Dose rate effects in radiation damage of plastic scintillator

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Plastic scintillators in HEP – past

Many experiments have used them in the past:

- **CDF**
  - Hadronic Calorimeter
- **DØ**
  - outer tracker (scintillating fiber)
  - Preshower detector
Plastic scintillators in HEP – today

Many **experiments** are using them or planning to use them:

- **CMS**
  - HCAL
  - HGCal

- **ATLAS**
  - TileCal

**Future experiments** considering their use:

E.g., **FCC-ee**: the **IDEA** detector (in the form of scintillating fiber)
Importance of radiation hardness

• Radiation tolerance has been important for applications with high particle fluxes. (doses > $10^3$ Gy)

• At CMS, during the 50 fb$^{-1}$ running at 13 TeV in 2017, the HE tiles received doses up to a few kGy. $^{[12]}$

• Typical dose rates from $10^{-3}$ to 1 Gy/h.

• During the HL-LHC run, the HGCal detector’s scintillator is expected to absorb doses up to O(100 Gy). $^{[13]}$
Plastic scintillators – structure

Plastic scintillators consist of:

- **Substrate material**: Common choices include:
  - Polystyrene (PS)
  - Polyvinyl toluene (PVT)

- **Dopants**:
  - **Primary fluors**, like:
  - **Secondary fluors**, like:
Plastic scintillators – inner workings

The scintillation process for a particle that enters the scintillator follows these steps \[^1,^2\]:

1. The particle excites/ionizes the electrons of the substrate.
2. Energy transfer from substrate to primary fluor:
   i. Radiative transfer
   ii. Non-radiative transfer through the Förster mechanism[^3]
3. Primary fluor emits photon.
4. Secondary fluor absorbs photon from primary and reemits at different wavelength.
5. Detection of secondary fluor emission with photodetector.
Radiation damage

Mechanisms for radiation damage can be categorized as follows:

• Decrease in the initial light production
  - Fluor destruction
  - Absorption of light between primary and secondary fluors.
  - Suppression of Förster mechanism.

• Formation of color centers\(^4\)
  - Absorption of light emitted from the secondary fluor.
Radiation damage

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  - Fluor destruction
  - Absorption of light between primary and secondary fluors.
  - Suppression of Förster mechanism.
- Formation of color centers\textsuperscript{[4]}
  - Absorption of light emitted from the secondary fluor.

Figure taken from [1].
Radiation damage

To quantify radiation damage, the **dose constant** $D$ is used

$$D = -\frac{d}{\ln \left( \frac{L_f}{L_i} \right)}$$

where $L_i, L_f$ are the light yields before and after irradiation and $d$ is the dose.

- **Note:** Larger $D$ means **more resistant to radiation**.
Dose rate dependence on damage

- Radiation breaks substrate bonds and creates free radicals.
- Radicals absorb visible light (stronger at low $\lambda$). Temporary damage
- After irradiation, radicals recombine. Their density $[Y]$ for a dose rate $R$ is given by $^{5, 6}$

$$\frac{d[Y]}{dt} = gQR - k[Y]^2$$

- The dose constant is expected to be

$$D = (gQ\sigma l)^{-1}$$

- Oxygen is needed for oxide formation, but oxygen diffusion and radical formation are competing processes.
- The oxygen diffusion depth depends on dose rate $R$:

$$z^2_0 = \frac{2MC_0}{\gamma R}$$

- Using the sample thickness, we can calculate the $R$ that allows full oxygen penetration.

*symbols explained in backup slides
Related work

Many studies of the **dose rate dependence** exist:

- Previous measurements without wavelength-shifting fiber were limited to high dose rates. \(^{[7-12]}\)
- Power-law dependence between \(D\) and \(R\) was published by CMS in 2020. \(^{[13]}\)
- These low-\(R\) measurements are for tiles with wavelength-shifting fibers and 20% of the observed damage was in the fibers.
Methodology – Irradiations

• Our samples are scintillating rods supplied by Eljen Technology (EJ-200 & EJ-260).

• EJ-200 has blue and EJ-260 green-emitting fluors. Green is expected to be harder to radiation since color center formation is expected to be much larger at shorter $\lambda$.

• Rods vary in width and concentrations of fluors and antioxidants. (Tables 1 and 2)

• We have performed irradiations at three different facilities. (Table 3)

### Table 1: 1x1x5 cm samples (units of nominal concentration)

<table>
<thead>
<tr>
<th>Scintillator type</th>
<th>Substrate</th>
<th>Primary fluor</th>
<th>Secondary fluor</th>
<th>Antioxidants</th>
</tr>
</thead>
<tbody>
<tr>
<td>EJ200, EJ260</td>
<td>PS</td>
<td>1</td>
<td>1</td>
<td>0, 1, 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>PVT</td>
<td>1</td>
<td>1</td>
<td>0, 1, 2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

### Table 2: Variable width samples

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Width (cm)</th>
<th>Fluors/Antioxidants</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS</td>
<td>0.2, 0.4, 0.6, 0.8, 1.0</td>
<td>Nominal concentrations</td>
</tr>
<tr>
<td>PVT</td>
<td>0.2, 0.4, 0.6, 0.8, 1.0</td>
<td></td>
</tr>
</tbody>
</table>

### Table 3: Irradiations

<table>
<thead>
<tr>
<th>Irradiation facility</th>
<th>Source</th>
<th>Dose (kGy)</th>
<th>Dose rate (Gy/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSFC REF</td>
<td>Gamma</td>
<td>12.6, 42</td>
<td>3.1, 9.8</td>
</tr>
<tr>
<td>NIST</td>
<td>Co-60</td>
<td>47</td>
<td>470</td>
</tr>
<tr>
<td>GIF++</td>
<td>Cs-137</td>
<td>70</td>
<td>2570, 3900</td>
</tr>
</tbody>
</table>
Methodology – Measuring $D$

Charge integration over 100 ns

Tektronix TDS7104 oscilloscope

Light yield values before and after irradiation used to extract $D$. 

Fit peak of curve
Methodology – Measuring $T$

- Used a Varian Cary 300 spectrophotometer to measure transmission.

- The **pseudo inverse of $D$** is defined as:

$$D^{-1} = \frac{\ln(T_o) - \ln(T_f)}{d}$$

where $T_o$ and $T_f$ are the transmissions before and after irradiation, and $d$ is the total dose.

- The values of $D^{-1}$ indicate:
  - increase in $T$ when negative
  - decrease in $T$ when positive

- A typical **unirradiated** sample:
  - very low transmission at the absorption spectrum of the fluors
  - high transmission at the emission spectrum of the fluors
About the comparison:
• Comparing rods with PS and PVT substrates.
• Both blue (EJ200) and green (EJ260) fluors are considered.
• Fluors and antioxidants concentrations are nominal.

Results:
• **Linear trend** \( (\text{vs } \log R) \) until 70 Gy/hr.
• PS and PVT show different dose constant behavior above that level:
  - for PVT, remains **constant or continues to rise**.
  - for PS, remains **constant or decreases**.

  **Depending on the fluor concentrations.**
Results – Fluor concentrations

Varying fluor concentrations:
- **1X1P**: nominal primary and secondary
- **1X2P**: double primary and nominal secondary
- **2X1P**: nominal primary and double secondary

Some observations:
- **No significant effect** observed until 70 Gy/hr.
- Behavior above that amount depends on dopant concentrations.
- Increasing the primary dopant concentration benefits PS samples.
- No dependence observed for PVT within uncertainties.
Results – Transmission

Some general remarks:
• Large positive values of $\mathcal{D}^{-1}$ indicate color center formation.
• Negative values probe fluor destruction.

Both are strong indicators of radiation damage.

Our observations show:
• Radiation damage for both scintillator types.
• Strong fluor destruction for the blue scintillator (EJ200).

Black arrows indicate the emission spectrum of the secondary.
Results – Varying thickness

The two radiation damage mechanisms show different dependences of $D$ on rod thickness:

- Color center formation gives $D$ that scale as $l^{-1}$.
- Damage to initial light production is independent of $l$.

Results:

- During the recovery period, the dose constant is strongly dependent on the sample thickness.
- Indication that color centers form during irradiation but their number reduces after annealing.
- Final dose constants do not depend strongly on thickness.
- Dominant radiation damage mechanism is reduction in initial light production after annealing.
- The maximum sample thickness (1 cm) is not large enough to make color centers dominant.

Note: For full oxygen penetration dose rates need to below 10 Gy/h, 4.4 Gy/h, 2.5 Gy/h, and 1.6 Gy/h for thicknesses 4, 6, 8, and 10 mm, respectively.
Conclusions

• $D$ increases linearly vs logR for dose rates up to 70 Gy/hr.

• Above 70 Gy/hr:
  • for PVT, it is constant or continues to rise
  • for PS, it is constant or decreases

• Results from varying thickness rods suggest that damage to the initial light output is dominant for thicknesses up to 1 cm.

• Thicker samples will be more sensitive to color center absorption.

• For the blue scintillator (EJ-200), the transmission measurements indicate damage to the fluors.
References


References


Backup
Dose rate dependence on damage

- The radical density \([Y]\) is given by \([5, 6]\)

\[
\frac{d[Y]}{dt} = gQR - k[Y]^2
\]

where \(g\) is the chemical yield, \(Q\) is the scintillator density, \(R\) is the dose rate, and \(k\) is the reaction constant for the decay of the radical.

- The dose constant is expected to be

\[D = (gQ\sigma l)^{-1}\]

where \(\sigma\) is the cross-section absorption of light by the color centers and \(l\) is the light’s path length through the scintillator to the photodetector.

- There is an oxygen diffusion depth that depends on dose rate \(R\):

\[z_0^2 = \frac{2MC_0}{YR}\]

where \(M\) is the diffusion coefficient for oxygen, \(C_0\) is the oxygen concentration at the substrate’s surface, \(Y (= gQ)\) is the specific rate constant of active site formation, and \(R\) is the dose rate.

*symbols explained in backup slides*
Plastic scintillator structure

Substrate material

- Primary fluor
- Secondary fluor