Investigation of the properties of the heavy scintillation fibers for hadron therapy monitoring

Katarzyna Rusiecka, Aleksanda Wrońska, Andrzej Magiera
M. Smoluchowski Institute of Physics, Jagiellonian University, Kraków, Poland

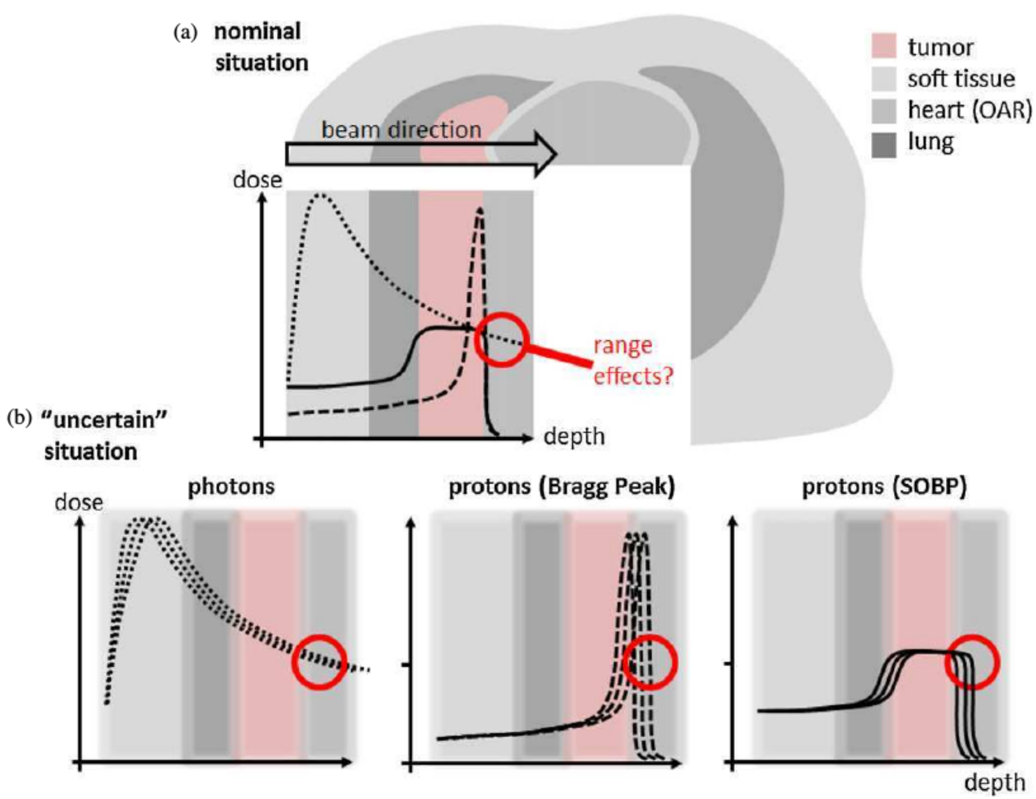
Jonas Kasper
Physics Institute 3B, RWTH Aachen University, Aachen, Germany

ISMART Conference
Minsk 2018

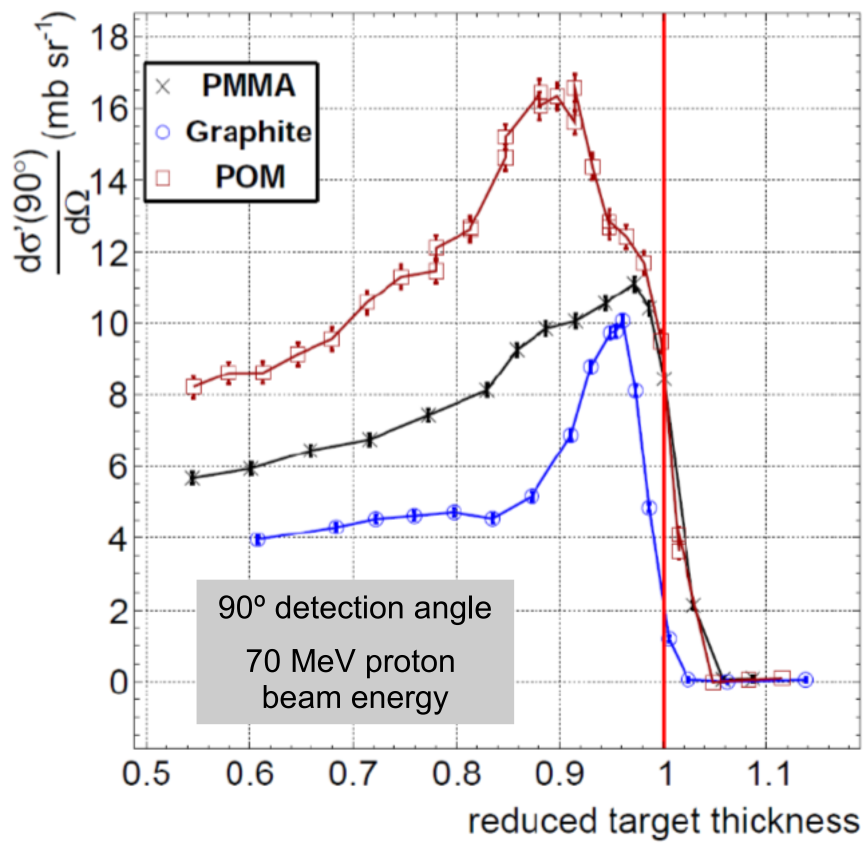
Motivation – on-line monitoring of hadron therapy

- Cancer causes ~25% of deaths in EU
- Possible options for treatment: surgery, chemotherapy and **radiotherapy**
- **Proton therapy** is highly precise and selective provided that we know the distribution of tissues in the patient's body
- Uncertainties: transformation of CT images (*dE/dx*), patient positioning, anatomical changes

- Need for precise and efficient on-line monitoring method
- **Prompt γ radiation** – emitted as a result of nuclear reactions occurring during treatment
- Energy spectrum up to 10 MeV
- Strong correlation with the position of the Bragg peak

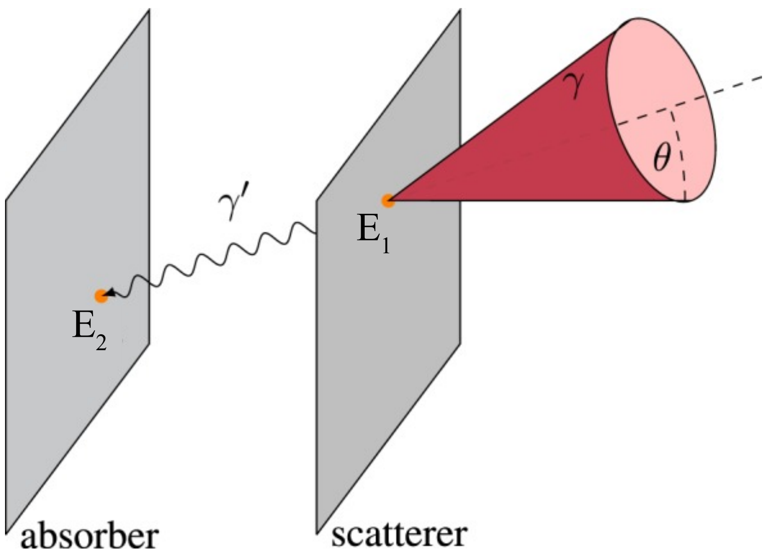


src: A. C. Knopf, A. Lomax, Phys. Med. Biol. 58 (2013) R131

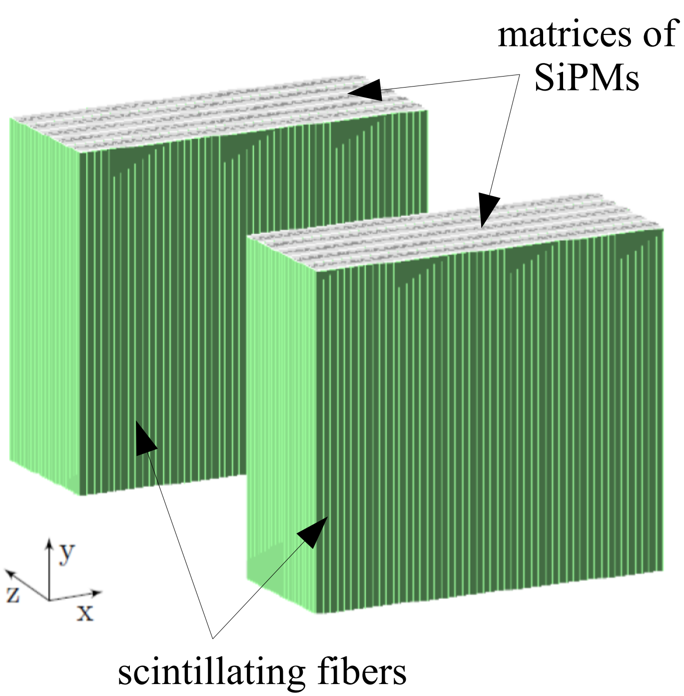


src: L. Kelleter *et al.*, Phys. Med. 34 (2017) 7-17

Motivation – Compton Camera



src: F. Hueso-Gonzalez et al., Front. Oncol. 6 (2016) 80



src: Jonas Kasper, Master's Thesis

- Compton camera allows to reconstruct the origin of a primary photon on the surface of the 'Compton cone'
- It typically consists of two parts: a scatter detector and an absorber detector
- Primary γ undergoes Compton scattering in scatterer detector and deposits energy E_1. Secondary γ' is absorbed in the absorber detector and the remaining energy E_2 is deposited
- Points of interaction in scatterer and absorber define axis and vertex of the Compton cone
- Half-opening (scattering) angle:

$$\cos\theta = 1 - m_e c^2 \left(\frac{1}{E_1} - \frac{1}{E_0}\right)$$

- Technique proposed and tested for proton therapy monitoring purposes
- Issues: small statistics (efficiency) and background coming from random coincidences
- Proposed solution: detectors with larger efficiency and better time resolution (electronic collimation) → Compton camera based on thin fibers made of heavy inorganic scintillator

Requirements for scintillating material:

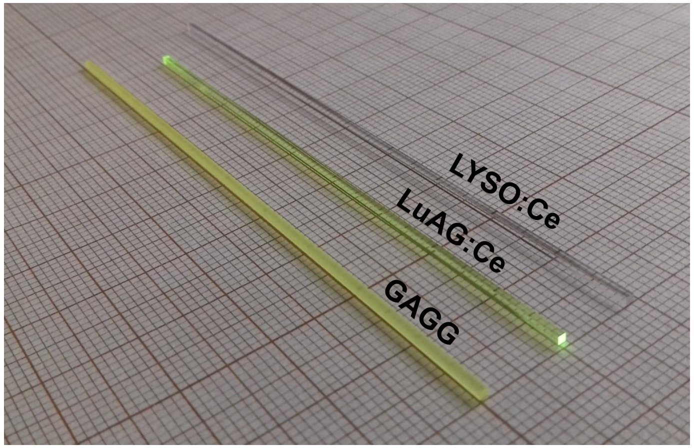
- Large ρ and Z_{eff}
- Emission spectrum compatible with SiPMs
- Short decay constant
- Large photon yield
- Attenuation length above 10 cm
- Good energy resolution
- Small intrinsic activity

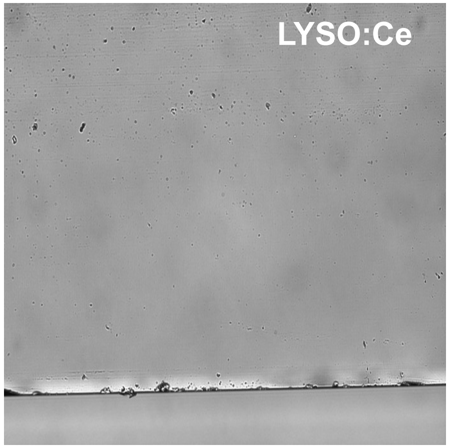
Geometry:

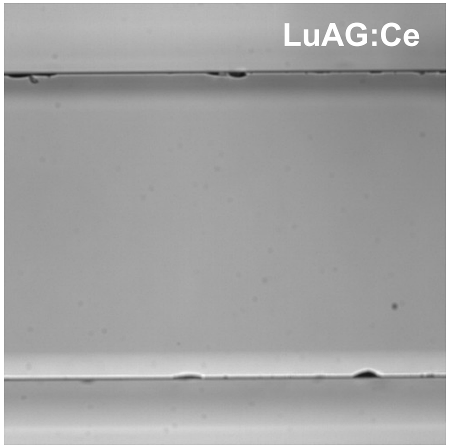
- 1 mm x 1 mm x 100 mm

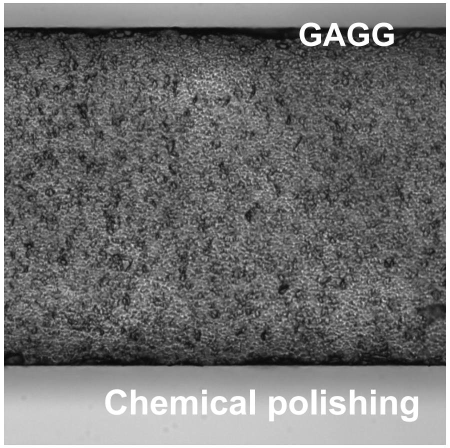
	LuAG:Ce Crytur	**LYSO:Ce** Epic Crystal	**GAGG:Ce,Mg** C&A Corporation
Formula	$Lu_3Al_5O_{12}$:Ce	$Lu_{1.8}Y_{0.2}SiO_5$:Ce	$Gd_3Al_2Ga_3O_{12}$:Ce,Mg
Density [g/cm^3]	6.73	7.1	6.63
Z_{eff}	63	65	55
Refraction index (at max emission)	1.84	1.81	-
Maximum of emission [nm]	535	420	520
Decay constant [ns]	70 (44%) 1063 (56%)	40-45	45 (58%) 135 (42%)
Photon yield [ph/MeV]	2.5 x 10^4	3 x 10^4	5.6 x 10^4
Photoelectron yield [% of NaI:Tl]	20	75	-
Radiation length at 511 keV [cm]	1.3	1.2	-
Attenuation length [cm]	5-30	40	-
Energy resolution at 662 keV [%]	8-8.5	7	5-6

src: K. Kamada *et al.*, IEEE Trans. Nucl. Sci. 63 (2016) 443-447



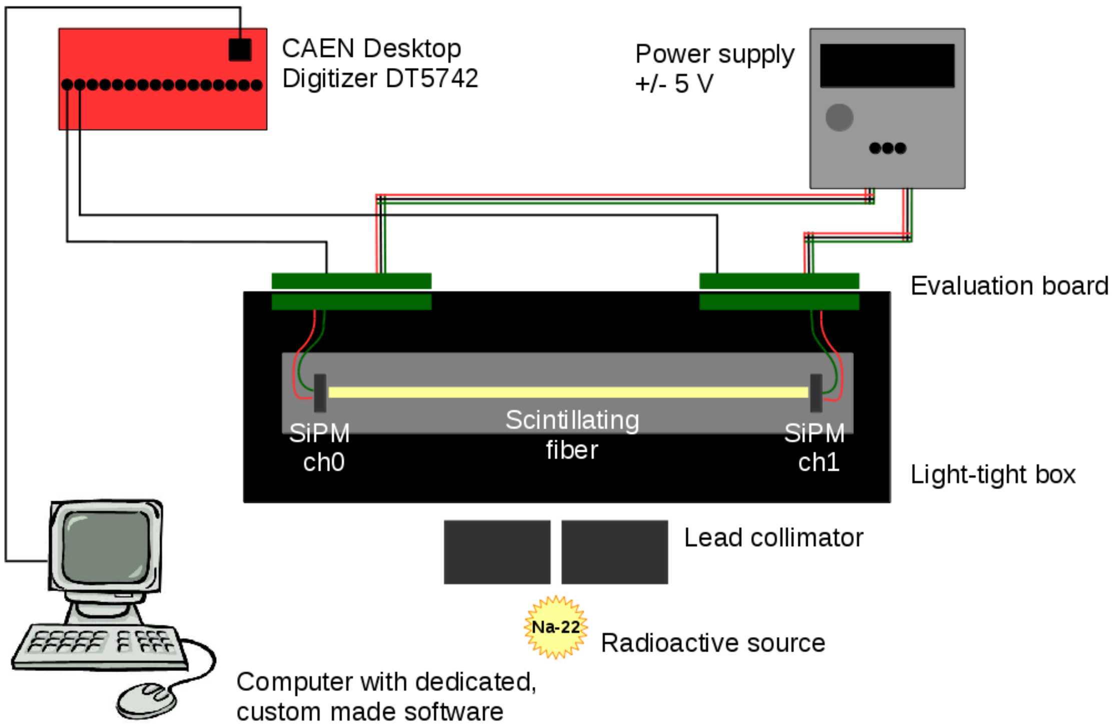


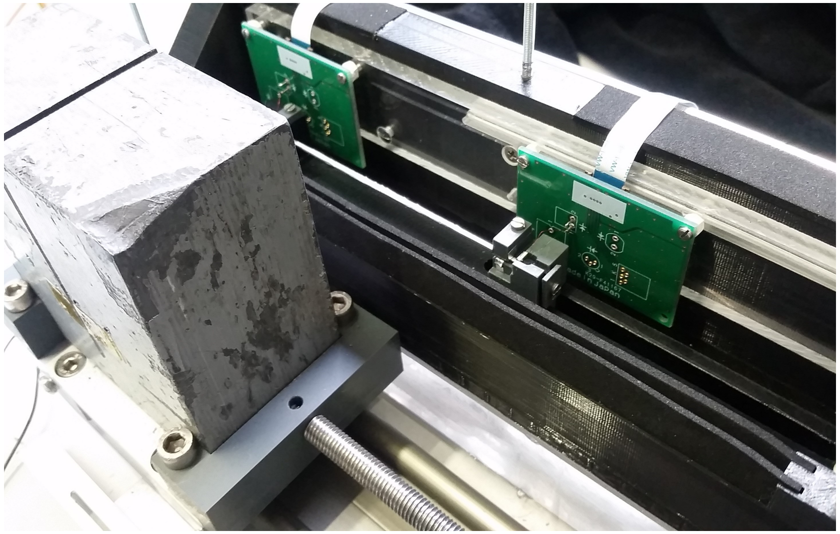




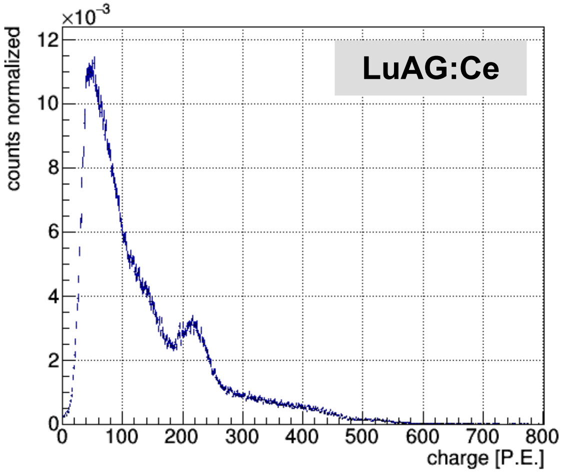
Microscopic pictures: Axio Observer Z1 Zeiss, bright field mode
mgr T. Kołodziej, mgr inż. Z. Baster, Department of Molecular and Interfacial Biophysics of JU

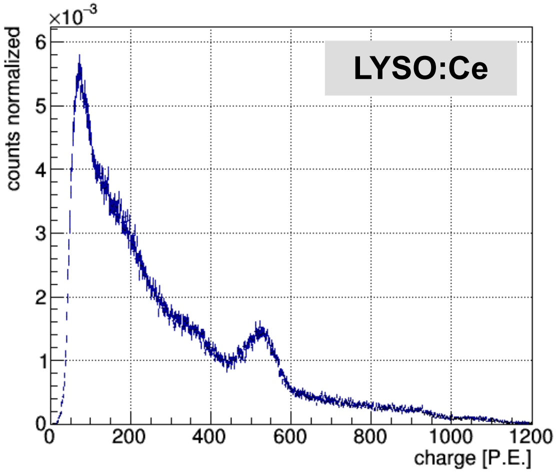
Experimental setup

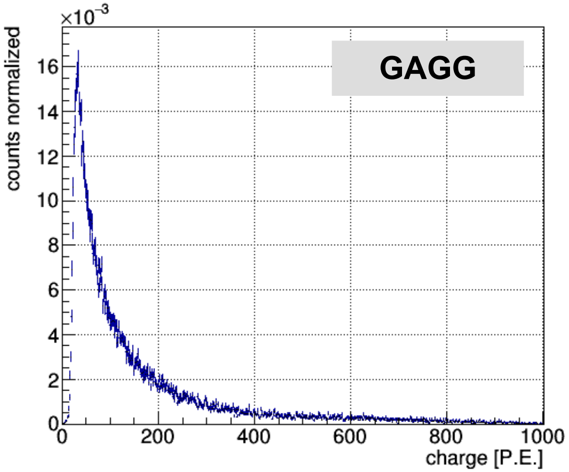


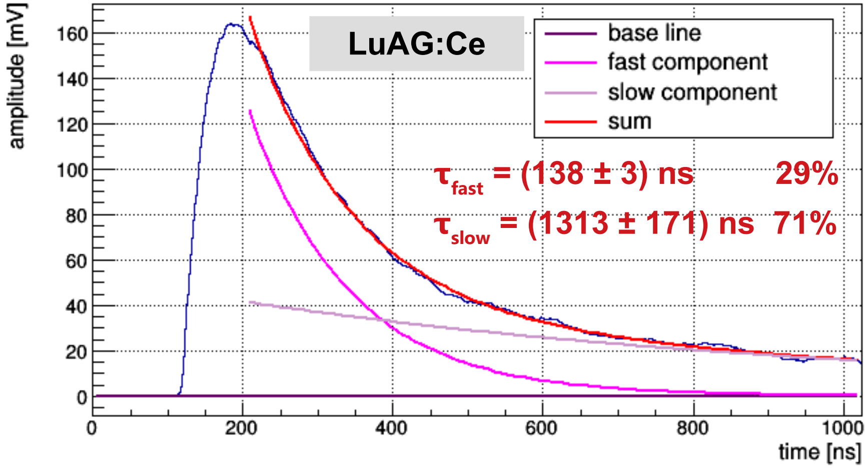


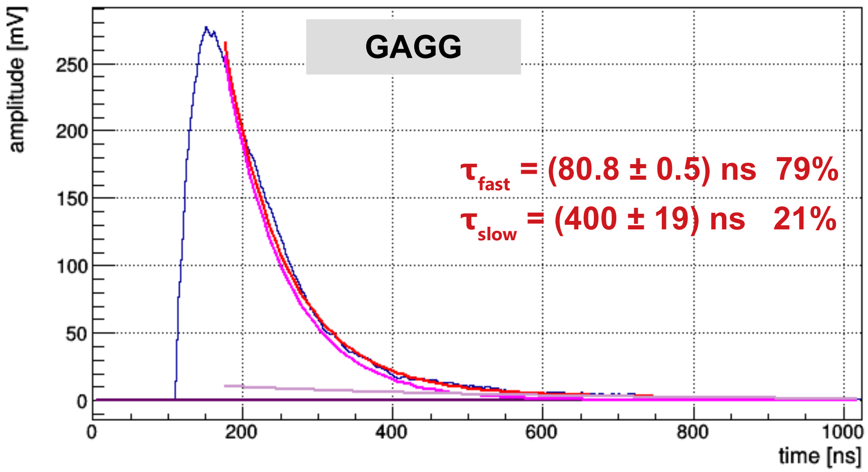
Hamamatsu Evaluation Board C12332-01
Hamamatsu SiPMs S13360-3050VE

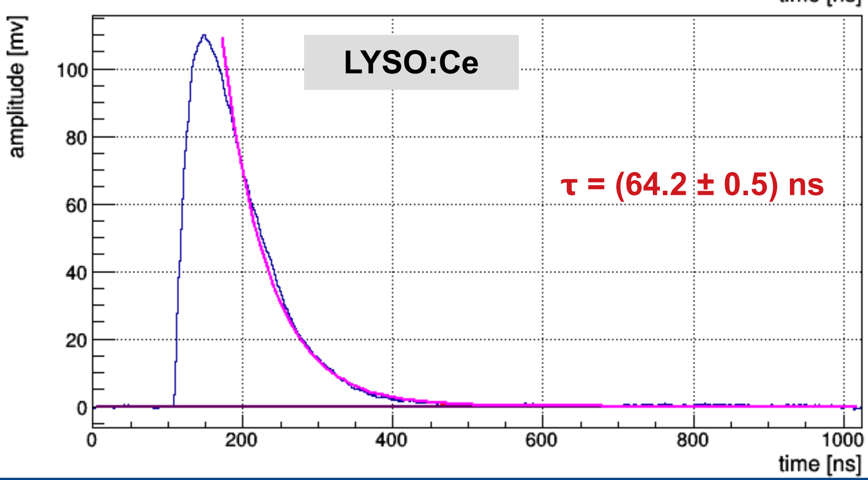












The decay process in LuAG:Ce and GAGG consists of two components – fast and slow:

$$f(t) = A_{fast}\, e^{-(t-t_0)/\tau_{fast}} + A_{slow}\, e^{-(t-t_0)/\tau_{slow}} + BL$$

Intensities of each component:

$$I_{fast} = \frac{\tau_{fast} \cdot A_{fast}}{\tau_{fast} \cdot A_{fast} + \tau_{slow} \cdot A_{slow}} \cdot 100\,\%$$

$$I_{slow} = 100\,\% - I_{fast}$$

A_{fast} – amplitude of the fast component
A_{slow} – amplitude of the slow component
τ_{fast} – fast decay constant
τ_{slow} – slow decay constant
t_0 – time offset
BL – base line

LYSO:Ce is characterized by single decay:

$$f(t) = Ae^{-(t-t_0)/\tau} + BL$$

J. Iwanowska et al., Nucl. Instr. And Meth. In Phys. Res. A 712 (2013) 34-40

Attenuation length

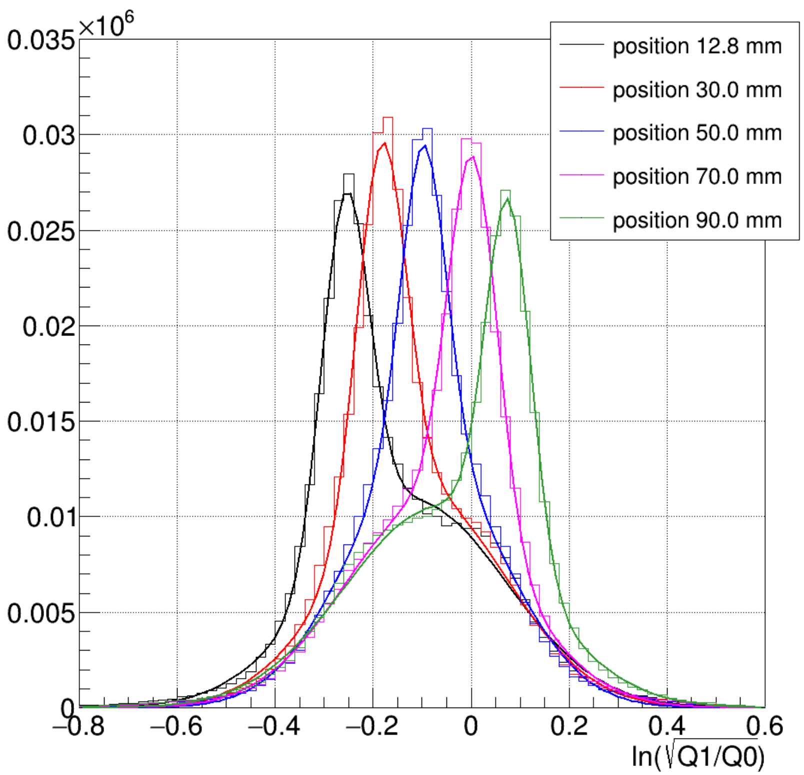
Attenuation length indicates the penetration depth of the light emitted in the scintillation process inside the scintillator itself.

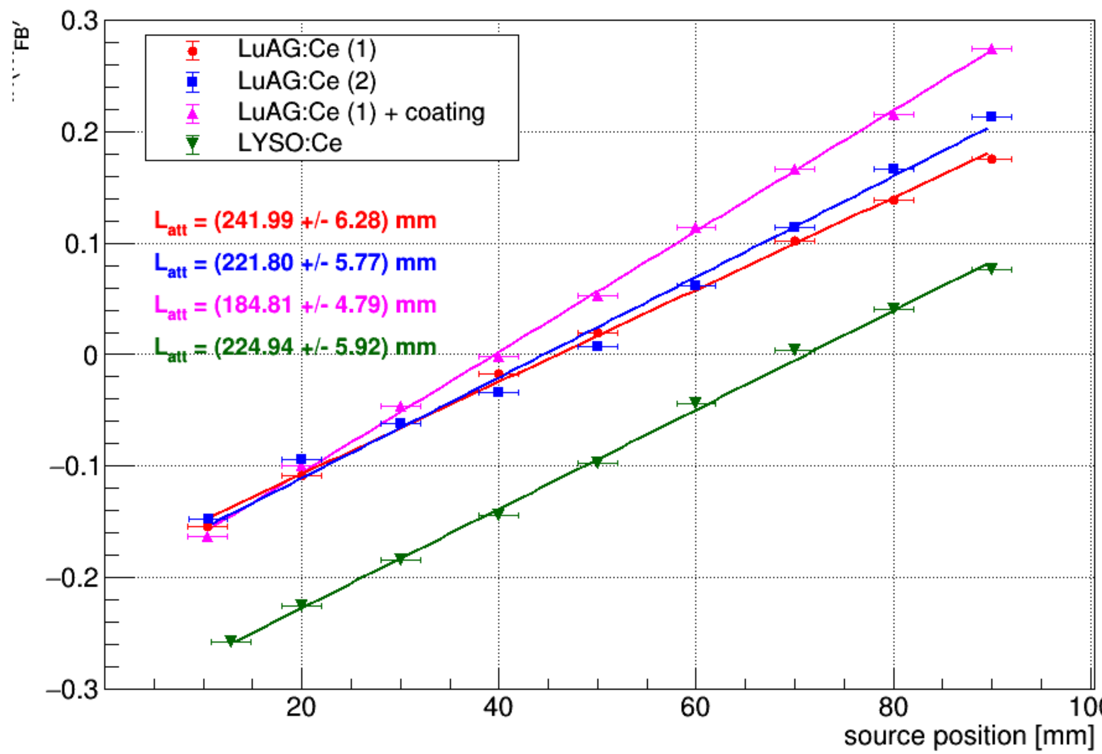
Having charge spectra registered at different positions z along the investigated fiber the attenuation length L_{att} can be determined as:

$$\ln\left(M_{FB}(z)\right) = A_0 + \frac{z}{L_{att}}$$

Where $M_{FB}(z)$ describes relative light output at both ends of the fiber and it's given as:

$$M_{FB}(z) = \sqrt{\frac{Q_1(z)}{Q_0(z)}}$$





K. Pauwels *et al.*, JINST 8 (2013) P09019

Light output and energy resolution

The light output has been determined as follows:

$$LO=\frac{n_{PE}}{E\cdot C_{PDE}\cdot e^{z/L_{att}}}$$

where E is an energy, n_{PE} is number of photoelectrons and C_{PDE} is SiPMs photodetection efficiency.

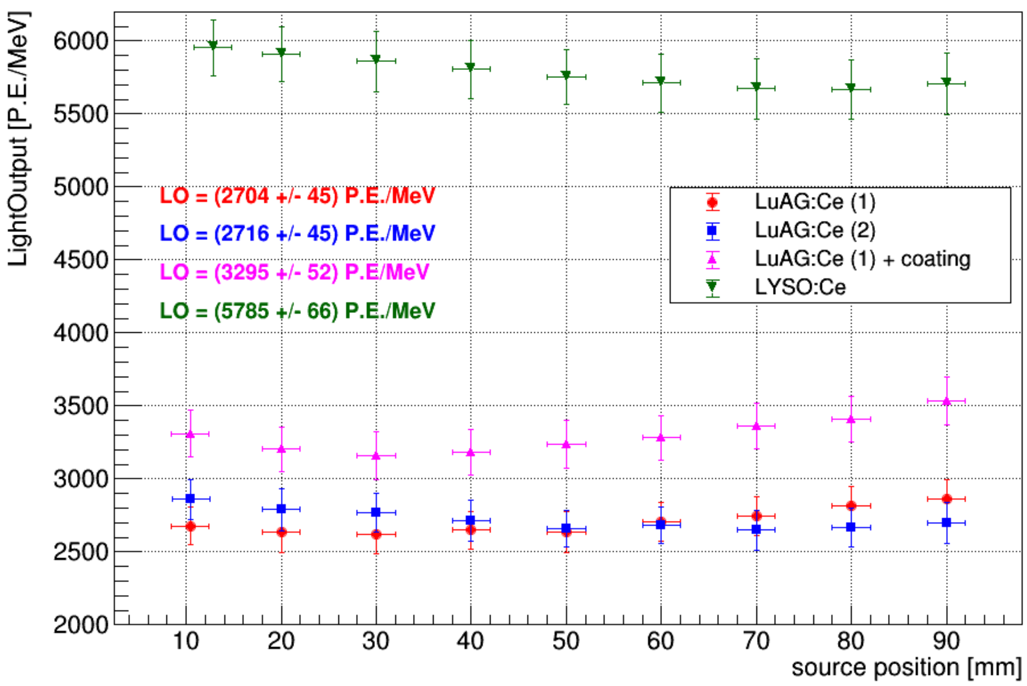
Having relative light output on both ends of the investigated fiber position resolution can be determined as:

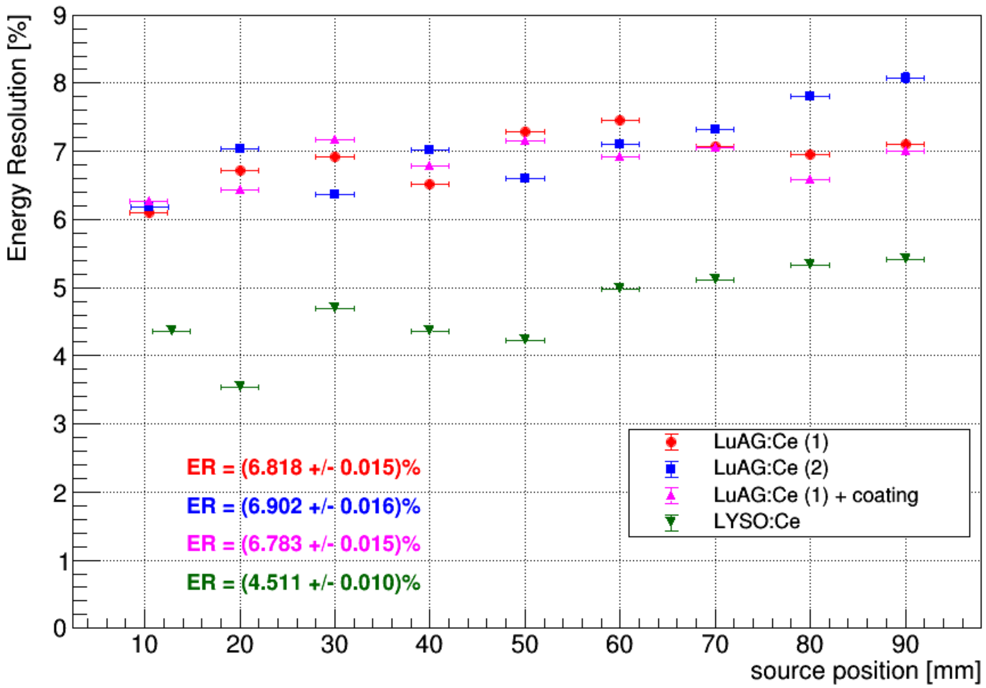
$$PR(z)=L_{att}\cdot\sigma_{MFB}(z)$$

The energy resolution has been determined the for 511 keV peak:

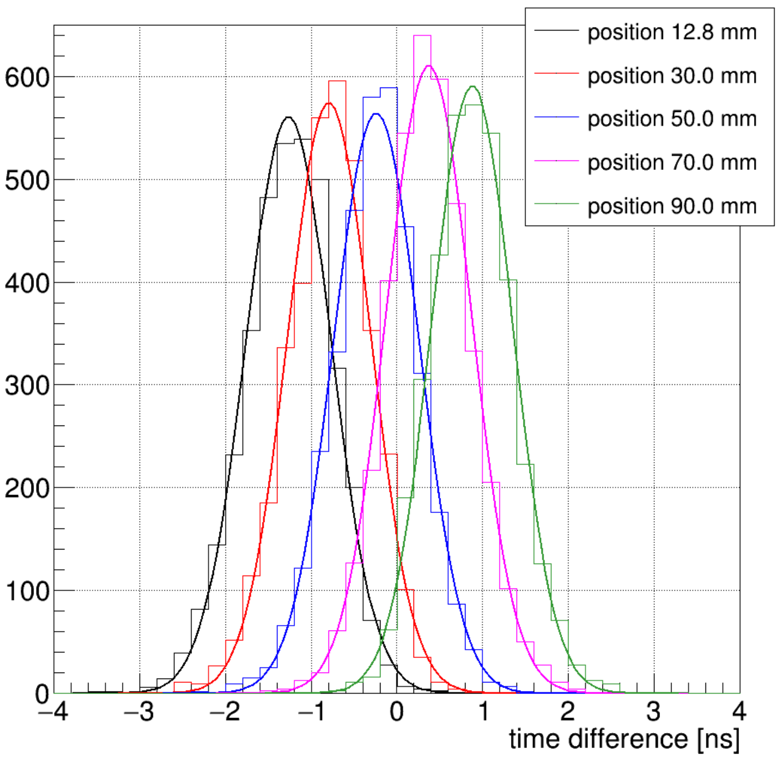
$$ER=\frac{\sigma_{511\,keV}}{PE_{511\,keV}}\cdot 100\,\%$$

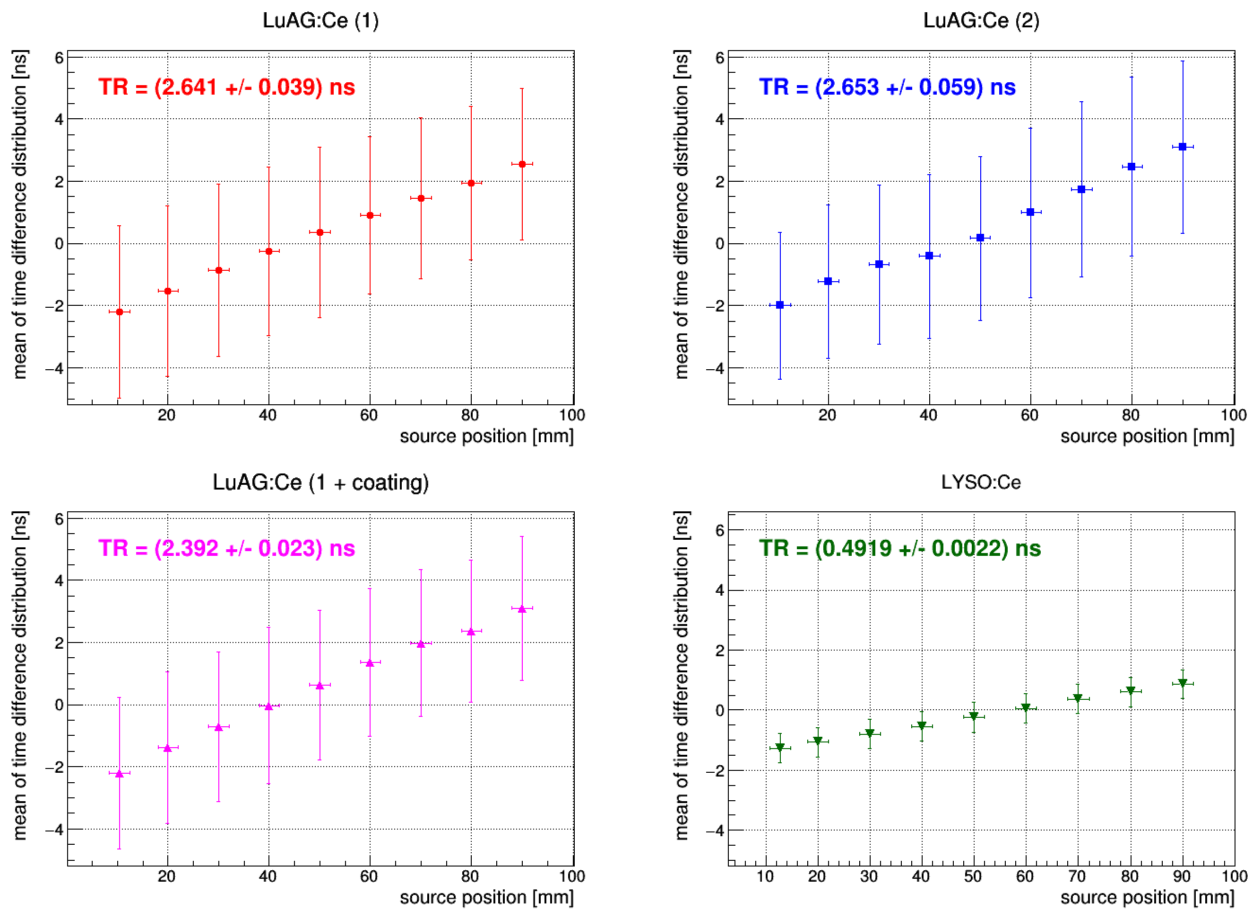
Charge spectra were corrected for the attenuation of the scintillating light.





- Timing resolution of the investigated scintillator results from the time difference between correlated events being registered at both ends of the fiber.
- The $T_{0\,ch0} - T_{0\,ch1}$ distribution is described by Gaussian function and timing resolution is its σ.
- Only events from 511 keV peak have been taken into account in the timing resolution determination in order to further improve this characteristics.





Conclusions:

• Comparison between the two scintillating fibers from the same production batch showed no significant differences in light output, timing and energy resolution, while they differ slightly in attenuation length

• Comparison between naked fiber and fiber coated with the Al foil showed, that coating reduces attenuation length, but at the same time improves light output.

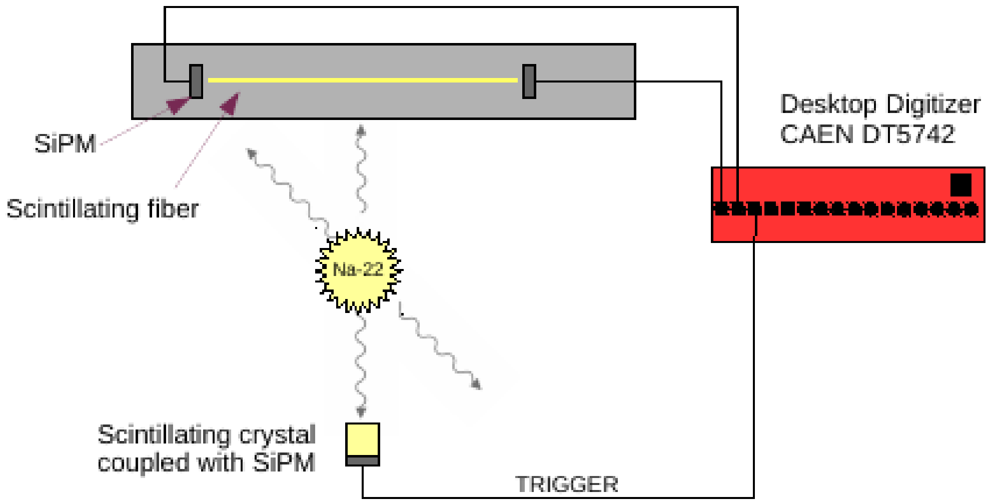
• From the three investigated materials LYSO:Ce shows timing properties, light output and energy resolution which is the most suitable for future application in medical imaging detector.

Further research:

• Investigating an influence of different coatings, *e.g.* Teflon tape, white paint.

• Replacing the lead collimator with an 'electronic collimator', which will result in significant background suppression

• Further tests with GAGG:Ce,Mg – mechanical polishing



Thank you for your attention

The research is founded under the DSC 2017 and DSC 2018 grant intended to finance the development of young researchers and PhD students of the Faculty of Physics, Astronomy and Applied Computer Science. MNiSW decision number: 7150/E-338/M/2017 and 7150/E-338/M/2018.

The research has been conducted with the collaboration with C&A Corporation Japan: K. Kamada, A. Yoshikawa, Y. Shoji