Research Institute for Nuclear Problems
BSU

Limits of Scintillation Materials For Future Experiments at High Luminosity LHC and FCC

Mikhail Korjik

Demand for the radiation tolerant detecting materials and designs

- LHC with high luminosity starts in 2025
- FCC became an attractive strategy for future study in HEP

There is a crucial demand for radiation resistant materials surviving in a complex irradiation environment (electromagnetic + charged and neutral hadrons)

Have scintillation materials a chance to be applied in new designs?

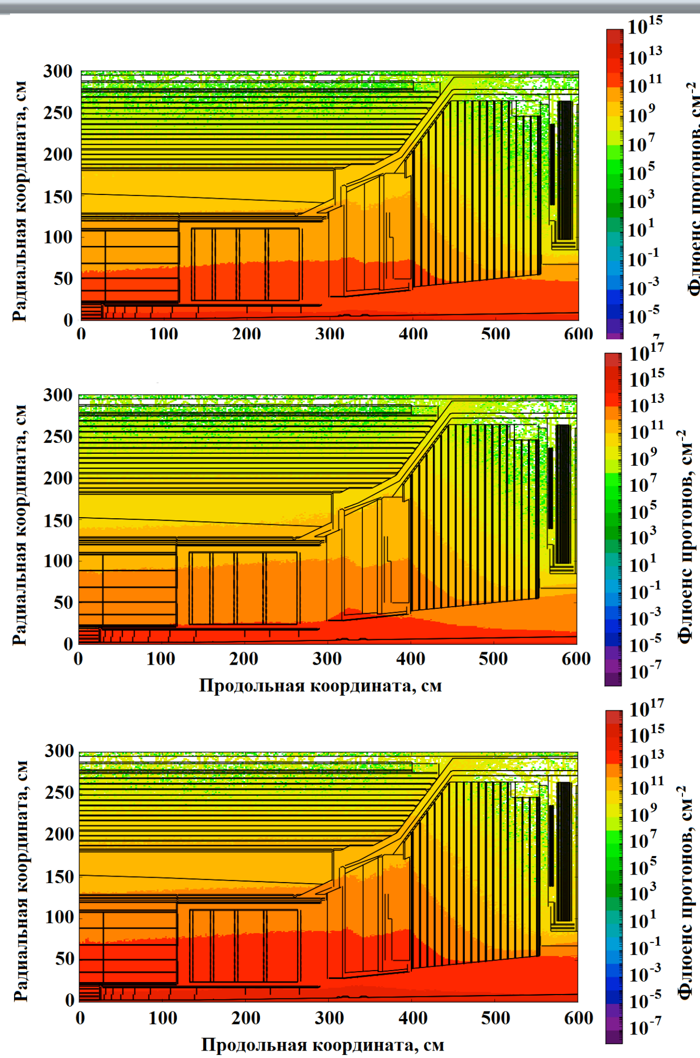
- Inorganic crystalline materials
- Composite inorganic/organic materials
- Light materials (inorganic and organic)
- Induced radio-isotopes in scintillators
- Addressing to time resolution
- Effects prior to scintillation
- Concluding remarks

Irradiation environment at collider experiment. Case of CMS at LHC.

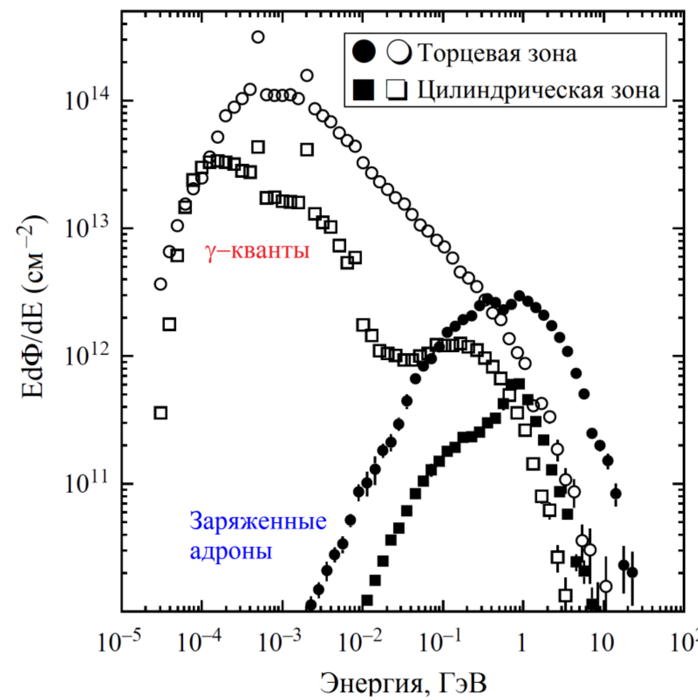
$20fb^{-1}$

$500fb^{-1}$

$3000fb^{-1}$



Fluence of protons in different parts of the CMS detector at different luminosity



Energy spectrum of ionizing radiation
In collider experiment (example of
CMS at LHC)

Interconnection of the scintillator Light Yield (LY) and energy resolution of electromagnetic homogeneous calorimetric detector

Energy resolution:

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

stochastic noise constant terms

$$a \sim \frac{1}{\sqrt{LY}} \qquad b \sim \frac{1}{LY} \qquad c \sim \frac{1}{LY}\frac{\partial(LY)}{\partial z}\delta z$$

	Essential effects to change LY	ϒ-quanta	Charged hadrons	Neutral hadrons
1	Change of the thermodynamic equilibrium due to creation of colour centers	✔	✔	✔
2	Creation of new defects and dedicated colour centers	+/-	✔	✔
3	Creation of non recoverable damages		✔	✔
4	Change of the material composition due to nuclear reactions (radio isotopes and fragments)		✔	✔

Systematic study of the radiation damage effect in inorganic scintillation materials

1. **Korzhik M, Barysevich A, Dormenev V, Mechinski V, Missevitch O, Fedorov** A (2010) On the radiation hardness of the optical properties of scintillation crystals under high energy protons. Proceedings of the National academy of sciences of Belarus 54: 53–57 (in Russian)
2. **Barysevich A, Dormenev V, Korjik M et al** (2013) Stimulation of Radiation Damage Recovery of Lead Tungstate Scintillation Crystals Operating in a High Dose-Rate Radiation E IEEE Trans on Nucl Sci 60: 1368–1372
3. **Auffray E. et al** (2011) Experimental Study of the Lead Tungstate Scintillator Proton-Induced Damage and Recovery. Proc. SCINT 2011, Giessen, Germany, 11-16 September 2011
4. **Auffray E, Barysevich A, Fedorov A, Korjik M, Koschan M, Lucchini M, Mechinski V, Melcher CL, Voitovich A** (2013) Radiation damage of LSO crystals under γ- and 24 GeV protons irradiation. Nucl Instr Meth Phys Res A721: 76–82
5. **Barysevich A, Korjik M, Singovski A et.al.,** (2013) Radiation damage of heavy crystalline detector materials by 24 GeV protons, Nucl Instr Meth Phys Res A701: 231–234
6. **Dormenev V, Korjik M, Kuske T, Mechinski V, Novotny RW** (2013) Comparison of radiation damage effects in PWO crystals under 150 MeV and 24 GeV high fluence proton irradiation. Proceedings SCINT 2013, Shanghai, China, 15-19 April 2013
7. **Brinkman K-T, Borisevich A, Dormenev V, Kalinov V, Korjik M et al** (2014) Radiation damage and Recovery of medium heavy and light inorganic Crustalline, Glass and Glass Ceramic materials after Irradiation with 150 MeV protons and 1.2 MeV gamma-rays. Presented at IEEE 2014 NSS and MIC Conference, October 2014, USA
8. **Auffray E, Korjik M, Singovski A** (2012) Experimental Study of Lead Tungstate Scintillator Proton-Induced Damage and Recovery. IEEE Trans Nucl Sci 59: 2219–2223
9. **Auffray E, Fedorov A, Korjik M, Lucchini M, Mechinski V, Naumenko N, Voitovich A** (2014) Radiation Damage of Oxy-Orthosilicate Scintillation Crystals Under Gamma and High Energy Proton Irradiation. IEEE Trans Nucl Sci 61: 495–500
10. **Auffray E, Fedorov A, Korjik M, Kozlov D, Lucchini M, Mechinski V** (2013) The impact of proton induced radioactivity on the Lu_2SiO_5:Ce, Y_2SiO_5:Ce scintillation detectors. Approved for oral presentation at Nucl. Sci. Sump. and Med. Imag. Conf., Seul, Korea, 27 Oct. 2013
11. **Borisevich A, Dormenev V, Korjik M, Kozlov D, Mechinskuy V, Novotny RW** (2015) Optical transmission radiation damage and recovery stimulation of DSB:Ce3+ inorganic scintillation materials. Journal of Physics: Conference Series 587: 012063
12. **Auffray E, Akchurin N, Benaglia A et al** (2015) DSB:Ce3+ scintillation glass for future. Journal of Physics: Conference Series 587: 012062

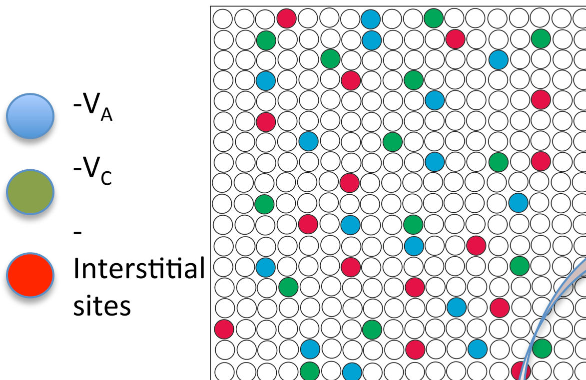
List of the scintillation materials studied

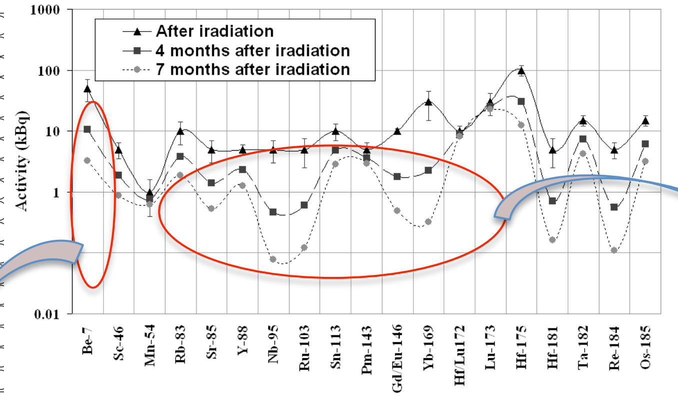
ϒ-quanta 60Co(1.22MeV), absorbed doses 10-2000Gy	24 GeV & 150 MeV protons	reactor neutrons
PWO, PWO-II	**PWO, PWO-II**	**PWO, PWO-II**
LSO:Ce(LYSO:Ce)	LSO:Ce(LYSO:Ce)	
LuAG:Ce	LuAG:Ce	**plastics**
BSO	BSO	
PbF_2	PbF_2	
BaF_2	BaF_2	
GSO:Ce	GSO:Ce	
YSO:Ce	YSO:Ce	
YAG:Ce(Pr)	YAG:Ce(Pr)	
YAP:Ce (Pr)	YAP:Ce (Pr)	
DSB:Ce(glass and glass-ceramics)	DSB:Ce(glass and glass ceramics)	
Y_2O_3 (micro-ceramics)	Y_2O_3 (micro-ceramics)	
LiF	LiF	

Similarity and difference of the colour centres created under ϒ-quanta and hadrons

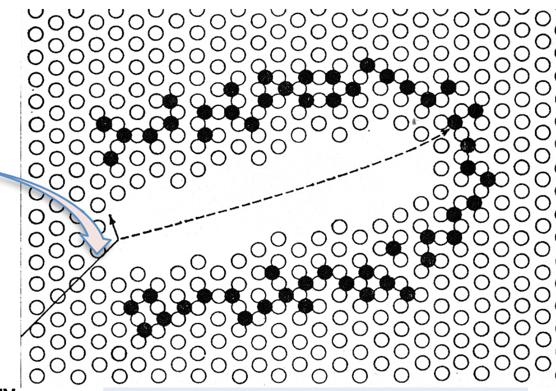
Point defects due to crystal growth

Stars created by fission products





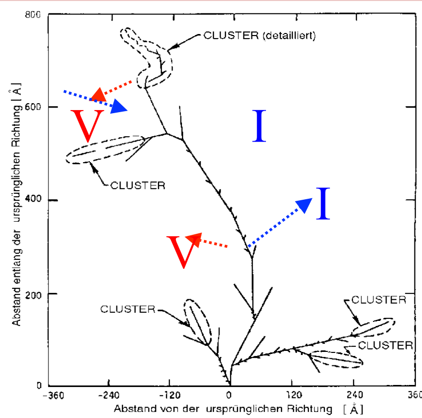
Set of isotopes identified in PWO crystal : measured activity 4 months after irradiation and the extrapolated values at 24 h and 7 months after the end of irradiation.

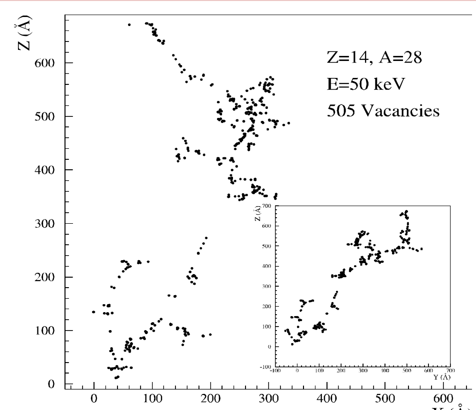


L.T.Chadding, 1965

Point defects and their clusters which are created by knocked ions

Van Lint 1980

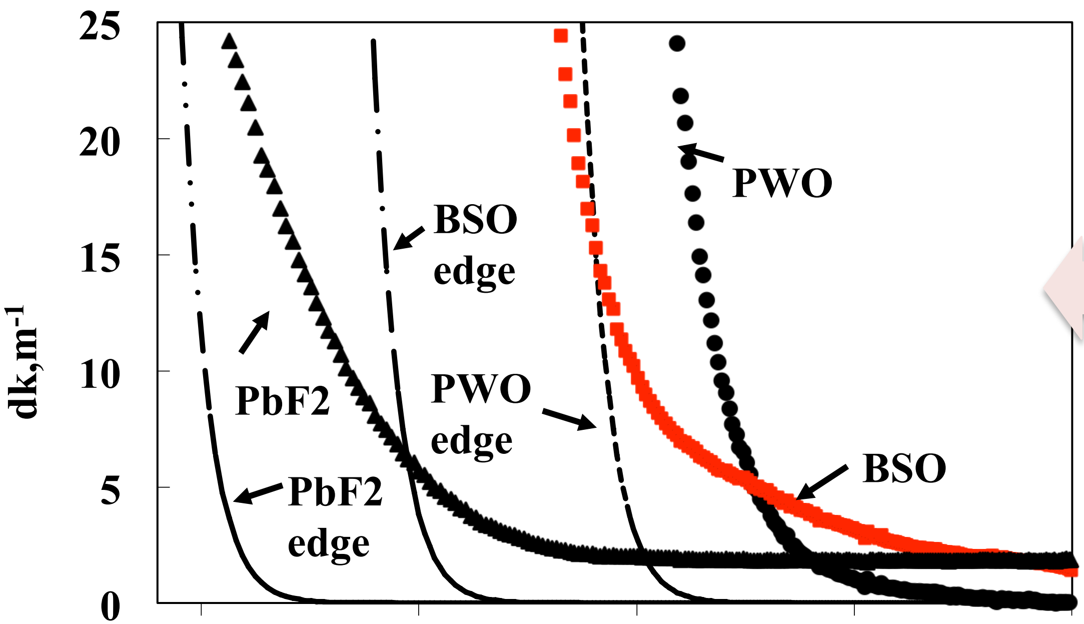




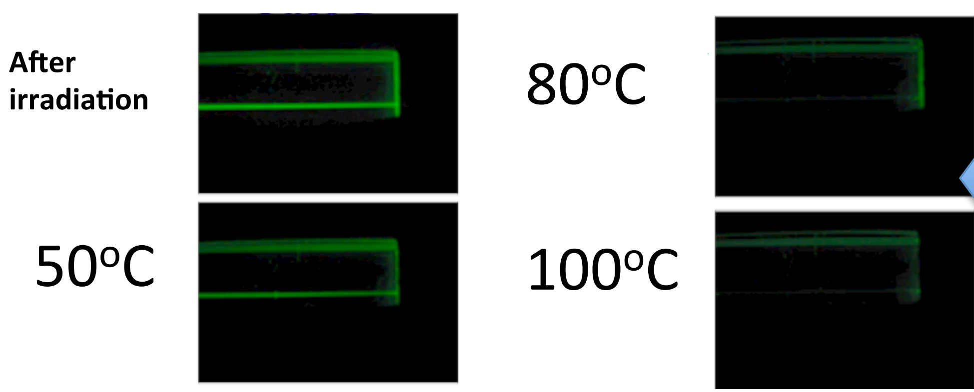
M.Huttienen 2001

Shift of absorption spectrum cutoff after irradiation with protons is a general property of the damage optical transmission damage in a heavy inorganic materials

Heavy self activated scintillators and Cherenkov radiators



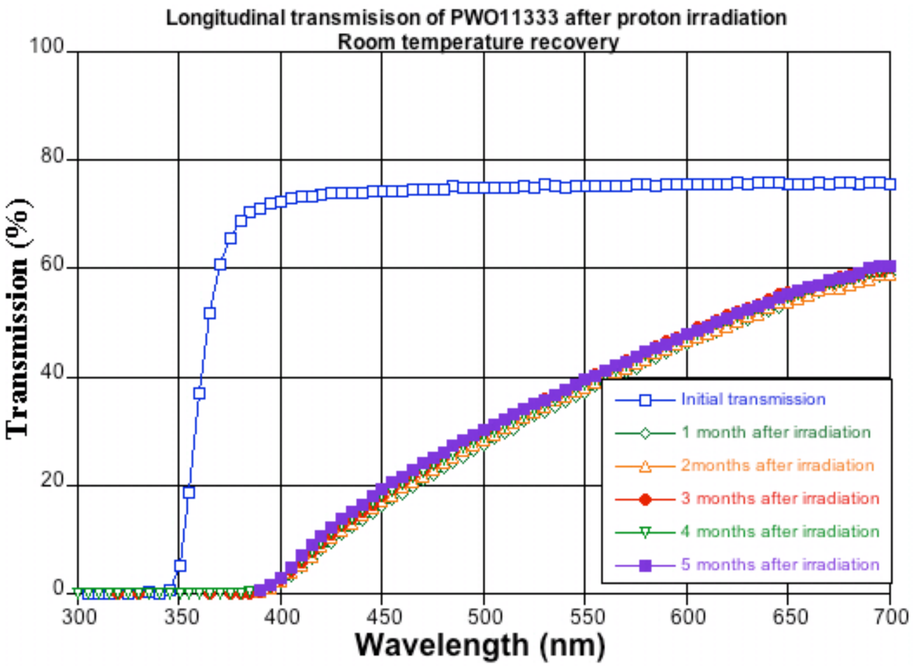
Cutoff of fundamental absorption of PWO, BSO and PbF_2 and the proton irradiation-induced absorption spectra after Integral fluence $3 \cdot 10^{13}$p/cm^2

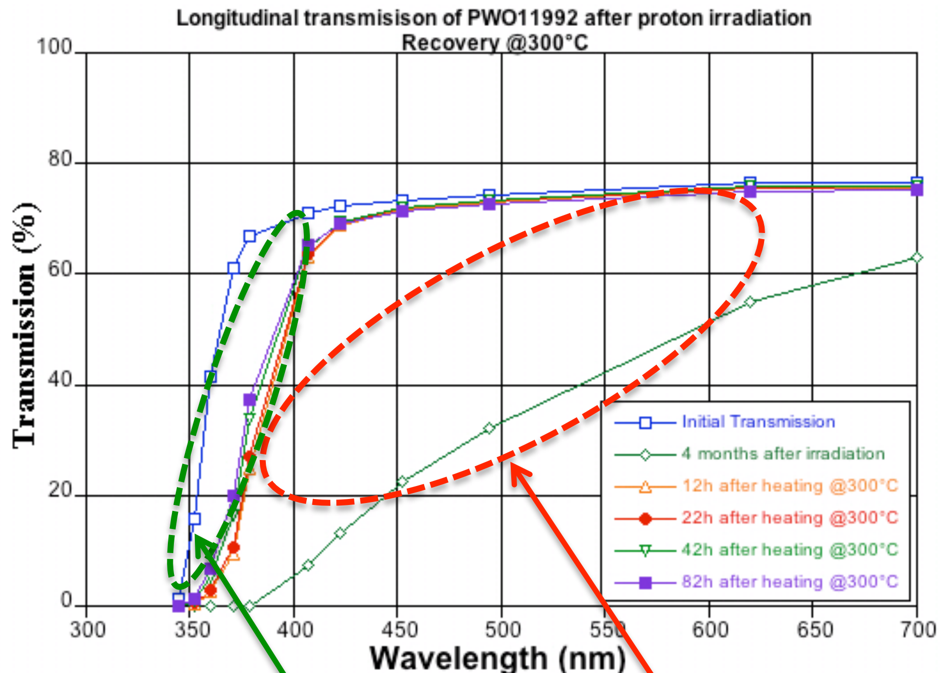


Laser beam scattering in a PWO crystal after proton irradiation and thermal treatment

Recoverable and unrecoverable damage of the optical transmission in PWO crystals under irradiation with 24GeV protons($3,6x10^{13} p/cm^2$)

Spontaneous | **Thermally stimulated**

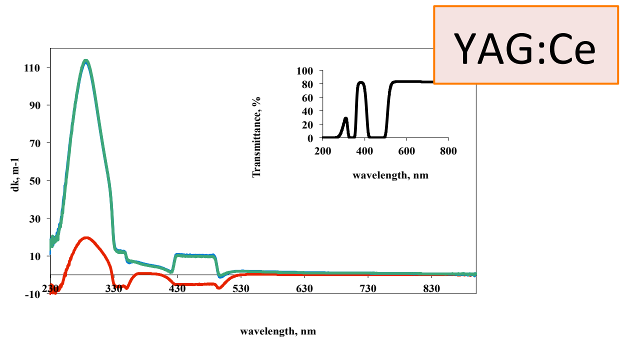


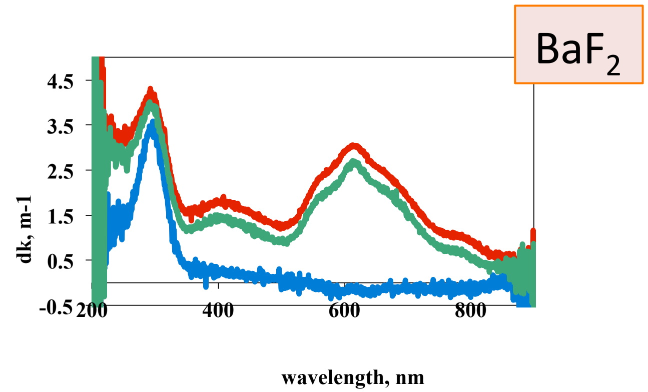


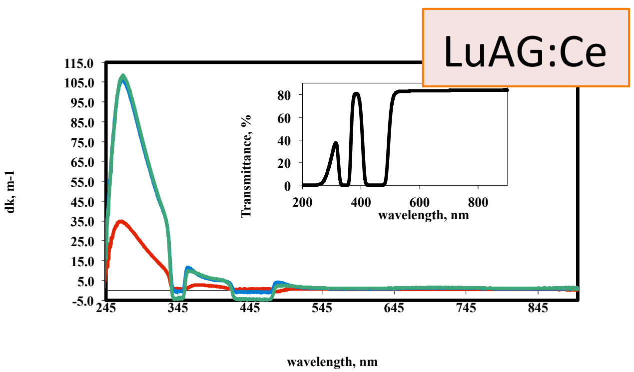
Non recoverable part of the transmission which is caused by unrecoverable defects

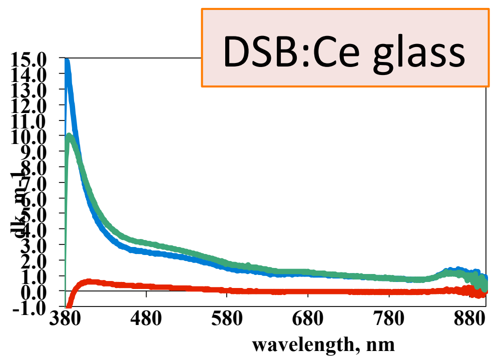
Recoverable part of the transmission which is caused by single defects and clusters

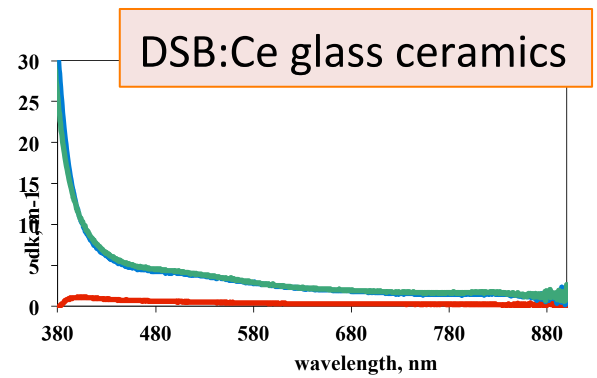
Comparison of damage of light and medium inorganic crystalline, glass and glass ceramic materials after irradiation with 150MeV protons and ϒ- irradiation









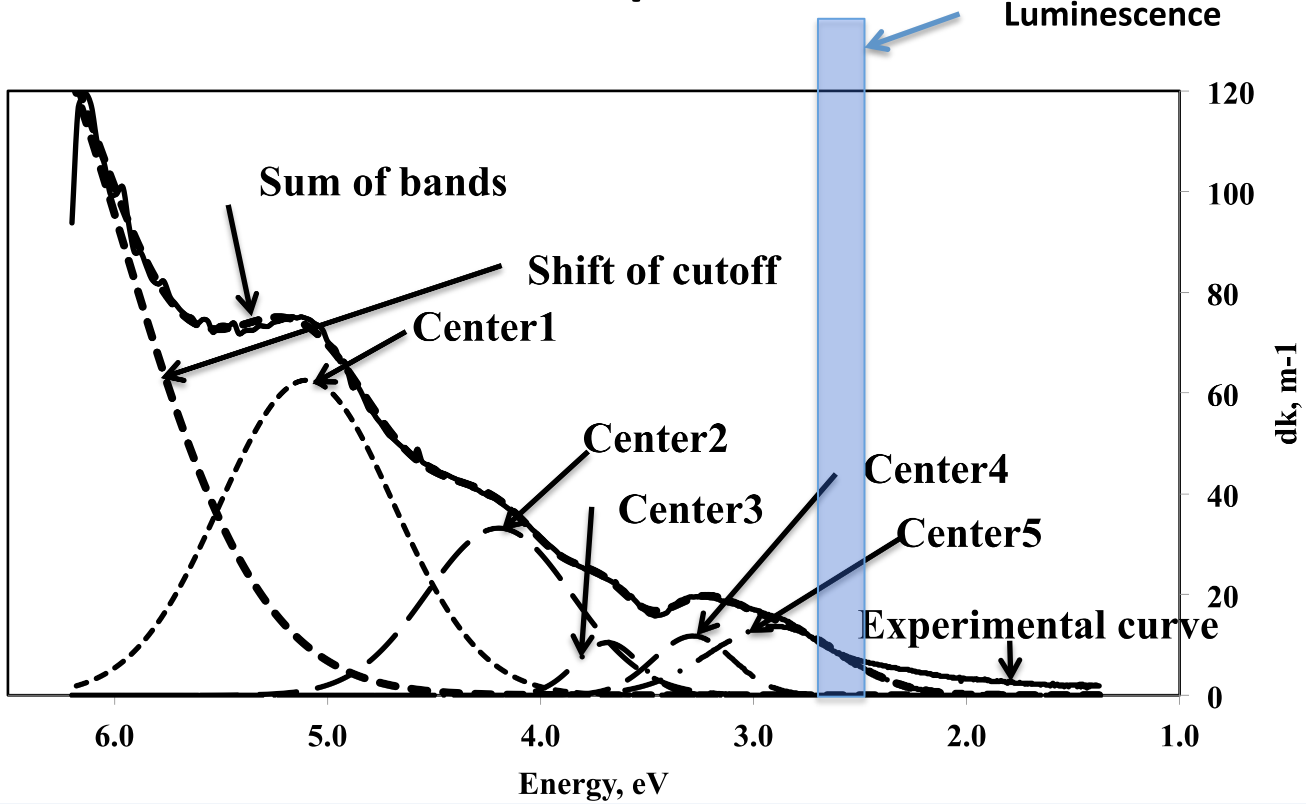


Induced absorption in several inorganic scintillation materials:

- after ϒ- irradiation (60Co, 1,2 MeV, 100Gy),
- in 3 months after 150 MeV proton irradiation
- repeated ϒ- irradiation

Colour centers in the wide band gap oxide materials suitable for doping with Ce

LSO-undoped

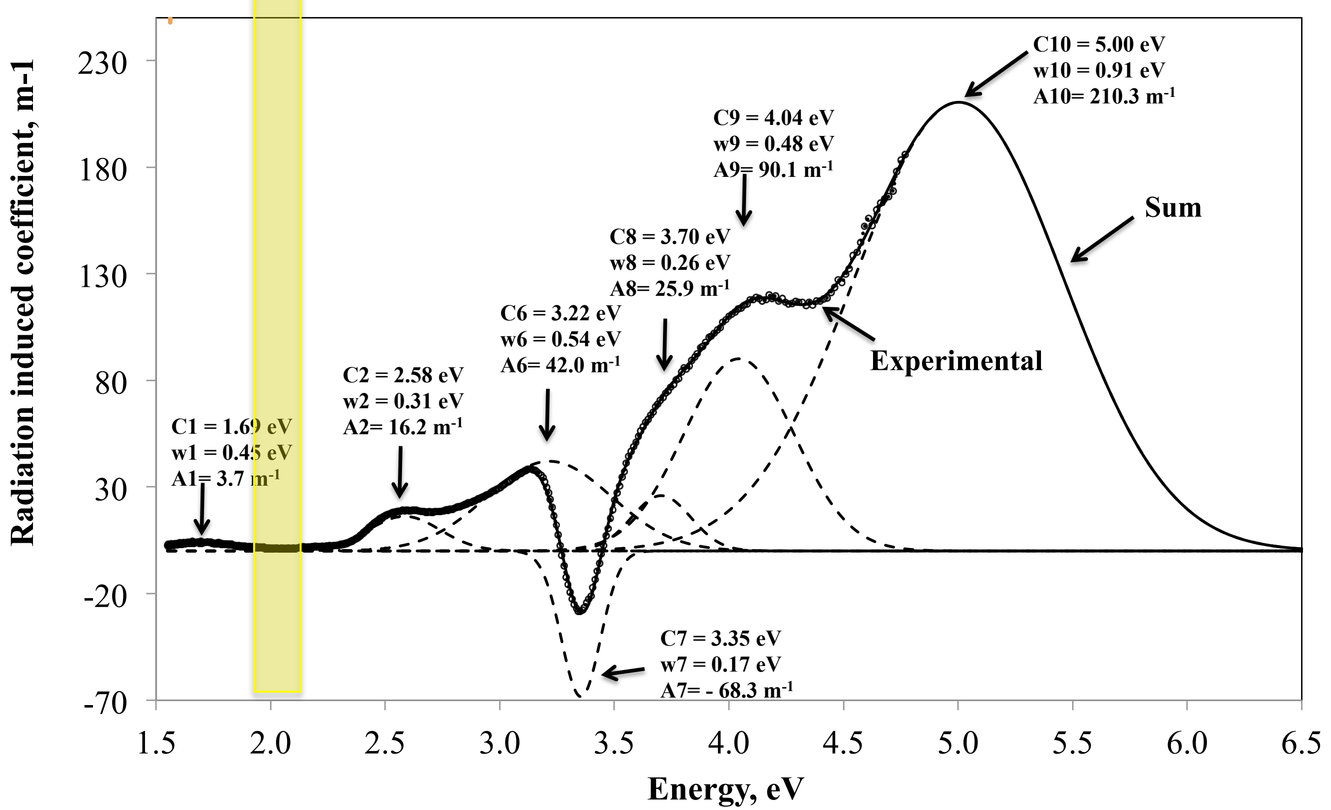


Proton irradiation induced absorption spectrum and its approximation with set of Gaussians

Colour centers in wide band gap oxide materials suitable for doping with Ce

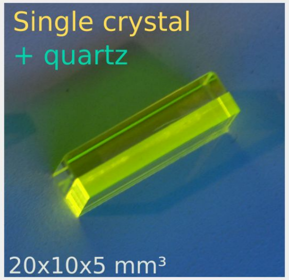
Luminescence band

YAG-undoped

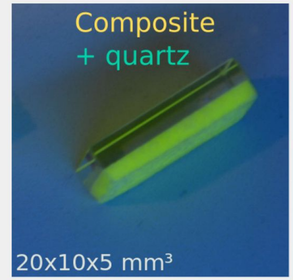


Proton-irradiation-induced absorption spectrum of YAG sample and its approximation by a set of Gaussian type bands.

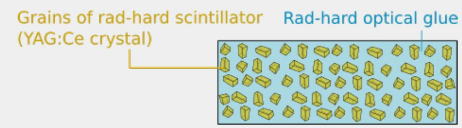
YAG:Ce scintillator versus YAG:Ce based composite

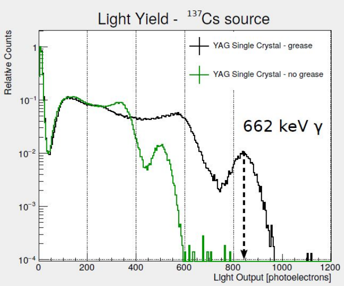


YAG:Ce single crystal produced via standard Czochralski technique, fully polished and glued to a quartz plate ($\rho \sim$ **4.6** g/cm^3).

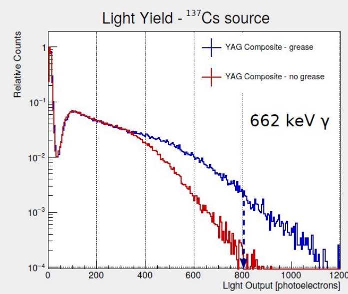


Composite scintillator obtained from mixture of YAG:Ce grains and optical glue (Sylgard-184) coupled to a quartz plate ($\rho \sim$ **2.3** g/cm^3)

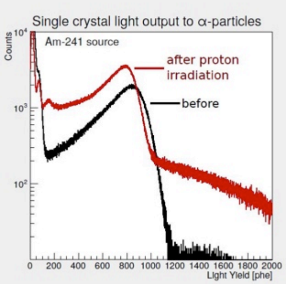




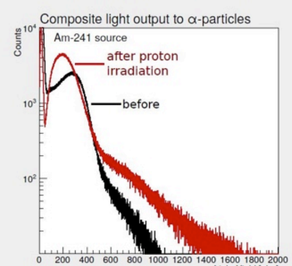
- Light yield of samples was measured by coupling the quartz plate to a PMT (Hamamatsu R2059) with quantum efficiency of 6.5% at YAG:Ce emission peak (530 nm).
- Single crystal shows about **20000 ph/MeV** in wrapped configuration with optical grease.



- Composite scintillator shows about **18000 ph/MeV** in wrapped configuration with optical grease.
- Light output of composites is as high as for single crystal but photopeak events are fewer due to **lower density** and resolution is poorer suggesting non-uniform light collection.



- **Irradiation with 24 GeV protons** performed at CERN PS to a fluence of **7** $\times$ **10^{13}** cm^{-2}. Both single crystal and composite were placed after a 15 cm PWO crystal to emulate effect of secondary particles due to absorber in real calorimeter.
- A drop of about 7% in light output is observed for single crystal and small increase in radioactivity of the sample (background).



- Before irradiation, **response of composite to alpha particles is smaller** than single crystal due to surface energy deposition combined with a strong bulk attenuation.
- After proton irradiation composite scintillator shows a drop of light output of about 30% most likely due to a darkening of the optical glue due to interactions of protons with light elements (H,C).

Lightweight of the material does not mean tolerating to proton irradiation

Fragments of the nuclear reactions and secondaries destroy polymer matrix

Prerequisites for damage under protons-secondary particles (EXFOR и ENDF data bases)

[7]Be radio-isotope was clearly detected in 4 months after irradiation by Ge detector in EJ260

C	O	H
${}^{12}_{6}C + {}^{1}_{1}H \rightarrow {}^{1}_{1}H + ...$	${}^{16}_{8}O + {}^{1}_{1}H \rightarrow {}^{3}_{1}H + ...$	${}^{1}_{1}H + {}^{1}_{1}H \rightarrow {}^{2}_{1}H + ...$
${}^{12}_{6}C + {}^{1}_{1}H \rightarrow {}^{2}_{1}H + ...$	${}^{16}_{8}O + {}^{1}_{1}H \rightarrow {}^{7}_{3}Li + ...$	${}^{1}_{1}H + {}^{1}_{1}H \rightarrow {}^{1}_{1}H + {}^{1}_{1}H + \gamma$
${}^{12}_{6}C + {}^{1}_{1}H \rightarrow {}^{3}_{1}H + ...$	${}^{16}_{8}O + {}^{1}_{1}H \rightarrow {}^{9}_{3}Li + ...$	${}^{1}_{1}H + {}^{1}_{1}H \rightarrow {}^{1}_{0}n + ...$
${}^{12}_{6}C + {}^{1}_{1}H \rightarrow {}^{3}_{2}He + ...$	${}^{16}_{8}O + {}^{1}_{1}H \rightarrow {}^{7}_{4}Be + ...$	
${}^{12}_{6}C + {}^{1}_{1}H \rightarrow {}^{4}_{2}He + ...$	${}^{16}_{8}O + {}^{1}_{1}H \rightarrow {}^{10}_{5}B + ...$	
${}^{12}_{6}C + {}^{1}_{1}H \rightarrow {}^{6}_{2}He + ...$	${}^{16}_{8}O + {}^{1}_{1}H \rightarrow {}^{11}_{6}C + ...$	
${}^{12}_{6}C + {}^{1}_{1}H \rightarrow {}^{6}_{3}Li + ...$	${}^{16}_{8}O + {}^{1}_{1}H \rightarrow {}^{13}_{7}N + ...$	
${}^{12}_{6}C + {}^{1}_{1}H \rightarrow {}^{7}_{3}Li + ...$	${}^{16}_{8}O + {}^{1}_{1}H \rightarrow {}^{15}_{8}O + ...$	
${}^{12}_{6}C + {}^{1}_{1}H \rightarrow {}^{9}_{3}Li + ...$	${}^{16}_{8}O + {}^{1}_{1}H \rightarrow {}^{17}_{9}F + \gamma$	
${}^{12}_{6}C + {}^{1}_{1}H \rightarrow {}^{7}_{4}Be + ...$	+	
${}^{12}_{6}C + {}^{1}_{1}H \rightarrow {}^{8}_{4}Be + ...$	${}^{16}_{8}O + {}^{1}_{1}H \rightarrow {}^{1}_{0}n + ...$	
${}^{12}_{6}C + {}^{1}_{1}H \rightarrow {}^{9}_{4}Be + ...$		
${}^{12}_{6}C + {}^{1}_{1}H \rightarrow {}^{8}_{5}B + ...$		
${}^{12}_{6}C + {}^{1}_{1}H \rightarrow {}^{9}_{5}B + ...$		
${}^{12}_{6}C + {}^{1}_{1}H \rightarrow {}^{10}_{5}B + ...$		
${}^{12}_{6}C + {}^{1}_{1}H \rightarrow {}^{11}_{5}B + ...$		
${}^{12}_{6}C + {}^{1}_{1}H \rightarrow {}^{9}_{6}C + ...$		
${}^{12}_{6}C + {}^{1}_{1}H \rightarrow {}^{10}_{6}C + ...$		
${}^{12}_{6}C + {}^{1}_{1}H \rightarrow {}^{11}_{6}C + ...$		
${}^{12}_{6}C + {}^{1}_{1}H \rightarrow {}^{12}_{7}N + ...$		
${}^{12}_{6}C + {}^{1}_{1}H \rightarrow {}^{13}_{7}C + \gamma$		
+		
${}^{12}_{6}C + {}^{1}_{1}H \rightarrow {}^{1}_{0}n + ...$		

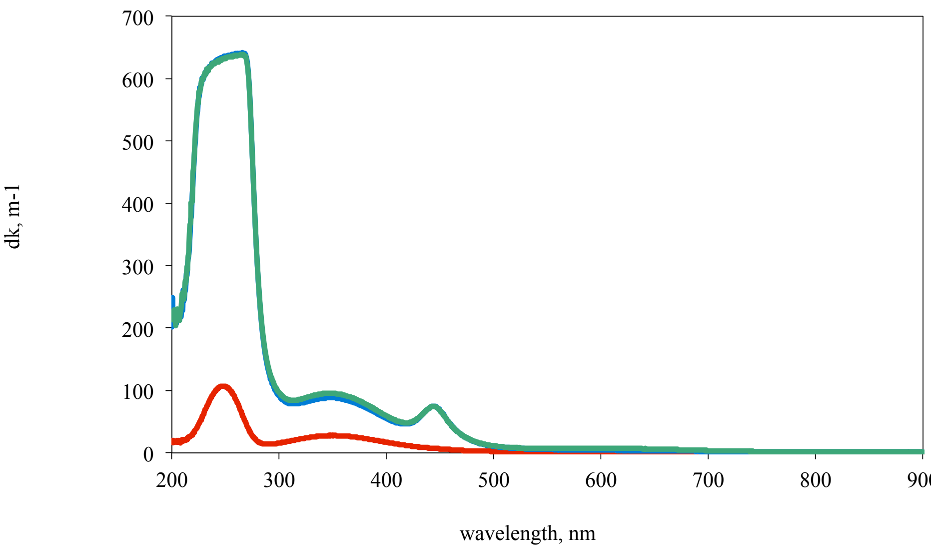
Challenge :

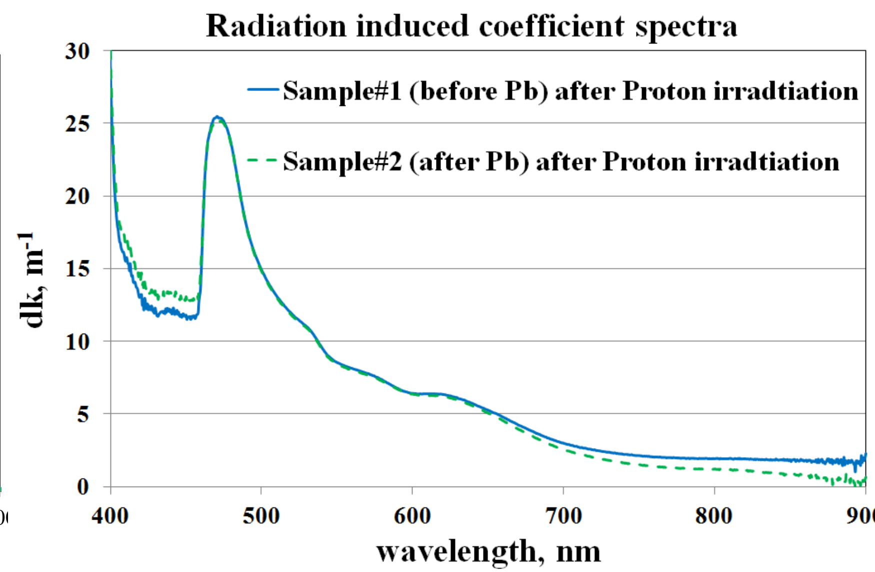
Any polymerized organics will be damaged under high energy hadron irradiation .

No plastic or polymerized glue may be survived in a high fluence of hadron irradiation, particularly in a high pseudorapidity regions.

.

Lightweight of the material does not mean tolerating to proton irradiation





Comparison of induced absorption in LiF crystal after irradiation with 150MeV protons (green) and ϒ- irradiation (red)

Comparison of induced absorption in EJ260 plastic after irradiation with 150MeV protons

Lightweight of the material brings less radio-isotopes

PbF$_2$			PbWO$_4$		
Nuclide	Halflife, days	Activity, Bq/unit	Nuclide	Halflife, days	Activity, Bq/unit
Be-7	5,31E+01	3,12E+05	Be-7	5,31E+01	1,17E+04
Sc-46	8,38E+01	1,29E+04	Sc-46	8,38E+01	5,30E+02
			Ca-47	4,54	1,70E+02
V-48	1,60E+01	4,36E+03	V-48	1,60E+01	1,74E+02
Mn-54	3,13E+02	4,61E+03	Mn-54	3,12E+02	1,83E+02
Co-56	7,71E+01	1,57E+03			
Co-58	7,08E+01	1,37E+04	Co-58	7,09E+01	4,36E+02
Fe-59	4,46E+01	1,21E+04	Fe-59	4,45E+01	3,13E+02
Co-60	1924,889	8,80E+02			
Zn-65	2,44E+02	5,40E+03	Zn-65	2,44E+02	2,33E+02
As-74	1,78E+01	2,10E+04	As-74	1,78E+01	3,50E+02
Se-75	1,20E+02	3,99E+04	Se-75	1,20E+02	1,12E+03
Rb-83	8,62E+01	4,11E+04	Rb-83	8,62E+01	8,77E+02
			Rb-84	3,28E+01	2,21E+02
Sr-85	6,48E+01	4,85E+04	Sr-85	6,48E+01	1,38E+03
Y-88	1,07E+02	2,27E+04	Y-88	1,07E+02	5,39E+02
Zr-88	8,34E+01	3,72E+04	Zr-88	8,34E+01	1,22E+03
Nb-95	3,50E+01	4,24E+04	Nb-95	3,50E+01	4,80E+02
Zr-95	6,40E+01	1,50E+04	Zr-95	6,40E+01	2,29E+02
Ru-103	3,93E+01	4,26E+04			
Ag-105	4,13E+01	3,27E+04			
Ag-110	2,50E+02	3,15E+03			
Te-121	1,68E+01	4,32E+04	Te-121	1,68E+01	1,40E+03
Xe-127	3,64E+01	6,27E+04	Xe-127	3,64E+01	1,96E+03
			Ba-131	1,15E+01	1,56E+03
Ce-139	1,38E+02	2,14E+04	Ce-139	1,38E+02	1,77E+03
Pm-143	2,65E+02	1,70E+04	Pm-143	2,65E+02	6,75E+02
Eu-146	4,59E+00	1,01E+06	Eu-146	4,59E+00	3,76E+03
			Gd-146	4,83E+01	5,15E+03
Eu-147	2,40E+01	8,02E+04	Eu-147	2,40E+01	2,95E+03
			Eu-148	5,45E+01	2,46E+02
Yb-169	3,20E+01	1,71E+05	Yb-169	3,20E+01	9,77E+03
Lu-171	8,24E+00	2,81E+04	Lu-171	8,24E+00	2,07E+03
Lu-172	6,83E+02	1,57E+04	Lu-172	6,83E+00	1,62E+03
Lu-173	5,00E+02	3,46E+04	Lu-173	5,00E+02	3,06E+03
Hf-175	7,00E+01	1,43E+05	Hf-175	7,00E+01	1,62E+04
Ta-182	1,14E+02	1,26E+04	Ta-182	1,14E+02	2,80E+03
Re-183	7,00E+01	2,05E+05			
			Re-184	3,80E+01	8,02E+02
Os-185	9,36E+01	1,78E+05	Os-185	9,36E+01	2,09E+03
Tl-202	1,22E+01	2,86E+05	Tl-202	1,22E+01	3,61E+03
Bi-205	1,53E+01	1,51E+05	Bi-205	1,53E+01	1,95E+03
			Bi-206	6,24E+00	4,30E+02

$(Lu_{0.8}\text{-}Y_{0.2})_2SiO_5$:Ce (1at. %)		
Nuclide	Halflife, days	Activity, Bq/unit
Rb-83	8,62E+01	4,85E+01
Sr-85	6,48E+01	1,25E+02
Y-88	1,07E+02	3,55E+02
Eu-146	4,59	1,27E+02
Tm-158	9,31E+01	1,47E+02
Yb-169	3,20E+01	6,81E+02
Lu-171	8,24E+00	4,43E+02
Lu-172	6,70E+00	2,63E+02
Lu-173	5,00E+02	4,97E+02
Lu176(naturally present)	1,38E+13	1,39E+02

Y_2SiO_5:Ce (1 at. %)		
Nuclide	Halflife, days	Activity, Bq/unit
Rb-83	8,62E+01	7,67E+02
Rb-84	3,28E+01	3,57E+02
Sr-85	6,48E+01	8,50E+02
Y-88	1,07E+02	3,33E+03
Zr-88	8,34E+01	1,32E+02

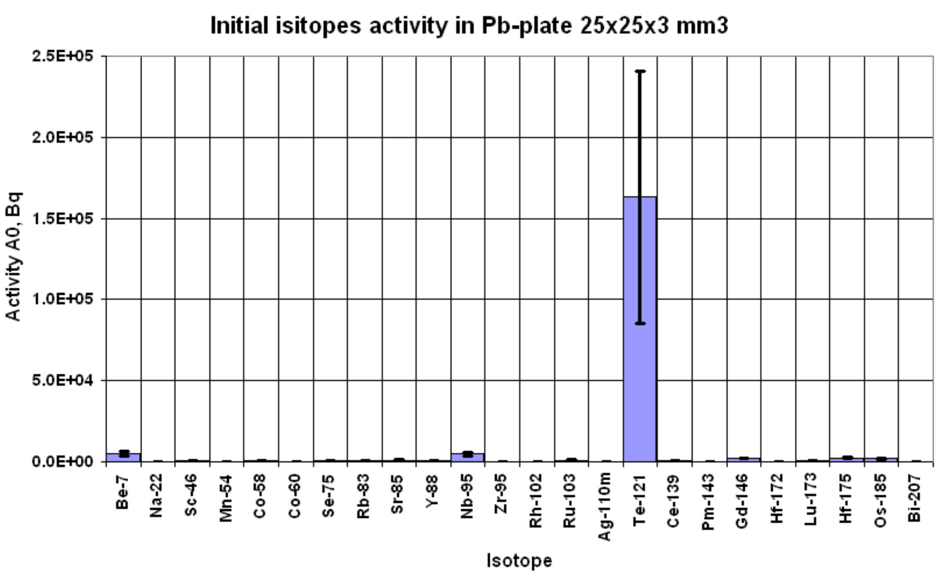
43.2 GeV/(s·cm^3) from β+γ emitters	6.4 GeV/(s·cm^3) from β+γ emitters	Total energy, deposited in 1cm3 by induced radioisotopes

Set of the radio-isotopes generated in some inorganic scintillation crystals after irradiation with 24GeV protons with fluence 3_*10^{13} p/cm^2

Long-lived radioisotopes generated in absorbing materials (Pb or W) after irradiation by 24GeV protons with fluence $3^{*}10^{13}$ p/cm^2

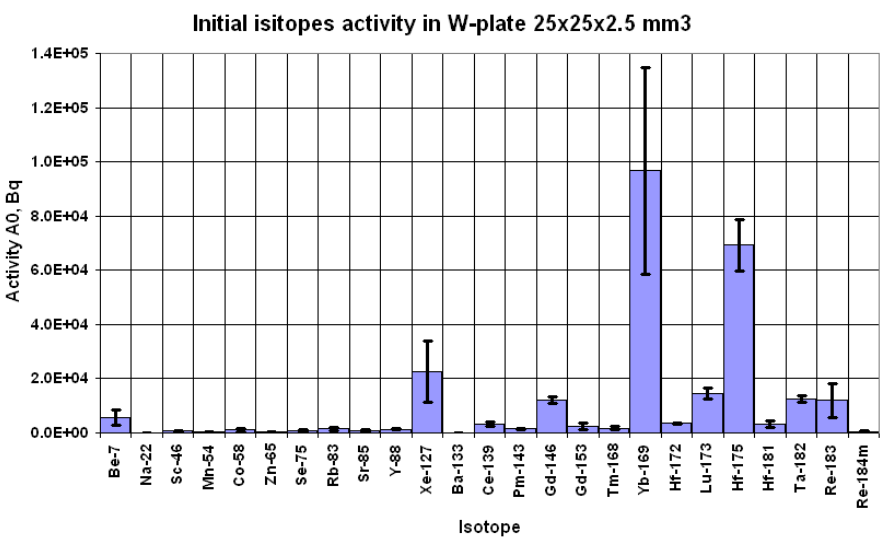
Isotopes measured in Pb and W plates 6 months after irradiation with protons. This set can be used as a starting point to simulate set of short-living isotopes.

Pb plate(25*25*3mm^3)



Dominating Isotope : ^{121}Te

W plate(25*25*3mm^3)



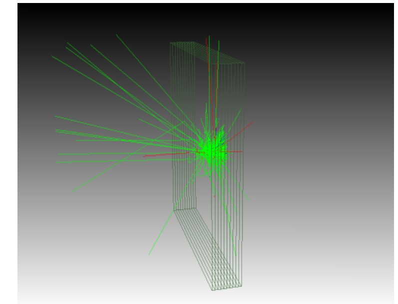
Dominating Isotopes : ^{169}Yb, ^{175}Hf, ^{127}Xe

Expected contribution of different damage effects in deterioration of the scintillation material properties at their operation in a high dose rate irradiation environment with a strong energetic hadron component

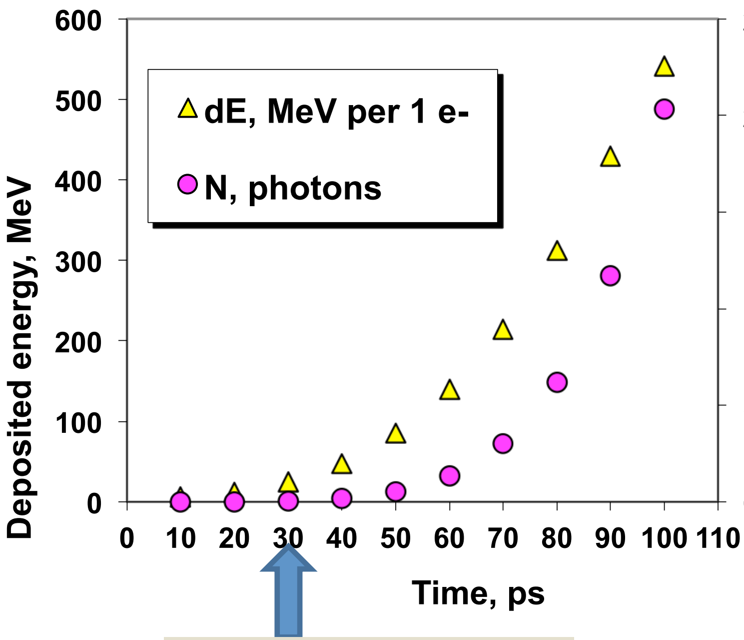
Scintillation materials	Average atomic number	Light yield	Expected damage effects		
			Damage of optical transmission	Phosphorescence	Photon background due to induced radio-isotopes
Cross luminescent	Low	Low	Large	Low	Low
	Average	Low	Large	Low	Low
	Large	Low	Large	Low	Low
Doped	Low	Low	Moderate	Low	Low
		Average	Moderate	Moderate	Low
		Large	Moderate	Large	Moderate
	Average	Low	Moderate	Low	Moderate
		Average	Moderate	Moderate	Moderate
		Large	Moderate	Large	Large
	Large	Low	Large	Low	Moderate
		Average	Large	Moderate	Large
		Large	Large	Large	Large
Self-activated	Low	Low	Moderate	Low	Low
		Average	Moderate	Low	Low
		Large	Moderate	Moderate	Moderate
	Average	Low	Moderate	Low	Low
		Average	Moderate	Moderate	Moderate
		Large	Moderate	Large	Moderate
	Large	Low	Large	Low	Moderate
		Average	Large	Moderate	Large
		Large	Large	Large	Large

Energy deposit due to pairs creation in an initial part of the shower development

GEANT4 simulation of the 100GeV e$^-$ interaction with virtually sliced LSO:Ce scintillator. (10 slices of 3mm long wafers, each wafer is equivalent to 10 ps of particle flight)

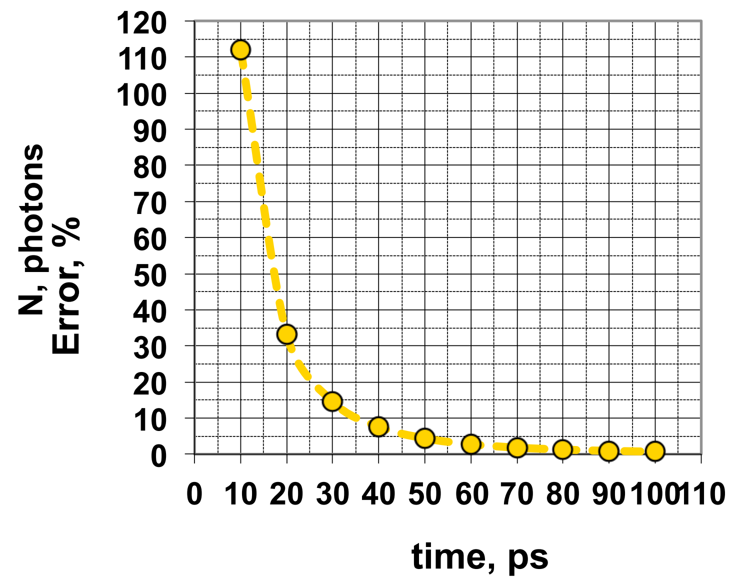


Deposited energy per particle. It is averaged for 3000 Incident particles.



Shower beginning

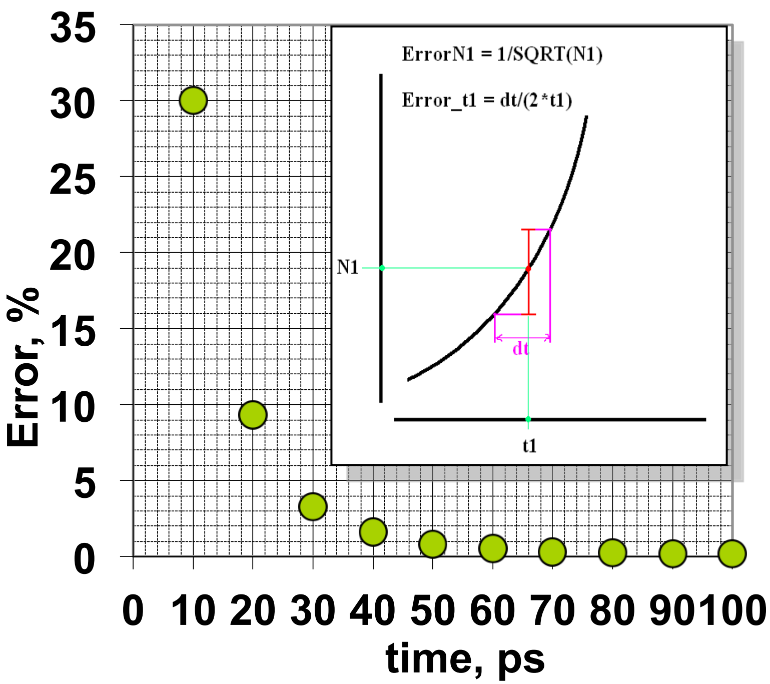
Relative error of the amplitude measurement at the beginning of the 100 GeV electron shower development



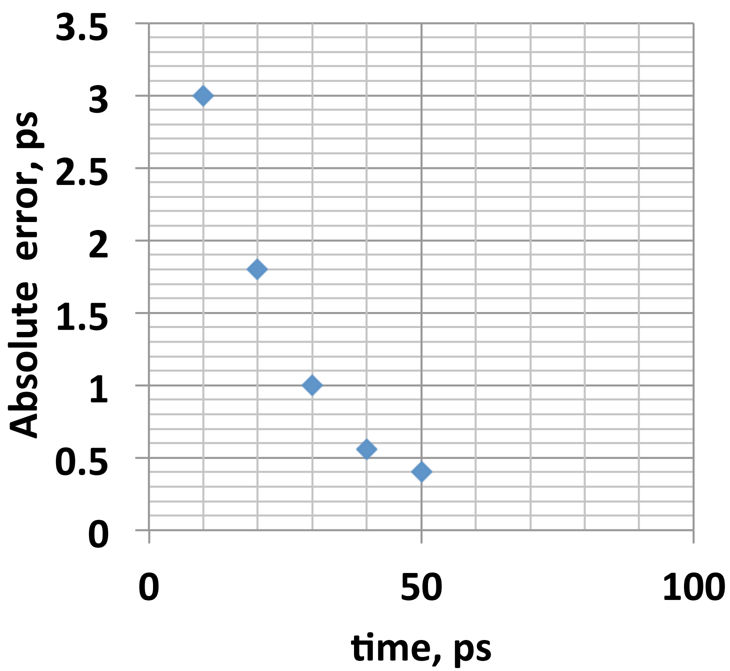
+/-10% is reachable at 30ps with scintillator like LSO:Ce

The scintillator Internal Time Resolution (ITR) at registration of 100GeV electrons

Relative Error of Time measurements.



Absolute Error of Time Measurements (AET).



Time resolution FWHM is 2,3*AET. AET~Time interval at 8-9 ps.

Effect of phosphorescence & induced radio-luminescence due to radioisotopes on the time resolution

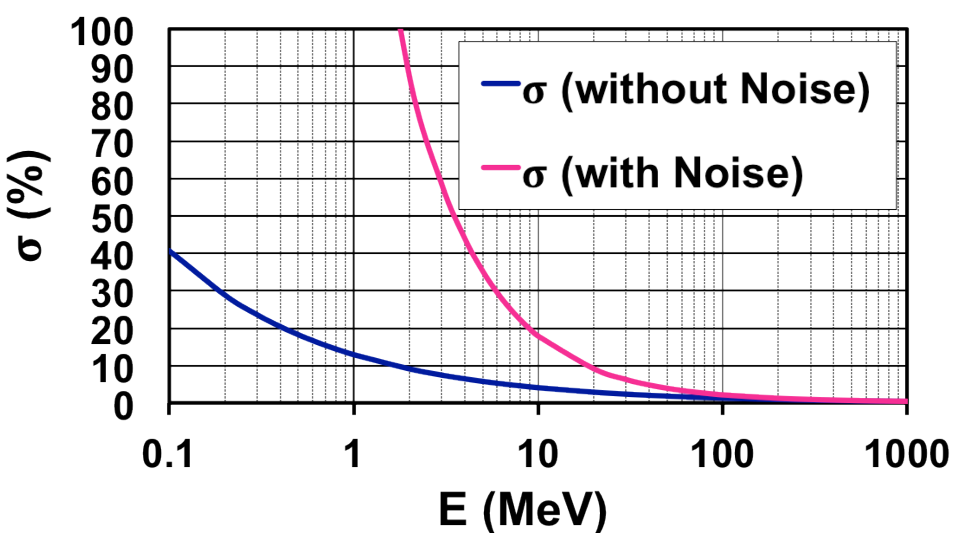
Time resolution σ_t of a scintillator:

$$\sigma_t = \sigma_{tscint} \oplus \underbrace{\sigma_{tphos} \oplus \sigma_{tradiol}}_{\text{Noise terms}}$$

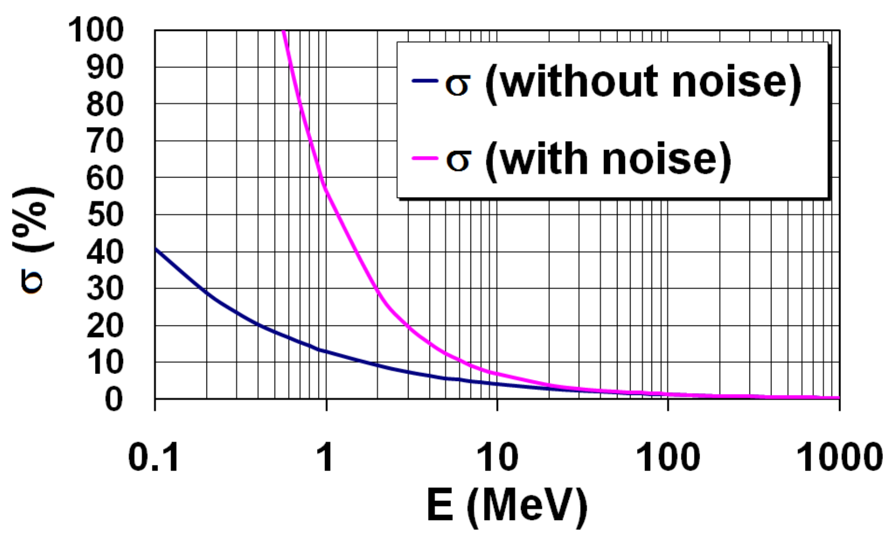
σ_{tscint}: *Pure photostatistics*
σ_{tphos}: *Induced phosphorescence*
σ_{tradio}: *Radioluminescence from induced radioisotopes*

Induced phosphorescence and induced radioluminescence due to radioisotopes in the crystal contribute to noise terms of time resolution: σ_t degradation in proton irradiated LSO:Ce bulk crystal with volume 300 cm^3 (25Xo)

LSO



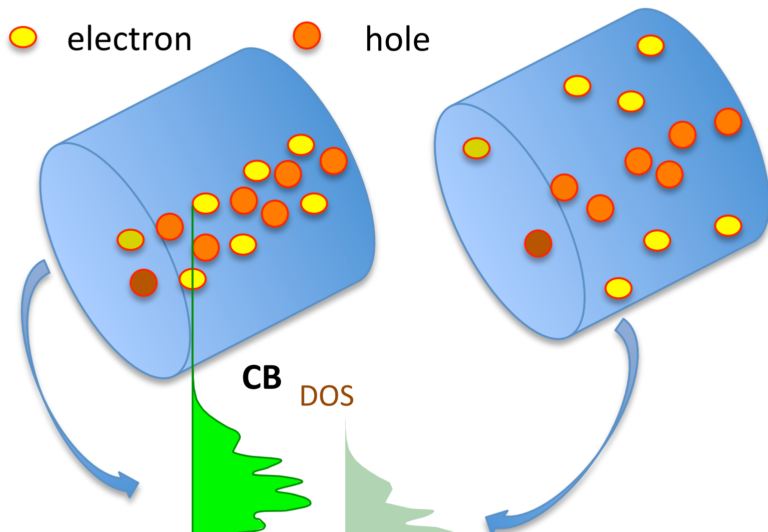
YSO

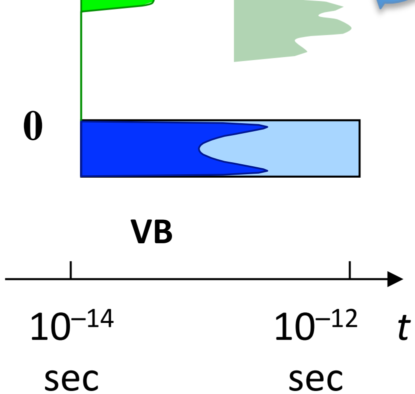


Alternative solution. Two–photon absorption probing of the radiation excited media

Elastic polarization of the dielectric due to the local lattice distortion caused by the displacements of electrons and holes generated by the ionization.

Fragment of track of the ionizing particle





Spatial separation of holes and electrons leads to creation of electric field which distortscrystal lattice.

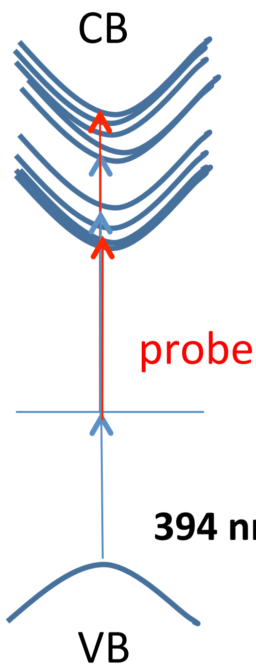
This local distortion in the lattice results in redistribution of the density of states (DOS) of electron in the conduction band in close vicinity of the hole.

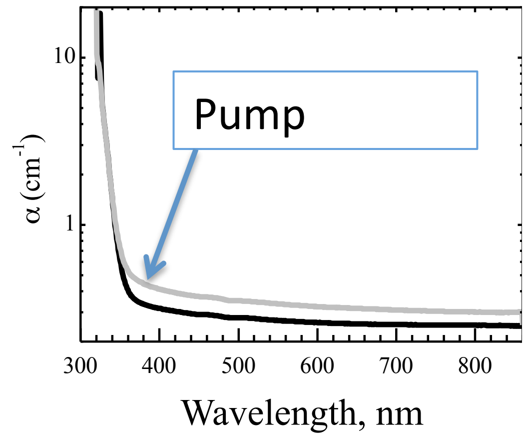
The key feature of the elastic polarization: short response time

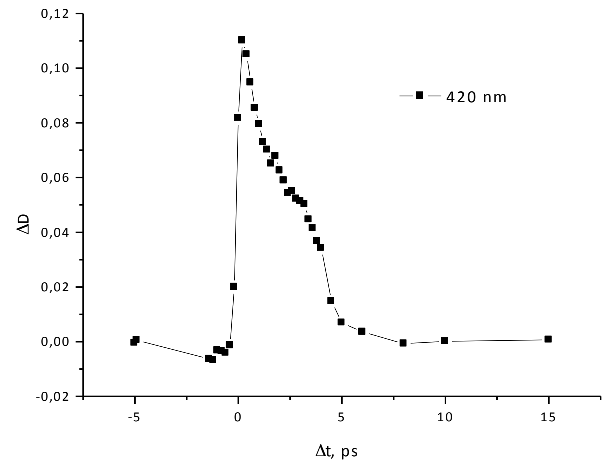
- **One-photon absorption** is not convenient to explore changes in the DOS due to strong absorption of single photons via electronic transitions between valence and conduction bands.
- **Two-photon absorption** becomes preferable due to change of the selection rules for interband transitions

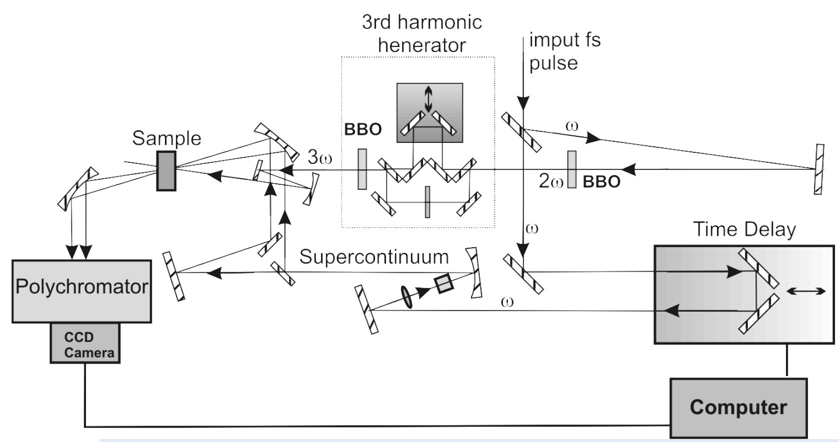
Two–photon absorption in PWO

Two photon(2,97+3.16eV) absorption in 1 cm thick PWO .





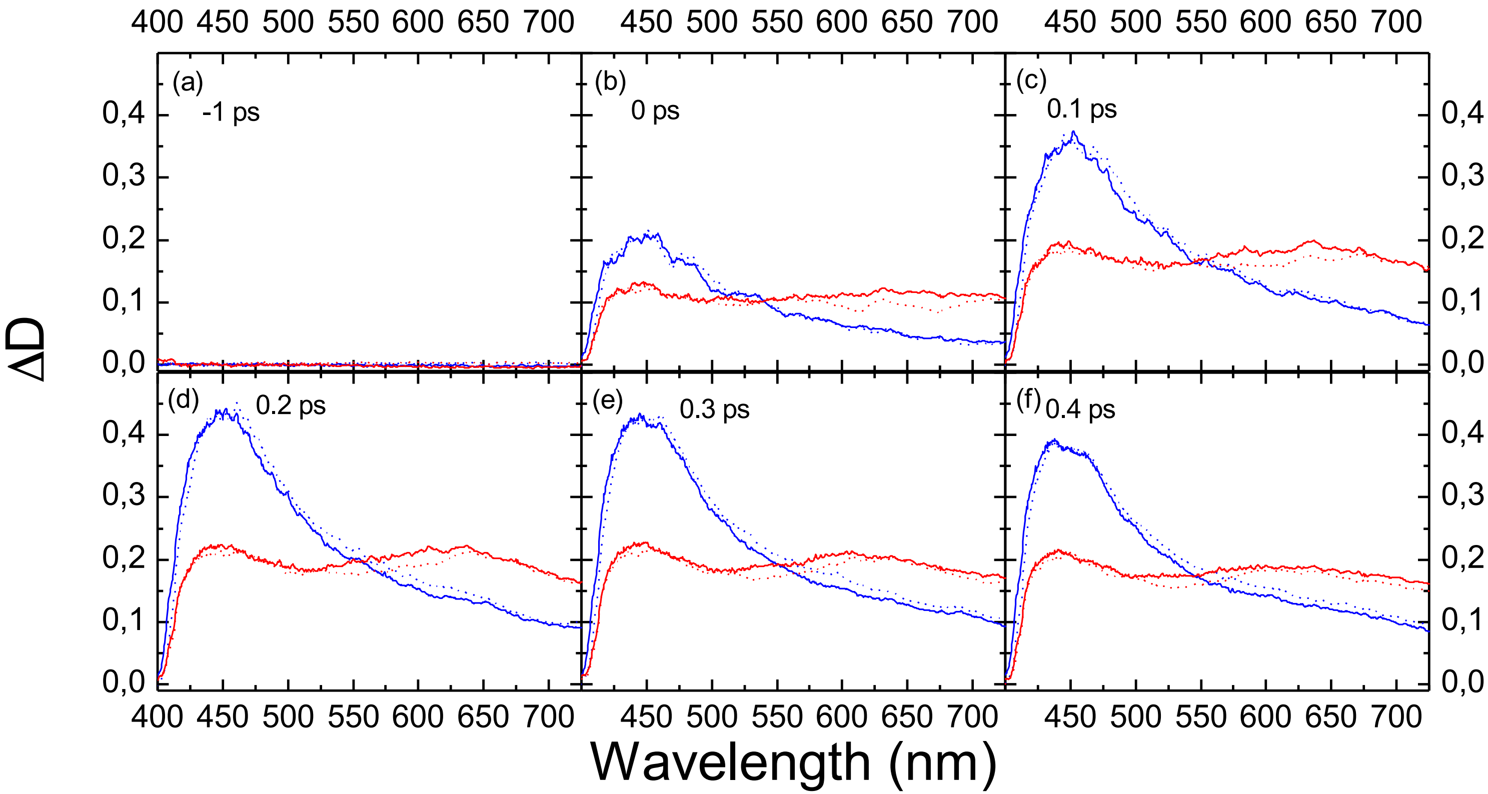




E. Auffray, O.Buganov et al., New detecting techniques for future calorimetry, Journal of Physics: Conf. Series 587(2015) 012056

Experimental bench for 2 photon absorption measurements

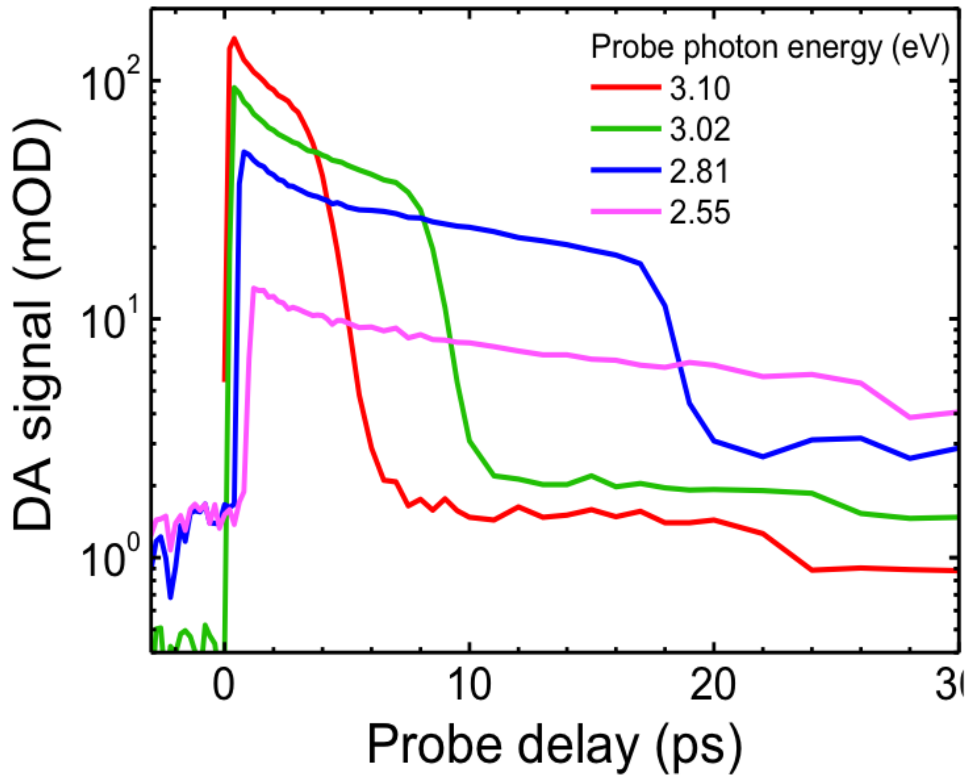
Spectra of differential optical transmittance in PWO induced by 500 mJ/cm² pump at 395 nm



Pump polarized along the crystal axis **b** (blue lines) and polarized at 75° to the crystal axis **b** (red lines) under (dashed lines) and without (solid lines) gamma irradiation. Delays of probe pulse are indicated.

E. Auffray, O. Buganov, M. Korjik, A. Fedorov, S. Nargelas, G. Tamulaitis, S. Tikhomirov, A. Vaitkevicius, Application of two-photon absorption in PWO scintillator for fast timing of interaction with ionizing radiation, Nuclear Instruments and Methods in Physics Research Section A, 2015.

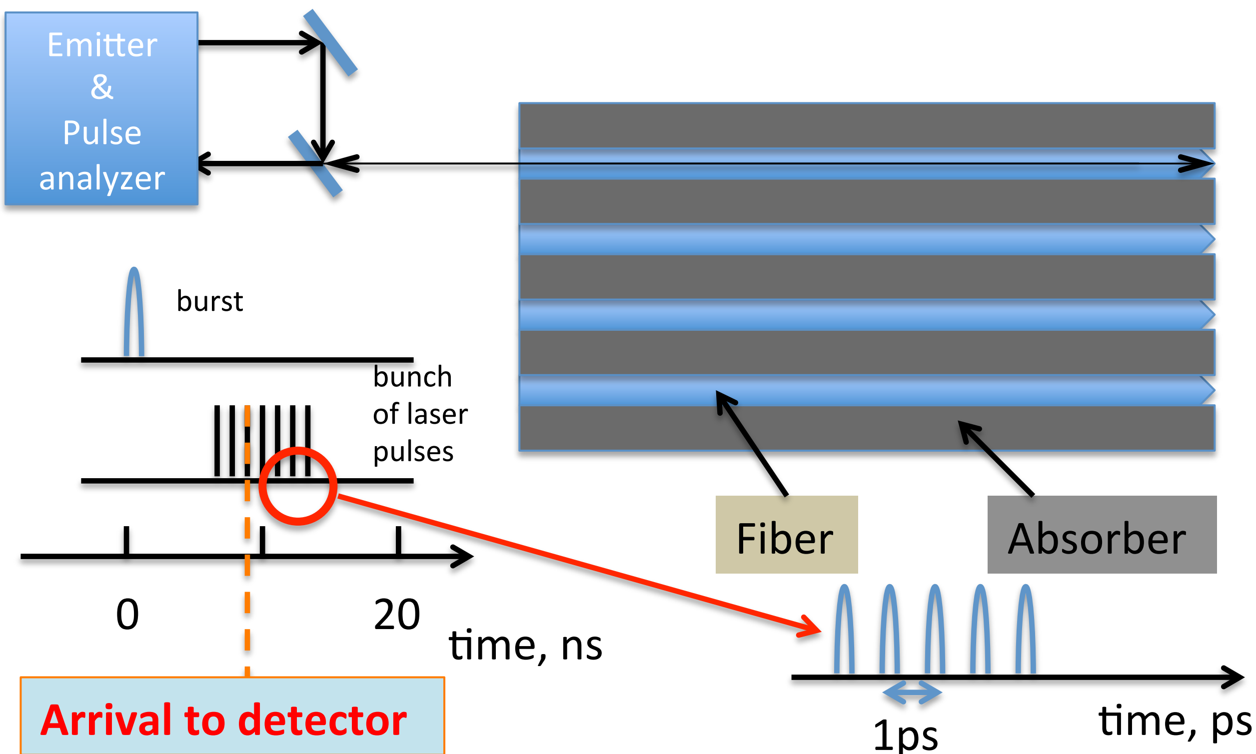
Kinetics of differential absorption in PWO scintillation crystal for 394(3.17eV) nm pump at different probe wavelengths.



Leading edge of the differential absorption is limited by laser pulse shape rather than by material properties

How it may be implemented in the detecting cells

The second harmonic of their radiation can be used to produce the light in the wavelength range of 500-530 nm, which is optimal for PWO.



1. **Fibers can have different refraction index to control light speed**
2. **Fibers can be also scintillating**
3. **Registration can be managed in a regime of standing or travelling wave**

The light propagating along the scintillation crystal and reflected from the front face of the crystal could be used to observe the two-photon absorption.

Conclusions. Damage

1. Irradiation with charged hadrons produces a sort of the damage of the ordered structure (crystalline or polymer) which is different from those which is produced by gamma-quanta irradiation.
2. Heavy self-activated materials, actively developed earlier for electromagnetic calorimetry and HEP applications, are most vulnerable in terms of the damage effects from high-energy protons. Fluence of the order of $1 \cdot 10^{14}$p/cm^2 seems to be the limiting value for the use of such crystals as PWO in homogeneous calorimeters.
3. Medium heavy self-activated materials have an advantageous combination of damage effects. The most extensively studied material - YAG:Ce, has demonstrated the least damage of optical transmittance under 24GeV of all studied crystals. YAG:Ce also is the best material combining good radiation hardness and commercial availability.
4. Compact homogeneous calorimeters operating in the vicinity of the vertex at further high luminosity collider experiments, especially in the detector near-beam region, will give way to segmented detector modules incorporating small-sized middle heavy scintillation elements.

Conclusions. Timing

1. The recently observed effects, appeared prior to scintillation, might be exploited for timing of the detector material interaction with ionizing radiation in parallel with the detection of scintillation signal in the same material.

2. The change in two-photon absorption can be used to form a time mark to detect the initial moment of the interaction of the ionizing radiation with the detector material, while the scintillation signal provides the information on absorbed energy.

3. Meanwhile, the effect is quite strong in PWO and BGO and sensitive to the presence of ionizing radiation.

Acknowledgement

Author expresses gratitude to their colleagues from CMS, Crystal Clear Collaboration at CERN and PANDA Collaboration at FAIR(GSI), especially, E. Auffray, A. Fedorov, R. Novotny for a long time joint research of the radiation damage effects in inorganic scintillation materials, V.Dormenev, V.Mechinsky, M.Lucchini, for a productive joint research and fruitful discussions, A.Singovski, M.Glaser, A. Machard,V. Panov, R. Zoueusky, and A.Barisevich for assistance in the measurements. We also grateful to COST FAST and MSC RISE Intelum for support of the performed research.