Exploration of fast materials and light production mechanisms for high energy charged particles time detectors

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Why are timing detectors needed?

High collision rates expected at future particle colliders → **high track density and pile-up** will seriously challenge events reconstruction algorithms.

- Up to **200 vertices** expected at HL-LHC **every 25 ns** over ~ 4.5 cm in space.

Precise evaluation of the time information both at the calorimeter and vertex levels → possibility to select only the events exhibiting coherent energy deposition with the primary vertex timestamp.

- **Time resolution of O(20) ps** needed for such application **for the HL-LHC**.

Other benefits brought by precise time tagging:

- ➜ Capability of **particle identification for charged hadrons** (kaons, pions, and protons) through their **time-of-flight**.
- ➜ **Identification of potential long-lived particles (LLPs)** through precise time reconstruction of distanced vertices.

Scintillator-based MIPs timing detector

- ➜ A combination that already demonstrated to approach (and sometimes break) this limit is given by

Fast inorganic scintillators

(LYSO:Ce, LSO:Ce,Ca, aluminium garnets)

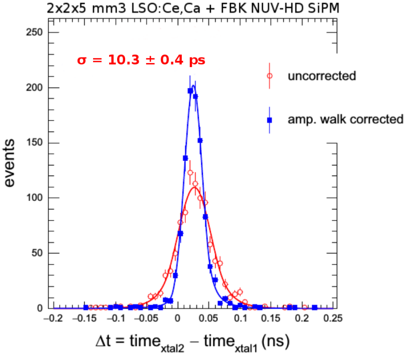
+

silicon photomultipliers (SiPMs)

A. Benaglia et al., NIM A 830 (2016) 30-35

M. T. Lucchini et al.,NIM A (2017) 1-19

  - LYSO:Ce for Barrel Timing Layer at CMS for the HL-LHC.



A. Benaglia et al., NIM A 830 (2016) 30-35

- ➜ Numerous R&D efforts are currently underway across many groups to investigate novel materials and light-based processes to fulfil the demand for fast detectors in numerous fields such as medical imaging and high-energy physics. Therefore...

can we delve into new scintillators and ultra-fast light emission processes for timing detectors in high-count rate environments?

Test beam activities and materials tested

Testbeams at CERN SPS facility - MIPs detectors

August 2021:

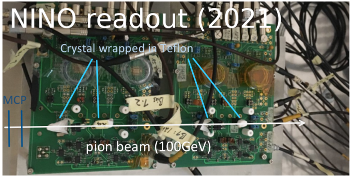
- Readout performed with **NINO ASIC electronics**

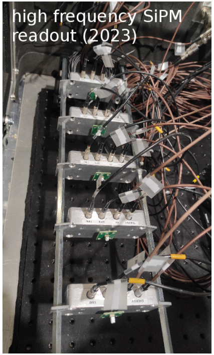
September 2022:

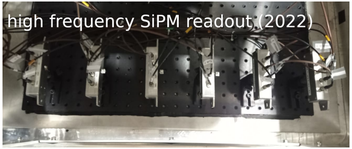
- Custom **high frequency** SiPMs readout
- 6 crystals measured in a row
- 150 GeV charged pion beam
- Pulses were recorded for offline analysis

June 2023:

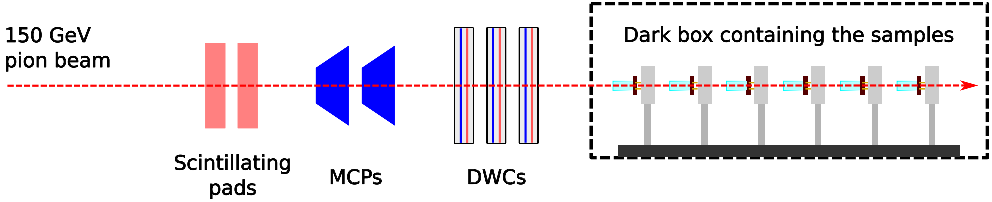
- **Same readout chain as 2022 test beam**
- Up to 5 crystals measured in a row
- 150 GeV charged pion beam
- **Temperature stabilization system implemented**





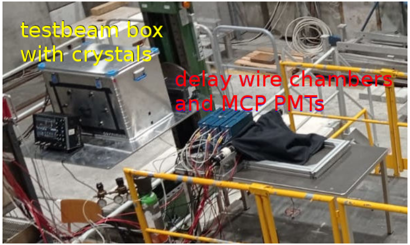


Sept. 2022 and June 2023 TBs at CERN SPS - Test beam setup



Setup from the beam:

- **2 scintillating pads** for trigger
- **2 micro-channel plates (MCPs)** in combination as time reference (T_0)
  → Intrinsic time resolution of $\sim$**13 ps**
- **3 Delay Wire Chambers (DWC)** for tracking
- Prototype enclosed in a dark box on a moving stage
- In 2023 TB: cooling of the dark box implemented



Pulses recorded with a V1742 CAEN digitizer (DRS4-based), 5 Gs/s, bandwidth 500 MHz.

Sept. 2022 and June 2023 TBs at CERN SPS - Materials tested

Sept. 2022 TB

“Standard” reference materials

- **LYSO:Ce** and **LSO:Ce,Ca**,
- **GFAG**,
- **Highly co-doped GAGG:Ce,Mg**,
- Plastic scintillators (**EJ232**).

Materials exploiting Cherenkov light

- **PWO**,
- **PbF$_2$**,
- **BGO** and mixed **BGSO**.

Cross-luminescent materials

- **BaF$_2$** and **BaF$_2$:Y** ($3 \times 3 \times 10\,\text{mm}^3$).

June 2023 TB

“Standard” reference materials

- **GFAG**,
- **Highly co-doped GAGG:Ce,Mg** - different sample.

Materials exploiting Cherenkov light

- **BGO**, **BSO** and mixed **BGSO**.

Cross-luminescent materials

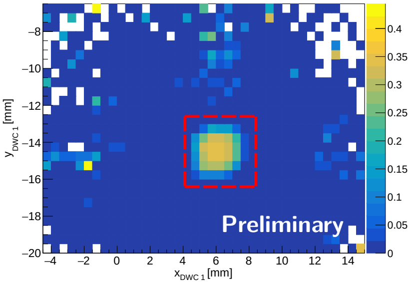
- **BaF$_2$** and **BaF$_2$:Y** ($2 \times 2 \times 10\,\text{mm}^3$).

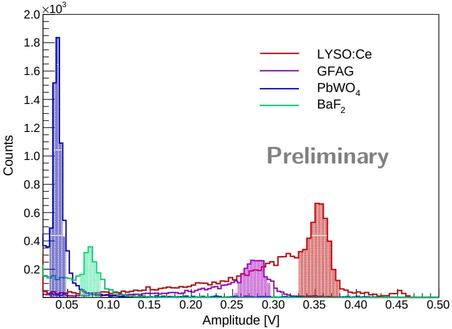
All samples have dimension $2 \times 2 \times 10\,\text{mm}^3$ with the exceptions of:

- EJ232 ($3 \times 3 \times 3\,\text{mm}^3$),
- BaF$_2$ and BaF$_2$:Y - Sept. 2022 TB ($3 \times 3 \times 10\,\text{mm}^3$).

Data analysis

Position and energy selections

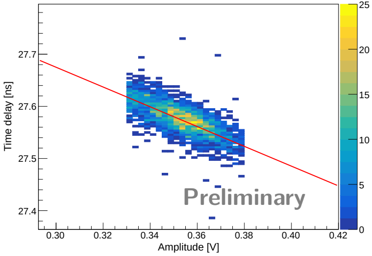


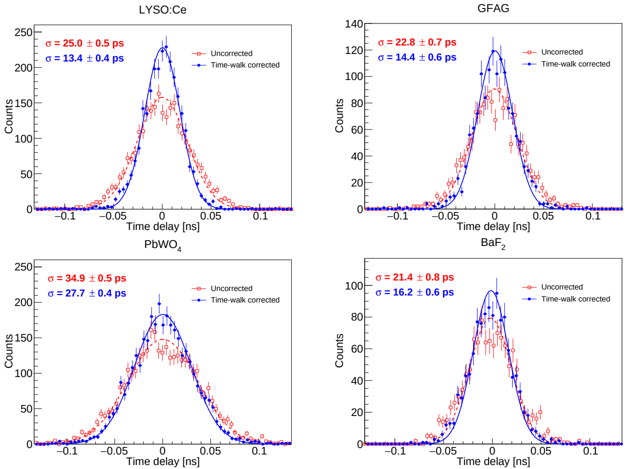


- Transverse x-y coordinates of the beam provided by the DWCs employed to cut the events where the pion missed the sample

- Peaks highlighted → events where the pion travelled and deposited energy through the entire sample length

Time-walk effect

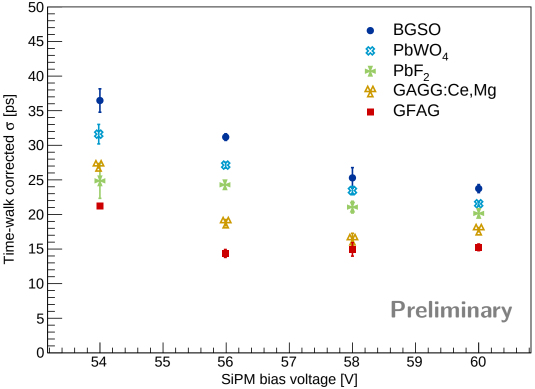




A time-walk effect was observed in the samples tested

➜ correction applied to improve the detector time performance

September 2022 TB - Timing dependency from the SiPMs bias voltage

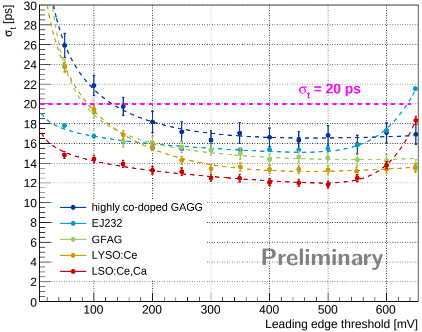


SiPMs employed for this study: HPK S13360, $3 \times 3\,\text{mm}^2$ active area, 50 μm spad size, $V_{br} \sim 53\,\text{V}$.

- An overall improvement of the time resolution obtained is observed powering the SiPM at higher voltage.
- We observe an increase in both the noise level and the dark count rate for voltages above 56 V.
  - ➜ **The *Hamamatsu* devices were therefore operated at 56 V during the rest of the measurement campaign.**

Results discussion

Sept. 2022 TB - Time resolution of some standard scintillators



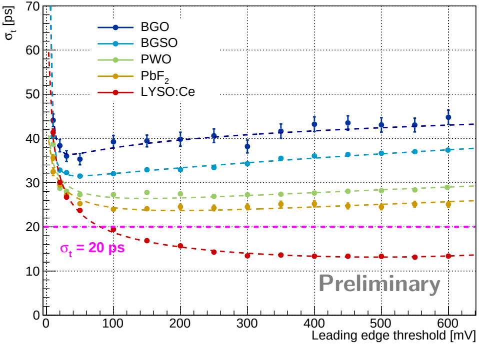
Crystal	**Size**	**Time resolution** σ_t (ps)	**Energy deposited** (MeV)
GAGG:Ce,Mg	$2 \times 2 \times 10\,\text{mm}^3$	$\mathbf{16.4 \pm 0.9}$	9.5
EJ232	$3 \times 3 \times 3\,\text{mm}^3$	$\mathbf{15.3 \pm 0.2}$	0.54
GFAG	$2 \times 2 \times 10\,\text{mm}^3$	$\mathbf{14.3 \pm 0.6}$	9.5
LYSO:Ce	$2 \times 2 \times 10\,\text{mm}^3$	$\mathbf{13.1 \pm 0.4}$	10.6
LSO:Ce,Ca	$2 \times 2 \times 10\,\text{mm}^3$	$\mathbf{12.1 \pm 0.4}$	10.8

- Crystals Teflon wrapped and Meltmount coupled to HPK S13360-3050PE SiPMs.

Extremely promising results ($<$ 20 ps) for many materials as timing detectors!

R. Calà, et al., paper in preparation

Sept. 2022 TB - Time resolution of some materials exploiting Cherenkov



Crystal	**Size**	**Time resolution** σ_t (ps)	**Energy deposited** (MeV)
BGO	$2 \times 2 \times 10\,\text{mm}^3$	$\mathbf{36.4 \pm 1.5}$	9.9
BGSO	$2 \times 2 \times 10\,\text{mm}^3$	$\mathbf{31.1 \pm 0.5}$	9.9
PWO	$2 \times 2 \times 10\,\text{mm}^3$	$\mathbf{27.0 \pm 0.4}$	11.2
PbF_2	$2 \times 2 \times 10\,\text{mm}^3$	$\mathbf{24.2 \pm 0.6}$	10.3
LYSO:Ce	$2 \times 2 \times 10\,\text{mm}^3$	$\mathbf{13.1 \pm 0.4}$	10.6

- ➜ **BGSO** presented better timing than **BGO**.
- ➜ **PWO** and **PbF_2** showed a resolution well below **30 ps**.
- ➜ Exploiting Cherenkov photons may provide a **cost-effective timing capability**.

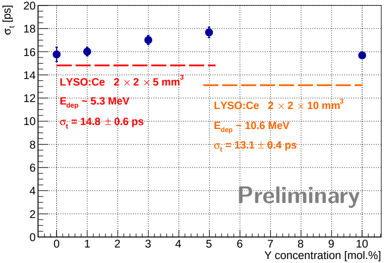
- Crystals Teflon wrapped and Meltmount coupled to HPK S13360-3050PE SiPMs.

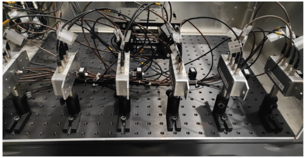
R. Calà, et al., paper in preparation

Sept. 2022 TB - Time resolution of BaF_2 and BaF_2:Y

- **BaF_2** and **BaF_2:Y**
  - $3 \times 3 \times 10\,mm^3$ crystals
  - Viscasil coupling
  - $6 \times 6\,mm^2$ HPK S13370 VUV-SiPMs (50 μm spad size)
  - Energy deposited: 6.7 MeV/cm

- **LYSO:Ce**
  - $2 \times 2 \times 5\,mm^3$ and $2 \times 2 \times 10\,mm^3$ crystals
  - Meltmount coupling
  - $3 \times 3\,mm^2$ HPK S13360 SiPMs (50 μm spad size)
  - Energy deposited: 10.6 MeV/cm





- **$\sigma_t < 20$ ps achieved for all samples.**
- Time resolution almost independent of yttrium concentration.
- Results obtained close to those of LYSO:Ce but with **sub-20% weighted PDE** (LYSO ~ 55%) of SiPMs.

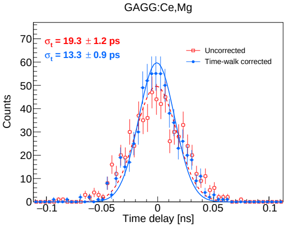
BaF_2 and BaF_2:Y good candidates for timing layer detectors

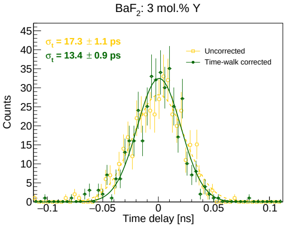
R. Calà, et al. (2022), *Exploring BaF_2:Y Ultra-fast Emission for Future HEP Applications*, oral presentation at SCINT 2022 conference
R. Calà, et al., paper in preparation

June 2023 TB - Time resolution of the samples tested

Crystal	**Time resolution** σ_t (ps)		**Energy deposited** (MeV)
	Sept. 2022 TB	**June 2023 TB**	
GFAG	**14.3** ± **0.6**	**14.1** ± **0.8**	9.5
GAGG:Ce,Mg - 1	**16.4** ± **0.9**	-	9.5
GAGG:Ce,Mg - 2	-	**13.3** ± **0.9**	9.5
BGO	**36.4** ± **1.5**	**37.9** ± **0.9**	9.9
BGSO	**31.1** ± **0.5**	**32.9** ± **1.7**	9.9
BSO	-	**35.7** ± **1.3**	9.9
BaF$_2$ *	**15.8** ± **0.6**	**14.3** ± **0.6**	6.7
BaF$_2$:Y *	**17.0** ± **0.4**	**13.4** ± **0.9**	6.7

* Sept. 2022 TB: $3 \times 3 \times 10\,\mathrm{mm}^3$ samples measured with $6 \times 6\,\mathrm{mm}^2$ VUV-SiPMs.
June 2023 TB: $2 \times 2 \times 10\,\mathrm{mm}^3$ samples measured with $3 \times 3\,\mathrm{mm}^2$ VUV-SiPMs.

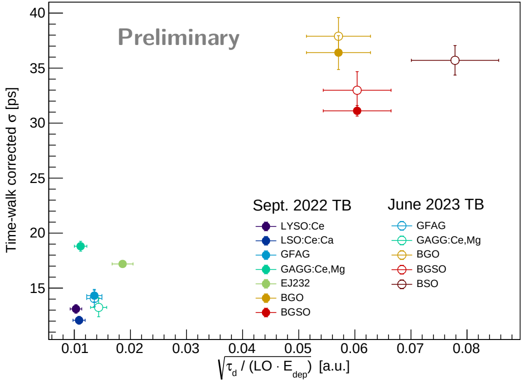




- ➜ Good match between the two TB measurements.
- ➜ **BGSO** exhibits a slightly better time resolution compared to pure BGO and BSO
- ➜ **GFAG**, **GAGG:Ce,Mg**, **BaF$_2$** and **BaF$_2$:Y** achieve a time performance compatible with a LYSO:Ce sample of the same dimension ($\sigma = 13.1\,\mathrm{ps}$).

R. Calà, et al., paper in preparation

Materials scintillating and timing properties correlated to the time performance



$$\sigma_t \propto \sqrt{\frac{\tau_r\,\tau_d}{\mathrm{LO}\cdot \mathrm{E}_{dep}\cdot \mathrm{LCE}\cdot \mathrm{PDE}}}$$

τ_r: rise time
τ_d: decay time
E_{dep}: energy deposited inside the sample
LO: light output in ph/MeV
LCE: light collection efficiency
PDE: SiPM photon detection efficiency

We can assume τ_r, LCE, and PDE almost independent from the sample.

Conclusions

- **Test of many materials and their fundamental properties for high-energy physics applications is currently ongoing**

- **Measurements of the timing properties of many scintillators coupled to SiPM devices and readout by high-frequency electronics under 150 GeV charged pions irradiation**
  - Best performance of $\sigma = 12\,\mathrm{ps}$ obtained for LSO:Ce,Ca with 10.8 MeV energy deposition.
  - GFAG and GAGG:Ce,Mg exhibited a time performance compatible with the LYSO:Ce one.
  - Timing performance close to 20 ps for materials exploiting Cherenkov radiation.
  - Cross-luminescence in BaF_2 and BaF_2:Y produces a time performance similar to LYSO:Ce.

Thank you for your kind attention!

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We thank: J. Chen, M. Nikl, and O. Sidletskiy for the crystals provided, M. Baschiera and D. Deyrail for technical support and D. Arora, A. Bordelius, C. Lowis, F. Pagano, and G. Terragni for their participation to the shifts.

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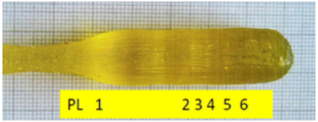
Backup slides

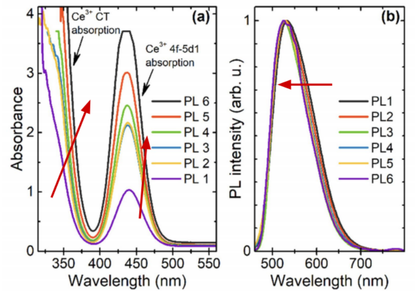
GAGG:Ce scintillation acceleration through heavy Ce^{3+}/Mg^{2+} doping (1)

Increase of Ce^{3+} and Mg^{2+} →

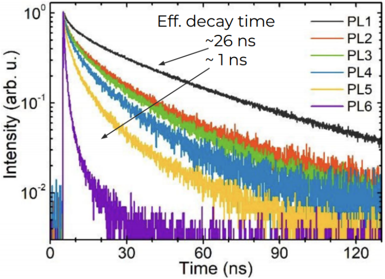


Increase of Ce^{3+} and Mg^{2+} concentrations ⇒ **10 × reduction of the effective decay time & slow component suppression**.

Absorbance and photoluminescence



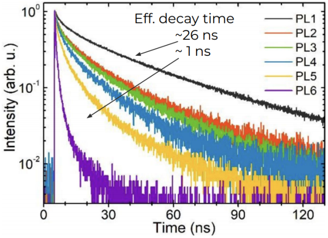
Scintillation kinetics distributions



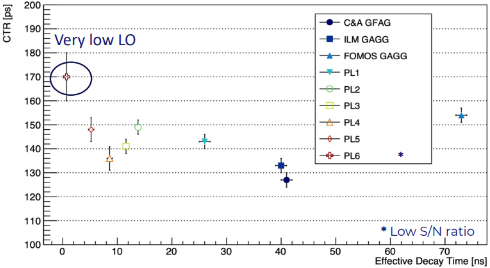
L. Martinazzoli, et al. (2022), *Mater Adv*, 3:6842-52

GAGG:Ce scintillation acceleration through heavy Ce^{3+}/Mg^{2+} doping (2)

Scintillation kinetics distributions



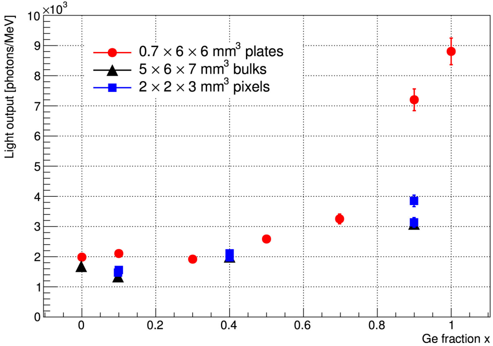
CTR FWHM versus effective decay time

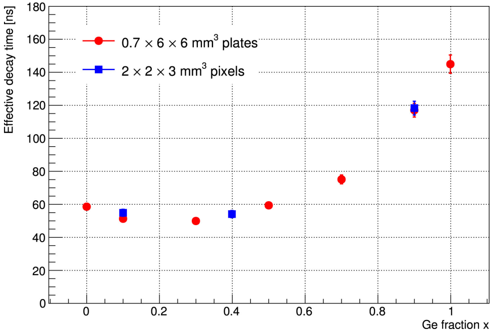


Scintillation kinetics acceleration ⇒ loss in light output
No major loss of time resolution!
Direction for future R&D on GAGG to be employed in LHCb phase II calorimeter.

L. Martinazzoli, et al. (2022), *Mater Adv*, 3:6842-52

Light output and decay time of BGSO



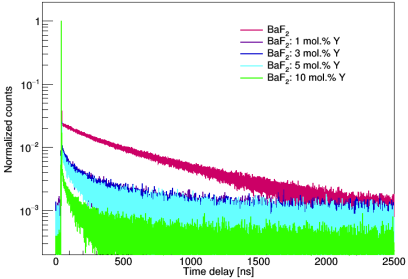


For a **Ge fraction** between **30% and 50%**: **constant light output**, but **faster decay time** with respect to BSO ($x = 0$).

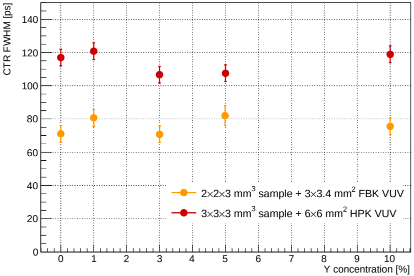
R. Cala', et al. (2022), *NIM A*, 1032:166527

BaF_2 and BaF_2:Y scintillating and timing properties

Emission kinetics under X-ray excitation



CTR at 511 keV



Increasing the amount of yttrium used as dopant the slow component is heavily suppressed, while the fast one is left unmodified.

- ➜ Light output significantly drops when Y-doping is employed.

No impact on timing despite a reduction in light output **varying Y concentration**.

- ➜ Possibility to employ BaF_2 in high radiation environments.

R. Cala', et al. (2022), *Exploring BaF_2:Y Ultra-fast Emission for Future HEP Applications*, oral presentation at SCINT 2022 conference