Performance of the GAGG crystal for LHCb Upgrade II ECAL

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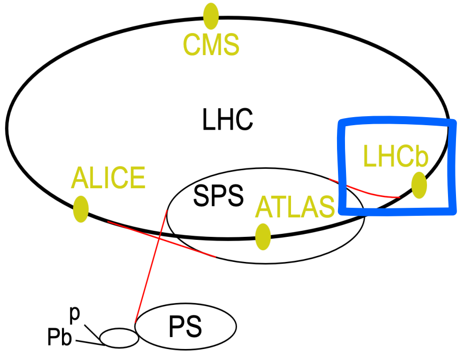
on behalf of the China LHCb ECAL Upgrade II R&D group

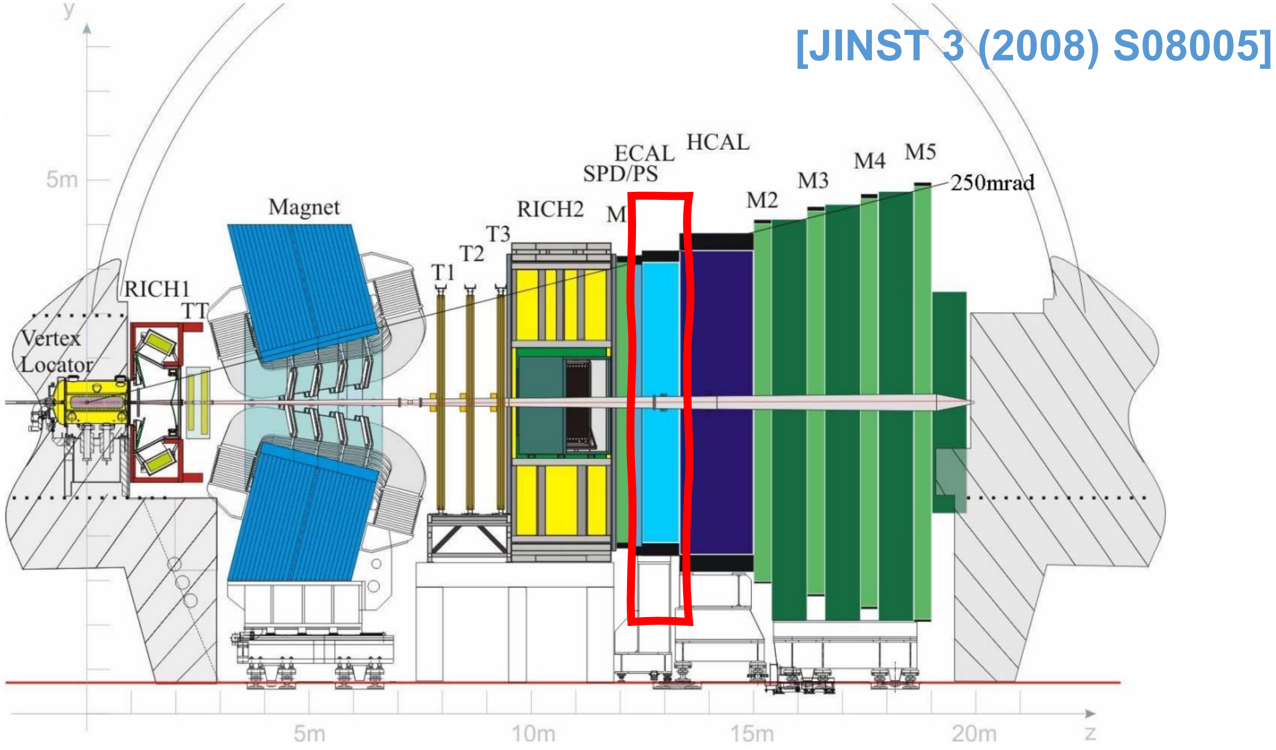
Outline

- Background and Motivation
- Performance of GAGG crystal
- Summary and Outlook

LHCb detector

- A single-arm forward region detector covering $2<\eta<5$
- Designed for heavy flavour physics

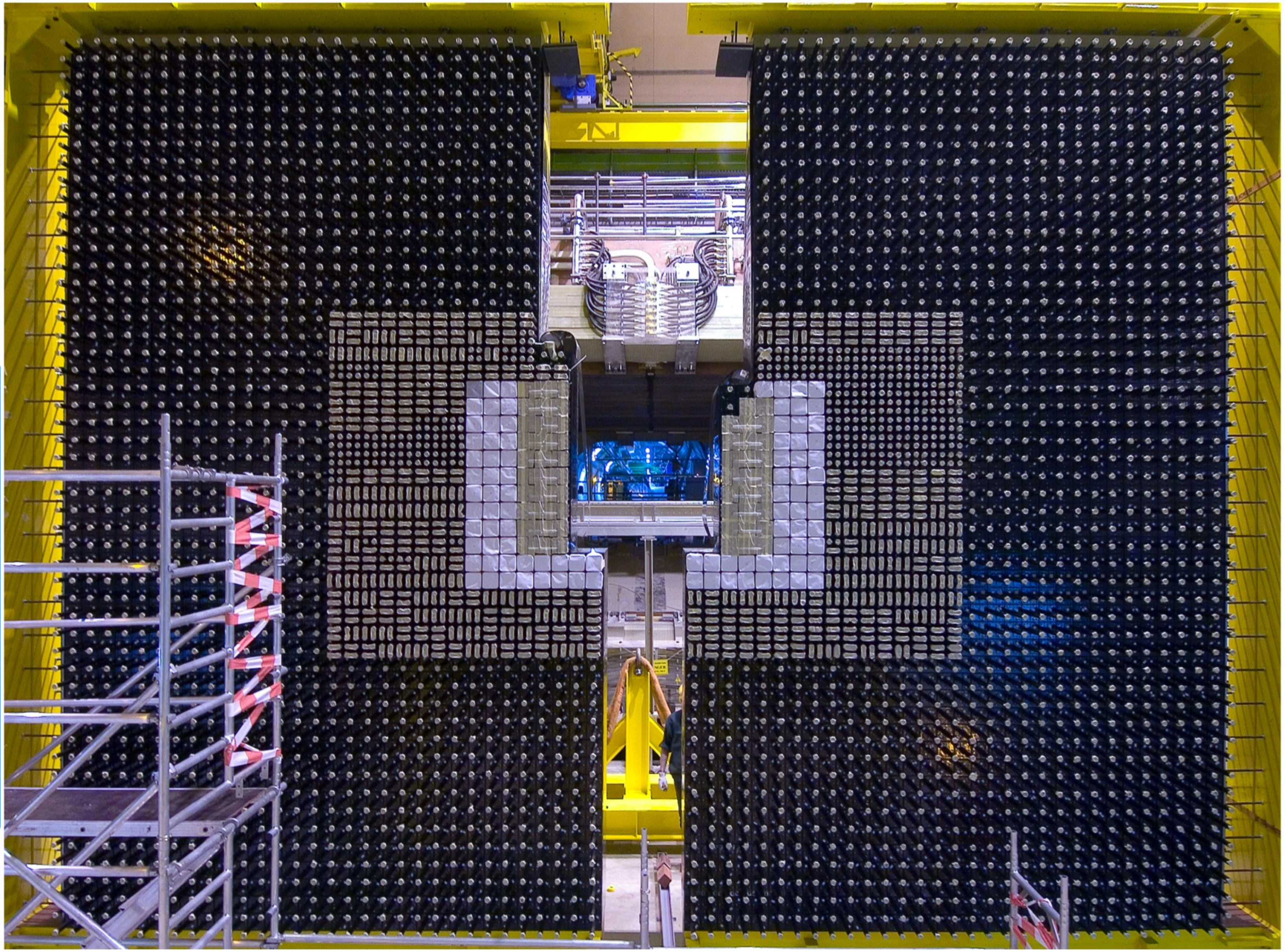




ECAL: essential to all measurements involving neutrals and electrons

Current LHCb ECAL

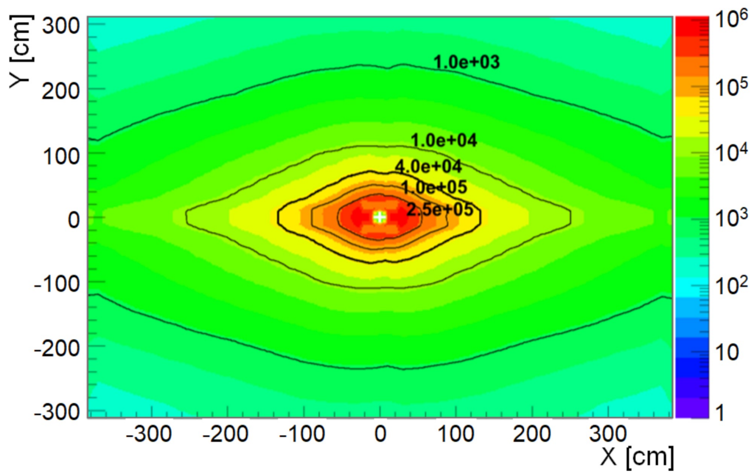
- Shashlik technology with 4×4, 6×6 and 12×12 cm^2 cell size
- Radiation hard up to **40 kGy**
- Energy resolution:
  $\sigma(E)/E \approx 10\%/\sqrt{E} + 1\%$
- Large array of $\approx 50\ \mathrm{m}^2$ with 3312 modules and 6016 channels

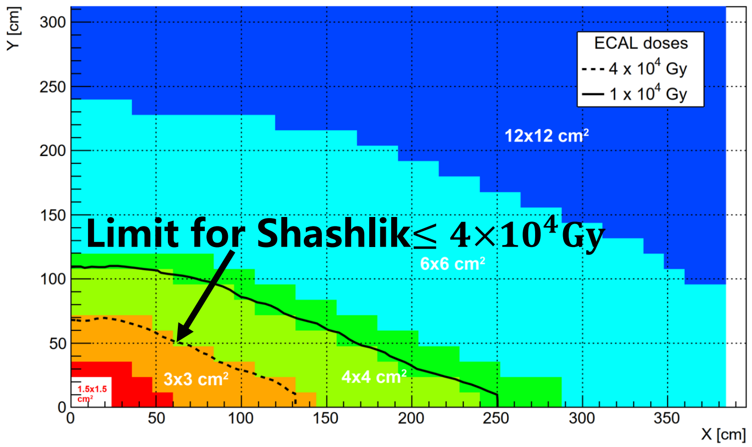


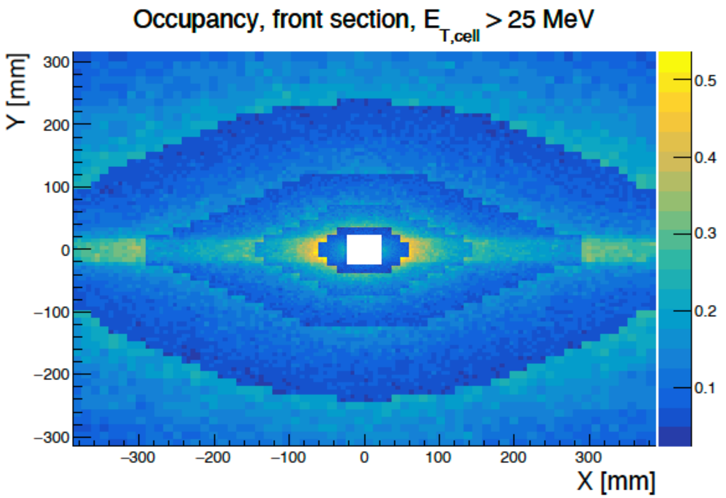
The current ECAL and motivation to upgrade

Upgrade II to be installed at LS4: operation at $1{\sim}2\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Accumulated radiation dose [Gy] after $300\ \mathrm{fb}^{-1}$







Radiation doses up to 1 MGy and $\leq 6\times10^{15}$ 1 MeV neq/cm² in the centre for $300\mathrm{fb}^{-1}$

- **New technologies required for the center**

Pile-up mitigation crucial

- **Timing $\mathcal{O}(10\ \mathrm{ps})$ precision**
- **Increased granularity**
- **longitudinal segmentation**

Keep current energy resolution of $\sigma(E)/E \approx 10\%/\sqrt{E} \oplus 1\%$

Technologies for ECAL Upgrade Ⅱ

SpaCal technology for inner region:

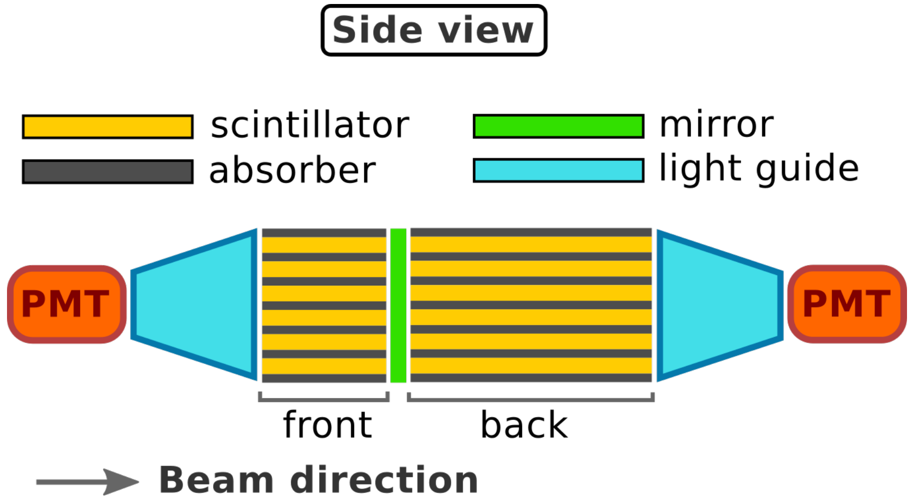
- scintillating crystal fibres + W absorber
  → Development of radiation-hard scintillating crystals
- $40-200\ \mathrm{kGy}$ region with scintillating plastic fibres and Pb absorber
  → Need radiation-tolerant organic scintillators

Scintillators for calorimeter

- Investigation of crystals properties
  - Good timing performances
  - Excellent energy resolution
  - Radiation tolerance

Advantages:

- Used in the harsh irradiation environment
- Flexible technology for tuning radiation length, Moliere radius, and energy resolution



Furthermore:

- longitudinal segmentation to improve timing resolution, reconstruction, particle identification and have less effect from radiation damage

Advantages of GAGG as Scintillator

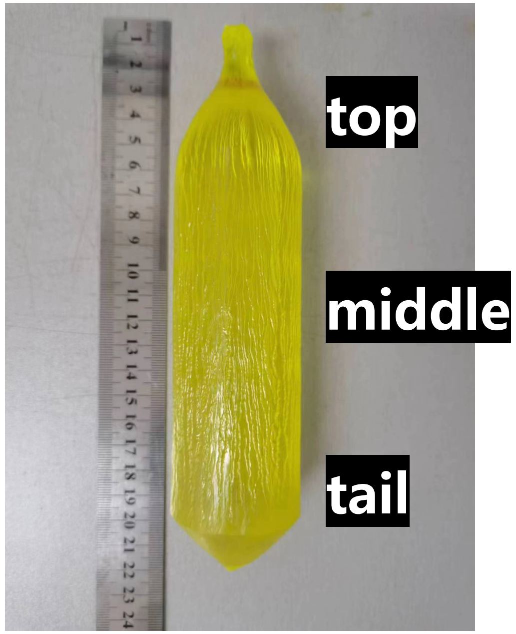
- ✓ **High Light Yield**
- ✓ **Fast decay**
- ✓ **Attractive time resolution to minimum-ionizing particles**

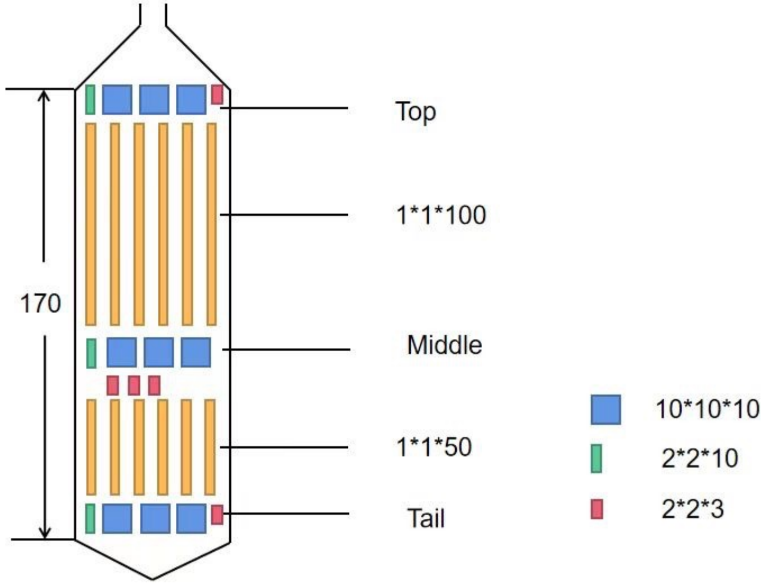
	Density (g/cm^3)	Decay Time (ns)	Light Yield (MeV^{-1})	Deliquesce
NaI(Tl)	3.67	230	38,000	yes
BGO	7.17	300	8,000	no
LSO	7.4	47	25,000	weak
LuAG(Ce)	6.7	68	25,000	no
LuAG(Pr)	6.7	22	20,000	no
GAGG-F	6.6	50	30,000	no
GAGG-T	6.6	90	42,000	no
GAGG-HL	6.6	150	54,000	no

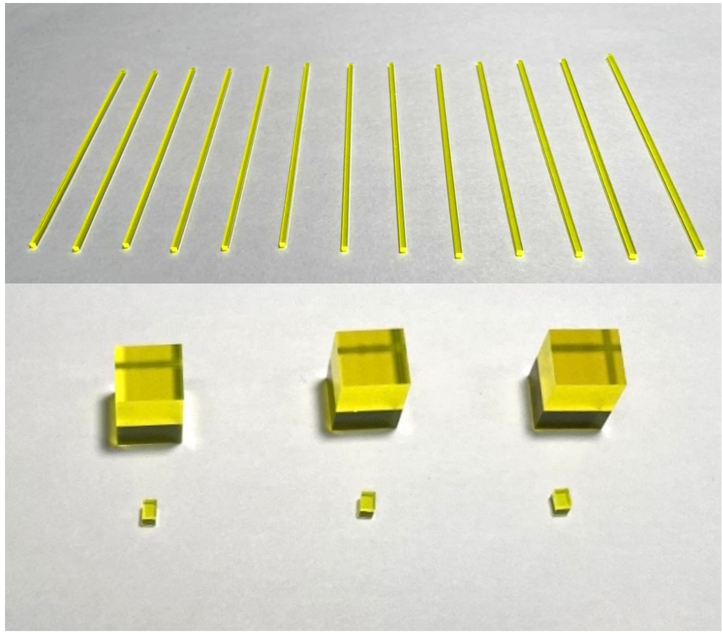
Samples

- **Naming scheme**
  - **Batch 1 (CN-Jan-2023): samples received in January, 2023**
  - **Batch 2 (CN-Apr-2023): samples received in April, 2023**
    - ✓ **Ingot 1 (CN-Apr-2023-1)**
    - ✓ **Ingot 2 (CN-Apr-2023-2)**

For the first characterization, we used only the $2\times2\times3\ \mathrm{mm}^3$ samples







Characterisation

- **Photoluminescence spectrum**
- **Transmission and absorbance**

} **Optical properties**

- **Scintillation kinetics**
- **Light output**
- **Coincidence time resolution (CTR)**

} **Detector properties**

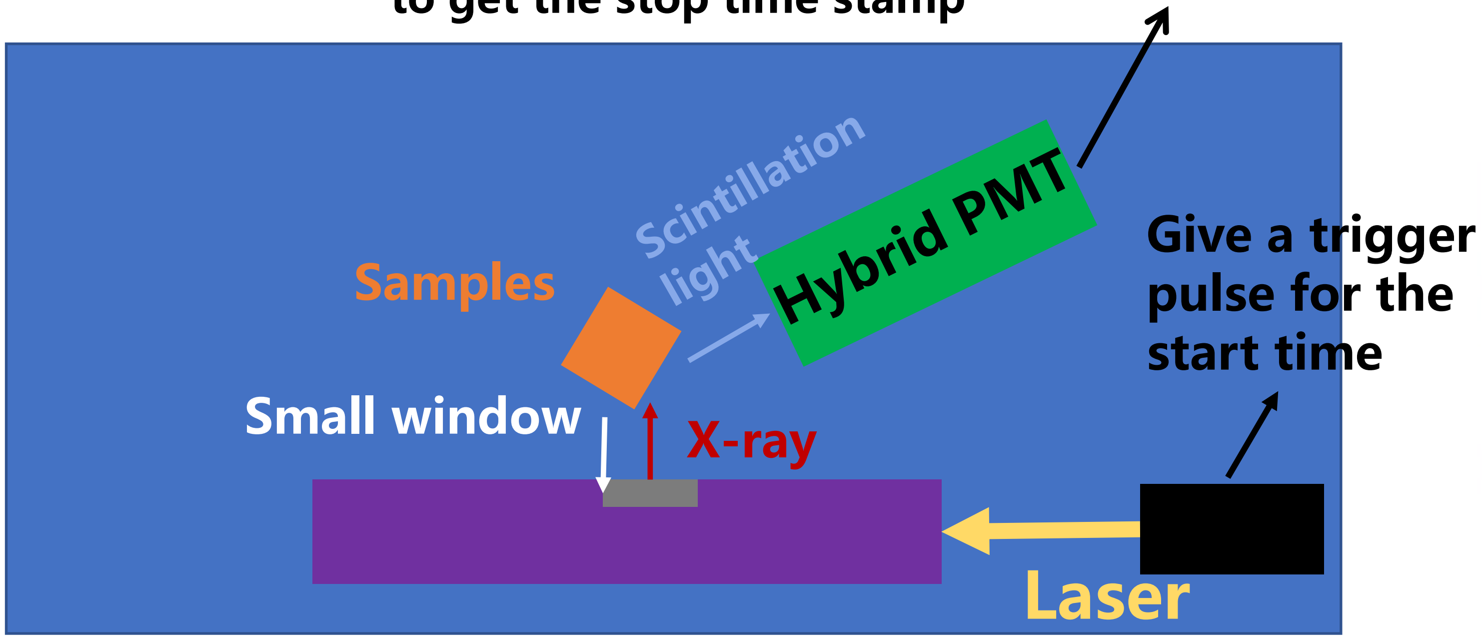
Part 1

- Scintillation kinetics
- Light output

Scintillation kinetics: bench diagram

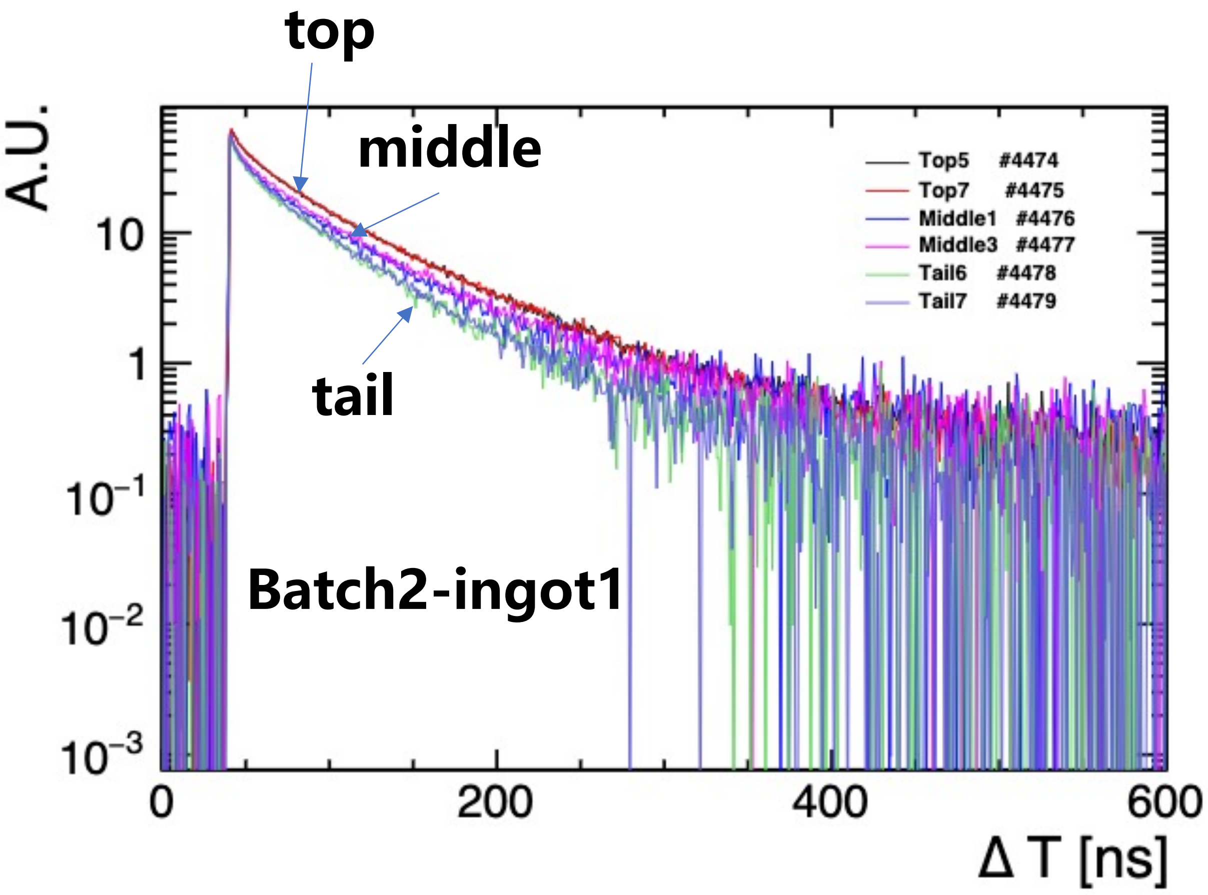
- Scintillation kinetics refers to the study of the time-dependent behavior of the scintillation light
  - Measure $\Delta T = \text{stop time} - \text{start time}$

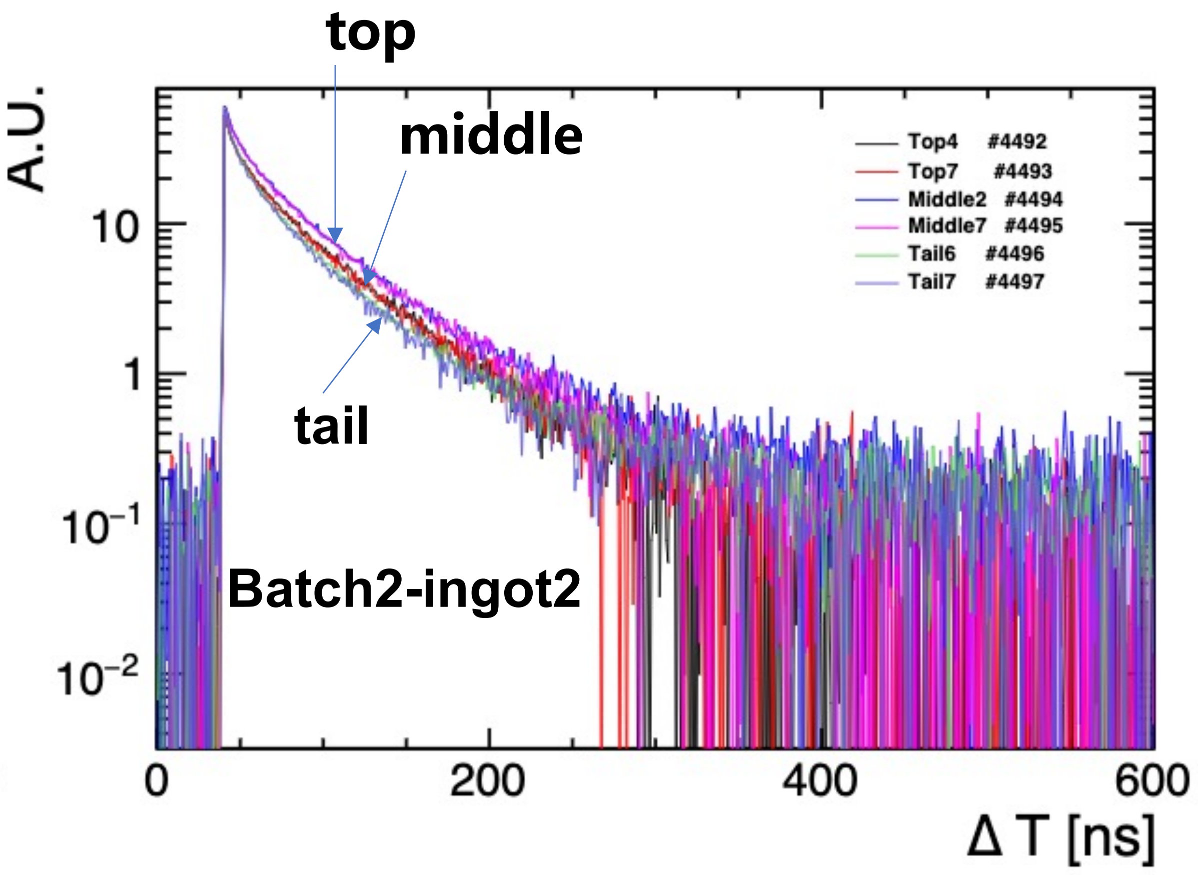
- The bench:



Scintillation kinetics: raw data

➢ **Decay time decreases from the top to the tail**





Scintillation kinetics: fit method

➢ **Fit ΔT distribution with**

impulse response function (Time resolution)

Decay time

Rise time

$$f(t|\theta)\otimes \mathrm{IRF} = \left\{ \Theta(t-\theta) \sum_{i=1}^{N} \frac{e^{-(t-\theta)/\tau_{d,i}} - e^{-(t-\theta)/\tau_{r,i}}}{\tau_{d,i} - \tau_{r,i}} \times \rho_i \right\} \otimes IRF$$

Heaviside step function

start time

fraction of i

$$\frac{1}{\tau_{d,eff}} \equiv \sum_{i=1}^{N} \frac{\rho_i}{\tau_{d,i}}$$

- **Three decay time and one rise time are used**

Scintillation kinetics: result

- **Decay time decreases from the top to the tail**

Decay time: https://doi.org/10.1039/d2ma00626j

Table 2: Scintillation rise time (τ_r), three decay times (τ_{d1}, τ_{d2}, τ_{d3}), and relative intensities of the corresponding components R_1, R_2, R_3. The uncertainty is 25 ps and 5%, for the rise and decay times, respectively. The first three rows in the table were taken from reference [3].

GAGG SIPAT	τ_r [ps]	τ_{d1} [ns]	R_1 [%]	τ_{d2} [ns]	R_2 [%]	τ_{d3} [ns]	R_3 [%]	$\tau_{d,eff}$ [ns]
C&A CFAG	32	6.0	4.6	45	69.2	222	26.3	41
ILM GAGG	37	4.0	3.2	40	56.4	238	40.4	40
Fomos GAGG	30	2.2	0.5	53	41.7	166	57.8	73
Batch1 Top2 #4424	62	9.2	6.2	54	68.7	267	25.1	49
Batch1 Top7 #4425	83	7.8	5.8	54	69.1	242	25.1	47
Batch1 Middle7 #4426	47	6.2	5.0	46	64.5	149	30.5	41
Batch1 Middle8 #4427	16	7.3	6.5	49	68.8	180	24.7	41
Batch1 Tail3 #4428	24	6.5	6.9	43	69.2	188	23.9	36
Batch1 Tail8 #4429	87	7.7	8.7	46	70.3	210	21.0	36
Batch2-ingot1 Top5 #4474	23	7.0	[illegible]	48	66.6	162	28.1	43
Batch2-ingot1 Top7 #4475	27	7.1	5.3	46	62.9	134	31.8	43
Batch2-ingot1 Middle1 #4476	28	6.4	6.7	47	70.5	172	22.8	37
Batch2-ingot1 Middle3 #4477	21	4.9	4.6	43	65.4	147	30.0	37
Batch2-ingot1 Tail6 #4478	26	5.4	6.7	42	70.5	206	22.9	33
Batch2-ingot1 Tail7 #4479	27	4.8	6.8	40	69.1	134	24.1	30
Batch2-ingot2 Top4 #4492	17	3.8	6.7	30	59.5	101	33.8	25
Batch2-ingot2 Top7 #4493	7	4.5	8.3	34	67.8	139	23.9	25
Batch2-ingot2 Middle2 #4494	21	5.0	8.6	36	69.1	134	22.4	26
Batch2-ingot2 Middle7 #4495	10	5.3	8.1	36	65.2	128	26.7	28
Batch2-ingot2 Tail5 #4496	11	3.6	8.8	29	66.0	124	25.3	20
Batch2-ingot2 Tail6 #4497	10	4.1	10.4	30	67.6	138	22.0	20

Preliminary

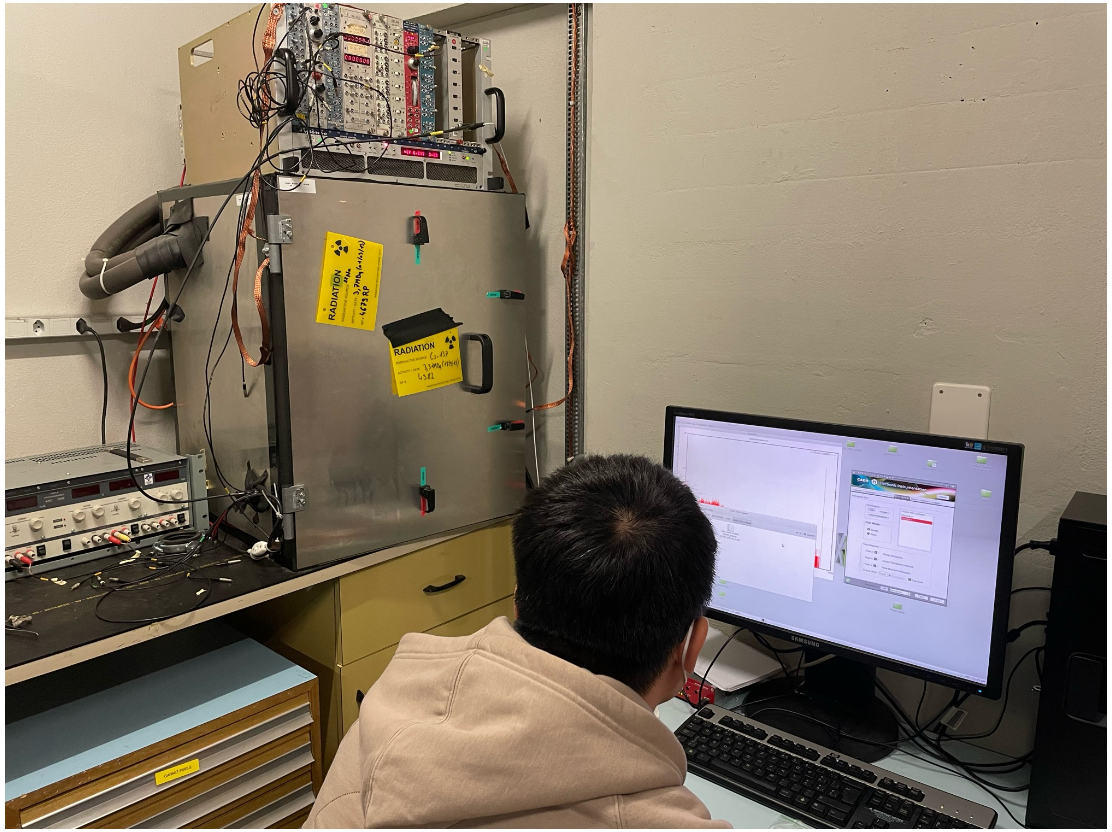
Decreasing

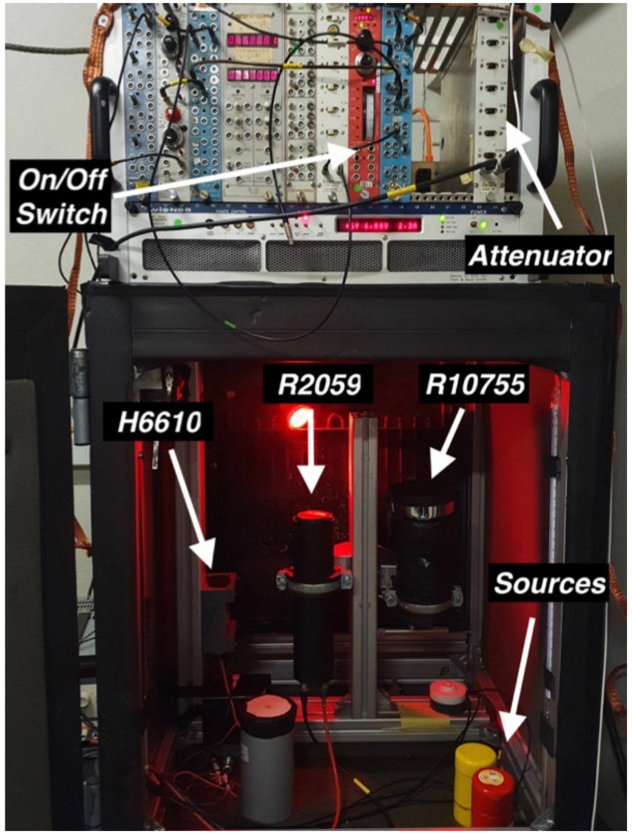
The uncertainty is 25 ps for rise time and 5% for decay time

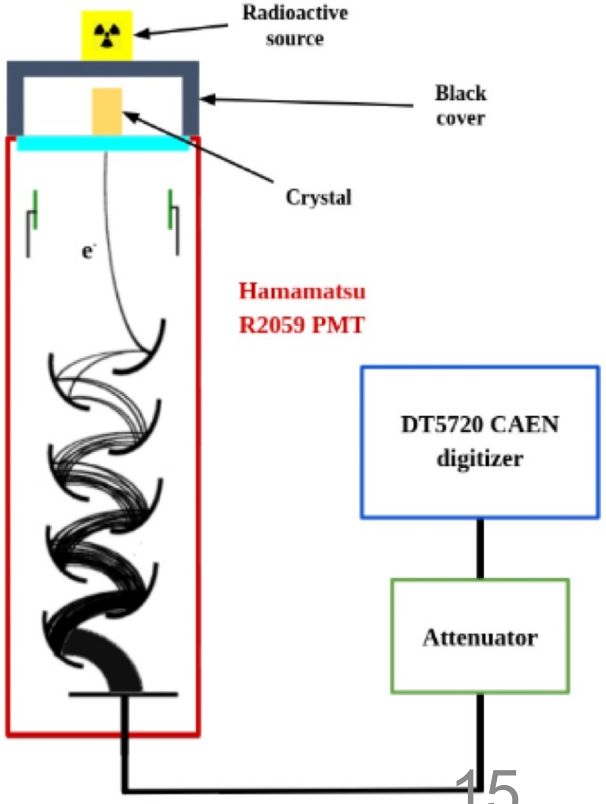
Light output: bench diagram

- **Definition:**
  - **Number of photons per unit of energy deposited**

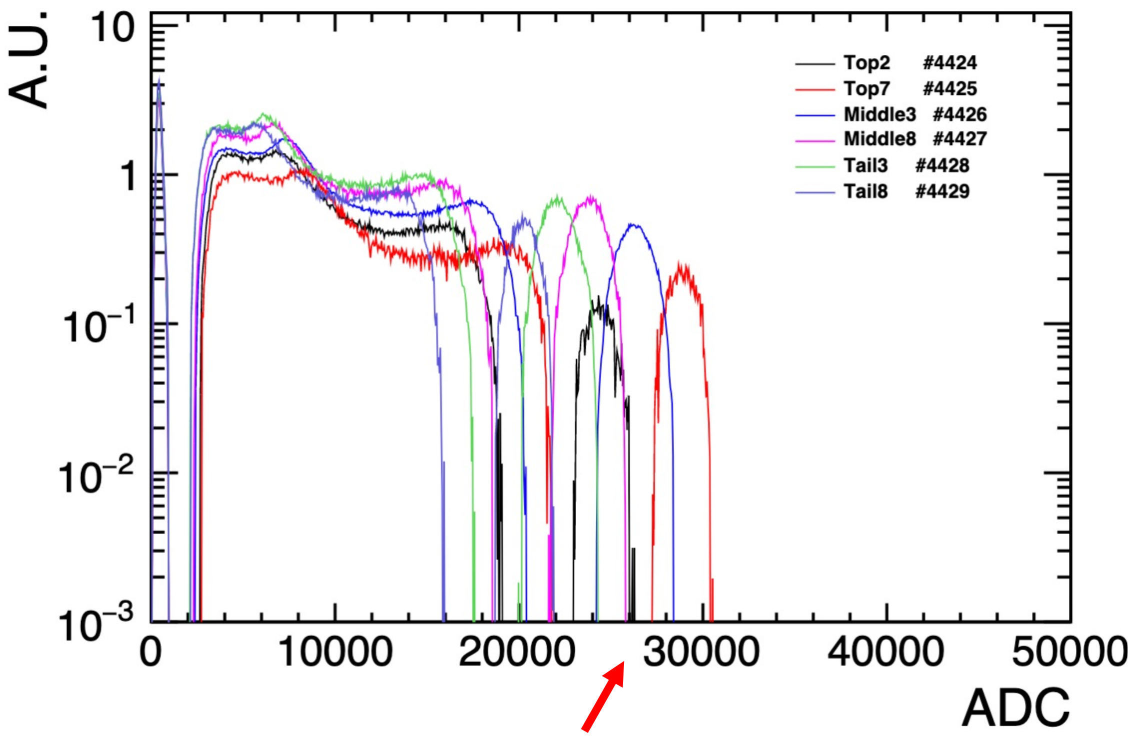
- **The bench:**



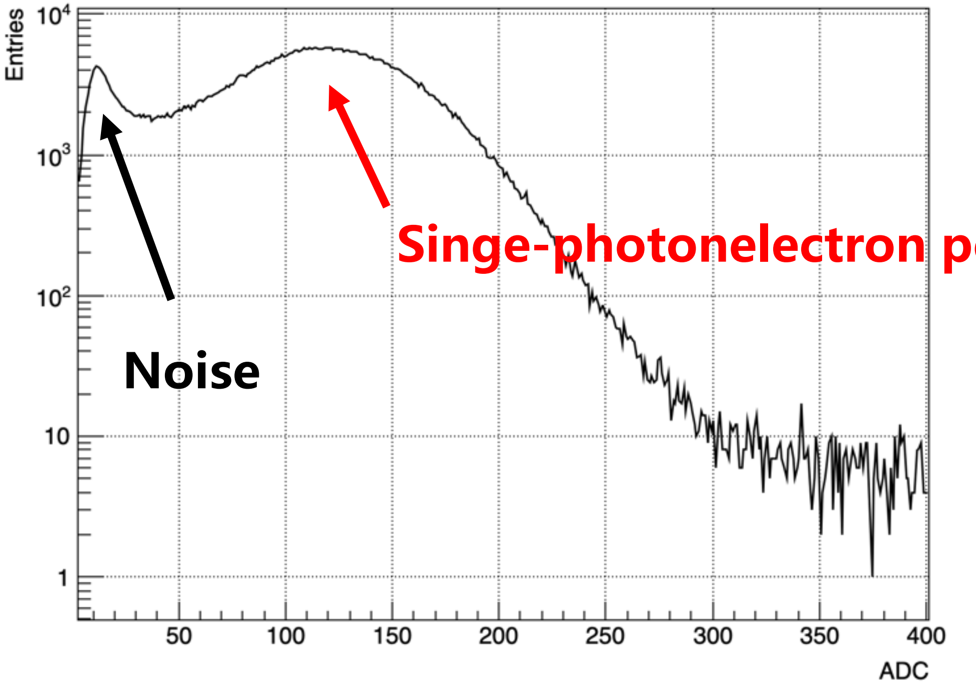




Light output: fit method



Care about **full energy peak**



$$\text{Light output} = \frac{\text{peak}_{\text{full energy peak}} \times \text{ChS}_{\text{full energy } peak}}{peak_{1e} \times \text{ChS}_{1e}} \times 10^{\frac{\text{Att[db]}}{20}} \times \frac{1}{\text{Energy[MeV]}} \times \frac{1}{\text{QE}}$$

Light output: result

Table 1: Light yield of the smaller samples, upon 661.7 keV excitation with a ^{137}Cs gamma source. The relative uncertainty is ±5%. The first three rows in the table were taken from reference [2].

crystal	Light output [MeV^{-1}]
C&A CFAG	32140 ± 1610
ILM GAGG	27900 ± 1400
Fomos GAGG	37700 ± 1890
Batch1 Top2 #4424	30810 ± 1540
Batch1 Top7 #4425	35890 ± 1790
Batch1 Middle3 #4426	32820 ± 1640
Batch1 Middle8 #4427	29610 ± 1480
Batch1 Tail3 #4428	27660 ± 1380
Batch1 Tail8 #4429	25290 ± 1260
Batch2-ingot1 top5 #4474	27439 ± 1370
Batch2-ingot1 top7 #4475	27739 ± 1390
Batch2-ingot1 Middle1 #4476	250[illegible]0 ± 1250
Batch2-ingot1 Middle3 #4477	26930 ± 1350
Batch2-ingot1 Tail6 #4478	21530 ± 1080
Batch2-ingot1 Tail7 #4479	20650 ± 1030
Batch2-ingot2 Top4 #4492	21320 ± 1070
Batch2-ingot2 Top7 #4493	20190 ± 1010
Batch2-ingot2 Middle2 #4494	21480 ± 1070
Batch2-ingot2 Middle7 #4495	22480 ± 1120
Batch2-ingot2 Tail5 #4496	15400 ± 770
Batch2-ingot2 Tail6 #4497	15600 ± 780

Preliminary

Light output: https://doi.org/10.1016/j.nima.2021.165231

- Light output decreases from top to the tail

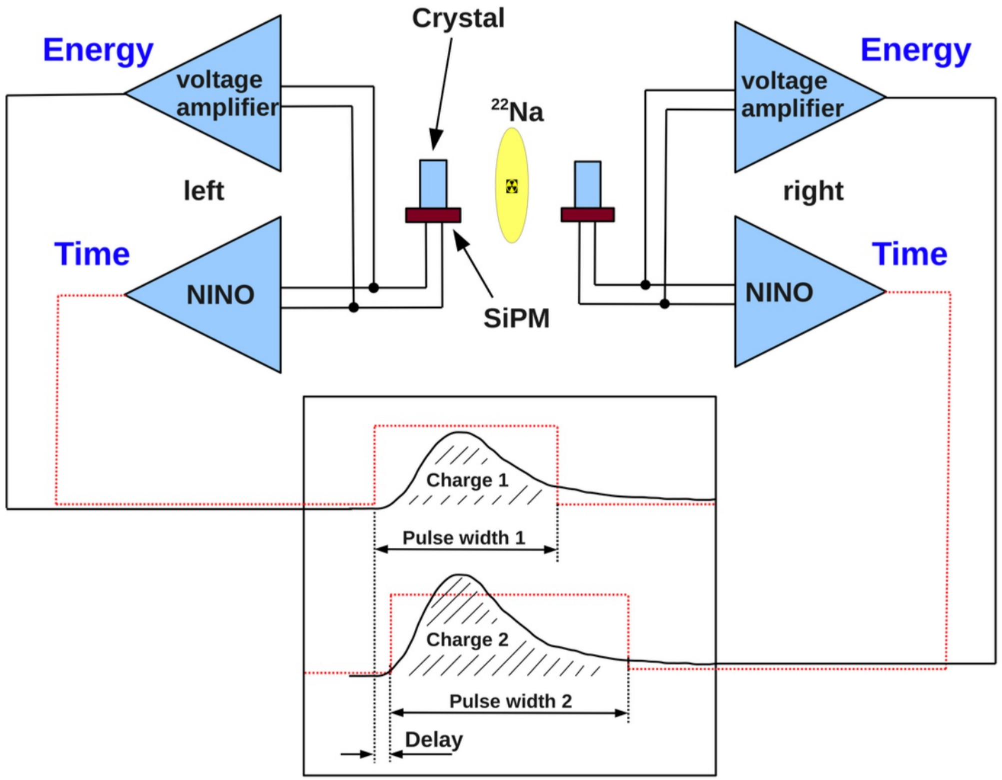
Decreasing

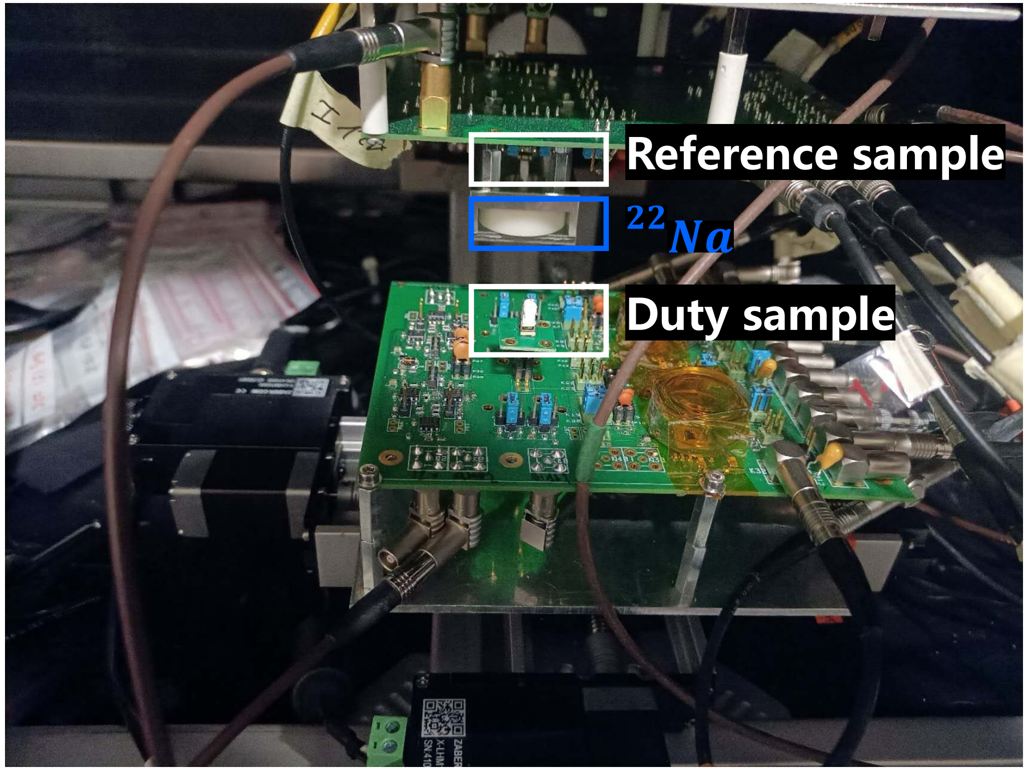
Part 2

➢ **Coincidence time resolution (CTR)**

CTR: bench diagram

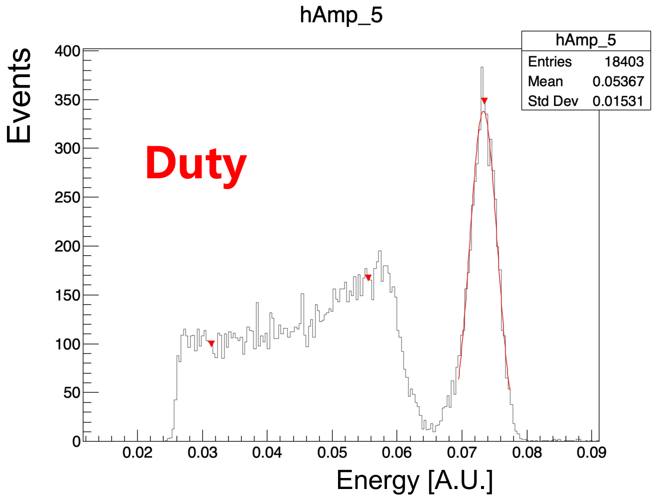
- CTR obtained by measuring the arrival time difference of the two 511 KeV gamma signal with leading edge discriminator

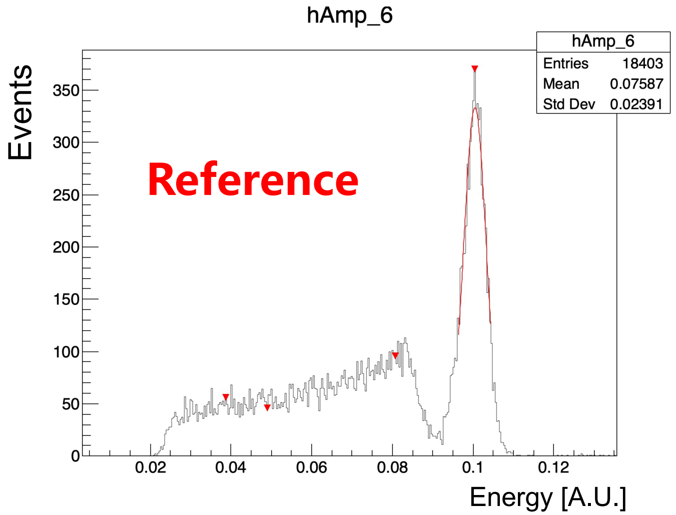




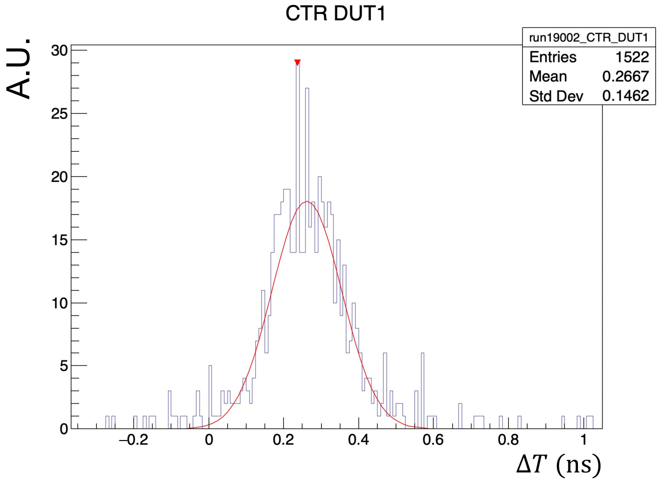
CTR: fit method

- **Only full energy peak events used**





- **Gaussian used to fit the time difference**



CTR: result

Table 3: CTR measurement results for the small samples. The first three rows in the table were taken from reference [2].

CTR: https://doi.org/10.1016/j.nima.2021.165231

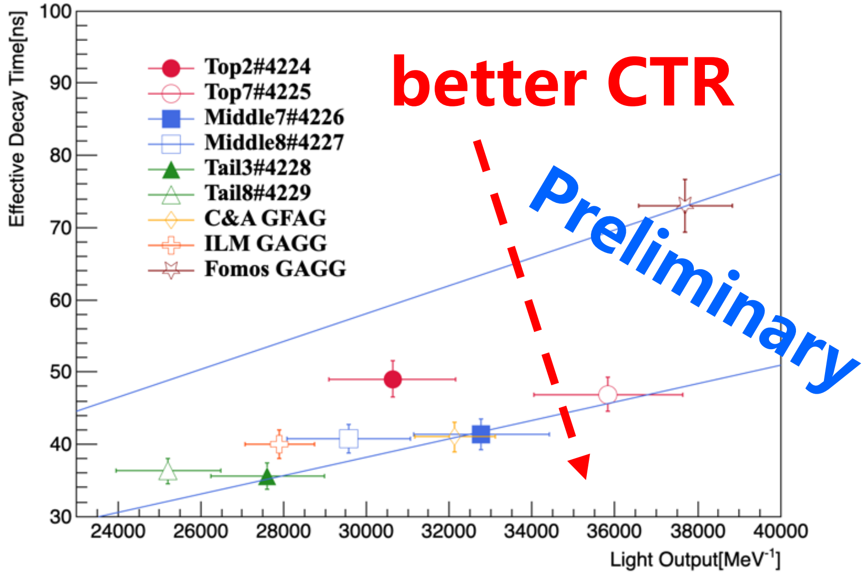
crystal	CTR [ps]
C&A CFAG	109 ± 3
ILM GAGG	116 ± 3
Fomos GAGG	129 ± 3
Batch1 Top2 #4424	121 ± 3
Batch1 Top7 #4425	120 ± 3
Batch1 Middle3 #4426	118 ± 3
Batch1 Middle8 #4427	134 ± 3
Batch1 Tail3 #4428	124 ± 3
Batch1 Tail8 #4429	113 ± 3
Batch2-ingot1 Top5 #4474	118 ± 3
Batch2-ingot1 Top7 #4475	123 ± 3
Batch2-ingot1 Middle1 #4476	118 ± 3
Batch2-ingot1 Middle3 #4477	113 ± 3
Batch2-ingot1 T6 #4478	119 ± 3
Batch2-ingot1 T7 #4479	117 ± 3
Batch2-ingot2 Top4 #4492	117 ± 3
Batch2-ingot2 Top7 #4493	112 ± 3
Batch2-ingot2 Middle2 #4494	111 ± 3
Batch2-ingot2 Middle7 #4495	111 ± 3
Batch2-ingot2 Tail5 #4496	118 ± 3
Batch2-ingot2 Tail6 #4497	117 ± 3

Preliminary

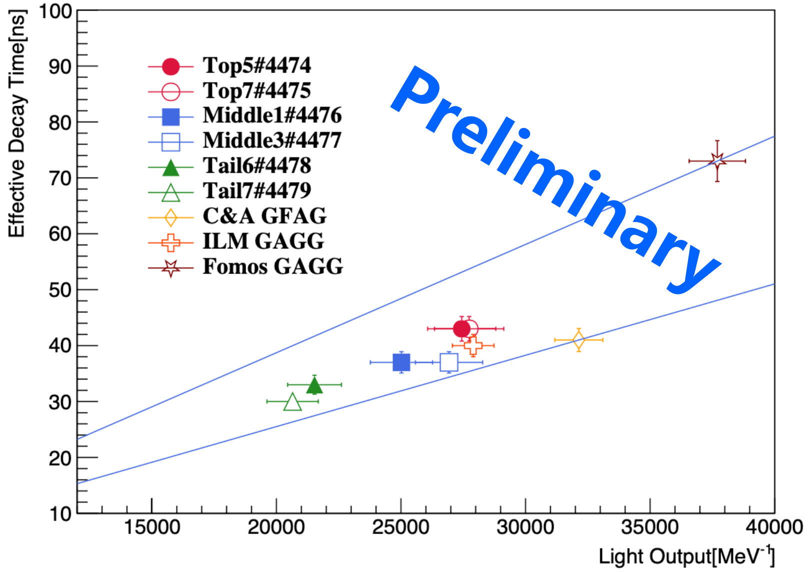
- The CTR for different parts are close to each other

Effective decay times vs. light output(LO)

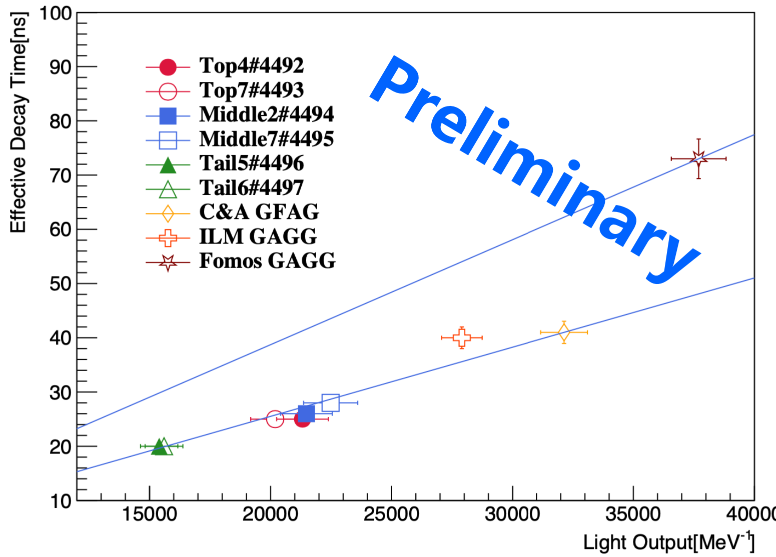
➢ Timing performance for different part are close to each other



Batch1



Batch2-ingot1



Batch2-ingot2

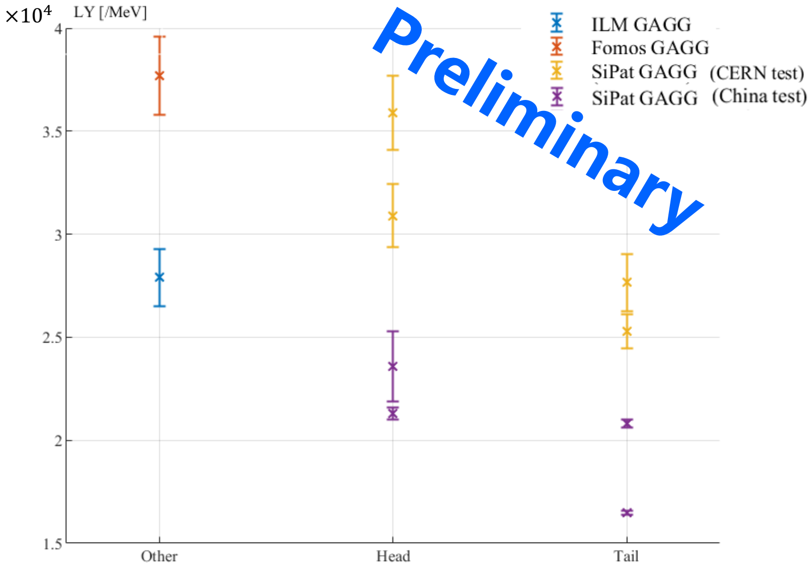
➢ The blue lines represent constant ratios(CTR): moving along them grants the same decay time-light output ratio and thus same timing resolution

$$\mathrm{CTR} \propto \sqrt{\frac{\tau_{decay}}{\mathrm{LO}}}$$

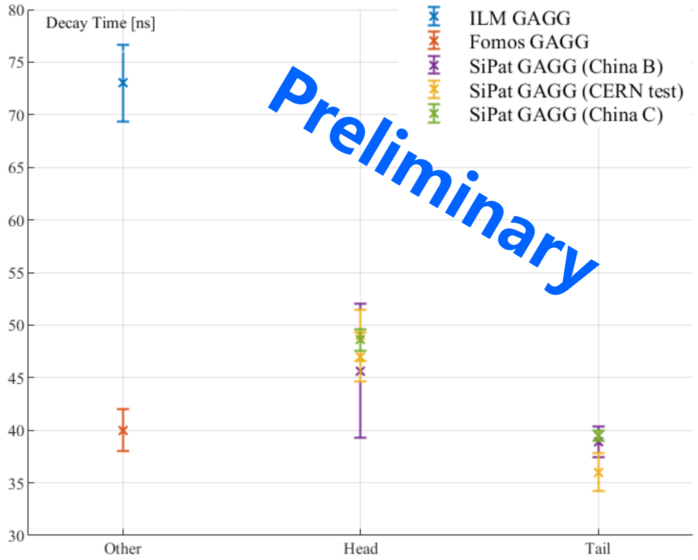
CTR: https://doi.org/10.1016/j.nima.2021.165231

Result Comparison

Light output



Decay time



China B: TCSPC method
China C: Average waveform method

- **Setup a scintillator performance testing system @THU**
- **Compared with CERN results for Batch 1 (CN-Jan-2023)**
- **The results have a good consistency**
- **Need to take different slight of different methods into account**

Summary and Outlook

Chinese group has very close collabration with Chinese institution of scintlator.

- Very good results have obtained - High-quality large samples

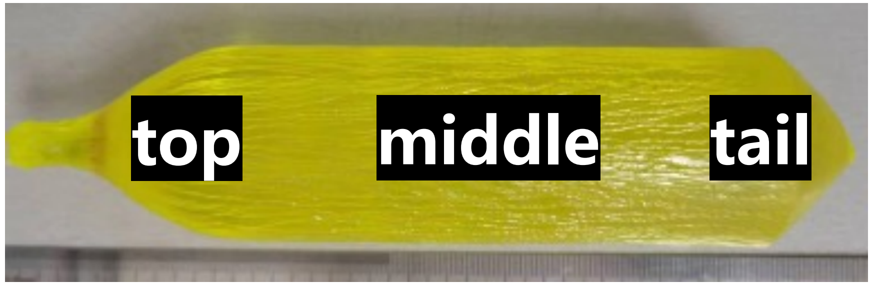
For current GAGG samples:

- Light output reaches ~15000 per MeV
- Decay time reaches the level of ~20 ns
- Competitive with the GAGG from C&A, ILM, and Fomos

Ongoing R&D has the Chinese group optimistic about results.

- The Chinese scintlator institution's improvement direction is clear, with hopes to reach the target in upcoming crystal batches.

The test platform has been setup in China to improve the progress of R&D.



Absorbance: less → more

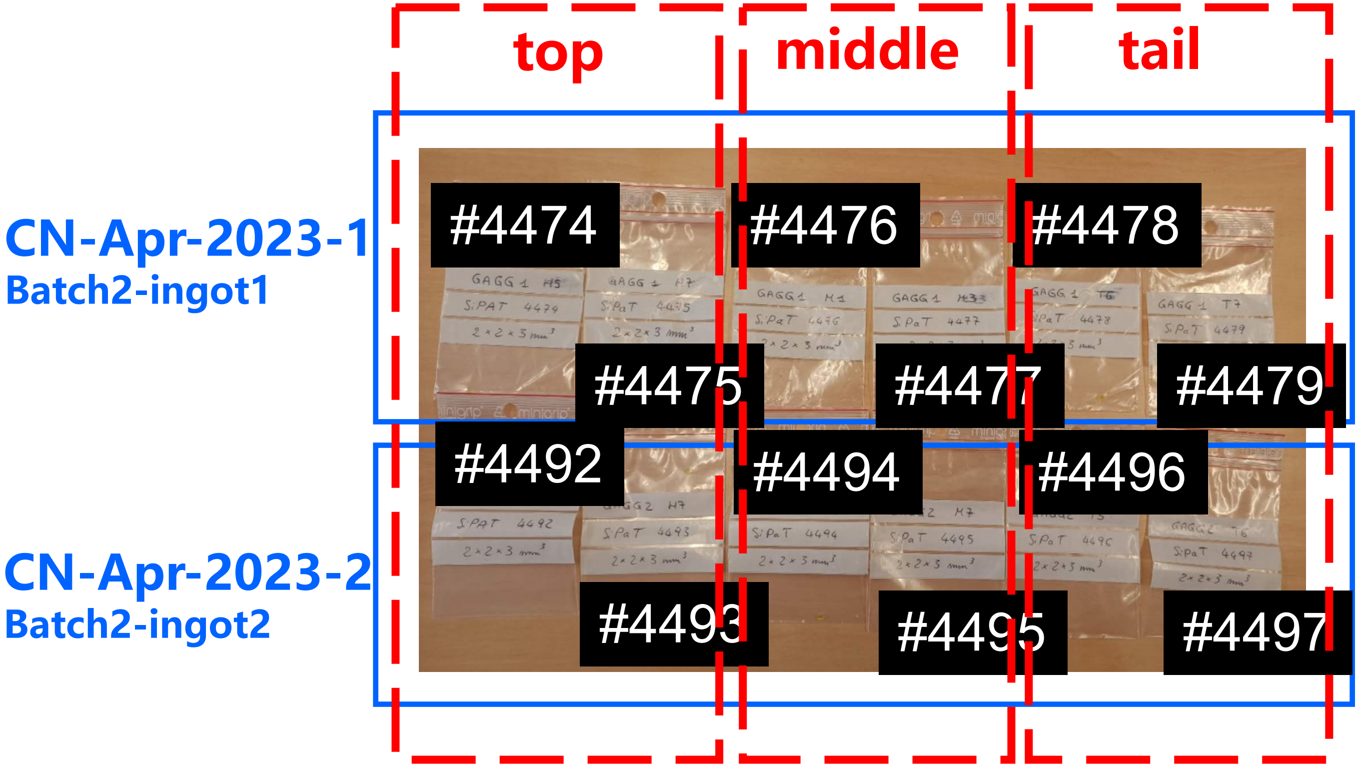
Decay time: slow: 28.0ns ← fast: 20.0 ns

Light output: more: 22480/MeV ← less: 15400/MeV

Thanks for your attention!

Back up

Samples


top
middle
tail
CN-Apr-2023-1
Batch2-ingot1
#4474
#4476
#4478
#4475
#4477
#4479
CN-Apr-2023-2
Batch2-ingot2
#4492
#4494
#4496
#4493
#4495
#4497

Samples (cont.)

- Numbering correspondence

Sipat	CERN
GAGG1 H5 $2\times2\times3$ mm^3	Top5 #4474
GAGG1 H7 $2\times2\times3$ mm^3	Top7 #4475
GAGG1 M1 $2\times2\times3$ mm^3	Middle1 #4476
GAGG1 M3 $2\times2\times3$ mm^3	Middle3 #4477
GAGG1 T6 $2\times2\times3$ mm^3	Tail6 #4478
GAGG1 T7 $2\times2\times3$ mm^3	Tail7 #4479

Batch2-ingot1

Sipat	CERN
GAGG2 H4 $2\times2\times3$ mm^3	Top4 #4492
GAGG2 H7 $2\times2\times3$ mm^3	Top7 #4493
GAGG2 M2 $2\times2\times3$ mm^3	Middle2 #4494
GAGG2 M7 $2\times2\times3$ mm^3	Middle7 #4495
GAGG2 T5 $2\times2\times3$ mm^3	Tail5 #4496
GAGG2 T6 $2\times2\times3$ mm^3	Tail6 #4497

Batch2-ingot2

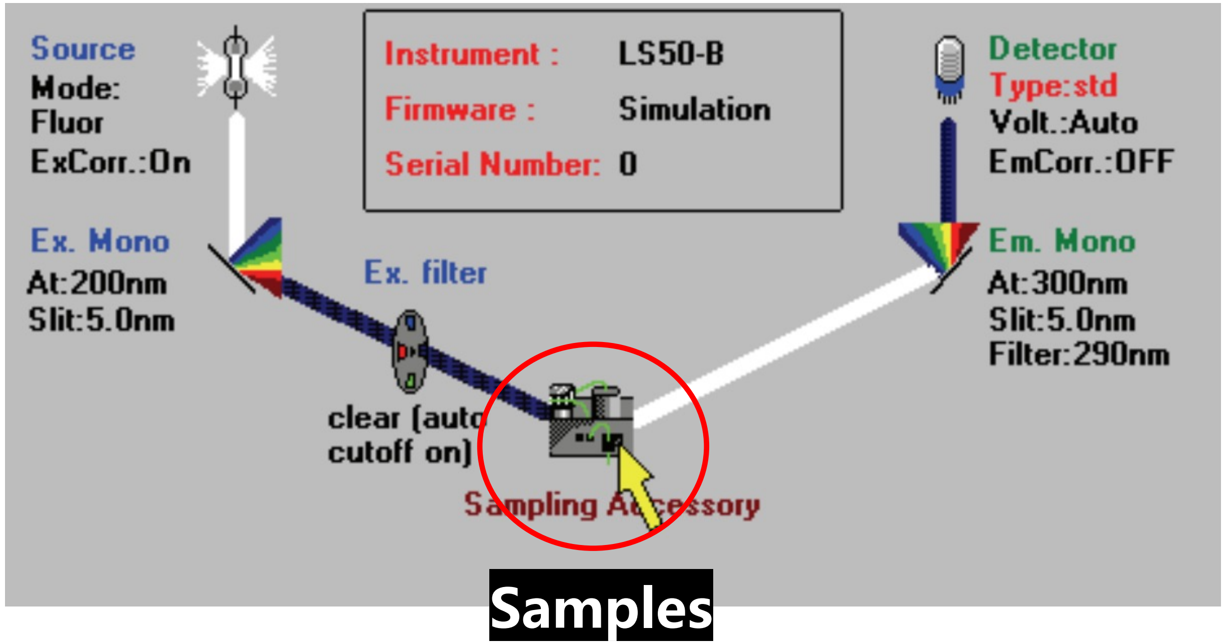
Part 0

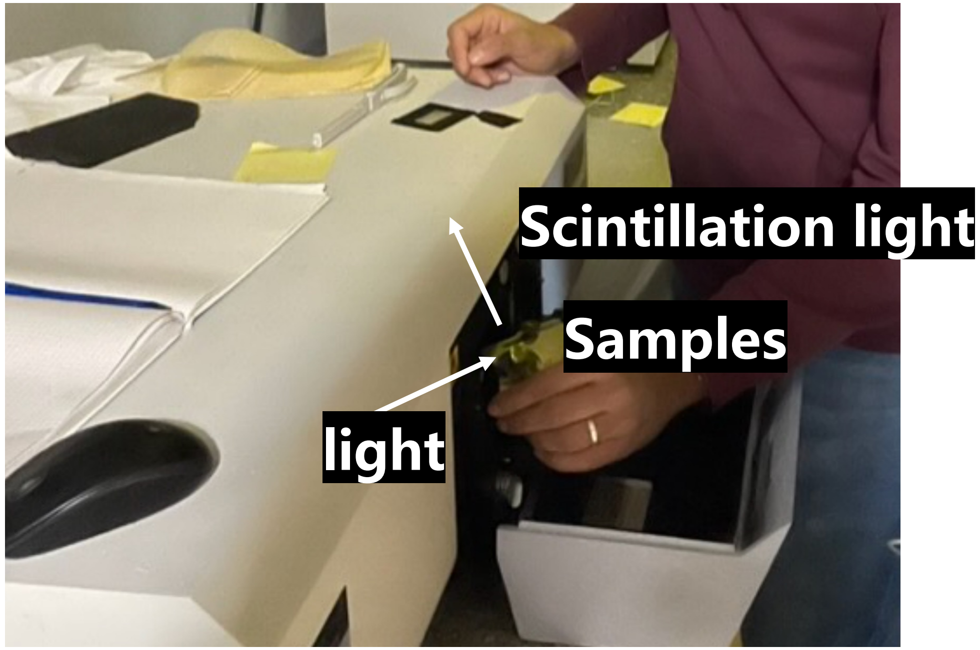
- **Photoluminescence spectrum**
- **Transmission and absorbance**

Photoluminescence spectrum

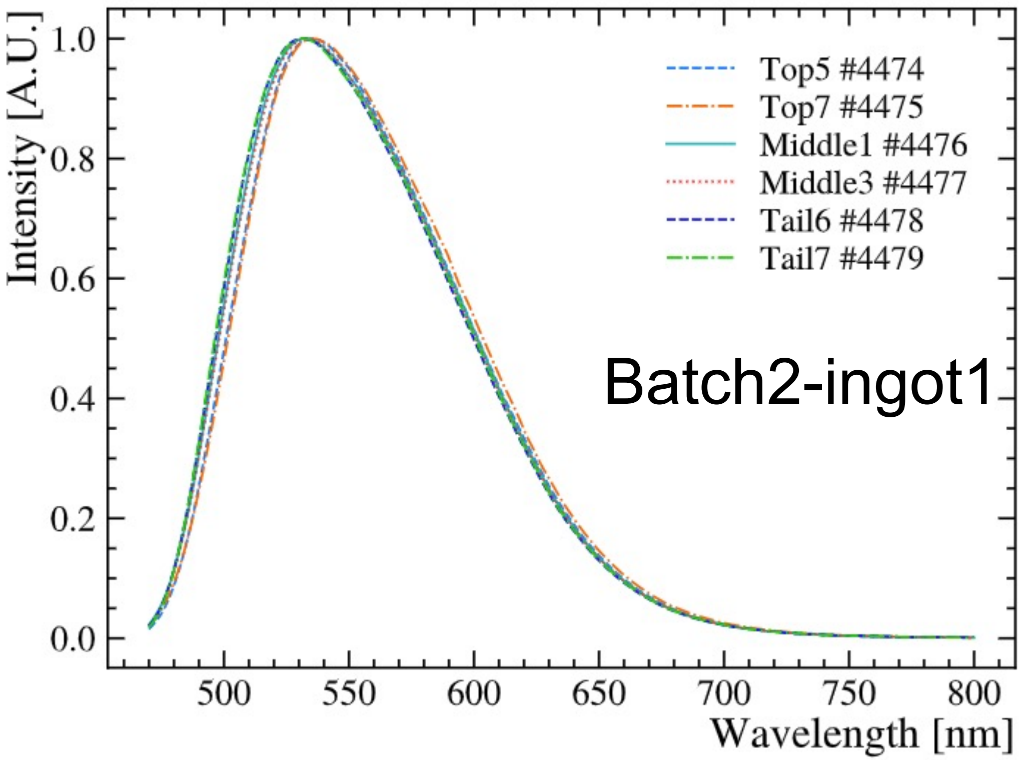
- Perkin Elmer LS55 Luminescence spectrometer
- The sample is excited with 450nm light
- Scan the wavelength of scintillation light

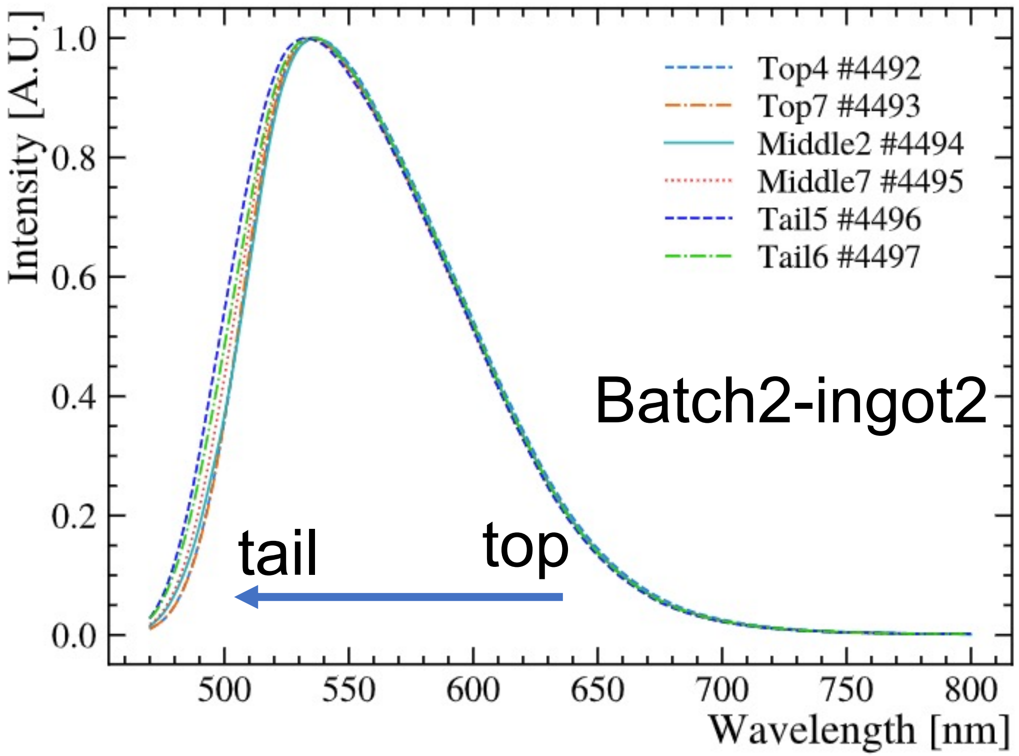
Perkin Elmer LS55 Luminescence spectrometer



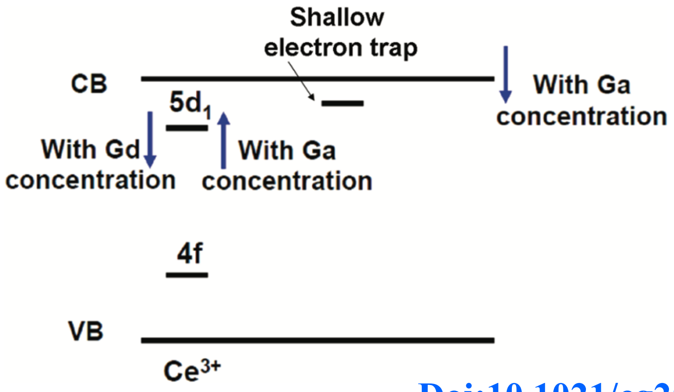


Photoluminescence spectrum





- **Blue shift from the top to the tail of the GAGG ingot**
- **Probably larger Ga concentration from the top to the tail**



Doi:10.1021/cg200694a

Transmission (T) and Absorbance (A)

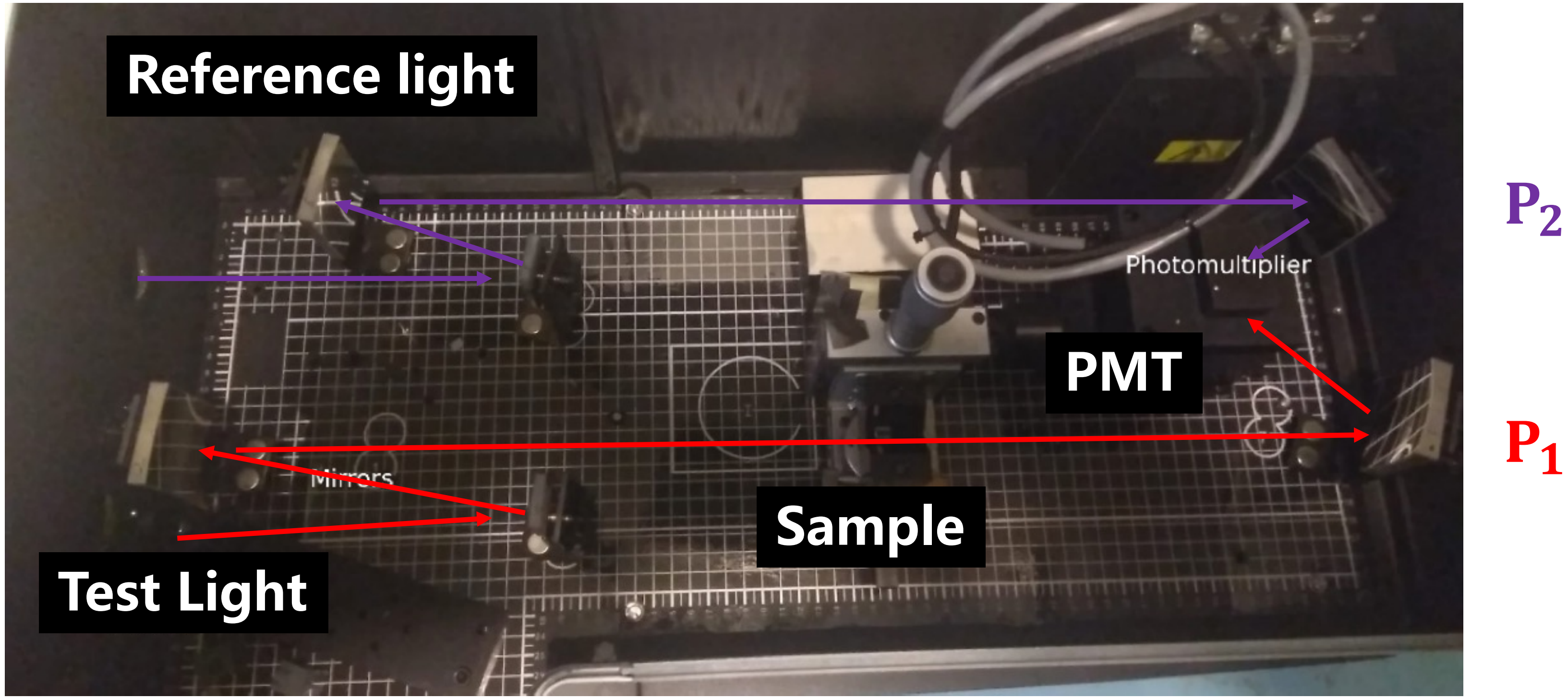
- Measured with Perkin Elmer Lambda 650 spectrophotometer

- Transmission

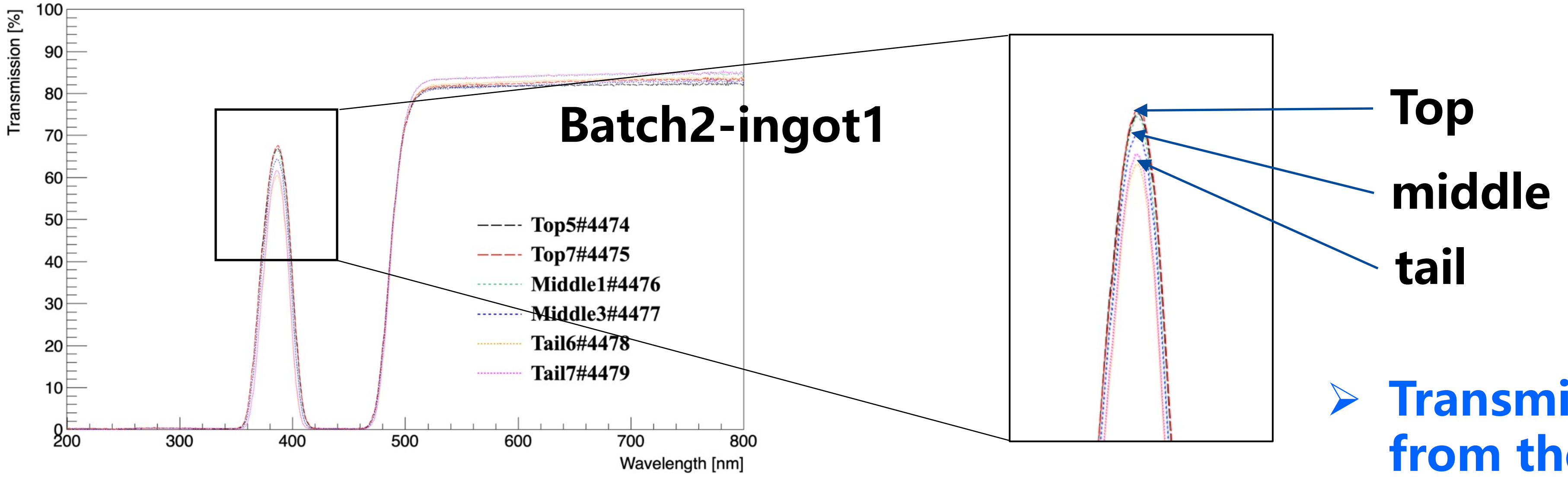
$$T = \frac{P_1}{P_2}$$

- Absorbance

$$A = -\log_{10} T$$

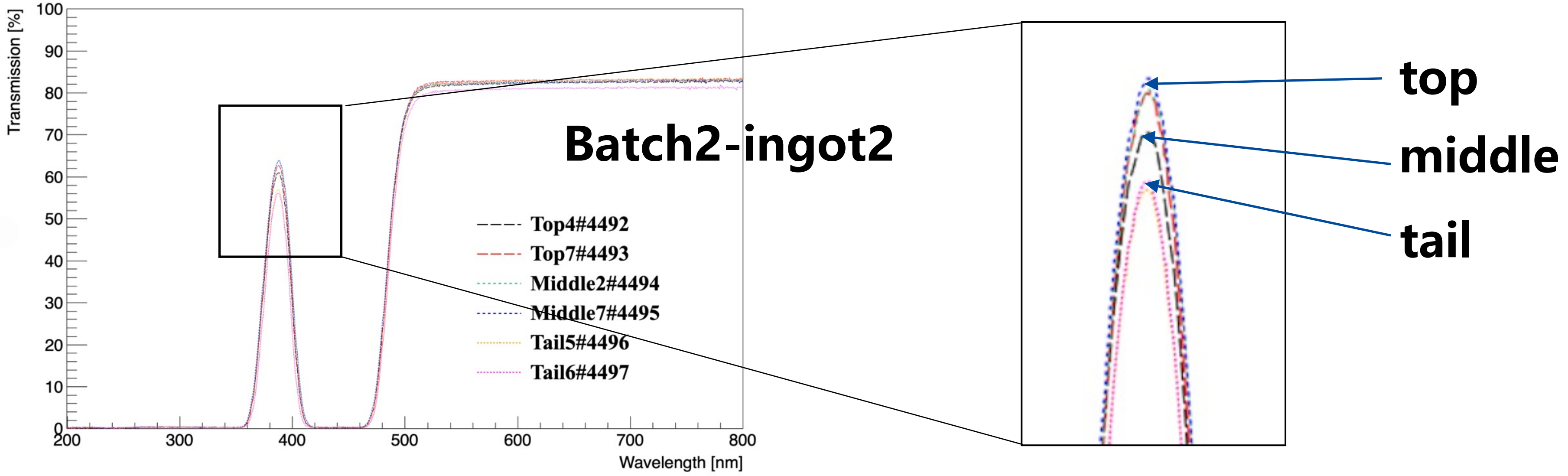


Transmission (T)

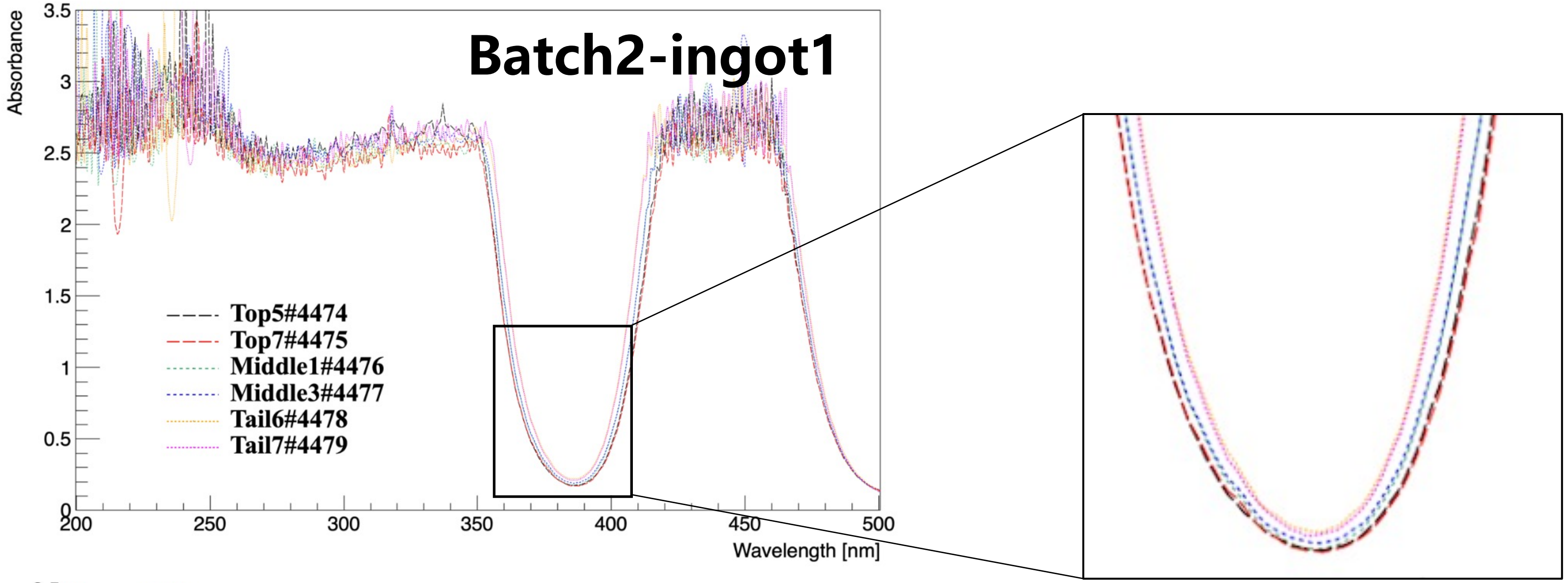


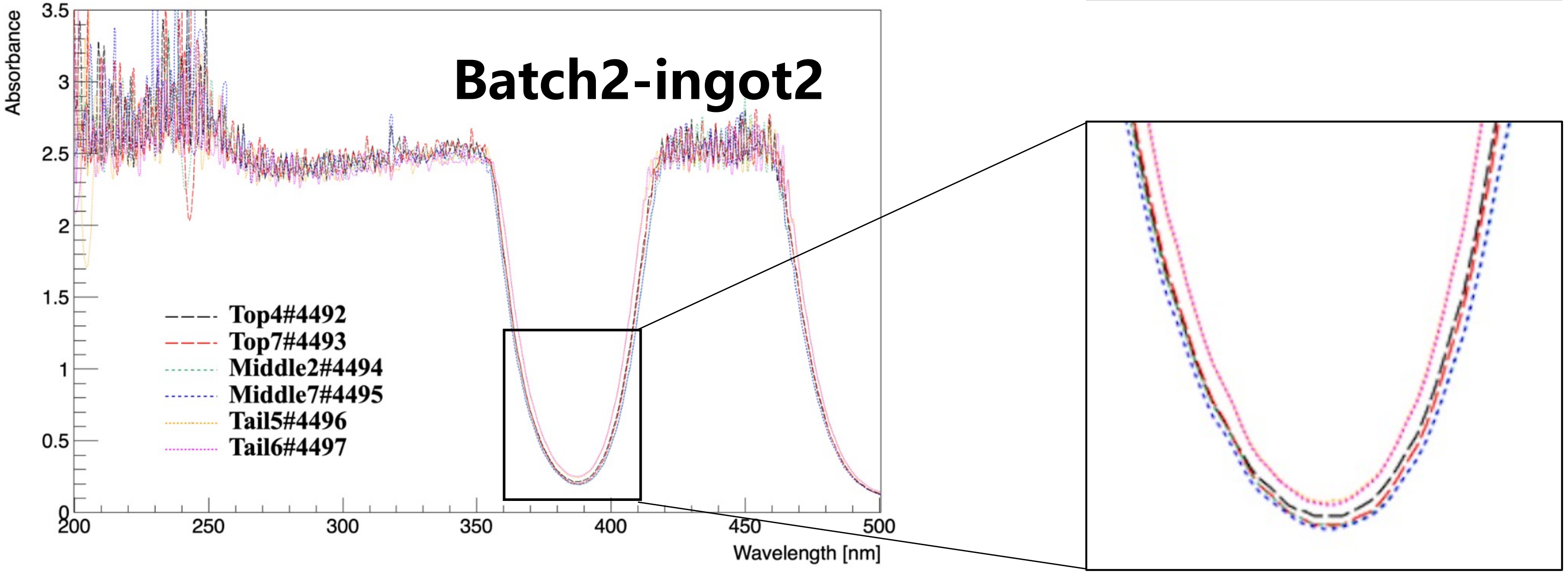
Possible reason: less cerium

- **Transmission decrease from the top to the tail**



Absorbance (A)





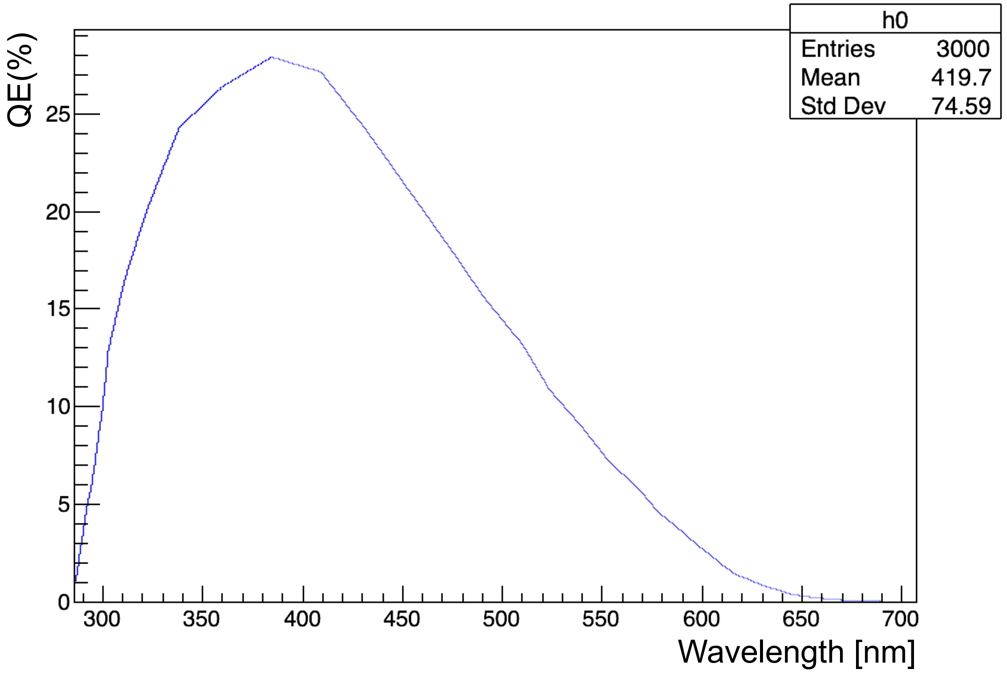
$$\mathbf{A} = -\log_{10} \mathbf{T}$$

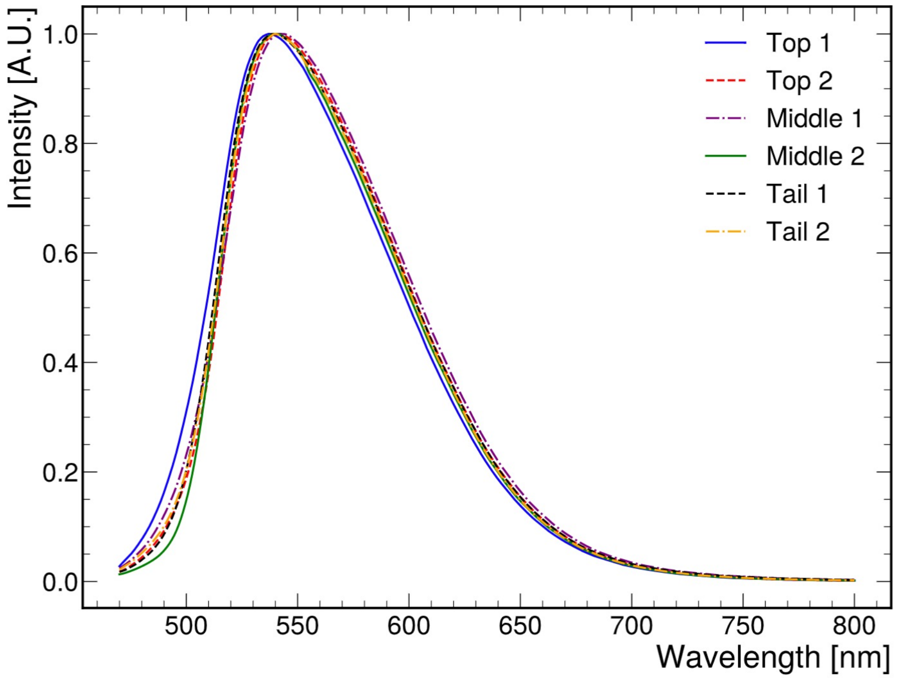
- **Similar results for absorbance**

Quantum efficiency (QE)

➢ **Definition:**

$$\mathbf{QE} = \frac{\#\ \text{of photoelectrons}}{\#\ \text{of photons}} \longrightarrow \langle \mathbf{QE} \rangle = \frac{\int g(\lambda) f(\lambda)\, d\lambda}{\int g(\lambda)\, d\lambda}$$





$f(\lambda)$

Quantum efficiency spectrum

⟷ **weighted**

$g(\lambda)$

Photoluminescence spectrum

CTR: fit method

- **Threshold scan performed to the optimal setting**

- **CTR of reference sample is measured firstly**

$$\mathbf{CTR_{meas1}} = \sqrt{\mathbf{DTR_{ref1}^2 + DTR_{ref2}^2}}$$

Detector time resolution

- **CTR of duty samples are measured with**

$$\mathbf{CTR_{dut}} = \sqrt{2} \times \sqrt{\mathbf{CTR_{meas2}^2 - DTR_{ref}^2}}$$

78 ps