Novel Material Studies and Characterizations @ JLU Giessen

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Justus-Liebig-Universität Giessen

HighD Consortium Meeting

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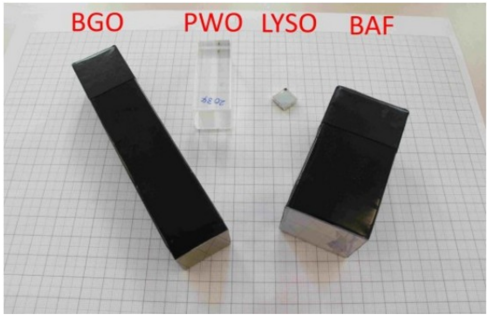
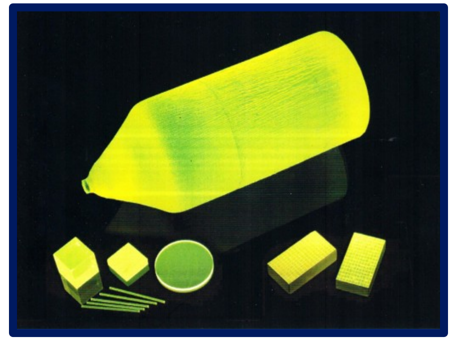
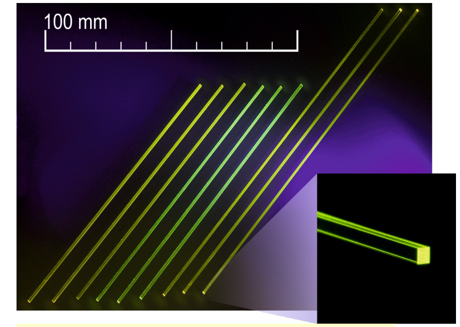
Scintillators



Standard Scintillators



GAGG grown ingods and cut crystals



Courtesy of Crytur (CZ)

YAG:Ce fibers (cut or drawn by µ-PD)

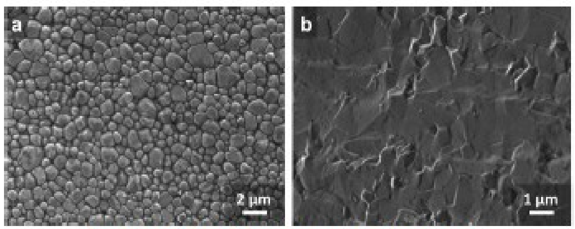


Fig. 1. SEM of YAG:Ce ceramics: a) surface, b) scale.

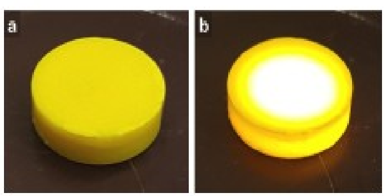
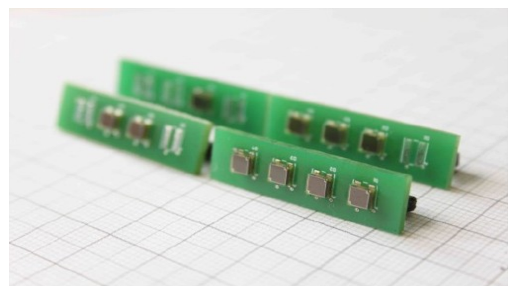
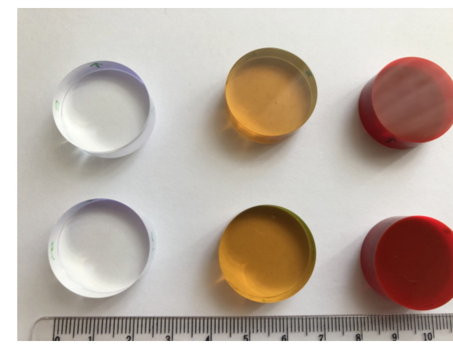


Fig. 2. Photography of translucent YAG:Ce ceramics under visible light (a) and illuminated with 460 nm LED from below (b).

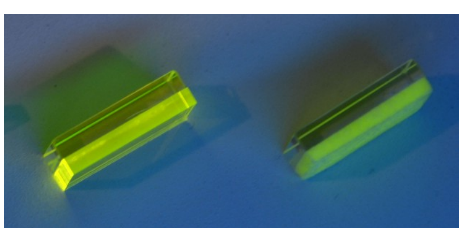
Translucent garnet ceramics (NRC Kurtchatov)



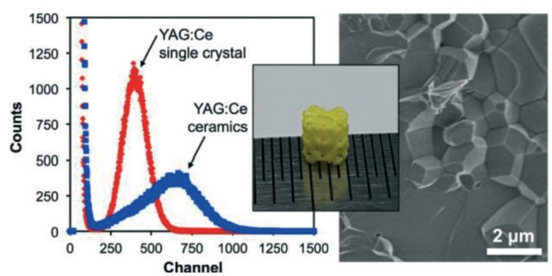
Optimize matching with SiPM Photosensors



Optimized Organic scintillators



Stochiometric optimization of garnets



YAG:Ce 3D printed ceramics

Scintillating glass/ glass ceramics

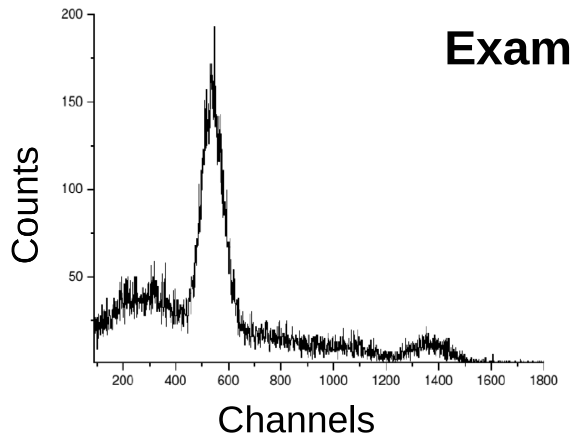
Minicalorimeter arrays

Scintillators

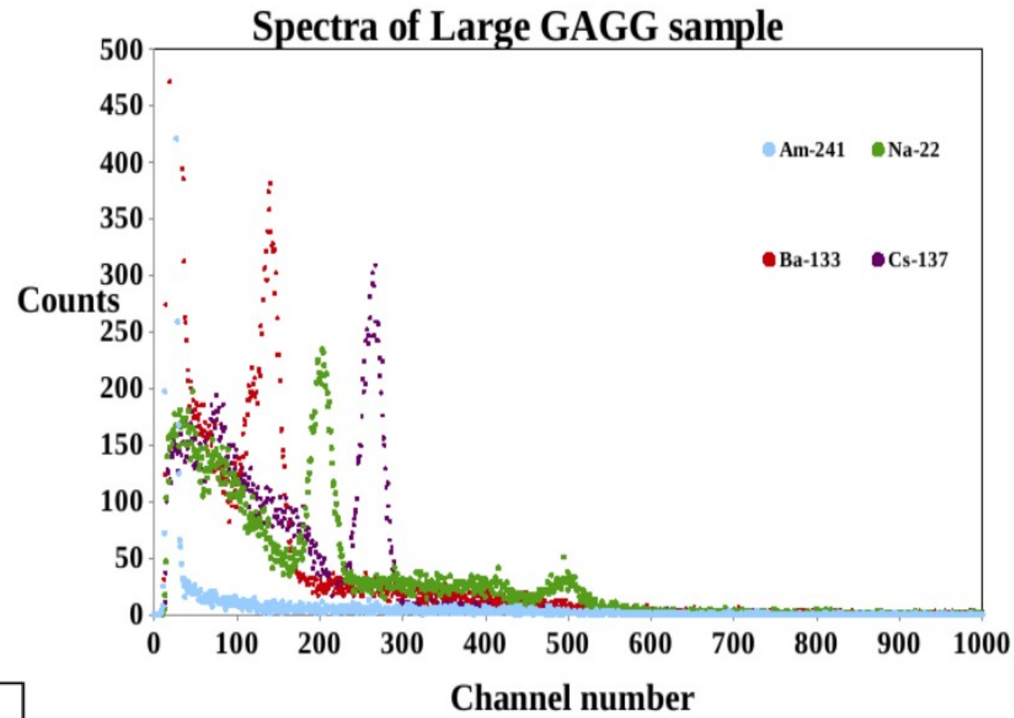
Material	ρ, g/cm^3	Z_{eff}/ radiation length X_0,cm	Yield, ph/MeV	τ_{dec}, ns	λ_{Max}, nm
Glass ceramics $BaO*2SiO_2$:Ce (DSB)	3.8	51/ 3.0	300	22/ 72/ 450	440
$PbWO_4$ (PWO-II)	8.3	75.6/ 0.89	100	6	420
$Gd_3Al_2Ga_3O_{12}$:Ce (GAGG)	6.67	50.6/ 1.61	46,000	80/ 800	520
$(Gd\text{-}Y)_3(Al\text{-}Ga)_5O_{12}$:Ce	5.8	45/ 1.94	60,000	100/ 600	560
$Y_3Al_5O_{12}$:Ce (YAG)	4.55	32.6/ 3.28	11,000	70	550
$YAlO_3$:Ce (YAP)	5.35	32/ 2.2	16,200	30	347
$(Y_{0.3}\text{-}Lu_{0.7})\ AlO_3$:Ce (LuYAG)	7.1	60/ 1.3	13,000	18/ 80/ 450	375
Lu_2SiO_5:Ce (LSO)	7.4	66/ 1.1	27,000	40	420
$(Lu\text{-}Y)_2SiO_5$:Ce (LYSO)	7	60/ 1.35	30,000	37	420
Plastic (Polyvinyltoluene/ N-tolylcarbazole)	1.023	4.5/ 45	9,200	9.2	420/490
PEN (Polyethylene-Naphtalate)	1.33	?/ ?	Up to 10,500	35	430

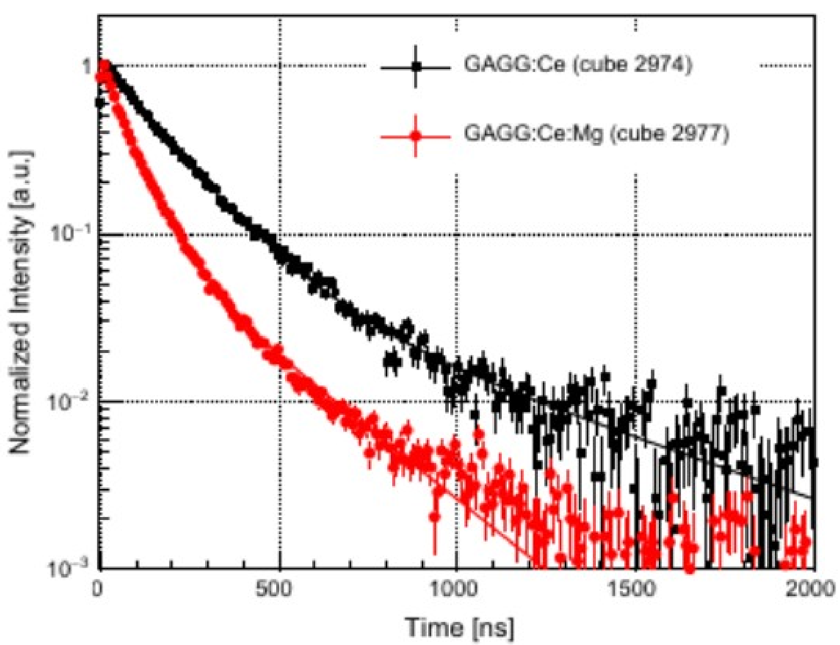
Scintillator Characterization

Examples

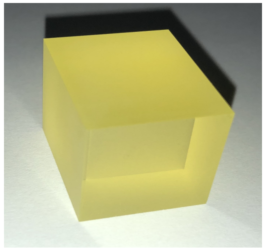


LYSO:Ce + SiPM S10362-33-025C
Na22 response



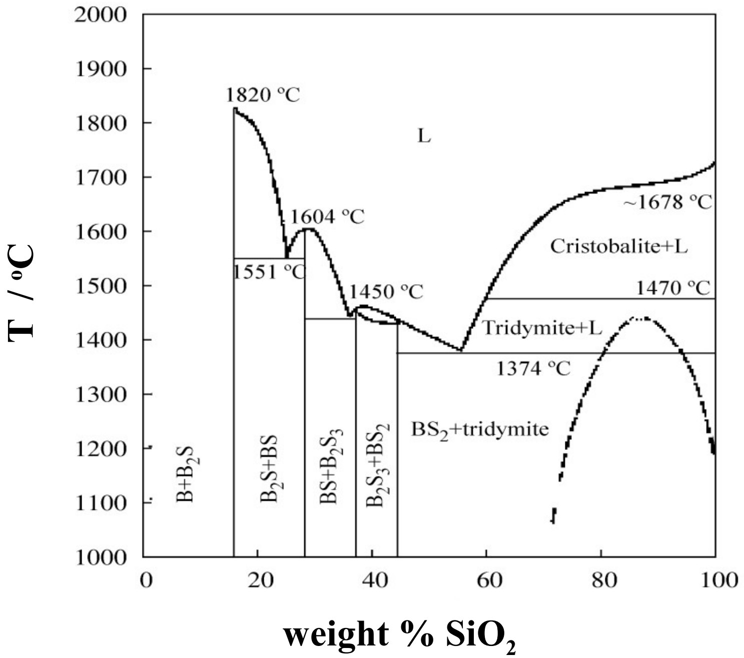


GAGG:Ce
(20x20x25mm)
+ PMT Ham. R329



→ codoping with Mg shifts ratio between slow/fast components

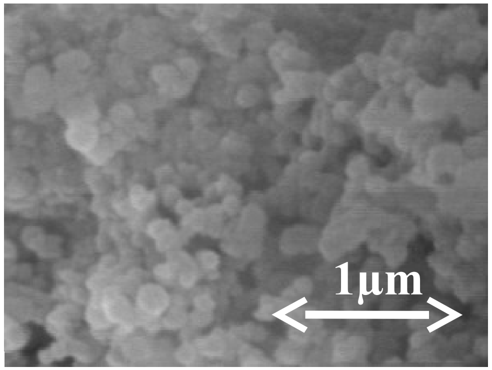
DSB Glass Ceramics



phase diagram of the $BaO*SiO_2$ system

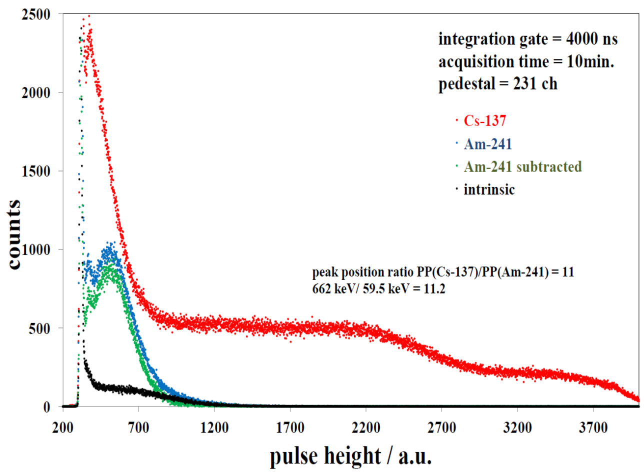
material	ρ g/cm^3	Z_{eff}	X_0 cm	λ_{max} nm	cutoff undoped material nm
$(BaO*2SiO_2)$:Ce glass	3.7	51	3.6	440, 460	310
DSB:Ce	3.8	51	3.5	440, 460	310
$(BaO*2SiO_2)$:Ce glass heavy loaded with Gd	4.7 - 5.4*	58	2.2**	440, 460	318

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



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

- nano-sized particles of **$BaSi_2O_5$** improve scintillation!
- Ba-Si system allows to incorporate trivalent ions: **Lu, Gd, Yb**

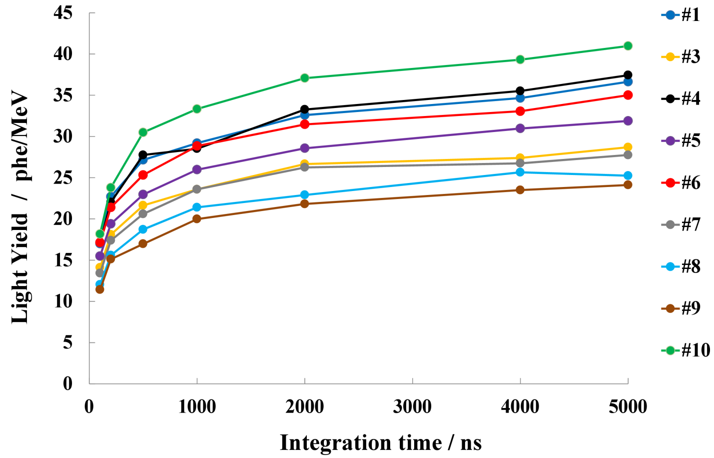


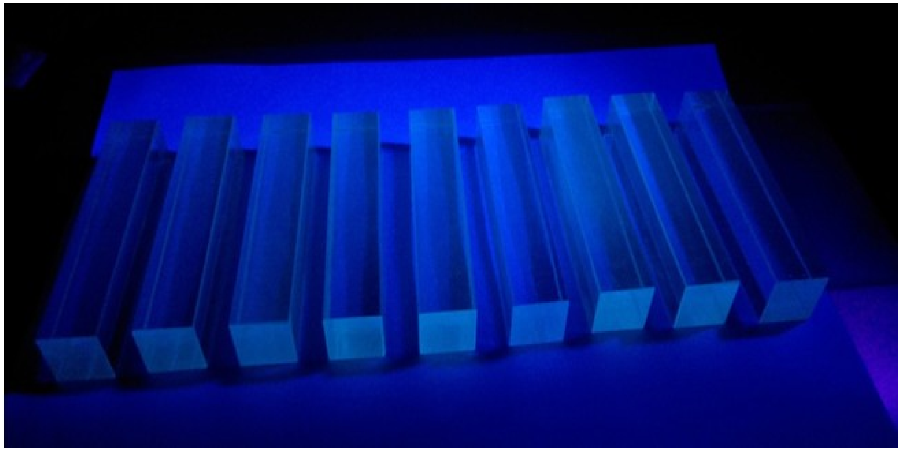
γ-response (small sample), PMT R/O

Early samples JLU Gi & INP Minsk

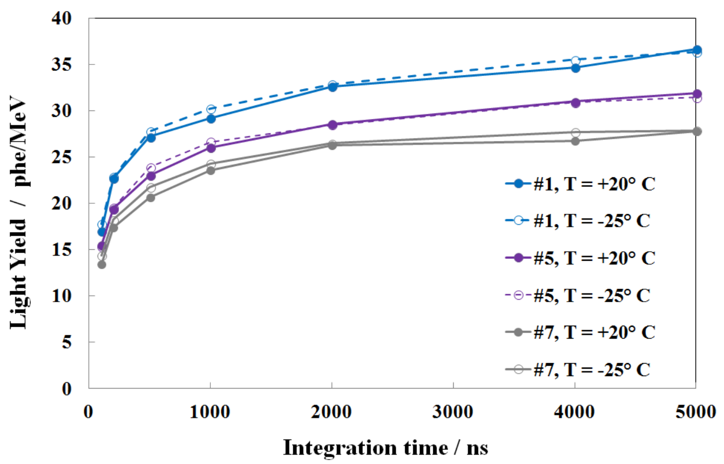
DSB Glass Ceramics

Light yield vs integration time @ room temperature

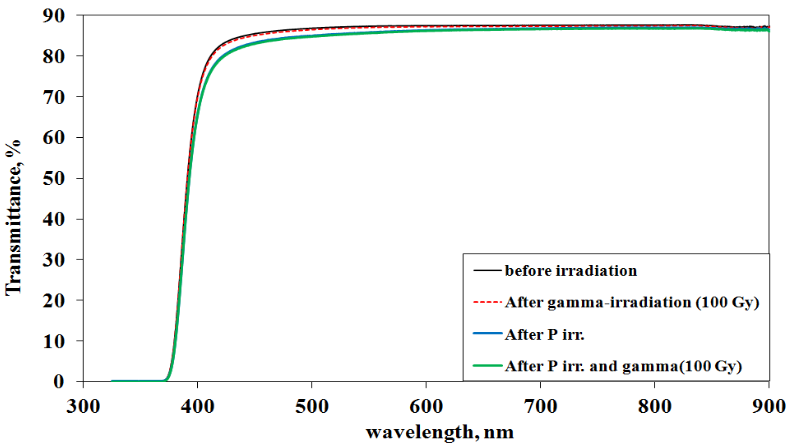




Light yield vs temperature

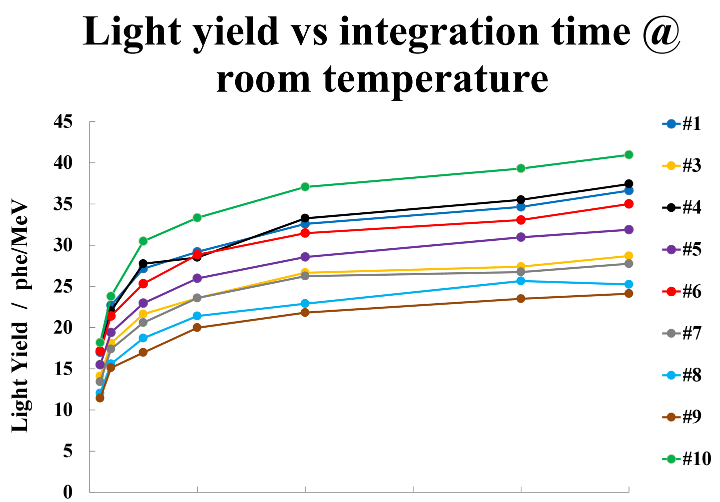


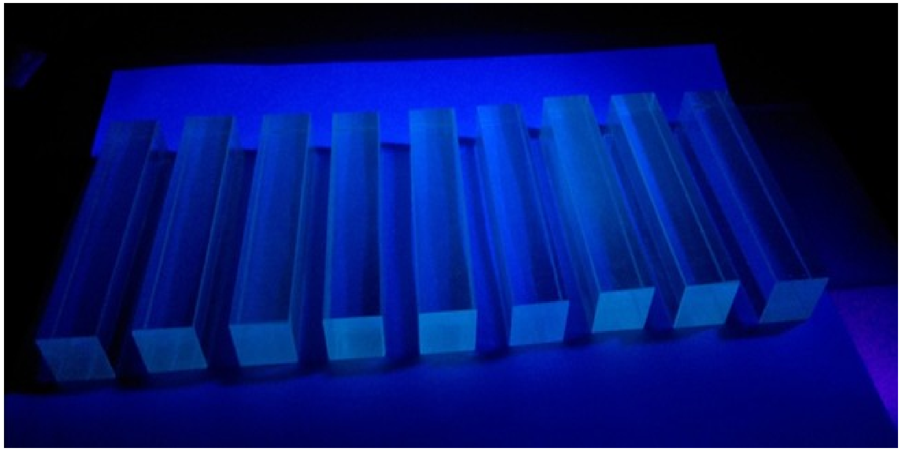
Radiation induced transmittance change



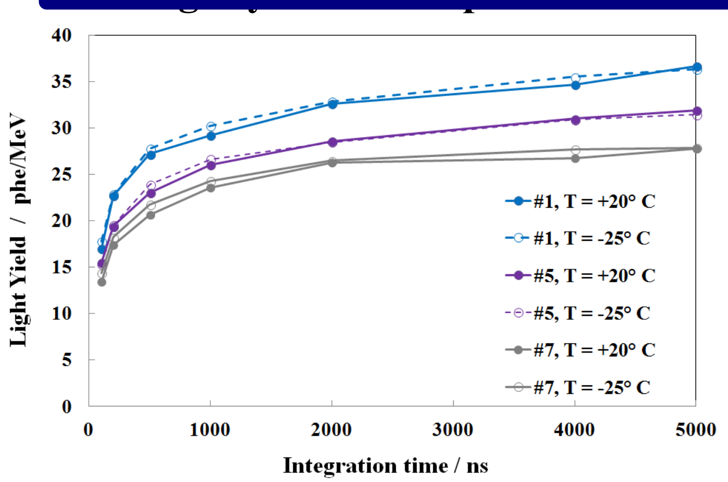
- 150 MeV protons + ^{60}Co gammas
- Int. p fluence: 5×10^{13} p/cm^2

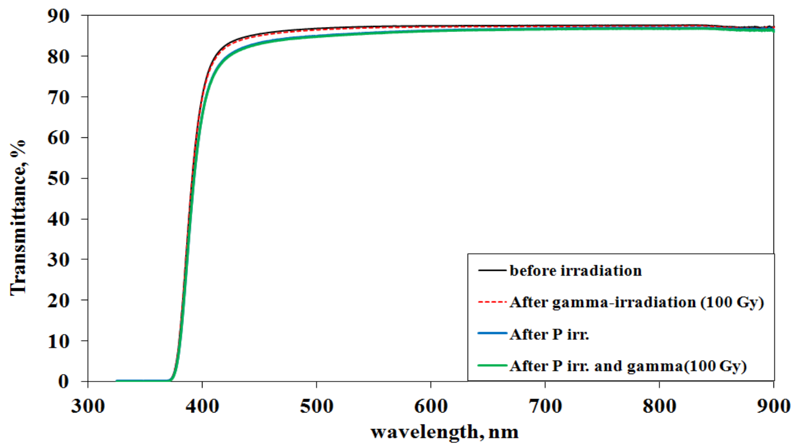
DSB Glass Ceramics





Much more Details in talk of Valera Dormenev





- 150 MeV protons + ^{60}Co gammas
- Int. p fluence: $5x10^{13}$ p/cm^2

Garnet Scintillators

Garnets are good candidates for future HEP applications (fast, bright, rad hard)

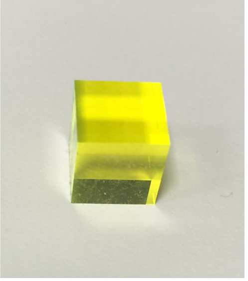
Garnet scintillation materials like

$Y_3Al_5O_{12}$ (YAG), $Y_3Al_2Ga_3O_{12}$, $Gd_3Al_2Ga_3O_{12}$, $(Gd\text{-}Y)_3(Al\text{-}Ga)_5O_{12}$

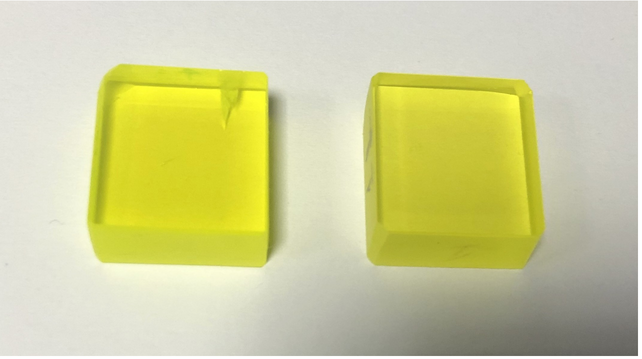
co-doped with divalent ions of group-II elements are candidates to improve the scintillation response.

Aims:
- Improve scintillation kinetics by suppressing slow scintillation component(s)
- Suppress deterioration due to radiation damage
- Applicability of stimulated radiation damage recovery

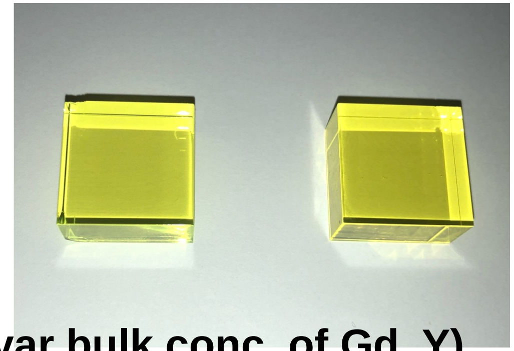
Some current DUTs:



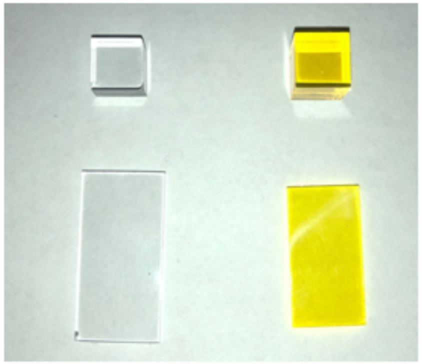
YAG:Ce (fixed dopant conc.)



GAGG:Ce (var dopant conc.)



GYAGG:Ce (var bulk conc. of Gd, Y)

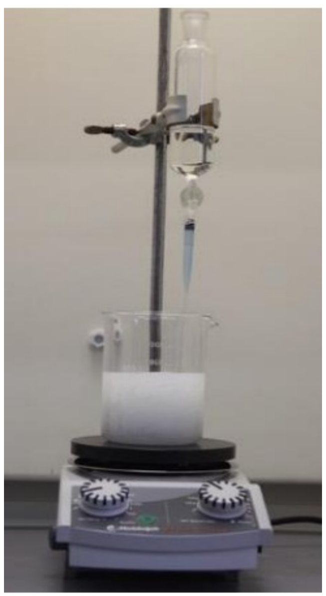


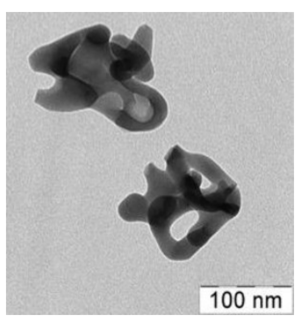
YAG:C,Ce (dopant+codopant)

Optimization of Garnets - Ceramics

Process Flow

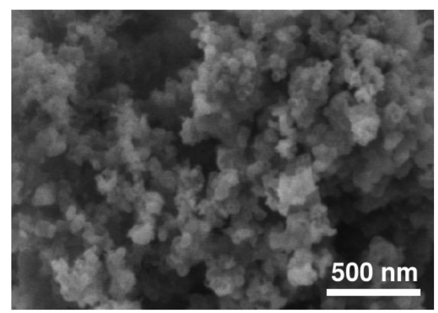
Nanopowder synthesis



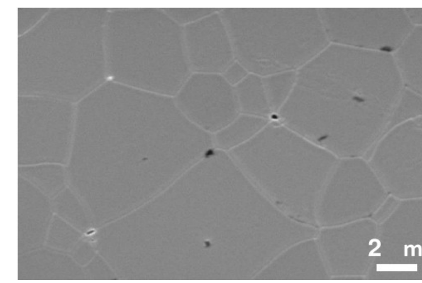


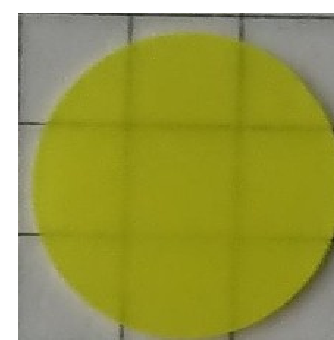
Compactification

- Pressing
- Casting
- Moulding
- 3d-printing



Sintering

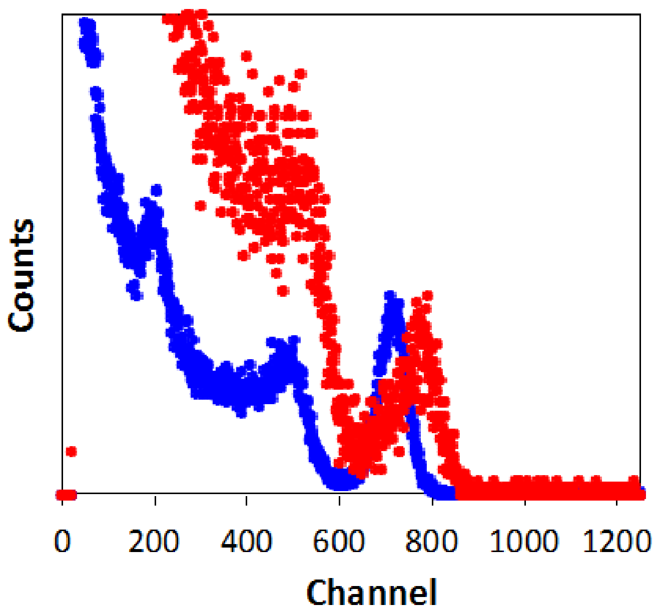




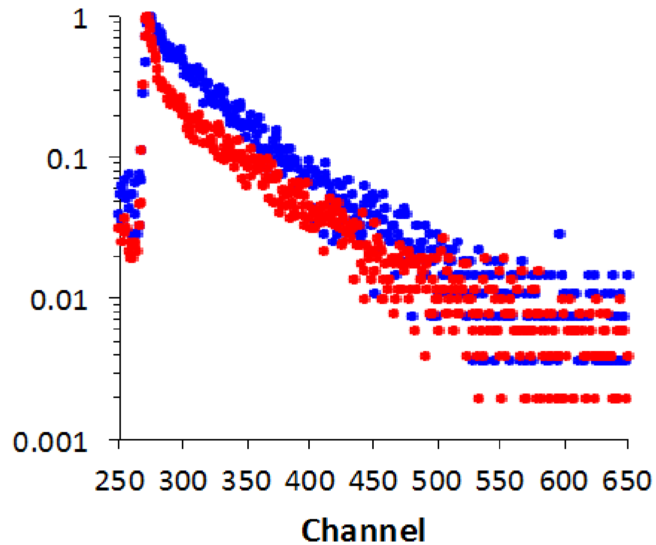
NRC “Kurchatov Institute” - IREA, Moscow, Russia

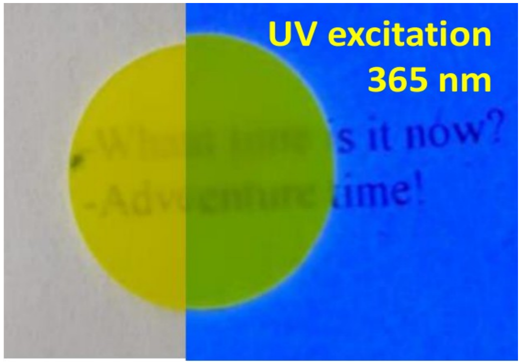
Sample: 1.5 mm thick GYAGG ceramic plate

Cs-137, 662 keV



Na-22, 511 keV, start-stop
Scintillation kinetics



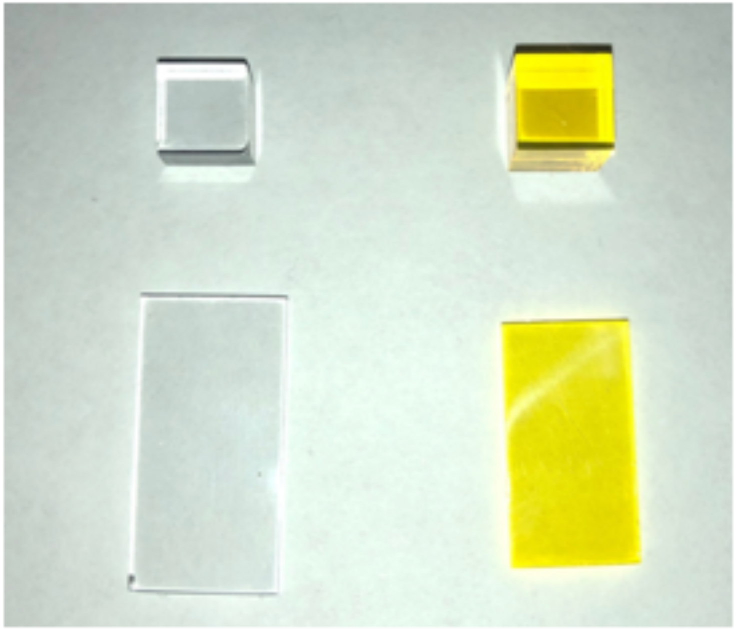


Ref.: GAGG crystal (2 mm thick) LY ~25k Ph/MeV, ΔE/E – 8.7%
LY ~28k Ph/MeV, ΔE/E 13-15%

Ref.: YAP, τ = 28 ns
τ_1 = 5 ns (70%)
τ_2 = 40 ns (30%)

Optimization of Garnets: Example YAG

Influence of Dopant and Codopants: YAG:C,Ce

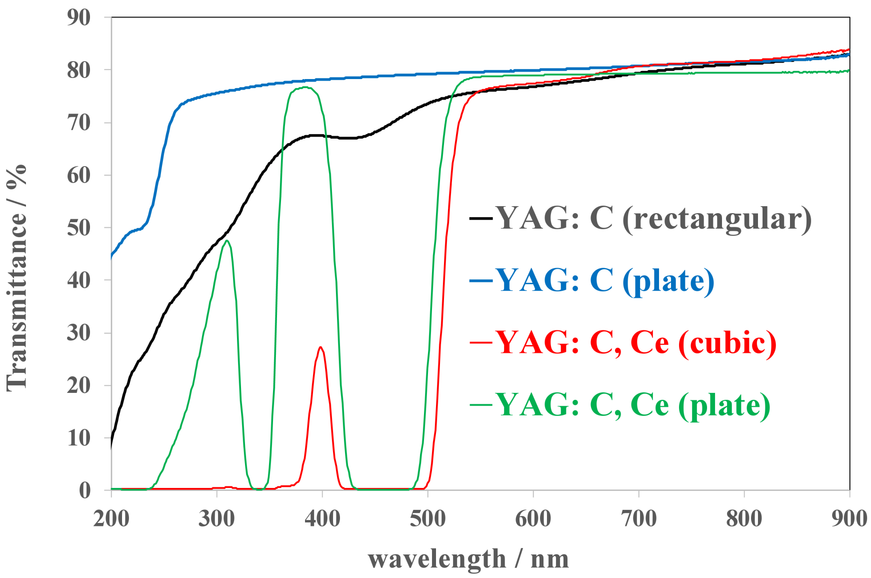


- **Two YAG: Ce, C and two YAG: C samples produced by Czochralski method by ISMA (Kharkiv, Ukraine)**
- **Main dopant: C, secondary (co)dopant: Ce**
- **Samples were annealed at different conditions after production (see table below).**

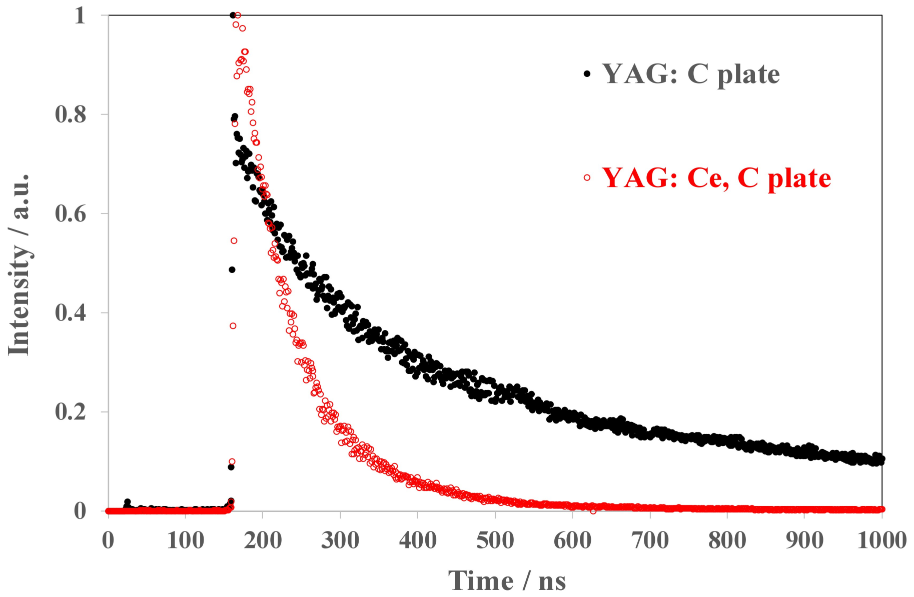
Sample type	Dimensions, mm	Annealing conditions
top left –YAG: C (rectangular)	10x10x6	Annealing in air
bottom left –YAG: C (plate)	30x15x2	Optimized annealing in air
top right - YAG: Ce, C (cubic)	10x10x10	Annealing in Ar+CO
bottom right - YAG: Ce, C (plate)	25x13x2	Optimized annealing in air

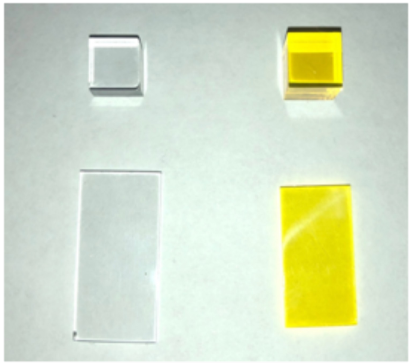
Optimization of Garnets: Example YAG

Optical transmittance



Scintillation kinetics





→ Doping and codoping concentrations can be tuned to reduce the contribution of long-term component

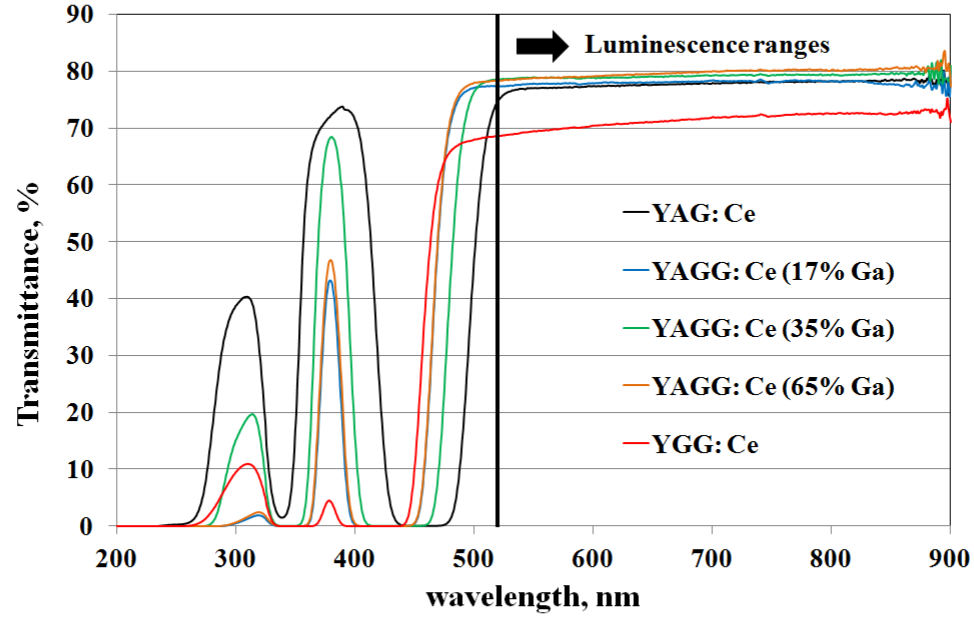
$Y_3(Al_x\text{-}Ga_{1-x})_5O_{12}$

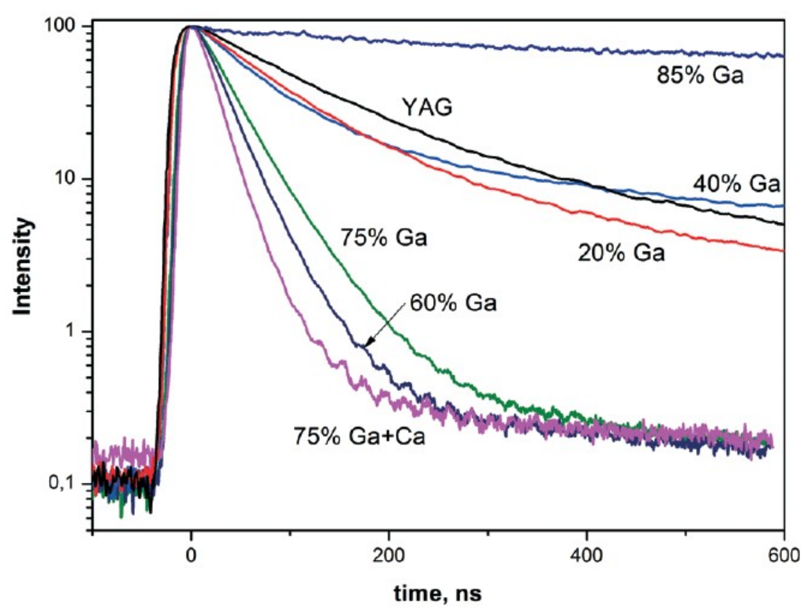
Gradually replacing bulk Al content by Ga

5 samples:

- **YAGG:Ce**
- **YAGG:Ce (17 %Ga)**
- **YAGG:Ce (35 %Ga)**
- **YAGG:Ce (65 %Ga)**
- **YGG:Ce**

Increasing Ga content





Scintillation decay under ^{137}Cs γ-excitation (662keV)

Radiation Damage

Current and future HEP detectors have to deal with significant radiation damage

- Loss in light output/transmittance
  → degradation of enery resolution

Radiation damage in scintillators subdivided in:

<u>Electromagnetic component</u>

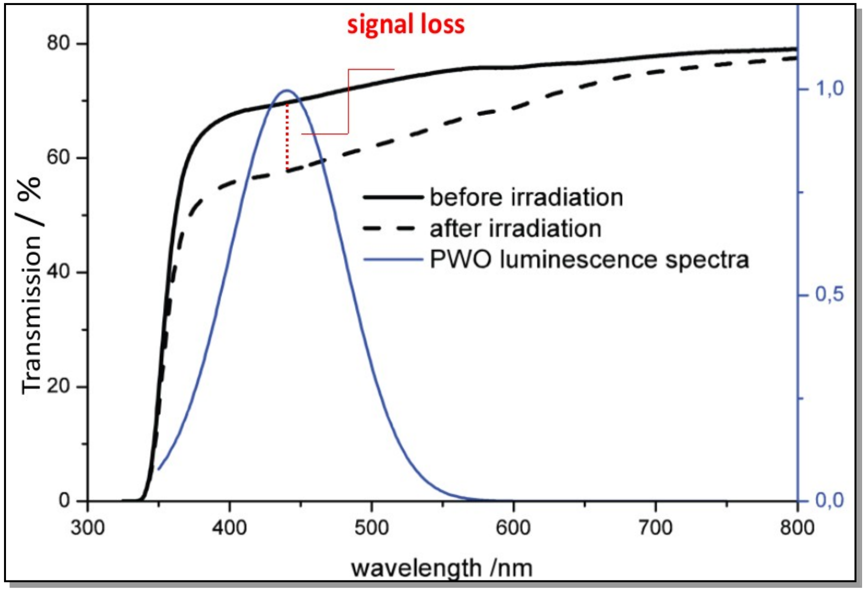
- Leads to saturation of deep traps
- Is recoverable (spontaneous and stimulated recovery)

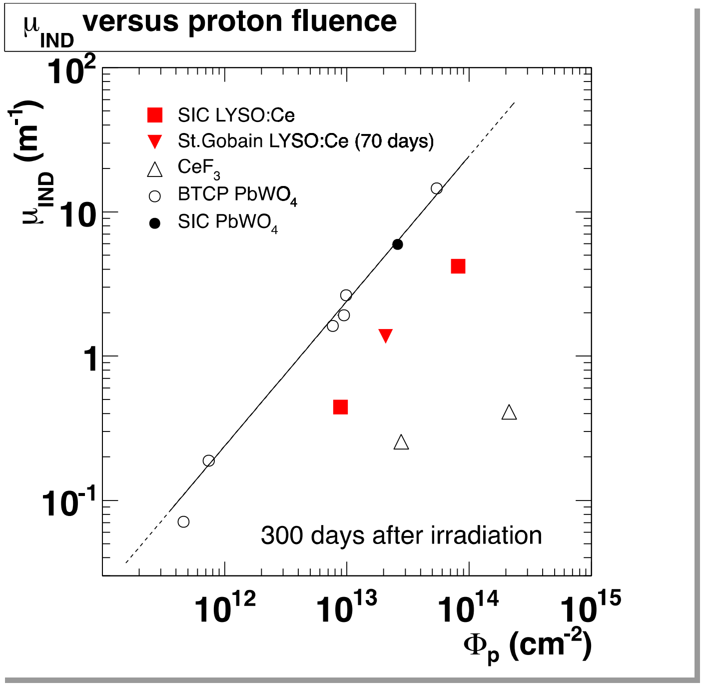
<u>Hadronic component</u>

- Damages the crystal structure
- Is not recoverable

Criterion: Rad induced absorption coeff:

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

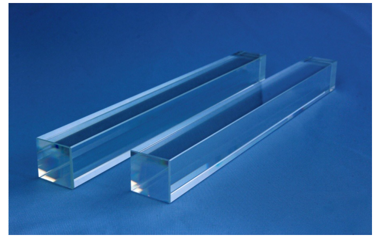




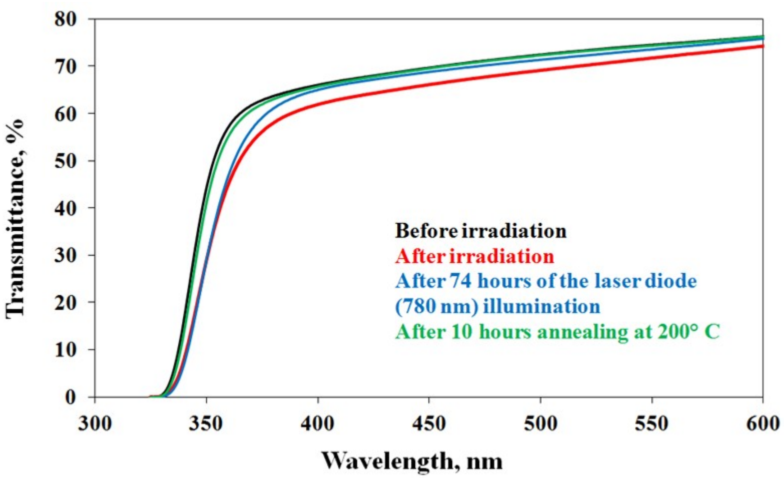
Francesca Nessi-Tedaldi(ETH Zürich, Switzerland)

Radiation Damage

Example:
PWO

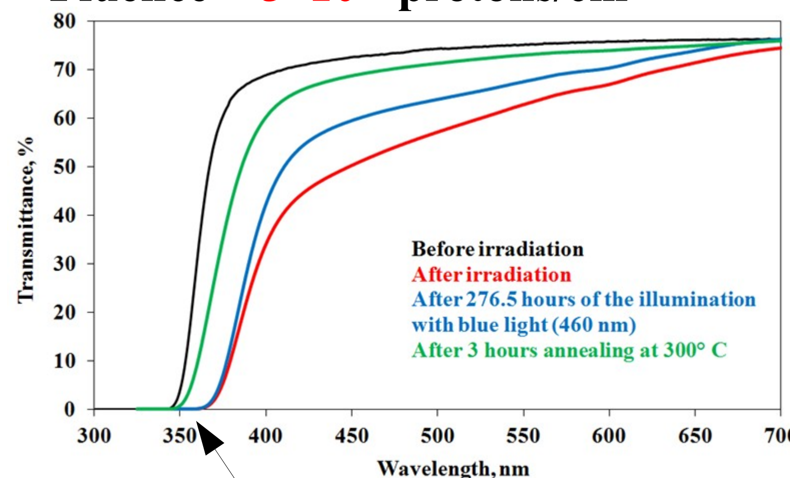


$PbWO_4$ irradiated by 150 MeV protons
@CART-KVI, Groningen, Netherlands
Fluence = 1.8×10^{13} protons/cm^2



Mostly em damage → recoverable

$PbWO_4$ irradiated by 24 GeV protons
@CERN, Switzerland
Fluence = $3*10^{13}$ protons/cm^2



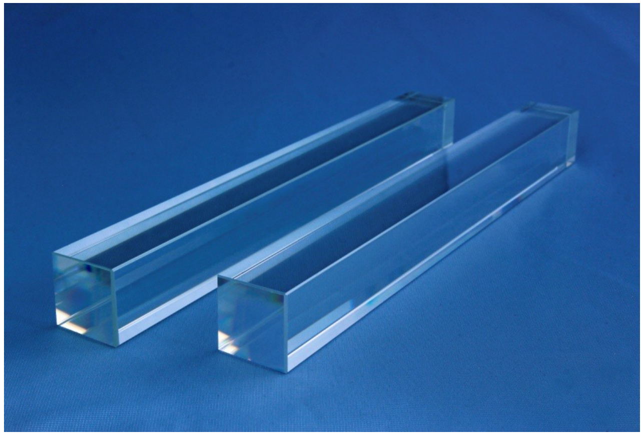
Permanent shift of absorption edge

more hadronic damage → permanent effects visible

lower Z material required
sampling calorimetry
cheap for mass production

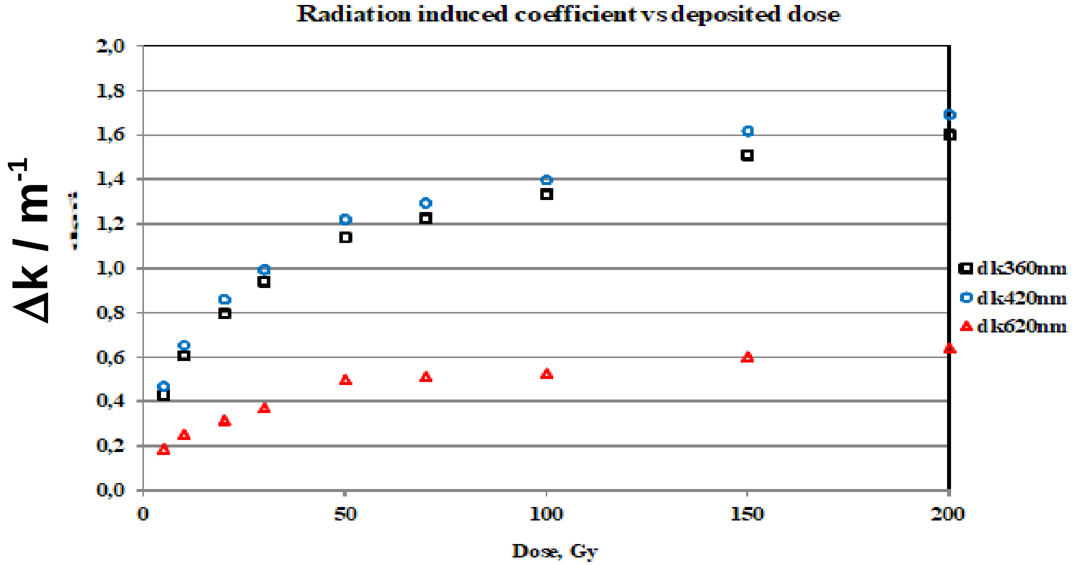
- **creation of macro defects**
- **highly ionizing fission products**
- **ion displacements**

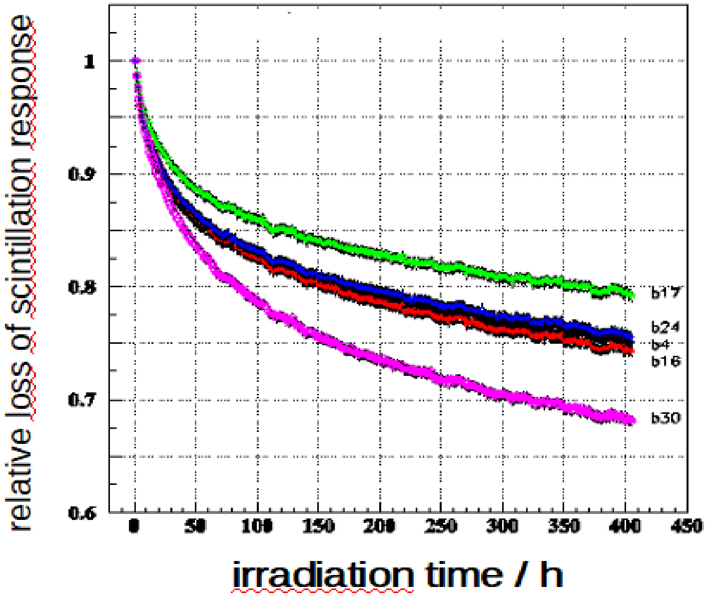
Radiation Damage (example PWO)

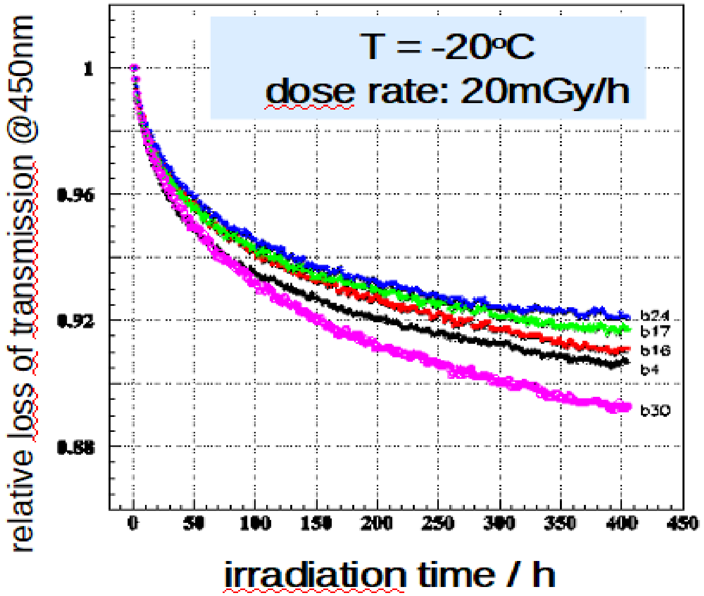


$PbWO_4$ for compact high-resolution calorimetry of GeV photons

Light attenuation coefficient as a function of applied dose



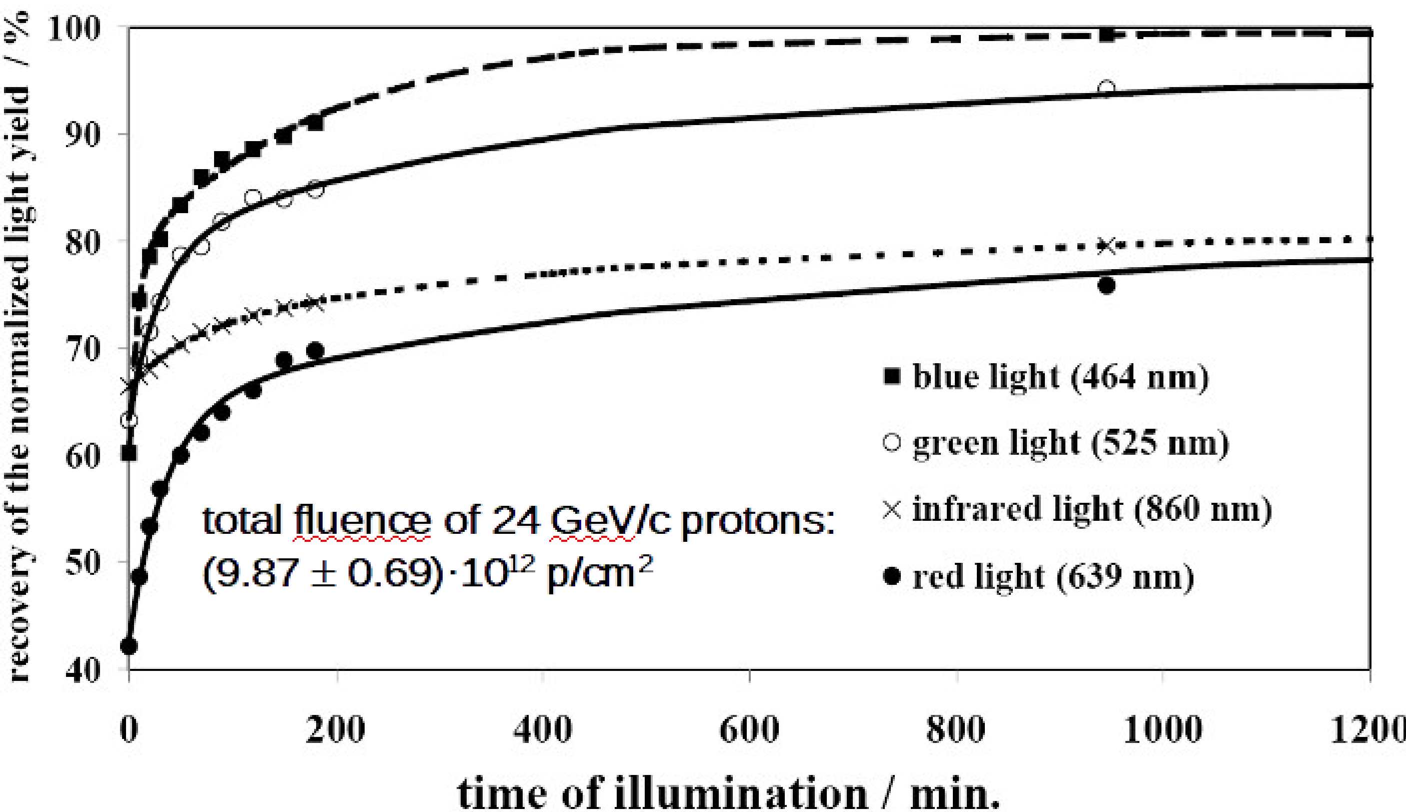


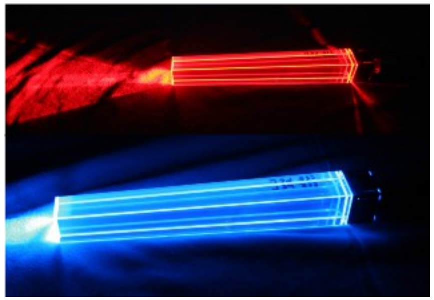


$$\Delta k = \ln\left(\frac{T_{bef}}{T_{after}}\right)\cdot\frac{1}{d}$$

Stimulated Recovery

Partial (hadronic) or total (em) recovery of radiation induced deterioration





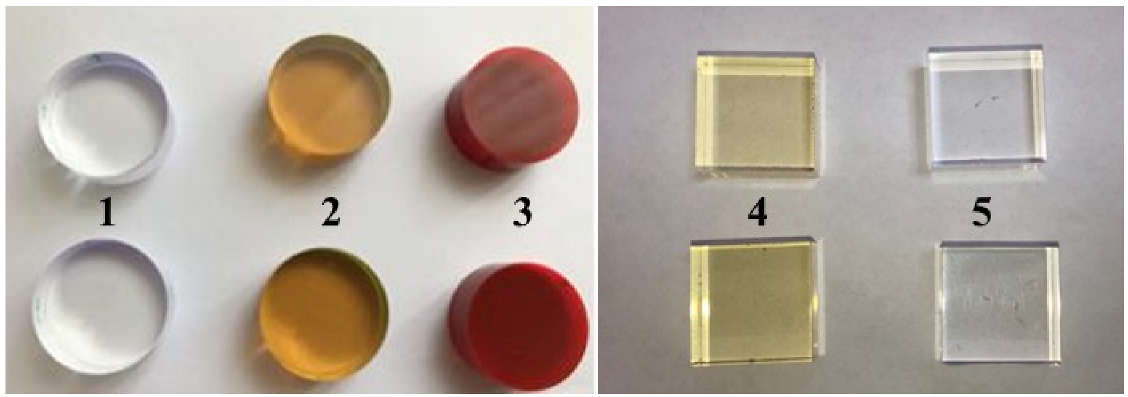
JLU Giessen in collaboration with
F. Nessi-Tedaldi et al. (CMS Exp.)

More details in next talk by P. Orsich

Organic Scintillators

- Currently: active developments together with manufacturers of PS-based scintillators wrt/ radiation hardness

Detailed report later today by Valera Dormenev



- Currently ongoing: PEN scintillation material characterization for alpha and neutron detector applications using thin foils

Problem with thick pieces: casting of clear samples in lab difficult
→ need to find partner for injection-moulding

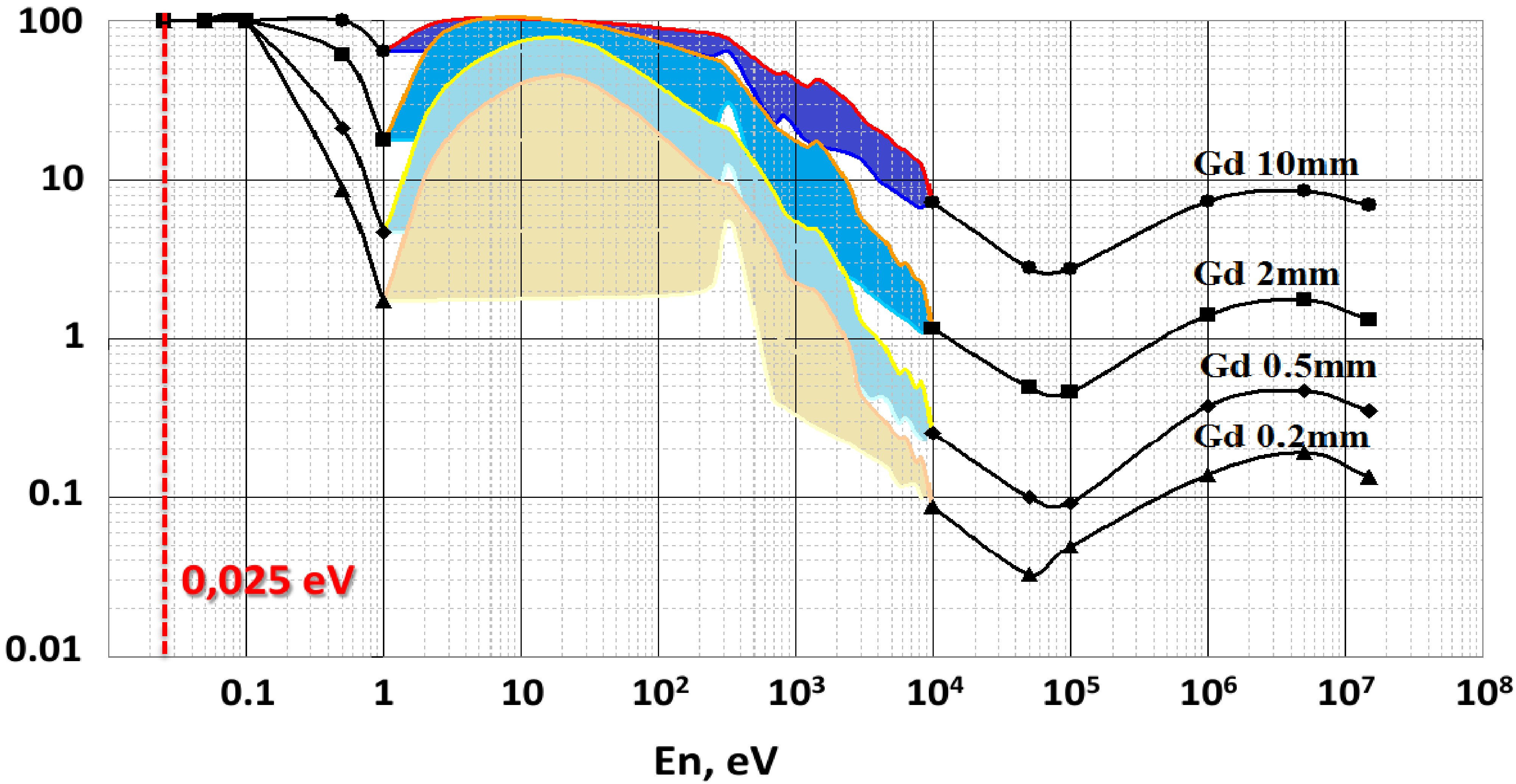
G(Y)AGG as Neutron Detector

	Absorbing isotope content, at./cm^3	n absorption cross-section for the isotope, b		Absorbing layer thickness, mm	Absorption efficiency for the given layer, %	
		En = 0.025 eV	En = 1 MeV		En = 0.025 eV	En = 1 MeV
^{3}**He** tube (16 bar)	$4{,}3*10^{20}$	5319.6	2.9	20	98.96	0.25
^{6}**Li**$_2$O•2SiO$_2$:Ce^{3+} glass (90% ^{6}Li)	$1{,}7*10^{22}$	955.4	1.3	5	99.99	1.05
Gd$_3$Al$_2$Ga$_3$O$_{12}$:Ce^{3+} crystal (nat. Gd)	$1{,}3*10^{22}$	46095.4	5.1	5	99.99(99)	3.25

Neutron detection efficiency for 5 mm GAGG plate: Thermal (0.025 eV) – 99.99%
Fast (1 MeV) – ~3%

G(Y)AGG as Neutron Detector

GEANT4 modelling of neutron absorption in natural Gd (metallic)



Neutron detection efficiency for 5 mm GAGG plate: Thermal (0.025 eV) – 99.99%
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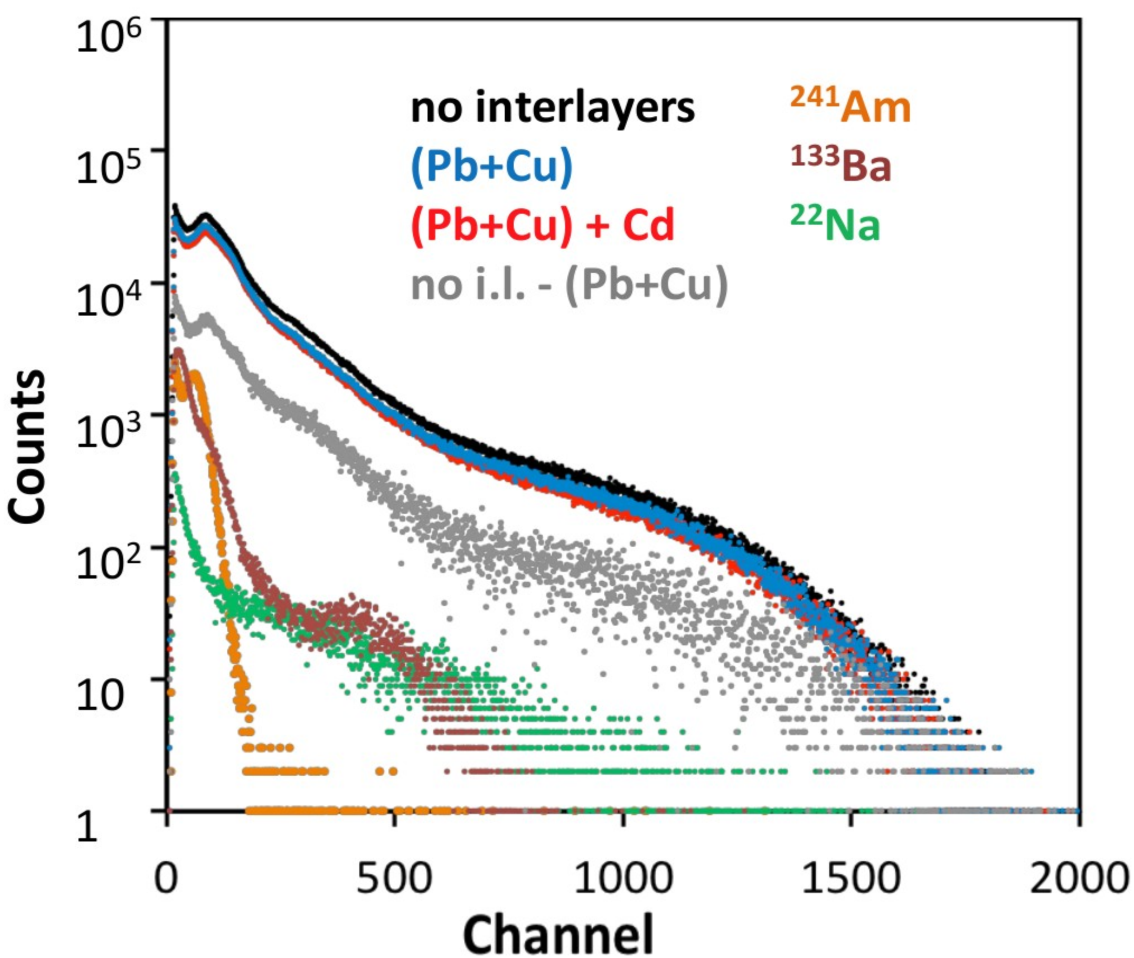
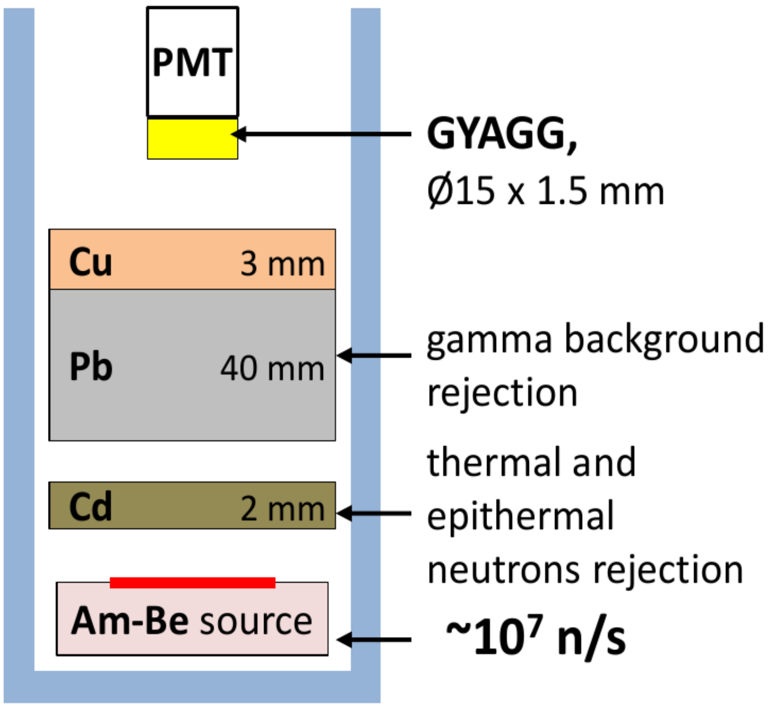
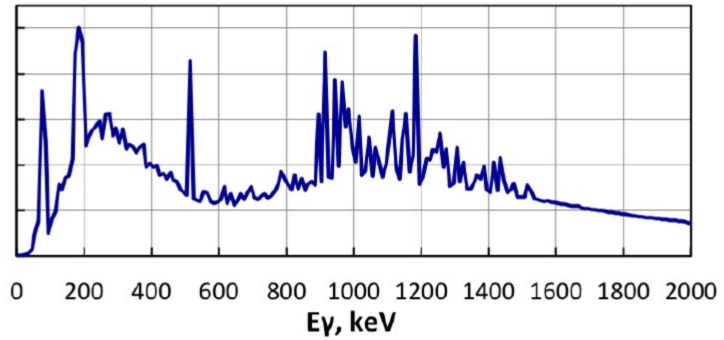
G(Y)AGG as Neutron Detector

γ-Spectra generated in GYAGG ceramics under AmBe neutron exposure





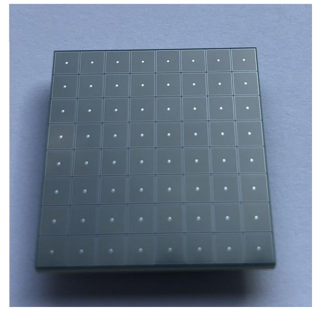
γ in Gd under AmBe neutrons



No distinct γ–lines due to light scattering in ceramics

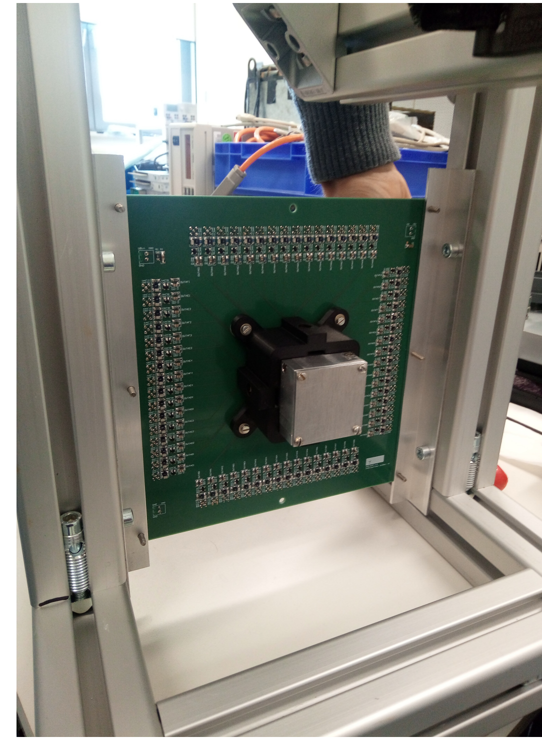
64 GAGG pixels (3x3x40mm) + 64 channels SIPM array
Read-out with high time and energy resolution

GAGG rods inside reflective alveole receptacle: 100um thin, 3d printed

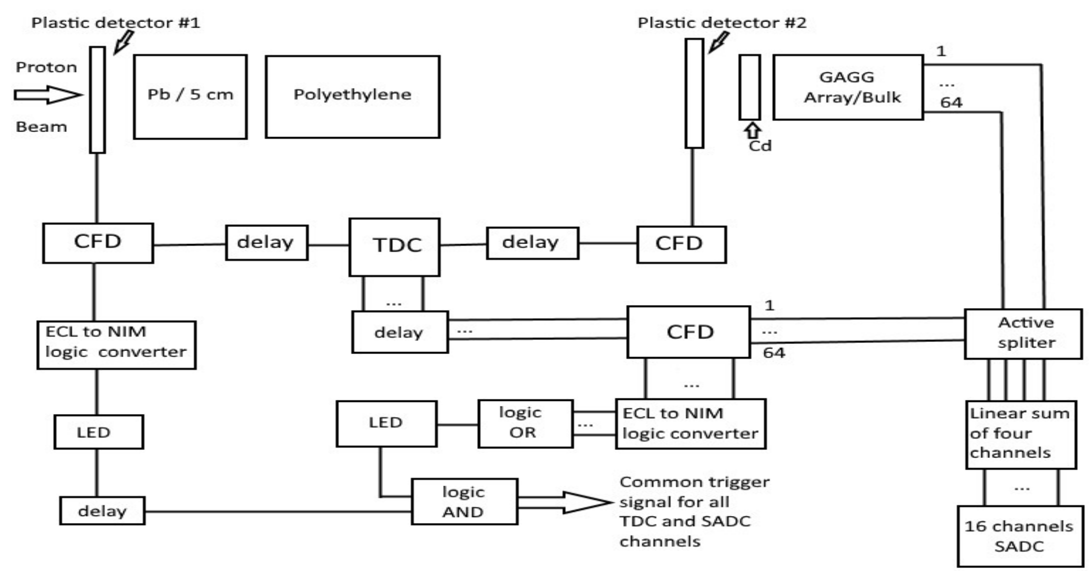


Hamamatsu S13361-3050AS-8 8x8 SiPM Array

64 pixel GAGG+SiPM +preamp assembly

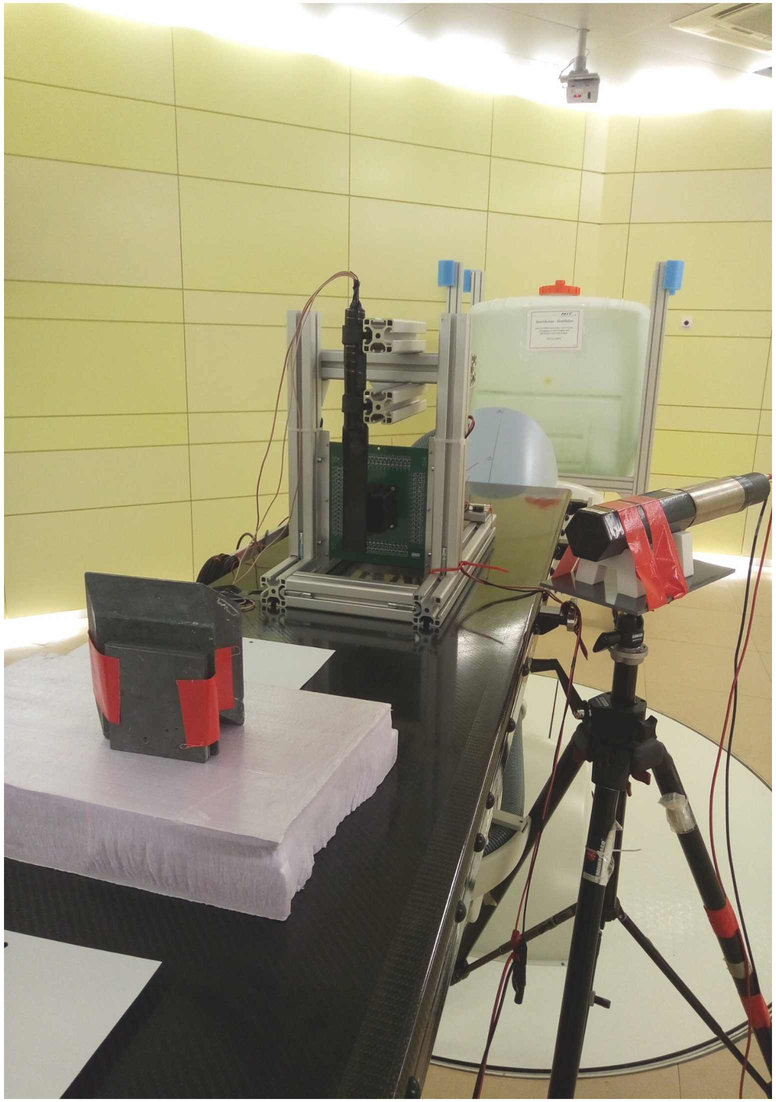


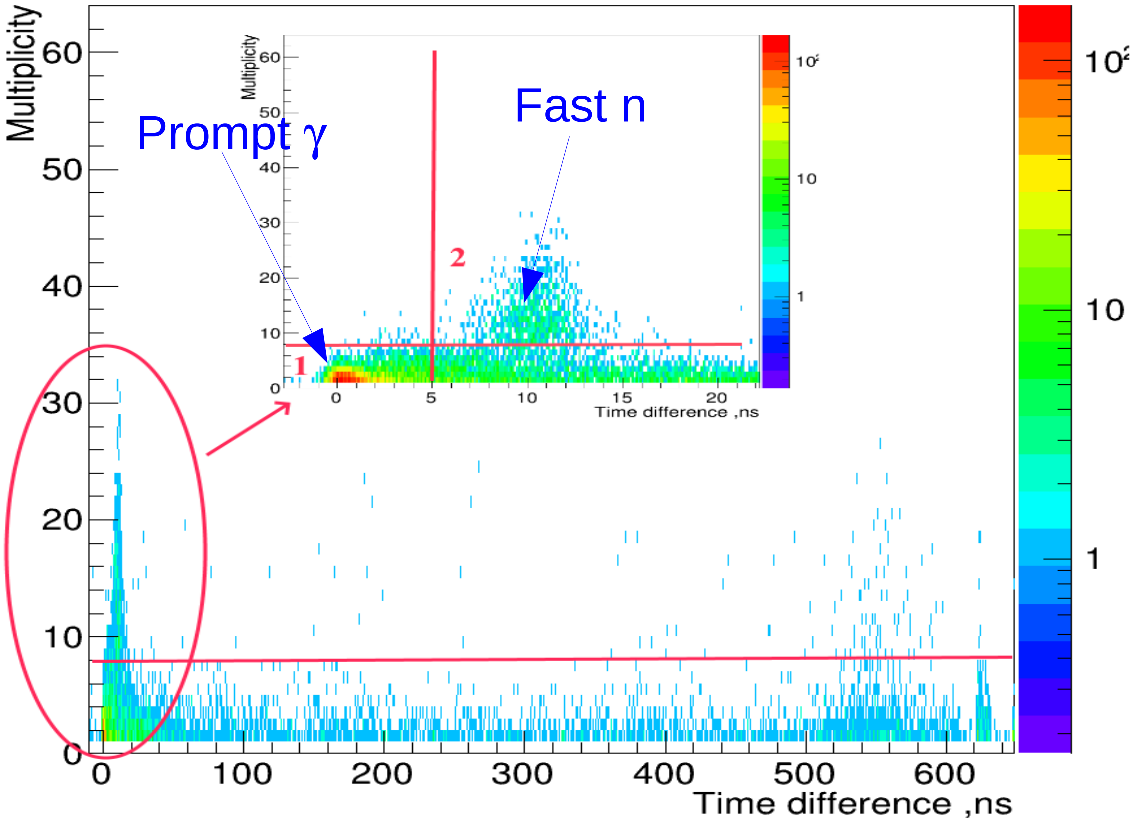
Successfull In-beam test at MIT (Marburg) in Nov 2019, 220 MeV protons



GAGG Minicalorimeter

64 GAGG pixels (3x3x40mm) + 64 channels SIPM array
Read-out with high time and energy resolution





ToF-Spectrum between start plastic and GAGG-array signals

The End