NEW RADIATION-HARD MATERIALS

Yasar ONEL

CPAD Instrumentation Frontier Meeting
October 5-7, 2015
University of Texas at Arlington

Outline

1. The need for new radiation-hard materials in high energy physics experiments

2. Advances in intrinsically radiation-hard scintillators

3. Microprocessing for radiation-hard detectors

4. Radiation-hard wavelength shifting fibers

5. Conclusions

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1. The need for new radiation-hard materials in high energy physics experiments

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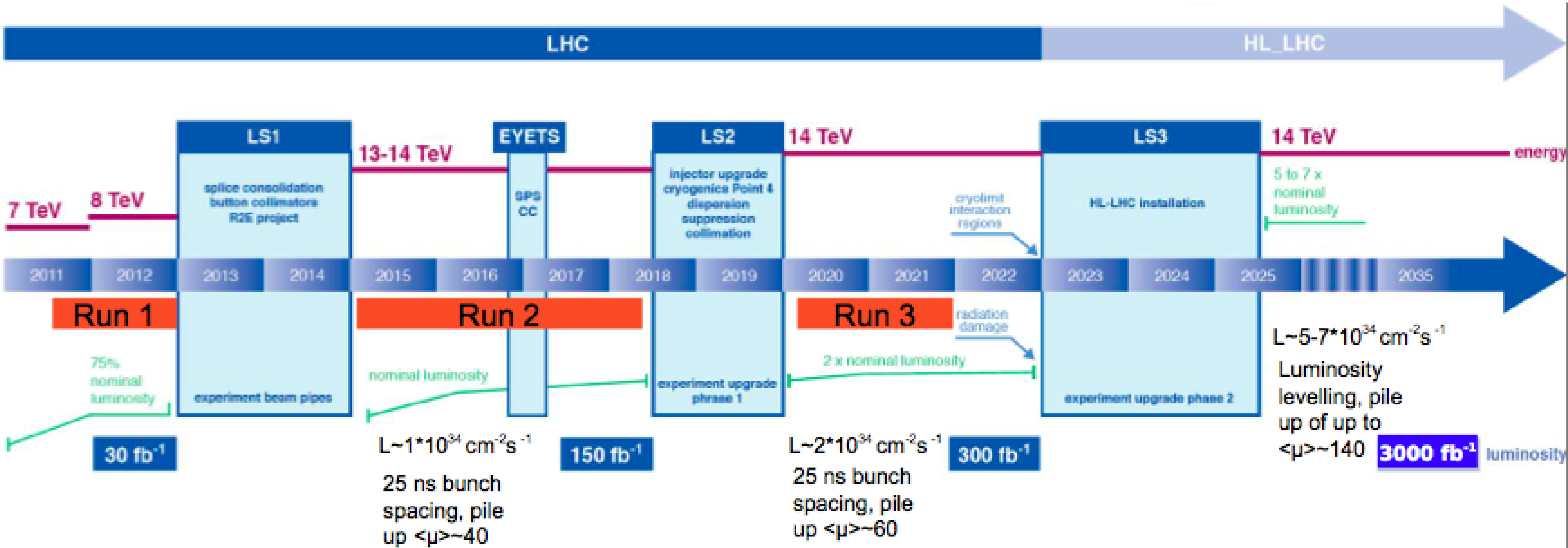
High Luminosity LHC



From LHC to HL-LHC

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

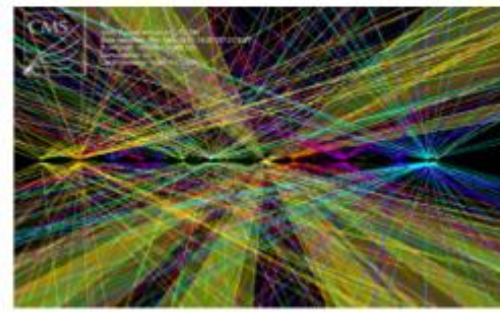
Integrated luminosity x10 (for ATLAS, CMS, LHCb) → Radiation damage x10

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

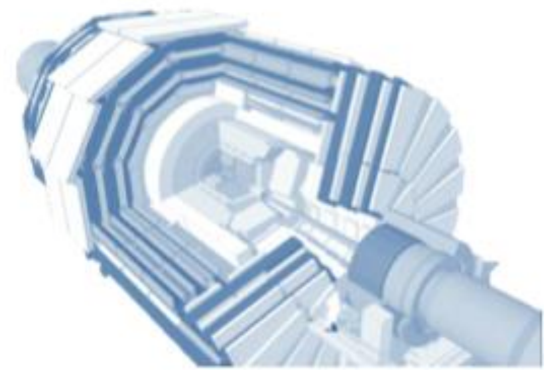
High Luminosity LHC

Phase II Upgrades

- from LHC design to ultimate performance
  - **luminosity** **$1x10^{34}cm^{-2}s^{-1}$ → $5x10^{34}cm^{-2}s^{-1}$** leveled (**ATLAS + CMS**), **$4x10^{32}cm^{-2}s^{-1}$ → $2x10^{33}cm^{-2}s^{-1}$** (**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



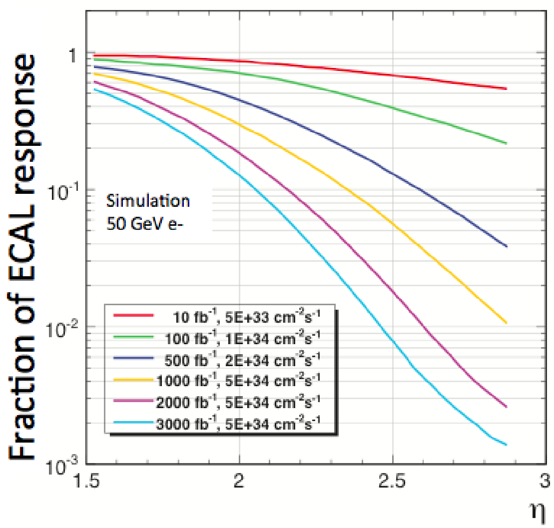
- the casualties (radiation damage and/or performance loss)
  - pixel
  - tracker
  - trigger
  - end-cap calorimetry, electronics
  - end-cap muon system, electronics



- 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)

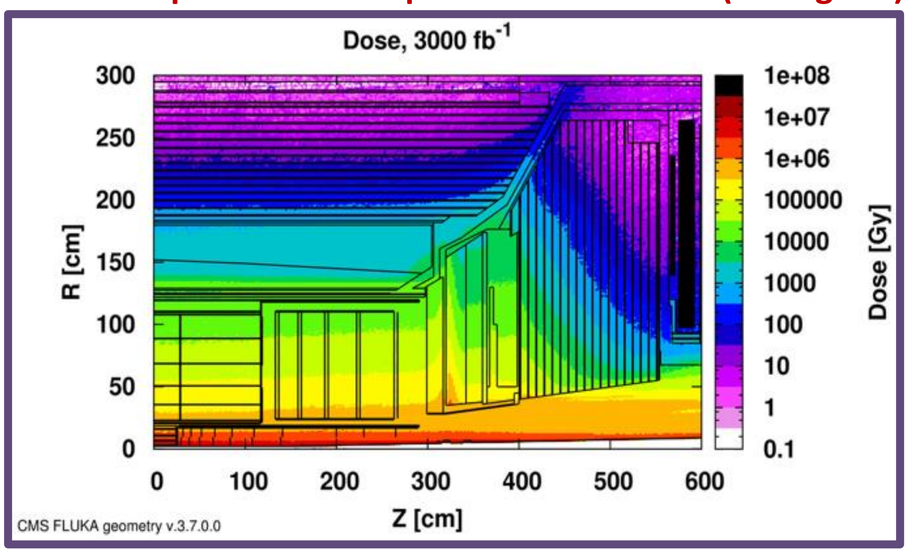
Example: CMS Forward Region (1-100 Mrad at 500 fb^{-1})

ECAL Endcap

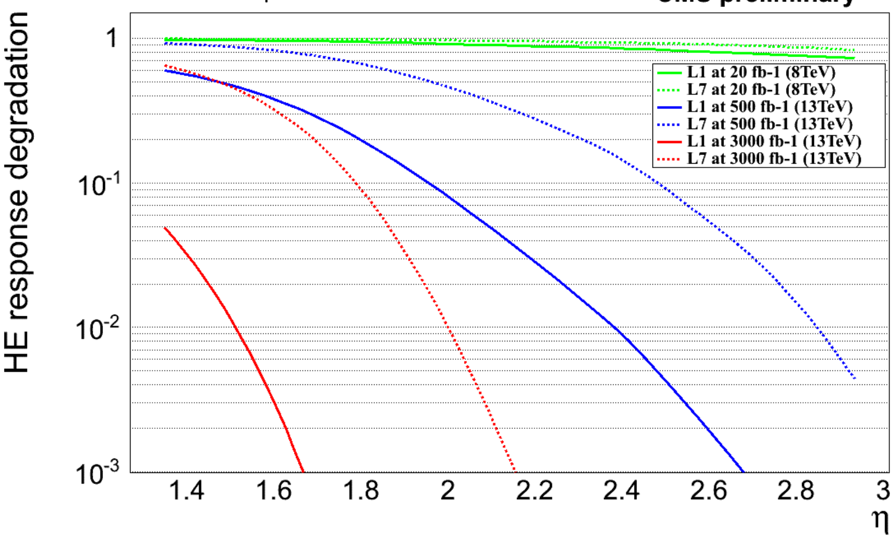


Progressive deterioration of energy resolution and trigger efficiency, with strong η dependence

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

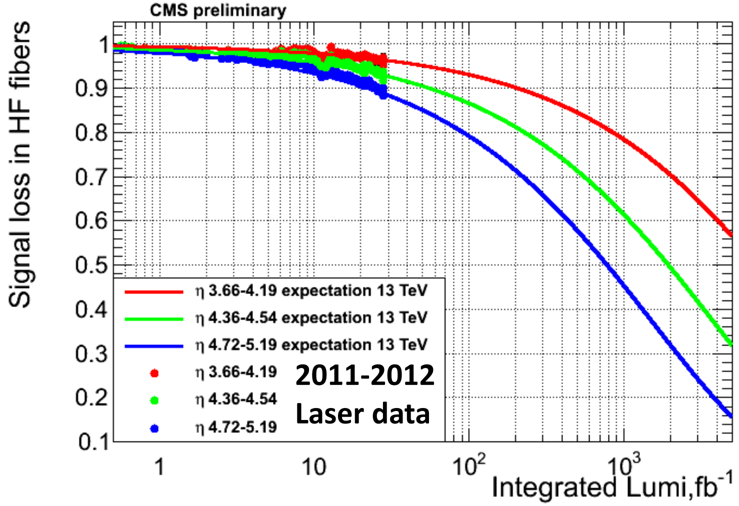


HCAL Endcap



HCAL endcaps should be upgraded/replaced during LS3

HCAL Forward



HCAL forwards require no/minimal upgrade

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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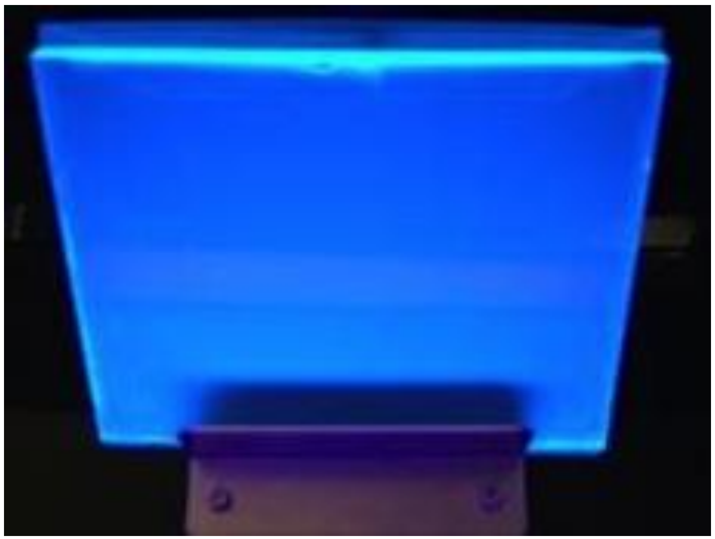
Intrinsically Rad-Hard Scintillators

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

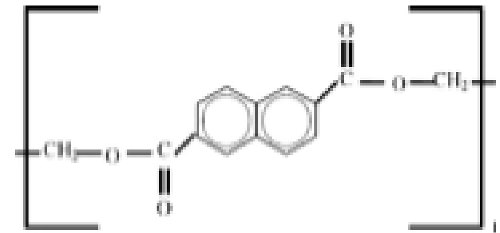


Fig. 1 The inside of a survey meter. From the left, a) light-shielding curtain of thin aluminum foil, b) PEN sheet, c) acrylic sheet support, d) reflection section of white celluloid, and e) photomultiplier tube.

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.

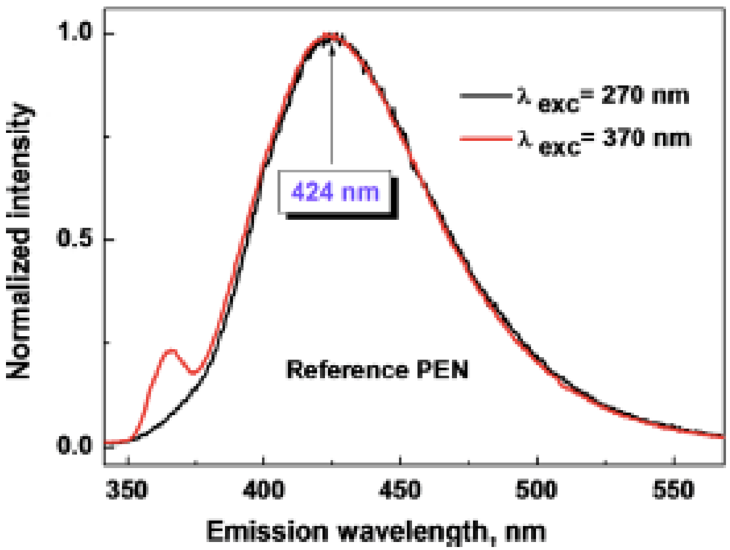
Material	Polyethylene naphthalate	Organic scintillator (ref. [14])	Plastic bottle (ref. [13])
Supplier	Teijin Chemicals	Saint-Gobain	Teijin Chemicals
Base	$(C_{14}H_{10}O_4)_n$	$(C_9H_{10})_n$	$(C_{10}H_8O_4)_n$
Density	$1.33\,g/cm^3$	$1.03\,g/cm^3$	$1.33\,g/cm^3$
Refractive index	1.65	1.58	1.64
Light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

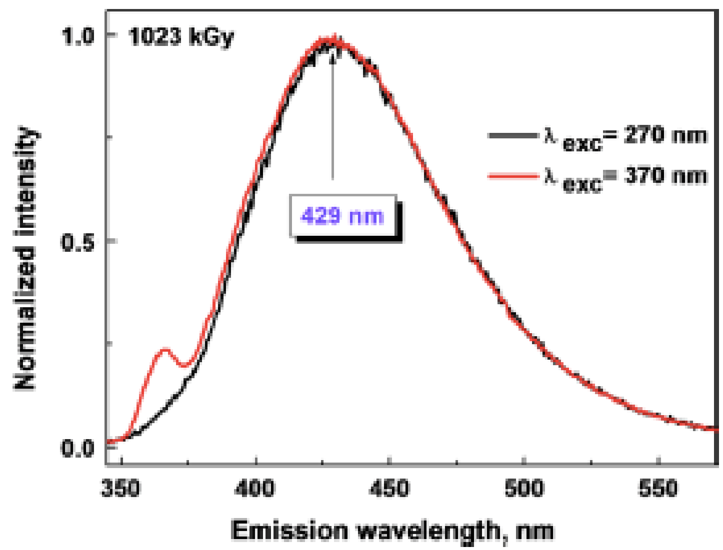
Intrinsically Rad-Hard Scintillators - PEN

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.*



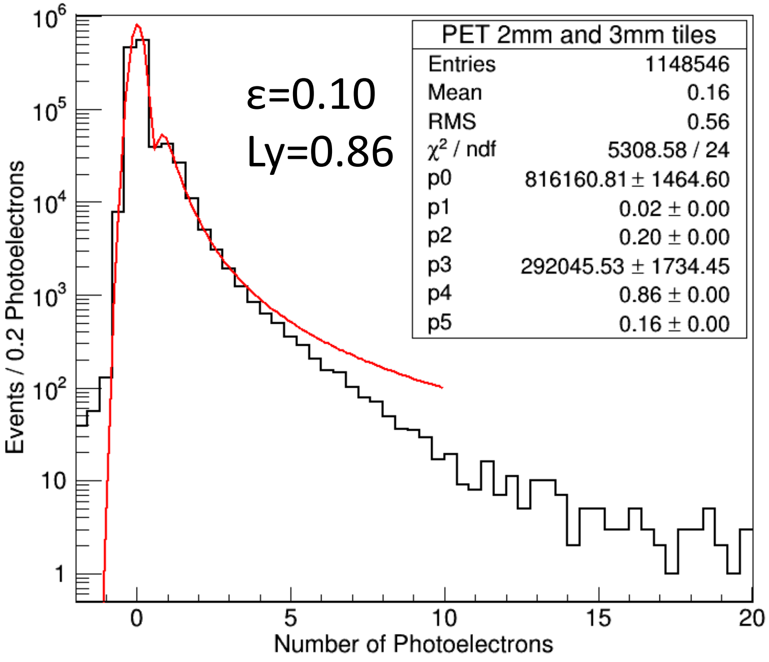


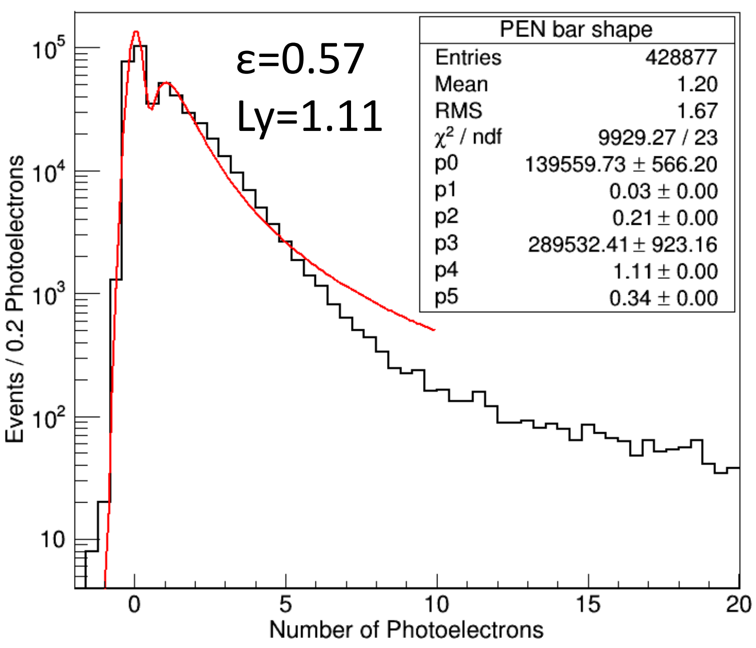
PL intensity at peak maximum (relative units) versus irradiation dose.

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

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.

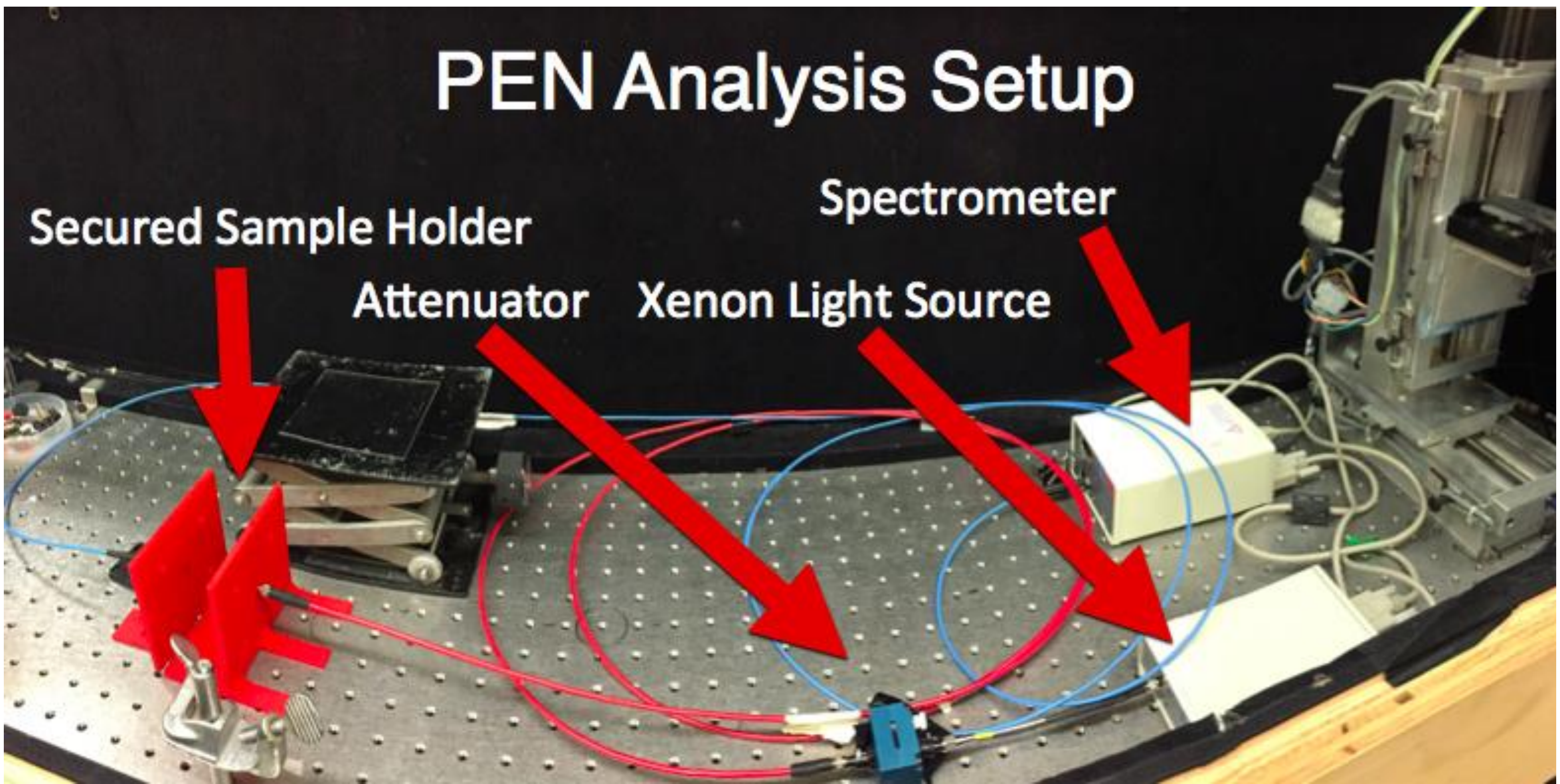




PEN Radiation Damage Studies (MSU)

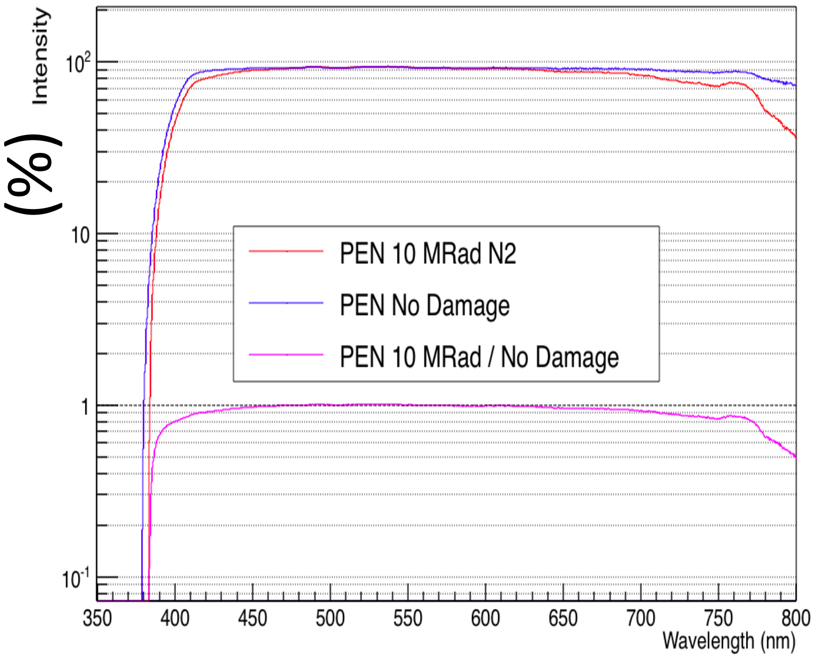
Facilities:
- National Superconducting Cyclotron Laboratory
- Used ^{60}Co, 1.33 MeV Gammas

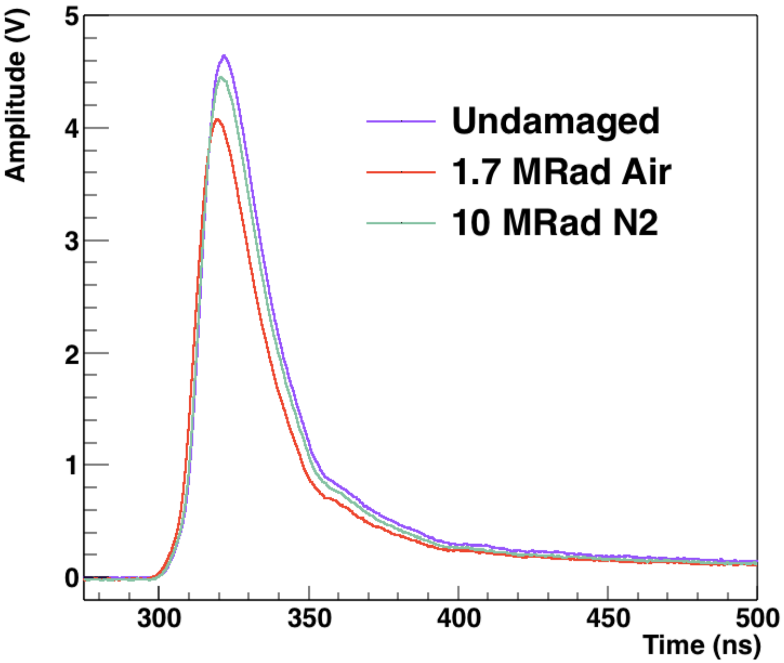
Two Samples:
- 1.7 MRad in Air
- 10 MRad in N_2



PEN Radiation Damage Studies (MSU)

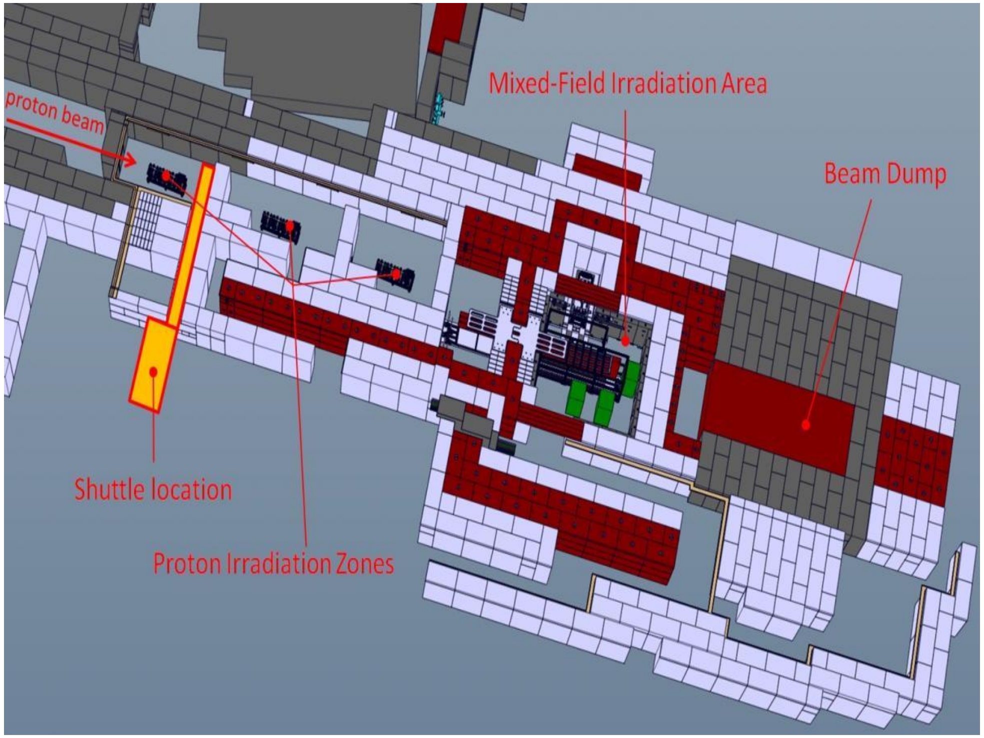
Transmission





	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

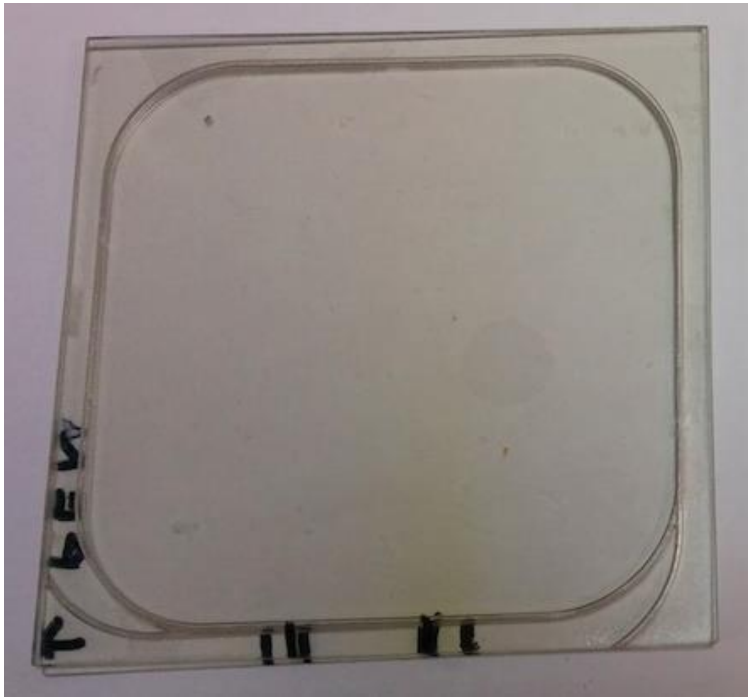


24 GeV protons ,
beam spot (FWHM) 15x15 mm^2
proton flux - ~$6x10^9$ p cm^{-2} s^{-1}

- 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)

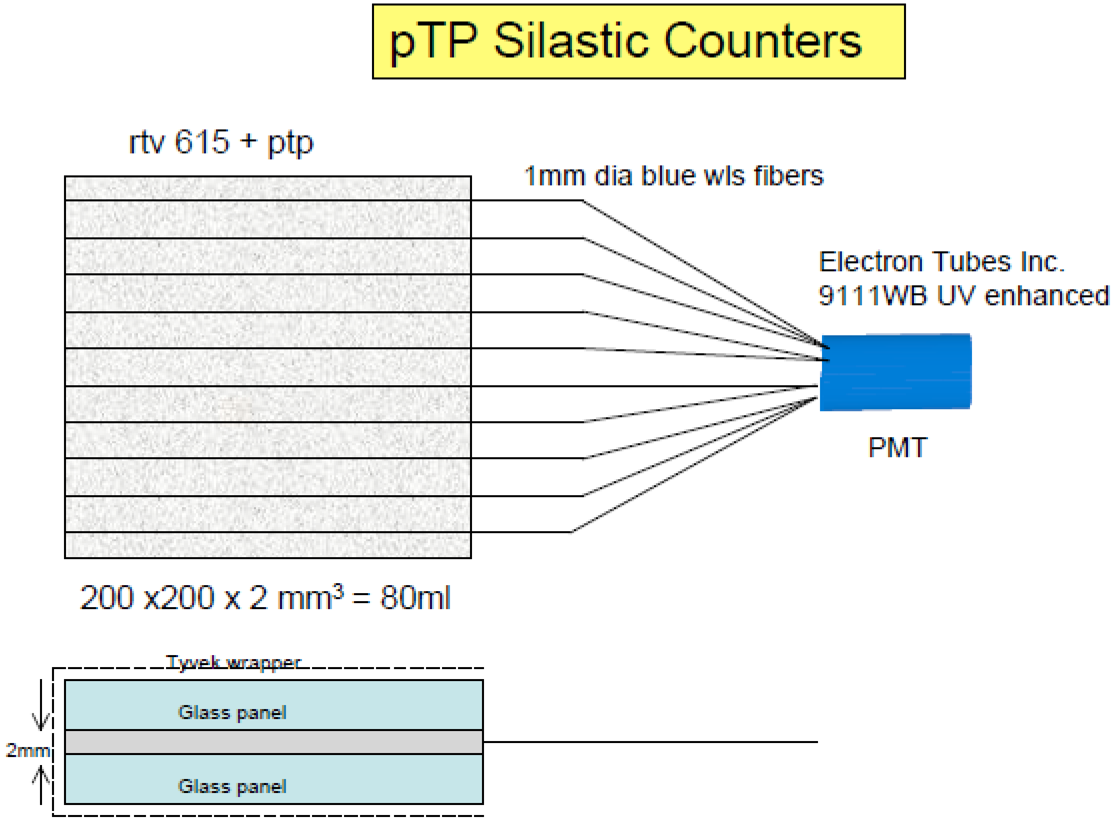
- Average of 125 nA , with lowest 123 nA and highest 128 nA were produced by radioactive source on not irradiated PEN tile

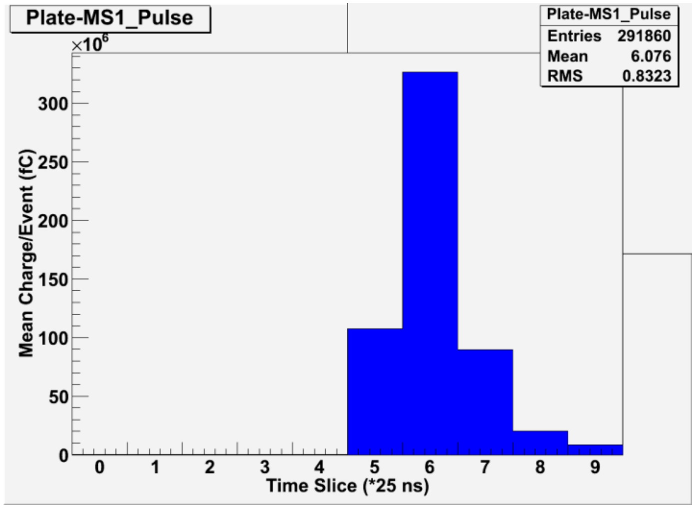
- Average of 30 nA, with lowest 27 nA and highest 35 nA were produced by radioactive source on irradiated PEN tile

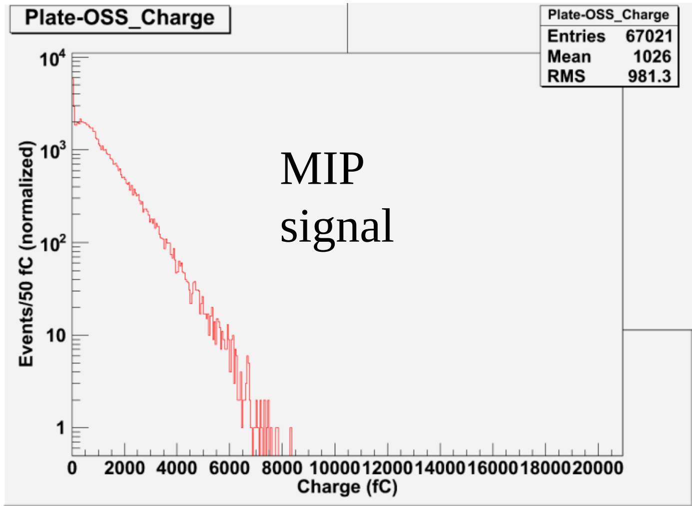
➔ 75% loss at 30- 40 Mrad.

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.





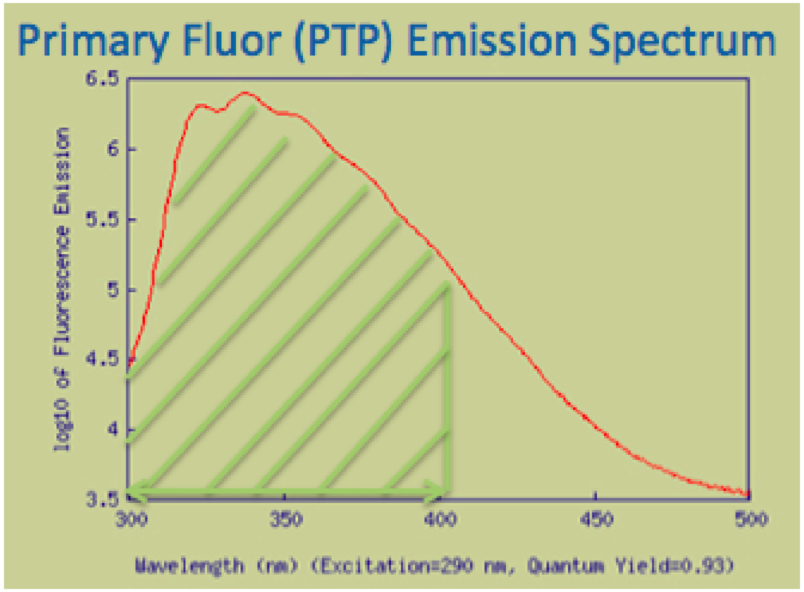


New "P-S" Scintillators

- 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.



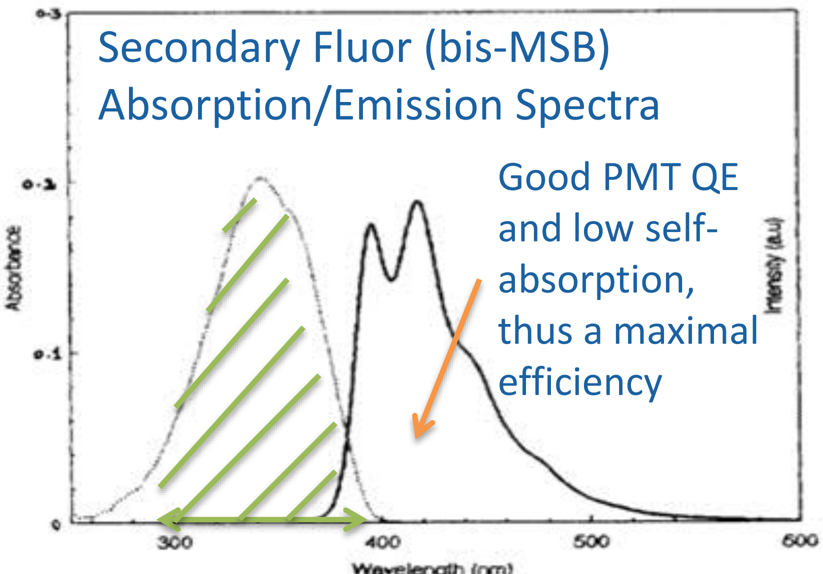
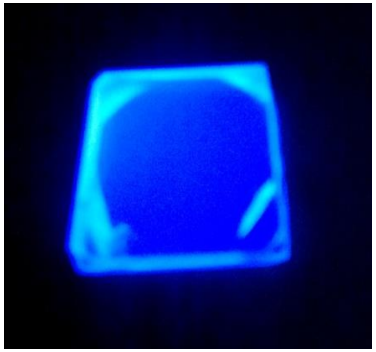


Fig. 1. Absorption (· · ·) and emission (———)



New "P-S" Scintillators

Lose only 7 % transmission after 40 Mrad proton radiation

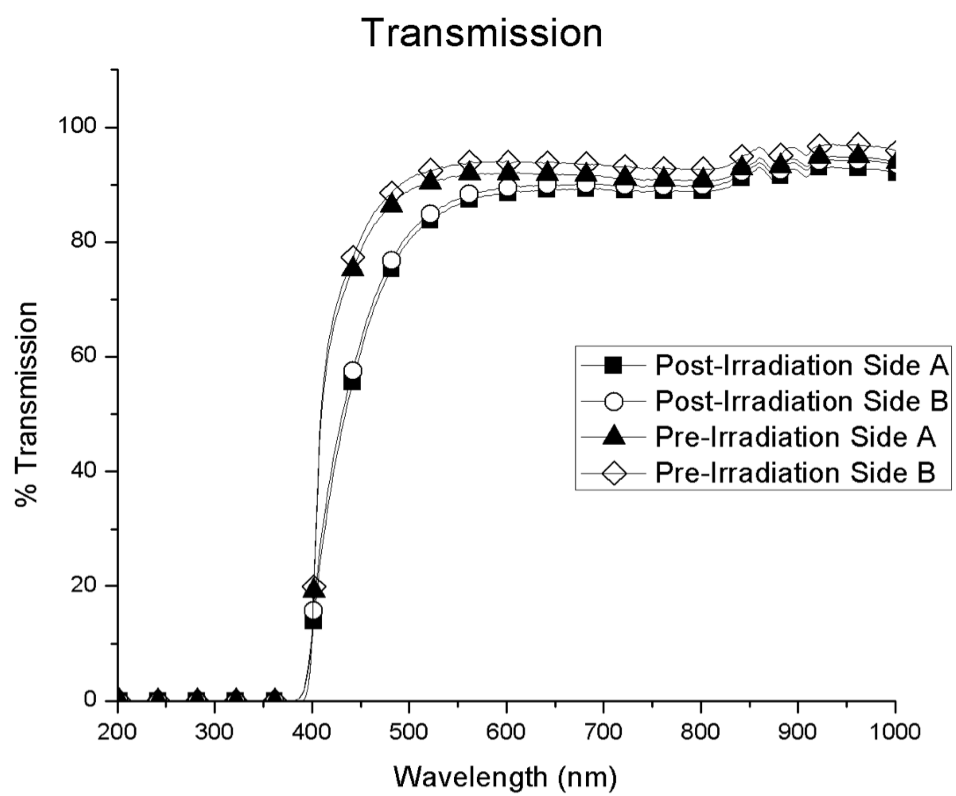


Figure 3: The transmission before and after irradiation;

New “P-S” Scintillators

Almost no change on emission and absorption after irradiation

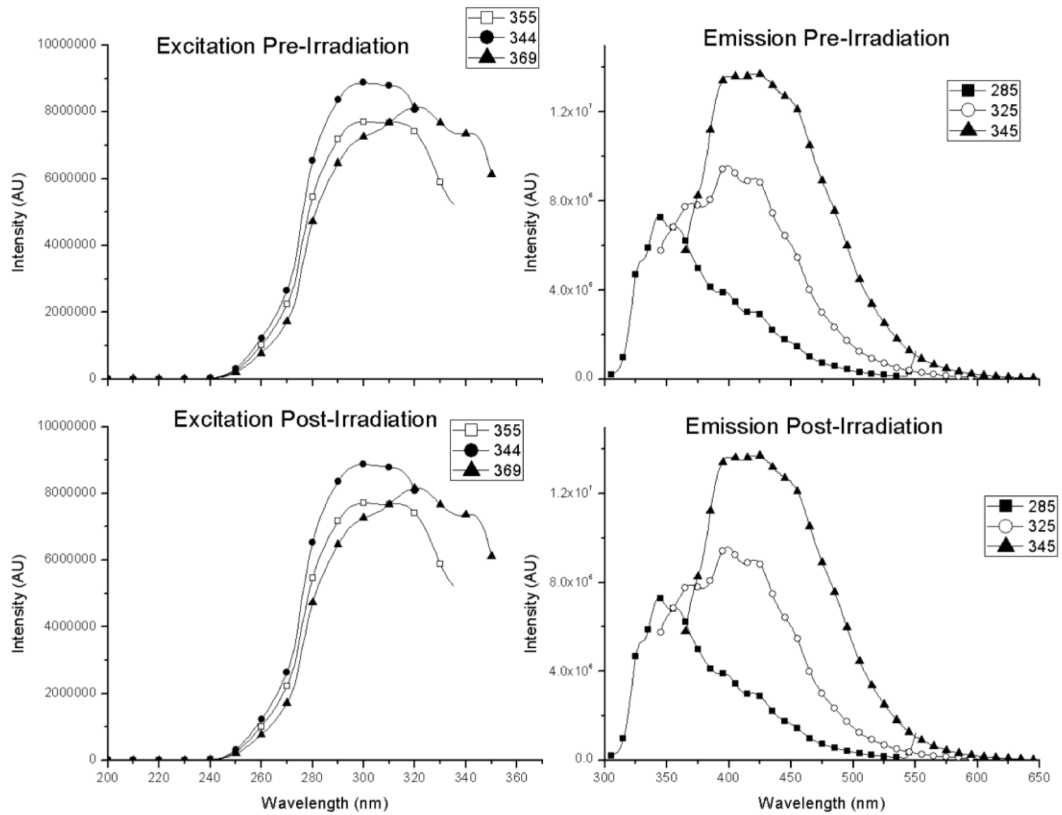


Figure 3: The excitation/emission taken before and after irradiation

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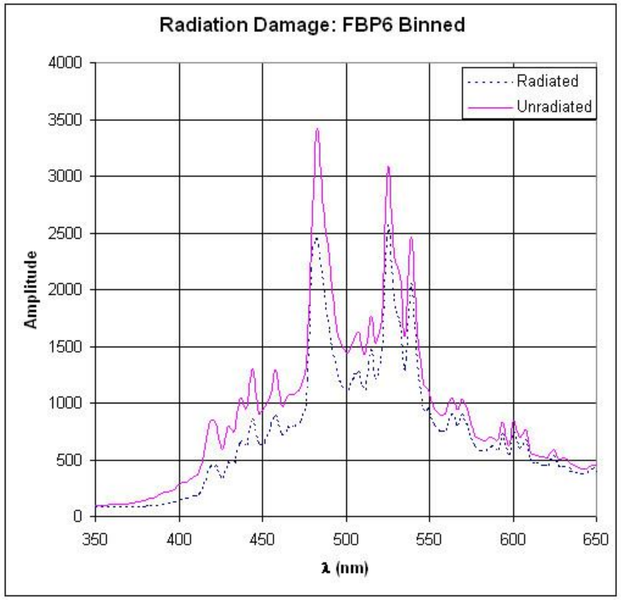
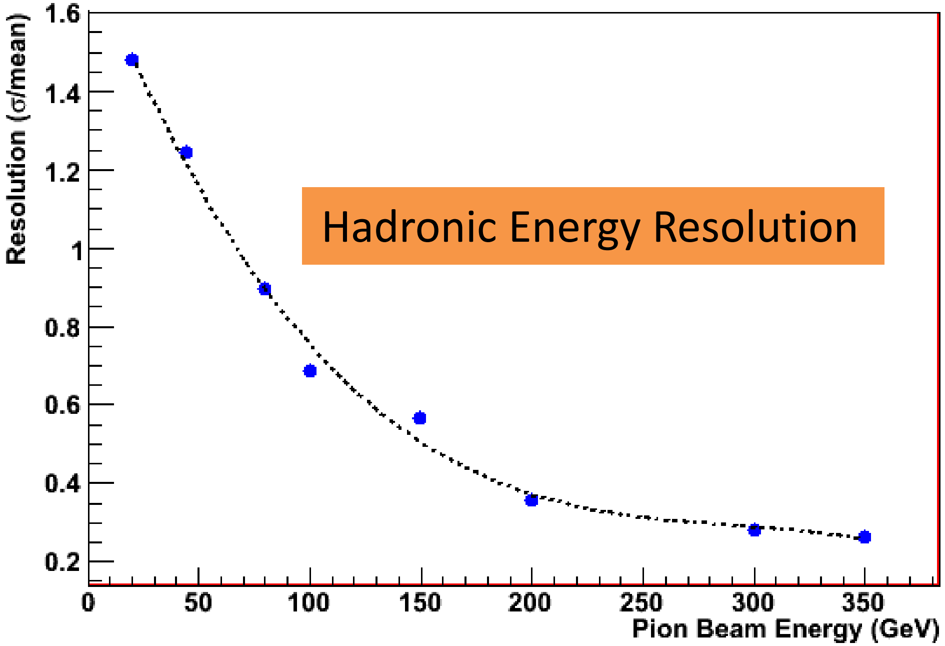
Quartz Radiation Damage Studies

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.

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.**

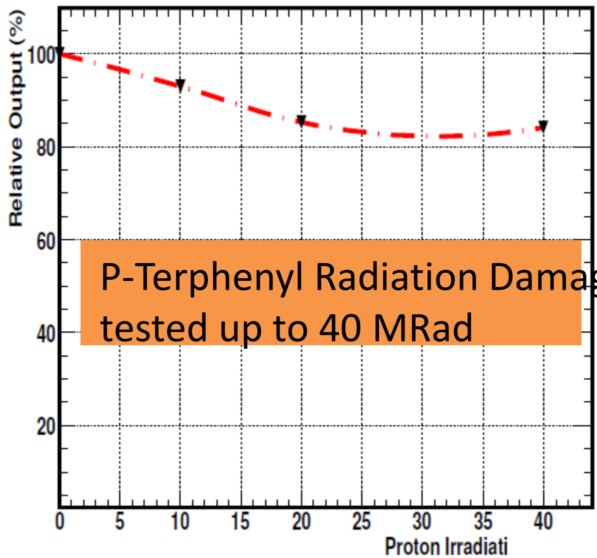
1. Double-sided Single Plate: coated 300 µm ≤ 3 mm thick tiles (thickness & optical finish chosen for the lowest cost, up to 3mm thick), 10 x 10cm; coating thickness up to ~10 µm. Minimum 2 Tiles each of 2 downselected materials. Readout: WLS fibers.

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

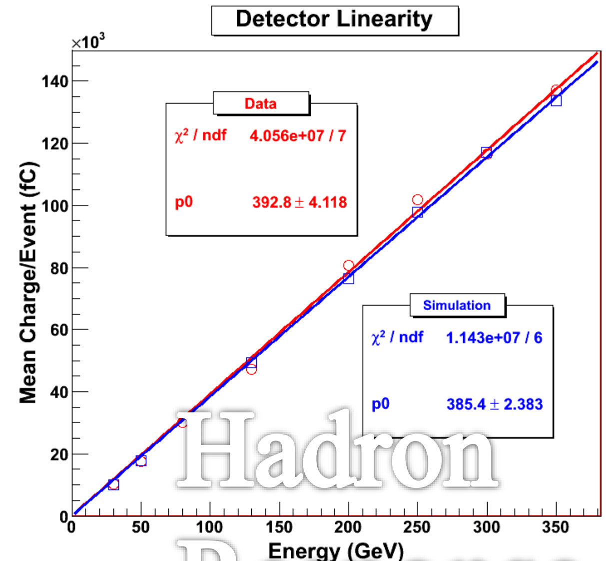
Fermilab's THIN FILM Facility Coating Systems at Lab 7

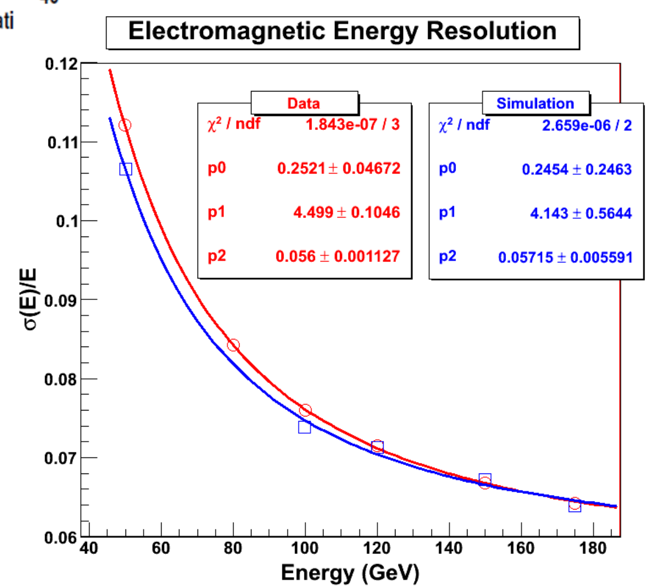
- 2 Bell Jar sputtering systems
  - Al, Ag, Au, Cr, Cu, Ir, Ni, PtIr, Ti, ZnO2-Ga
- 2 tube sputtering systems-dedicated to 99.999% pure aluminum sputtering
  - Optical fiber mirroring
- 1 Bell Jar system for resistive evaporation
  - Al, Ag, Au, Cr, Cu, Al & MgF2 surface mirrors, Ni, NiCr, TiN
- 1 Pyrex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

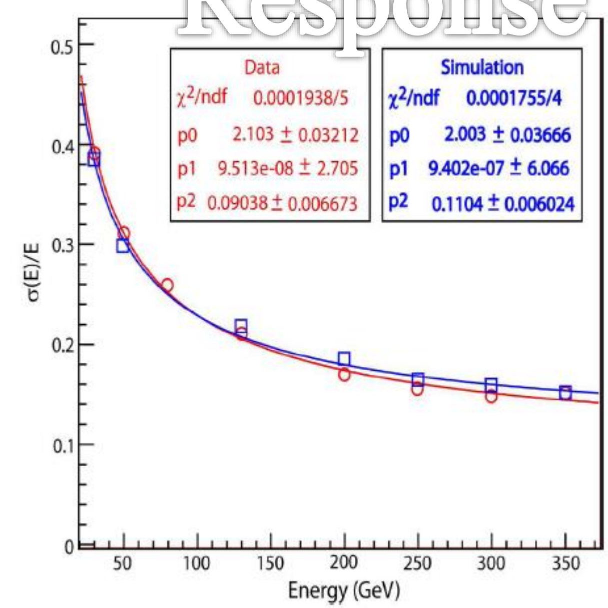


P-Terphenyl Radiation Damage tested up to 40 MRad



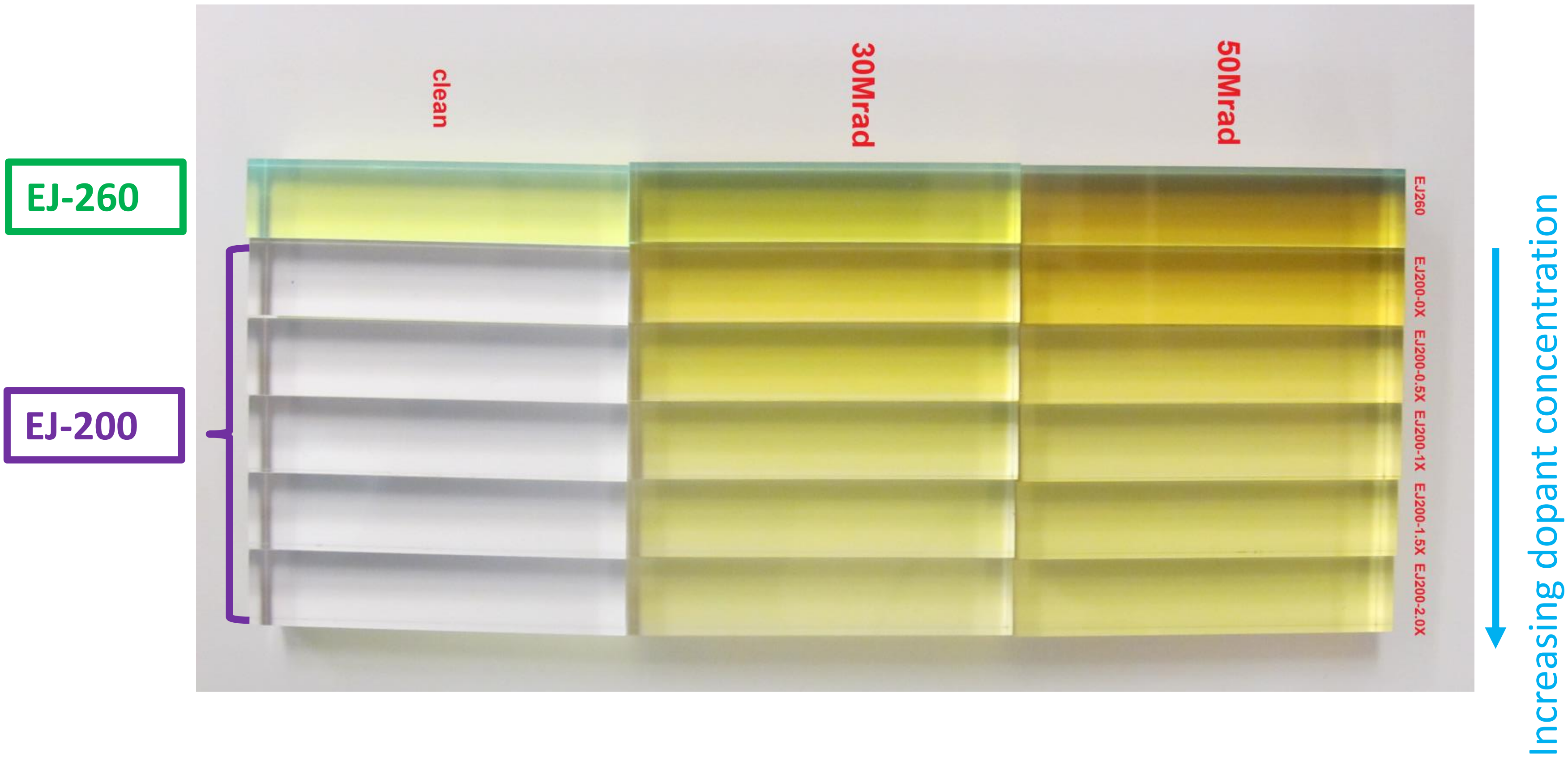


Hadron Response



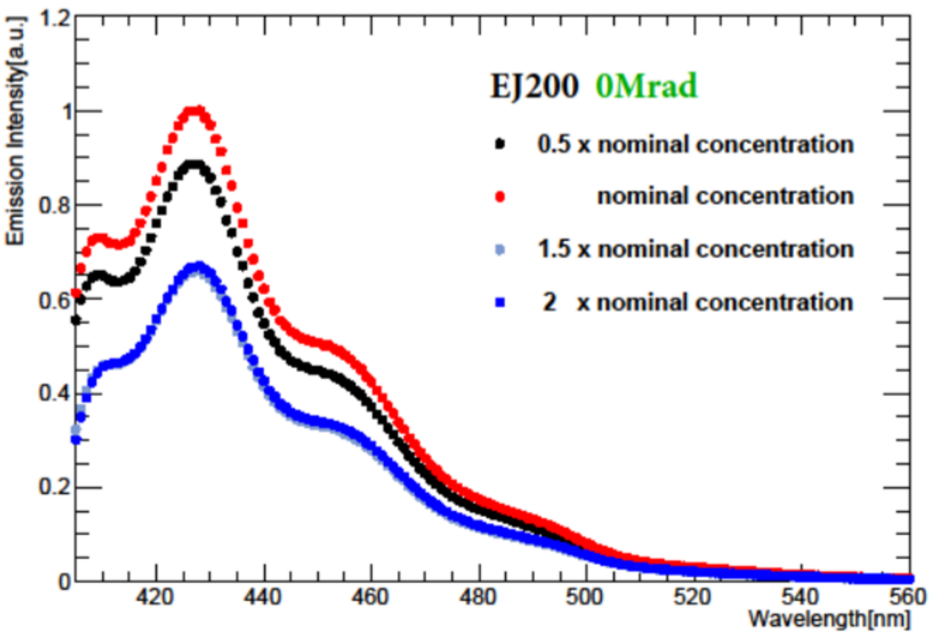
Over-doped Scintillators

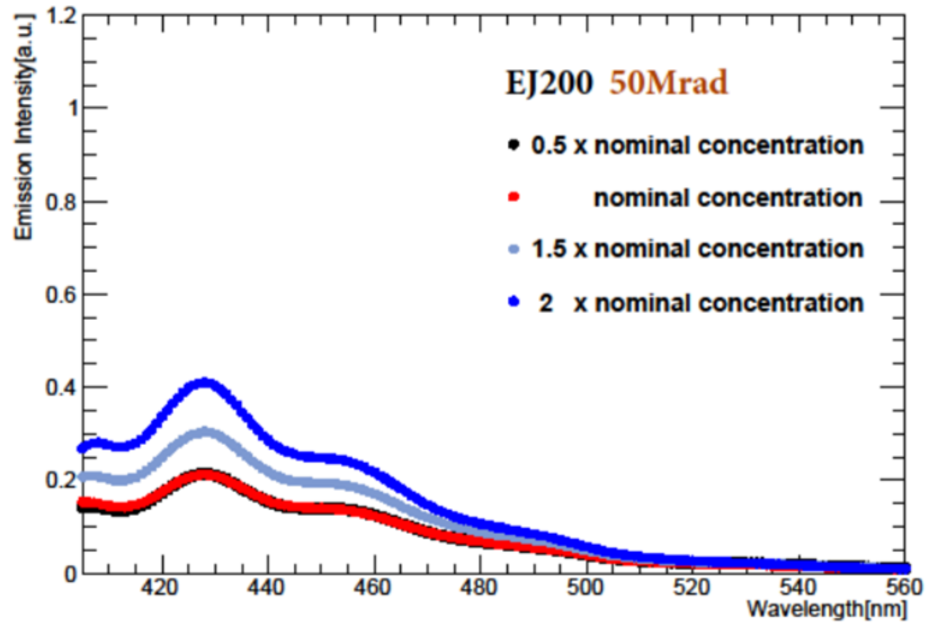
- A set of PVT rods with different concentrations of primary dopant were produced by Eljen and irradiated at UMD
  - Increasing the dopant concentration is suggested to be a way of improving radiation tolerance: radiation damages the dopant thus decreasing both the light yield and self-absorption



Over-doped Scintillators - Emission Spectra

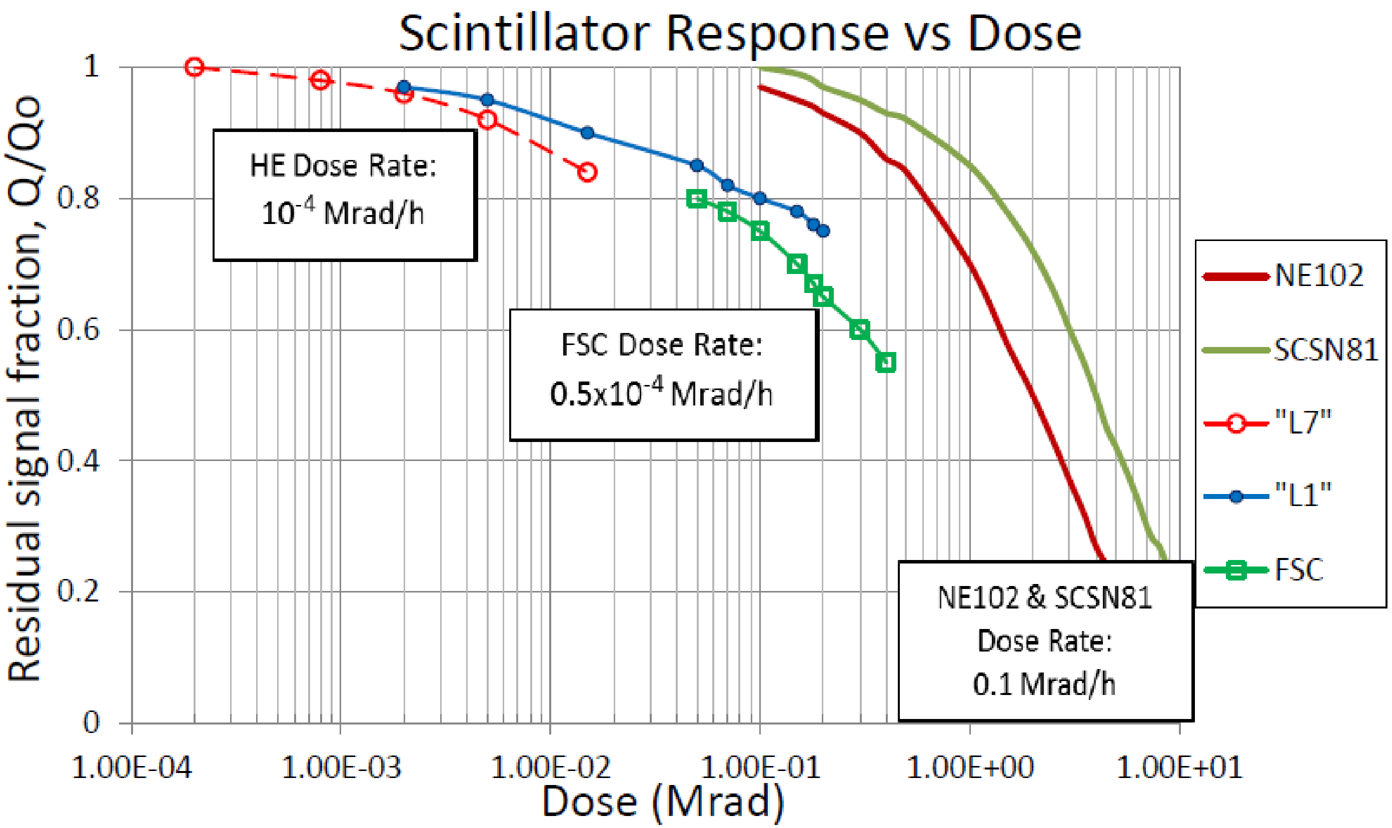
- The comparison among emission spectra shows that increasing the doping helps increasing the resiliency to radiation damage
  - The 2x sample starts with a smaller light yield w.r.t. the 1x sample (the nominal EJ-200 concentration), but after 50Mrad emits twice as much light with respect to it, after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

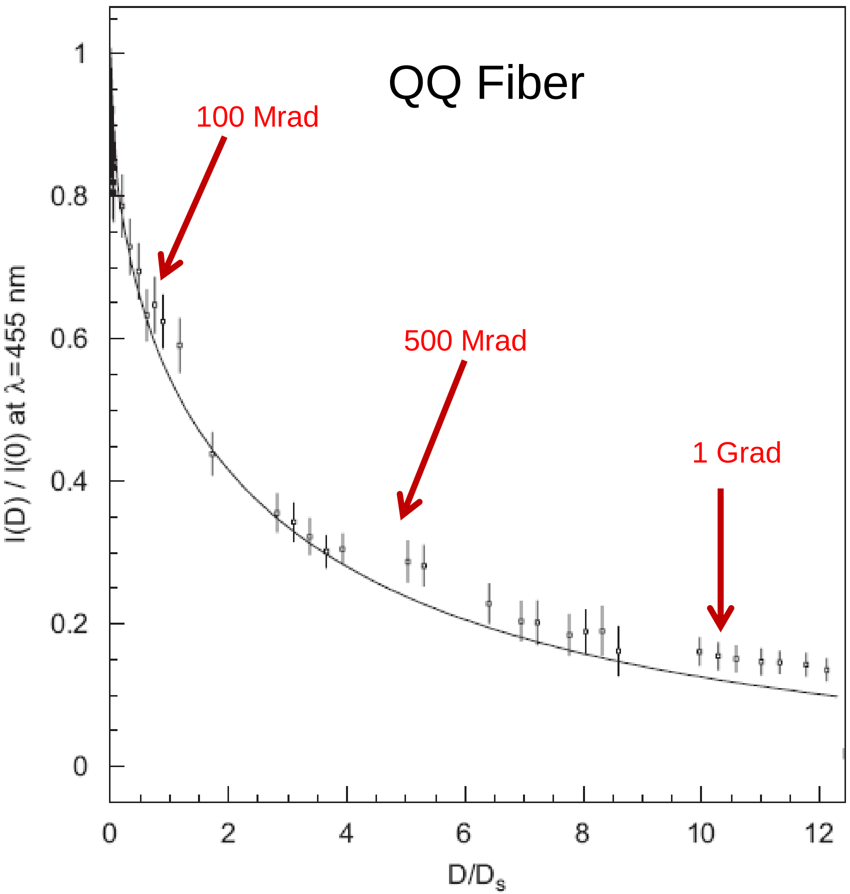
2 green coats Orange fiber 17.8 17.8/115=15.5%

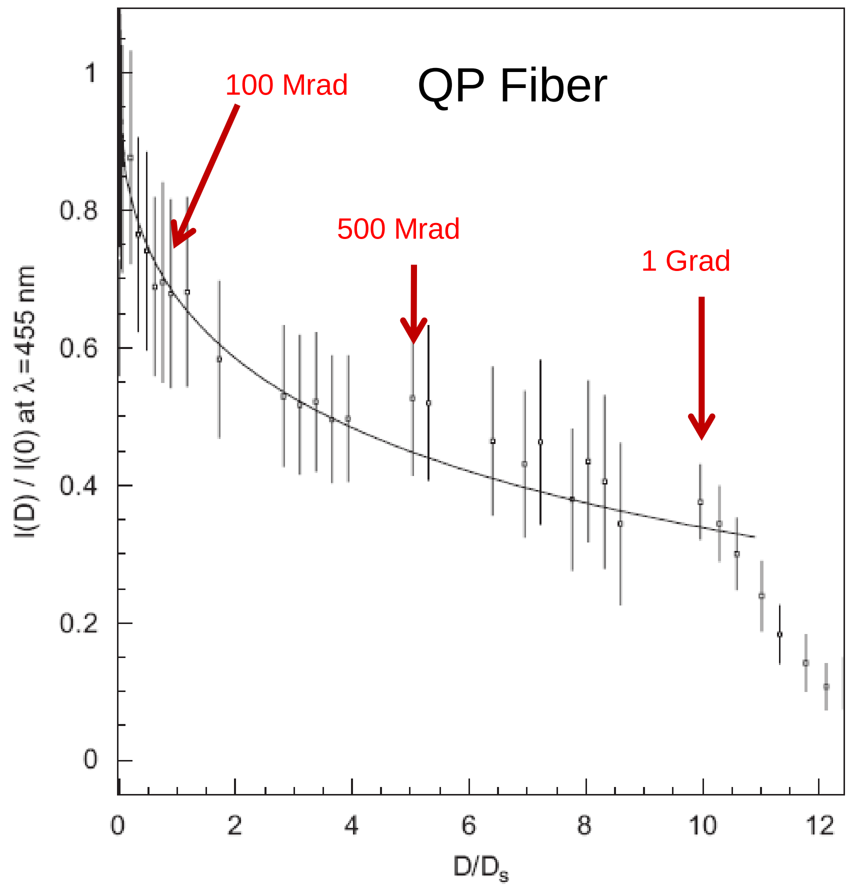
A. Bodek – J. Han

Outline

1. The need for new radiation-hard materials in high energy physics experiments
2. Advances in intrinsically radiation-hard scintillators
3. Microprocessing for radiation-hard detectors
4. Radiation-hard wavelength shifting fibers
5. Conclusions

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

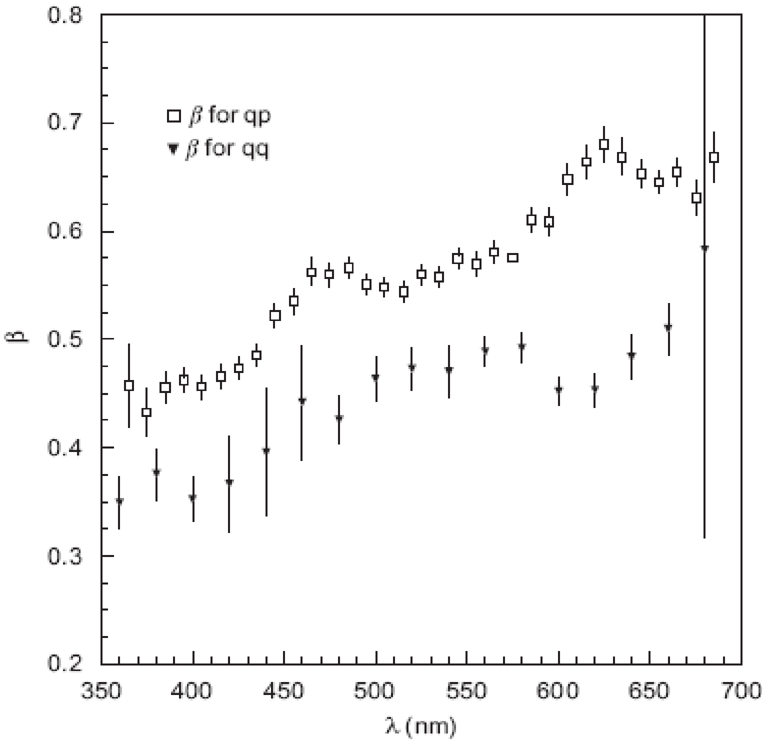


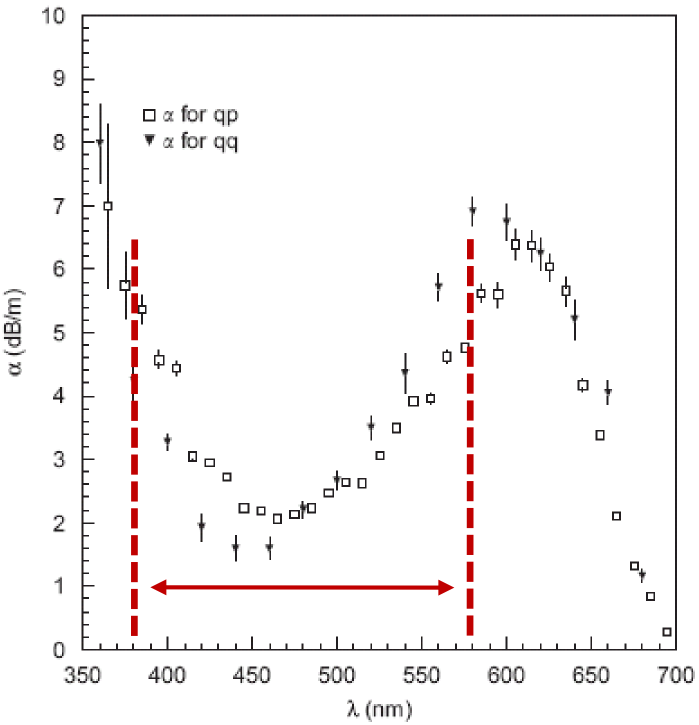


D_s: transmission after 100 Mrad

Attenuation in QQ and QP Fibers due to Radiation

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

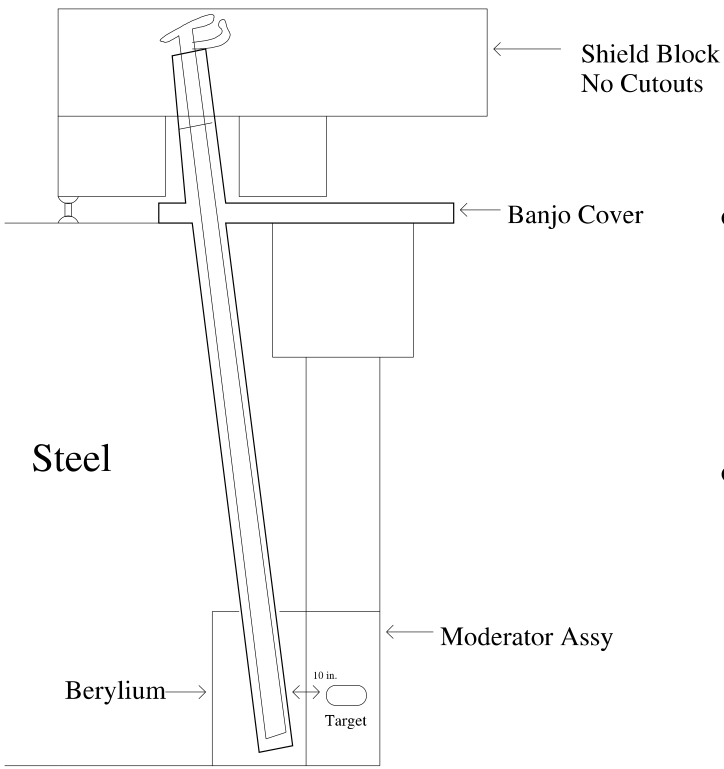




“Sweet range” : The fibers get less damage between 400 nm and 580 nm range.

D_s: transmission after 100 Mrad

Irradiation Setup at ANL

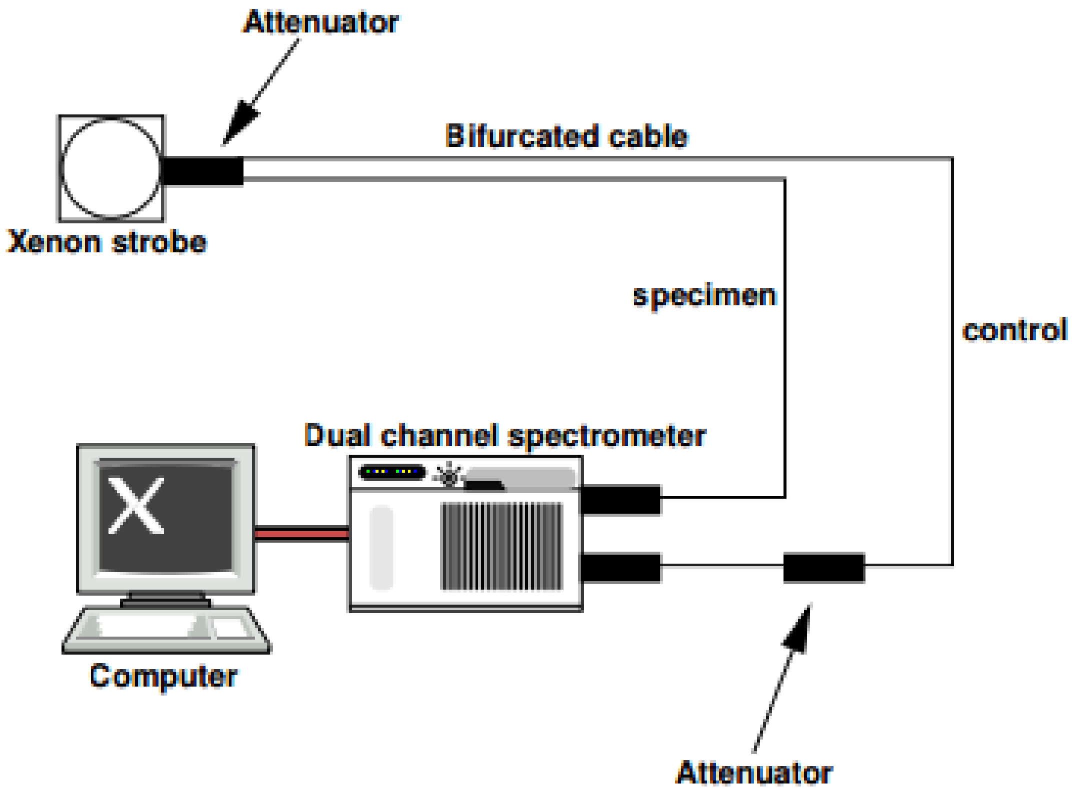


Note: Not to scale

Figure 3: REM Hole Diagram

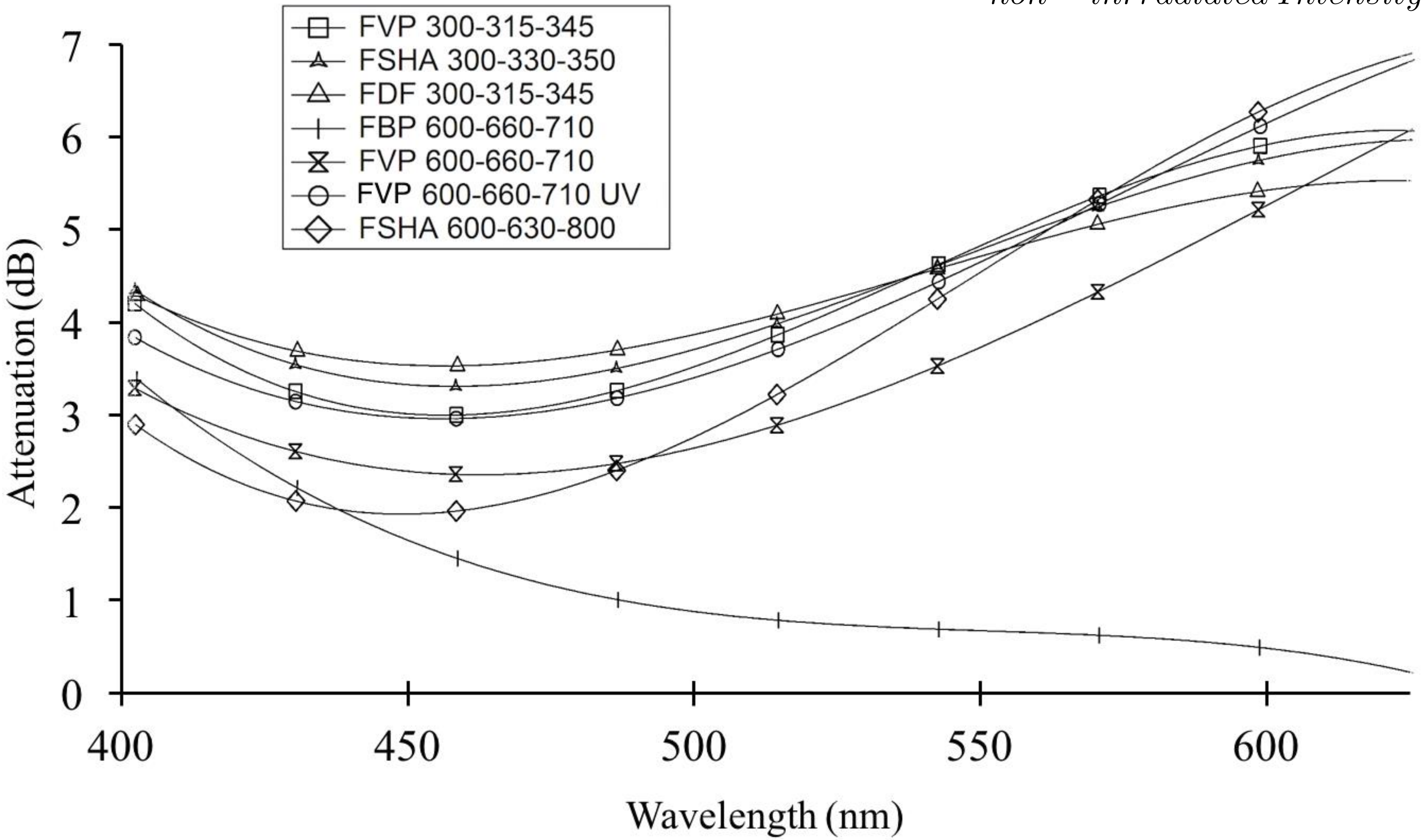
- The fiber sets were irradiated at the Argonne National Laboratory (ANL) Intense Pulsed Neutron Source (IPNS), Radiation Effects Module (REM) for 313 hours.
- At, currently decomissioned, IPNS the protons at an energy of 450 MeV struck a depleted uranium target, creating neutrons as well as gamma rays by spallation and fission.
- The tube holding all the fiber samples was positioned about 25 cm behind this target, and the radiation was directed towards the bottom of the irradiation tube, about 6.7 cm from the end.
- During the irradiation runs, the integrated proton beam current to the uranium target was 4456 μA − hrs.

Test Setup at University of Iowa



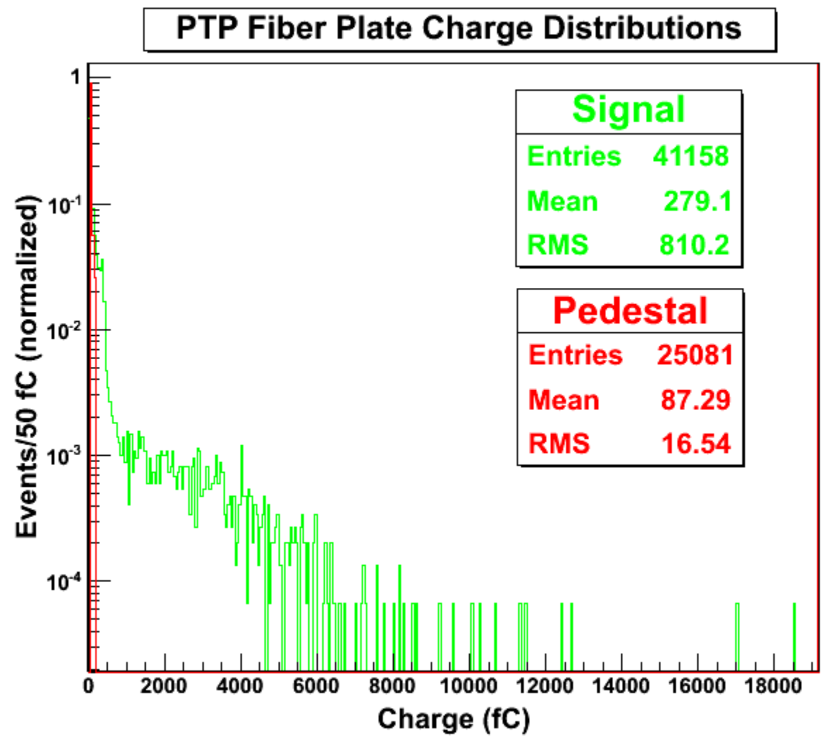
Attenuation

$$dBloss = -10log(\frac{irradiated\ Intensity}{non-inrradiated\ Intensity})$$



Quartz Fibers with pTp Coating

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



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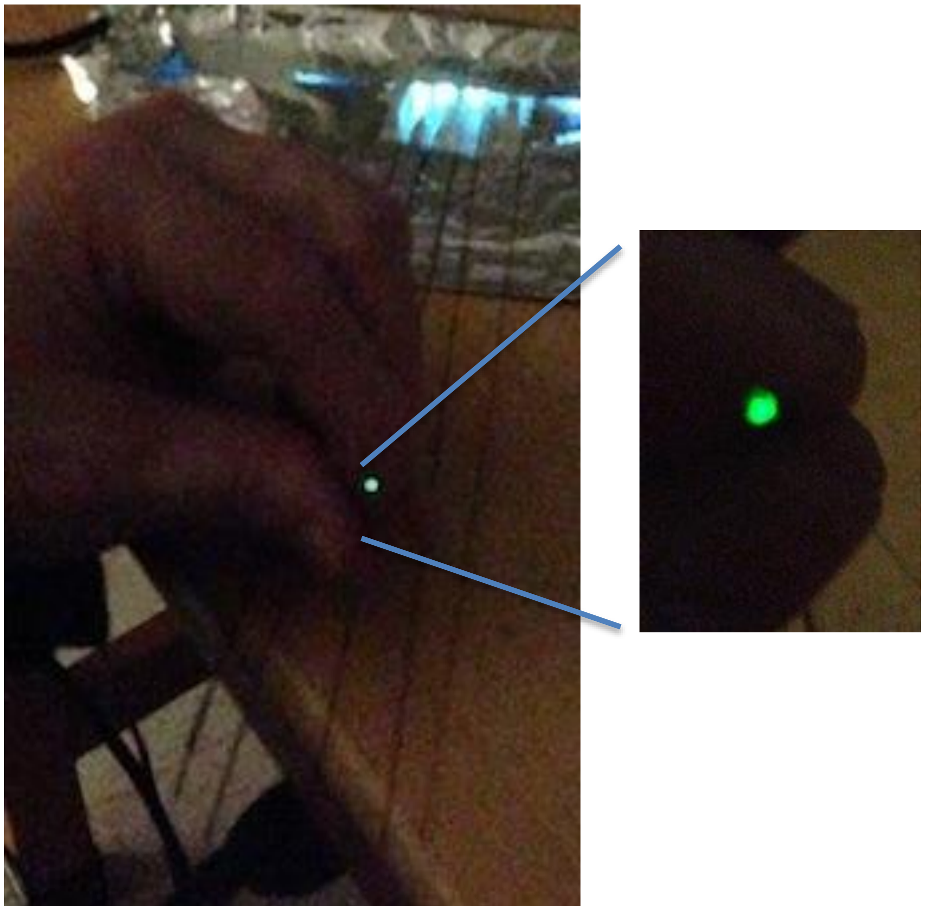
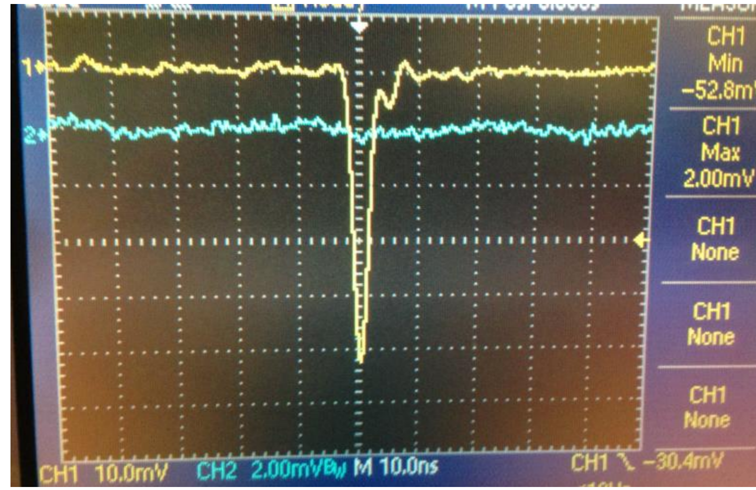
Capillary Tubes Filled with Anthracene

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

UV light





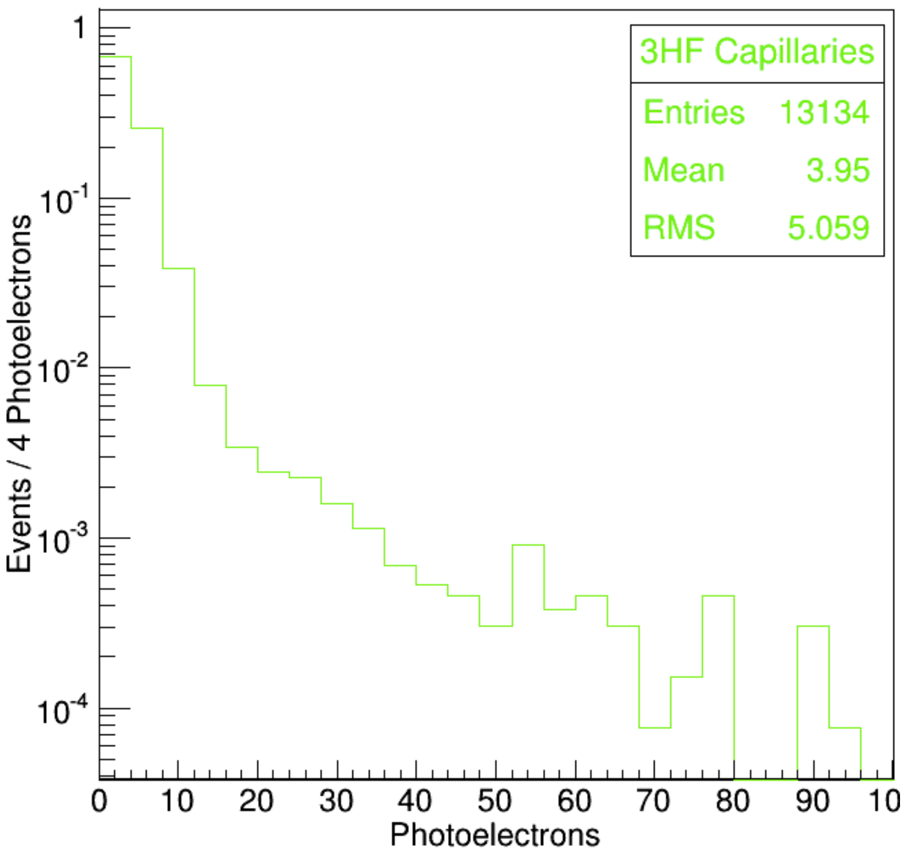
Typical pulse in 80GeV e^- beam

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

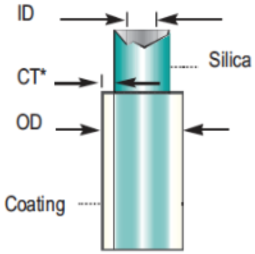
Typical Observed Pulse:
~ 8-9 p.e.

3HF Core Quartz WLS Capillaries

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



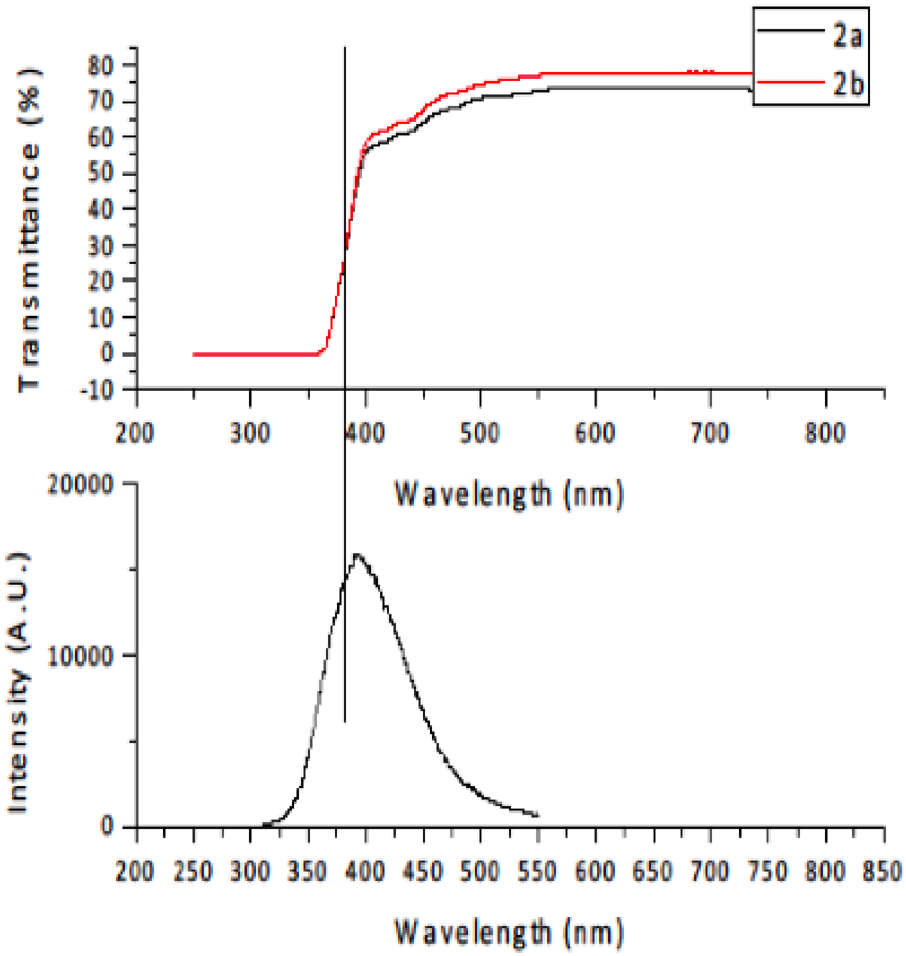
Cut at 1 pe



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!

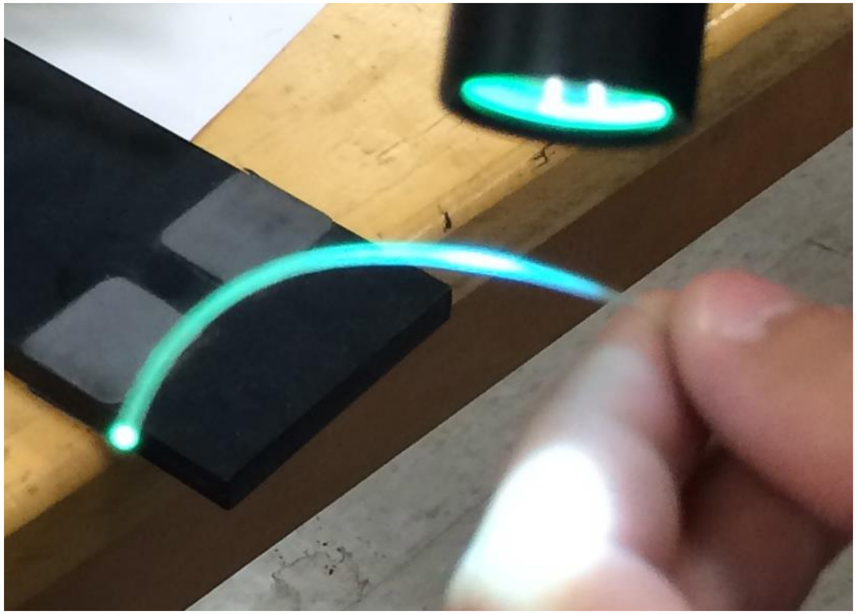
Cerium-doped Scintillating Glasses

Measured at Clemson University- Optical Science Labs

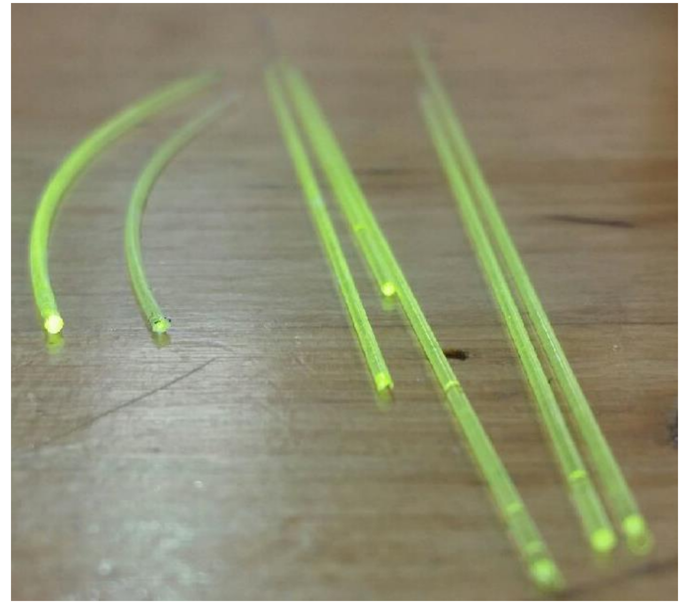


Can be drawn into fiber

3HF+Meltmount injected TeflonAF 800µm ID



CdSeZnO nanodots in Sylgard 184
Injected into Capillaries Teflon; AFQuartz



Fairfield UNIVERSITY

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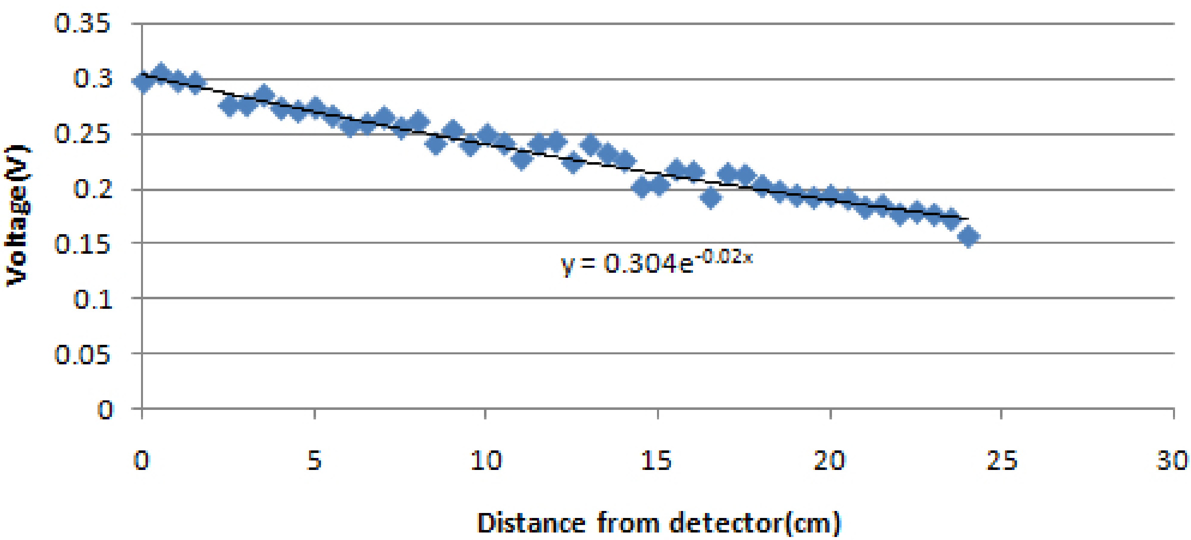
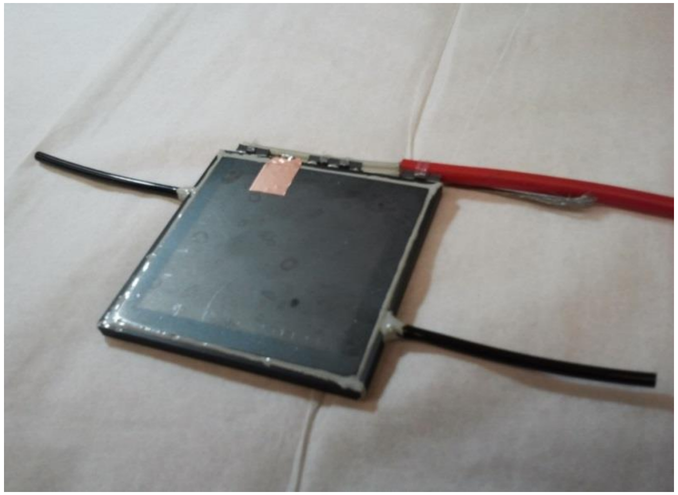


Attenuation length: 3HF in polyurethane in Quartz Capillary: L= 50 cm 1/e.

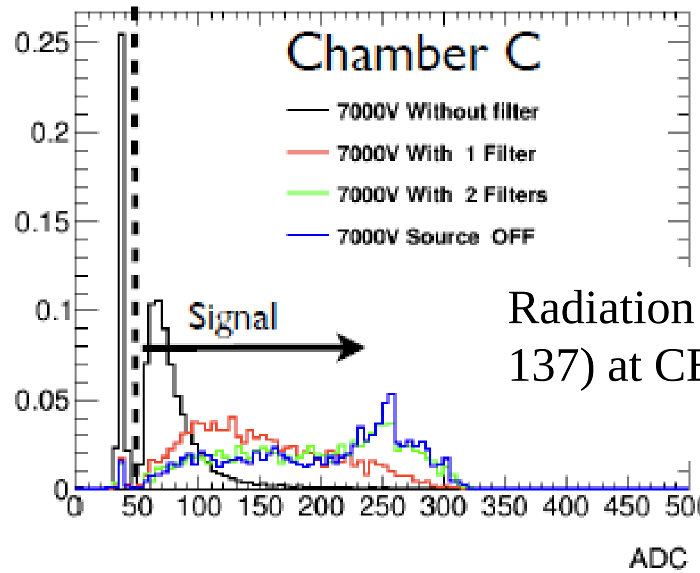
CdSeZnO Nanodots in Sylgard 184
for hot injection into capillaries

Other Radiation-Hard Detectors

RPCs with low resistivity glass

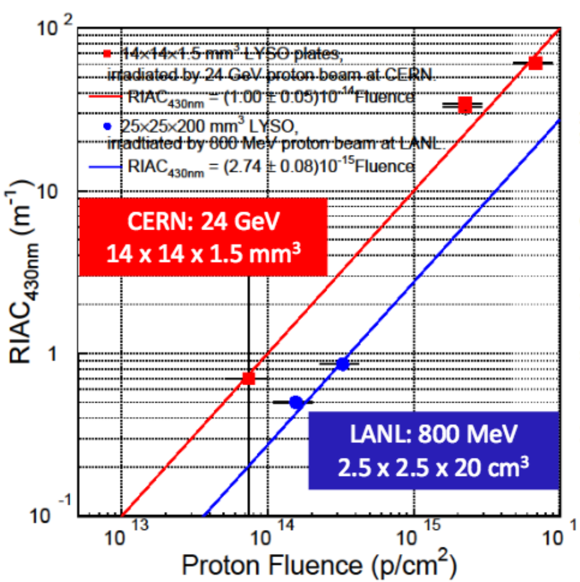


Bakelite RPCs



Radiation test (Cs-137) at CERN GIF

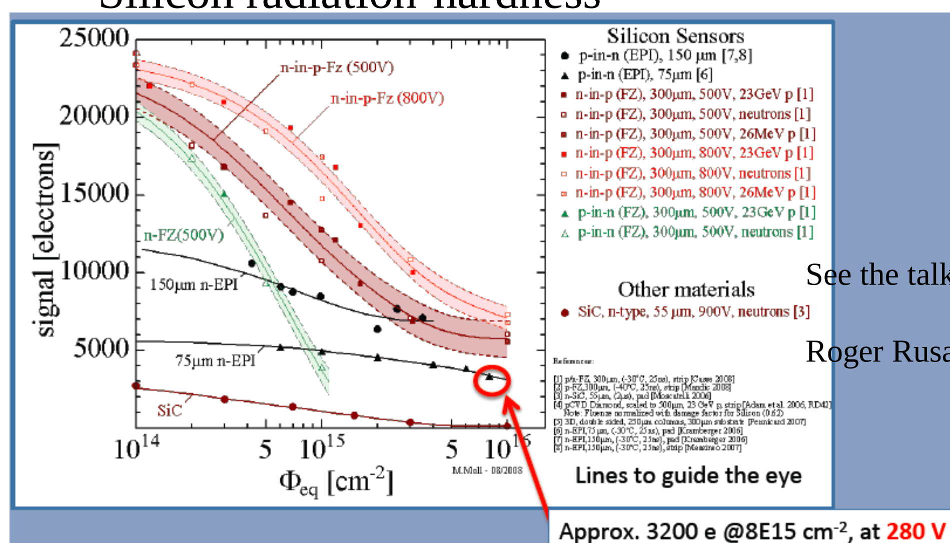
Radiation-hard crystals and capillaries



See the talks by

Ren-Yuan Zhu
Pavel Murat
Adam Para
Randy Ruchti

Silicon radiation-hardness



See the talk by

Roger Rusack

Outline

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Conclusions

- Not too many options in terms of intrinsically radiation-hard scintillators. Different combinations can be probed e.g. PEN+PET.
- 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.

Back-up

FIBER TYPES

a) FVP 300-315-345 is a 300 µm quartz core, quartz clad fiber with a polyamide buffer. It is UV enhanced with high OH- concentration. It has a numerical aperture of 0.22 and a core deflection of 25.4°.

b) FSHA 300-330-350 is a 300 µm quartz core, hard polymer fiber clad with an acrylate buffer. This quartz is enhanced with high OH- concentration. Its numerical aperture is 0.33 and core deflection is 38.5°.

c) FDP 300-315-345 is a 300 µm quartz core, quartz clad fiber with a polyamide buffer.

d) FBP 600-660-710 is a 600 µm quartz core, quartz clad fiber with a polyamide buffer.

e) FVP 600-660-710 is a 600 µm quartz core, quartz clad fiber with a polyamide buffer. It is UV enhanced with high OH- concentration. It has a numerical aperture of 0.22 and a core deflection of 25.4°.

f) FVP 600-660-710 is a 600 µm quartz core, quartz clad fiber with a polyamide buffer. Its core is modified to accommodate 210 to 214 nm color centers.

g) FSHA 600-630-800 is a 600 µm quartz core, quartz clad fiber with an acrylate buffer. The quartz is enhanced with high OH- concentration. Its numerical aperture is 0.33 and core deflection is 38.5°.

MNCPX Monte Carlo calculations performed by the IPNS staff to predict the neutron and gamma exposure delivered to the fibers during irradiation.

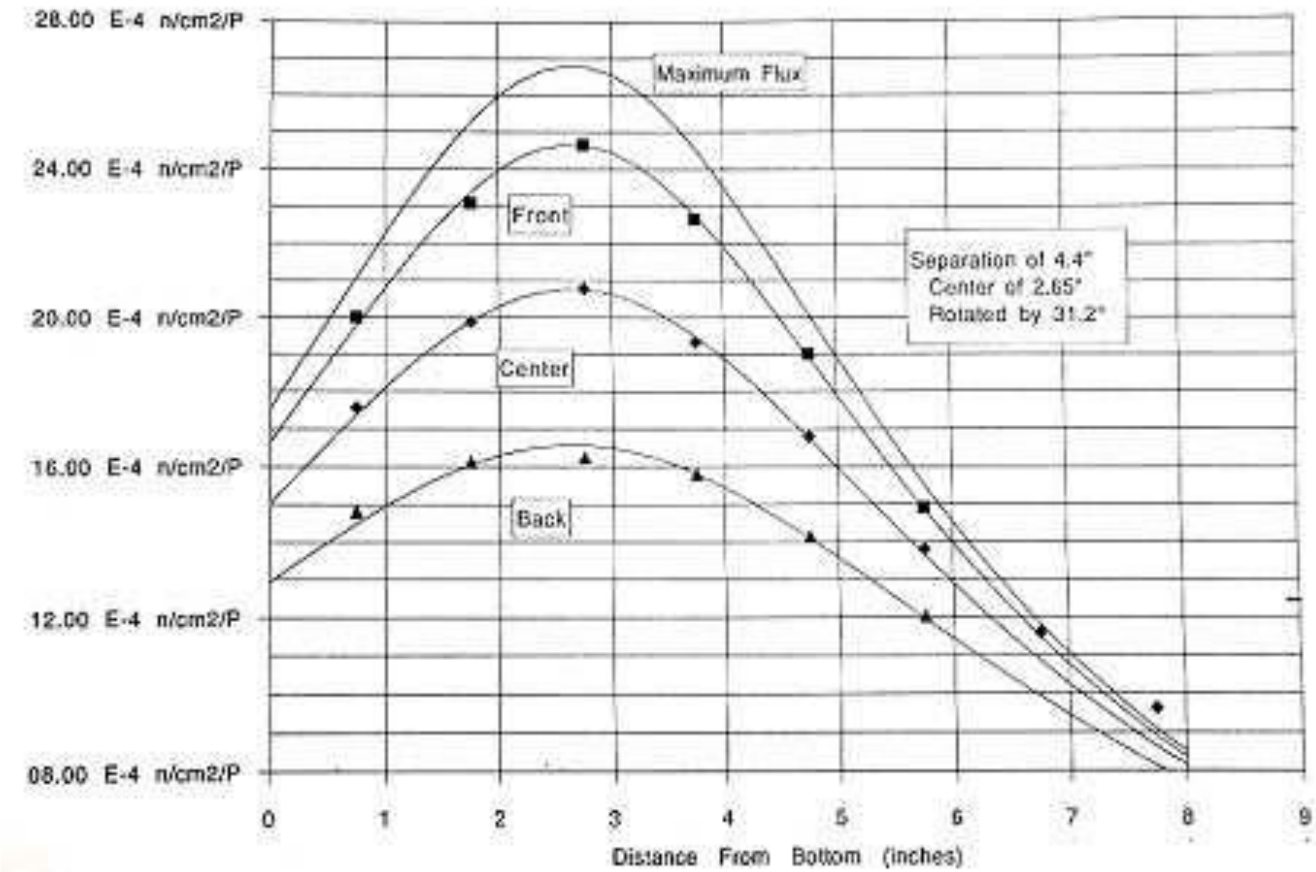
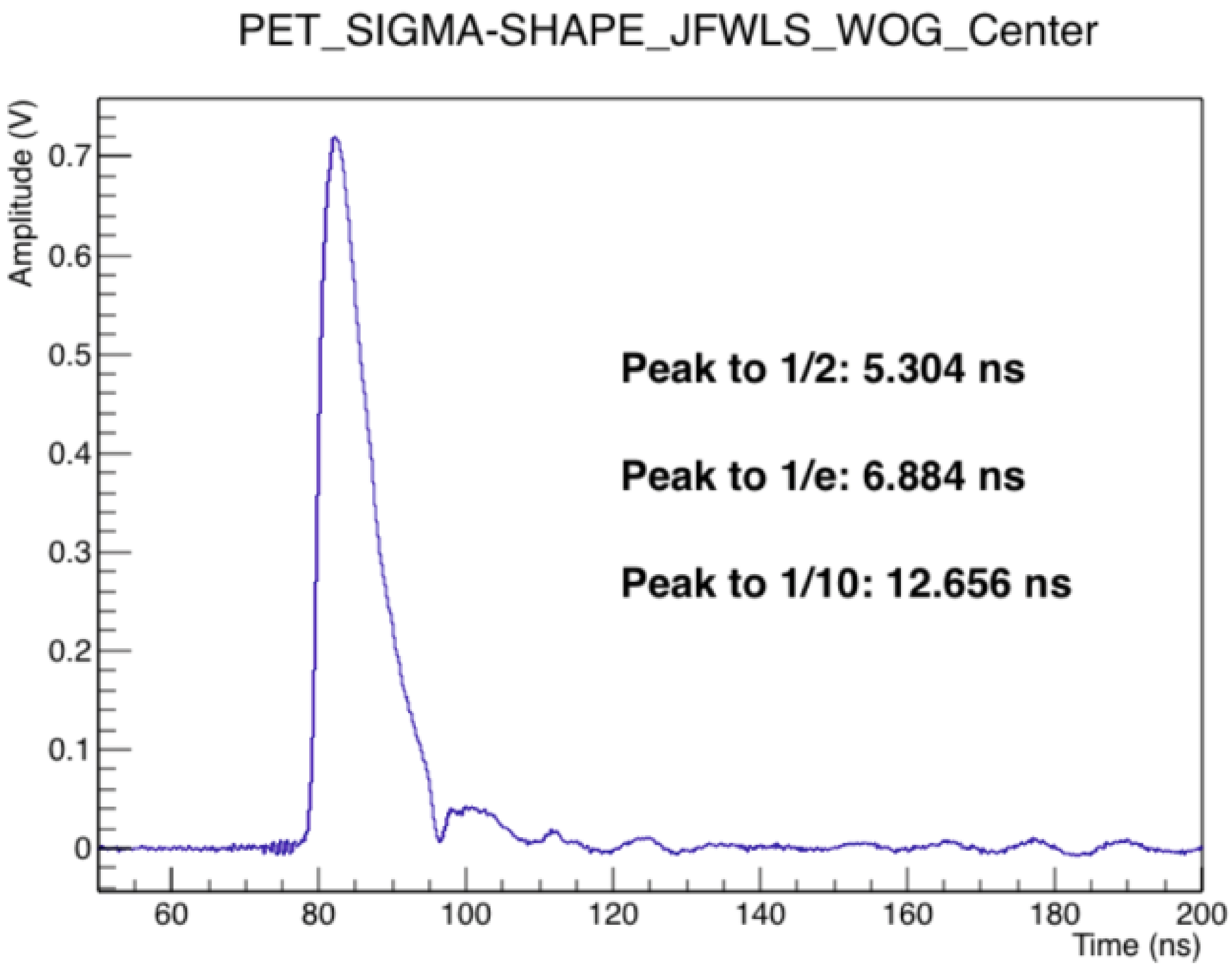


Figure 5: Neutron flux versus height in the chamber

IOWA Optics lab measurements



IOWA Optics lab measurements