Advancement and Innovation for Detectors at Accelerators

WP8
Innovative calorimeters with optical readout
Task 8.3.1:
R&D on Crystal and nanomaterial scintillators

E. Auffray, CERN EP_CMX
on behalf of Sub task 8.3.1 team

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Fyzikální ústav Akademie věd České republiky

Research Institute for Nuclear Problems BSU

Task 8.3.1: Partner Institutes

- **Main Benificiaries:**
  - CERN: E. Auffray, N. Kratochwil with all CERN CCC team
  - FZU Prague: M. Nikl, V. Babin, J. Vitezslav,
  - INFN Frascati: M. Moulson, L. Bandiera,
  - INFN Perugia: C. Cecchi, G. De Nardo, E. Manoni, M. Merola
  - INFN Torino: N. Pastrone, I. Sarra
  - Vilnius: G. Tamulaitis, S. Nargelas, A. Vaitkevicius
- **Associated partners:**
  - CERN
    - Minsk: M. Korzhik
  - INFN
    - GlassToPower, Italy (company): S. Brovelli,
- **Other partner:**
    - Crytur, Czech republic (company): J. Houzvicka, S. Sykorova

Task8.3.1: Objectives

- Optimisation of crystal materials and processes for fast timing applications in radiation environments

- Industrialisation of the production process of fast and radiation-hard crystals

Task activities

- **Material investigation**
  - Optimisation of “standard” scintillating Materials to improve timing performance:
    - Garnet, PWO, BGO
    - Study of crossluminescence materials
  - Study of scintillating nanomaterials
- **Development of instrumentation for timing characterisation (Milestone** Achieved in March 2022 (see link)
  - Transient absorption
  - Time resolved spectroscopy
  - Time resolution
- **Test beam study:**
  - Timing performance with mip and electron
  - Test of various prototypes for future calorimeter
  - Test Nanocal prototype (bluesky project)

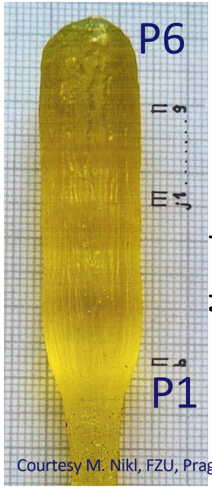
Investigation of scintillating materials

GAGG:Ce Scintillation acceleration by heavy Ce/Mg doping

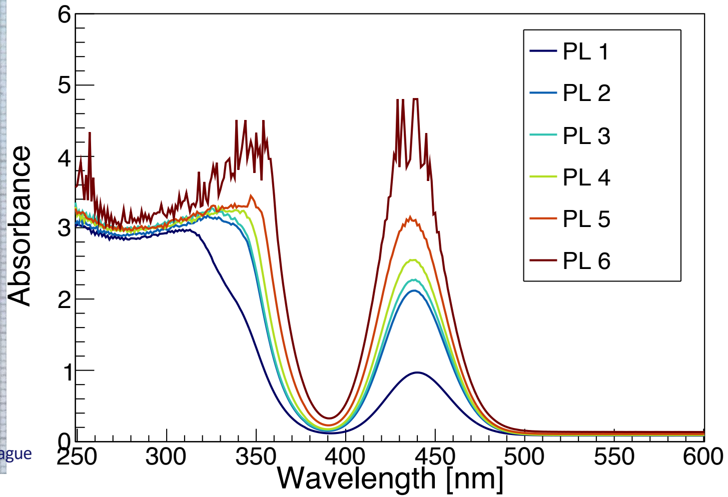
CERN, FZU; VILNIUS:

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

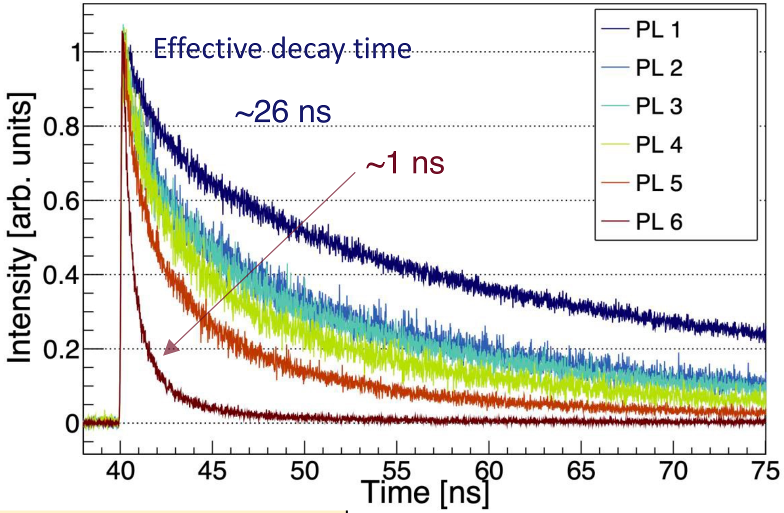
Increase of Ce^{3+} & Mg^{2+}



Absorbance spectra



Decay time



Increased concentration of Ce,Mg

⇒ Effective decay time reduced by > 10x

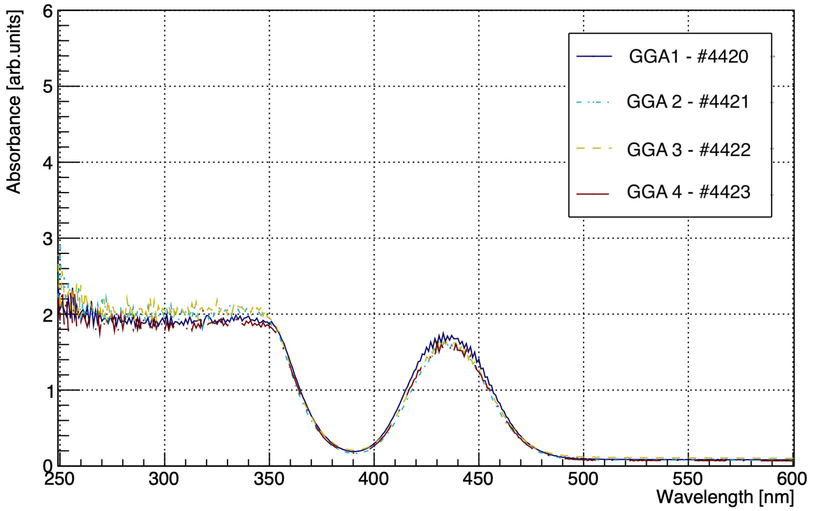
⇒ No slow component

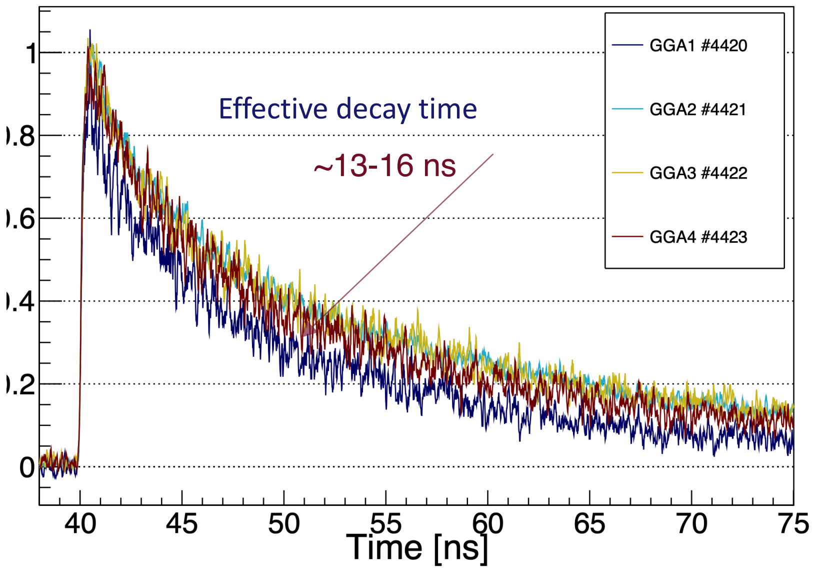
Joint paper CERN; FZU; Vilnius, L. Martinazzoli et al, Mater. Adv., 2022,3, 6842-6852 .

New produced samples with one selected composition

CERN, FZU

Test of reproducibility with one selected composition





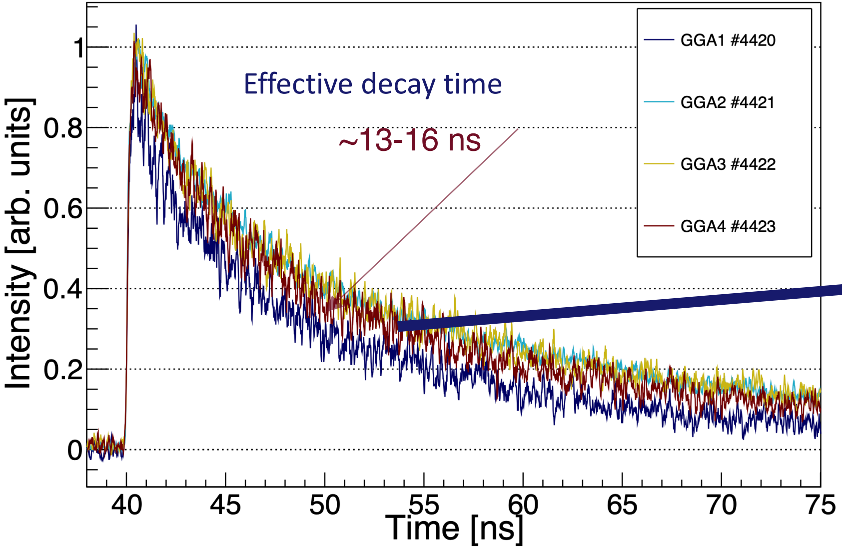
Uniformity of the properties among 4 tested samples

New produced samples with one selected composition

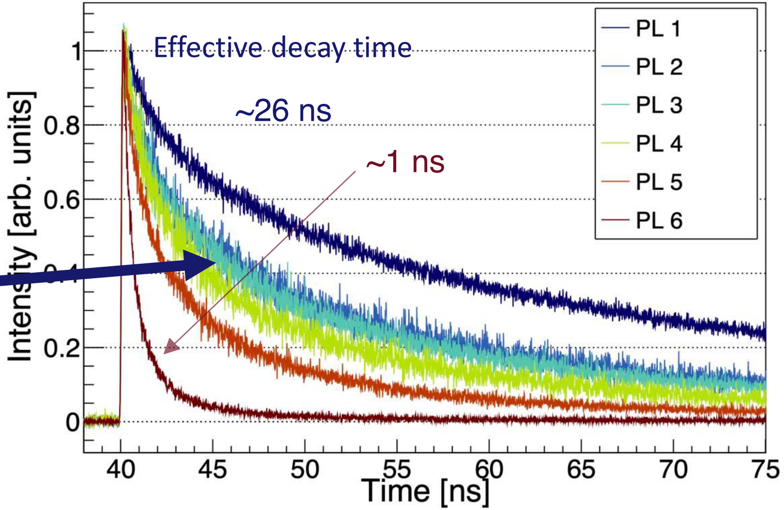
CERN, FZU

Decay time

New samples



Previous study



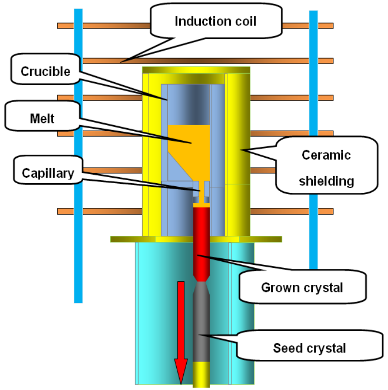
L. Martinazzoli et al, Mater. Adv., 2022,3, 6842-6852 .

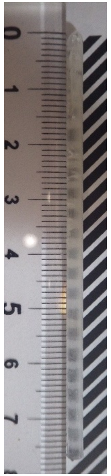
Next step=> larger sample

Micropulling down growth technology in FZU

Single crystal preparation for scintillator screening in Task 8.3.1

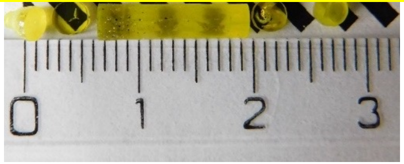
FZU

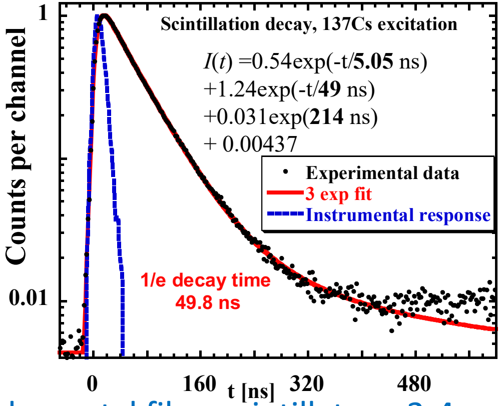




Set-up, scheme of the method and 7.5 cm fiber of Al2O3 crystal

GAGG:Ce,Mg single crystal fiber

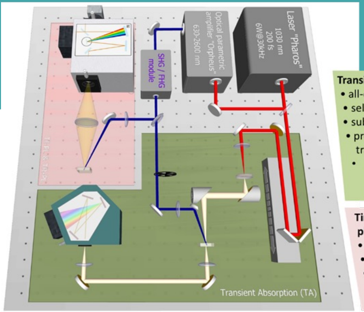




Micropulling down technology allows preparation of single crystal fiber scintillators, 3-4mm in diameter up to several tens of cm length. Heavily (Ce,Mg)-doped GAGG scintillator can be prepared with accelerated decay, currently below 50ns, limits of the doping and decay acceleration (target of 10-15ns) are under study.

TEST Bench @ Vilnius University

TEST BENCH FOR CHARACTERIZATION OF SCINTILLATOR TIMING PROPERTIES

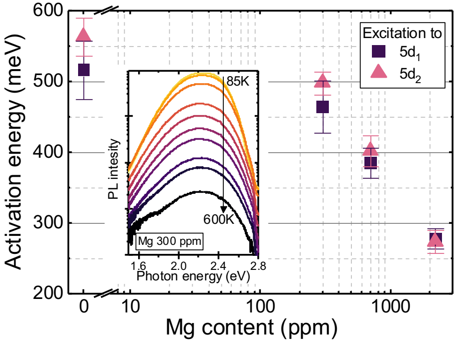


Key properties and capabilities

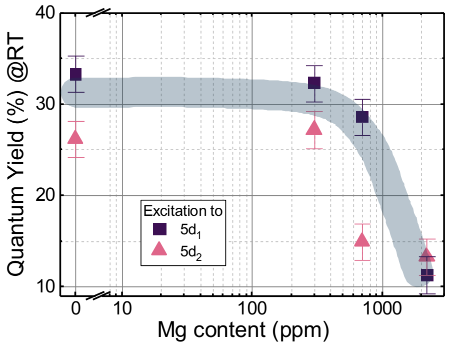
Transient absorption technique
- all-optical, i.e., nondestructive and contactless
- selective excitation
- subpicosecond time resolution
- probing the kinetics of populations of free and trapped carriers and those at emitting centers
- global analysis software based on kinetic equations describing the dynamics of the populations is adopted for data analysis

Time-integrated & time-resolved photoluminescence
- all-optical, i.e., nondestructive and contactless
- selective excitation
- sensitivity range 200 – 1100 nm
- TCSPC for time-resolved PL with 200 ps time resolution

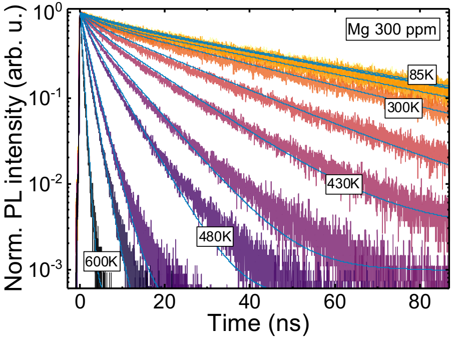
Influence of heavy Mg codoping on emission properties of LuGAGG:Ce layers



The increase in Mg-codoping level in LuGAGG:Ce layers results in a decrease in the effective activation energy for emission quenching.



The observed reduction in the quantum yield of LuGAGG:Ce layers at increasing Mg content evidences the increasing influence of nonradiative recombination pathway.



The temperature dependence of PL decay can be interpreted by involvement of two types of emission centers with the same radiative recombination rate ($1/\tau_{rad}$) and different quenching rates ($1/\tau_{q1}$ and $1/\tau_{q2}$).

$$I(t) \sim w_1 e^{-t\left(\frac{1}{\tau_{rad}}+\frac{1}{\tau_{q1}}\right)} + w_2 e^{-t\left(\frac{1}{\tau_{rad}}+\frac{1}{\tau_{q2}}\right)}$$

Conclusion

Magnesium codoping results in the formation of Ce-based emission centers with lower energy barrier for the depopulation of Ce^{3+} ions and subsequent nonradiative recombination.

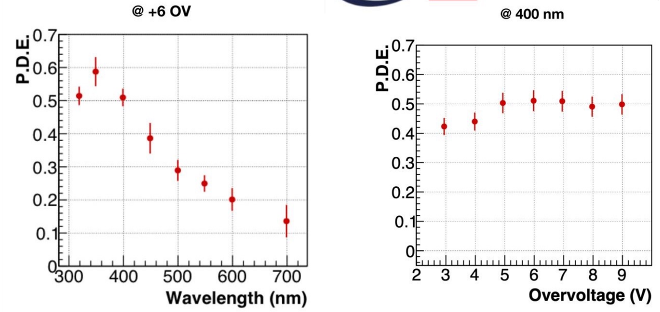
This effect becomes pronounced at Mg contents approaching Ce content.

Crystal characterization

Crystal characterization with:

SiPM developed by FBK for CTA

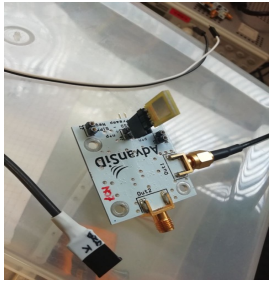
- UV-enhanced (P.D.E. peaked at 350 nm), -50%@310 nm
- Breakdown at ~ 26.5 V
- Active area 6 mm x 6 mm (effective active area ~80%)
- At breakdown, 1.1 x 10^6 electrons/p.e. (
- gain increases linearly with overvoltage → 2 – 3 x 10^6 @ +5 OV)



Thanks to L.Tosti and G.Ambrosi

<u>AdvanSid</u> SiPM Evaluation Board Signal amplifier

- Takes directly the SIPM bias
- Transimpedance signal amplifier → low gain output **Z = 500 Ω** →
  - output is amplified by factor x10^3 (another output is available with Z=2500 Ω)
- Needs ±5 V
- The integral of the output signal is proportional to the charge



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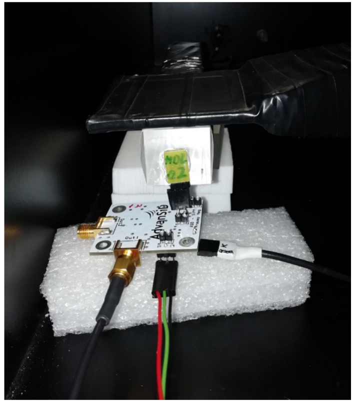
Crystals characterization



Experimental Setup:

- Couple SiPM directly to crystal surface with Silicone optical grease (EJ-550)
- Test different crystals
    - Pure CsI from Amcrys
    - LYSO from SuperB
    - LaBr3 from Saint Gobain
    - CsI (Tl) from Belle
- All crystals are wrapped, to optimize photon collection
- Trigger cosmics with scintillator (coupled to PMT)
- Save full waveforms at the scope

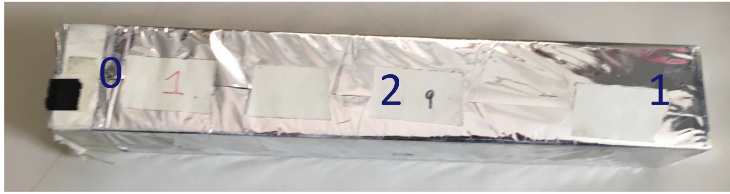
Geometry study

Investigate shower shape triggering events at different depth.

3 different configurations: edge on SiPM side (0), edge opposite to SiPM (1), center (2)

Two crystals:

- Pure CsI Amcrys → parallelepiped: 30x6x6 cm^3
- LYSO → slightly trapezoidal: length20cm faces 3x3 cm^2 2.5x2.5 cm^2



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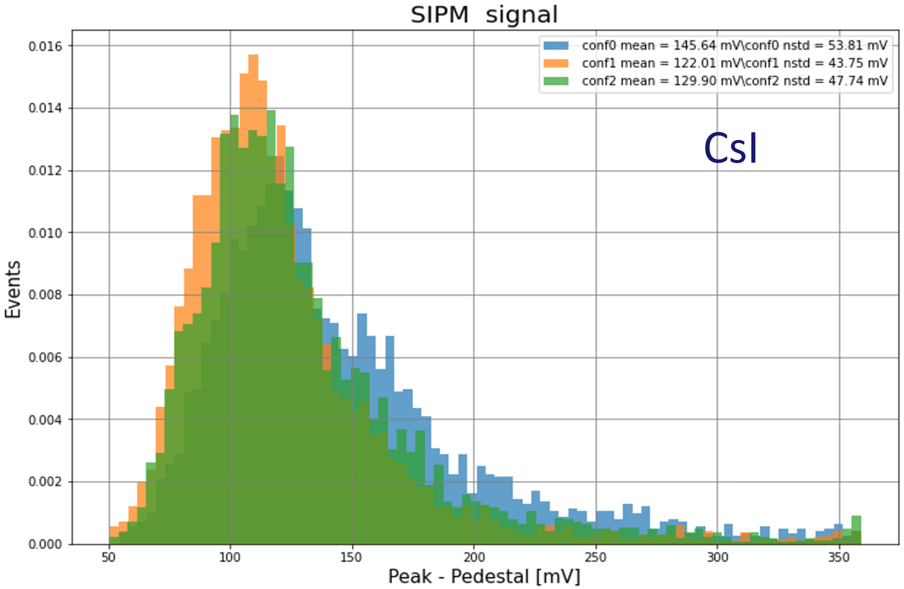
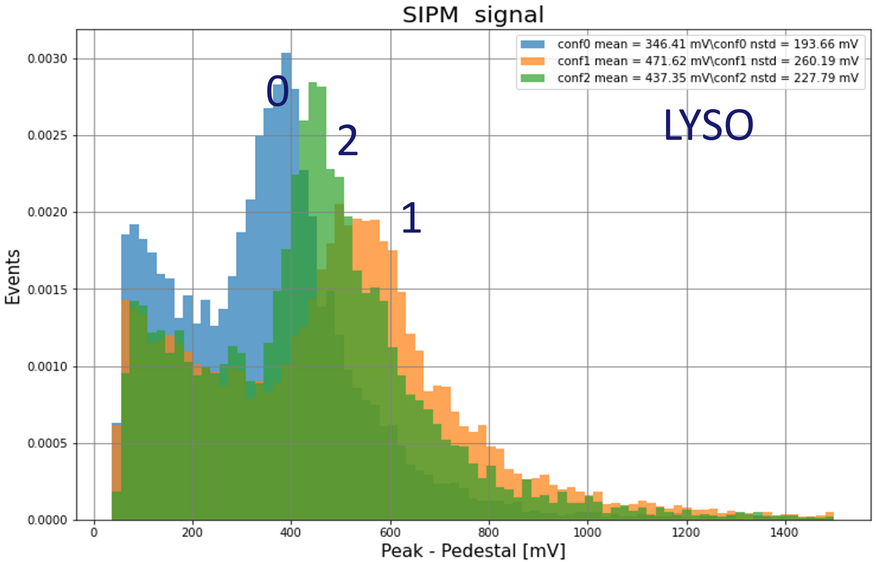
CsI,LYSO characterization with SiPM

INFN Perugia,Napoli

Light output along the crystal length





No difference is observed, position dependent, in signal amplitude for CsI crystal

A shift in the signal amplitude is observed when triggering events in different position along the crystal
The largest amplitude is observed when taking data on the oppostie side with respect to the photodetector edge (config_1)

Over crystals characterization

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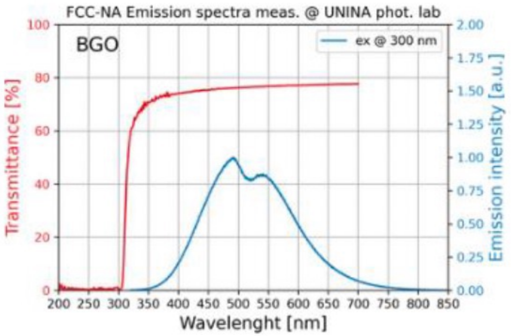
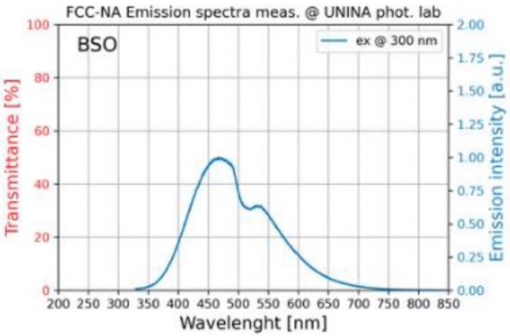
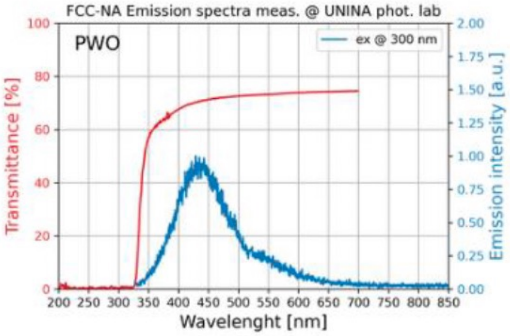
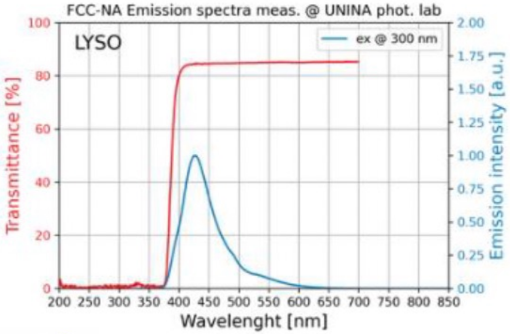
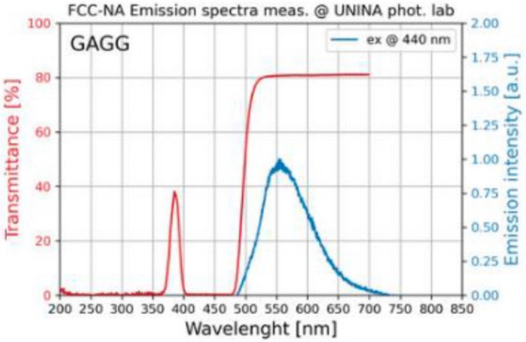










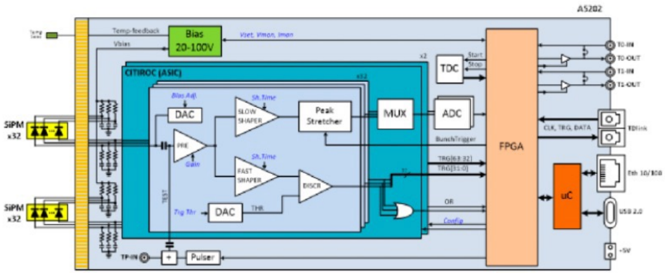
Read-out options

INFN Perugia,Napoli

- Two CITIROC ASICs
  - 64ch frontend.
- Onboard power supply with temperature correct

Read out scheme:

- Each channel:
  - preamplifier
  - slow shaper with peak sensing (variable shaping time)
  - fast shaper followed by a discriminator
- One ADC digitize multiplexed peak values:
  - info on the peak amplitude and trigger time.



Conclusion

INFN Perugia,Napoli

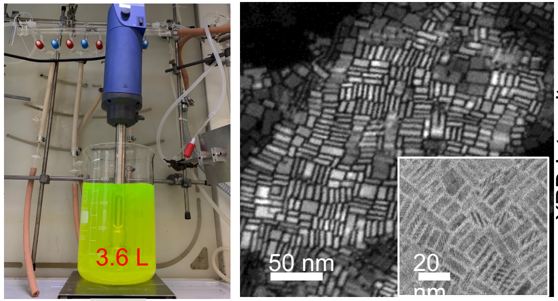
- SiPM readout much simpler than APD
  - high gain
  - no need of signal shaping
- For the moment, main studies with pure CsI and CsI(Tl), cross checks with high output yield crystals (LYSO, LaBr3)

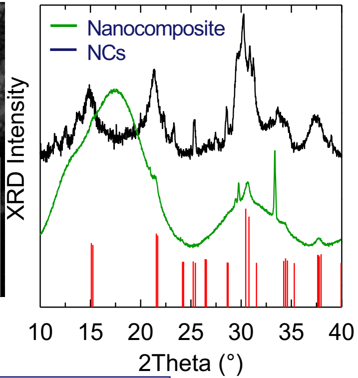
In the next future:

- Radioactive sources are now available for further studies Cs^{137}, Co^{60} and Bi^{207}
- BSO, BGO, PWO, GAGG also under study: transmittance and emission spectrum have been measured
- New readout FE options are under study: reading of 16 channels at the same time
- Setting up specific Geant4 simulation for single crystal 14

Large scale in situ synthesis of $CsPbBr_3$ NCs in polyacrylates

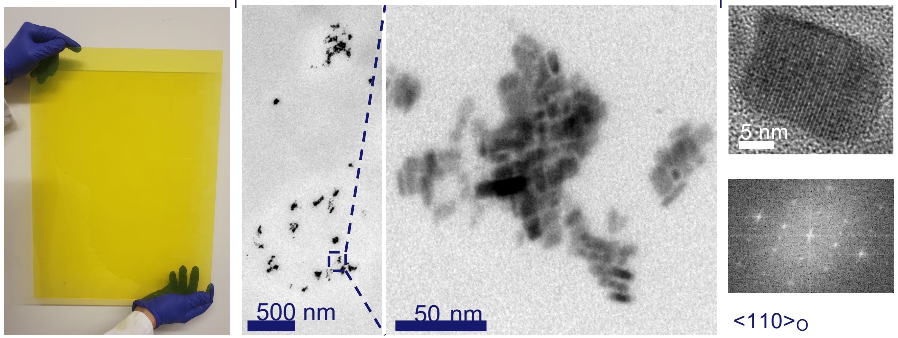
Turbo-emulsion synthesis





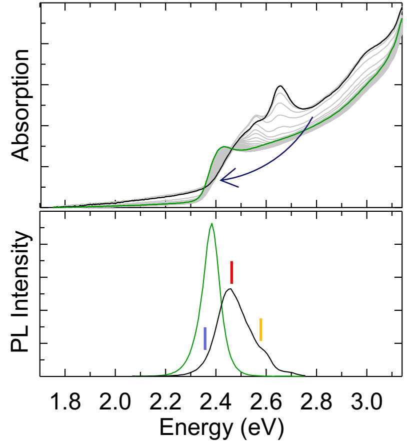
Polymerization

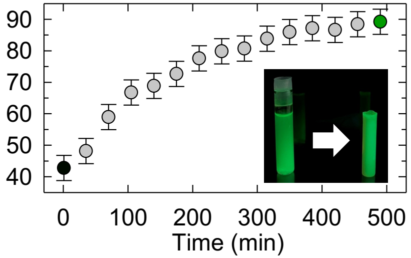
NC Evolution

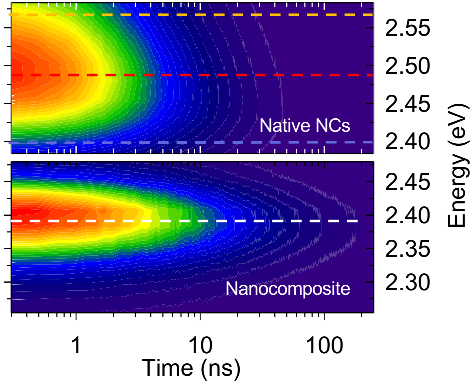


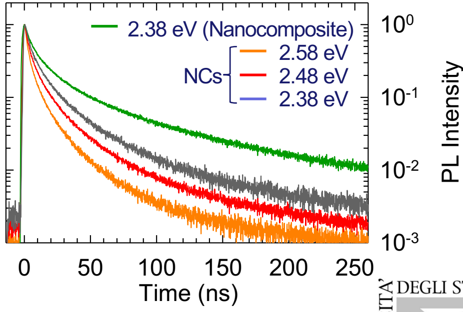
<110>O Orthorombic

In-situ evolution

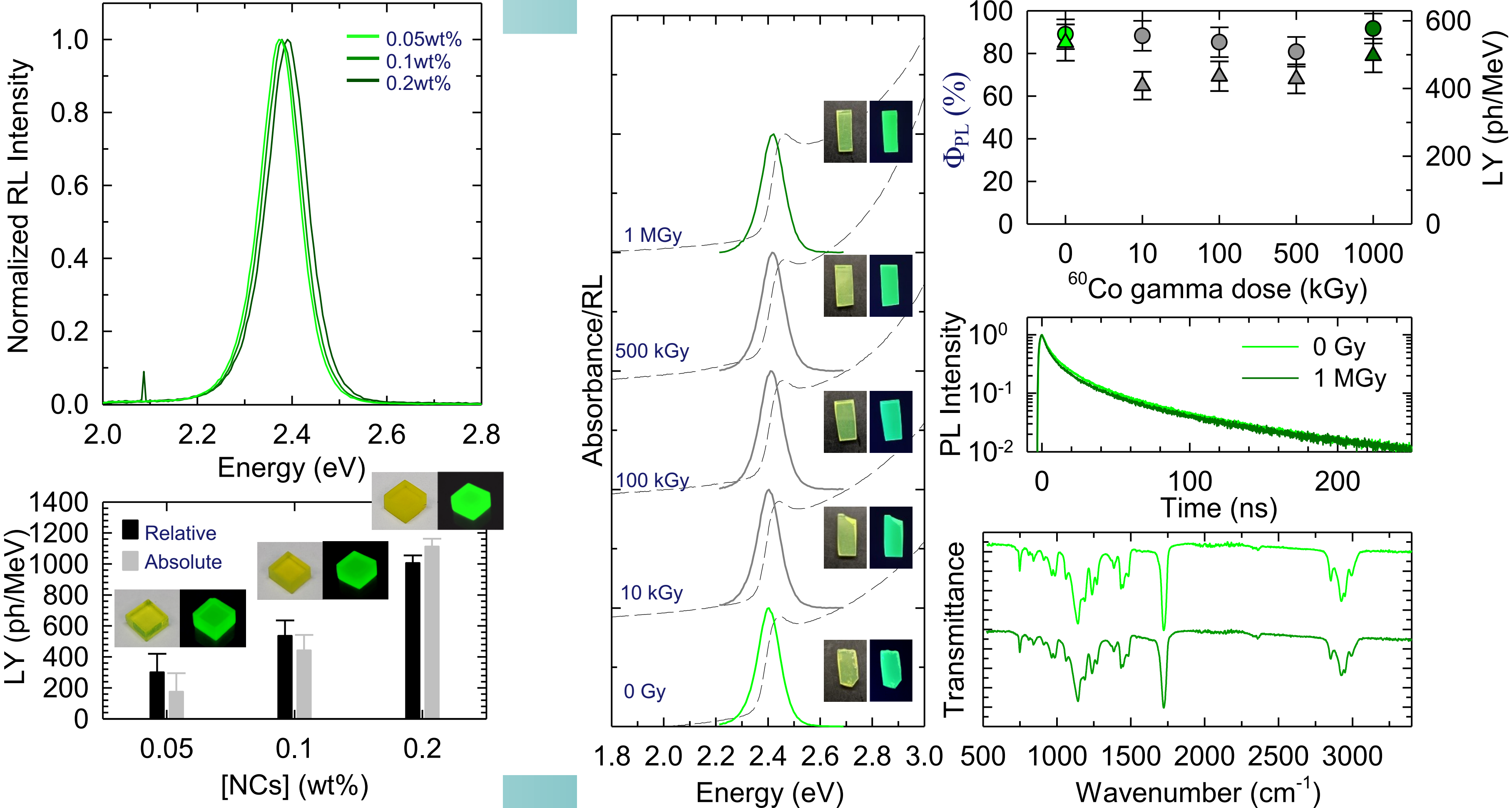






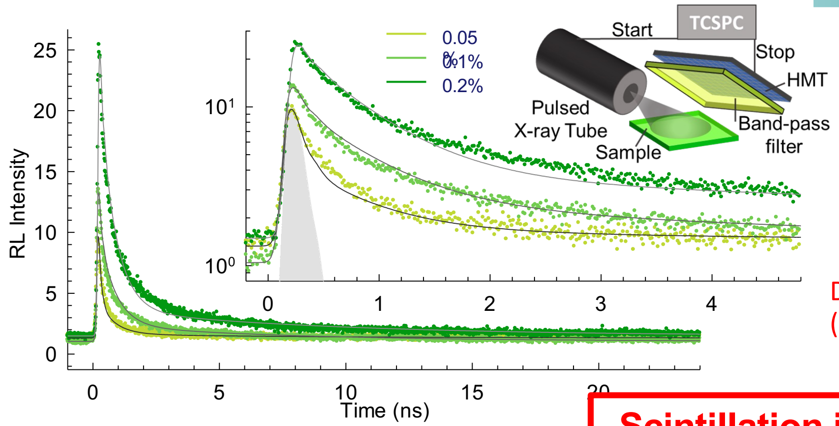


LY and radiation hardness



Origin of the decay components

[NC] (wt %)	Prompt	t₁		t₂		t_EFF	LY	N	CTR
	R_P	R_1	ns	R_2	ns	ns	ph/MeV	Estimated at 511keV	Estimated (ps)
0.05	0.30	0.37	0.61	0.33	22	1.13	238	121	93
0.1	0.32	0.21	0.62	0.47	8.7	1.76	489	250	81
0.2	0.34	0.22	0.60	0.44	6.8	1.54	1056	541	51

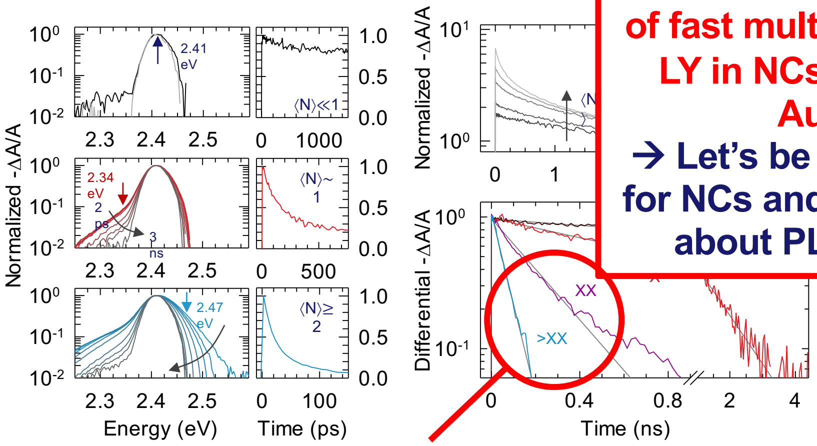


$$DTR = \sqrt{\frac{\tau_{EFF}\times(1.57\tau_{RISE}+1.13\sigma_{INST})}{LY}} = CTR/\sqrt{2}$$

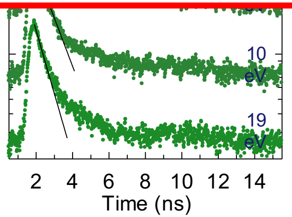
Detector Time Resolution (measured in single mode)

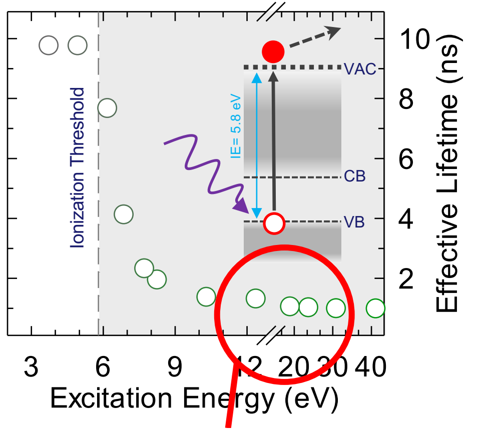
Coincidence Time Resolution (measured in coincidence mode)

Scintillation is dominated by the decay of fast multi- and/or charged exciton → LY in NCs is strongly influenced by Auger recombination
→ Let's be careful when comparing LY for NCs and bulk crystals…it is not just about PLQY and stopping power!



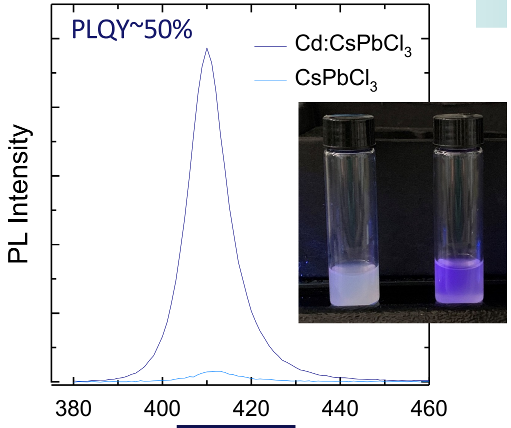
Corresponding to ultrafast RL components

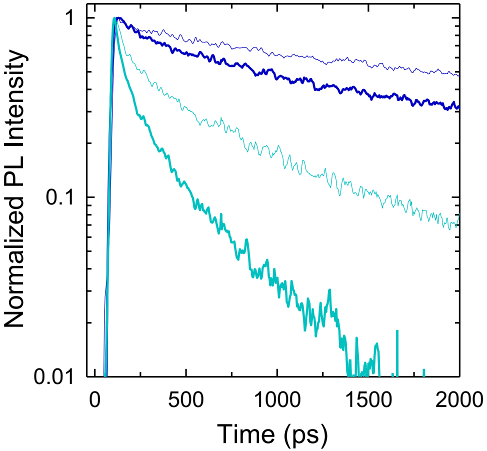


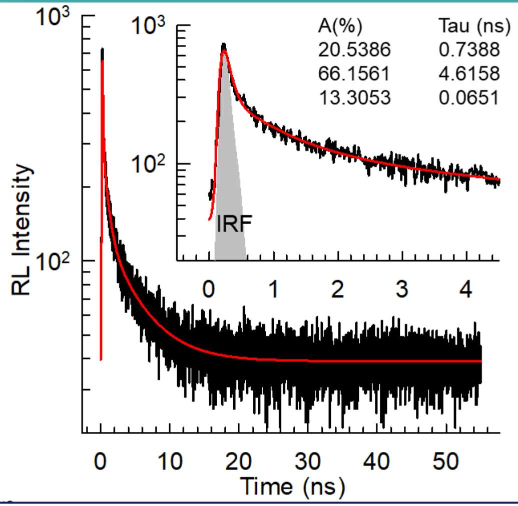


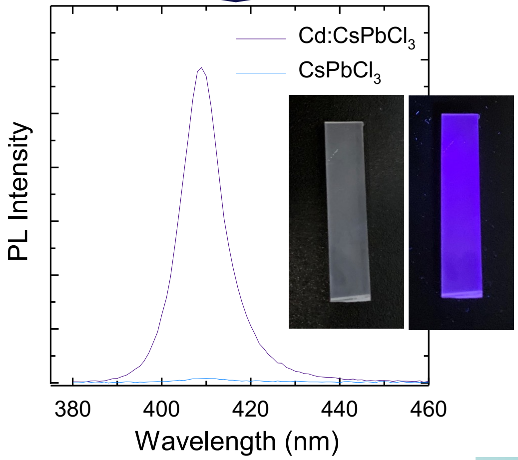
Matching intermediate RL component

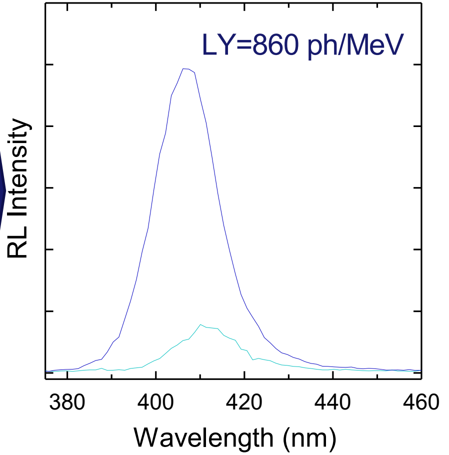
Cd:$CsPbCl_3$-polyacrylate ultrafast UV-scintillators

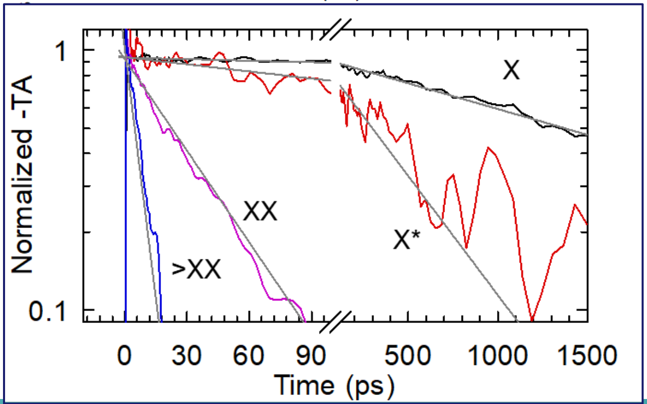












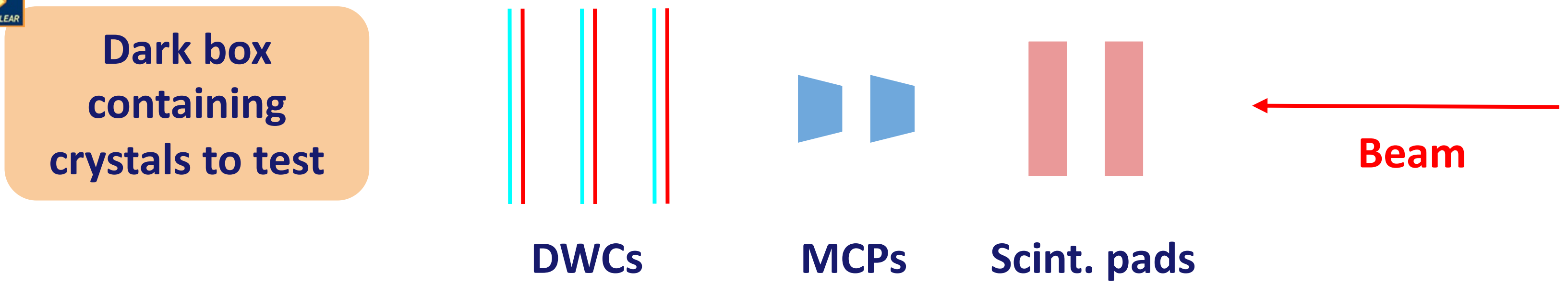
Test beam activities

Test beam activities

In 2022 many test beam activities were performed:

- **CERN team in H2 07/09-12/09:**
  - Assessment of timing resolution of several scintillating materials with mip
    - “Standard” scintillating crystals, Cerenkov, Crossluminescence, nanomaterial
  - Some very preliminary tests with electrons
    - To discriminate by filter and pulse shape scintillation/Cerenkov light on PW0
    - Test response of nanomaterial
- **INFN Frascatti, Torino, Ferrara, Napoli**
  - STORM in H2 and T9, 27/07-17/08
    - Oriented PWO crystals
  - KLEVER; CRILIN H2 28/09-05/10:
    - R&D for future Fast, compact crystal calorimetry with PWO and PbF2
- **INFN Frascatti, Glass to Power, Torino, Ferrara, Napoli, CERN** H2 28/09-05/10:
  - Performance comparison of “standard” Shashlyk and Nanocal Shashlyk using nanocomposite (AidaInnova Bluesky project)

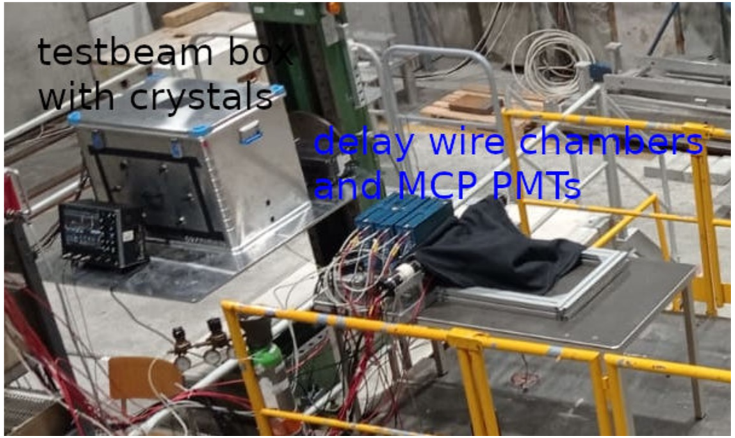
Test beam in SPS: Assesment of timing performance under MIP



Setup from the beam:

- 2 scintillating pads for trigger
- 2 MCP-PMTs in combination as time reference (T_0)
  - ➔ Intrinsic time resolution of **15 ps**
- **3 Delay Wire Chambers** for tracking
- Samples in a dark box

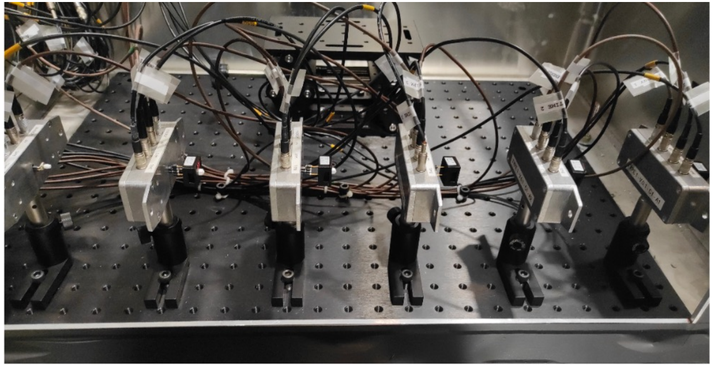
Pulses recorded with a V1742 CAEN digitizer (DRS4-based), 5 Gs/s, bandwidth 500 MHz.



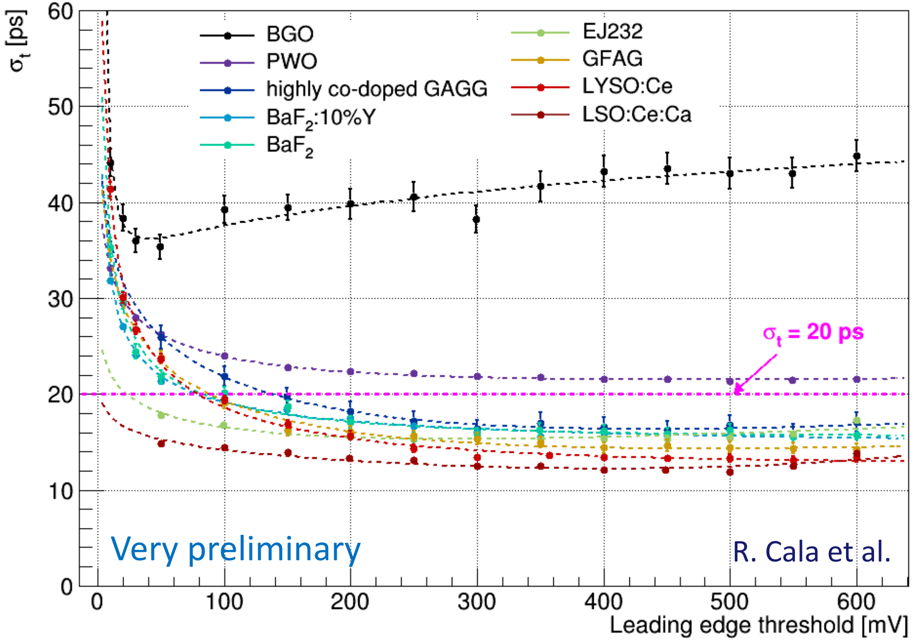
From R. Cala' talk 7.10.2022

Test conditions :

- Scintillator length 10mm except EJ232 (3mm)
- Crystals Teflon wrapped and Meltmount coupled to SiPM
- SiPM used HPK S13360-3050PE SiPMs (except for LSO:Ce:Ca (FBK NUV-HD)
- Readout with HF amplifier



Very promising results

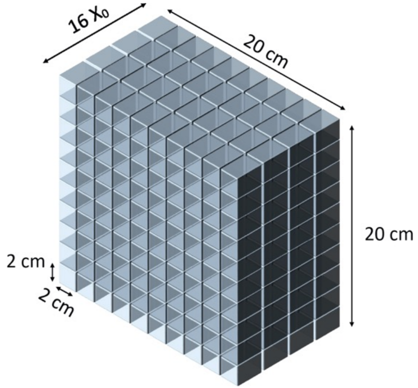


Beam tests in 2023:

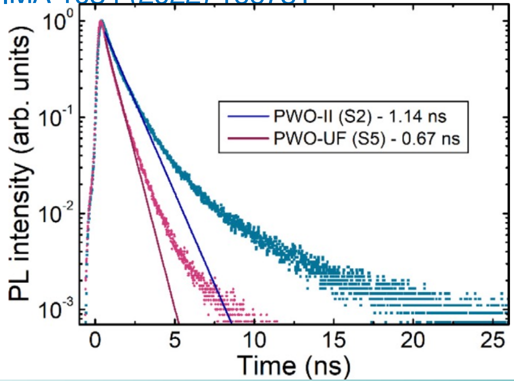
- Few days at SPS in June

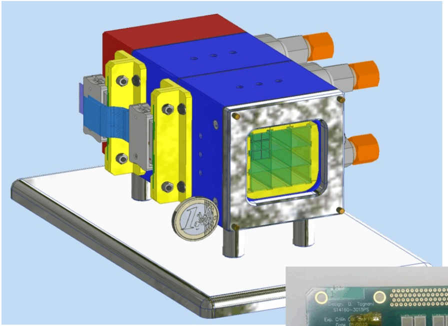
R&D for future experiments to develop new concepts for crystal calorimeters

- Cerenkov radiators like PbF_2 or ultra-fast scintillators such as PWO-UF
- Transverse and longitudinal segmentation for γ/n discrimination
- Exploit coherent interactions in crystals to reduce thickness?

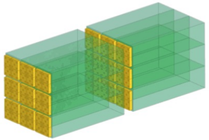


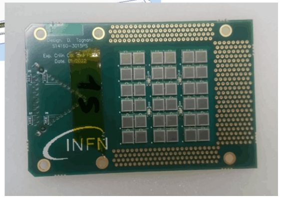
PWO-UF (ultra-fast):
Dominant emission with $\tau < 0.7$ ns
M. Korzhik et al., NIMA 1034 (2022) 166781





CRILIN prototype:
arXiv:2206.05838
- 3x3x2 crystals
- 40x10x10 mm^3



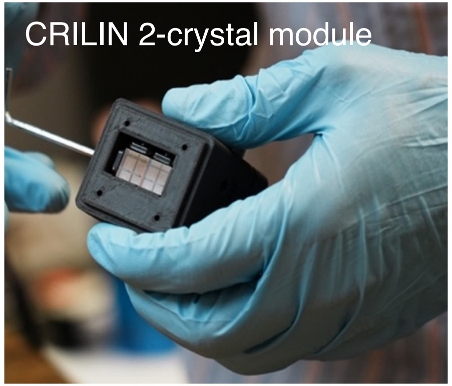


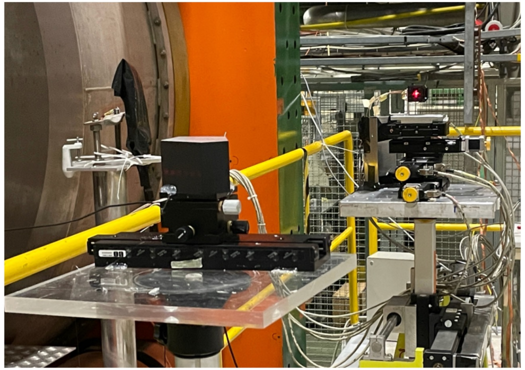
Tests with single crystals in 2022

INFN Frascatti, Torino, Napoli

Sept/Oct 2022 run at SPS H2 beamline:

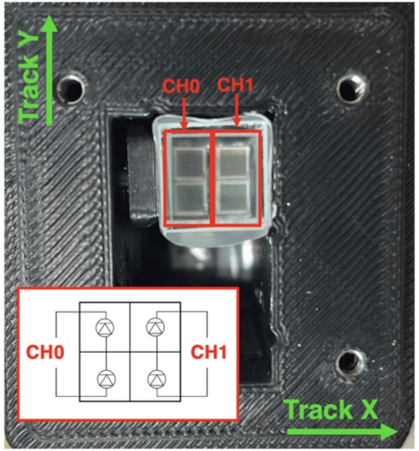
- 20-120 GeV *e*− and MIPs (150 GeV π)
- Validate CRILIN readout electronics
- Study systematics of light transport in small crystals with high *n*
- Measure time resolution achievable for PbF_2 and PWO-UF

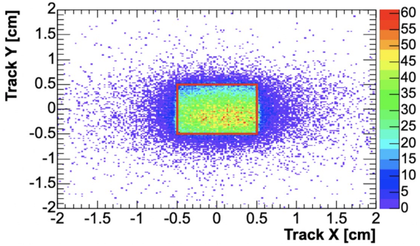




Positioning of module on beamline

SiPM readout scheme



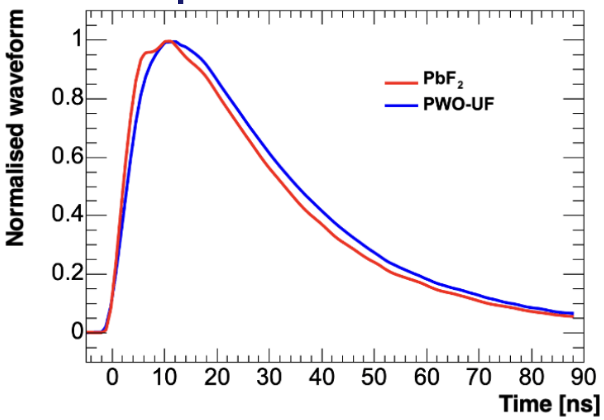


Beam image from Si-strip tracker with condition on signal from crystal

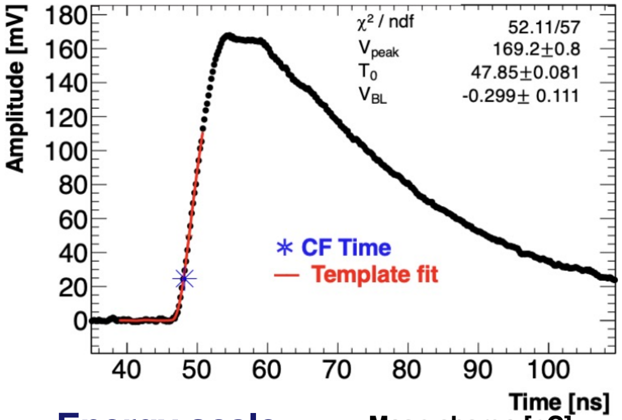
2022 data analysis and simulation

INFN Frascatti, Torino, Napoli

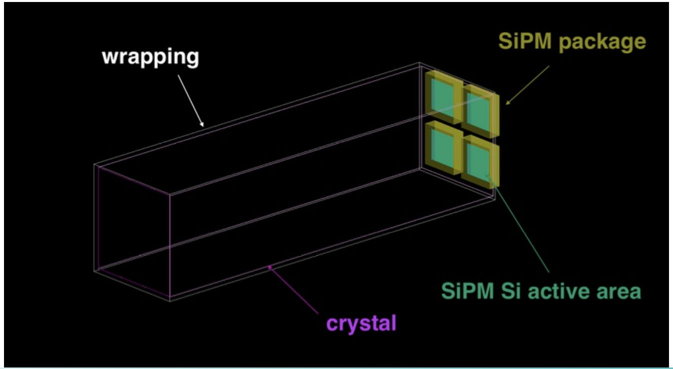
Comparison of waveforms



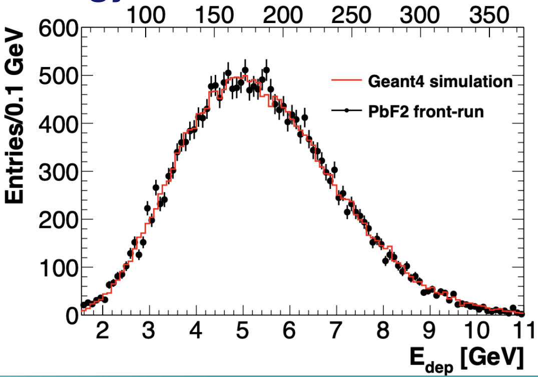
Template fit for timing analysis



Simulation of crystal/SiPM geometry



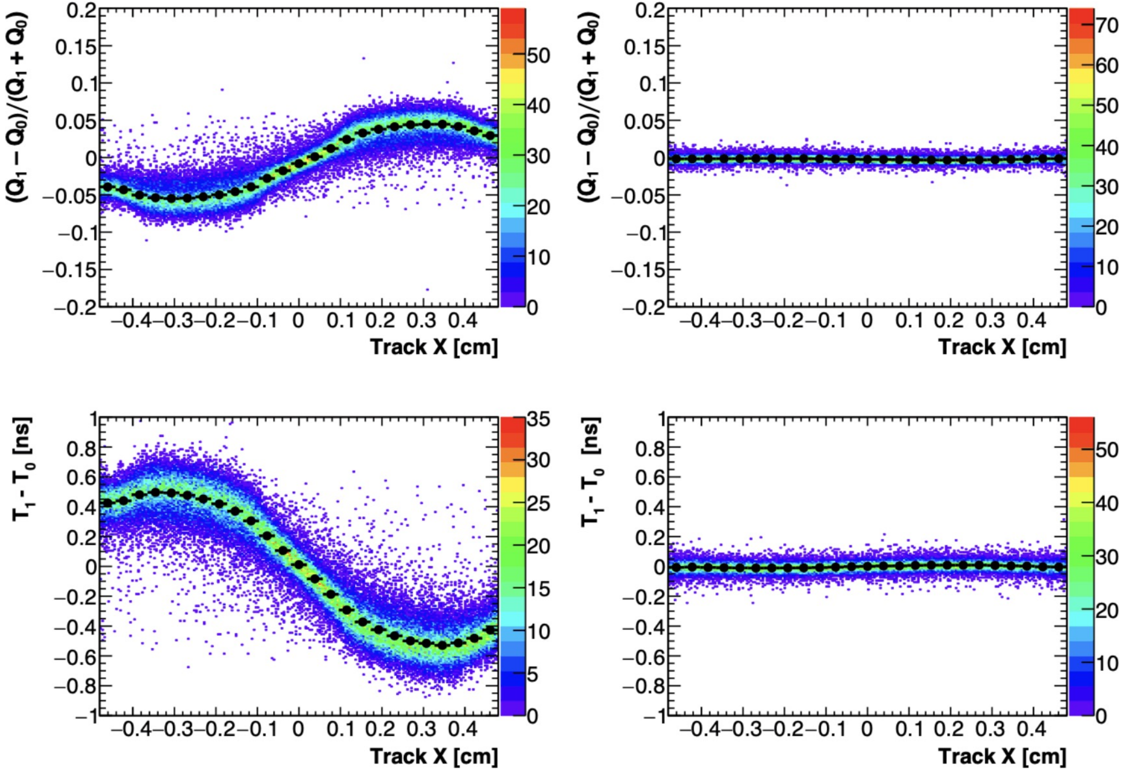
Energy scale



Light transport in small crystals

INFN Frascatti, Torino, Napoli

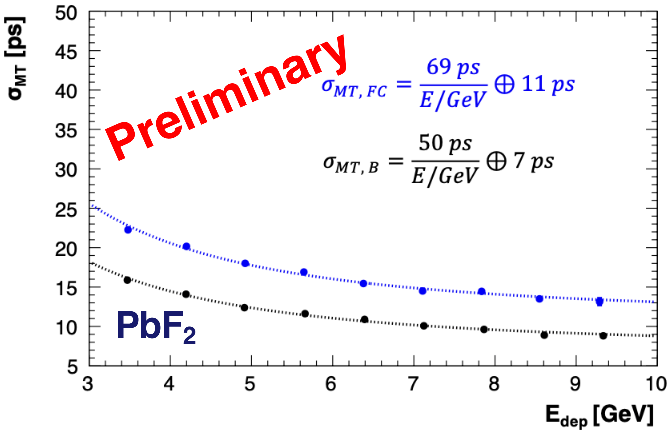
PbF_2, beam incident from front | **PbF_2, beam incident from back**

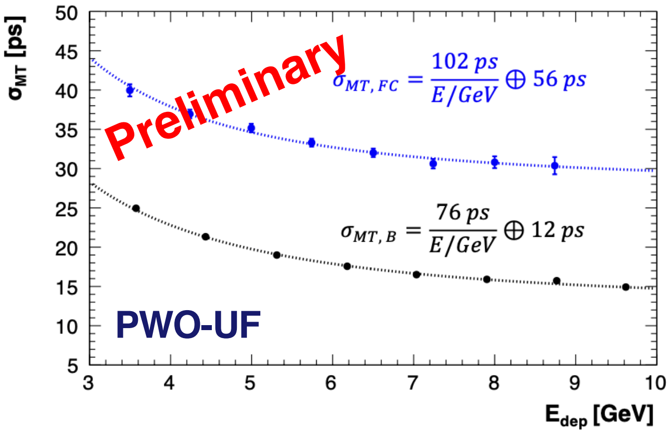


Non-homogeneity of light collection gives rise to charge asymmetry and timing effects qualitatively understood by Geant4 simulation

Time resolution for single crystals

INFN Frascatti, Torino, Napoli





$\sigma_{MT} = \sigma(t_{ch0} - t_{ch1})/2$

FC Beam incident from front

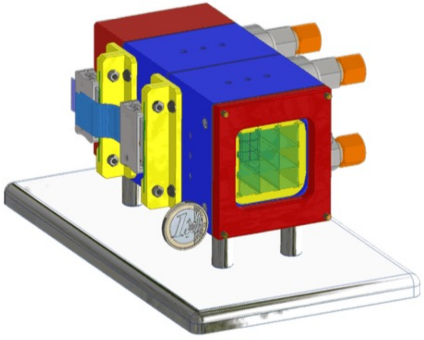
BC Beam incident from back (SiPM side)

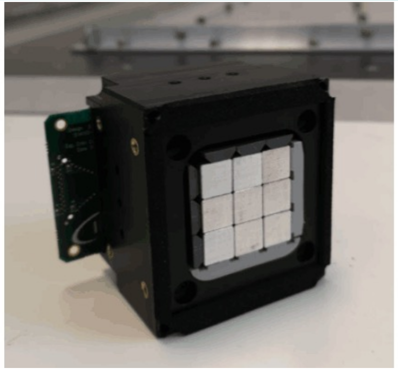
Preliminary conclusions:

- Effects of light transport degrade timing resolution for frontal incidence, despite higher light yield
- PbF_2 provides better time resolution due to pure Cerenkov emission, even with 50% light yield of PWO-UF
- Both single crystals give σ_t **< 30 ps** for $E_{dep} > 3$ GeV!

Tests of CRILIN prototype in 2023

INFN Frascatti, Torino, Napoli



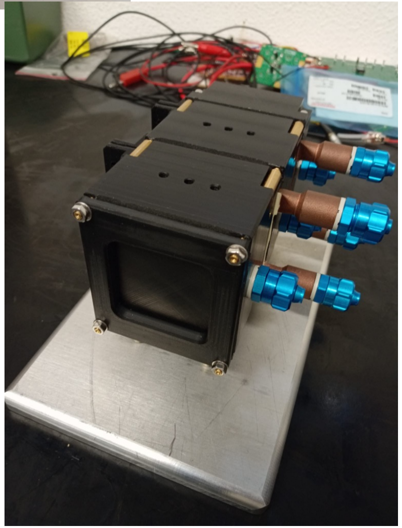


Two 3x3 CRILIN test layers, with PbF_2 and PWO-UF

Simple test setup: 20-120 GeV e^-

Test objectives:

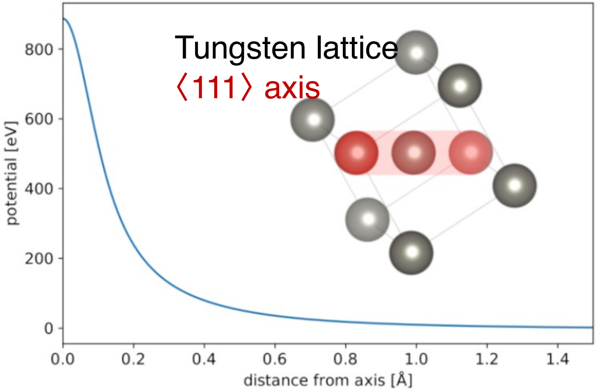
1. Test different crystal materials and surface treatments, to damp internal reflections
2. Perform complete operational test, including cooling
3. Test cluster reconstruction capability
4. Conceptual test of longitudinal segmentation
5. Study angular effects by aligning beam with axis of central crystal



Coherent effects in crystals
INFN Frascatti, Torino, Napoli

Coherent effects increase cross-section for electromagnetic shower processes (bremsstrahlung, pair production)

- **Decrease effective value of X_0**
- **Exploit coherent effects for calorimetry?**



Coherent superposition of Coulomb fields

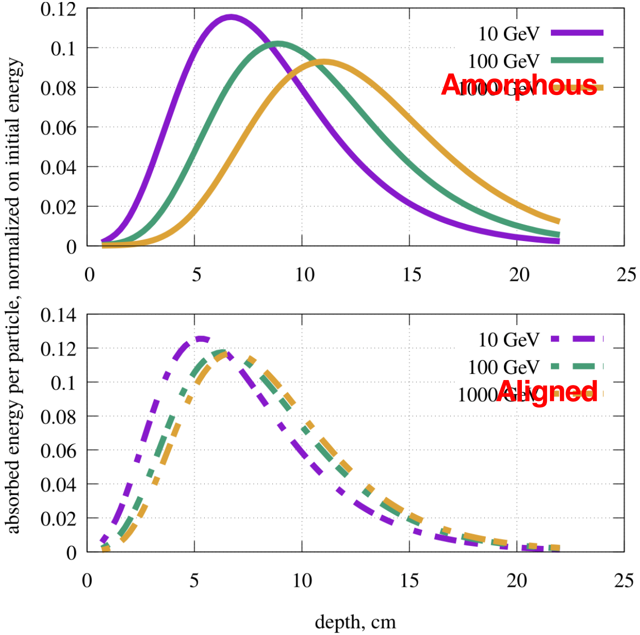
Electric field ε approx. const. ~ 10^{10}-10^{12} V/cm

Effective field $\varepsilon' = \gamma_{\text{eff}}$ $(\gamma_{\text{eff}} = E/m_e c)$

For $\varepsilon' \sim \varepsilon_0 = 2\pi m^2 c^3/eh$ virtual pairs disassociate

Geant4 simulation

Bandiera et al., NIMA 936 (2019)



- Early initiation of EM showers
- Minimize fluctuations of deposited energy vs depth

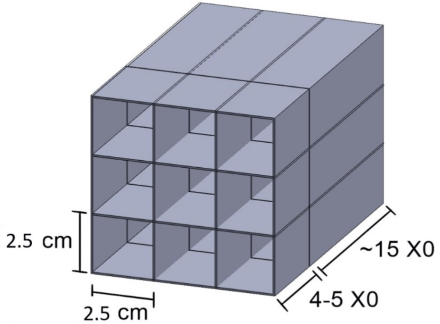
Pair production enhanced by coherent effects at small θ_γ and high E_γ

OREO: An oriented-crystal calorimeter

INFN Frascatti, Torino, Napoli

Exploit coherent interactions in crystals to develop a highly compact calorimeter

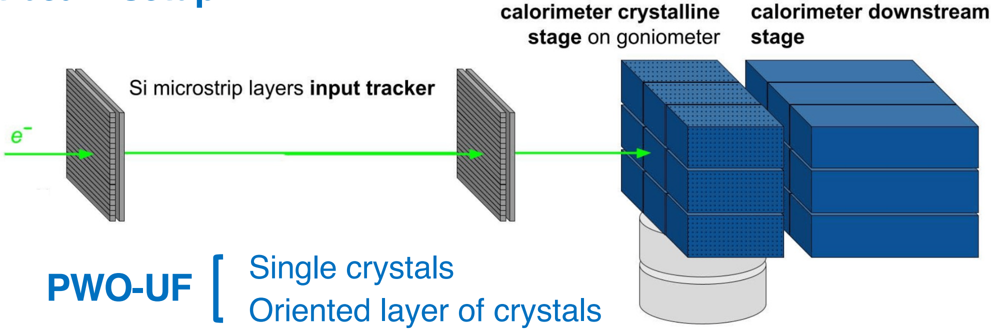
E.g. Small-angle calorimeter for HIKE:
Require good response to photons, high transparency to neutrons



Areas of R&D:

- Development of techniques for crystal characterization, shaping, alignment and assembly
- Development of mechanics, SiPM readout, interface, and front-end

OREO test beam setup:

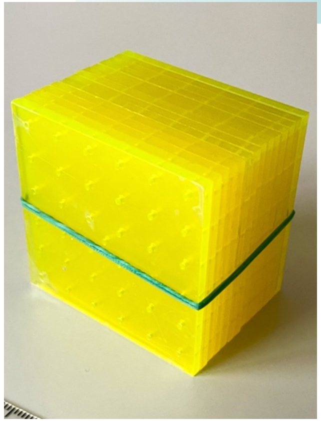


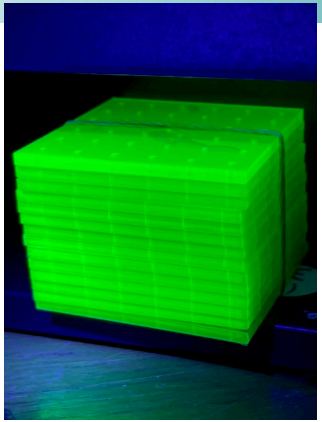
PWO-UF [Single crystals
Oriented layer of crystals

Beam tests in 2023:

- 1 week at PS (1-10 GeV e-)
- Few days at SPS (20-150 GeV e-)

Nanomaterial composites (NCs)





Semiconductor nanostructures can be used as sensitizers/emitters for ultrafast, robust scintillators:

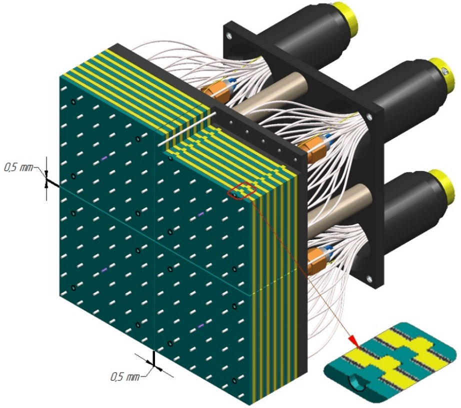
- Perovskite (ABX_3) or chalcogenide (oxide, sulfide) nanocrystals
- Cast with polymer or glass matrix
- Decay times down to O(100 ps)
- Radiation hard to O(1 MGy)

Despite promise, **applications in HEP have received little attention to date**

No attempt yet to build a **real calorimeter with NC scintillator** and **test it with high-energy beams**

Shashlyk design naturally ideal as a test platform:

- Easy to construct a shashlyk calorimeter with very fine sampling
- Primary scintillator and WLS materials required: both can be optimized using NC technology

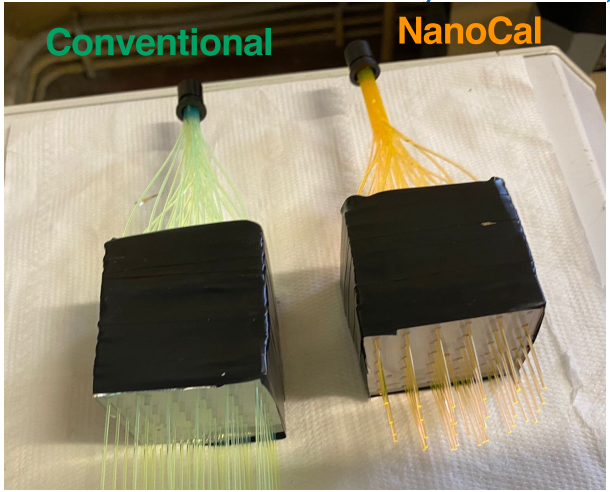


KOPIO/PANDA design
Fine-sampling shashlyk

NanoCal project status

Schedule:

- **Oct 2022: First shashlyk component test at CERN: fibers/tiles/SiPMs**
- **2023**: Further iterations to improve performance of NC scintillator prototype
- **2024:** Construction of full-scale shashlyk modules; performance comparison

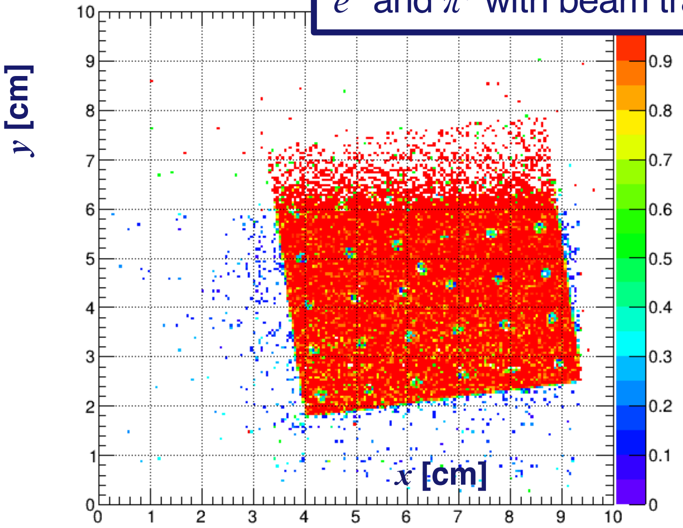


2 prototypes with 12 fine sampling layers 1.3X_0 in depth: MIP deposit = 10 MeV

Known formulation for NC scintillator:

- 0.2% $CsPbBr_3$ in UV-cured PMMA
- 50% of light emitted with $\tau < 0.5$ ns

Oct 2022 test: SPS H2 beamline e^- and π^+ with beam tracking



Conclusion of 2022 test:

NC prototype seems to work but with low light yield and many open questions

NanoCal goals for 2023

Big effort in 2022 to test first prototype only 5 months after project start!

Beam test results ambiguous due to construction errors for NC prototype

2023 NanoCal beam test
14-21 July, T9 at CERN PS
e^- and MIPs, 1-10 GeV

Comprehensive test program for 2023, prototypes under construction:

Conventional scintillator Nanocal scintillator, 0.2% (rebuilt)	Re-establish quantitative baseline with errors corrected
Nanocal scintillator, 0.2% + custom fibers	New fiber developed with Kuraray specifically optimized for CsPbBr3 emitter: fast de-excitation, high Stokes shift
High concentration (0.8%?) + custom fibers	Test improvement in light yield with increased concentration
New formulation with $CsPbCl_3$ + intermediate WLS dye	Test improvement in light yield with increased absorption length

Publications/Presentations

- Publications:
  - L. Martinazolli et al., Compositional engineering of multicomponent garnet scintillators: Towards an ultra-accelerated scintillation response, , Mater. Adv., 2022,3, 6842-6852
  - G. Tamulaitis et al, Transient optical absorption as a powerful tool for engineering of lead tungstate scintillators towards faster response, J. Materials Chemistry C, 10, 9521 (2022), DOI: 10.1039/d2tc01450e.
  - F. Pagano et al., A new method to characterize low stopping power and ultra-fast scintillators using pulsed X-rays, Front. Phys. 10:1021787.doi: 10.3389/fphy.2022.1021787
- Presentations:

  At SCINT2022: 16th Int. Conference on Scintillating Materials & their Applications, September 19-23, 2022, Santa Fe, USA
  - G. Tamulaitis: Transient Optical Absorption Technique as a Tool for Routine and In-depth Characterization of Fast Scintillators, (keynote)
  - N. Kratochwil: Characterization of dense Cherenkov/Scintillation/Semiconductor materials for fast timing at future colliders
  - R. Cala' : Exploring BaF2:Y Ultra-fast Emission for Future HEP Applications
  - L. Martinazolli: Acceleration of the scintillation response in garnet type multicomponent scintillators

Conclusion

- Milestone MS32 is completed:
  Many characterisation benches available

- Different scintillating materials have been investigated
  Many synergies between participants and Joint activities

- Fruitful test beam activities in 2022 and many others foreseen for 2023