Radiation hardness of plastic scintillators for the Tile Calorimeter of the ATLAS detector

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In collaboration with:

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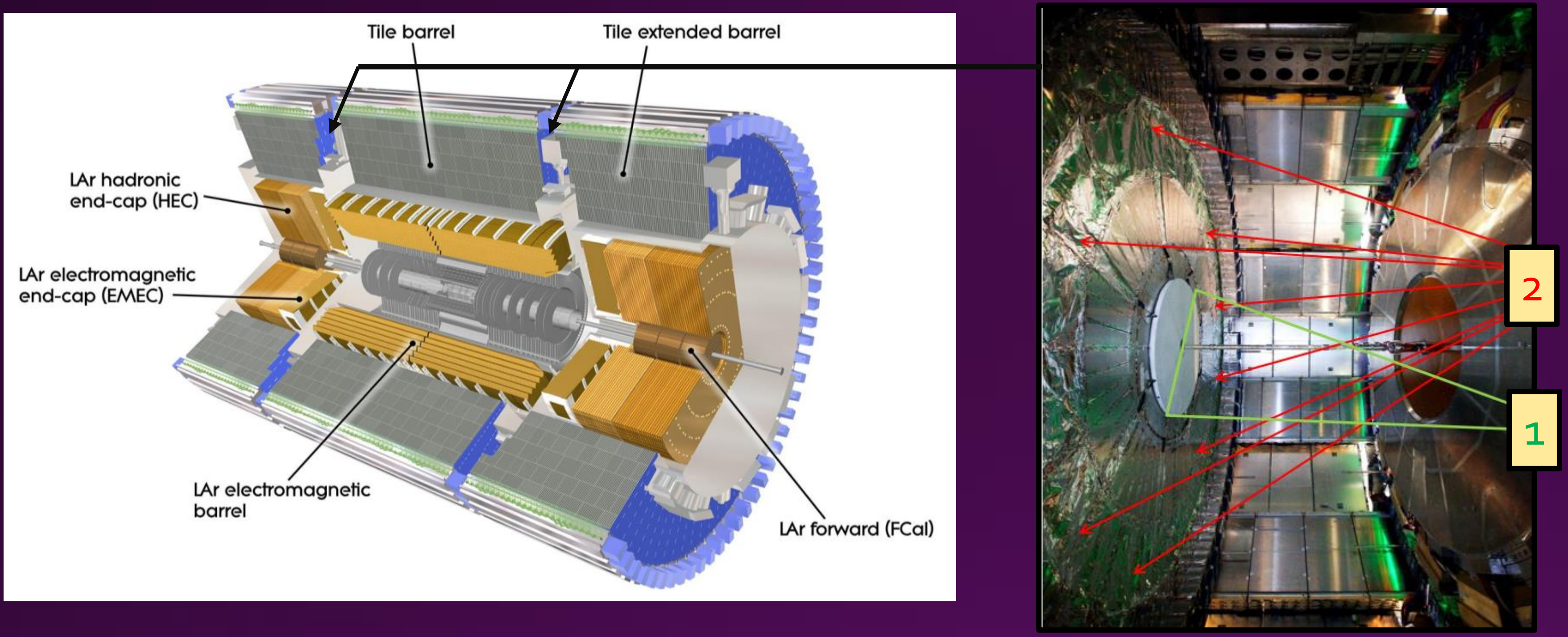
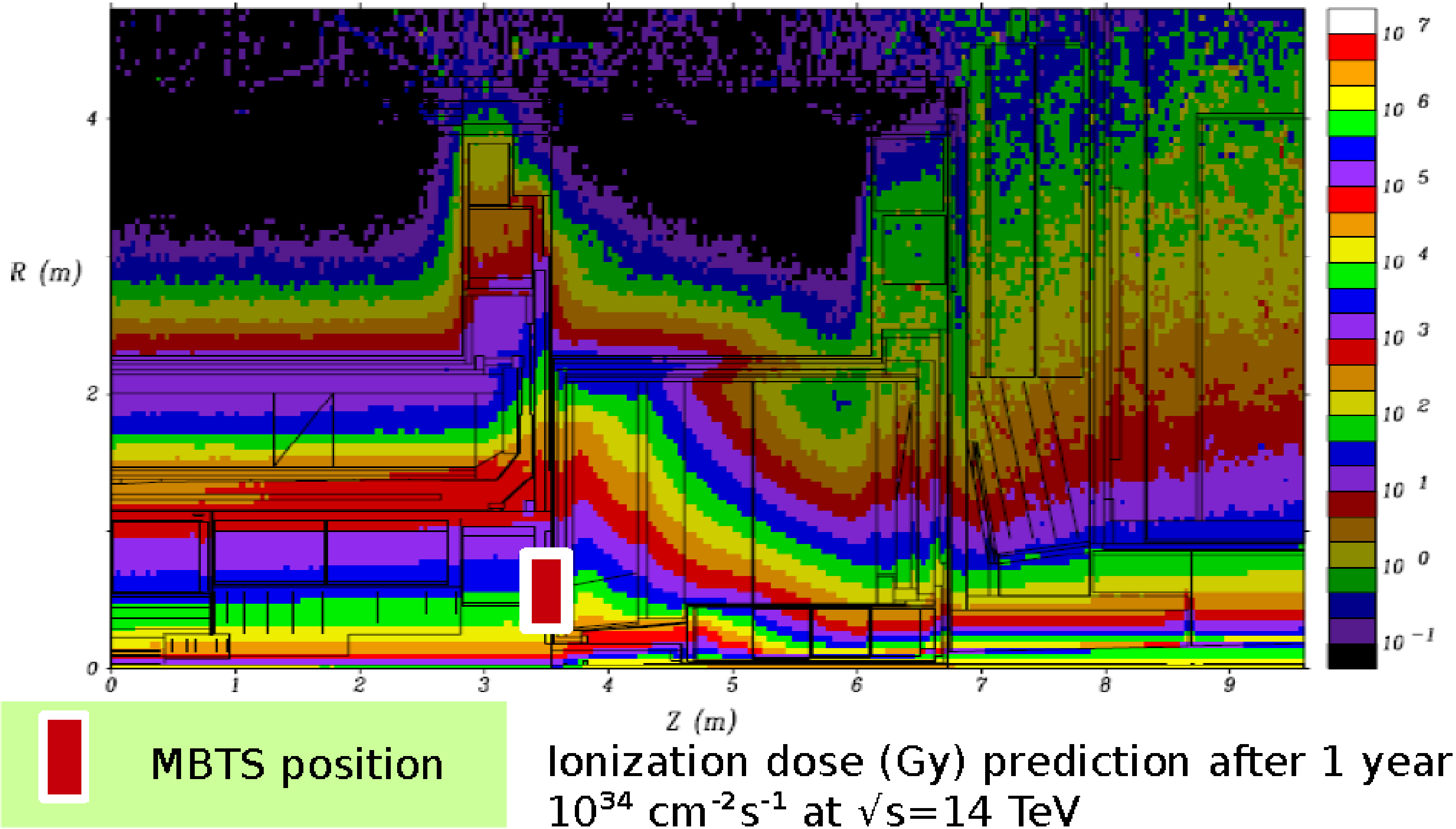
The Tile Calorimeter of ATLAS



- The Tile Calorimeter is the hadronic calorimeter responsible for detecting hadrons, taus and jets of quarks and gluons.
- Gap regions contain additional scintillator plates distributed radially, which correct for energy losses across the gap. MBTS form first level hardware trigger system and provide a trigger signal for when to record events which have potential for physics of interest.
  [1: MBTS scintillators, 2:Crack scintillators]
- During Run1, crack scintillators were exposed to ~100 Grays per year. Expected to increase with Run2. [1 Gray = 1 joule of energy deposited per kg]
- It is predicted that scintillators in the Gap will sustain a significant amount of radiation damage during HL-LHC run time and may require replacement during the 2018 upgrade.
- Thus, conducting a comparative study into radiation hardness of several “radiation hard” scintillators available.

Radiation environment



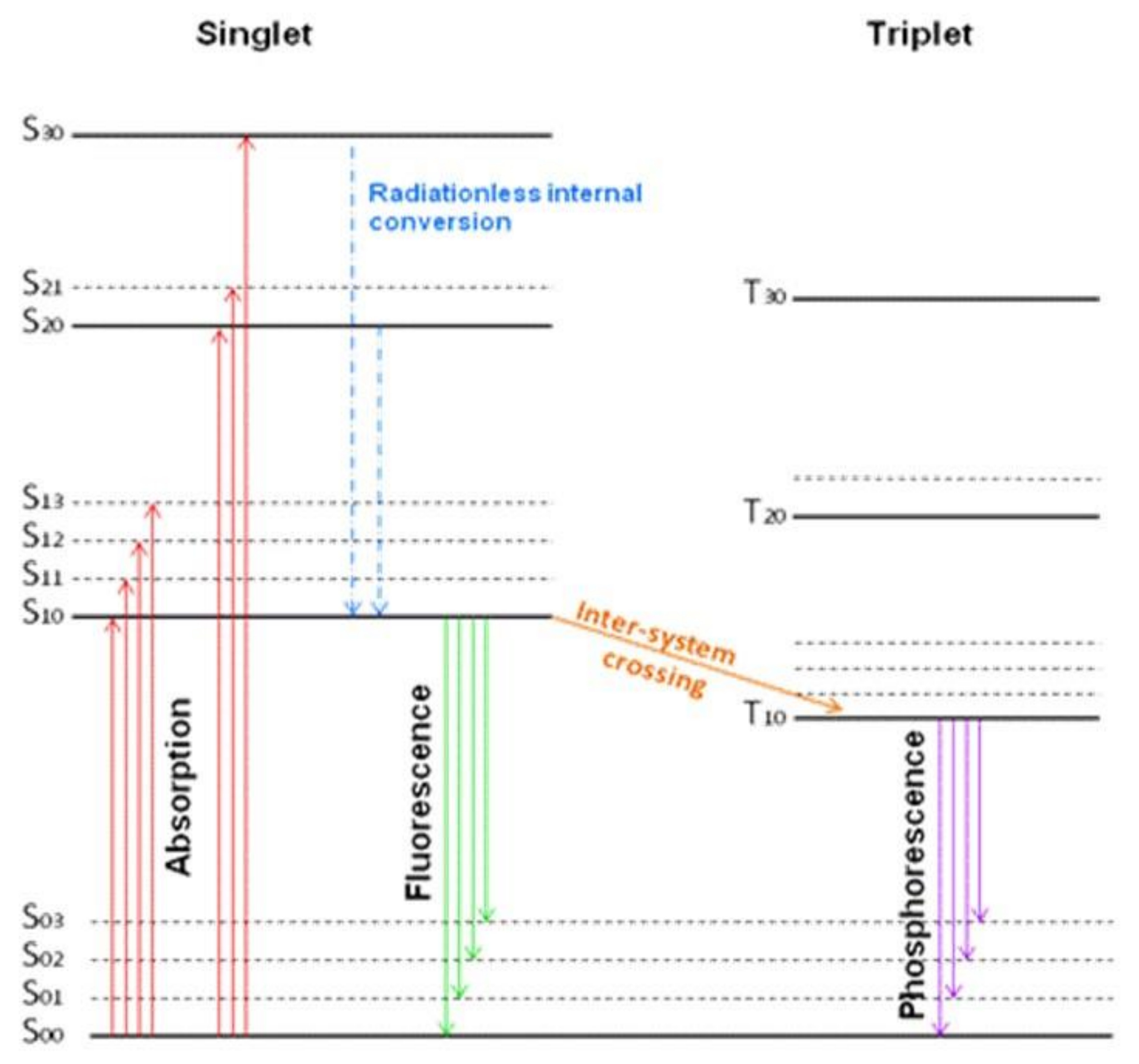
Ionization dose (Gy) prediction after 1 year at 10^{34} cm^{-2}s^{-1} at $\sqrt{s}$=14 TeV

- During Run 1 ➔ MBTS accumulated ~ [0.1-0.4] x 10^4 Gy
- At 10^4 Gy ➔ Predict ~50% Light loss due to transmission

Ref.: A. Sidoti 2014 *JINST* **9** C10020 doi:10.1088/1748-0221/9/10/C10020

The Scintillation Mechanism

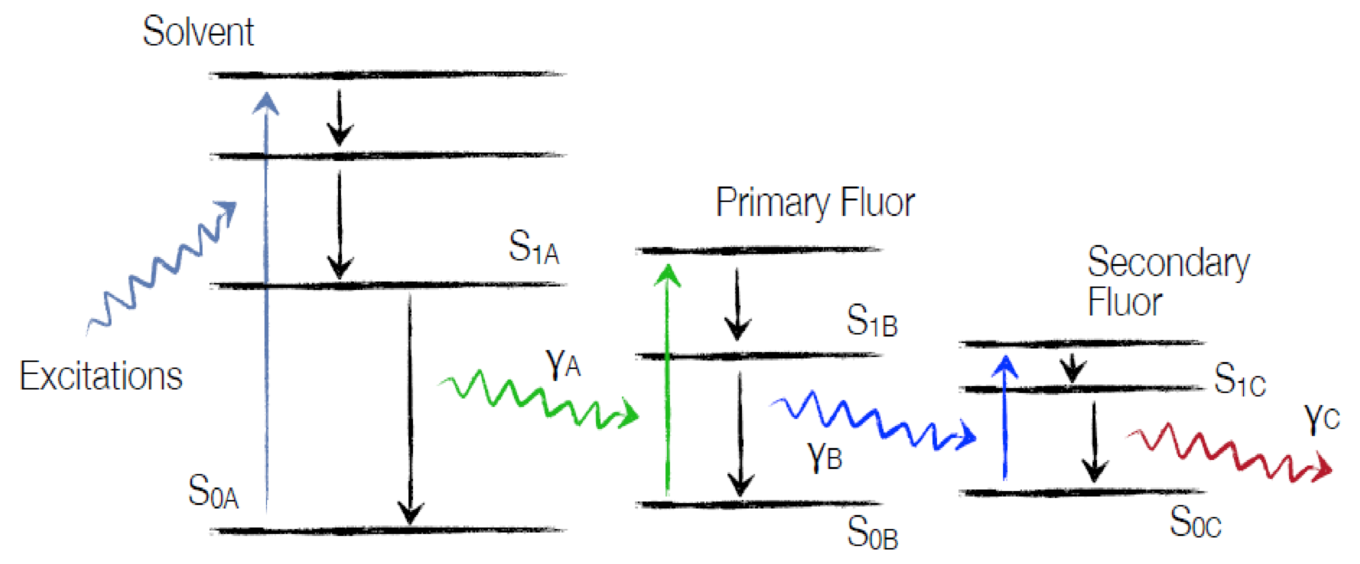
- Plastic scintillators are composed of organic molecules and exhibit the effect of scintillation.
- The basic mechanism behind scintillation is the fluorescence process undergone by delocalized π-electrons arising within the benzene ring type structure.
- Other processes such as internal conversion, inter-system crossing and subsequent phosphorescence act as quenching factors to the fluorescence light yield of a scintillator.



Energy level diagram of an organic molecule with π-electron structure

Scintillation mechanism and radiation damage effects.

- Plastic scintillator is composed of a polymer base with ~0,3% added primary fluors and ~0,01% wavelength shifting secondary fluors.
  - Excitation occurs in the base, which then undergoes fluorescence (light emission) typically around 300-350 nm.
  - Light transferred to primary fluor through non-radiative "Forster transfer" or radiative re-absorption. Subsequent fluorescence around 350-400 nm.
  - Radiative light transfer from primary to secondary fluor, with fluorescence typically in blue-green range. (400-500 nm)

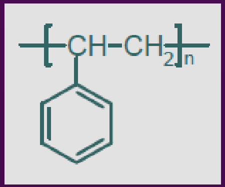


- Damage can result in structural changes, formation of colour centres and hence a loss in optical properties. → Loss to intrinsic light output or loss to transmission character (emphasised in bulk scintillators)

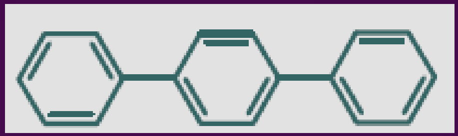
The Plastic scintillators studied

- Scintillators produced for the Tile Calorimeter and presently used in detector:
    - Dubna scintillator (MBTS)
    - Protvino scintillator (TileCal barrels)

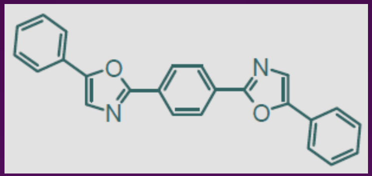
Base: Polystyrene



Primary fluor: PTP

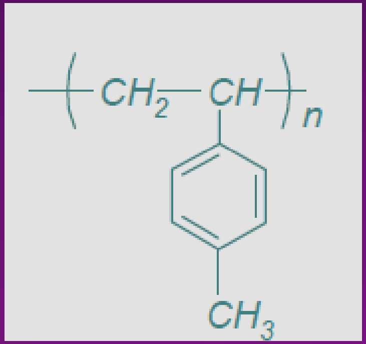


Secondary fluor: POPOP



- Commercially obtained
    - from ELJEN Technologies :
        - EJ200
        - EJ208
        - EJ260 (green emitting)
    - From Saint Gobain Crystals:
        - BC408

Base: Polyvinyl Toluene

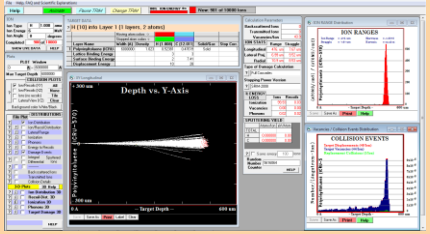


3% added organic fluors

Experimental procedure

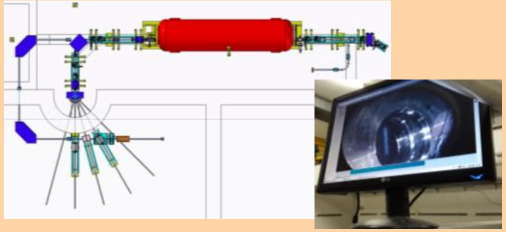
- For our small scale comparative study, we required that:
    - **Protons pass through samples**
    - **Leading energy loss through ionisation**
- The following experimental procedure was followed:

Simulations for Proton damage using SRIM



Sample cutting and polishing

Proton irradiation with 6 MeV protons at iThemba LABS, Gauteng.



Light transmission testing

Light yield response to 0,5 MeV beta electrons from SR90 source

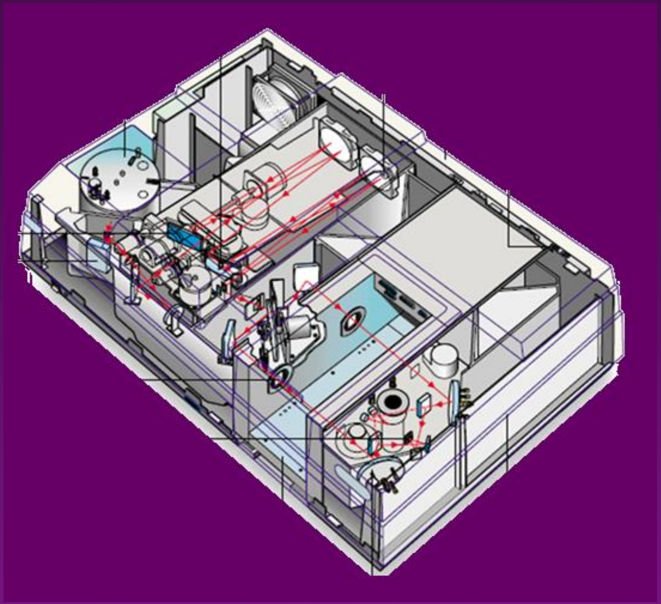
Structural damage analysis using Raman characterization of bonding structure

Light response to 229 nm laser excitation (Fluorescence)

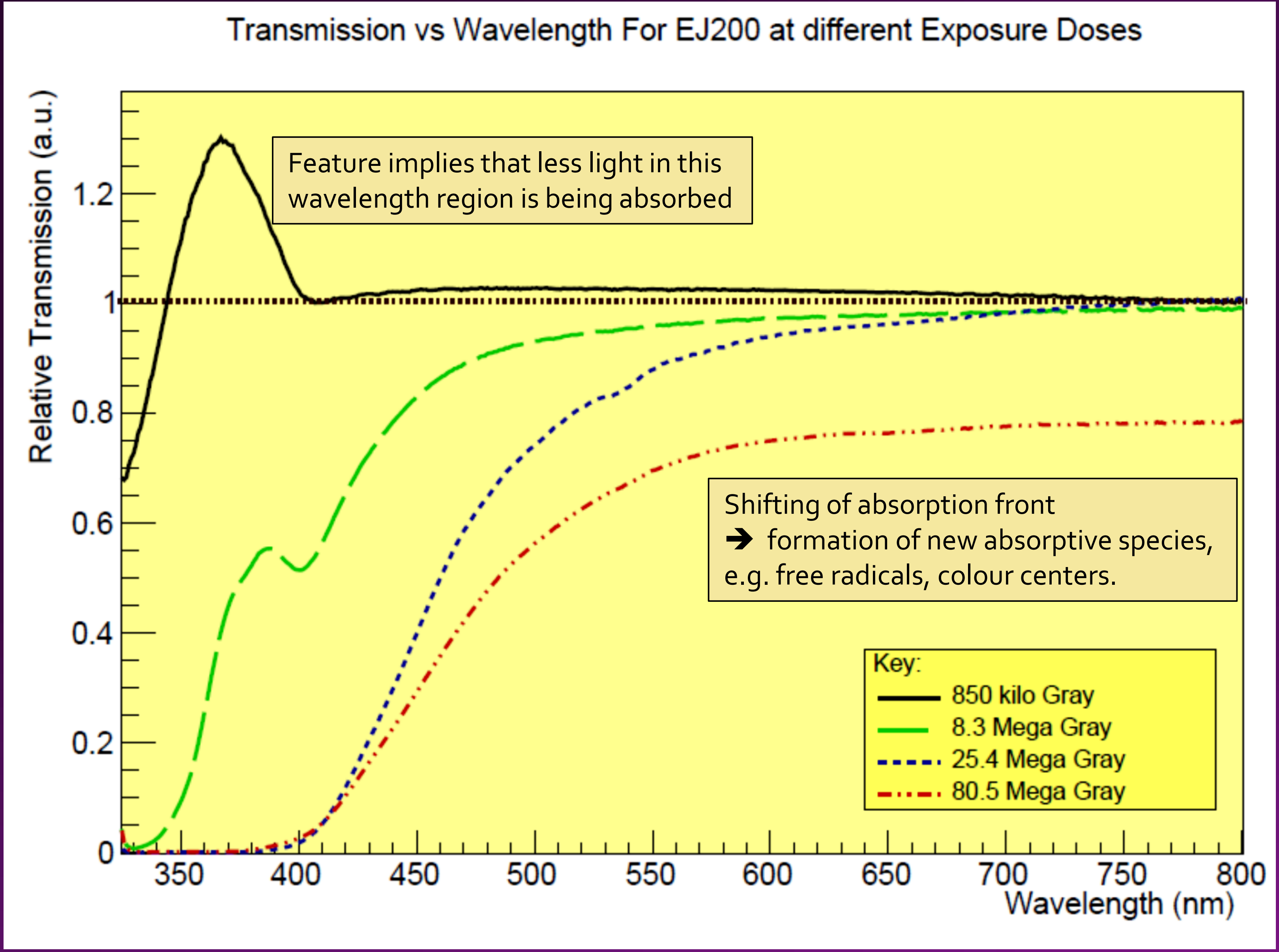
- For this talk, I will present the results of the transmission and fluorescence light yield testing

Light Transmission Testing

- Conducted using the Varian Cary Spectrophotometer.
- Taken over wavelength range of 200-800 nm.
- Spectra are measured before and after irradiation.
- The ratio of transmission in the irradiated vs un-irradiated sample is then taken



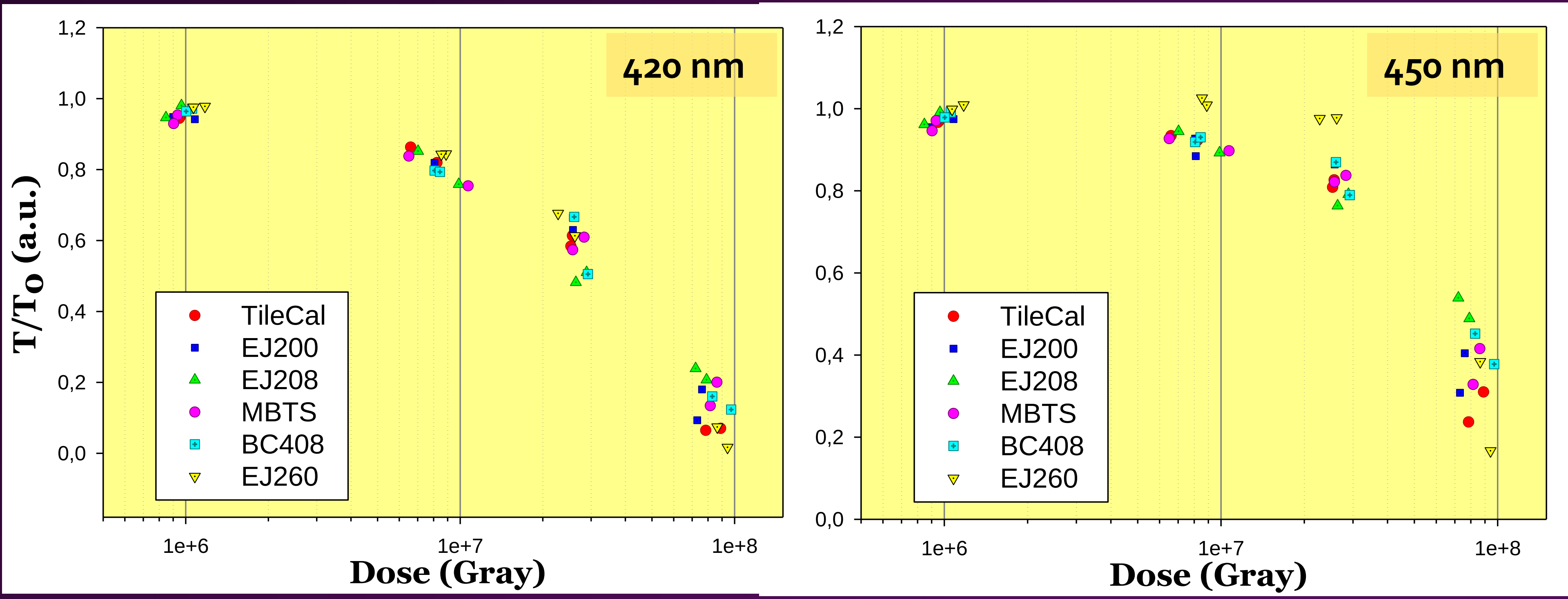
Light Transmission Results for EJ200 samples



Feature implies that less light in this wavelength region is being absorbed

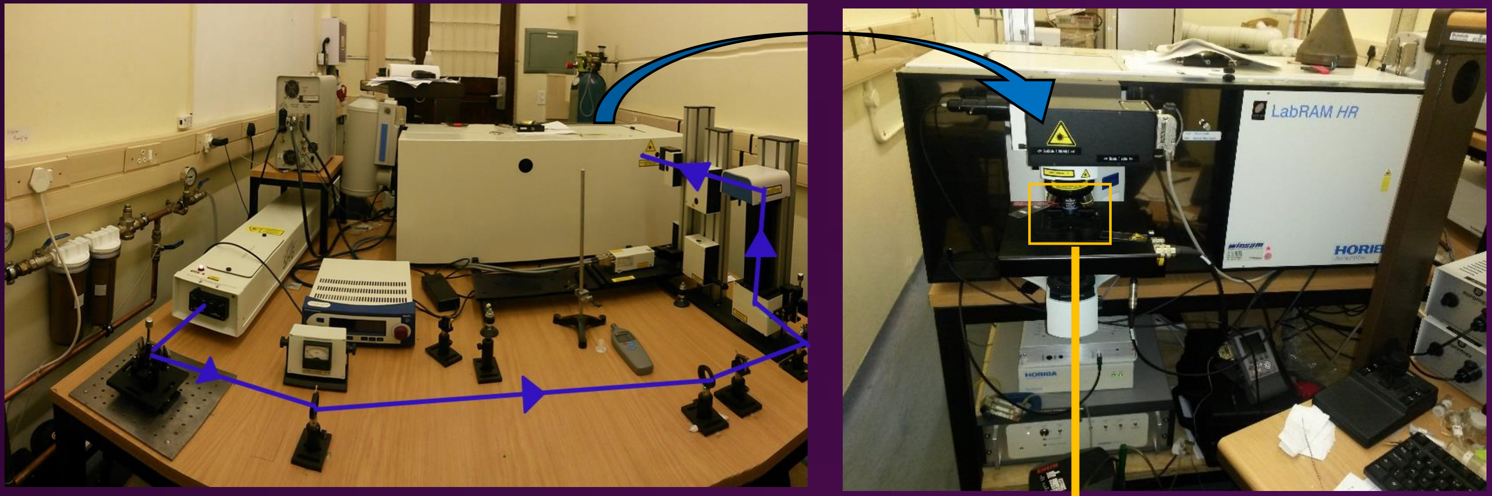
Shifting of absorption front
➔ formation of new absorptive species, e.g. free radicals, colour centers.

Relative Transmission loss at 420 nm and 450 nm

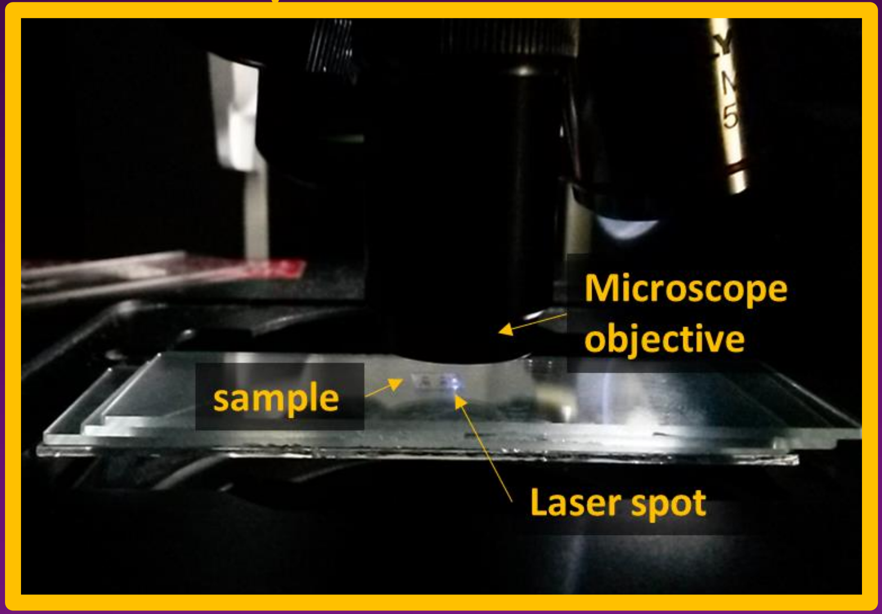


- Consider transmission loss around 420 nm and 450 nm. Wavelength range where blue scintillators typically emit and absorption peaks in Y11 fibers occur.
- NB: EJ260 is green and has an emission with maximum peak around 490 nm, and still absorbs light in the region of 410-450. Will not be compatible with Y11 fibers currently used.
- Blue scintillators appear to exhibit very similar behavior.

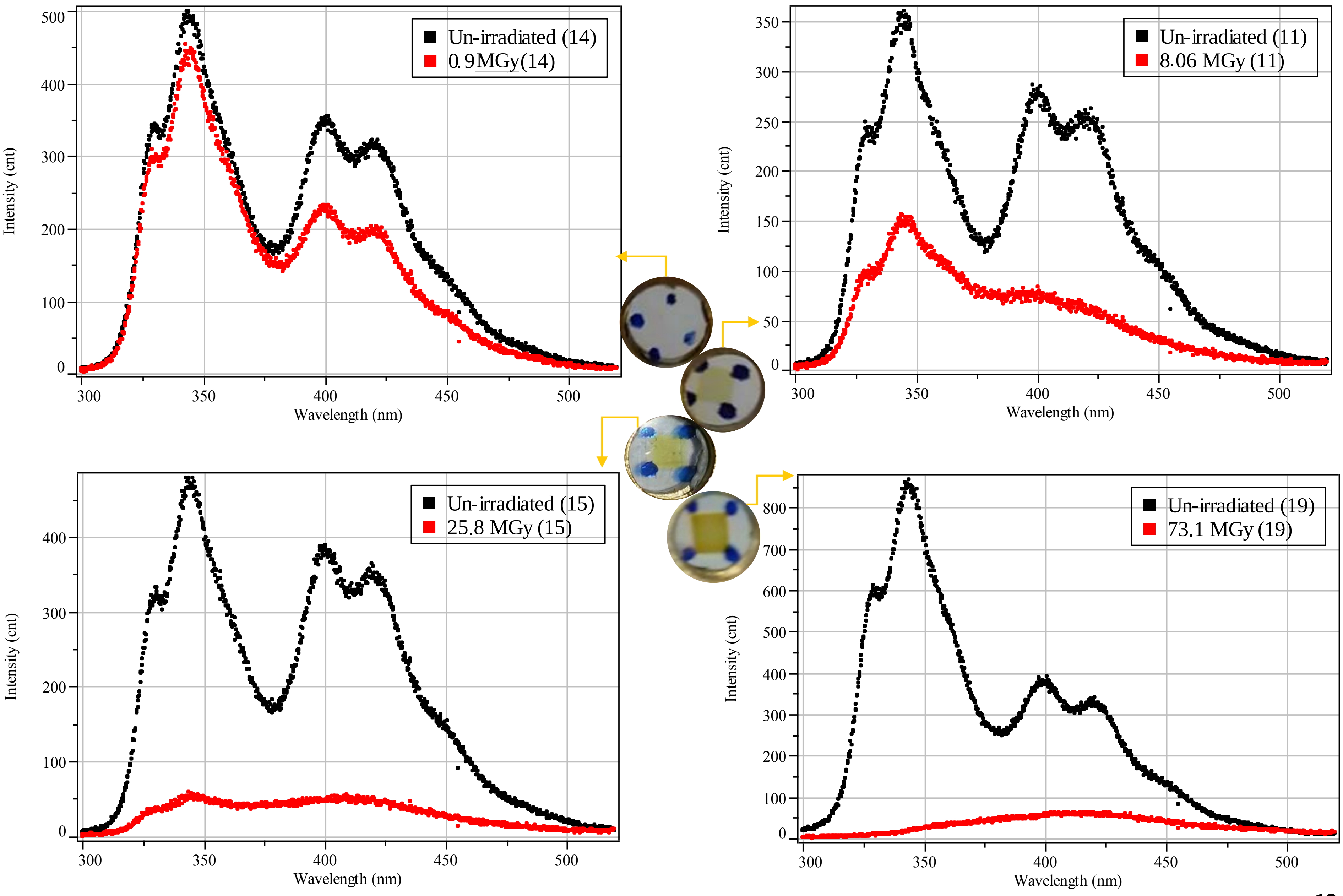
Testing fluorescence light yield in damaged samples



- Test response to a 229 nm laser with power ~3-5 mW. 229 nm is sufficient to excite the base material.
- Laser is focussed through objective onto sample and scanned over 20 μm x 20 μm square.
- Measure fluorescence over 300-500 nm, with 1 sec collection time.
- Take 3 measurements along irradiated region and 3 along un-irradiated region.
- Integrate spectra between 350-500 nm and take ration of average irradiated to average un-irradiated.



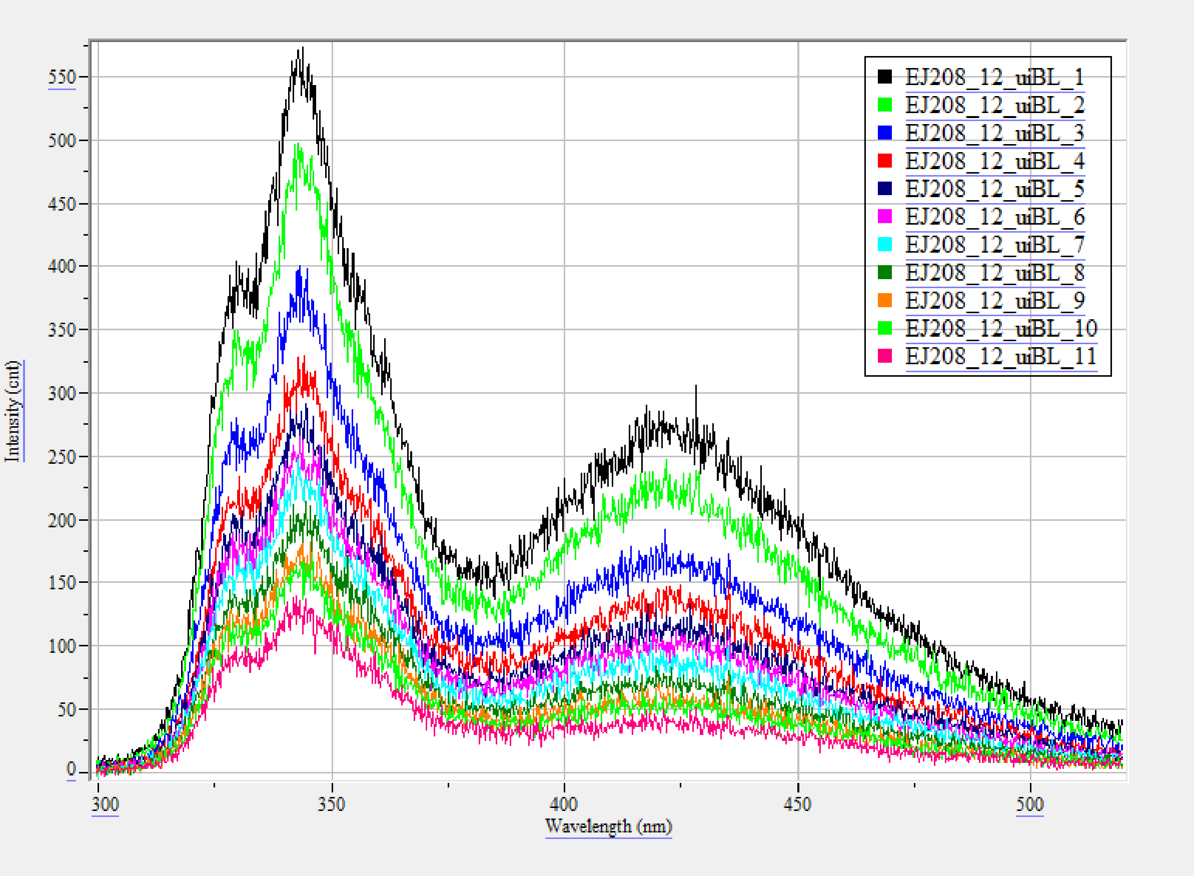
Average spectra for EJ200 samples



The photo-bleaching effect

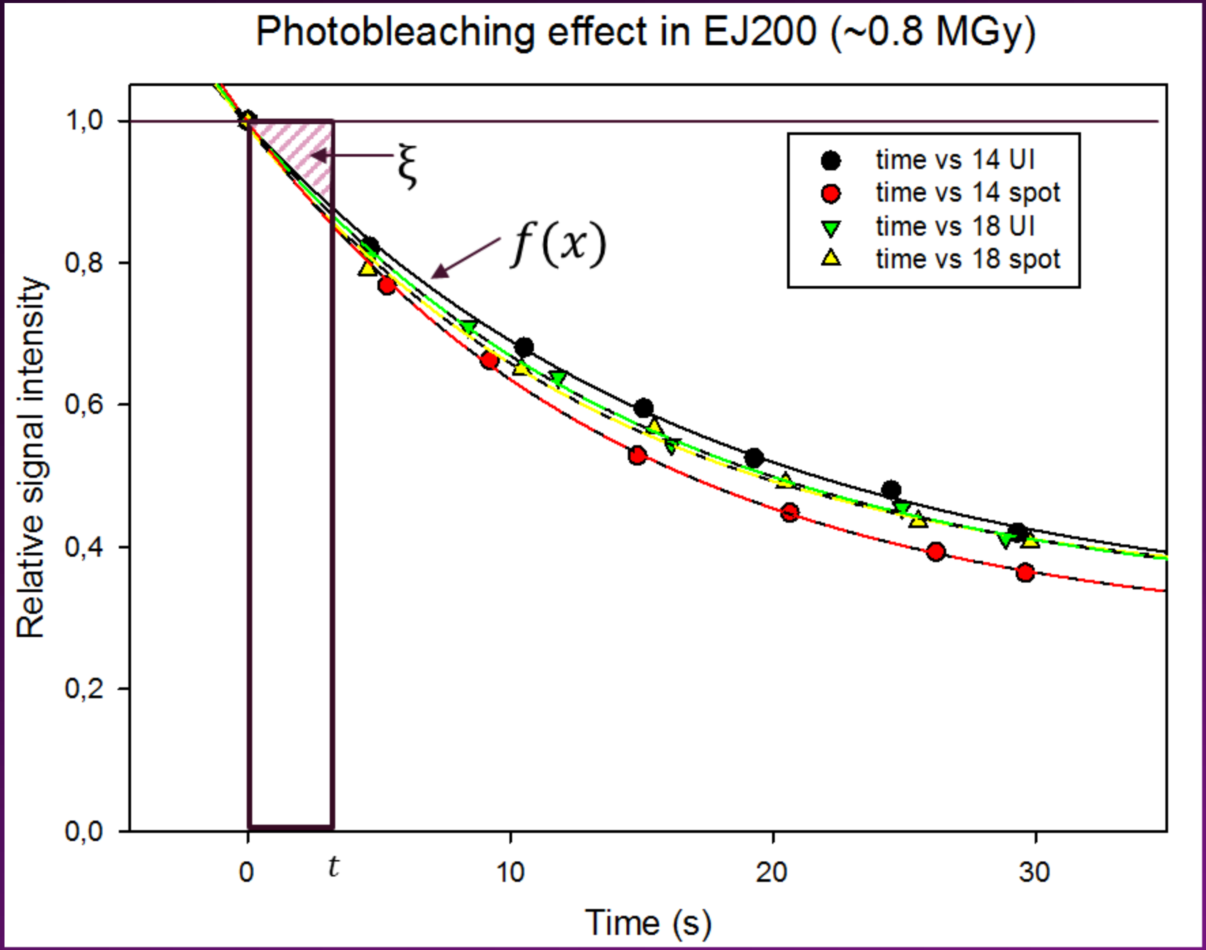
- Photo-bleaching is the effect observed when a molecule loses its ability to fluoresce due to it undergoing photon induced chemical damage.
- The destruction of the molecule is proportional to:

  The emission intensity x The emission time x The number of excitation and fluorescence cycles undergone
- For excitation wavelengths below 250 nm, the probability of exciting the electron to the triplet state increases. This is a stable state with a long lifetime and can interact with other molecules to produce irreversible covalent modifications.



Correcting for photo-bleaching effect

- Photo-bleaching time correlation curves were therefore used to apply a correction (C) to the fluorescence data due to ~3s delay between laser switch on and acquisition start time.



$$f(x) = y_0 + ae^{-tb}$$

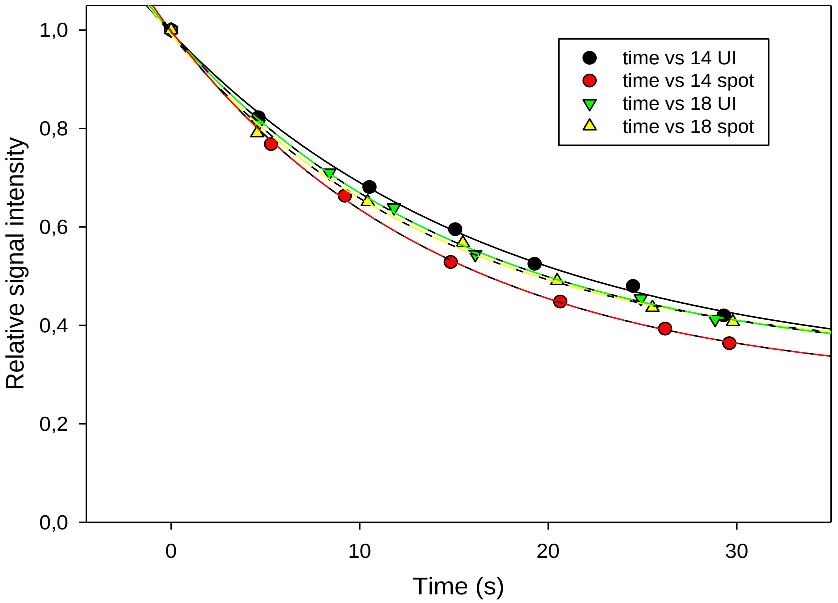
$$\xi = \int_t^0 [1 - f(x)]dx$$

$$\xi = t(1 - y_0) + \frac{a}{b}\left(e^{-tb} - 1\right)$$

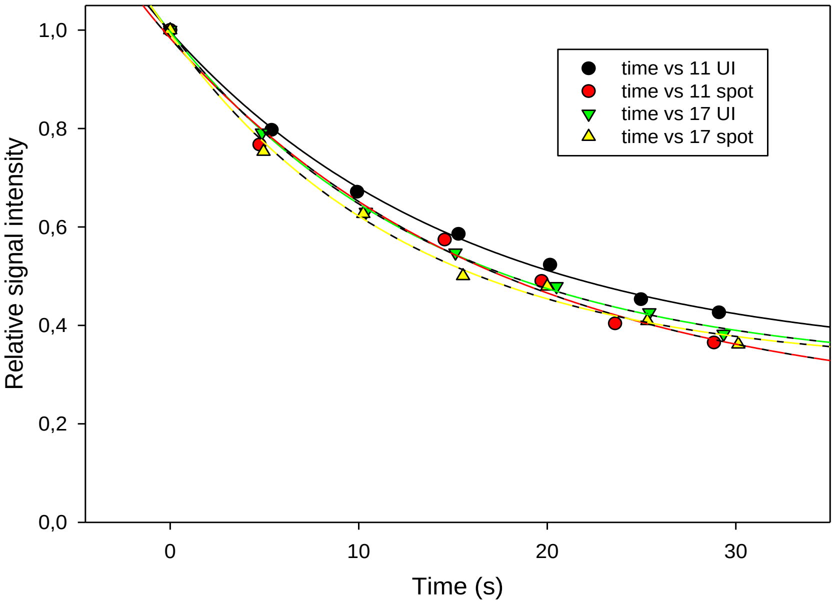
$$C = \frac{t}{t - \xi}$$

Photo-bleaching plots for corresponding EJ200 samples

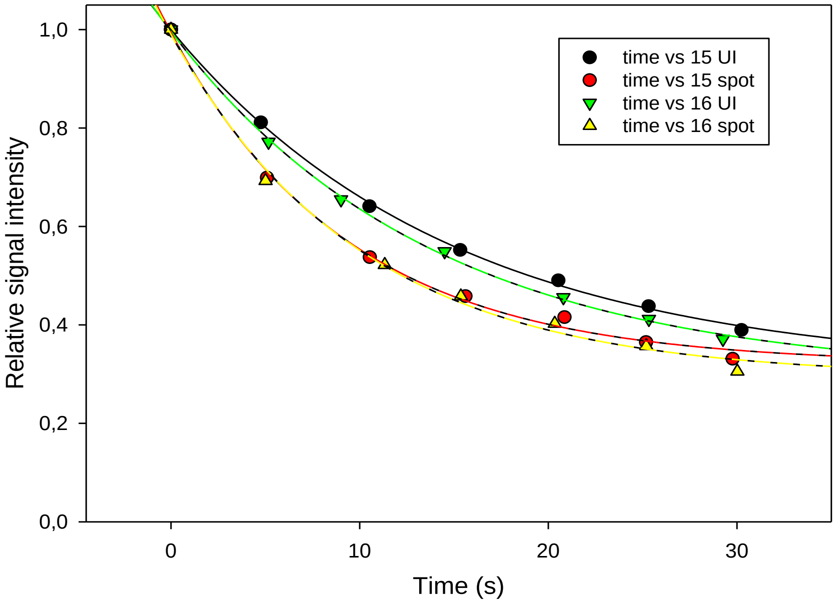
Photobleaching effect in EJ200 (~0.8 MGy)



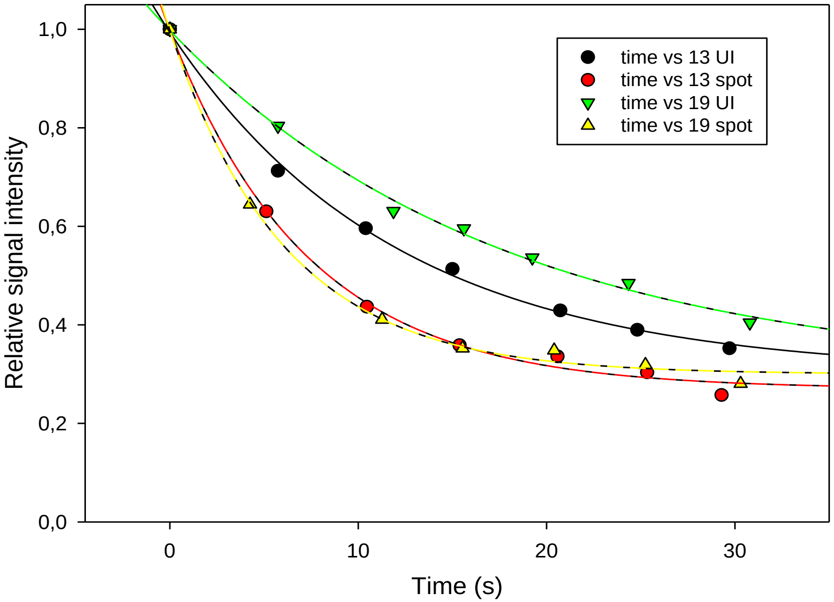
Photobleaching effect in EJ200 (~8 MGy)



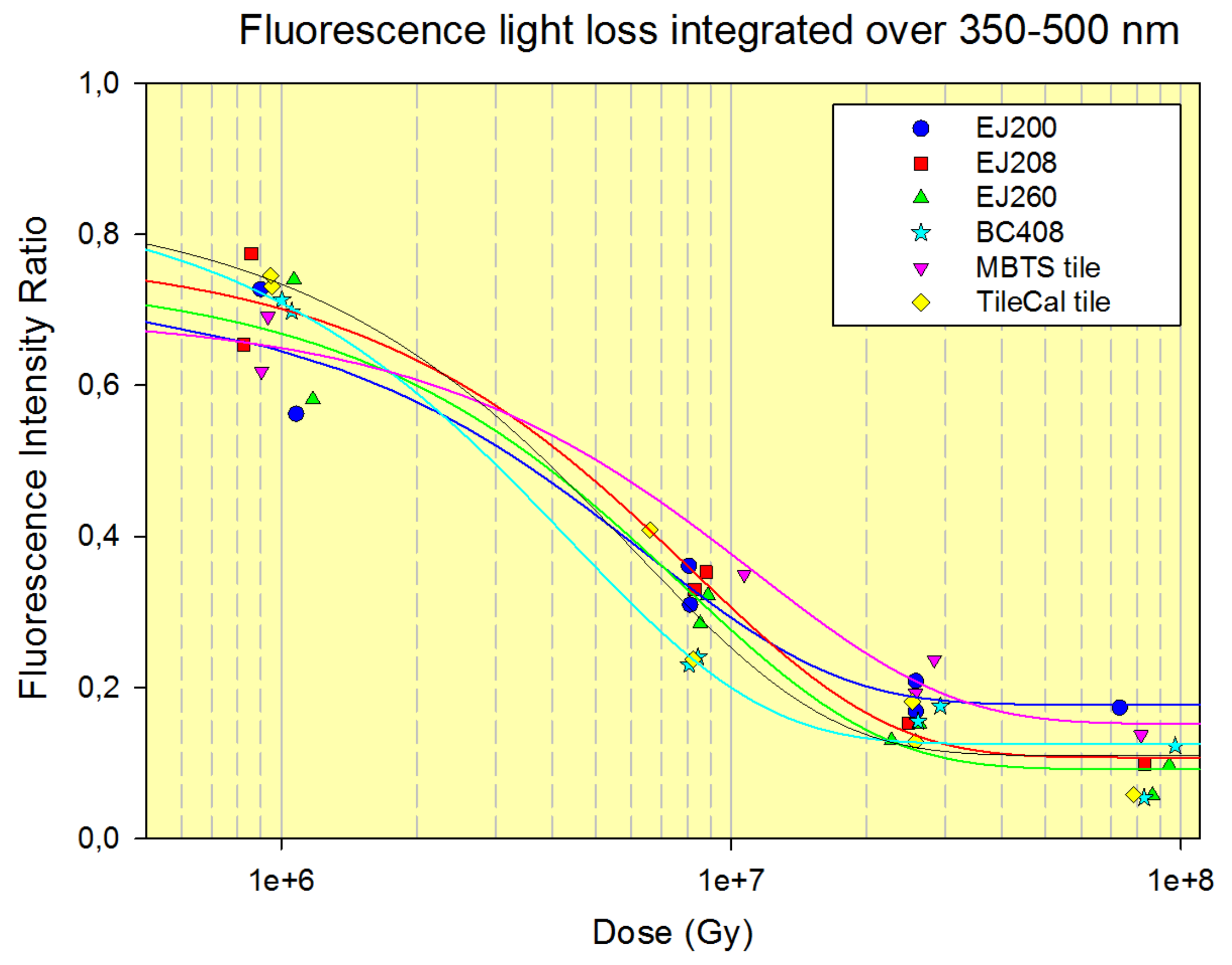
Photobleaching effect in EJ200 (~25 MGy)



Photobleaching effect in EJ200 (~80 MGy)



Comparative of fluorescence ratio's



$$Ratio = \frac{Irr\ Ave\ \times\ C_{irr}}{Un-irr\ Ave\ \times\ C_{ui}}$$

- Fit with exponential function $f(x) = y_0 + ae^{-tb}$
- 20% variation in performance between scintillators

Discussion

- Radiation damage affects the optical response of plastic scintillators.
- Scintillators become increasingly less transparent to their own light and emit less fluorescent light as their exposure dose is increased.
- This is due to the formation of radicals which absorb light and dissipate it through different quenching mechanisms. Visible discolouration on samples is observed.
- Scintillators behave very similarly against transparency loss and fluorescence light loss.
- The MBTS and EJ200 scintillators seem to exhibit the best hardness against light loss from damage. EJ200 has a slightly larger light yield and faster response time.
- It is predicted that radiation damage predominantly affects the base of the scintillator. Since all the plastics are either polyvinyl toluene or polystyrene based, it may be reasonable that they perform similarly.
- This study was conducted on thin plastic scintillator samples. Additional damage may be observed in thicker samples since damage effects the light attenuation length. These effects can vary depending on the type of fluors that the scintillator has.

Funding Acknowledgements

DST-NRF CENTRE OF EXCELLENCE • IN STRONG MATERIALS •

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SCIENTIA ET LABORE
JOHANNESBURG

NRF National Research Foundation

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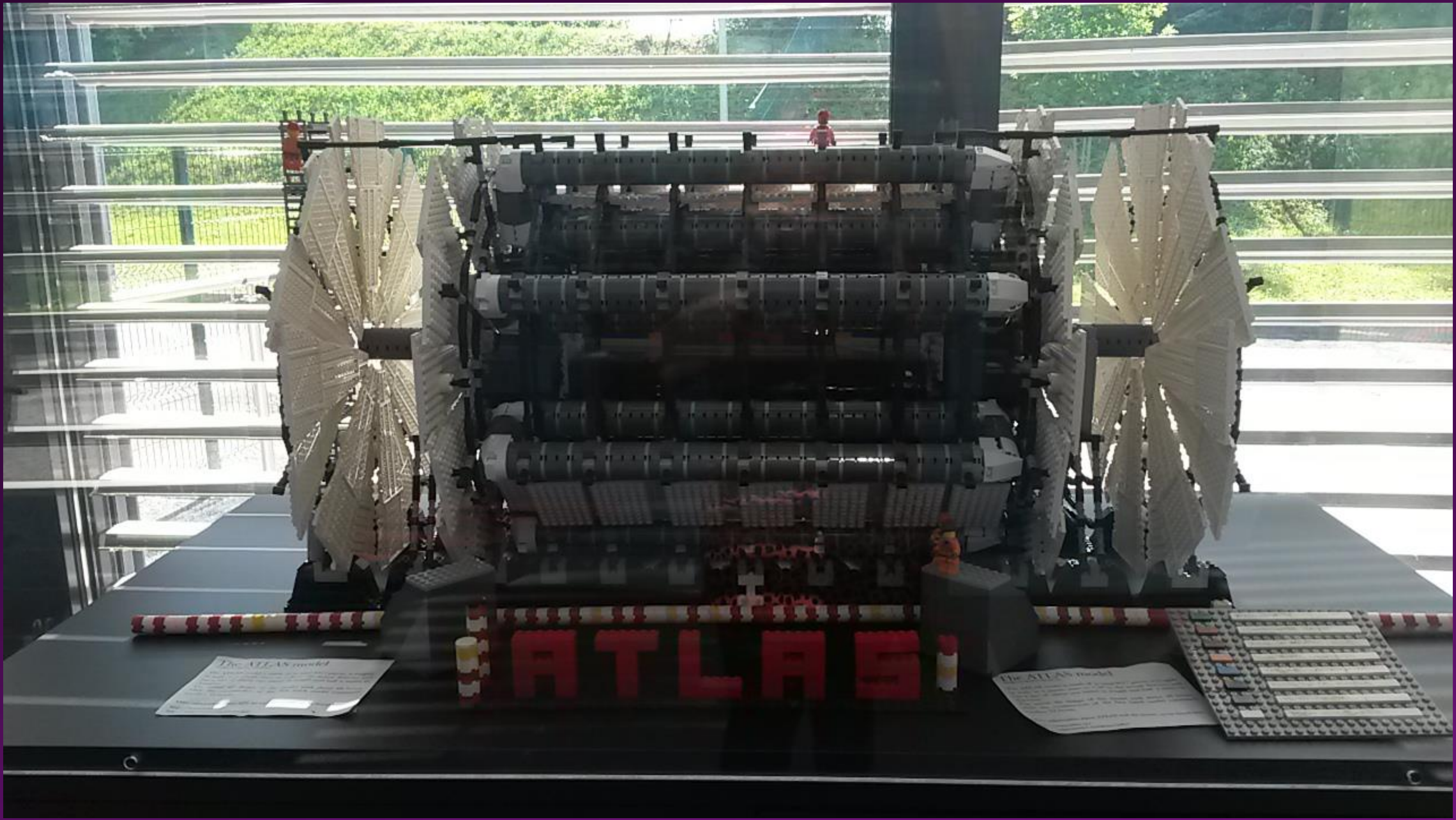
Thank You for your time…



Back-up

Scintillator	**EJ200** [1]	**EJ208** [1]	**EJ260** [1]	**BC408** [2]	**UPS923A** [3]	**Protvino** [4]
Manufactured by:	Eljen Technology	Eljen Technology	Eljen Technology	Saint Gobain Crystals	Institute of Scintillating Materials, Kharkiv. (Used in MBTS)	Institute of High Energy Physics, Protvino in association with SIA luch, Podolsk. (Used in Tile Barrel)
Base	PVT	PVT	PVT	PVT	PS	PS
Primary Fluor	0.3% organic fluors	0.3% organic fluors	0.3% organic fluors	Not available (However, listed as a performance equivalent of EJ200)	2% PTP	1.5% PTP
Secondary Fluor					0.03% POPOP	0.044% POPOP
Light Output, % Anthracene	64	60	60	64	60	Not available Studies conducted by the IHEP team, into the effect of changing concentration of the fluors: for an increase in PTP concentration from 0.1% to 0.2%, the light output increased by 10%. Whilst an increase in concentration of POPOP from 0.02% to 0.1% had little effect on light yield.
Wavelength of Max. Emission, nm	425	435	490	425	425	
Rise Time, ns	0,9	1	~	0,9	0,9	
Decay Time, ns	2,1	3,3	9,2	2,1	3,3	
Density, g/cc:	1,023	1,023	1,023	1,032	1,06	
Refractive Index	1,58	1,58	1,58	1,58	1,6	
Light attenuation length (cm)	~400*	~400*	~	380**	400	

*In a cast sheet of dimensions 2 cm x 20 cm x 300 cm
**In a cast sheet of dimensions 1 cm x 20 cm x 200 cm

Date specifications from manufacturers

1. http://www.eljentechnology.com/index.php/products/plastic-scintillators
2. http://www.crystals.saint-gobain.com/Plastic_Scintillators.aspx.
3. http://www.scintitech.com/CompanyPage.aspx?MenuId=39&MainId=3
4. A. N. Karyukhin, S. V. Kopikov, M. E. Kostrikov, V. Lapin and A. Zaitsev, “Injection molding scintillator for ATLAS Tile Calorimeter,” ATL-TILECAL-96-086, ATL-L-PN-86, 14 October 1996.