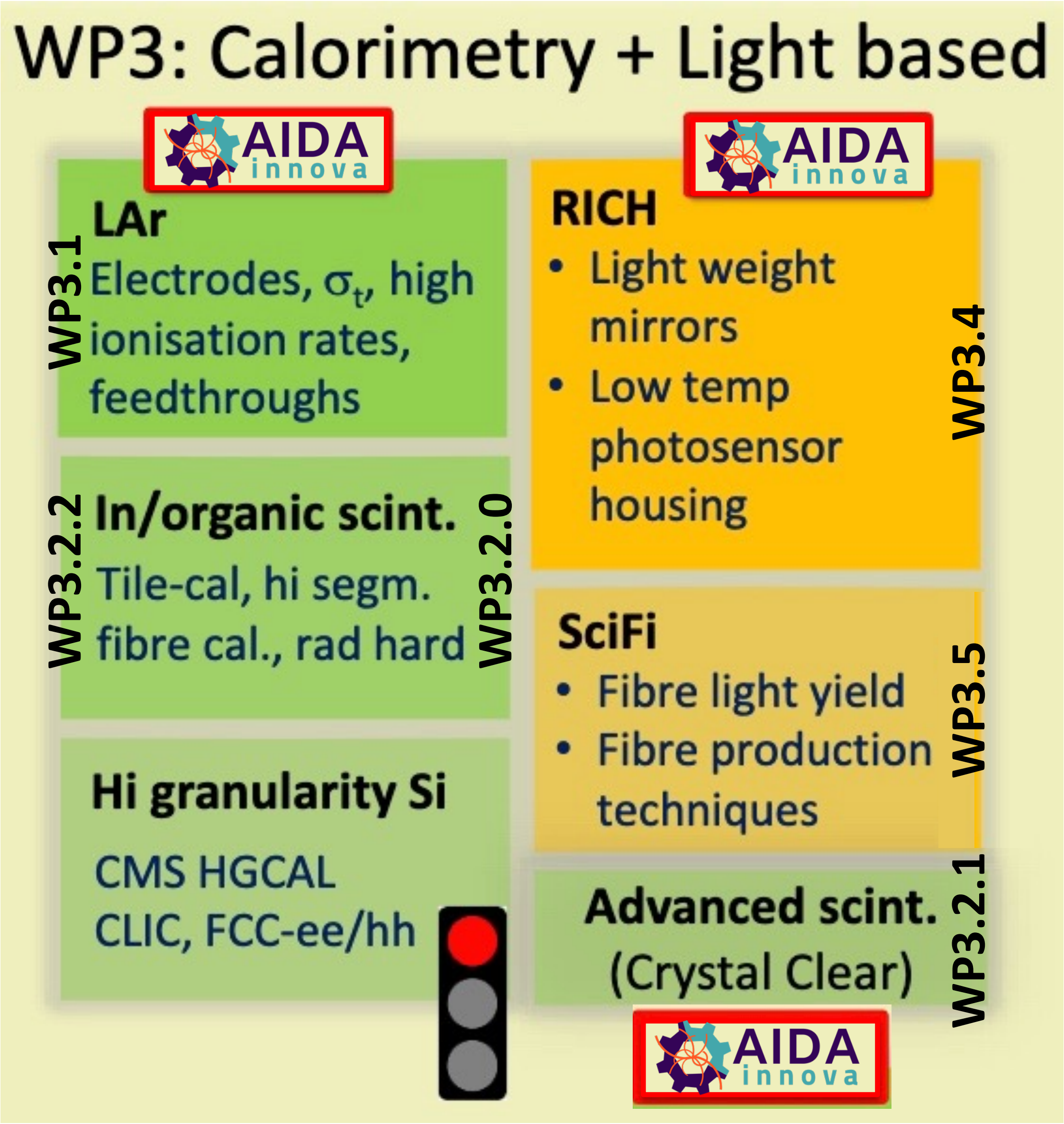
EP R&D WP3 – Summary

Floris Keizer and Philipp Roloff for EP R&D WP3

Sub-Workpackages – Current Status



- **WP3.1: Noble-Liquid Calorimetry (part by J. Pekkanen)**
  - 1 fellow on read-out electrodes, electronics, performance + 1 fellow (shared with FCC) on absorbers, test-module design
  - 1 doctoral student (Gentner programme)
  - Supported by AIDAinnova
  - New: Part of DRD-on-Calorimetry
- **WP3.2: Scintillator-Based Calorimetry (part by L. Martinazzoli)**
  - 1 fellow + 1 doctoral student on SpaCal R&D
  - 1 student on scintillator development
  - 1 fellow (shared with ATLAS): FCC HCAL R&D – Sci/Pb/Steel TileCal
  - International collaboration (e.g. CrystalClear, LHCb), synergy with AIDAinnova and quantum initiative
  - New: Part of DRD-on-Calorimetry
- **WP3.4: RICH (part by F. Keizer)**
  - Recruitment of ORIGIN (shared with LHCb) ongoing
  - Supported by AIDAinnova
  - New: Part of DRD4 (Photon Detectors & PID)
- **WP3.5: High Light Yield Scintill. Fibres**

CERN EP-R&D Day

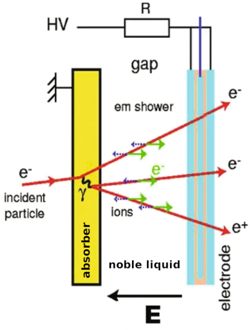
Status of WP 3.1
R&D on Noble-Liquid Calorimetry

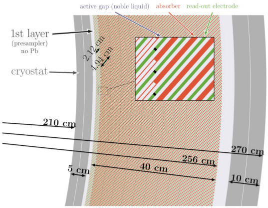
Juska Pekkanen
juska@cern.ch
CERN

May 22, 2024

Noble-liquid calorimetry

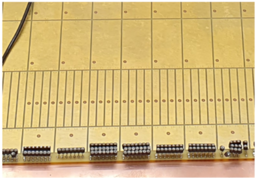
- Sampling calorimetry relying on ionization of the active material (liquefied noble gas)
- Based on alternating layers of absorbers, noble liquid and read-out electrodes
  - Voltage applied over noble-liquid gap
  - Incident particle ionizes noble liquid
  - e^- (and ions) drift to electrodes and induce current signal
- Successful in many HEP experiments
  - MarkII, DØ, H1, NA48/62, ATLAS
- Excellent E resolution, linearity, stability and uniformity, good timing properties
- Challenges: complex mechanical structure inside cryostat, signal feed-thru, granularity

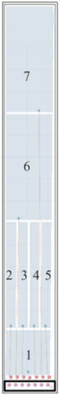


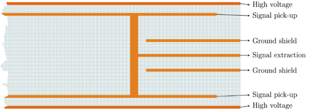


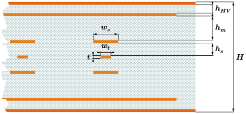
High-granularity noble-liquid calorimeter

- Printed circuit board (PCB) technology allows "arbitrarily" high granularity
  - Signal traces inside the electrode
  - Target: at least 10x ATLAS granularity
- 7-layer prototype PCB with complex internal structure done & being studied→
- Signal traversing inside PCB induces cross-talk that worsens resolution
  - Mitigated by shielding signal traces
- **Trade-off between x-talk and electronics noise**
  - Shields reduce x-talk but increase capacitance to ground and hence noise



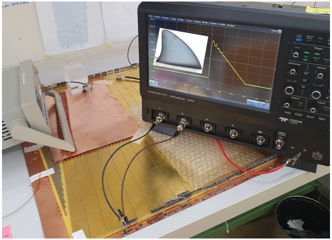


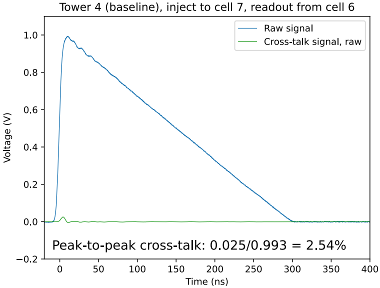


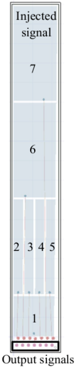


PCB lab measurements & x-talk

- Electrical properties measured with a table-top setup
- Function generator used for injecting shark-fin signal
  - 300 ns wide 1 V peak, mimicing real signal
- Signal read with oscilloscope and analyzed offline
- Raw peak-to-peak x-talk >1%, **too much!**

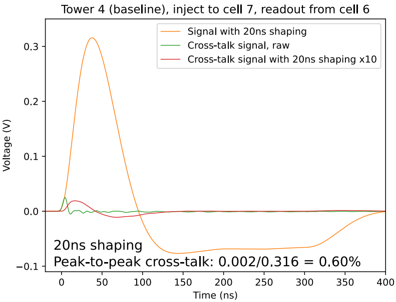


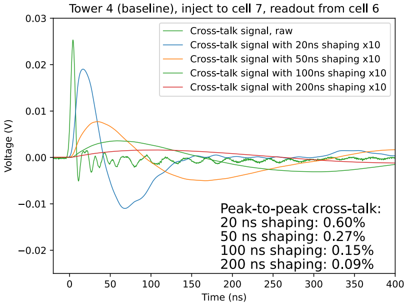




PCB lab measurements & x-talk

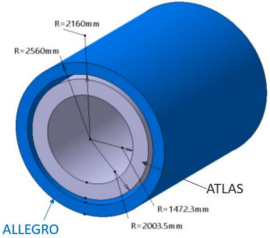
- X-talk down to «1% after **shaping**
  - Here using ATLAS-style CR-RC^2 shaper
- X-talk of 0.1% achieved with long shaping time (200 ns)
  - Long shaping not good at LHC for PU, but fine with e^+e^-



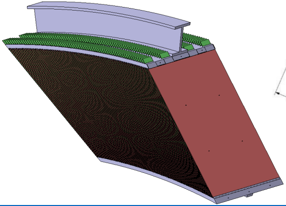


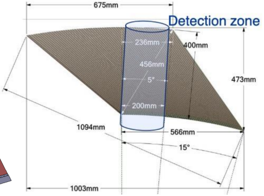
Mechanical design & test-beam prototype

- ATLAS LAr ECAL used as reference
  - Larger radius, new electrode geometry
- FEM used for structural element design (strength, size)
- First prototype of two absorbers and one electrode built in 2023
  - Tested in liquid nitrogen bath
- Test beam prototype design frozen by late 2025
  - 64 electrodes and absorbers
  - Placed in a cryostat for beam tests



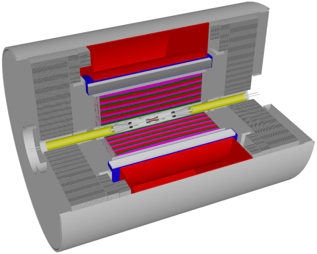
EM calorimeter size comparison





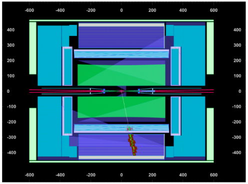
ALLEGRO detector concept

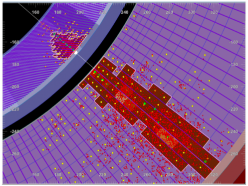
- General-purpose detector for FCC-ee
- Recently coined as ALLEGRO
  - A Lepton-Lepton collider Experiment with Granular Read-Out
- High-granularity noble-liquid ECAL a central and most studied feature
  - LAr or LKr with Pb or W absorbers
  - Multi-layer PCB as read-out electrode
- Vtx detector, drift chamber and ECAL inside 2 T solenoid, sharing cryostat
- HCAL and muon system outside solenoid
- Optimized for full FCC-ee physics program
  - Focus on PFlow & particle ID performance

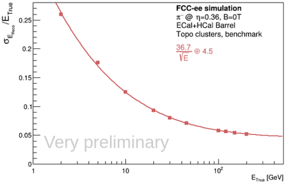


Simulation studies & next steps

- Optimal granularity & materials studied with simulations
  - Find optimal granularity for π/γ^0 separation
  - LAr or LKr as liquid, Pb or W as absorbers
- Full-Sim of ALLEGRO being built to FCC-SW
  - ECAL+HCAL topo-clustering implemented
  - Next: add tracking and Particle Flow
- New prototype PCB being designed at CERN
- Test-beam prototype to be built by 2027-28
- ECFA DRD6 Calorimetry collaboration founded in April
- Team is growing fast, already 18 institutions joined!
  - **Ideal time to join ALLEGRO!**







WP3.2: Scintillator-based Calorimetry

Loris Martinazzoli[1]
on behalf of the EP R&D WP 3.2

[1] CERN, Geneva, Switzerland

22nd May 2024

WP 3.2 Activities

Focus on **electromagnetic** calorimetry:

WP 3.2.0 R&D on SpaCal technology with dense absorbers and picosecond time resolution
WP 3.2.1 R&D for scintillation-based calorimeters

Focus on **hadronic** calorimetry:

WP 3.2.2 TileCal-like demonstrator for FCC

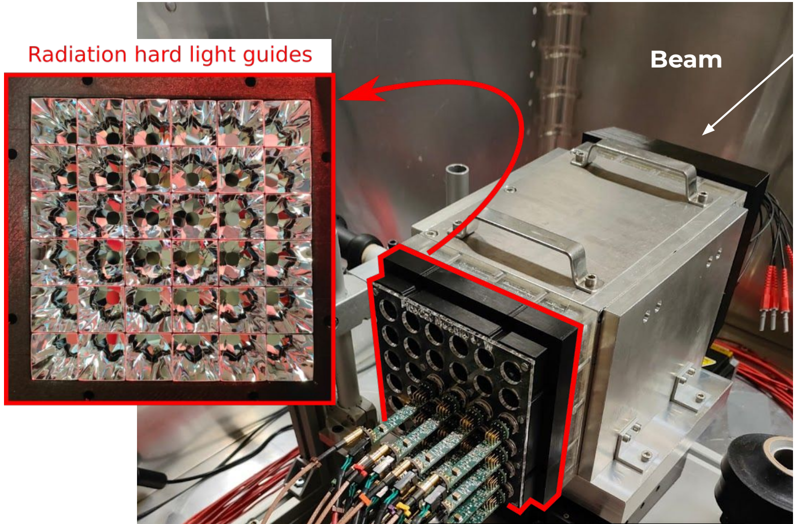
These R&D activities are included in the ECFA DRD6 collaboration in WP3, "Optical Calorimeters"

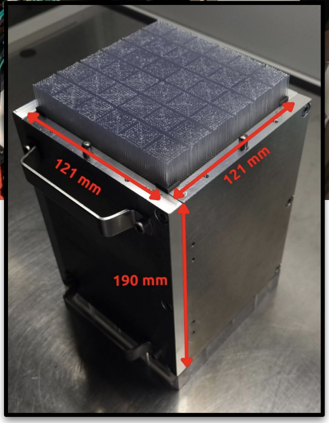
WP 3.2.0

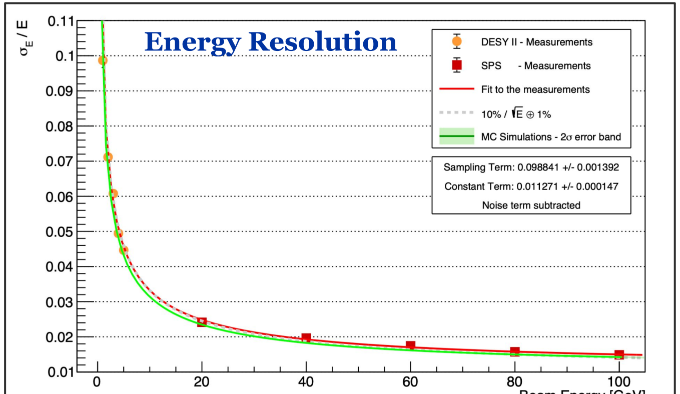
R&D on SpaCal Technology

- First full-size prototype using tungsten absorber targeting single-sided readout
  - **Tungsten** absorber 3D printed (with EOS, Germany)
  - Kuraray SCSF-78 polystyrene fibres 1x1 mm^2
  - Radiation-hard **“hollow” (air) light guides**
  - Readout with **fast PMTs** single- and multi-anode

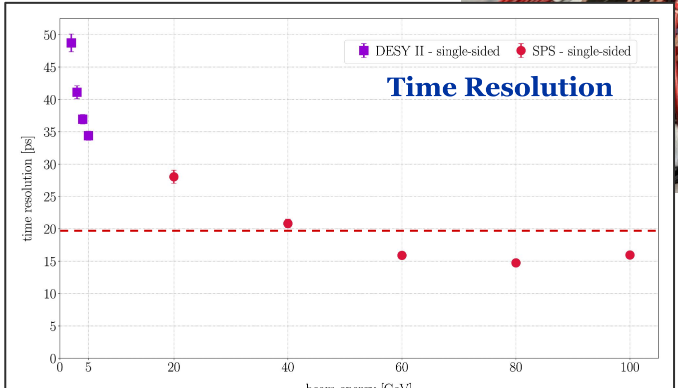
  - Initial testbeam measurements at DESY II, Hamburg and SPS, CERN
  - **Better than 20 ps** time resolution with high-energy e^-
  - Results in **agreement with Monte Carlo simulations**







LHCb TDR 24



LHCb TDR 24

Future R&D

PicoCal

Aim: building **full-size prototype ECAL modules**, validate **performance** and all aspects of the **technical designs**

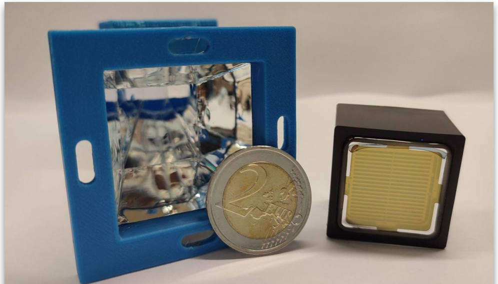
- **Scintillating fibres** (*with WP 3.2.1*)
  R&D on **radiation-hard crystal** and **radiation-tolerant organic** scintillating fibres, including production techniques

- **Absorbers** for fibre ECAL
  Produce and validate module-size **Lead** absorber with **new casting technique**
  Study a novel **3D-printing** approach for ECAL absorber using **Tungsten granules** with a binder

- **Light Collection and Detection**
  See also "Performance studies and design optimization of Spaghetti Calorimeter prototypes" today at the poster session.
  Optimisation of readout, including the **photodetectors** to achieve linearity in a wide energy range keeping excellent timing performance and the **light guides** for a uniform response.
  Feasibility study for SiPMs for designs with space constraints

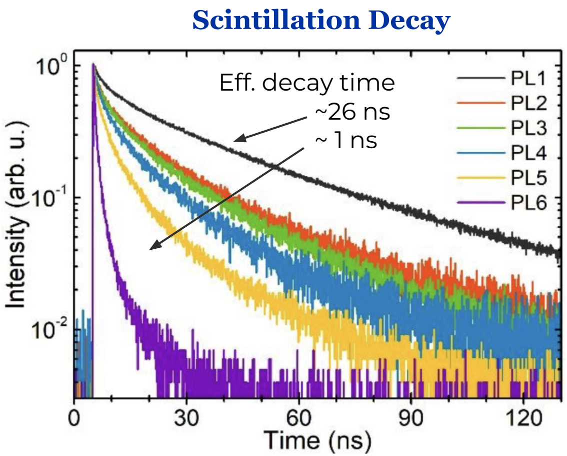
- **Performance Validation**
  Testbeam measurements of prototypes to demonstrate the performance of the technologies


Prototype Lead Absorber


Light Guides and Photodetector

R&D on Ultra-accelerated Garnet Scintillators

PAST



Mater. Adv., 2022,3, 6842-6852

Ultra-accelerated Garnets developed with WP 3.2 and AidaInnova in collaboration with FZU, Prague

- Large doping accelerates scintillation
- No loss of time resolution

PRESENT

R&D to produce **large-size** and **homogeneous** Czochralski ingots

3 lines of collaboration with:
- LHCb Chinese institutes and SiPAT
- FZU and Crytur, Czech Republic
- European project TWISMA including ILM, Lyon and ISMA, Kharkiv

Multiple crystal garnet compositions explored:

GAGG
- **Several samples produced** with Czochralski and u-PD technique
  - Tuning composition to balance decay time and light yield
- Significant **acceleration** (decay ~20 ns) achieved **with ingot homogeneity of ~10%**

YAG

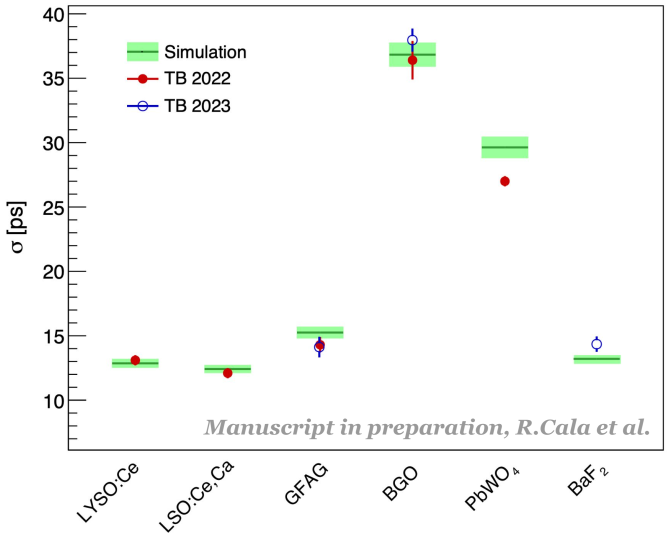
First samples produced **accelerated to ~20 ns**
- No Iridium crucible required
- Multiple dopings under test

WP 3.2.1

R&D for Timing Detectors and Calorimeters

CRYSTAL CLEAR

Time Resolution with MIPs



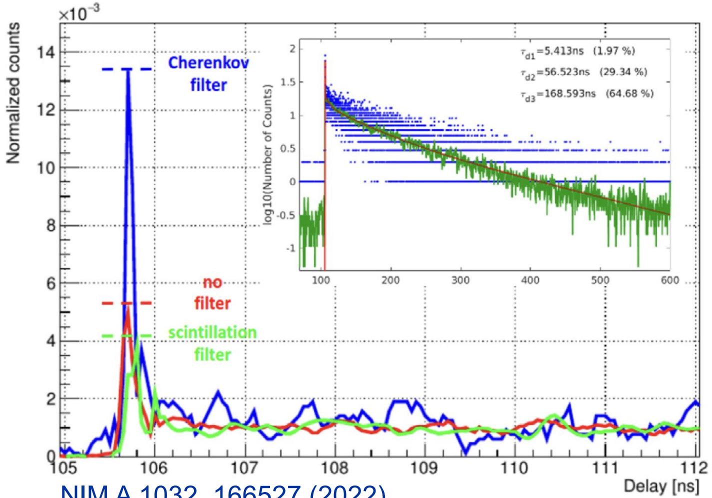
Several **materials and scintillation processes** tested

- Intrinsic and Ce-activated scintillation
- Cross-luminescence
- Cherenkov emission

Excellent time resolution as MIP timing detectors achieved, in agreement with simulations and predictions

Exploring **nano-materials** in **radiation-tolerant plastics**

Cherenkov - Scintillation Separation



NIM A 1032, 166527 (2022)

BGSO is a candidate for **homogeneous calorimeters**

- Faster than pure BGO but just as cost-effective
- Cherenkov and Scintillation light give Dual Readout capabilities

TWISMA

Ongoing R&D

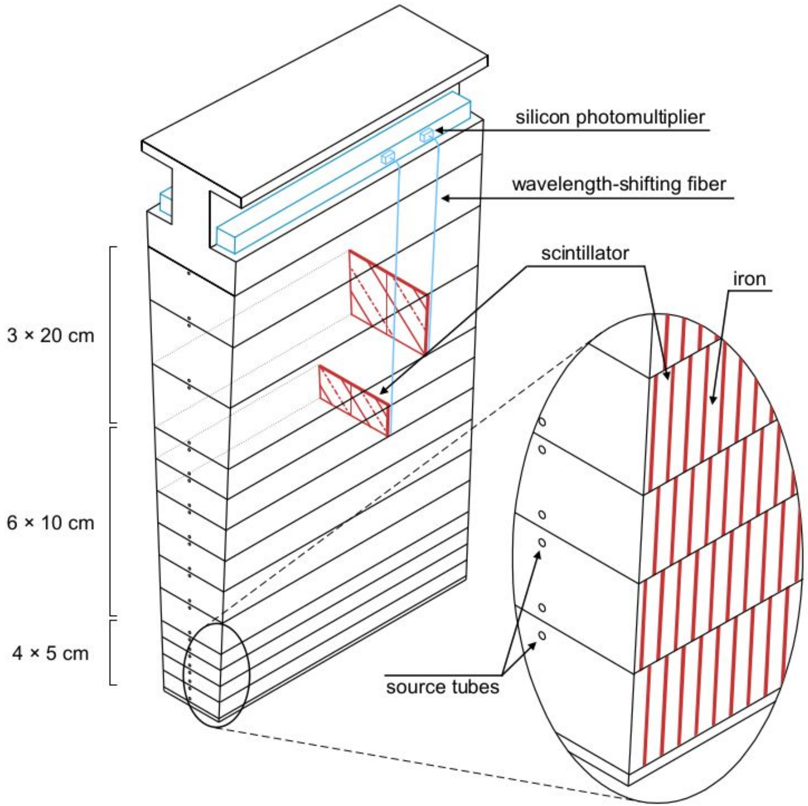
- Search for **dopants providing congruent melting**
- Testing **novel algorithms** to maximise information extraction from the pulse shape

Barrel hadronic calorimeter

- ATLAS **TileCal-like** design
  - 5mm steel absorber plates alternating with 3mm scintillator plates
  - 1400mm deep (8-9 λ)
  - 13 radial layers (4x5 cm, 6x10 cm, 3x20 cm)
  - $\Delta\theta$ ~ 0.022 (grouping 3-4 tiles)
  - 128 modules in ϕ, 2 tile/module → $\Delta\phi$ = 0.025
  - Removed the Pb plates compared to FCC-hh design (HCal acts as return yoke for the central solenoid)

  - Integrated in the ALLEGRO detector concept together with the noble liquid ECal

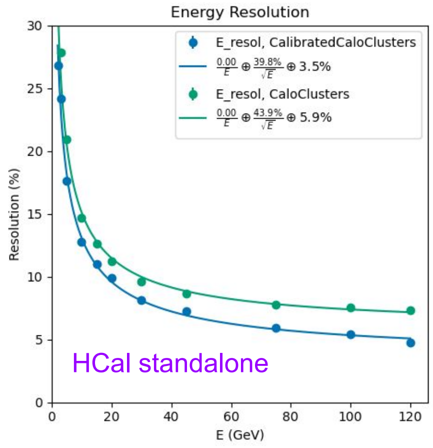
  - Ongoing performance studies and design optimization



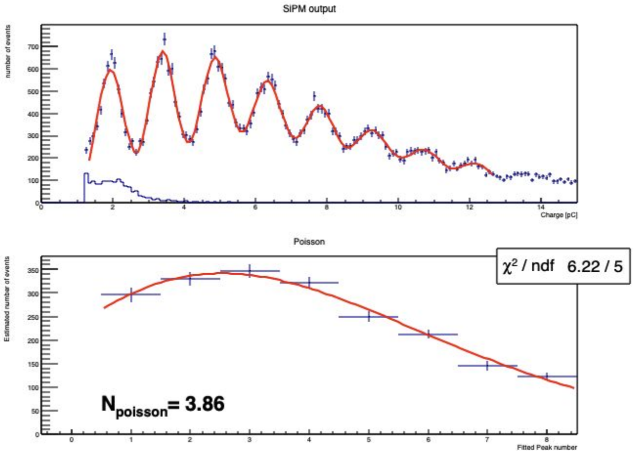
WP 3.2.2

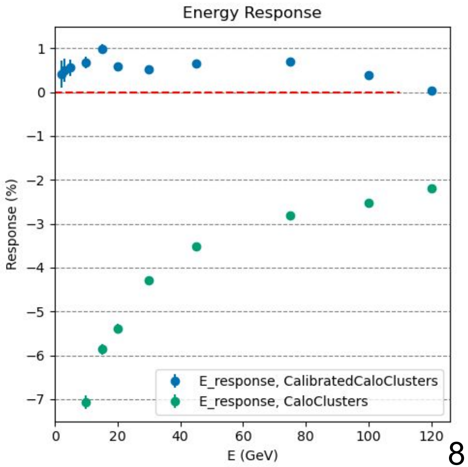
Ongoing studies

- Implemented digitization and cluster reconstruction
  - Sliding window and topological clustering algorithms
- Cluster energy calibration (simulating single π^-)
  - Cell-based approximate calibration using 100 GeV π^-
  - MVA calibration, using boosted decision tree
    - Constant term decreased from 5.9% to 3.5%
    - Big improvement in the energy response $E_{cluster}/E_{true}$ → within 1%
- Ongoing performance studies on ECal+HCal simulation



- Re-started studies of the light response of plastic-scintillator tiles with SiPM readout
  - Previous extensive studies conducted in 2017-2019
  - One SiPM and one scintillator tile, using cosmic muon events to get single photon spectra





EP R&D on RICH detectors for future high energy experiments

Floris Keizer on behalf of EP R&D WP3.4

EP R&D day 2024

22 May 2024

R&D plans for future RICH detectors

The CERN Team has proposed a **new design** with improved Cherenkov angle resolution (0.1-0.2 mrad), based on **cooled SiPMs and Carbon-Fibre support mirror optics**.
The electronics will feature **ps-time resolution** within a ns-readout window.

It is **now the accepted framework** on which to build the Upgrade II.
More details are available in the LHCb Framework TDR for Upgrade II:
https://cds.cern.ch/record/2776420
As well as the LHCb PID Enhancement TDR:
https://cds.cern.ch/record/2866493

A **robust R&D project** needs to be carried out, aiming at the **next generation of time- and space-precision RICHes** for LHCb. Moreover, we participate also in the **DRD4** and the **AidaInnova** (Innovative SiPMs and future applications in PID detectors) WPs.

All these objectives are fully compliant with the recent **ECFA Roadmap** (10.17181/CERN.XDPL.W2EX , ex. DRDT 4).

R&D activities for future RICH detectors

Main activities of our group (EP-LBD/LBO) together with the LHCb RICH Collab. are

(in green the support from other CERN Groups):

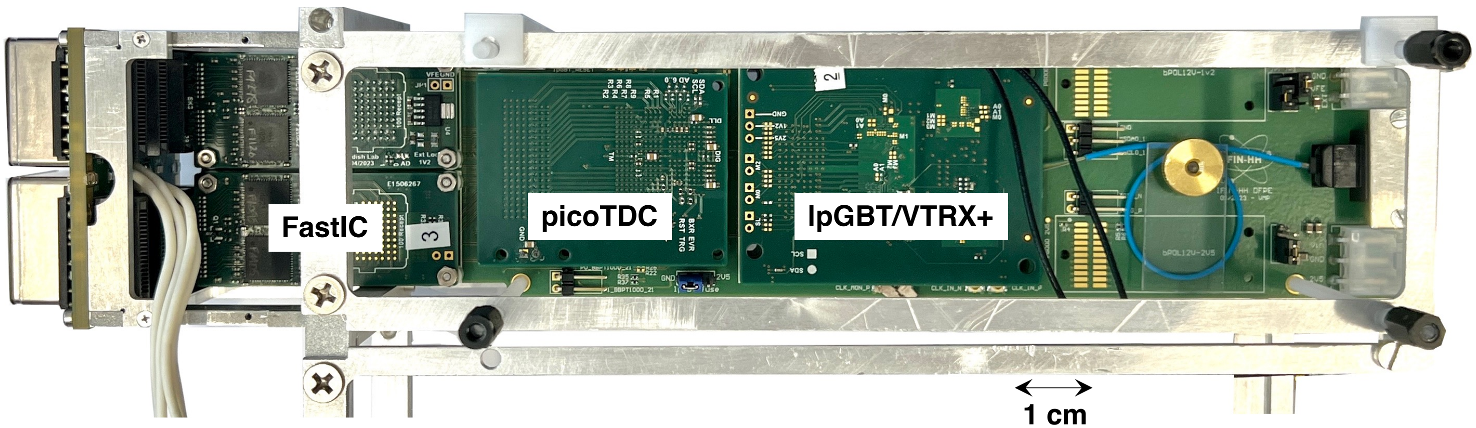
- Detector **novel designs, simulations, and software**.
- **New materials** for future Cherenkov radiators: ex., **Green Gases**; Photonic Crystals, Aerogels (EP-DT).
- **Photodetectors** with enhanced green QE (EP-DT).
- Development of a **gated optoelectronic chain**:
  Support for specific ASIC developments (**FastRICH**); (EP-ESE)
  Characterisation of systems in the laboratory or by **test-beams**. (EP-ESE, EP-DT)
- High Rates Rad. Hard **DAQ** digital architectures. (EP-ESE)
- Development of **Mechanics and Optics**:
  Composite Mirrors for both RICH1 and RICH2; Lenses and optical arrays;
  Special coatings; Precision mechanics. (EP-DT)
- Cooling/**cryogenic** systems. (TE-CRG-CI)

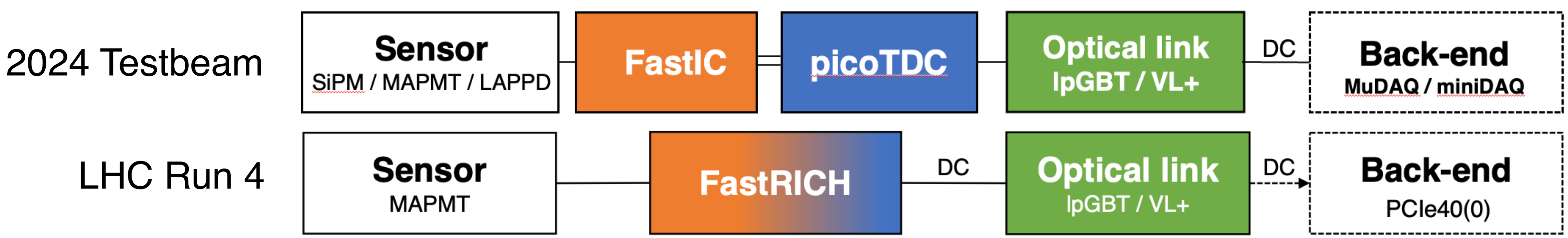
Update today focuses on May 2024 SPS testbeam campaign, FastRICH and cryostat preparations.

The 2024 testbeam and LS3 Enhancements readout chains

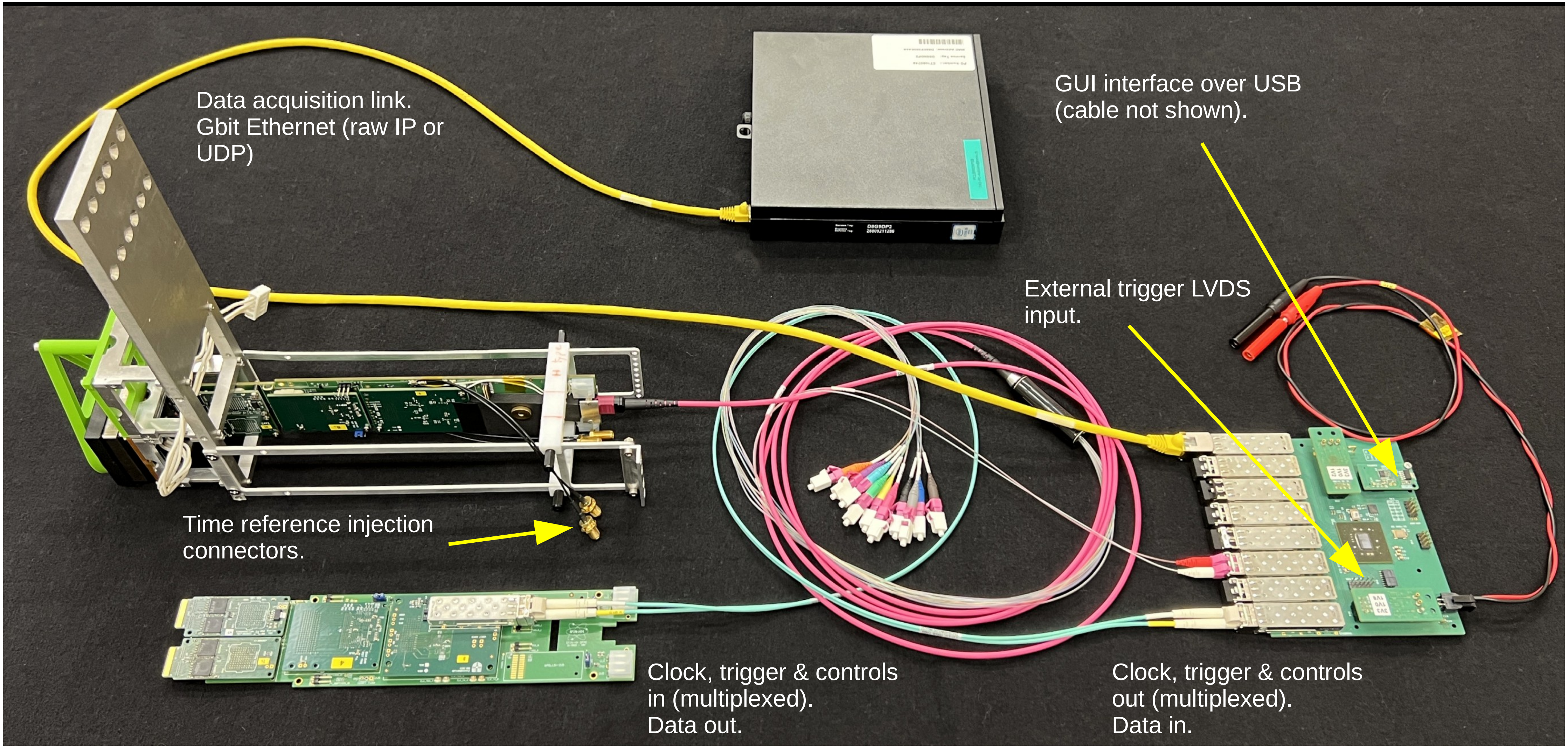
Successful testbeam campaign at the SPS facility in May 2024.
Installed 7 readout chains, including **56 FastICs**, and nearly 500 readout channels.
Readout through the **lpGBT plugins with VTRX+**.

Readout electronics are designed to be highly modular, and compatible with a “plugin swap” to replace the FastIC+picoTDC by the new **FastRICH ASIC plugin** for testing for the LS3 Enhancements.



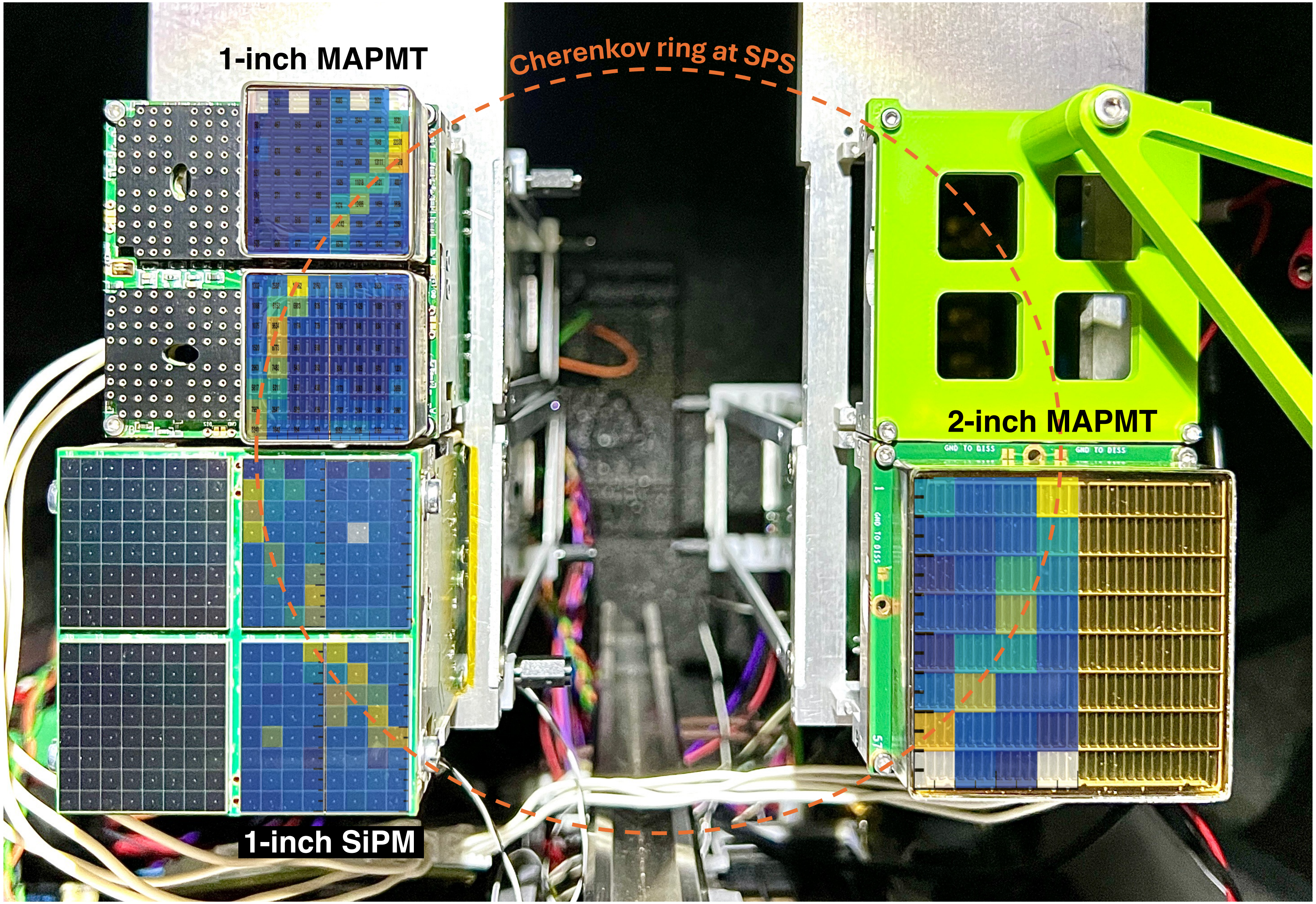


The readout chain and DAQ

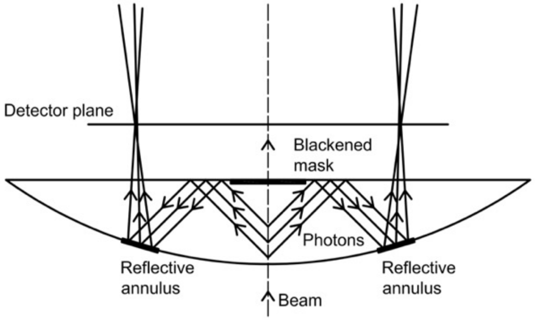


More detail in DRD4 WG3 (electronics) presentation:
https://indico.cern.ch/event/1416002/contributions/5959505/subcontributions/484389/attachments/2860908/5005328/RICHTbDaq.pdf

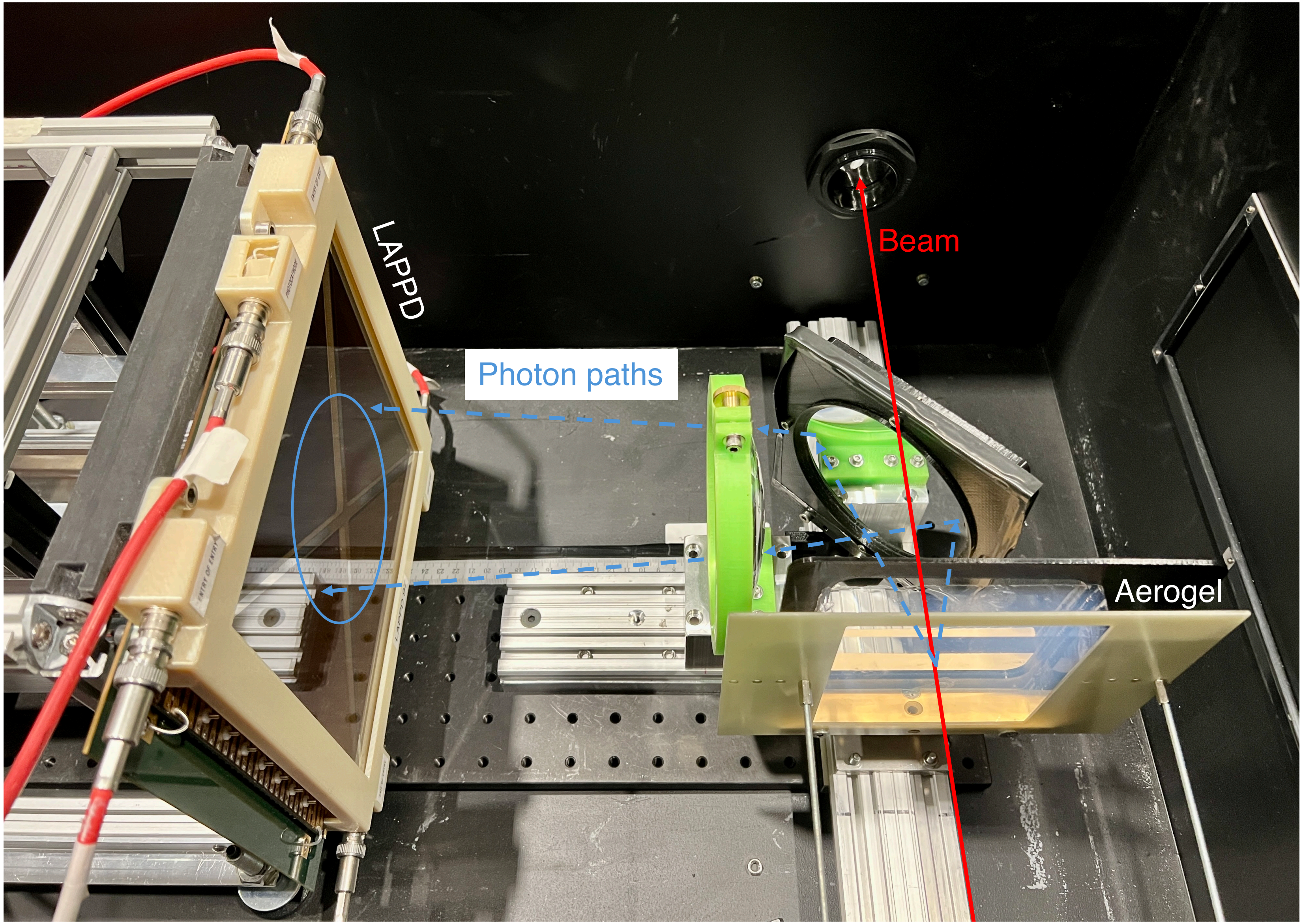
SPS testbeam campaign 24 Apr – 8 May 2024



Recorded hit maps from the Cherenkov ring arcs superimposed on the active area read out by the FastIC chain.

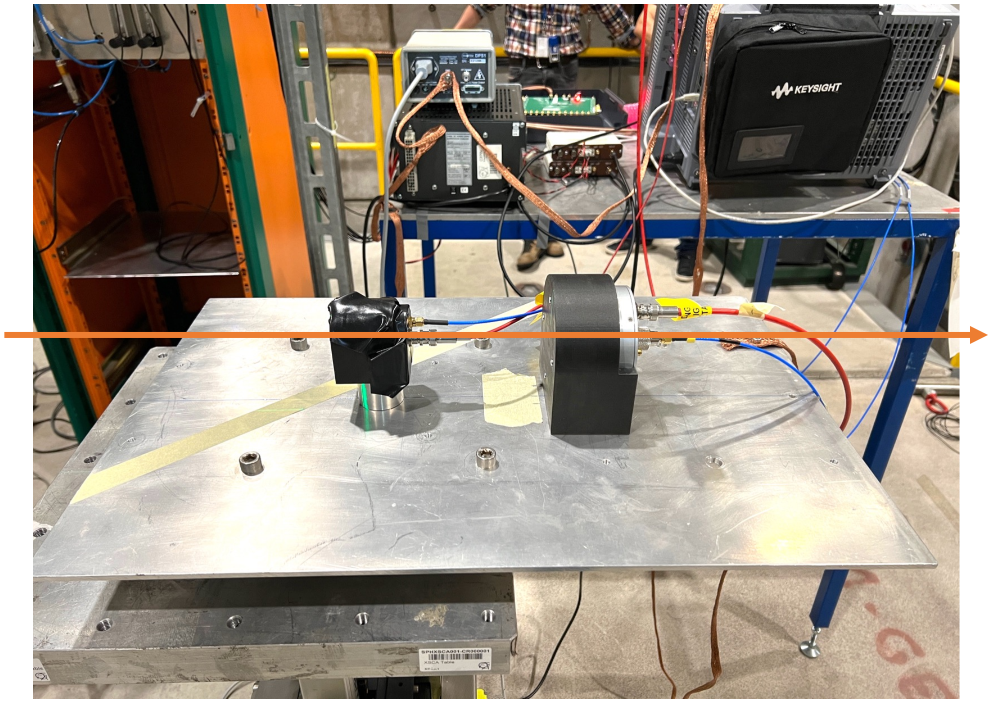


SPS testbeam campaign (Aerogel + LAPPD)

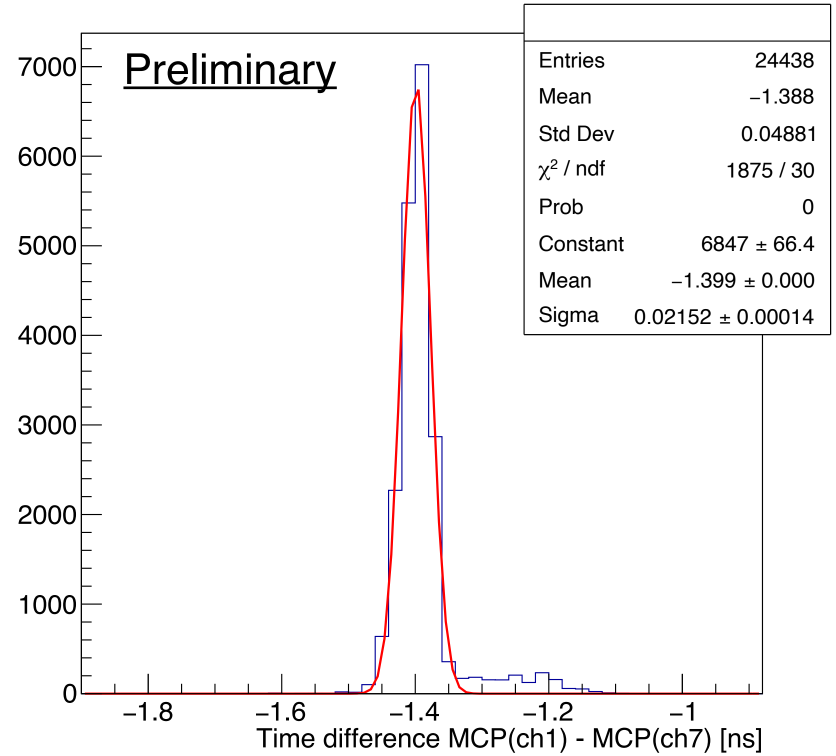


MCP-PMT beam track time reference system

Two MCP-PMTs placed in the beam, signals discriminated in external CFD and injected into **picoTDC channels on the RICH readout boards**.



The SPS beam traverses the MCP-PMT (Cherenkov photons generated in entrance window).



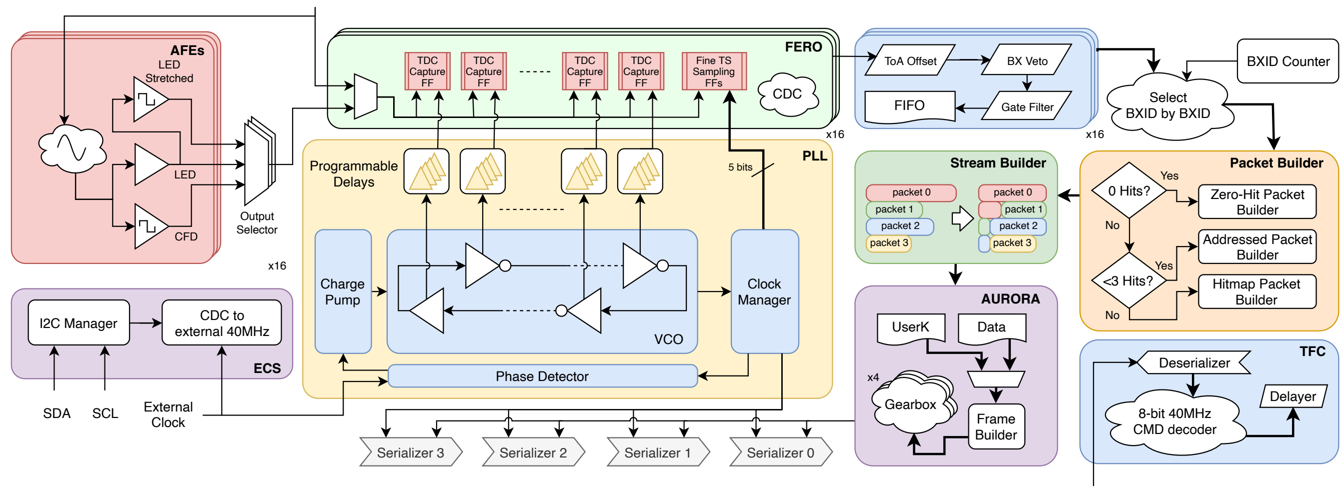
First checks include track timing **difference** between the two MCPs shows **σ ~ 22 ps**, including RICH picoTDC readout chain resolution.

Large statistics data sets were recorded and full analysis of optoelectronic performance is ongoing.

The FastRICH ASIC

The FastRICH ASIC is being designed in **65-nm CMOS by the CERN EP-ESE department and the University of Barcelona** with strong input in the specifications from our group and the LHCb RICH collaboration.

- **16-channel** design.
- Integrated TDC with **25 ps** bins.
- Constant Fraction Discrimination (**CFD**).
- Input signal dynamic range **30 μA - 2 mA** for coupling MAPMT / SiPM / MCP sensors.
- Radiation hardness using **triplication**.
- **Compressed** data-driven format (40 MHz) and configurable output serialisers.
- Close integration with **lpGBT**.

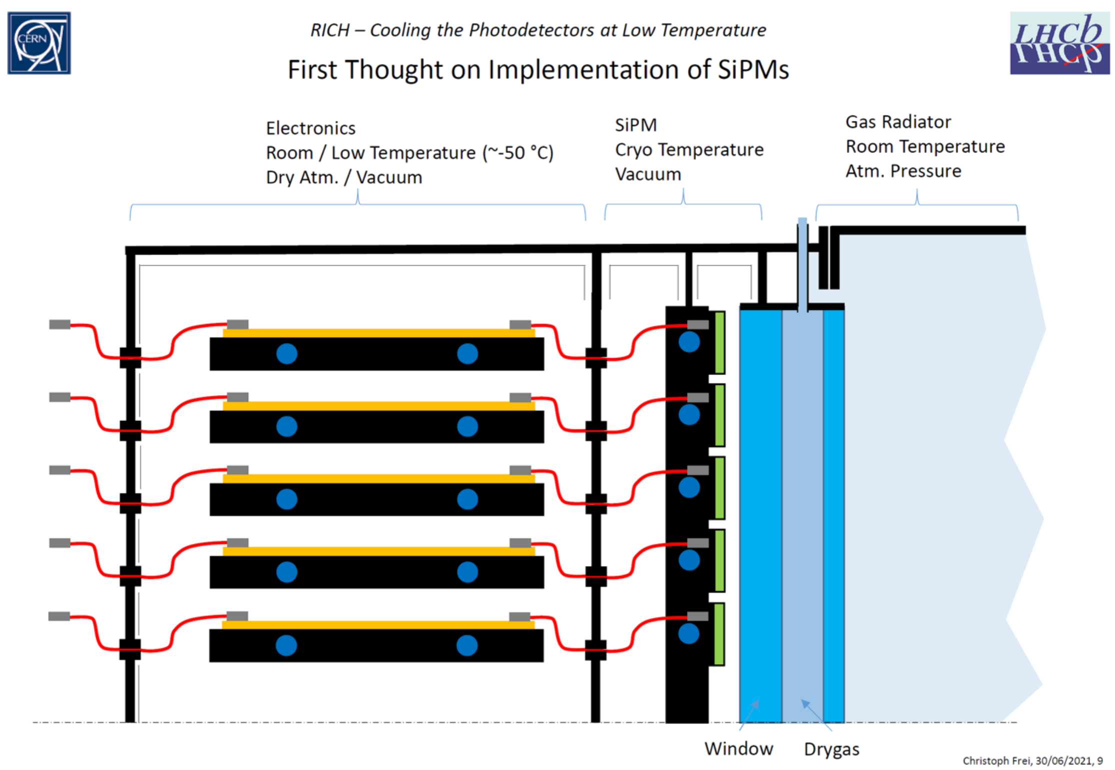


More information on https://fastrich.docs.cern.ch

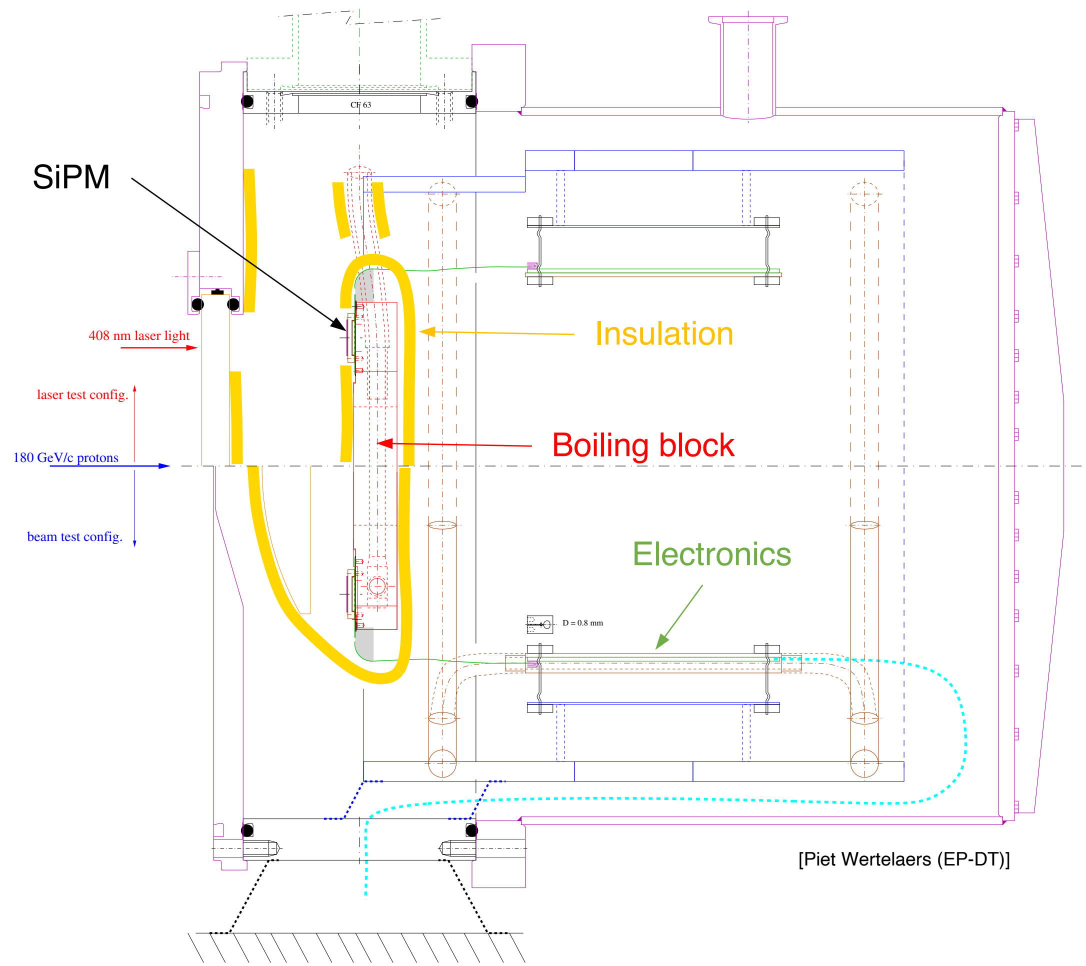
The FastRICH design is advancing strongly and the first chips from the multi-wafer run are expected at the end of the year. Preparations are ongoing for full testing (dedicated test card) and integration into the testbeam system (plugin to replace FastIC+picoTDC).

Cryogenic cooling of photon detectors (SiPM)

R&D into compact vessel structures has started and several meetings held with the cryogenics experts at CERN (TE-CRG-CI).



- Design of a small-scale demonstrator is ongoing.

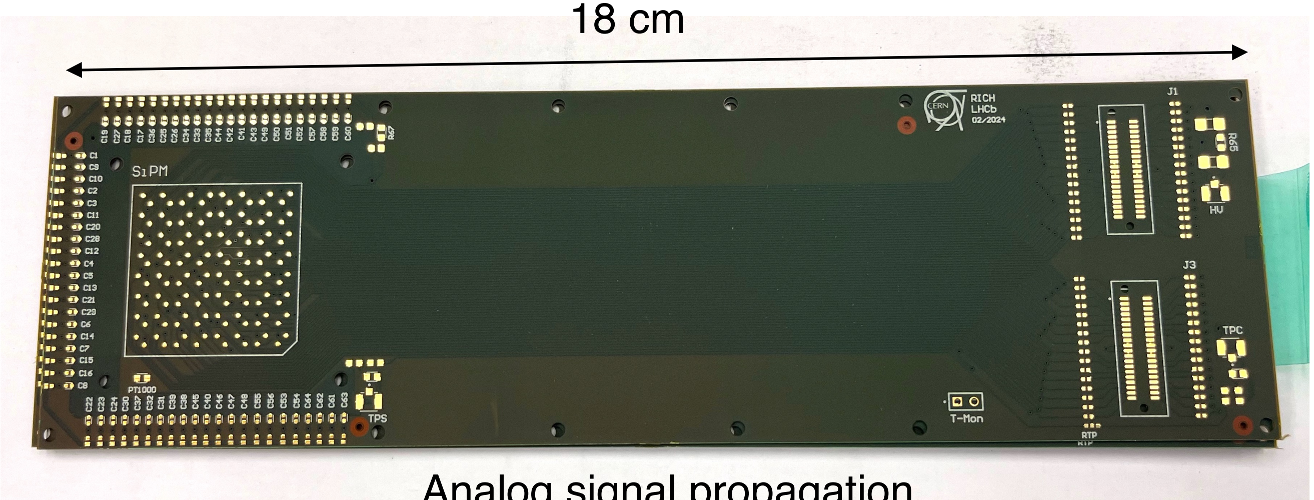


Flex-PCB to transport analog signals to FastRICH

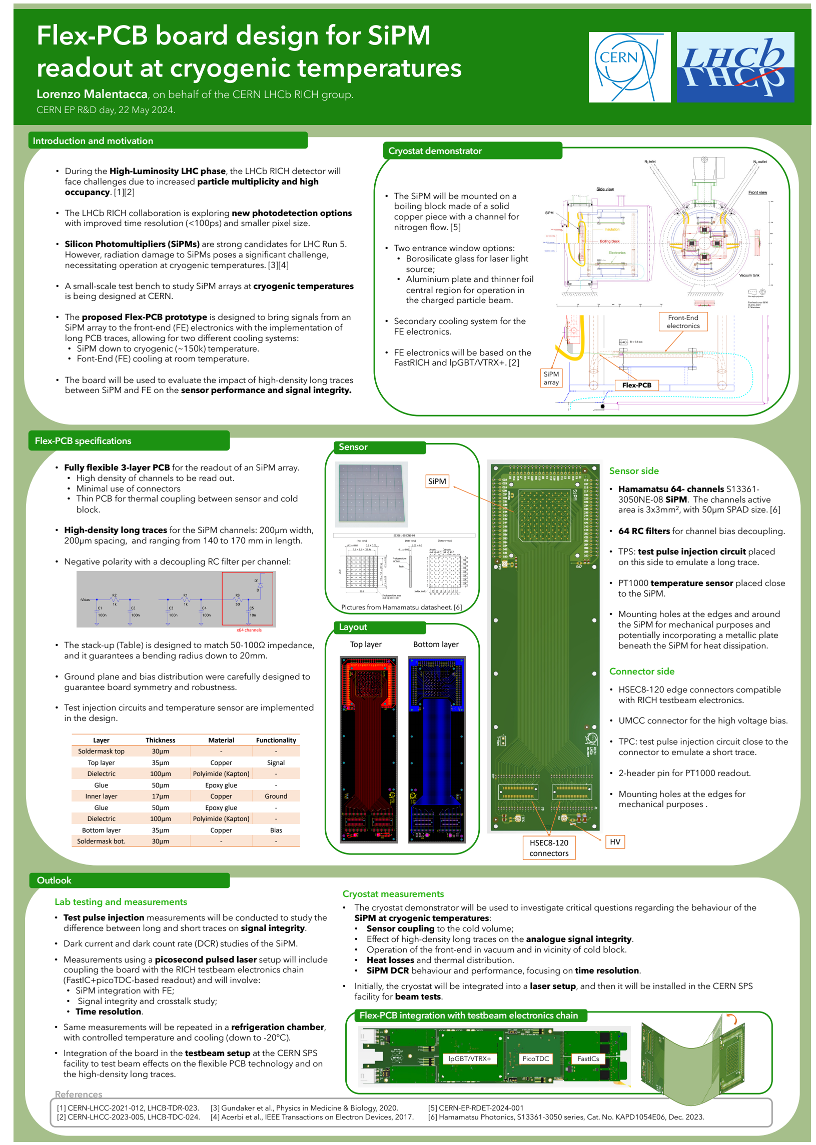
Aim to study the effect of the **transmission line on the analog single-photon signal integrity and time resolution** in a flex-PCB designed to couple the (cold) SiPM to the (room-T) FastRICH-based readout.

➢ Poster by Lorenzo Malentacca today.

18 cm



Analog signal propagation →



Flex-PCB board design for SiPM readout at cryogenic temperatures

Lorenzo Malentacca, on behalf of the CERN LHCb RICH group.
CERN EP R&D day, 22 May 2024.

Introduction and motivation

- During the **High-Luminosity LHC phase**, the LHCb RICH detector will face challenges due to increased **particle multiplicity and high occupancy**. [1][2]
- The LHCb RICH collaboration is exploring **new photodetection options** with improved time resolution (<100ps) and smaller pixel size.
- **Silicon Photomultipliers (SiPMs)** are strong candidates for LHC Run 5. However, radiation damage to SiPMs poses a significant challenge, necessitating operation at cryogenic temperatures. [3][4]
- A small-scale test bench to study SiPM arrays at **cryogenic temperatures** is being designed at CERN.
- The **proposed Flex-PCB prototype** is designed to bring signals from an SiPM array to the front-end (FE) electronics with the implementation of long PCB traces, allowing for two different cooling systems:
  - SiPM down to cryogenic (~150k) temperature.
  - Font-End (FE) cooling at room temperature.
- The board will be used to evaluate the impact of high-density long traces between SiPM and FE on the **sensor performance and signal integrity.**

Cryostat demonstrator

- The SiPM will be mounted on a boiling block made of a solid copper piece with a channel for nitrogen flow. [5]
- Two entrance window options:
  - Borosilicate glass for laser light source;
  - Aluminium plate and thinner foil central region for operation in the charged particle beam.
- Secondary cooling system for the FE electronics.
- FE electronics will be based on the FastRICH and lpGBT/VTRX+. [2]

Front-End electronics
SiPM array
Flex-PCB

Flex-PCB specifications

- **Fully flexible 3-layer PCB** for the readout of an SiPM array.
  - High density of channels to be read out.
  - Minimal use of connectors
  - Thin PCB for thermal coupling between sensor and cold block.
- **High-density long traces** for the SiPM channels: 200µm width, 200µm spacing, and ranging from 140 to 170 mm in length.
- Negative polarity with a decoupling RC filter per channel:

x64 channels

- The stack-up (Table) is designed to match 50-100Ω impedance, and it guarantees a bending radius down to 20mm.
- Ground plane and bias distribution were carefully designed to guarantee board symmetry and robustness.
- Test injection circuits and temperature sensor are implemented in the design.

Layer	Thickness	Material	Functionality
Soldermask top	30µm	-	-
Top layer	35µm	Copper	Signal
Dielectric	100µm	Polyimide (Kapton)	-
Glue	50µm	Epoxy glue	-
Inner layer	17µm	Copper	Ground
Glue	50µm	Epoxy glue	-
Dielectric	100µm	Polyimide (Kapton)	-
Bottom layer	35µm	Copper	Bias
Soldermask bot.	30µm	-	-

Sensor

SiPM

Pictures from Hamamatsu datasheet. [6]

Layout

Top layer
Bottom layer

Sensor side

- **Hamamatsu 64- channels** S13361-3050NE-08 **SiPM**. The channels active area is 3x3mm², with 50µm SPAD size. [6]
- **64 RC filters** for channel bias decoupling.
- TPS: **test pulse injection circuit** placed on this side to emulate a long trace.
- PT1000 **temperature sensor** placed close to the SiPM.
- Mounting holes at the edges and around the SiPM for mechanical purposes and potentially incorporating a metallic plate beneath the SiPM for heat dissipation.

Connector side

- HSEC8-120 edge connectors compatible with RICH testbeam electronics.
- UMCC connector for the high voltage bias.
- TPC: test pulse injection circuit close to the connector to emulate a short trace.
- 2-header pin for PT1000 readout.
- Mounting holes at the edges for mechanical purposes .

HSEC8-120 connectors
HV

Outlook

Lab testing and measurements

- **Test pulse injection** measurements will be conducted to study the difference between long and short traces on **signal integrity**.
- Dark current and dark count rate (DCR) studies of the SiPM.
- Measurements using a **picosecond pulsed laser** setup will include coupling the board with the RICH testbeam electronics chain (FastIC+picoTDC-based readout) and will involve:
  - SiPM integration with FE;
  - Signal integrity and crosstalk study;
  - **Time resolution**.
- Same measurements will be repeated in a **refrigeration chamber**, with controlled temperature and cooling (down to -20°C).
- Integration of the board in the **testbeam setup** at the CERN SPS facility to test beam effects on the flexible PCB technology and on the high-density long traces.

Cryostat measurements

- The cryostat demonstrator will be used to investigate critical questions regarding the behaviour of the **SiPM at cryogenic temperatures**:
  - **Sensor coupling** to the cold volume;
  - Effect of high-density long traces on the **analogue signal integrity**.
  - Operation of the front-end in vacuum and in vicinity of cold block.
  - **Heat losses** and thermal distribution.
  - **SiPM DCR** behaviour and performance, focusing on **time resolution**.
- Initially, the cryostat will be integrated into a **laser setup**, and then it will be installed in the CERN SPS facility for **beam tests**.

Flex-PCB integration with testbeam electronics chain

lpGBT/VTRX+
PicoTDC
FastICs

References
[1] CERN-LHCC-2021-012, LHCB-TDR-023.
[2] CERN-LHCC-2023-005, LHCB-TDC-024.
[3] Gundaker et al., Physics in Medicine & Biology, 2020.
[4] Acerbi et al., IEEE Transactions on Electron Devices, 2017.
[5] CERN-EP-RDET-2024-001
[6] Hamamatsu Photonics, S13361-3050 series, Cat. No. KAPD1054E06, Dec. 2023.

Cryostat optical window for LHCb-RICH sized system

LHCb / RICH

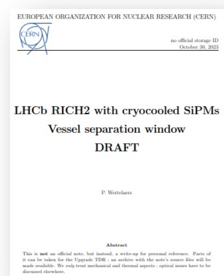
Upg-2 – Investigation of the Window for Cryostat

Requirements:

- Vacuum tight
- Withstand: 1 bar (~120 kN)
- Transparent window: ~300..700 nm
- Large optical window, 0.72 m × 1.46 m
- Provide thermal barrier
  - External side: Convection
  - Heat Radiation, IR reflective coating
- Radiation-hard
- Small effect on the single-photon optical path
- Minimal Cherenkov / scintillation
- No impact on chromatic dispersion in time

Preliminary outcome:

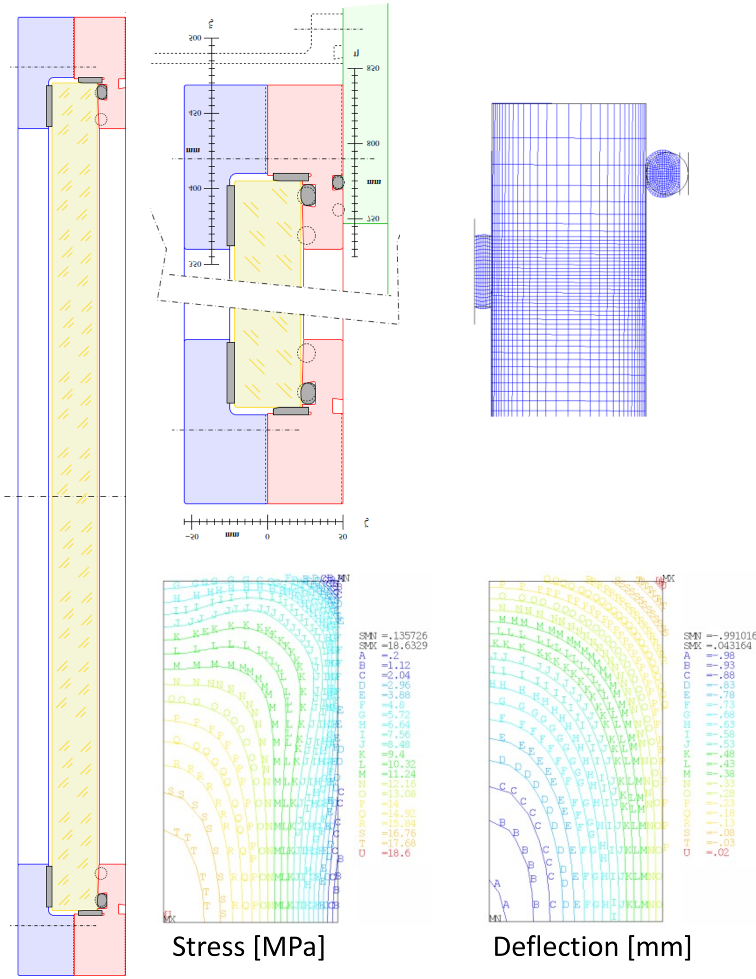
- Material: borosilicate
- Max stress: < 20 MPa
- Thickness: 45 mm
- Weight: 125 kg


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

LHCb RICH2 with cryocooled SiPMs
Vessel separation window
DRAFT

Challenging procurement and polishing.

Further studies and measurements (optical / thermal) on small-scale test pieces foreseen.


Stress [MPa]   Deflection [mm]

Christoph Frei, 21/05/2024, 1

Conclusion

A successful **RICH testbeam campaign** was performed at the SPS facility,
- ➢ Data taken with ~500 readout channels of SiPM / MAPMT / MCP-based sensors and prototype readout.

The **FastRICH ASIC** design is advancing well.
- ➢ Integration of chips into test benches is being prepared for first testing at the end of the year.

A **demonstrator cryostat for SiPM operation** is being designed.
- ➢ Focus on flex-PCB for front-end analog signal coupling and studies of the large optical window.