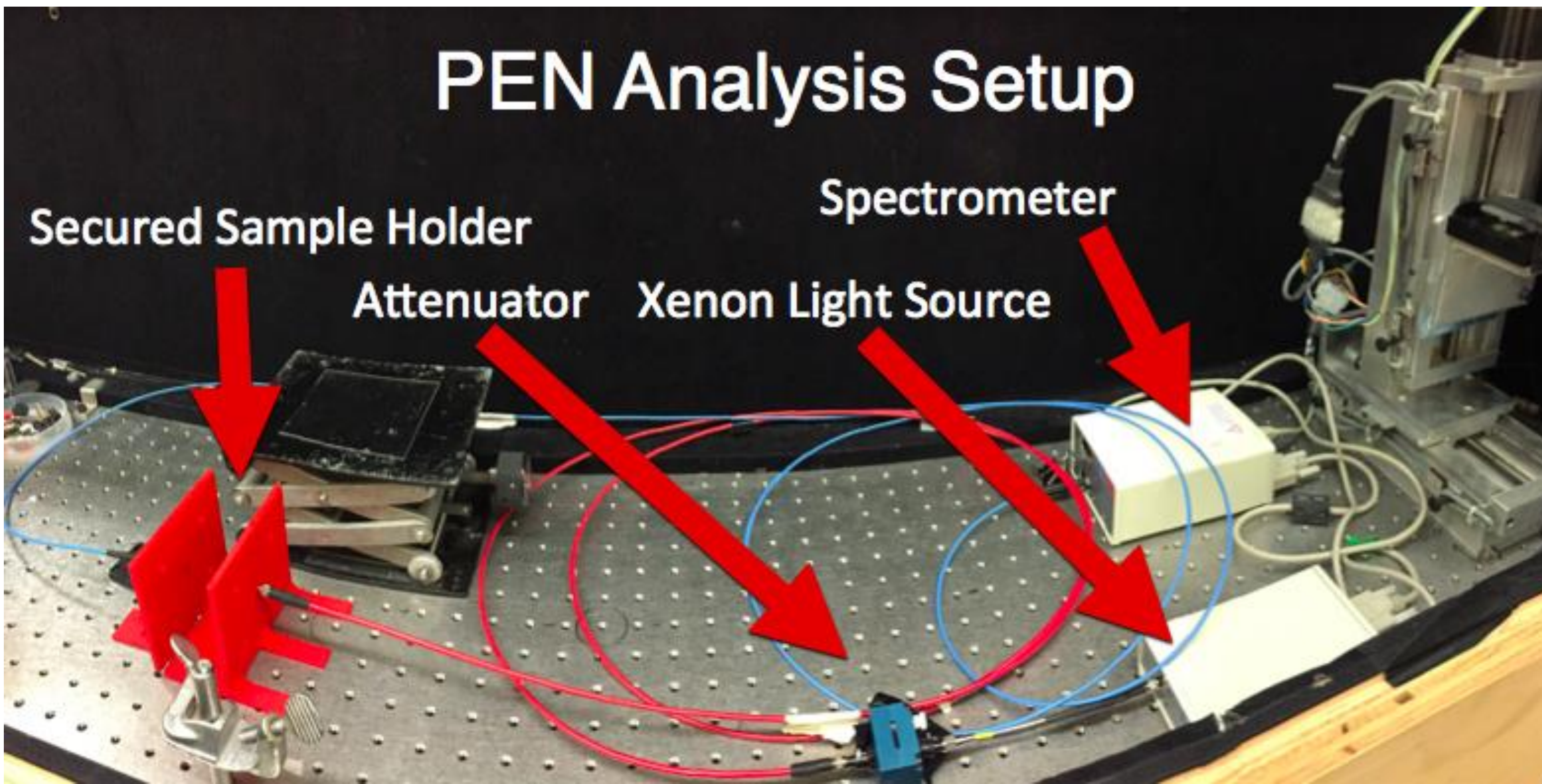
FW @ 1/10 ~ 15 ns



PEN Radiation Damage Studies (MSU)

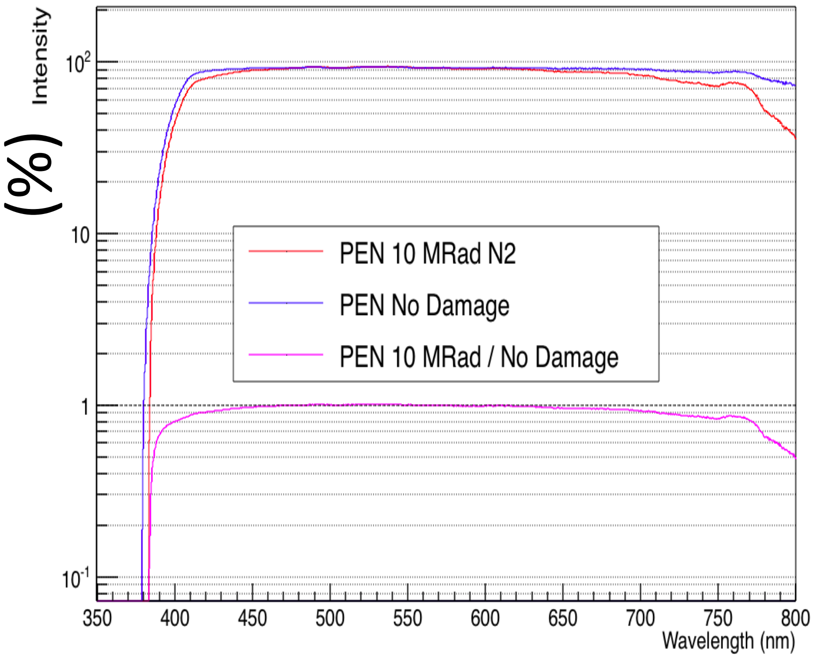
Facilities:
- National Superconducting Cyclotron Laboratory
- Used ^{60}Co, 1.33 MeV Gammas

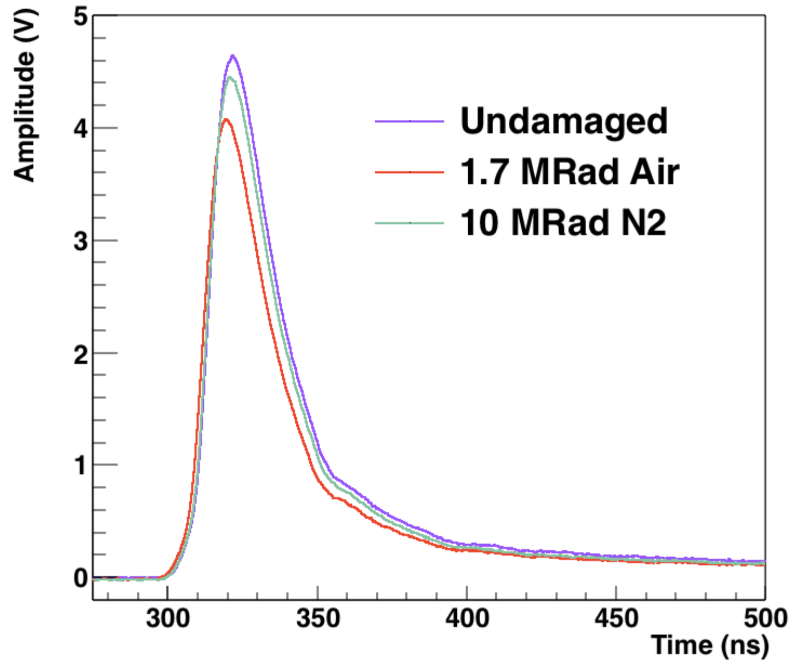
Two Samples:
- 1.7 MRad in Air
- 10 MRad in N_2



PEN Radiation Damage Studies (MSU)

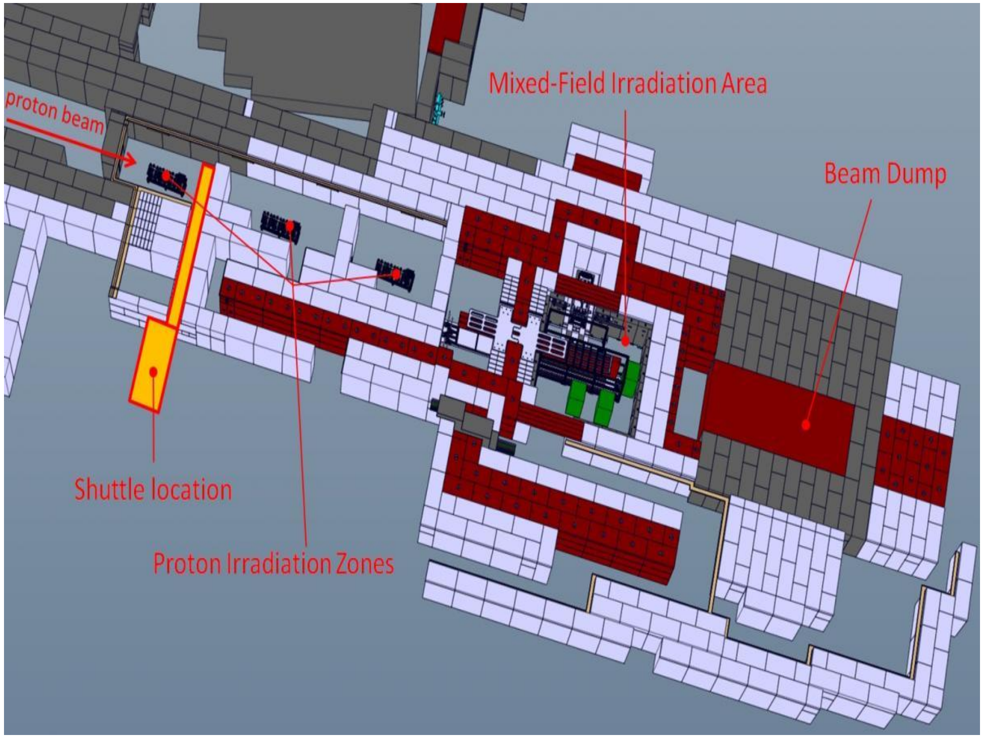
Transmission





	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

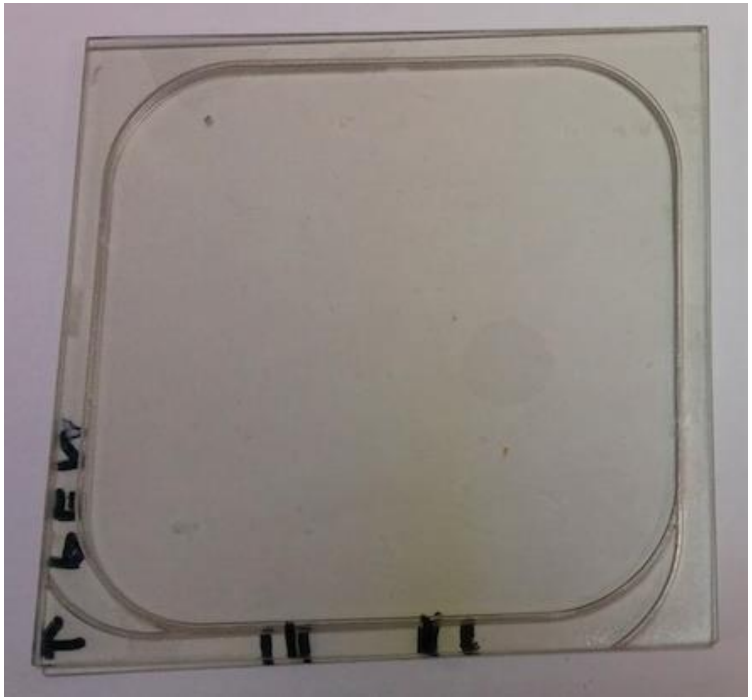


24 GeV protons ,
beam spot (FWHM) 15x15 mm^2
proton flux - ~$6x10^9$ p cm^{-2} s^{-1}

- 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.

New "SX" Scintillators

Lose only 7 % transmission after 40 Mrad proton radiation

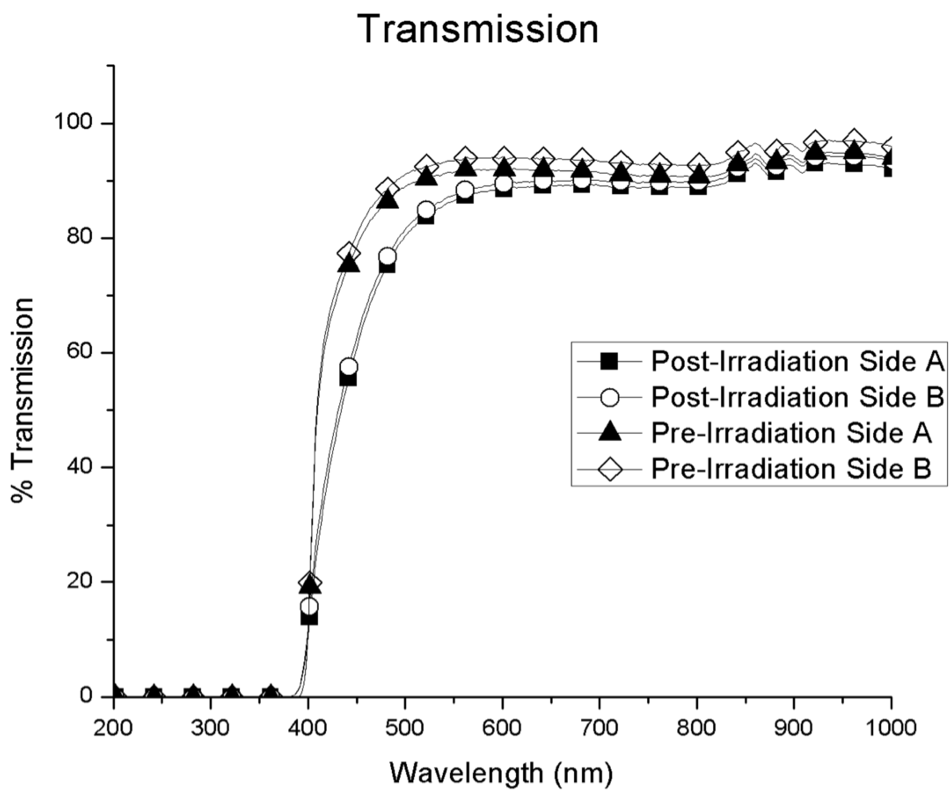


Figure 3: The transmission before and after irradiation;

New “SX” Scintillators

Almost no change on emission and absorption after irradiation

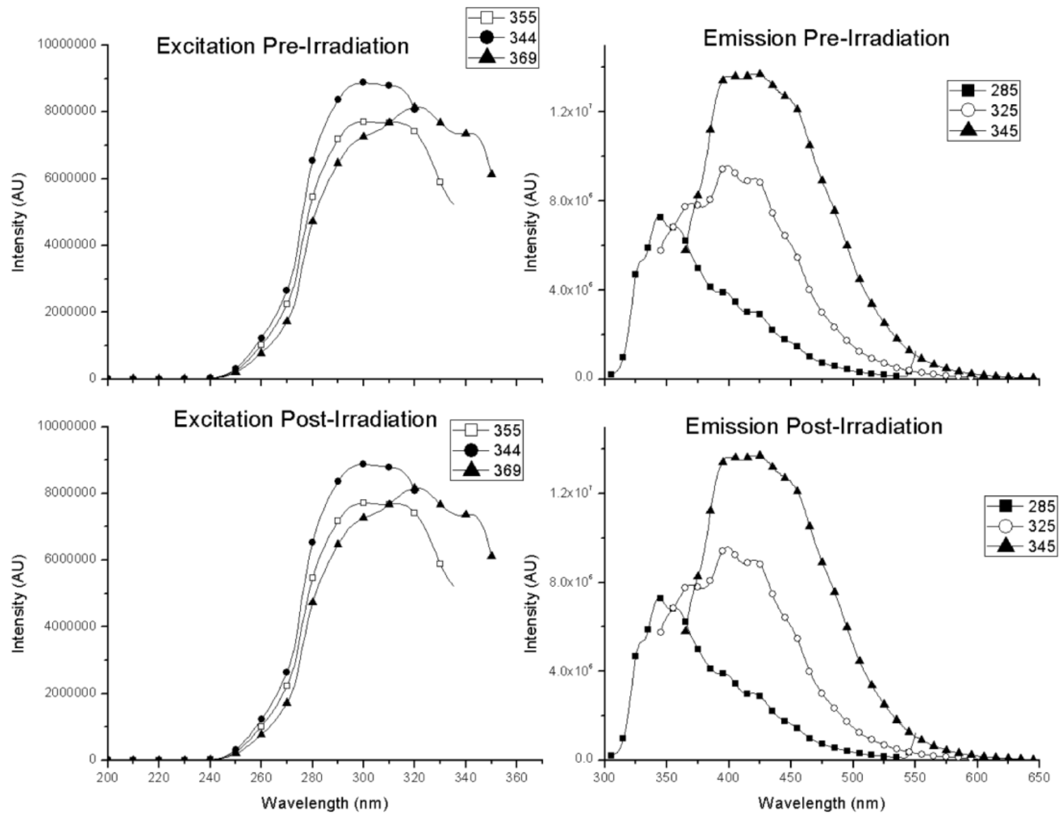


Figure 3: The excitation/emission taken before and after irradiation

Radiation Damage Studies (Iowa)

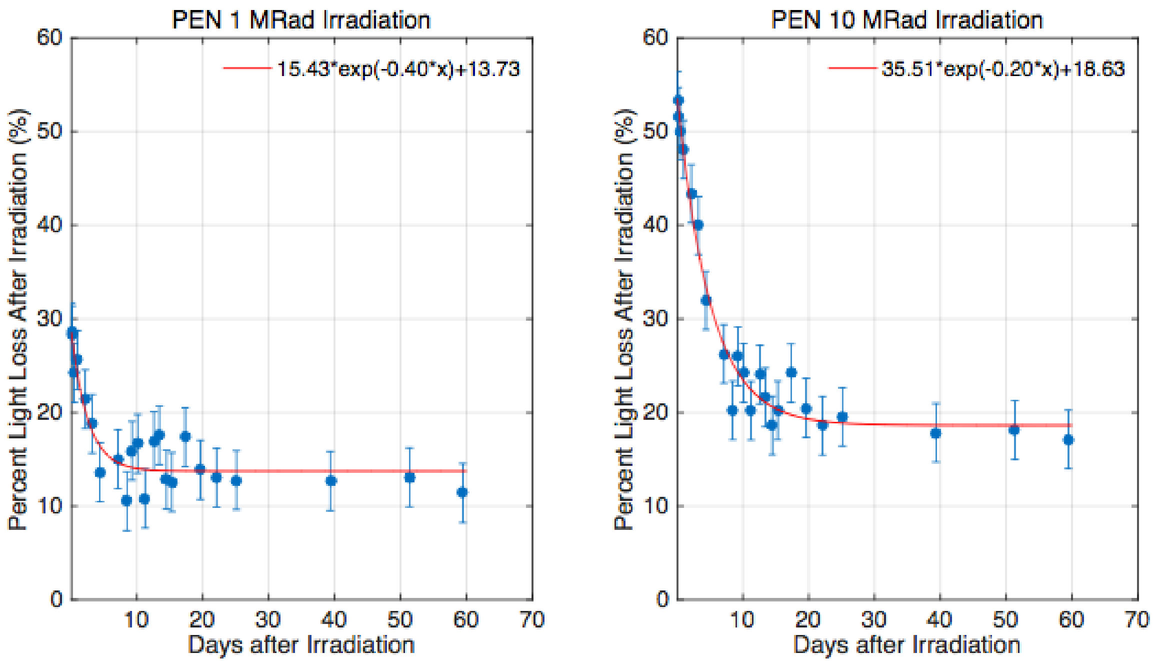
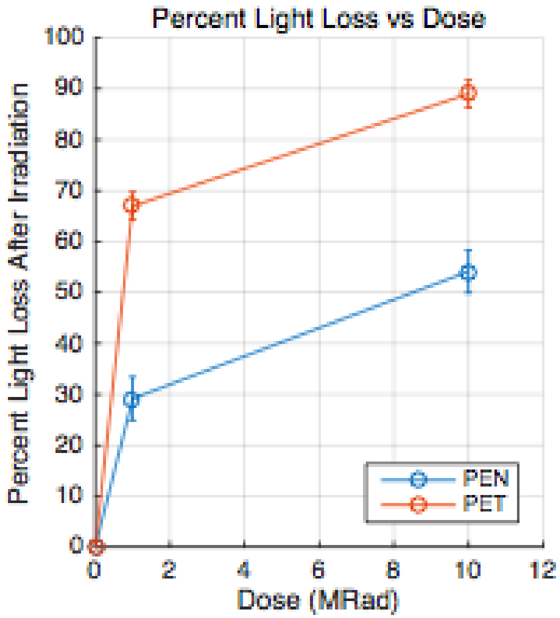


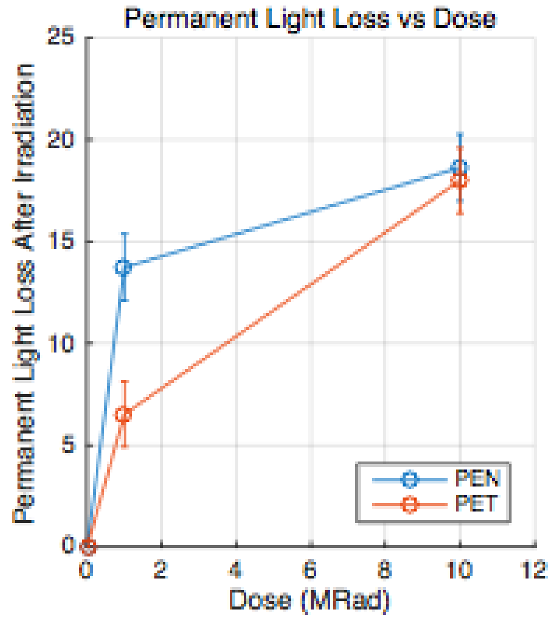
Table 1. Summary of PEN irradiation results

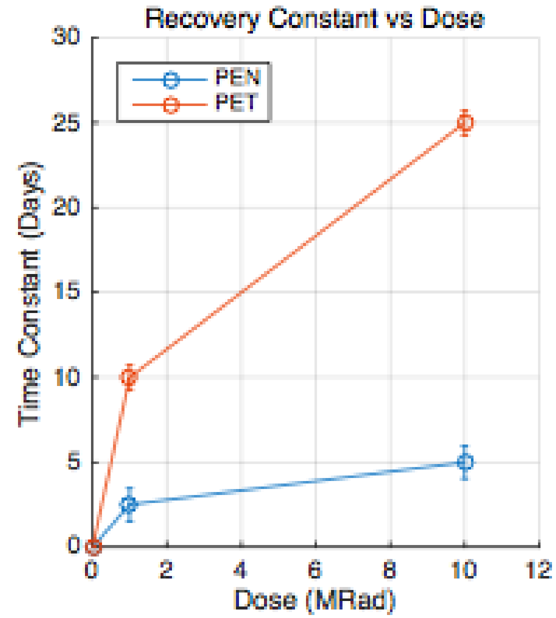
Total Dose	Initial Light Yield	Recovered Light Yield	Recovery Time (days)
1.4 Mrad	71.4 ± 2.4%	85.9 ± 2.4%	5
14 Mrad	46.7± 2.7%	79.5 ± 2.7%	9

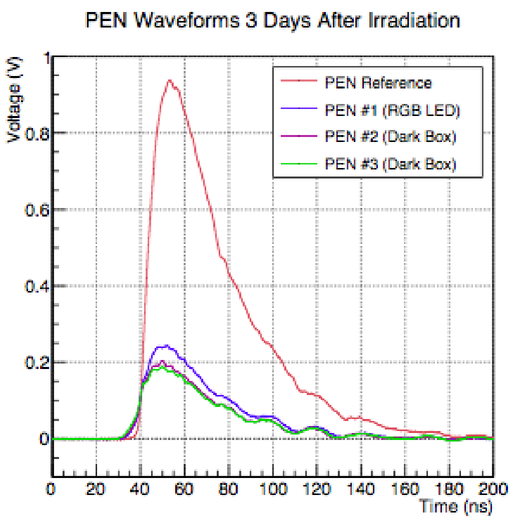
JINST 11 P08023, 2016

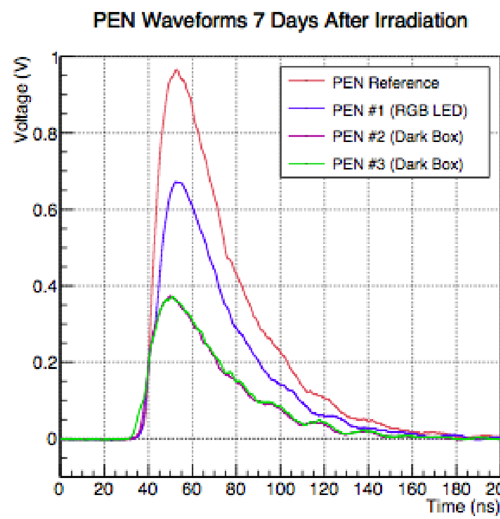
Radiation Damage Studies (Iowa)





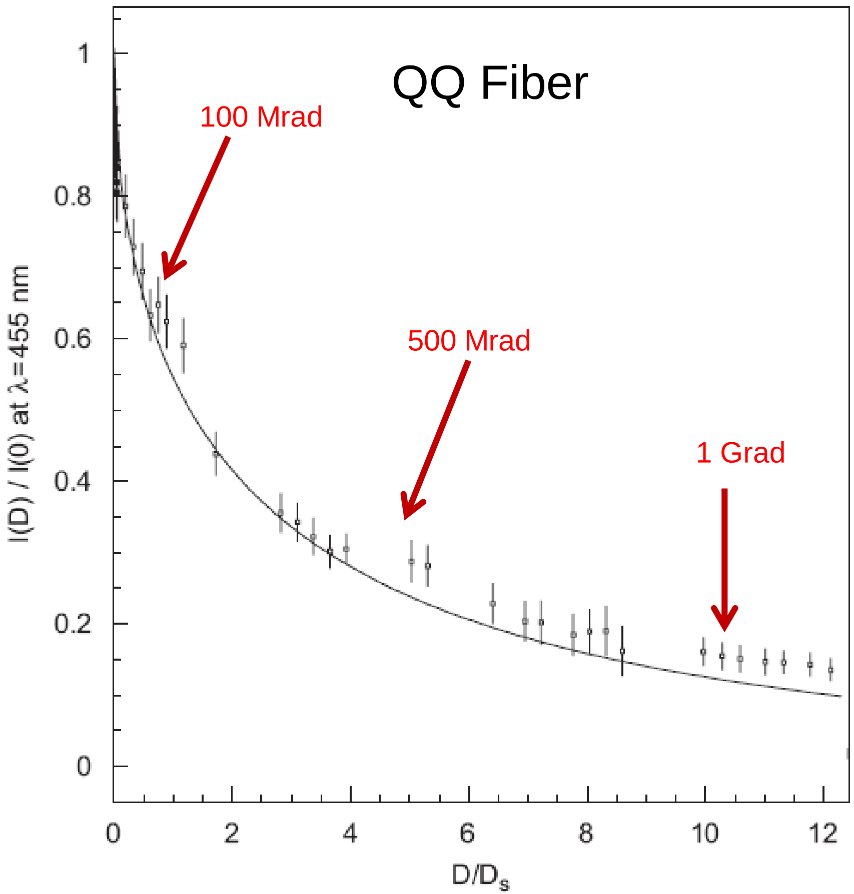


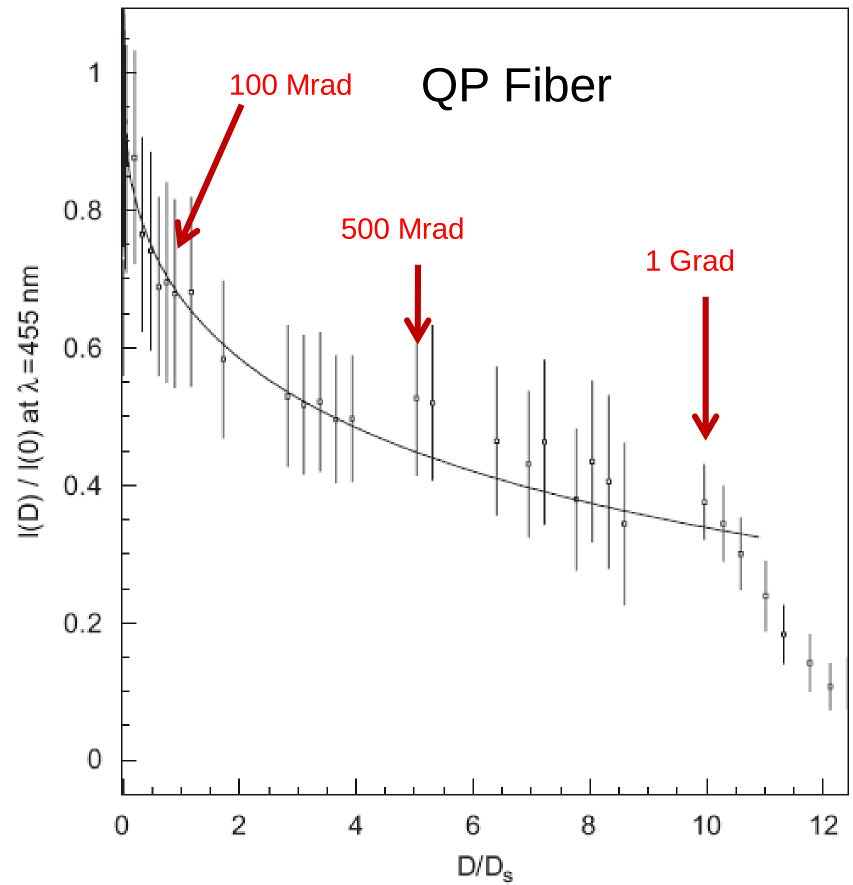




JINST 11 P08023, 2016

QQ vs. QP Fibers: Radiation up to 1.25 Grad at CERN

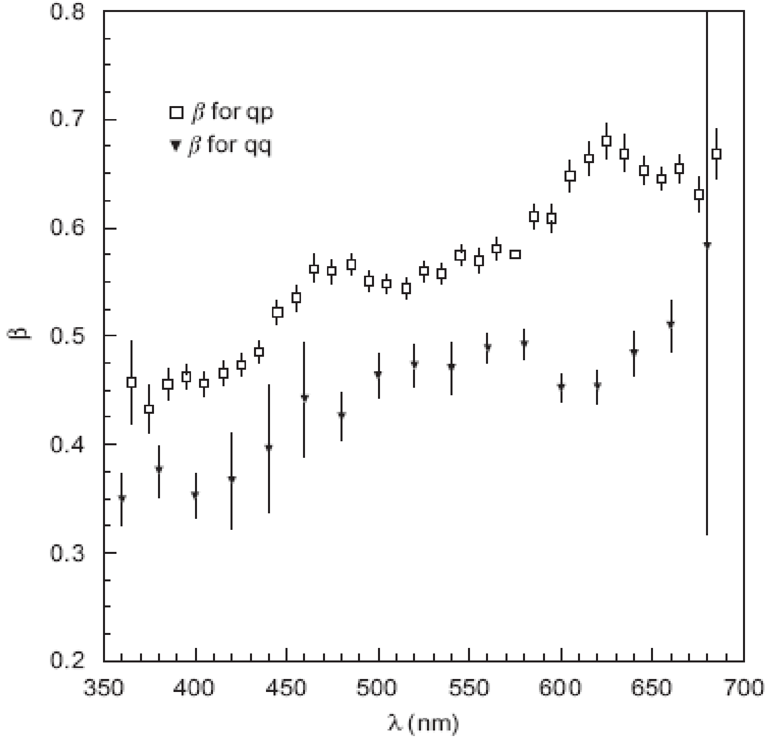


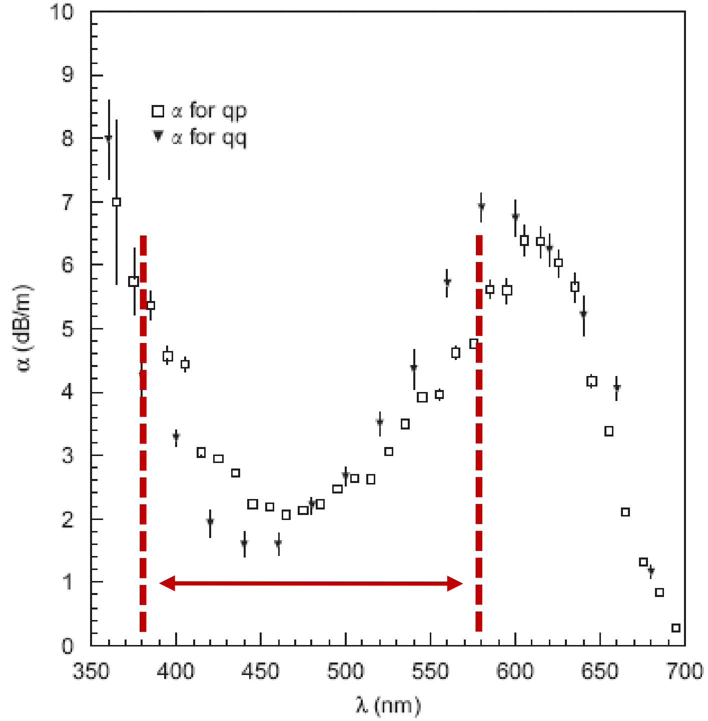


D_s: transmission after 100 Mrad

Attenuation in QQ and QP Fibers due to Radiation

$$A(\lambda, D) = \alpha(\lambda)[D/D_s]^{\beta(\lambda)}$$





“Sweet range” : The fibers get less damage between 400 nm and 580 nm range.

D_s: transmission after 100 Mrad

Outline

1. The necessity of new radiation-hard materials in high energy physics experiments
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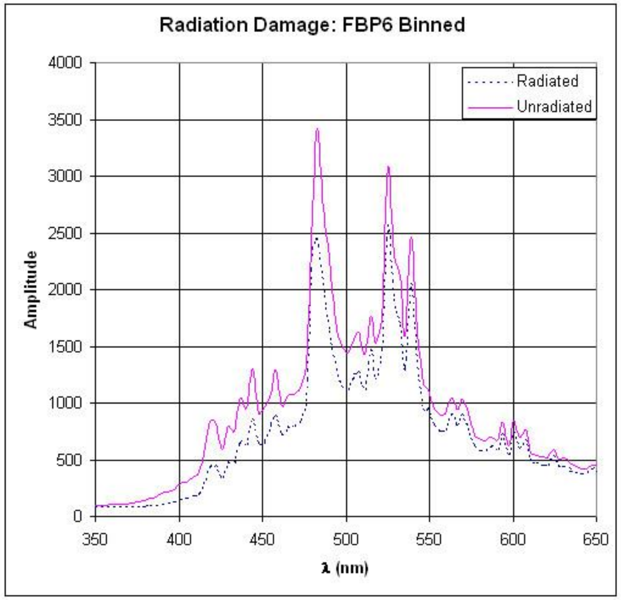
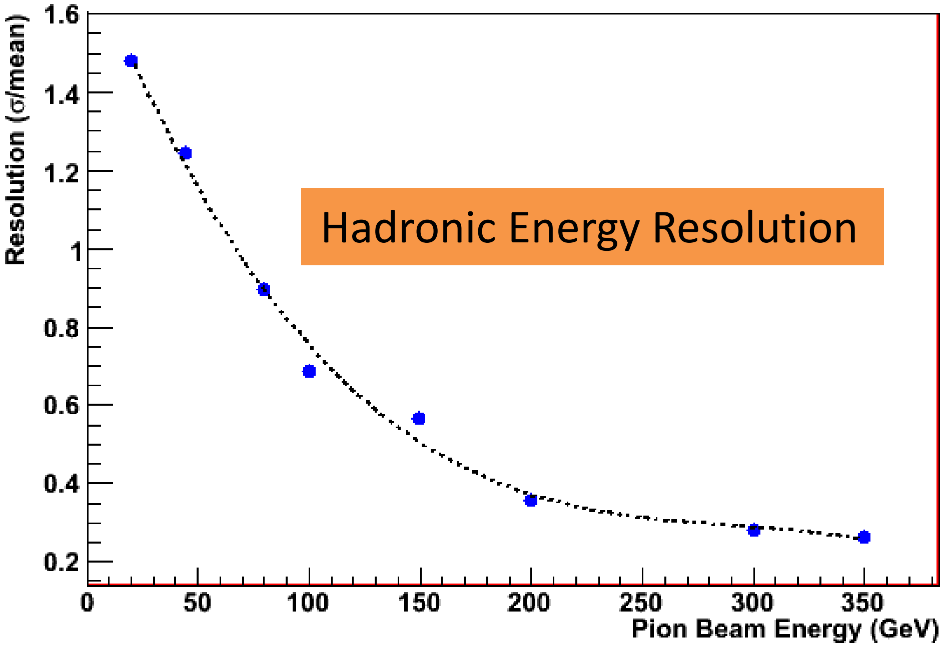
Quartz Radiation Damage Studies

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.

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.**

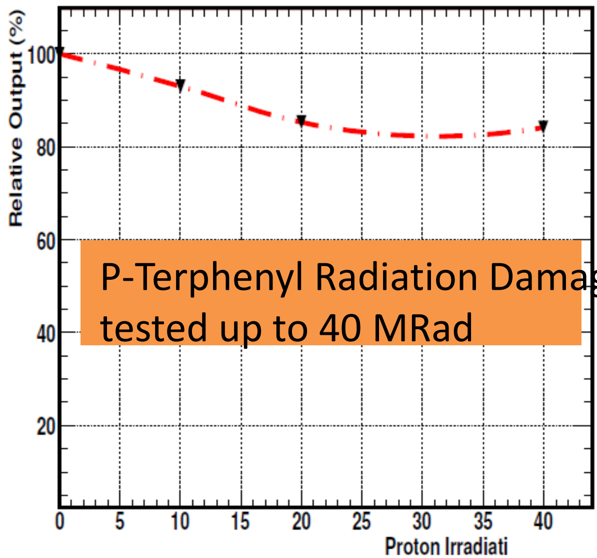
1. Double-sided Single Plate: coated 300 µm ≤ 3 mm thick tiles (thickness & optical finish chosen for the lowest cost, up to 3mm thick), 10 x 10cm; coating thickness up to ~10 µm. Minimum 2 Tiles each of 2 downselected materials. Readout: WLS fibers.

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

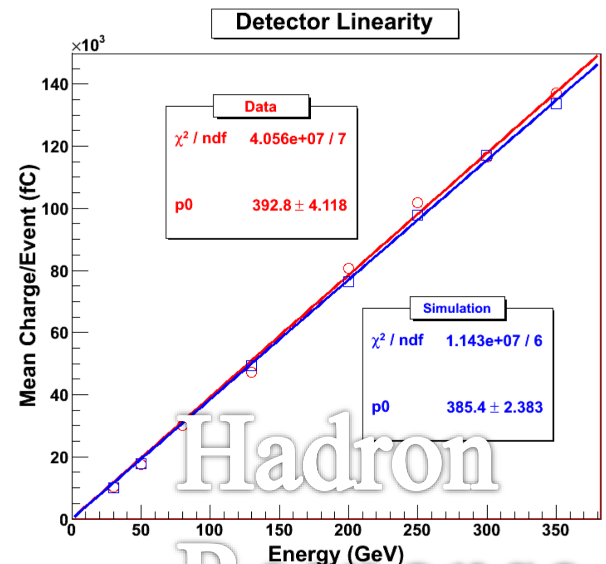
Fermilab's THIN FILM Facility Coating Systems at Lab 7

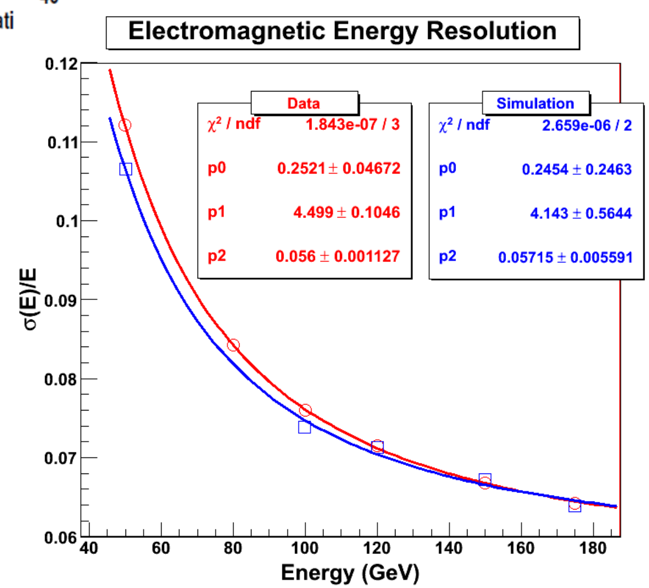
- 2 Bell Jar sputtering systems
  - Al, Ag, Au, Cr, Cu, Ir, Ni, PtIr, Ti, ZnO2-Ga
- 2 tube sputtering systems-dedicated to 99.999% pure aluminum sputtering
  - Optical fiber mirroring
- 1 Bell Jar system for resistive evaporation
  - Al, Ag, Au, Cr, Cu, Al & MgF2 surface mirrors, Ni, NiCr, TiN
- 1 Pyrex 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

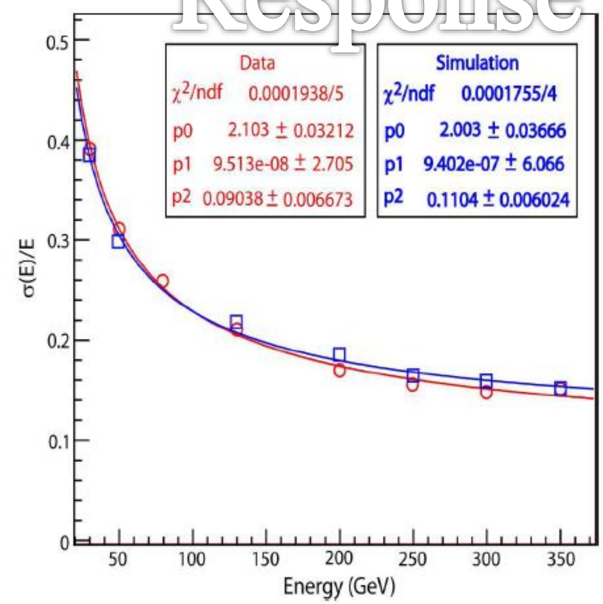


P-Terphenyl Radiation Damage tested up to 40 MRad

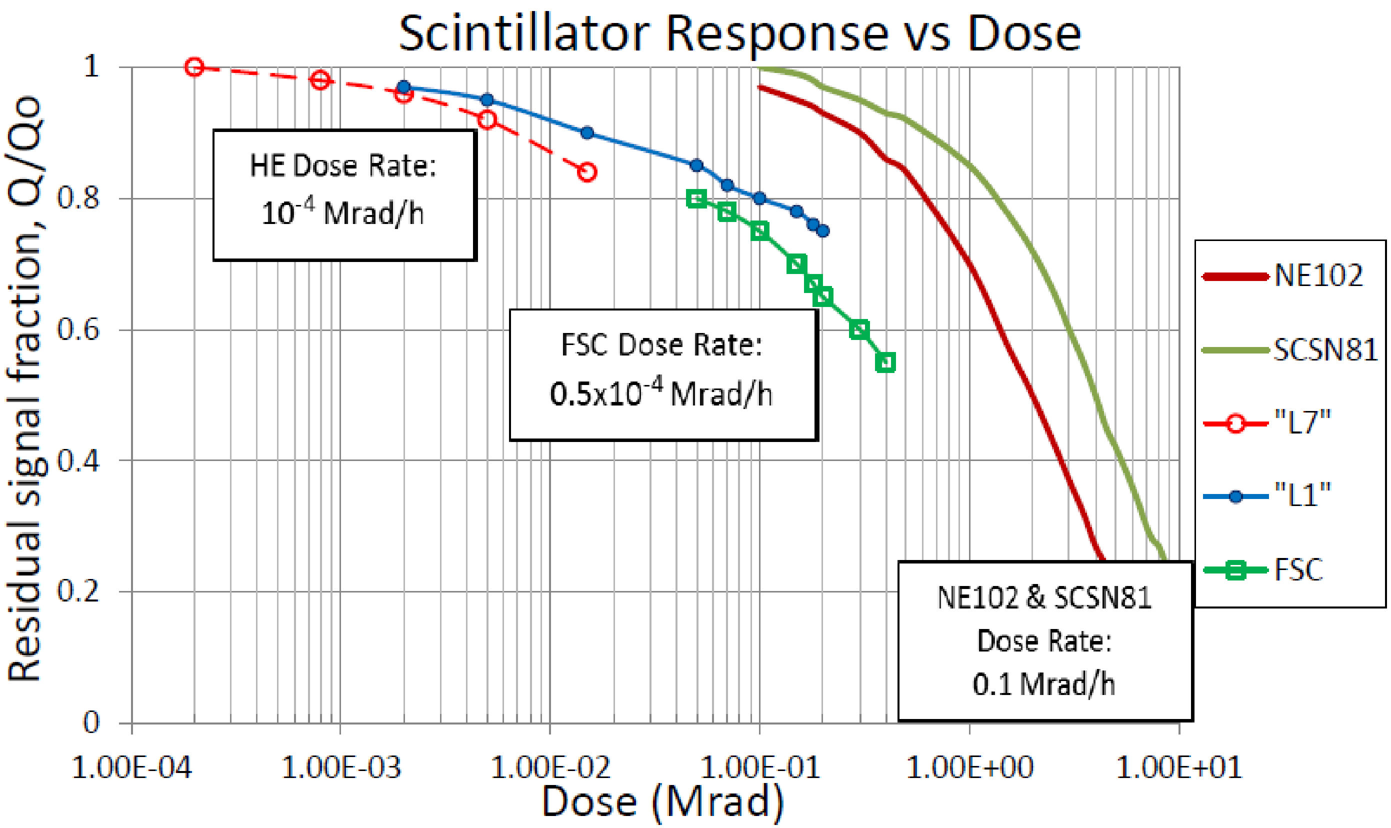




Hadron Response



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

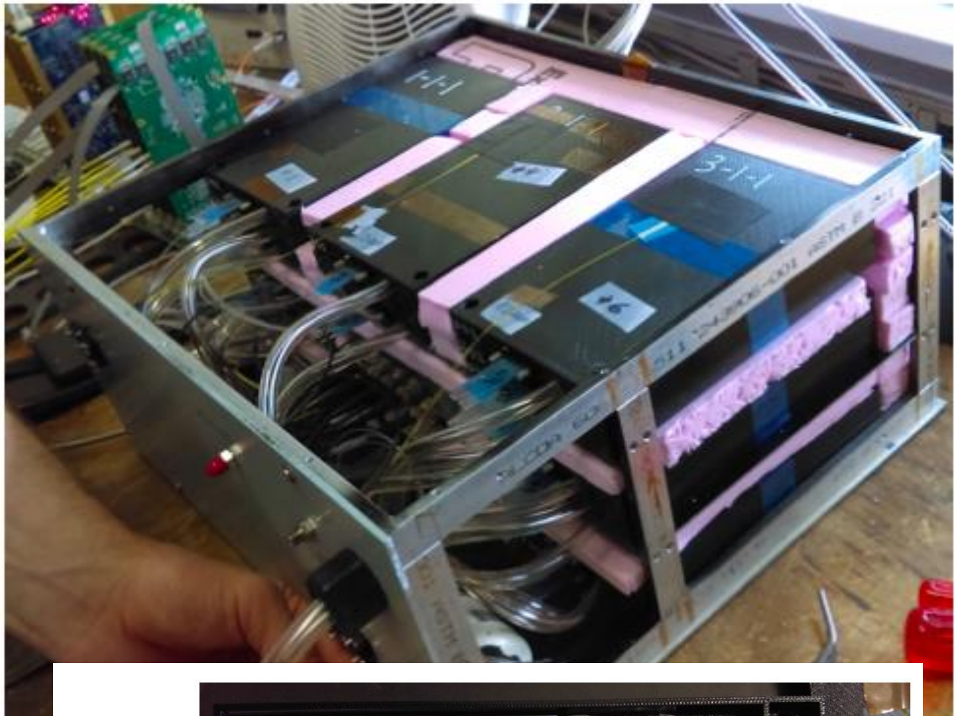


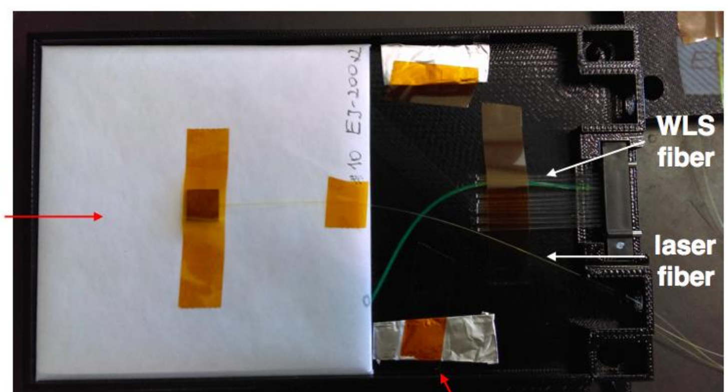
Scintillator radiation damage (and recovery) depend on "Dose Rate" and presence of O_2

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

CMS Castor Table Irradiation Study

Interior of a Dark Box





- **Purpose**:
  - take samples of different scintillator materials, candidates for Plan B or Phase II
  - irradiate samples near beam line
  - measure Dark Box signals (laser runs); normalize them to signal from reference tile outside high-radiation zone
  - measure light yield loss and recovery via normalized signal size
- Scintillator samples in two “Dark Boxes” will be irradiated on the CASTOR table

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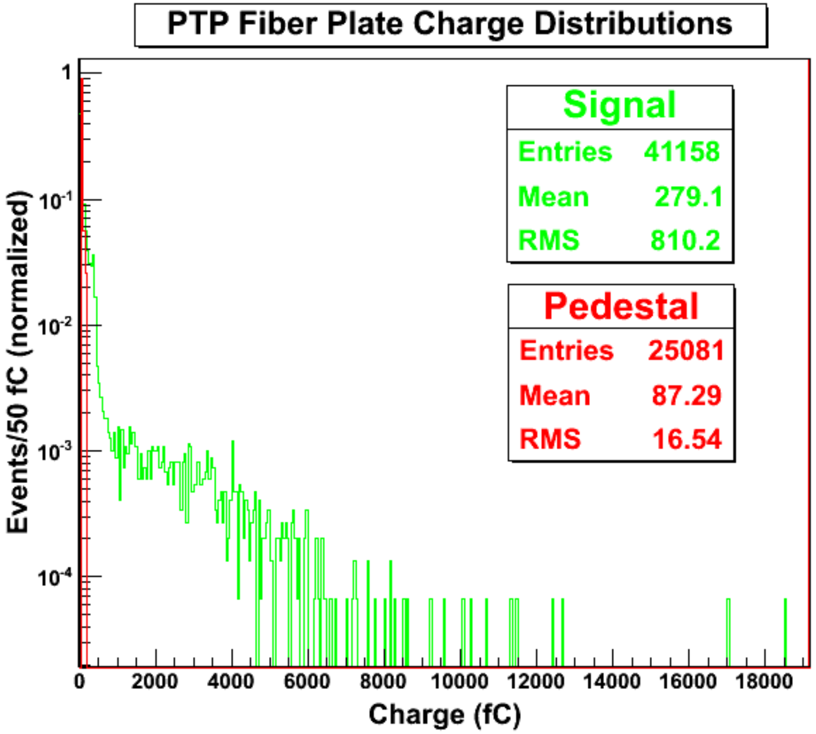
Quartz Fibers with pTp Coating

We deposited pTp on the stripped region, on both face. Then the whole ribbon was sandwiched between quartz plates.

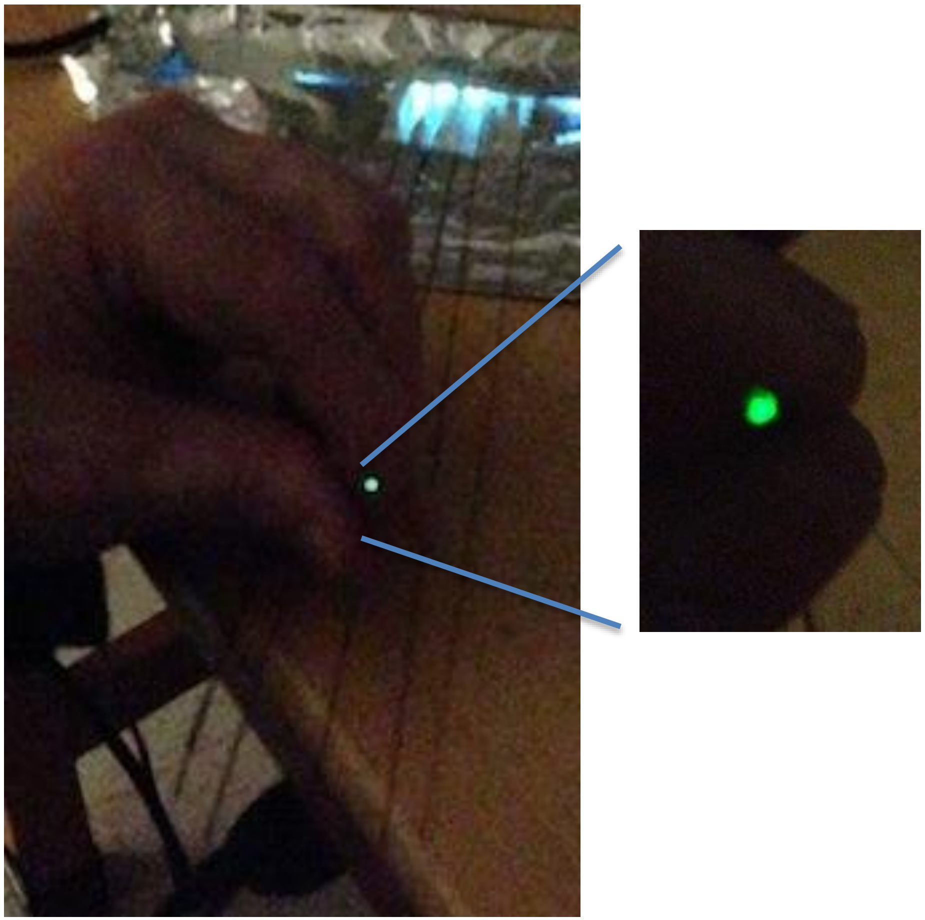


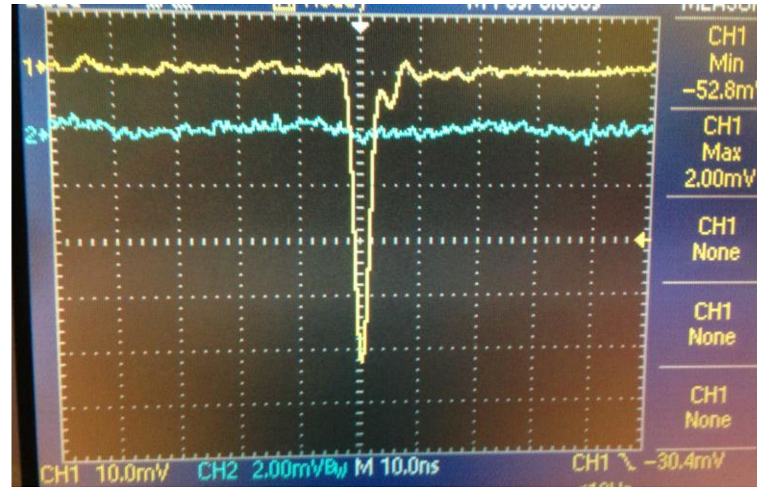
The University of Iowa

Capillary Tubes Filled with Anthracene

7 Anthracene-filled Scintillating fibers: Anthracene Cores with Quartz Claddings

UV light





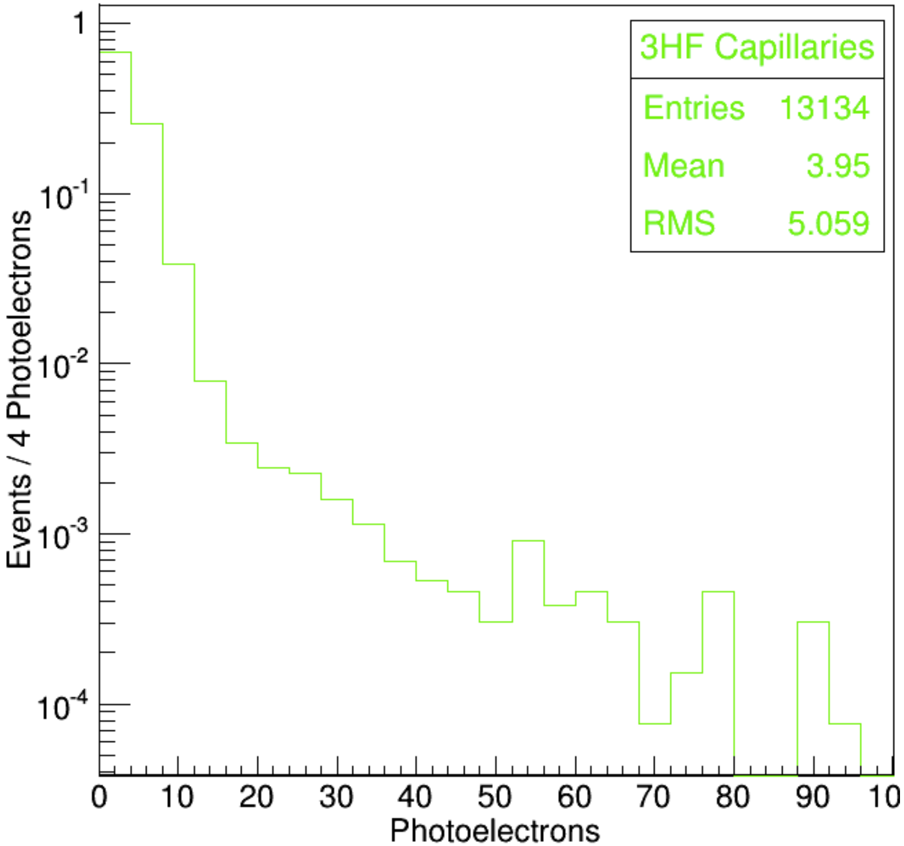
Typical pulse in 80GeV e^- beam

Expected Anthracene Fiber Pulse:
~200 KeV/mm x 0.25mm x 40 photons/KeV x 2% transmission x 20% QE ~ 8 p.e.

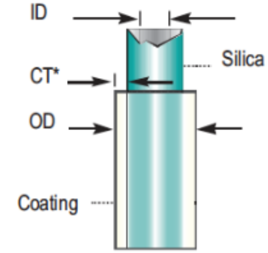
Typical Observed Pulse:
~ 8-9 p.e.

3HF Core Quartz WLS Capillaries

melt-conveyed or solvent conveyed
3 x100 µm core capillaries, ~15-20 cm long, in grooved HE Scintillator bar



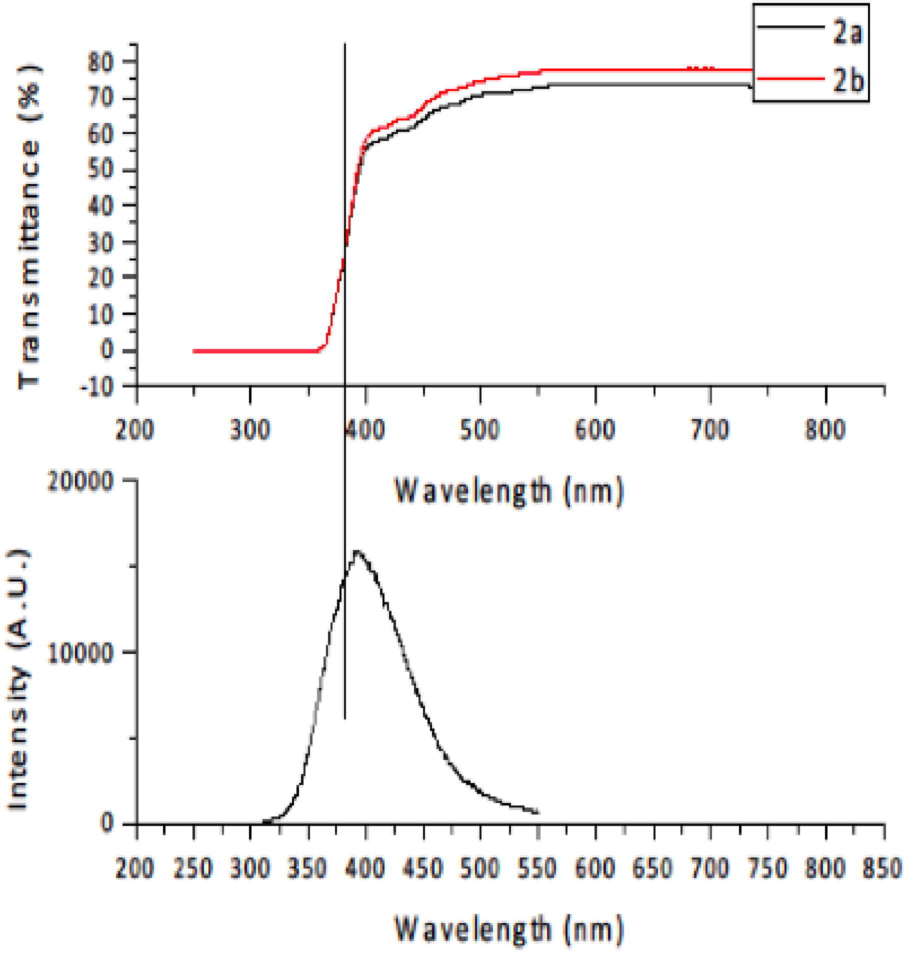
Cut at 1 pe



100 µm core, 360 µm OD
with UV transparent buffer
(< 1/25 HE WLS Core Volume)
Only 3 fibers in this test.
Larger Capillaries Needed!

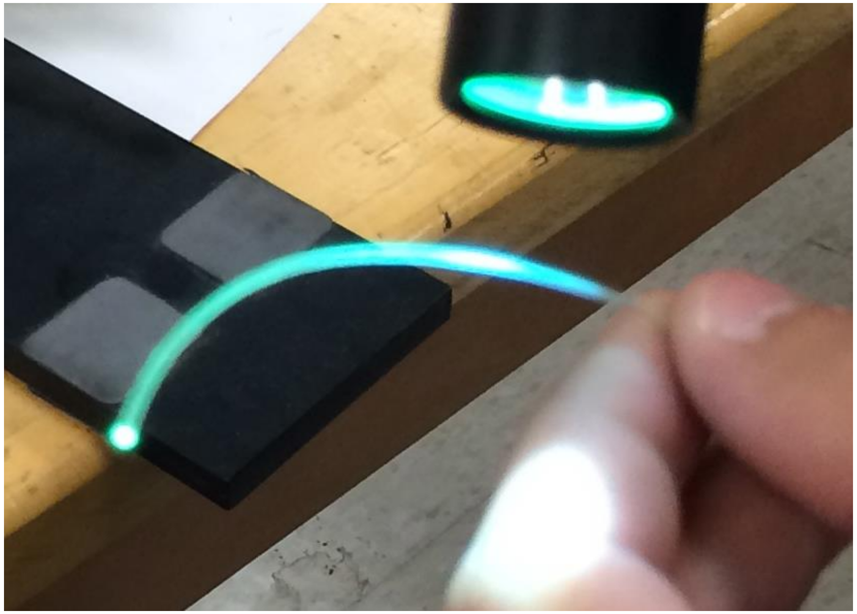
Cerium-doped Scintillating Glasses

Measured at Clemson University- Optical Science Labs

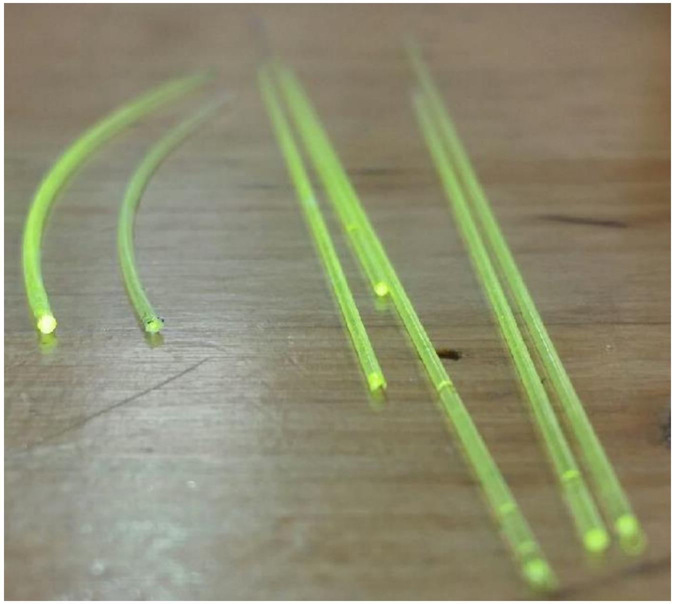


Can be drawn into fiber

3HF+Meltmount injected TeflonAF 800µm ID

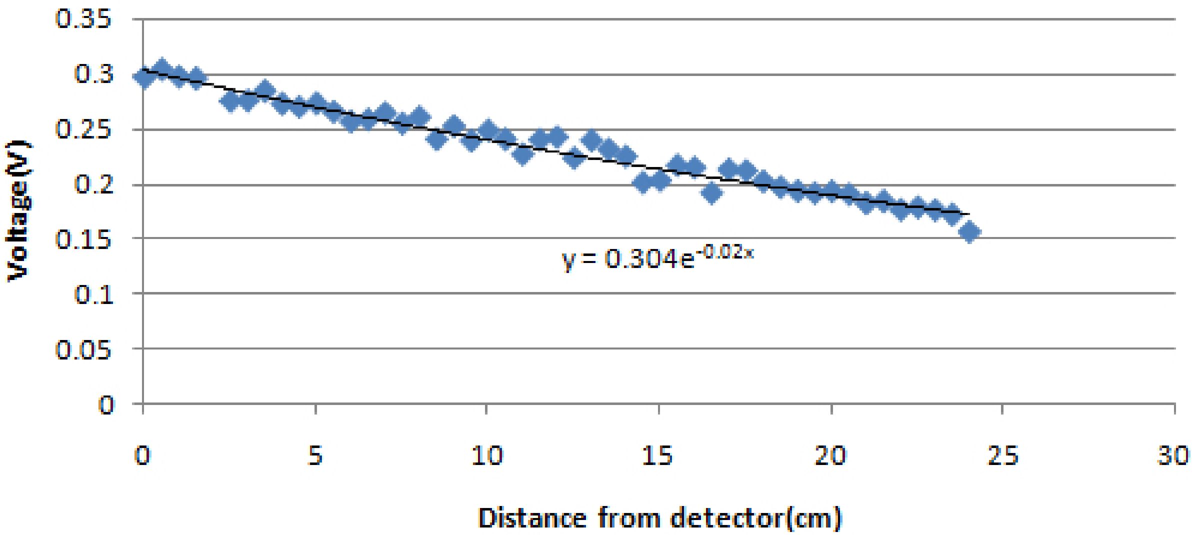


CdSeZnO nanodots in Sylgard 184
Injected into Capillaries Teflon; AFQuartz

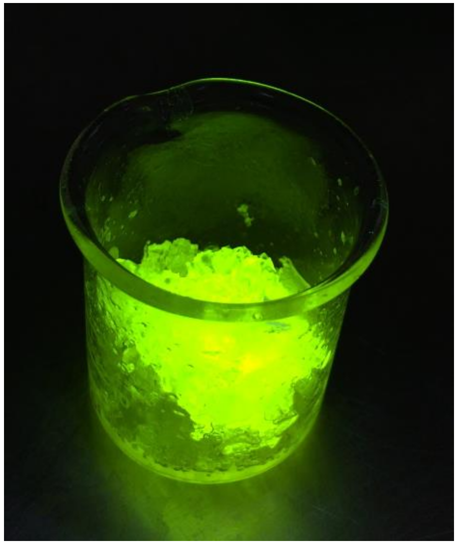


Fairfield UNIVERSITY

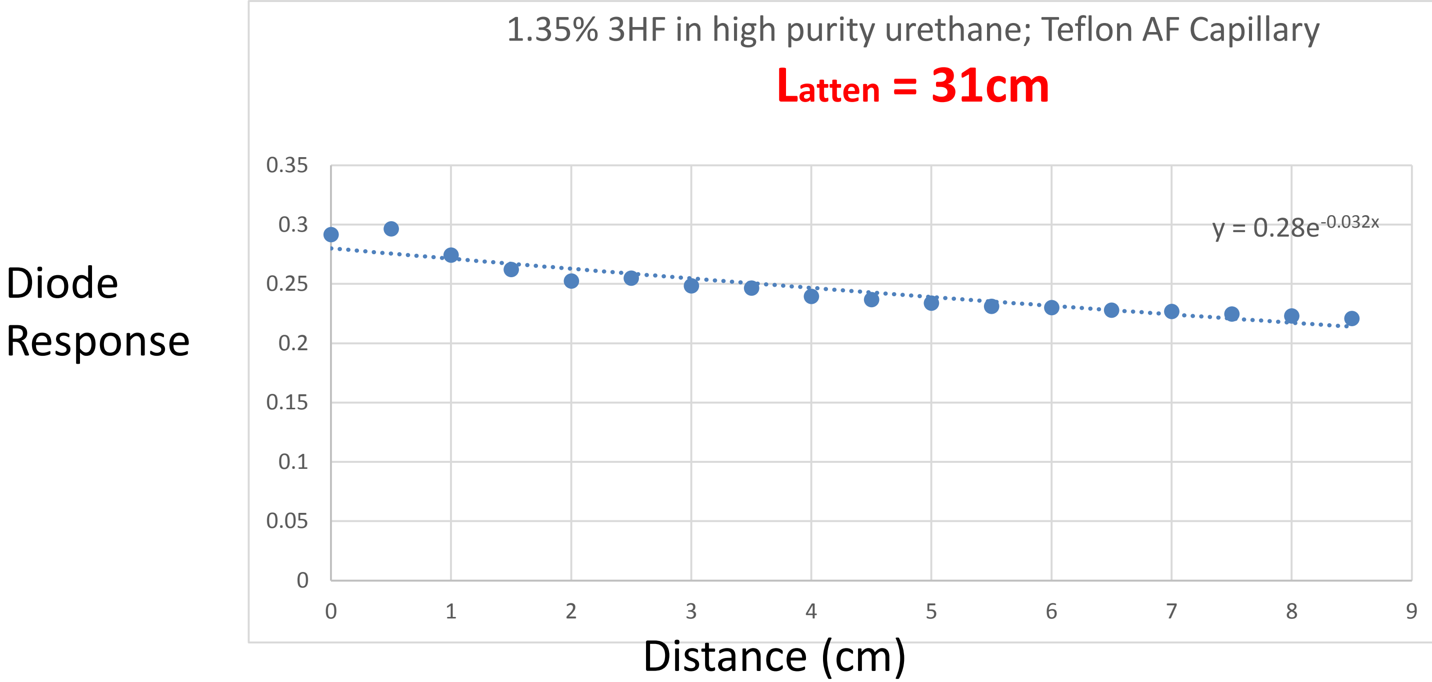
THE UNIVERSITY OF IOWA

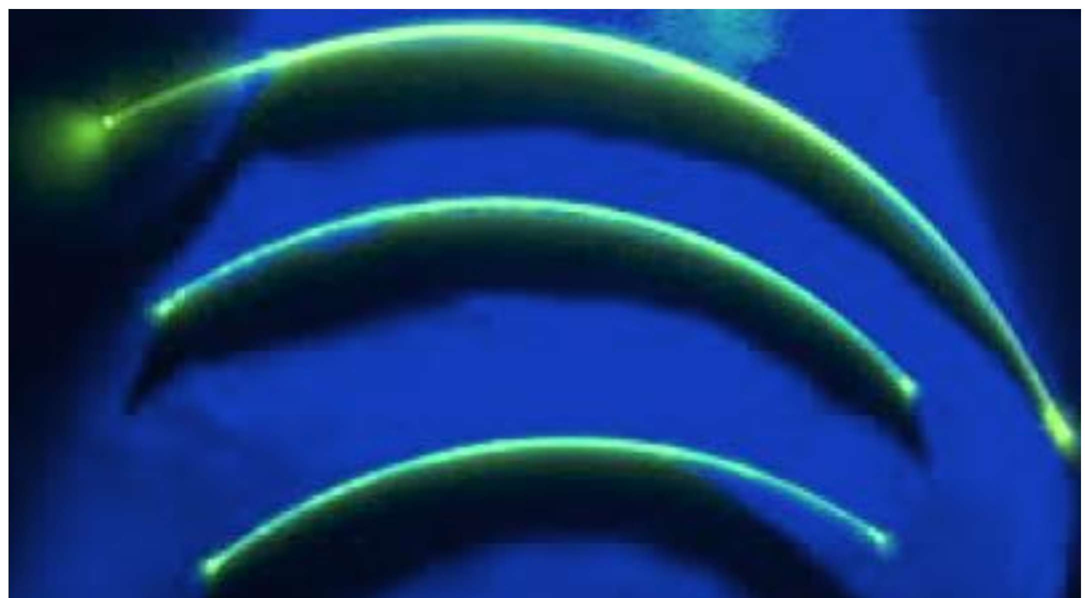


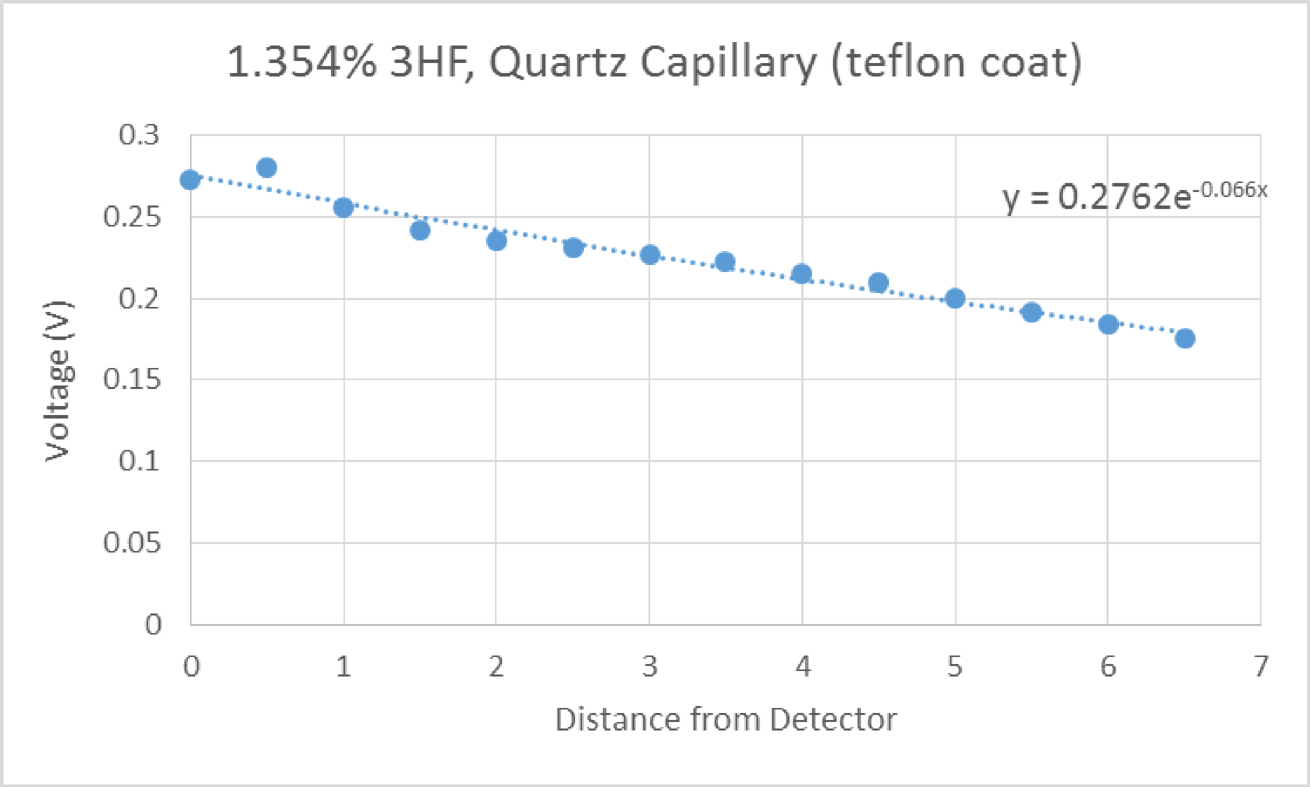
Attenuation length: 3HF in polyurethane in Quartz Capillary: L= 50 cm 1/e.

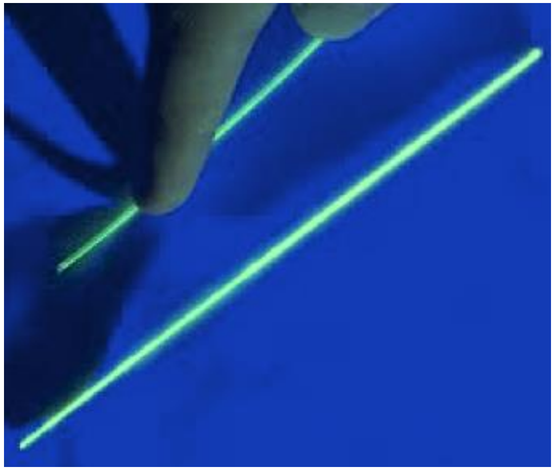


CdSeZnO Nanodots in Sylgard 184 for hot injection into capillaries


1.35% 3HF in high purity urethane; Teflon AF Capillary
Latten = 31cm
Diode Response
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
1
2
3
4
5
6
7
8
9
Distance (cm)
$y = 0.28e^{-0.032x}$







Attenuation: 15 cm

800 µm core Quartz Capillary With Teflon AF Outer buffer

+

3HF in Sylgard Polysiloxane

(100 Mrad)

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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.
- Radiation-hard wavelength shifting fibers need to be studied in further detail. Need more and realistically sized samples.

Conclusions

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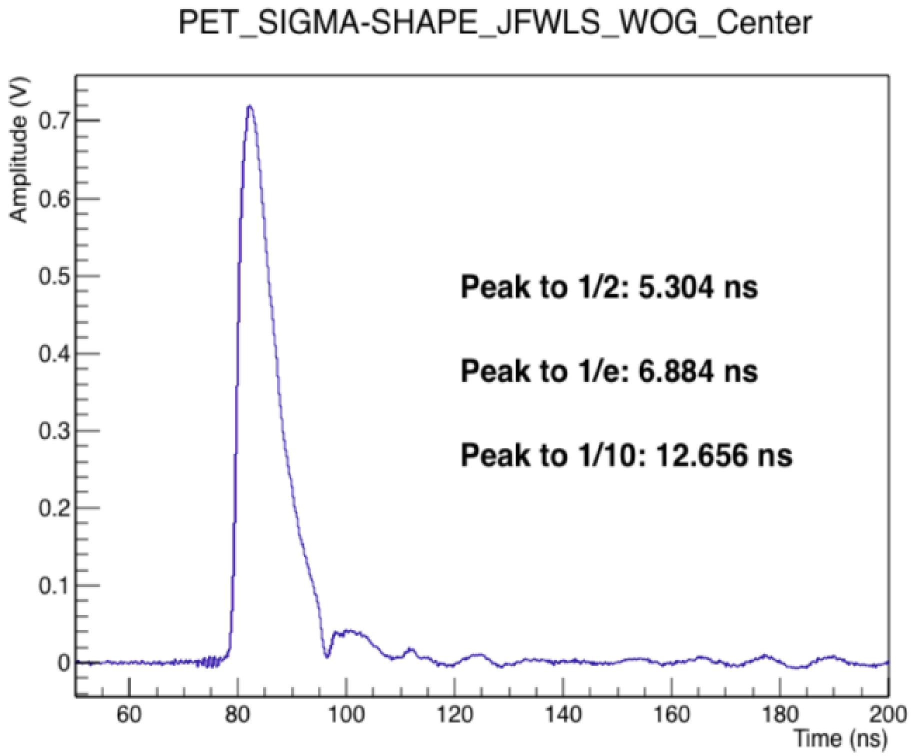
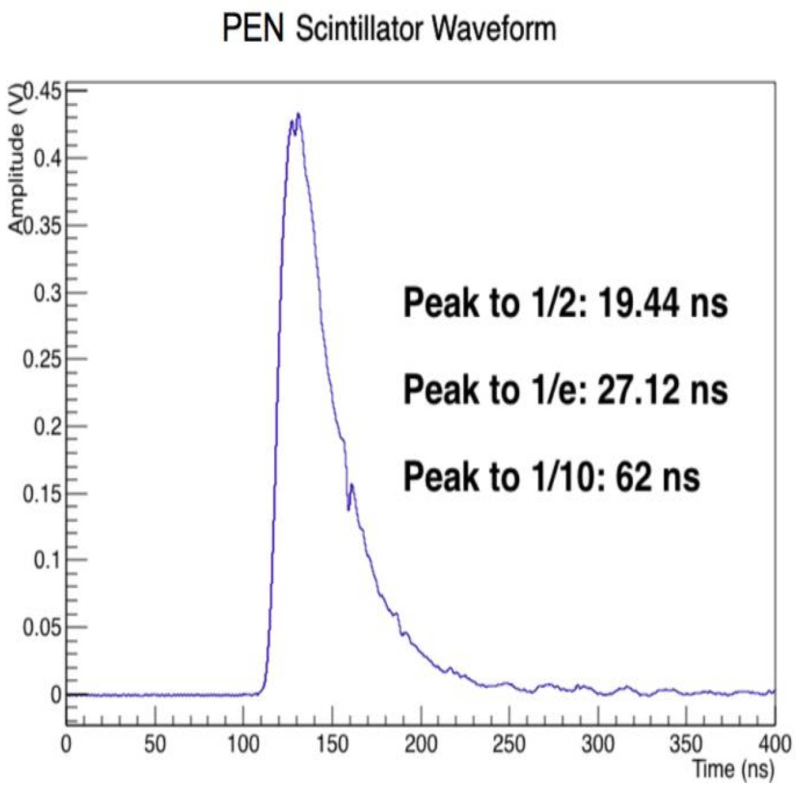
Back-up-I

IOWA Optics lab measurements





Inventory of Radiation-Hard Tiles

Material	**Light Output (Compared to HE tile)**	**Timing**	**Radiation-Hardness**	**Availability/ Cost**
Quartz (2 mm)	10%	Excellent	Excellent	Excellent
Coated quartz (pTp, anthracene) (2 mm)	50%	Excellent	Excellent	Excellent
PEN (2 mm w/WLS, 4 mm DC)	90%	Poor	Good	Good
PET (2 mm w/WLS)	50%	Good	Good	Good
PEN+PET	?	?	?	?
SX-1	90% - >100%	Excellent	Excellent	?