Fast LYSO and GAGG Scintillators for CMS MTD and LHCb Upgrade II

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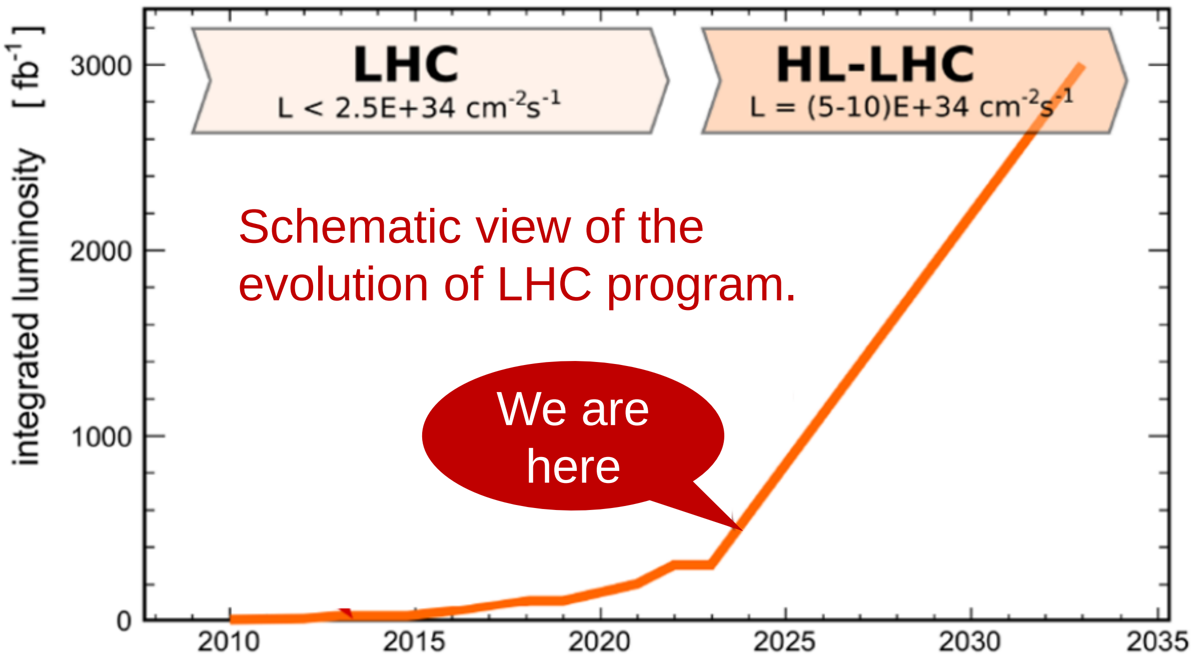
01 Background

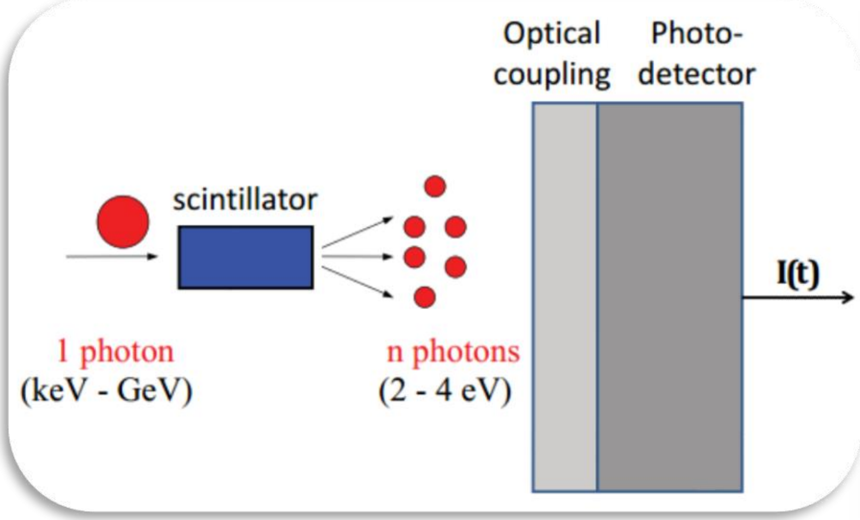
❖ R&D on Scintillators for High Luminosity LHC (HL-LHC) ECAL



The **High Luminosity LHC (HL-LHC)** will resume operations in 2026 reaching a luminosity of $5-7\cdot10^{34}$ cm^{-2} s^{-1} (10 times). At the end of the HL-LHC in ~2038 about 3000 fb^{-1} of data will be collected, a factor 10 higher than LHC, largely increasing the physics potential of the experiments.

01 Background

❖ **Ce:LYSO and Ce:GAGG crystals have been considered as good candidates for CMS MTD and LHCb upgrade Ⅱ respectively, which could solve the problems of pile-up and radiation damage of ECAL.**



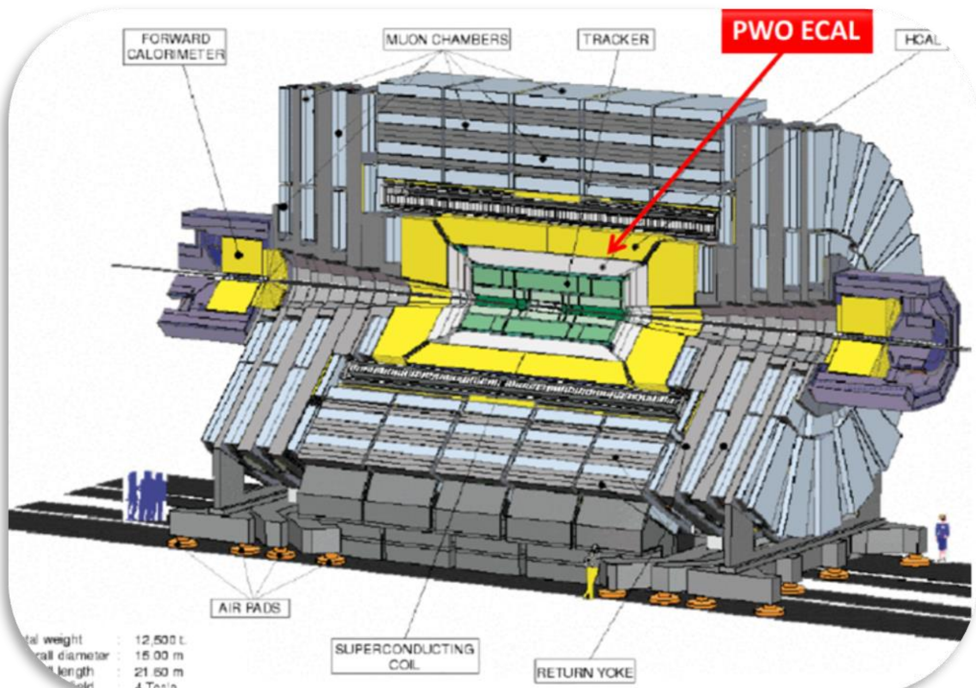
The Common Requirements of Scintillators for HL-LHC ECAL

- Fast decay time and rise time
- Harsh radiation hardness
- High density and large Z_{eff}
- **Low cost** (easy to grow, high yield, cheap raw materials, low power consumption, and low precious metal loss)

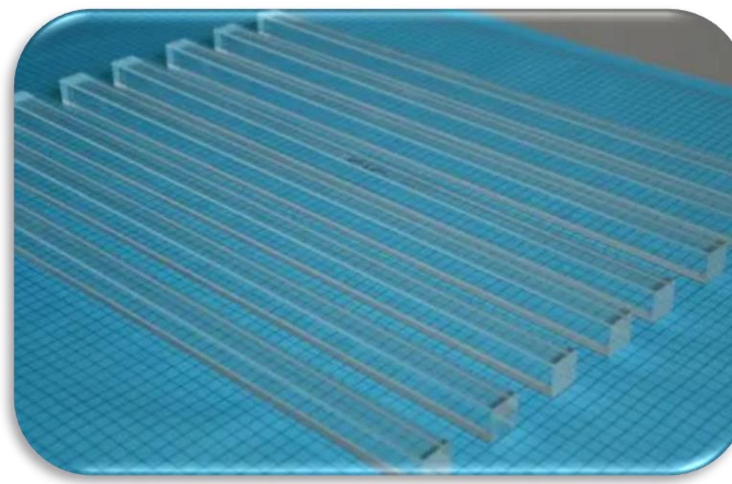
02 Ce:LYSO Arrays for CMS MTD

- **In Phase Ⅰ, $PbWO_4$** was chosen by its small radiation length (**0.89 cm**) and small Molière radius (**2.19 cm**), allowing a compact design, fitting into the CMS solenoid. Totally ~**76,000** $PbWO_4$ crystals arranged in CMS ECAL (barrel and two endcaps).

CMS Experiment at LHC



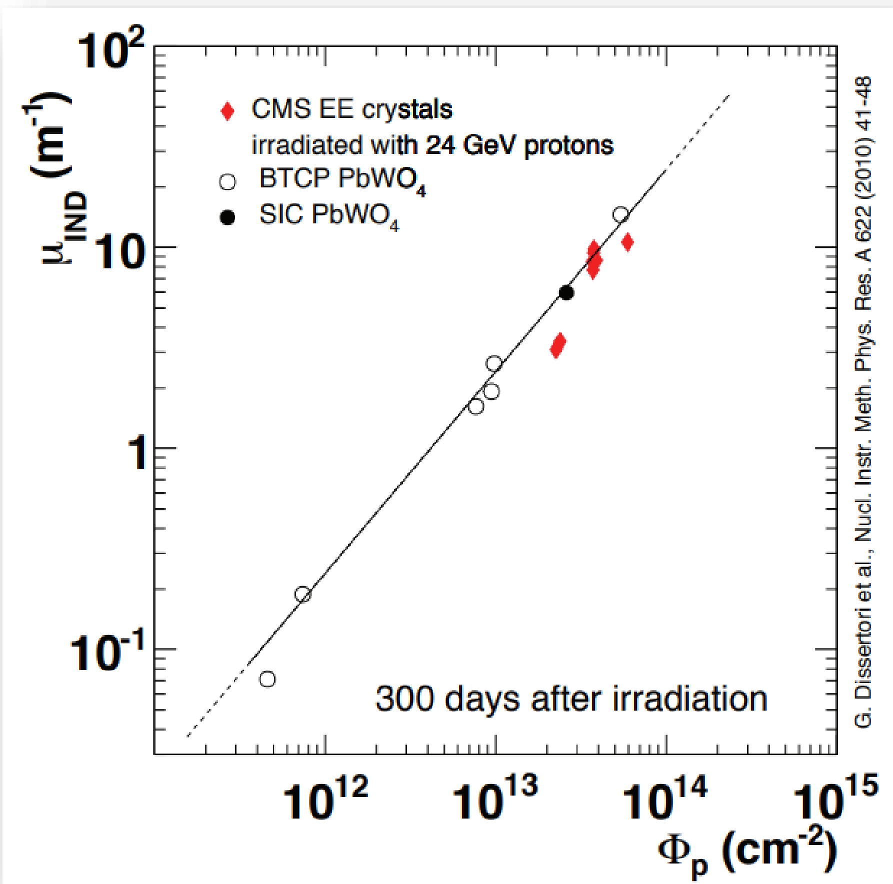
$PbWO_4$ crystals

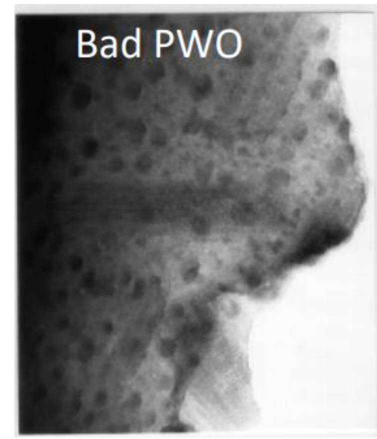


During 2005~2008, **SICCAS** had supplied about 5,000 $PbWO_4$ crystals for CMS.

02 Ce:LYSO Arrays for CMS MTD

❖ The light output of $PbWO_4$ reached equilibrium during irradiations under a defined dose rate, showing dose rate dependent **radiation damage**, producing many **Color Centers**.



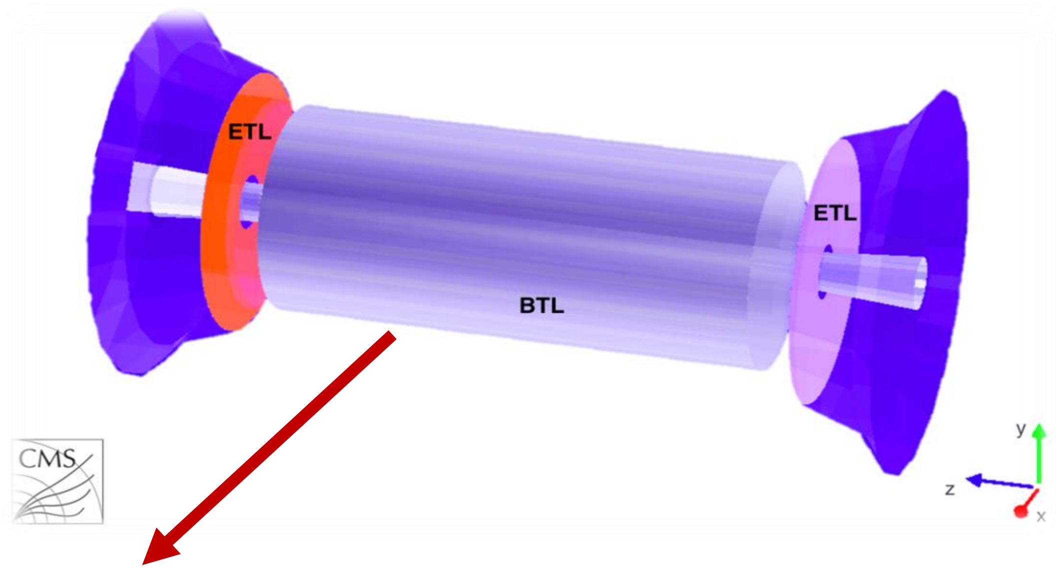


☹ Oxygen Vacancies identified by TEM/EDS

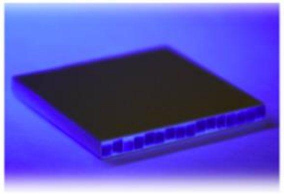
☹ Change of the **induced absorption μ** irradiated at different levels of hadron irradiation.

02 Ce:LYSO Arrays for CMS MTD

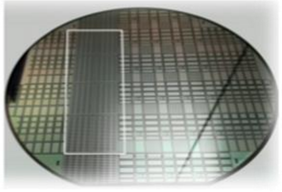
❖ CMS detector in **Phase Ⅱ upgrade**, a new timing layer will measure minimum ionizing particles (MIPs) with a time resolution of **~30-40 ps**. This MIP Timing Detector (**MTD**) will consist of a central barrel timing layer (**BTL**) and two end-caps instrumented with radiation-tolerant Low Gain Avalanche Detectors (LGADs)



BTL: LYSO bars + SiPM readout:
- TK / ECAL interface: $|\eta| < 1.45$
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: 2x10^{14} n_{eq}/cm^2



ETL: Si with internal gain (LGAD):
- On the CE nose: $1.6 < |\eta| < 3.0$
- Radius: 315 < R < 1200 mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 m^2; ~8.5M channels
- Fluence at 4 ab^{-1}: up to 2x10^{15} n_{eq}/cm^2



02 Ce:LYSO Arrays for CMS MTD

❖ The detectors will have received radiation doses of up to about **30 kGy and a "1 MeV neutron equivalent fluence", n_{eq}/cm^2 , of up to 1.9×10^{14} n_{eq}/cm^2 in the barrel,** and 450 kGy and 1.6×10^{15} n_{eq}/cm^2 in the high-η part of the endcap.

	LYSO:Ce	LuAG;Ce	LuAG;Pr	GGAG:Ce	CsI	BaF_2	BaF_2:Y	$CeBr_3$	$LaBr_3$	CeF_3
Density(g/cm³)	7.4	6.76	6.76	6.5	4.51	4.89	4.89	5.23	5.29	6.16
Melting points (℃)	2050	2060	2060	1850	621	1280	1280	722	783	1443
X_0 (cm)	1.14	1.45	1.45	1.63	1.86	2.03	2.03	1.96	1.88	1.68
R_M(cm)	2.07	2.15	2.15	2.20	3.57	3.1	3.1	2.97	2.85	2.63
Z_{eff}	64.8	60.3	60.3	51.8	54.0	51.6	51.6	45.6	45.6	21.3
λ_{peak}(nm)	420	520	310	540	310	300 220	300 220	371	360	300 340
Absorption Edge(nm)	170	160	160	190	200	140	140	n.r.	220	280
Refractive Index	1.82	1.84	1.84	1.92	1.95	1.50	1.50	1.9	1.9	1.6
Normalized Light Yield	100	35 48	44 41	40 75	4.2 1.3	42 5.0	1.7 5.0	99	153	5.6 8.4
Light yield (ph/MeV)	30,000	25000	25,800	34,700	1,700	13,000	2,100	30,000	46,000	4,180
Decay time[a](ns)	31~40	981 64	1208 26	319 101	30 6	600 <0.6	600 <0.6	17	20	5 30

Finally **Ce:LYSO** crystals has been chosen, due to its high density, fast decay time, good radiation hardness and affordable price.

02 Ce:LYSO Arrays for CMS MTD

❖ **The route of R&D on Ce:LSO/LYSO crystals in the past ~ 30 years.**

1990 — **Ce:LSO** was invented by **C.L. Melcher**

1998 — SIPAT **started** to develop Ce:LSO crystal for military

2000 — **Ce:LYSO** was invented by C.L. Melcher

2008 — SIPAT had capability of **massive production** of LYSO, considered as the only supplier in China

~2010 — Ce:LYSO had been considered as one of the candidates for **CMS-MTD BTL**

2014 — SIPAT made breakthrough on **fast and 4 inches Ce,Ca:LYSO** ingots

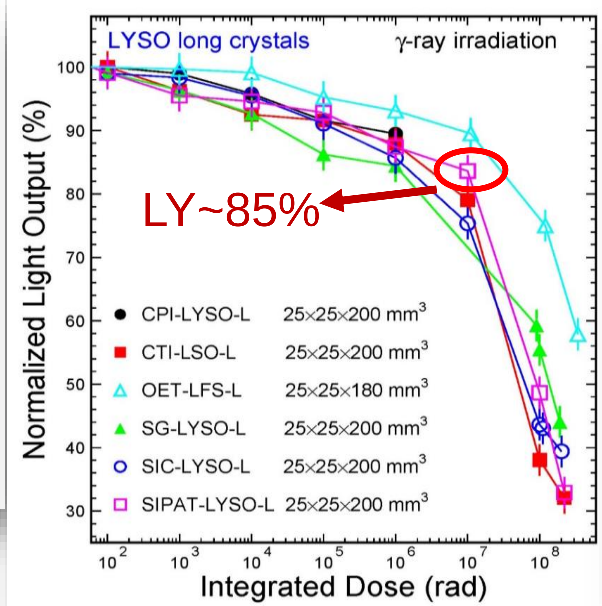
~2019 — **Technical Design Report** of MTD for the CMS Phase-2 Upgrade finished

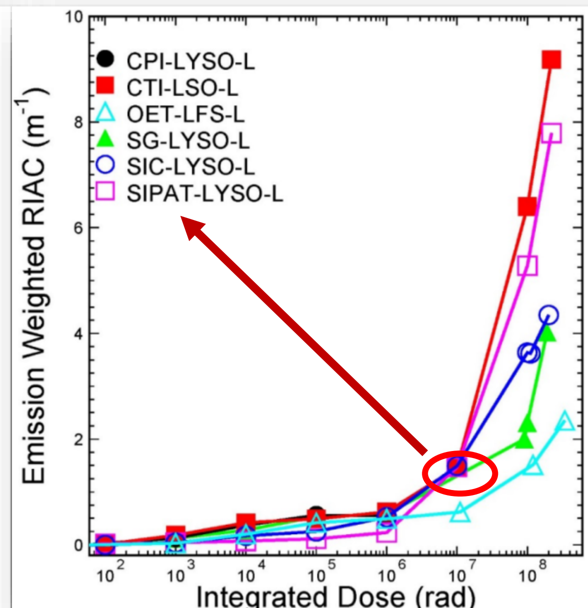
- **G.Y. Zhu**, who worked in CAEP, suggested SIPAT to develop and research on Ce:LSO scintillator for nuclear detector.
- **R.Y. Zhu** helped SIPAT to test and improve the performance of Ce:LYSO, and introduced SIPAT to CERN for CMS MTD.

02 Ce:LYSO Arrays for CMS MTD

- **LYSO crystal were expected to meet CMS BTL radiation hardness specification**: Induced absorption < 3 m^{-1} for Total Dose of Ionization (TDI) of 3.7 M rad, TF: p of 3 x 10^{13} p/cm^2 and TF: n of 3 x 10^{14} p/cm^2.

Size:25×25×200mm^3





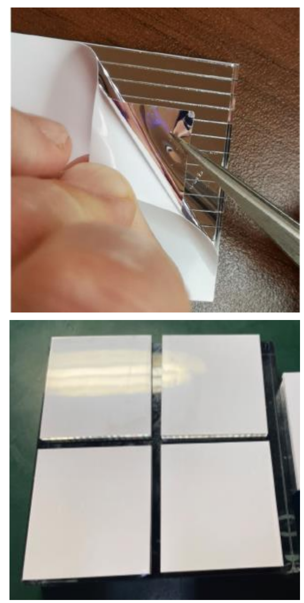
F. Yang, L.Y. Zhang, Z. Y. Zhu, et al., IEEE Trans. Nucl. Sci. 63, pp. 612-619 (2016)

02 Ce:LYSO Arrays for CMS MTD

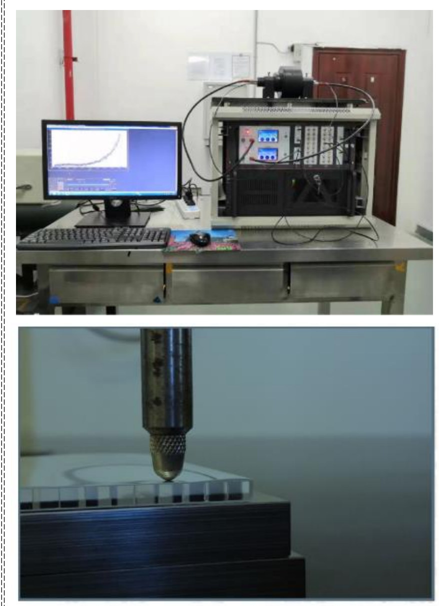
- **SIPAT has large manufacturing capability of Ce:LYSO crystals for HEP and other applications, and is considered to be an important supplier all over the world.**

LYSO Growth

Processing



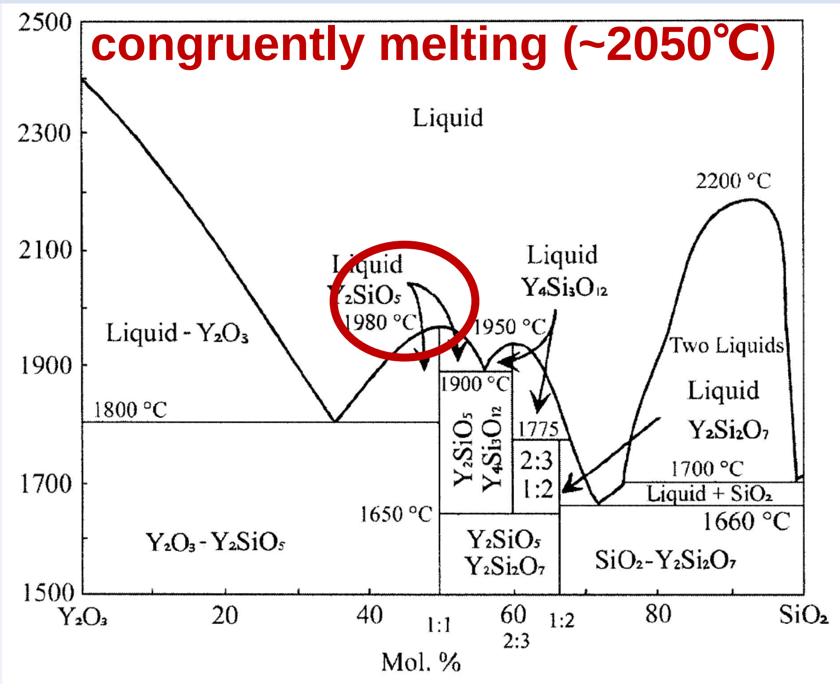
Array Assembling



Testing and Characterization

02 Ce:LYSO Arrays for CMS MTD

(1) Crystal Growth: Ce:LYSO crystals are usually grown by using Czochralski method on the condition of inert atmosphere.



The phase diagram of Lu_2O_3-SiO_2 is similar with that of Y_2O_3-SiO_2

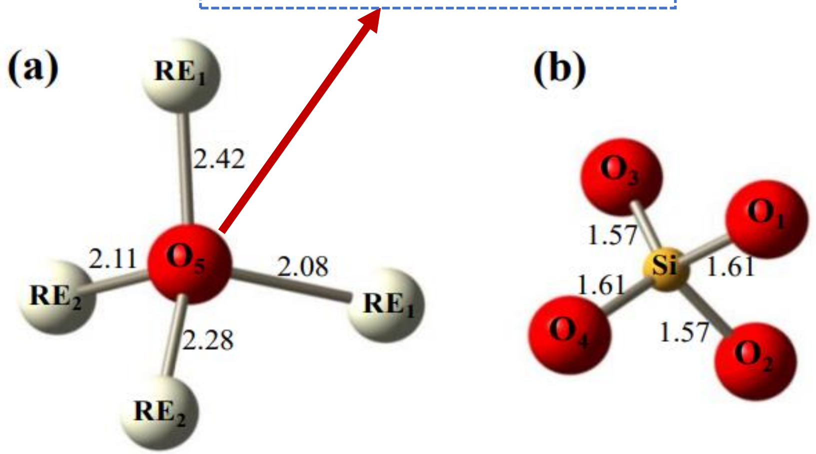
Czochralski method

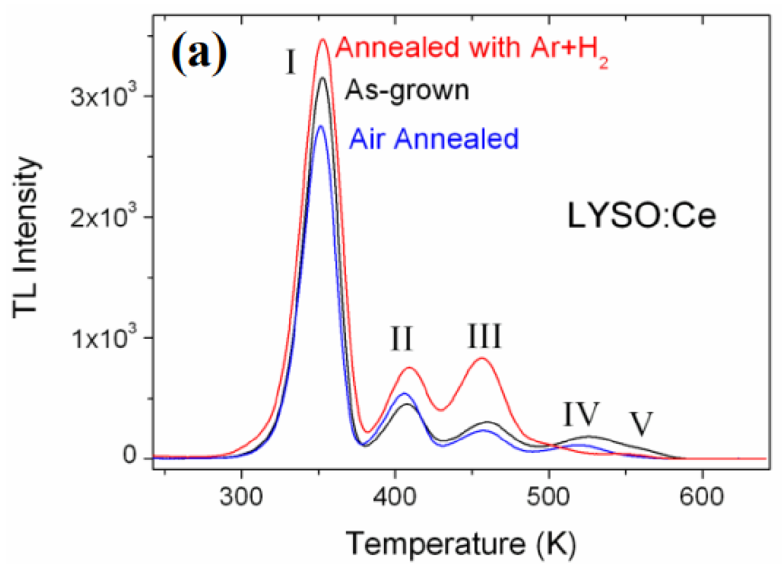
Ce:LYSO ingot

02 Ce:LYSO Arrays for CMS MTD

(2) Annealing in Air: this is an effective method to eliminate the **Oxygen Vacancy**, consequently increasing the light yield of Ce:LYSO crystal.

O_5 atom is inclined to leaving away

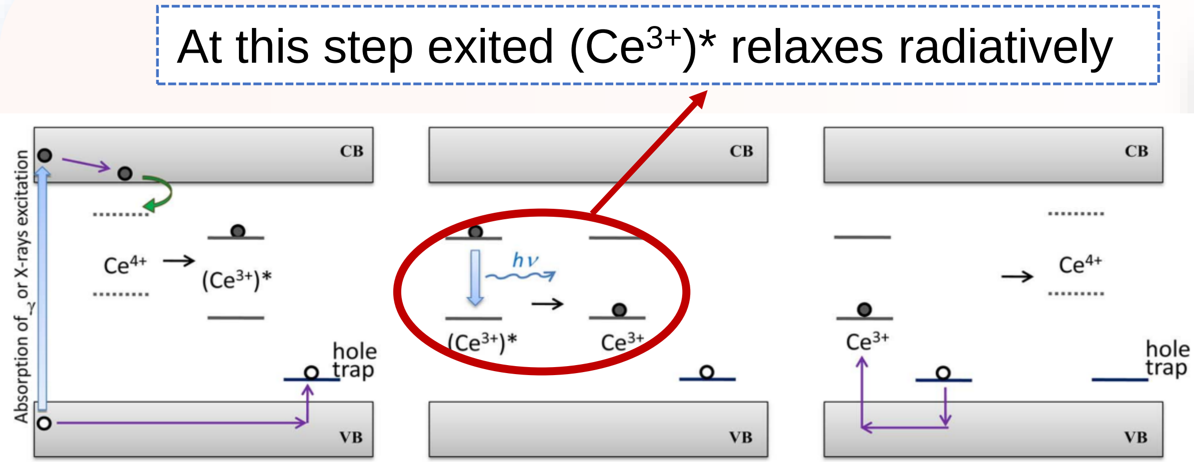


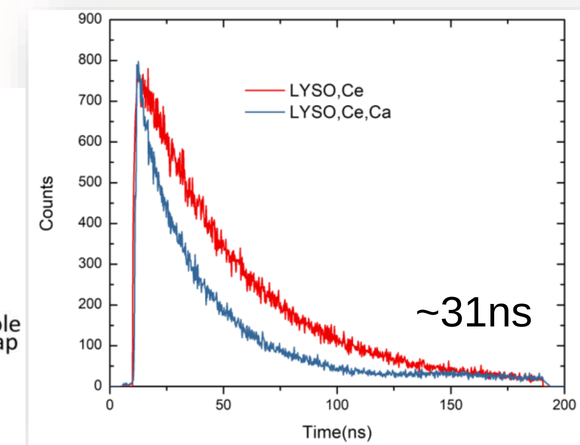


O_1 to O_4 are related to SiO_4 polyhedra whereas O_5 is not bonded to silicon and is solely linked to Lu/Y, thus forming [O-RE_4] tetrahedra, many Oxygen Vacancies appeared during crystal growth due to low oxygen content in the furnace atmosphere.

02 Ce:LYSO Arrays for CMS MTD

(3) Codoping with Ca^{2+}: Codoping with Ca^{2+} has been verified to form stable Ce^{4+}, which is a fast transition channel. The decay time of Ce:LYSO is shorten to ~31 ns.





Mechanism suggested to explain Ce luminescence originating from Ce in co-doped Ce,Ca:LYSO. Electrons are symbolized by filled circles and holes by empty circles. Suggested positions of Ce energy levels are represented in dotted line.

02 Ce:LYSO Arrays for CMS MTD

(3) Codoping with Ca^{2+}: Ca^{2+} codoping also increases the surface tension of the LYSO melt. At the end of crystal growth, the Solid-Crystal interface becomes instable, consequently causing twining and spiral.

Spiral growth and more fragile

02 Ce:LYSO Arrays for CMS MTD

(4) Array Assembling: 3 types of arrays with different thickness are required for CMS MTD, The total number of **1×16** LYSO arrays is **11,226** (the number for each one is 3742) .

Discussion between SIPAT and CERN on BTL project technical specifications for LYSO arrays

CERN
28/07/2021

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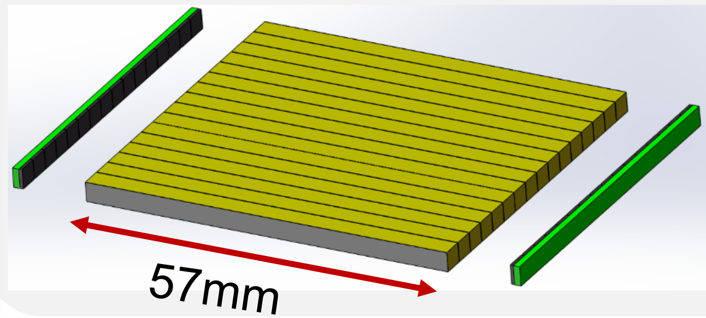
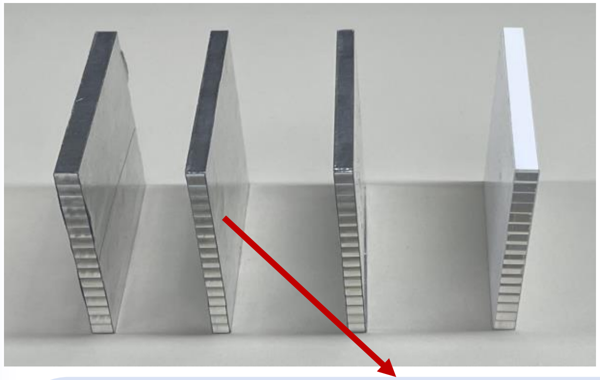
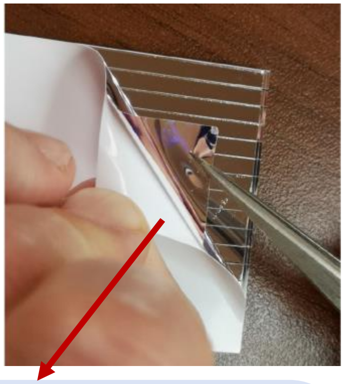
Type	Material	Pixel dimensions (mm)		
		a(*)	*b*	*L*
#1	LYSO:Ce	3.12	3.75	57.00
#2	LYSO:Ce	3.12	3.00	57.00
#3	LYSO:Ce	3.12	2.40	57.00



Pixel number 1×16





Wrapped with ESR, there is no glue between ESR and crystal.

02 Ce:LYSO Arrays for CMS MTD

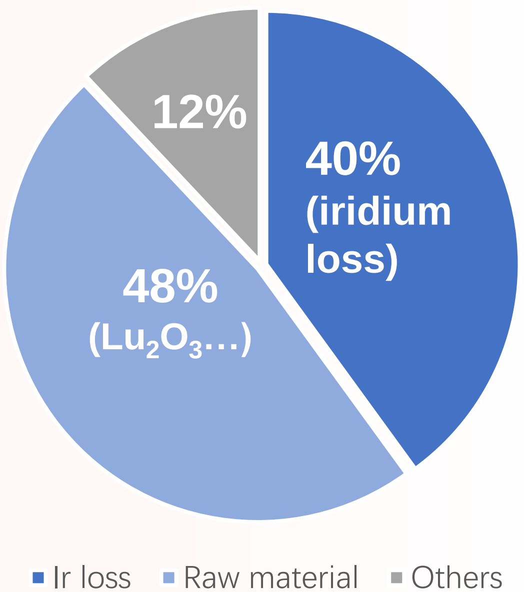
(5) The Cost: The crystal cost is an important factor to make decision for HEP scientists. Here below is the price of different crystals, reported by *R.Y. Zhu* in 2019.

Item	Size	$1m^3$	$10m^3$	$100m^3$
BGO	2.23×2.23×28 cm	\$8/cc	\$7/cc	\$6/cc
BaF_2:Y	3.10×3.10×50.75 cm	\$12/cc	\$11/cc	\$10/cc
LYSO	20.7×20.7×285 mm	\$36/cc	\$34/cc	\$32/cc
PWO	20×20×223 mm	\$9/cc	\$8/cc	\$7.5/cc
BSO	22×22×274 mm	\$8/cc	\$7.5/cc	\$7.0/cc
CsI	3.57×3.57×46.5 cm	\$4.6/cc	\$4.3/cc	\$4.0/cc

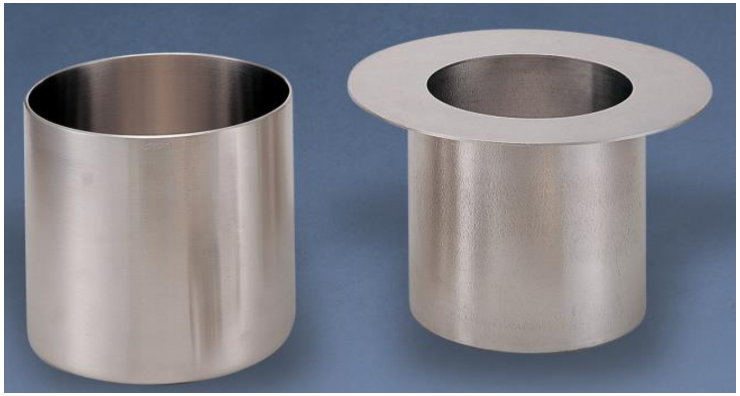
02 Ce:LYSO Arrays for CMS MTD

(5) The Cost: mainly consists of Ir loss, Raw material (Lu_2O_3 is very expensive), electricity consumption, thermal parts, cycling water, inert gas and so on.

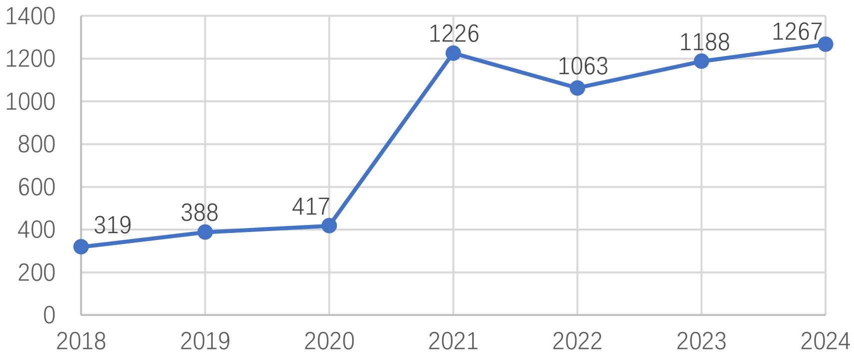
Cost proportions



Note: each crucible is made of ~5 kg iridium.



Iridium Price Trend (RMB/g)



03 Ce:GAGG Crystal Fibers for LHCb upgrade Ⅱ

❖ R&D strategy for the ECAL upgrade II of LHCb experiment

New configurations of shaslik modules in outer part (＜40 kGy)

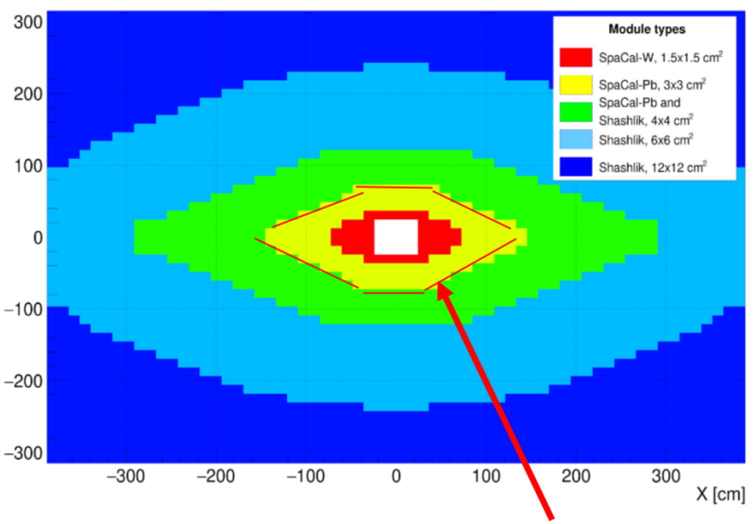
12×12 cm^2 1344 refurbished modules
6×6 cm^2 896 rebuilt+448 refurbished modules
4×4 cm^2 272 new+176 refurbished modules

SPACAL technology

In the inner region (＞40 kGy):

SPACAL-Pb: 3 ×3 cm^2:
136 modules, rad-hard up to 200 kGy
⇒ plastic fibers

SPACAL-W: 1.5 x 1.5 cm^2:
40 modules, rad-hard up to **1 MGy**
=> crystal fibers



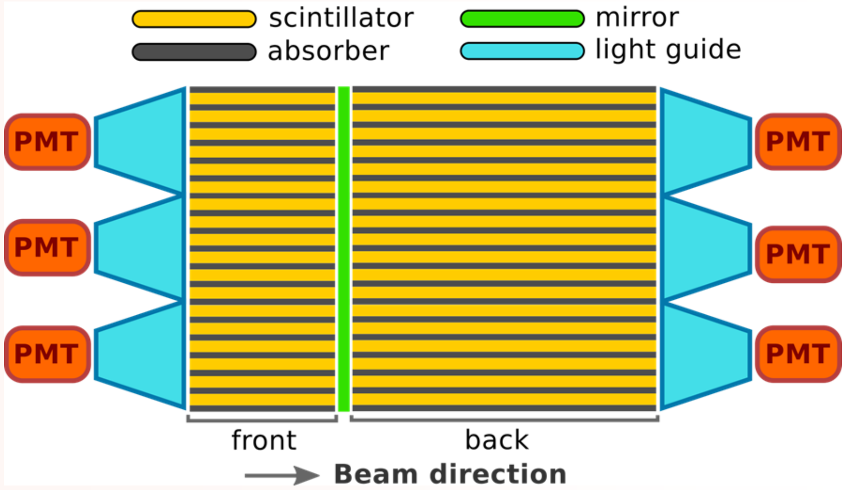
Radiation limit of current Shashlik technology

A main decay time of **up to 25 ns** and a light yield of at least **10,000 photons/MeV** are targeted.

03 Ce:GAGG Crystal Fibers for LHCb upgrade II

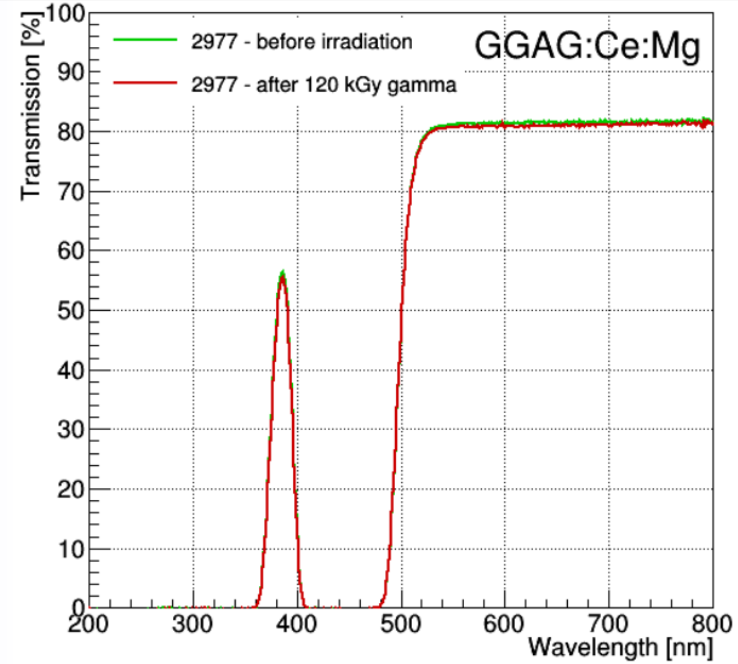
❖ Garnet scintillators for SPACAL

SPACAL module configuration



	Density g/cm^{-3}	Z_{eff}	Light Yield	Decay time/ns	Radiation hardness
Ce:GAGG	6.6	54	~50,000	40~150	good
Ce:YAG	4.5	33	~25,000	~60	good

No impact on radiation hardness



03 Ce:GAGG Crystal Fibers for LHCb upgrade Ⅱ

❖ **Many groups in the world have devoted to develop Ce:GAGG scintillator, and its scintillation properties are greatly improved to be used in many kinds of applications.**

Japan，Kamada
2011

$(Ce_xGd_{1-x})_3(Ga_yAl_{1-y})_5O_{12}$

Ce:GAGG

2013 SIPAT

Codoped with B/Ce
Light yield increased to 60000ph./MeV

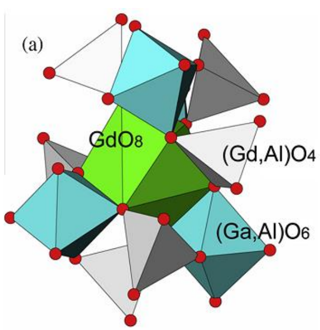
2015
USA，Meng
US2015/0353822

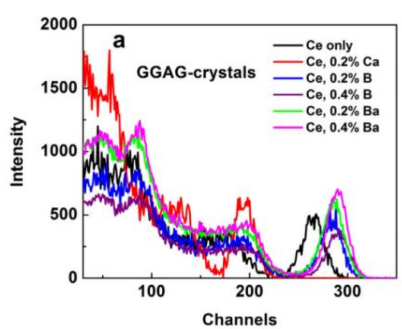
Switzerland，Lucchini
2016

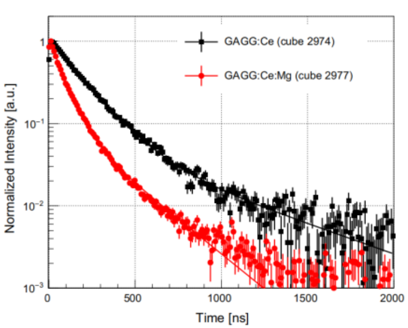
Codoped with Mg/Ce
Decay time was reduced to ~ 50ns

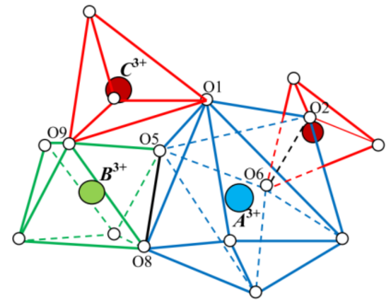
Codoped with Sc/Ce
Good uniformity and **low Afterglow**

2020
China，Ding. et al.
ZL202011065989.6
US2021/096212







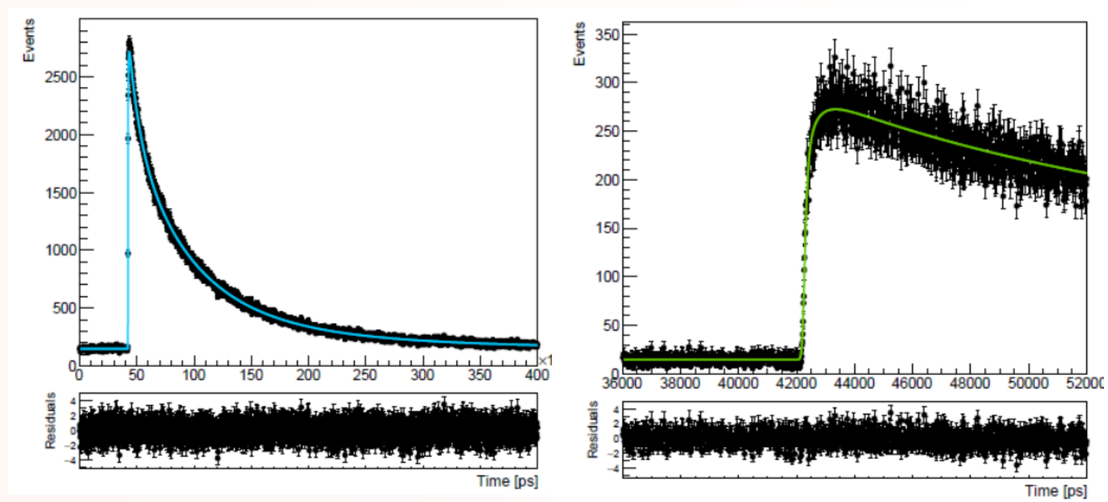


03 Ce:GAGG Crystal Fibers for LHCb upgrade Ⅱ

❖ **In 2018, SIPAT had grown Mg,Ce:GAGG crystal and characterized by CERN. The decay time reached to ~50 ns.**

Dia.60mm×120mm

Rise and decay time measurement with single photon counting setup with pulsed X-rays

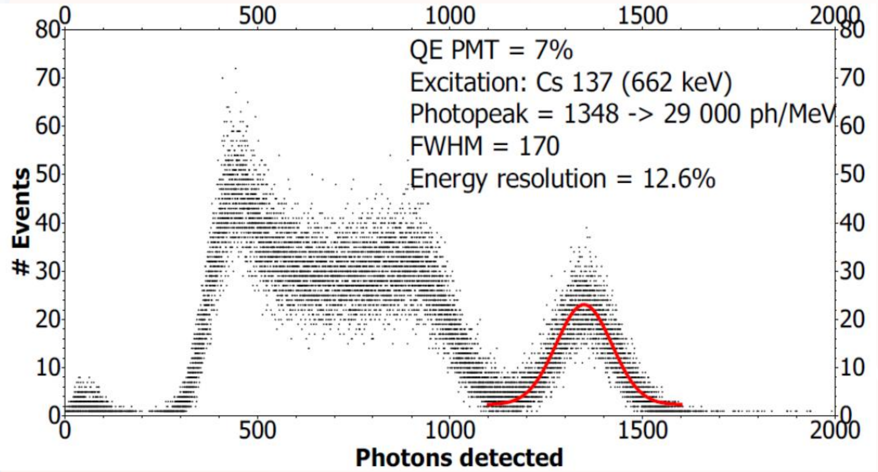


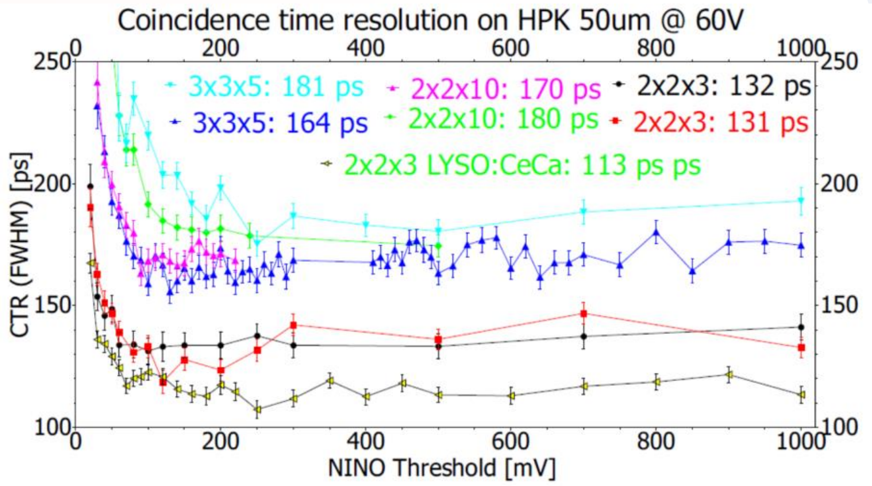
- $\tau_{d1} = 9.4 \pm 0.4$ ns (5.1%)
- $\tau_{d2} = 49.5 \pm 0.6$ ns (56%)
- $\tau_{d3} = 139 \pm 6$ ns (39%)
- $\tau_{d,effective} = 51.2$ ns

- $\tau_{r1} = 11 \pm 600$ ps (5.1%)
- $\tau_{r2} = 85 \pm 50$ ps (56%)
- $\tau_{r3} = 390 \pm 47$ ps (39%)

03 Ce:GAGG Crystal Fibers for LHCb upgrade Ⅱ

❖ **The light yield decreased from ~50,000 ph./MeV to 29,000 ph./MeV, the CTR is about ~131 ps measured by using 2mm×2mm×3mm Ce,Mg:GAGG samples.**





Measurement condition:

- Light Yield with PMT (R2059) with teon wrapping and optical grease.
- Coincidence time resolution with optical grease and teon wrapped with 3×3 mm^2 HPK 50m SPAD size.

03 Ce:GAGG Crystal Fibers for LHCb upgrade Ⅱ

❖ SPACAL prototype tested at DESY with electrons of 1-5.8 GeV

◻ Prototype configuration:

- ✓ Crystal garnet fibers with 1x1 mm^2 square section, 4 and 10 cm length
- ✓ Tungsten absorber with hole pitch of 1.7 mm
- ✓ Longitudinal segmentation at the shower Maxium

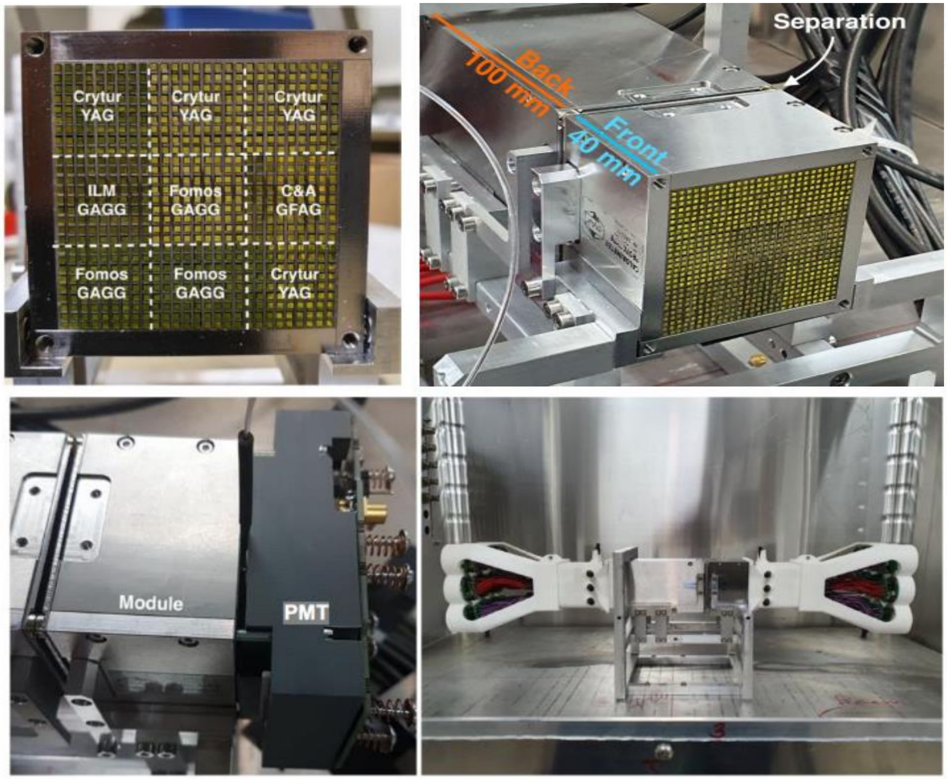
◻ Two photodetectors employed:

- ✓ Hamamatsu R12421 and PMMA light guides
- ✓ Hamamatsu R7600U-20 metal channel dynodes (MCD) PMTs in direct contact

◻ 4 garnet types tested:

- ✓ Crystur – YAG
- ✓ Fomos – GAGG
- ✓ **ILM – GAGG (Grown by SIPAT)**
- ✓ C&A - GFAG

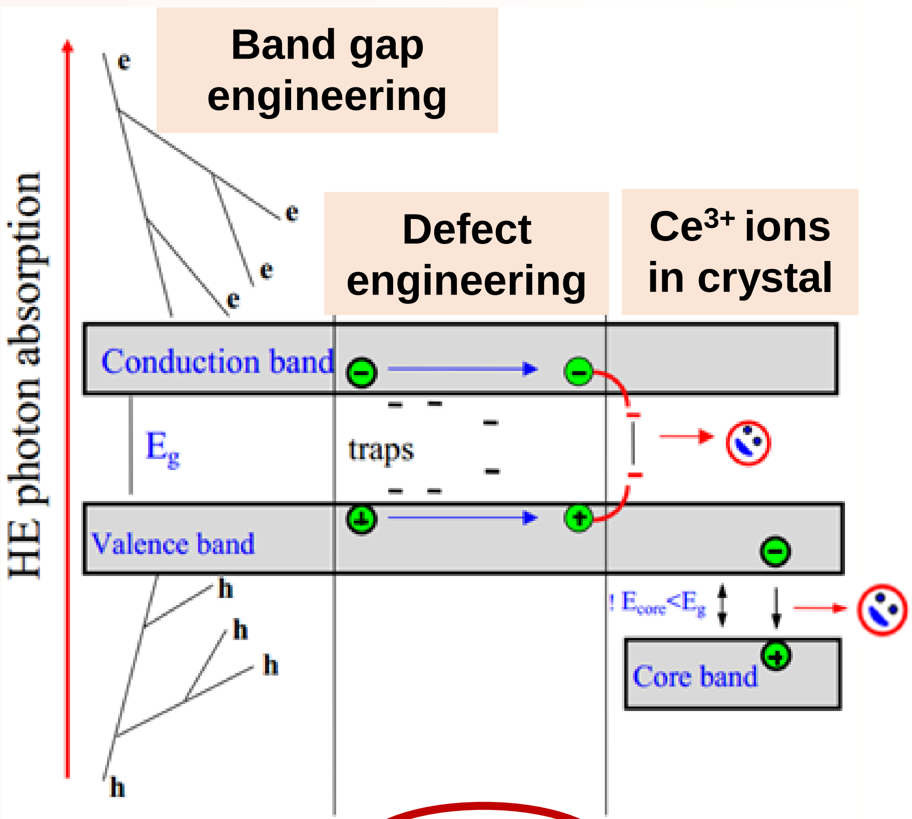
The testing results have been published in 2023.



**Nuclear Inst. and Methods in Physics Research, A, 1045(2023) 167629*

03 Ce:GAGG Crystal Fibers for LHCb upgrade Ⅱ

❖ **Improvement of its decay time of Ce:GAGG scintillator, aiming at less than 25 ns.**



① Conversion ②Transport ③ Luminescence

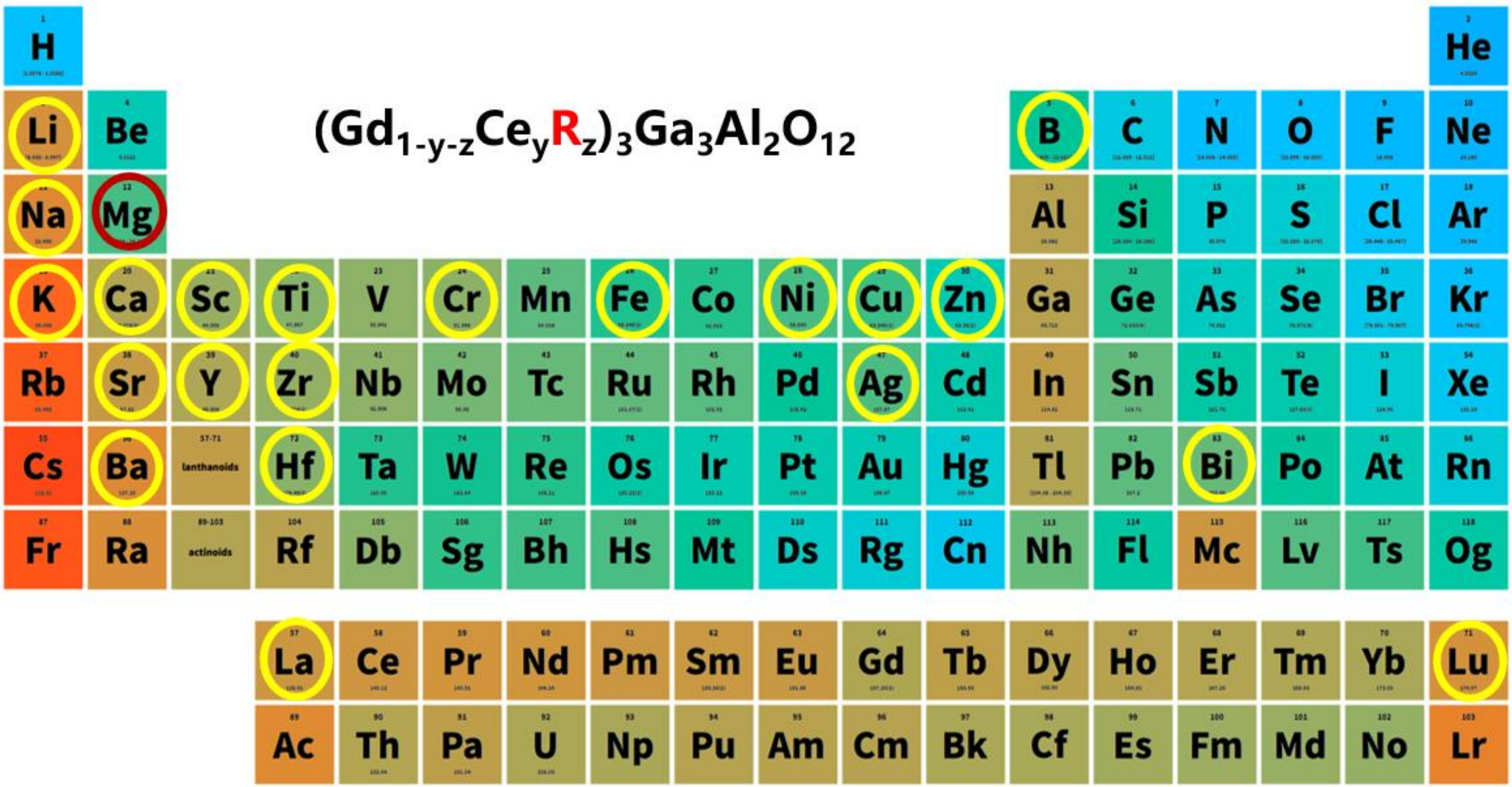
① **Conversion-** interaction of a high-energy photon with a material through photoeffect, Compton effect, pair production, appearance of electron-hole pairs and their thermalization.

② **Transport-** diffusion of electron-hole pairs (excitons) through the material, possible (repeated) trapping at defects, nonradiative recombination.

③ **Luminescence-** trapping of charge carriers at the luminescence center and their radiative recombination.

03 Ce:GAGG Crystal Fibers for LHCb upgrade Ⅱ

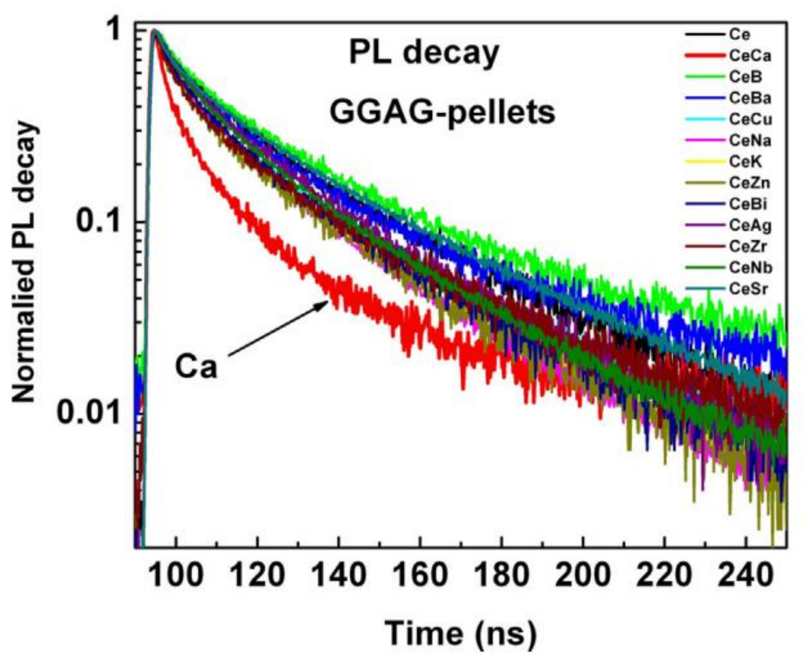
❖ **Elements screening based on “defect engineering”**

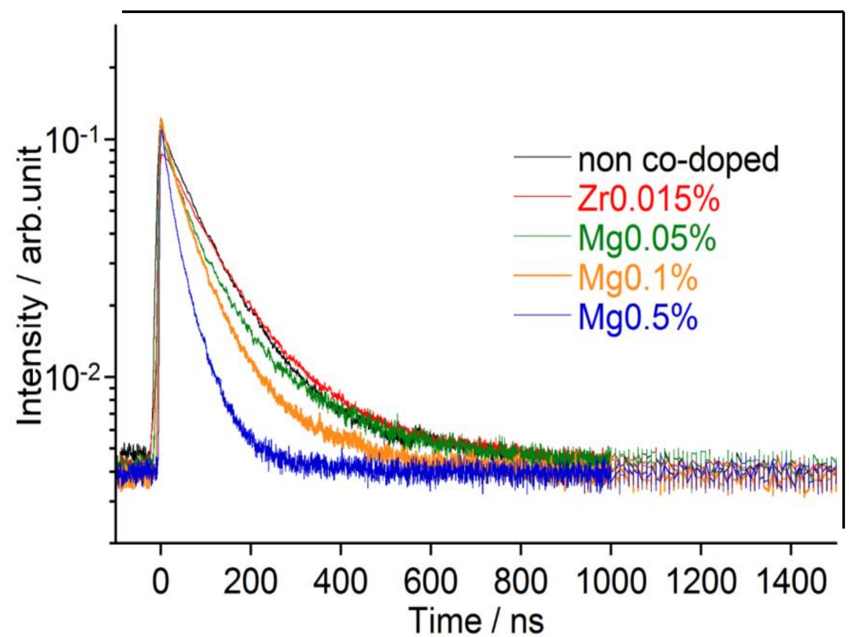


03 Ce:GAGG Crystal Fibers for LHCb upgrade Ⅱ

❖ **Ce:GAGG samples codoped with different metal ions (Ca, Sr, Ba, Mg, Na, K, Ag, Cu, Zn, Bi, B, Nb, Ti, Hf, et al…) had been fabricated and characterized. Magnesium codoping effectively accelerates the decay time.**

Scintillation emission kinematics



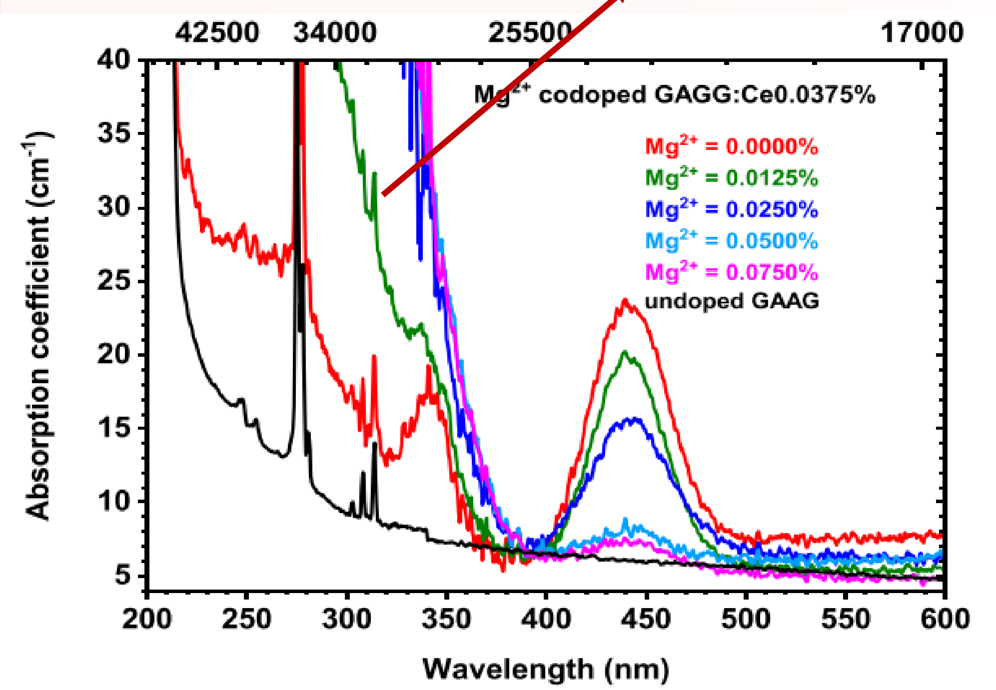


- *Meng, et al. Materials Science and Engineering B 193(2015) 20-26*
- *Kamada et al.Journal of Crystal Growth (2016)*
- *M.Yoshino, et al. Journal of Crystal Growth (2018)*

03 Ce:GAGG Crystal Fibers for LHCb upgrade II

❖ **Acceleration mechanism I :** A stable Ce^{4+} ions provides a fast radiative recombination pathway.

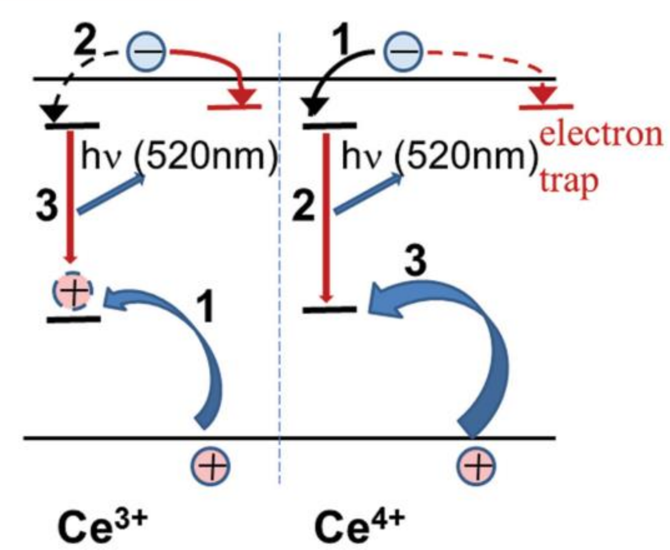
CT absorption of Ce^{4+} ions



$Ce^{4+} + e^- \rightarrow Ce^{3+*}$

$Ce^{3+*} \rightarrow Ce^{3+} + h\nu$

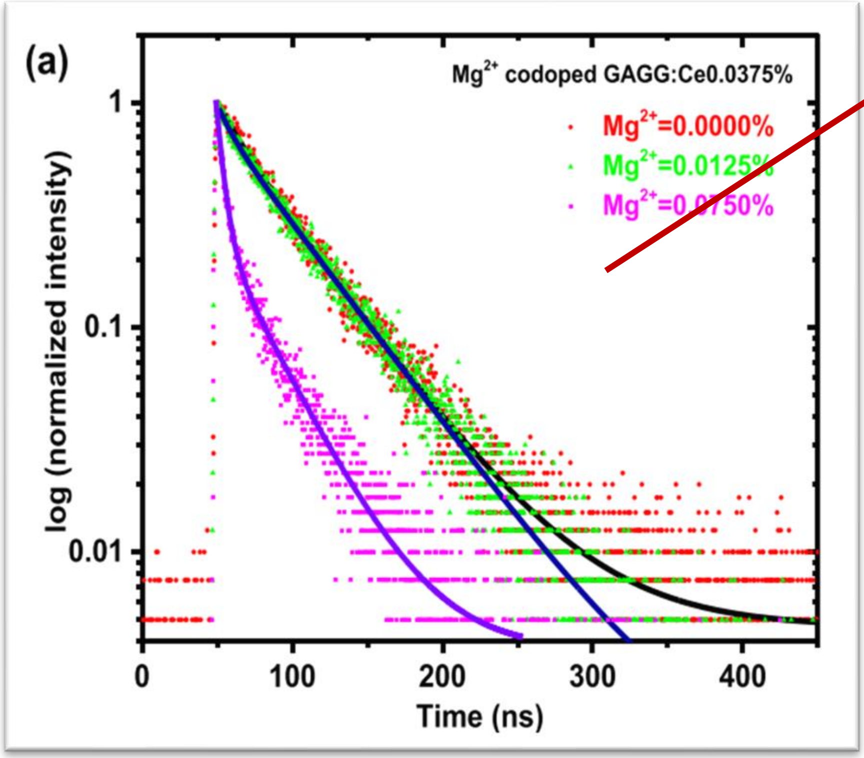
$Ce^{3+} + h^+ \rightarrow Ce^{4+}$



**Martin Nikl, et al. Defect Engineering in Ce-Doped Aluminum Garnet Single Crystal Scintillators. Cryst. Growth Des. 2014, 14, 4827-4833*

03 Ce:GAGG Crystal Fibers for LHCb upgrade Ⅱ

❖ **Acceleration mechanism Ⅱ:** Additional quenching channels for Ce^{3+} luminescence were formed. Hence, the photoluminescence and scintillation responses were significantly accelerated, but the overall light yield performance was diminished.



Decay kinetics curves of Mg^{2+} codoped measured for the Ce^{3+} emission (λ_{ex}= 450 nm, λ_{em}= 550 nm)

- **The luminescence quenching** might occur by two simultaneous mechanisms:
  i) charge transfer between Ce^{3+}/Ce^{4+} ions and $O_O^{\bullet}$ and $V_O^{\bullet\bullet}$ defect centers,
  ii) nonradiative $5d_1 \rightarrow 4f$ transitions in $5d_1$ excited state of $(Ce_{Gd}-Mg_{Ga/Al}O_O)^x$ defect clusters.

$$1/\tau_{eff} = 1/\tau_{radiative} + 1/\tau_{nonradiative}$$

**Karol Bartosiewicz, et al. A study of Mg^{2+} ions effect on atoms segregation, defects formation, luminescence and scintillation properties in Ce^{3+} doped $Gd_3Al_2Ga_3O_{12}$ single crystals. Journal of Alloys and Compounds 905 (2022) 164154*

03 Ce:GAGG Crystal Fibers for LHCb upgrade Ⅱ

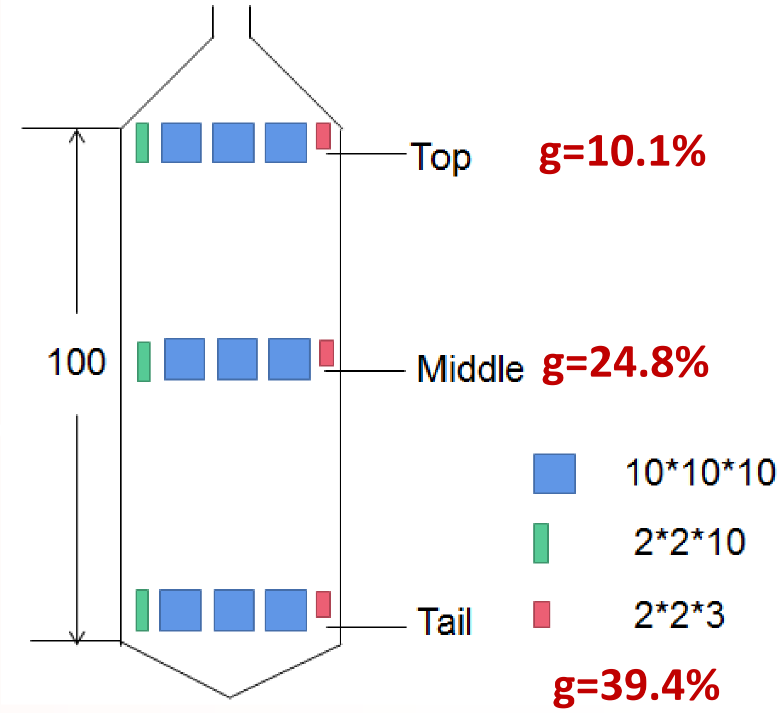
❖ Recent works on fast GAGG crystal fibers Ⅰ: Decay time improving

NO.	C_{Ce}	C_{Mg}	size (mm)	g	τ_{eff}* (ns)	Light Yield* (ph./MeV)
#0	C_c	C_m	5*5*5	45%	47.30	28500
#1	$1.5C_c$	$2C_m$	5*5*5	41%	45.75	25900
#2	$1.5C_c$	$5C_m$	5*5*5	40%	33.12	16200
#3	$1.5C_c$	$4C_m$	5*5*5	40%	35.85	21700
#4	$1.5C_c$	$10C_m$	5*5*5	40%	26.82	9800
#5	$0.5C_c$	$5C_m$	5*5*5	40%	43.18	27600
#6	C_c	$10C_m$	5*5*5	28%	33.43	17400
#7	$1.5C_c$	$8C_m$	5*5*5	21%	33.21	16600
#8	$1.5C_c$	$9C_m$	5*5*5	40%	26.01	10600
#9	$0.5C_c$	C_m	5*5*5	40%	56.52	40800
#10	$1.5C_c$	$6C_m$	5*5*5	40%	28.12	13600
#11	$2C_c$	$10C_m$	5*5*5	13%	32.79	15300
#12	$2C_c$	$5C_m$	5*5*5	40%	27.90	3800
#13	$1.5C_c$	$15C_m$	5*5*5	40%	22.4	8500
#14	$0.5C_c$	$10C_m$	5*5*5	40%	35.43	23375
#15	C_c	$5C_m$	5*5*5	40%	37.48	22950

By increasing Mg and Ce doping levels the decay time decreases from ~50 ns to **~25 ns** and Light yield is about **~10,000 ph./MeV**, measured in SIPAT.

03 Ce:GAGG Crystal Fibers for LHCb upgrade Ⅱ

❖ **Recent works on fast GAGG crystal fibers Ⅰ: Decay time improving**



GAGG ingot with size of Dia.50 mm × 100 mm, and samples from different parts for further measurement.

03 Ce:GAGG Crystal Fibers for LHCb upgrade Ⅱ

❖ **Recent works on fast GAGG crystal fibers Ⅰ: Decay time improving**

GAGG 4# SIPAT	$\tau_{d,eff}$ (ns)	Light yield (ph/MeV)	CTR (ps)
Top1 4549	26	14972.51±449.18	112±3
Top2 4550	23	15738.32±472.15	114±3
Top3 4551	23	15641.19±469.24	122±3
Mid1 4552	21	12773.65±383.21	121±3
Mid2 4553	20	13262.84±397.89	121±3
Mid3 4554	18	12497.04±374.91	119±3
Taill 4555	21	13005.81±390.17	121±3
Tail2 4556	20	12799.88±384.00	124±3
Tail3 4557	16	10259.94±307.80	126±3

- Decay time decreases from the top to the bottom, but middle and bottom have similar decay time. Good homogeneity observed.

* Measured in CERN by Zhenwei Yang's group.

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03 Ce:GAGG Crystal Fibers for LHCb upgrade Ⅱ

❖ Recent works on fast GAGG crystal fibers Ⅱ: Crystal growth

Low doping level

$\Phi 80\times100$ mm^3

$\Phi 60\times200$ mm^3

High doping level

$\Phi 60\times130$ mm^3

$\Phi 60\times105$ mm^3

- High Mg concentration makes significant composition shift away from the Stoichiometric of GAGG, especially at the tail part of the ingot
- High Mg concentration also reduces the thermal conductivity of GAGG

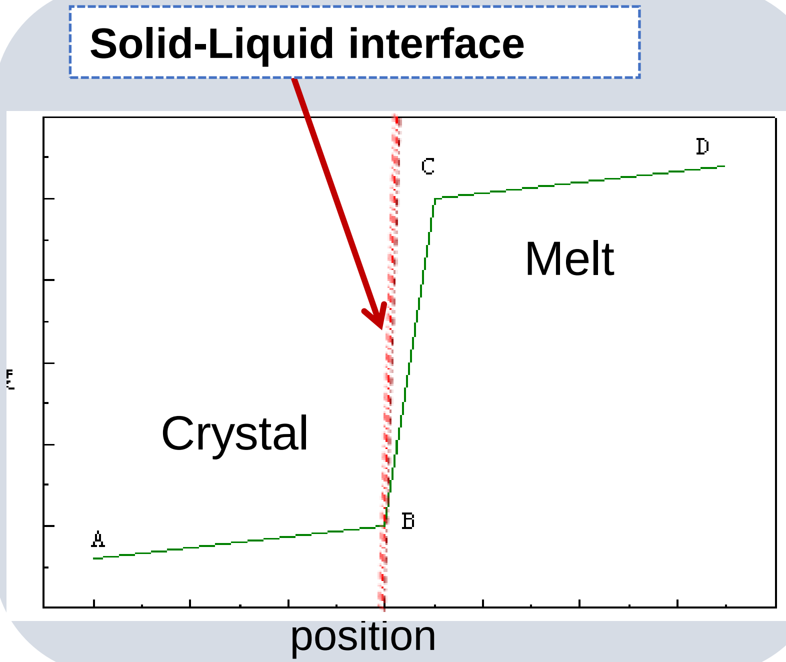
03 Ce:GAGG Crystal Fibers for LHCb upgrade Ⅱ

❖ Recent works on fast GAGG crystal fibers Ⅱ: Crystal growth

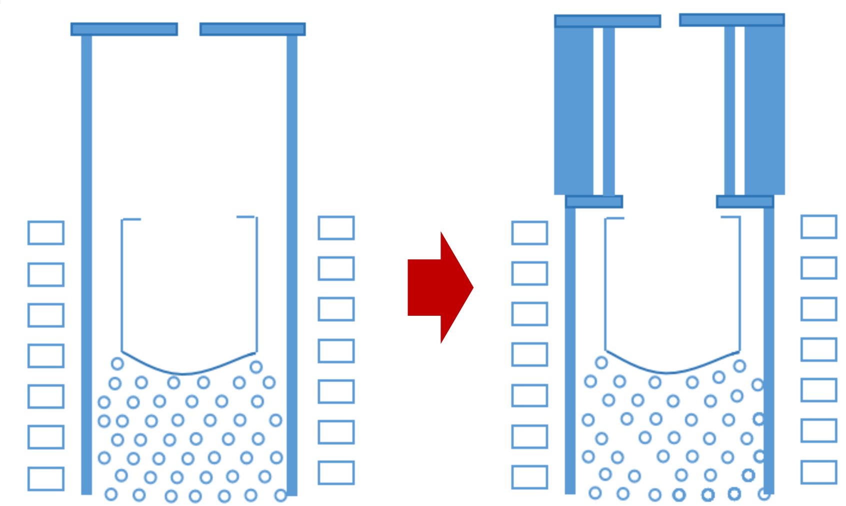
Our solutions:

- ✓ To get sharp temperature gradient
- ✓ Reducing pulling speed
- ✓ Excessive Ga_2O_3 in raw materials

$$\frac{G}{v} < \frac{mC_L(k_0 - 1)}{D[k_0 + (1 - k_0)exp(-\frac{v}{D}\delta)]}$$

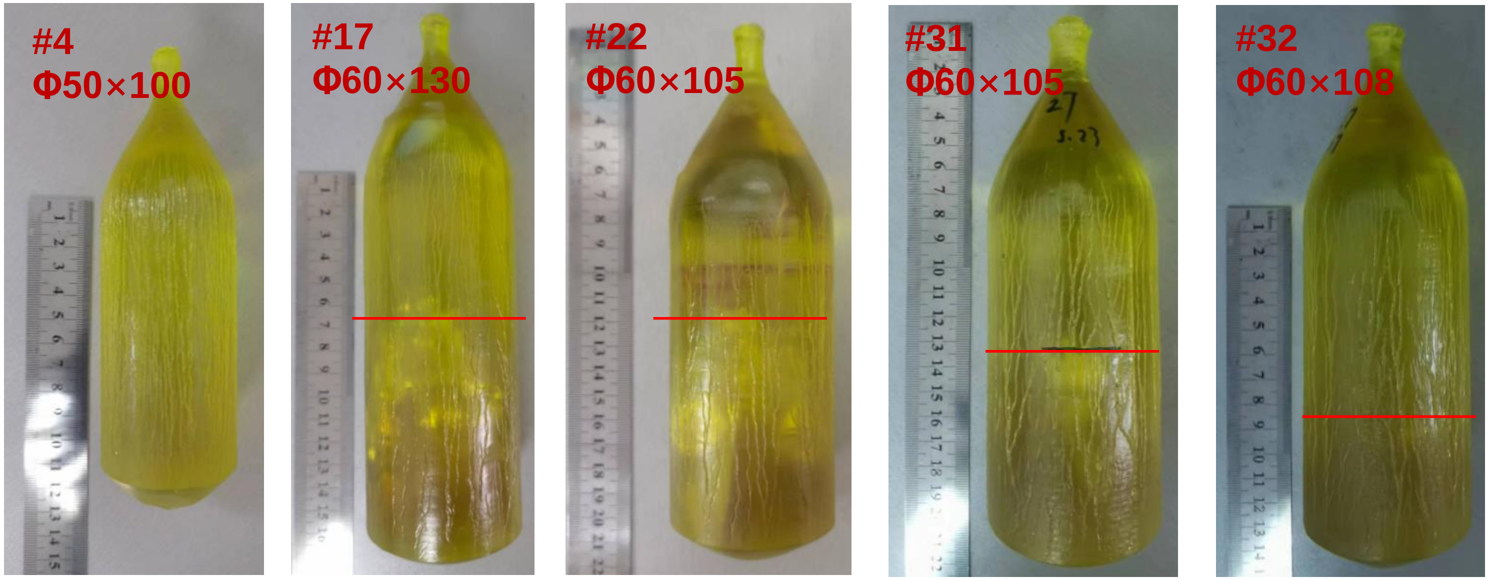


□ Temperature field is improved by reconstructing the thermal shields.



03 Ce:GAGG Crystal Fibers for LHCb upgrade Ⅱ

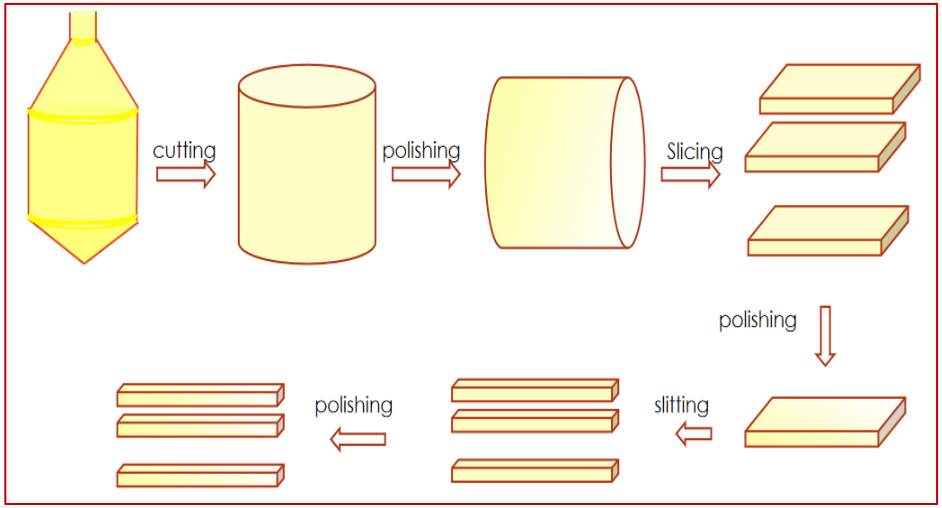
❖ **Recent works on fast GAGG crystal fibers Ⅱ: Crystal growth**



- The crystal quality is gradually improved by optimizing thermal field and growth parameters.
- Many clouds and bubbles mainly gathered in the tail part of the Ce:GAGG ingot.

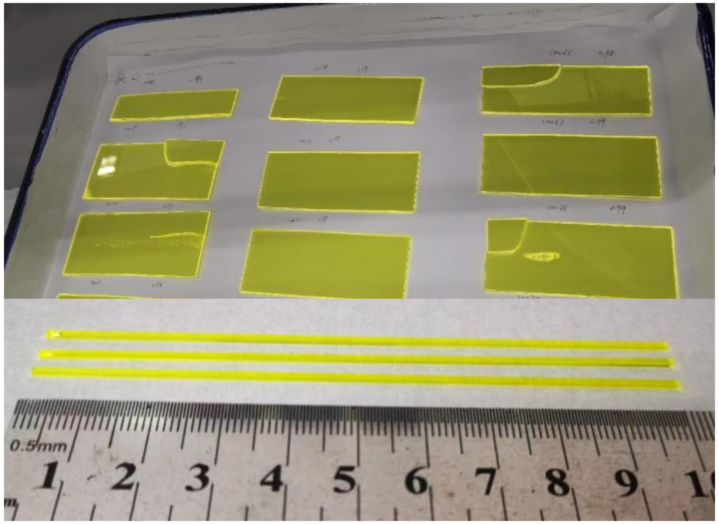
03 Ce:GAGG Crystal Fibers for LHCb upgrade Ⅱ

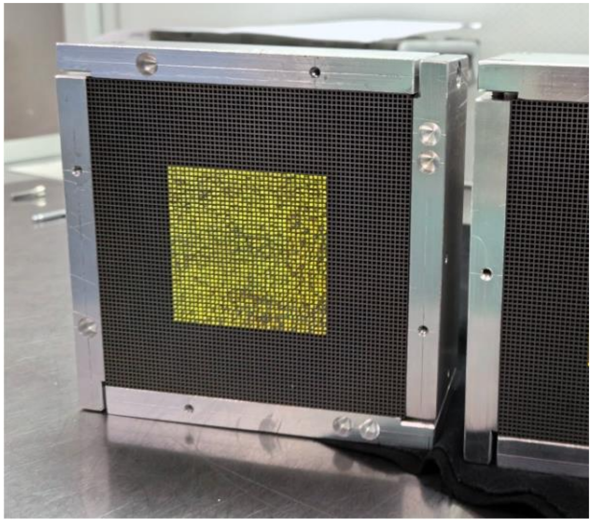
❖ Recent works on fast GAGG crystal fibers Ⅲ: Processing



- Thermal stress causes cracking at the stage of cutting.
- Ce:GAGG fiber is too fragile to make much edge collapsing.

	Yield	TTV	Chipping	Ra
Plan A	46%	≤8μm	more	~5nm
*Plan B	69%	≤3μm	less	~5nm





*Plan B has different processing parameters compared with that of Plan A.

In August 2024 the new prototype has been tested by the LHCb team.

04 Summary

- In the past 30 years LYSO crystal has been greatly improved. Its fast decay time (31ns ~40ns), high light yield, good radiation hardness, and affordable price make it well meeting the requirements of CMS MTD. In 2026, the CMS MTD will resume operations.

- GAGG crystal appears to be the most promising choice for SPACAL of LHCb upgrade Ⅱ. Currently its decay time has been shorten to ~20 ns by codoping with Mg ions, and at the same time its light yield decreased to ~12,000 ph./MeV. The new prototype of SPACAL has been measured in August 2024.

- In the future we will continue to optimize the decay time of Ce:GAGG, aiming at ~ 10 ns, and find a trade-off between decay time and light yield.

- Heavily doping level of Mg in Ce:GAGG crystal greatly changed its thermodynamic properties, consequently causing cracking and bubbles during crystal growth in the crystal. It is very important to find a trade-off between scintillation performance and crystal growth.

Acknowledgments

- Yuanning Gao, Zhenwei Yang and team members from Peking University, China
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