Radiation damage studies for phenyl-based plastic scintillators

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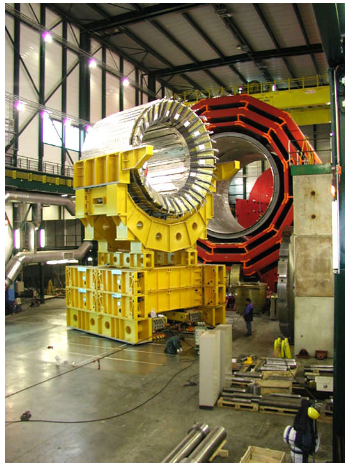
Overview

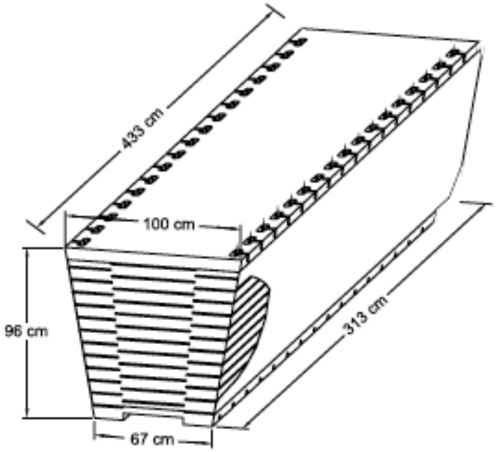
1. Plastic scintillators in HEP
2. Work principles
3. Mechanisms of radiation damage
4. Related work
5. Experimental methodology
6. Results
7. Conclusions

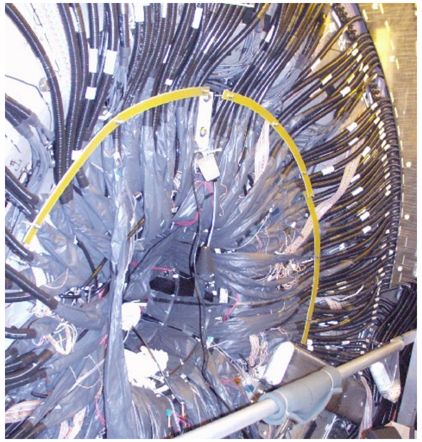
Plastic scintillators in HEP – past

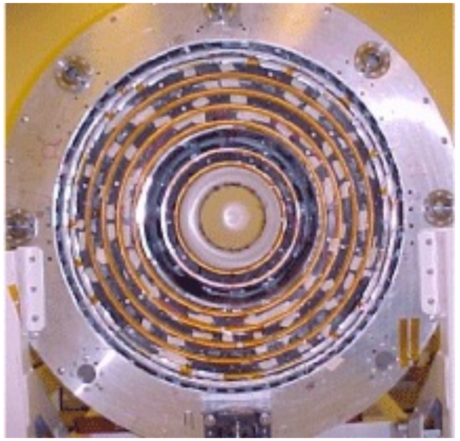
Many experiments have used them in the past:

- **CDF**
  - Hadronic Calorimeter
- **DØ**
  - outer tracker (scintillating fiber)
  - Preshower detector









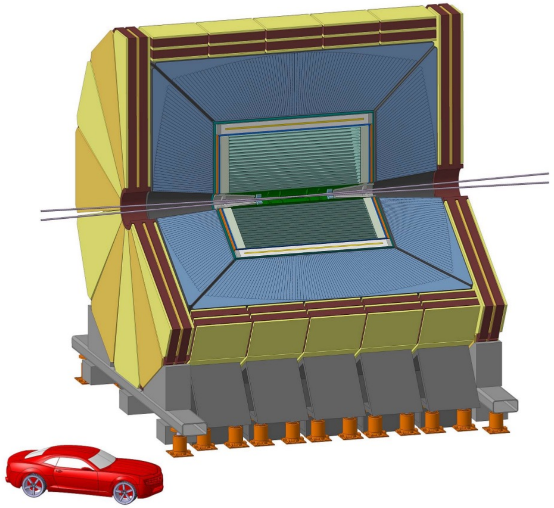
Plastic scintillators in HEP – today

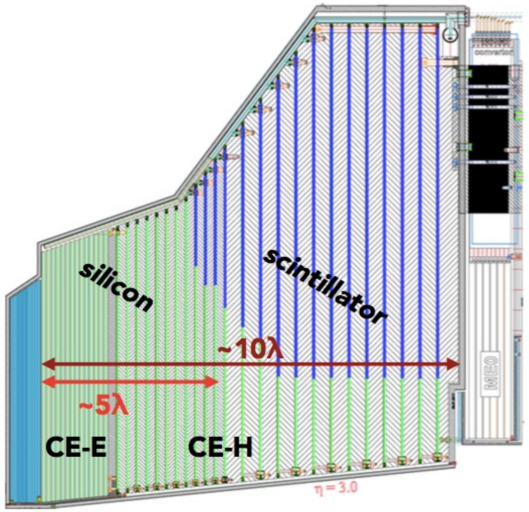
Many **experiments** are using them or planning to use them:

- **CMS**
  - HCAL
  - HGCAL
- **ATLAS**
  - TileCal

Future experiments considering their use:

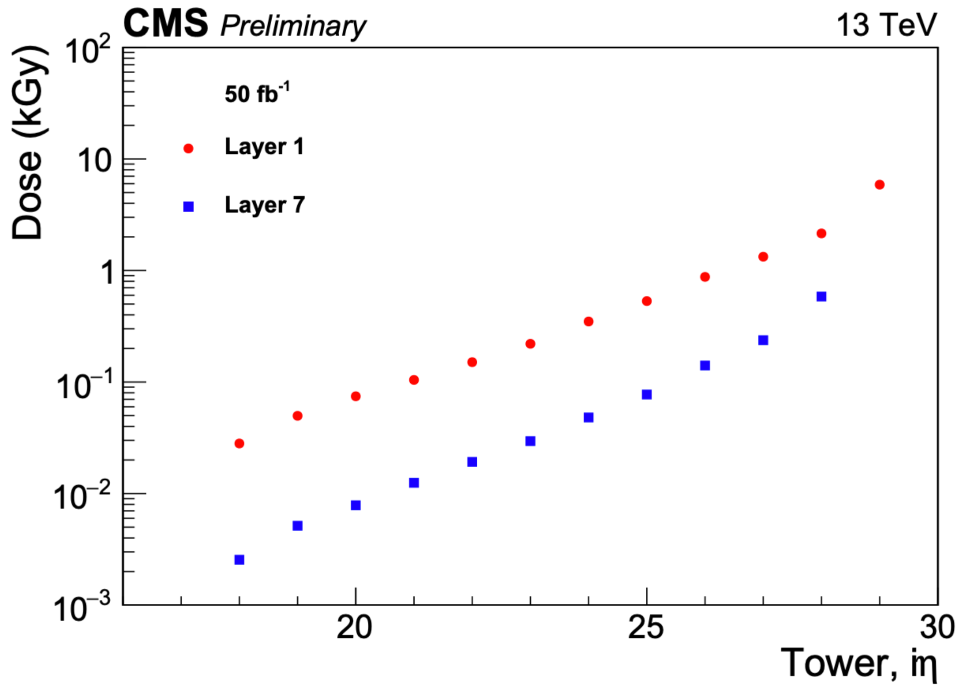
E.g., **FCC-ee**: the **IDEA** detector (in the form of scintillating fiber)

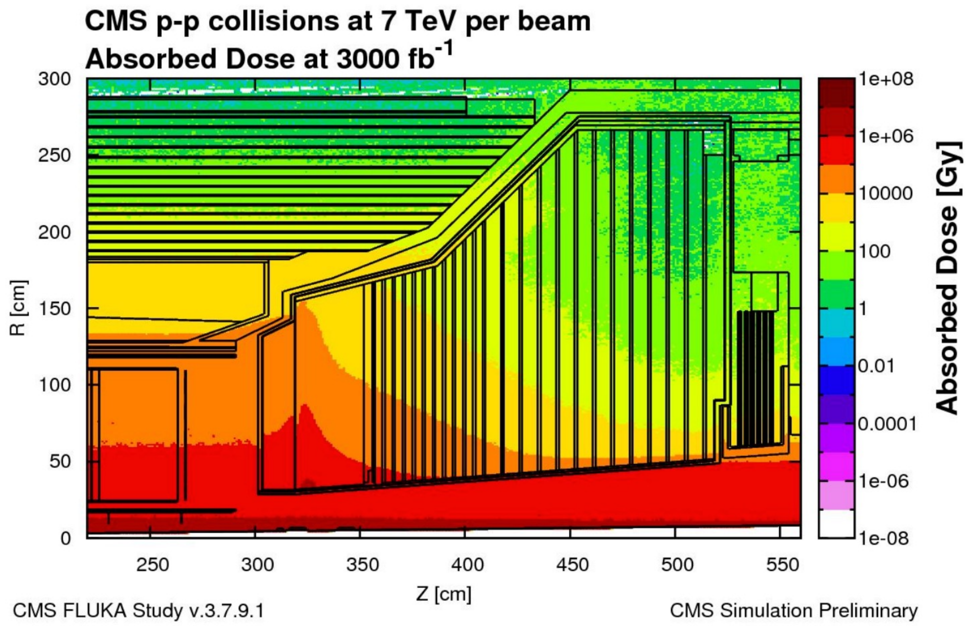




Importance of radiation hardness

- 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 kGy). [13]

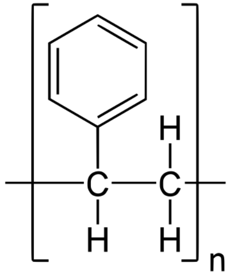
More details on Ted Koldberg's talk yesterday

Plastic scintillators – structure

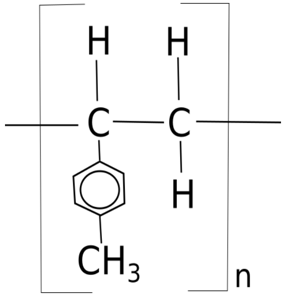
Plastic scintillators consist of:

- **Substrate material:** Common choices include:

polystyrene (PS)



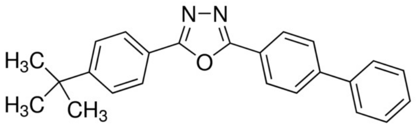
polyvinyl toluene (PVT)



- **Dopants:**
  - **Primary fluors**, like:

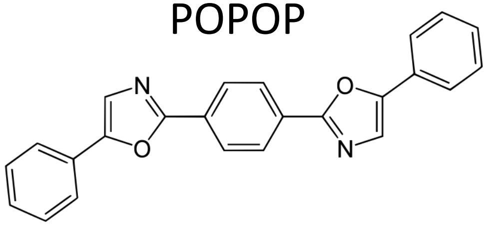
p-terphenyl (PTP)

BPBD



  - **Secondary fluors**, like:

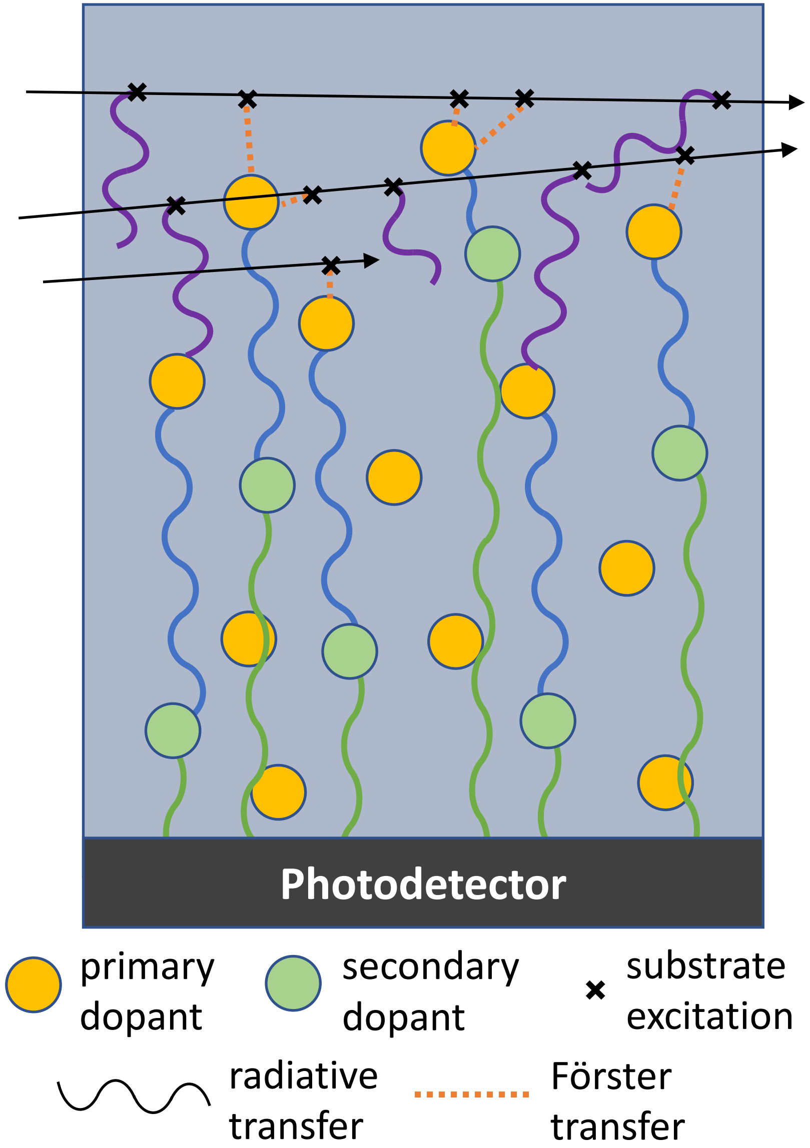
POPOP



Plastic scintillators – inner workings

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

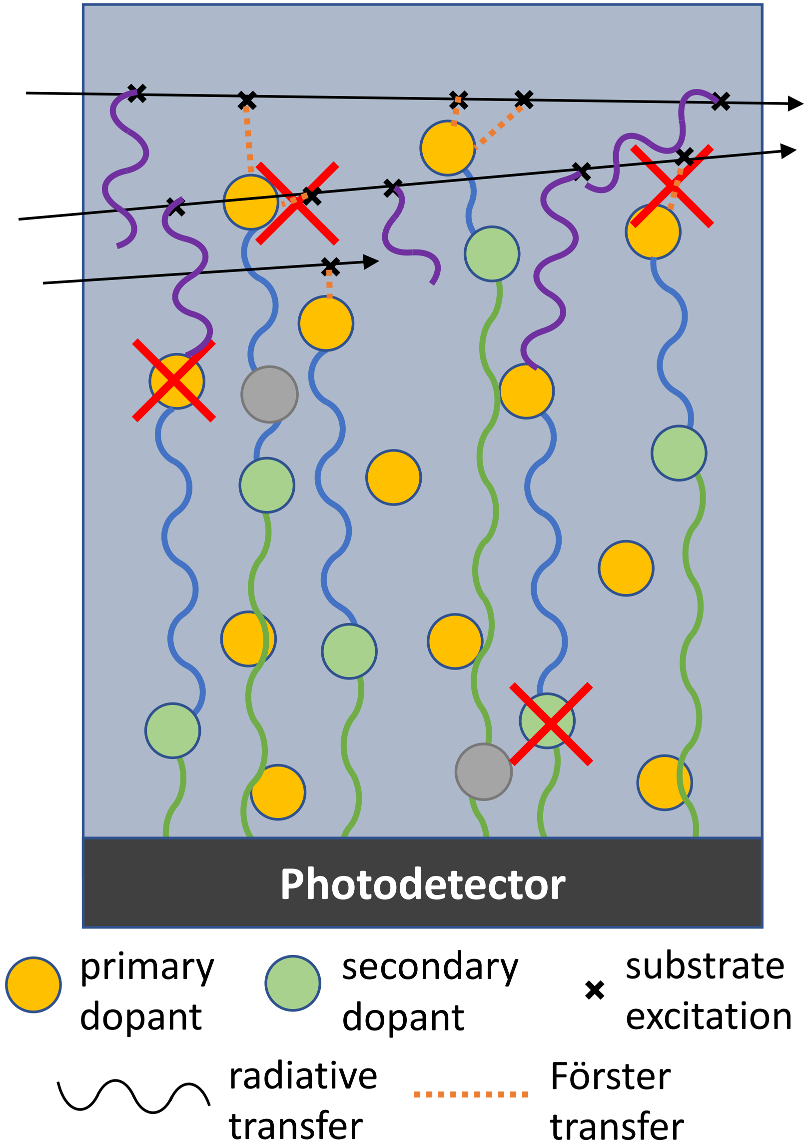
1. The particle **excites/ionizes** the the electrons of the substrate.
2. Energy transfer from substrate to primary fluor:
   1. Non-radiative transfer through the **Förster mechanism**.[3]
   2. Radiative transfer
3. Primary fluor **emits** photon.
4. Secondary fluor **absorbs** photon from primary 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

Mechanisms for **radiation damage** can be categorized as follows:

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  - ➢Suppression of Förster mechanism.
- Formation of **color centers**[4]
  - ➢Absorption of light emitted from the secondary fluor.

Differences:

- ❖**Color centers:** dependence on thickness
- ❖**Initial LY decrease:** independent of thickness

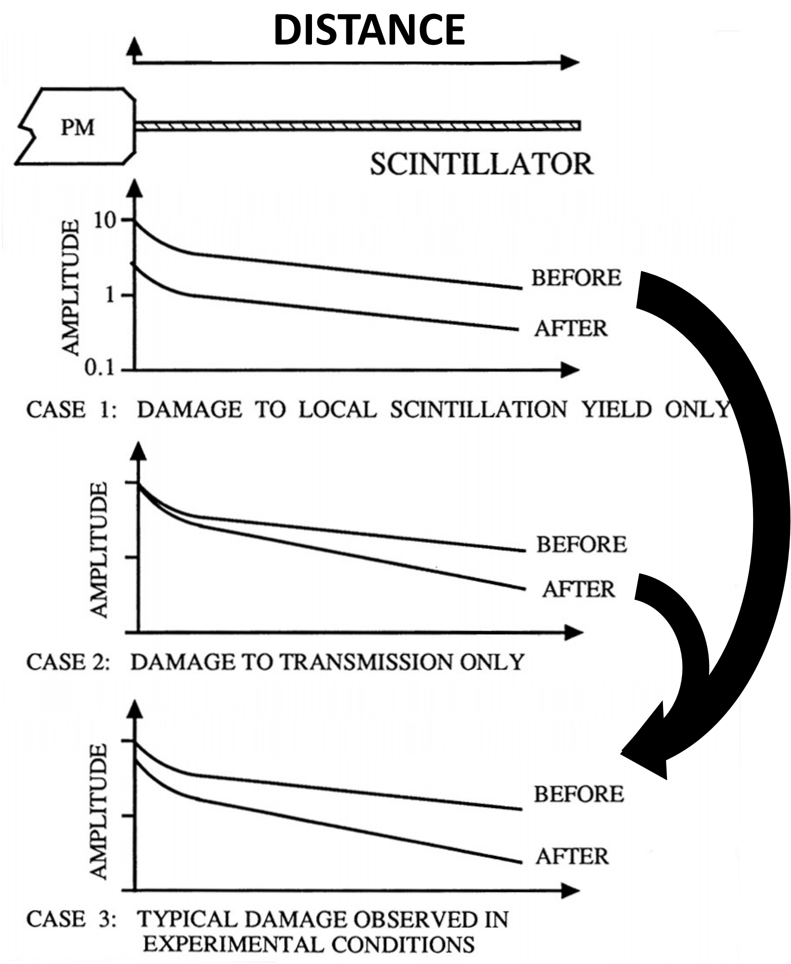


Figure taken from **[1]**.

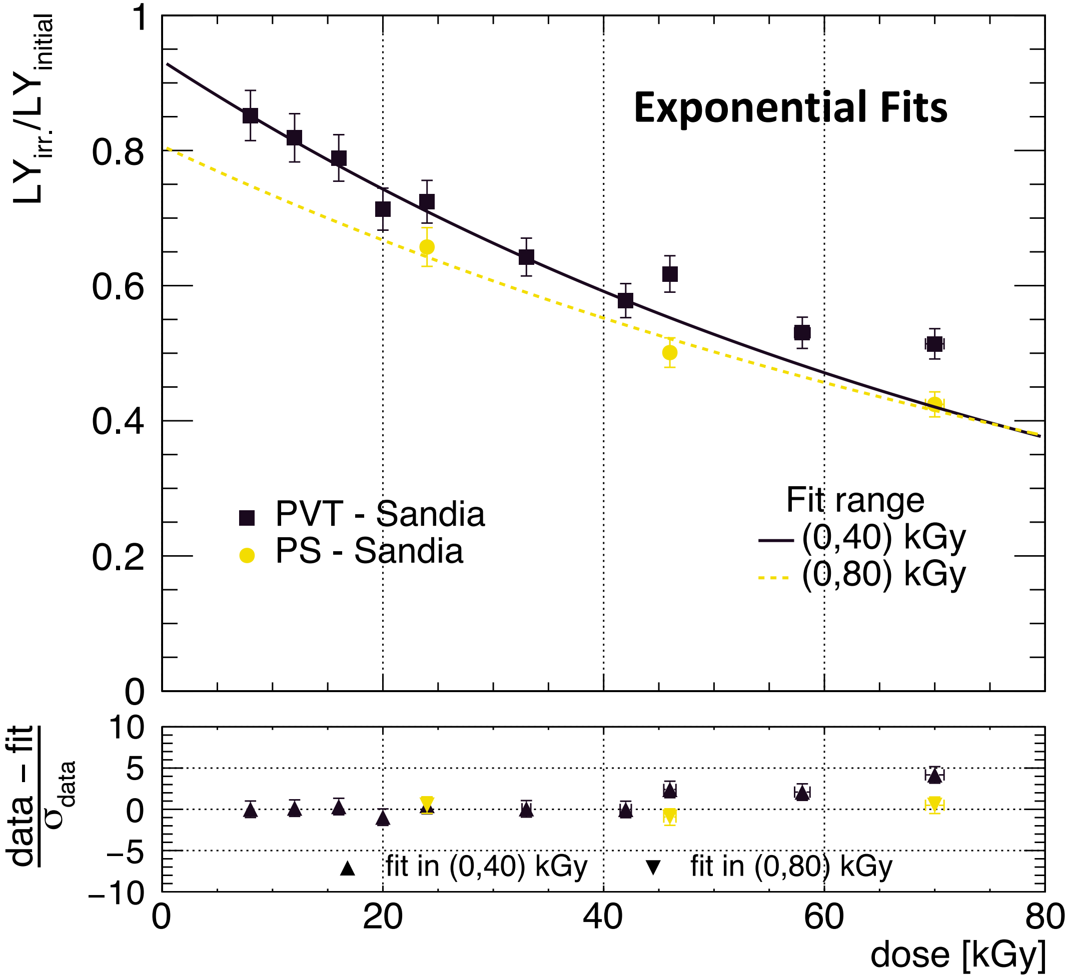
Dose constant

To quantify radiation hardness, the **dose constant *D*** is used

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

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 λ). ➡ **Temporary damage**
- Radicals also **recombine** and their density Y for a dose rate R is given by **[5, 6]**

$$\frac{dY}{dt} = aR - bY^2$$

- The dose constant is expected to be

$$D \propto l^{-1}$$

➡ **D scales with 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:

$$z_0 \propto R^{-1/2}$$

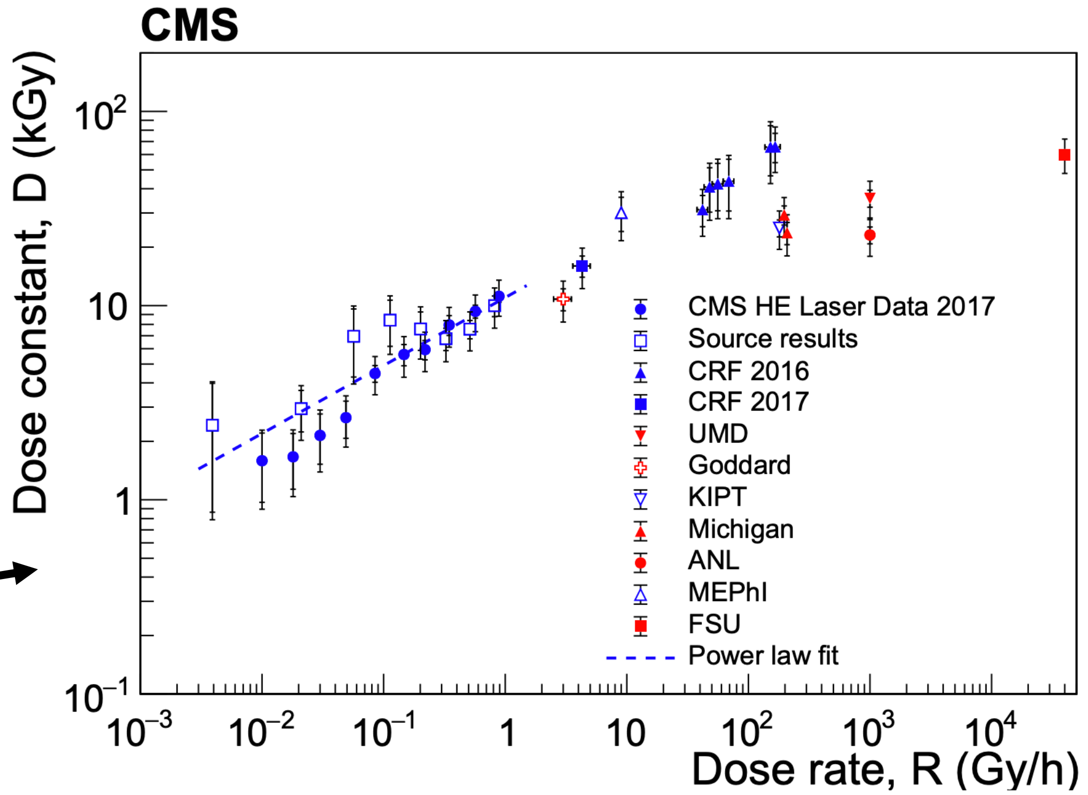
- Using the sample thickness, we can calculate the R that allows **full oxygen penetration**.

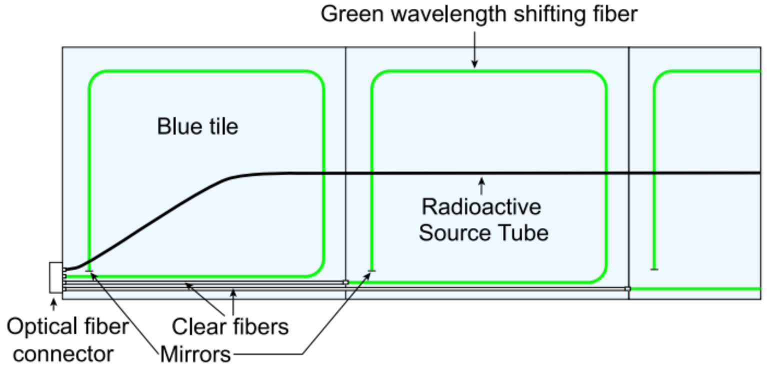
**symbols expanded and explained in backup slides*

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 λ.
- 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)

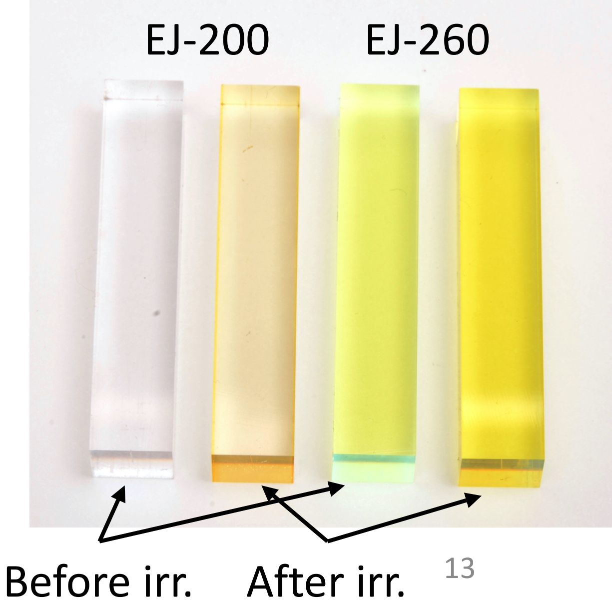
Scintillator type	Substrate	Primary fluor	Secondary fluor	Antioxidants
EJ200, EJ260	PS	1	1	0, 1, 2
			2	1
		2	1	1
	PVT	1	1	0, 1, 2
			2	1
		2	1	1

Table 3: Irradiations

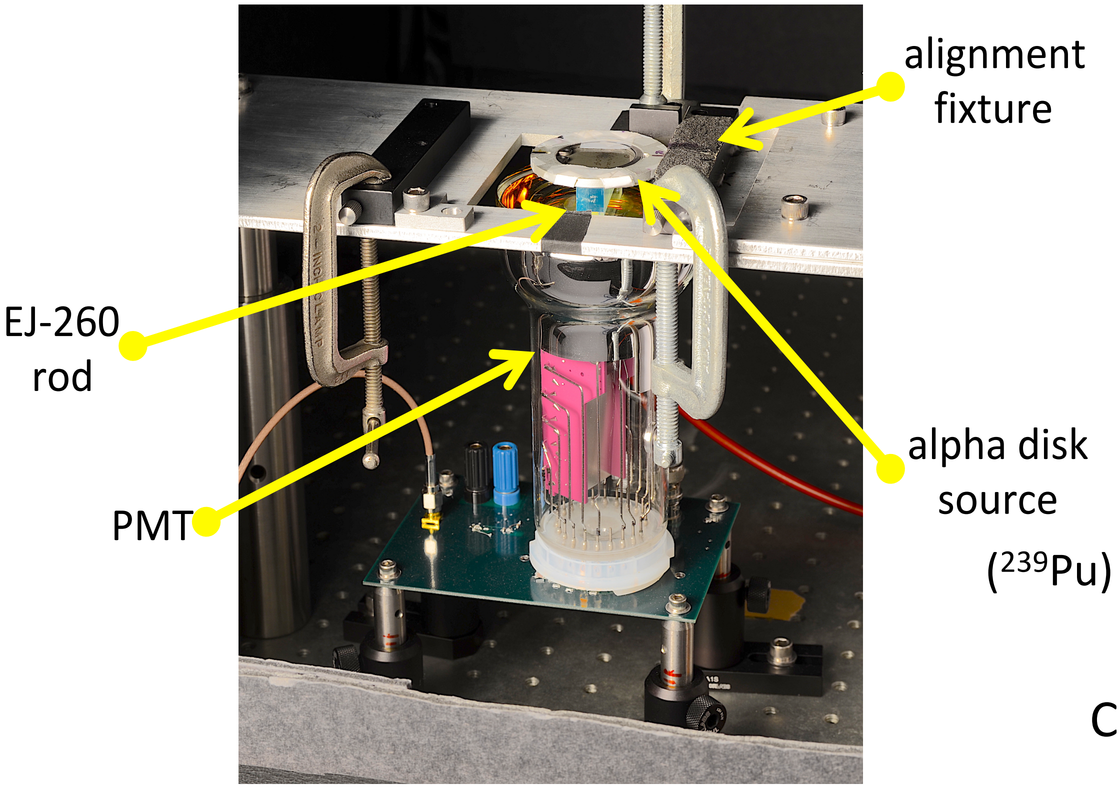
Irradiation facility	Source	Dose (kGy)	Dose rate (Gy/hr)
GSFC REF	Gamma	12.6	3.1
		42	9.8
NIST	Co-60	47	470
		70	83.4, 85.3
			744
			2570, 3900
GIF++	Cs-137	13.2	2.2

Table 2: Variable width samples

Substrate	Width (cm)	Fluors/ Antioxidants
PS	0.2, 0.4, 0.6, 0.8, 1.0	Nominal concentrations
PVT	0.2, 0.4, 0.6, 0.8, 1.0	

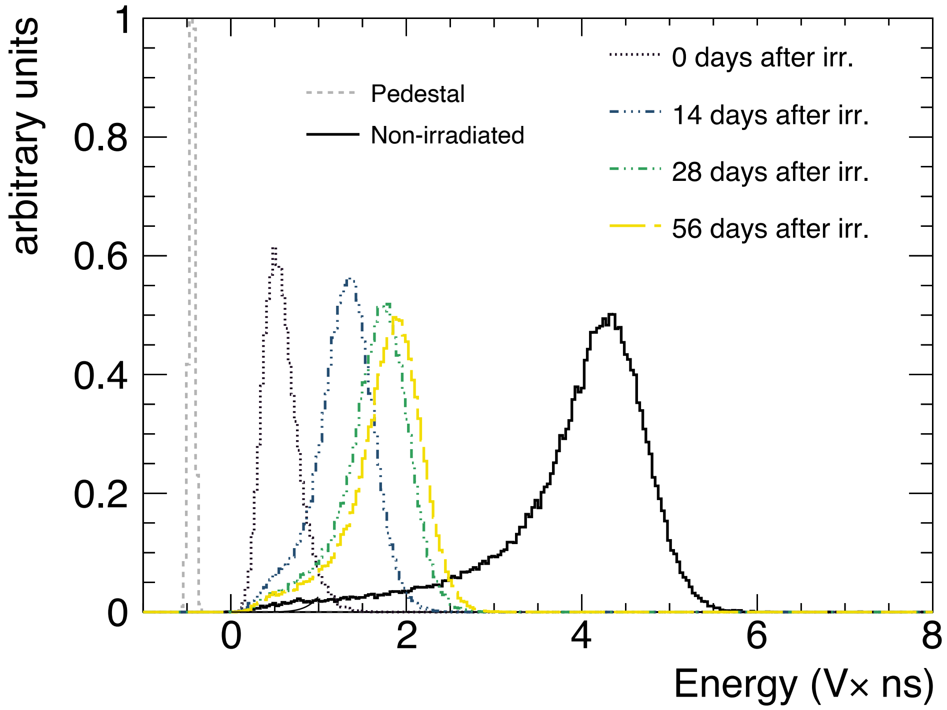


Methodology – Measuring D



Charge integration over 100 ns

Tektronix TDS7104 oscilloscope



Calibration measurements (dark current, gain) **+** →

↓ **Fit peak of curve**

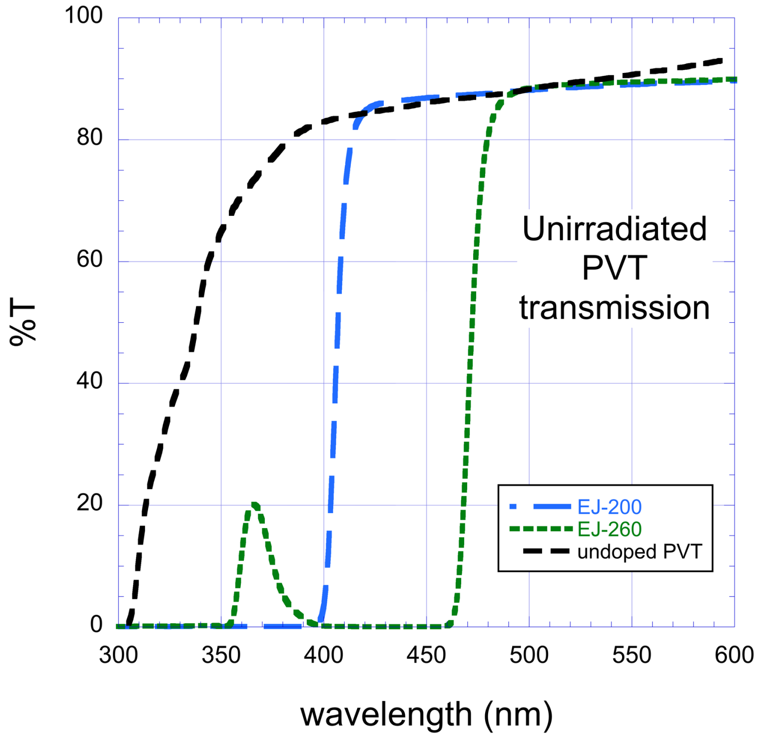
Light yield values **before** and **after** irradiation & annealing used to extract D.

Methodology – Measuring *T*

- Used a Varian Cary 300 spectrophotometer to measure **transmission**.
- The **pseudo inverse of *D*** is defined as:

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

  where T_o and T_f are the transmissions before and after irradiation, and d is the total dose.
- The **values of $\boldsymbol{\mathcal{D}^{-1}}$** 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



Results – PS vs PVT

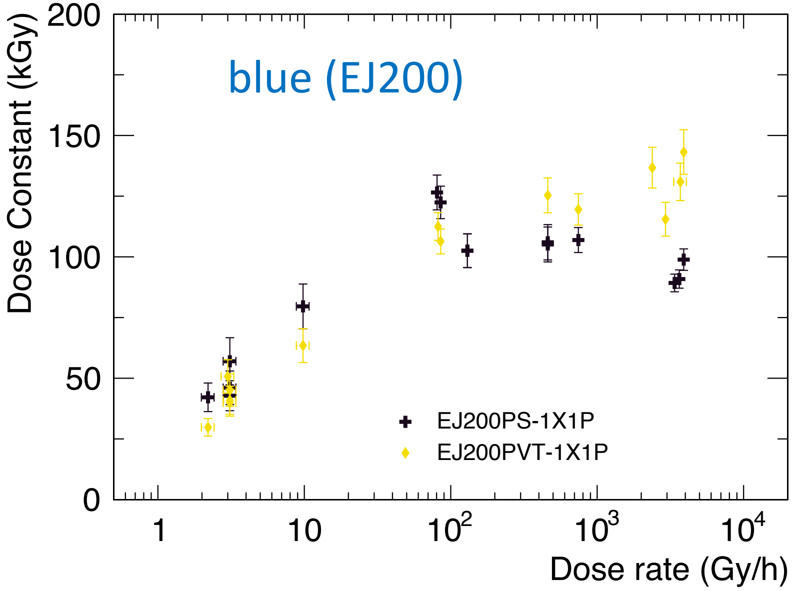
About the comparison:

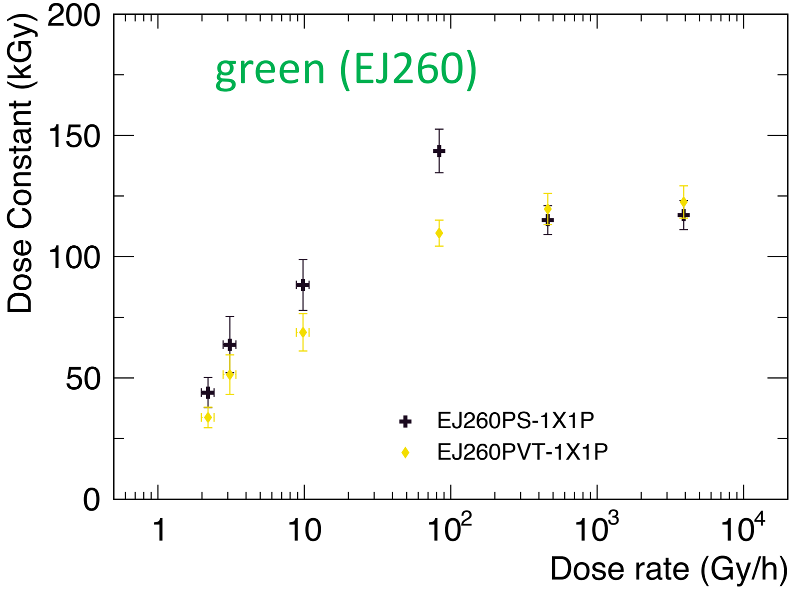
- Comparing rods with PS and PVT substrates.
- Both blue (EJ200) and green (EJ260) fluors are considered.
- Fluors and antioxidants concentrations are nominal.

Results:

- **Linear trend** (vs $\log R$) until $\sim$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.





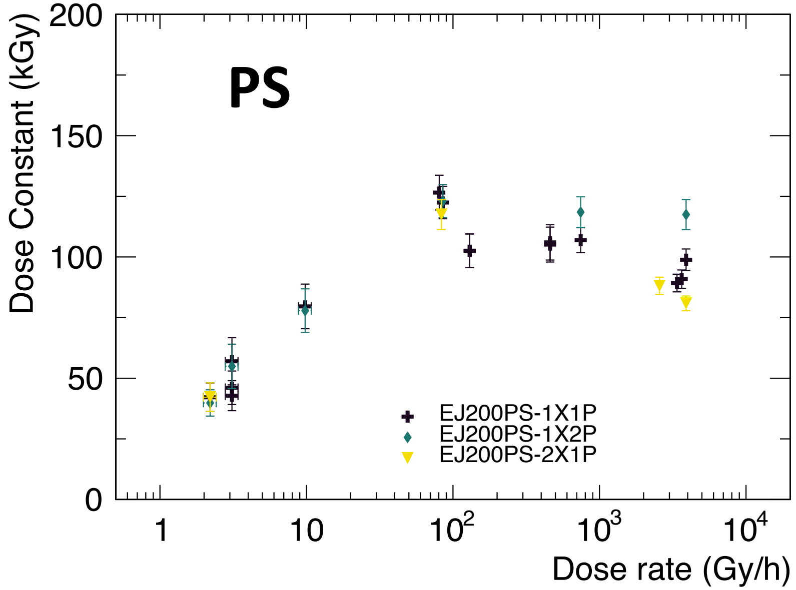
Results – Fluor concentrations

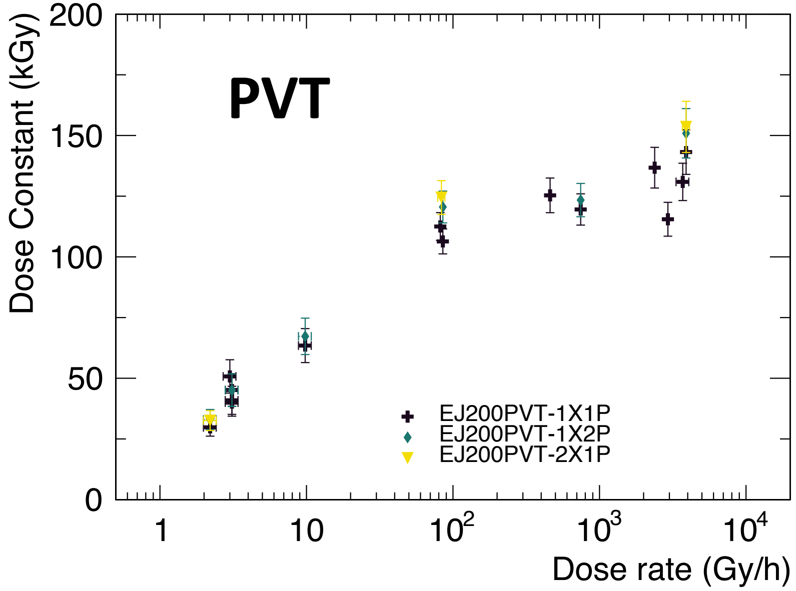
Varying fluor concentrations:

- **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

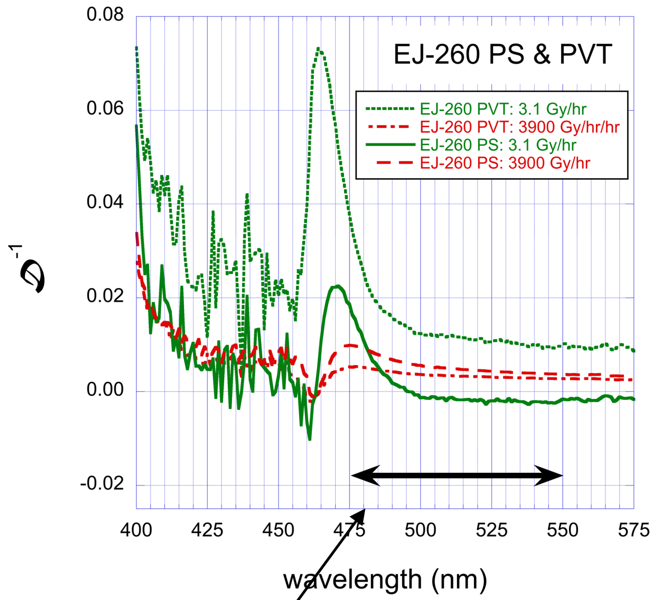
Some general remarks:

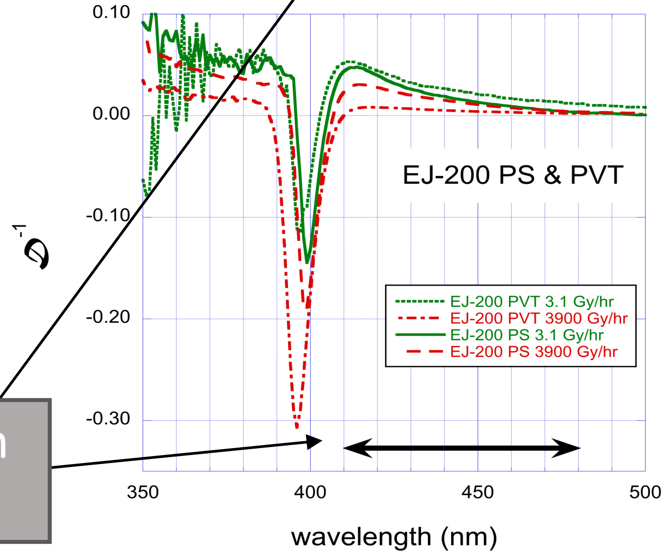
- Large positive values of $\mathcal{D}^{-1}$ indicate **color center formation**.
- Negative values probe **fluor destruction**.

Both are indicators of radiation damage.

Our observations show:

- Radiation damage for both scintillator types.
- **Fluor destruction** for the blue scintillator (EJ200).





Black arrows indicate the emission spectrum of the secondary.

Results – Varying thickness

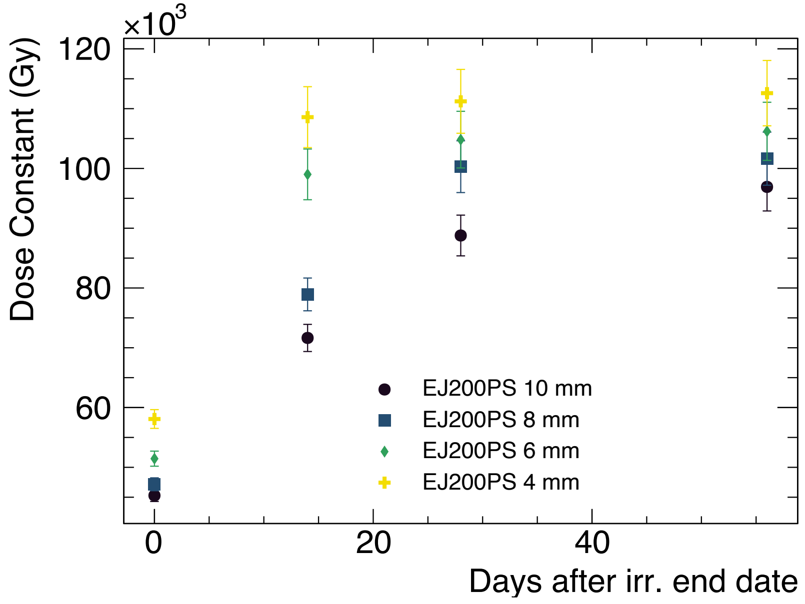
The two radiation damage mechanisms show **different dependences** of D on **rod thickness**:

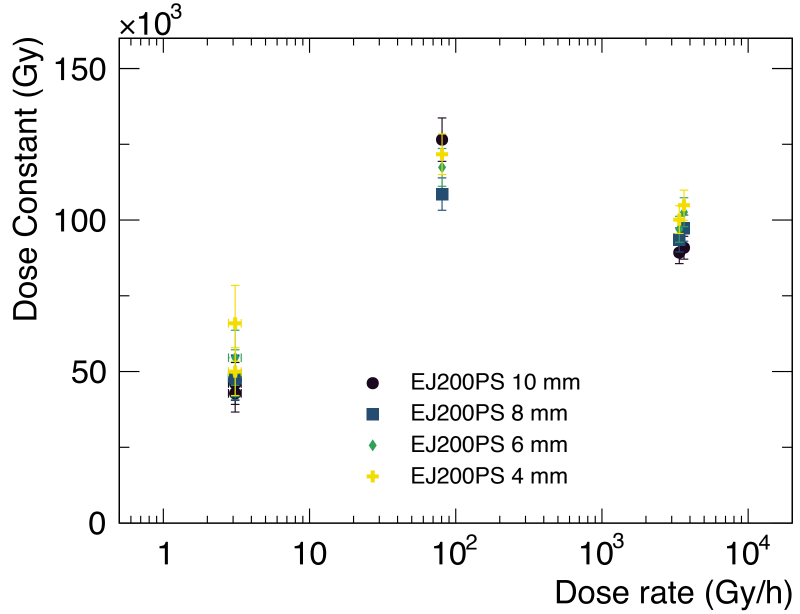
- Color center formation gives D that **scale as l^{-1}**.
- Damage to initial light production is **independent of l**.

Results:

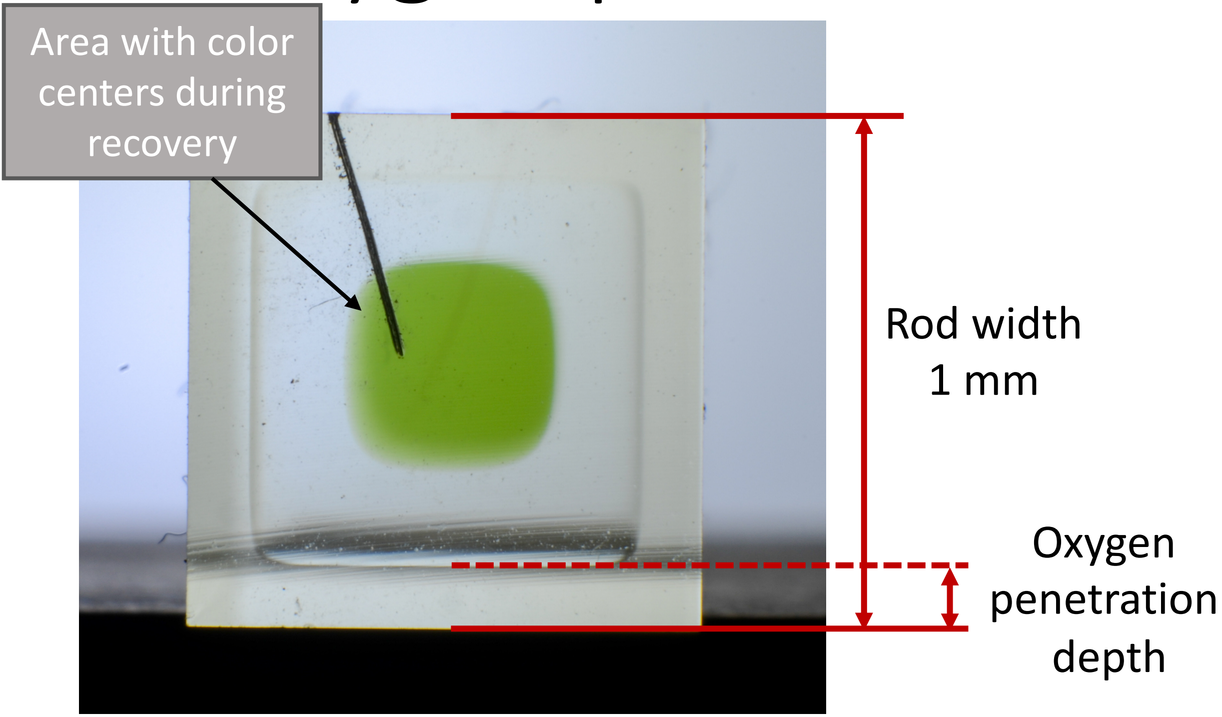
- During the recovery period, the dose constant is **strongly dependent** on the sample thickness.
- Indication that **color centers (radicals!)** form during irradiation but their number **reduces after annealing**.
- Final dose constants **do not depend strongly** on thickness.
- Dominant radiation 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.

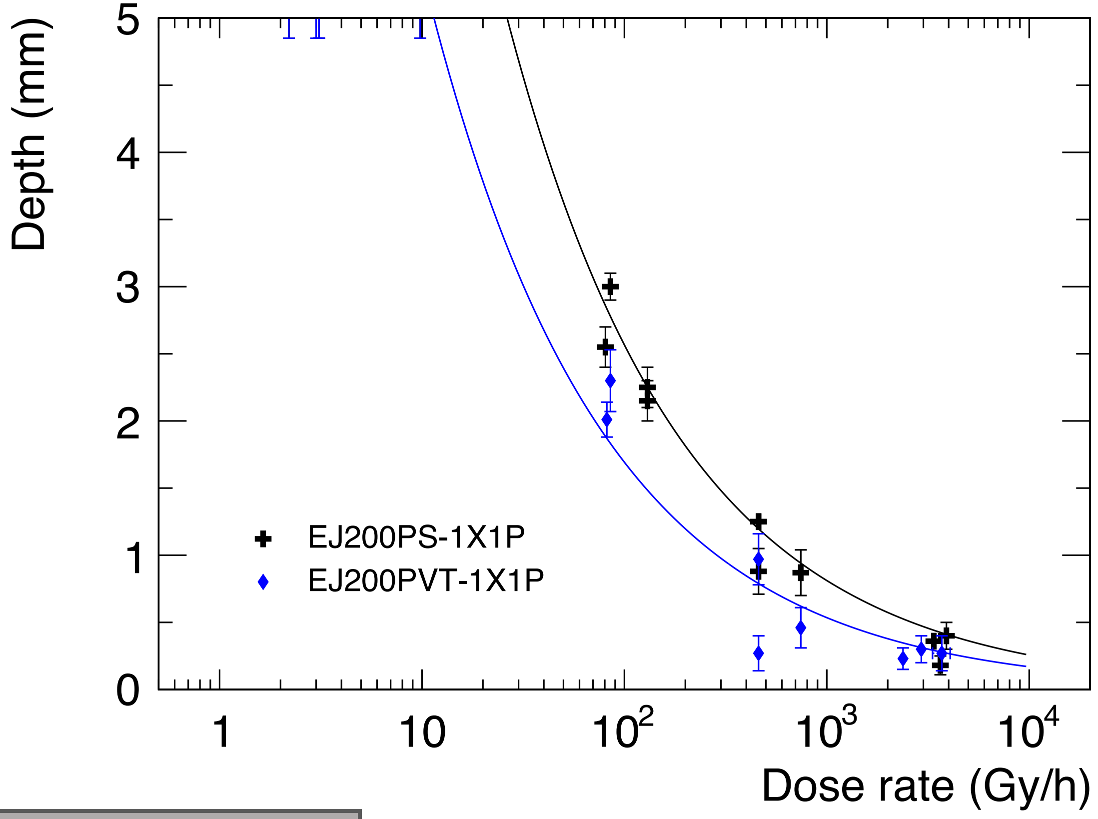




Oxygen penetration depth



- Scintillators acquire **distinct optical features** after irradiation. E.g., coloration, index change.
- Index change boundary can be used to **measure oxygen penetration depth**.



Results:

- Measurements of **depth vs dose rate fitted** with formula $z_0^2 = \frac{2MC_0}{\Upsilon R}$.
- Dose rates below 15 (30) Gy/h for PVT (PS) allow for **complete penetration**.
- Irradiations at **-30° C** show **deeper O_2 penetration** compared to 23° C ➡ **3.5 mm vs 0.9 mm**

operating temperature for HGCAL

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**

  $\Big\}$ **Depending on doping concentration.**
- 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**.
- **O_2 penetration depth** measured using optical features. Deeper penetration at -30^{o} C vs 23^{o} C.

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Backup

Dose rate dependence on damage

- Radiation breaks substrate bonds and creates **free radicals**.
- Radicals absorb visible light (stronger at low λ). ➡ **Temporary damage**
- Radicals also **recombine** and 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

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

➡ **D scales with 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:

$$z_0^2 = \frac{2MC_0}{\Upsilon R}$$

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

**symbols explained in backup slides*

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 σ 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:

$$z_0^2 = \frac{2MC_0}{\Upsilon R}$$

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*

Antioxidants

- Antioxidant concentrations:
  - 0.5 x nominal
  - nominal
  - 2 x nominal
- We do not see any significant effects of antioxidant concentration on radiation hardness.