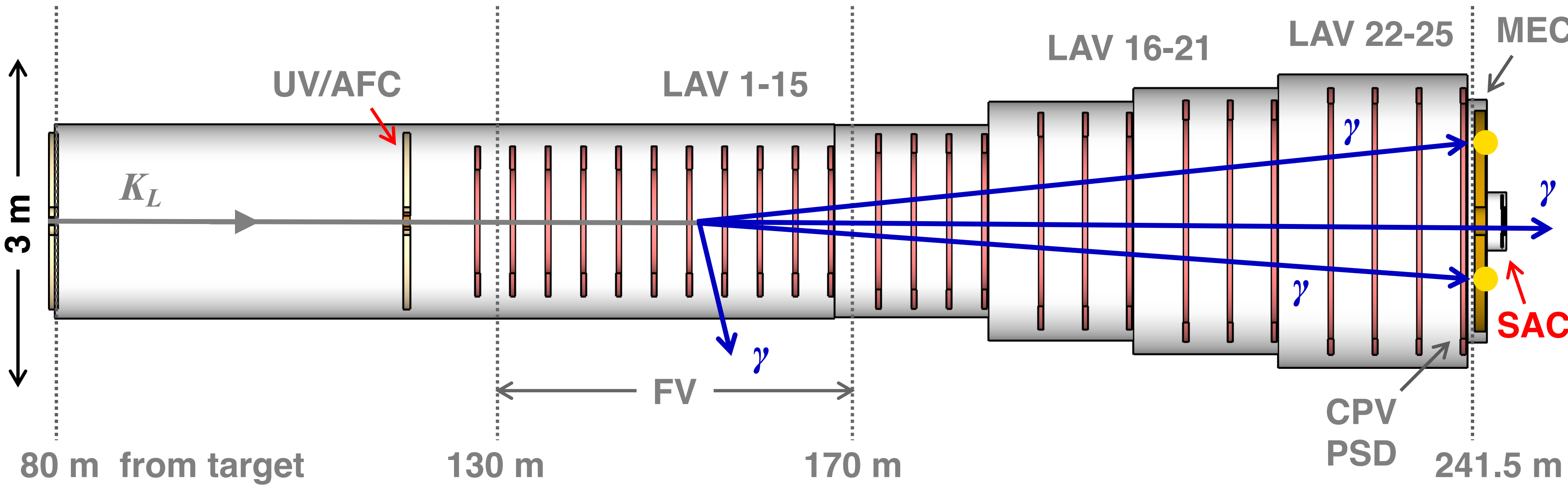
HIKE SAC:
Risultati test beam e progetti R&D

Matthew Moulson

Referee CSN1 – NA62

28 luglio 2023

Small-angle photon veto



Small-angle photon calorimeter system (SAC)

- Rejects high-energy γs from $K_L \to \pi^0\pi^0$ escaping through beam hole
- Must be insensitive as possible to 430 MHz of beam neutrons

Beam comp.	Rate (MHz)	Req. $1-\varepsilon$
γ, $E > 5$ GeV	**50**	**10^{-2}**
γ, $E > 30$ GeV	**2.5**	**10^{-4}**
n	**430**	**–**

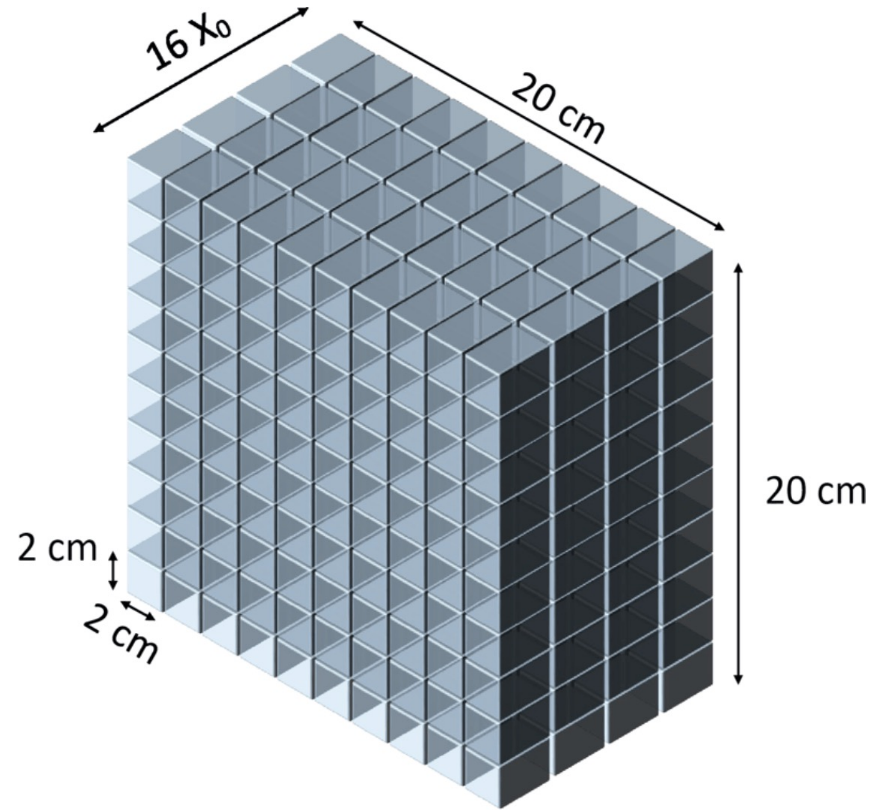
Baseline solution:

- **Ultra-fast heavy Cerenkov calorimeter (e.g. PADME, g-2)**

A Cerenkov SAC for HIKE

Proposed solution:
Ultra-fast, heavy Cerenkov calorimeter

- σ_t < 100 ps, 2-pulse separation at ~ 1 ns
- Optimize choice of crystal
- Optimize choice of photodetectors
- Study response to neutral hadrons
- Verify radiation hardness to 10^{13}-10^{14} n/cm^2 and 10^5-10^6 Gy
- Possibilities for γ/n discrimination: multilayer structure/longitudinal segmentation
- Explore idea of exploiting coherent interactions in crystals to reduce thickness



Overview of R&D directions

CRILIN

Highly granular, longitudinally segmented PbF_2 calorimeter independently proposed at LNF for Muon Collider

Collaboration with CRILIN to study:

- Materials: PbF_2 vs PWO-UF
- Radiation resistance of crystals
- Photosensors: SiPMs, front-end
- Light collection in small crystals
- Longitudinal segmentation
- Mechanics, cooling, integration

OREO

CSN5 project to develop proof of concept for calorimeter with aligned crystals, inspired in large part by needs of HIKE SAC

Collaboration with OREO to study

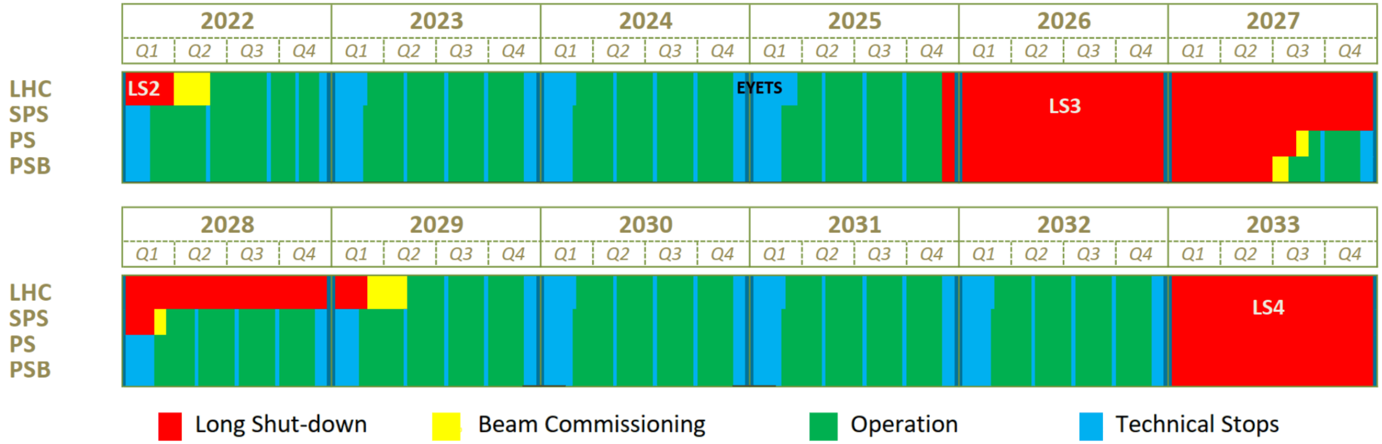
- Enhanced interactions in single crystals with alignment
- Techniques for crystal characterization
- Techniques for crystal alignmnent
- Performance of aligned planes

Design for HIKE SAC

HIKE members share resources with and participate in CRILIN and OREO
CRILIN and OREO members have signed the HIKE proposal

CRILIN people are non-signing members of the NA62 Collaboration
OREO people are full members of the NA62 Collaboration

Original timeline for SAC R&D



IEFC working baseline, March 2022 – https://indico.cern.ch/event/1134440/

Early 2022: **HIKE Phase 1 start in 2028** **→ SAC test at latest 2025**

SAC R&D timeline, early 2022

- **2021: CRILIN** tests with single crystals and SiPMs, repurposed front-end electronics; **OREO** tests of shower development in aligned single crystals
- **2022: CRILIN** tests with small matrices (3x3x2) of longitudinal segmentation concept with dedicated electronics, partial alignment; **OREO** tests of techniques for crystal alignment
- **2023-2024: HIKE** tests with hadron beams, construction and test of prototype with multi-crystal alignment, validation in principle of solutions for mechanics and readout
- **2025: HIKE** test of full-scale prototype

Revised timeline for SAC R&D

ECN3 High Intensity - Indicative Schedule & Constraints

Machine/Facility/Experiments	Comments	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
LHC	priority on available resources				LS3			Commissioning				LS4		
SPS	esp. (EL, CV, HE, BI, STI, etc.)				LS3							LS4		
EHN1+2 NA-CONS (baseline)	BA80 and general Infr. Focus	Preparation & YETS Implementation Phase			LS3 Deployment		Commissioning + Operation					LS4		
ECN3 HI TT20/TCC2/TDC2/TTs	critical equipment & servics (limited work in TCC2)	Engineering Preparation & Implementation Phase			Installation (LS3)		Commissioning					LS4		
ECN3 HI TCC8 Target Complex	HL-LHC + NA-CONS overlapping resources/schedule	Engineering Design Phase			Final Opt. & PRR	Preparation, Dismantling	Procurement / Assembly	Procurement/ Installation	Installation/ Commissioning			LS4		
HIKE Experiment	Modifications and upgrades of detectors as required	Proposal	TDR	PRR	Upgrades and Installation		Detector Commissioning		Det./Beam Comm. (tbc)			LS4		
SHIP Experiment	Approval on critical path for TDR phase to be launched/financed	Proposal	TDR	TDR	TDR/PRR	Production / ECN3 Dismantling	Construction	Installation/Commissioning				LS4		
SHADOWS Experiment		Proposal	TDR	TDR	PRR	Production/ Area preparation	Construction /Installation	Installation/Commissioning				LS4		

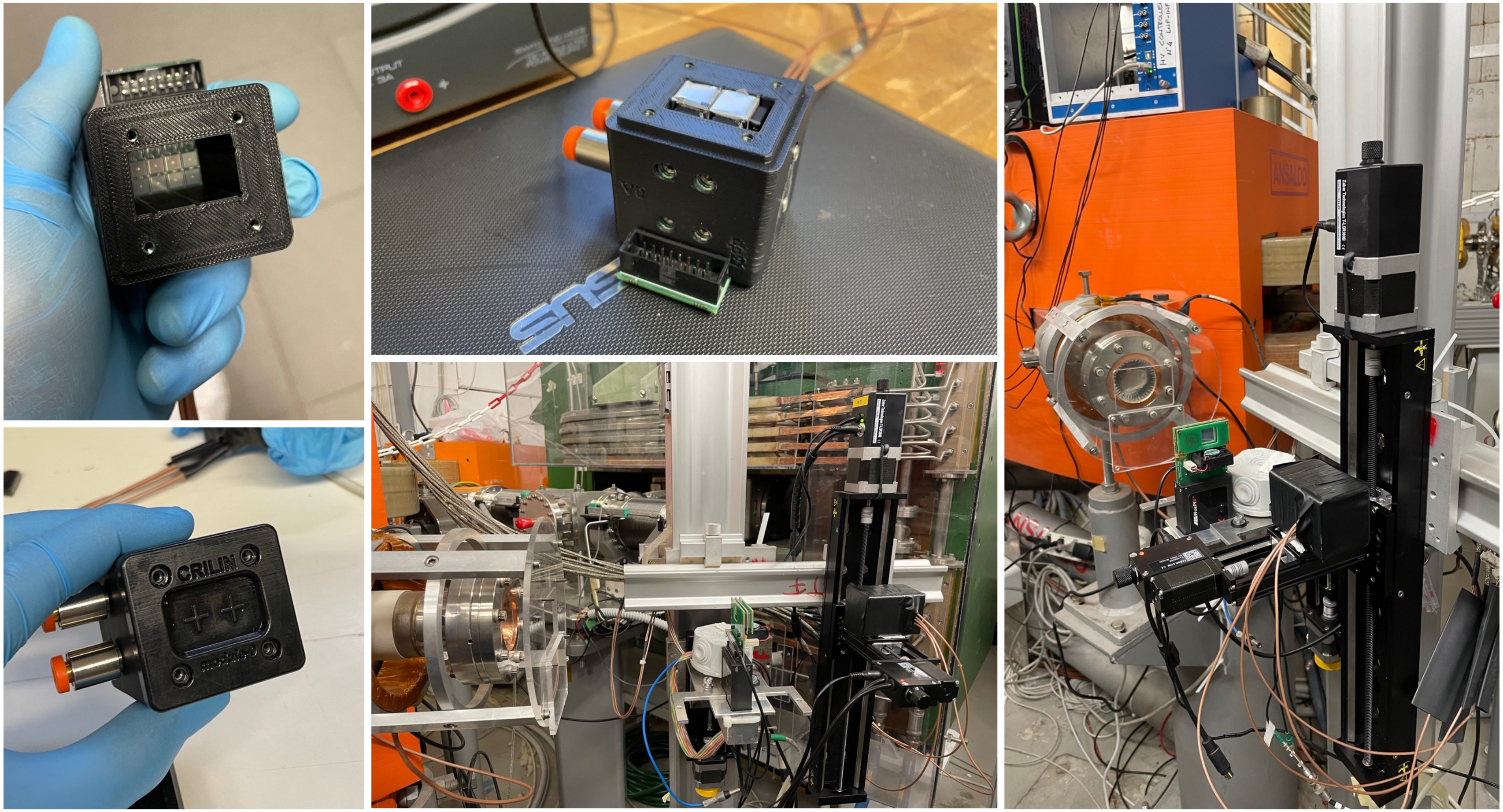
PBC ECN3 Beam Delivery Task Force, March 2023 – CERN-PBC-REPORT-2023-001

Current HIKE Phase 1 estimated start in 2031

Can test SAC in NA test beams in 2028 for final deployment in 2031

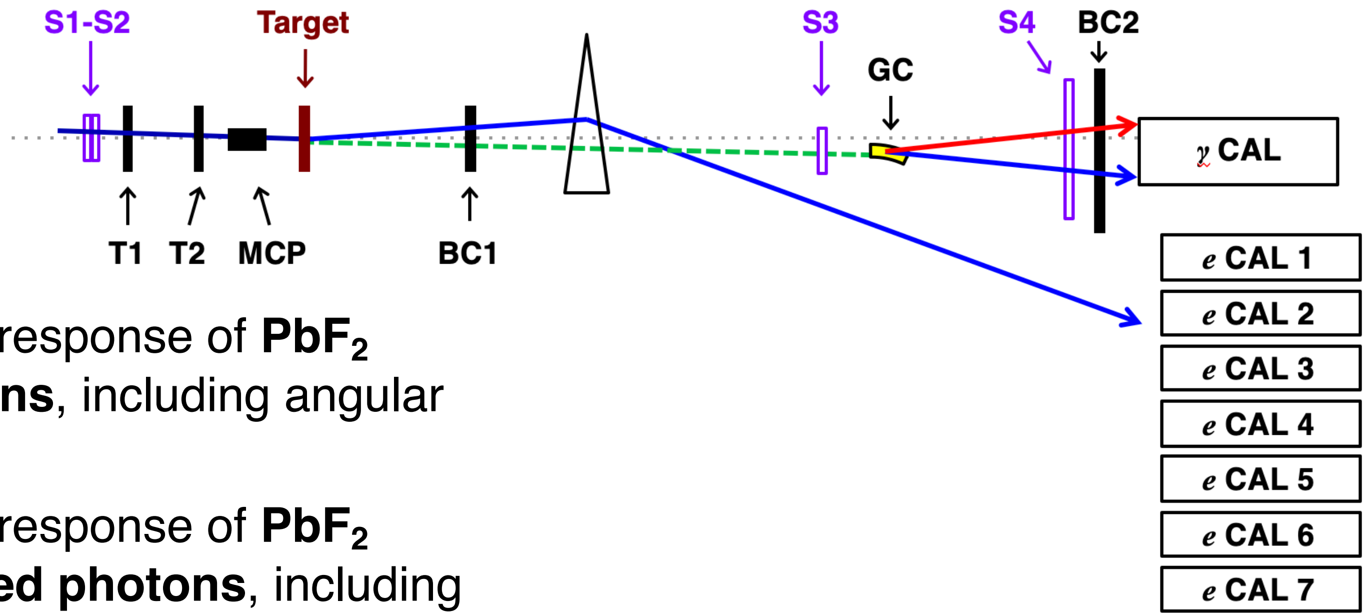
- **2021-2022: CRILIN** tests with single crystals and SiPMs; **OREO** tests of shower development in aligned single crystals
- **2023: CRILIN** tests with small matrices (3x3x2) of longitudinal segmentation concept with dedicated electronics; **OREO** tests of small matrices (3x1) with multi-crystal alignment
- **2024-2025**: **HIKE** tests with hadron beams, construction and test of prototype with multi-crystal alignment, validation in principle of solutions for mechanics and readout
- **2028: HIKE** test of full-scale prototype

Tests with single crystals: BTF, Jul 2021



- Debugging run (parasitic) during BTF-2 commissioning, 28 Jun - 9 Jul
- CRILIN module 0: 2 PbF_2 crystals ($10 \times 10 \times 40$ mm^3) each read out with 4 SiPMs 4x4 mm^2 series connected in pairs (2 ch/crystal)
- Mu2e front-end electronics used for test

Tests with single crystals: H2, Aug 2021

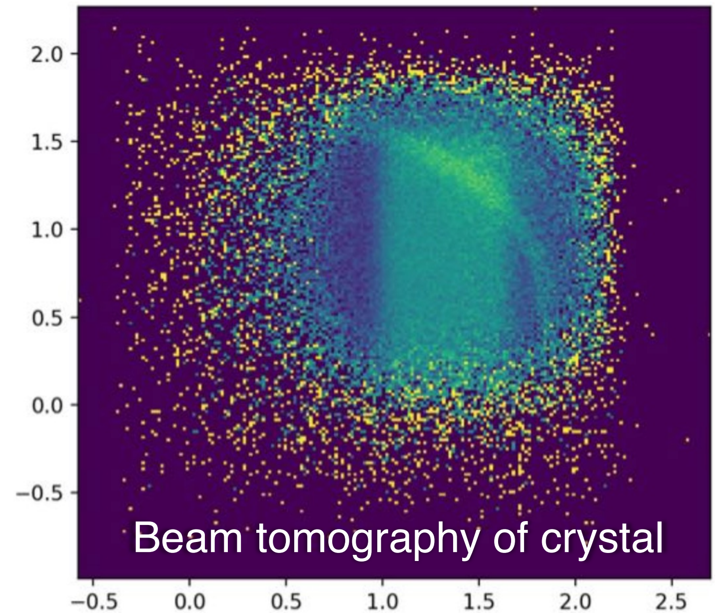


Program:

1. Measurements of response of **PbF_2** crystals to **electrons**, including angular effects
2. Measurements of response of **PbF_2** crystals with **tagged photons**, including angular effects
3. Measurements of response of **PWO-II(o)** crystal to **tagged photons**, including angular effects

Conclusions:

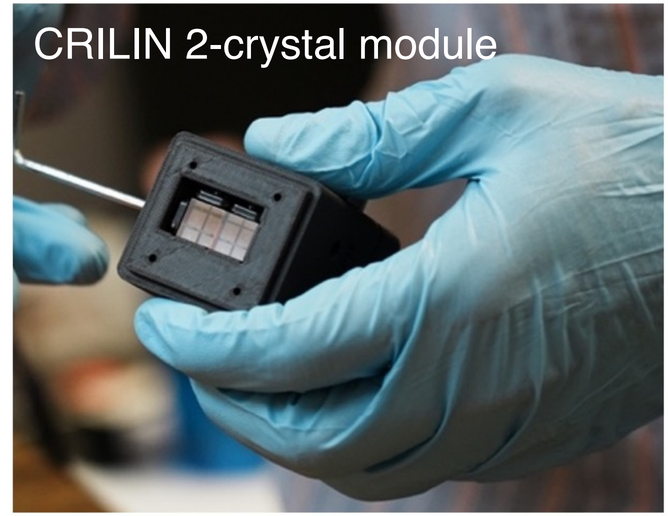
- Light collection systematics important!
- Crystal wrapping has significant effects on light collection systematics
- Time resolution limited by front-end electronics artifacts



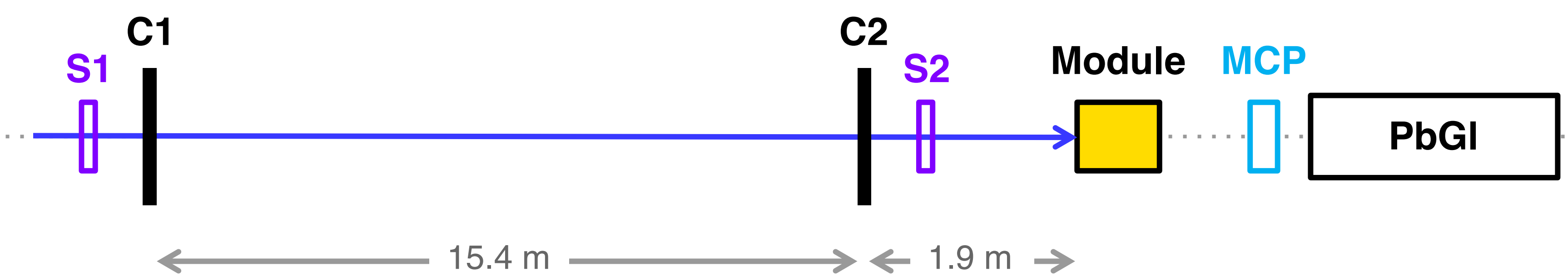
Tests with single crystals: H2, fall 2022

Program:

- 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



Simplified setup for measurements with e^- only:



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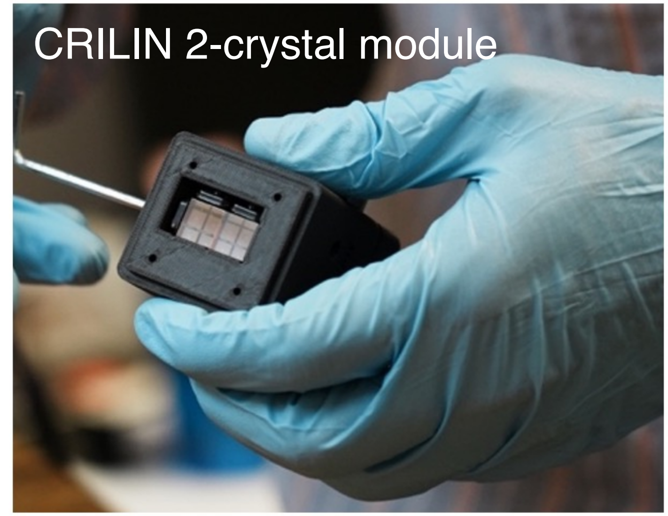
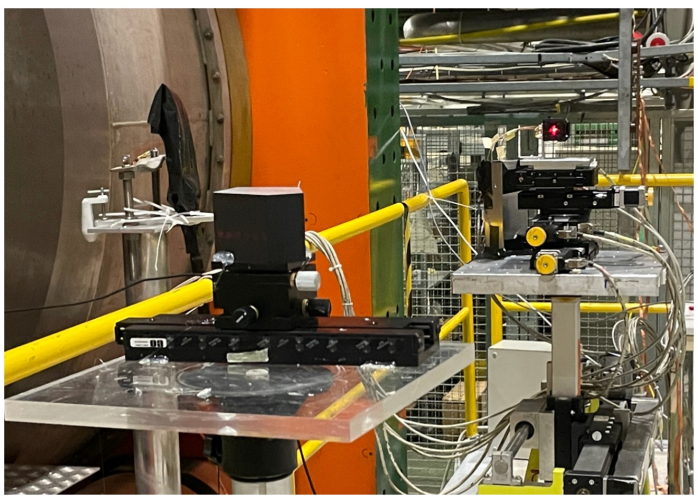
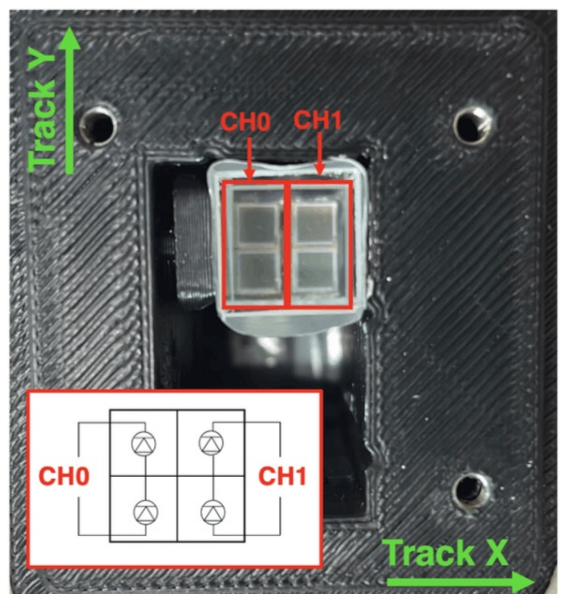
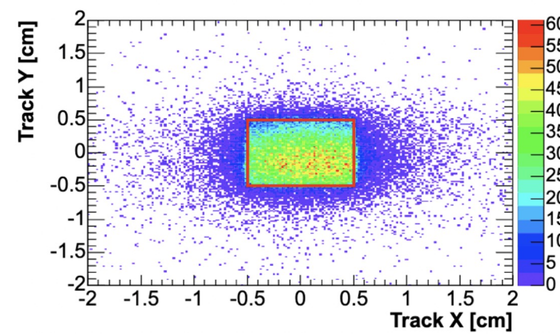




Positioning of module on beamline

SiPM readout scheme

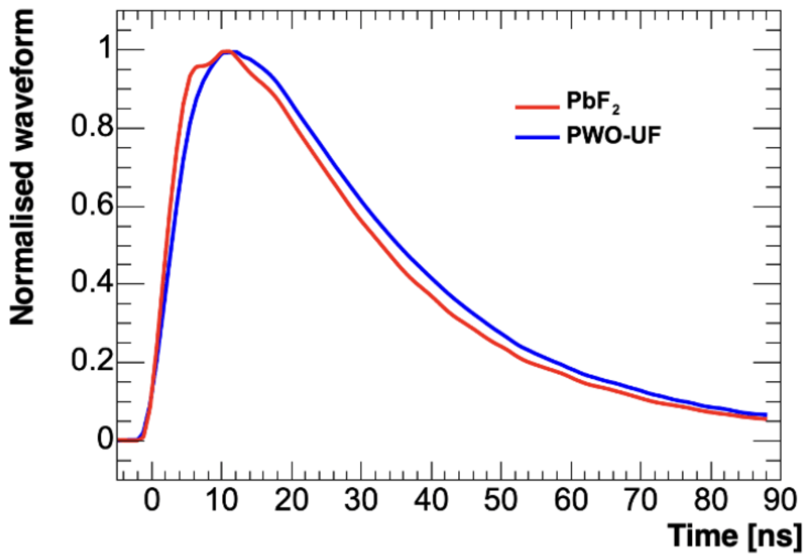




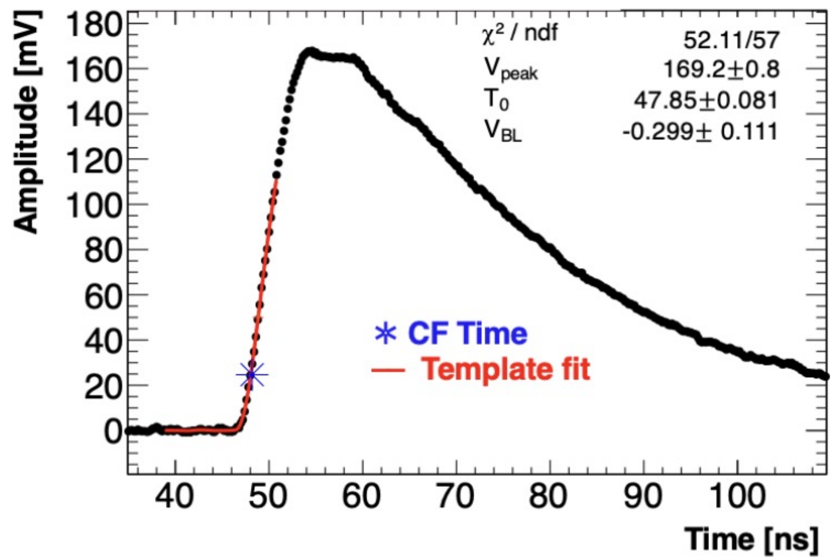
Beam image from Si-strip tracker with condition on signal from crystal

2022 data analysis and simulation

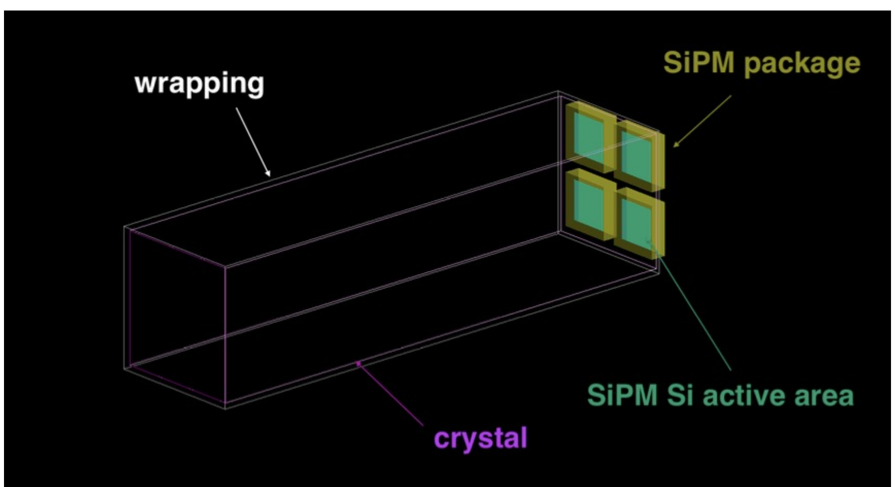
Comparison of waveforms



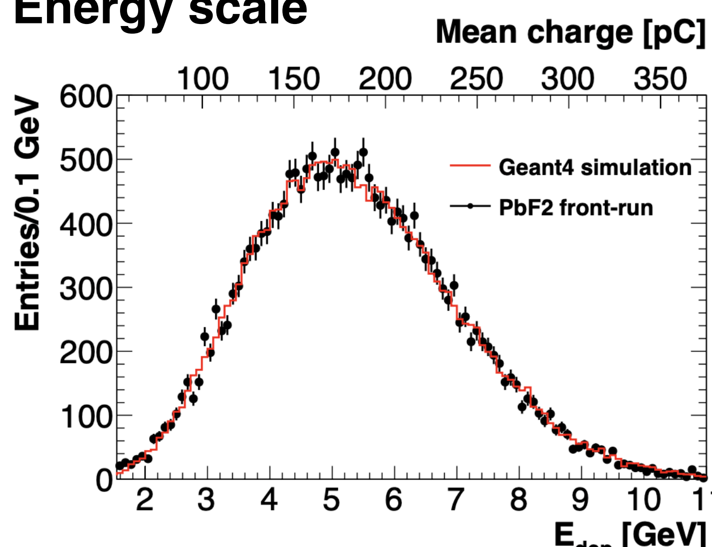
Template fit for timing analysis



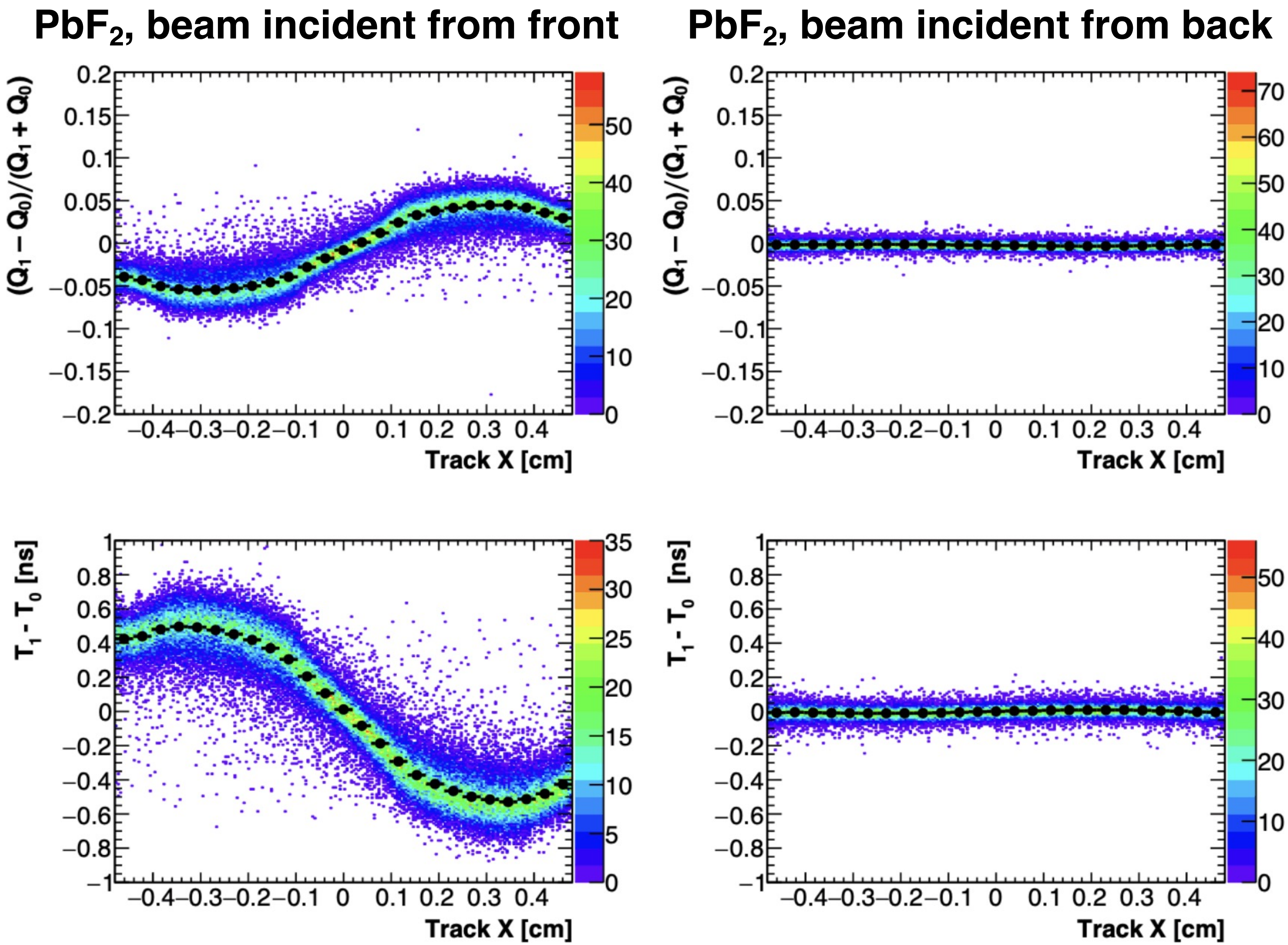
Simulation of crystal/SiPM geometry



Energy scale

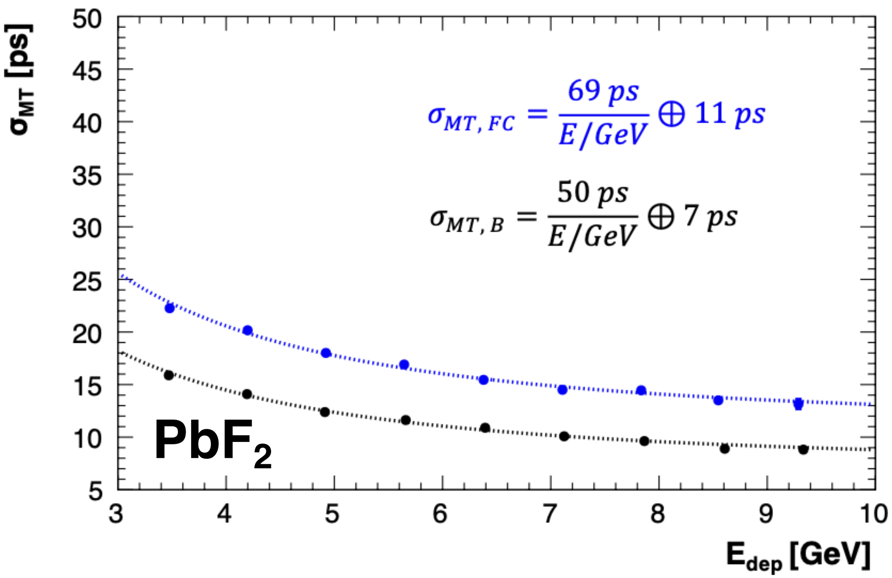


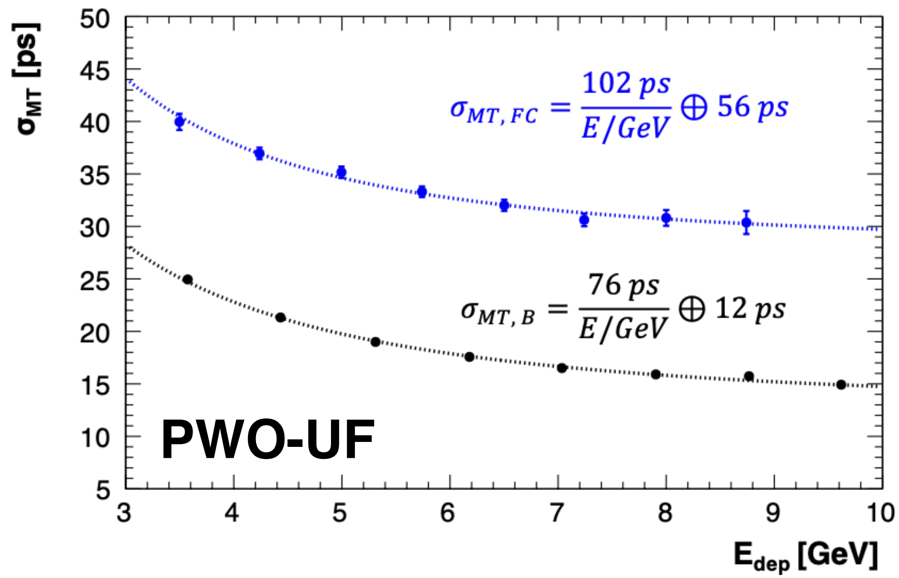
Light transport in small crystals



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

Time resolution for single crystals





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

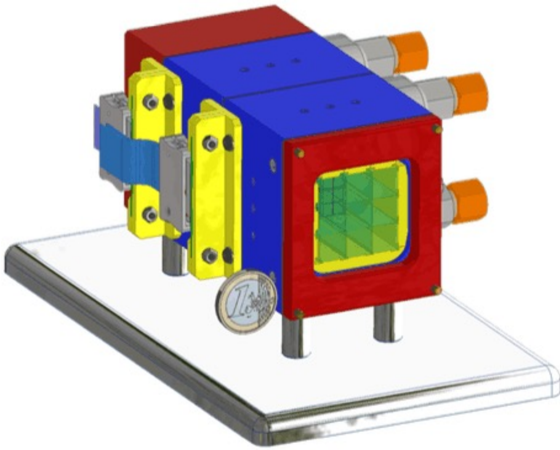
FC Beam incident from front

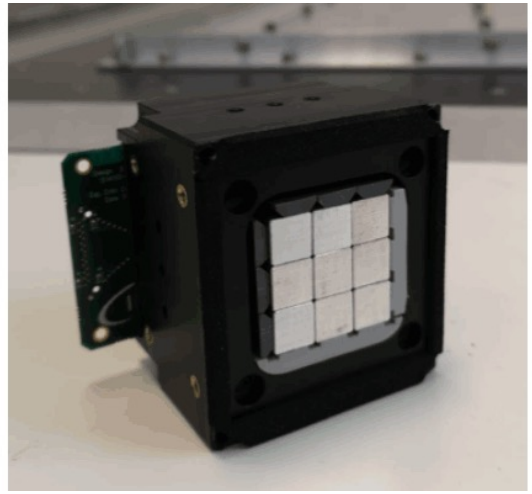
BC Beam incident from back (SiPM side)

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 **< 20 ps** for $E_{dep} > 5$ GeV!

Tests of CRILIN prototype in 2023

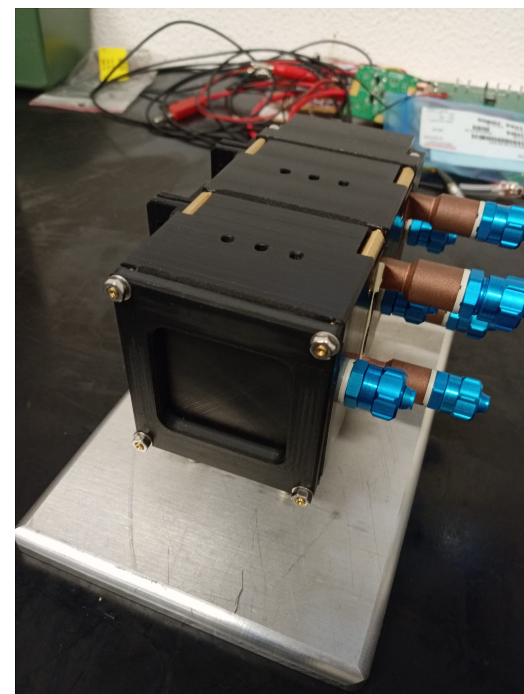




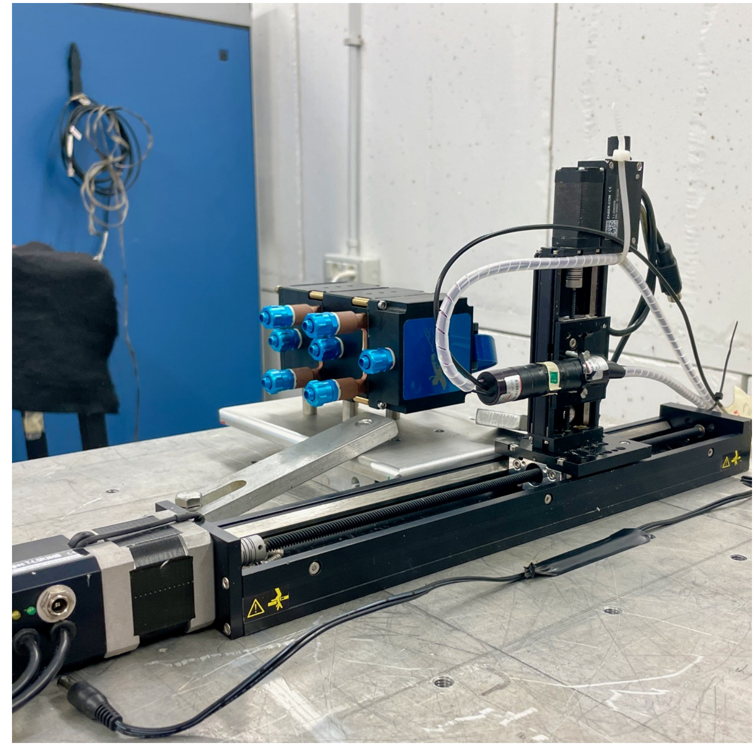
Two 3x3 CRILIN test layers, with PbF_2 and PWO-UF

Test objectives:

1. Perform complete operational test, including readout electronics (series vs parallel connection)
2. Test different crystal materials and surface treatments, to damp internal reflections
3. Conceptual test of longitudinal segmentation
4. Test cluster reconstruction capability and measure time resolution



CRILIN test at BTF, Jul 2023



03-10 July

- 3x3x2 CRILIN module
- 450 MeV single e^-
- 50 ps trigger

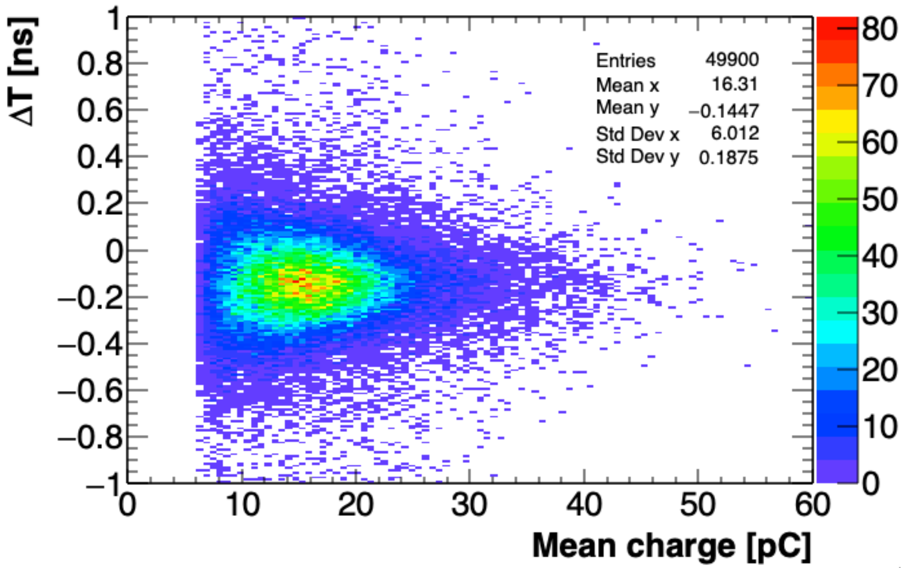
Configurations tested (front + back)

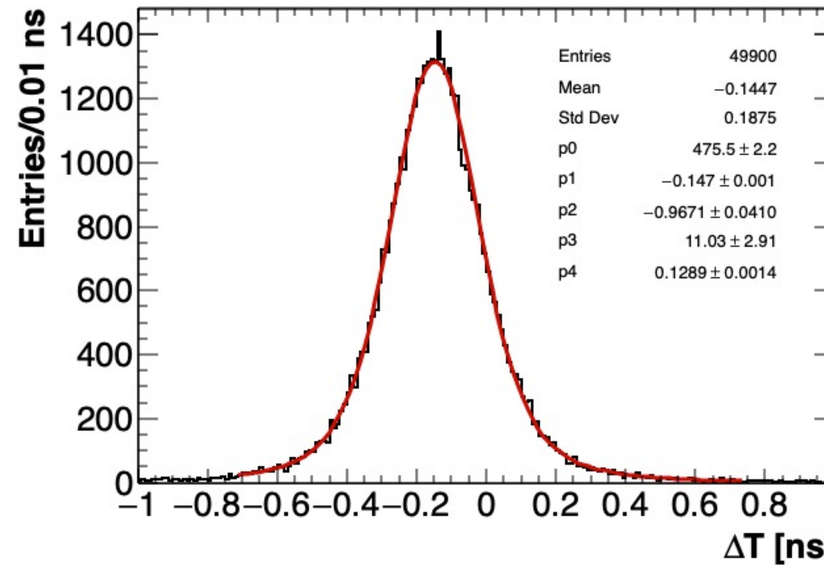
PbF_2
- polished + black + mylar
- matte + mylar
- matte + teflon

PWO-UF
- polished + ESR

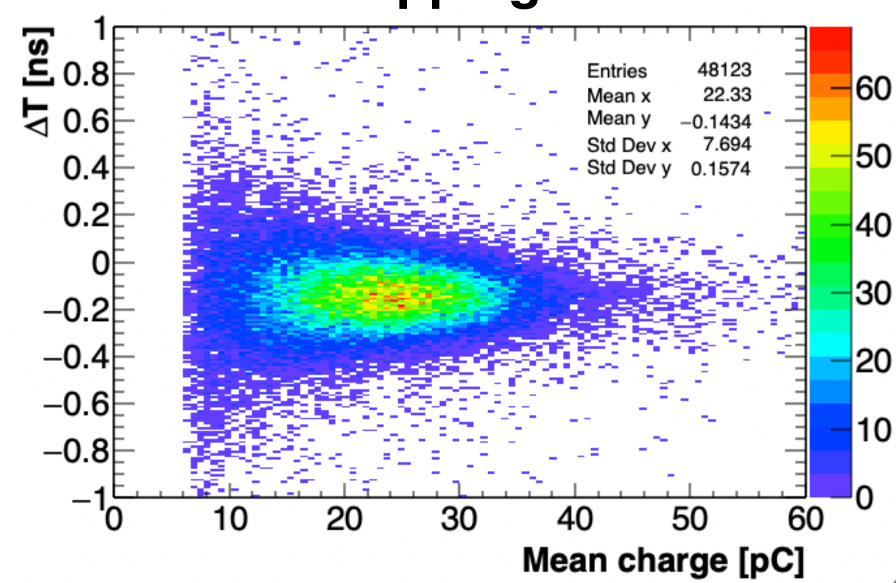
CRILIN test at BTF: Preliminary results

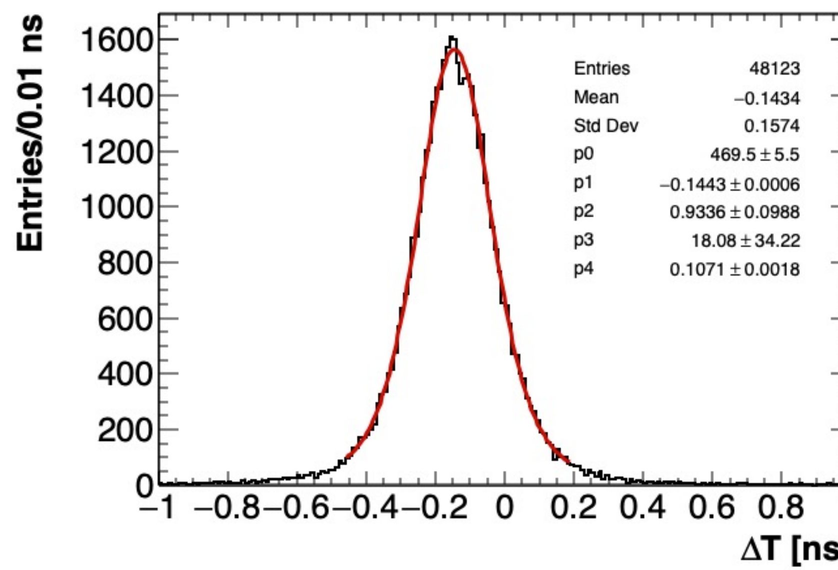
Mylar wrapping





Teflon wrapping

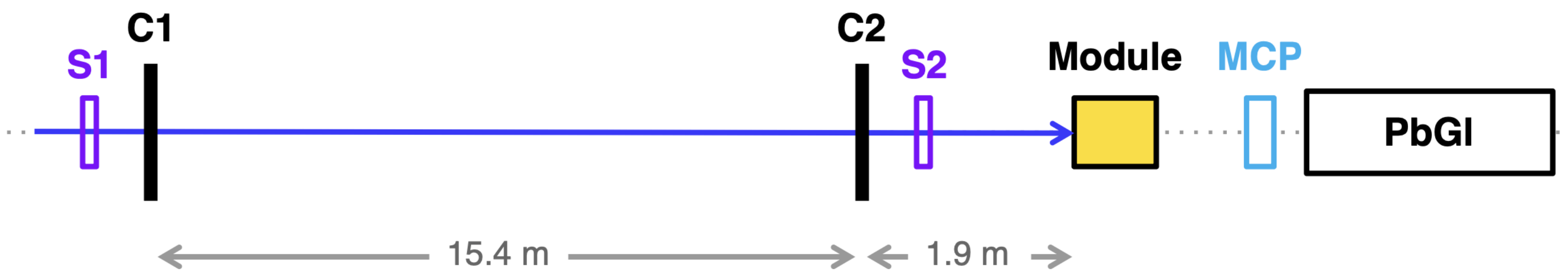




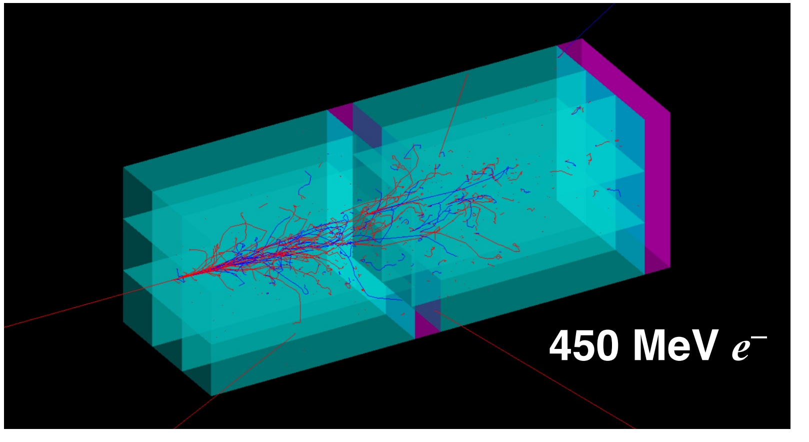
CRILIN test at H2: 16-19 Aug 2023

1 week (16-23 Aug) split with OREO to allow alignment studies at H2

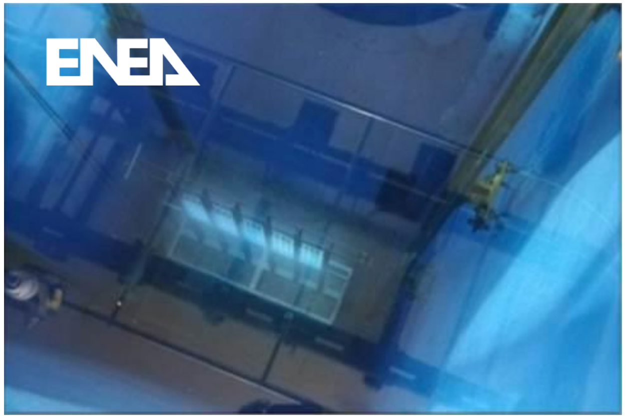
For CRILIN, use similar setup to 2022 run to test same configurations as in BTF (PbF_2, PWO-UF) with **20-120 GeV e^-** and **150 GeV mips**



Meanwhile, analysis and simulation work on 2023 data in progress!



Radiation hardness of PbF_2 and PWO-UF

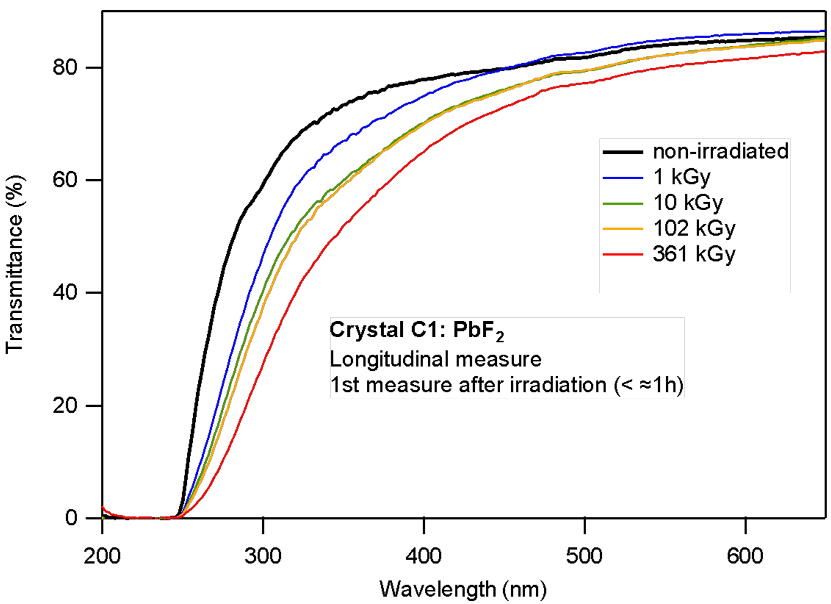


^{60}Co γ-irradiation tests at Calliope, ENEA Casaccia

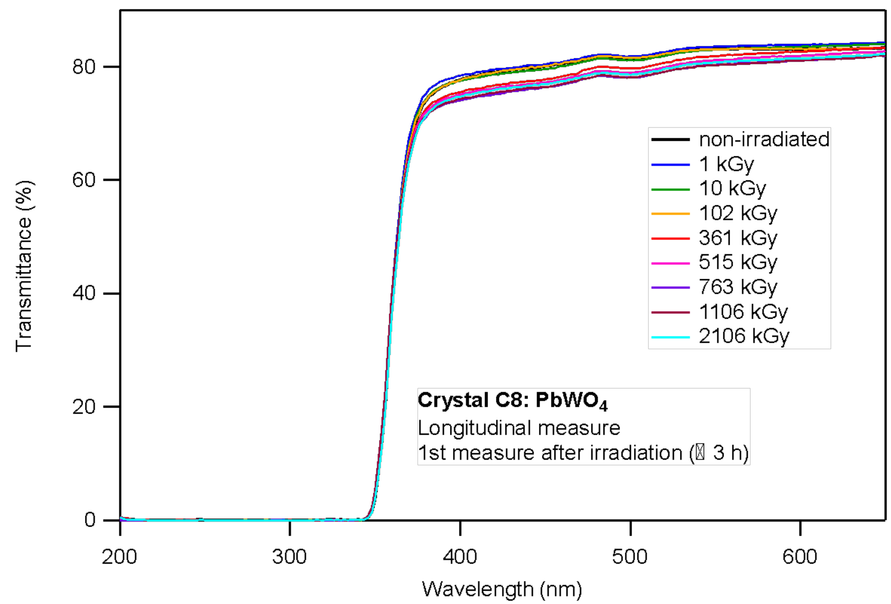
- Easy to accumulate MGy doses, full dosimetry support
- Support with transmission, light yield, fluorescence spectrometry measurements

Tests conducted April-May 2023 in collaboration between CRILIN and Calliope staff

PbF_2 irradiated to 361 kGy



PWO-UF irradiated to 2106 kGy!



Radiation hardness of PbF_2 and PWO-UF

Expected SAC ionizing radiation dose: **10^5-10^6 Gy**

Expected SAC neutron fluence: **10^{13}-10^{14} n/cm^2 1 MeV eq**

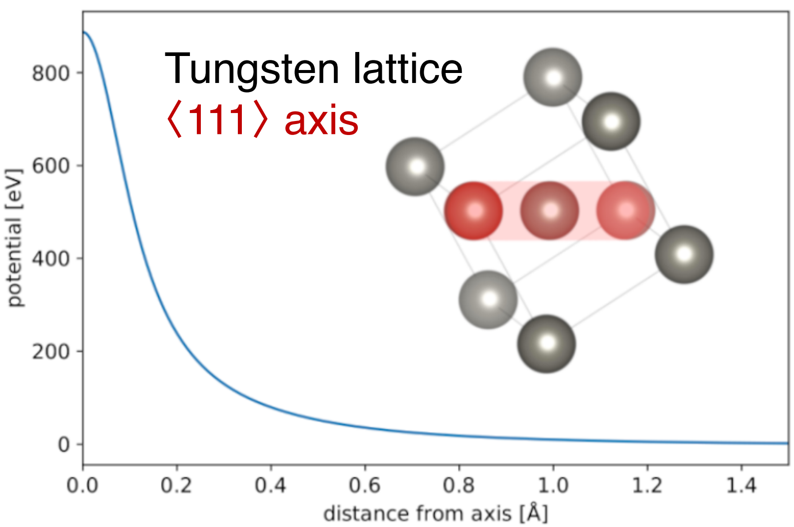
Preliminary conclusions:

- PbF_2 shows increased transmission threshold at low wavelength already at 10^4-10^5 Gy
- Blue-green transparency for PbF_2 can be recovered by exposure to blue light (e.g. natural light for several days)
- PWO-UF shows no shift in low-wavelength threshold and only ~2% loss of blue-green transparency even at 2 MGy!
- PWO-UF ionizing radiation robustness more than sufficient for SAC: next need validation with neutrons (protons)
- Czochralski-grown PWO (Crytur) is of high quality. Literature suggests that Bridgeman-grown PWO (SICCAS) may have inferior radiation hardness, requiring separate validation.

Coherent effects in crystals

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

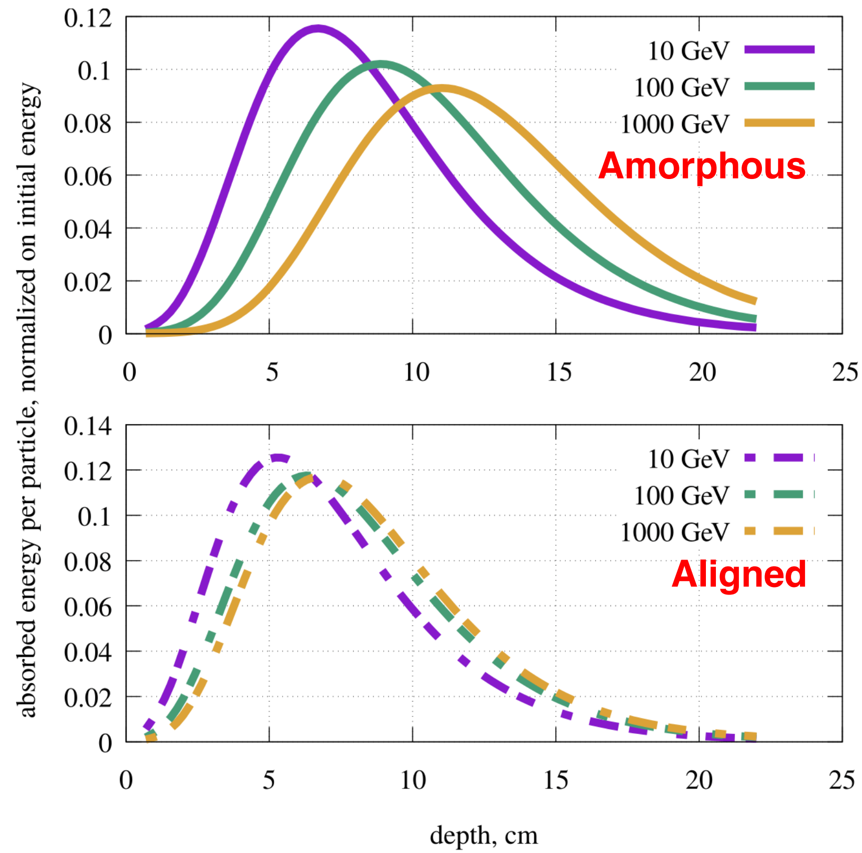
Electric field ε approx. const. ~ 10^{10}-10^{12} V/cm

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

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

Geant4 simulation

Bandiera et al., NIMA 936 (2019)

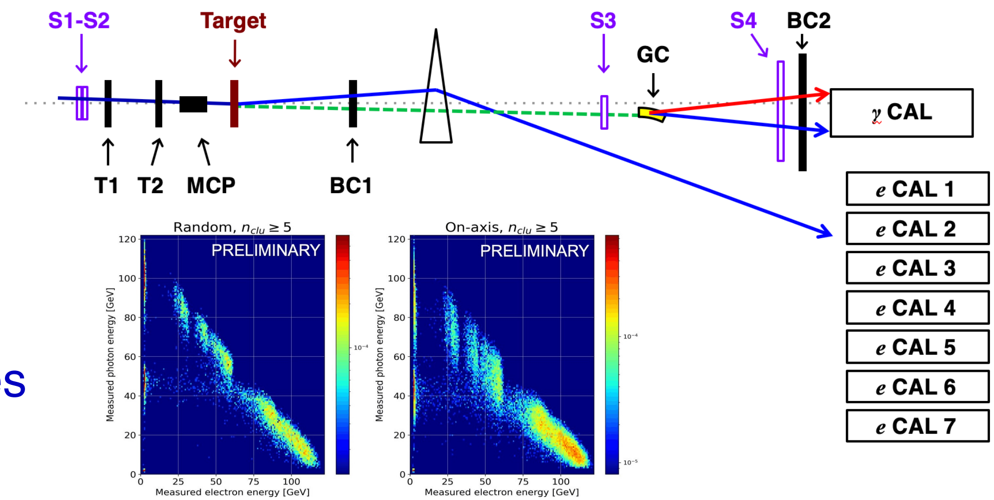


- Early initiation of EM showers
- Minimize fluctuations of deposited energy vs depth

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

Tests with aligned crystals, H2, Aug 2021

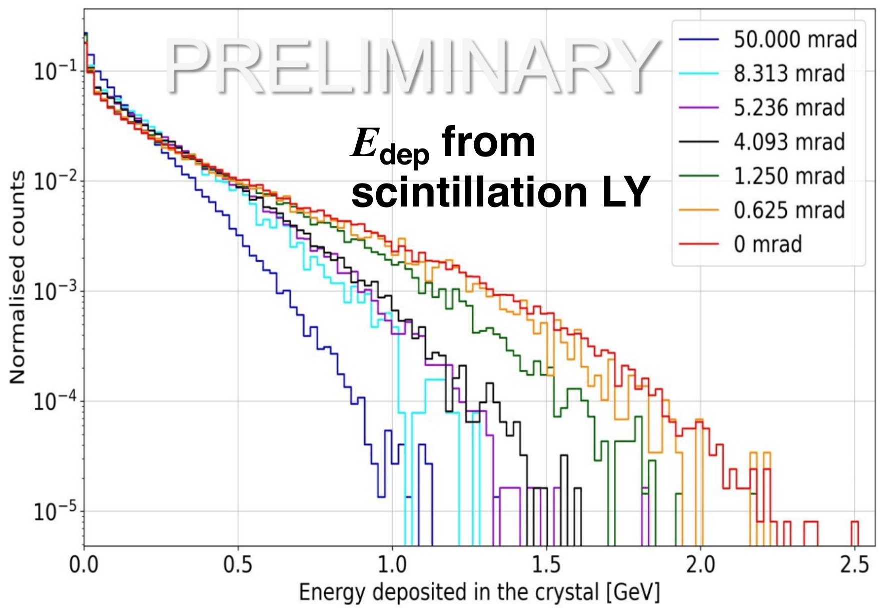
Many studies done by precursors to OREO (AXIAL, STORM) with NA62 participation (KLEVER)

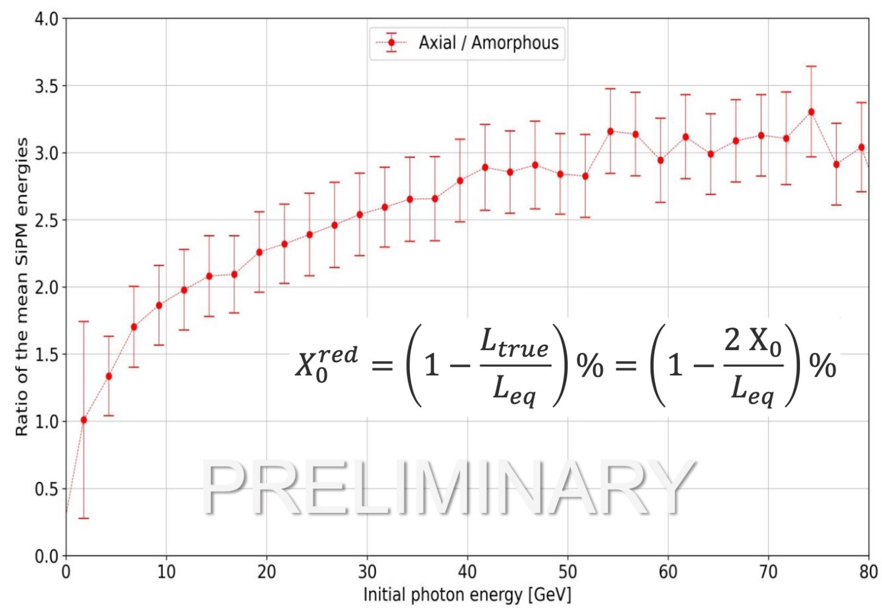


Aug 2021 H2:

- Tagged photons from 120 GeV e^-
- PbF_2 $1X_0$ and PWO-II(o) $2X_0$ samples

PbF_2 $1X_0$ aligned on ⟨111⟩





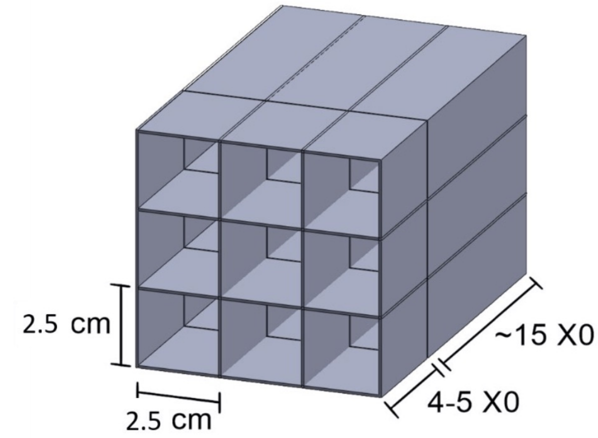
~30% reduction in effective X_0 for first interaction plane

OREO: An oriented-crystal calorimeter

Exploit coherent interactions in crystals to develop a highly compact calorimeter

E.g. Small-angle calorimeter for HIKE:

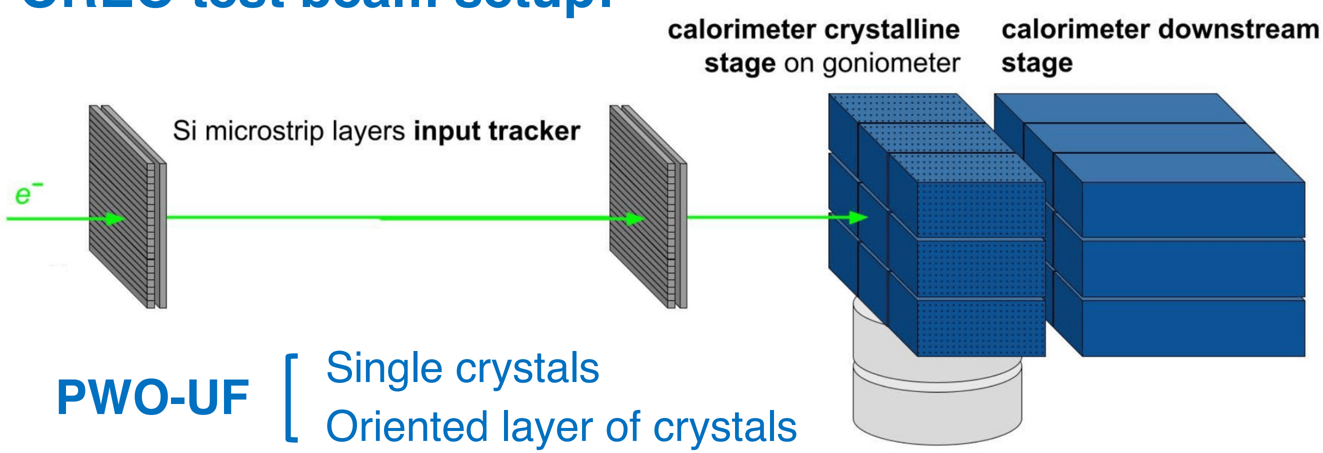
Require good response to photons, high transparency to neutrons



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:



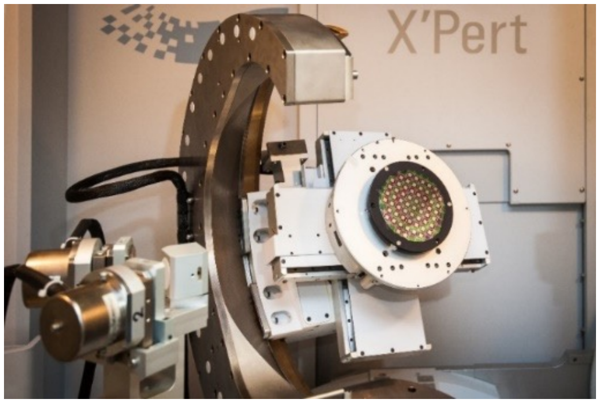
PWO-UF [Single crystals / Oriented layer of crystals

Beam tests in 2023:

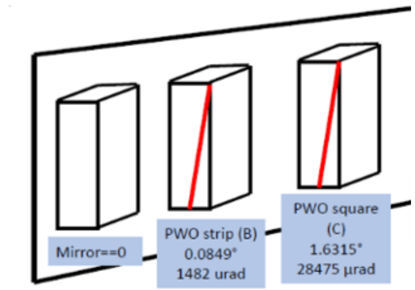
- 1 week at PS (1-10 GeV e-)
- Few days at SPS (20-150 GeV e-)

Techniques for crystal characterization

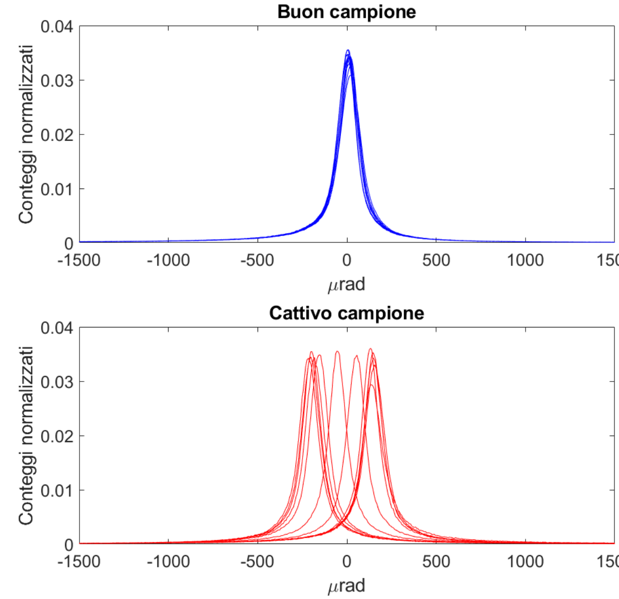
X-ray diffraction (Ferrara)
HR-XRD 8 keV



Measurement of axis inclination relative to face



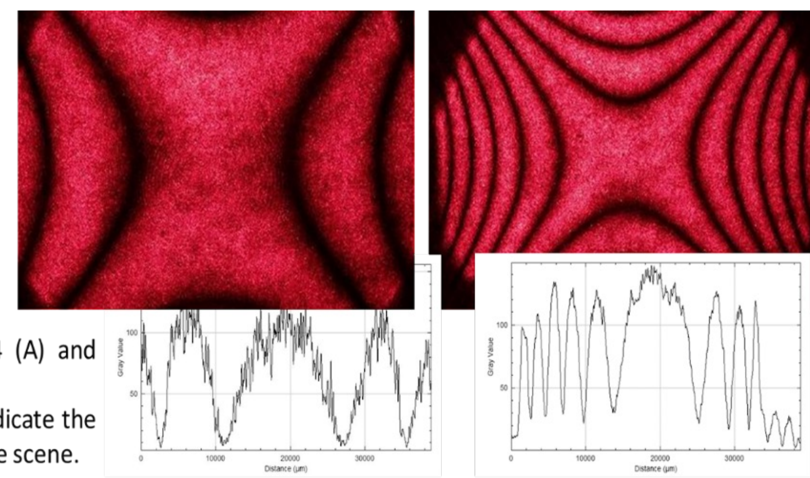
Surface scan of orientation



Photoelasticity measurements
Laser conoscopy (Ancona)

Internal stresses in crystal change polarization

Fringe order and symmetry contain information on crystallographic orientation and quality

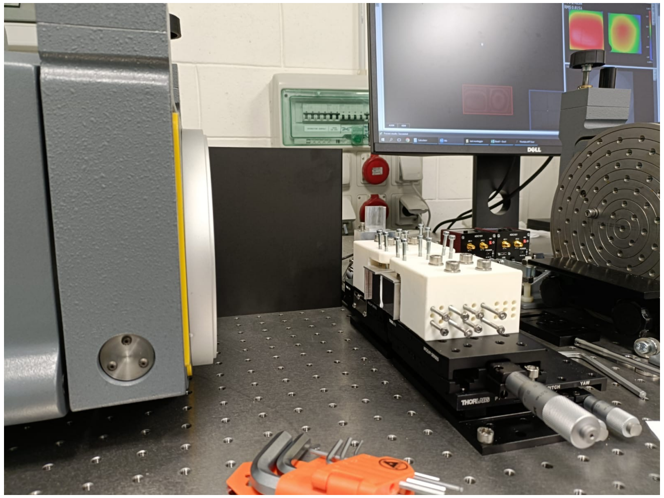


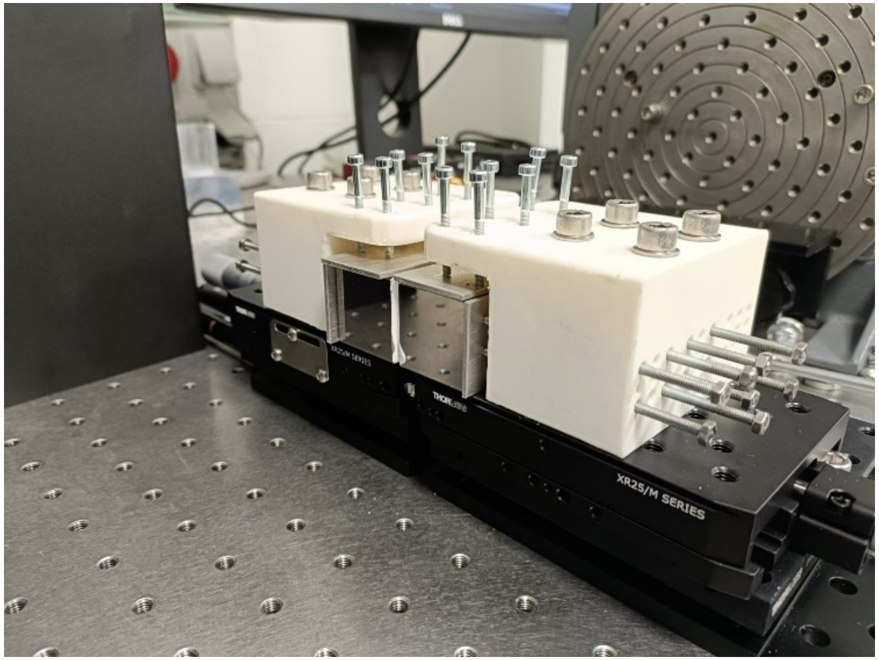
Typical image from face 4 (A) and face 1 (B).
The minima in the plots indicate the position of the fringes in the scene.

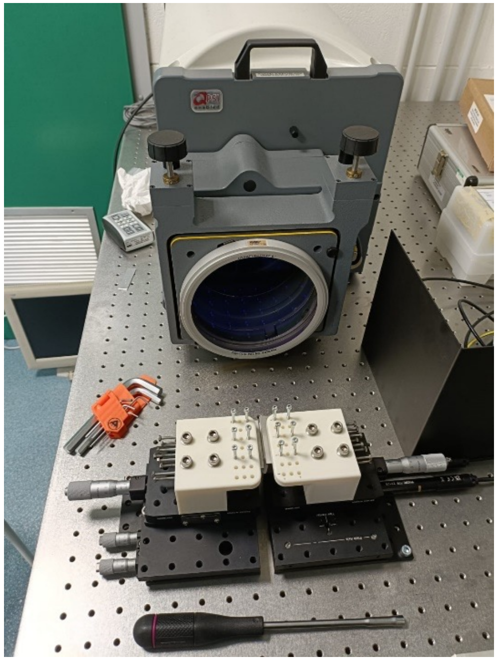
Techniques for multi-crystal alignment

Alignment system based on motorized optomechanical components and laser autocollimator control of final crystal orientation

- Developed at Ferrara
- Used July 2023 to obtain alignment of 3x1 PWO-UF matrix to < 500 μrad!





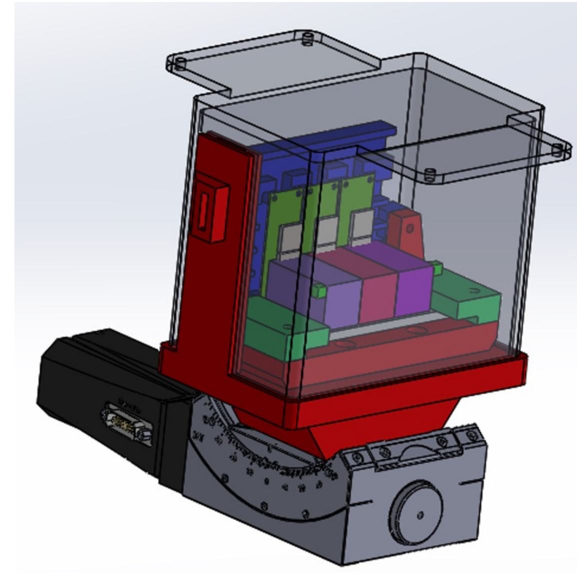


OREO status and plans for 2023-2024

2023

20-23 Aug test beam at H2

Characterize alignment of 3x1 PWO-UF crystal array



2024

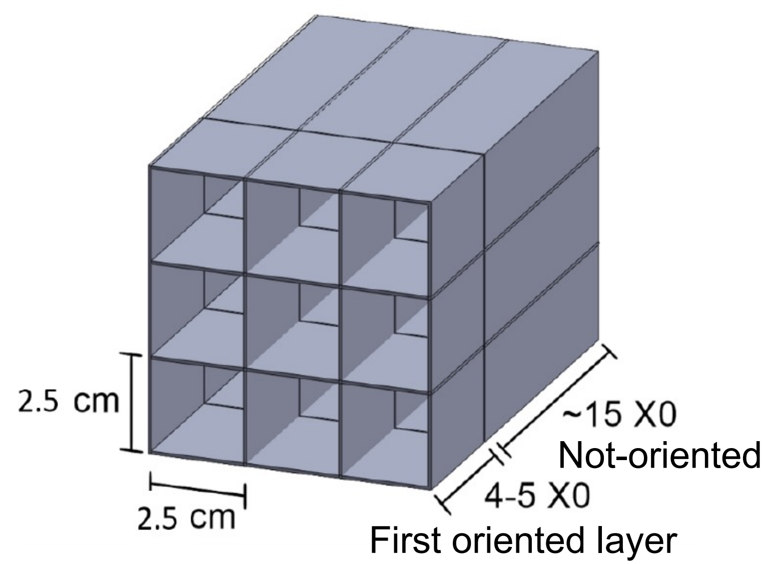
Construction of 3x3 crystal array

Backup layer $15X_0$ for shower containment

Beam time request at H2

Evaluate calorimetric properties of aligned crystal array

- Shower containment
- Transverse shower radius



Next steps for SAC R&D

CRILIN ▶ **HIKE** ◀ OREO

Performance goals achieved:

- Time resolution: < 20 ps for single crystals, $E > 5$ GeV
- High granularity & longitudinal separation:
  Light transport understood in small crystals with high n
- Radiation resistance for crystal: PWO-UF robust to > 2 MGy
- Single-crystal alignment: 30% reduction in effective X_0 for first interaction plane

Performance goals remaining:

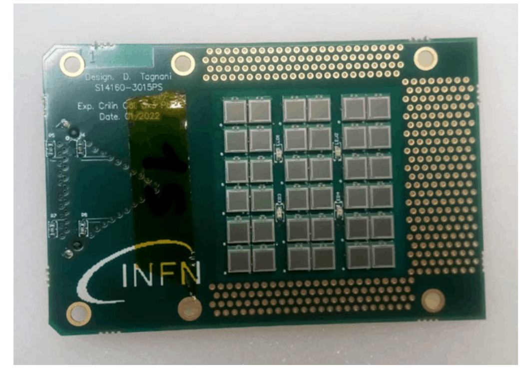
- Final granularity: Find optimal segmentation (ease of alignment, R_M = 2 cm)
- Double-pulse resolution: Current signal shaping at 70 ns → 2 ns!
- Radiation resistance for photosensor: Will rad-hard SiPMs be ready by 2028?
- Multi-crystal alignment: Develop final design to align stackable layers

For 2024, test 1-layer prototype with solutions meeting remaining goals

Ideas for HIKE SAC Layer 0

Stackable planes, like CRILIN, with PCB photosensor plane

- Layer mechanics to allow alignment of crystal plane
- Crystals pre-aligned à la OREO
- Input from A. Saputi (FE, CRILIN designer)

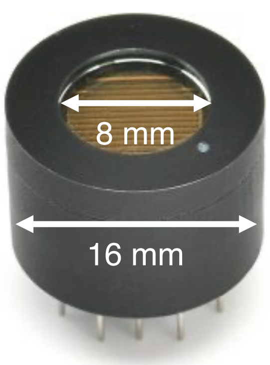


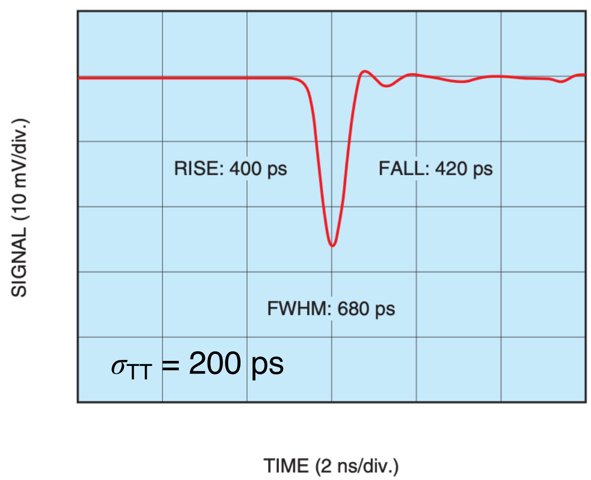
Move from SiPM to PMT readout

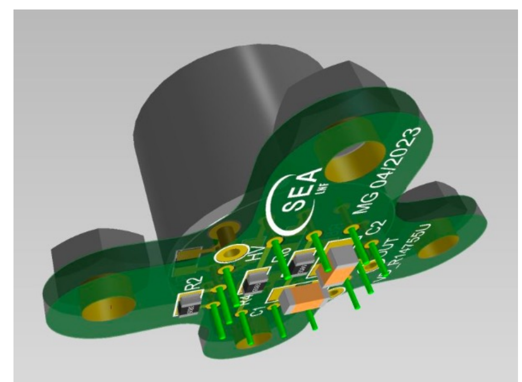
- Possibility to revert to SiPMs if needed!

Hamamatsu R14755 PMTs

- 2 PMTs already acquired for evaluation: custom divider can be implemented on sensor board







For 2024, test 1-layer prototype, 3x3 crystals 16x16x40 mm^3, with alignable mechanics and single-board PMT readout

HIKE SAC: Richieste R&D 2024

Consumi (LNF): 27 kE

Per costruzione prototipo SAC, 9 ch., 1 layer:

• 10 cristalli PWO-UF (Crytur), 16x16x40 mm3, orientati	**15**
• 10 fotomultiplicatori Hamamatsu R14755U-100	**7**
• Realizzazione stampato per PMT con partitori HT	**2**
• Meccanica, componenti stampate 3d	**3**

Missioni: 6 kE

Per test beam a SPS NA, s.j. beam time allocato

• Personale test beam: 4 settimane persona (LNF)	**4**
• Esperti allineamento Legnaro: 2 settimane persona (FE)	**2**

Manutenzione (FE): 3 kE

• Contributo contratto manutenzione diffrattometro raggi X	**3**

Totale: 39 kE