



R&D on GAGG for the LHCb ECAL Upgrade II

Fast, radiation-tolerant garnet fibres for the PicoCal

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on behalf of the LHCb ECAL Upgrade II R&D group

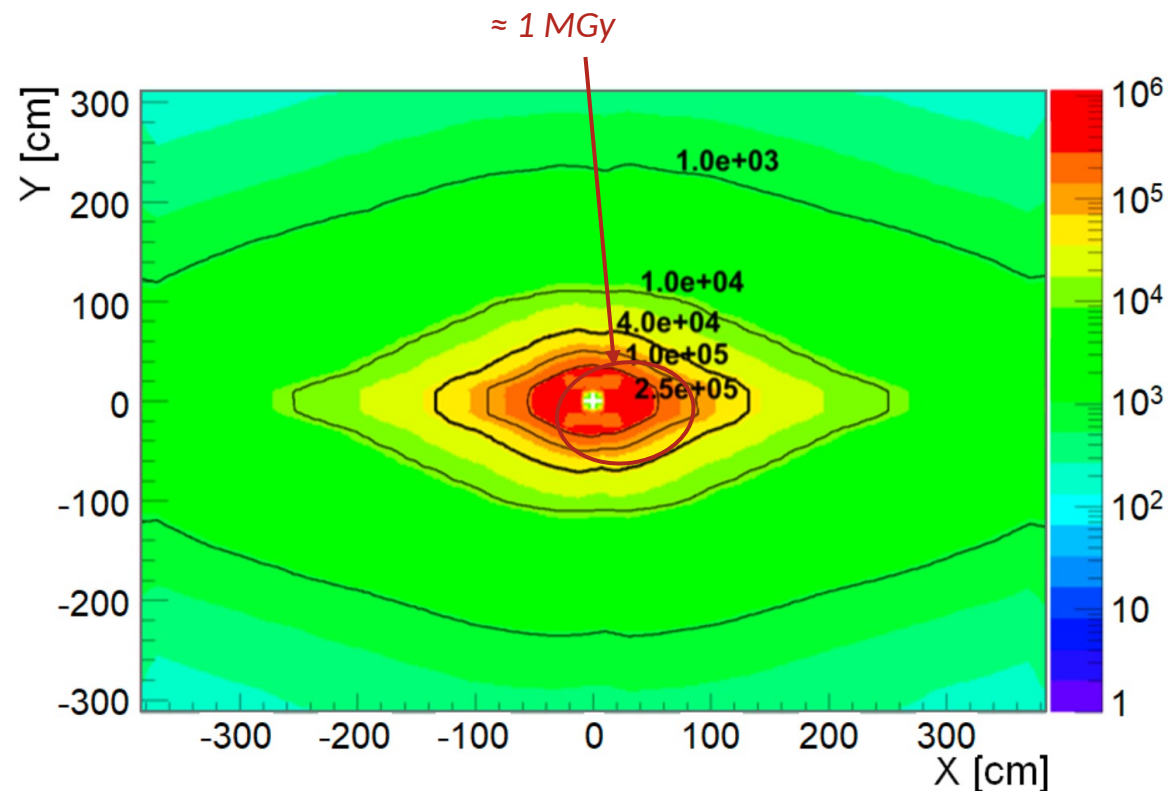
Crystals grown by SIPAT (CETC Chip Technology Group, Chongqing), characterized at PKU, Tsinghua University and CERN

CLHCP2026 · Wuhan · 28 Oct – 1 Nov 2026



A GAGG:Ce ingot grown by SIPAT

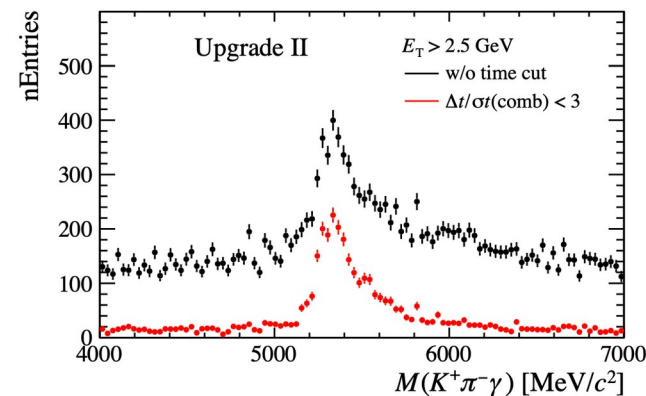
LHCb Upgrade II: why a new inner ECAL



- Run 5 from ~2036: $L = 1\text{--}1.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, $\sim 300 \text{ fb}^{-1}$
- up to ~ 40 pp collisions per crossing, every 25 ns
- $\approx 1 \text{ MGy}$ in the inner ECAL (today's Shashlik: $\sim 40 \text{ kGy}$)

The new ECAL has to

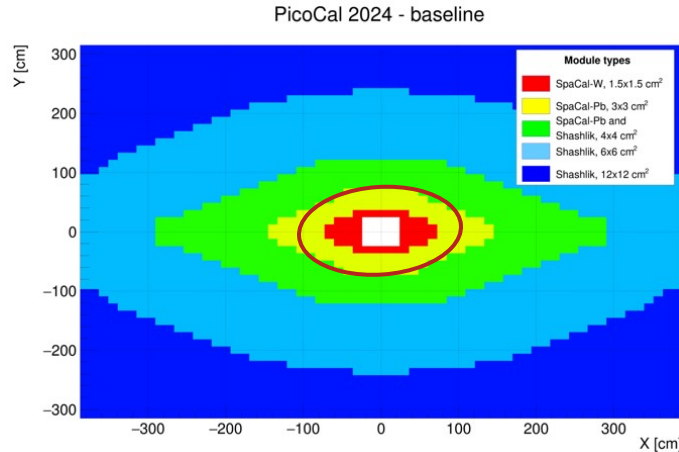
- keep $\sigma_E/E \approx 10\%/\sqrt{E} \oplus 1\%$
- add timing at the level of a few tens of ps



$B^0 \rightarrow K^+ \pi^- \gamma$: a timing cut removes most of the background

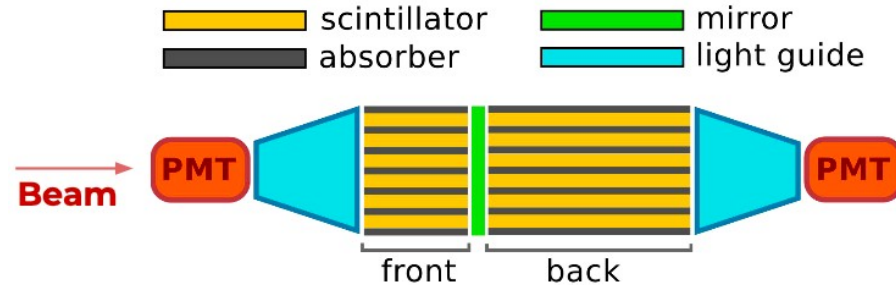
→ the inner modules need a fast, radiation-hard scintillator

PicoCal: the inner modules

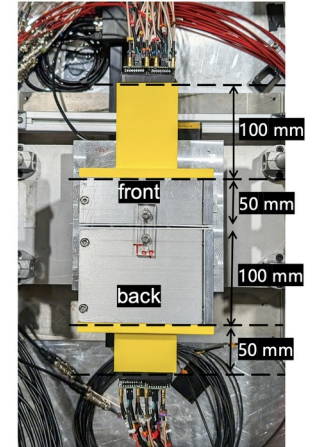


PicoCal baseline (2024); red = SpaCal-W, 1.5×1.5 cm² cells

- SpaCal-W: tungsten absorber, 1×1 mm² GAGG fibres
- two sections, 5 cm + 10 cm, read out at both ends
- ~40 modules × 10⁴ fibres = **~4×10⁵ fibres**



One cell: 5 cm front + 10 cm back, mirror in between, a PMT at each end



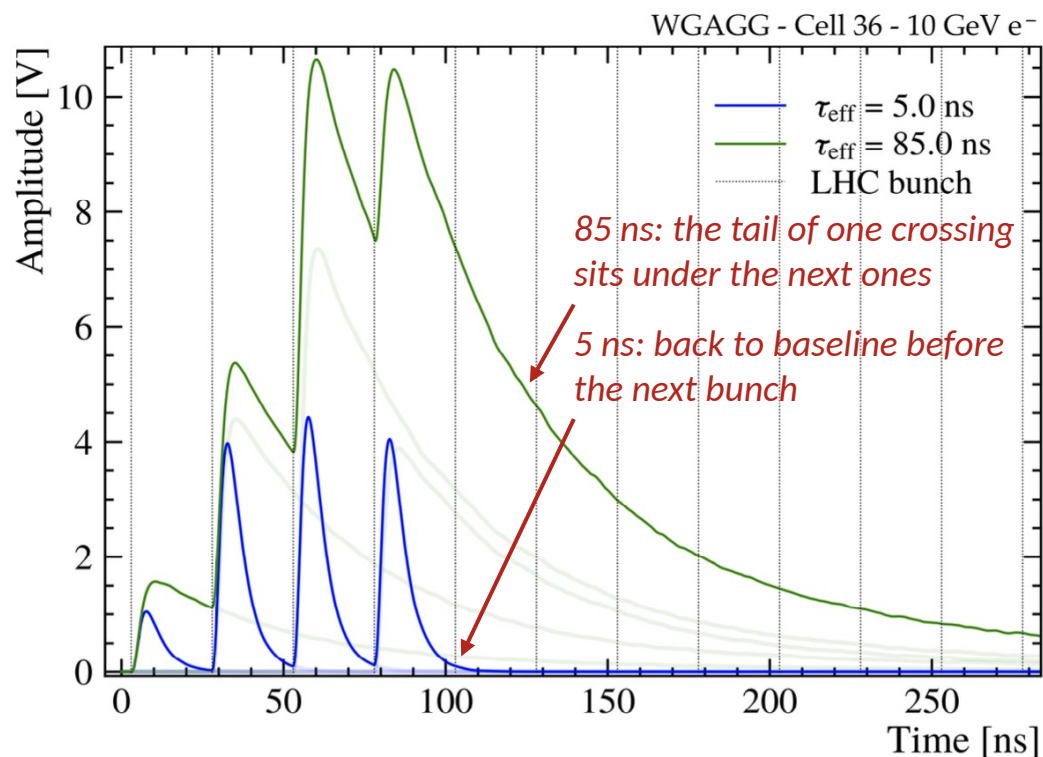
W-GAGG prototype

What one fibre has to deliver

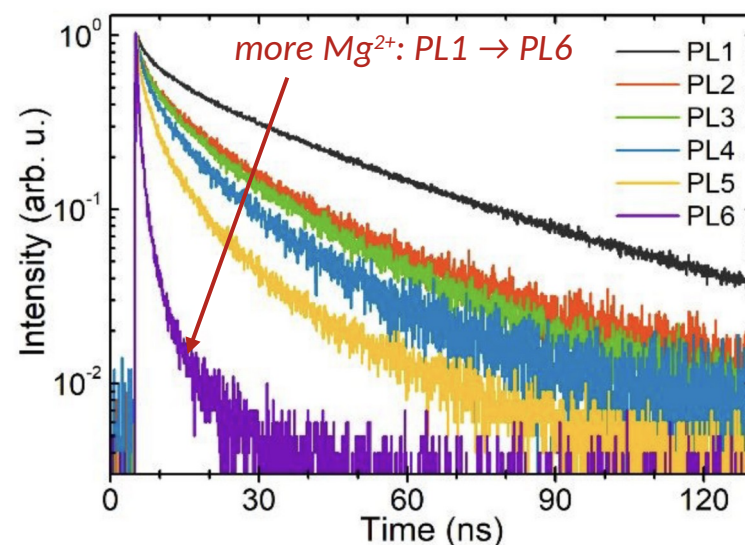
decay time	$\tau_{\text{eff}} < 15 \text{ ns}$, aiming at $\lesssim 10 \text{ ns}$
light output	$\gtrsim 10\,000 \text{ ph/MeV}$
radiation	$\geq 1 \text{ MGy}$
uniformity	$\leq 2 \text{ \%/cm}$ along the fibre
size	50 and 100 mm fibres
	→ need homogeneous ingot production

→ the fibre sets the timing and the radiation tolerance of the module

GAGG:Ce, and how Mg co-doping makes it fast



Simulated pulses in one W-GAGG cell, 10 GeV e^- ; dotted lines: LHC bunches



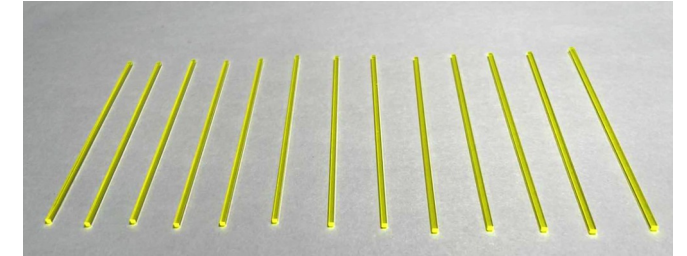
Decay curves for increasing Mg^{2+} co-doping [L. Martinazzoli et al., Mater. Adv. 3 (2022) 6842]

- **GAGG:Ce**: dense, bright ($\sim 35\,000$ ph/MeV), holds 1 MGy of protons
- but $\tau_{\text{eff}} \approx 80$ ns, with a large slow component
- **Mg²⁺** stabilizes $Ce^{4+} \rightarrow$ fast radiative recombination
- $\tau_{\text{eff}} 26 \rightarrow \sim 1$ ns on small samples, at the cost of light

→ since 2021: can it be grown fast, bright, uniform and large, at production scale?

The R&D programme on ultrafast GAGG production at SIPAT since 2021

end 2021	start: SIPAT for the growth, a new scintillator lab at PKU
2022	first ingots grown at SIPAT
Jan 2023	first SIPAT samples measured at PKU
Mar 2024	PKU benches complete, results agree with CERN
Jun 2024	7 ingots → ~3 600 fibres → prototype #1 (~20 ns), SPS and DESY
Jan 2025	tail samples reach $\tau_{\text{eff}} \approx 8$ ns
Jun-Jul 2025	batch 10: τ_{eff} 7–16 ns
Sep 2025	prototype #2 at the SPS, SIPAT fibres ~10 ns front / < 15 ns back
2026	> 80 ingots; paper submitted to IEEE TNS

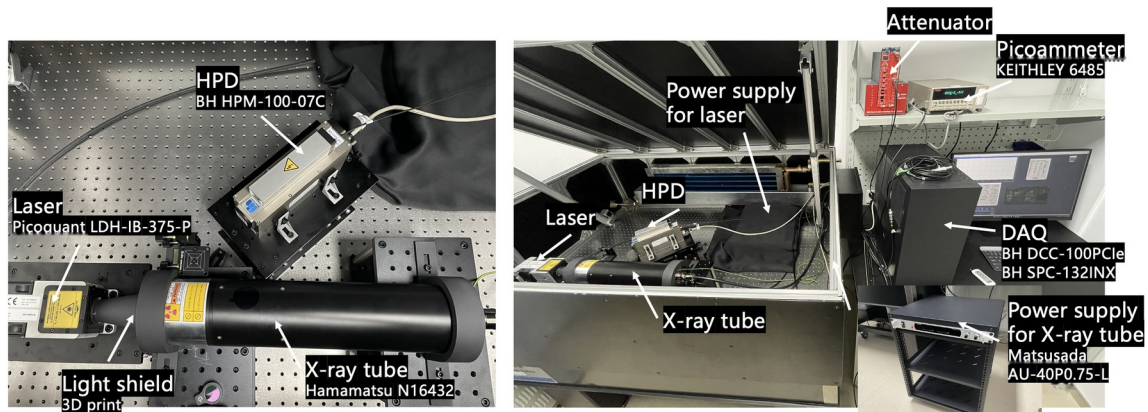


GAGG fibres from SIPAT

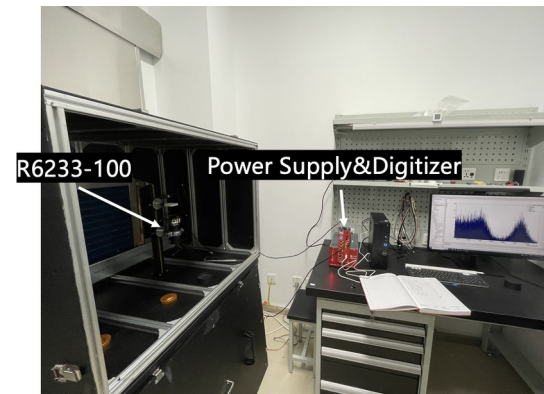
- **SIPAT:** composition and Czochralski growth
- **PKU / THU:** light output, kinetics, attenuation, fibre QC, prototype assembly
- **CERN:** cross-checks, test beams, simulation, statistical analysis

→ every ingot is sampled at head, middle and tail; the results steer the next growth runs

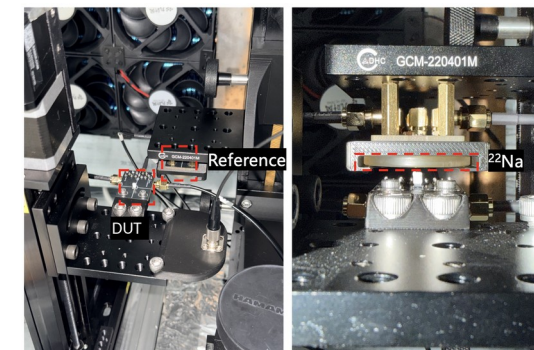
Characterization benches at PKU



Decay and rise time: laser-driven X-ray tube + hybrid PMT, TCSPC



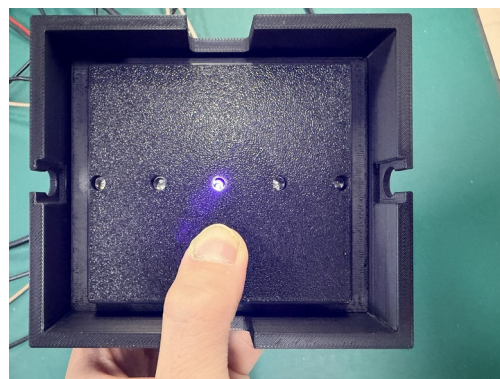
Light output: ^{137}Cs , R6233-100 PMT



CTR: ^{22}Na , LYSO reference



Emission (FLS1000), transmission (DS5)

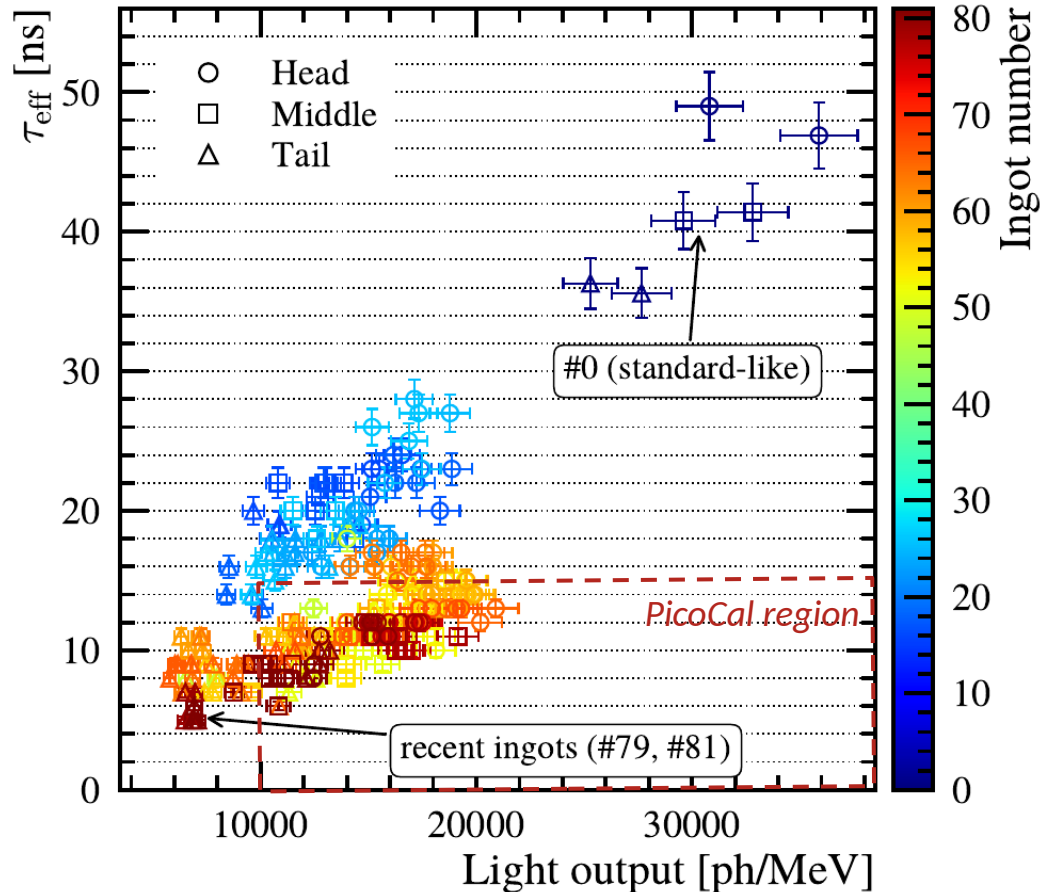


Attenuation: five 430 nm LEDs along the fibre

- similar characterization benches at CERN (Lab 27)
- same observables, fit model and τ_{eff} definition as at CERN (backup)
- PKU and CERN results agree

→ all SIPAT samples are measured at PKU; half of them are also measured at CERN

Decay time vs light output across the production



- 28 ingots, 250 samples, 5 % uncertainty on each axis
- τ_{eff} 48 $\rightarrow$ 5 ns, LO 33 350 $\rightarrow$ 6 200 ph/MeV
- one continuous gradient, set by the Mg level

PicoCal region (red box): $\tau_{\text{eff}} < 15$ ns, $\gtrsim 10\,000$ ph/MeV

19 of 28 ingots have at least one sample in it

13 of 28 more than half of their samples

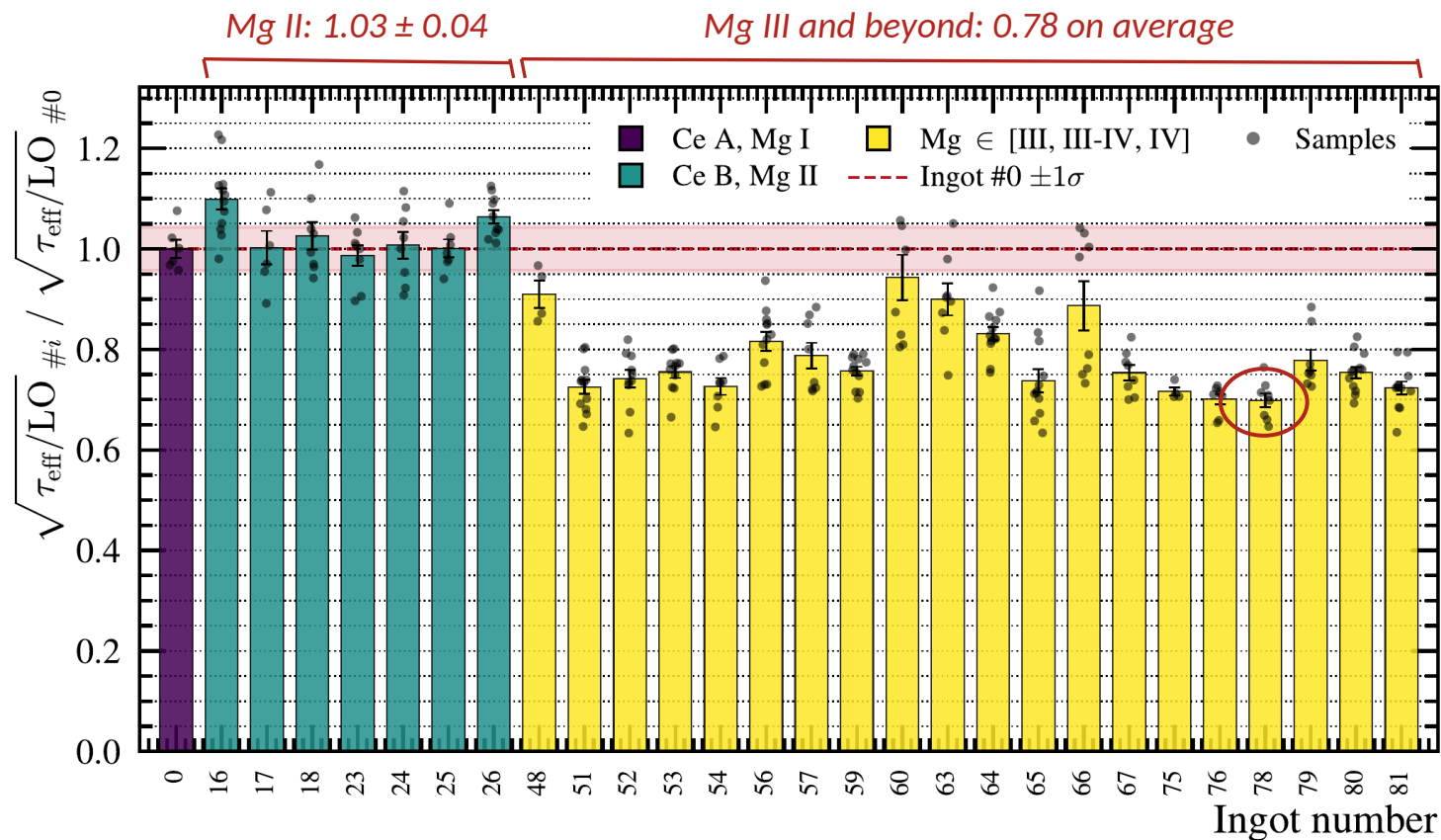
7 of 28 all of their samples

- at fixed Mg the spread is still $\gg 5$ %, not explained by diameter or crystallization ratio

All samples, coloured by ingot number. Roux et al., subm. to IEEE TNS; L. Roux, PhD thesis

→ the target is reached in many ingots; uniformity along the ingot is not there yet

Timing figure of merit per ingot

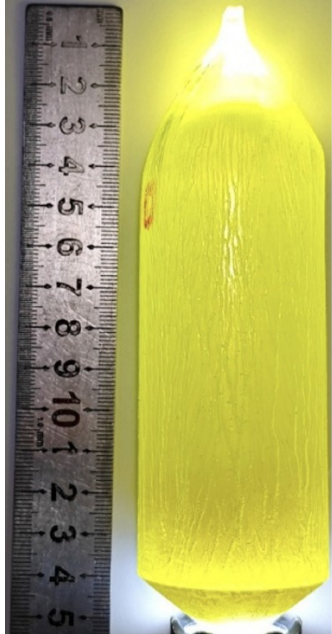


$\sqrt{\tau_{\text{eff}}/\text{LO}}$ per ingot relative to #0 (lower is better), in growth order; dots: samples. Roux et al., subm. to IEEE TNS

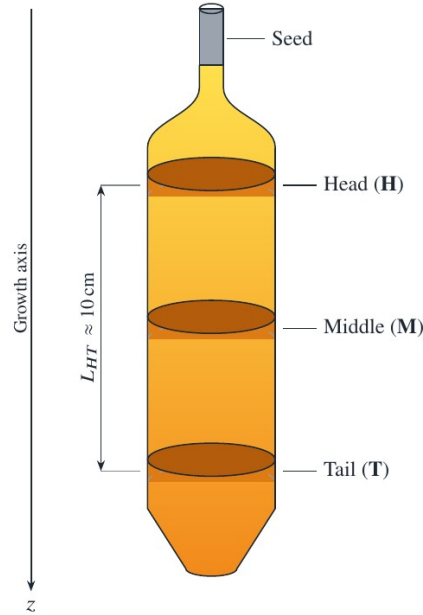
- time resolution: $\sigma_t \propto \sqrt{(\tau_r \tau_{\text{eff}} / N_{\text{ph}})}$
- Mg II: faster, but the speed is paid back in light
- Mg III and beyond: τ_{eff} drops faster than LO, best 0.70 (#78)
- I_{25} , light within 25 ns:
34 % for #0, 61–74 % for Mg III+

→ heavy co-doping is a real timing gain: σ_t up to 1.4× better than ingot #0

Czochralski growth and sampling

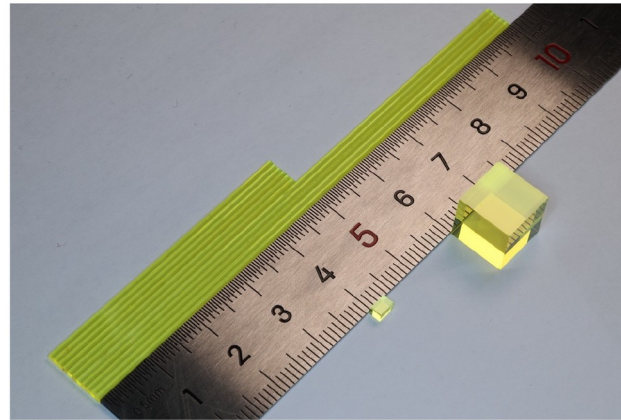


Ingot #79 ($\varnothing$ 45 mm) and the head / middle / tail positions, $L_{HT} \approx 10$ cm. Roux et al., subm. to IEEE TNS



- **Growth:** Ir crucible, N_2 atmosphere, $\langle 100 \rangle$ seeds, 0.5–1.5 mm/h
- **Varied:** Ce (A, B), Mg (I to IV), $\varnothing$ 35–60 mm, crystallization ratio 9–42 %
- **Sampled:** head / middle / tail pixels, cubes, 50 and 100 mm fibres
- **Prototypes:** ~3 600 fibres from 7 ingots (2024), 2 ingots (2025)

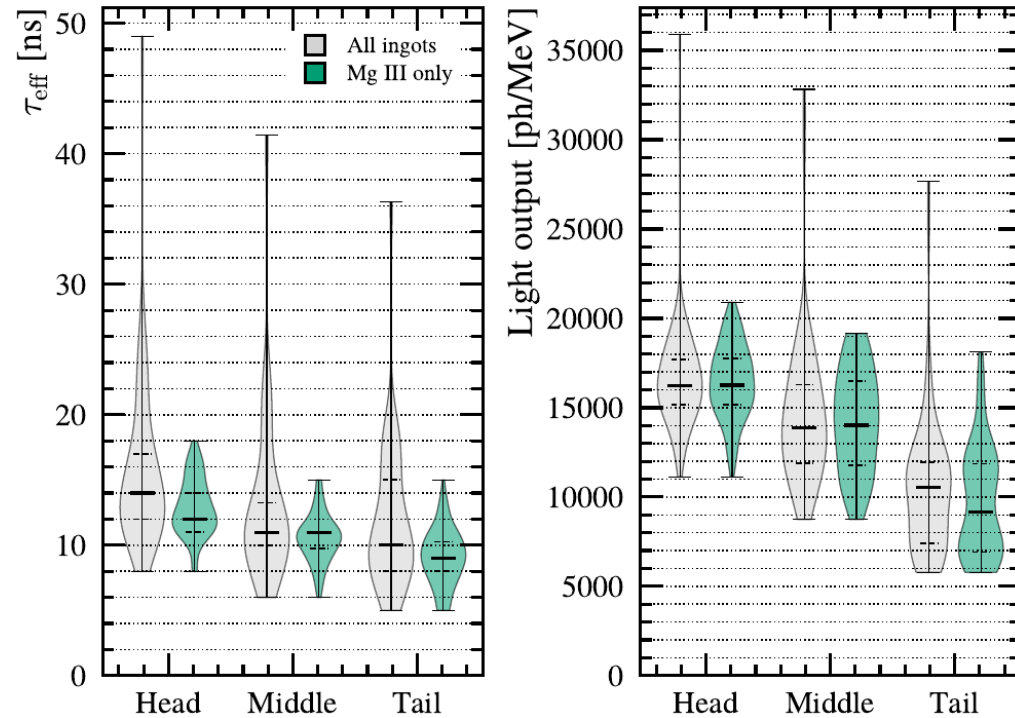
Crystallization ratio = fraction of the melt converted into crystal



Fibre 1×1×100, pixel 2×2×3 and cube 10×10×10 mm³, polished to 2–3 nm. Roux et al., subm. to IEEE TNS

→ at fixed Mg, diameter and crystallization ratio do not move the τ_{eff} / LO trade-off

Variation along the ingot



τ_{eff} and LO by position; grey = all ingots, green = Mg III. Roux et al., subm. to IEEE TNS

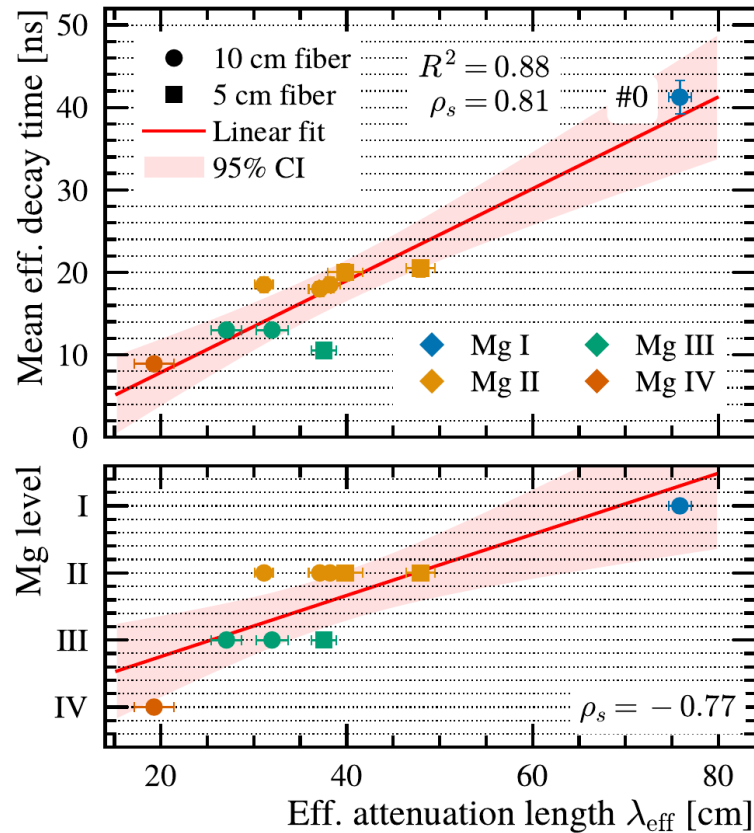
#57 (Mg III)	$\tau_1 (\rho_1)$	$\tau_2 (\rho_2)$	$\tau_3 (\rho_3)$	τ_{eff}	LO [ph/MeV]
head	3.3 ns (12 %)	17 ns (41 %)	47 ns (47 %)	14 ns	19 400
tail	5.0 ns (28 %)	12 ns (15 %)	31 ns (57 %)	11 ns	11 300

PKU fits, ingot #57 (4 head, 4 tail samples): the slow components (12–47 ns) still carry 70–90 % of the light

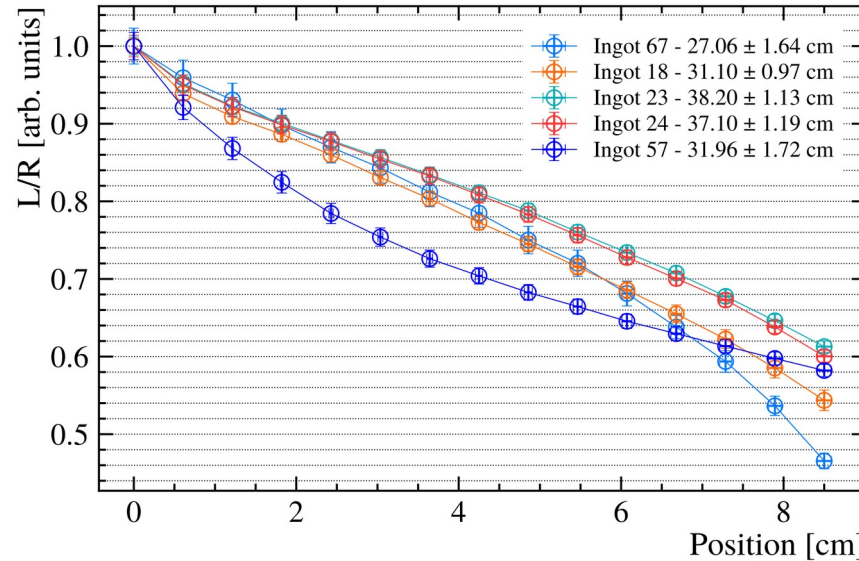
- head brighter and slower, tail faster and dimmer: Ce/Mg segregation
- $|\Delta_z \text{LO}| = 0.7\text{--}6.0 \text{ \%/cm}$ per ingot, median 4.4 %/cm (Mg III)
- PicoCal needs $\leq 2 \text{ \%/cm}$
- lever: crystallization ratio, +1.7 %/cm for every +10 % crystallized

→ a lower crystallization ratio gives flatter ingots: the gradient, not the speed, is now the limit

Attenuation length of the fibres



Ingot τ_{eff} (top) and Mg level (bottom) vs λ_{eff} of its 5 and 10 cm fibres. Roux et al., subm. to IEEE TNS



L/R ratio vs LED position, 10 cm SIPAT fibres (CERN bench, L. Roux)

- λ_{eff} follows τ_{eff} ($R^2 = 0.88$) and falls with the Mg level ($\rho_s = -0.77$)
- the Ce^{4+} absorption band overlaps the emission

Light from the far end of a 10 cm section

#0, Mg I ($\lambda_{\text{eff}} = 76$ cm)

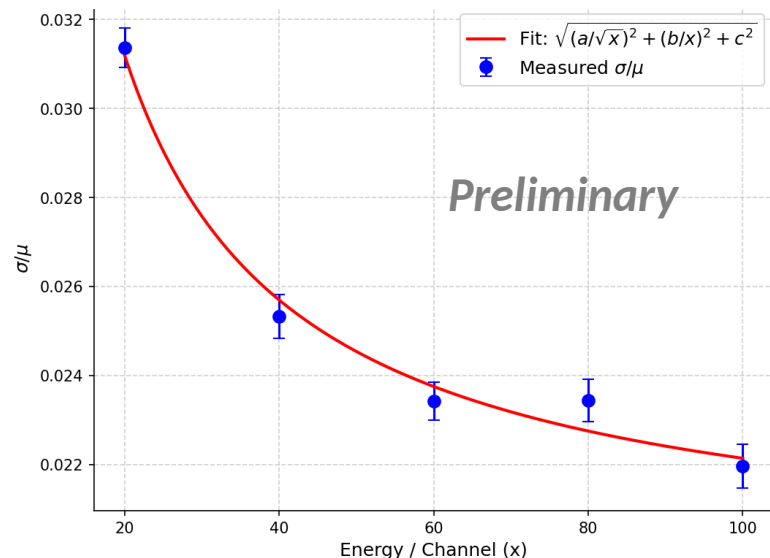
88 % transmitted

#79, Mg IV ($\lambda_{\text{eff}} = 19$ cm)

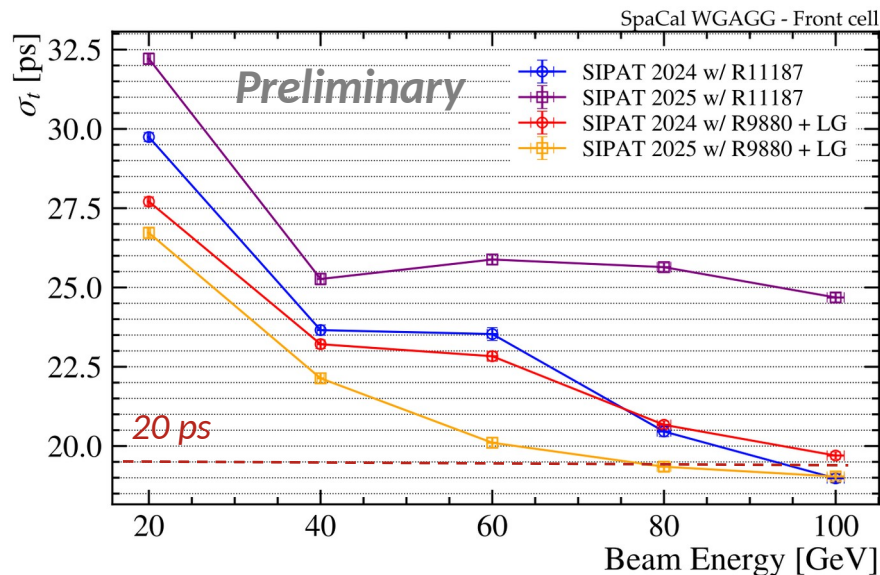
59 % transmitted

→ transparency has to be optimized together with speed and uniformity

Test beam at the CERN SPS: SpaCal-W with SIPAT fibres



Energy resolution, SIPAT fibres, R9880U readout (2025)



Time resolution, front section: 2024 (~20 ns) vs 2025 (~10 ns) fibres; LG = light guide

Energy

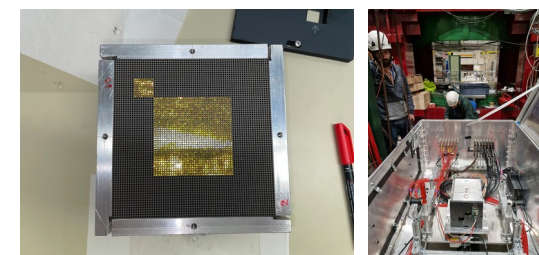
sampling	10.2 %
constant	2.0 %
noise	17 %

Time (front only)

20 GeV	27 ps
100 GeV	19 ps

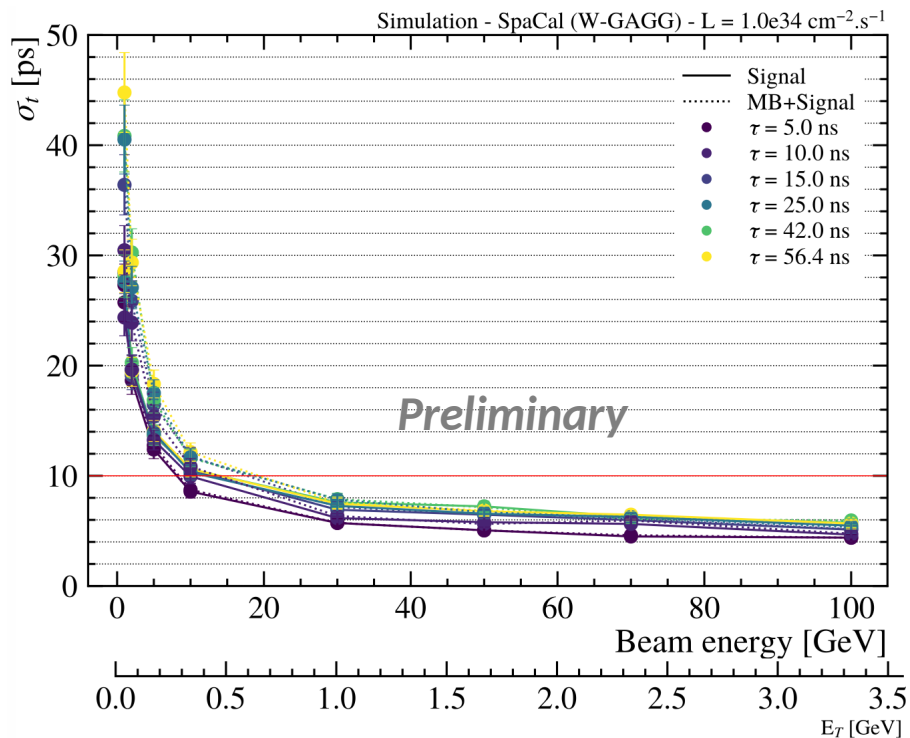
- constant term 2 %: cell homogeneity not yet perfect (same with MaPMT)
- with R9880U: 2025 fibres (~10 ns) beat 2024 (~20 ns), as expected from the lab
- front + back combination of the 2025 data: analysis ongoing

→ ~10 ns SIPAT fibres: 10 %/ $\sqrt{E}$ sampling term and < 20 ps above 60 GeV

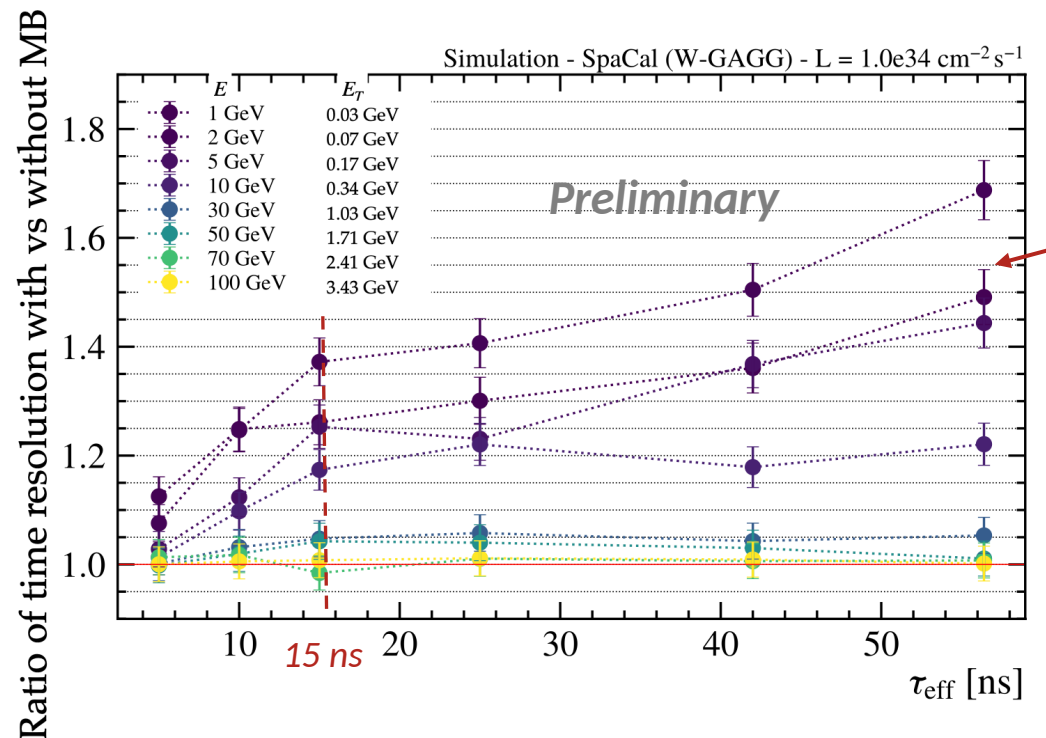


Prototype #2 at the CERN SPS, Sep 2025: SIPAT and Crytur/FZU fibres, R9880U-20 PMTs

How fast is fast enough? Spill-over simulation



Time resolution vs energy for $\tau_{\text{eff}} = 5\text{--}56 \text{ ns}$; solid: signal only, dotted: with pile-up



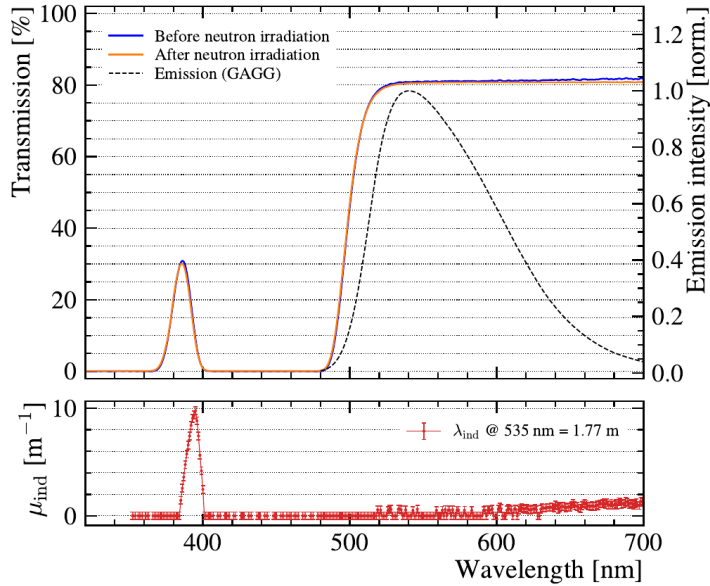
Ratio with / without pile-up vs τ_{eff} , by energy (E_T 30 MeV - 3.4 GeV)

only the lowest E_T suffer

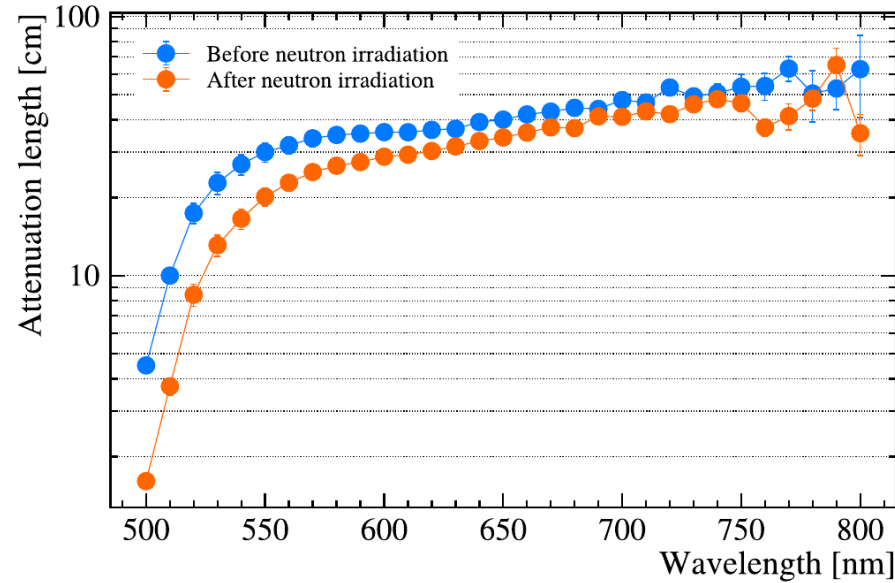
➤ one SpaCal-W-GAGG module, $L = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, a chain of 40 crossings of Run 5 minimum bias; no pulse shaping yet

→ $\tau_{\text{eff}} \leq 15 \text{ ns}$ keeps the loss below 20 % above 350 MeV E_T : the working target

Neutron irradiation of SIPAT GAGG



SIPAT 1 cm³ sample (ingot #1, Mg II): transmission before / after, and the induced absorption μ_{ind}



SIPAT 10 cm fibre (ingot #67, Mg III): attenuation length before / after. Roux et al., subm. to IEEE TNS



SIPAT samples packed for JSI

- first neutron test of accelerated GAGG: SIPAT samples, JSI TRIGA reactor, thermal neutrons, $1 \times 10^{15} \text{ n/cm}^2$
- 1 cm³ sample: **transmission unchanged**, $\lambda_{ind} \approx 1.8 \text{ m}$; 10 cm fibre: λ_{att} unchanged above 550 nm
- protons: GAGG holds 1 MGy [NIM A 916 (2019) 226]; SIPAT's accelerated compositions still to be tested

→ next for SIPAT GAGG: protons and γ up to 1 MGy, light output and τ_{eff} after irradiation

Summary and outlook

Where we are

- > 80 Cz ingots: τ_{eff} 5–48 ns, LO 6 200–33 350 ph/MeV, set by Mg concentration
- Mg III+: timing figure of merit 0.78 of #0 on average, best 0.70
- **19 of 28 ingots reach the PicoCal specifications, 7 entirely**
- test beam: 10 %/ $\sqrt{E}$, < 20 ps above 60 GeV
- thermal neutrons, 10^{15} n/cm²: no significant optical degradation

Still limiting

- LO gradient along the ingot: median 4.4 %/cm, ≤ 2 %/cm needed
- fibre attenuation: down to 19 cm at the highest Mg
- slow components (12–47 ns)
- proton / γ hardness of SIPAT's accelerated compositions

Next

- fix the composition around Mg III; tune the growth for uniformity and transparency
- reproducibility and mass production → PicoCal TDR
- NSFC–CERN joint project (PKU + SIPAT)

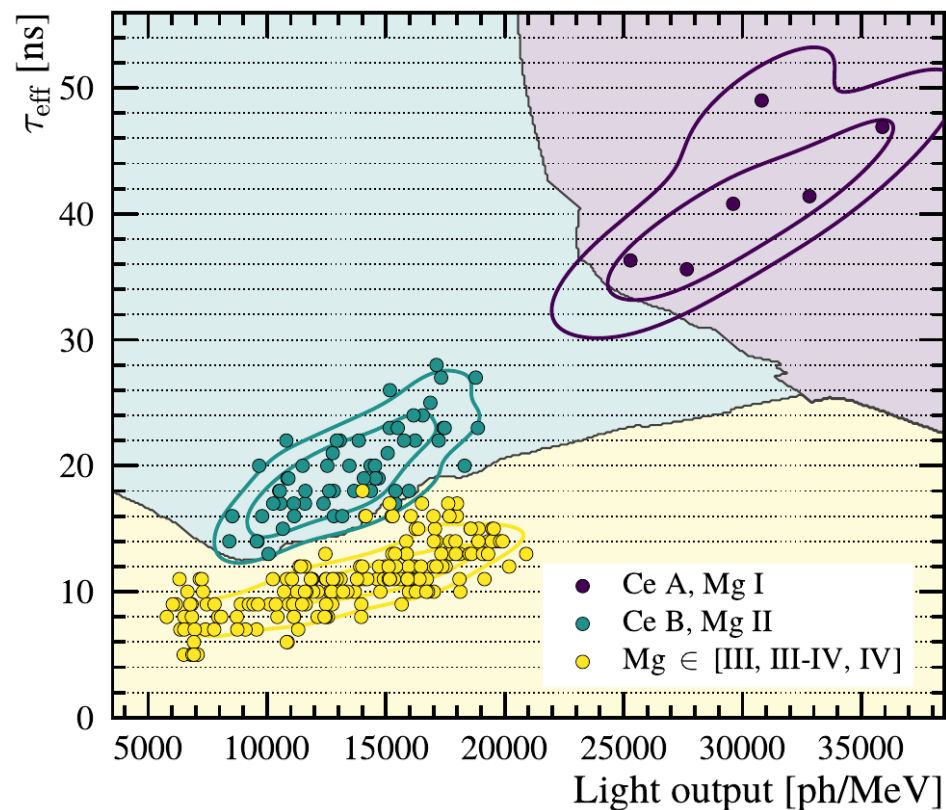
Thanks to the PicoCal R&D group, SIPAT, and the students at PKU and THU.

Details: L. Roux et al., submitted to IEEE Trans. Nucl. Sci. (SCINT 2026). Supported by the National Key R&D Program of China (2022YFA1601900), NSFC (11925504, 1252500590, 1259300032), the PKU Faculty Start-up Fund and CERN EP-R&D.

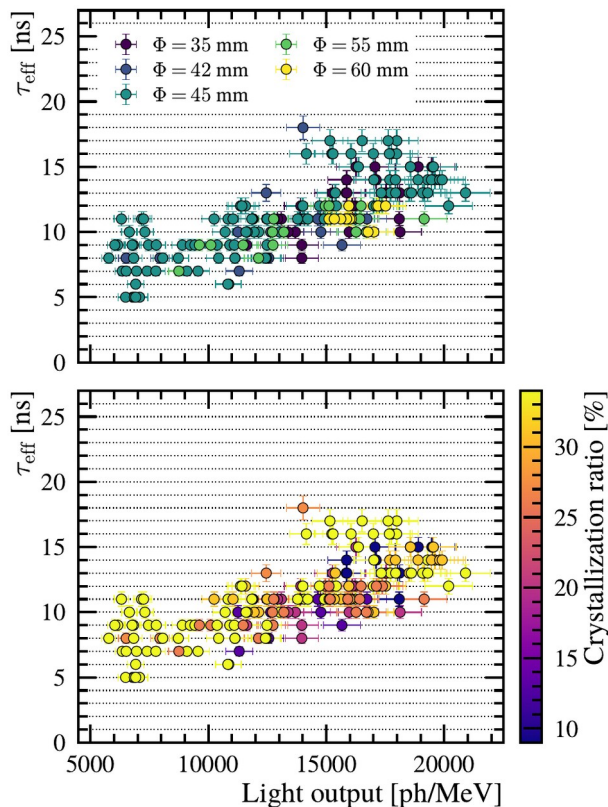
→ fast and bright GAGG at production scale: the focus now moves to uniformity and reproducibility

Backup

Composition vs growth conditions (paper Figs. 5, 6)



τ_{eff} vs LO by nominal composition; shaded: k-NN decision regions (97.6 % cross-validated accuracy for Mg I / II / III); contours: 25 % and 60 % of peak density



Heavily co-doped subset (20 ingots, 185 samples) by diameter (top) and crystallization ratio (bottom). Roux et al., subm. to IEEE TNS

- mixed-effects model, Mg II and III ingots: II $\rightarrow$ III shortens τ_{eff} by 8.5 ± 0.7 ns
- diameter, crystallization ratio: no resolvable effect on τ_{eff} / LO at fixed Mg
- but the crystallization ratio sets $|\Delta_z \text{LO}|$: $+1.71 \pm 0.29$ %/cm per +10 % (22 Mg II / III ingots)
- gap statistic: one cluster, a continuous gradient

Figures of merit (paper Table II) and growth parameters (Table I)

Ingot ID	Mg conc.	Cryst. ratio [%]	LO [photons MeV ⁻¹]	τ_{eff} [ns]	I_{25} [%]	$ \Delta_z \text{LO} $ [% cm ⁻¹]
#0	I	42	33 350	48.0	33.6	2.1
#16	II	37	16 150	23.2	52.2	3.5
#23	II	20	14 500	18.0	58.1	1.4
#26	II	30	16 450	26.0	51.4	3.9
#48	III	27	13 250	15.5	61.8	4.5
#52	III	20	16 450	12.5	65.4	1.8
#53	III	9	17 950	14.7	64.1	0.7
#60	III	34	17 250	16.2	60.9	6.0
#65	III	34	19 150	12.5	62.5	5.2
#67	III	34	18 400	13.0	64.0	4.0
#79	IV	34	15 150	11.8	68.7	5.6
#80	III	26	14 750	11.2	67.1	1.4
#81	III–IV	34	12 100	8.2	73.9	4.3

Head samples: LO and τ_{eff} averaged, I_{25} from one sample, $|\Delta_z \text{LO}|$ from head and tail; 5 % relative uncertainty

TABLE I
GROWTH PARAMETERS OF A REPRESENTATIVE SUBSET OF THE GAGG
INGOTS GROWN BY SIPAT. CE CONCENTRATIONS SATISFY $A < B$ AND
MG CONCENTRATIONS INCREASE FROM I TO IV.

Ingot ID	Ce	Mg	Cryst. ratio [%]	$\varnothing \times L$ [mm $\times$ mm]
#0	A	I	42	60 $\times$ 170
#1	B	II	41	45 $\times$ 130
#16	B	II	37	45 $\times$ 120
#17	B	II	36	60 $\times$ 170
#18	B	II	31	45 $\times$ 100
#23, #24	B	II	20	50 $\times$ 110
#25, #26	B	II	30	42 $\times$ 110
#48	B	III	27	42 $\times$ 130
#51	B	III	13	42 $\times$ 120
#52, #53, #54	B	III	20, 9, 20	35 $\times$ 110
#56, #60	B	III	34	45 $\times$ 110
#57, #59	B	III	31	45 $\times$ 100
#63, #64, #65, #66	B	III	34	45 $\times$ 110
#67	B	III	34	45 $\times$ 110
#75, #76	B	III	31	60 $\times$ 110
#78, #80	B	III	26	55 $\times$ 110
#79	B	IV	34	45 $\times$ 110
#81	B	III–IV	34	45 $\times$ 110

Crystallization ratio: fraction of the melt mass converted into crystal by the end of the growth.

Methods and instruments, PKU vs CERN

Characterisation	Method-instrument in China	Method-instrument in CERN
Photoluminescence spectrum	Edinburgh FLS1000	Perkin Elmer LS55
Transmission and absorbance	Edinburgh DS5	Perkin Elmer Lambda 650
Scintillation kinetics	255 nm laser ^{*1,4} (5 eV γ) X-ray tube ^{*2,4} $\mathcal{O}(15 \text{ keV})$	X-ray tube ^{*3,4} $\mathcal{O}(15 \text{ keV})$
Light output	Calibration with dark count ^{*5} Calibration with LED control ^{*6}	Calibration with dark count ^{*5}

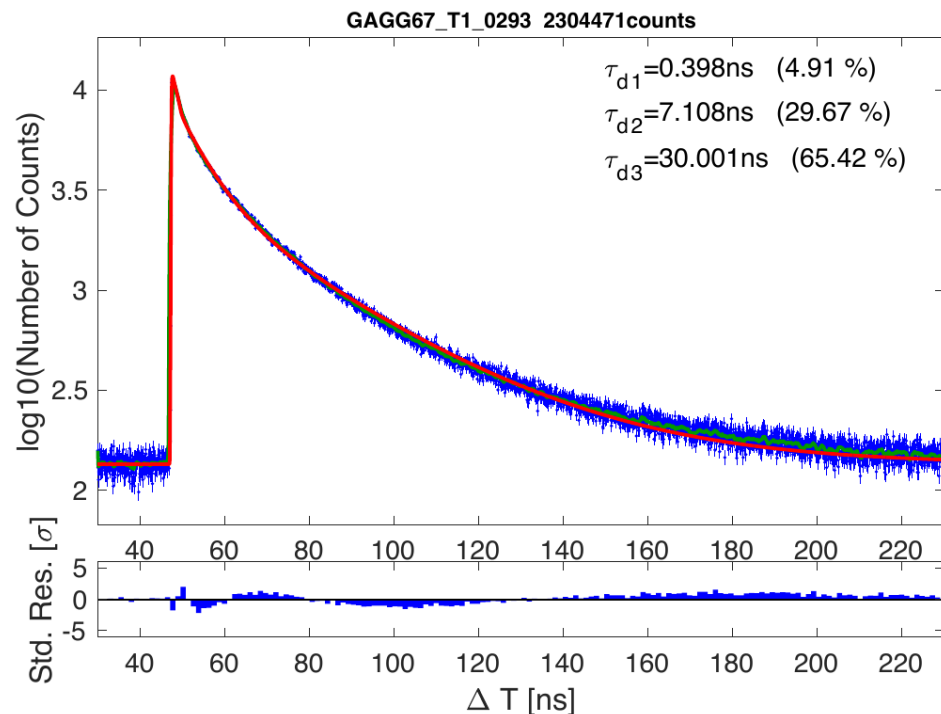
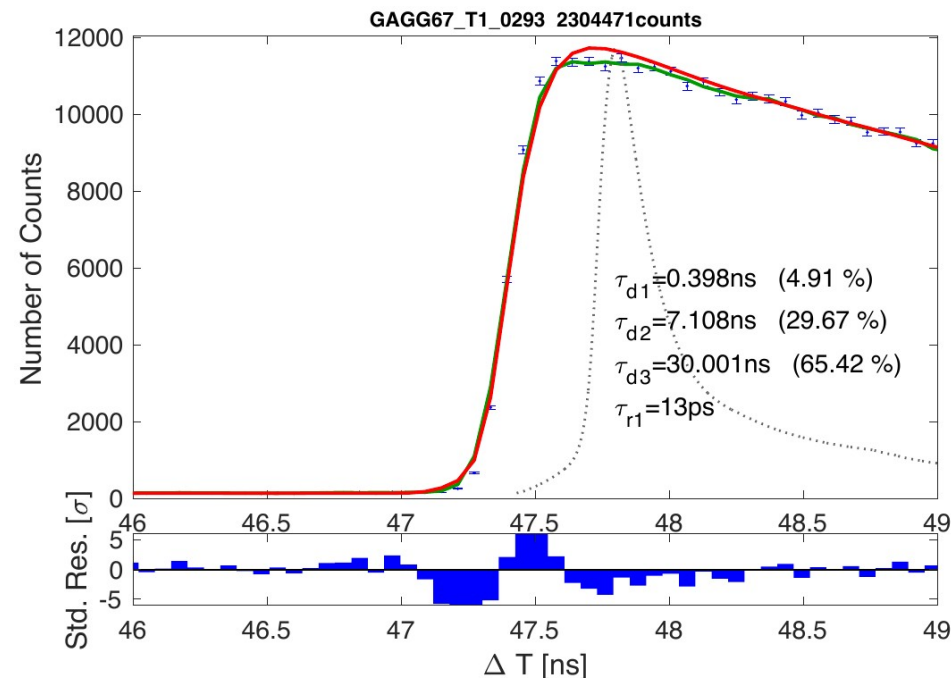
- *1. Fit with 2 τ_d and no IRF convolution.
- *2. Fit with 3 τ_d and no IRF convolution.
- *3. Fit with 3 τ_d , 1 τ_r and IRF convolution.
- *4. Time-correlated single-photon counting(TCSPC) method.
- *5. Fit with Gaussian method.
- *6. Fit with PMT response method.

Comparison as of Jan 2025 (from the group's earlier slides)

PKU kinetics bench since then

- X-ray tube (N16432) driven by a 375 nm laser
- hybrid PMT (HPM-100-07C), TCSPC card SPC-132
- 3 $\tau_d + 1 \tau_r$, convolved with the IRF (0.34 ns FWHM), same τ_{eff} as CERN (next slide)

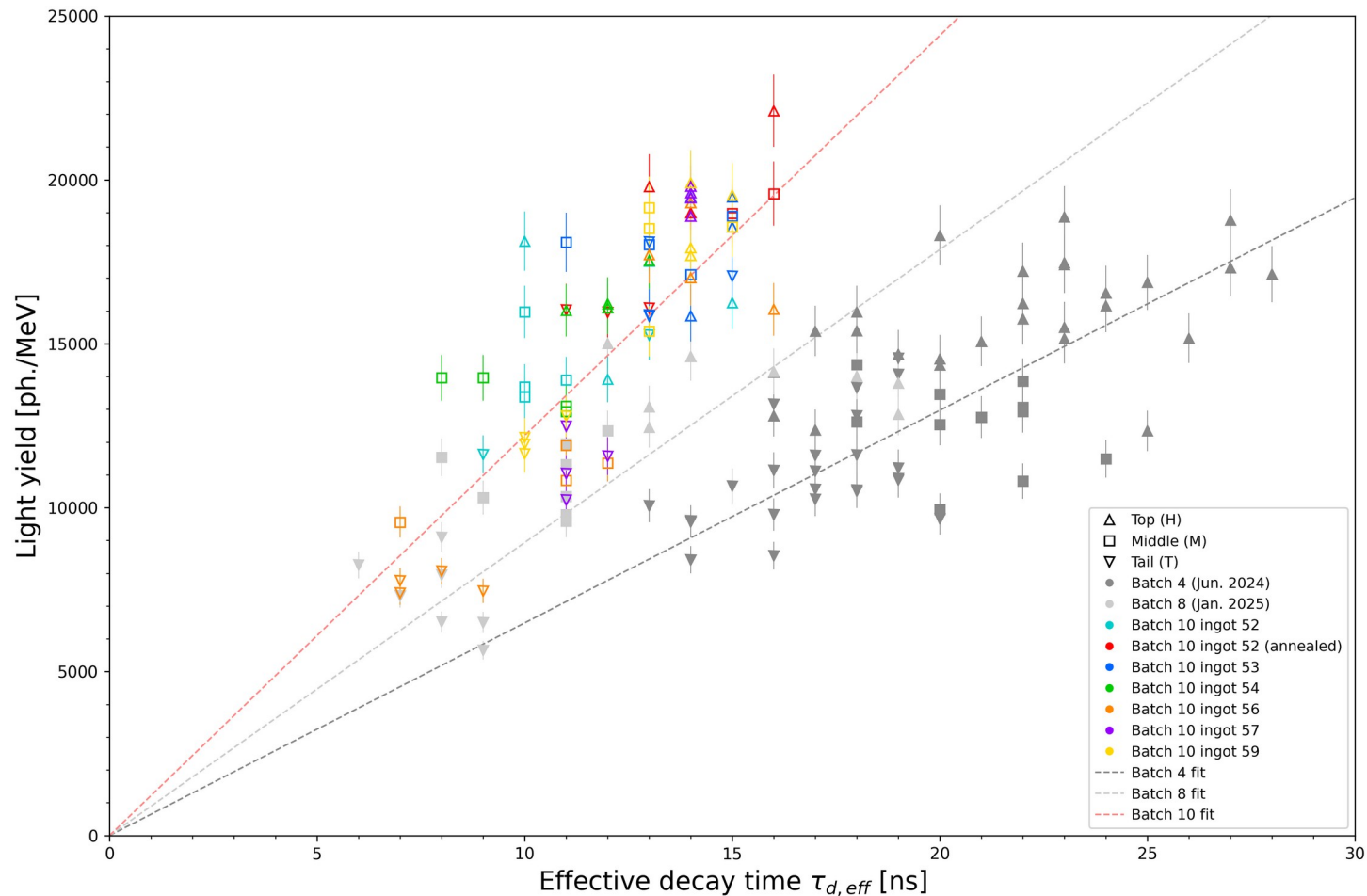
τ_{eff} : the fit and the definition



X-ray-excited TCSPC curve of one SIPAT sample (ingot #67, tail) with a three-component fit convolved with the instrument response; right: the rise, $\tau_r \approx 13$ ps

- $I(t) = \sum_i \rho_i [\exp(-(t-\theta)/\tau_{d,i}) - \exp(-(t-\theta)/\tau_{r,i})] / (\tau_{d,i} - \tau_{r,i}) \cdot \Theta(t-\theta) + \epsilon$, $\sum \rho_i = 1$
- $\tau_{\text{eff}} = (\sum_i \rho_i / \tau_{d,i})^{-1}$: weights each component by its share of the initial photon rate
- I_{25} : fraction of the light emitted within 25 ns of the onset (of the total in 1 μs)

τ_{eff} vs light output by batch (PKU, 2024–2025)



- Nov 2024 ingot: $\tau_{\text{eff}} \approx 24$ ns (head)
→ 12 ns (tail)
- Jan 2025 ingot: tail ≈ 8 ns at $\sim 7\,500$ ph/MeV
- batch 10: τ_{eff} 7–16 ns, 7 000–22 000 ph/MeV
- fit slopes grow from batch to batch

Batch 4 (Jun 2024), batch 8 (Jan 2025), batch 10 (Jun–Jul 2025); markers: head / middle / tail; dashed: fit through the origin per batch [Z. Yuan et al., PoS(EPS-HEP2025)520]

Ingots #57 (batch 10) and #60 (batch 11): full PKU tables

GAGG SIPAT	τ_{d1} [ns]	R_1 [%]	τ_{d2} [ns]	R_2 [%]	τ_{d3} [ns]	R_3 [%]	$\tau_{d,eff}$ [ns]	χ^2/ndf
Batch10-ingot57 H7 #0221	3.3	12.6	17.1	41.1	47.5	46.3	14	3879/3505
Batch10-ingot57 H8 #0222	3.4	13.1	17.7	42.2	47.6	44.7	14	3909/3505
Batch10-ingot57 H9 #0223	3.3	12.3	17.8	43.8	49.0	44.0	14	3804/3505
Batch10-ingot57 H10 #0224	3.0	11.2	15.6	37.5	44.1	51.3	14	3803/3505
Batch10-ingot57 T7 #0225	5.0	28.5	12.0	14.9	31.8	56.5	11	4760/3505
Batch10-ingot57 T8 #0226	5.0	28.5	12.0	13.2	30.7	58.2	11	4634/3505
Batch10-ingot57 T9 #0227	5.0	27.9	12.0	15.7	31.6	56.4	12	4582/3505
Batch10-ingot57 T10 #0228	5.0	28.4	12.0	16.3	31.1	55.3	11	4509/3505

GAGG SIPAT	μ	σ	Light output*1 [MeV ⁻¹]	Light output*2 [MeV ⁻¹]
Batch10-ingot57 H7 #0221	7886.99 ± 8.16	515.28	20276 ± 1013	19609 ± 980
Batch10-ingot57 H8 #0222	7673.34 ± 6.53	532.44	20117 ± 1005	19456 ± 972
Batch10-ingot57 H9 #0223	7597.74 ± 6.98	503.99	19532 ± 976	18890 ± 944
Batch10-ingot57 H10 #0224	7811.62 ± 7.36	483.98	20480 ± 1024	19806 ± 990
Batch10-ingot57 T7 #0225	3839.53 ± 8.43	351.65	10590 ± 529	10242 ± 512
Batch10-ingot57 T8 #0226	4140.28 ± 11.86	396.67	11420 ± 571	11044 ± 552
Batch10-ingot57 T9 #0227	4338.51 ± 10.74	399.57	11966 ± 598	11573 ± 578
Batch10-ingot57 T10 #0228	4488.61 ± 10.30	410.02	12919 ± 645	12494 ± 624

*1. Fit using PMT response function under LED control.

*2. Fit using Gaussian function under dark count.

GAGG SIPAT	τ_{d1} [ns]	R_1 [%]	τ_{d2} [ns]	R_2 [%]	τ_{d3} [ns]	R_3 [%]	$\tau_{d,eff}$ [ns]	χ^2/ndf
Batch11-ingot60 H1 #0241	4.6	14.9	21.3	45.2	52.6	39.9	16	3938/3504
Batch11-ingot60 H2 #0242	3.9	12.5	20.6	47.4	52.5	40.1	16	3909/3505
Batch11-ingot60 H3 #0243	4.0	13.3	20.3	46.1	51.2	40.7	16	4143/3505
Batch11-ingot60 H4 #0244	4.5	14.1	22.4	50.3	55.5	35.6	17	4010/3504
Batch11-ingot60 T1 #0245	5.0	33.5	12.0	7.7	28.5	58.8	11	4661/3505
Batch11-ingot60 T2 #0246	2.4	12.1	12.2	43.8	37.1	44.0	10	3977/3505
Batch11-ingot60 T3 #0247	2.2	11.3	11.0	42.8	35.0	46.0	10	3851/3505
Batch11-ingot60 T4 #0248	2.2	9.1	37.0	45.7	11.5	45.2	11	3986/3505

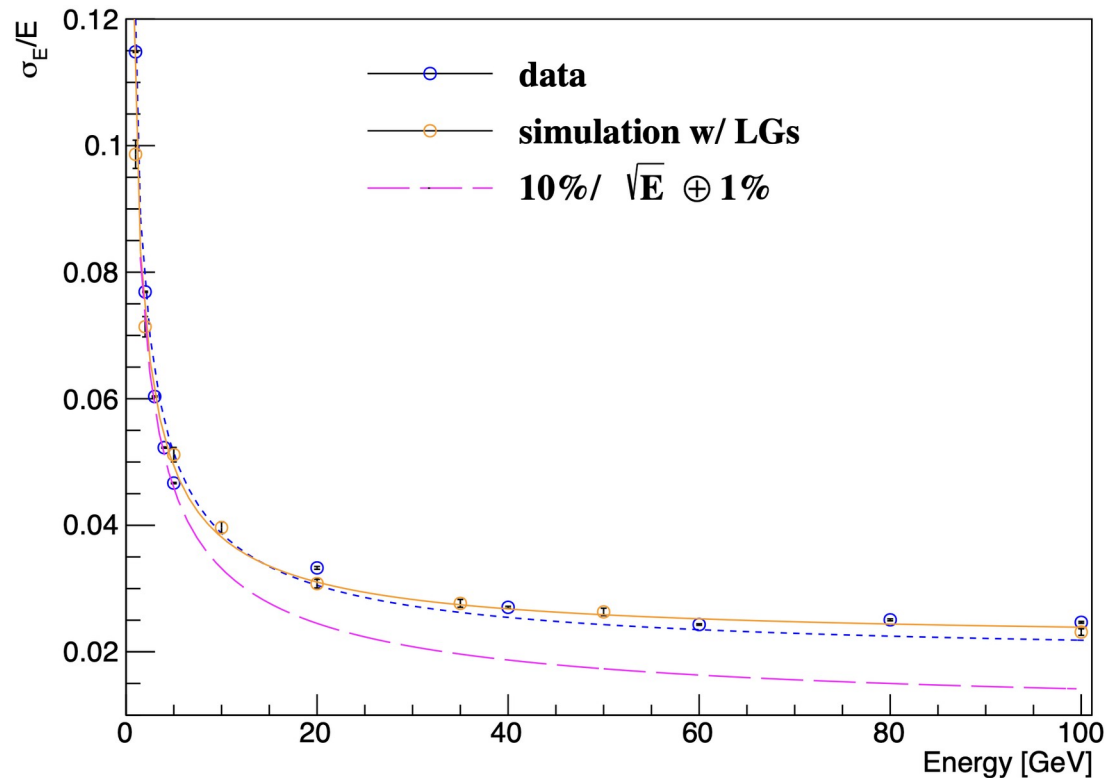
GAGG SIPAT	μ	σ	Light output*1 [MeV ⁻¹]	Light output*2 [MeV ⁻¹]
Batch11-ingot60 H1 #0241	6484.96 ± 4.66	372.24	15754 ± 787	15236 ± 761
Batch11-ingot60 H2 #0242	7422.92 ± 9.24	489.15	18369 ± 918	17765 ± 888
Batch11-ingot60 H3 #0243	7513.35 ± 8.22	519.53	18593 ± 929	17982 ± 899
Batch11-ingot60 H4 #0244	7727.43 ± 8.66	503.53	18601 ± 930	17990 ± 899
Batch11-ingot60 T1 #0245	3106.74 ± 17.20	375.65	7411 ± 370	7167 ± 358
Batch11-ingot60 T2 #0246	2648.98 ± 4.36	273.28	6876 ± 343	6650 ± 332
Batch11-ingot60 T3 #0247	3110.38 ± 8.58	309.50	7556 ± 377	7307 ± 365
Batch11-ingot60 T4 #0248	2737.12 ± 7.19	213.27	6529 ± 326	6314 ± 315

*1. Fit using PMT response function under LED control.

*2. Fit using Gaussian function under dark count.

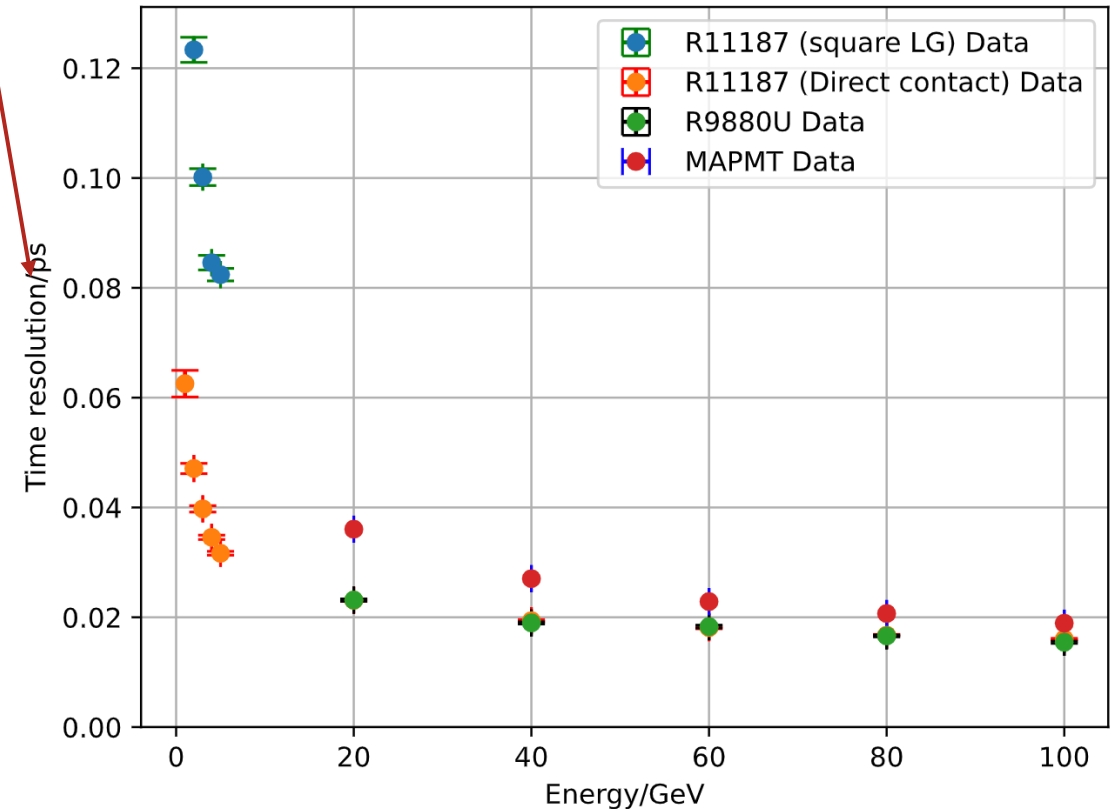
X-ray TCSPC three-component fits and ¹³⁷Cs light output, head (H) and tail (T) samples; the paper uses the dark-count calibration (*2)

2024 prototype ($\tau_{\text{eff}} \approx 20$ ns fibres)



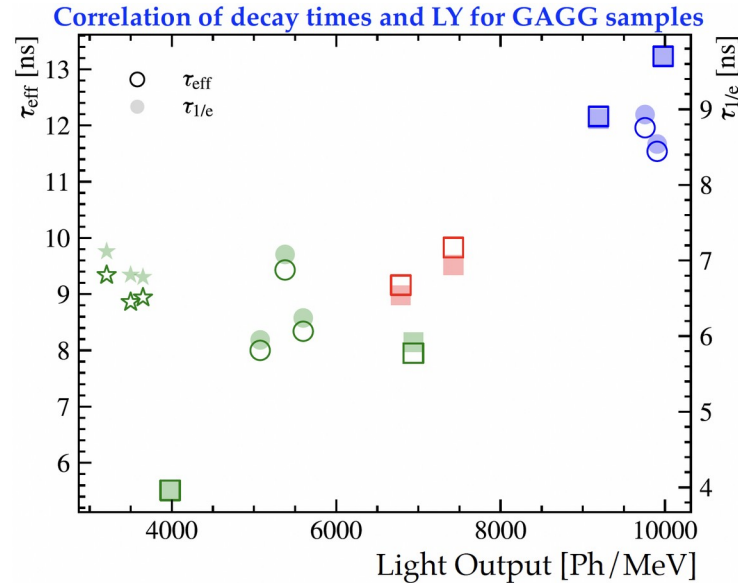
Energy resolution, MaPMT readout, vs simulation with light guides: sampling
 10.6 ± 0.2 %, constant ~ 2 % ($3^\circ + 3^\circ$, 4×4 cells) [Z. Yuan et al., PoS(EPS-HEP2025)520]

values are in ns, not ps

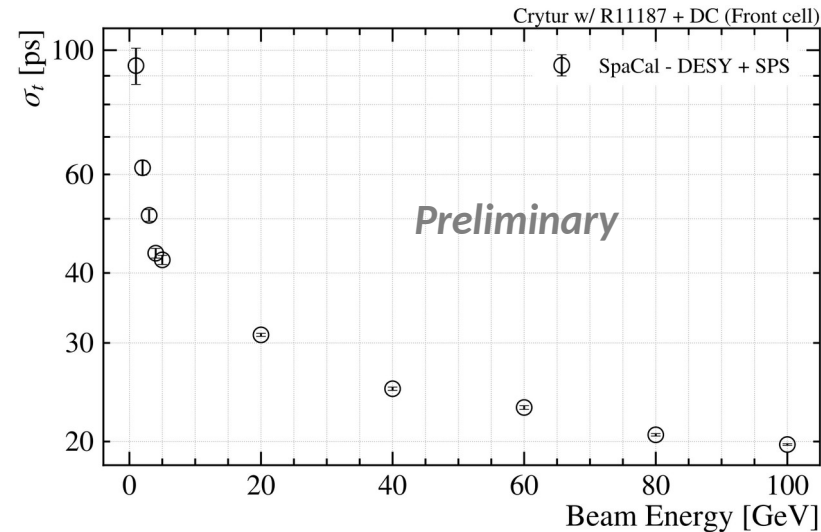


Time resolution: R11187 (direct contact) and R9880U, front and back weighted,
 < 20 ps above 20 GeV; MaPMT and R11187 with square light guides (front only)
 much worse [Z. Yuan et al., PoS(EPS-HEP2025)520]

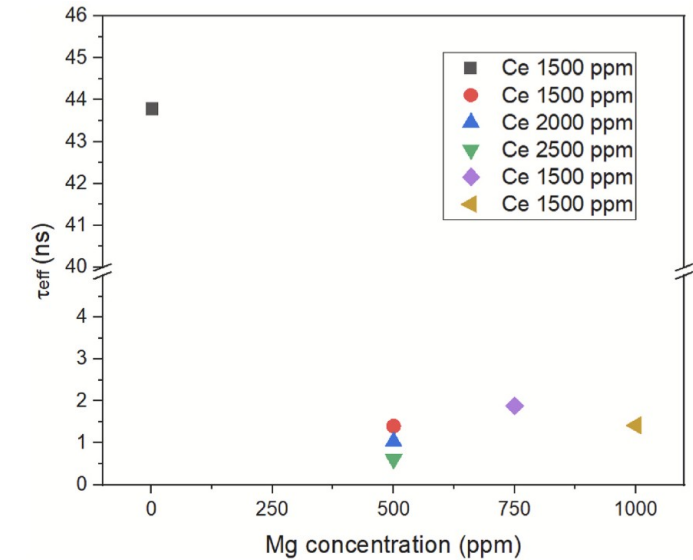
Other garnet producers in the PicoCal R&D



Crytur/FZU GAGG: τ_{eff} 5–13 ns at 3 000–10 000 ph/MeV
[L. Roux et al., NIM A 1094 (2027) 172102]



Front section with Crytur fibres, R11187 direct contact: ~20 ps at 100 GeV



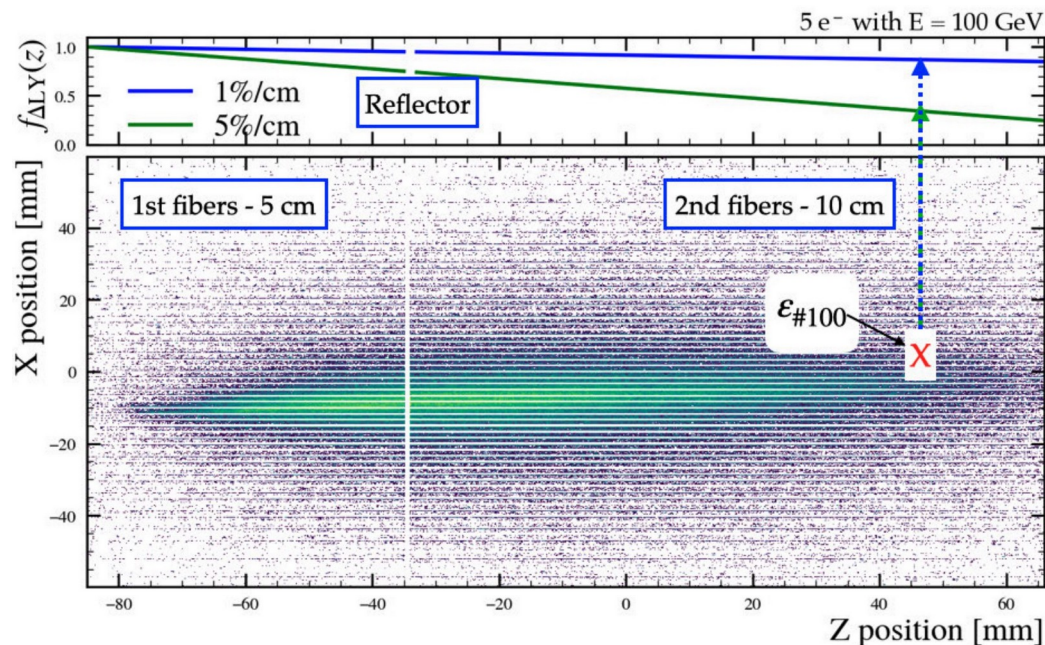
TWISMA (ILM): τ_{eff} vs Mg concentration



ISMA YAG:Ce samples (1.5–4 % Ce): no Ir crucible needed, but ~100 ns; co-doping aims at ~20 ns. Work supported by the European TWIN project TWISMA (GA: 101078960)

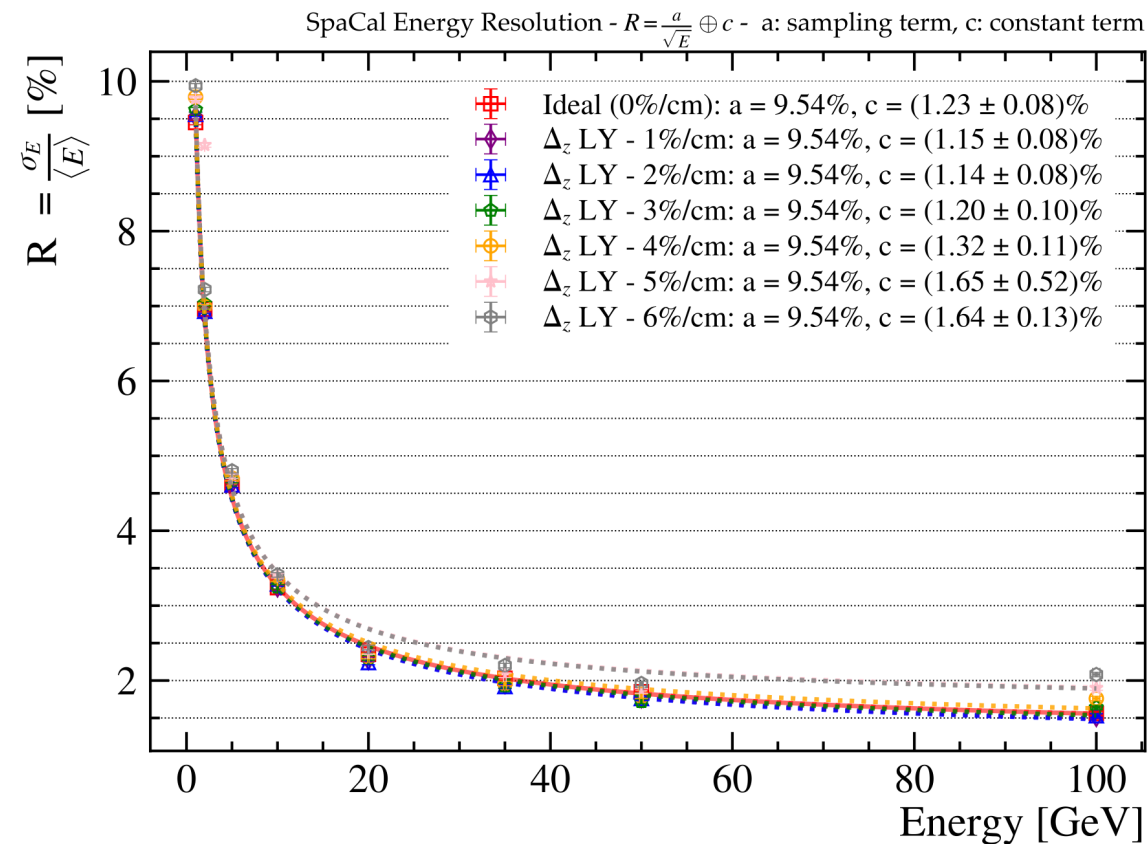
- Crytur/FZU GAGG: no major optical change after 1 MGy of protons (IRRAD)
- Kononets et al., Opt. Mater. 169 (2026) 117547; Gerasymov et al., CrystEngComm 27 (2025) 4528

Simulated light-output gradient in the SpaCal



Five 100 GeV electrons; the energy deposited in each fibre is weighted by a linear profile (1 %/cm, 5 %/cm)

- electrons 1–100 GeV, LO gradient 0–6 %/cm in both sections
- sampling term 9.54 % at every gradient
- constant term 1.2 % up to 3 %/cm, 1.3 % at 4 %/cm, 1.65 % at 5–6 %/cm
- limit: ≤ 2 %/cm, i.e. ≤ 20 % over a 10 cm fibre



Simulated energy resolution for gradients of 0–6 %/cm [L. Roux et al., IEEE TNS 72 (2025) 2076]