Properties overview of plastic scintillators and DSB glass/glass ceramics scintillator

Valerii Dormenev
on behalf of Giessen group

Test results of
- **Organic plastic scintillators**
- **DSB material**

Radiation damage of scintillation materials

Future Accelerating Systems should have High Luminosity to detect rare events.

Radiation damage of the optical transmittance of the scintillator leads to the degradation of the energy resolution of the electromagnetic calorimeter (EMC)

The radiation damage of scintillation materials can be subdivided on two components:

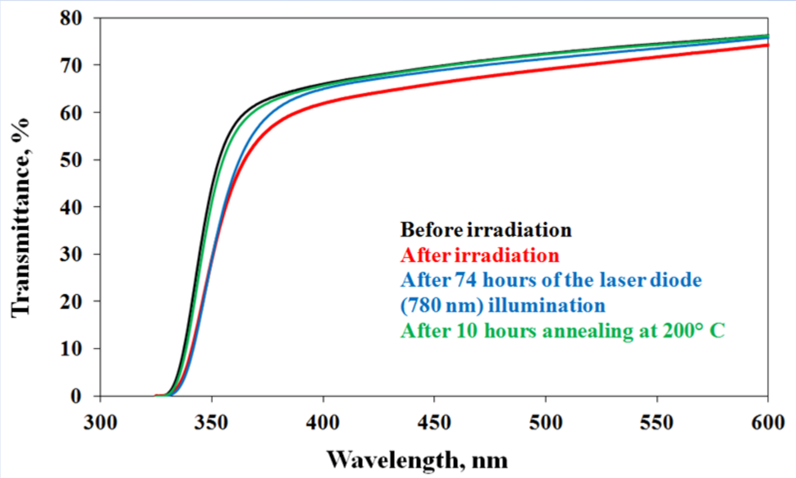
•Electromagnetic component (γ-quanta, e-, e+)

•Hadron component (p, n, and fragments due to interaction with heavy nuclei)

$PbWO_4$ irradiated by 150 MeV protons

@CART-KVI, Groningen, Netherlands

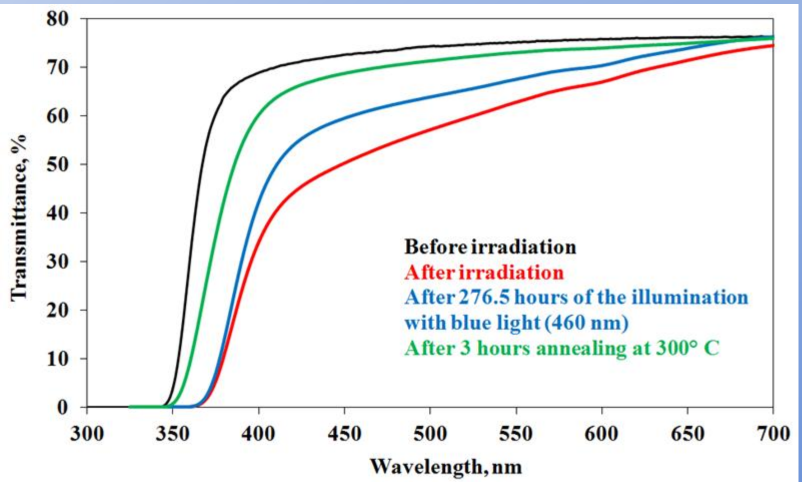
Fluence = 1.8×10^{13} protons/cm^2



$PbWO_4$ irradiated by 24 GeV protons

@CERN, Switzerland

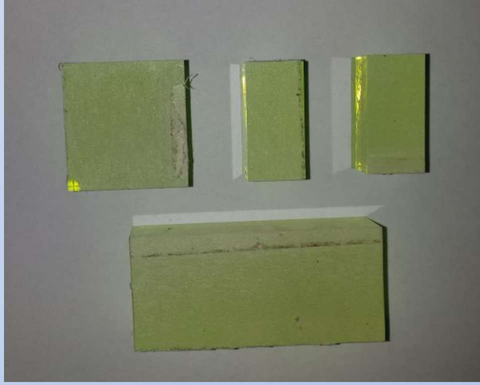
Fluence = $3 \cdot 10^{13}$ protons/cm^2



- creation of macro defects
- highly ionizing fission products
- ion displacements

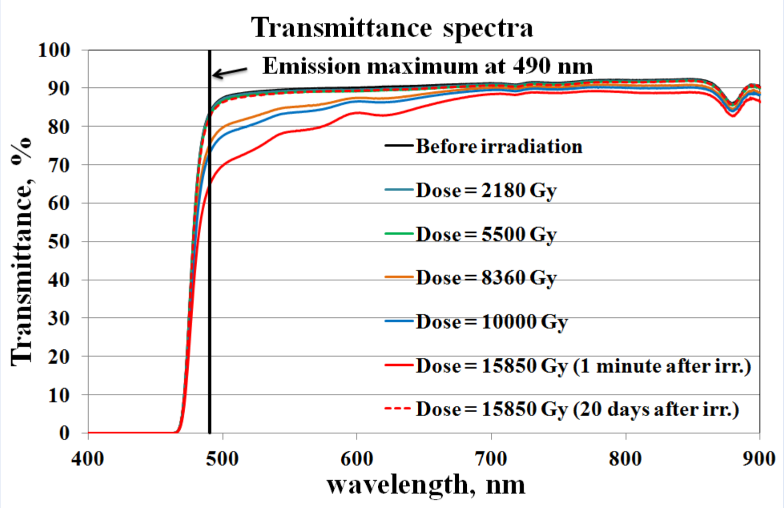
lower Z material required
sampling calorimetry
cheap for mass production

Organic plastic scintillator EJ260

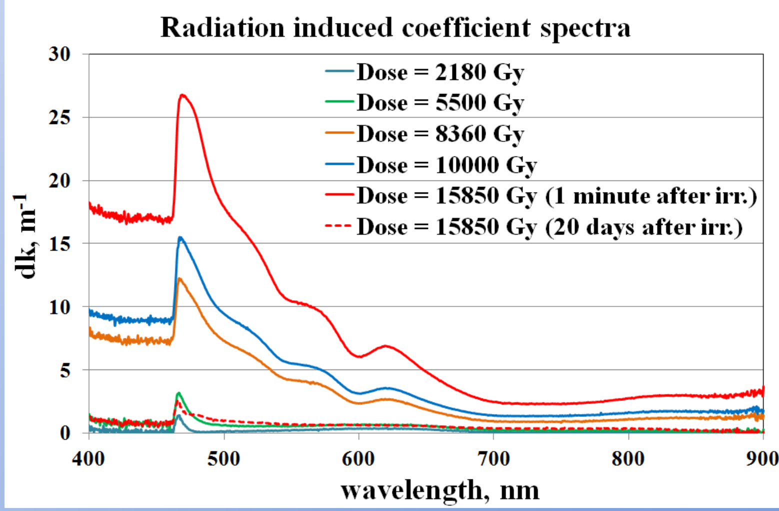


Few samples of plastic scintillator EJ260 (based on Polyvinyltoluene) were delivered by <u>Eljen Technology (Sweetwater, USA)</u>

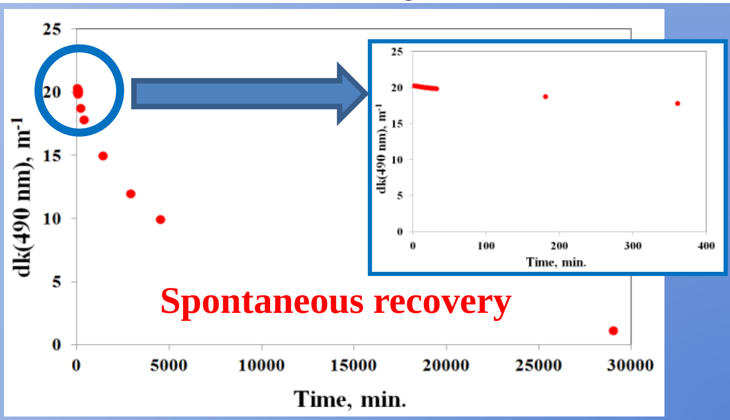
Irradiation with gamma quanta (^{60}Co source, Dose rate=1.4 Gy/min.)



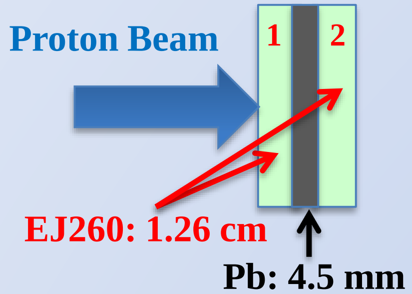
$$\Delta k = \ln\left(\frac{T_{bef}}{T_{after}}\right) \cdot \frac{1}{d}$$



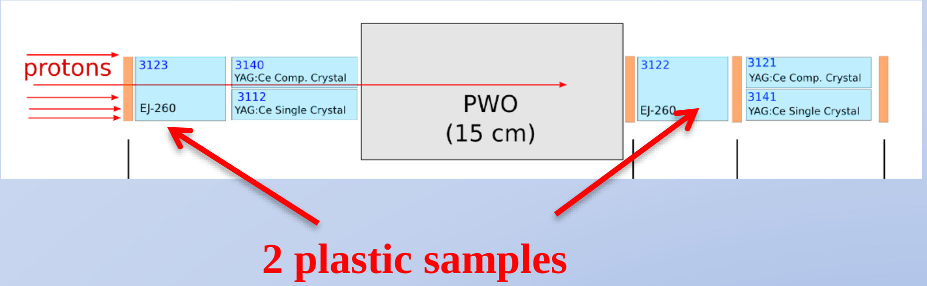
- ➢**Observable damage appears after the irradiation with integral dose of few kGy**
- ➢**More than 90 % of the damage recovered in 3 weeks due to thermodynamical process (spontaneous recovery)**

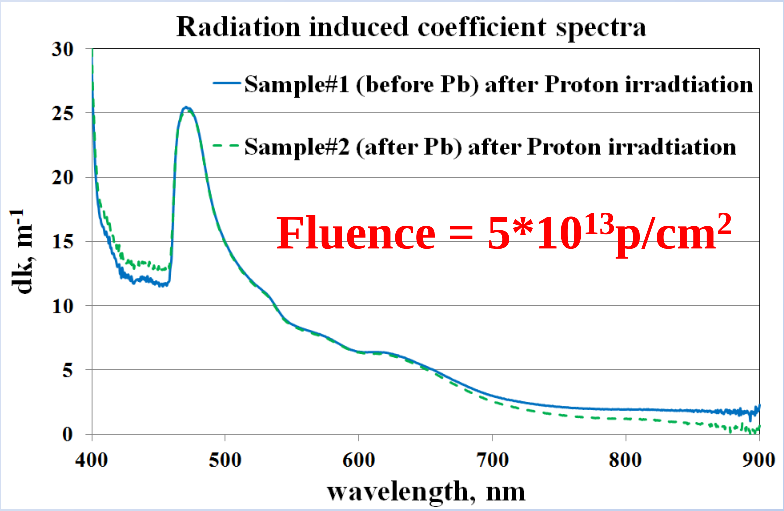


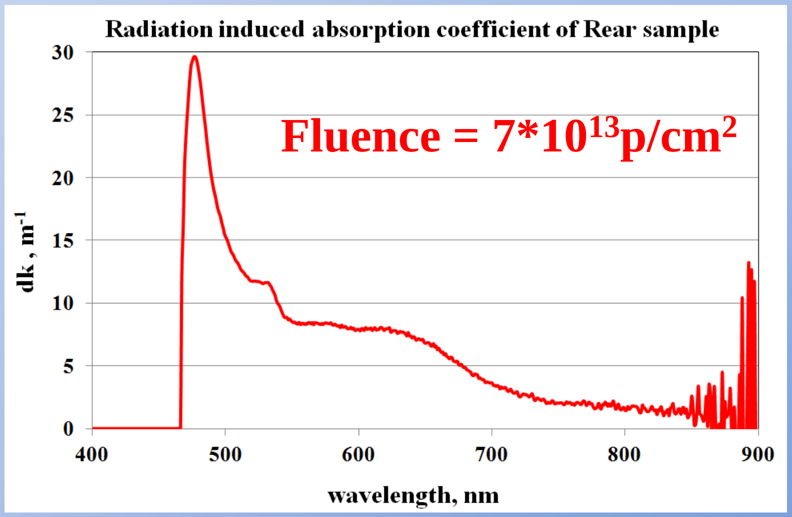
Irradiation with 190 MeV protons @CART-KVI (Groningen)



Irradiation with 24 GeV protons @CERN

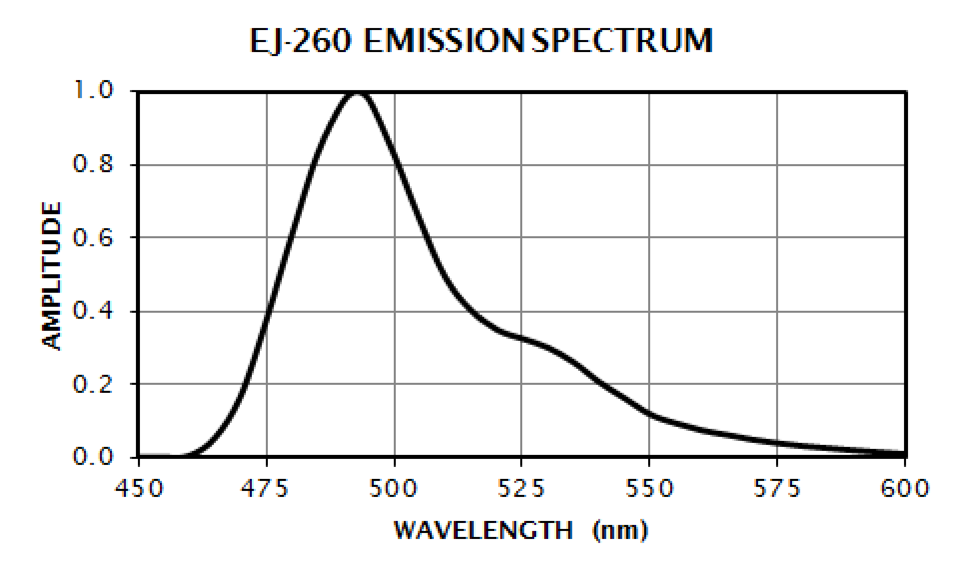






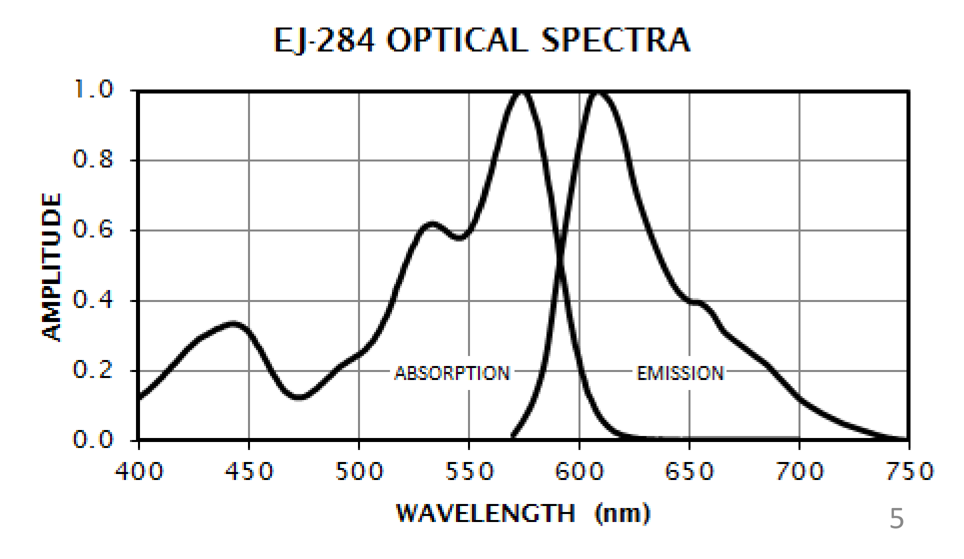
- **Irradiation with gamma quanta, 190 MeV and 24 GeV protons produces in the plastic material the same colour centers. It indicates that at a given fluences protons do not produce macro-defects, the defects created are identical to those which appear at polymerization of the plastic.**
- **Spontaneous recovery of the colour centers is fast enough after irradiation with gammas, whereas it is suppressed after proton irradiation. It indicates, that similar to inorganic materials, most of the defects created under protons, are concentrated in clusters.**

Organic plastic scintillator: EJ260 vs EJ284



EJ260 has a high radiation damage in the emission spectrum range

<u>More promising can be a usage of a scintillator with luminescence in longer wavelength region</u>



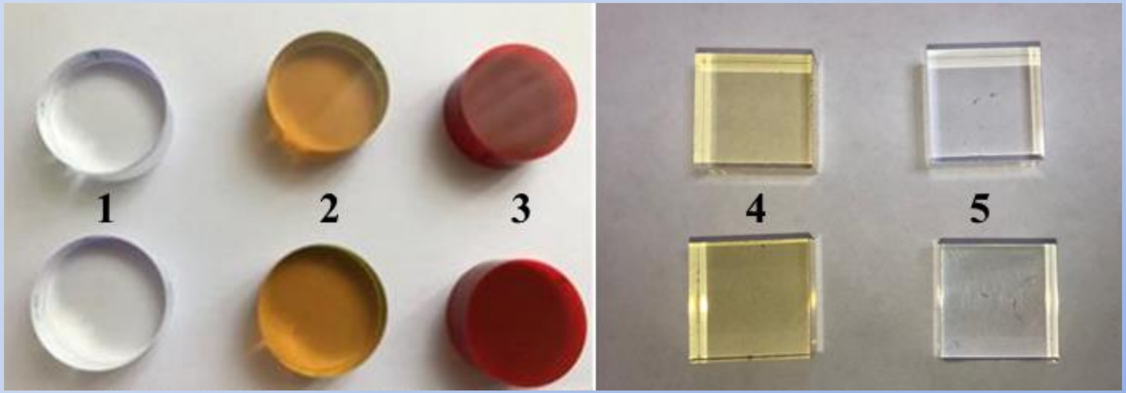
Possible candidate from Eljen: EJ284

Organic plastic scintillator produced by ISMA

5 types of plastic scintillator based on polystyrene were delivered by ISMA (Kharkiv, Ukraine):

1) Blue
2) Green
3) Red
4) Improved Green
5) Pure

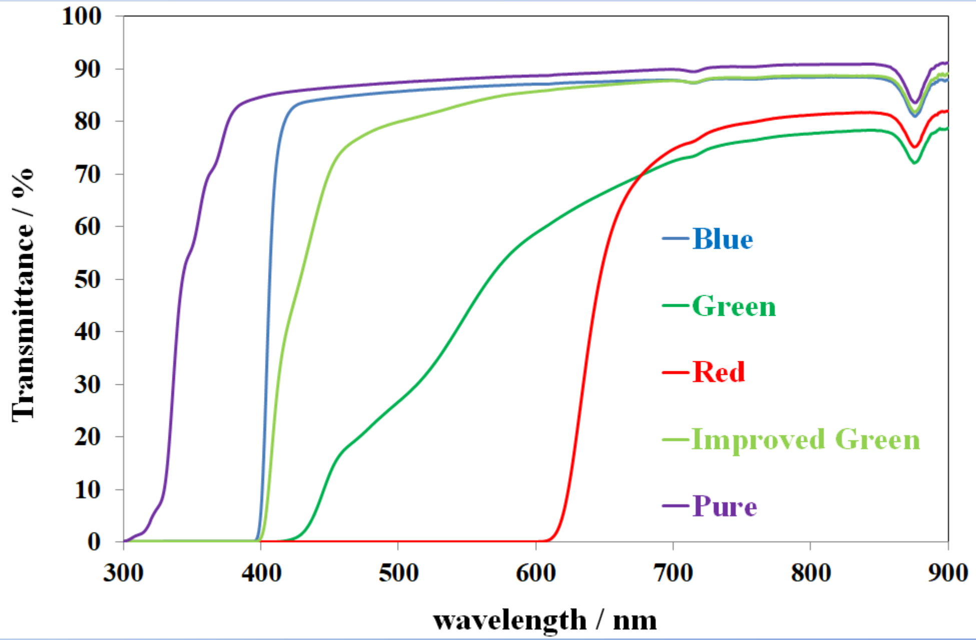
Thickness = 10 mm



Type	basic material	prime activator	WLS	Luminescence, nm	rise/decay time, ns
Pure	polystyrene	para-terphenyl(2 wt. %)	no	375	
Blue	polystyrene	para-terphenyl(2 wt. %)	POPOP (0.02 wt %)	425	0.2/2.1
Green	polystyrene	3HF (1.5 wt. %) with 2 introduced fluorine atoms	no	530	0.5/7-7.6
Green improved	polystyrene	3HF (1.5 wt. %) with 2 introduced fluorine atoms	no	530	0.5/7-7.6
Red	polystyrene	3HF (1.5 wt. %) with 2 introduced fluorine atoms	5nf (0.05 wt. %)	590	

Properties characterization

Optical transmittance spectra

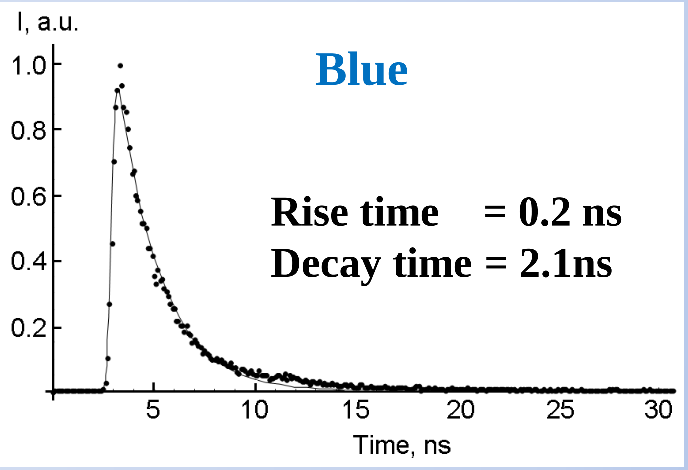


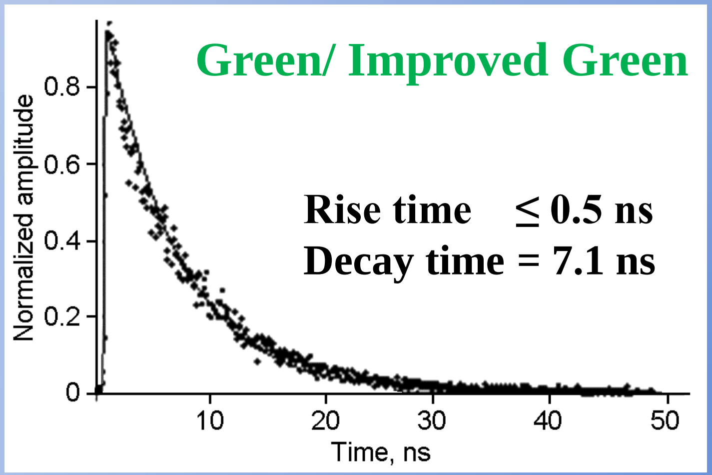
3HF is an activator with large Stokes shift, no need WLS for both Green plastics
2 fluorine atoms were introduced to improve radiation hardness

Improved Green has better transmittance as result of higher purification of the raw materials from impurities

Shift of the transmittance cut-off due to WLS for blue and red

Scintillation kinetics





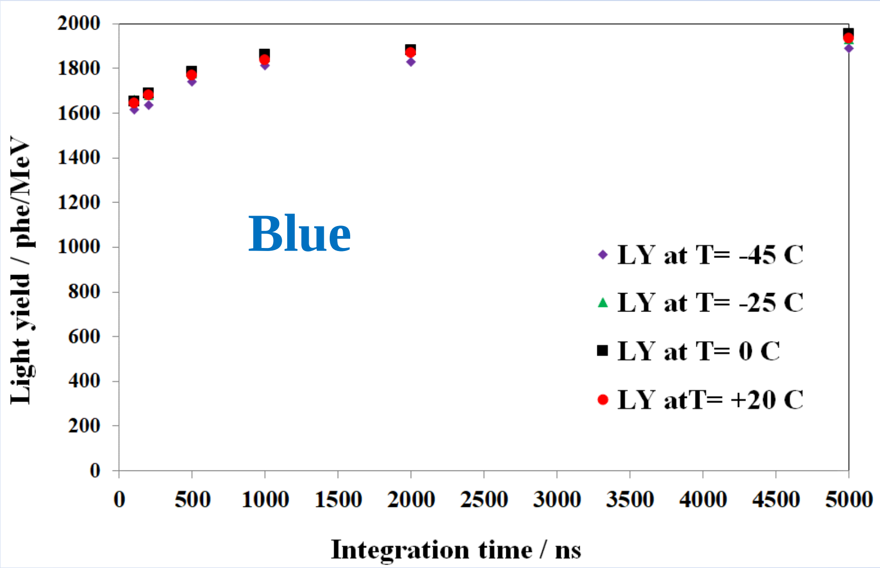
Light yield measurements

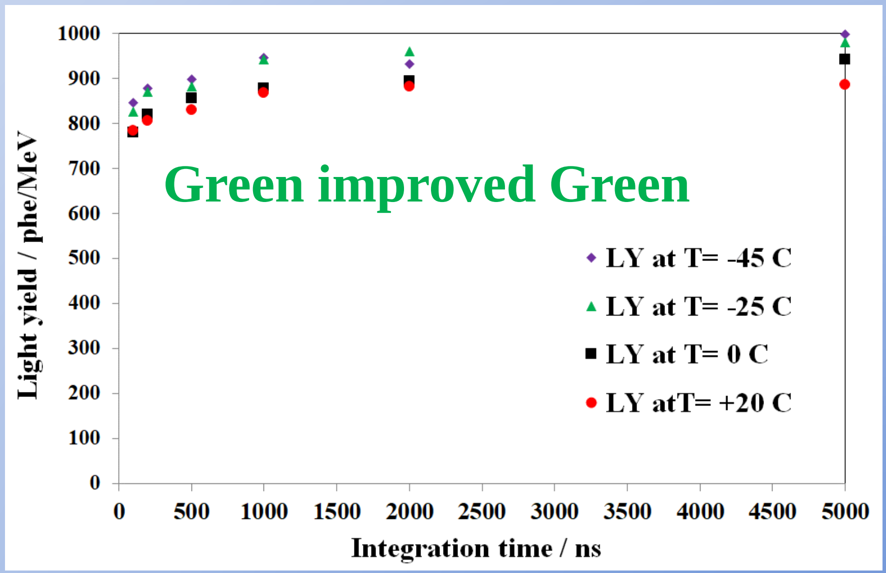
Measurements were done with PMT Hamamatsu R2059 with standard bialkali photocathode

Samples were wrapped with 10 layers of thin Teflon foil as a reflector

Response on ^{241}Am (E_{γ} = 59.5 keV) γ-source was measured

Reasonable results were obtained only for blue and improved green samples



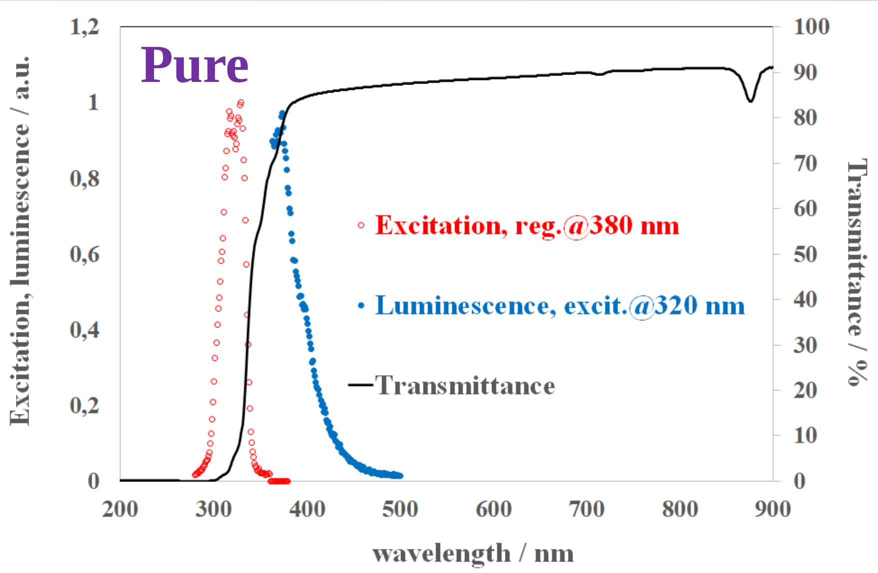


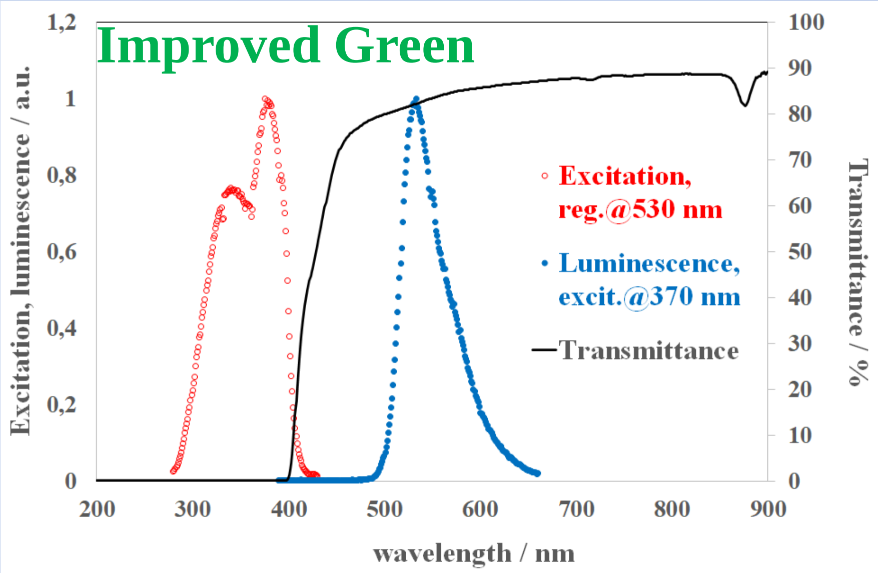
Taking to account QE 23 % @ 425 nm and 11 % @ 530 nm we can evaluate absolute values of the light yield at room temperature as

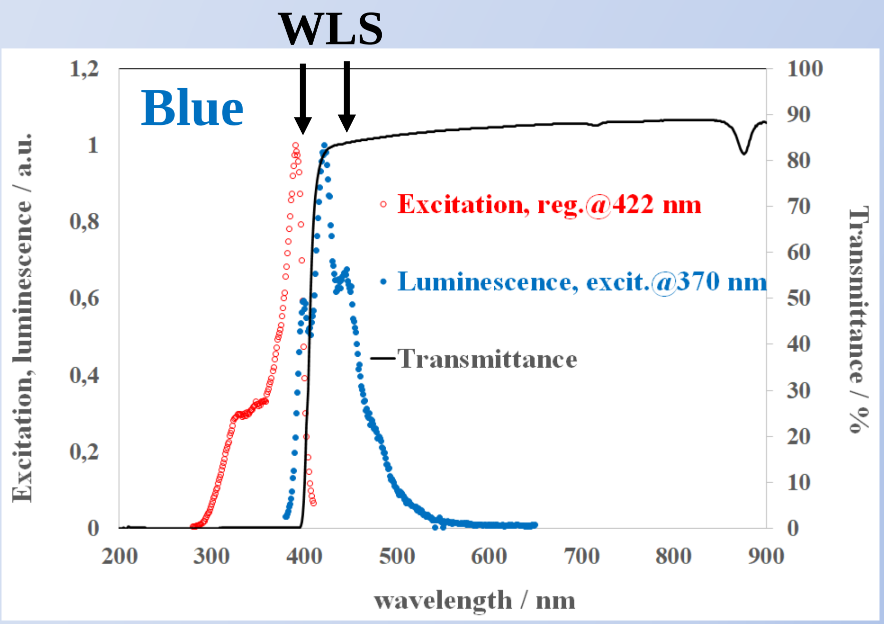
7000 – 8500 photons/MeV for blue plastic

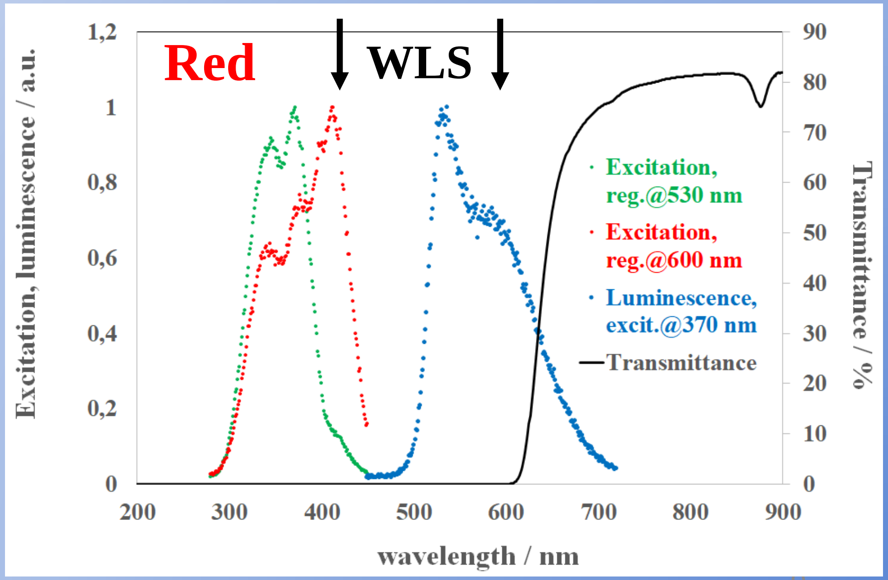
7200 – 8200 photons/MeV for improved green plastic

Luminescence/Excitation vs Transmittance





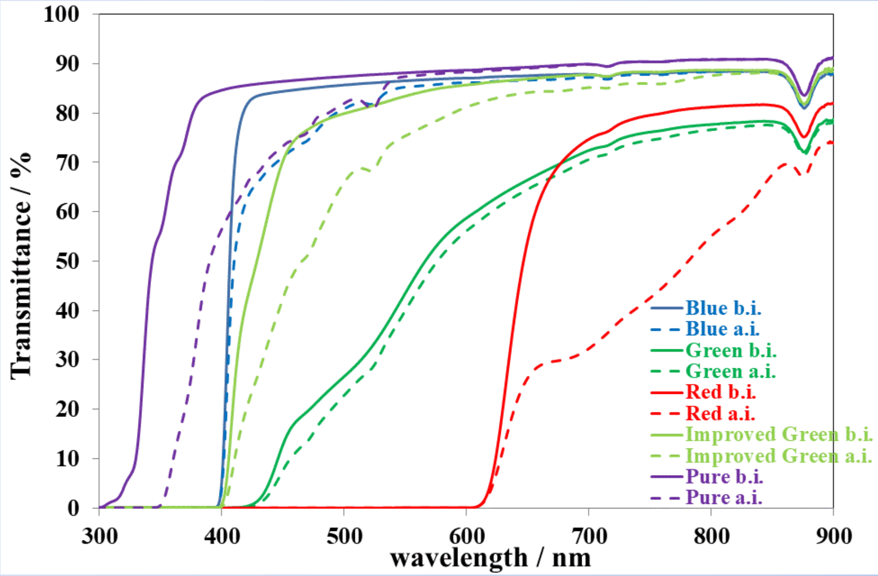




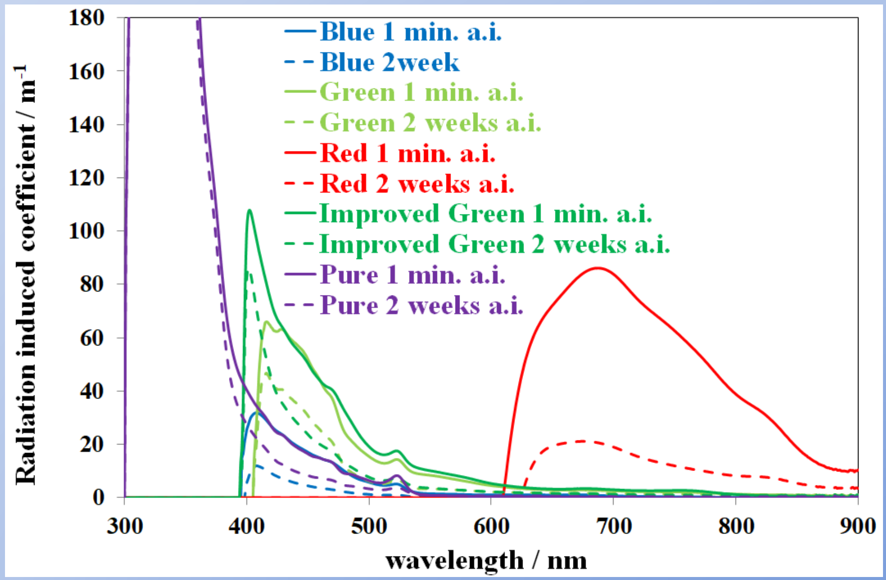
Radiation damage: gamma irradiation

The irradiation was performed at Radiation Center of Justus-Liebig-University (Giessen, Germany): ^{60}Co, Dose rate = 1 Gy/min, Integral dose = 20 kGy

Transmittance spectra



Radiation induced absorption coefficient spectra

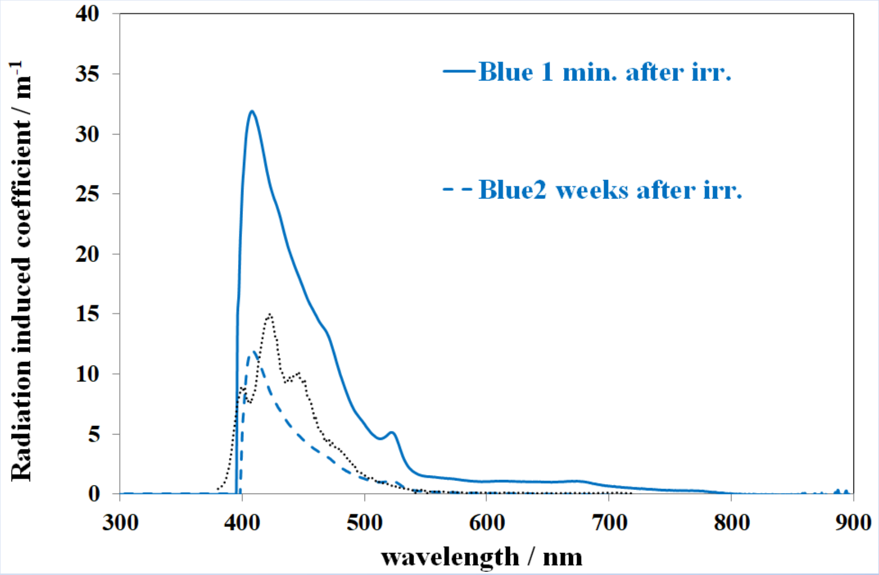


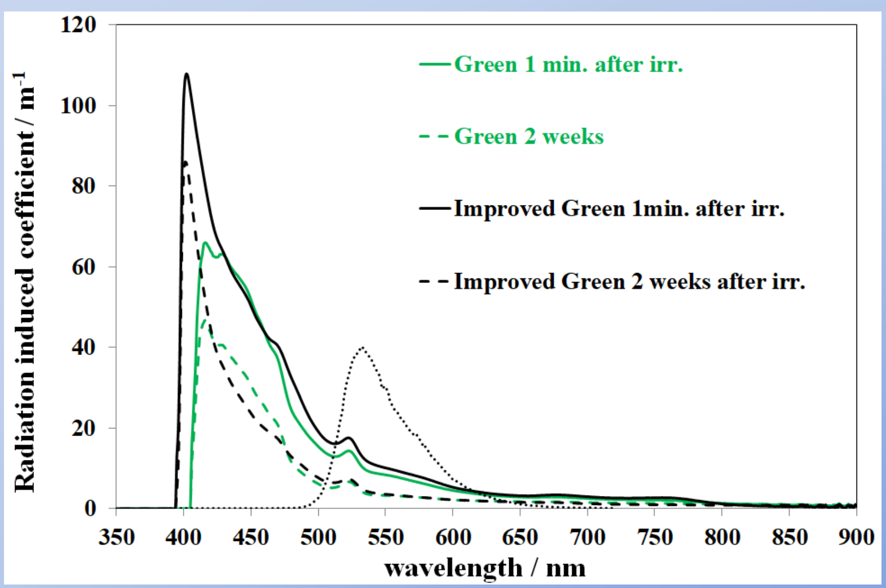
b.i. and a.i. mean before and after the irradiation correspondently

All samples showed spontaneous recovery in the luminescence range after γ-irradiation. The red plastic has fastest recovery rate.
Most promising candidates are both green and blue plastics.

Radiation damage: gamma irradiation

Radiation induced absorption coefficient spectra





dk = 10-30 m^{-1}

Radiation induced absorption spectra curves look similar for blue and both green plastics. So, it can be consider as sign that no damage of dyes is observed and the idea to shift the luminescence to area with lower induced damage seems reasonable.

Radiation damage under 190 MeV protons

Prototypes of sampling units were irradiated

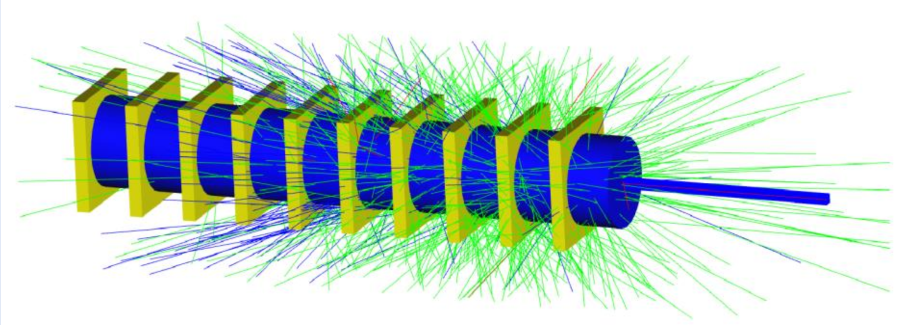
Sampling unit consisted of

5 plastics (1 cm) and 4 W plates (3 mm)

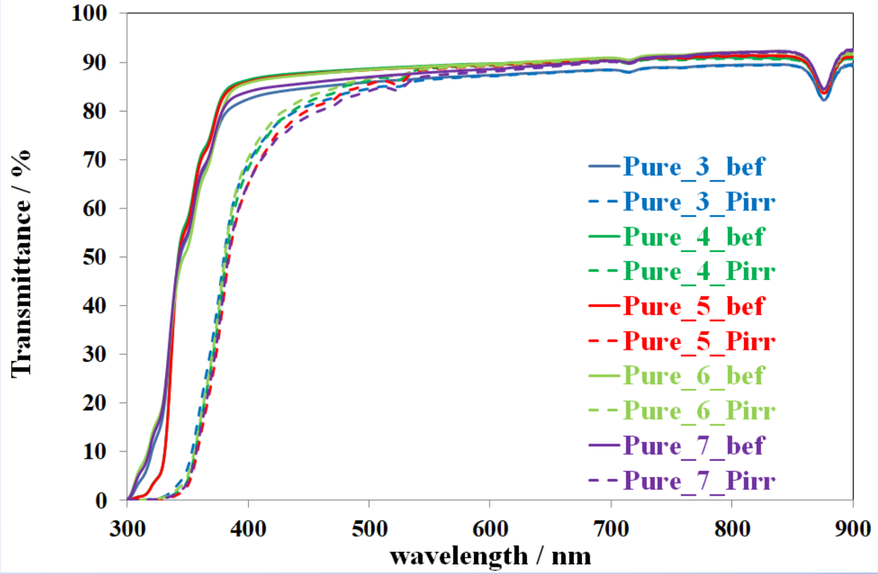
Irradiation were done at CART-KVI (Groningen, Netherlands) with 190 MeV proton beam

Integral fluence = $5*10^{13}$ p/cm^2

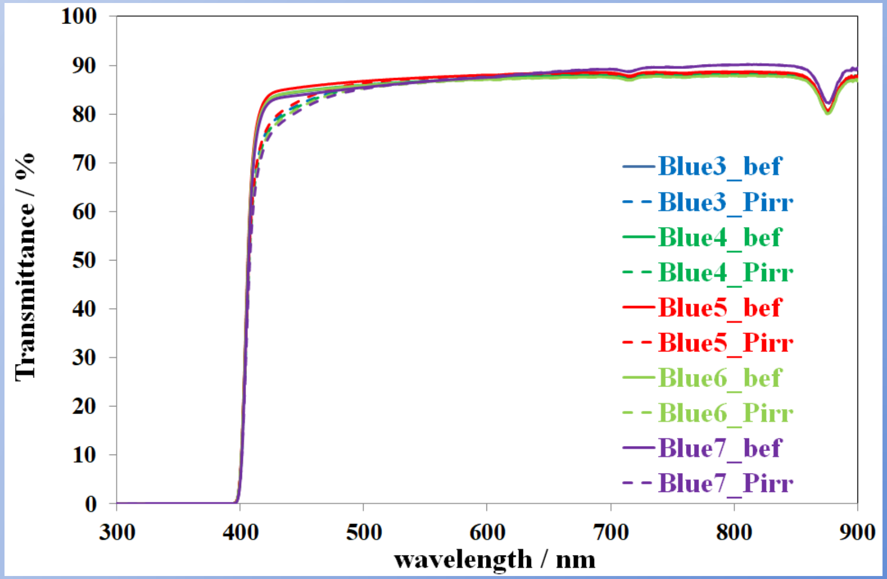
GEANT4 simulation of plastic/W sampling unit



Pure



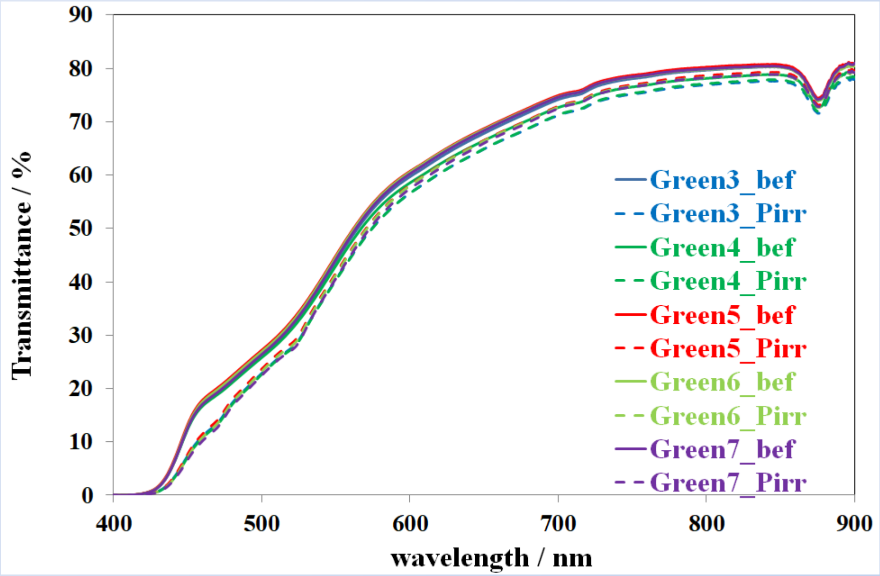
Blue



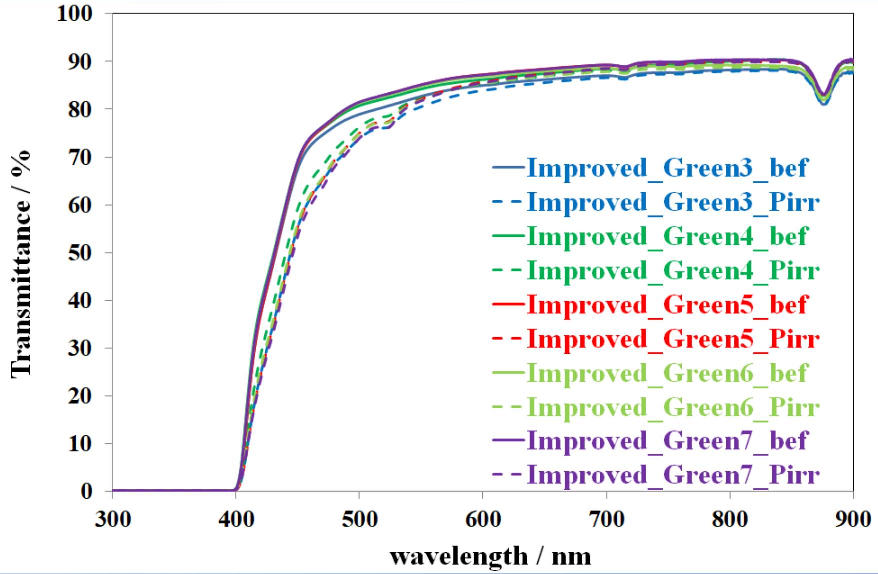
Samples numbering increases with distance from impact point of proton beam

Radiation damage under 190 MeV protons

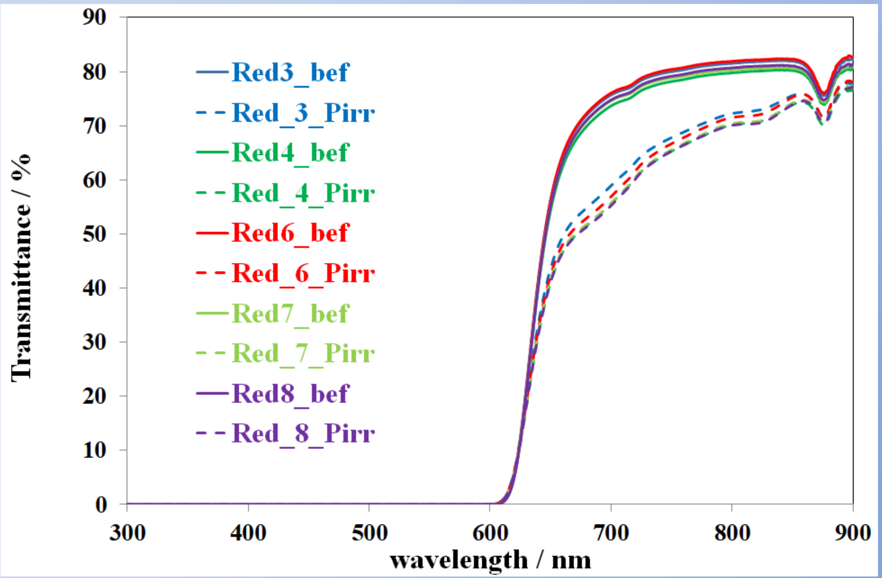
Green



Improved Green

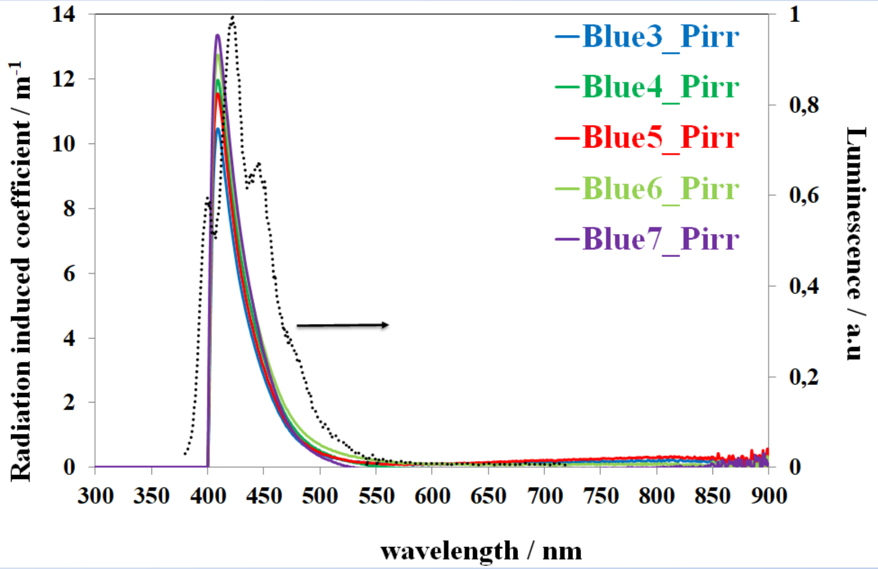


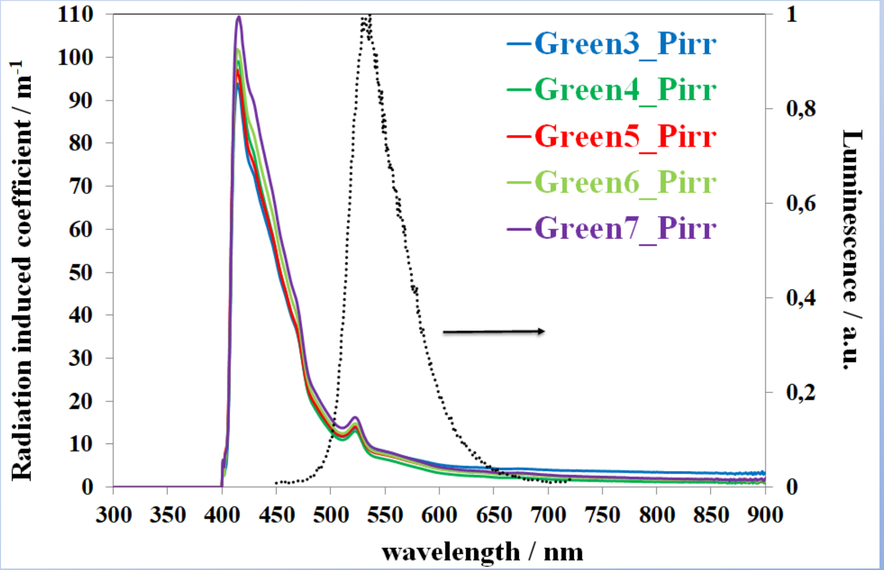
Red

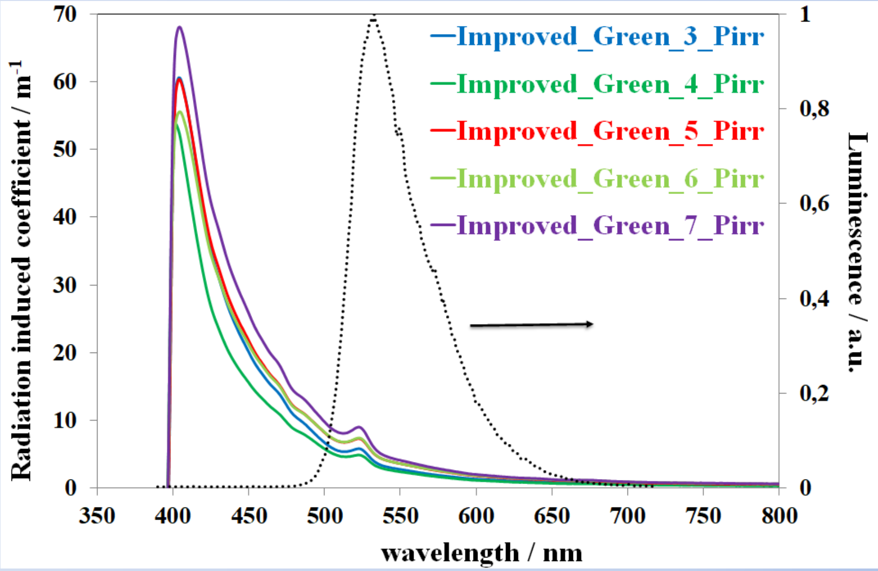


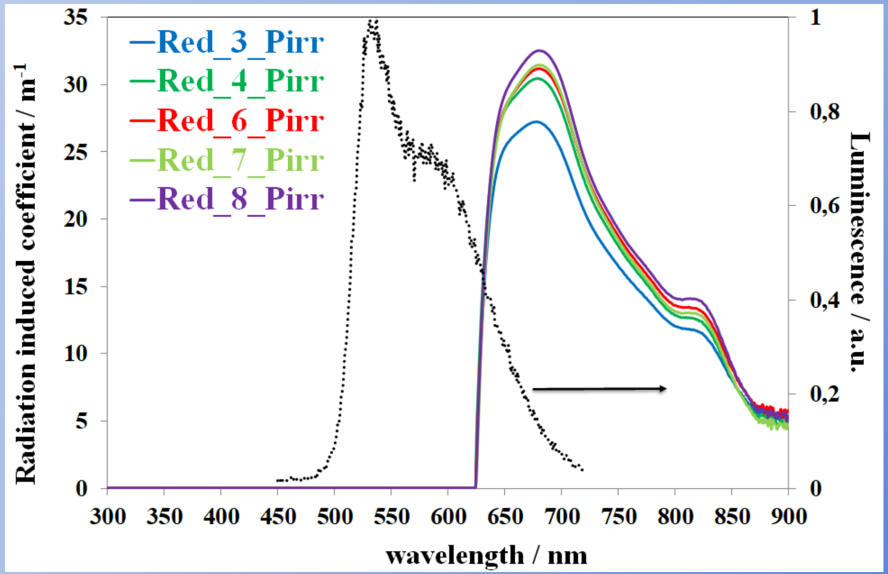
Samples numbering increases with distance from impact point of proton beam

Radiation damage under 190 MeV protons





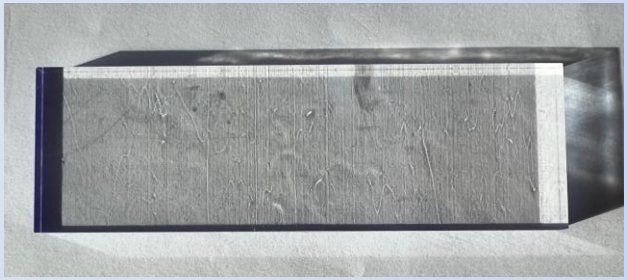


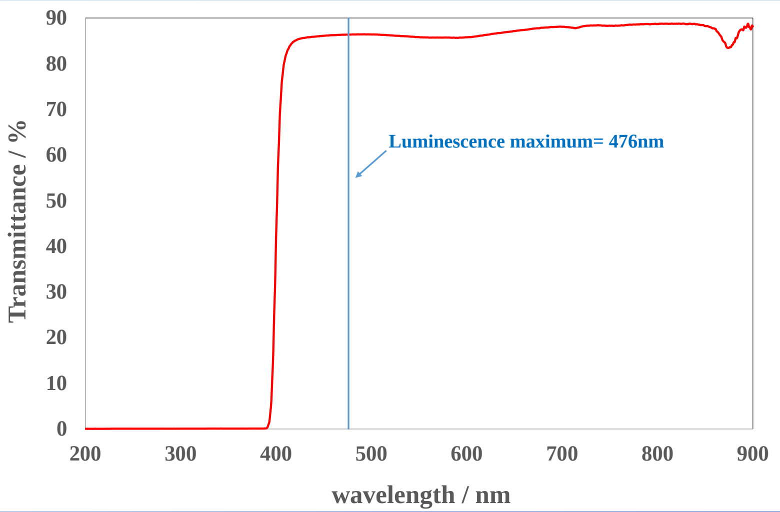


Extruded plastic scintillator: UNIPLAST, Humboldt University of Berlin

Optical transmittance

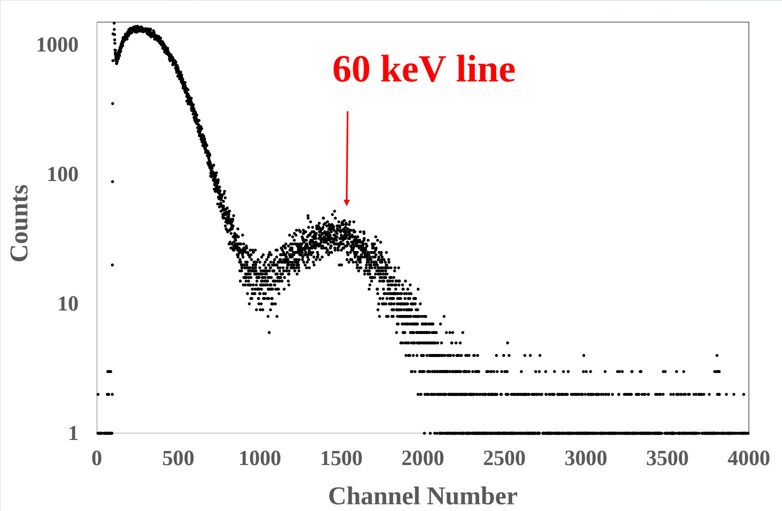
120 x 38 x 7 mm



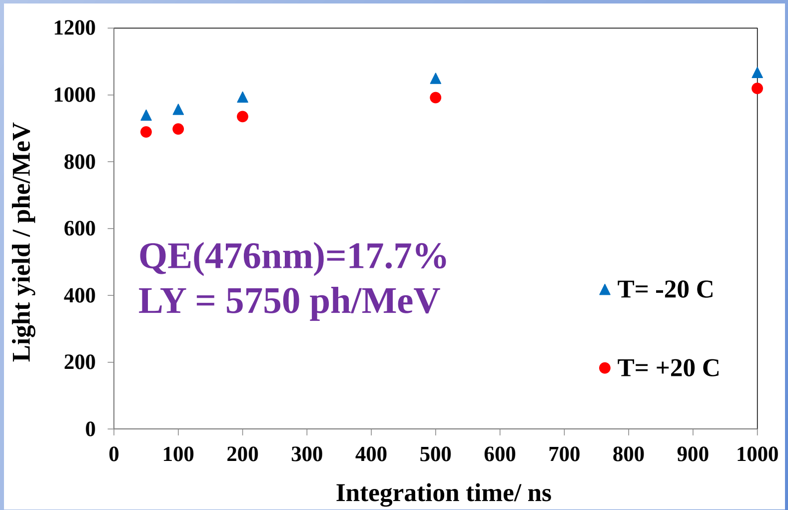


Measured with Hamamatsu R2059 PMT, Teflon film as reflector ^{241}Am gamma-source (60 keV)

^{241}Am spectrum



Light Yield



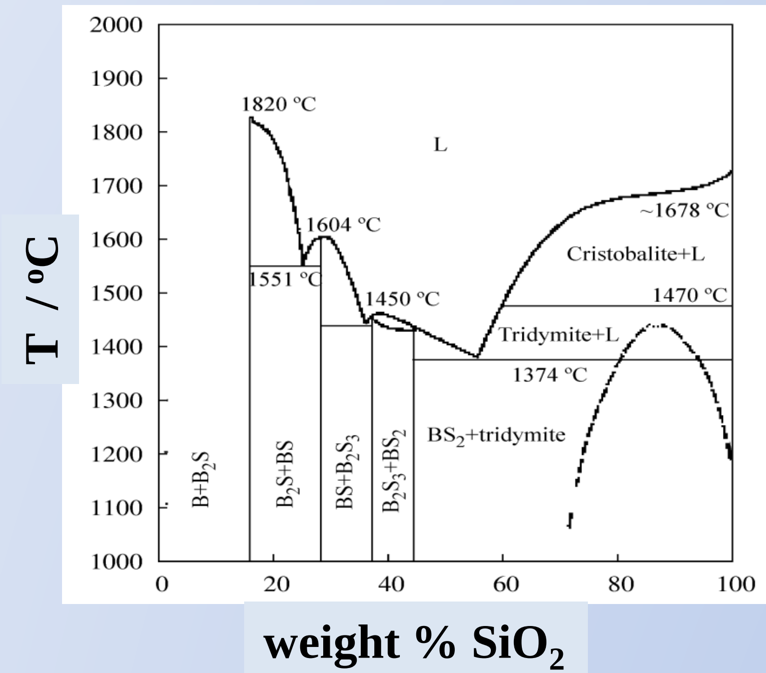
Conclusions

- **Blues and green plastic samples have decay time ≤ 10 ns**
- **Light yield can be evaluated as 5700 – 8500 photons/MeV**
- **Both green plastics have value of the radiation induced coefficient on the level of 10 m^{-1} at luminescence maximum after gamma (20 kGy) and proton (2.6-5x10^{13} p/cm^2) irradiations**
- **The main contribution of the radiation induced damage under gammas and protons appears outside the luminescence spectrum of green plastics**
- **All samples demonstrate spontaneous recovery after the gamma irradiation**
- **Further tests of radiation hardness at higher doses are needed**

The material BaO*2SiO2 Doped with Ce

material	ρ g/cm^3	Z_{eff}	X_o cm	λ_{max} nm	cutoff undoped material nm
$(BaO*2SiO_2)$:Ce glass	3.7	51	3.0[1]	440, 460	310
DSB:Ce	3.8	51	3.5	440, 460	310
$(BaO*2SiO_2)$:Ce glass heavy loaded with Gd	4.7 - 5.4*	58	2.2**	440, 460	318

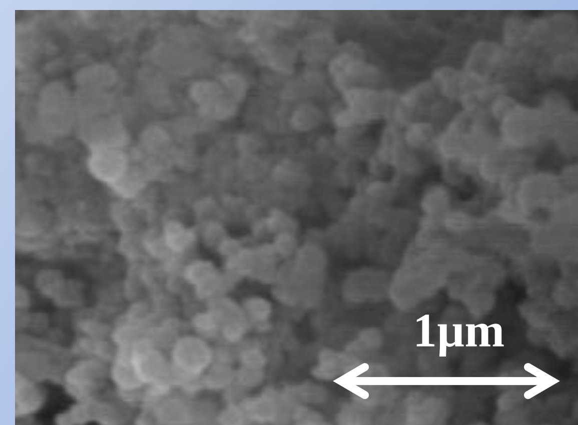
[1])GEANT4; *,**at highest Gd content in the composition



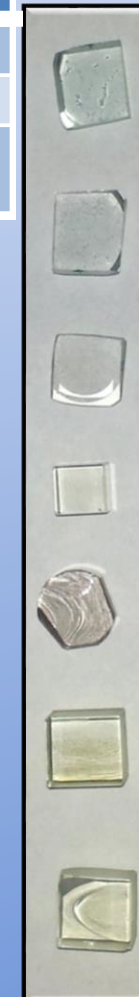
phase diagram of the $BaO*SiO_2$ system

- nano-sized particles of Ba_2SiO_5 in the glass improve ther yield and kinetics of the scintillation!
- Ba-Si system allows to incorporate trivalent ions: **Lu, Gd, Yb, Y**

technology: glass production combined with successive thermal annealing (800 – 900°C)

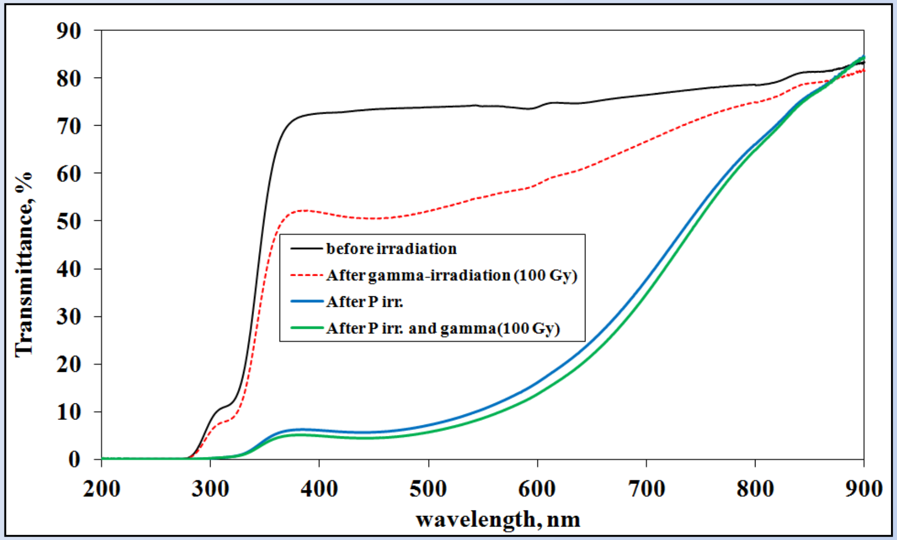


SEM image of recrystallized $BaO*2SiO_2$ at 950°C



Samples from early development Giessen& INP BSU, Minsk

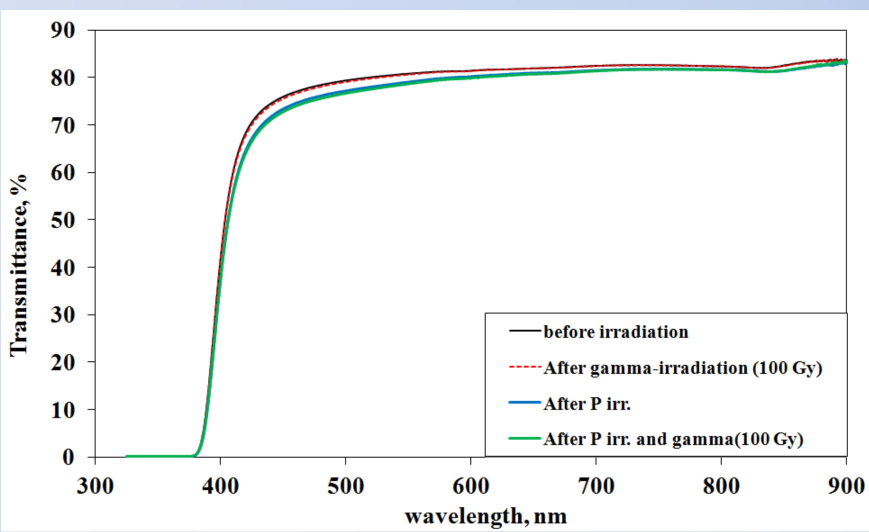
irradiation and recovery studies: with 150MeV protons



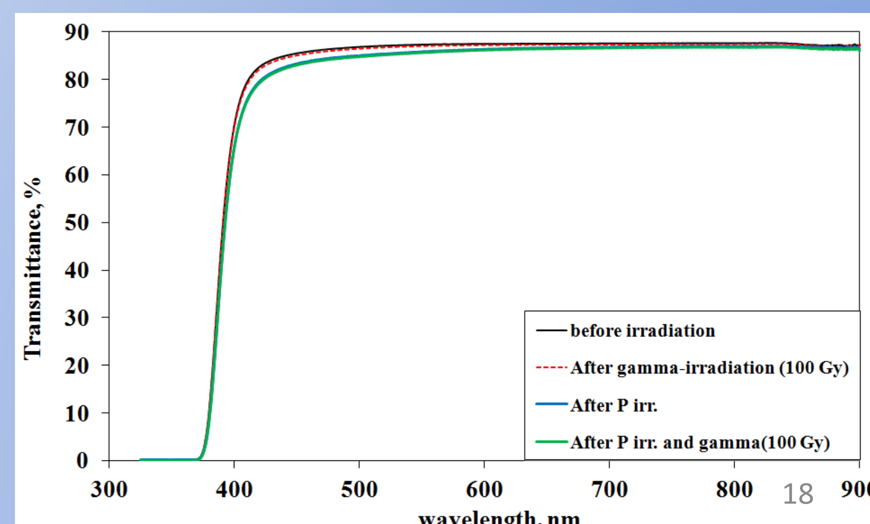
flux $\leq 2x10^{11}$ p/s cm^2
integral fluence = $5x10^{13}$ p/cm^2

$BaO \times 2SiO_2$ (mother glass)

$BaO \times 2SiO_2$: Ce (without thermal treatment)



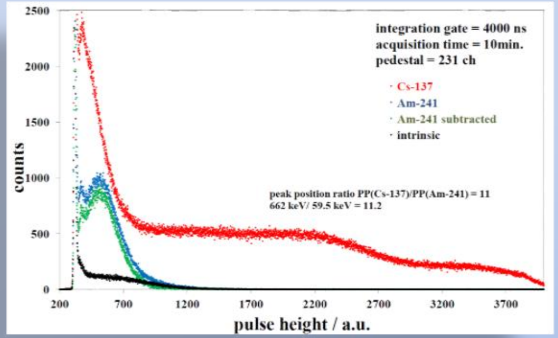
DSB: Ce (after thermal treatment)



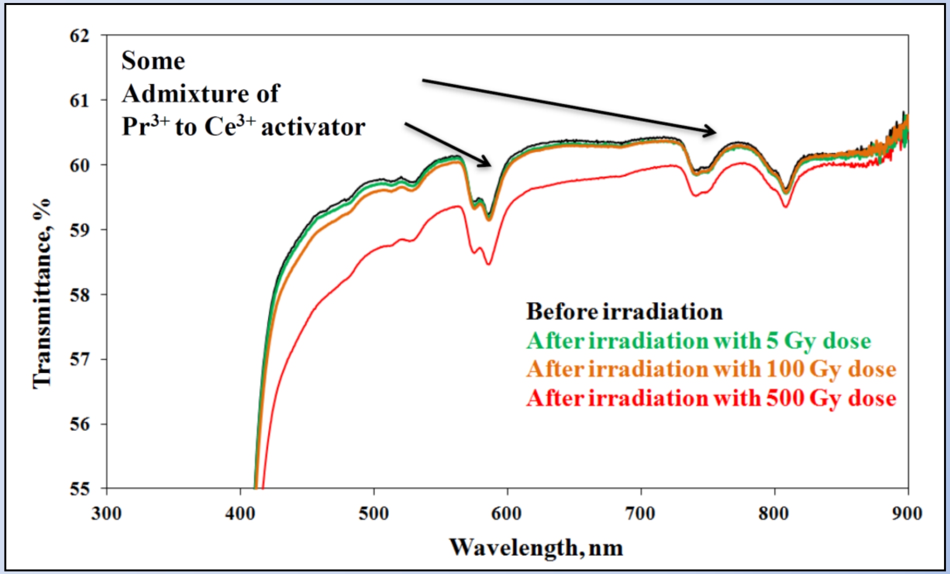
Irradiation and recovery studies:

Quality of samples:

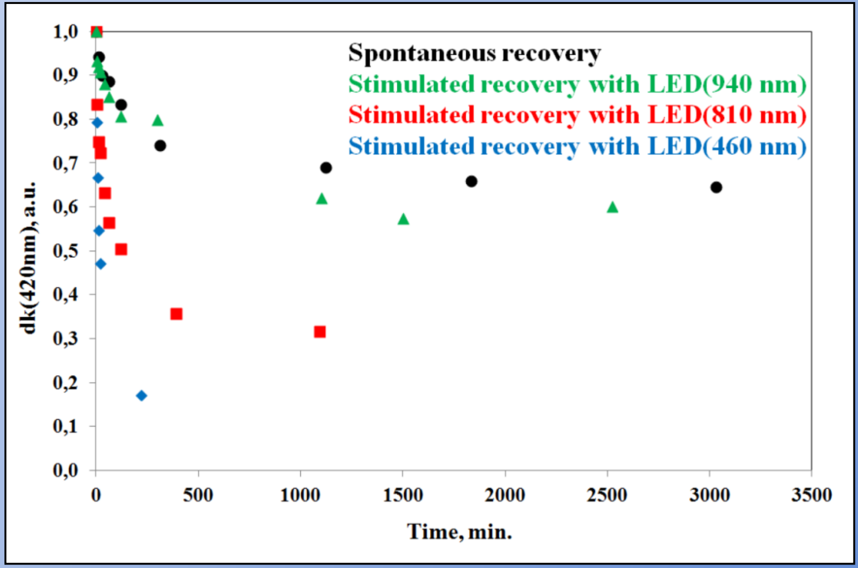
@RT, integration 4µs
dLY:/dT: +0.05%/°C
LY @ RT: 110 phe/MeV (4µs)



Irradiation with ^{60}Co, 2Gy/min



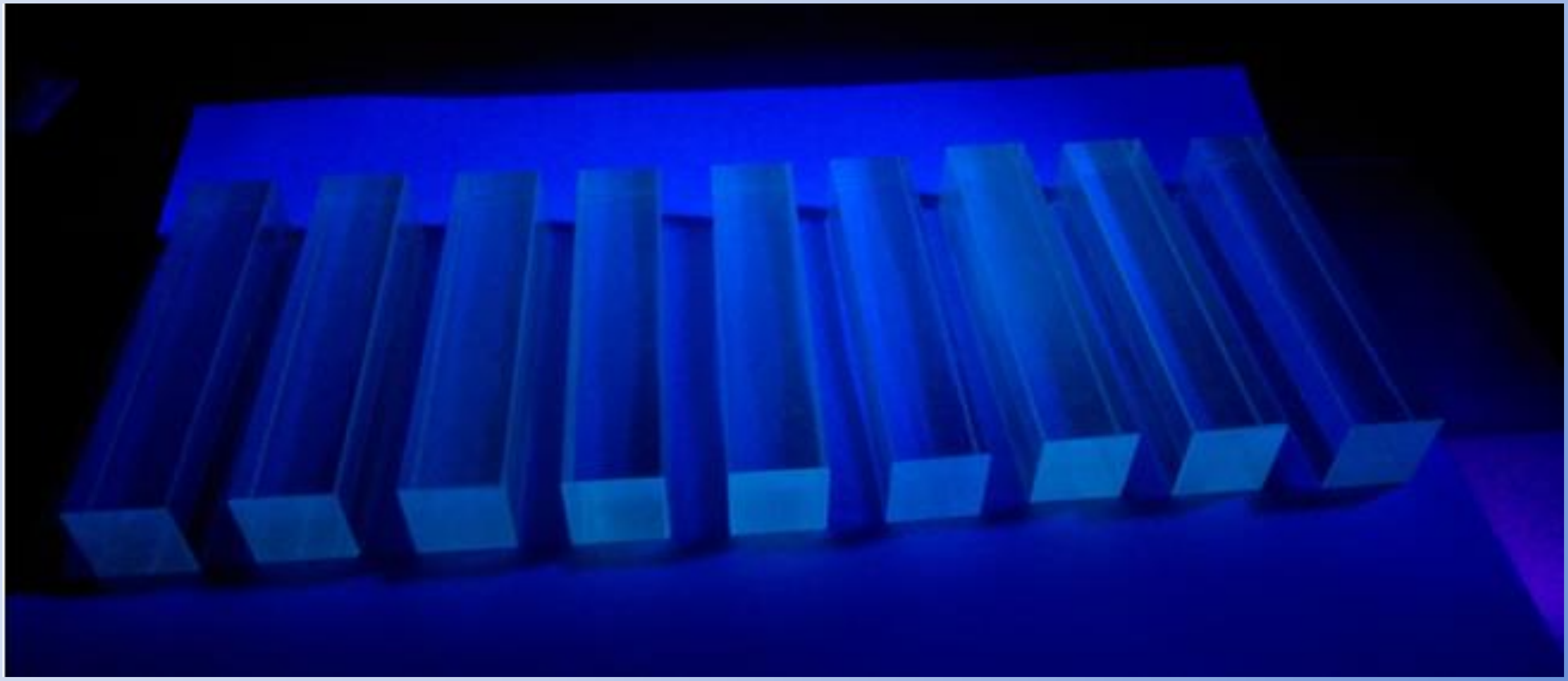
Spontaneous and stimulated recovery



Beam test of 3x3 DSB matrix

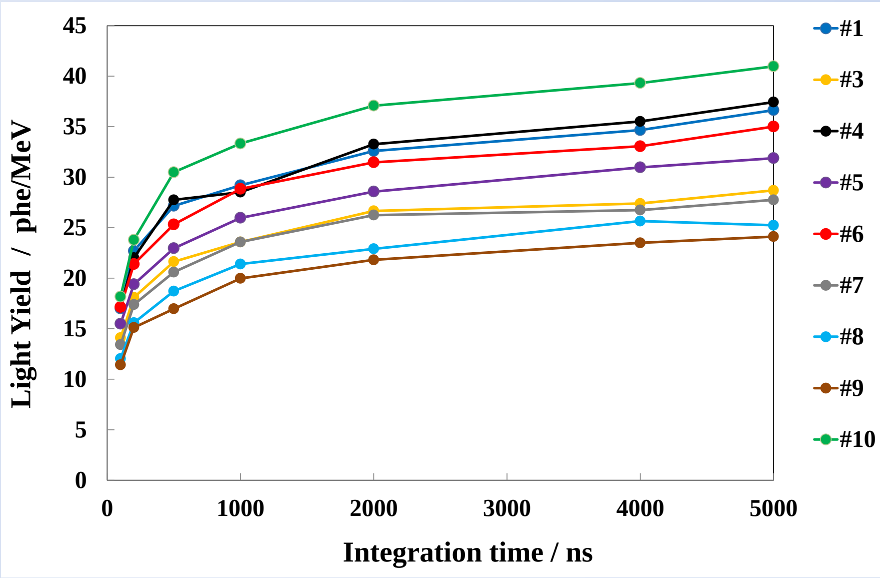
➢9 full size (2x2x10cm) samples of DSB:Ce material were delivered in June 2017

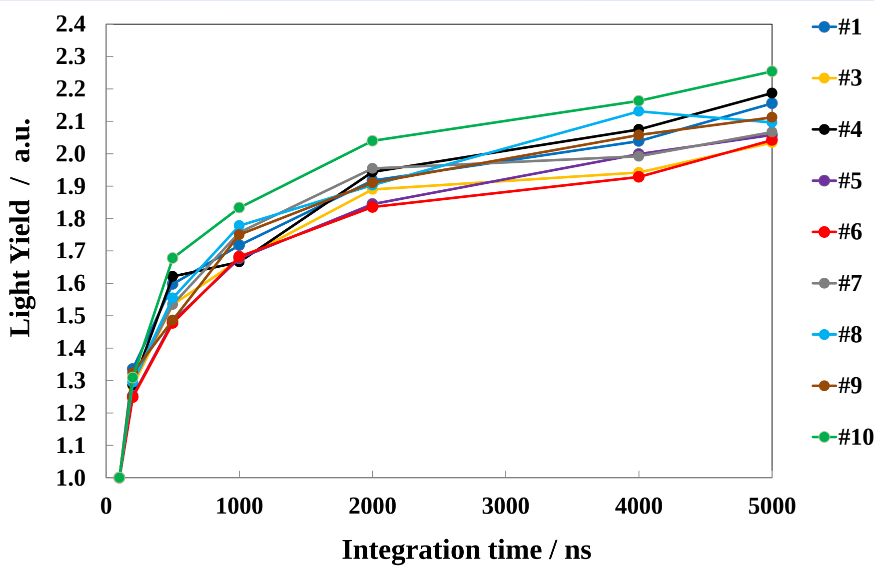
➢Beam time with gamma-quanta (20-200 MeV) took place at MAMI (Mainz, Germany) in March 2018.



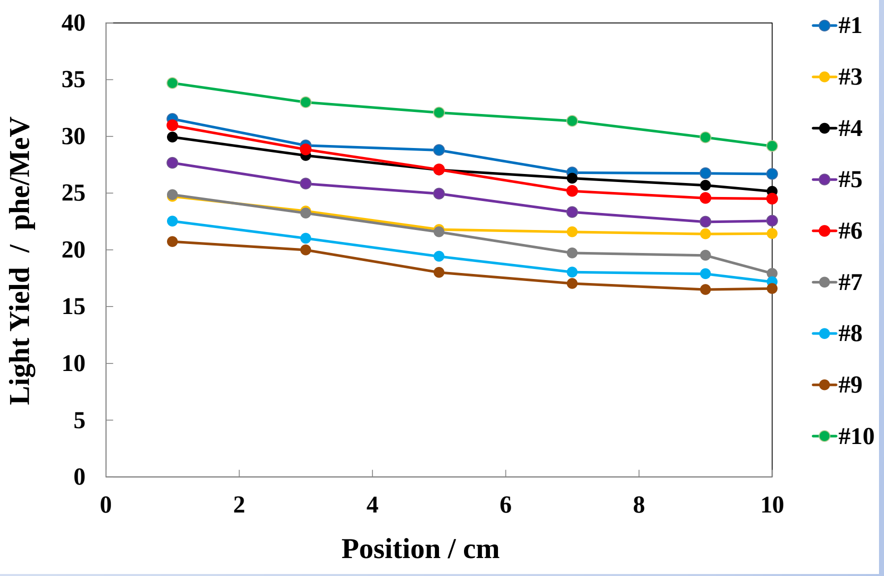
Properties measurement of 9 DSB samples

Light yield vs integration time @ room temperature

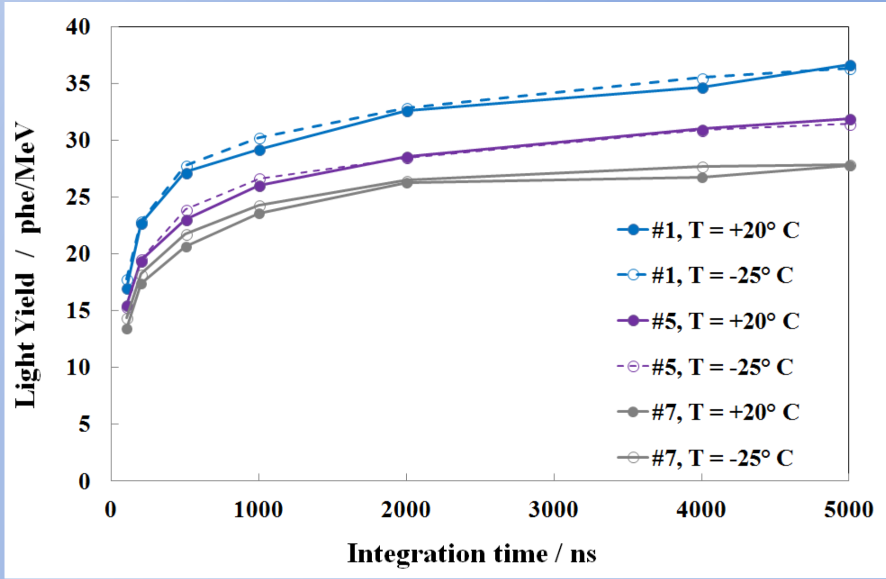




Nonuniformity of the Light Yield

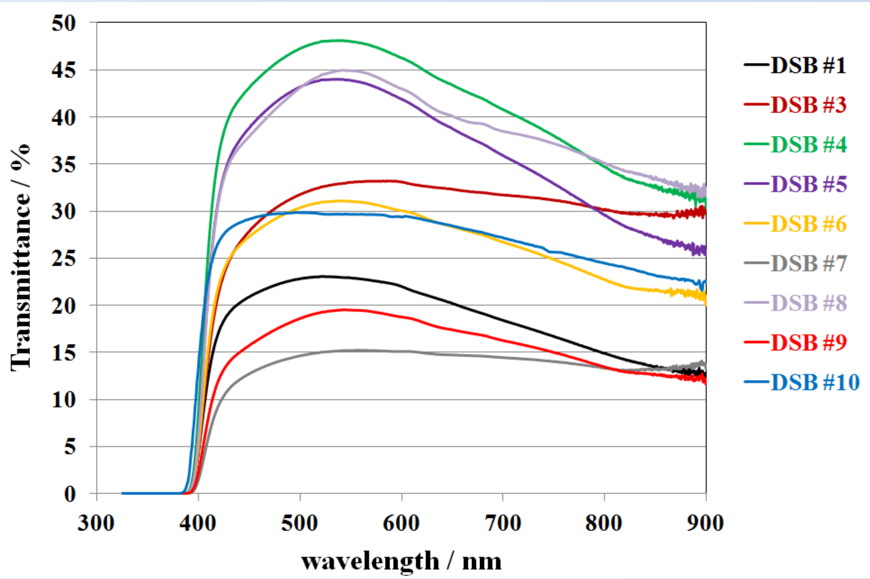


Light yield vs temperature

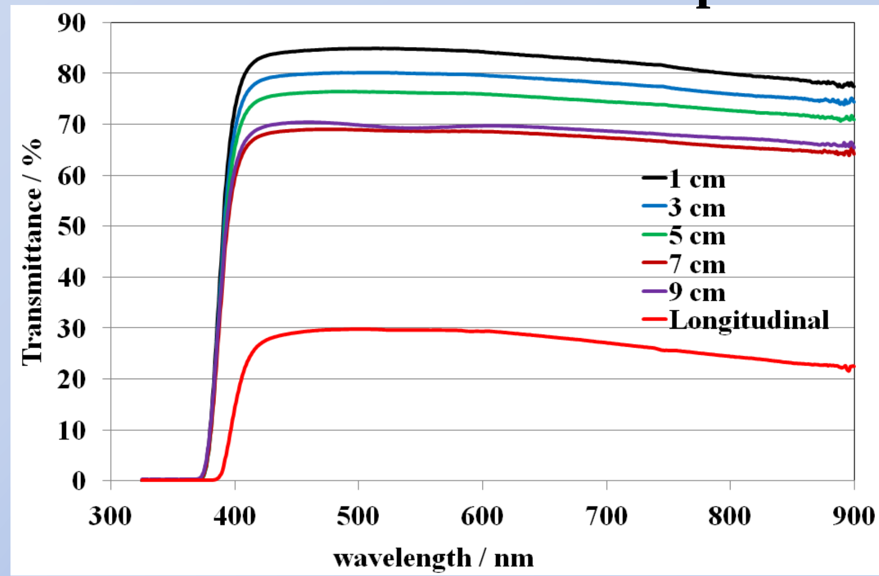


Properties measurement of 9 DSB samples

Longitudinal transmittance

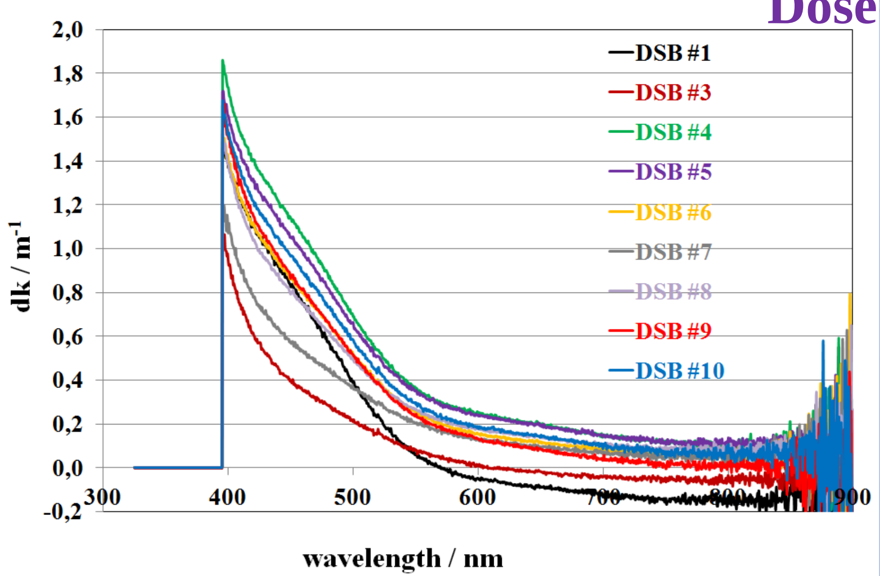


Transversal transmittance of sample #10

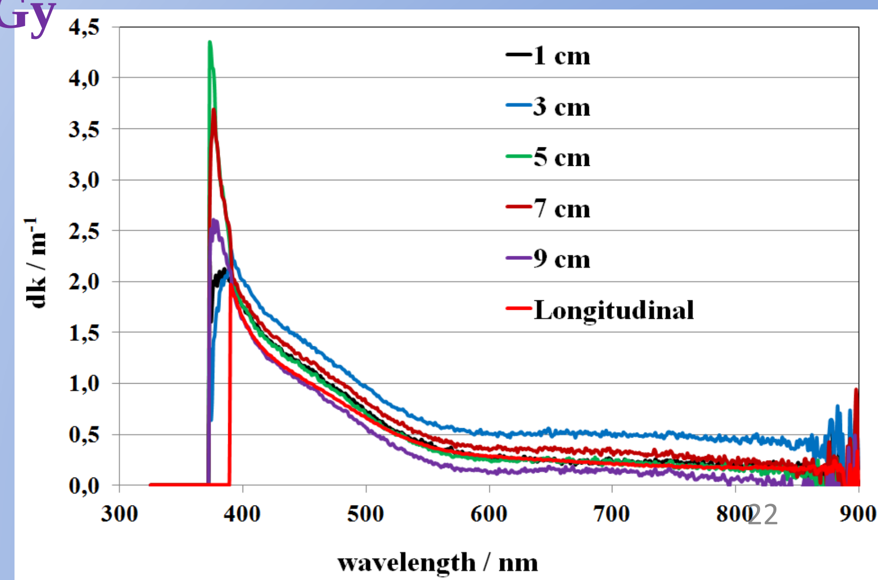


Longitudinal dk

Dose= 100 Gy



Transversal dk of sample #10

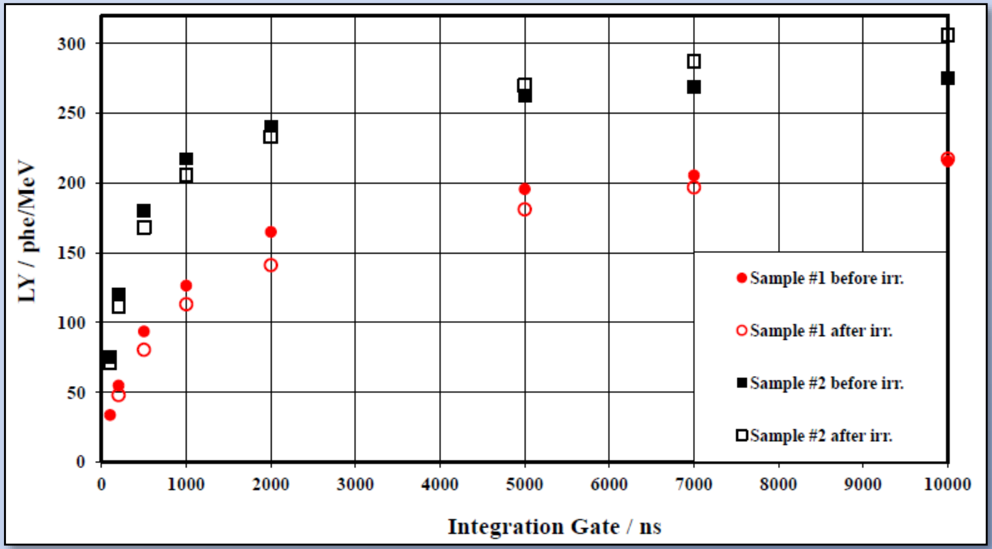


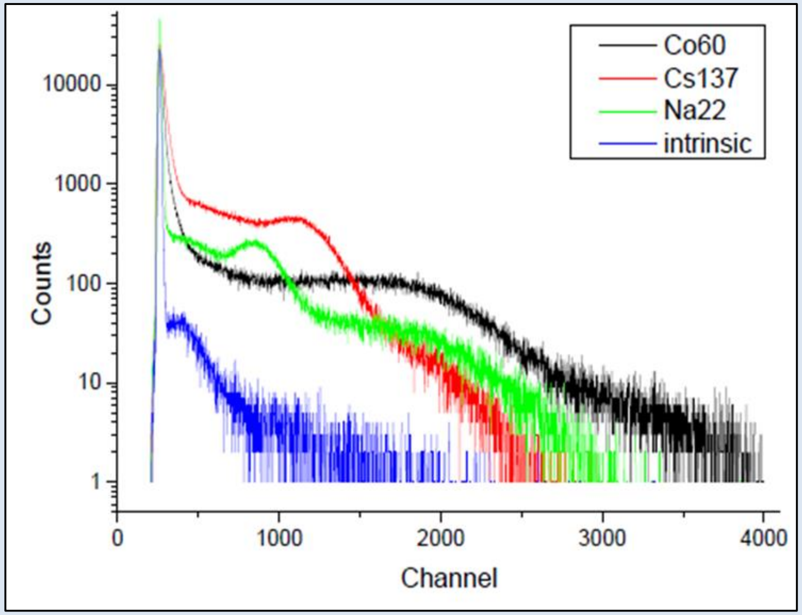
Scintillation properties of Gd-loaded samples

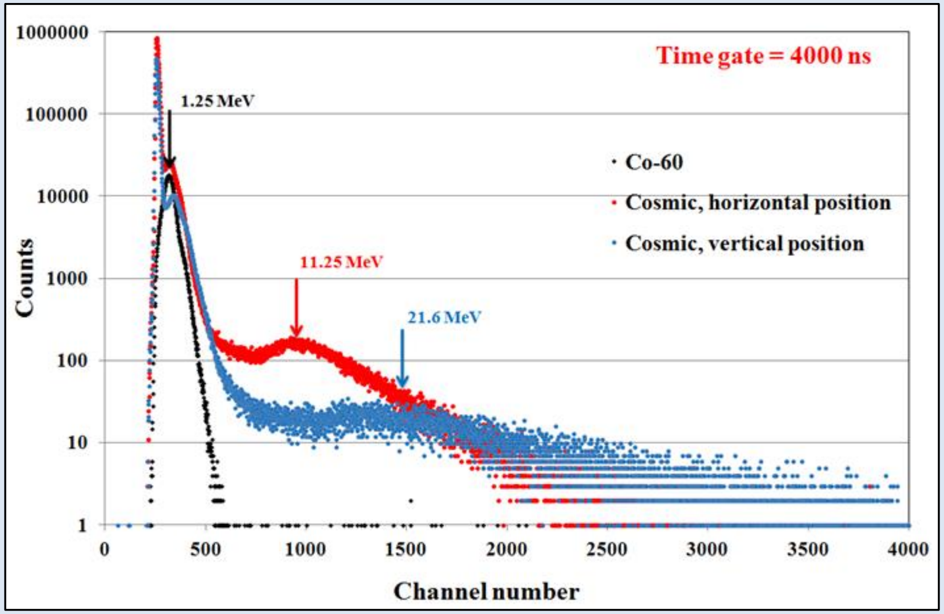
#1: 10 weight% Gd_2O_3
#2: 20 weight% Gd_2O_3
both: 0.5 weight% Ce

light yield as a function of integration length

Two samples with 5 mm thickness



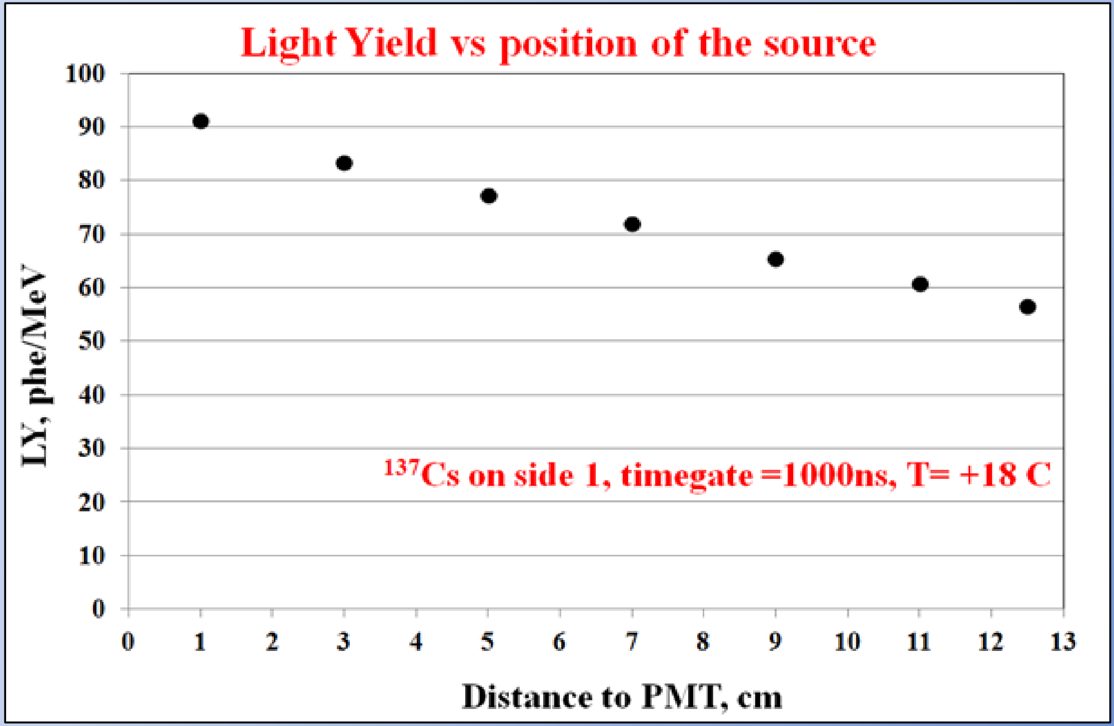




large volume samples : $25x25x125mm^3$

DSB:Ce / Gd loaded   large volume 25 x 25 x 125 mm^3

Non-uniformity of the light yield

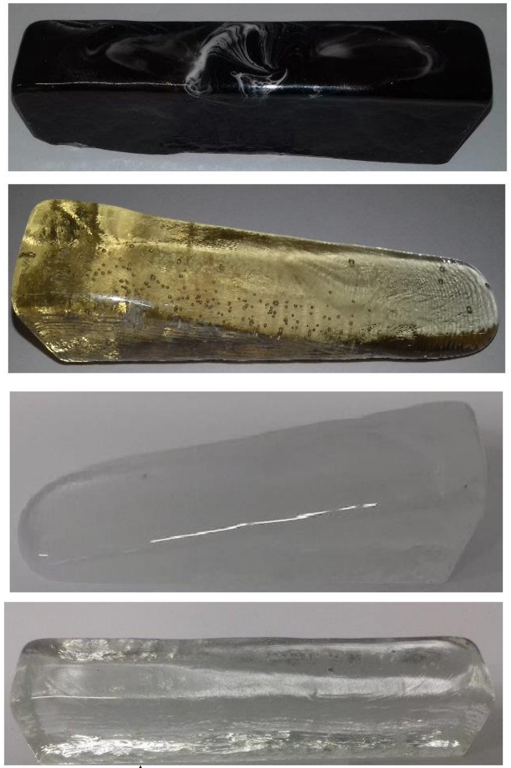


Next step in development with an industrial partner in frames of ATTRACT Project:

PRECIOSA

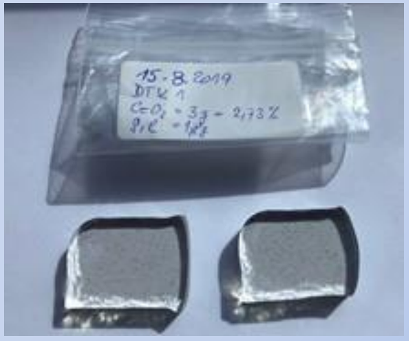
www.preciosa-ornela.com
468 61 Desná, Czech Republic

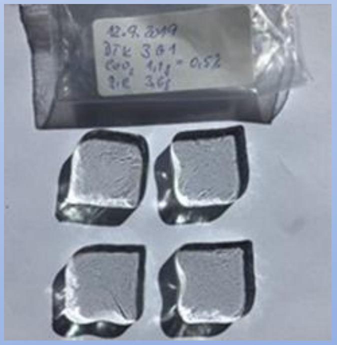
Technology evolution



One ingot from the first probes

First ingot with reasonable Light Yield



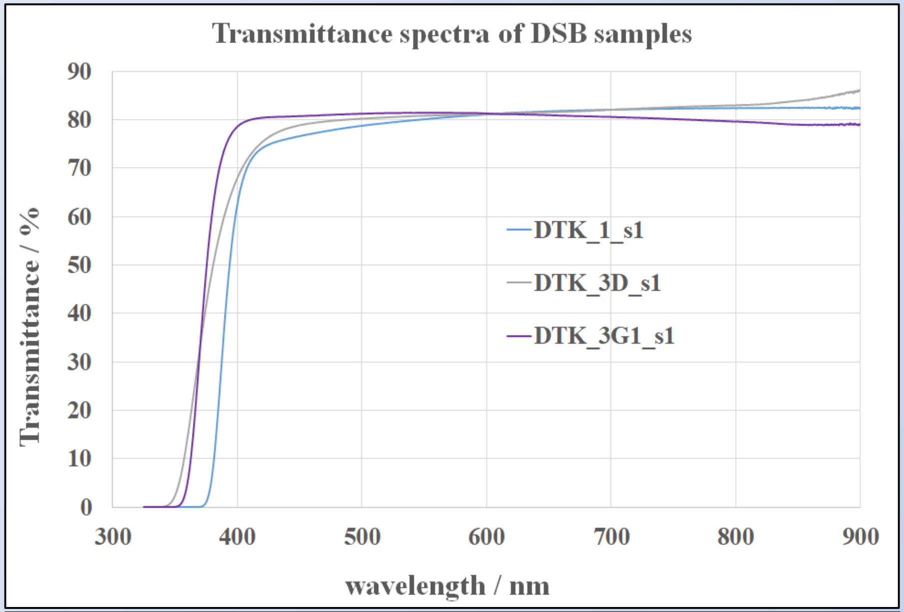


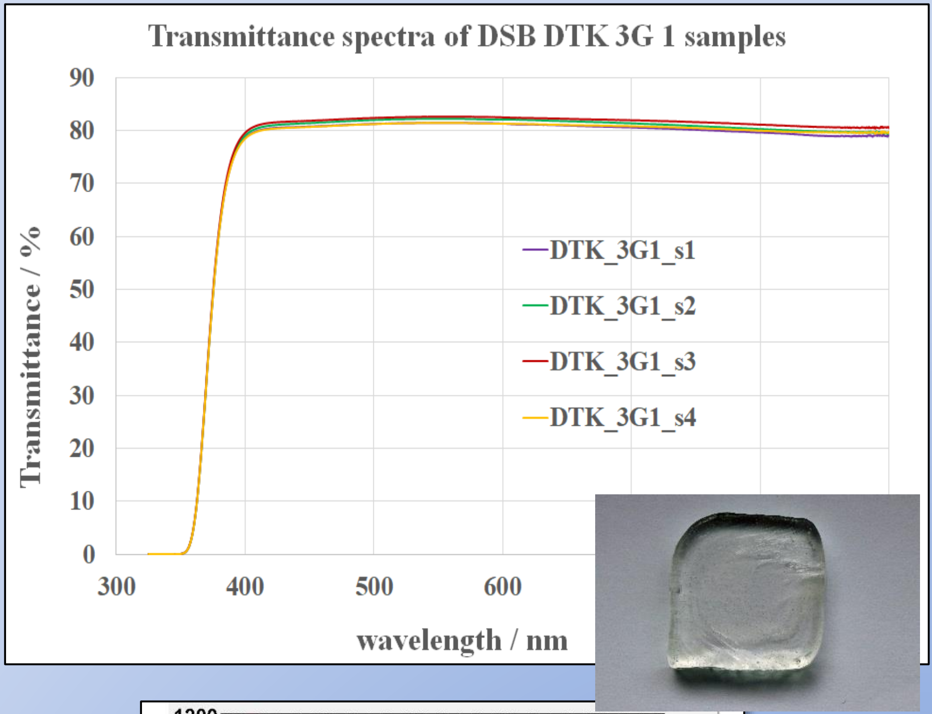
produced:
Sept. 12, 2019

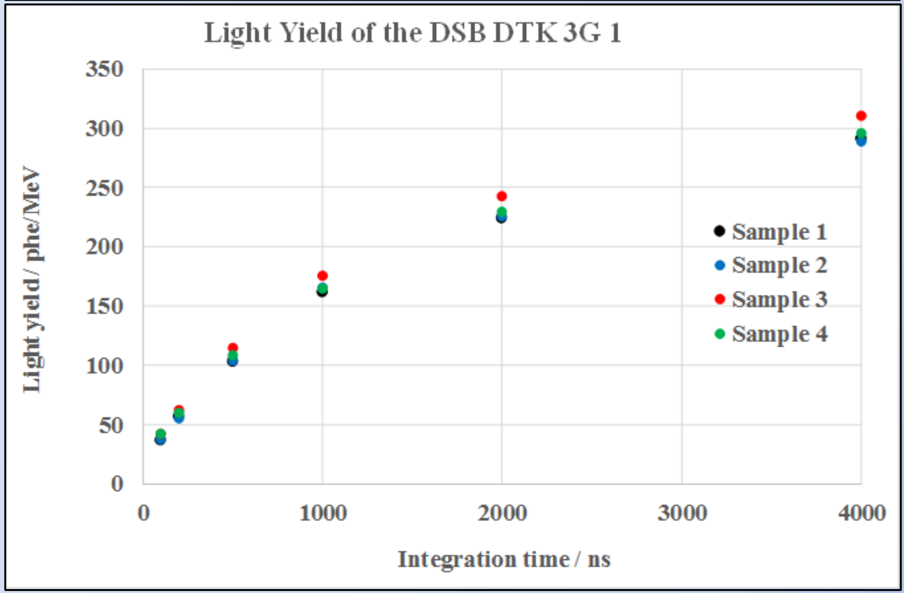
CeO_2 = 0.5%
SiC = 3.6g

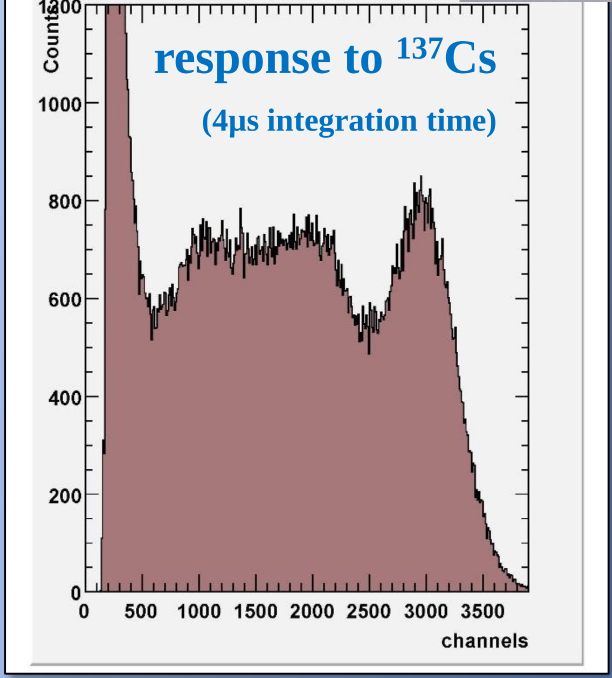
Significant reduction of the macrodefects („bubbles“) was achieved

basic properties



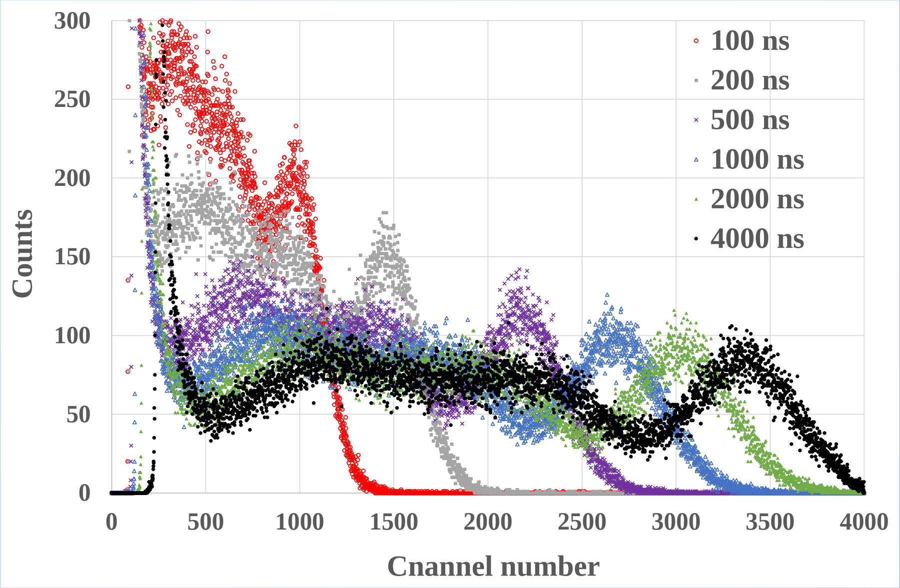




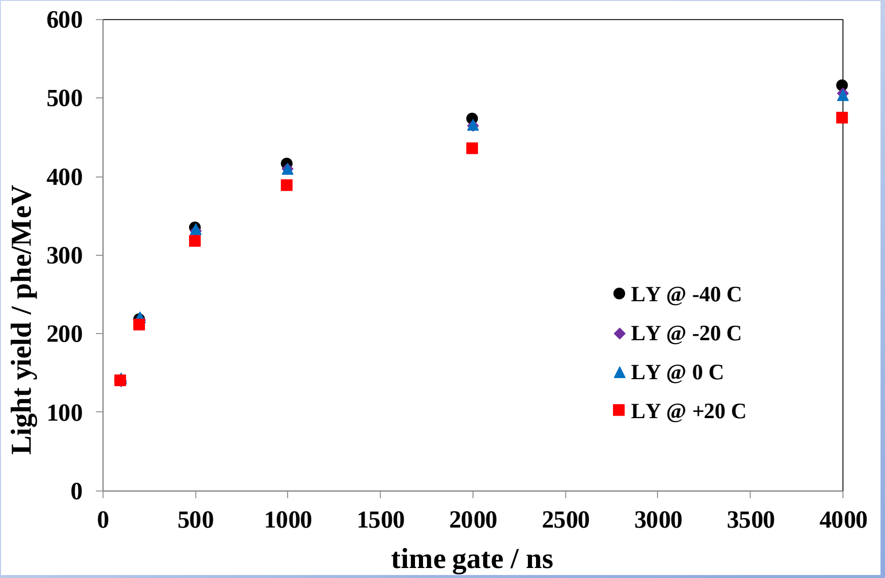


Start of mass production for first protypes

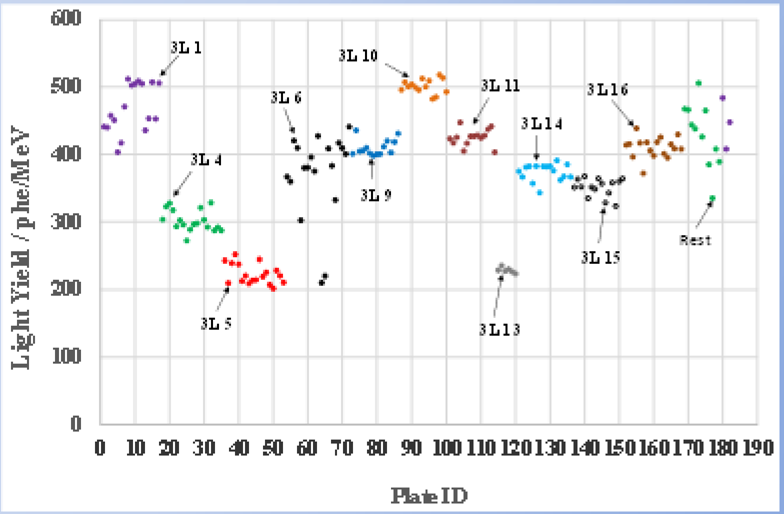
^{137}Cs spectrum measured at T= +20 C, integration time = 4 μs



Light yield vs integration time measured at different temperatures

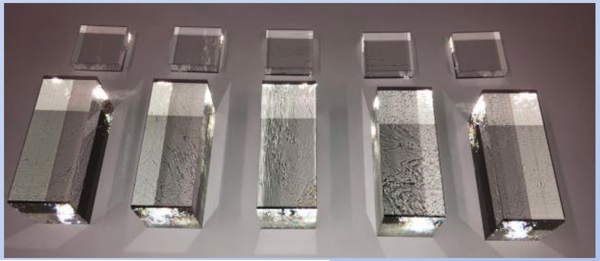


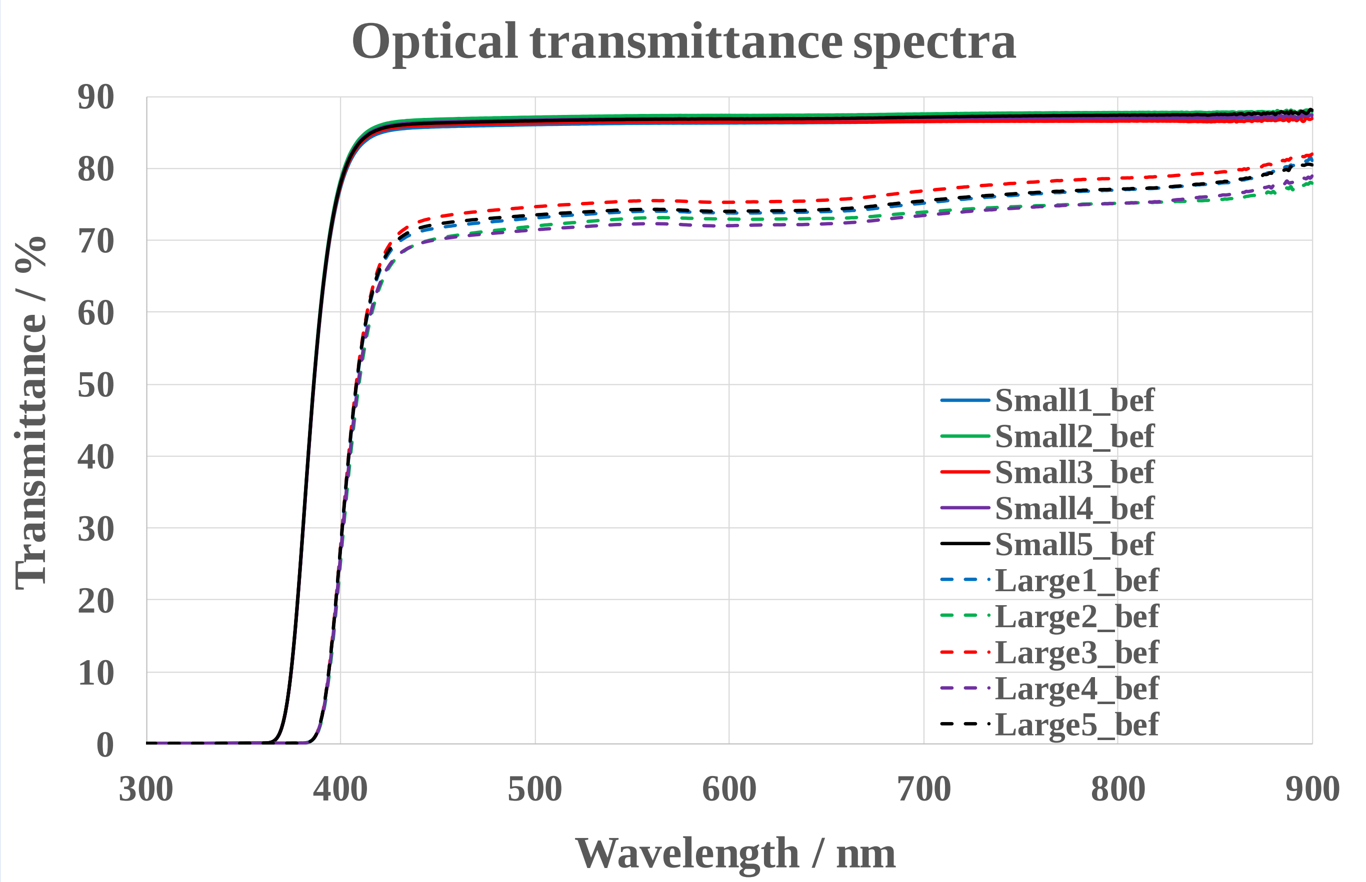
Light yield values measured at +20 C, integration time 4μs



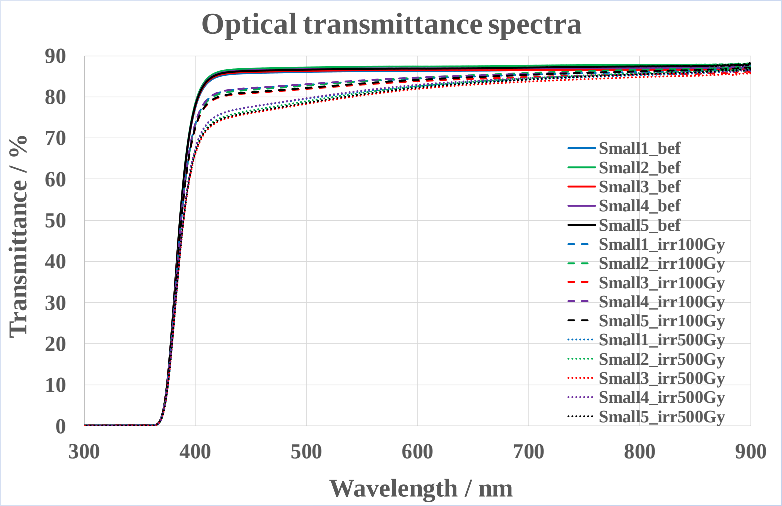
DSB glass samples

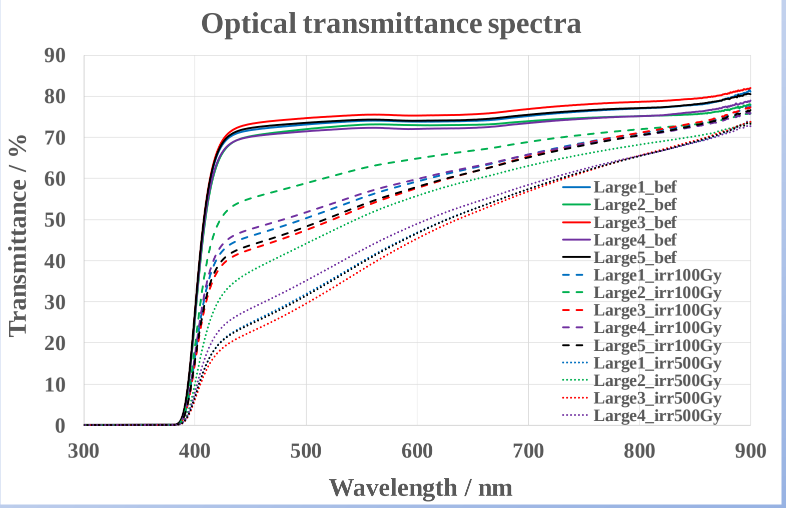
Two types of the glass materials have been delivered by Schott Company:
5 samples with 20x20x5 mm^3 dimensions;
5 samples with 20x20x50 mm^3 dimensions;

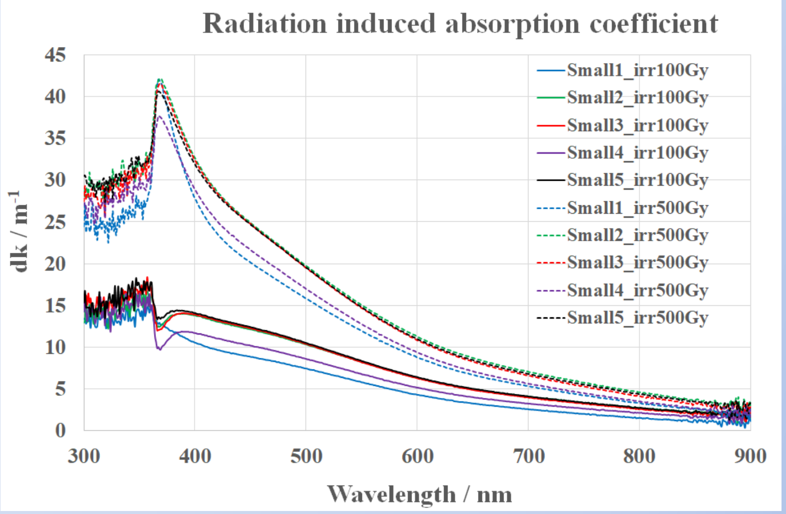


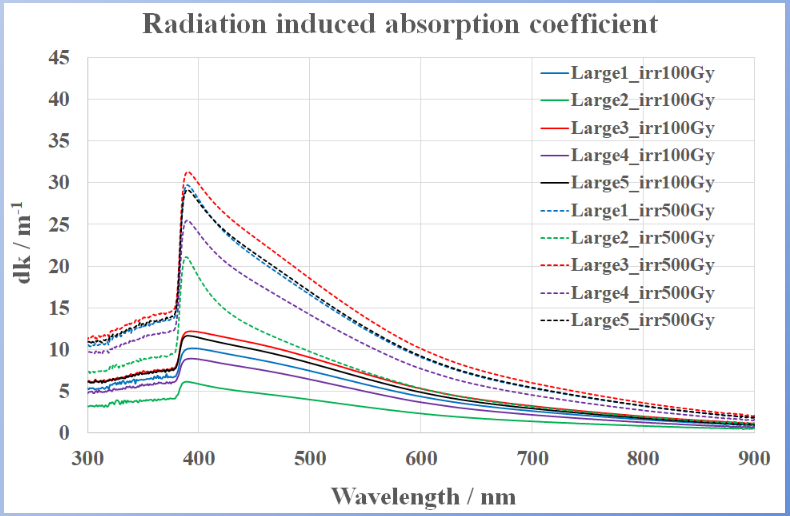


DSB glass samples: radiation damage

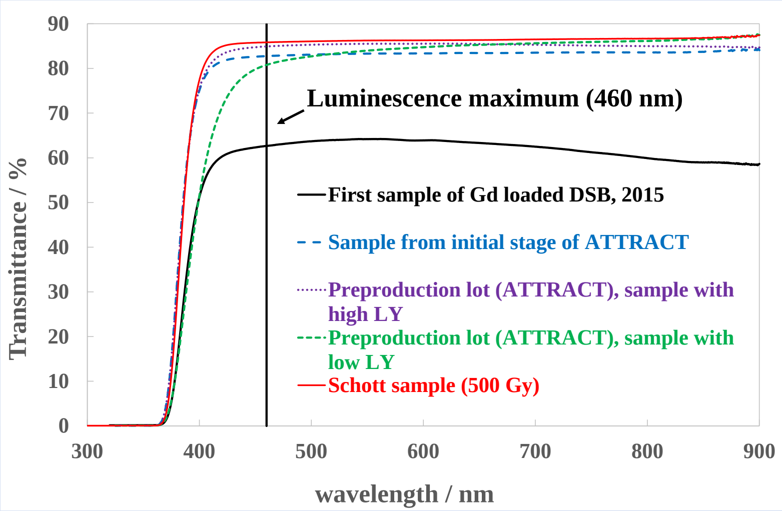


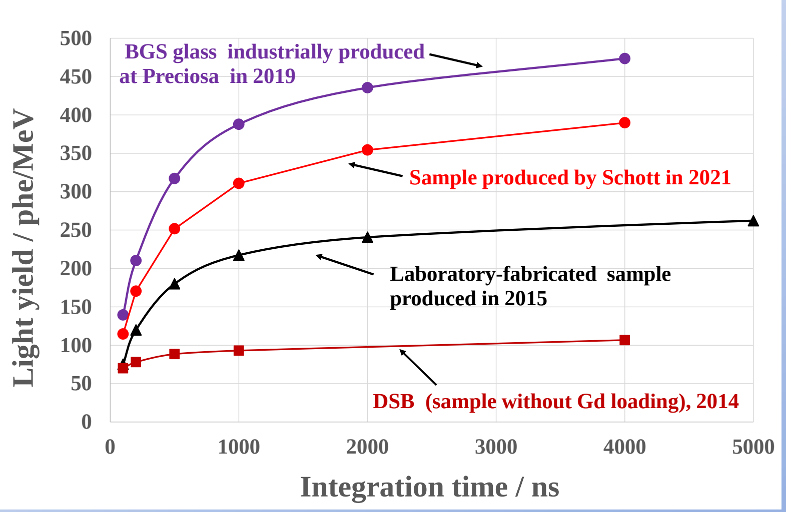


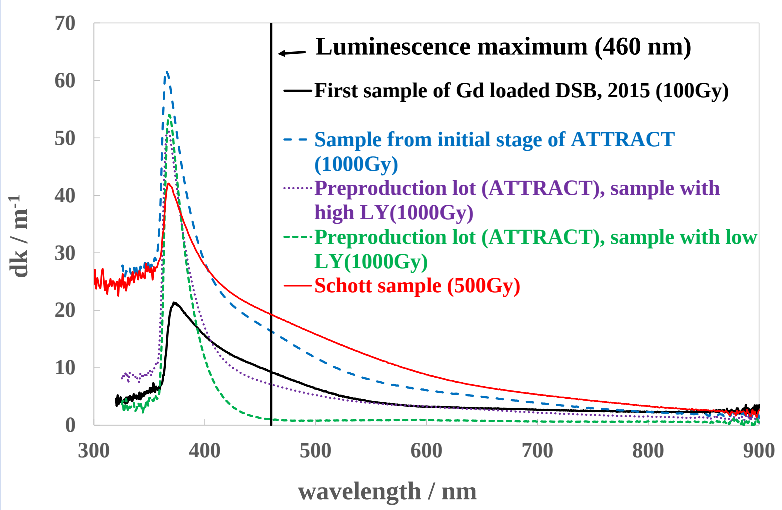


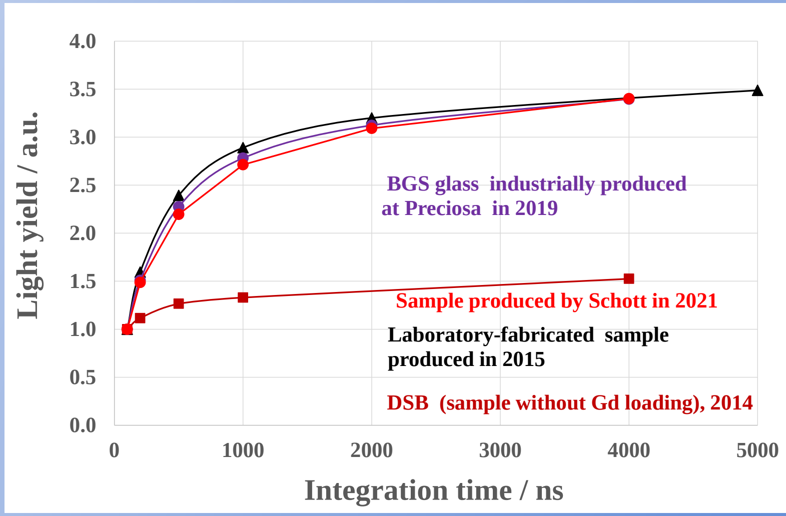


DSB glass samples: comparison results









DSB glass material

- **The DSB glass material is a cheap material. Properties can be adopted to application conditions. It has 3-4 times higher density in comparison to plastic scintillators, allows variable scintillator shapes**

- **Glass material can be fabricated in various sizes and shapes, such as blocks, plates, and thin fibers. Large quantities of the detection units can be produced in a relatively short period of time**

- **The lead-free glass $BaO \cdot 2SiO_2$: Ce (DSB: Ce) has a density of 3.7 g/cm^3 and is found to be radiation hard. Further technology optimization showed that the loading of the DSB: Ce glass by gadolinium increases the material density up to 4.4 g/cm^3 and results in an increase in the light output by a factor of four, significantly improving the efficiency of the electromagnetic radiation registration and making the material sensitive to neutrons**

- **Further technology optimization should be targeted to improve timing characteristics of the material and the radiation hardness**