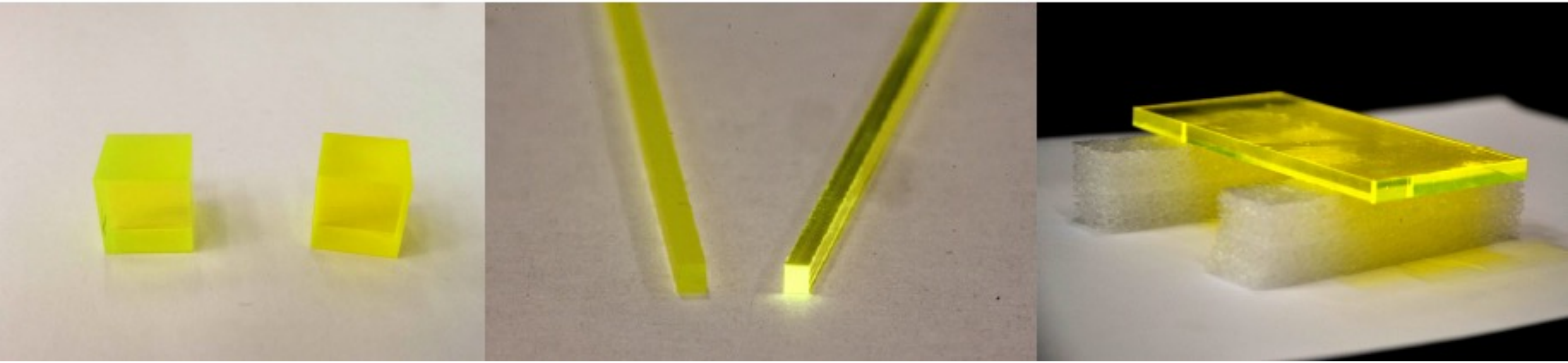
R&D on garnet crystal fibres

E. Auffray, CERN EP-CMX



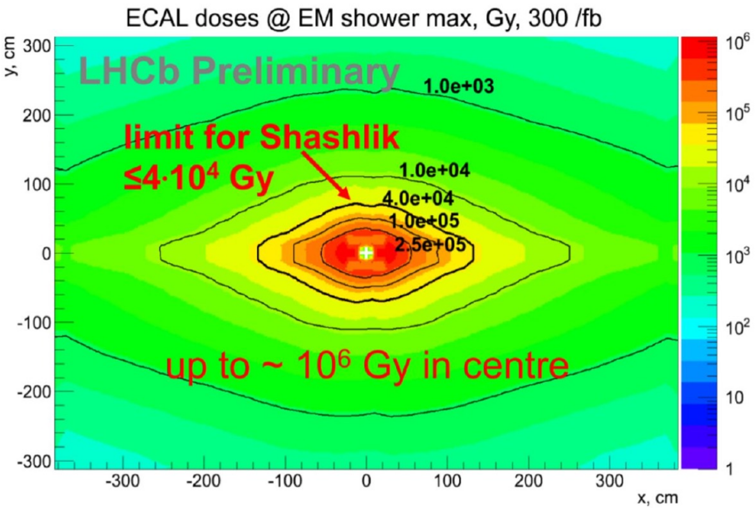
EP R&D

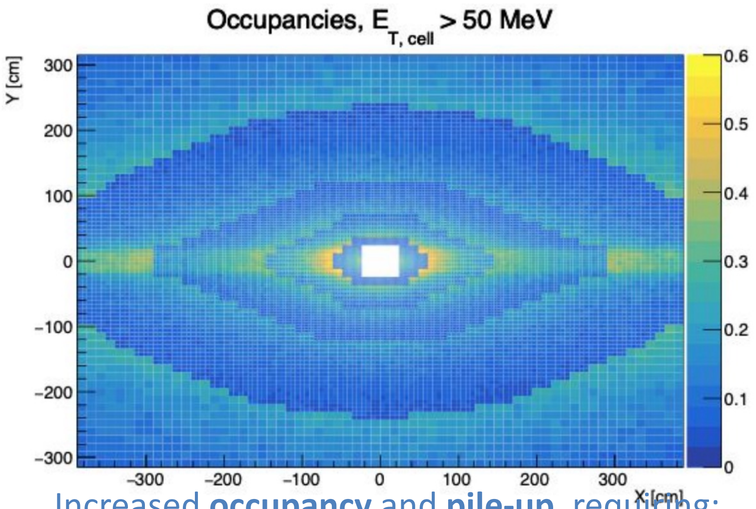
CRYSTAL CLEAR

LHCb

Requirements for ECAL Upgrade II

Keep the current energy resolution of $\sigma(E)/E \approx 10\%/\sqrt{E} \oplus 1\%$ with the new operating conditions:





Radiation doses:

up to 1 MGy and 6×10^{15} 1 MeV neq/cm^2 in the center for 300 fb^{-1}:

=> **New technologies more radiation hard than shashlik required in the centre**

Increased **occupancy** and **pile-up**, requiring:

- **Timing O(10ps)**
- Increased granularity
- Longitudinal segmentation

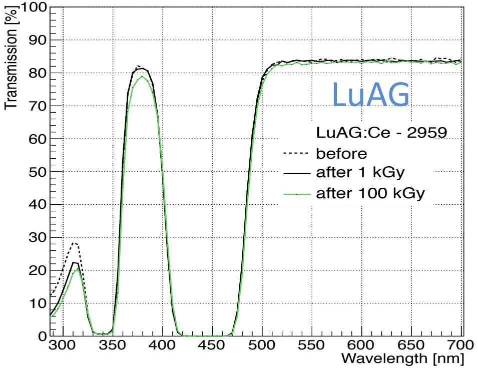
Need very fast and radiation tolerant scintillators

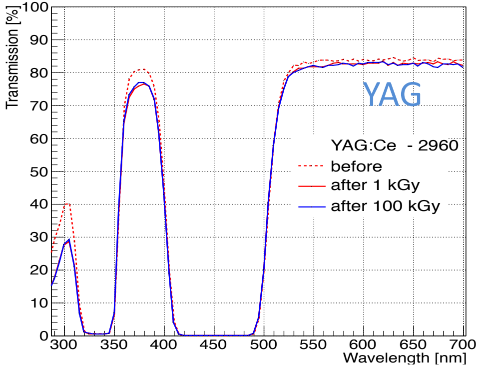
=> Fast radiationn hard crystal (fibres of 1x1x50mm3, 1x1x100mm3)

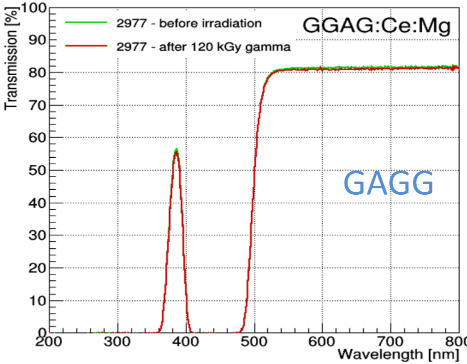
Why garnet materials?

Very good radiation tolerance under gamma & proton radiations

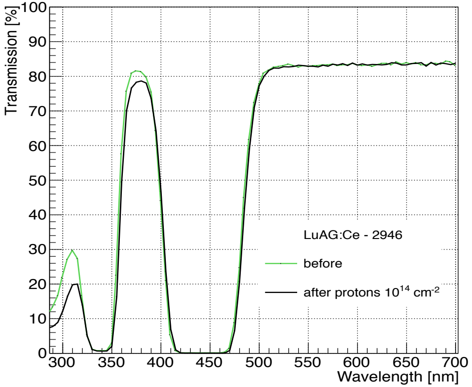
Gamma

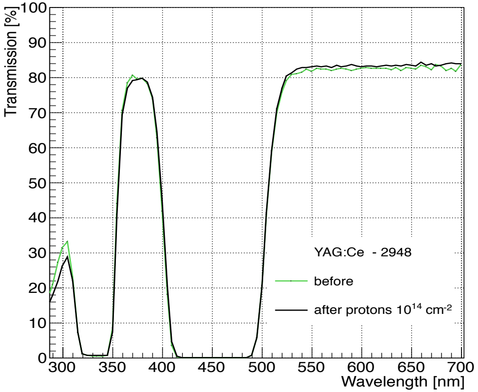


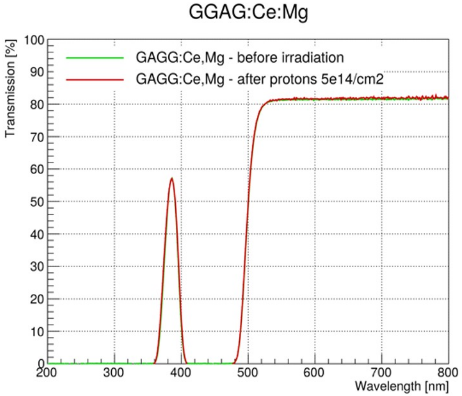




Protons





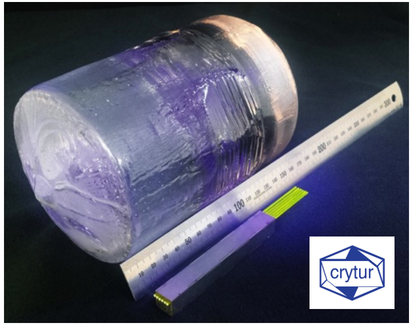


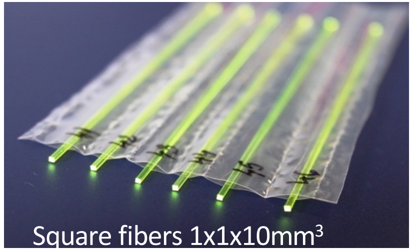
M. T. Lucchini, et al.,, IEEE Transactions on Nuclear Science (2016), 63, 2/
E. Auffray, et al, Rad. Phys.Chem. (2019), 164, 108365/V. Alenkov, et a., NIM A (2019), 916, 418 226{229

Why garnet materials?

Various growth methods exists to produce fibres

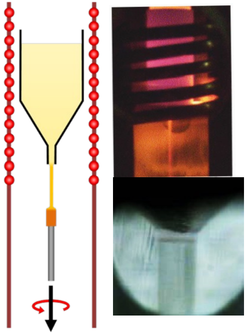
Czochralski method
Cut from large ingot

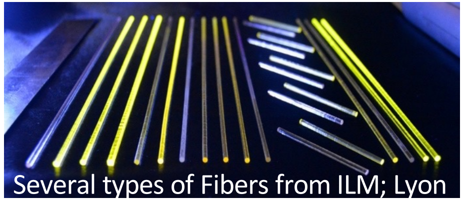




Square fibers 1x1x10mm^3

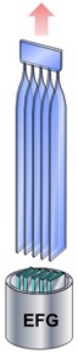
Micropulling down technique

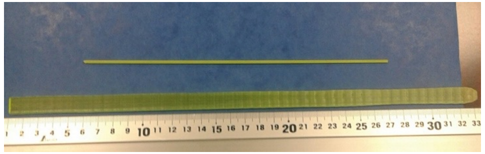




Several types of Fibers from ILM; Lyon

EFG





EFG-grown plate & fiber of LuAG:Ce from Adamant Namiki Co , Japan

⇒ Feasibility study was the main goal of Intelum project (European Rise project grant 644260) with 16 Partners (many from CCC) from 12 different countries: 11 academia and 5 companies

Why Garnet material?

Properties of Garnet Ce doped crystal

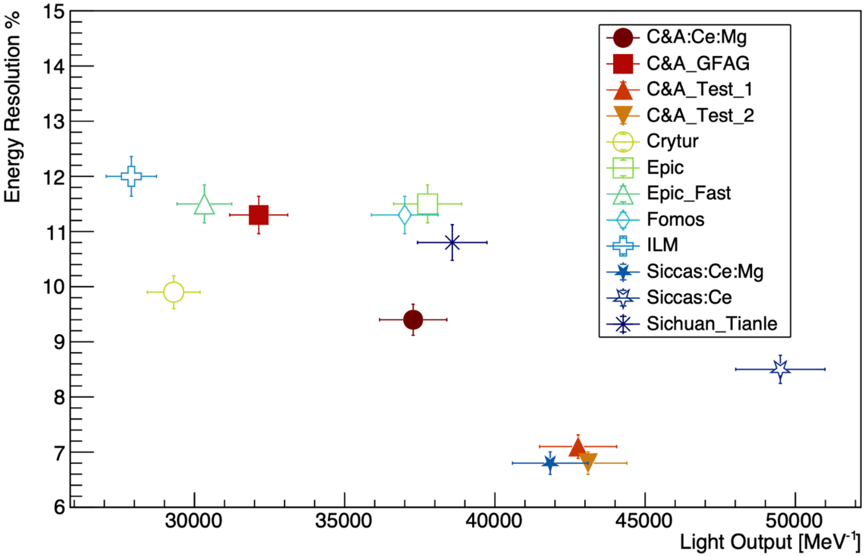
	$Y_3Al_5O_{12}$:Ce (YAG)*	$Lu_3Al_5O_{12}$: Ce (LuAG)*	$Gd_3Al_2Ga_3O_{12}$: Ce (GAGG)*	Lu_2SiO_5:Ce (LSO)
density (g/cm^3)	4.57	6.73	6.63	**7.4**
X_0 (cm)	3.5 cm	1.3	1.59	1.1
Refraction index	1.82	1.84	1.9	1.82
Λ_{max} (nm)	**550**	**535**	**520**	**420**
LY @ RT (ph/MeV)	**30000**	**25000**	**50000****	**30000**
decay time (ns)	**70 + slow component	**70 + slow component	**60 + slow component	**40**

*https://www.crytur.cz/materials/gagg/
** varying from Composition see next slides

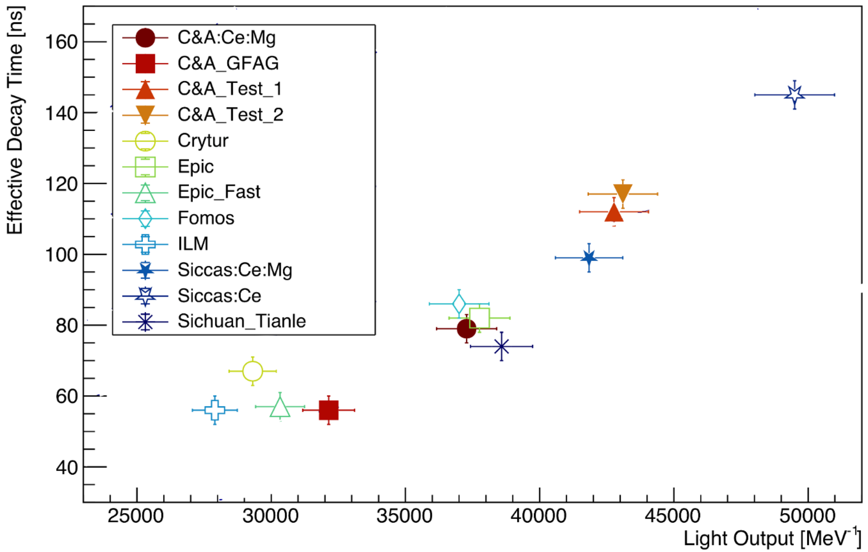
Focus on GAGG

GAGG: Tunable properties with composition

Energy resolution versus Light output



Effective decay time versus Light output



Light output varies almost a factor 2x from 27 900 to 49 500 photons/MeV

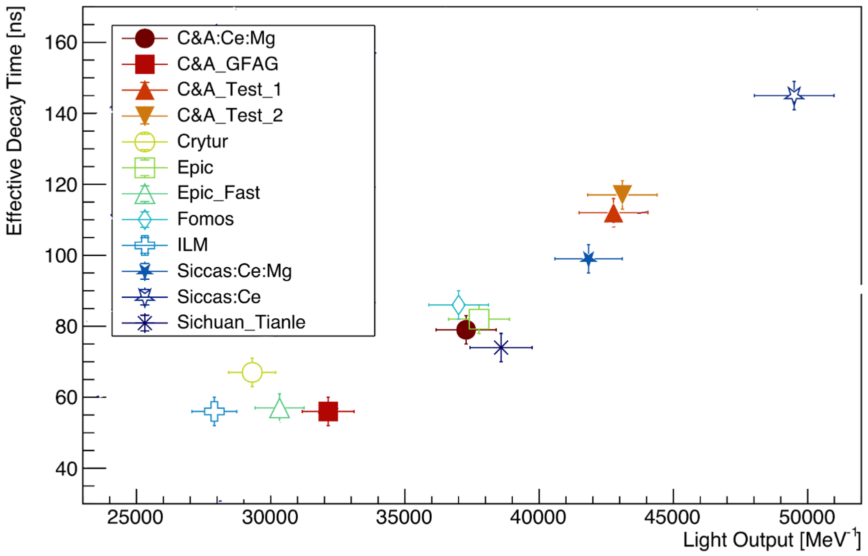
→

Correlation between light output and decay time
High light yield → slow decay time

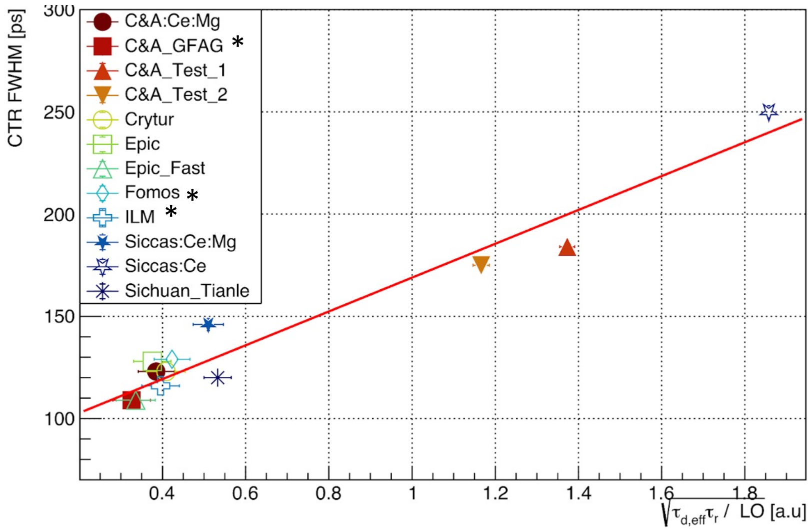
L. Martinazzoli et al., NIM A, 2021, 165231

GAGG: Tunable properties with composition

Effective decay time versus Light output



Coincidence time resolution (CTR) versus photon density



Photon time density:

$$\frac{LO}{t_{d\,eff}}$$

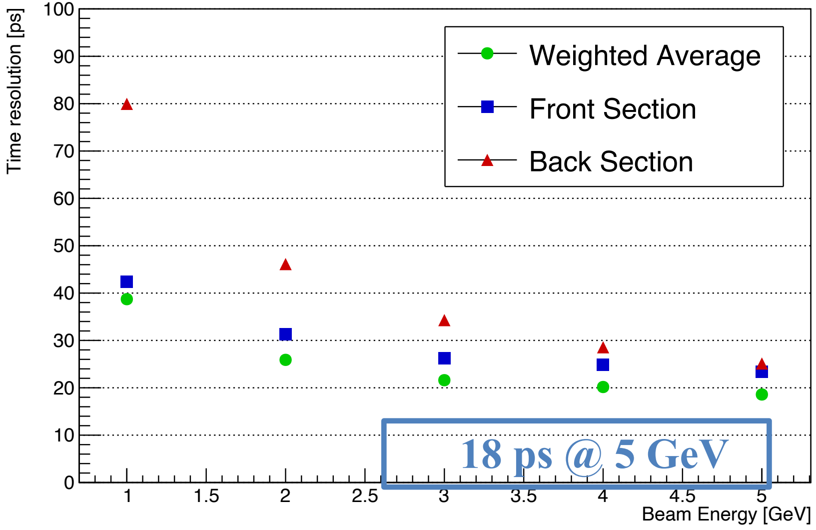
CTR inversely proportional to the photon time-density:

* Material tested in SPACAL

L. Martinazzoli et al., NIM A, 2021, 165231

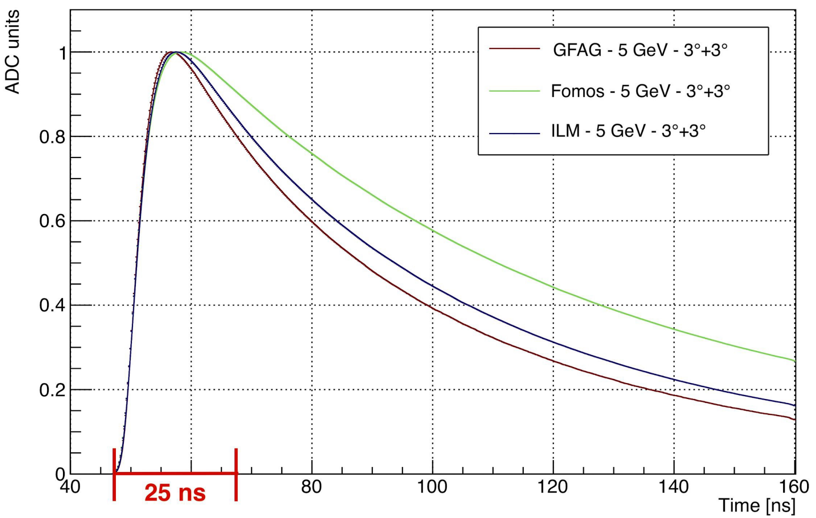
Performance in SPACAL

Time resolution GFAG cell @ incident angle of 3o + 3o
(DESY 2020 , R7600-20)



Excellent timing performance in TB

Pulse shape comaparison



But what will be the impact of pulse shape at HL-LHC ?

L. Ann, NIMA, 1045 (2022) 167629 arXiv:2205.02500

L. Ann, submitted to NIMA, arXiv:2205.02500

Performance in SPACAL

Time resolution GFAG cell @ incident angle of 3o + 3o
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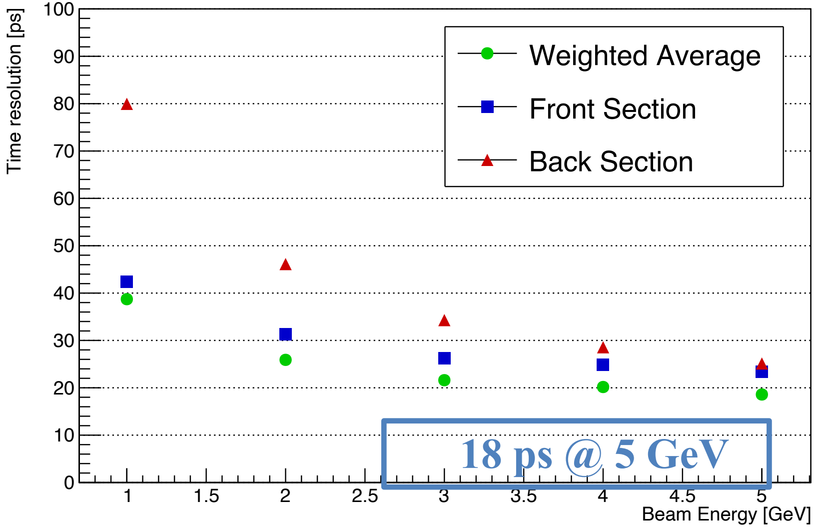
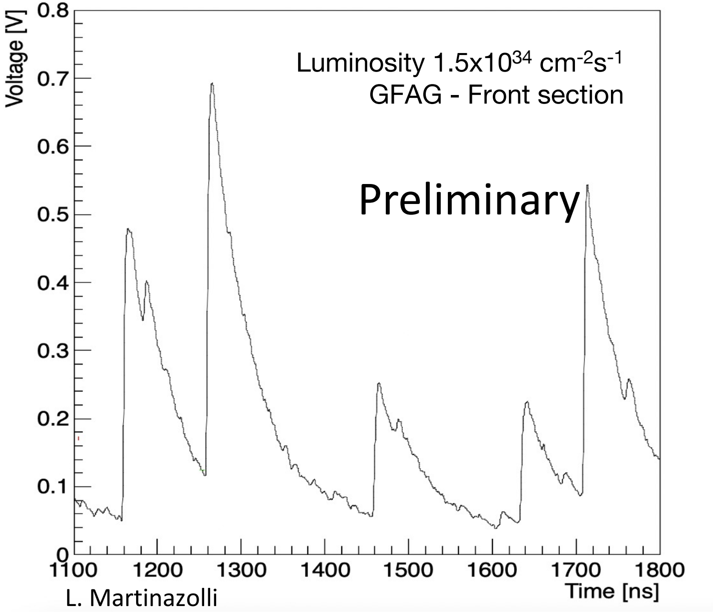


Excellent timing performance in TB
But what will be the impact of pulse shape at HL-LHC ?

SPACAL Signal Simulated



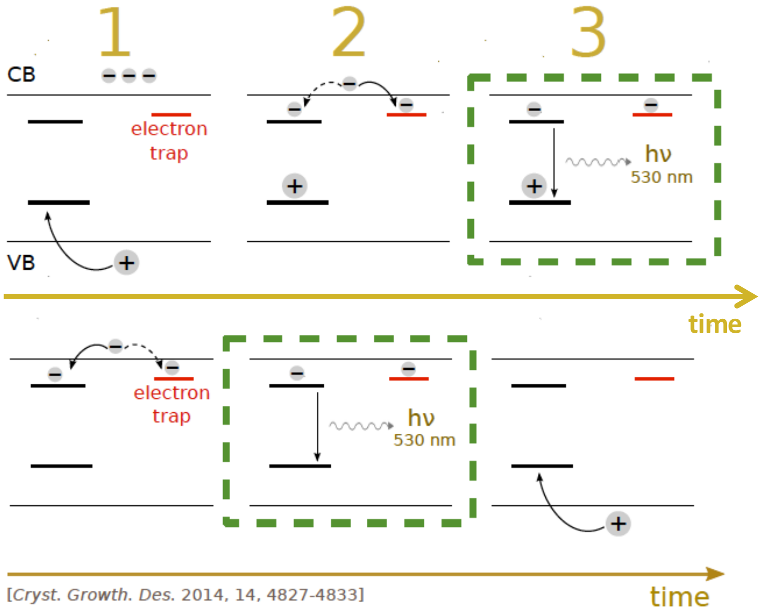
Spillover
=> Need to suppress slow component and shorten the main decay component

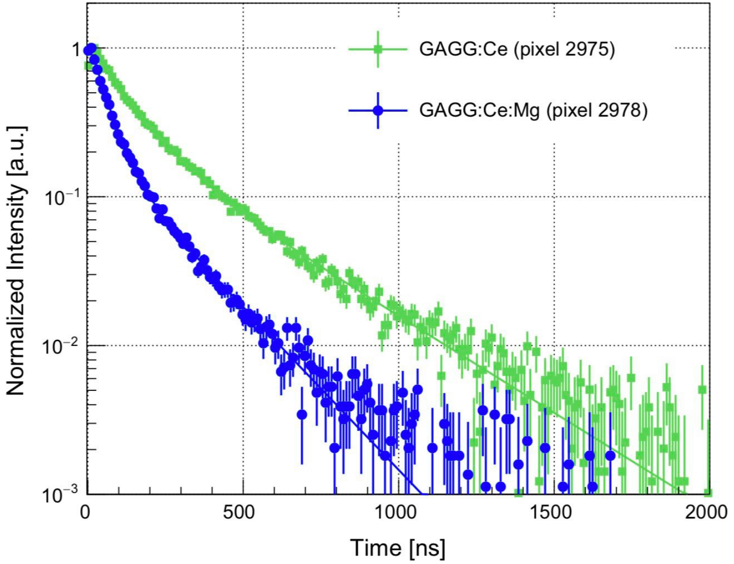
L. Ann, NIMA, 1045 (2022) 167629 arXiv:2205.02500

Role of Ce^{4+} in timing properties

Ce^{3+}

Ce^{4+}





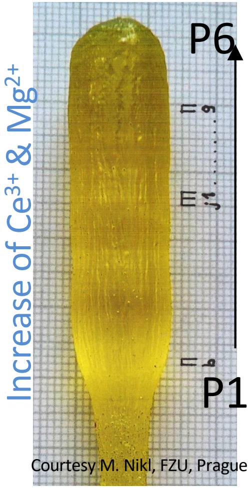
Ce^{4+} center can directly compete with any electron trap for electron capture in the first instants of scintillator mechanism
=> Expected faster decay time and lower slow component

Faster decay time with codoping Ce^{3+}/Mg^{2+}

M. T. Lucchini et al., NIM A, 816 (2016) 176

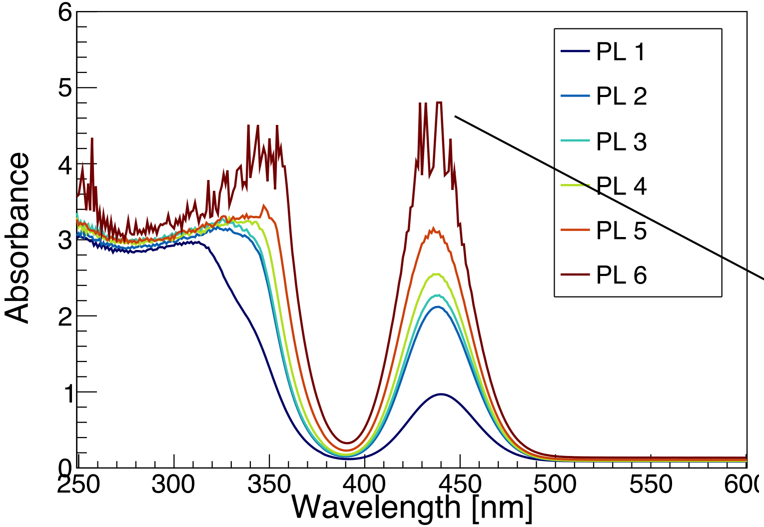
Further acceleration of the emission

Heavy codoping Ce^{3+}/Mg^{2+}

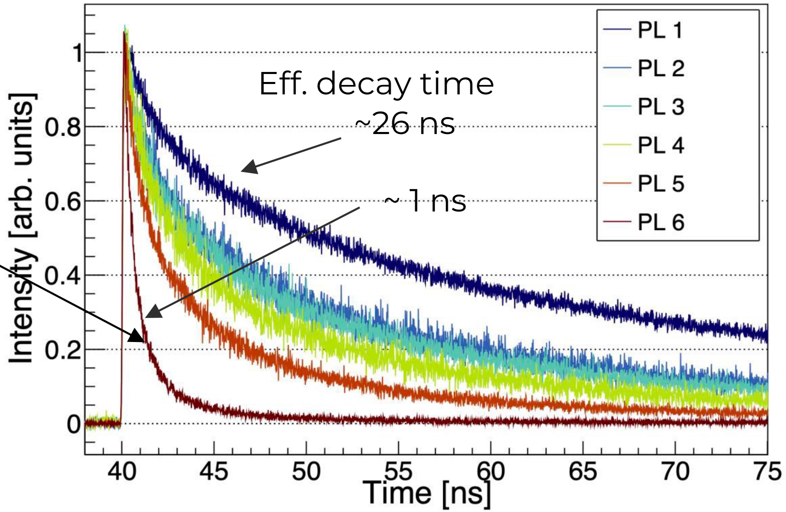


Courtesy M. Nikl, FZU, Prague

Absorbance spectra



Decay time spectra



increased concentration of Ce,Mg

$\Rightarrow$ **Effective decay time reduced by > 10x**

$\Rightarrow$ **No slow component**

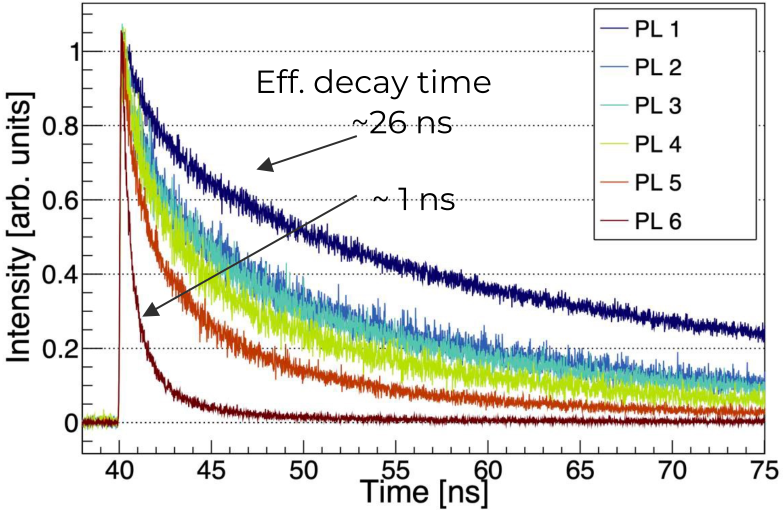
Joint collaboration with CERN, FZU Prague, Uni Vilnius (CCC+ Aidainnova)

L. Martinazzoli et al., Mater. Adv., 2022, 3, 6842

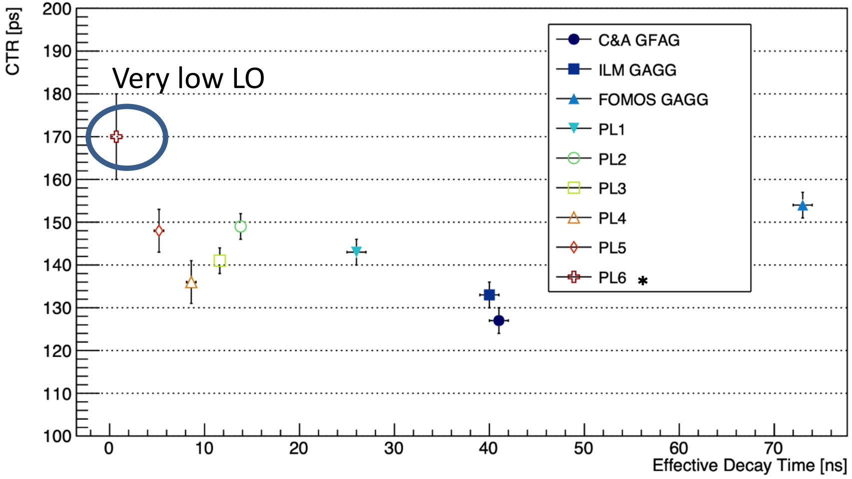
Further acceleration of the emission

Heavy codoping Ce^{3+}/Mg^{2+}

Scintillation decay - Pulsed X-Rays



CTR vs Eff. Decay Time



* Low S/N ratio

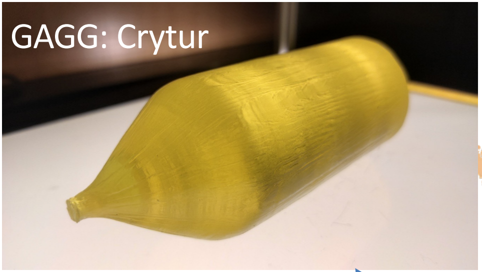
No major loss of time resolution!
Decay time decrease compensated the Light output reduction
=> the same photon time-density

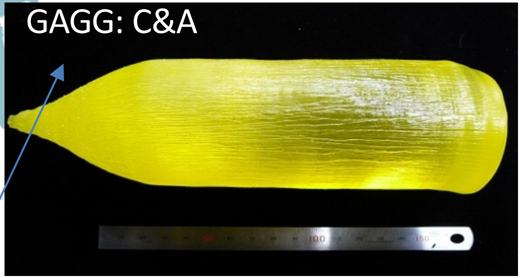
Joint collaboration with CERN, FZU Prague, Uni Vilnius (CCC+ Aidainnova)

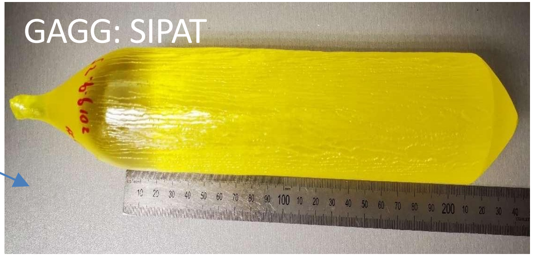
L. Martinazzoli et al., Mater. Adv., 2022, 3, 6842

Current status of GAGG production

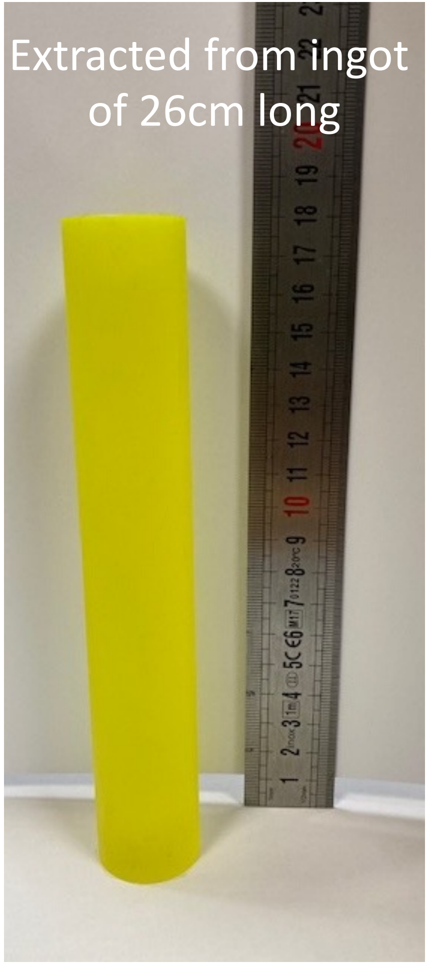
Several producers in the world







GAGG from ILM Lyon France

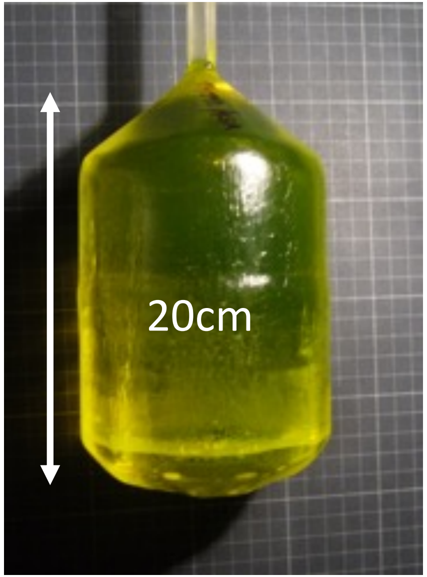


Already produced GAGG fibres for 5 cells SPACAL prototype

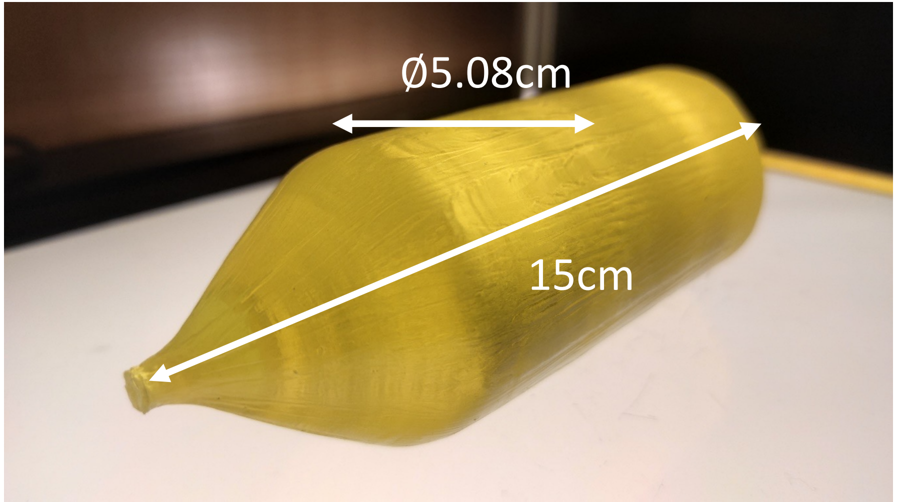
Courtesy K. lebbou, ILM, France

Garnets from Crytur, Turnov, Czech republic

YAG ingots



GAGG ingot

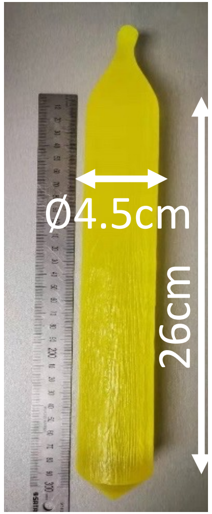


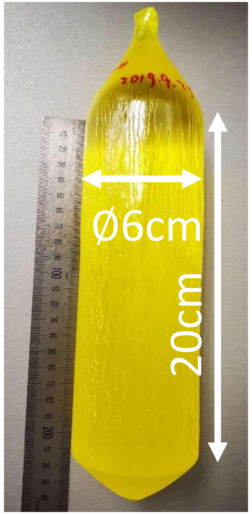
Mass production already exists

Already produced YAG fibres for 6 cells SPACAL prototype

Courtesy S. Sykorova, J. Houzvika, Crytur, Czech Republic

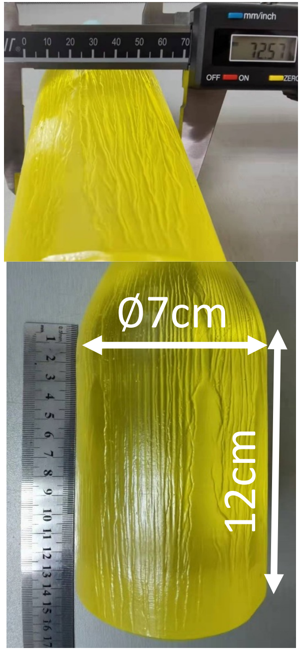
GAGG from SIPAT, China



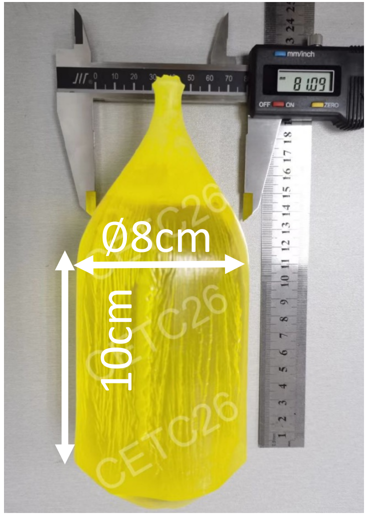


2019

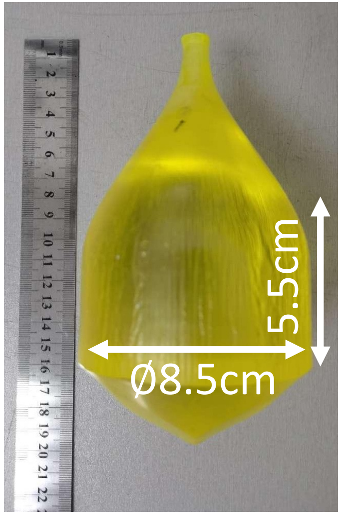
Mass production already exists



2020



2022



2022

Development to increase diameter

Will start to produce fibres for SPACAL prototype

Courtesy Y. Ding, SIPAT, China

NEXT STEPS TOWARD RUN5

R&D on GAGG

- Continue simulation to define the exact requirements in term of
  - Decay time
  - Light output

    => Spill over impact

    ⇒ Input for or from electronic readout
- Pursue the investigation on bulk material to decrease the decay time :
  - R&D on going with FZU Prague on small ingots
  - R&D on going with ILM Lyon on larger ingots
    - TWIN European project between ISMA, Kharkhov, ILM Lyon, CERN
    - Start collaboration between ILM Lyon, SIPAT China
- R&D to prepare mass production with optimised composition
  - Impact of new composition on the crystal growth characteristics
  - Optimisation of crystal ingot dimension (maximise production yield)
  - Fibre production from crystal ingots

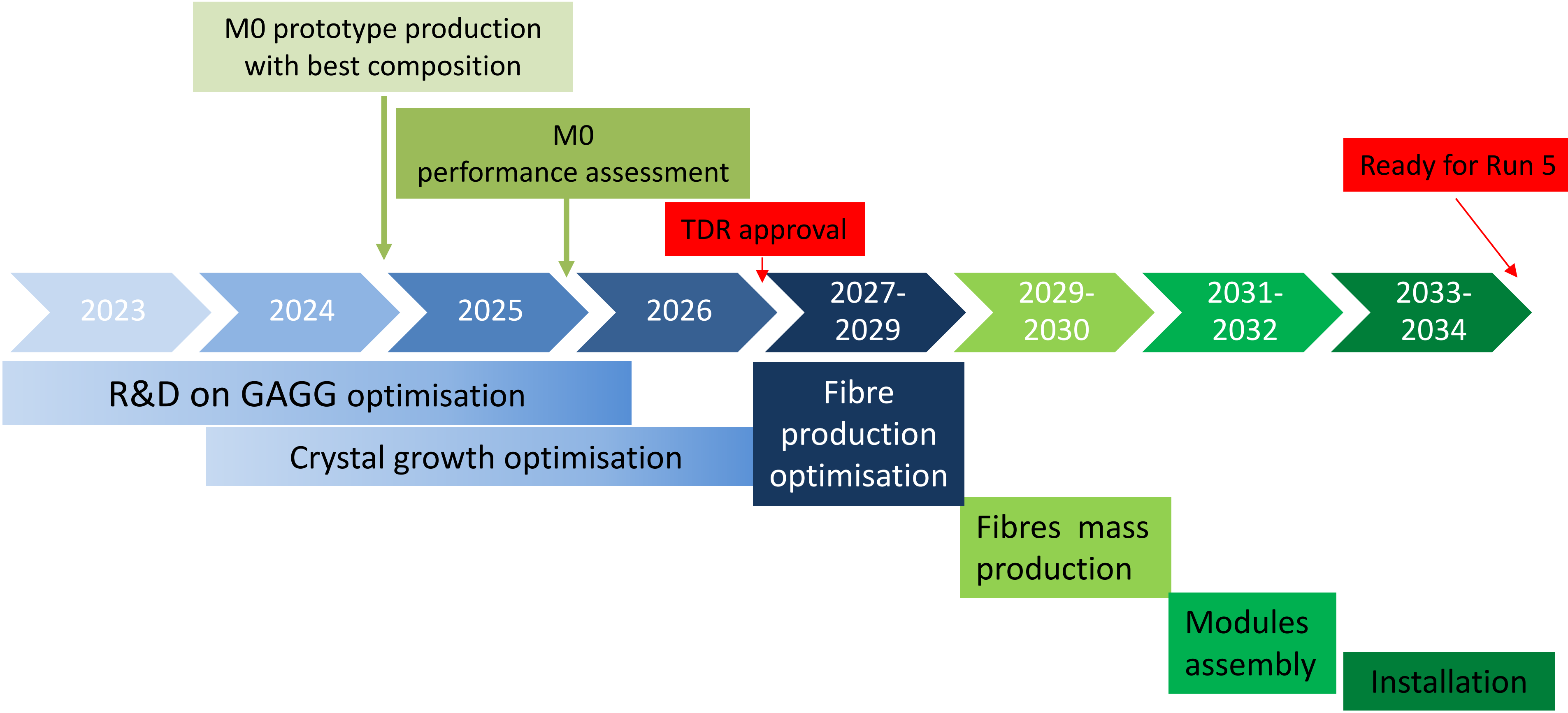
Other R&D lines in "background"

- Alternatives to GAGG:
  - Eg. YAG crystals in Crytur

  ⇒ Impact on detector geometry due to lower density to be analysed

- Alternatives of crystal growth method
  - Micropulling down technique
    - Optimisation crystal fibres quality
    - Multiple crucible

Schedule for R&D



Conclusion

Need to produce for 2031 :

∼166000 crystal fibres of 1x1x50mm3 & 1x1x100mm^3

- The technology to mass produce GAGG exists in various places
- Need to optimise it for LHCb upgrade II operating conditions in 6 years

Garnet crystal fibres, Courtesy K. Lebbou, ILM, Lyon, France