JAGIELLONIAN UNIVERSITY IN KRAKÓW

J-PET
Jagiellonian Positron Emission Tomography

Comparative studies of commercial and synthesized plastic scintillators for medical applications

Łukasz Kapłon[1,2,3]

on behalf of the J-PET Collaboration

[1] Faculty of Physics, Astronomy and Applied Computer Science, Jagiellonian University in Krakow, Poland

[2] Total-Body Jagiellonian-PET Laboratory, Jagiellonian University in Krakow, Poland

[3] Center for Theranostics, Jagiellonian University, Krakow, Poland

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http://koza.if.uj.edu.pl/pet **lukasz.kaplon@uj.edu.pl**

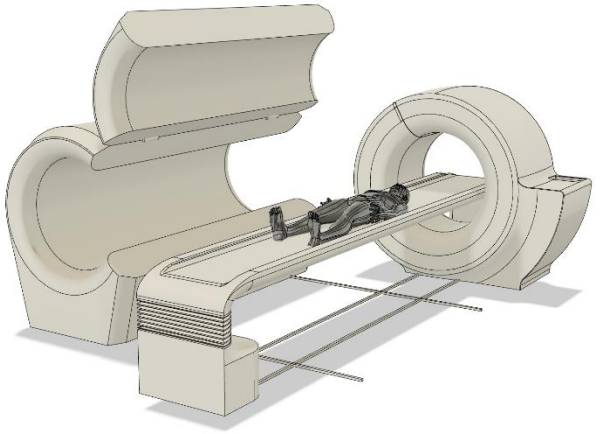
Outline

1) Motivation
2) Chemistry of plastic scintillators
3) Comparative studies of commercial plastic scintillator strips with high technical attenuation length:
    a) emission spectra,
    b) transmission spectra,
    c) technical attenuation length,
    d) influence of scintillator's cross-sections on light attenuation.
4) Synthesis of plastic scintillators via bulk polymerization
5) Properties of polystyrene scintillators with blue and green emission:
    a) emission spectra,
    b) light output,
    c) concentration optimization of fluorescent dyes.
6) Conclusions

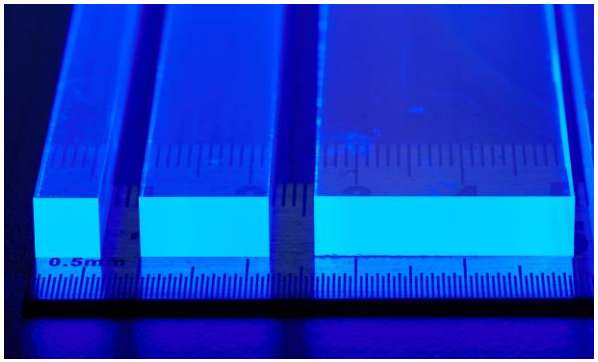
Motivation

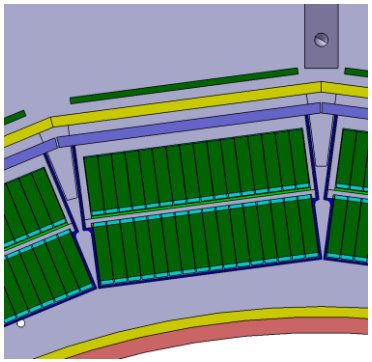
The primary aim of the J-PET group is to elaborate a technology for:

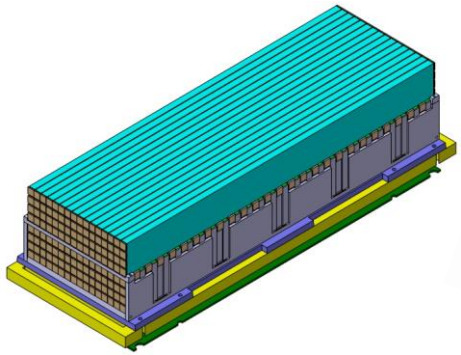
- **the cost-effective total-body PET scanner based on plastic scintillators;**
- **PET scanner with positronium and multiphoton imaging capabilities;**
- **modular and transportable PET scanner with the field-of-view adjustable to the patient size.**

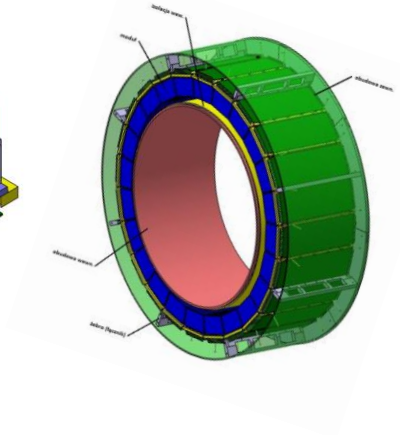


Total-body J-PET scanner



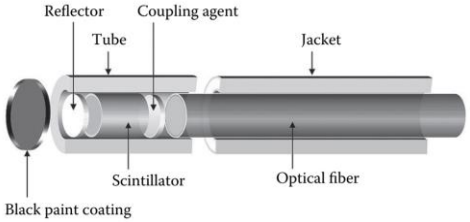






Motivation for research in materials science:

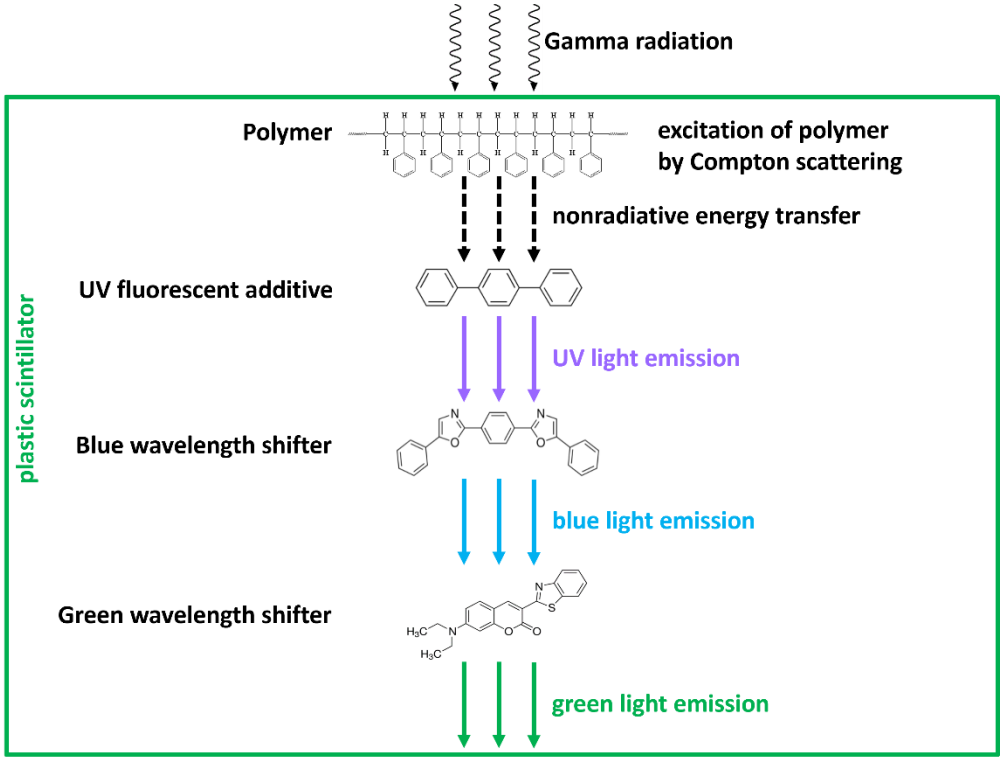
- **synthesize polyvinyl toluene- and polystyrene-based scintillators for time-of-flight PET detectors;**
- **develop blue- and green-emitting plastic scintillators with high light output for plastic scintillation dosimetry.**



Plastic scintillation dosimeter

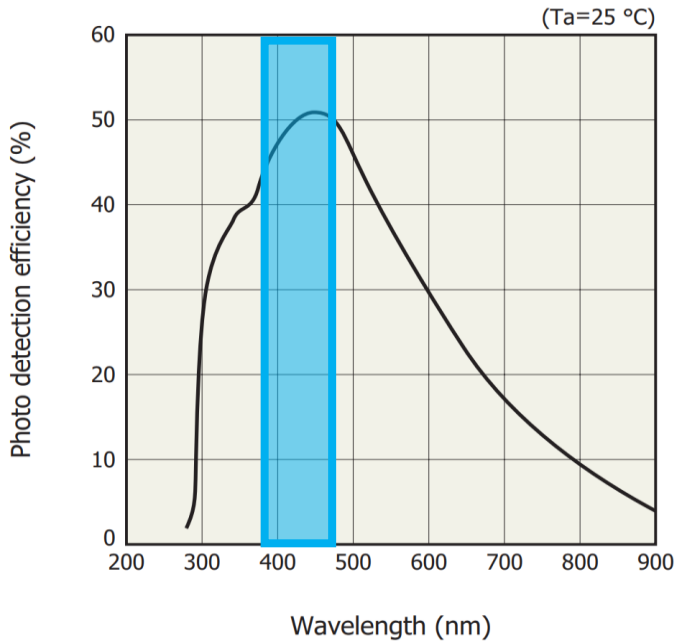
Chemistry of plastic scintillators and scintillation principle

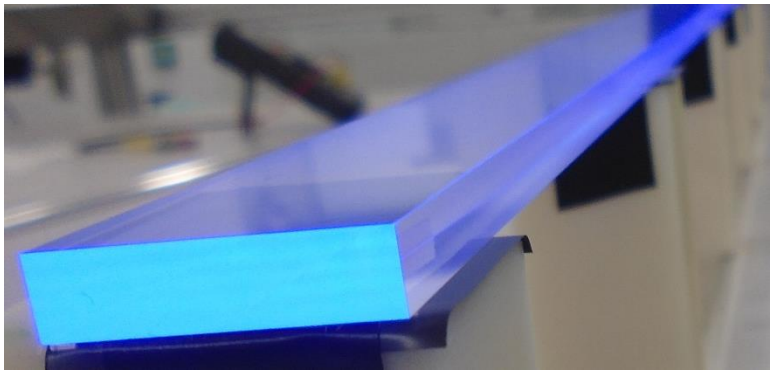
Light emission mechanism



Scintillator emission vs QE

Max. QE of SiPM 50% at 450 nm





Efficient energy transfer conditions:

- **emission/absorption spectra of fluorescent dyes are overlapping;**
- **high fluorescence quantum yield of both substances;**
- **optimum concentration in the polymer.**

Ł. Kapłon, Synthesis and characterization of plastic scintillators for the total-body J-PET scanner. Acta Phys Pol B. 51 (2020) 225

Part I

Commercial plastic scintillators

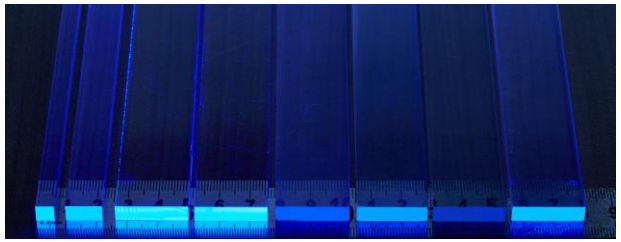
for total-body J-PET scanner

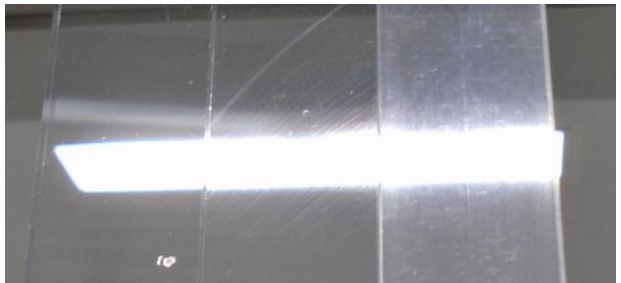
Plastic scintillator strips with high technical attenuation length:
properties based on data sheets

Plastic scintillator	Light output (ph/MeV)	Decay time (ns)	Wavelength of maximum emission (nm)	Light attenuation length (cm)	Polymer base	Refractive index	Density (g/cm³)
BC-408	10 000	2.1	425	380	PVT	1.58	1.023
EJ-200	10 000	2.1	425	380	PVT	1.58	1.023
RP-408	10 000	2.1	425	400	PVT	1.58	1.032
Epic	8 600	2.4	415	200	PS	1.58	1.050
SP32	8 750	2.5	425	ND	PS	1.57	1.030
UPS-923A	8 750	3.3	418	400	PS	1.60	1.060

The same properties

Similar properties

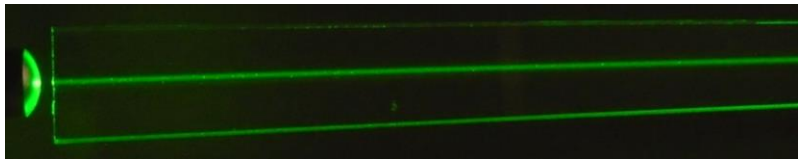




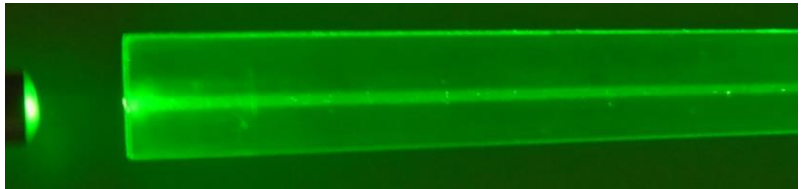
General purpose plastic scintillators that combine:

- long optical attenuation length
- blue emission close to max. QE
  - high light output
    - fast timing.

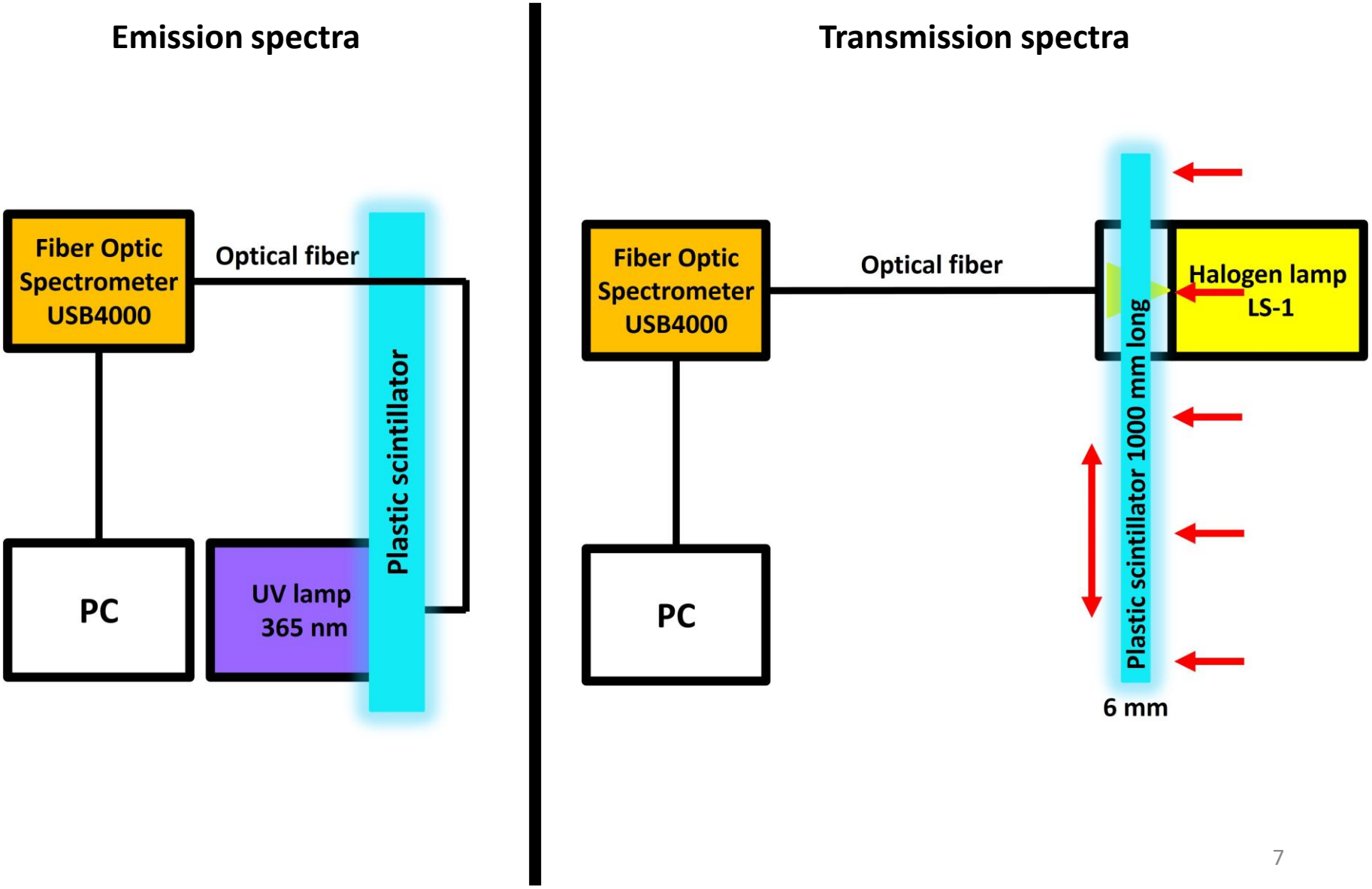
BC-408 = faces as-cast, edges diamond-milled



RP-408 = buffing polishing

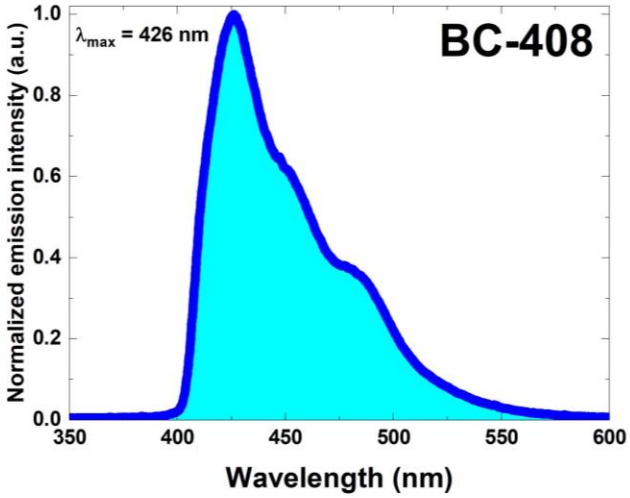


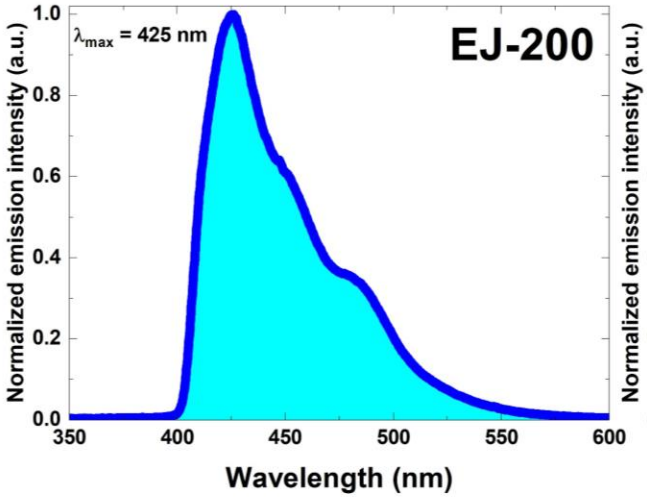
Plastic scintillator strips with high technical attenuation length: measurement setups

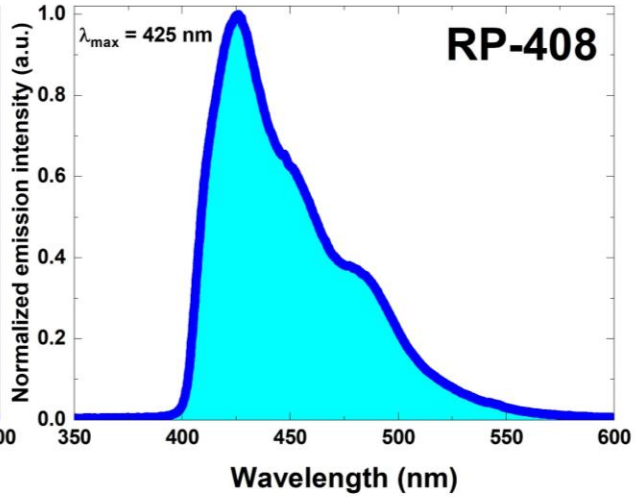


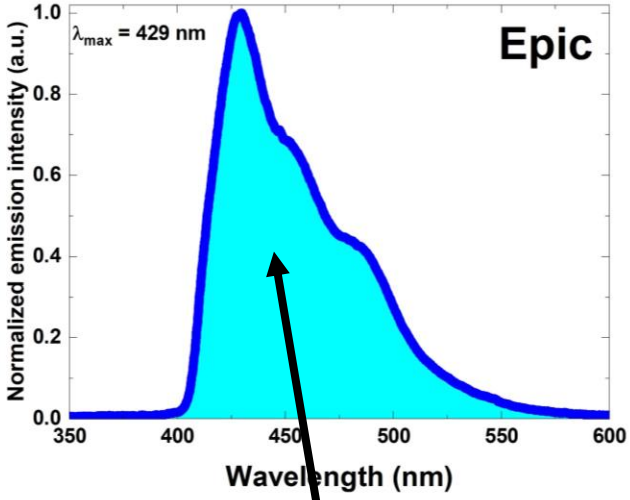
Plastic scintillator strips with high technical attenuation length:

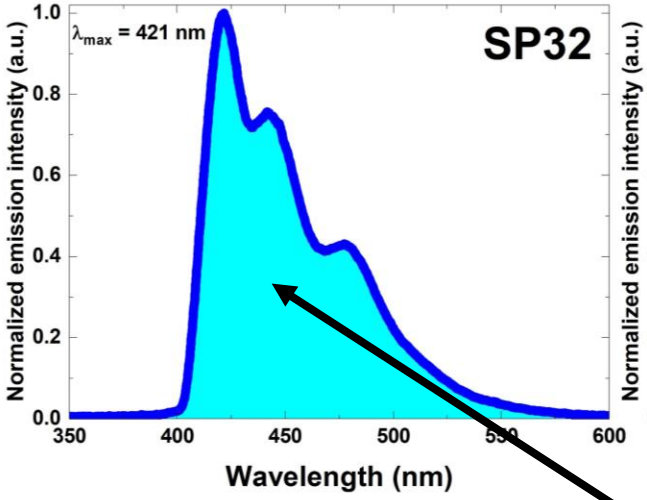
emission spectra

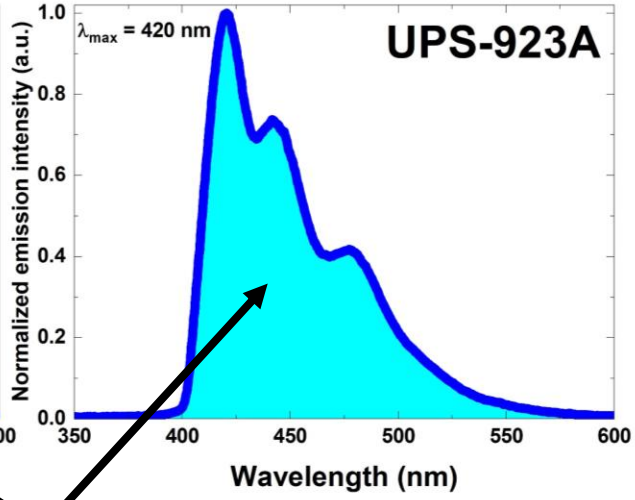




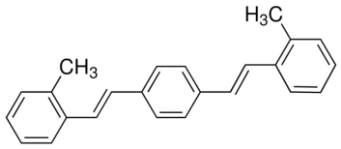


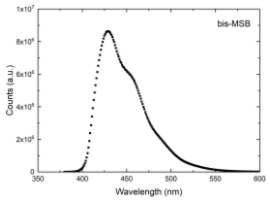




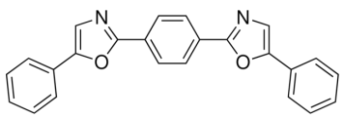


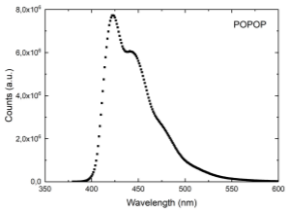
bis-MSB





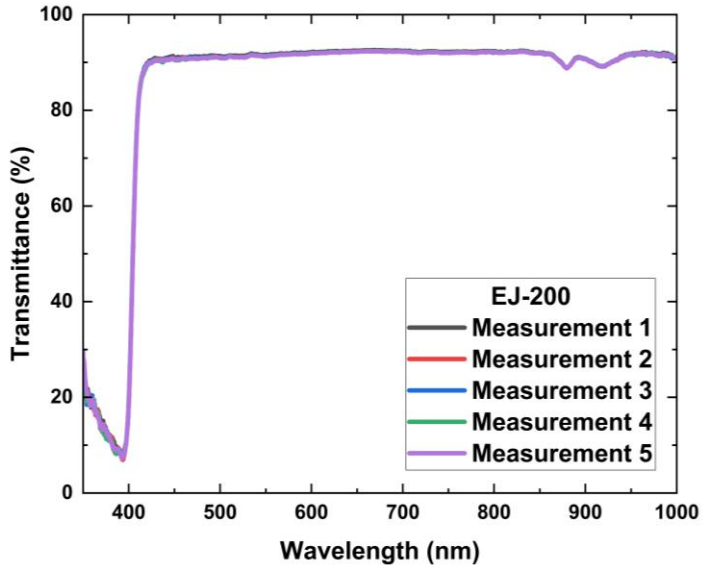
POPOP

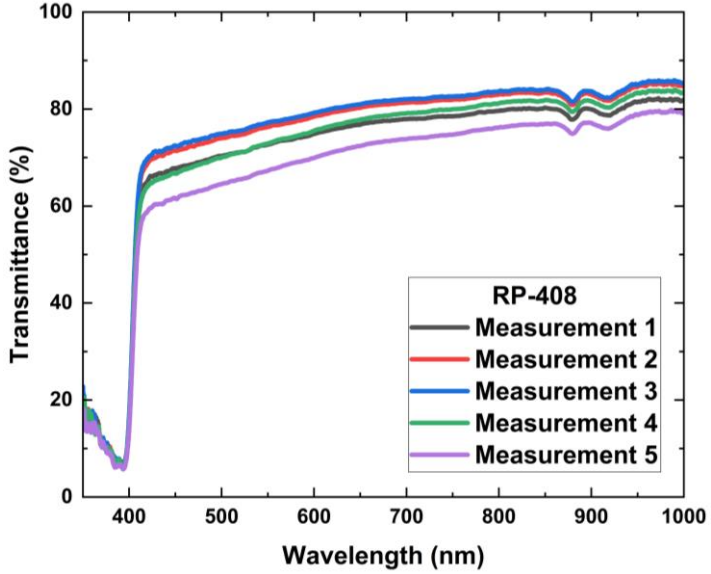


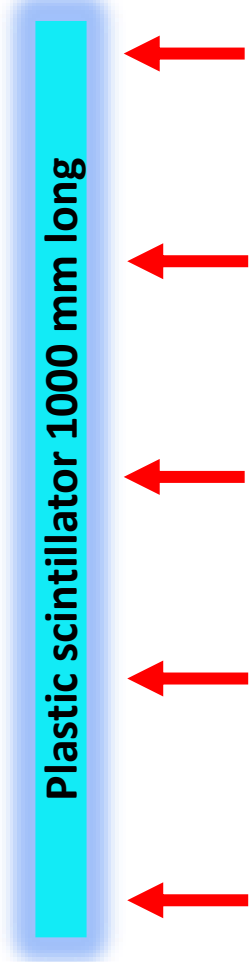


Plastic scintillator strips with high technical attenuation length:
transmission spectra through 6 mm thick strip

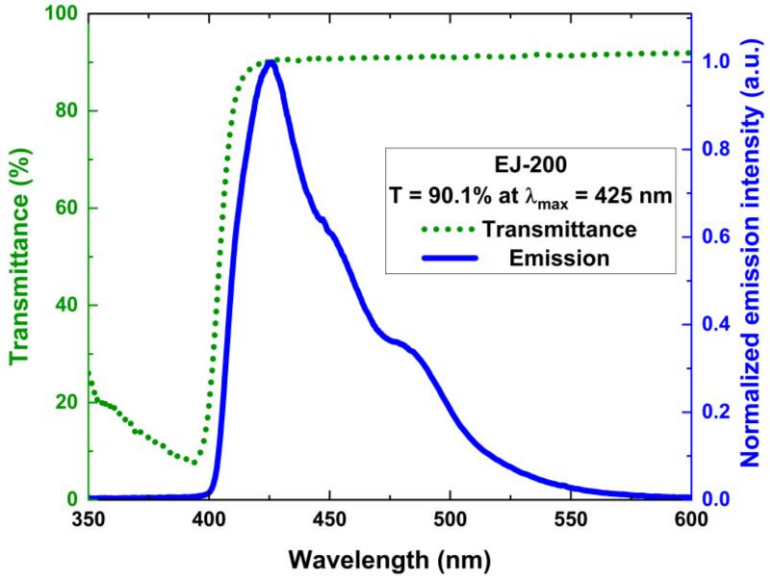
Five measurements 200 mm away

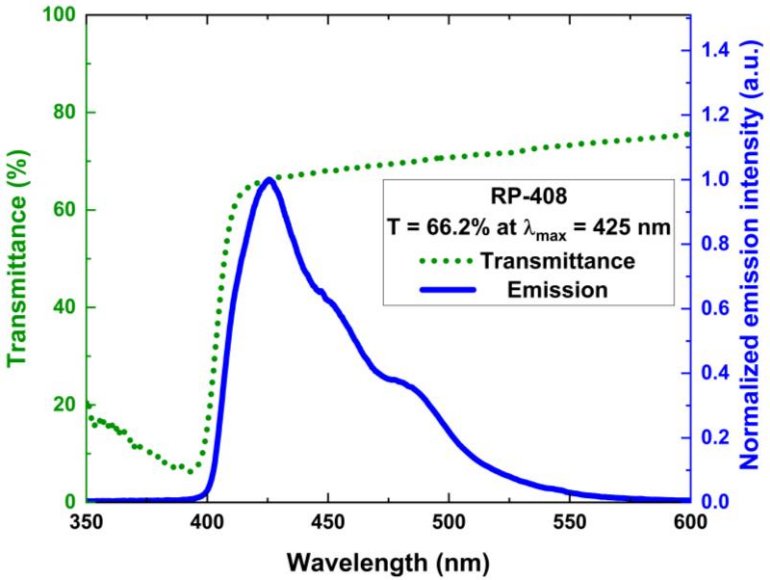






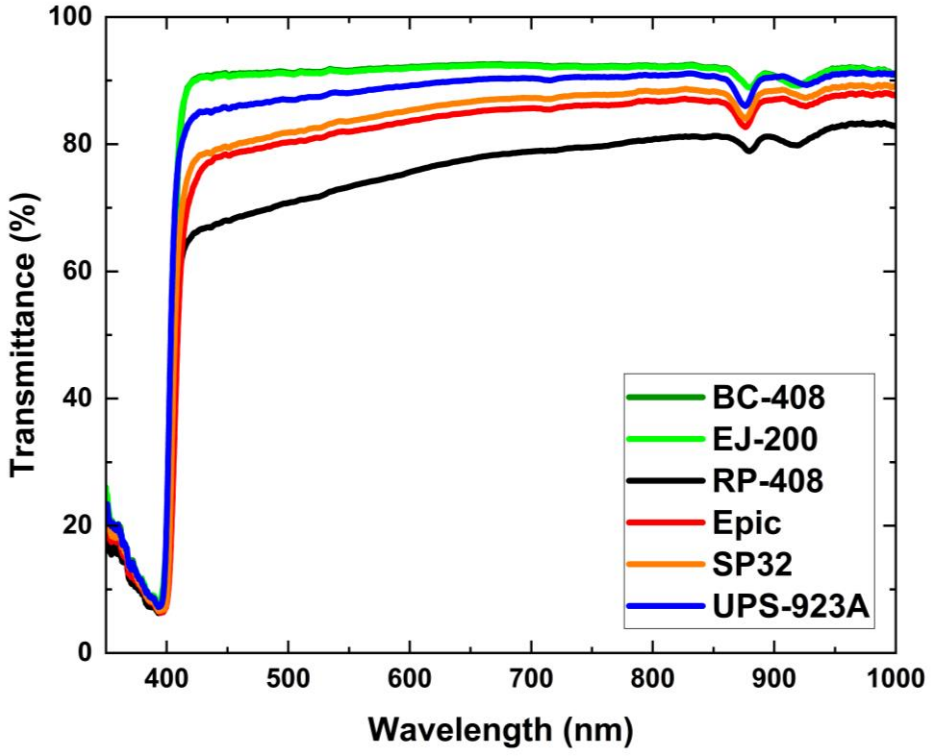
Averaged transmission spectra

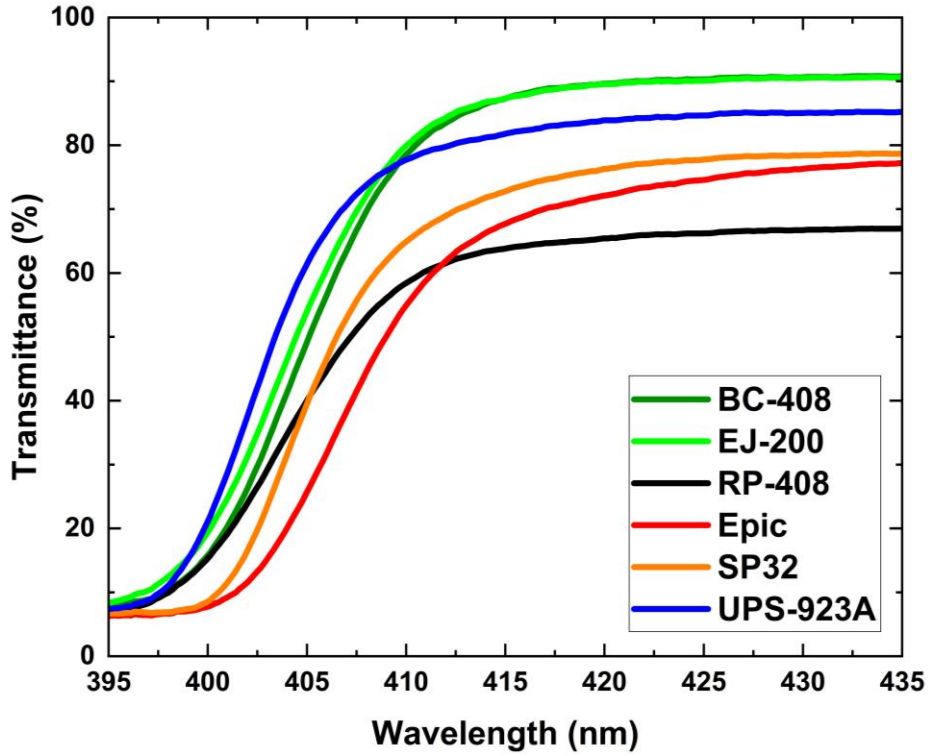




Plastic scintillator strips with high technical attenuation length:
transmission spectra through 6 mm thick strip

Plastic scintillator	Wavelength of maximum emission (nm)	FWHM of emission spectrum (nm)	Transmittance at the wavelength of maximum emission (%)
BC-408	426	51	90.5 ± 0.18
EJ-200	425	50	90.1 ± 0.18
RP-408	425	53	66.2 ± 4.33
Epic	429	55	76.1 ± 1.66
SP32	421	48	76.8 ± 0.52
UPS-923A	420	48	83.9 ± 0.26

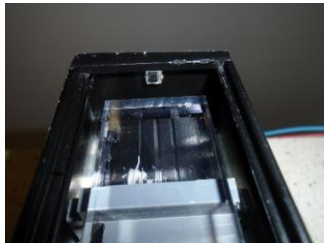


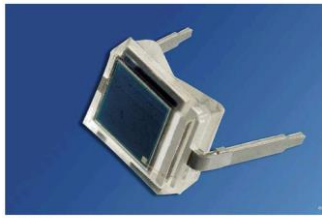


Plastic scintillator strips with high technical attenuation length: measurement setups

The **technical attenuation length (TAL)** of a plastic scintillator bar is defined as the length of scintillator reducing the light signal by a factor of *e* and depending upon:

- bulk transmission of the scintillator material,
- scintillator thickness,
- shape of the scintillator,
- reflective property of the surfaces.





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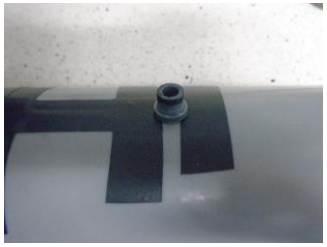
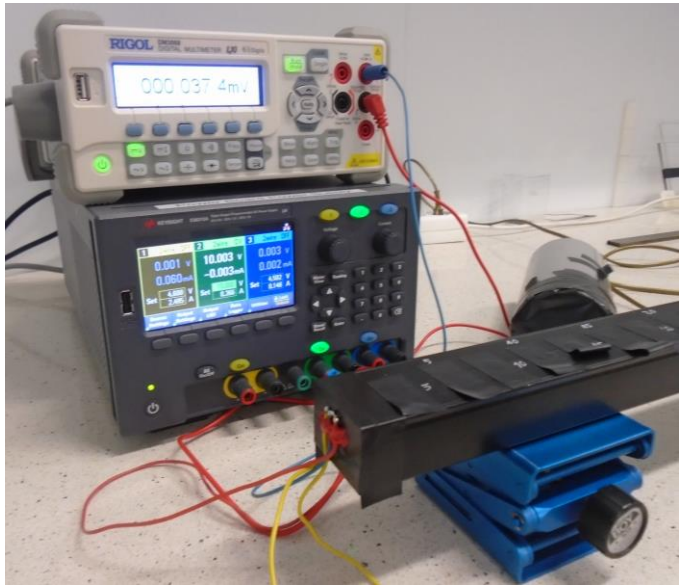
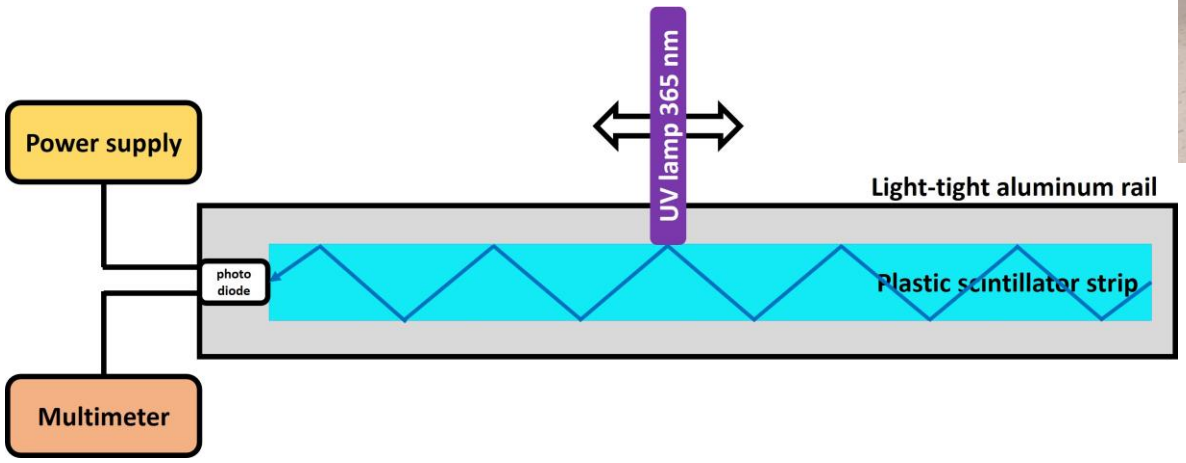
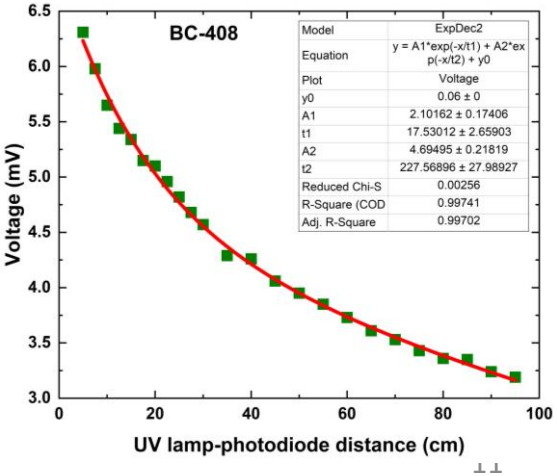




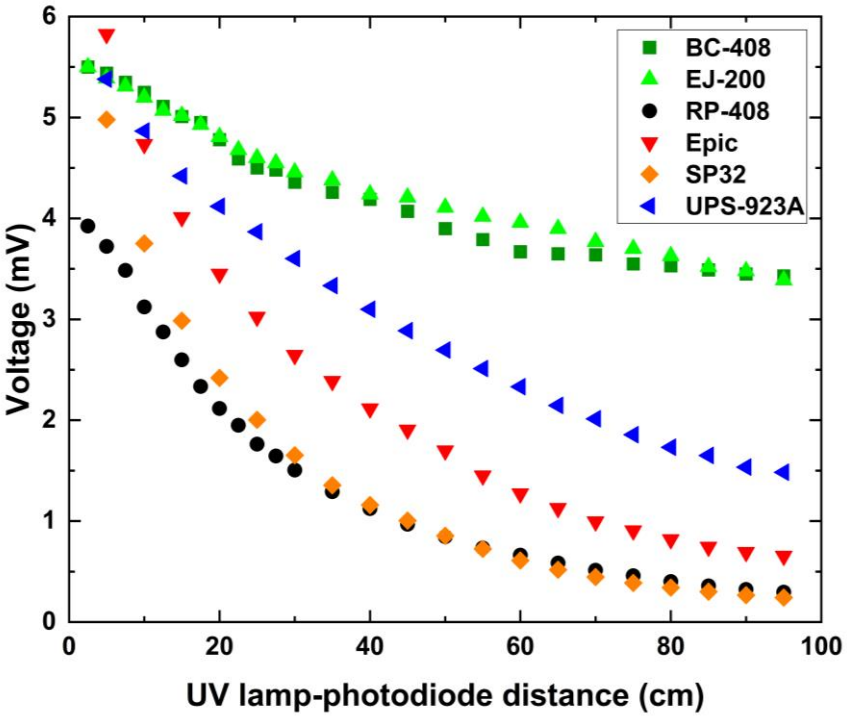


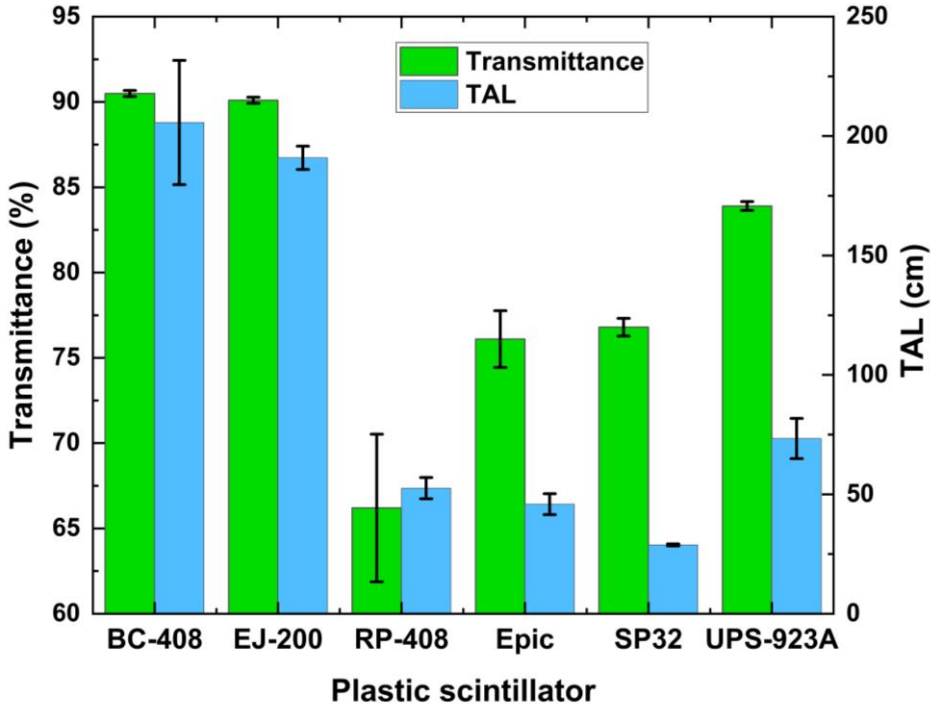


Ł. Kapłon, Technical attenuation length measurement of plastic scintillator strips for the total-body J-PET scanner, IEEE Trans. Nucl. Sci. 67 (2020) 2286

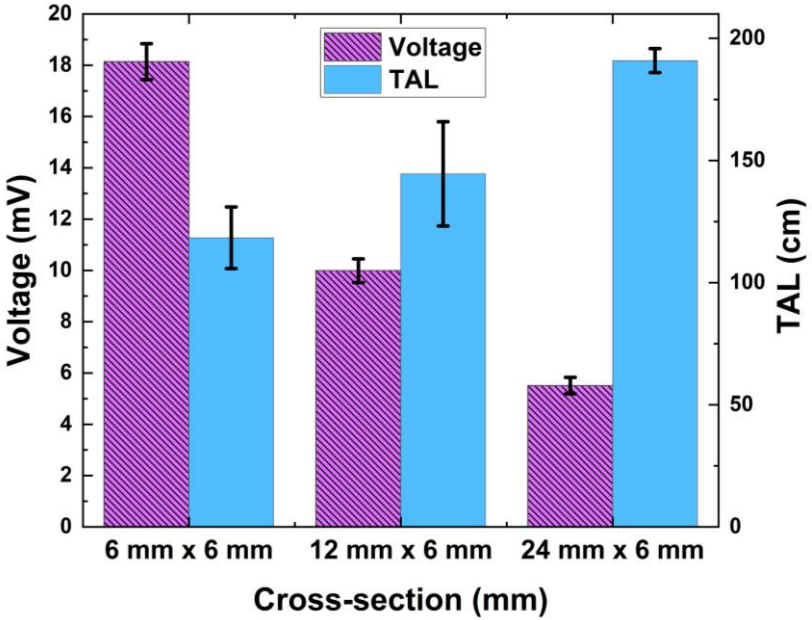
Plastic scintillator strips with high technical attenuation length:
technical attenuation length - scintillator types

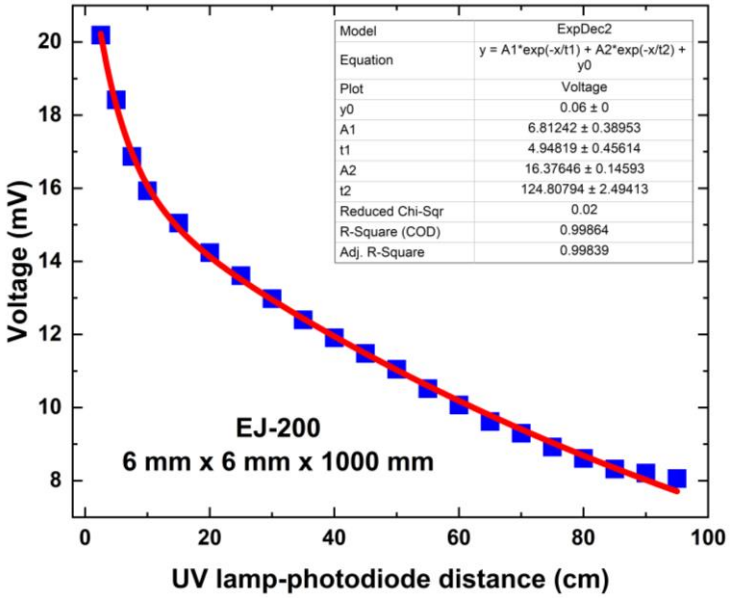
Plastic scintillator	Wavelength of maximum emission (nm)	FWHM of emission spectrum (nm)	Transmittance at the wavelength of maximum emission (%)	Technical attenuation length (cm)
BC-408	426	51	90.5 ± 0.18	205.68 ± 26.02
EJ-200	425	50	90.1 ± 0.18	190.90 ± 4.89
RP-408	425	53	66.2 ± 4.33	52.61 ± 4.45
Epic	429	55	76.1 ± 1.66	45.85 ± 4.37
SP32	421	48	76.8 ± 0.52	28.84 ± 0.41
UPS-923A	420	48	83.9 ± 0.26	73.37 ± 8.40





Plastic scintillator strips with high technical attenuation length:
technical attenuation length – EJ-200 scintillator cross-sections

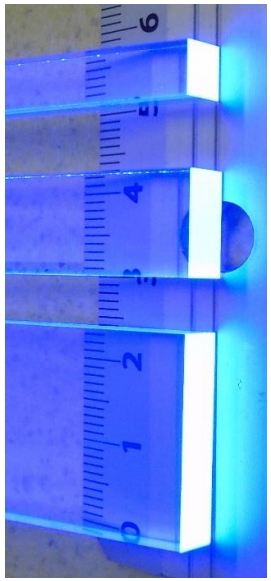


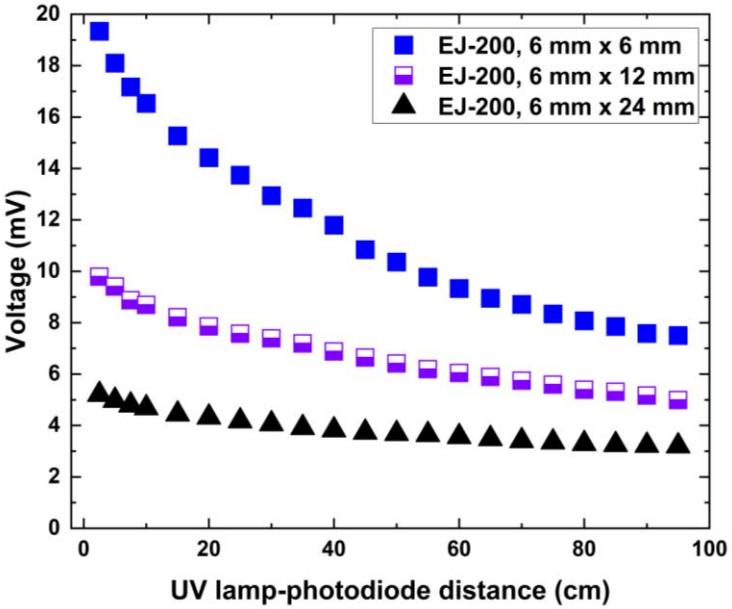


6 mm x 6 mm

6 mm x 12 mm

6 mm x 24 mm





Part II

Synthesized plastic scintillators

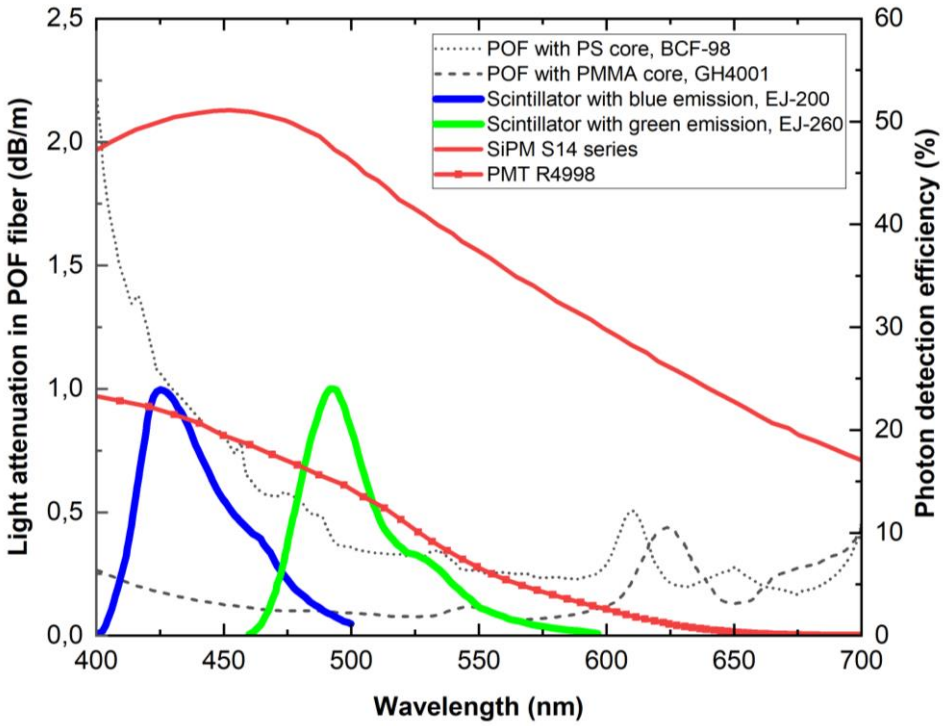
for plastic scintillation dosimetry

Motivation

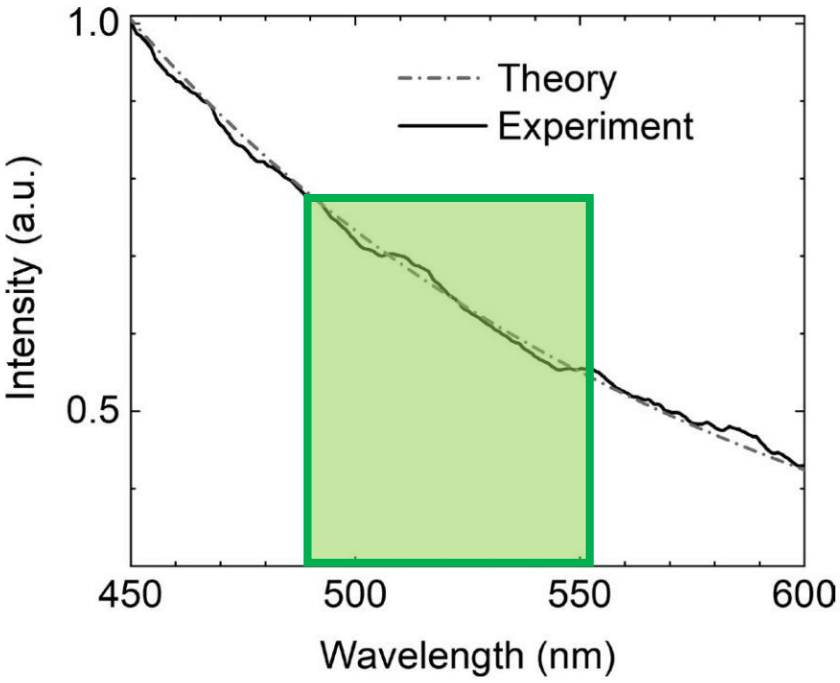
Green-emitting plastic scintillators have several advantages over blue-emitting scintillators:

- they are more resistant to radiation;
- green light above 500 nm is the least attenuated in plastic optical fibers used for PSD;
- the longer the wavelength of scintillators light, the smaller portion of Czerenkov light is emitted in plastic dosimeter and subtraction of this stem signal is easier.

Light attenuation in plastic optical fibers and PDE of light detectors

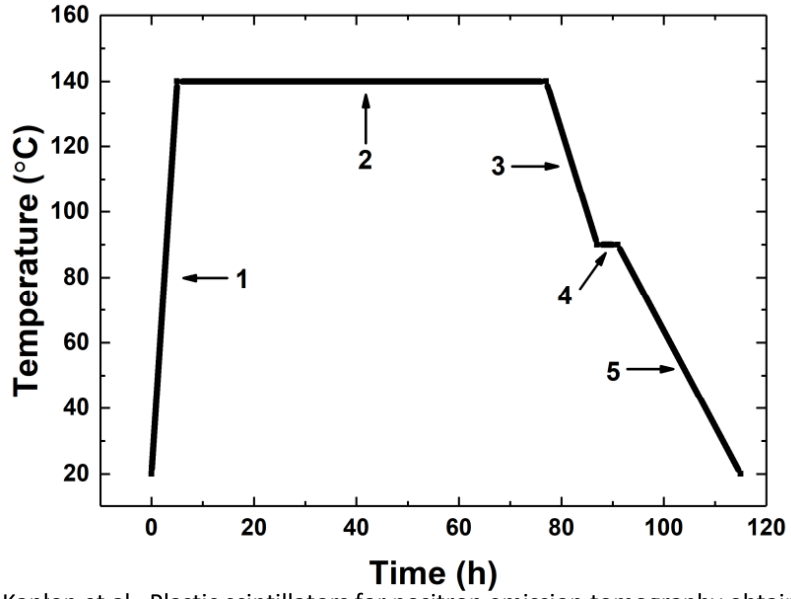


Typical spectrum of Cherenkov radiation collected by optical fiber

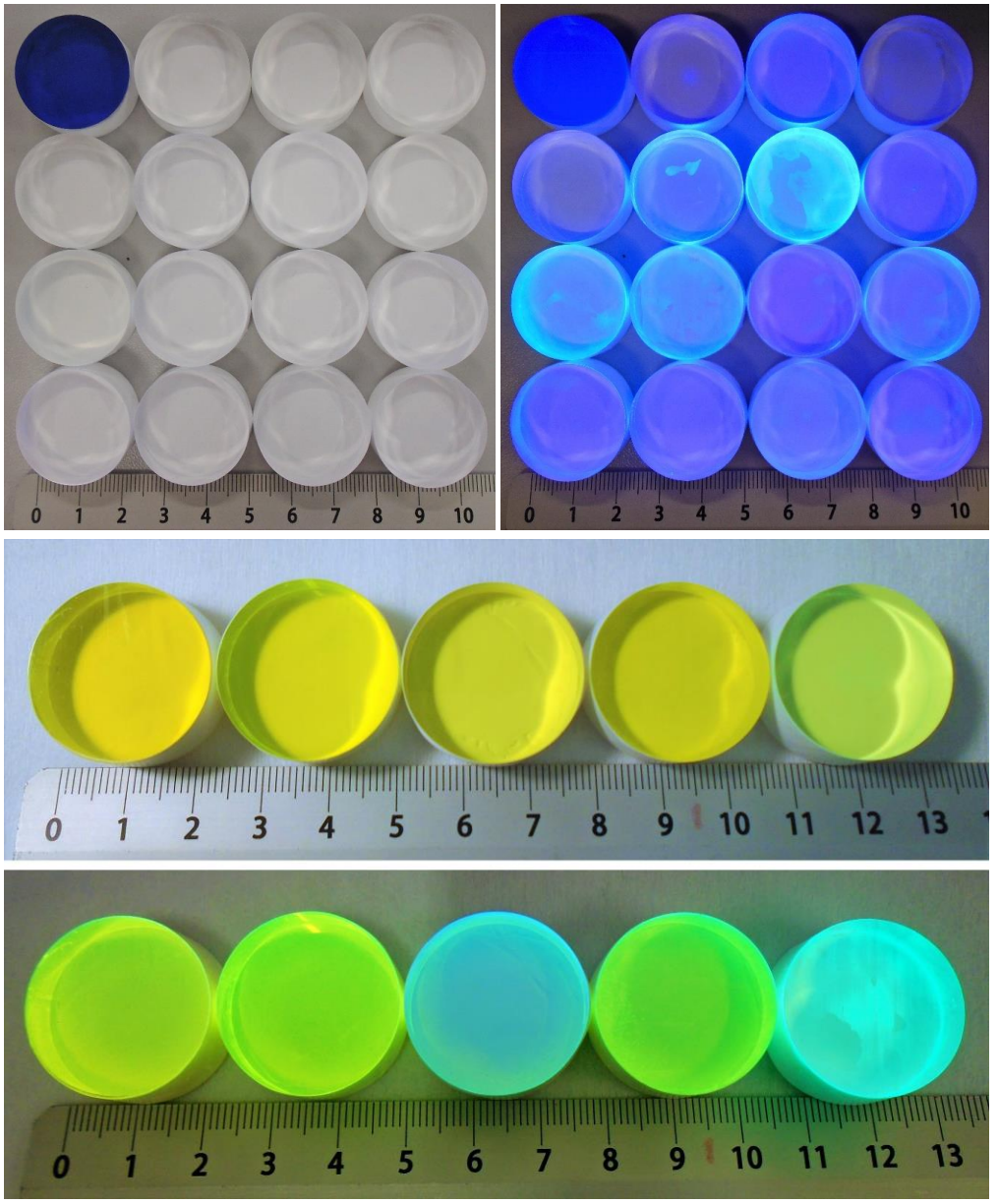


Radiation Therapy Dosimetry. A Practical Handbook, A. Darafsheh 2021

Free-radical bulk polymerization of styrene



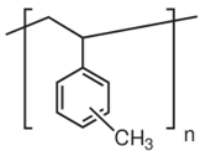
Ł. Kapłon et al., Plastic scintillators for positron emission tomography obtained by the bulk polymerization method, BAMS 10 (2014) 27



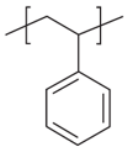
Plastic scintillator samples, 25 mm diameter x 10 mm height
Different blue- and green-emitting wavelength shifters

Chemical components for plastic scintillator manufacture: polymers and UV-emitting fluorescent substances

Polymer bases

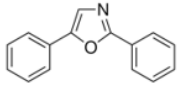


PVT, poly(vinyltoluene)



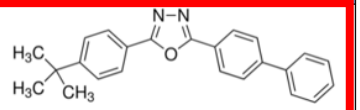
PS, polystyrene

Primary fluorescent additives, 1-4 wt. %

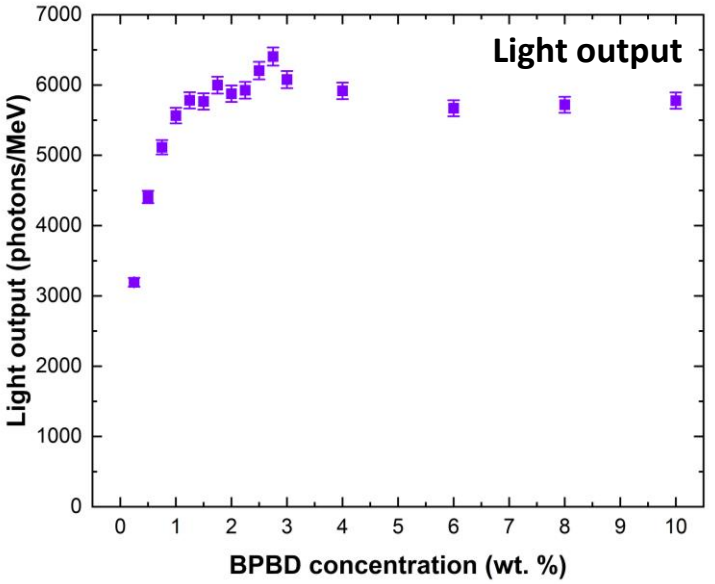


PPO

PTP



BPBD

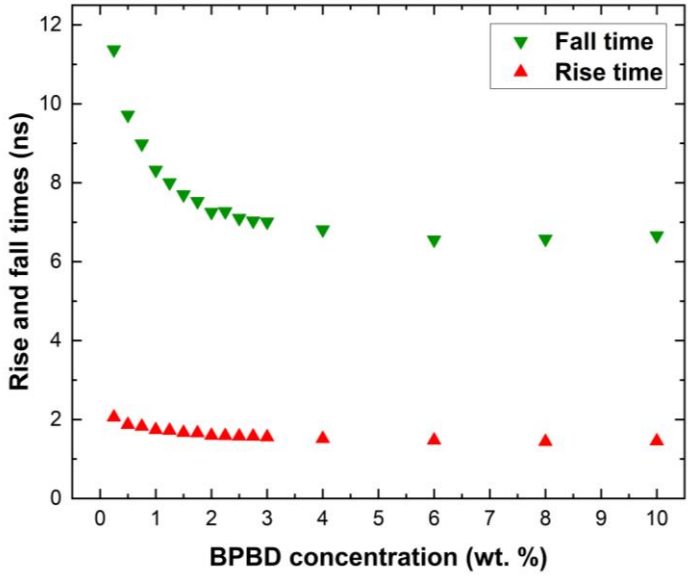


Relative light output values:

- **PPO 0.87**
- **PTP 0.89**
- **BPBD 1.00**

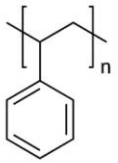
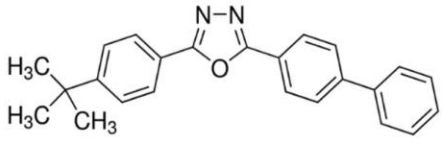
Concentrations in polystyrene:

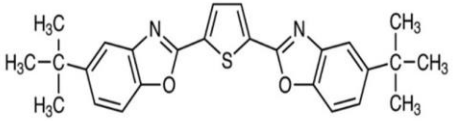
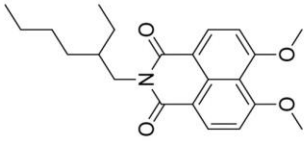
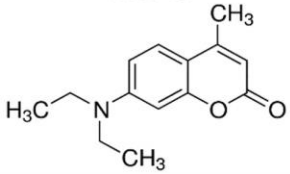
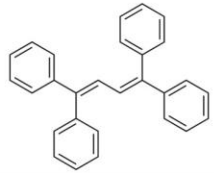
- **2.75 wt. % of BPBD**
- **0.05 wt. % of blue and green WLS.**

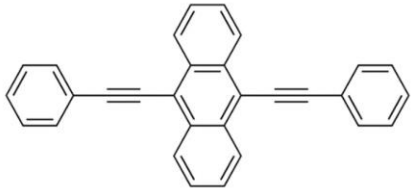
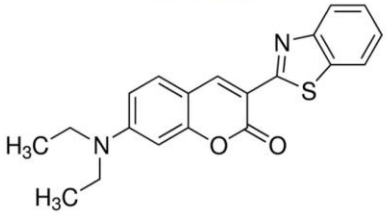
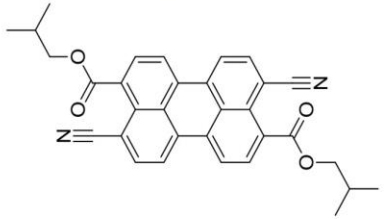
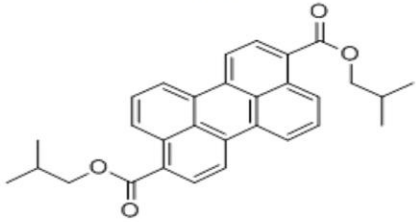


Ł. Kapłon, Synthesis and Characterization of Plastic Scintillators for the Total-body J-PET Scanner, Acta Physica Polonica B 51 (2020) 225

Chemical components for plastic scintillator manufacture:

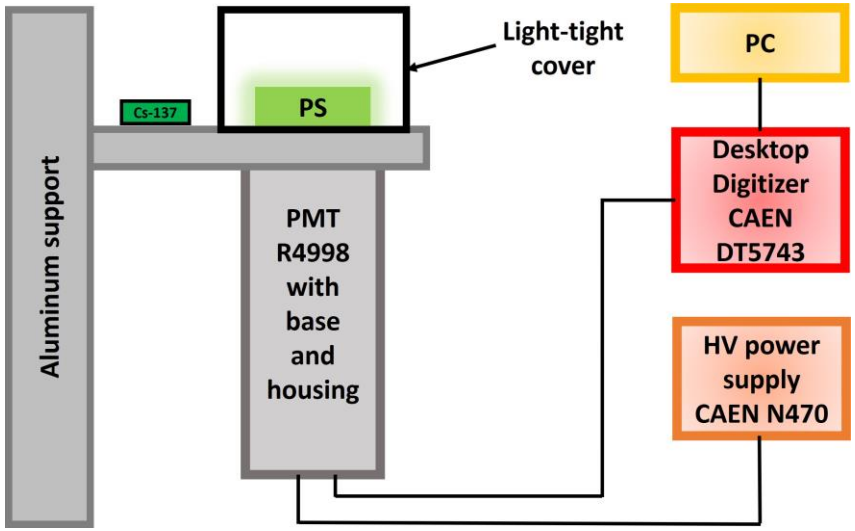
Polymer	UV-emitting dye
polystyrene (PS) 	BPBD 

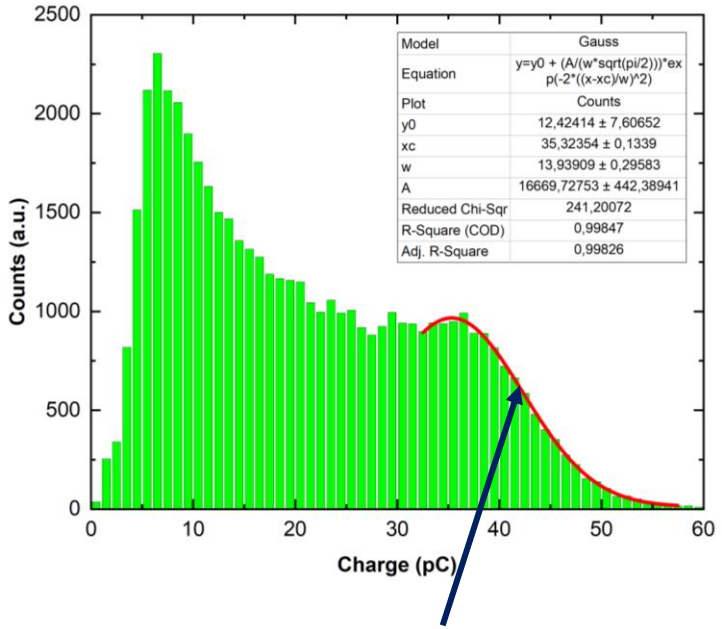
Blue-emitting wavelength shifters				
BBOT 	DPA 	LFV 570 	MDAC 	TPB 

Green-emitting wavelength shifters			
BPEA 	Coumarin 6 	LFY 083 	SG 5 

Ł. Kapłon, G. Moskal, Blue-emitting polystyrene scintillators for plastic scintillation dosimetry, Bio-Algorithms and Med-Systems 17 (2021) 191–197
Ł. Kapłon, G. Moskal, Green-emitting polystyrene scintillators for plastic scintillation dosimetry, Submitted to Optical Materials: X (2022)

Optical properties measurement: light output





$$\mathbf{LO} = \frac{\mathbf{charge}_{\mathbf{sam}}}{\mathbf{charge}_{\mathbf{ref}}} \times \mathbf{10000\ photons/MeV}$$

charge $_{sam}$ – middle of Compton edge for sample
charge $_{ref}$ – middle of Compton edge for reference scintillator EJ-200

Rise time:

from 10% to 90% of signal maximum.

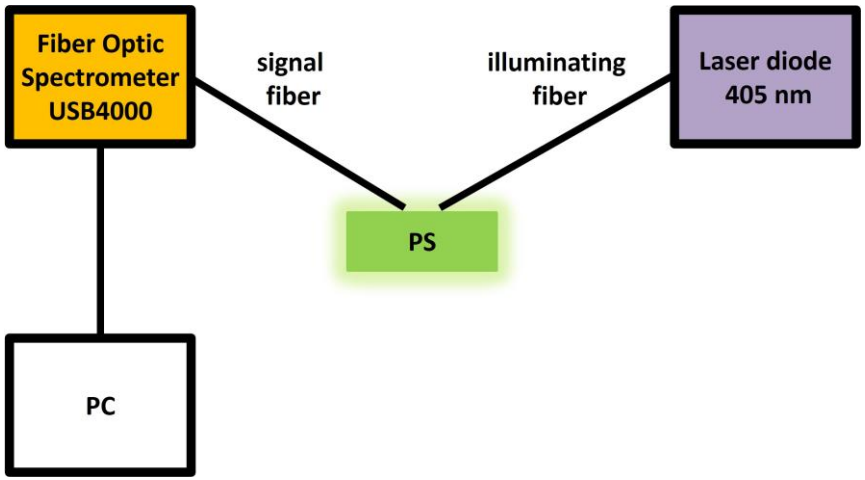
Fall time:

from 90% to 10% of signal maximum.

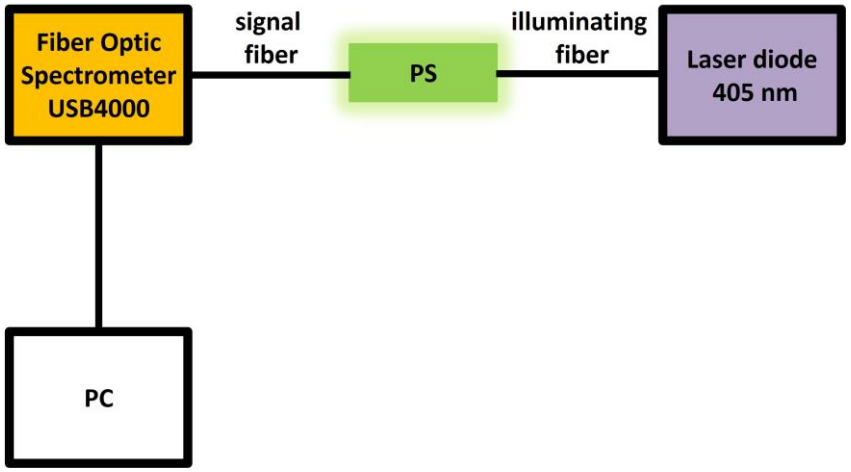
Rise and fall times were averaged from 50 000 signals.

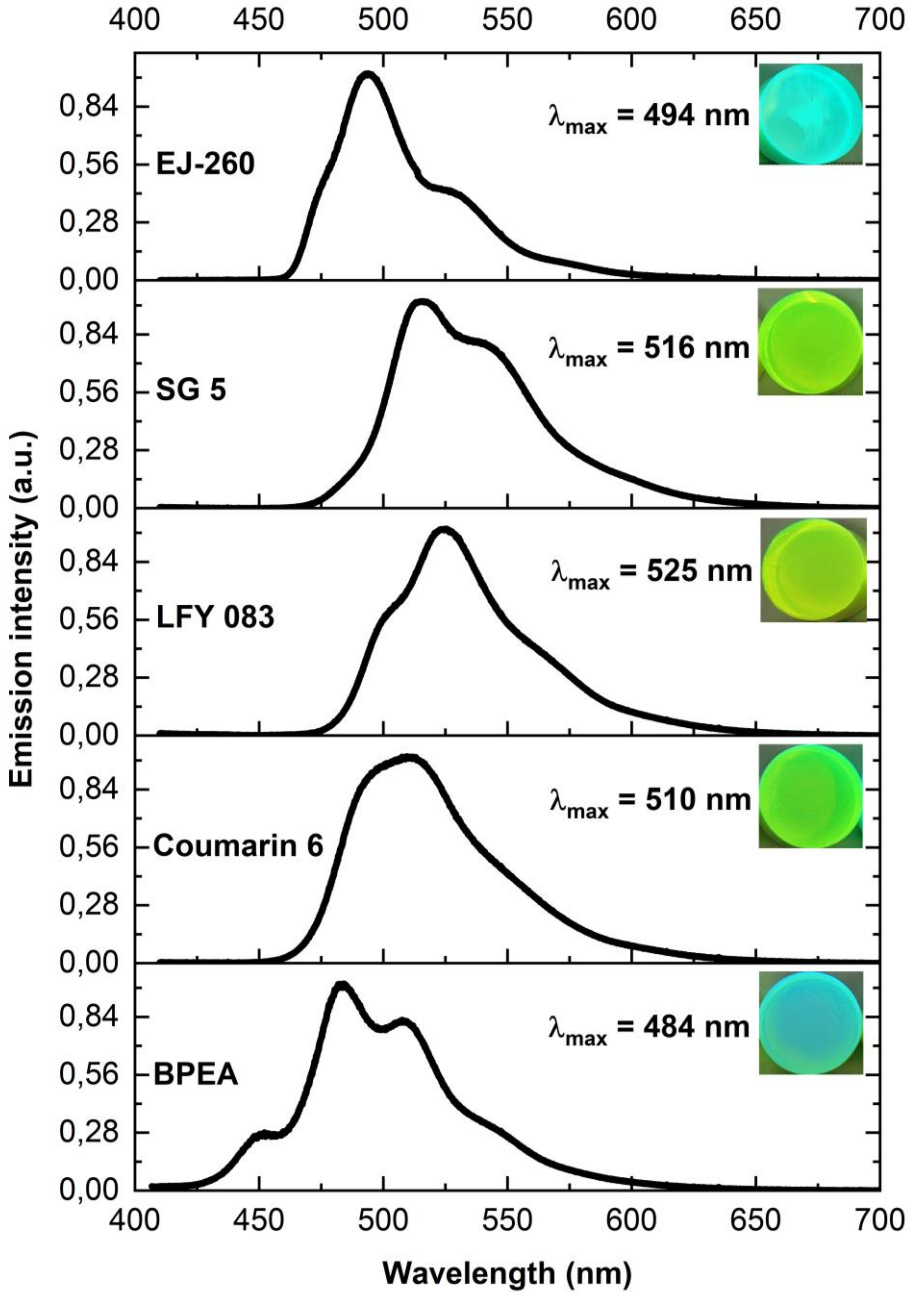
Optical properties measurement: emission spectra

Front surface excitation

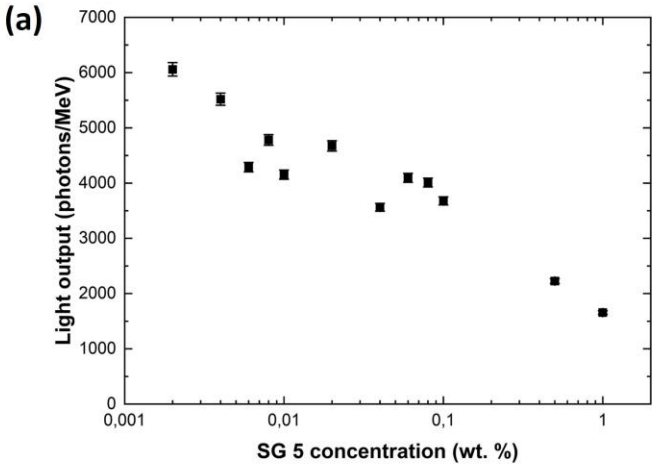


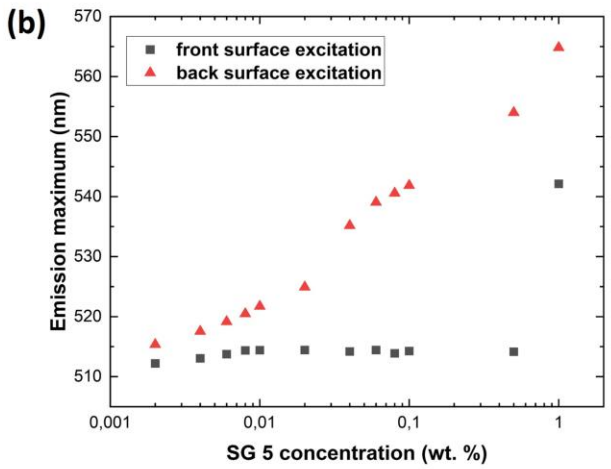
Back surface excitation



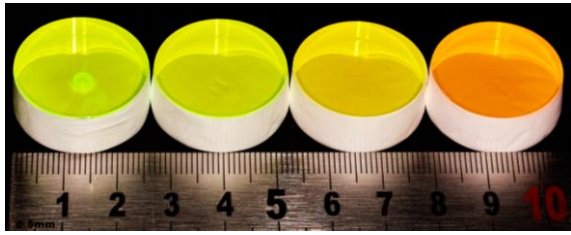


Influence of Solvent Green 5 concentration in polystyrene scintillator on light output and emission spectra

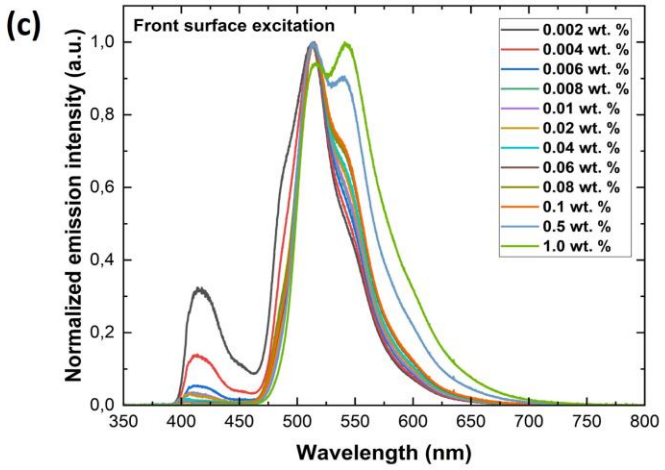


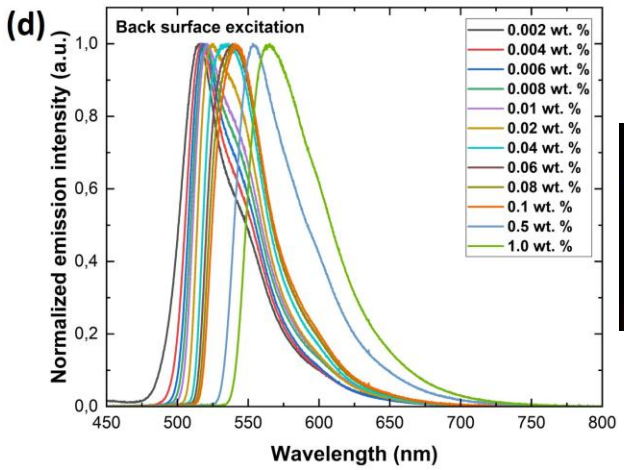


Ambient light

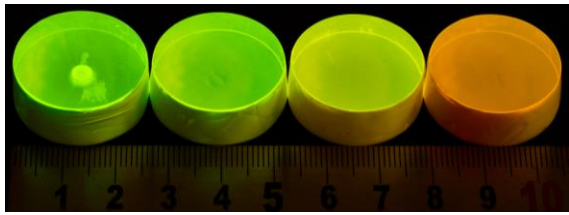


0.002 – 0.01 – 0.1 – 1 wt.%



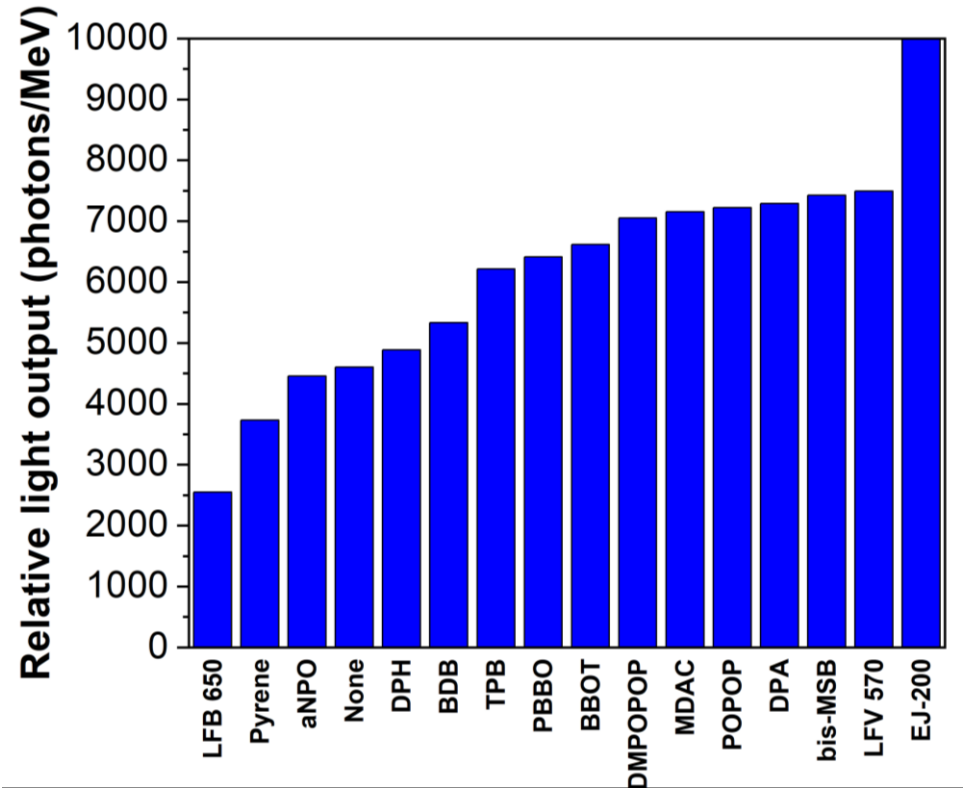


UV 365 nm light

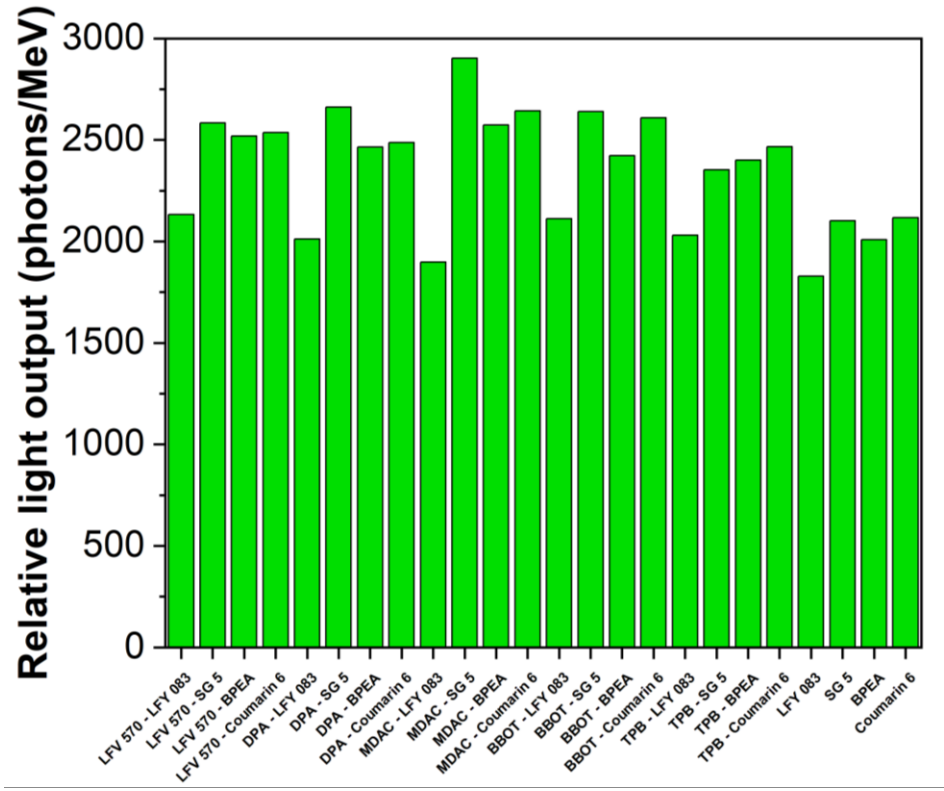


Optical properties measurement: light output

UV dye + blue WLS



UV dye + blue WLS + green WLS

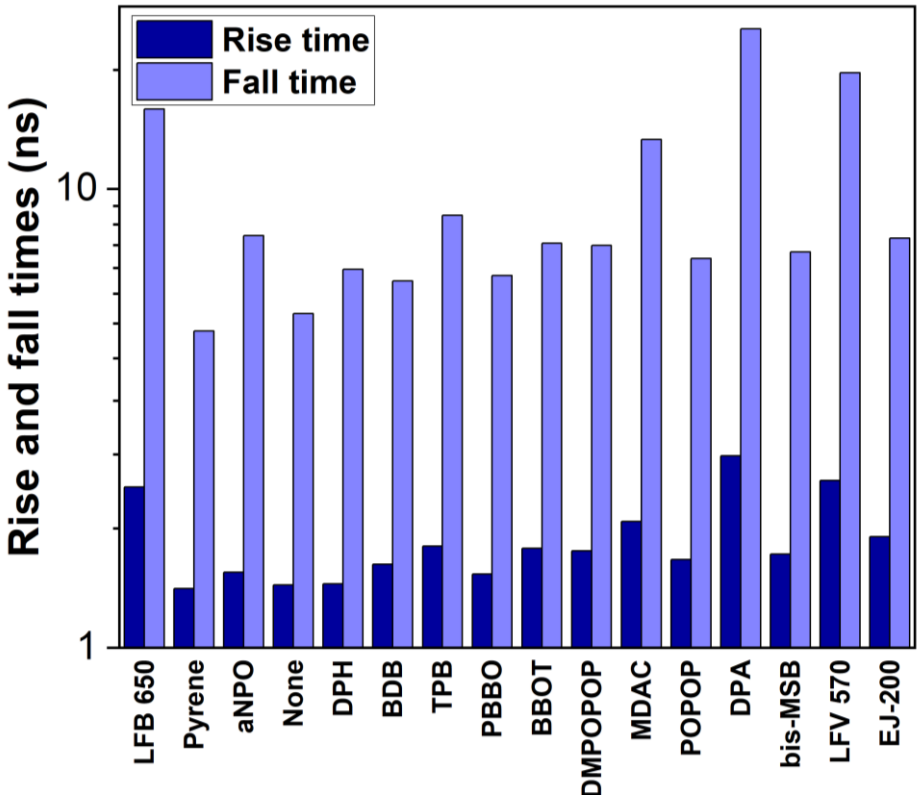


Best sample MDAC – Solvent Green 5 emits 2900 photons/MeV

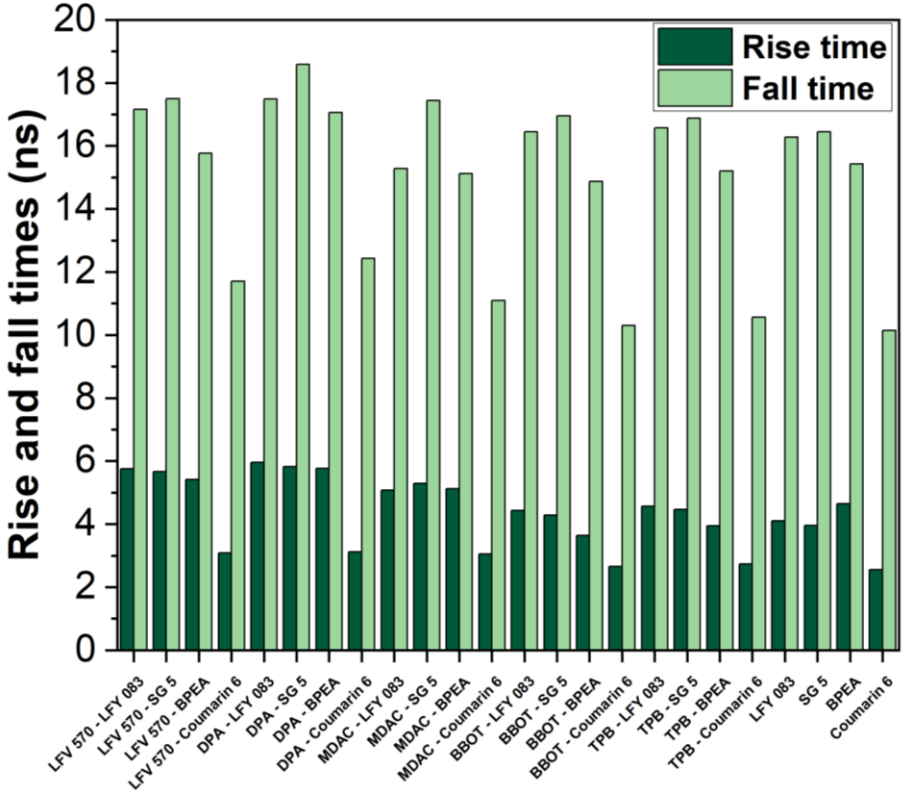
Commercial green scintillator BC-428 emits 5600 photons/MeV

Optical properties measurement: rise and fall times

UV dye + blue WLS



UV dye + blue WLS + green WLS



Fall time for samples ranging from 10 to 18 ns

Commercial scintillator BC-428 has fall time 20 ns

Summary

- Conditions of polymerization process and quality of surface machining influence transmission for visible light and technical attenuation length of long scintillators.
- From investigated six types of plastic scintillators for TB-J-PET scanner only BC-408 and EJ-200 possess highest transparency for emitted blue light.
- Measured TAL values up to 200 cm allow to construct long modules of TB-J-PET scanner.
- Decreasing width of the plastic scintillator increases amount of light reflecting to photodetector but decreases light attenuation length.

- Blue-emitting polystyrene-based scintillators have light output and timing performance close to the commercial plastic scintillators.
- Green-emitting polystyrene-based scintillators with the best light output are those containing Solvent Green 5.
- Energy transfer in plastic scintillators with UV-blue-green fluorescent dyes is not efficient.
- Optimization of concentration of UV dye increased performance of plastic scintillators, but optimization of Solvent Green 5 dye got mixed results.