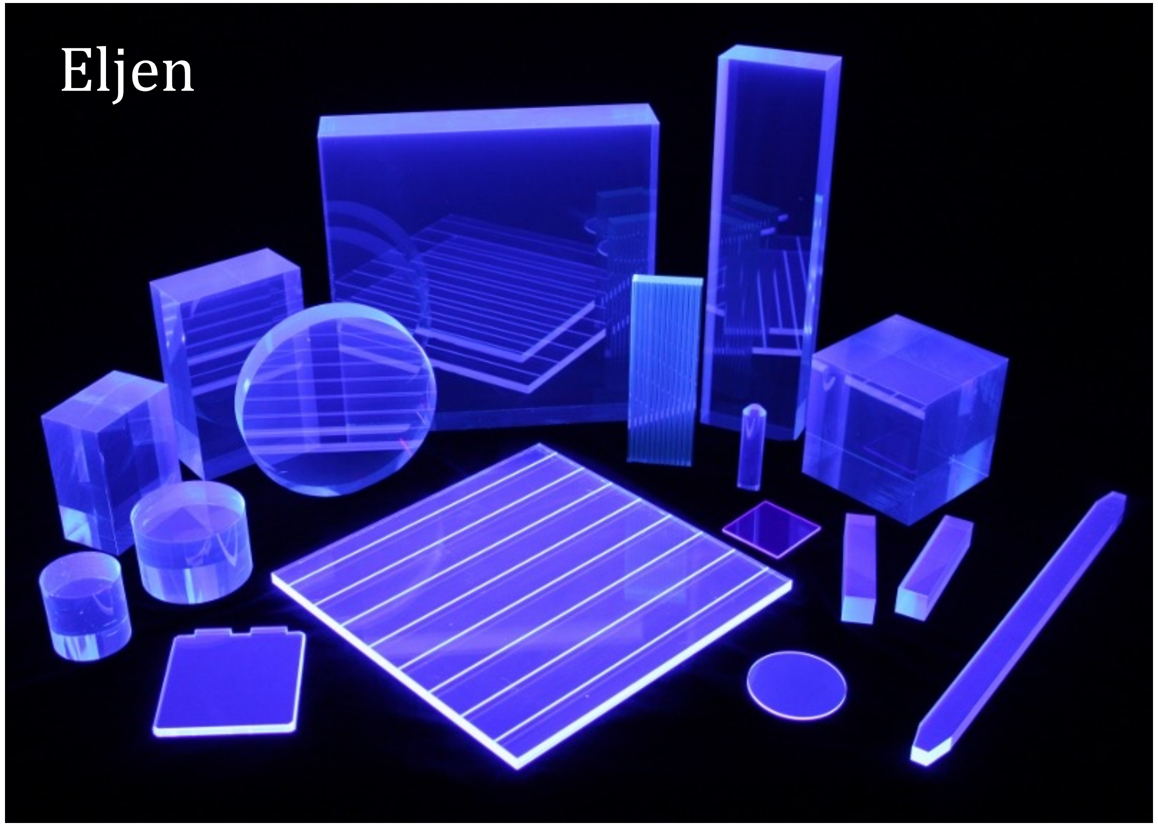
DEPARTMENT OF PHYSICS

Measurement of refractive index of phenyl-based scintillators before and after irradiation

Y. Aamir , T. Edberg, S. Eno, C. Papageorgakis

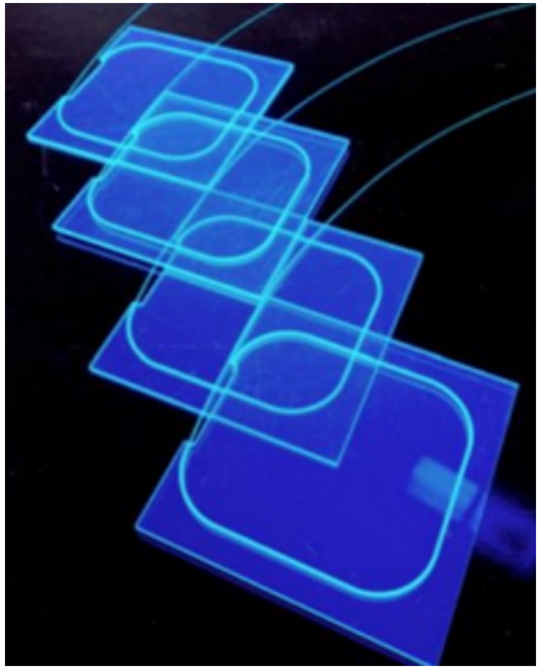
Motivation for Scintillator Studies in HEP

- Plastic scintillators are used in HEP detectors for particle detection
- They emit light when charged particles pass through them

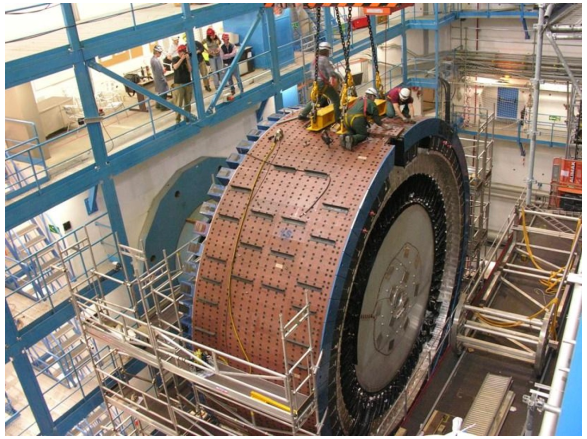


Scintillators in HEP

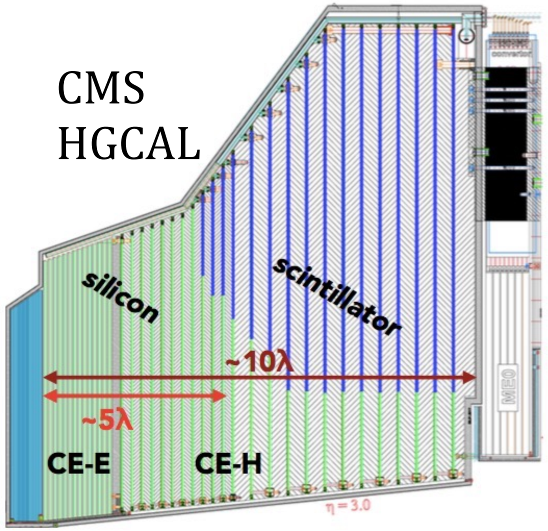
Some current and future HEP experiments using scintillators:

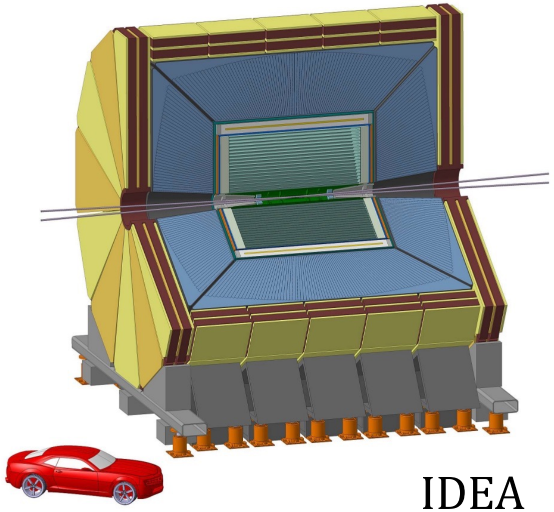


ATLAS TileCal



CMS
HGCAL



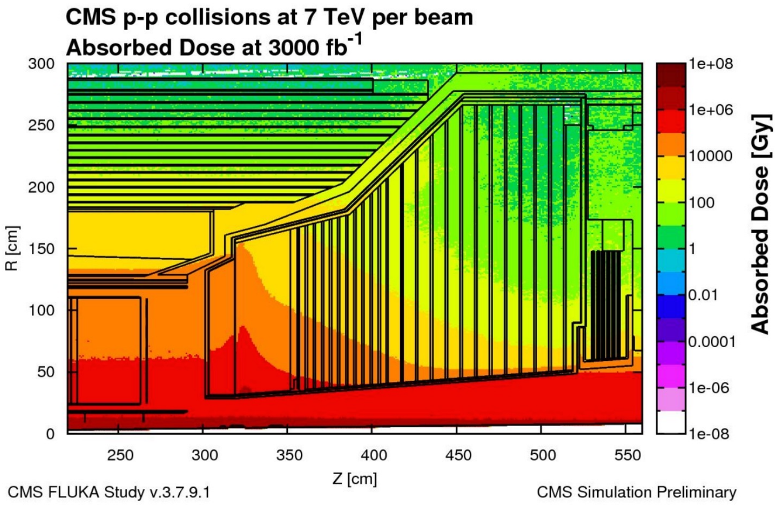


IDEA

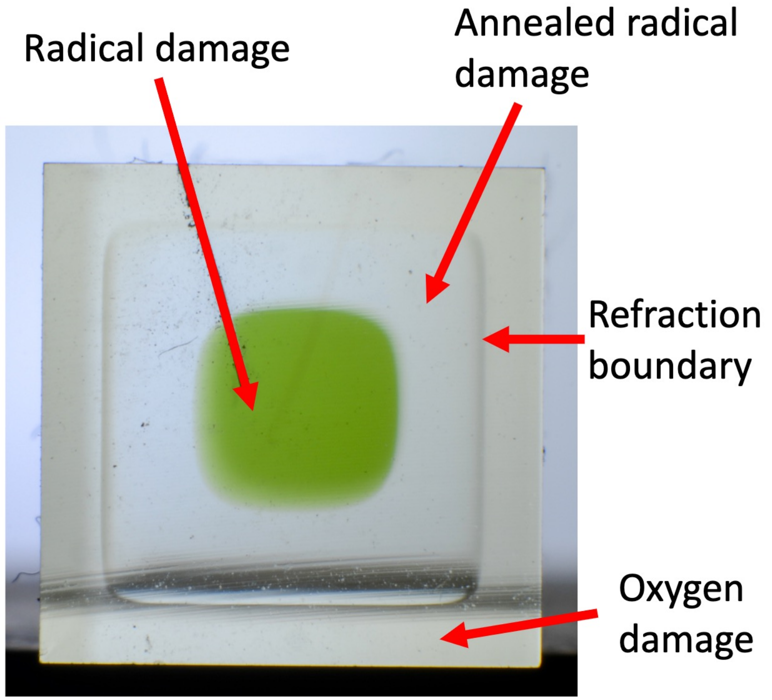
MICE Fiber Tracker

Radiation Damage In Plastics With and Without Oxygen

- Radiation tolerance is crucial for detectors with high particle fluxes (CMS typical net dose ~10-100 kGy)
- During irradiation:
  - Radicals create uniformly throughout the material
  - Oxygen diffuses into material from the outside and annihilates radicals
  - There is a well-defined penetration depth dependent on dose rate


CMS p-p collisions at 7 TeV per beam
Absorbed Dose at 3000 fb^{-1}

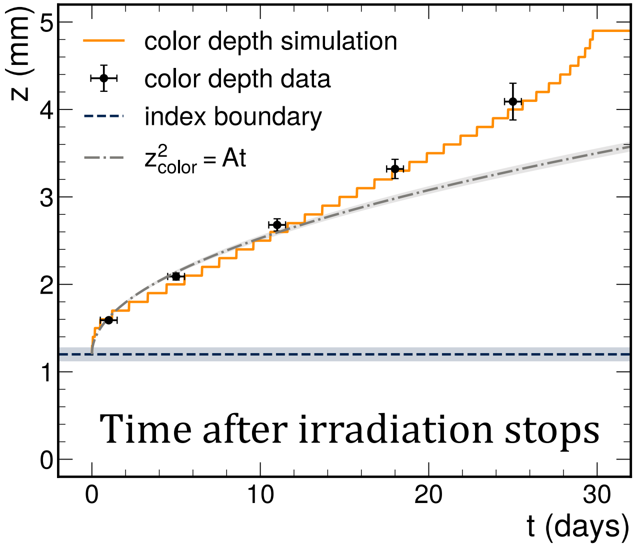
CMS FLUKA Study v.3.7.9.1
CMS Simulation Preliminary

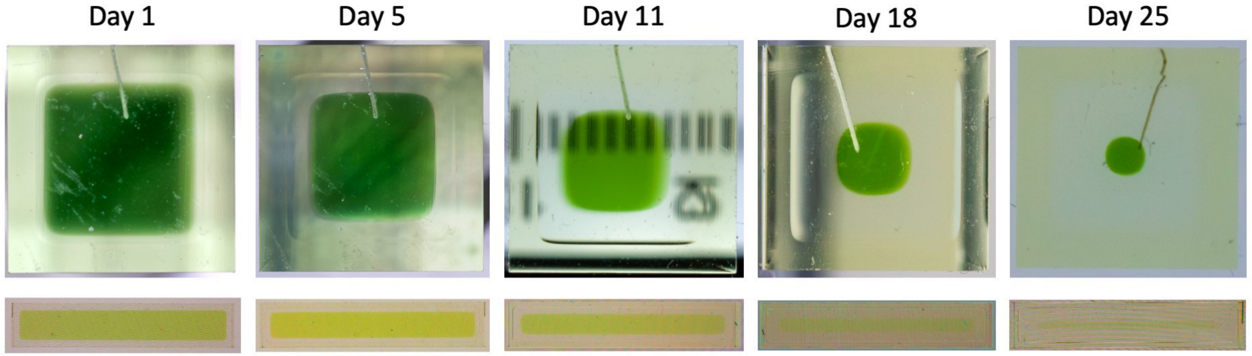


Scintillator a few days after irradiation stops

Radiation and Oxygen Damage In Plastics

- Permanent damage to scintillators
- **Maryland has found that radiation affects refractive indices differently in regions with and without oxygen**
  - We could use change in index to measure the penetration depth of oxygen
- ${z_{color}}^2 = At$, where z_{color} is the depth into the plastic till the green color (thin film approximation)
- Fick's diffusion law
  - $\frac{\partial C(x,t)}{\partial t} = D\frac{\partial^2 C(x,t)}{\partial x^2} - k_2[\mathrm{P}^\cdot]C(x,t)$





Radiation Details

Samples were irradiated at NIST (Co-60), Goddard(γ), GIF++ (Cs-137) and Sandia (Co-60)

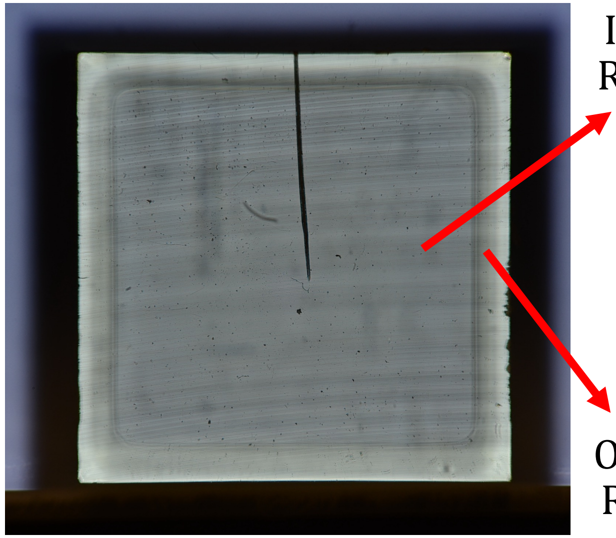
PVT

Rod	Dose Rate (Gy/hr)	Dose (kGy)
EJ200PVT-1X1P-N2	2380	70
EJ200PVT-1X1P-N4	744	70
EJ200PVT-1X1P-N5	85.3	70
EJ200PVT-T1-2	81.9	70
EJ200PVT-T1-3	3700	70
EJ200PVT-AO-1-2	2930	60
EJ200PVT-AO-1-3	2380	70
EJ200PVT-L3R	460	70
EJ200PVT-1X1P-N8	2.2	13.2
EJ200PVT-1X1P-N15	3.1	12.6
EJ200PVT-1X1P-N16	9.8	42
EJ200PVT-T1-5	3.1	12.6
EJ200PVT-T1-N1	3.1	12.6
EJ200PVT-A0-1-1	3	17.1

PS

Rod	Dose Rate (Gy/hr)	Dose (kGy)
EJ200PS-1X1P-5	85.3	70
EJ200PS-1X1P-8	744	70
EJ200PS-1X1P-9	3900	70
EJ200PS-T1-2	80.6	70
EJ200PS-T1-3	3640	70
EJ200PS-T1-4	3380	70
EJ200PS-L7R	130	69
EJ200PS-L8R	130	69
EJ200PS-L9R	460	70
EJ200PS-L10R	460	70
EJ200PS-L11R	460	70
EJ200PS-1X1P-4	2.2	13.2
EJ200PS-1X1P-13	9.8	42
EJ200PS-1X1P-15	3.1	12.6

EJ200PS-1X1P-8



Inside Region

Outside Region

After radiation and annealing

Refractive Index Theory

- Refractive index of a material
  - $n = \sqrt{\epsilon_r \mu_r} \approx \sqrt{\epsilon_r}$ since $\mu_r \approx 1$ for plastic scintillators
  - ϵ_r can be calculated and provides information about the types of bonds in the plastic
  - **$\boldsymbol{\epsilon_r}$ changes after irradiation due to bond breaking and reformation**
  - We can connect ϵ_r to the molecular properties of a material

- Clausius-Mossoti Equation
  - $\frac{\epsilon_r - 1}{\epsilon_r + 2} = \frac{N\alpha}{3\epsilon_0}$ where N is number density of molecules, α is molecular polarizability ($\alpha = \frac{\|p\|}{\|E\|}$)

- Molecular Refractivity and Lorentz-Lorenz Equation

$$R_M = \frac{n^2 - 1}{(n^2 + 2)N} = \frac{\alpha}{3\epsilon_0}$$

$$\alpha = \frac{3}{4\pi N}\frac{n^2 - 1}{n^2 + 2}$$

Refractive Index Theory

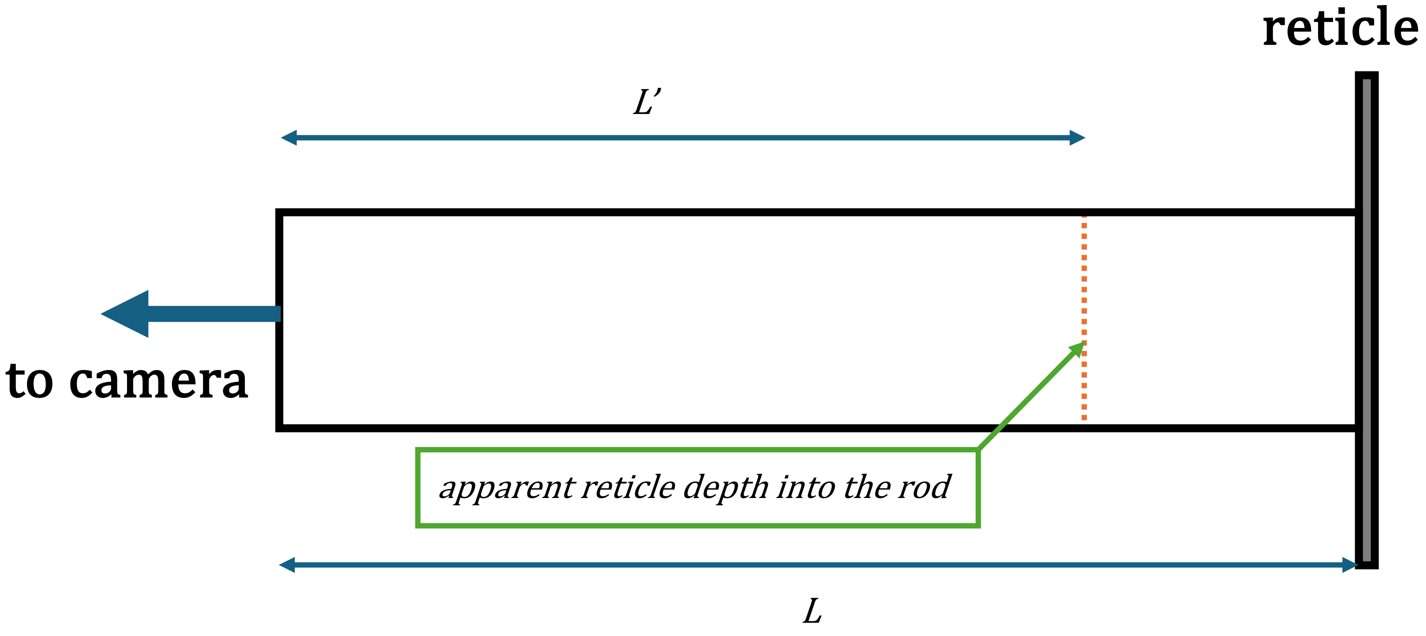
- Sellmeier Equation

$$n^2(\lambda) = 1 + \sum_{i=1}^{N} \frac{B_i \lambda^2}{\lambda^2 - C_i}$$

- B_i and C_i are experimentally determined Sellmeier coefficients
- This is an example of the kind of calculation we do to yield the index
- We fit our data and compare with this nominal curve

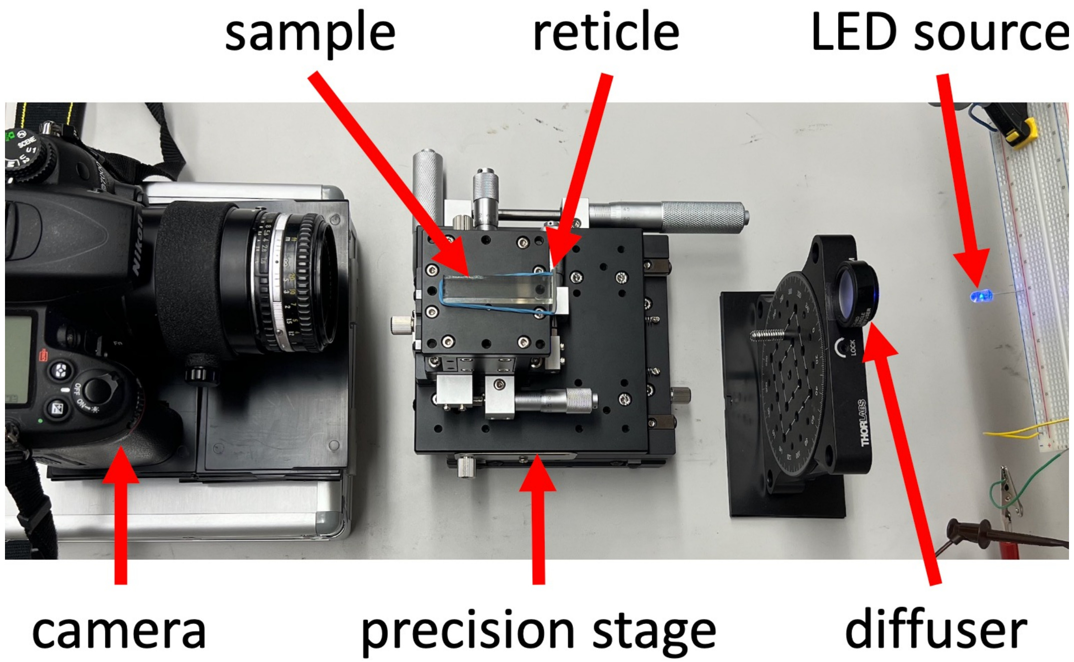
Index Measurement Technique

- $5 \times 1 \times 1$ cm samples
- Real and apparent depth
- $n = \frac{L}{L'}$
- Uncertainties have a near inverse proportionality to L
- Longer crystals = Better precision



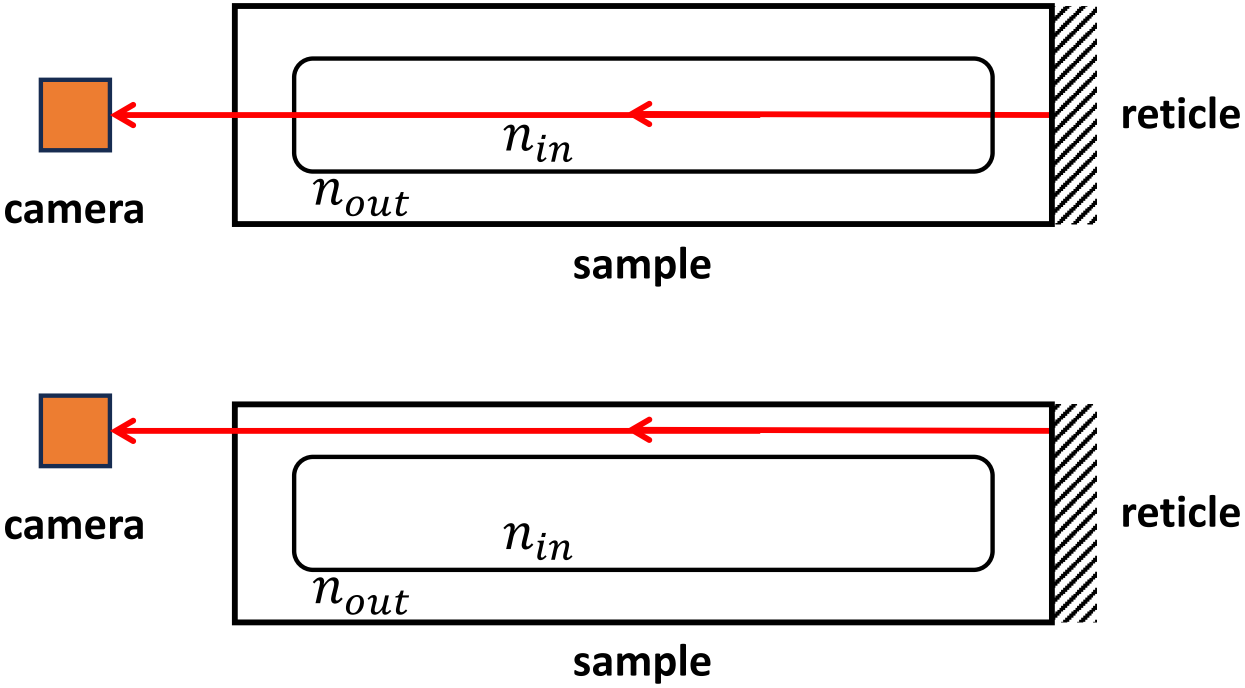
Measurement Apparatus

- Real Depth
  - Digital calipers
- Apparent Depth
  - Consumer-grade camera (Nikon D7000)
  - Precision translation stage with sample and reticle
  - LED light source and diffuser



Changes After Irradiation

- Inside and outside regions
- Index outside evaluated using usual method
- Index inside is complicated but possible
- $n_{out} = \frac{L}{L'}$
- $n_{in} = \frac{(L-2d)n_{out}}{L' n_{out} - 2d}$



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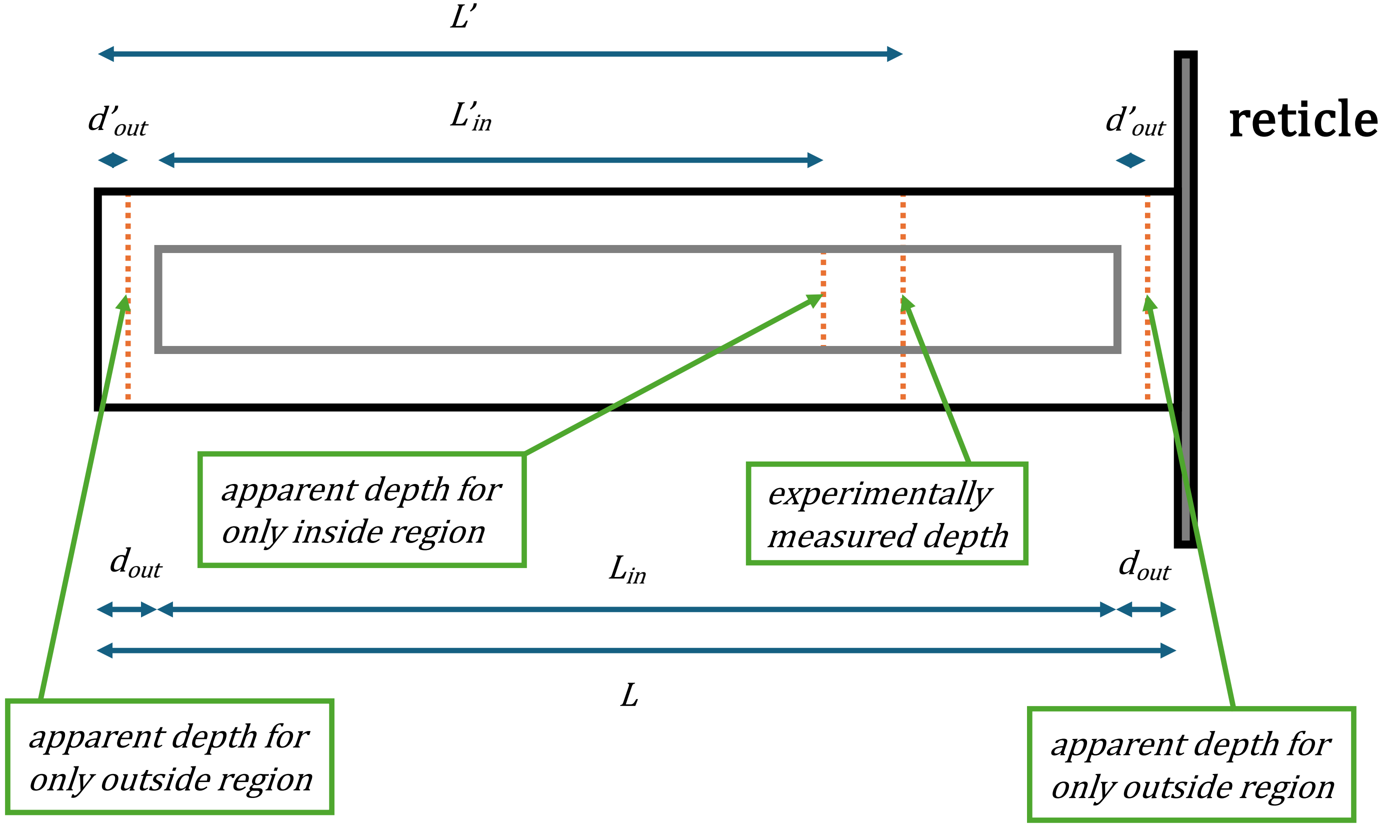
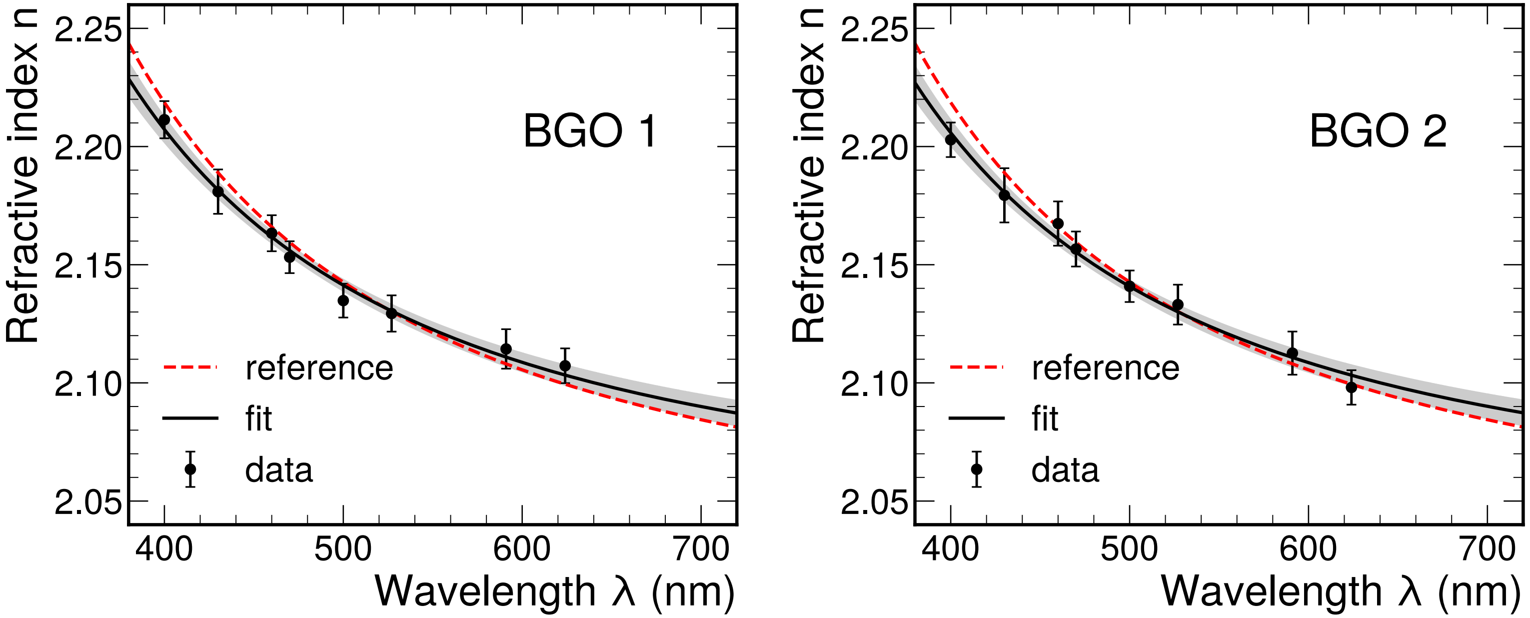
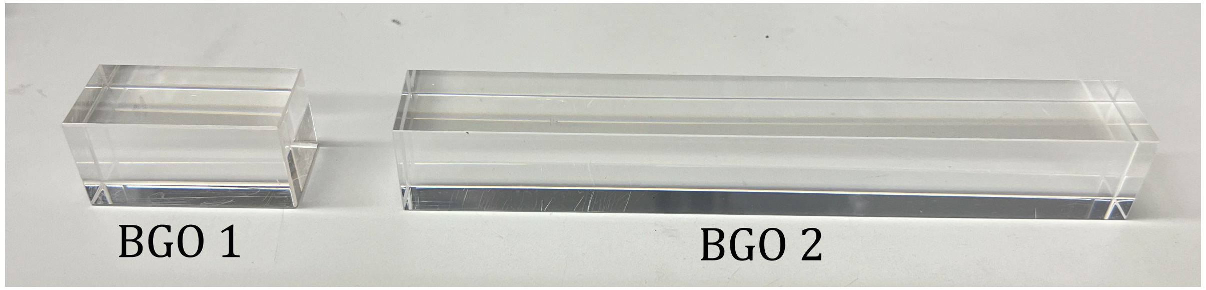


Verification of Measurement Method

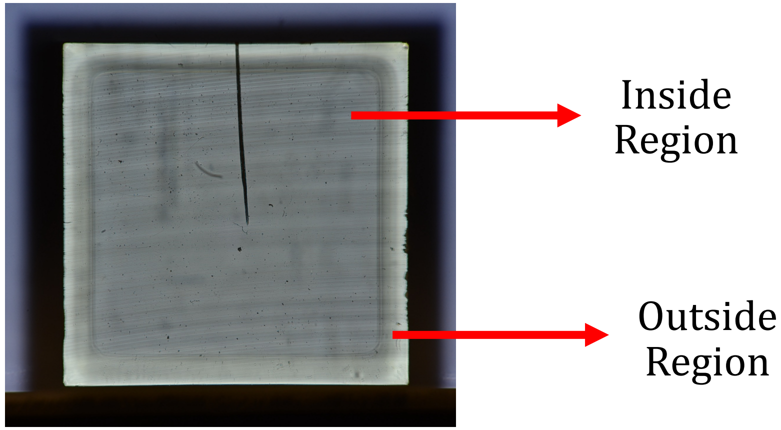
- Used 2 distinct samples of pure BGO
- Positives
  - Precision is of order ~0.3% and can improve with automation
- Potential issues
  - Systematic bias at 400 nm?

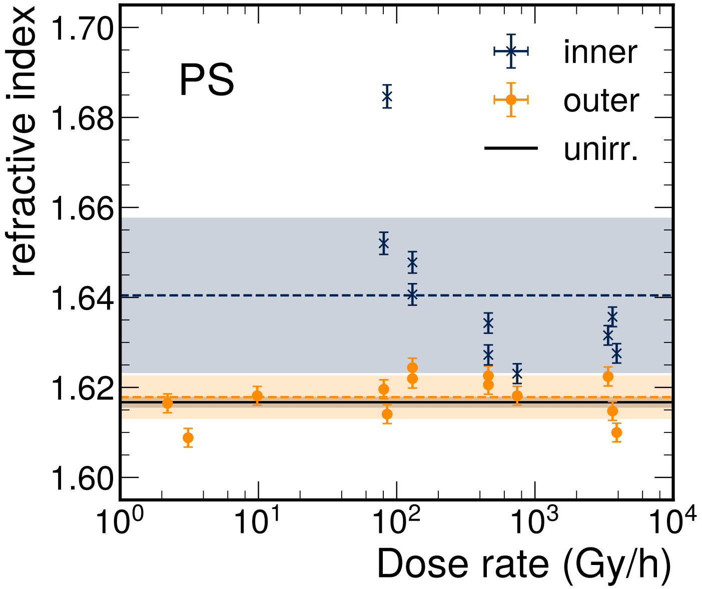


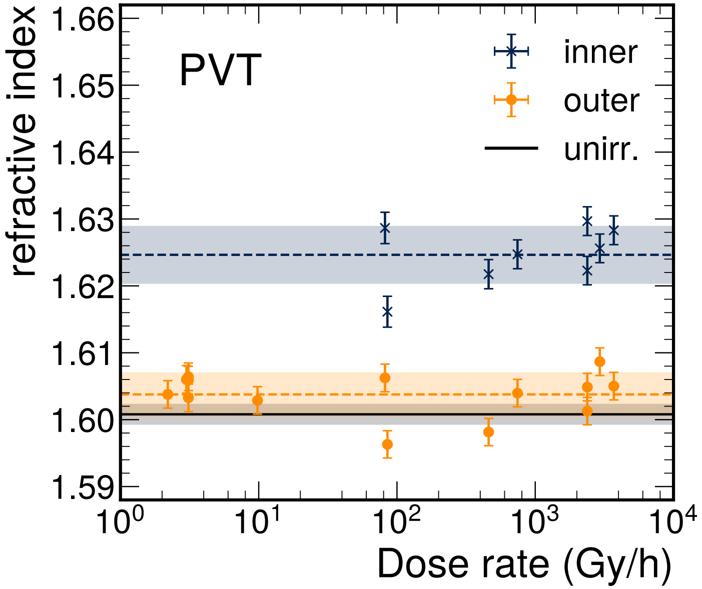


PVT and PS Sample Index Results

- Index Inside
  - Increases when irradiated and annealed from oxygen damage
- Index Outside
  - **Stays relatively the same as before irradiation**

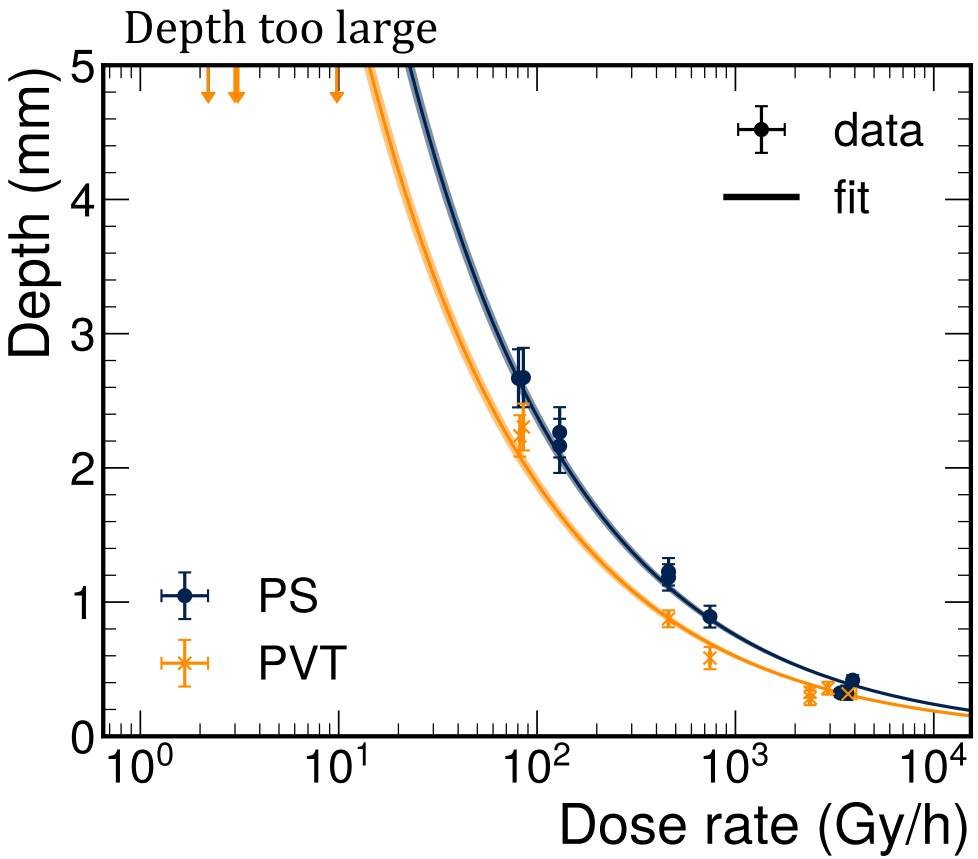






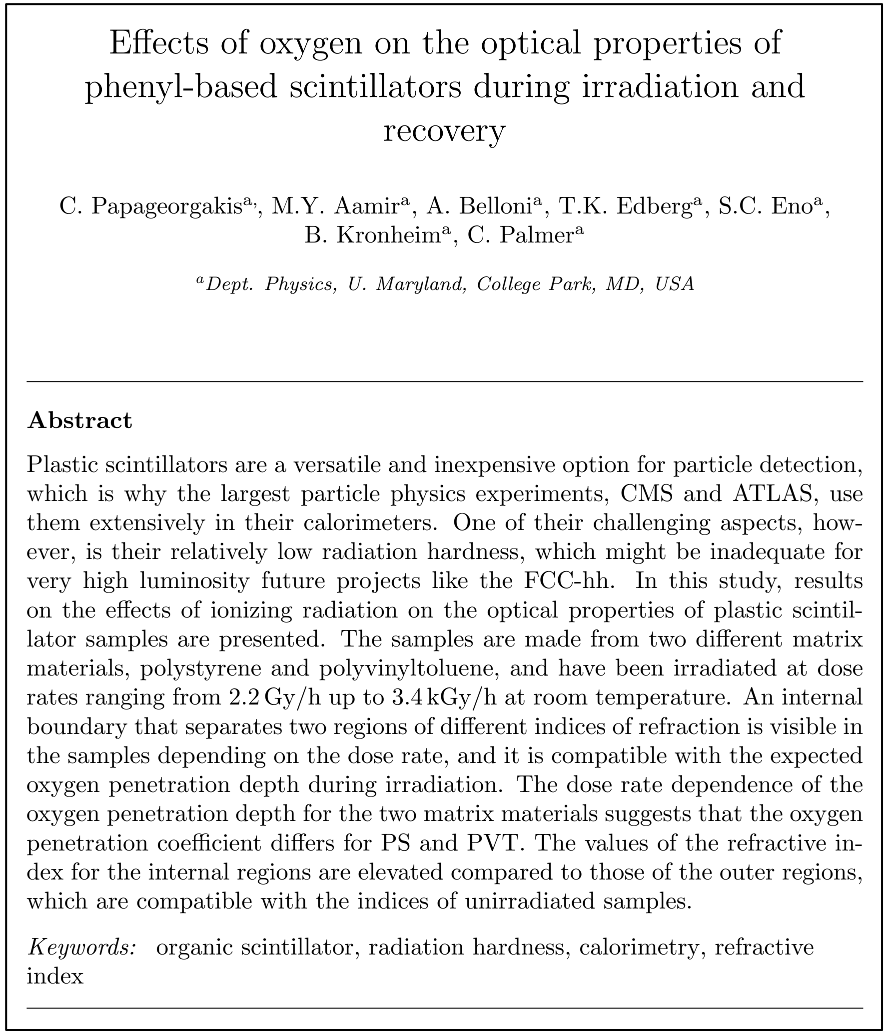
PVT and PS Sample Depth Results

- Penetration depth of oxygen into scintillator
- Samples with dose rate < 80Gy/h have no boundary
    - Depth > 5 mm
- **First measurement of oxygen penetration depth in PVT**



Conclusion

- Future detector experiments can benefit from radiation damage studies
- We present first measurements of oxygen penetration depth for PVT
- We present first evidence of change in index due to the presence of oxygen
- Chemists can assist in understanding how this affects scintillators and particle detection



Effects of oxygen on the optical properties of phenyl-based scintillators during irradiation and recovery

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Abstract

Plastic scintillators are a versatile and inexpensive option for particle detection, which is why the largest particle physics experiments, CMS and ATLAS, use them extensively in their calorimeters. One of their challenging aspects, however, is their relatively low radiation hardness, which might be inadequate for very high luminosity future projects like the FCC-hh. In this study, results on the effects of ionizing radiation on the optical properties of plastic scintillator samples are presented. The samples are made from two different matrix materials, polystyrene and polyvinyltoluene, and have been irradiated at dose rates ranging from 2.2 Gy/h up to 3.4 kGy/h at room temperature. An internal boundary that separates two regions of different indices of refraction is visible in the samples depending on the dose rate, and it is compatible with the expected oxygen penetration depth during irradiation. The dose rate dependence of the oxygen penetration depth for the two matrix materials suggests that the oxygen penetration coefficient differs for PS and PVT. The values of the refractive index for the internal regions are elevated compared to those of the outer regions, which are compatible with the indices of unirradiated samples.

Keywords: organic scintillator, radiation hardness, calorimetry, refractive index

arXiv:2310.14936

References

[1] C. Papageorgakis, M. Y. Aamir, A. Belloni, T. K. Edberg, S. C. Eno, B. Kronheim, C. Palmer. "Effects of oxygen on the optical properties of phenyl-based scintillators during irradiation and recovery." Nucl. Instrum. Methods Phys. Res., Sect. A 1059, 168977 (2024) [arXiv:2310.14936]

[2] CMS Collaboration, The Phase-2 Upgrade of the CMS Endcap Calorimeter, 2017. https://cds.cern.ch/record/2293646

[3] S. Lee, M. Livan, R. Wigmans, Dual-readout calorimetry, Reviews of Modern Physics. 90 (2018).

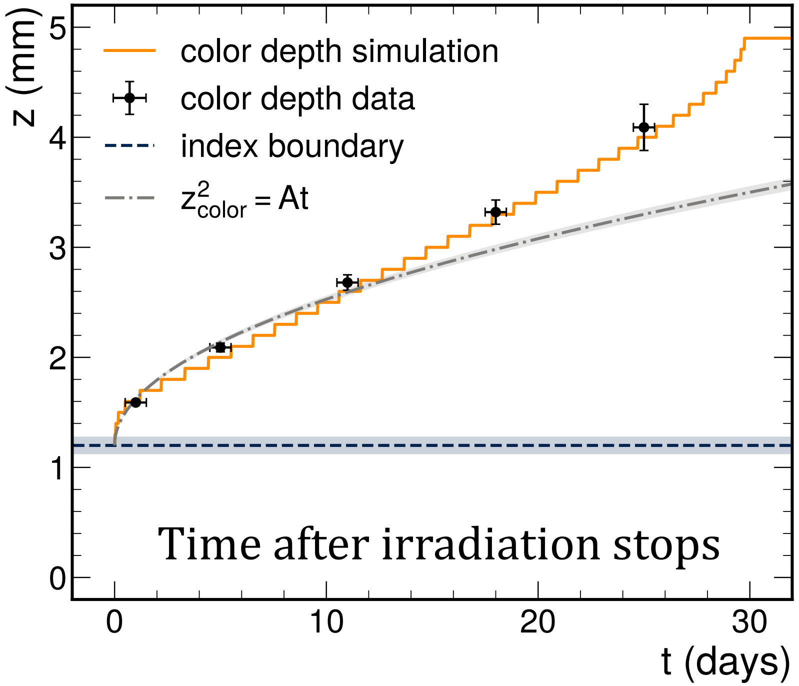
[4] Y. Kharzheev, Radiation Hardness of Scintillation Detectors Based on Organic Plastic Scintillators and Optical Fibers, Phys. Part. Nucl. 50 (2019) 42–76. doi:10.1134/S1063779619010027.

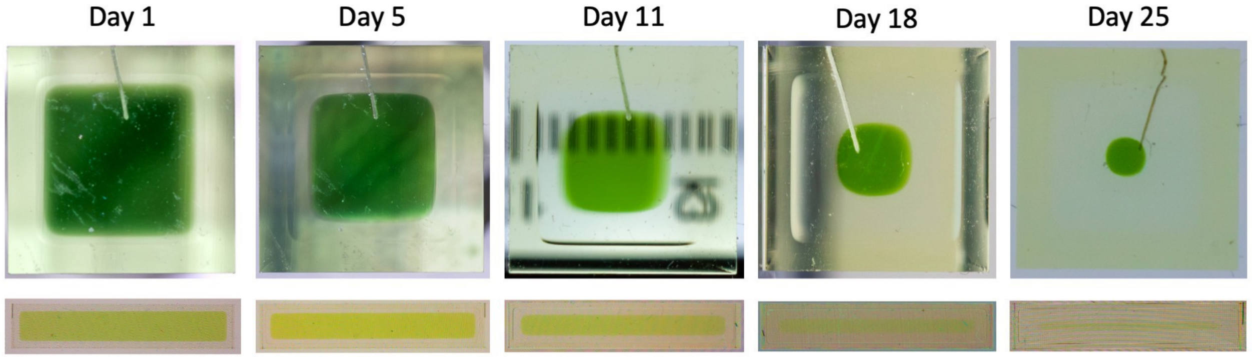
[5] C. Papageorgakis, Oxygen diffusion paper - GitHub repository, https://github.com/chrispap95/oxygen-diffusion-paper (2022).

Backup

Radiation Damage In Plastics

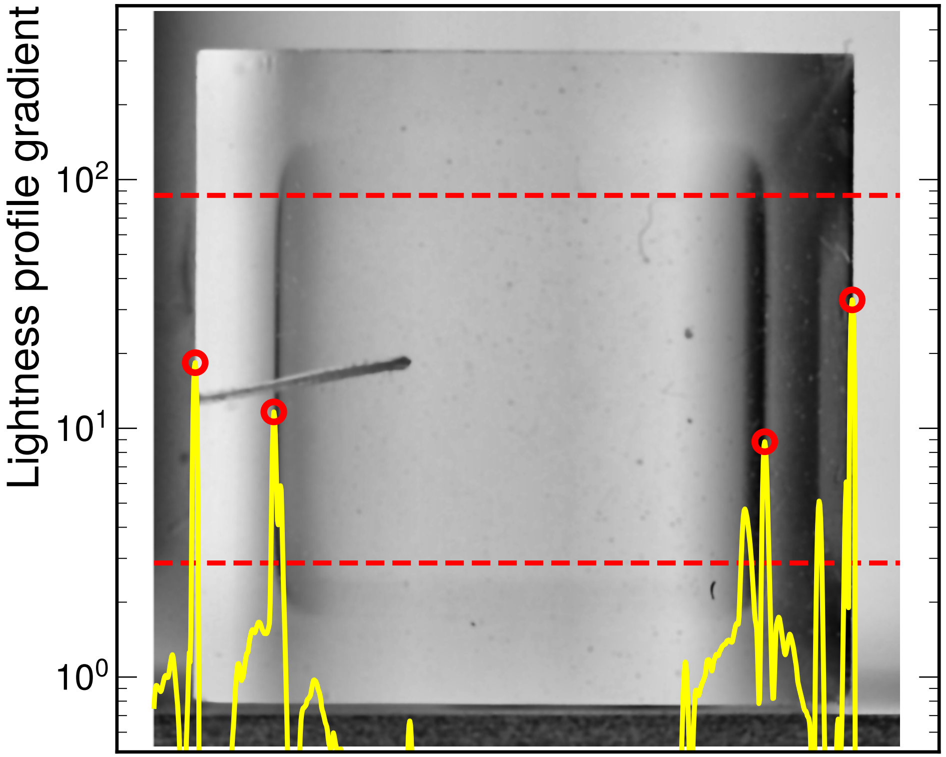
- 3-dimensional finite differences method
- Steps are in space and not time
- Most samples we use can be approximated as thin films ($z_{color}{}^2 = At$)





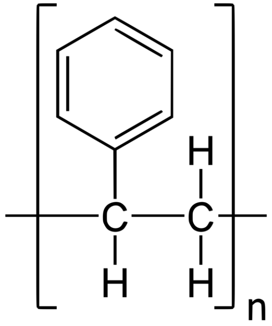
Depth Measurement Method

- Refractive index change is present for all dose rates > 10Gy/h
- We took images of the samples and used OpenCV (Open-Source Computer Vision) methods to process the images
- The code for this can be found in reference 5

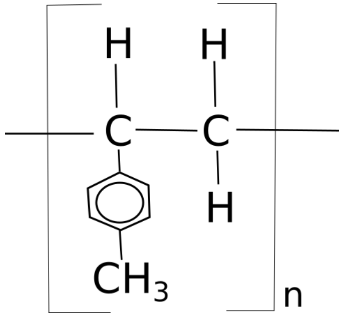


Plastic Scintillator Structure

- Substrate
  - Polystyrene (PS)

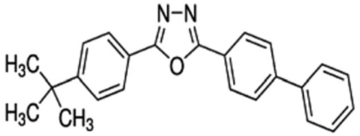


  - Polyvinyl Toluene (PVT)



- Dopants
  - Primary
    - p-Terphenyl

    - BPBD



  - Secondary
    - POPOP