# Stem effect removal in real time monitoring of therapy beams by $Eu^{3+}$-doped scintillating fibers

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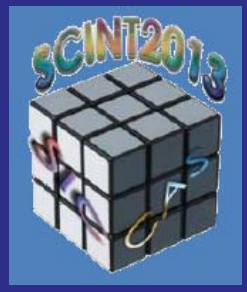


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# Real time *in-vivo* dosimetry

❖ It is a new challenging methodology in the medical dosimetry field

❖ It is necessary to ensure beam quality of new medical irradiation systems and to precisely control dose levels to patients

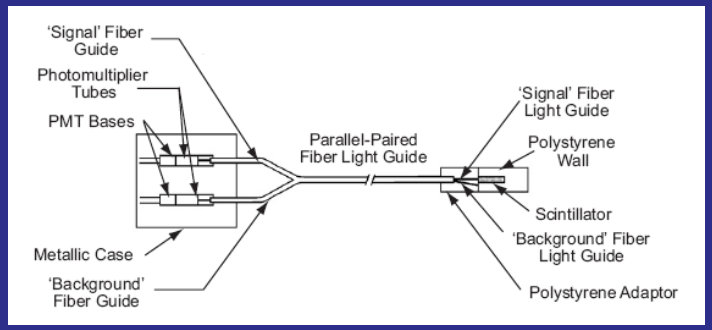
❖ Optical fibre based radioluminescence (RL) dosimeters are a promising option for these purposes

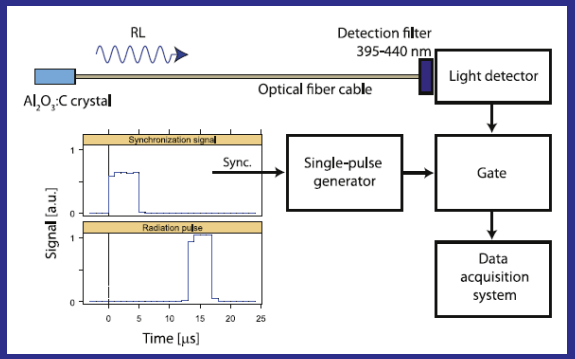
❖ However they can be affected by spurious luminescence (stem effect) due to emissions from defects and/or to Cerenkov light

# Available methods for removing the stem effect

- Second (reference) fibre

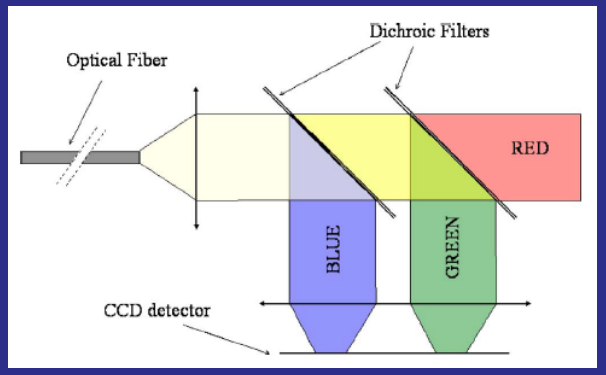
***(Beddar et al. 2007)***



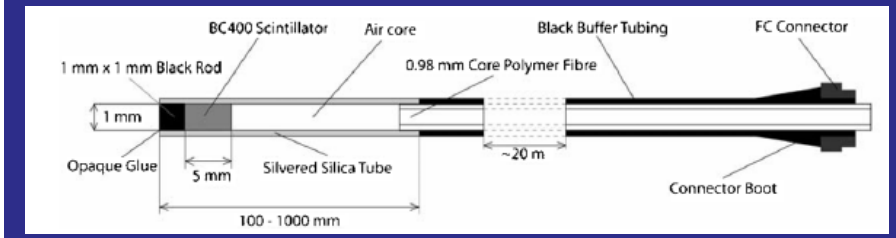

- Temporal gating

***(Andersen et al. 2011)***




- Optical filtration and chromatic analysis

***(Frelin et al. 2005)***



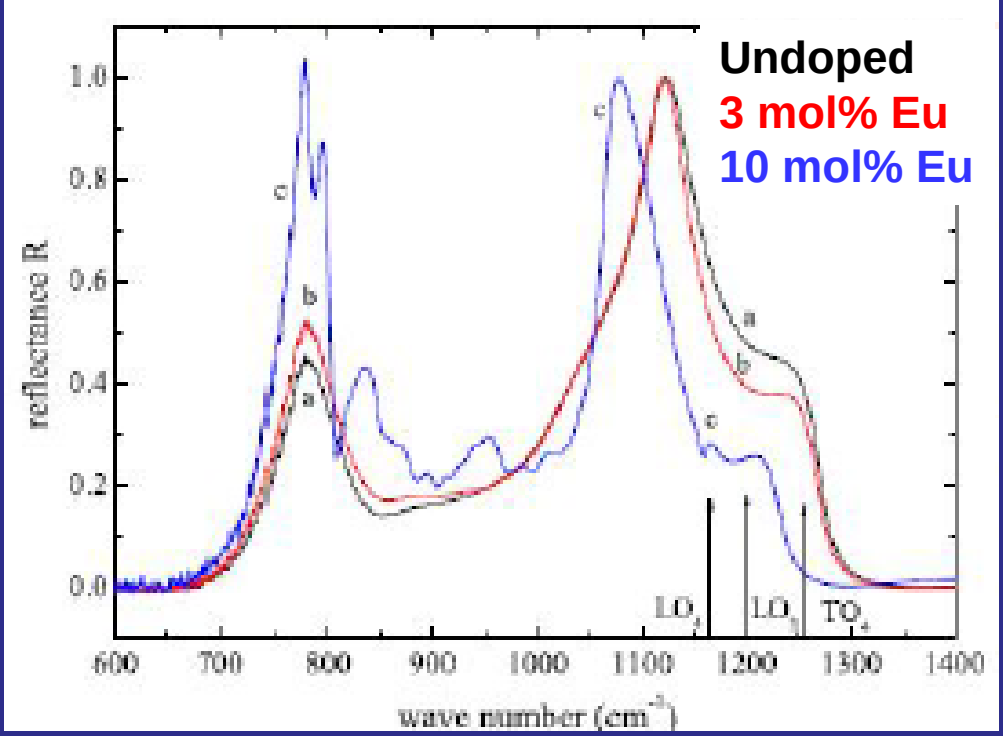

- Air core light guide

***(Lambert et al. 2008)***

# Objectives

- To investigate **the incorporation and luminescence properties** of $Eu^{3+}$ in sol-gel silica
- To study the spectral emission of **$Eu^{3+}$ doped silica optical fibres** under irradiation with photons and electrons of different energies, field sizes and orientations
- To discover the origin of **stem effect** and evaluate its influence on the RL spectral shape under different experimental conditions
- To set up and validate **a novel method** for removing the stem effect, based on RL spectral analysis

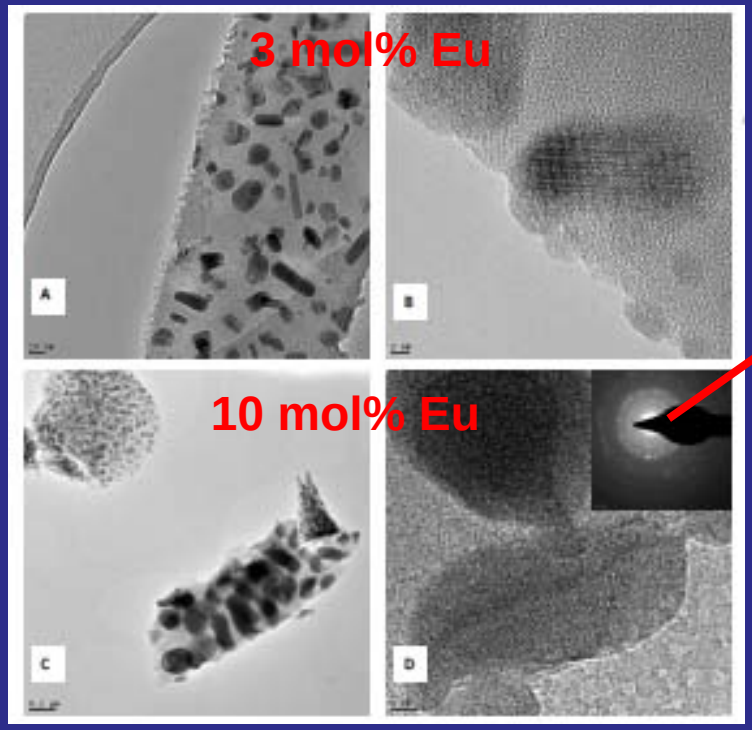
# $Eu^{3+}$ in silica: vibrational properties and evidence of clustering at high concentrations

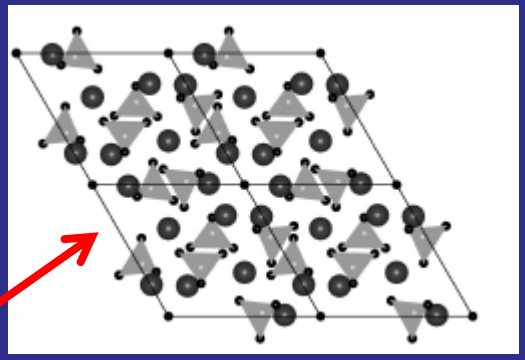



RT microreflectance spectra of $SiO_2$ glasses

Peaks at 780 and 1120-1250 cm-1 due to the bending and asymmetric stretching modes of O-Si-O groups. For $SiO_2$:10mol% (c) new peaks appear in the 860-950 $cm^{-1}$ range which may be attributed to vibrations within $Eu^{3+}$ rich clusters

# $Eu^{3+}$ in silica: morphology and structure

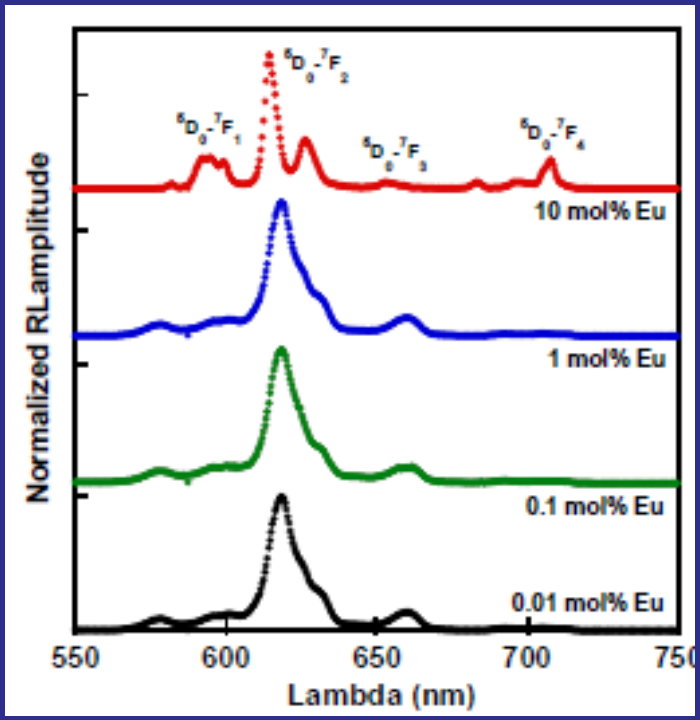


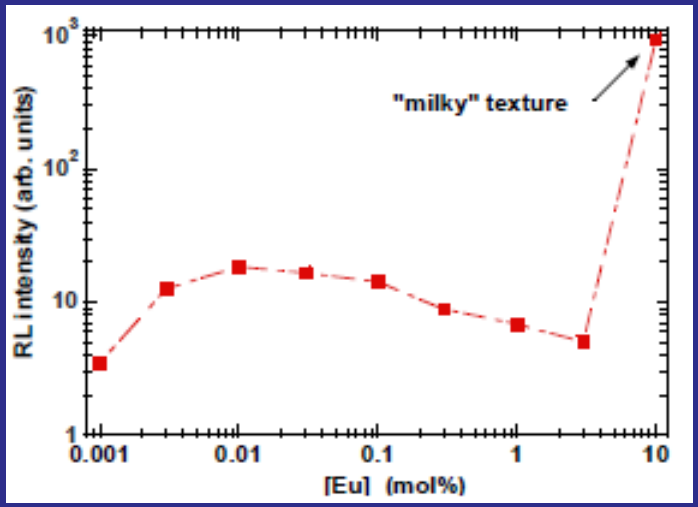
TEM measurements performed on doped glasses and schematic sketch of the $Eu_{4.67}O(SiO_4)_3$ crystalline structure along [001]

Presence of aggregates of increasing dimensions by increasing Eu concentration. At the highest magnification crystalline regions are observed in both samples. The diffraction pattern in the case of 10mol% $SiO_2$:$Eu^{3+}$ is in agreement with that of a rare earth oxide silicate with composition $Eu_{4.667}O(SiO_4)_3$, hexagonal structure and space group $P6_3/m$.

# $Eu^{3+}$ in silica: radioluminescence properties




RL spectra of $SiO_2$:Eu



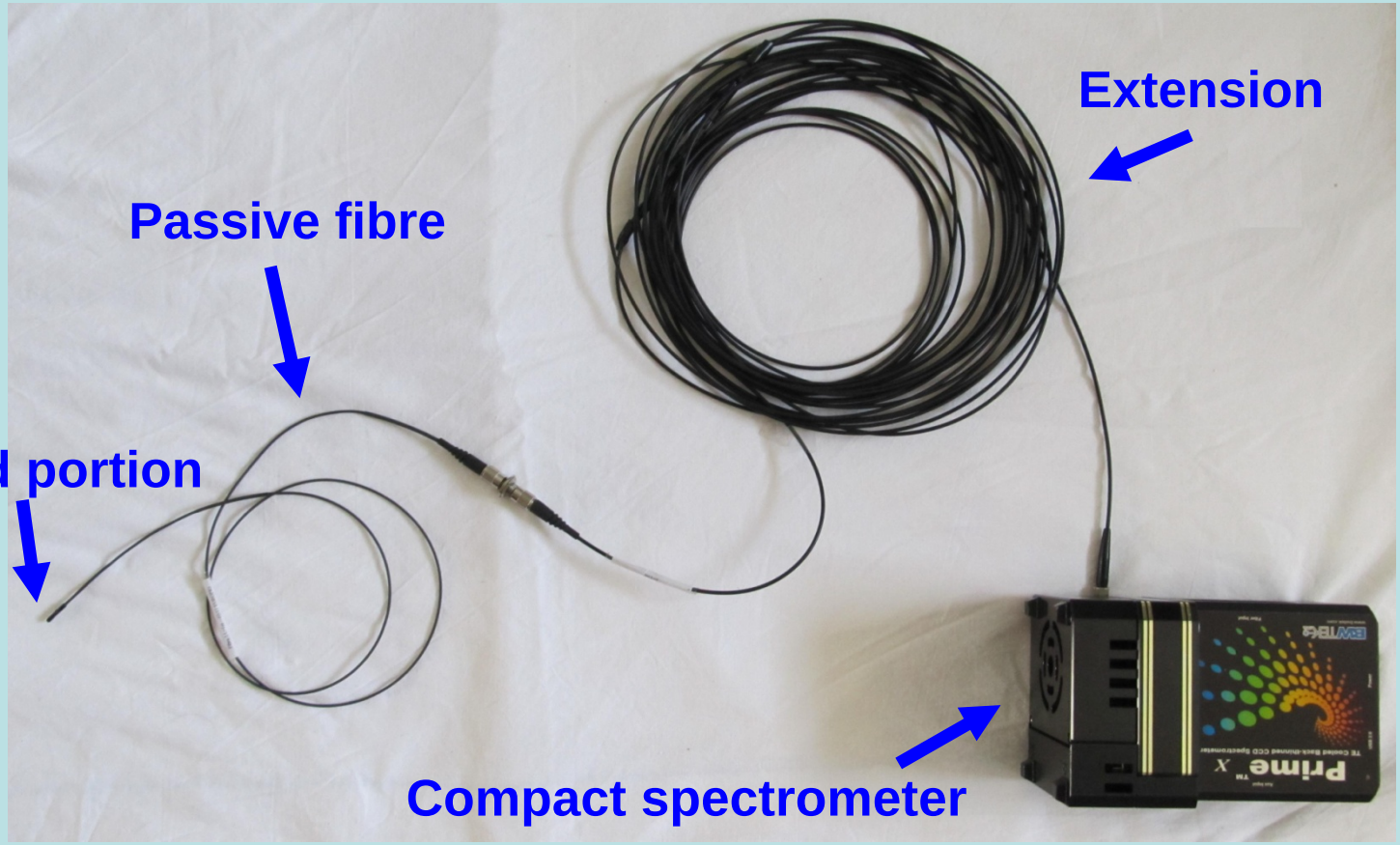

RL intensity versus Eu concentration (integration of RL signals in the 550-750 nm interval).The dashed line is a guide for eyes.

RL spectra feature $^5D_0$-$^7F_J$ transitions of $Eu^{3+}$. Cluster crystallization occurring mainly for $SiO_2$:10mol%Eu causes line narrowing . Strong increase of luminescence efficiency is also observed. However crystallized samples have a milky texture and present cracks. They are not suitable for fibre drawing.

## Methods: the dosimetric system

- Portion of a silica optical fibre, developed using the sol-gel method, doped with Eu (dopant concentration 600 ppm, diameter ~ 200 μm, length 1 cm)
- Passive fibre: 1 m commercial fibre and an additional 15 m long passive fibre extension
- Compact thermoelectric cooled back-thinned spectrometer (Prime™ X, B&W Tec Inc): CCD array cooled down to -10 °C

# Methods: the dosimetric system



## Methods: the irradiation facilities

- Laboratory irradiations:

  “soft” X-rays  (32 kV)

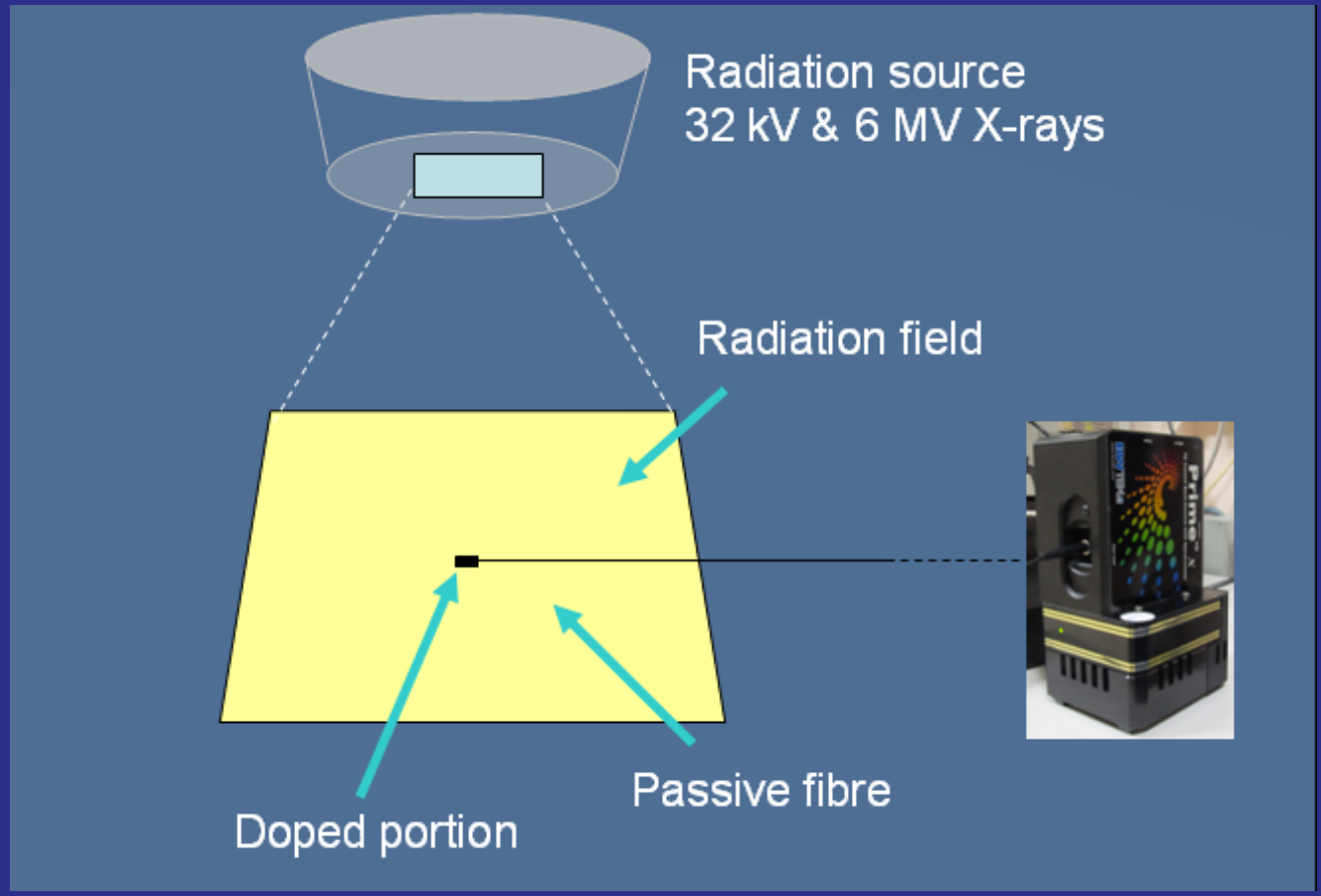
- Clinical irradiations:

  photons (6 MV) and electrons (6 MeV),  300 MU/min

## Methods: spectral measurements and analysis

- Background measurement and subtraction
- Integration time of 65 seconds
- Correction for the spectral response of the system

# RL of Eu doped silica fibre vs. stem effect



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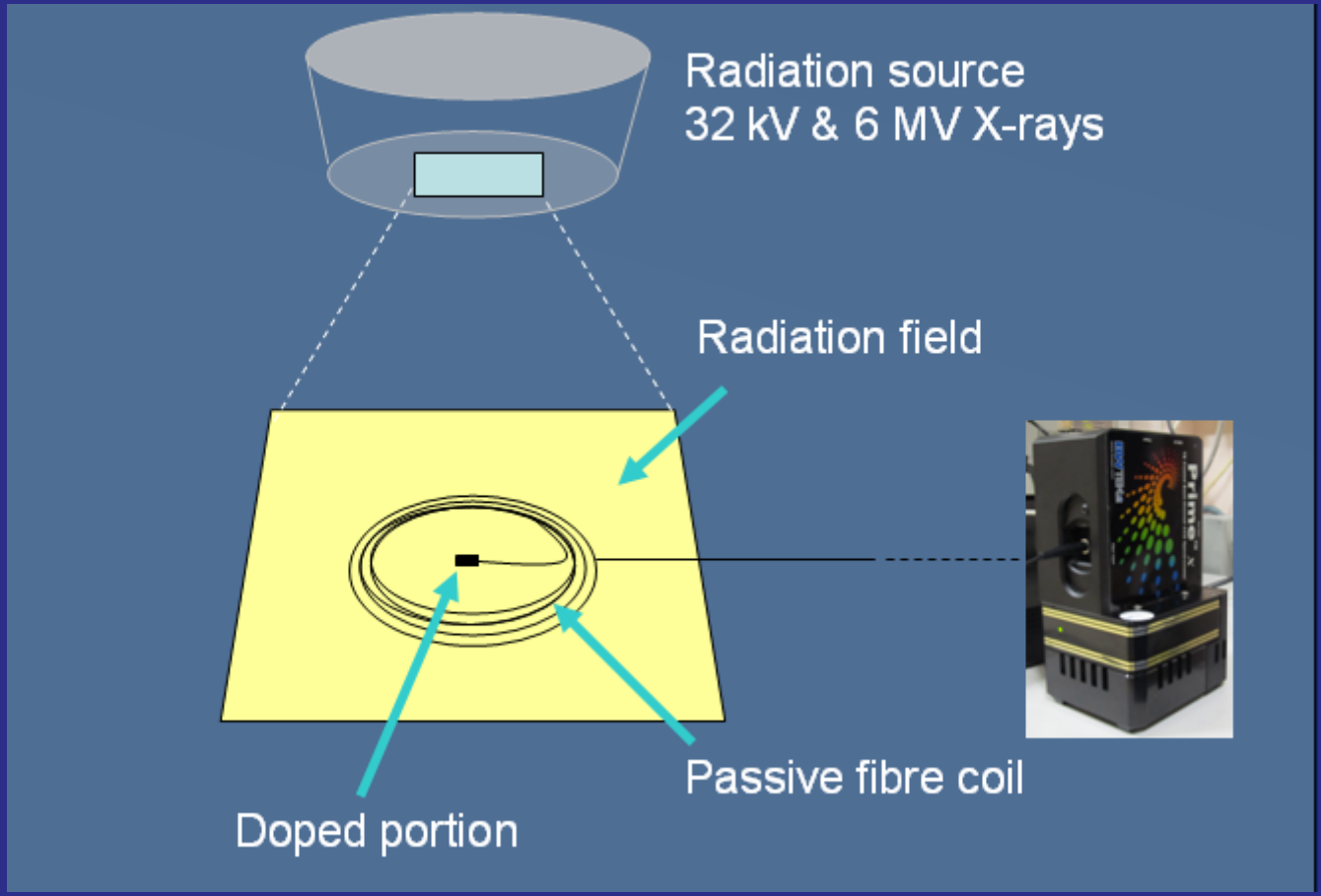

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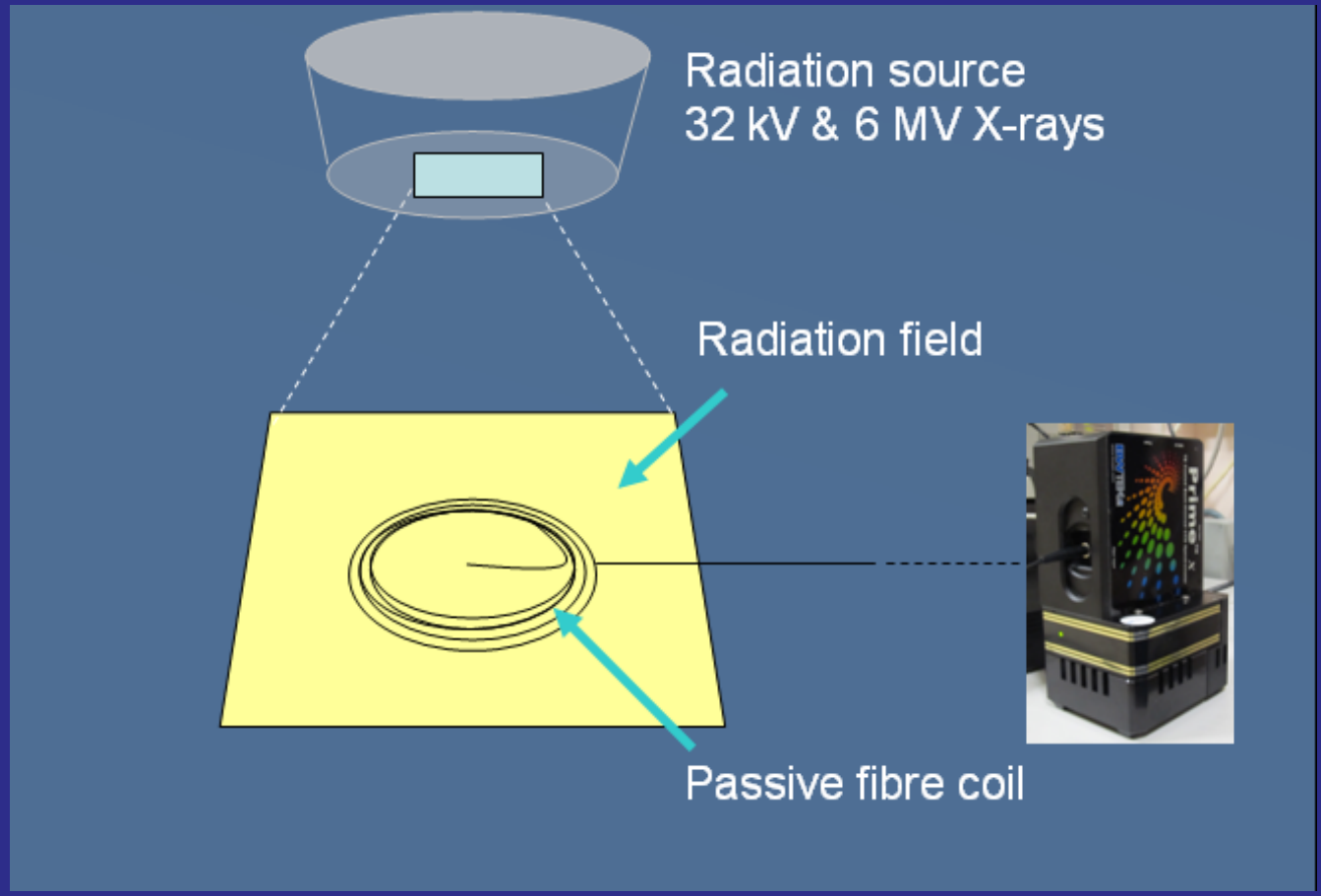
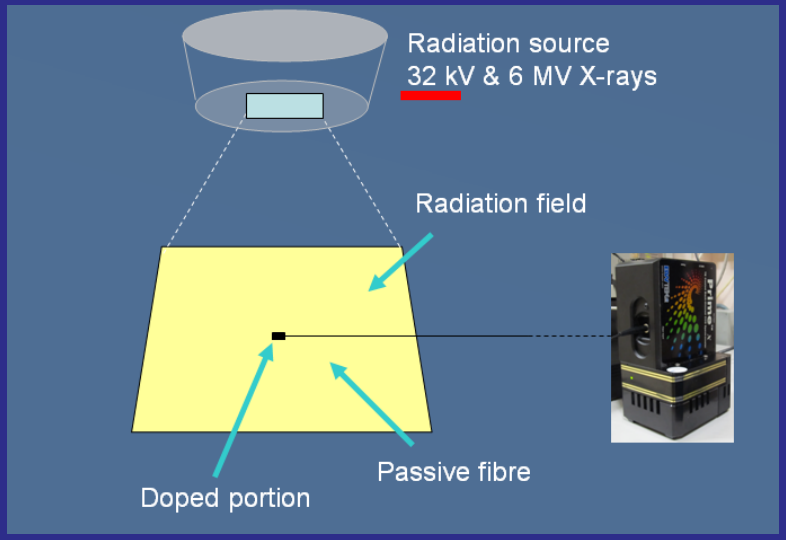
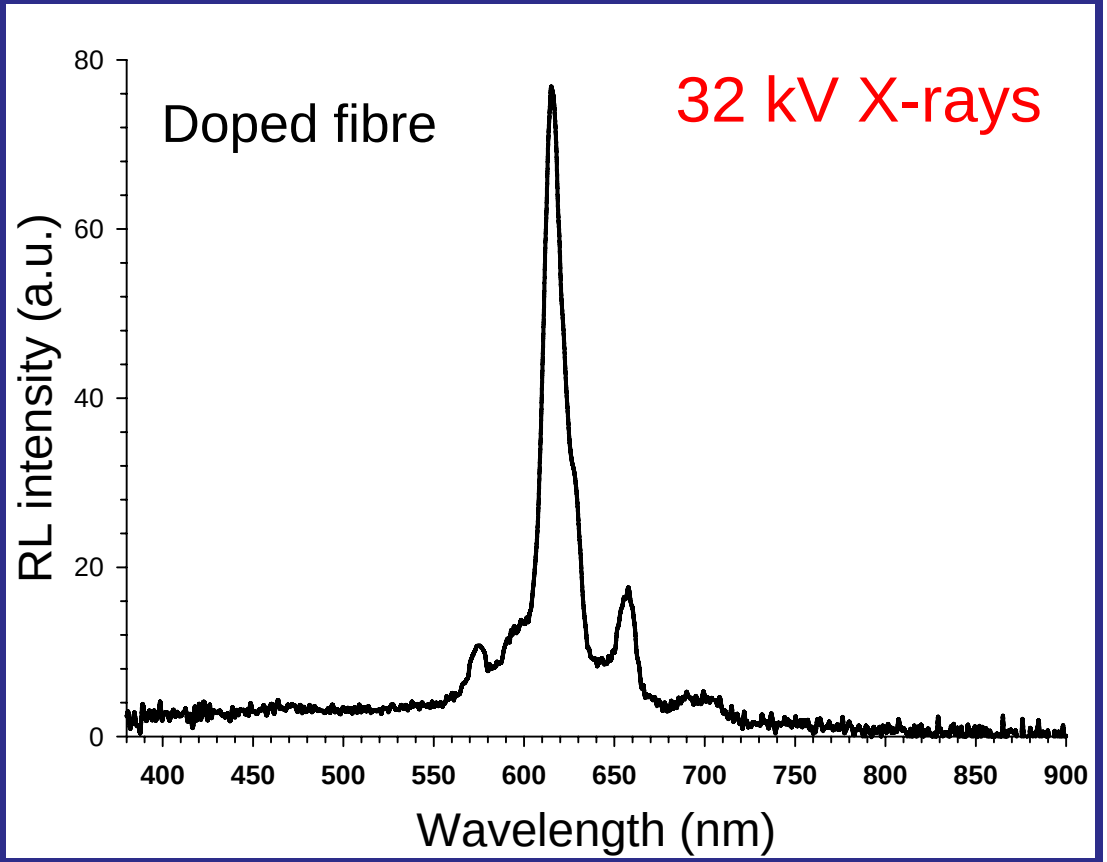


# RL of Eu doped silica fibre

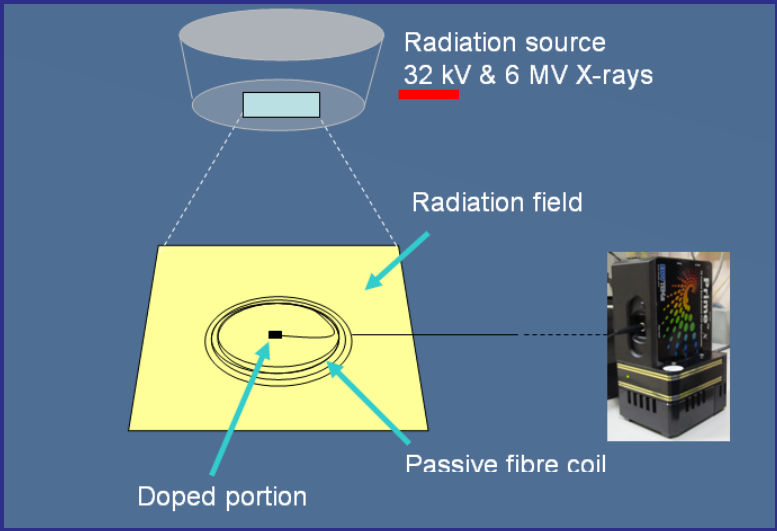



Main peak at ~ 620 nm and weaker peaks below and above this wavelength

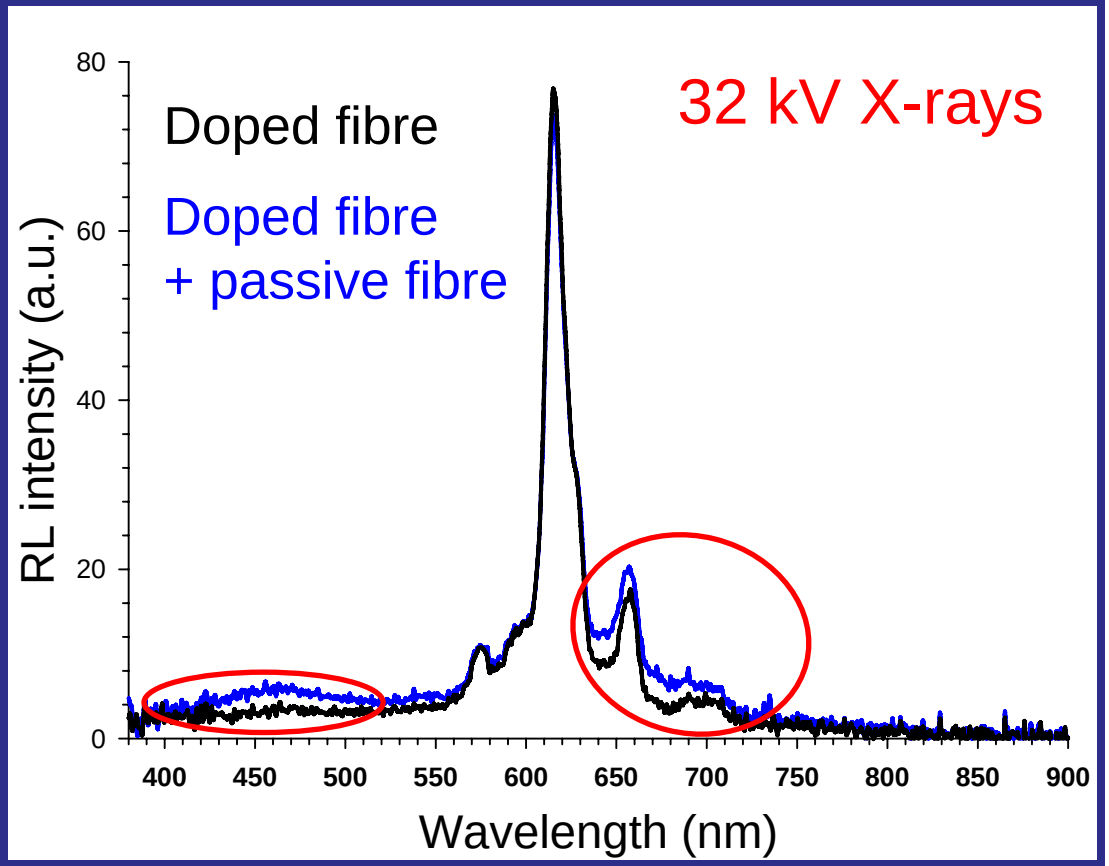



Emissions related to $^5D_0 - {}^7F_J$ (J = 1,2,3,4) transitions of $Eu^{3+}$

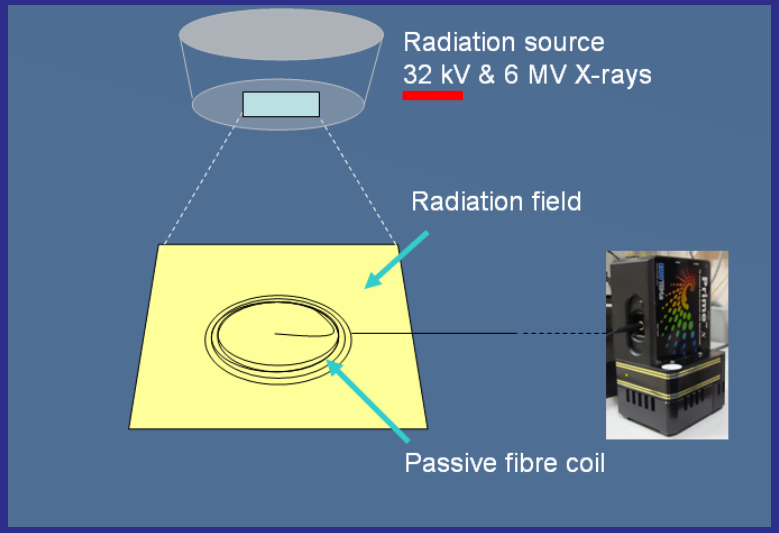
# RL of Eu doped silica fibre vs. stem effect



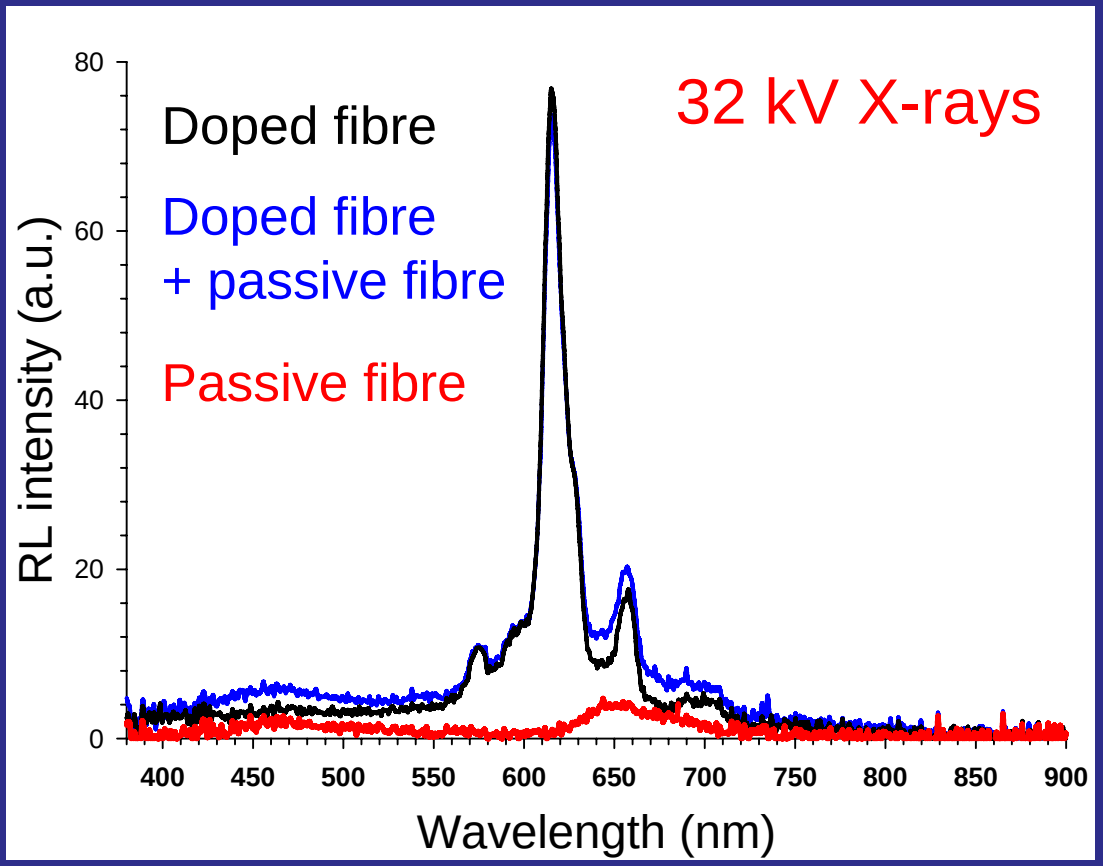

No significant spurious signal from the passive fibre was detected in the spectral region of the main Eu emission, i.e. 605-635 nm



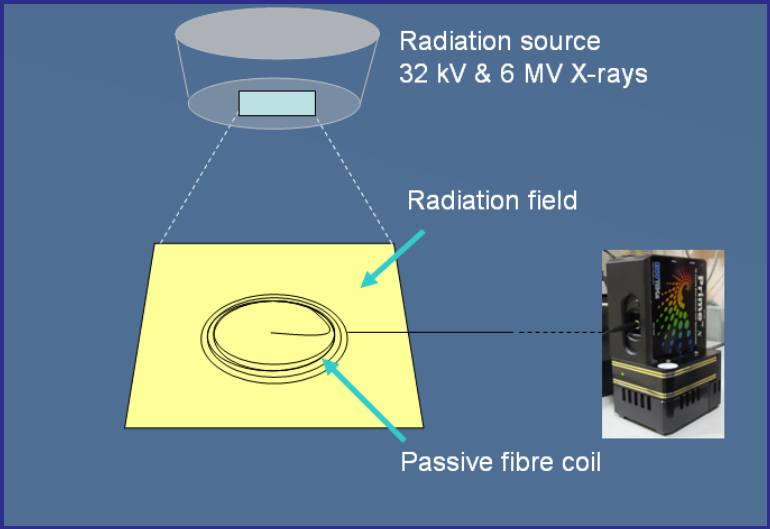
# RL of Eu doped silica fibre vs. stem effect



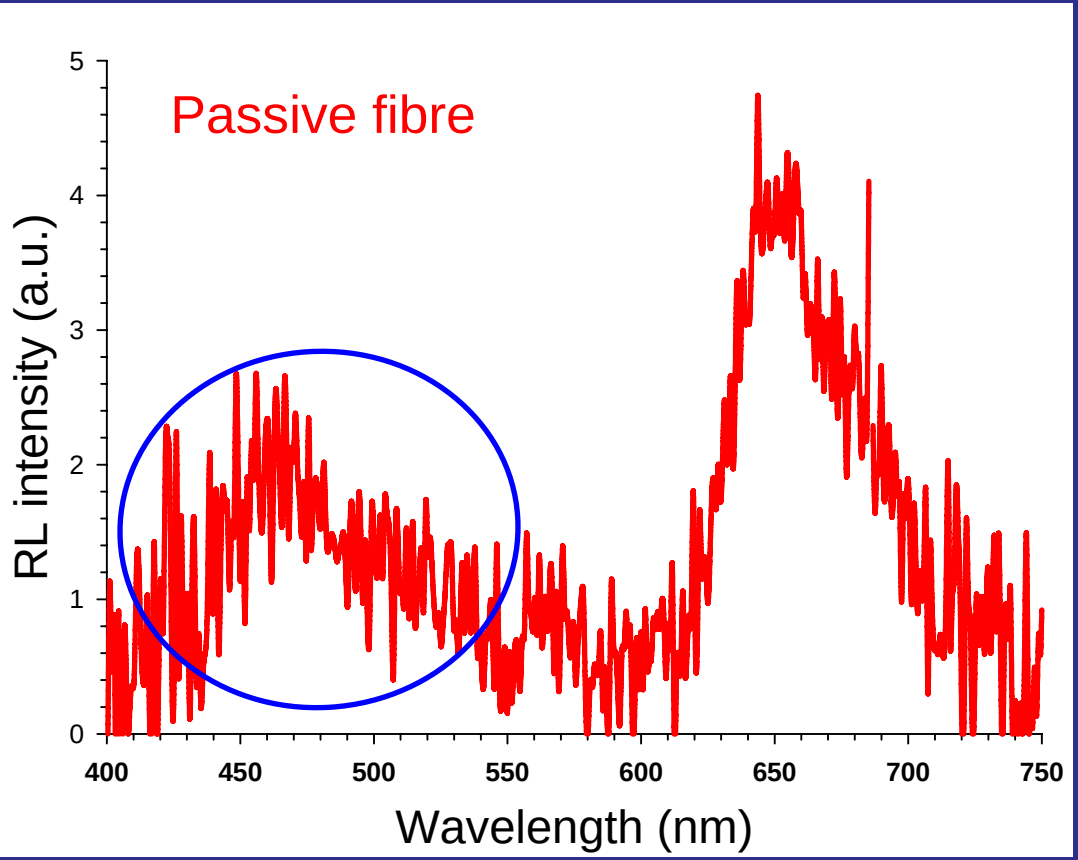

Two main emission bands, related to silica defects can be observed in the passive fibre spectrum



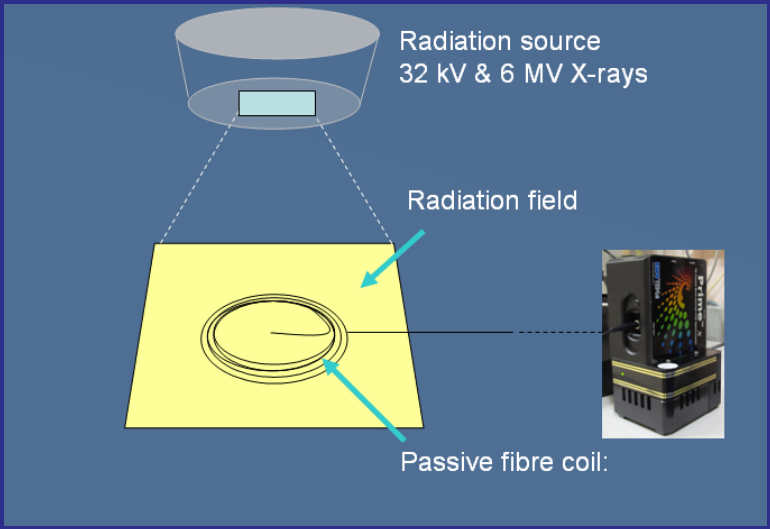
# Origin of the stem effect

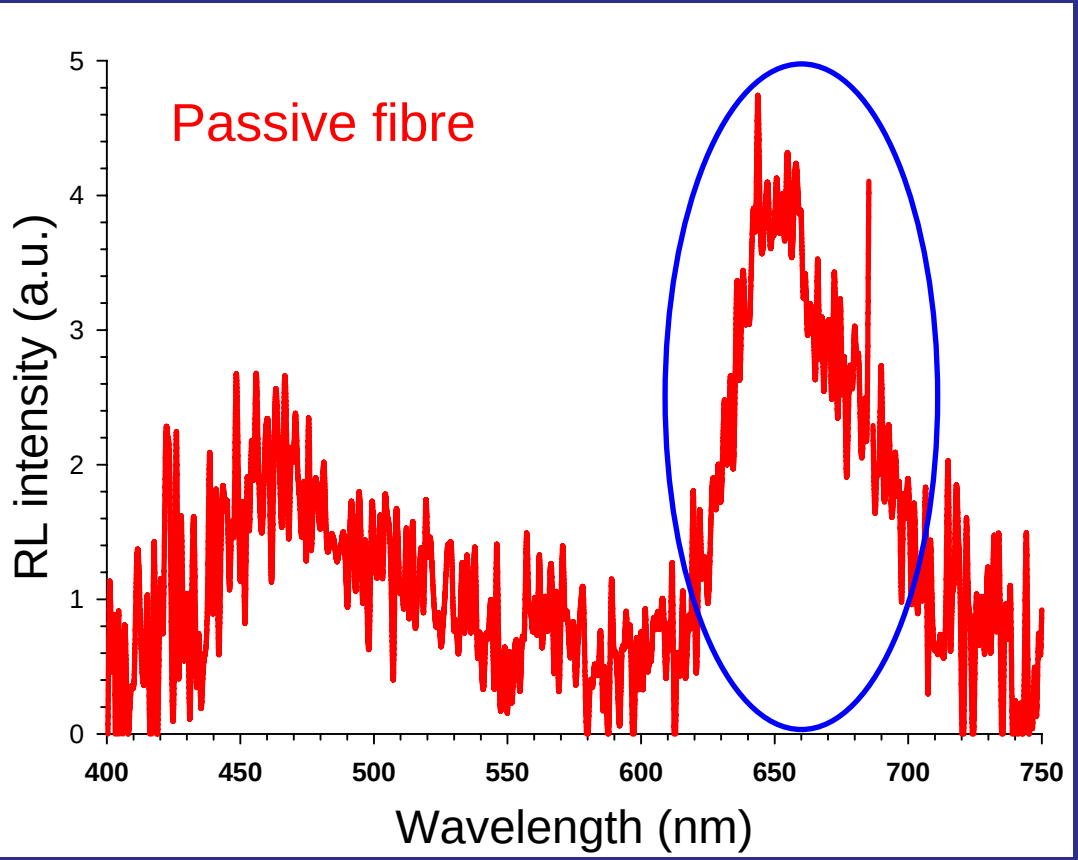



triplet-to-singlet transition of twofold coordinated silicon defects



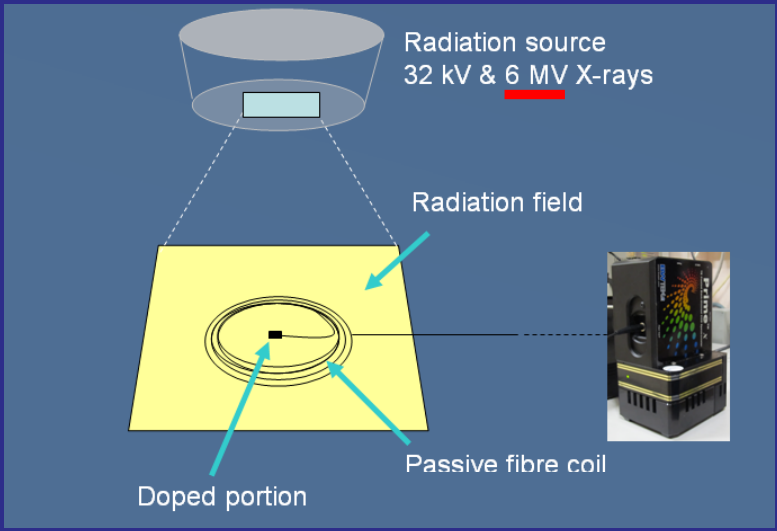
# Origin of the stem effect



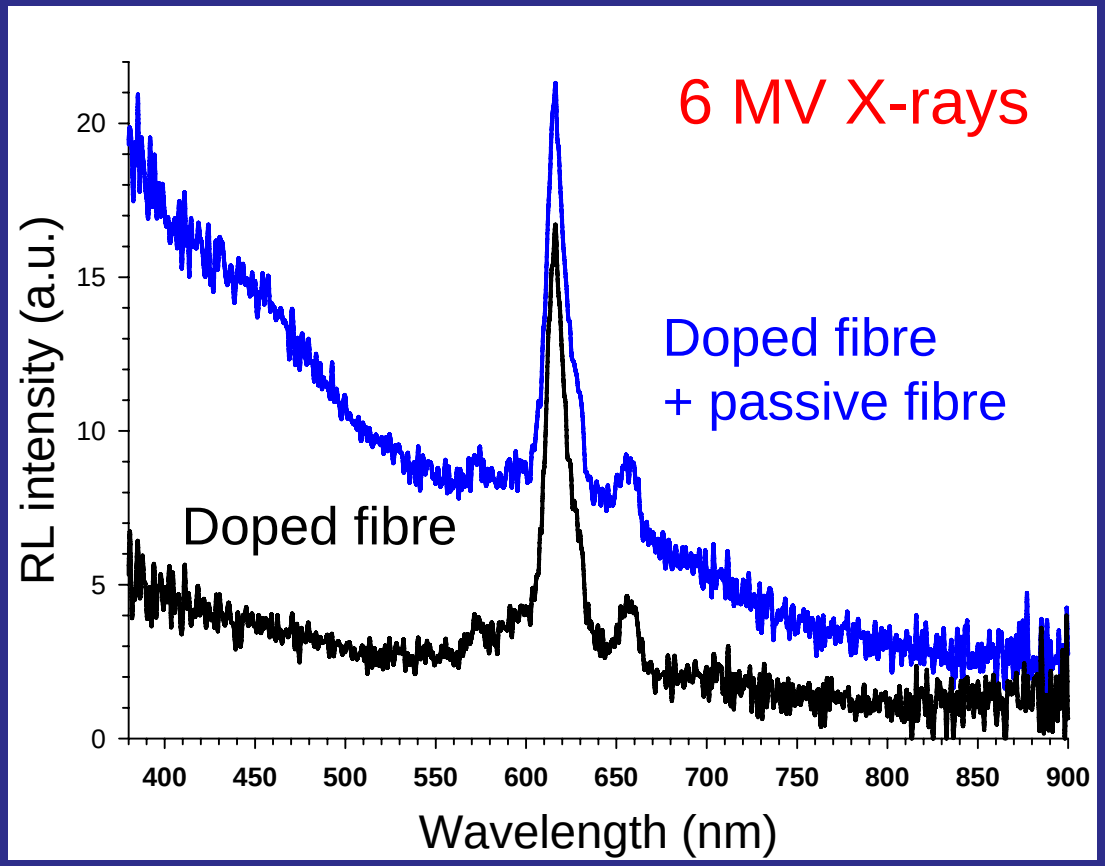




~ 650 nm (i.e. 1.9 eV):
non-bridging oxygen
hole centre

# RL of Eu doped silica fibre vs. stem effect

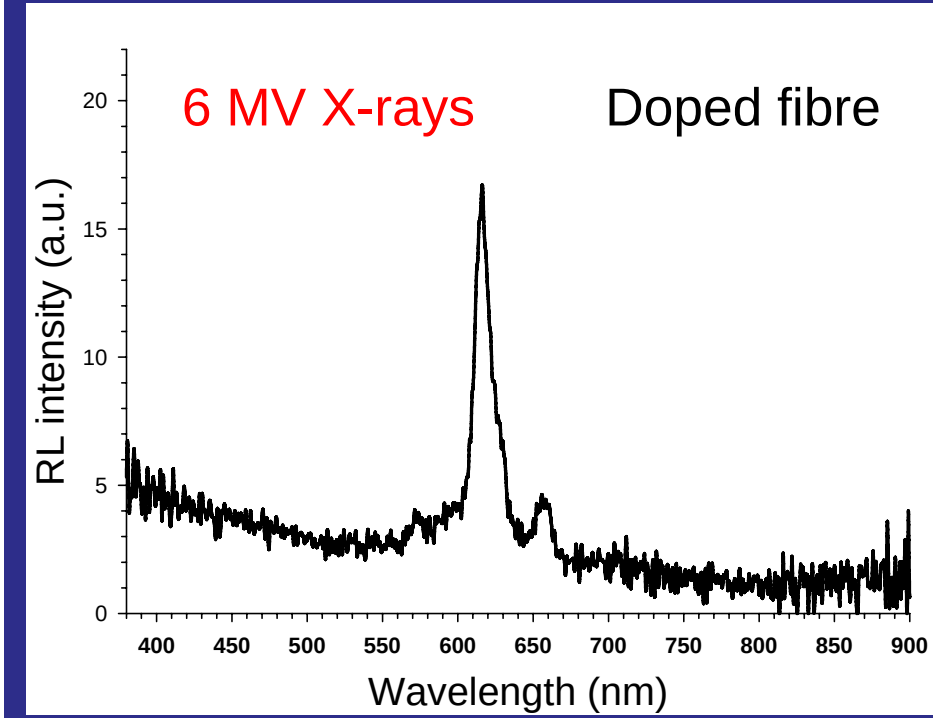


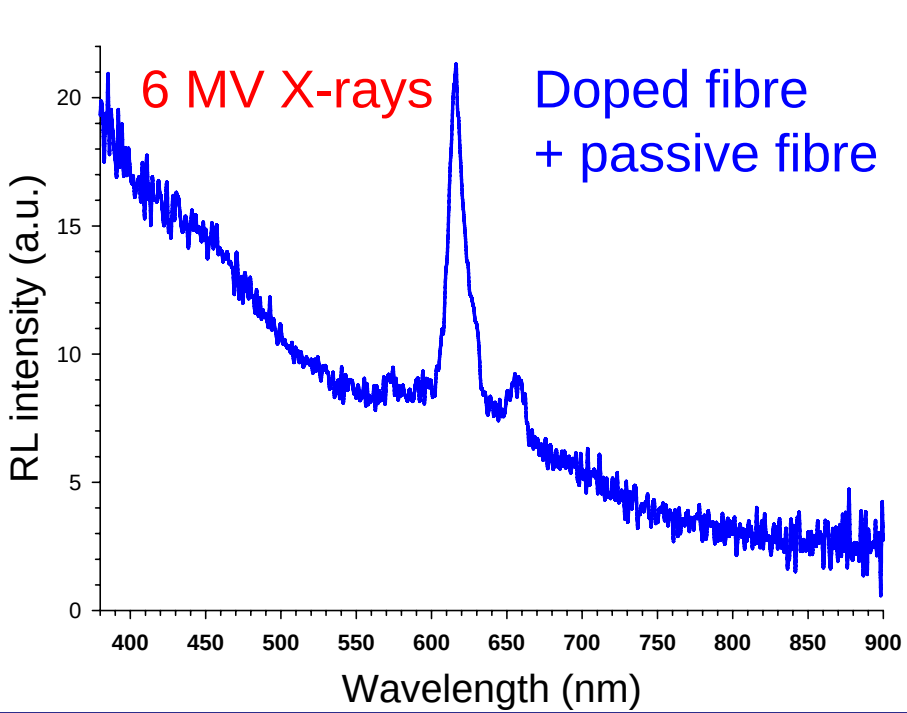

Above the threshold kinetic energy for Cerenkov radiation production (~ 200 keV) the situation is extremely different




A significant change in spectrum shape was observed due to the increasing contribution of the stem effect, mainly as a result of Cerenkov light.

# A new method for removing the stem effect



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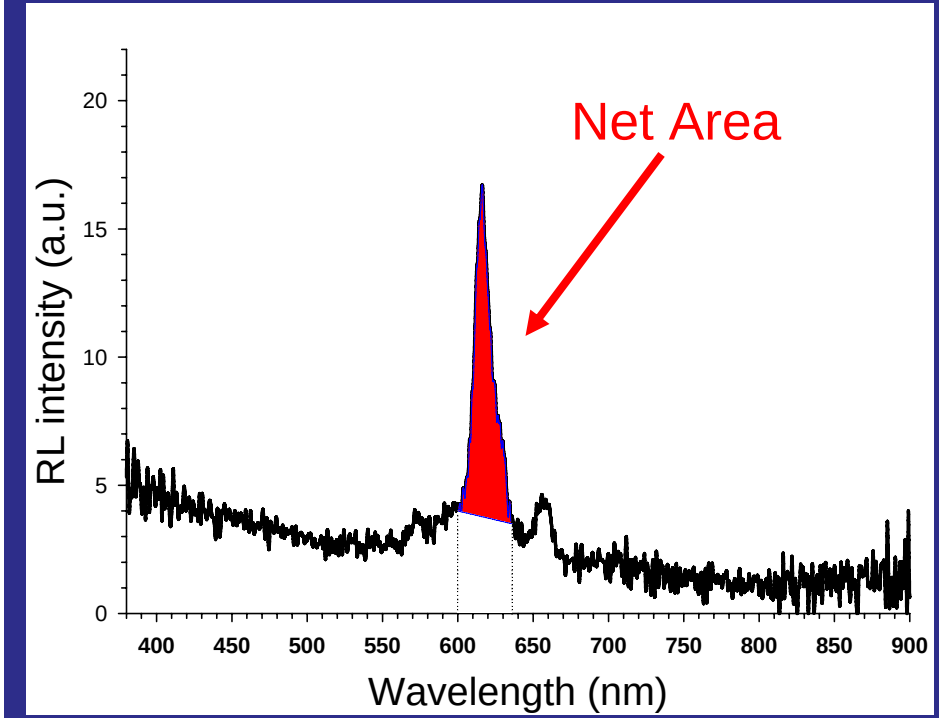
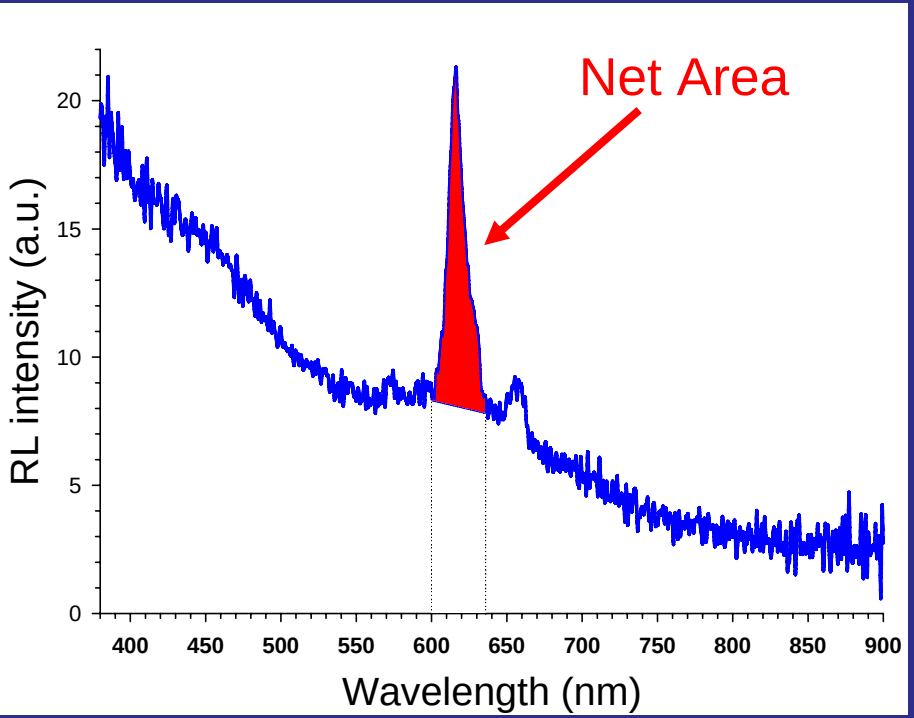


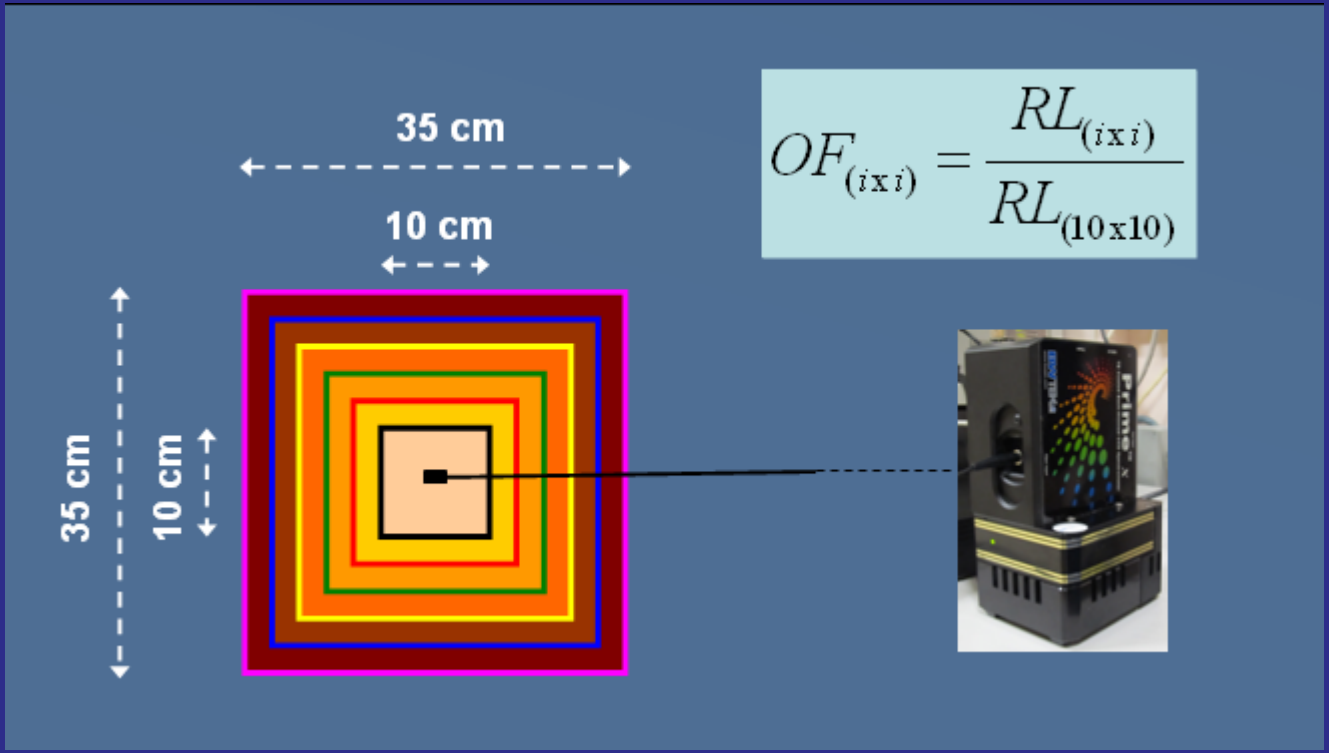

$$A_N = A_G - \overline{BG} \cdot N_{CH}$$

**Gross Area**

**Average background per channel** $\overline{BG} = \frac{B_1 + B_2}{2}$

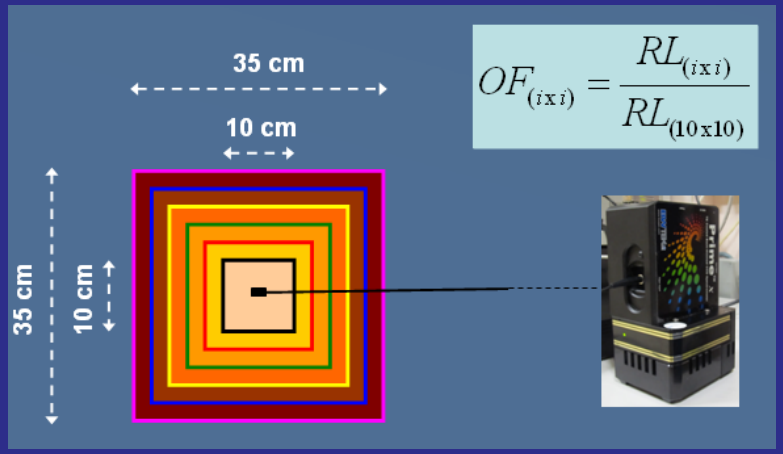
**Number of channels of the peak**

# Output factors measurement

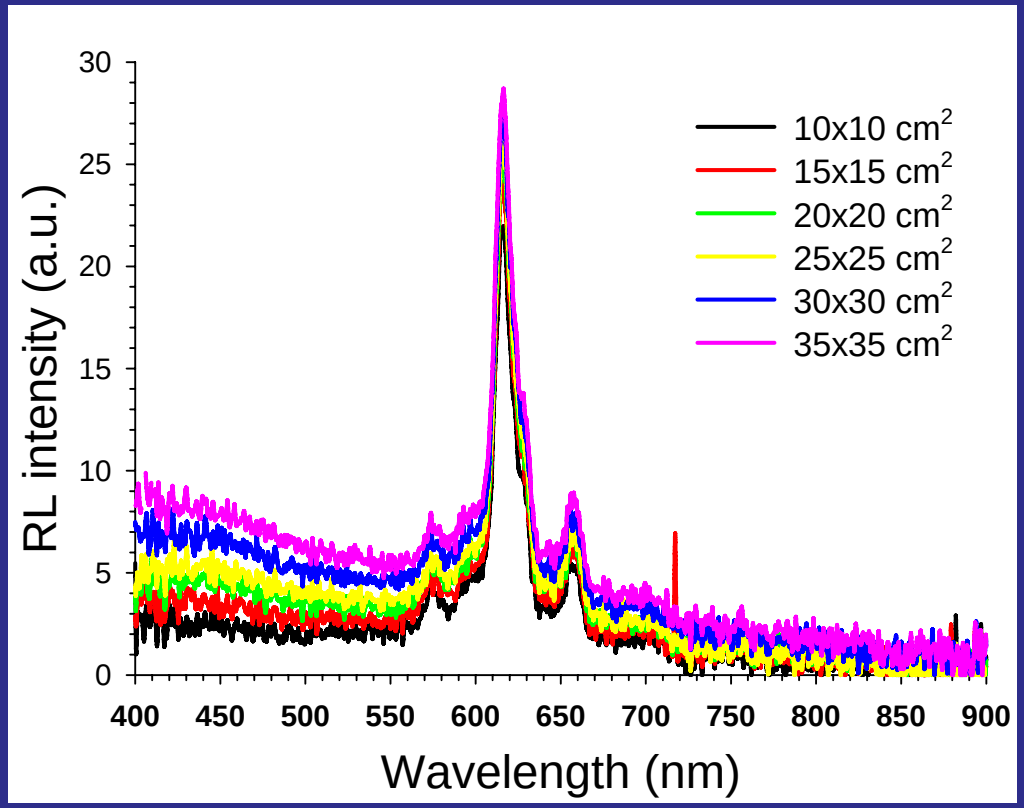



- 6 MV photon beams
- Fibre in a water phantom at a depth of 1.5 cm with the doped portion at the centre of the field (SSD 100 cm).
- For each measurement, 300 MU was delivered corresponding to doses ranging from 3.42 Gy to 4.03 Gy depending on field size.

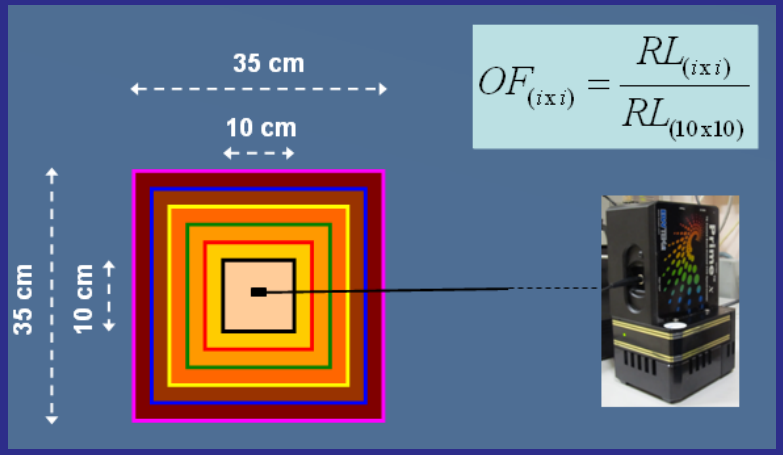
# Output factors measurement



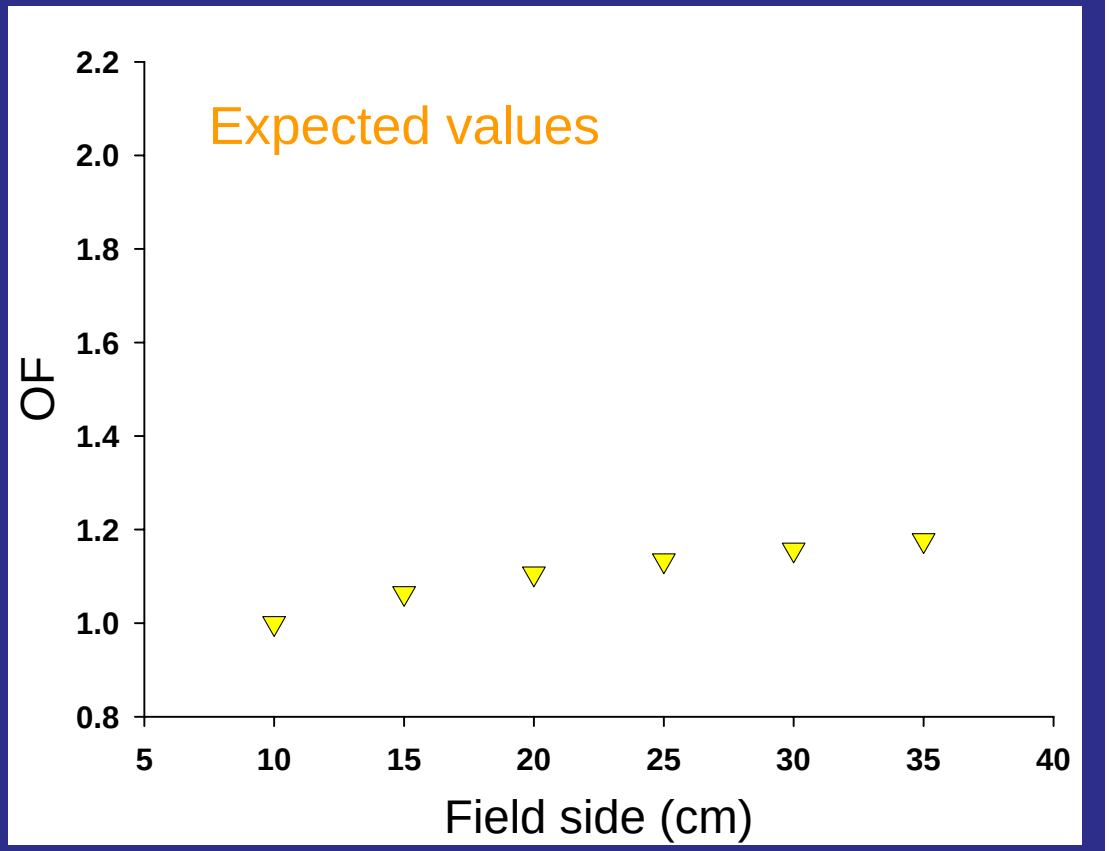

The increase in the stem effect contribution according to the increase in field size is evident. The stem effect is expected to strongly influences OF values.



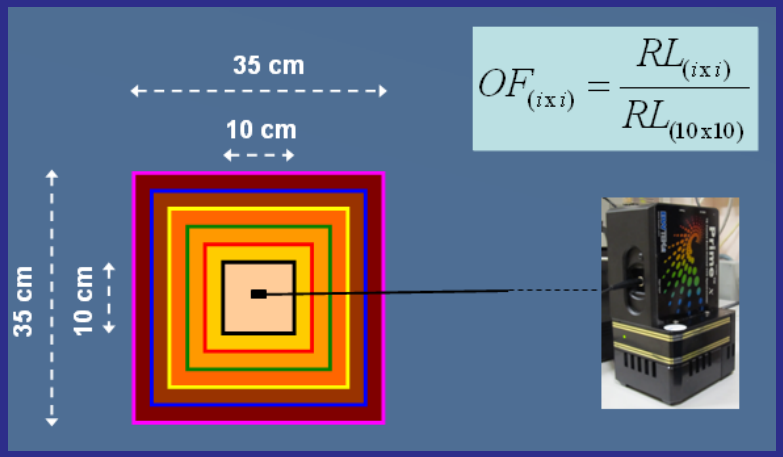
# Output factors measurement



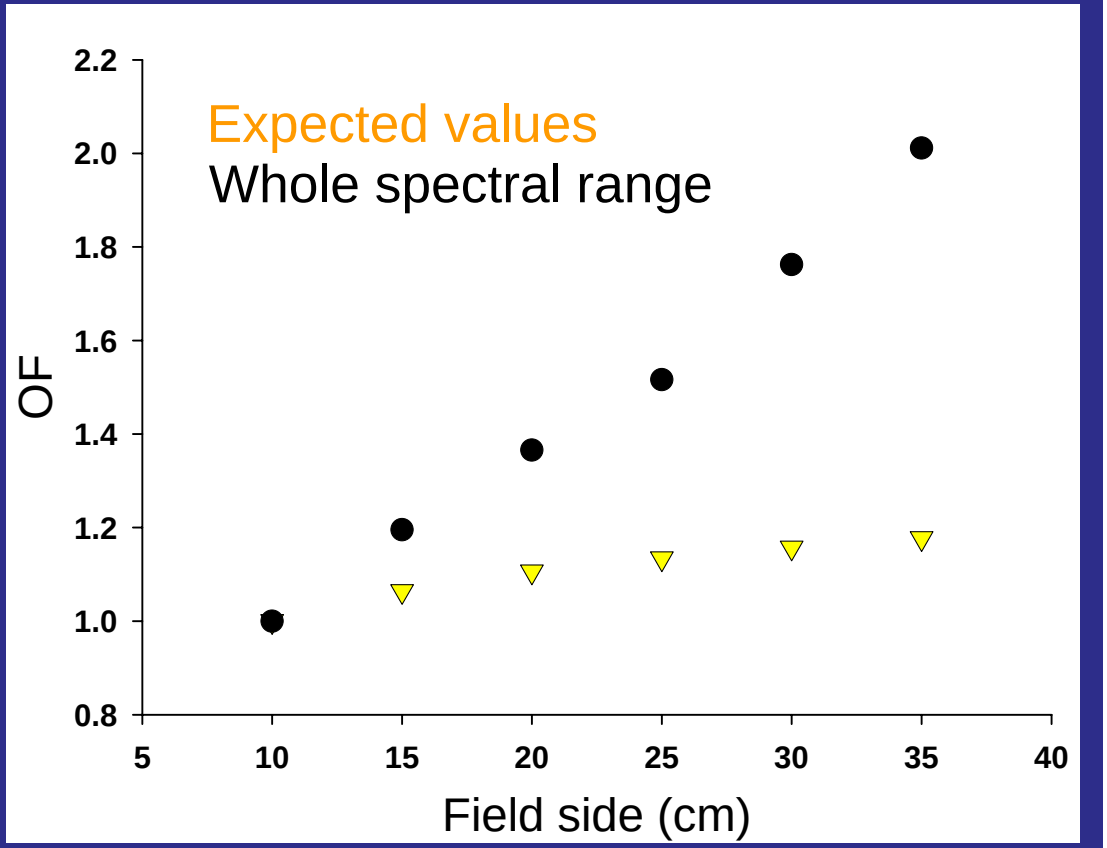

The expected values were evaluated with a calibrated ionization chamber



# Output factors measurement

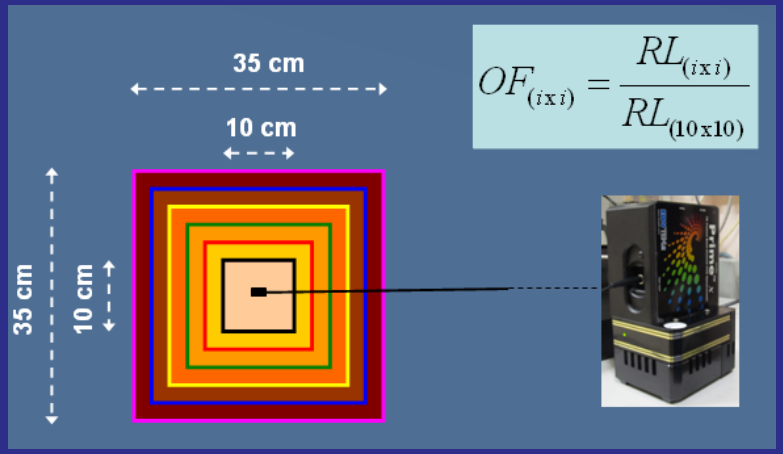



The stem effect increases almost linearly with increasing the irradiated passive fibre

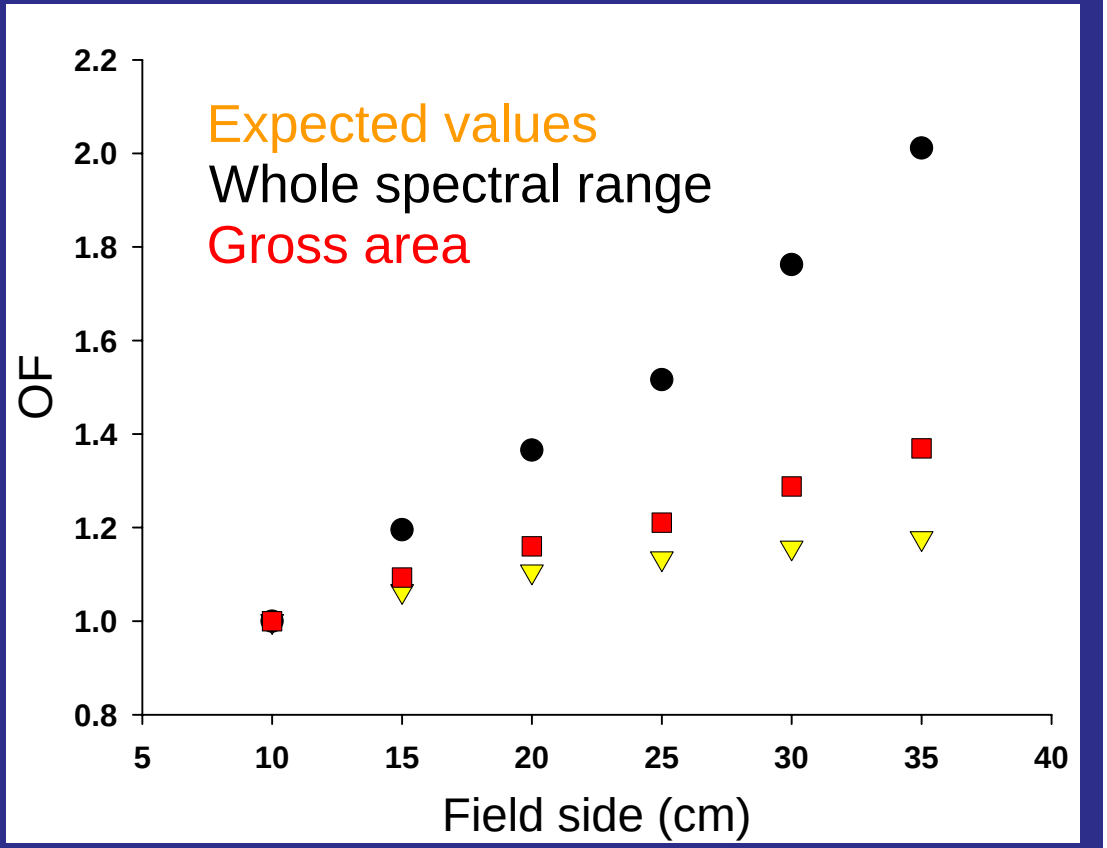



A significant overestimation of the OFs was obtained when the whole spectral range is used for the analysis

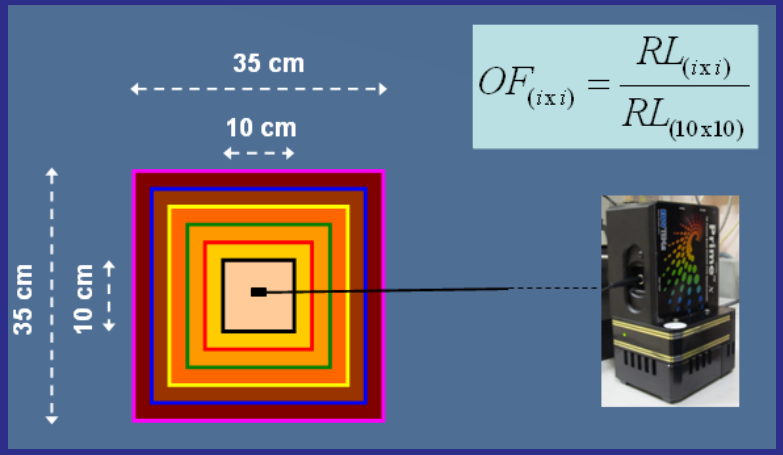
# Output factors measurement



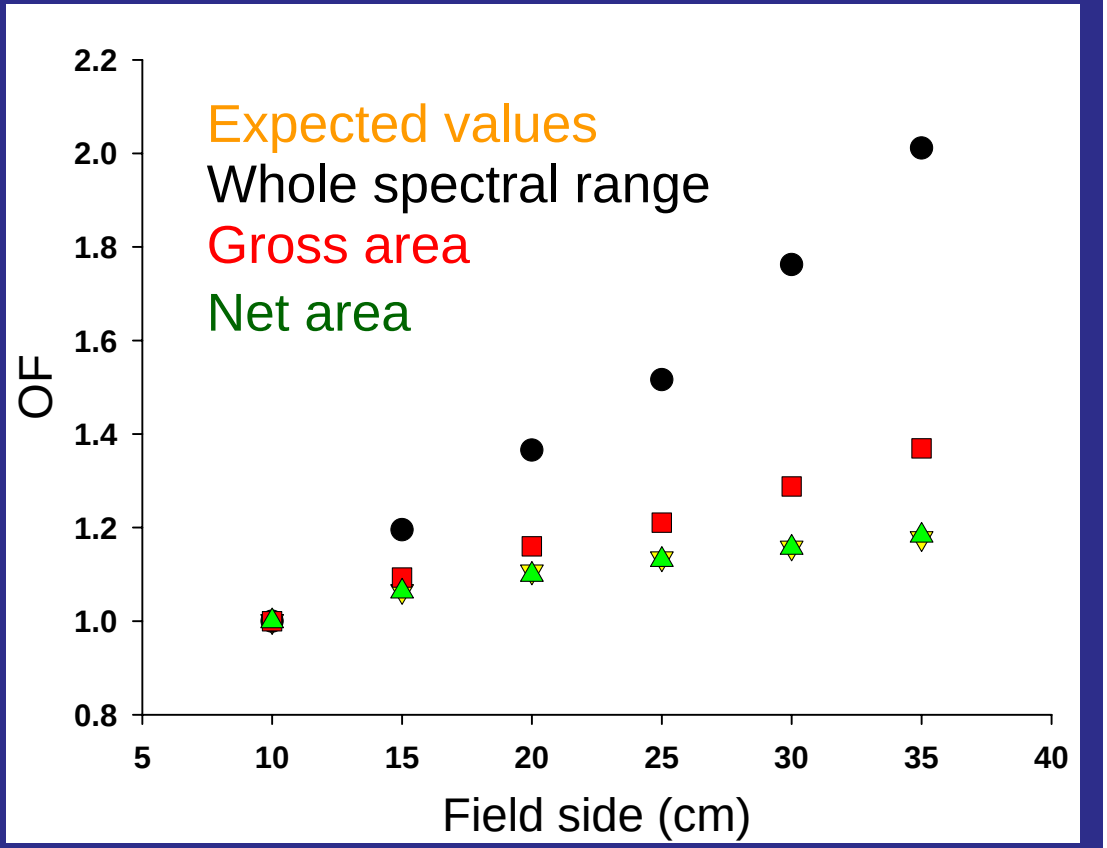

Also the OFs calculated by considering the gross area of the main Eu RL emission proved to be overestimated, especially for field sizes in excess of 15x15 cm$^2$.



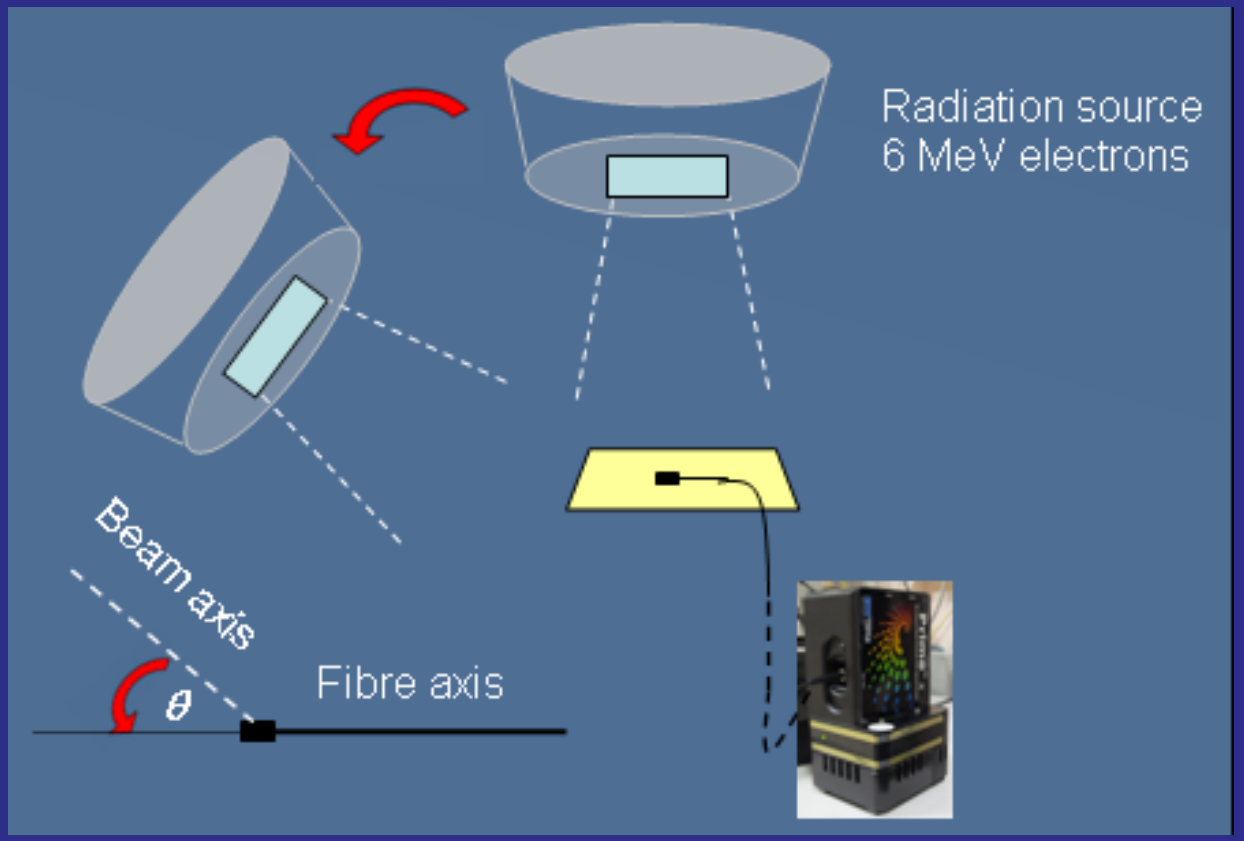
# Output factors measurement




The use of the net area of Eu RL main peak gave results that agreed well with the reference values

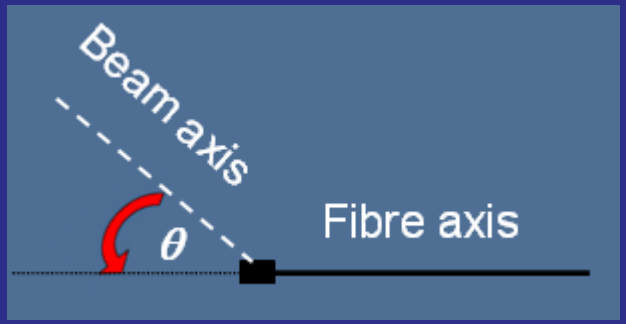


# Angular dependence



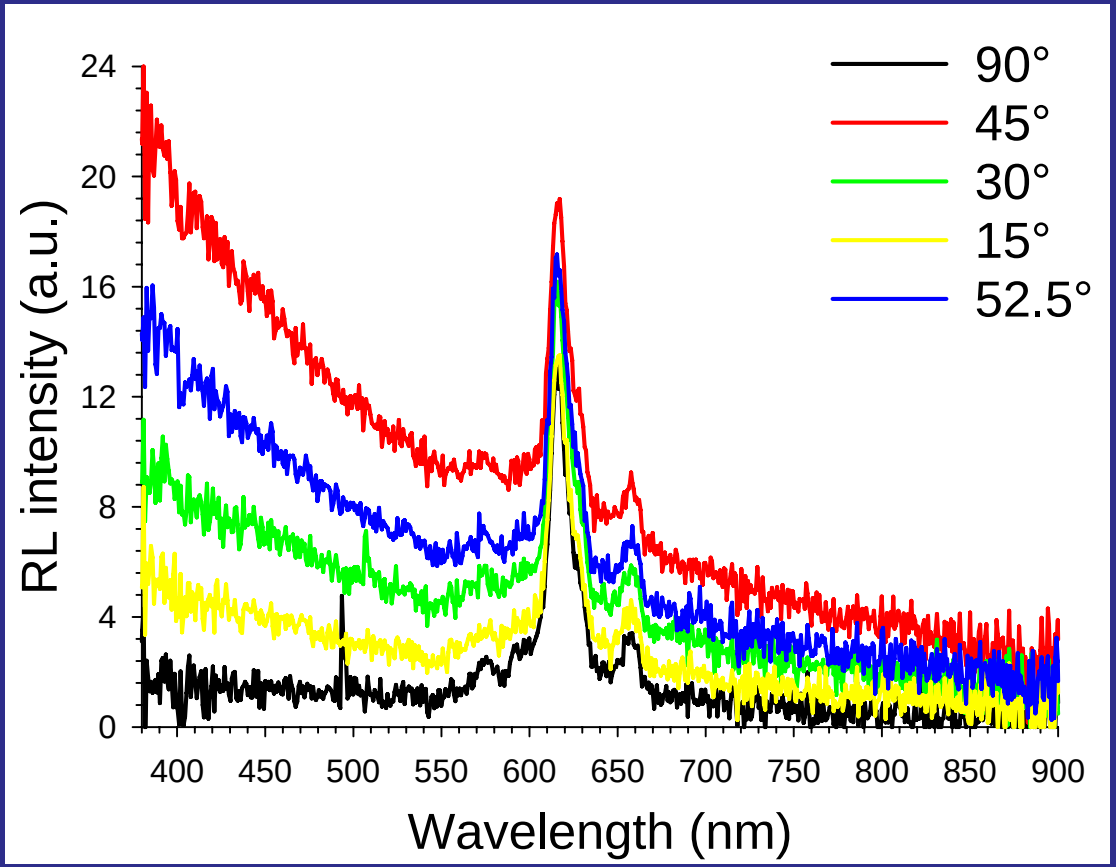

- 6 MeV electron beams
- Doped fibre in air at the isocentre
- Irradiation of the same portion of passive fibre independently of beam orientation

# Angular dependence

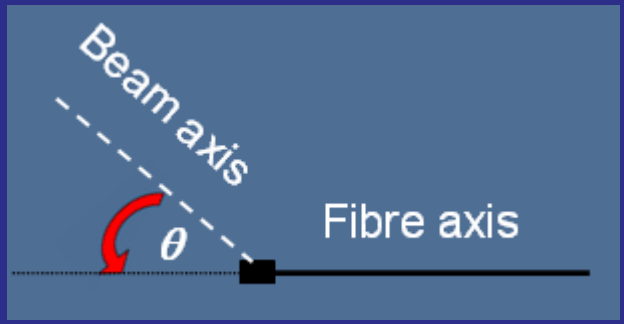


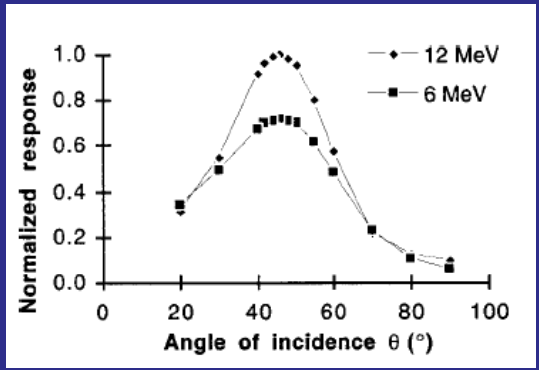

Different stem effect contribution according to the beam orientation.

The highest signal was observed for an angle of 45°.
Indeed for silica at 6 MeV, the angle at which the Cerenkov light is emitted relative to the direction of the particle is close to 45°.

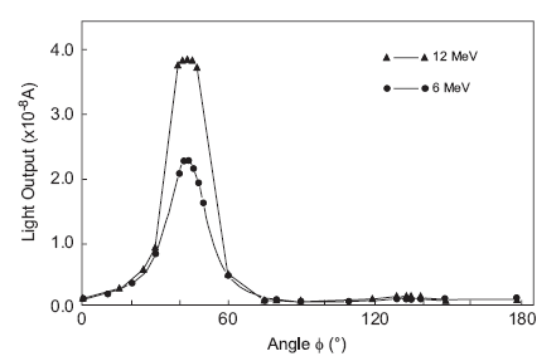


# Angular dependence

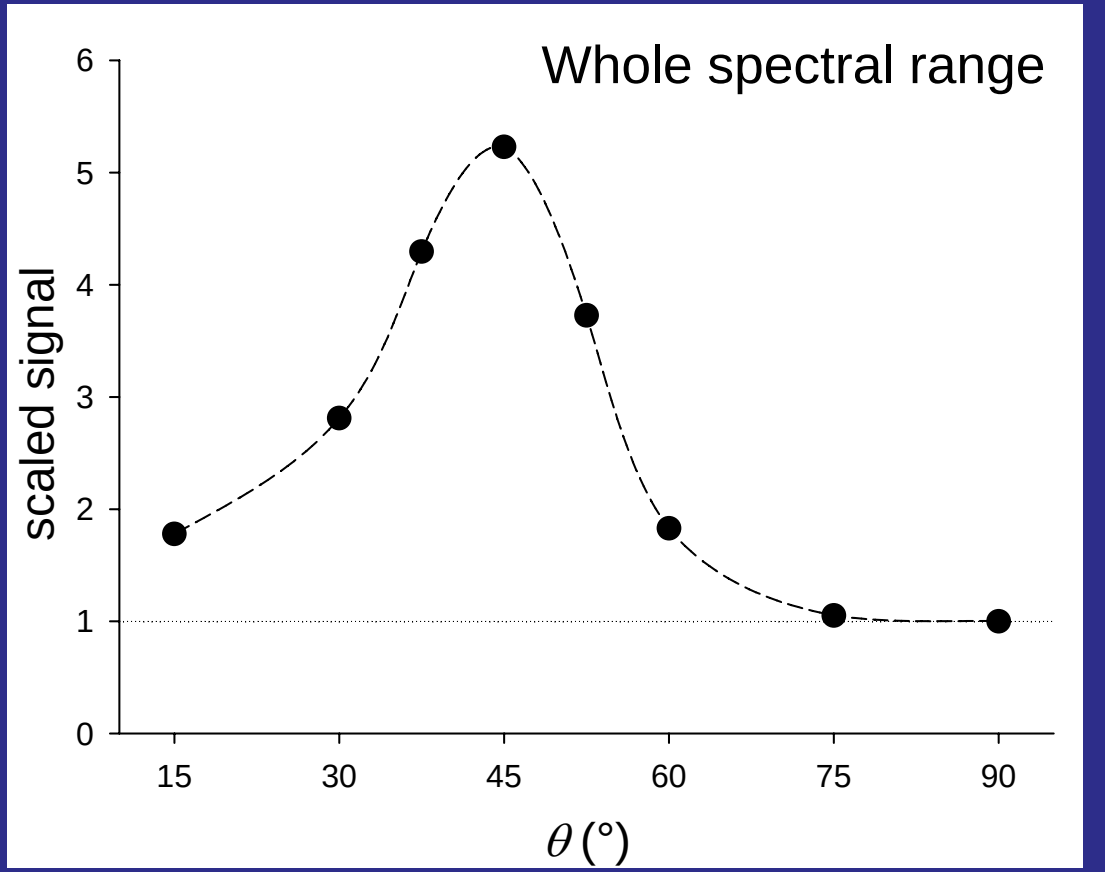


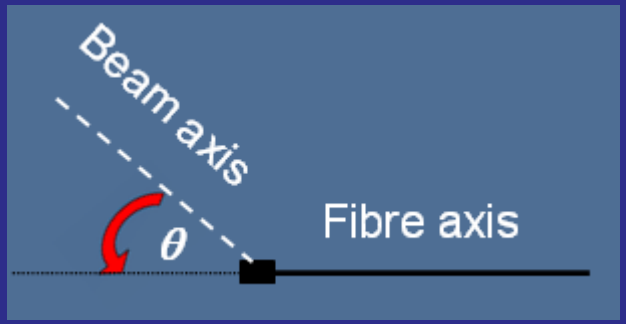

*(Lètormeau et al. 1999)*



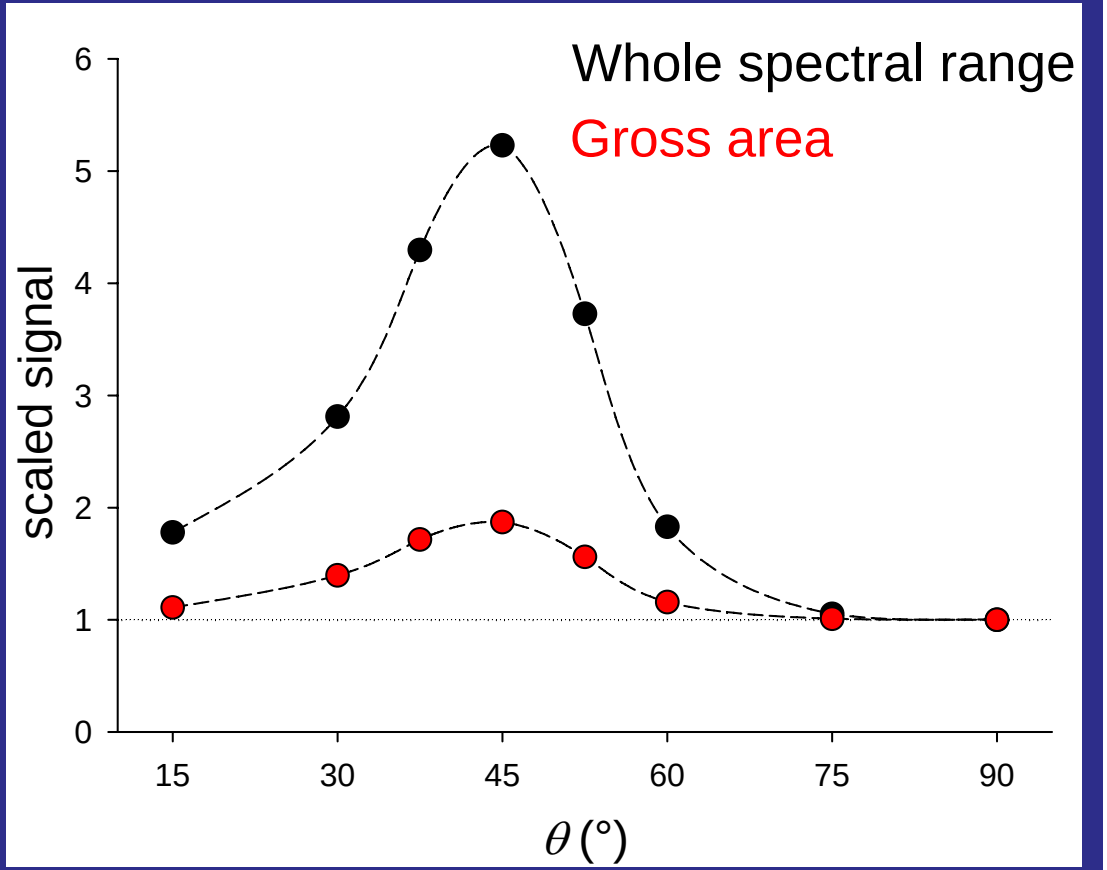

*(Beddar et al. 1992, 2007)*



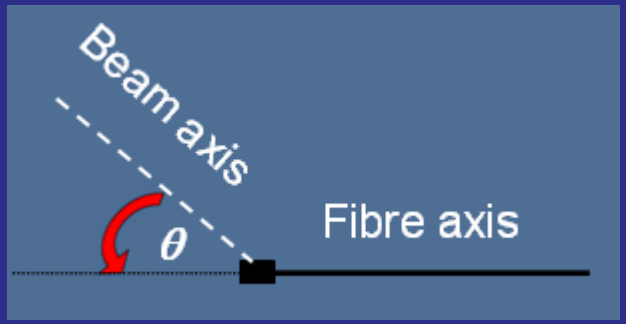
# Angular dependence



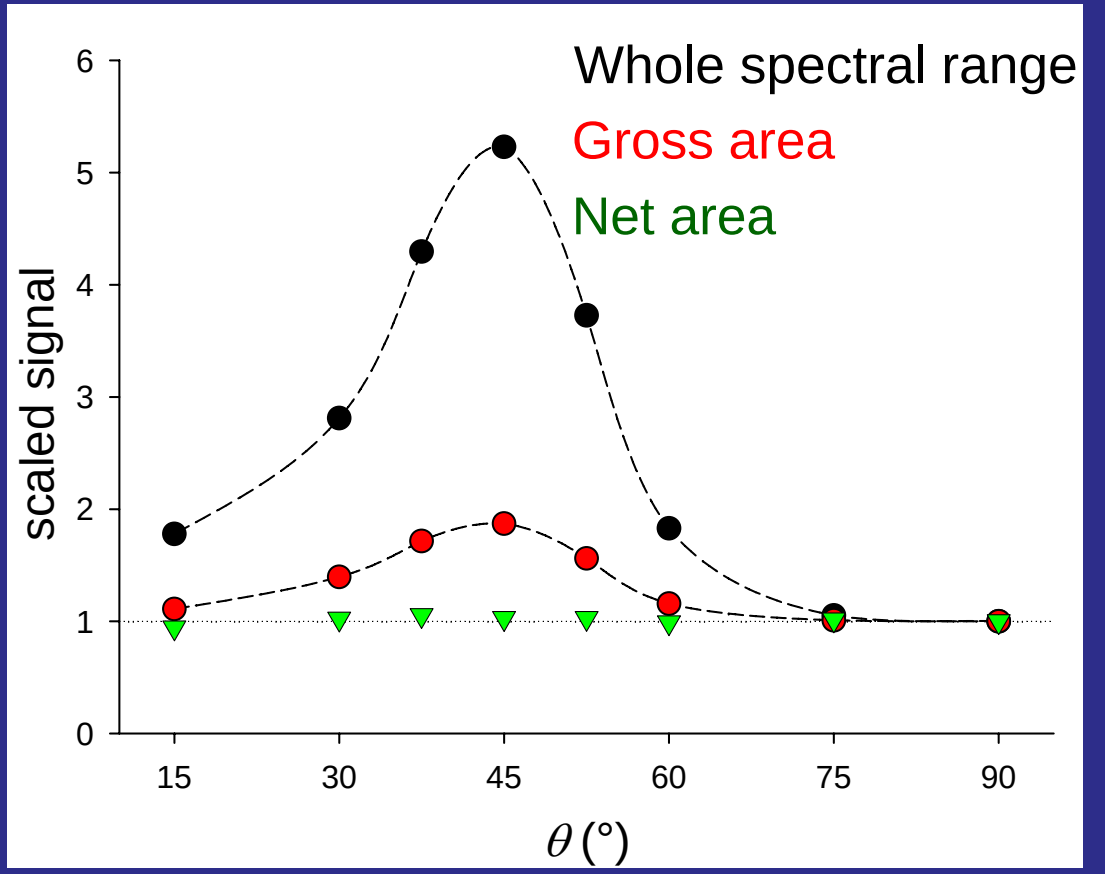

Also considering the total (gross) area in the narrower wavelength region of the main $Eu^{3+}$ emission, a non-negligible angular dependence was observed



# Angular dependence




The net area of the main Eu emission proved to be free from any stem effect contribution making the angular response of the fibre dosimeter almost independent in the range in question



# Sensitivity

- The integration times required to collect satisfactory RL spectra do not allow the dose rate to be measured in real time, as can be achieved, in principle, by using a photomultiplier tube.
- The *minimum detectable dose* was estimated equal to 0.28 Gy. Dose measurements and QA studies in conventional RT and brachitherapy can be performed
- Moreover, the sensitivity of the device may still enable sequential measurements of the dose during single fractions of treatments performed using the modern RT techniques characterized by a high dose per fraction

# Summary

- Eu-doped silica fibre is a promising material for optical fibre dosimetry.
- As expected, it suffers of stem effect.
- Below the Cerenkov radiation energy threshold only a slight contribution to the total RL signal due to fluorescence effects occurring in the passive was observed.
- Above the energy threshold, the stem effect was mainly caused by Cerenkov radiation which may significantly compromise the dosimetric properties.
- A new method for removing the stem effect, based on RL spectral analysis, was proposed and validated by measuring the output factors of extended photon fields and by studying the angular dependence of the dosimeter.

# Thank you for your attention

# Minimum Detectable Dose

Dose corresponding to a signal equal to three times the standard deviation of the background signal (ICRU, 1972):

$$MDD = 3 \cdot \sigma_{BG} \cdot \frac{D_S}{S}$$

- $D_S$: generic irradiation dose (3.4-4.0 Gy)
- S the net signal corresponding to $D_S$ $S = I_{MAX} - B_1$

where $I_{MAX}$ was the maximum intensity of the signal in the main Eu emission wavelength region, $B_1$ counts occurring before the main peak (background signal).