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

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FAST 2023 workshop

May 30, 2023

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** expected to be 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

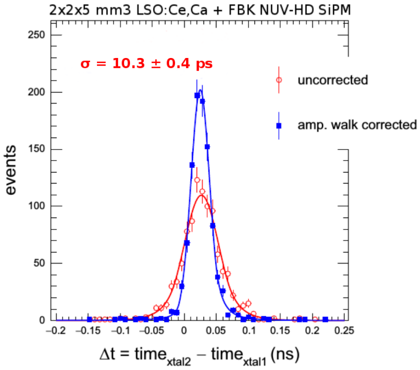
➜ A combination that already demonstrated to approach (and sometimes break) this limit is given by

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 large R&D is ongoing in many groups to investigate new materials and processes to fulfil the demand for fast detectors in medical imaging and high-energy physics application (*see E. Auffray talk, "Results of fast timing with scintillators"*). Therefore...



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

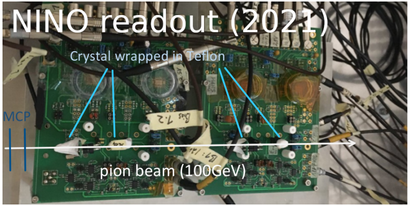
can we take advantage of the synergy with other fields and explore new scintillators and ultra-fast light emission processes for timing detectors in high-count rate environments?

Test beam activities and materials tested

Testbeams at CERN SPS - MIPs detectors

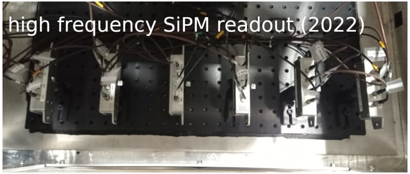
August 2021: first test beam for testing timing of promising pixels scintillators coupled to SiPMs

- Readout performed with **NINO ASIC electronics**
- Possibility to measure up to 4 crystals in a row
- 100 GeV pion beam

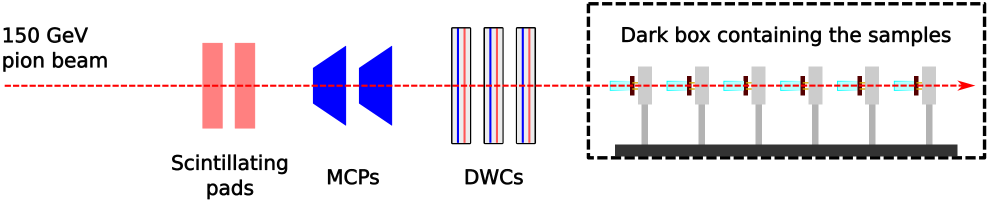


September 2022: second test beam for testing our crystals

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

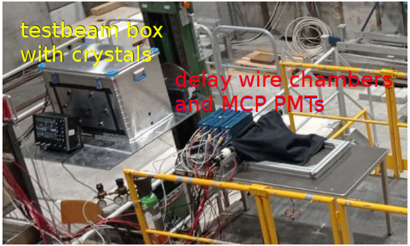


Sept. 2022 TB at CERN SPS - Test beam setup



Setup from the beam:

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



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

Sept. 2022 TB at CERN SPS - Materials tested

"Standard" reference materials

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

Materials exploiting Cherenkov light

- **PWO**,
- **PbF_2**,
- **BGO** and mixed **BGSO**.

Cross-luminescent materials

- **BaF_2**,
- **BaF_2:Y**.

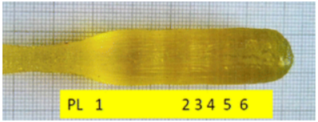
All samples have dimension $2 \times 2 \times 10\,mm^3$ with the exceptions of:

- EJ232 ($3 \times 3 \times 3\,mm^3$),
- BaF_2 and BaF_2:Y ($3 \times 3 \times 10\,mm^3$).

Scintillation and timing properties of some innovative materials tested

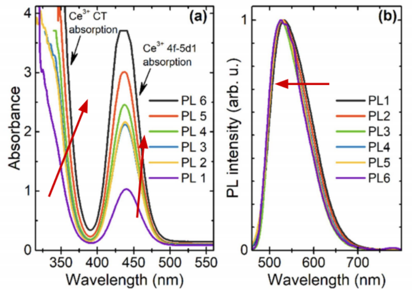
GAGG:Ce scintillation acceleration through heavy Ce^{3+}/Mg^{2+} doping (1)

Increase of Ce^{3+} and Mg^{2+} →

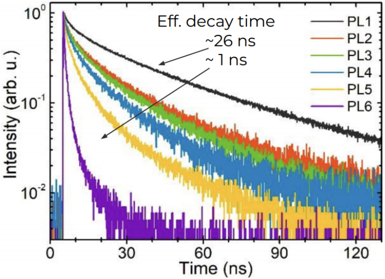


Increase of Ce^{3+} and Mg^{2+} concentrations ⇒ **10 × reduction of the effective decay time & slow component suppression**.

Absorbance and photoluminescence



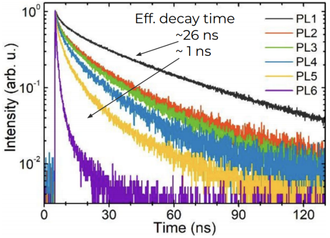
Scintillation kinetics distributions



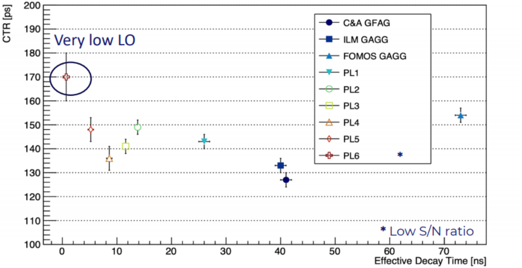
L. Martinazzoli, et al. (2022), *Mater Adv*, 3:6842-52

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

Exploration of BSO and mixed BGSO

Material	**BGO**	**BSO**	**PWO**
Density (g/cm^3)	7.13	7.12	8.28
Refr. index @ 550 nm	2.12	2.05	2.16
Emission wavelength (nm)	480	480	420
Cutoff wavelength (nm)	300	290	320
Light output (ph/MeV)	8 200	**1 200**	O(10)
Slowest decay time (ns)	300	**100**	8

Which advantages do BSO or mixed BGSO bring instead of BGO or PWO?

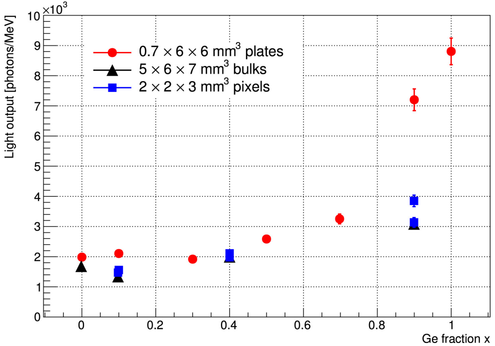
- ➜ **BSO** can be a good compromise on both decay time and light output.
- ➜ Possibility to **fine-tune light output and decay time** by varying the Ge-Si fraction in $\mathbf{Bi_4(Ge_xSi_{1-x})_3O_{12}}$.

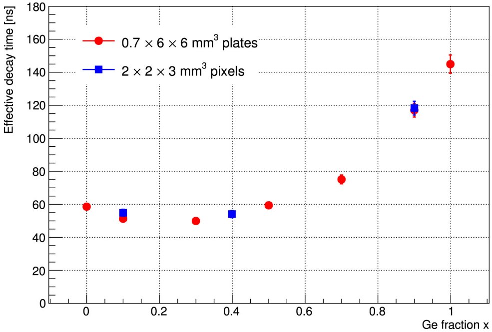
Work is ongoing in the frame of the TWISMA project (Grant Agreement: 101078960).

M. Ishii, et al (2002), *Opt Mater*, 19:201-12

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

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 ($x = 0$).

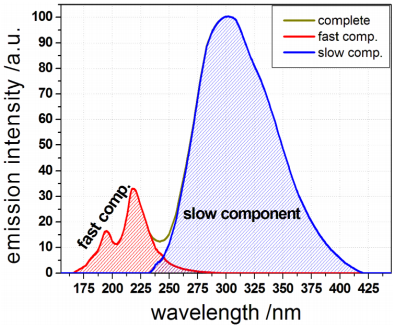
R. Cala', et al. (2022), *NIM A*, 1032:166527

BaF_2 in the inorganic scintillators panorama

Barium fluoride (BaF_2) is a scintillating material widely investigated* in the past due to its ultra-fast cross-luminescent component ($\tau_{d,fast}$ = 600 - 800 ps) and moderate light output. Its main drawbacks that limit this material applications are:

- the UV nature of its fast component
  - ➜ Recent developments in photodetector technologies in this spectral region (compact **UV** and **VUV SiPMs**).
- the existence of a slow emission component
  - ➜ Limit of the application of BaF_2 in high radiation environments
  - ➜ **Codoping** or **use of filters** to mitigate its contribution

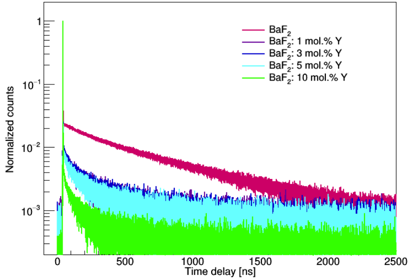
*C. W. E. Van Eijk (1994), Journal of Luminescence 60, 1994, 936-941
*P. Rodnyi et al (1991), J. Lumin. 47 1991
*J. Chen et al (2018), IEEE Trans. Nucl. Sci. 65 8
*R. H. Pots et al (2020), Front. Phys. 8 592875
*S. Gundacker et al (2021), Phys. Med. Biol. 66 114002



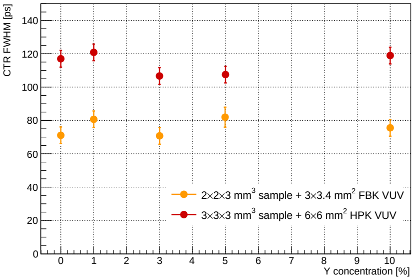
S. Diehl, et al. (2015), J. Phys.: Conf. Ser.

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.

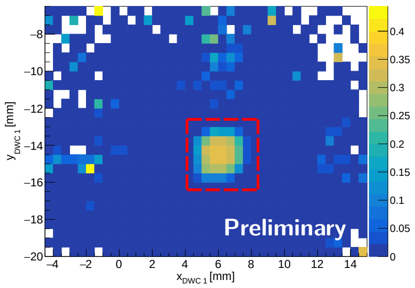
No impact on timing despite a reduction in light output **varying Y concentration**.

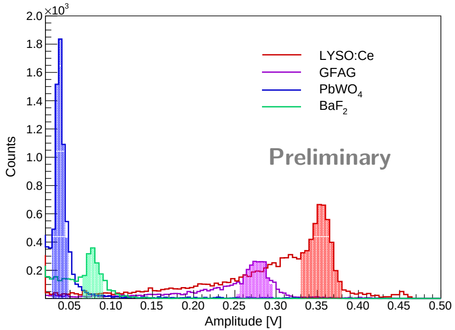
➜ Possibility to employ BaF_2 in high radiation environments.

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

Data analysis

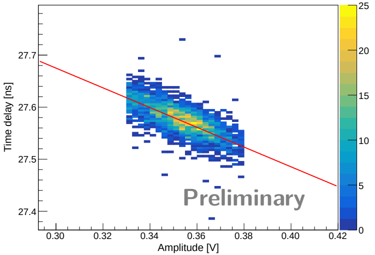
Position and energy selections

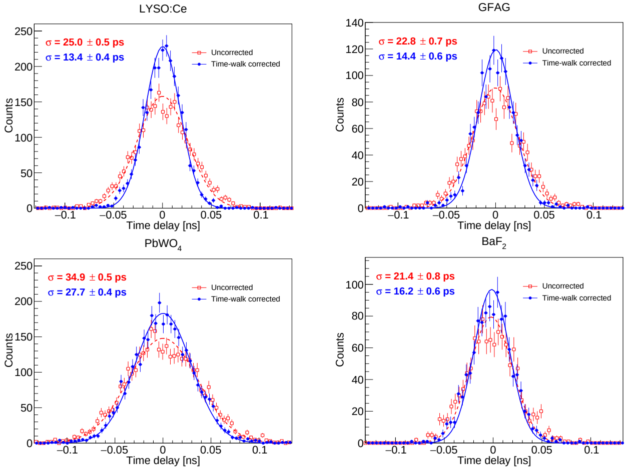




- Transverse x-y coordinates of the beam provided by the DWCs employed to cut the events where the pion missed the sample
- Peaks highlighted → events where the pion travelled and deposited energy through the entire sample length

Time-walk effect

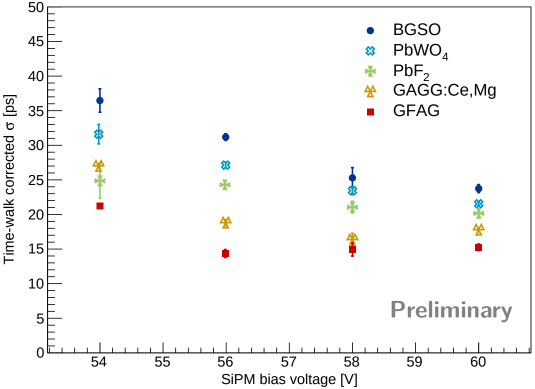




A time-walk effect was observed in the samples tested

➜ correction applied to improve the detector time performance

Timing dependency from the SiPMs bias voltage

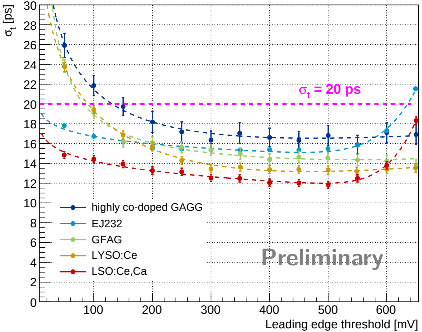


SiPMs employed for this study: HPK S13360, $3 \times 3\,\text{mm}^2$ active area, $50\,\mu$m spad size, $V_{br} \sim 53\,\text{V}$.

- 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

Time resolution of some standard scintillators with MIPs

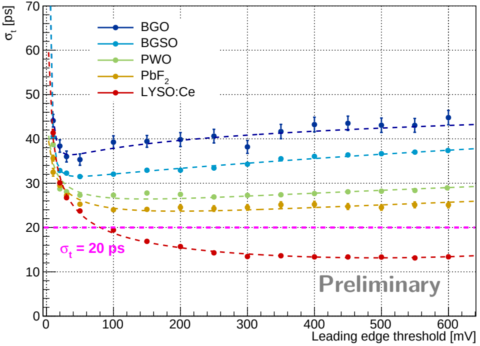


Crystal	Size	Time resolution σ_t (ps)	Energy deposited (MeV)
Highly co-doped GAGG	$2 \times 2 \times 10\,mm^3$	**16.4 ± 0.9**	9.5
EJ232	$3 \times 3 \times 3\,mm^3$	**15.3 ± 0.2**	0.54
GFAG	$2 \times 2 \times 10\,mm^3$	**14.3 ± 0.6**	9.5
LYSO:Ce	$2 \times 2 \times 10\,mm^3$	**13.1 ± 0.4**	10.6
LSO:Ce,Ca	$2 \times 2 \times 10\,mm^3$	**12.1 ± 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!

Time resolution of some materials exploiting Cherenkov with MIPs



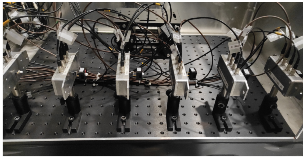
- Crystals Teflon wrapped and Meltmount coupled to HPK S13360-3050PE SiPMs.

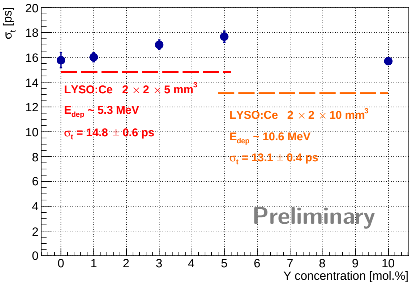
Crystal	Size	Time resolution σ_t (ps)	Energy deposited (MeV)
BGO	$2 \times 2 \times 10\,mm^3$	**36.4 ± 1.5**	9.9
BGSO	$2 \times 2 \times 10\,mm^3$	**31.1 ± 0.5**	9.9
PWO	$2 \times 2 \times 10\,mm^3$	**27.0 ± 0.4**	11.2
PbF_2	$2 \times 2 \times 10\,mm^3$	**24.2 ± 0.6**	10.3
LYSO:Ce	$2 \times 2 \times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

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

Time resolution of BaF_2 and BaF_2:Y with MIPs

- **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



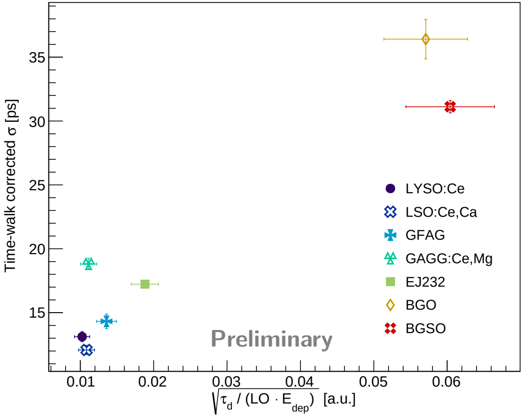


- **$\sigma_t < 20$ ps achieved for all samples.**
- Time resolution almost independent of yttrium concentration.
- Results obtained close to those of LYSO:Ce but with **sub-20% weighted PDE** (LYSO ~ 55%) of SiPMs.

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

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
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**

- As good as $\sigma = 12$ ps for LSO:Ce,Ca with 10.8 MeV energy deposition.
- Timing performance close to 20 ps for materials exploiting Cherenkov radiation.
- Cross-luminescence in BaF_2 and BaF_2:Y produces a time performance close to LYSO:Ce.

➜ **Future tests with other innovative materials and with better-performing SiPMs (higher PDE, lower noise) for BaF_2 are expected.**

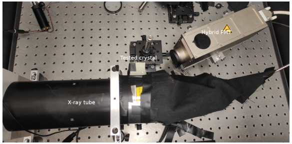
Thank you for your kind attention!

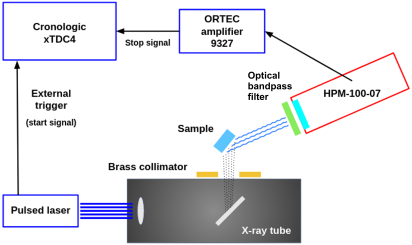
This work was carried out within the Crystal Clear Collaboration and supported by AIDAinnova (Grant Agreement No 101004761). We thank: J. Chen, M. Nikl, and O. Sidletskiy for the crystals provided, M. Baschiera and D. Deyrail for technical support and A. Bordelius, C. Lowis, F. Pagano, and G. Terragni for their participation to the shifts.

CERN CRYSTAL CLEAR UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

Backup slides

Test bench for scintillation kinetics measurement under X-rays excitation

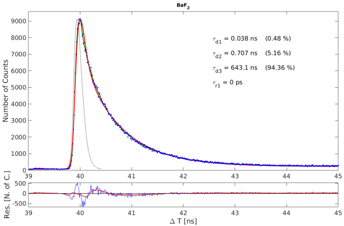




F. Pagano, et al. (2022), *Front Phys*, 10:1021787

TCSPC setup

- Pulsed diode laser (PDL 800-B, PicoQuant)
- X-ray tube (XRT N5084, Hamamatsu)
- Hybrid PMT (HPM-100-07, Becker and Hickl)
- Amplifier and timing discriminator (9327, ORTEC)
- Time-to-digital converter (xTDC4, Cronologic)

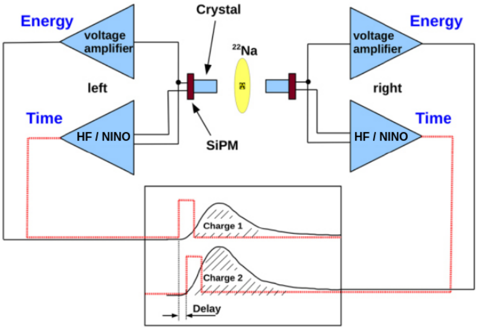


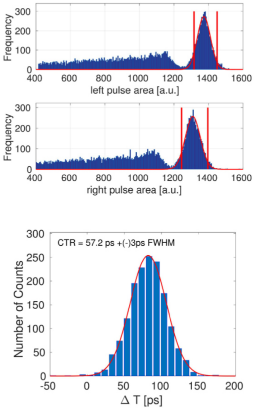
Example of scintillation-emission distribution

Test benches for coincidence time resolution (CTR) measurements

Two setups to measure coincidence time resolution:

one exploiting **high-frequency electronics**, the other using **NINO boards**.





S. Gundacker, et al. (2018), *NIM A*, 91:42-52

S. Gundacker, et al. (2020), *Phys Med Biol*, 65:025001