NEW RADIATION-HARD SCINTILLATORS FOR FCC DETECTORS

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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

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 ($p^+/-, p^0$)
- are too large to absorb as much particle energy as possible

Accelerated Beam

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

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

• different geometries:

- Tracking chamber
- Electromagnetic calorimeter
- Hadron calorimeter
- Muon chamber

• different photodetectors:

SiPM

PMT
Charged Particle Fluence in FCC

All Charged Particles Fluence Rate

- Fluence rates in the muon chambers:
  - barrel: \( \sim 300 \text{ cm}^2\text{s}^{-1} \)
  - end-cap chambers for \( z > 10 \text{ m} \): \( \sim 500 \text{ cm}^2\text{s}^{-1} \), but for the two chambers at \( z < 10 \text{ m} \): \( 10^4 \text{ cm}^2\text{s}^{-1} \)
  - max previous layout: \( < 100 \text{ cm}^2\text{s}^{-1} \), but with an hermetic detector

- Fluence rates in the tracker:
  - first IB layer (2.5 cm): \( \sim 1.2 \times 10^{10} \text{ cm}^2\text{s}^{-1} \)
  - external part: \( 3 \times 10^6 \text{ cm}^2\text{s}^{-1} \)

- Fluence rates in the calorimeters:
  - minimum in the barrel HAD-calo: \( \sim 100 \text{ cm}^2\text{s}^{-1} \)
  - max in the forward calorimeters: \( 10^{11} \text{ cm}^2\text{s}^{-1} \)
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)

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 Fukushima Survey Meter
Poly(Ethylene-2,6-Naphthalate)/PEN: intrinsic blue scintillation! 425 nm; 10,500 photons/MeV; short decay time....
Intrinsically Rad-Hard Scintillators - PEN

100 MRad (1 MGY) Radiation Resistance!


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.
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 ($p$Tp),
  - Gallium-doped Zinc Oxide ($\text{ZnO:Ga}$)
  - Anthracene (An)
- PEN, PET and HEM

What geometry and readout?
- Sigma & Bar shape
- SiPM, PMT
PEN → Light yield mean 44 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.

\[ \varepsilon = 0.10 \]
\[ L_y = 0.86 \]

\[ \varepsilon = 0.57 \]
\[ L_y = 1.11 \]
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

![Graph showing transmission intensity over wavelength (nm) for different conditions: PEN 10 MRad N2, PEN No Damage, and PEN 10 MRad / No Damage.]

![Graph showing amplitude over time (ns) for different conditions: Undamaged, 1.7 MRad Air, and 10 MRad N2.]

<table>
<thead>
<tr>
<th></th>
<th>Undamaged</th>
<th>10 MRad N2</th>
<th>1.7 MRad Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integral</td>
<td>20208</td>
<td>19012</td>
<td>17311</td>
</tr>
<tr>
<td>(300-450 ns)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative %</td>
<td>100%</td>
<td>94.1%</td>
<td>85.7%</td>
</tr>
<tr>
<td>(damaged / Undamaged)</td>
<td></td>
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</table>
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.

24 GeV protons, beam spot (FWHM) 15x15 mm², proton flux - ~6x10⁹ p cm⁻² s⁻¹
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
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.

Good PMT QE and low self-absorption, thus a maximal efficiency.
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.
We irradiated our samples with using $^{137}$Cs gamma source at Iowa Rad Core 1.4 Mrad and 14 Mrad.

- 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

- **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.

<table>
<thead>
<tr>
<th>Tile</th>
<th>‘a’, Total Recovery (%)</th>
<th>‘c’, Permanant Damage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiX RGB</td>
<td>56.3 ± 2.4%</td>
<td>30.7 ± 1.6%</td>
</tr>
<tr>
<td>SiX dark box</td>
<td>45.7 ± 2.5%</td>
<td>44.1 ± 1.9%</td>
</tr>
<tr>
<td>EJN RGB</td>
<td>24.0 ± 2.2%</td>
<td>6.92 ± 0.7%</td>
</tr>
<tr>
<td>EJN dark box</td>
<td>21.1 ± 1.8%</td>
<td>15.9 ± 0.6%</td>
</tr>
<tr>
<td>EJ2P RGB</td>
<td>26.9 ± 3.1%</td>
<td>15.2 ± 0.9%</td>
</tr>
<tr>
<td>EJ2P dark box</td>
<td>26.5 ± 2.2%</td>
<td>13.7 ± 0.7%</td>
</tr>
</tbody>
</table>
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, Ptlr, 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
  - pTTP, 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
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

<table>
<thead>
<tr>
<th>Tile</th>
<th>Fiber</th>
<th>Gamma Source response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue tile</td>
<td>green fiber</td>
<td>288.8</td>
</tr>
<tr>
<td>Blue tile 50 Mrad</td>
<td>green fiber</td>
<td>4.6 4.6/289=1.6% dead</td>
</tr>
<tr>
<td>**</td>
<td>Done with Tyvek wrapping</td>
<td>– expect better results with black paper</td>
</tr>
<tr>
<td>Blue tile 50Mrad</td>
<td>Orange fiber</td>
<td>12.0 12/106 =11.3% ***</td>
</tr>
<tr>
<td>Blue tile - 1 green coat</td>
<td>Orange fiber</td>
<td>138.4</td>
</tr>
<tr>
<td>Blue tile -50Mrad</td>
<td>Orange fiber</td>
<td>19.9 10/138=14.5%</td>
</tr>
<tr>
<td>Blue - 2 green coats</td>
<td>Orange fiber</td>
<td>114.9</td>
</tr>
<tr>
<td>Blue tile - (50Mrad)</td>
<td>Orange fiber</td>
<td>17.8 17.8/115=15.5%</td>
</tr>
</tbody>
</table>

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.