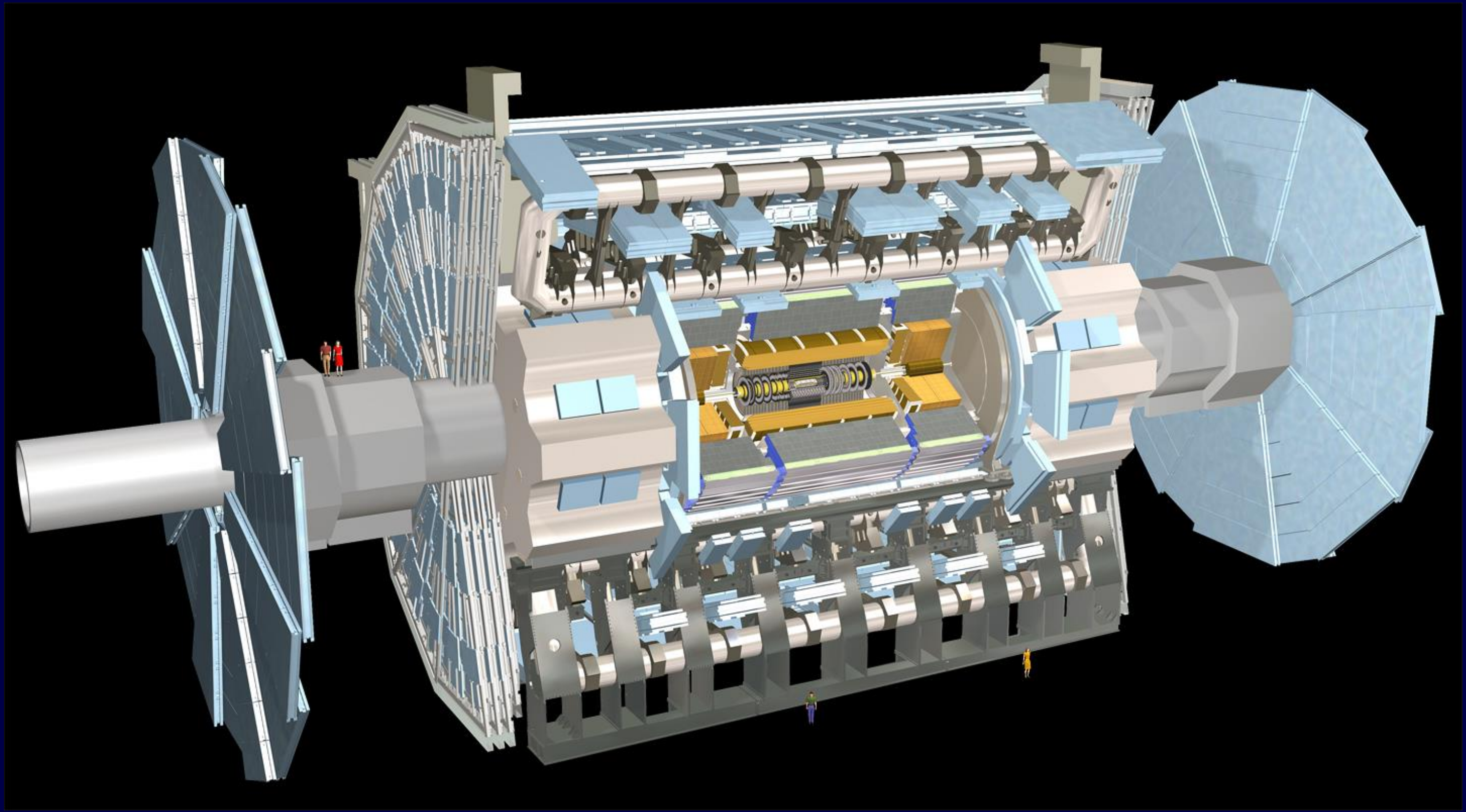
Comparative study of proton induced radiation damage in plastic scintillators for the Tile Calorimeter of ATLAS

Presented by: Harshna Jivan

On behalf of the Wits Scintilator team:

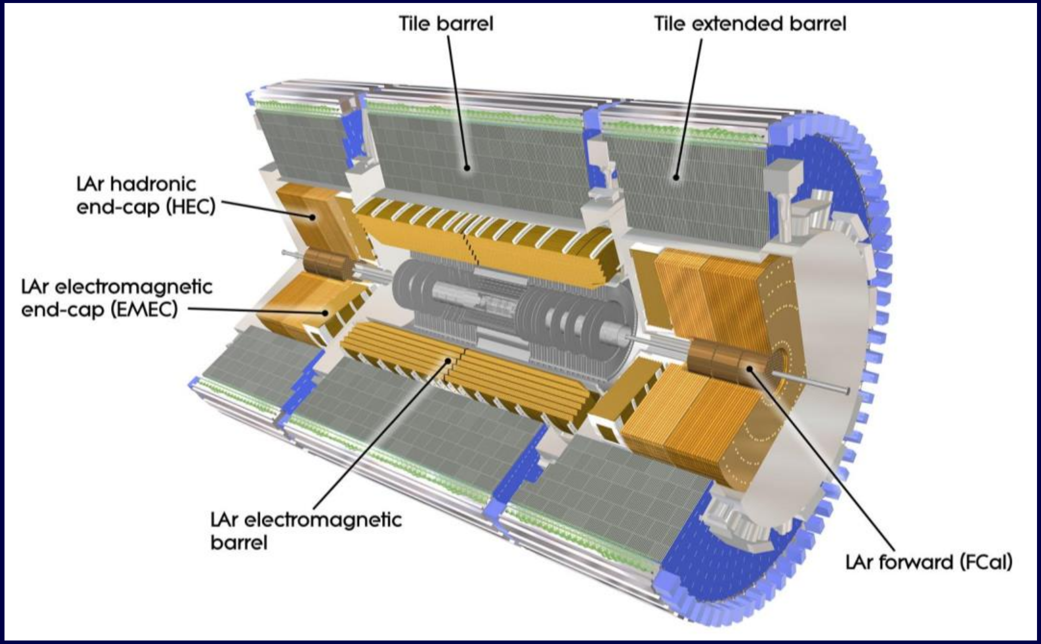
B Mellado, E Sideras-Haddad, R Erasmus, J Keartland, S Liao, M Madhuku, C Pelwan, G Peters, K Sekonya, O Solovyanov and H Tlou.

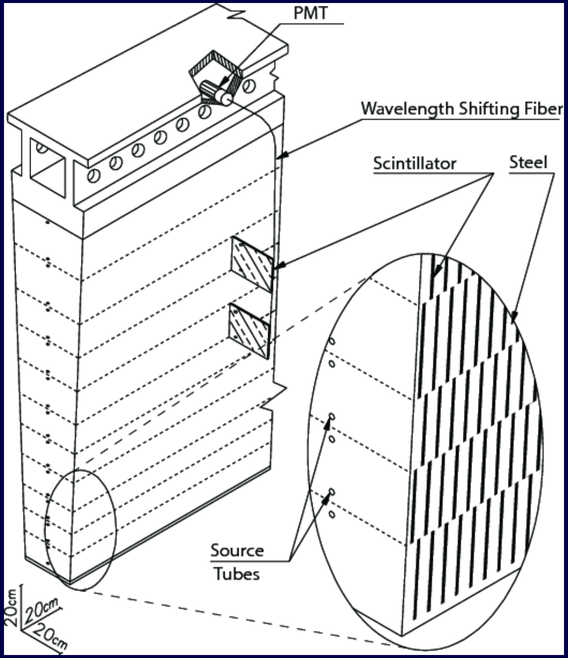
The Tile Calorimeter of ATLAS



- ATLAS (A Toroidal LHC Apparatus) is a particle physics experiment that is involved in the search for new particles through high energy proton-proton collisions at the Large Hadron Collider of CERN.
- The Tile Calorimeter is the hadronic calorimeter responsible for detecting hadrons, taus and jets of quarks and gluons.

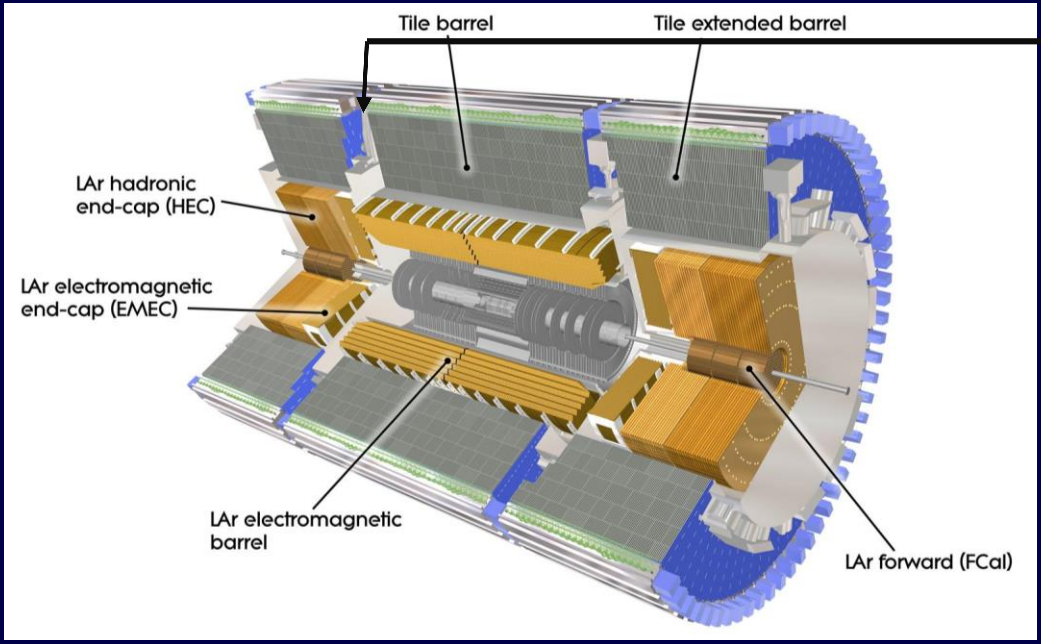
The Tile Calorimeter of ATLAS

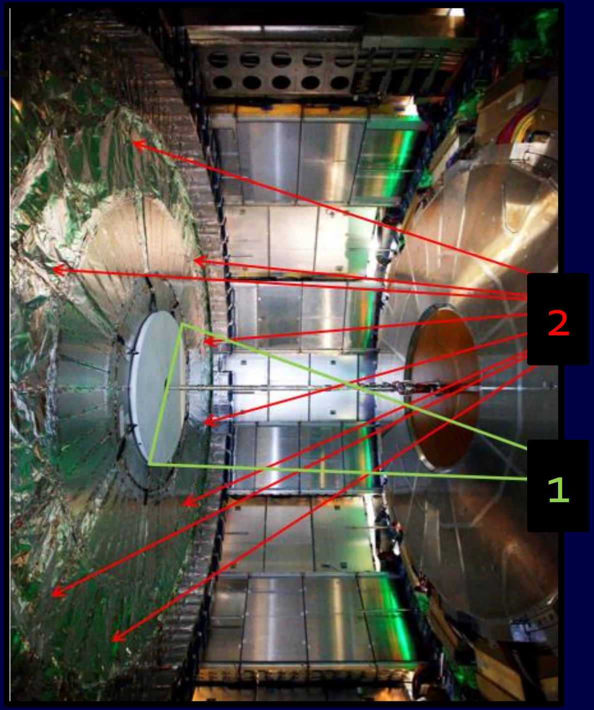




- Consists of a central barrel and two extended barrels.
- Each barrel contains 64 modules consisting of a matrix of steel and plastic scintillator plates.
- The steel plates act as an absorber medium, converting the incoming jets to a ‘shower’ of particles.
- The scintillator tiles absorb energy from the incoming particles and fluoresce to emit light.
- This light is passed through wavelength shifting optical fibers and detected by photomultiplier tubes.
- The signal is further processed with readout electronics in order to digitize the data for analysis thereafter.

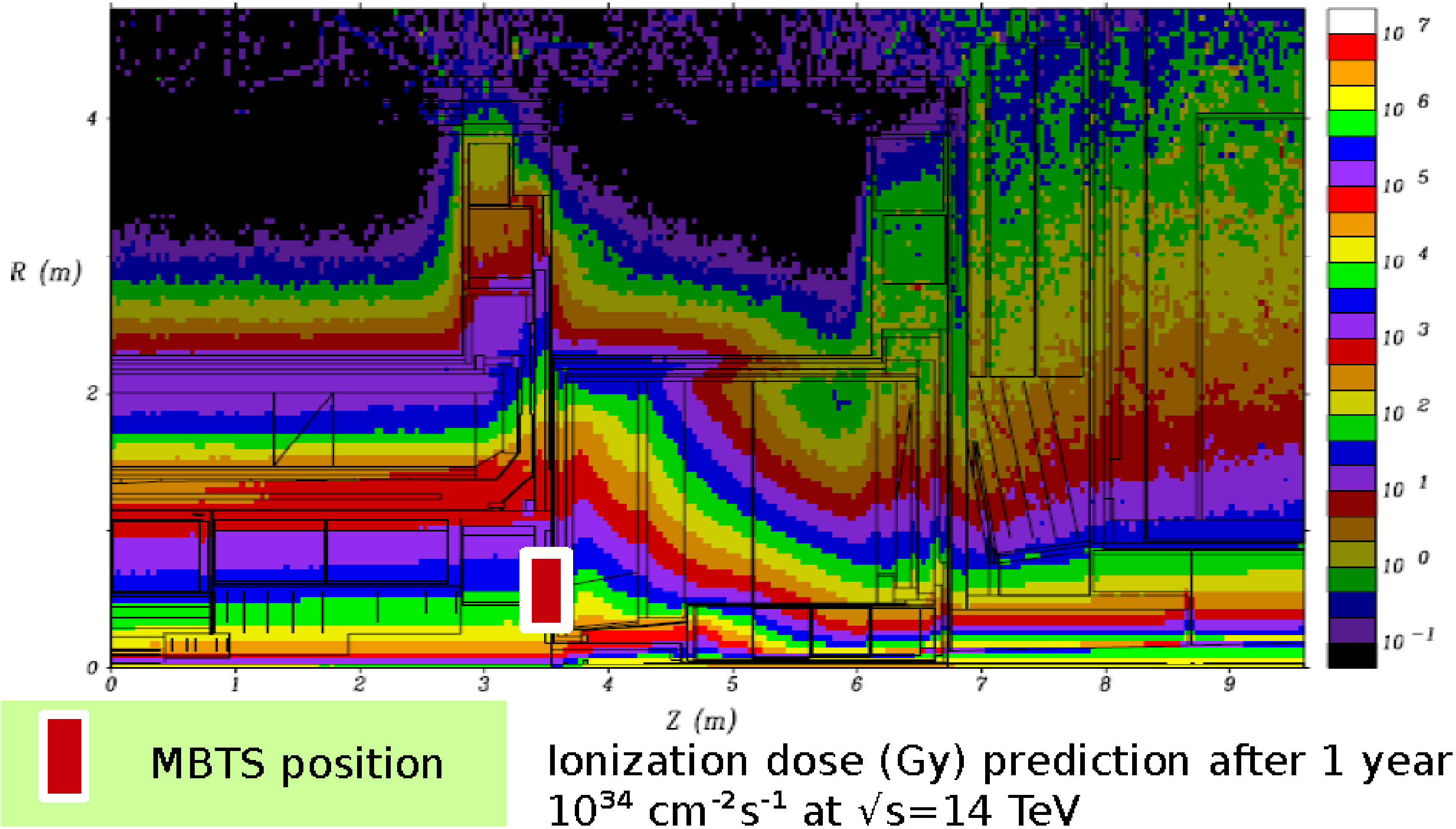
The Tile Calorimeter of ATLAS





- Gap regions contain additional scintillator plates distributed radially.
  [1: MBTS scintillators, 2:Crack scintillators]
- During Run1, crack scintillators exposed to ~100 Grays per year. Expected to increase with Run2.
- 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



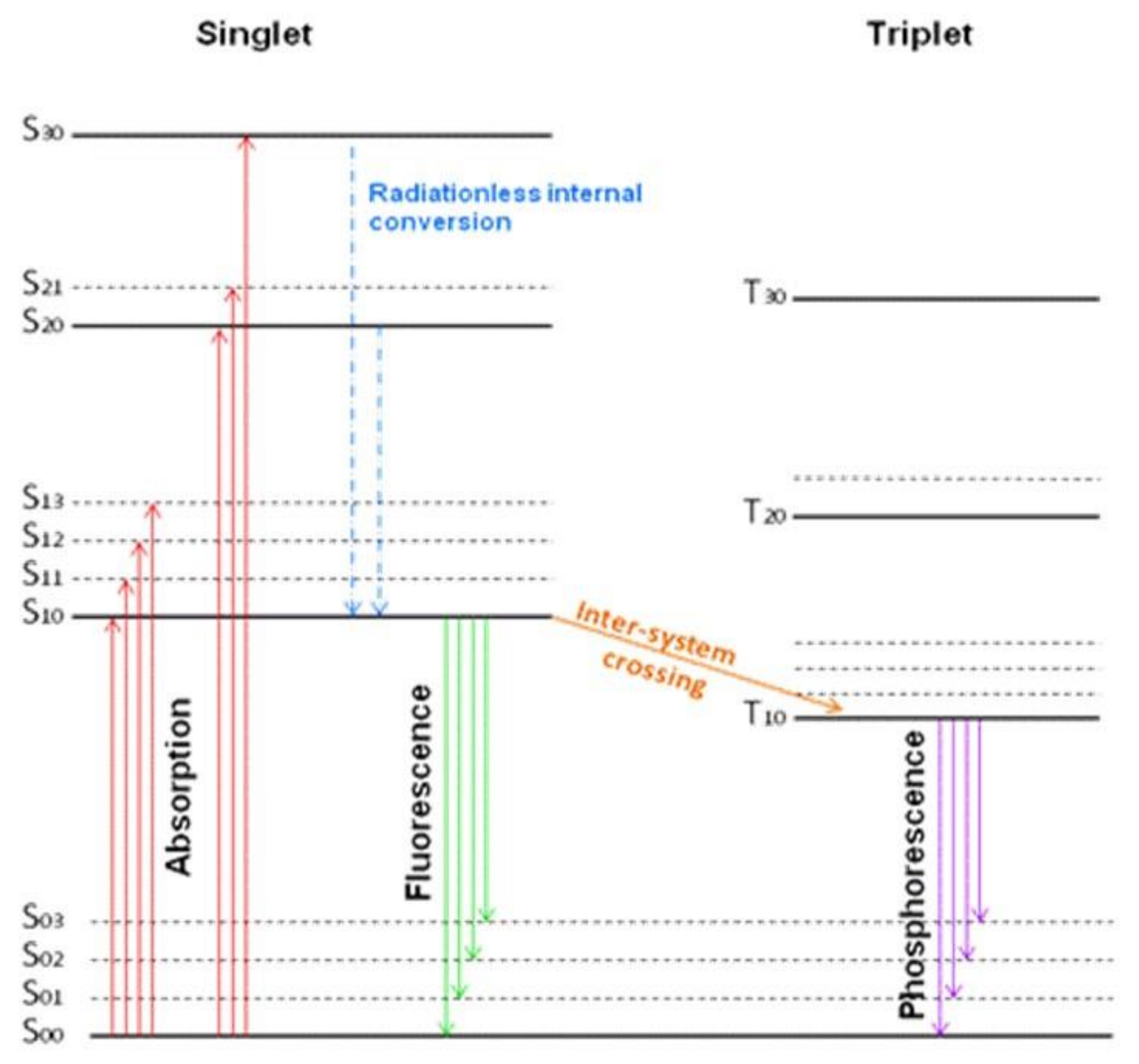
Ionization dose (Gy) prediction after 1 year at 10^{34} cm^{-2}s^{-1} at $\sqrt{s}$=14 TeV

- 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

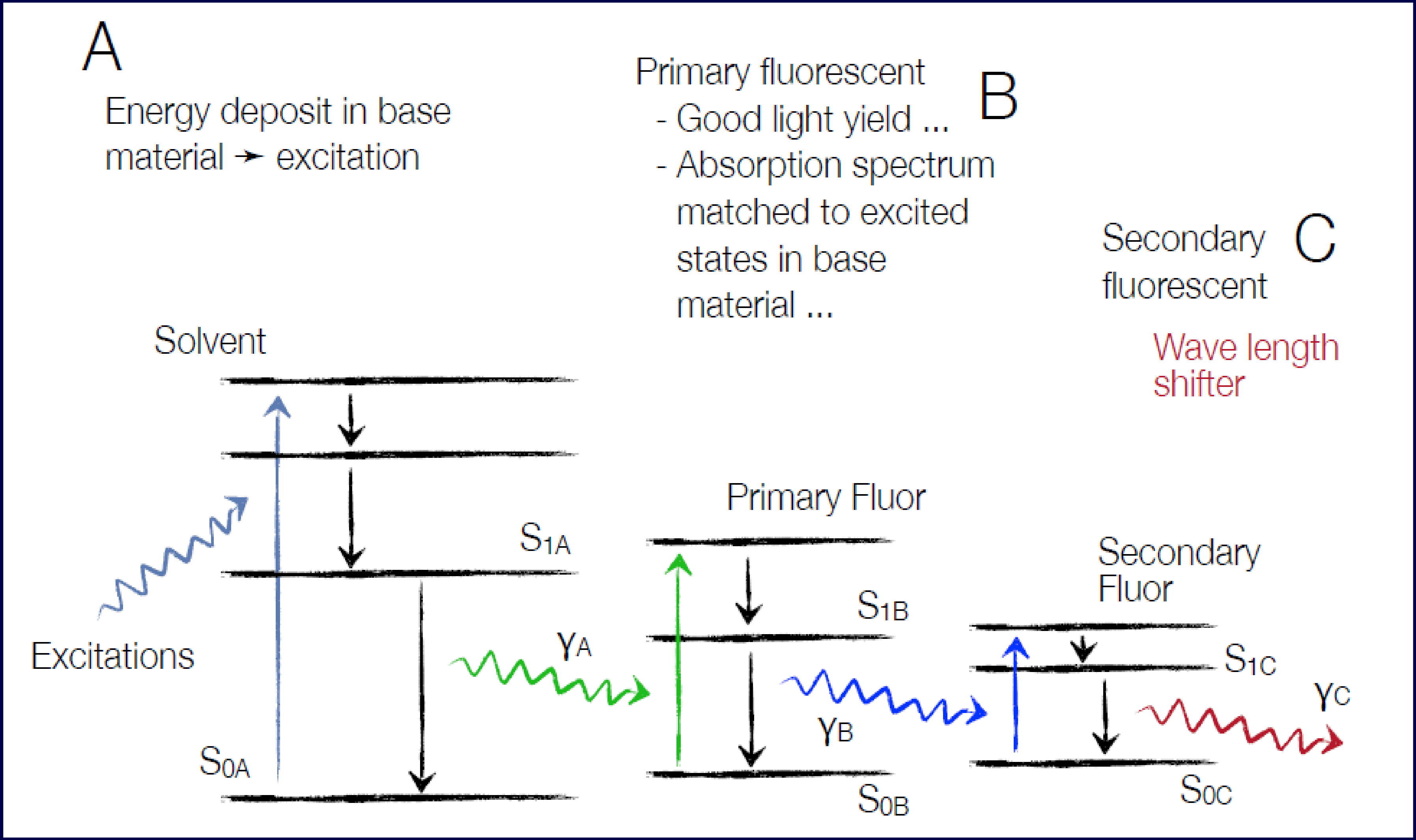
The Scintillation Mechanism

- The basic mechanism behind scintillation is the fluorescence process undergone by delocalized π-electrons arising within the benzene ring type structure.



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

The Scintillation Mechanism


A

Energy deposit in base material → excitation

Primary fluorescent
- Good light yield ...
- Absorption spectrum matched to excited states in base material ...

B

Secondary fluorescent

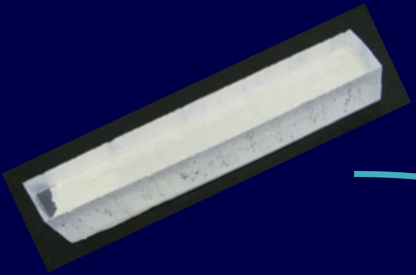
C

Wave length shifter

- Radiative transfer of energy from polymer base to primary and secondary fluors

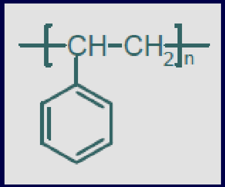
The Plastic scintillators studied

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

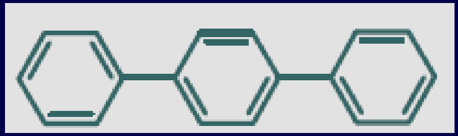


- **Commercially obtained**
  - from ELJEN Technologies :
    - EJ200
    - EJ208
    - EJ260 (green emitting)
  - From Saint Gobain Crystals:
    - BC408

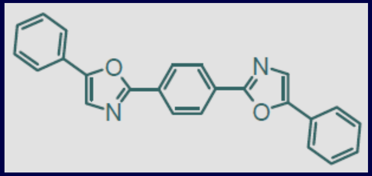
Base: Polystyrene



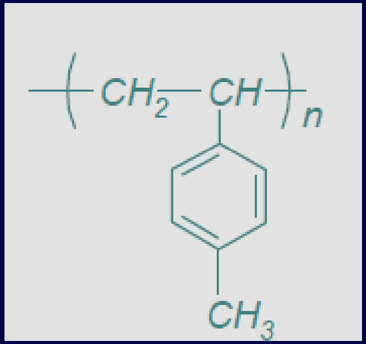
Primary fluor: PTP



Secondary fluor: POPOP



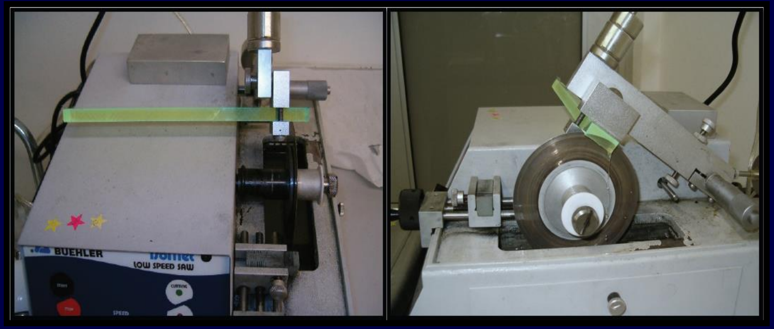
Base: Polyvinyl Toluene



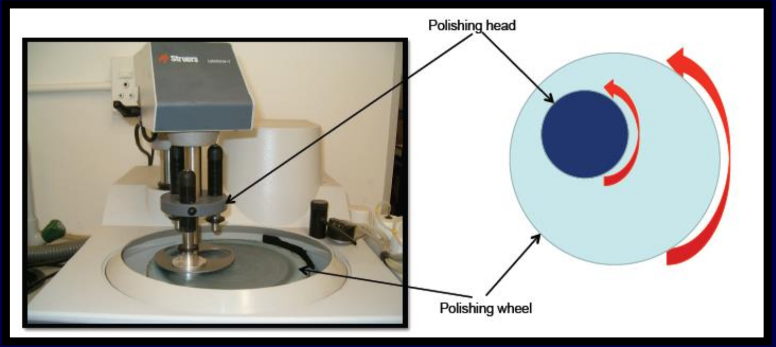
3% added organic fluors

Sample preparation

Samples of each grade were prepared to dimensions of 5 mm by 5 mm with thicknesses ranging between 0,32 and 0,38 mm. The following process was followed:



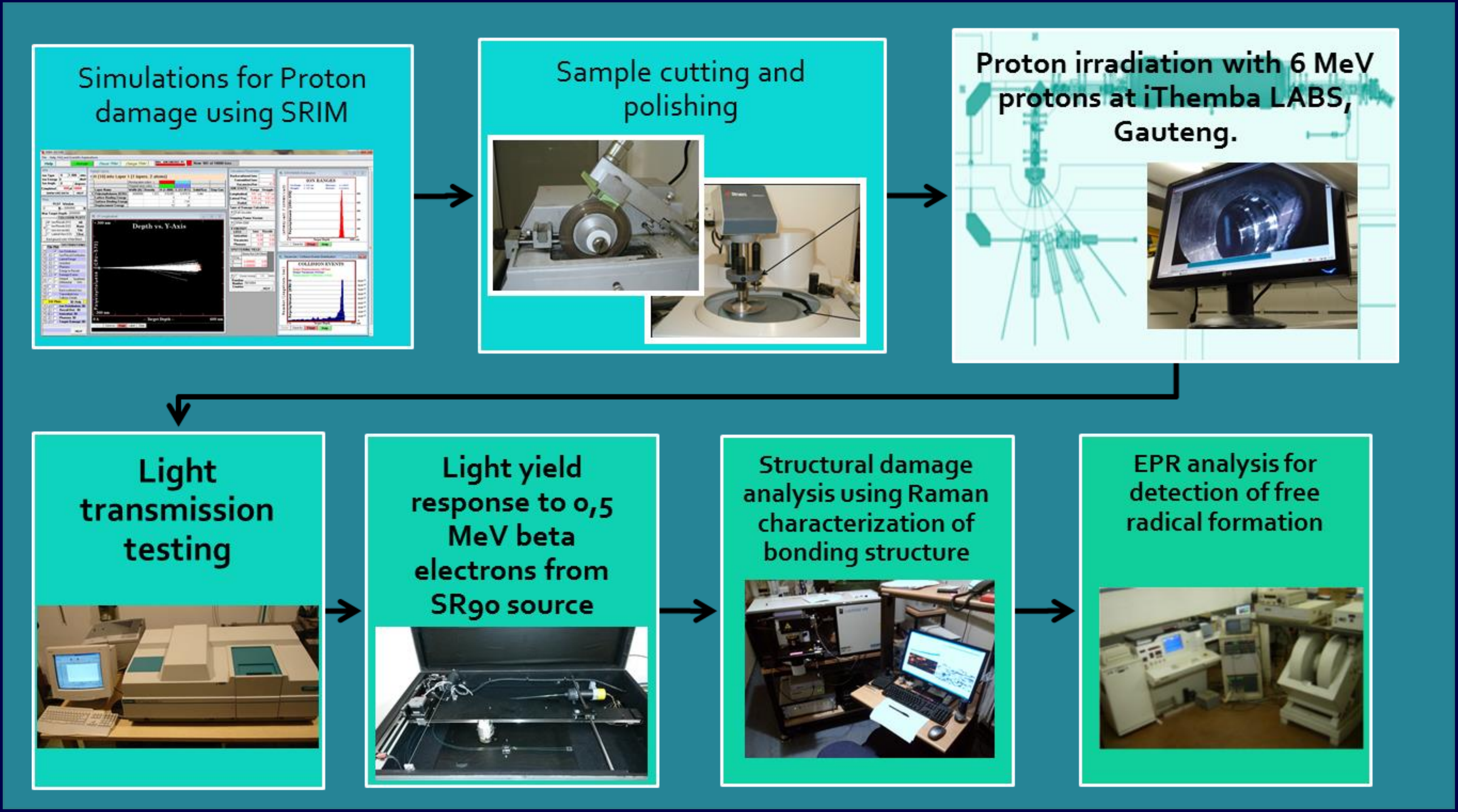
- 5 mm wide sections of each sample were cut using a Bueler Isomet low speed saw with a diamond finished blade.
- Slices of these sections were then cut to ~0.8 mm thickness.



- The samples were then mounted to a holder using carbon tape.
- A fine polishing process was followed using a complementary polishing direction.

- Polished samples were then placed in holders prior to irradiation.

- 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

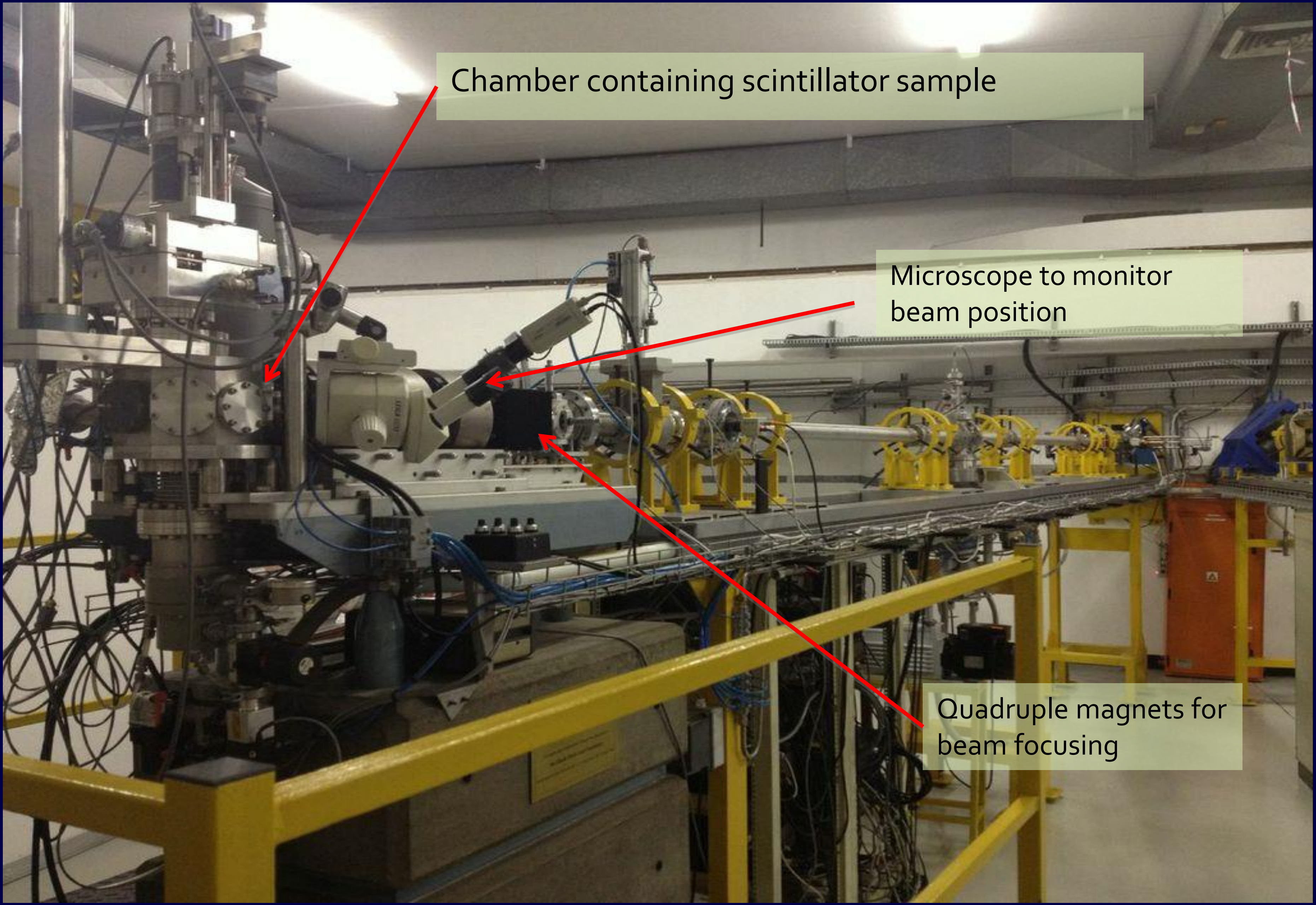
Proton irradiation with 6 MeV protons at iThemba LABS, Gauteng.

Light transmission testing

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

Structural damage analysis using Raman characterization of bonding structure

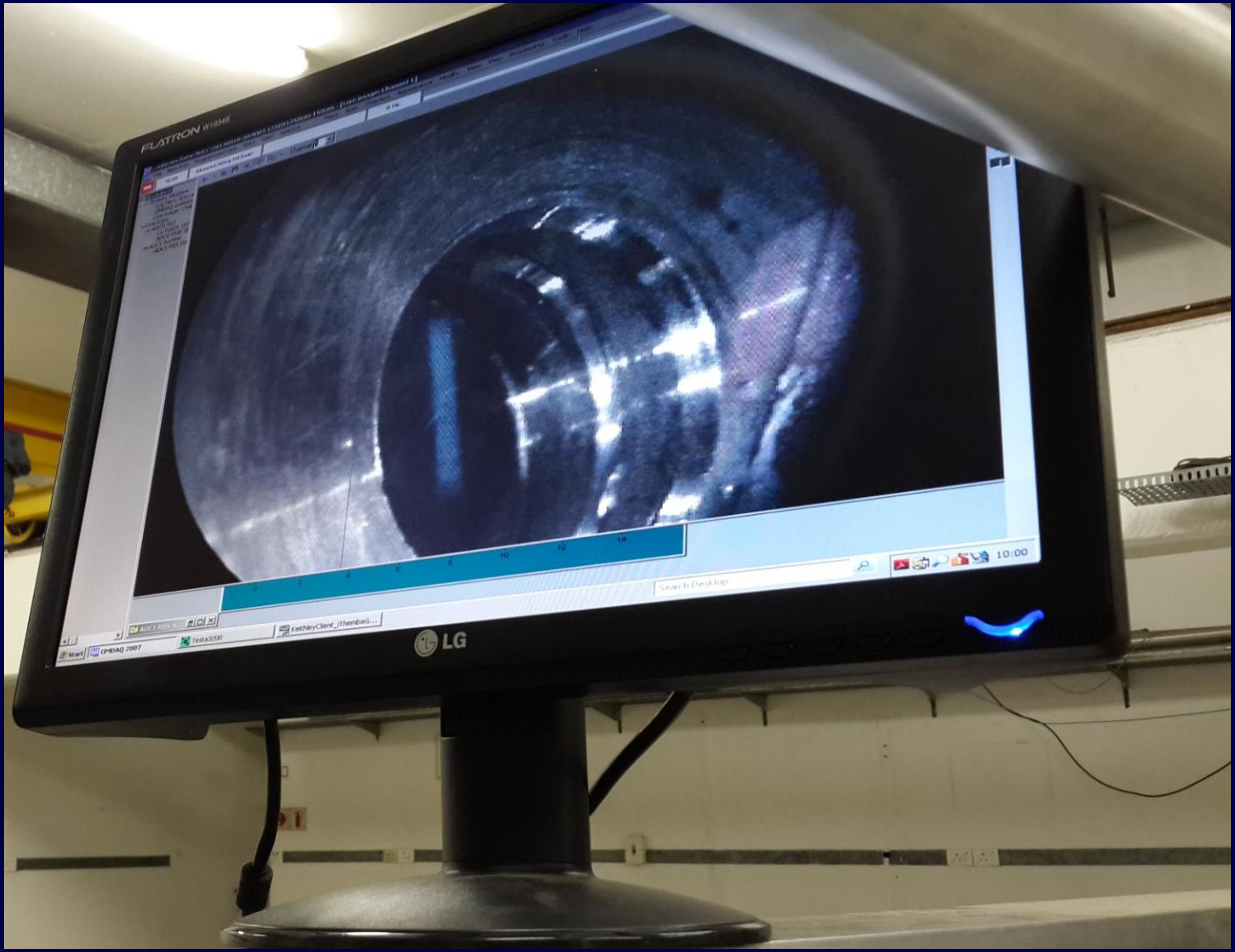
EPR analysis for detection of free radical formation



Chamber containing scintillator sample

Microscope to monitor beam position

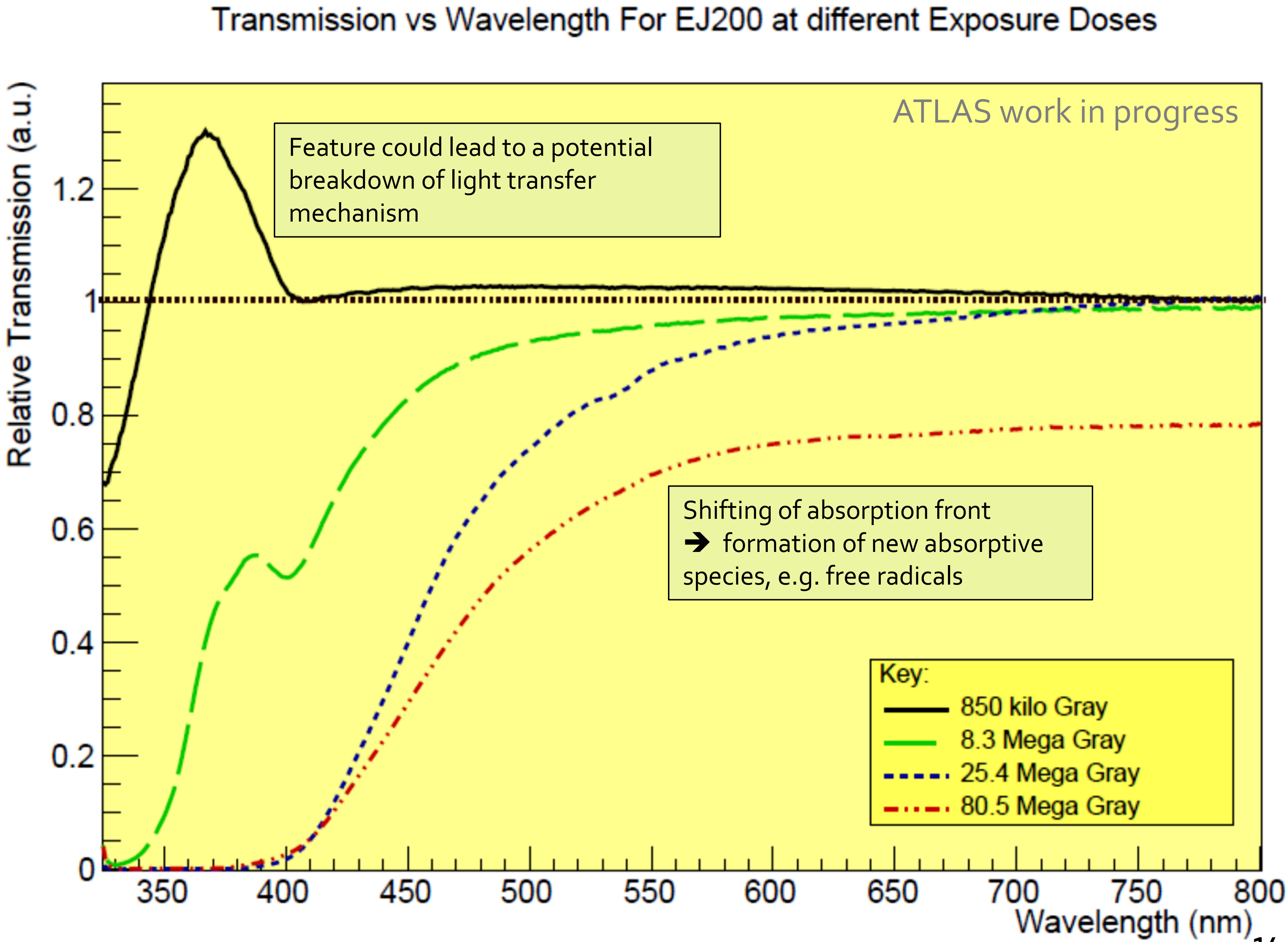
Quadruple magnets for beam focusing



- During irradiation, the proton beam is focused and then scanned in x and y across the sample to achieve an irradiation area of approximately 1.8 mm by 1.8 mm
- Two samples of each grade were irradiated to doses of 80 MGy, 25 MGy, 8 MGy and 800 kGy respectively.

Light Transmission Testing

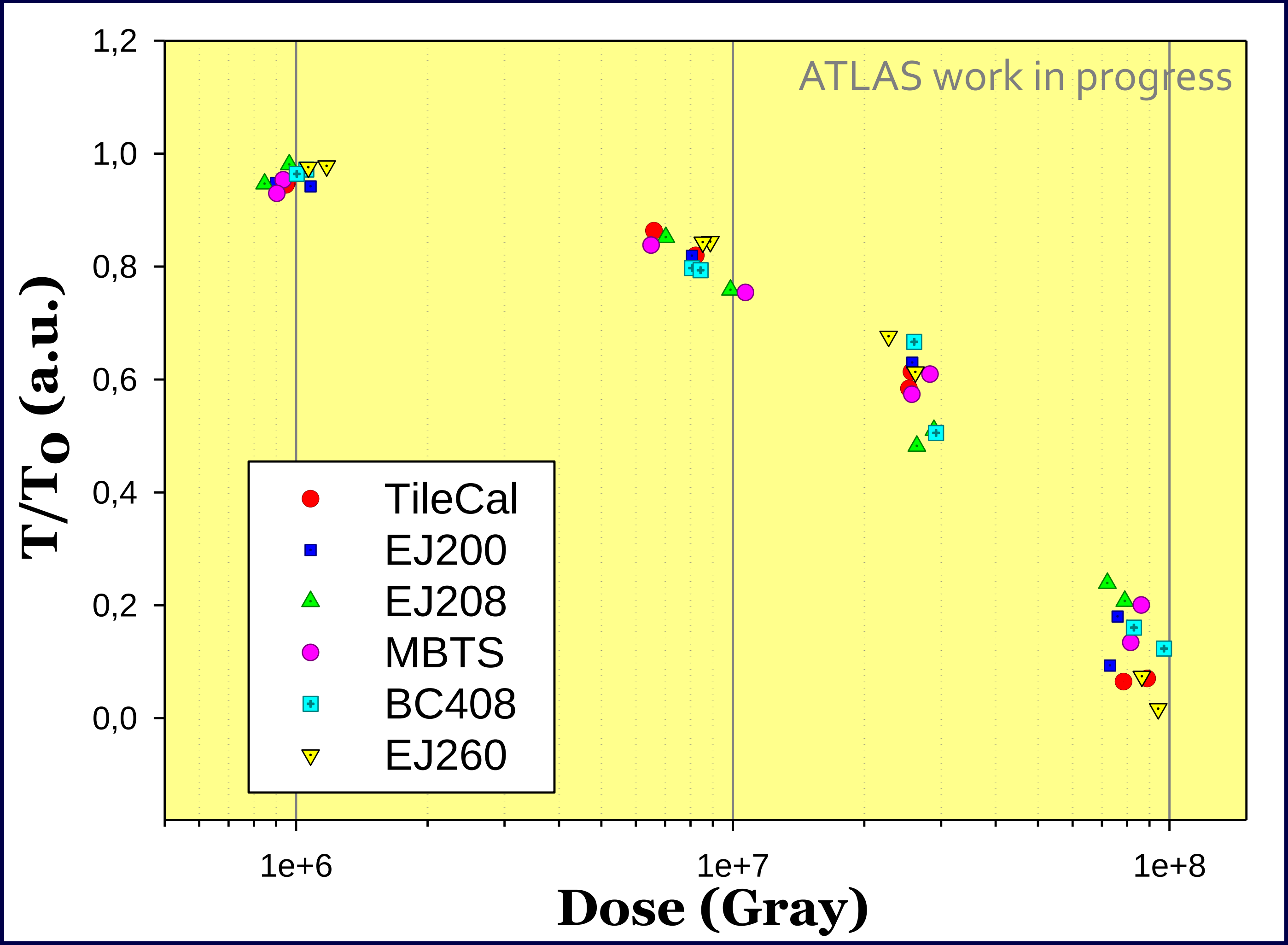
- Conducted using the Varian Cary Spectrophotometer.
- Taken over wavelength range of 200-800 nm.
- Spectra are measured before and after irradiation.
- The ratio of transmission in the irradiated vs unirradiated sample is then taken



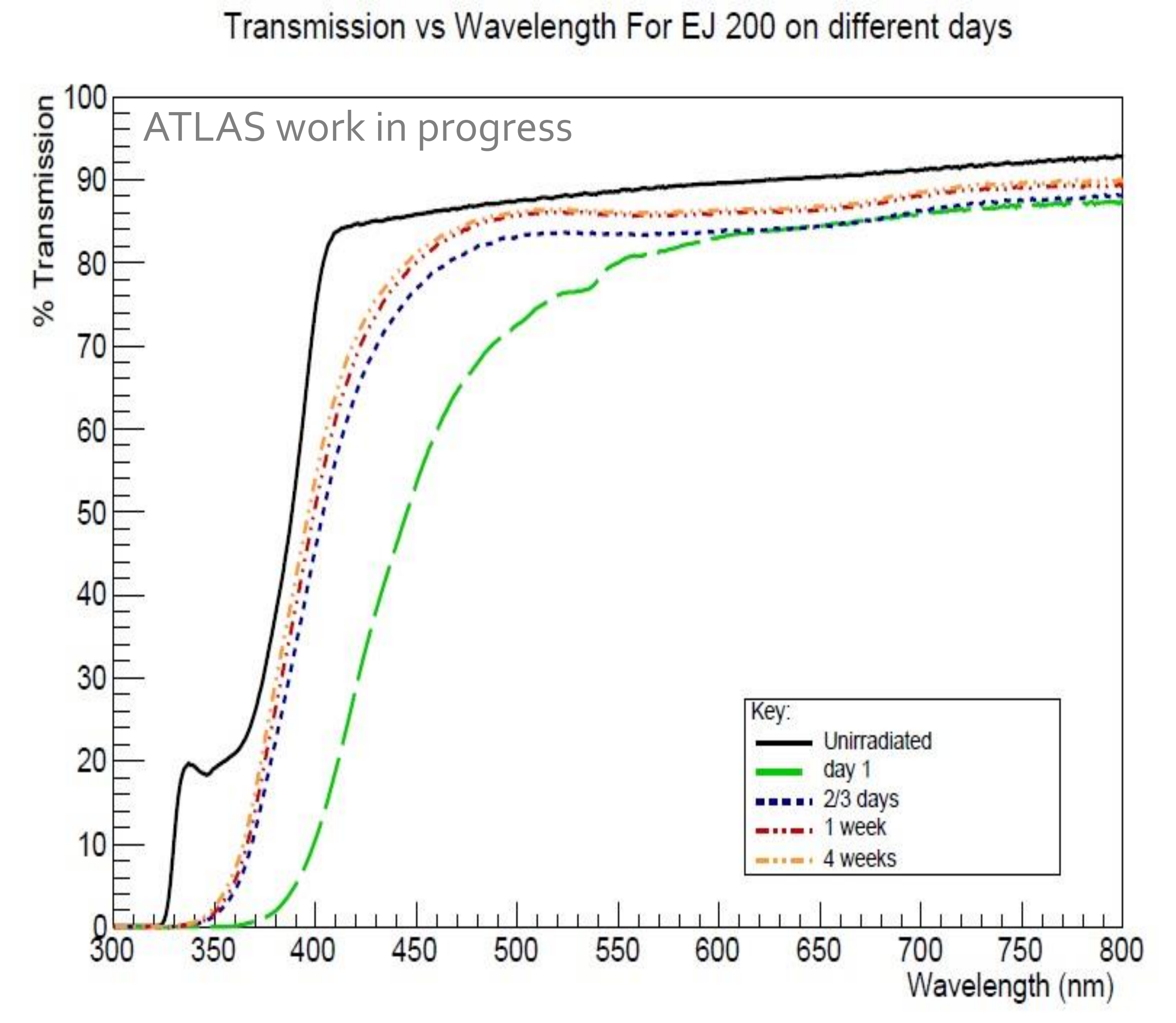
Feature could lead to a potential breakdown of light transfer mechanism

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

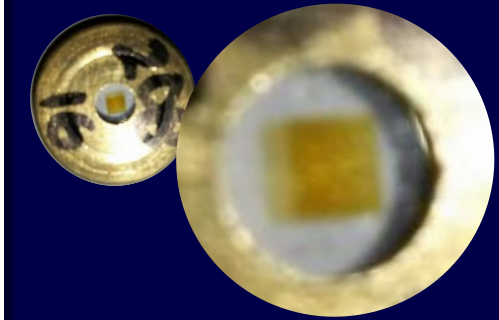
Relative Transmission loss at 420 nm



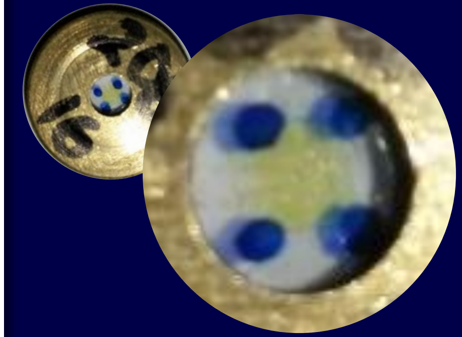
- Consider transmission loss around 420 nm. Wavelength range where blue scintillators typically emit and absorption peaks in Y11 fibers occur.
- EJ208, Bicron and Dubna (MBTS type) perform well.
- For overall transmission loss however, consider collective loss along regions coinciding with absorption regions.



Immediately after irradiation

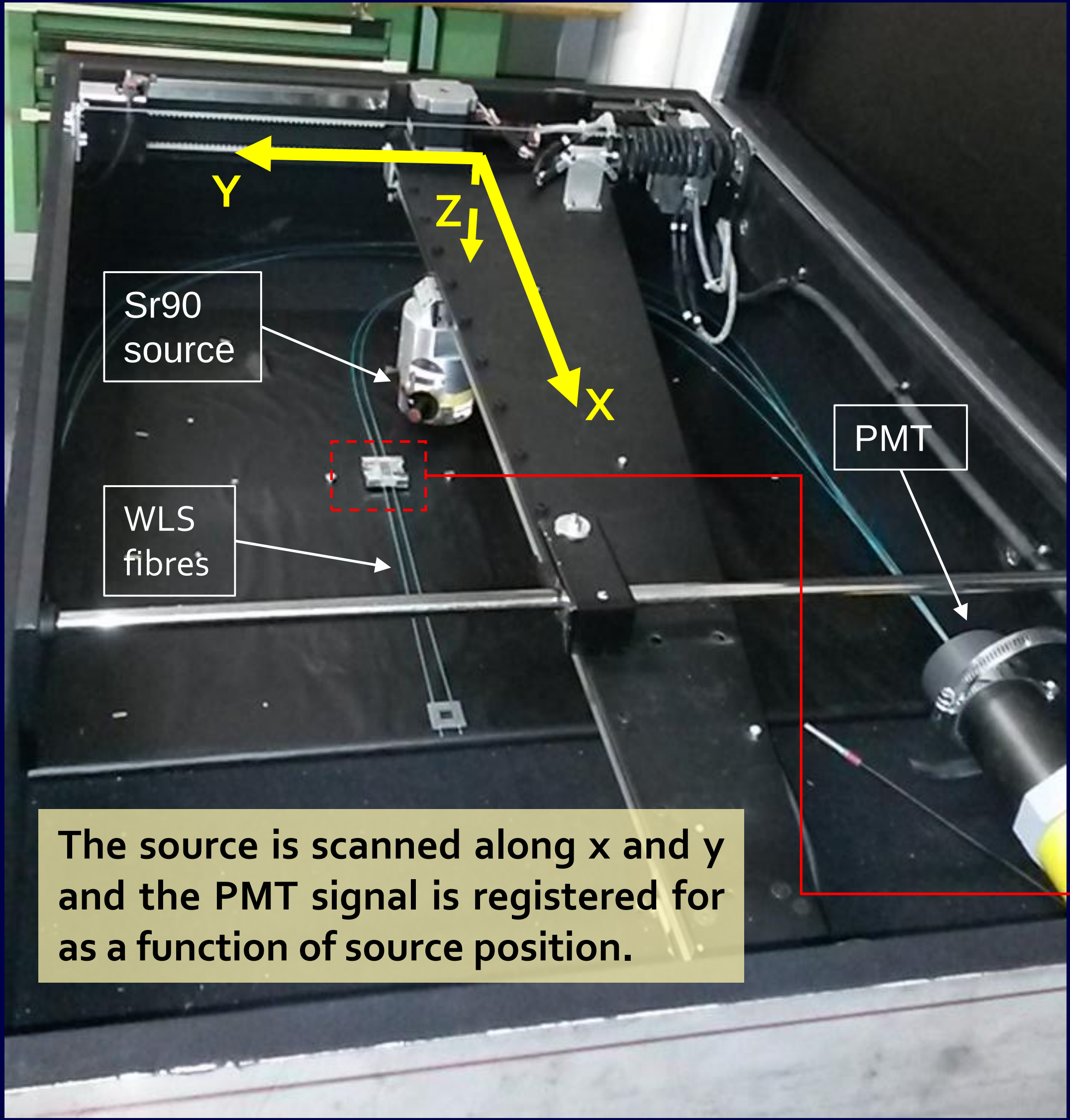


1 day after irradiation



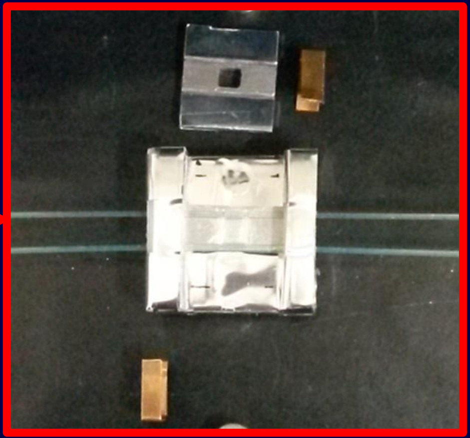
Healing of 25 MGy irradiated EJ200 scintillator sample.
Across all grades, healing occurs exponentially, with the most significant healing occurring overnight. Photobleaching is the likely cause of this healing.

Light Yield Testing



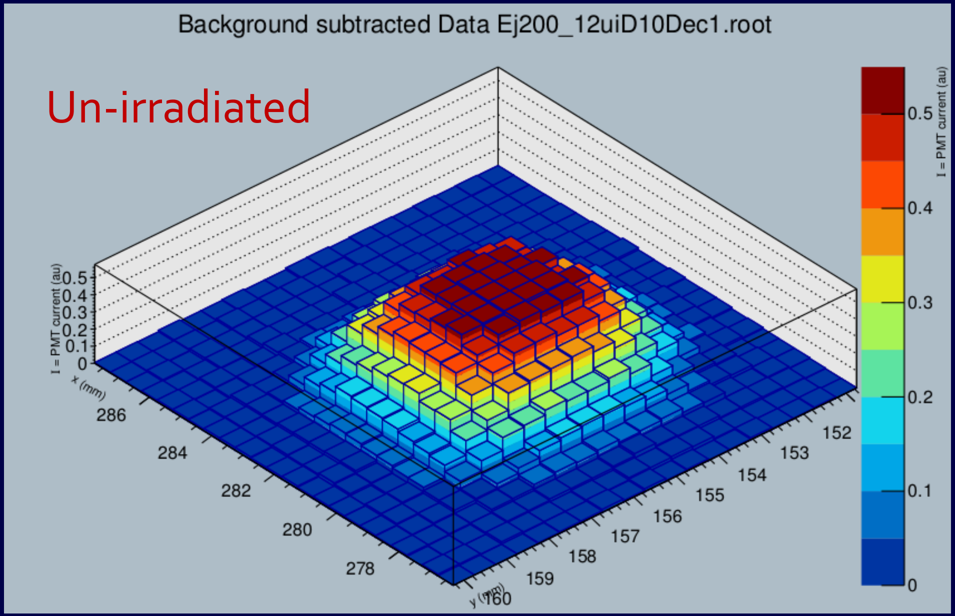
The source is scanned along x and y and the PMT signal is registered for as a function of source position.

- The scintillator light response to 0.5 MeV beta electrons emitted from a Sr90 source were measured using the light box set-up at CERN.
- Two wavelength shifting fibres were coupled along opposite edges of the sample as well as to a photomultiplier.
- Electrons impinge the sample and the integrated PMT response is registered.

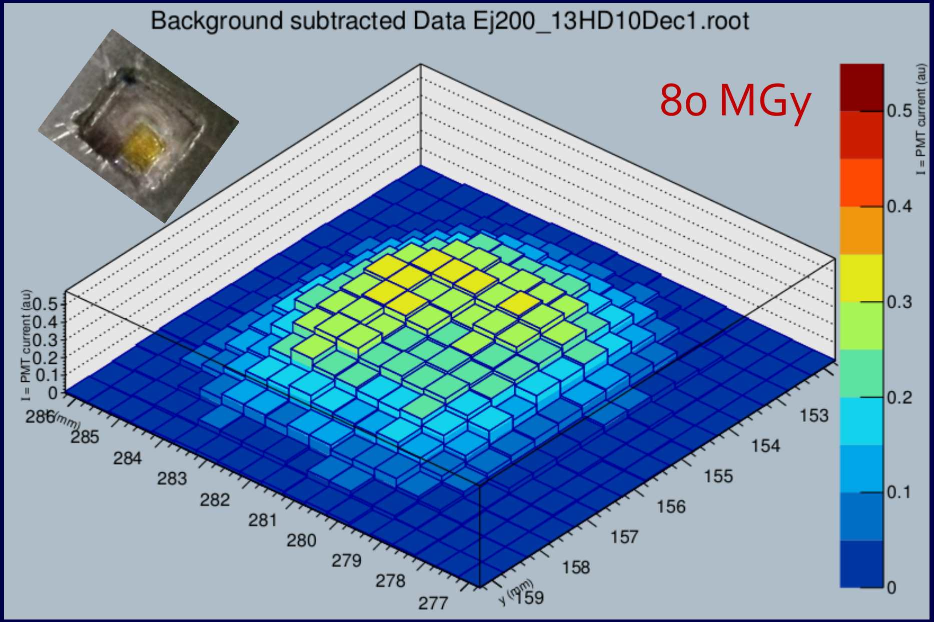


Sample in holder manufactured by Wits

Light Yield Testing


Background subtracted Data Ej200_12uiD10Dec1.root

Un-irradiated


Background subtracted Data Ej200_13HD10Dec1.root

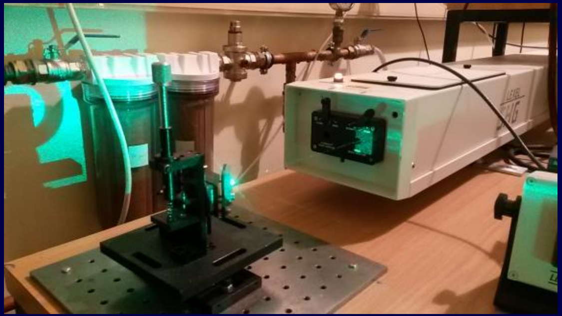
80 MGy

NB: Plots are an ATLAS work in progress

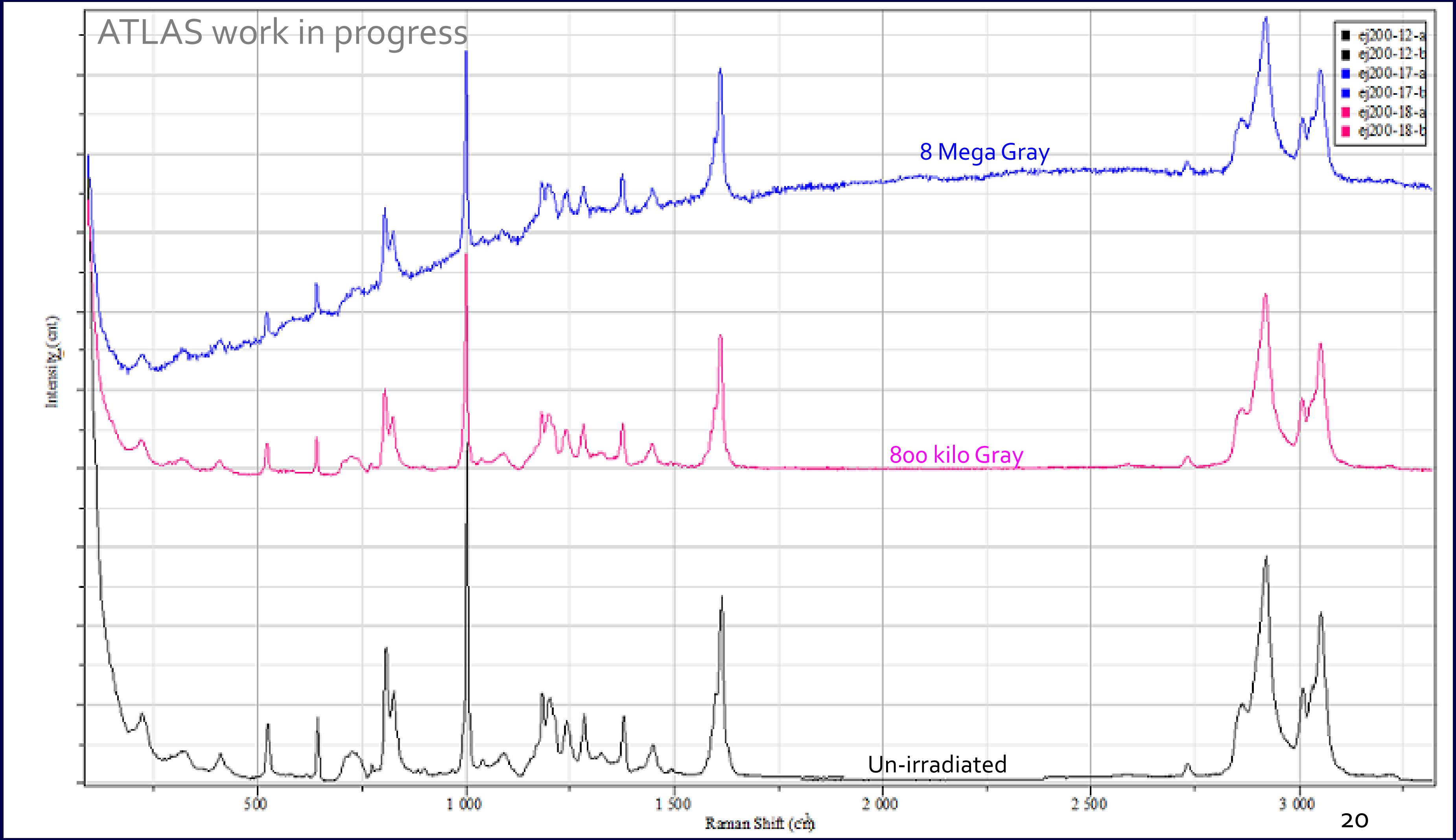
- Some preliminary results
- Can see decrease in overall light response of scintillator
- To gage loss, take ratio between integrated signal in irradiated sample to un-irradiated sample.
- Technique is very sensitive to systematics, therefore will also be testing light yield after UV laser excitation as well

Raman Spectroscopy

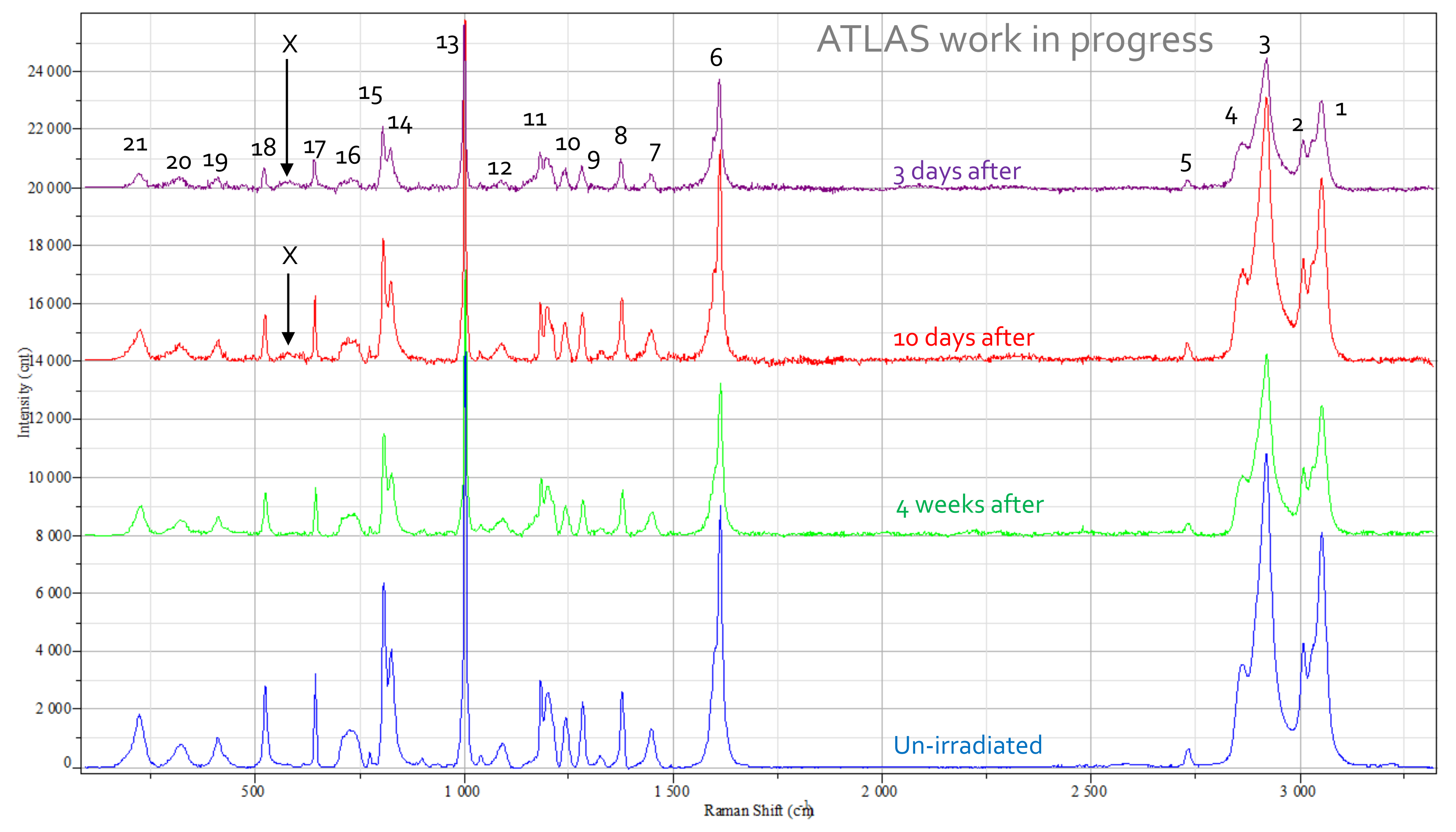
- A 514.53 nm Argon laser excites vibrational modes within the sample.
- These de-excite and release photons of a characteristic wavelength.
- The Raman spectrum obtained corresponds to the intensity of photons detected at various wavelengths
- Indicates vibrational modes and hence bonding structure present in the sample.



- Raman spectroscopy results for EJ200 shown below.
- Background fluorescence increases with dose, because sample absorbs more light at 514 nm with increased dose. (Seen in transmission spectra)
- NB: The various spectra overlap but I added a constant to the 800 kGy and 8MGy spectra for visual impact

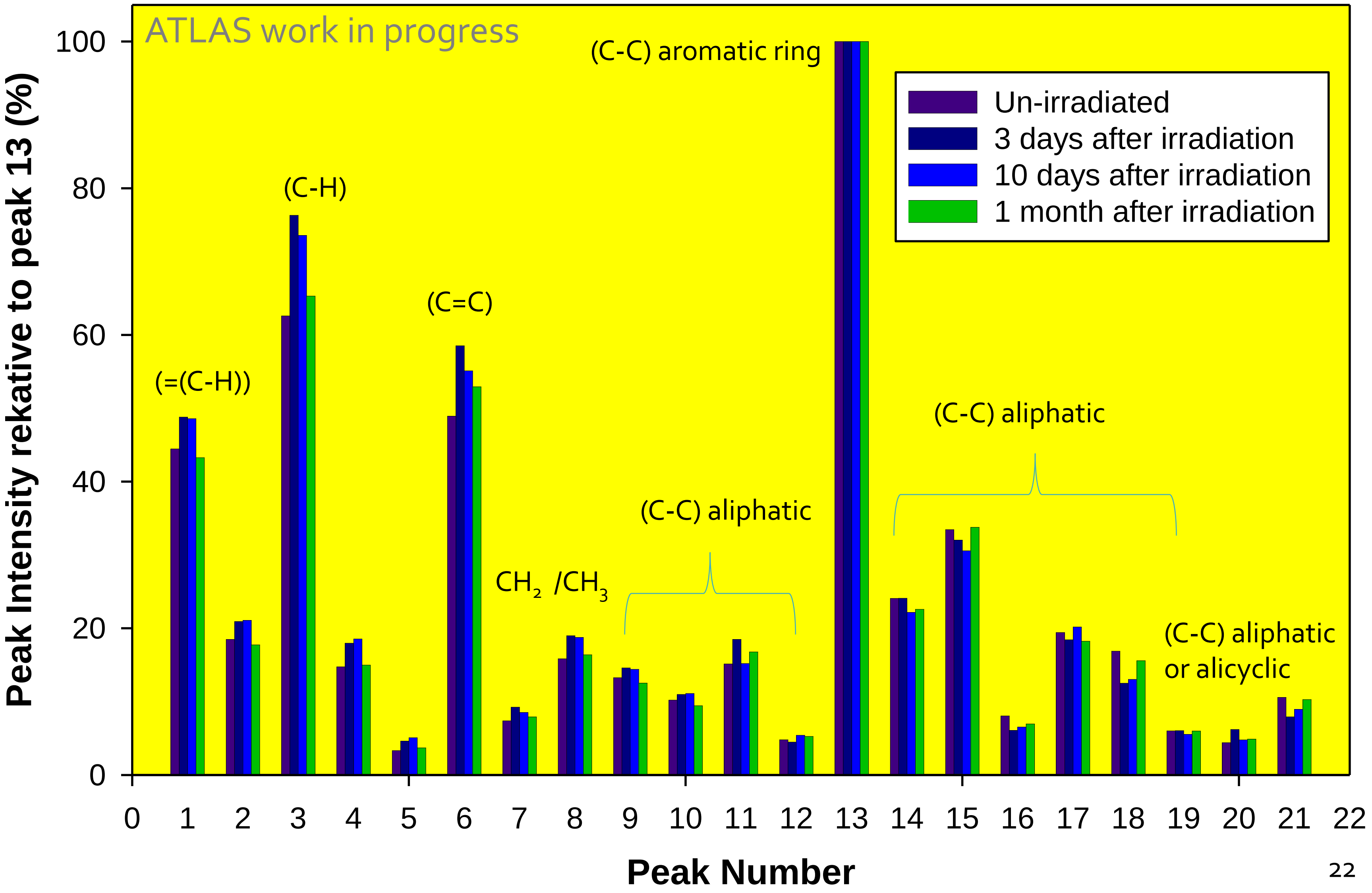


Background subtracted Raman spectra for EJ200 taken over consecutive days after irradiation to 8 Mega Gray:



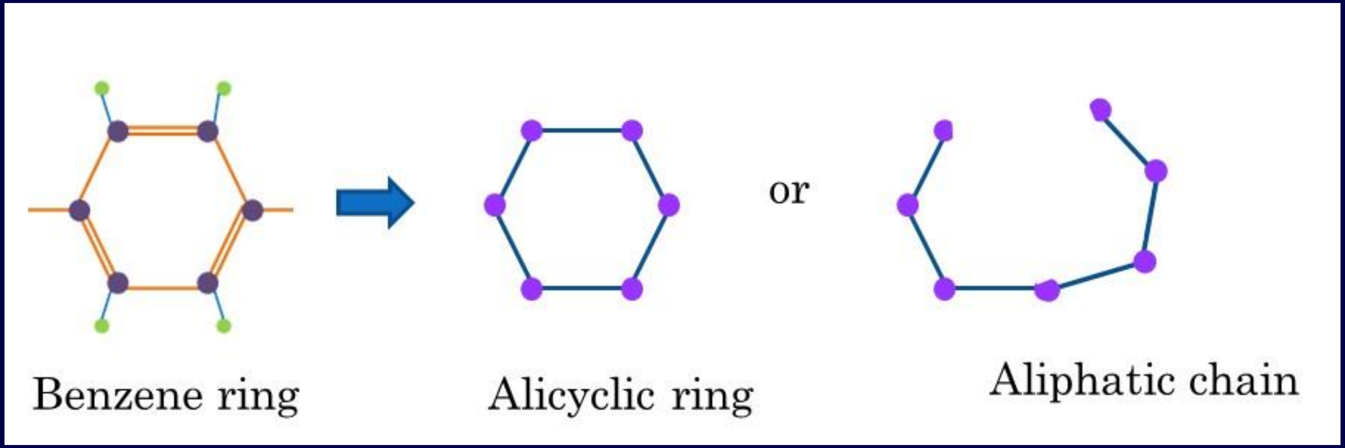
δ(C-C) aliphatic	20-21	**δ(CH_2) or δ(CH_3)asymmetric**	7
ν(C-C) alicyclic or aliphatic chain vibrations	9-12, 14-19, X	**ν(C=C)**	6
ν(C-C) aromatic ring chain vibrations	13	**ν(C-H)**	3-4
δ(CH_3)	8	**ν(=(C-H))**	1-2

The percentage of each peak's intensity to that of peak 13 gives an indication of the changes to the population of that functional group relative to the population of aromatic rings.



Implications of the Raman Results

- There is a small change in the specie content after irradiation. The scintillator heals significantly 4 weeks after irradiation
- Damage occurs to the benzene ring. As a result of the CH type bonds breaking, hydrogen lost from the benzene ring could be lost to free radicals.

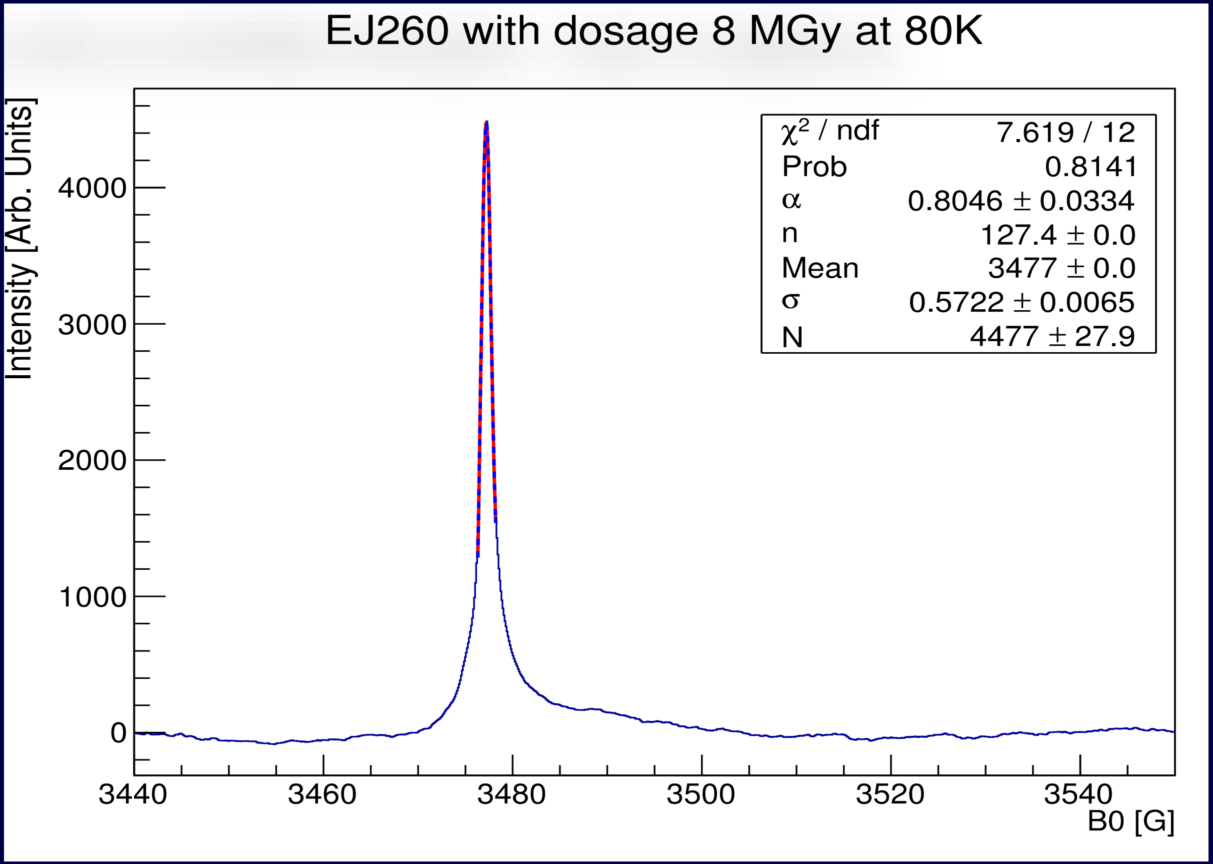


- Damage to the benzene ring directly affects the scintillation mechanism.
- EPR studies will give us a better idea of the structural damage undergone as free radicals may form when these bonds break.

Electron Paramagnetic studies

We study unpaired electrons in the plastic scintillators using EPR, by placing them in a large magnetic field and applying a resonant frequency that satisfies:

$$\Delta E = h\omega_0 = g\mu_B B_0.$$


EJ260 with dosage 8 MGy at 80K

From the value of the magnetic field at the peak, the g-factor can be computed using:

$$g = 2\pi\omega_0 \frac{m_e}{eB_0}$$

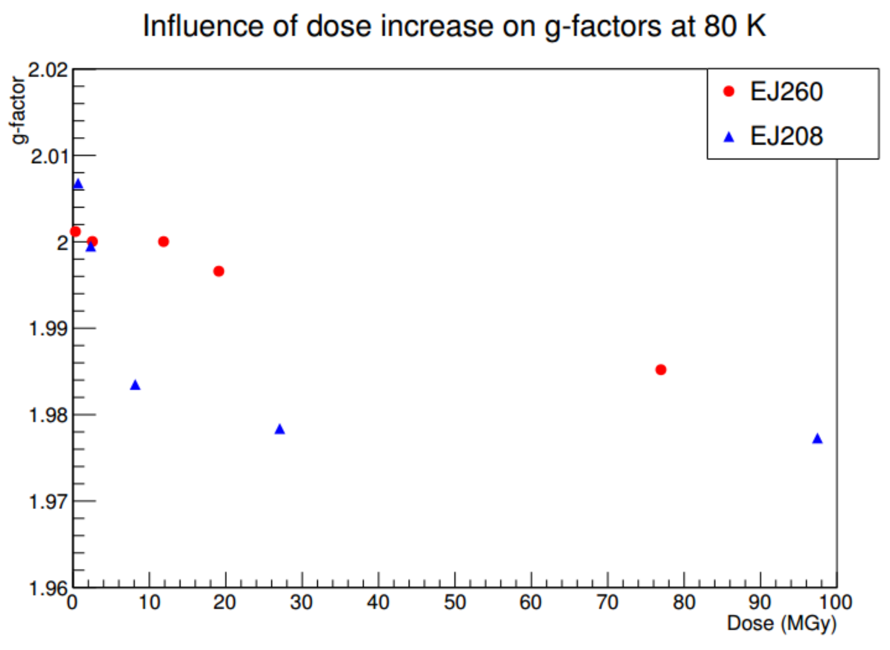
The spin density can be computed using the following equation:

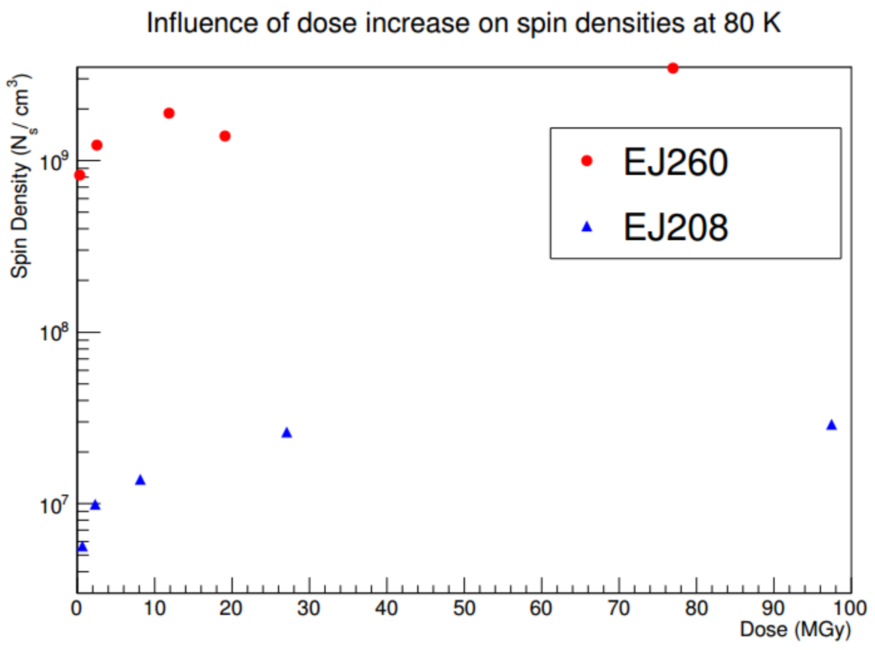
$$\int \frac{EPR\ Spectrum}{volume\ of\ sample}$$

EPR Results and Analysis

The g-factor tells us about the environment the unpaired electrons see. With an increase in dosage, the g-factor changes from that of the un-irradiated plastics.

The spin density gives an indication of the number of unpaired electrons in each sample. This increases as dosage is increased.





Summary

- Radiation damage in PVT and PS based scintillators subjected to proton damage is under study.
- Radiation damage at a lower dose of 800 kilo Gray causes damage to the light transfer mechanism between base and dopants. Structurally very little change is observed.
- At higher doses, an absorptive tint forms shifting to higher wavelengths and transmission decreases with increasing dose.
- Damage to the benzene ring is noted in these higher doses.
- The formation of free radicals could cause the additional absorption of light and the scintillator becomes less transparent to it’s own scintillation light. This results in a larger background fluorescence at higher wavelengths.
- A significant amount of healing is observed both in the transmission spectra and in the structural recombination seen from the Raman data 4 weeks after irradiation.
- EPR studies will give us a better indication of the free radicals formed by the damage.

Funding Acknowledgements

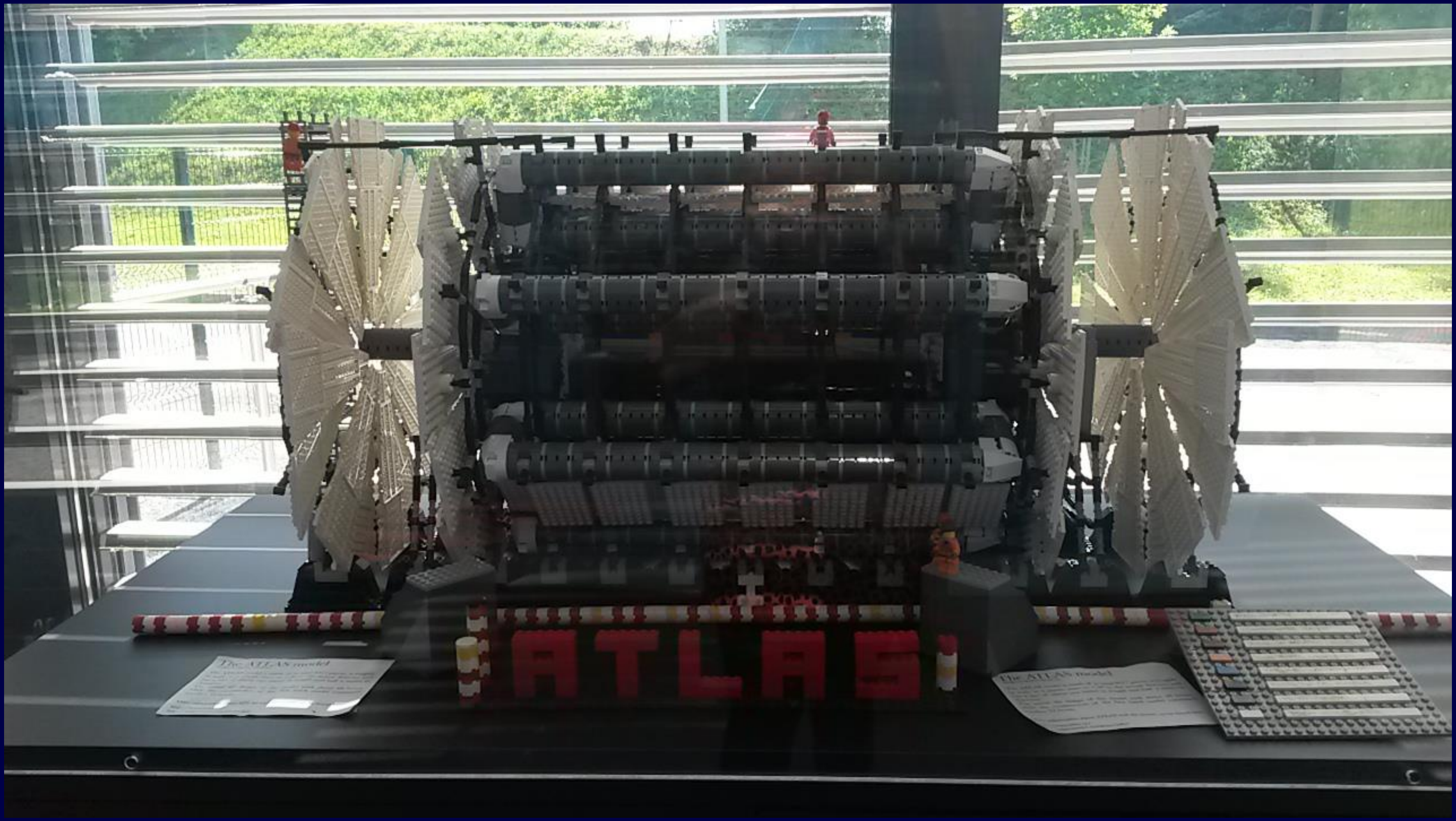
DST-NRF CENTRE OF EXCELLENCE • IN STRONG MATERIALS •

UNIVERSITY OF THE WITWATERSRAND
SCIENTIA ET LABORE
JOHANNESBURG

NRF National Research Foundation

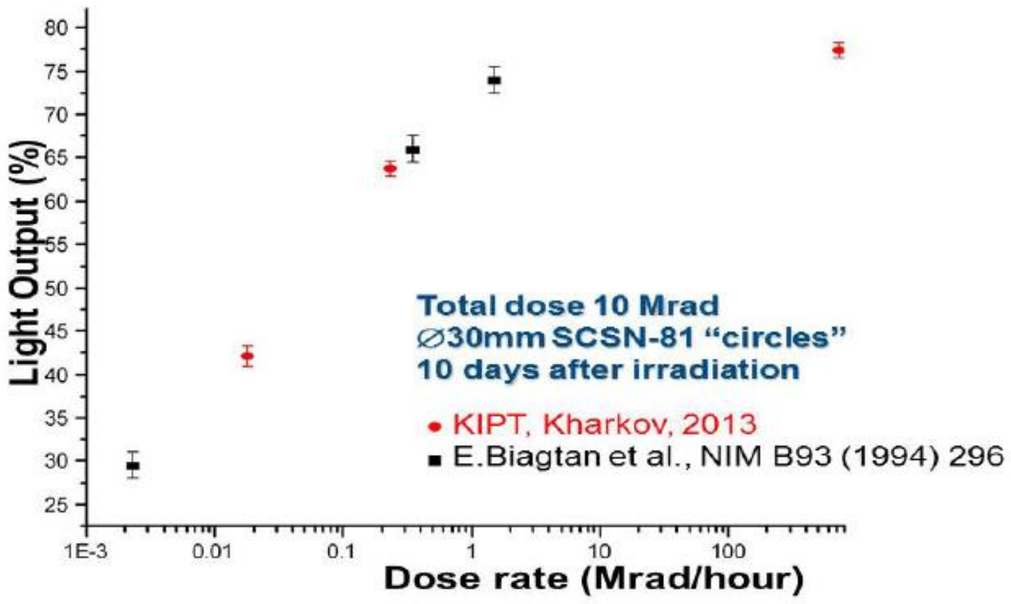
CERN

Thank You for your time…

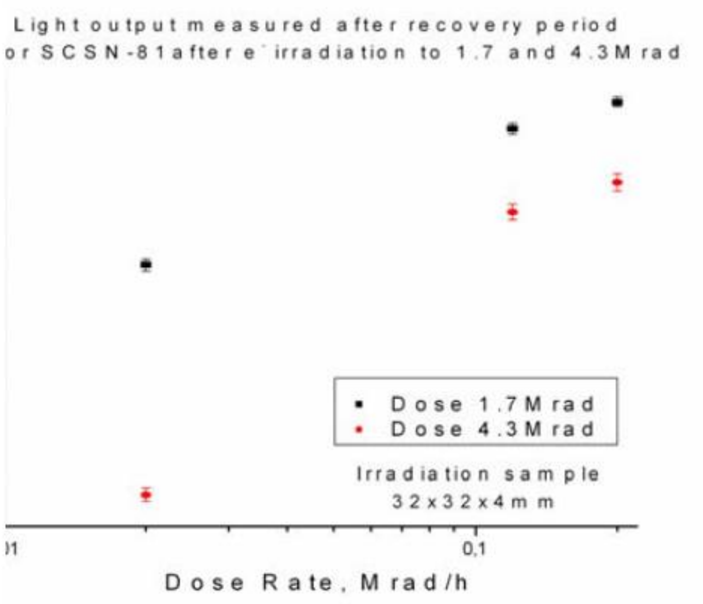


Back Up

Affect of dose rate on damage



a)

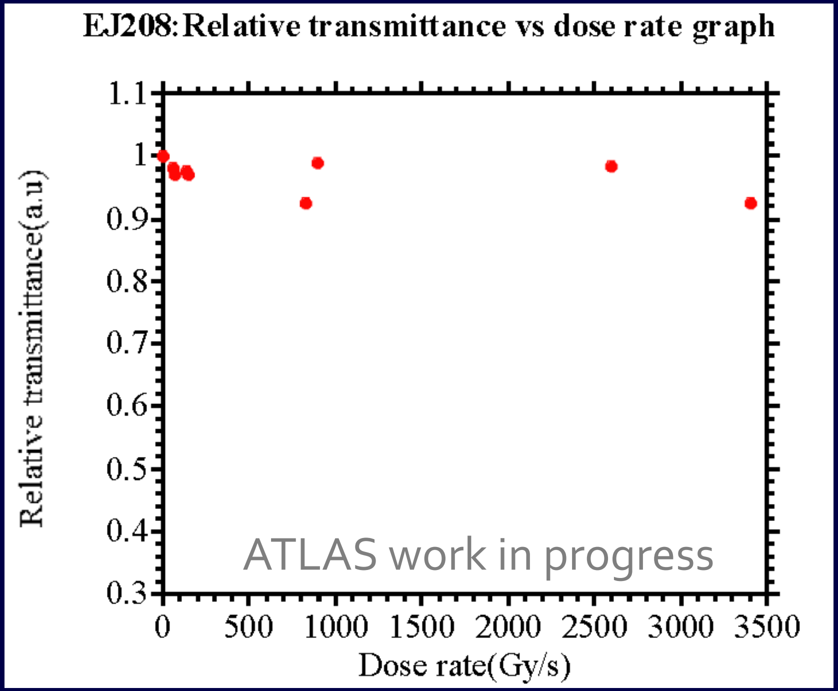


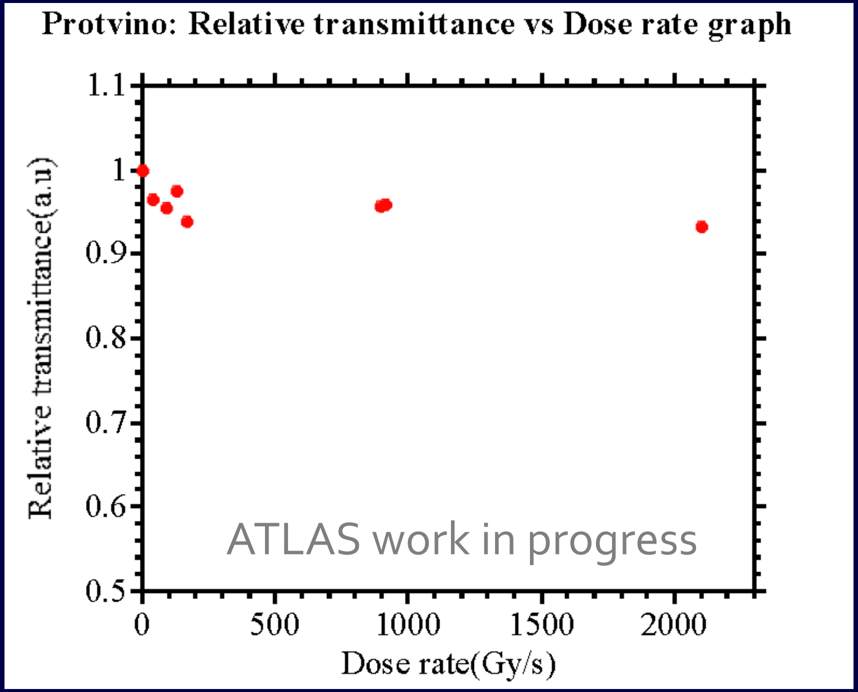
b)

- Study conducted by CMS which looked at the effect of irradiation dose rate on light degradation.
- Reference: CMS NOTE 2014/001 *"HE upgrade beyond phase 1. Finger scintillator*
- *option."* and CMS NOTE 2014/003 *"Experimental study of the plastic scintillator damage caused by radiation on IREN at JINR."*
- Our studies were conducted with large dose rates → may therefor see less damage.
- Hence conducted an investigation into the effect of dose rate on damage.

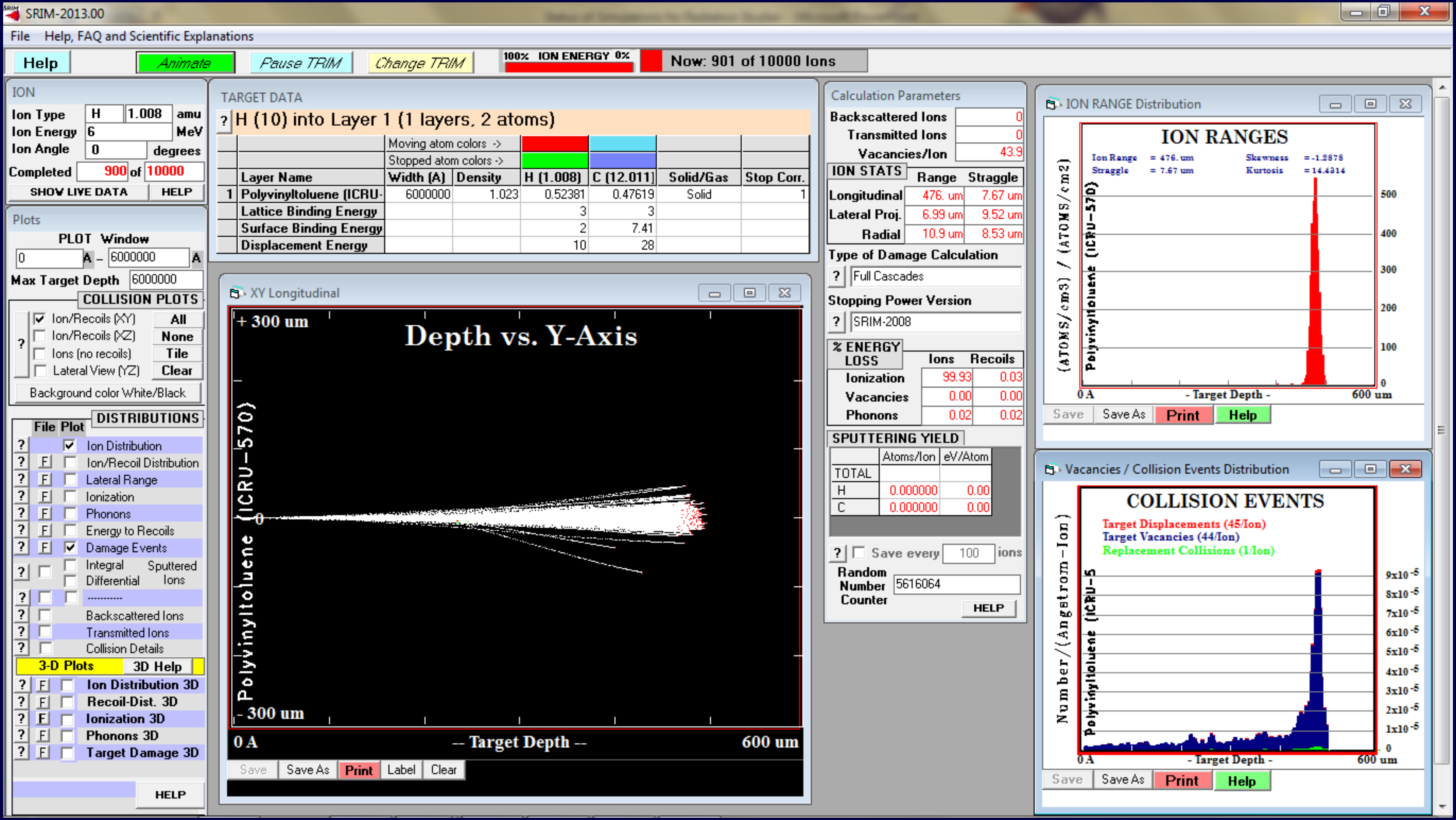
Effect of irradiation dose rate on damage in EJ208 and Protvino

- 8 samples per grade irradiated to dose of 1 MGy with dose rates of approx 50 Gy/s, 150 Gy/s, 750 Gy/s and 3kGy/s
- Found that varying dose rate did not affect damage to the scintillator transparency at a dose of 1 MGy. The effect on light yield is still to be tested however.





Simulating proton damage in plastic scintillators using TRIM



Now: 901 of 10000 Ions

ION

Ion Type: H 1.008 amu

Ion Energy: 6 MeV

Ion Angle: 0 degrees

Completed 900 of 10000

PLOT Window: 0 A – 6000000 A

Max Target Depth: 6000000

☑ Ion/Recoils (XY)
☐ Ion/Recoils (XZ)
☐ Ions (no recoils)
☐ Lateral View (YZ)

? ☑ Ion Distribution
? F ☐ Ion/Recoil Distribution
? F ☐ Lateral Range
? F ☐ Ionization
? F ☐ Phonons
? F ☐ Energy to Recoils
? F ☑ Damage Events
? ☐ Integral / Differential — Sputtered Ions
? ☐ Backscattered Ions
? ☐ Transmitted Ions
? ☐ Collision Details
? F ☐ Ion Distribution 3D
? F ☐ Recoil-Dist. 3D
? F ☐ Ionization 3D
? F ☐ Phonons 3D
? F ☐ Target Damage 3D

TARGET DATA

? H (10) into Layer 1 (1 layers, 2 atoms)

	Layer Name	Width (A)	Density	H (1.008)	C (12.011)	Solid/Gas	Stop Corr.
	Moving atom colors ->			🟥	🟦		
	Stopped atom colors ->			🟩	🟦		
1	Polyvinyltoluene (ICRU-	6000000	1.023	0.52381	0.47619	Solid	1
	Lattice Binding Energy			3	3		
	Surface Binding Energy			2	7.41		
	Displacement Energy			10	28		

Calculation Parameters

Backscattered Ions: 0

Transmitted Ions: 0

Vacancies/Ion: 43.9

ION STATS	Range	Straggle
Longitudinal	476. um	7.67 um
Lateral Proj.	6.99 um	9.52 um
Radial	10.9 um	8.53 um

Type of Damage Calculation: Full Cascades

Stopping Power Version: SRIM-2008

% ENERGY LOSS	Ions	Recoils
Ionization	99.93	0.03
Vacancies	0.00	0.00
Phonons	0.02	0.02

SPUTTERING YIELD

	Atoms/Ion	eV/Atom
TOTAL		
H	0.000000	0.00
C	0.000000	0.00

? ☐ Save every 100 ions

Random Number Counter: 5616064

- TRIM (Transport of Ions in Matter) simulations were run to predict the stopping range of 6 MeV protons through PVT.

Light yield testing currently being set-up

- Will encompass a Sr90 radio-active source housed in a lead container with a collimated outlet.
- Sample will be mounted on a holder attached to the lead container.
- Spectrometer will detect light emitted by the scintillator in response to 0,5 MeV beta particles emitted by source.
- Set-up will be housed in light tight box.