Plans for test beam

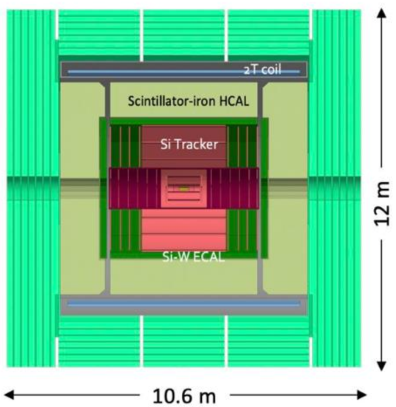
Romualdo Santoro

Università dell'Insubria and INFN – Milano

Many thanks to: M. Da Rocha Rolo, A. Andreazza, S. Senyukov, N. De Filippis, M. Poli Lener, M. Lucchini, G. Gaudio, N. Morange, V. Boudry

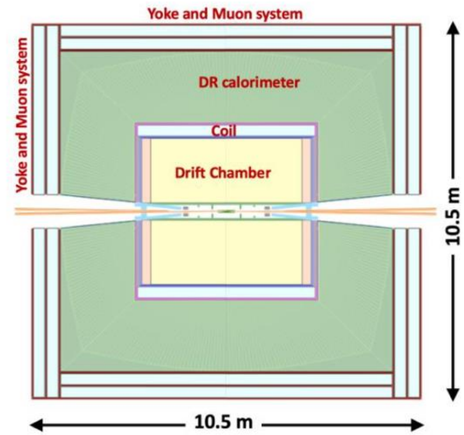
Detector concepts for FCC-ee

CLD

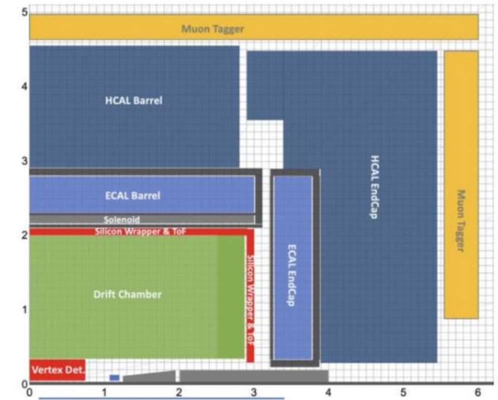


CDR

IDEA



Noble Liquid ECAL based



- Full Silicon vertex detector + tracker
- Very high granularity: CALICE-like calorimetry;
- Muon system
- Large coil outside calorimeter system

- Vertex: MAPS (ARCADIA / ATLASPIX3)
- Drift Chamber
- Silicon wrapper: strip, MAPS / DMAPS possibly with timing layer
- Dual Readout calorimetry: (Crystal +) fibre sampling
- Muon chamber (Preshower): μ-RWELL

- Vertex: MAPS / DMAPS possibly with timing layer
- Drift Chamber
- Silicon wrapper: MAPS / DMAPS possibly with timing layer
- High granular ECAL: Noble liquid + Pb or W
- High granular HCAL: Scintillator + Iron
- Muon tagger: RPC, Micro Megas

Interests in detector R&D topic for FCC-ee Subdetectors

France

- **Tracking**
  - **TPC** — IRFU;
  - **MCMOS** — CPPM, IPHC, IP2I, LPNHE;
  - DCH — IJCLab, Ganil, LPSC
- **Timing Layers**
  - **MicroMegas** — IRFU,
  - **MCMOS** — IPHC, IP2I, CPPM,
  - **Optical** — CPPM, IP2I
- **Liquid Argon calorimetry**
  - **ECAL** — APC, CPPM, IJCLAB, LPNHE, LAPP
  - **electronics** — Omega
- **Sampling calorimetry with fully embedded electronics**
  - **ECAL/SiW** (calice) — IJCLab, LLR, LPNHE;
  - **HCAL** — IP2I,
  - **electronics** — Omega
- **Optical calorimetry**
  - **ECAL GRAiNita** — IJCLAB, LPC-CF,
  - **Crystals** — IP2I
- **Muon hodoscope/tagger**
  - **Micromegas** — IRFU,
  - **(RPC** — experience at IP2I but no specific project)

G Bernardi: this workshop

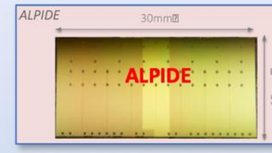
Italy

- Vertex
  - ARCADIA
  - ATLASPIX3
- Tracking
  - Drift Chamber
- Wrapper and timing layer
- Calorimetry
  - Dual readout
- Muon station
  - μ-RWELL

Experience with MAPS vertex detectors in France

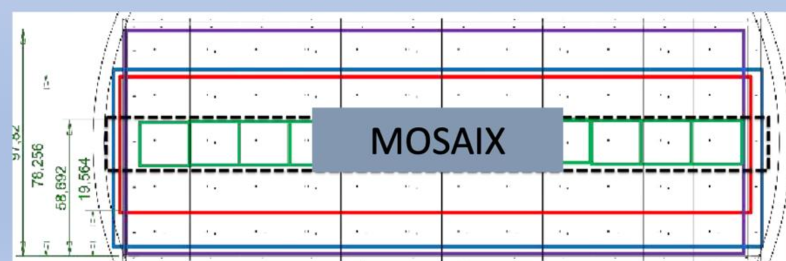
- STAR-PXL @ RHIC
  - ULTIMATE chip design (IPHC)
    - First MAPS for vertex detector

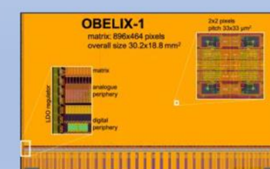
- ALICE-ITS2 @ LHC
  - ALPIDE chip design (IPHC, IRFU, IP2I)
    - First in TJ 180 nm
    - First MAPS tracker chip
  - Detector assembly (IPHC)



- CBM-MVD @ FAIR
  - MIMOSIS chip design (IPHC)
    - TJ180 nm
    - Hit rate: 70 MHz/cm² (ALIPDE x2)
- ALICE-ITS3 @ LHC
  - MOSAIX chip design (IPHC)
    - First in TPSCo 65 nm process
    - First large area stitched sensor ~260 cm²

- Belle II VXD @ KEK
  - OBELIX chip design (IPHC, CPMM)
    - TJ 180 nm
    - Time resolution: 100 ns
    - Hit rate: 120 MHz/cm² (triggered)





Details in Serhiy Senyukov's talk @ this workshop

OCTOPUS (DRD3/7)

Optimized **C**MOS **T**echnology f**O**r **P**recision in **U**ltra-thin **S**ilicon

- Simulation, development and characterization of MAPS targeting future Lepton Collider specifications:
  - Single point resolution: 3 μm
  - Time resolution: 5 ns
  - Power dissipation: 50 mW/cm^2
  - Thickness: 50 μm
  - Readout architecture scalable to large area
- Intermediate step – high resolution sensor for beam telescope
  - Time resolution: 100 ns
  - Power dissipation: $<$500 mW/cm^2

Details in Serhiy Senyukov's talk @ this workshop

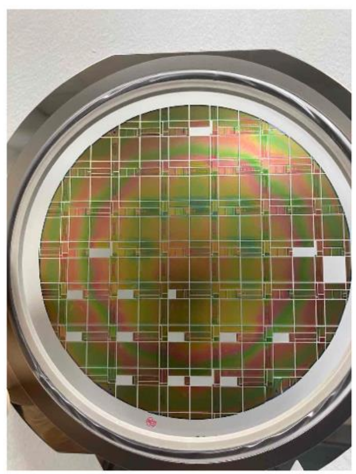
OCTOPUS: Milestones and deliverables

Number	Deliverable/Milestone Title	WP project #	Lead	Type	Dissemination Level	Due Date
M1	Report on Demonstrators	4	DESY	Report	DRD3 report	Month 9 (Q1 2025)
D1 **MPR2**	Beam Telescope Demonstrator Matrix Submission **3 µm**	1, 2	IPHC	Prototype **Full column height**	Manual / Presentation	Month 24 (Q2 2026)
M2	Report on Demonstrator Matrix Characterization	3, 4	DESY	Report	Publication	Month 36 (Q2 2027)
D2 **MPR3**	Full Beam Telescope Sensor Submission	2, 3	IPHC	Prototype **≥ 2cm² sensor**	Manual / Presentation	Month 48 (Q2 2028)
M3	Report on Beam Telescope Sensor Performance	3, 4	DESY	Report	Publication	Month 60 (Q2 2029)
D3 **ER**	LC Vertex Sensor Demonstrator Submission	1, 2	IPHC	Prototype	Manual / Presentation	Month 66 (Q4 2029)
M4	Report on LC Vertex Sensor Demonstrator Performance	3, 4	DESY	Report	Publication	Month 78 (Q4 2030)

Details in Serhiy Senyukov's talk @ this workshop

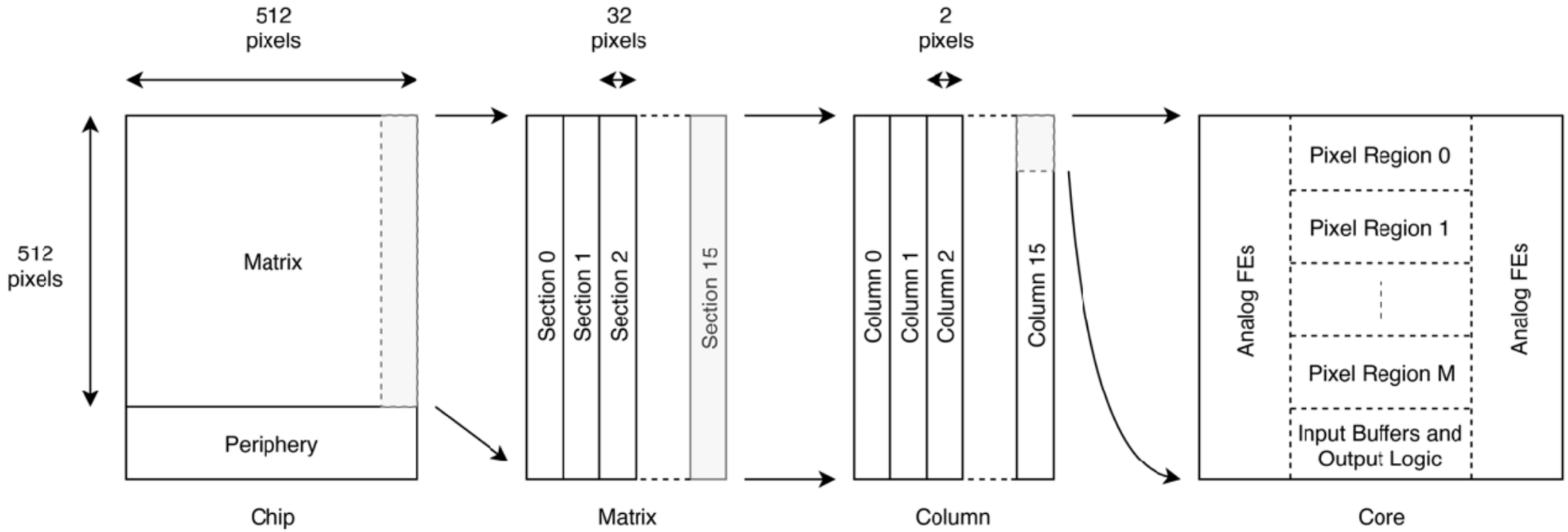
ARCADIA

- Monolithic active sensor thickness in the range 50 μm to 500 μm;
- Operation in full depletion with fast charge collection by drift, small collecting electrode for optimal signal-to-noise ratio;
- Scalable readout architecture with ultra-low power capability (10 mW/cm2);
- Compatibility with standard CMOS fabrication processes
- Technology LF11, 110nm CMOS node (quad-well, both PMOS and NMOS), high-resistivity bulk
- Custom patterned backside, patented process developed in collaboration with LFoundry



Details in Manuel Rolo’s talk @ this workshop

ARCADIA-MD3: Chip Architecture

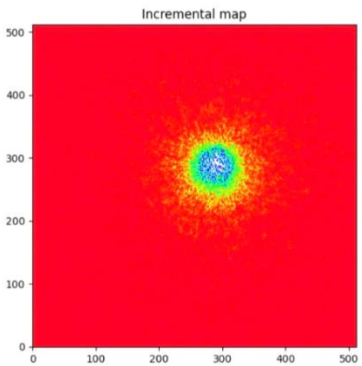


- Pixel size 25 µm x 25 µm, Matrix core 512 x 512, 1.28 x 1.28 cm^2 silicon active area, "side-abuttable"
- Triggerless data-driven readout and low-power asynchronous architecture with clockless pixel matrix
- Event rate up to 100 MHz/cm2 (design post-layout simulations, to be demonstrated)
- High-rate operation (16 Tx): 17-30 mW/cm^2 depending on transceiver driving strength (measured)
- Low-power operation (1 Tx): 10 mW/cm^2 (measured)

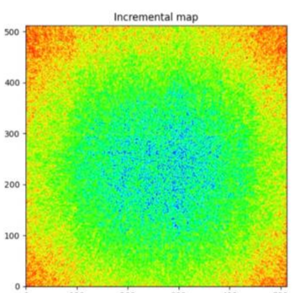
Details in Manuel Rolo's talk @ this workshop

ARCADIA-MD3: charged particles

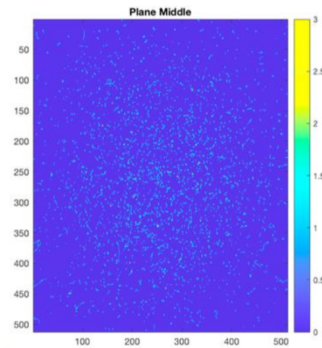
^{90}Sr
(collimated 1mm)

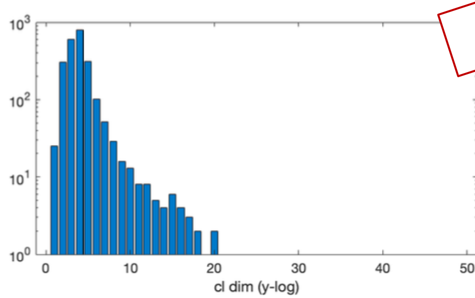


(uncollimated)

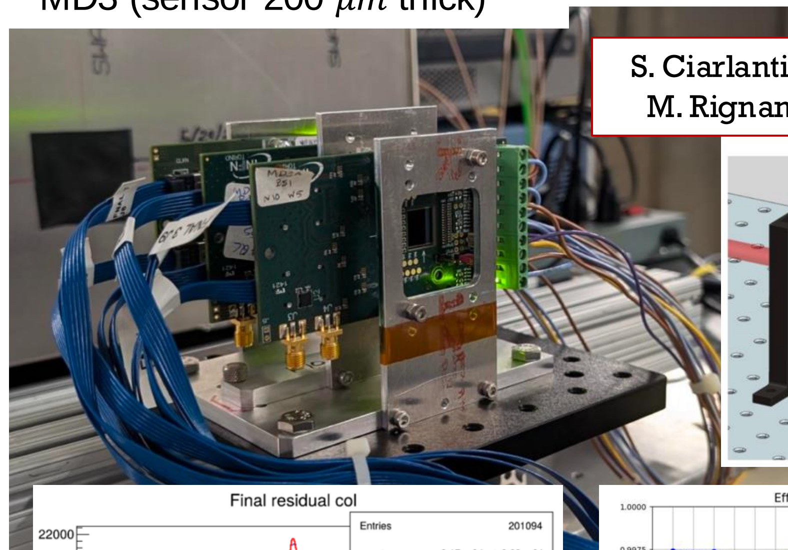


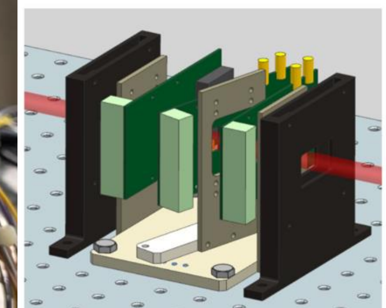
Cosmic run



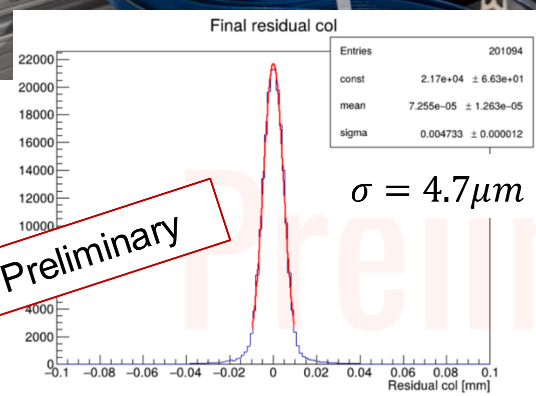


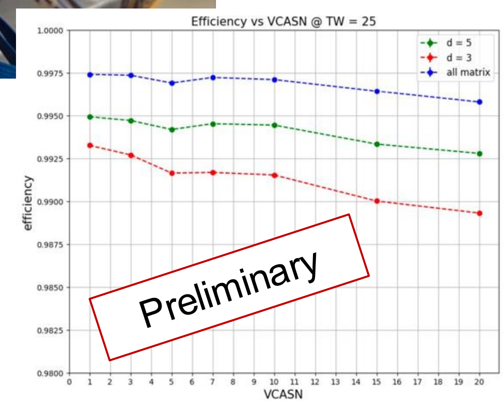
TB @ FNAL (120 GeV protons)
MD3 (sensor 200 μm thick)





S. Ciarlantini, C. Pantouvakis, M. Rignanese, A. Zingaretti



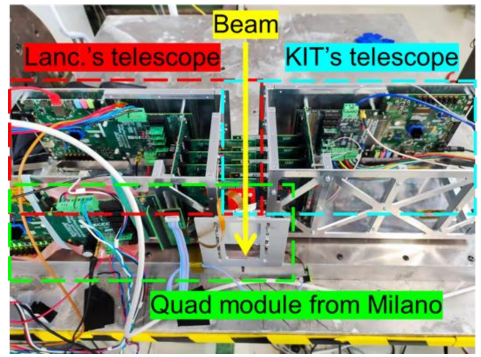


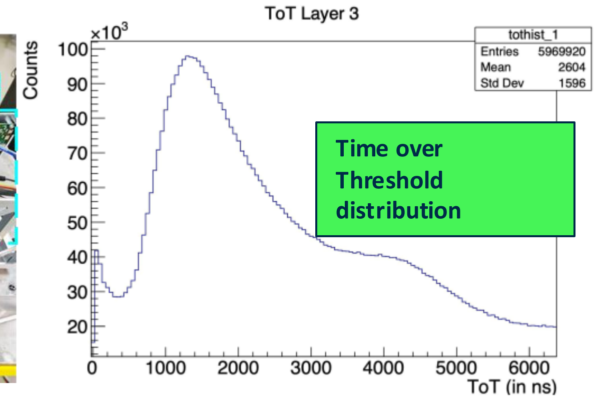
Residuals $\approx 4.7\ \mu m$
Efficiency better than 99% in the full threshold range

Details in Manuel Rolo's talk @ this workshop

ATLASPIX3 Test Beam Plans

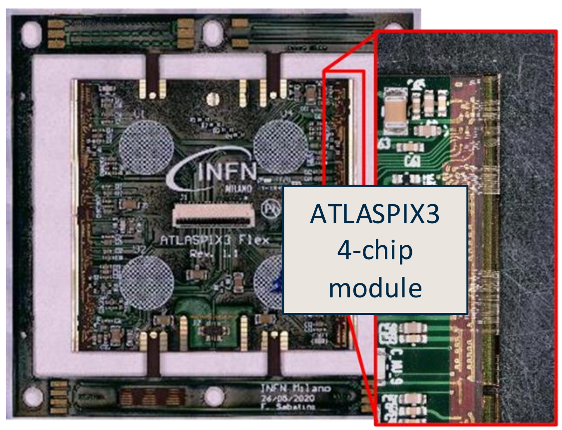
- ATLASPIX3 sensors are available since 2020
- General purpose DMAPs: characterized in test beam by many groups
  - KIT
  - FCCee/CEPC groups
  - LHCb Mighty Tracker community
- A focus for the future will be the system aspects:
  - multi-chip systems
  - multi-chip modules
  - multi-module operation





DESY 2022

Quad module and multi-chip telescopes operation



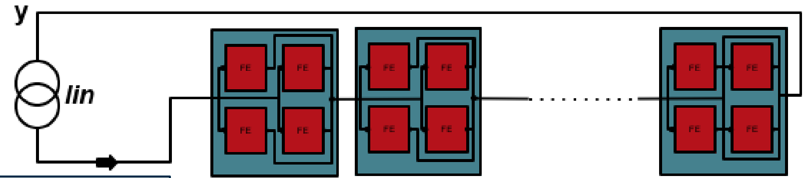
CERN H8 line 2024

Module inserted in the Hydra calorimeter test beam 28/08-04/09

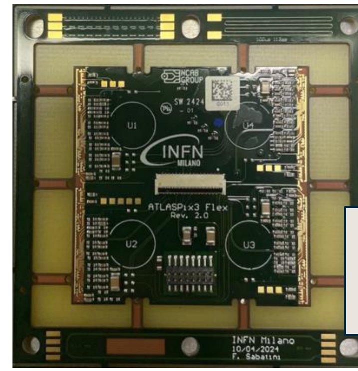
Testing the integration in a readout chain with other detectors

ATLASPIX3 Test Beam Plans

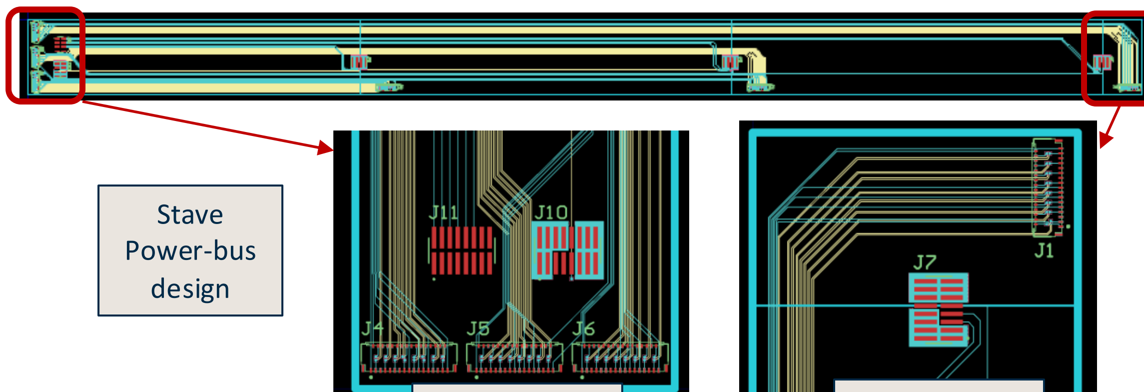
- 2025 R&D program
  - Available new set of quad modules in serial-power configuration
  - Building pseudo-staves in Italy and UK
  - Can be arranged in a large area telescope ($4x4\ cm^2$ cross section)
- 2026 R&D program
  - Probably switch to integration of MightyPixV2 systems
  - open collaboration with LHCb MightyTracker upgrade
  - should include also sensor characterization
- General comments:
  - Limited personpower: **join TB effort with other communities is essential**
  - Integrating the DAQ systems is a topic where injected personpower will be very beneficial



Serial power chain concept



Serial power PCB delivered in July



Stave Power-bus design

End of stave side

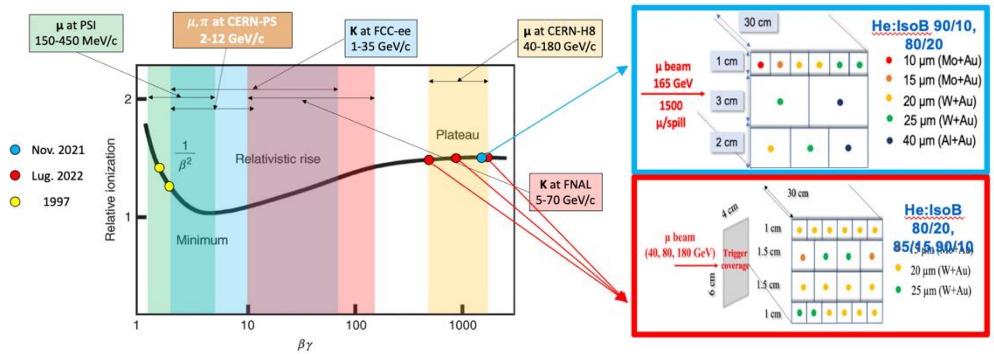
Last module side

Vertex: Tentative TB schedule for 2025 and beyond

- OCTOPUS (DESY/CERN)
  - Single column prototype (2026)
  - > 2cm^2 prototype (2028)
- ARCADIA MD3
  - TB2024 data analysis is still on-going (preliminary results very promising)
  - The collaboration is considering a TB in 2025 (DESY / CERN) to qualify 50 μm thick sensors
  - Stable system: it could be considered as tracking for other detectors
- ATLASPIX3
  - Beam tests in 2025 and 2026 if personpower available

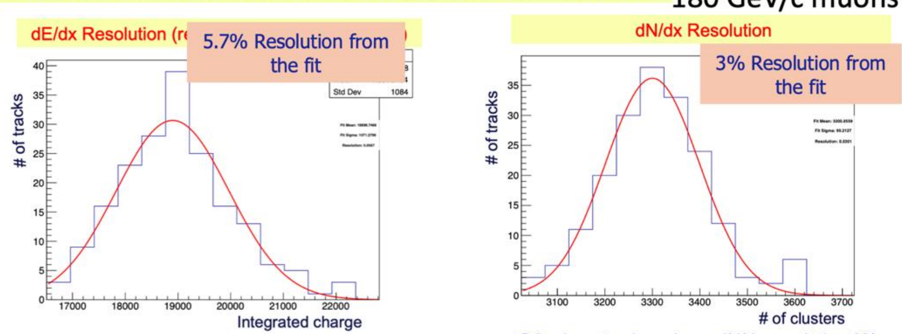
Drift Chamber: TB strategy

- Different beam tests to assess and optimize the performance of cluster counting/timing techniques:
  - Two muon beam tests performed at CERN-H8 ($\beta\gamma > 400$) in Nov. 2021 and July 2022 (pT = 165/180 GeV).
  - A muon beam test (from 4 to 12 GeV momentum) in 2023 performed at CERN. A new test beam, same configuration, done in July 2024
  - Ultimate test at FNAL-MT6 in 2025 with π and K ($\beta\gamma$ = 10–140) to fully exploit the relativistic rise.



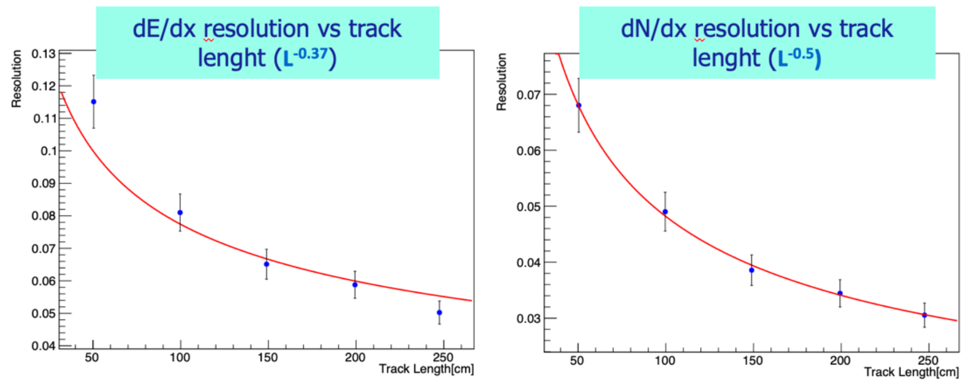
Study done using same tracks (2 m track length) made of the same hits.

180 GeV/c muons



@2m long track we have dE/dx resolution 5.7%

@2m long track we have dN/dx resolution 3%



~ 2 times improvement in the resolution using dN/dx method

Details in W. Elmetenawee's talk @ this workshop

R&D for the full-length prototype (2025)

- **Check the limits of the wires' electrostatic stability at full length and at nominal stereo angles**

- **Test different wires**: uncoated Al, C monofilaments, Mo sense wires, …, of different diameters
  - Test different wire anchoring procedures (soldering, welding, gluing, crimping, …) to the wire PCBs
  - Test different materials and production procedures for spokes, stays, support structures and spacers
  - Test compatibility of proposed materials with drift chamber operation (outgassing, aging, creeping, …)

- Validate the **concept of the wire tension recovery scheme** with respect to the tolerances on the wire positions
  - Optimize the layout of the wires' PCBs (sense, field and guard), according to the wire anchoring procedures, with aim at minimizing the end-plate total material budget

- Starting from the new concepts implemented in the MEG2 DCH robot, **optimize the wiring strategy**, by taking into account the 4m long wires arranged in multi-wire layers

- Define and validate **the assembly scheme** (with respect to mechanical tolerances) of the multi-wire layers on the end plates
  - Define the front-end cards channel multiplicity and their location (cooling system necessary?)

- **Optimize the High Voltage and signal distribution** (cables and connectors)

- Test performance of **different versions of front-end, digitization and acquisition chain**

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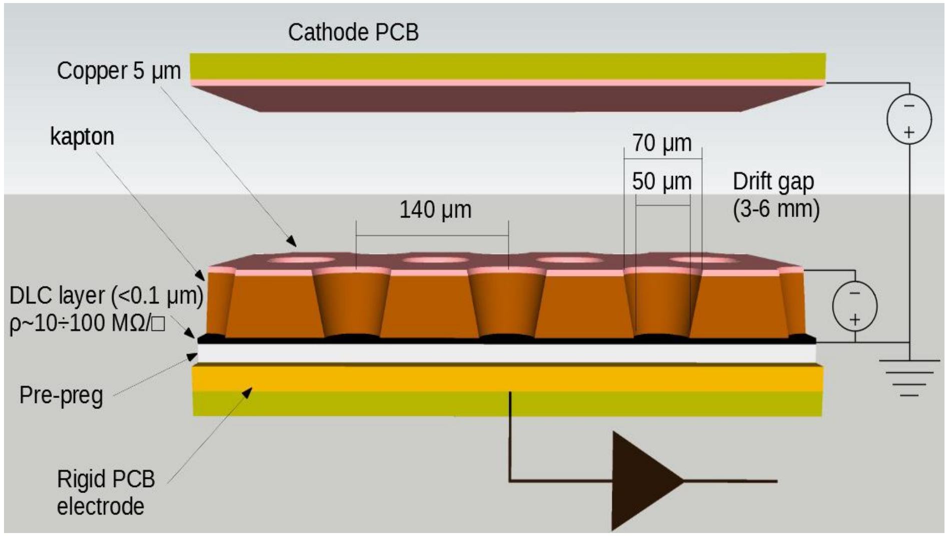
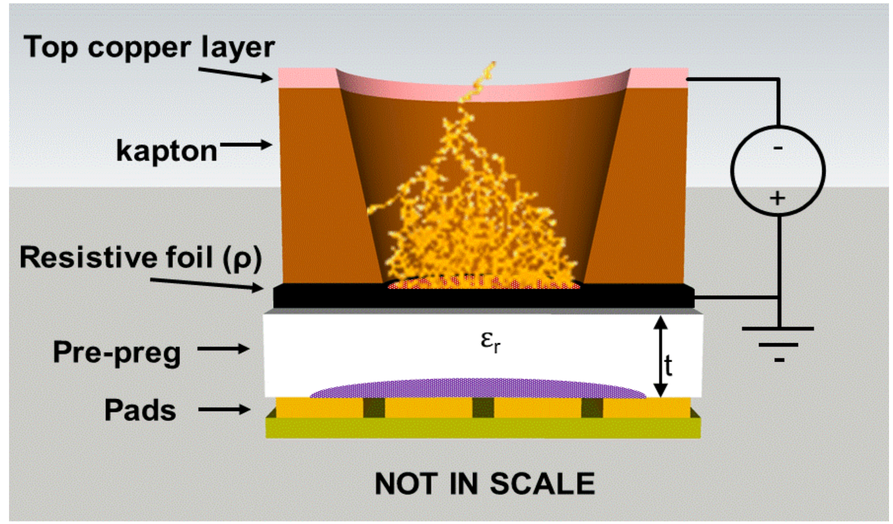
- **Optimize the High Voltage and signal distribution** (cables and connectors)
- Test performance of **different versions of front-end, digitization and acquisition chain**

Necessary R&D, done in parallel with small prototypes, not yet included in TB activities

The µ-RWELL - recap

G. Bencivenni et al., 2015 JINST 10 P02008





The **µ-RWELL** is a **resistive MPGD** composed of two elements:

- **Cathode**
- **µ-RWELL_PCB:**
  - a **WELL** patterned **Kapton foil** (**w/Cu-layer on top**) acting as **amplification stage**
  - a **resistive DLC** layer(*) w/ **ρ~10÷100 MΩ/□**
  - a standard **readout PCB** with **pad/strip** segmentation

(*) DLC foils are currently provided by the Japan Company – BeSputter

The **"WELL"** acts as a **multiplication channel** for the ionization produced in the drift gas gap.

The **resistive stage** ensures the **spark amplitude quenching.**

Drawback: capability to stand high particle fluxes reduced, but **largely recovered** with appropriate **grounding schemes** of the **resistive layer**

2

Details in G. Bencivenni's talk @ this workshop

R&D program 2024

The production of the 2023 & 2024 layouts has been delayed due to the increased workload at the Rui's workshop

Solution under study to increase detector stability:

1. **µ-RWELL "well optimization" →** This study was done with GEM detectors but never with uRWELL → well pitch from 140 µm to 90 µm with an increase in gain of about a factor of 2. **Designed at the beginning of 2024 & detector delivery in Sept. 2024.**

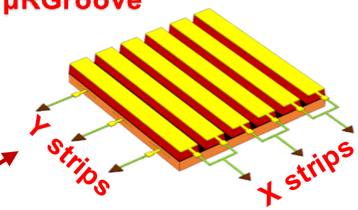
New layouts under study for Pre-shower and Muon systems:

1. **µ-RGroove layout→** new layout, where the amplification stage is not based on the **«wells» but on the «grooves».** This facilitates the realization of the strip readout on the top, without introducing dead-zones (introduced by Z. Yi in RD51). **Designed at the end of 2023 & detector delivery in Sept. 2024.**

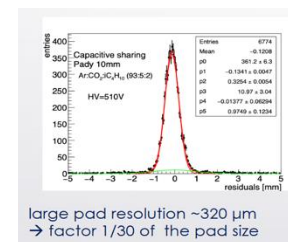
2. **" µ-RWELL CS" layout with pad readout →** new layout, where the readout PCB is not segmented in **strips but with pad.** This choice allows to collect all the charge on a single readout electrode with a small increase of FFE channels (30%). With pad of few cm2 a spatial resolution of ~300 um has been achieved (introduced by M. Iodice in RD51). **Designed in Oct. 2024.**

3. **"GEM + µ-RWELL CS" (strip/pad readout)→** GEM pre-amplification stage, to lower the operating point, greatly improving the RWELL stability and maintaining high spatial performance with millimetric pitches. **GEM production** will be produced in **January 2025**.

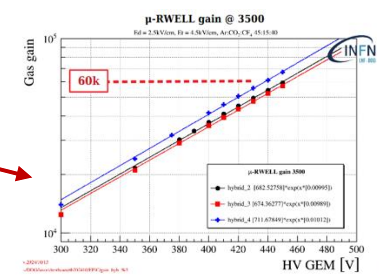
2D-readout (XY)
µRGroove



Z. Yi



M. Iodice



Details in G. Bencivenni's talk @ this workshop

Tentative schedule for 2024 & 2025

2024

- Gain measurement & Gain Uniformity with X-ray (November):”

1. **μ-RWELL pitch optimization;**
2. **"μ-RWELL CS" layout with strip readout;**
3. **μ-RGroove layout;**

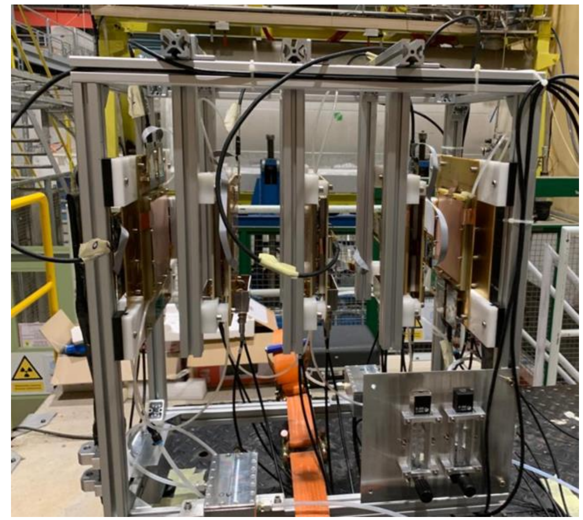
2025

- Gain measurement & Gain Uniformity with X-ray (June):

1. **"μ-RWELL CS" layout with pad readout;**
2. **"GEM + μ-RWELL CS" layout with strip readout;**

- TB (Oct/Nov.) @ H8-SPS-CERN: 5 new layout will be tested

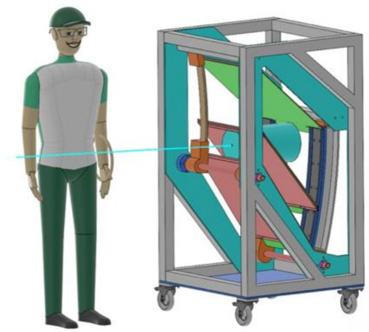
1. **"μ-RWELL CS” layouts (strip/pad)**
2. **"GEM + μ-RWELL CS" layouts (strip/pad);**
3. **μ-RGroove layout;**

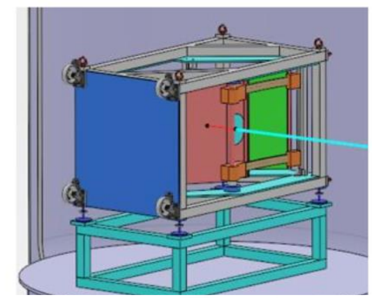


For the TB an external trackers with a spatial resolution better than 100 um will be used

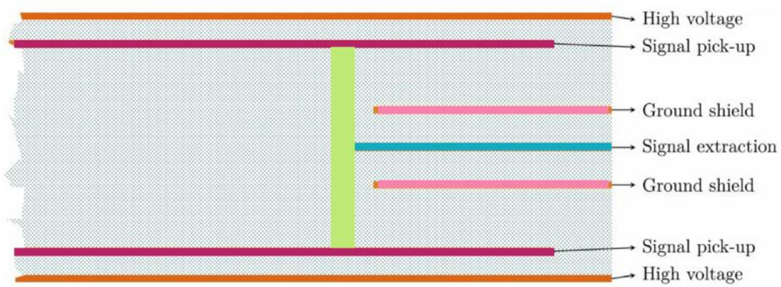
R&D on noble liquid ECAL for ALLEGRO

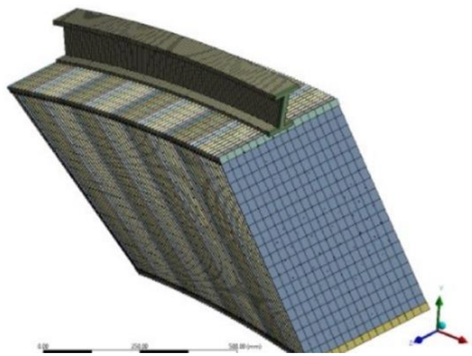
- Next goal: validation of a prototype large enough to fully contain EM showers (~2028)
- Main activities focused on the mechanical design of this prototype
- No test beam planned in the next years, performances with small scale prototypes have been assessed

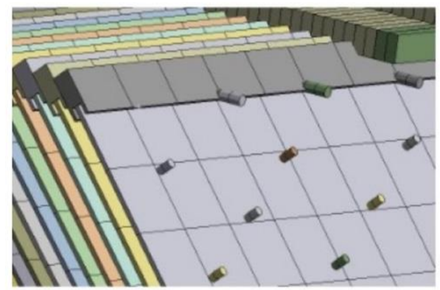




Implementation: multi-layer PCBs



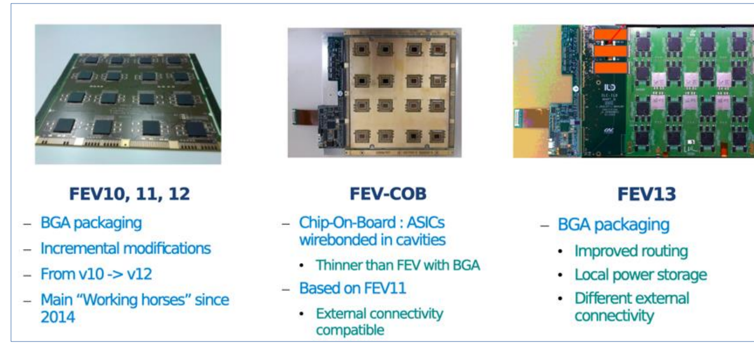


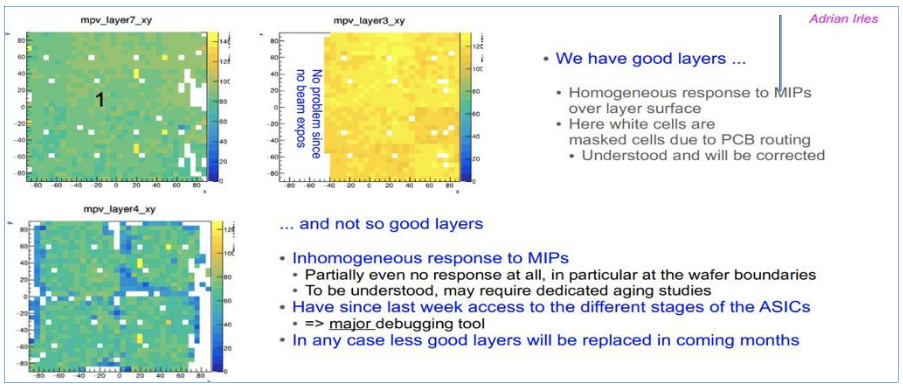


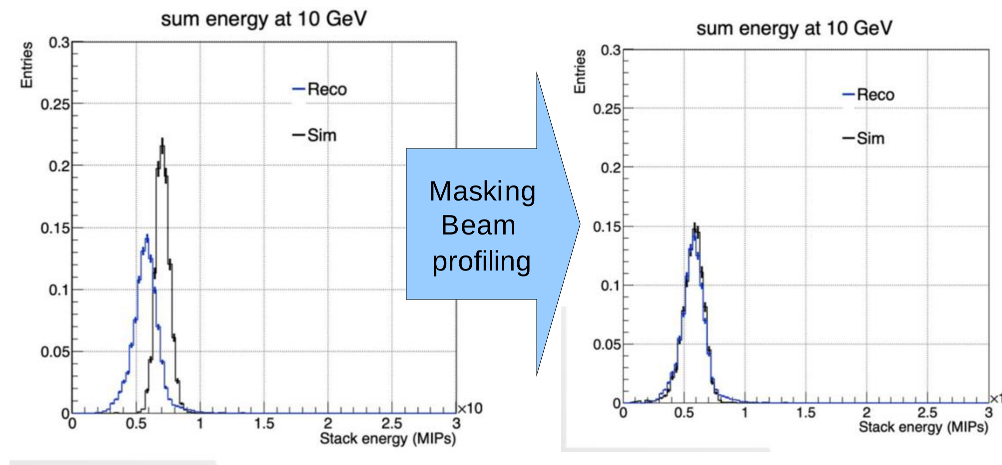
SiW-ECAL Beam test plans 2025

2022:

- With inhomogenous stack : 3 FEV versions, 3 sensor thicknesses
- Beam test at DESY (mip and low-E e^- response) and CERN (high-E e^-/π^+ responses with AHCAL)







- Many (some new) local defaults ➞ full modellisation needed

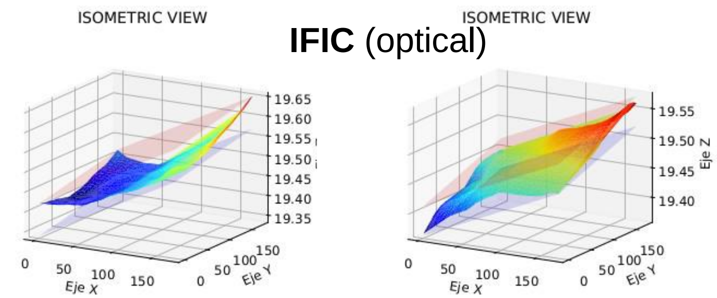
Yuichi Okugawa (PhD in Feb. 2024)

SiW-ECAL Beam test plans 2025

2025 (originally expected 2024)

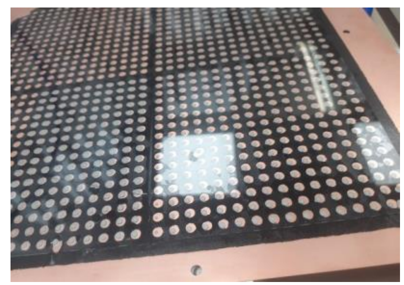
- New FEV version, with improved
  - Power distributions
    - Local power regulation: LDO's
    - Local High Voltage filtering & Supply
  - Signal distribution (buffering), data paths
  - Monitoring (single ID, temp, probe analogue line)
  - ASIC shielding/routing
- Fully revised gluing & assembly procedure
- All 500 μm sensors

IFIC (optical)



Same PCB before / after 10-day dry storage

Measurements by C. Orero, IFIC



Puncturated adhesive film and condutive glue dots

1 week DESY BT asked, for March 2025

- Two new layers + AHCAL + ALPIDE telescope
- Mip & Low-E e⁻ ➞ sub-cell uniformity response

Courtesy of V. Boudry

SDHCAL

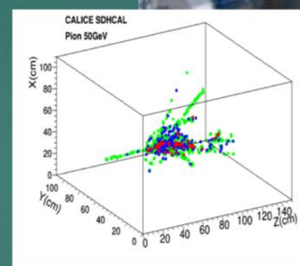
SDHCAL-RPC

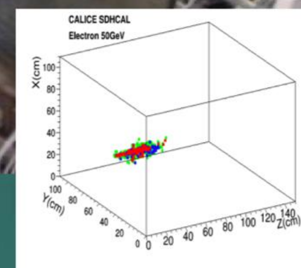
48 layers of 2 cm stainless steel interleaved with planes made of Glass RPC and their embedded readout 2-bit electronics allowing a lateral segmentation of 1 cm^2

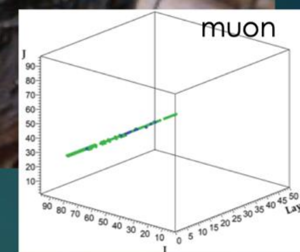
A technological prototype of 48 layers fulfilling all the ILD requirements :

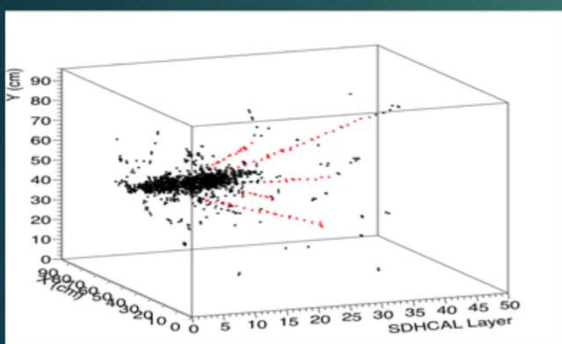
- compactness
- self-supporting mechanical structure.
- Triggerless mode
- Power-pulsing mode

was built and expensively and successfully tested

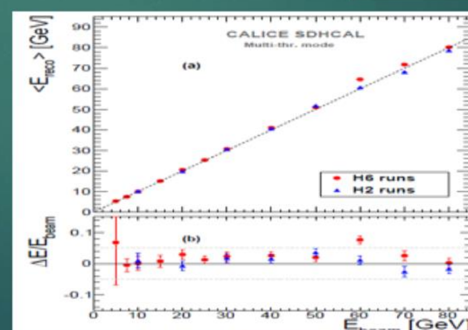


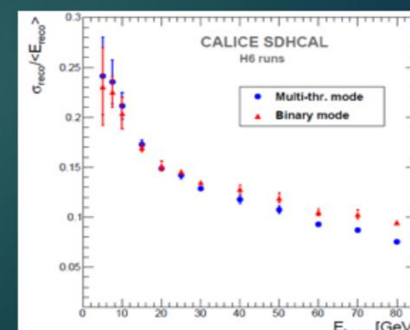






Hough transform tracks to control the

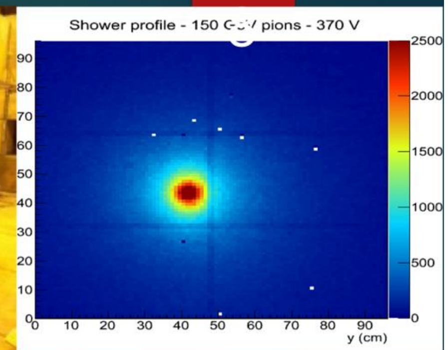




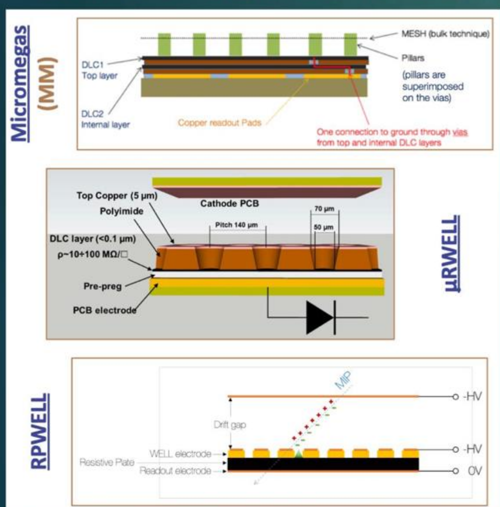
$$E_{rec} = \alpha(N_{tot})\, N_1 + \beta(N_{tot})\, N_2 + \gamma(N_{tot})\, N_3$$

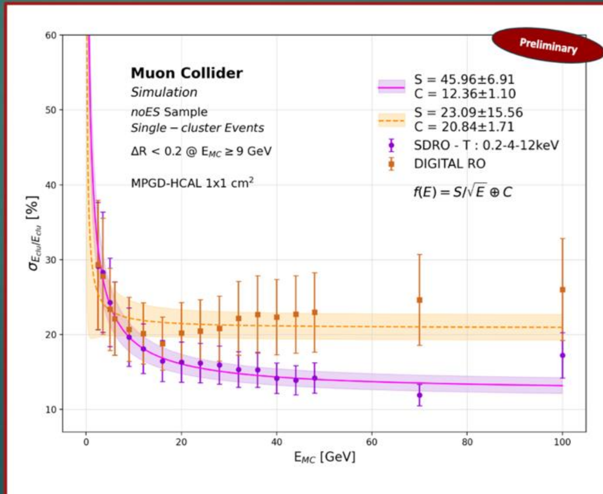
SDHCAL-MPGD

MPGD offers the possibility to operate with high particle rate (> 1 MHz/cm²) and excellent spatial resolution
First attempt was made with standard MM by LAPP colleagues using a variant of HR (allowing a few fC threshold)



10 years later, the second generation of MPGD using resistive anodes allows robustness against discharges



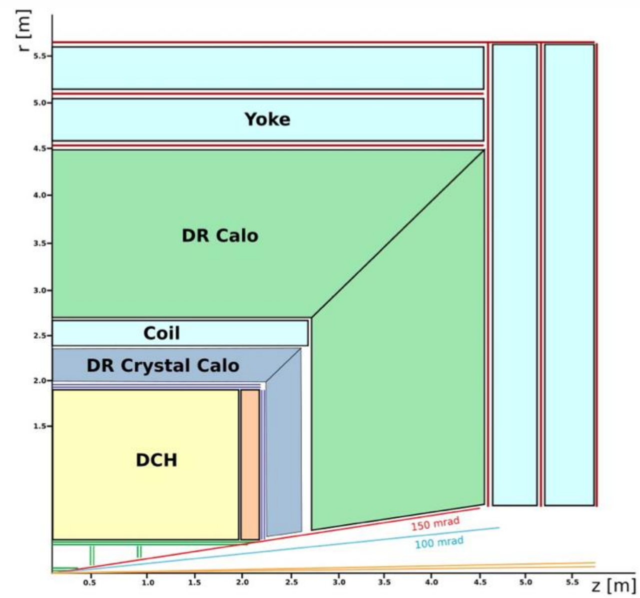


- $\pi^{\pm}$ guns with energy ranging from 2.5 to 100 GeV;
- **only pions not showering in ECAL**;
- reconstruction with Digital RO and SDRO:
  - Thresholds considered for SDRO: 0.2, 4, 12 keV
- fit function $f(E)=S/\sqrt{E}\oplus C$;
- comparable performances below 6 GeV between Digital RO and SDRO
- **Digital RO: saturation at high energies**
- **Overall, better performances of the SDRO**
  - **σ/E = 45.96%/$\sqrt{E}\oplus$12.36%**

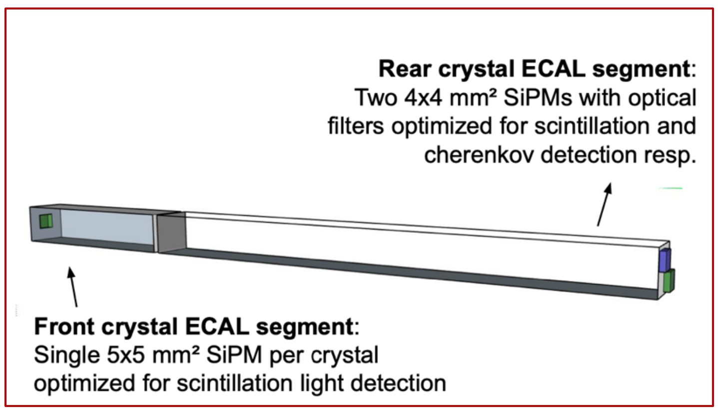
Details in I. Laktineh talk @ this workshop

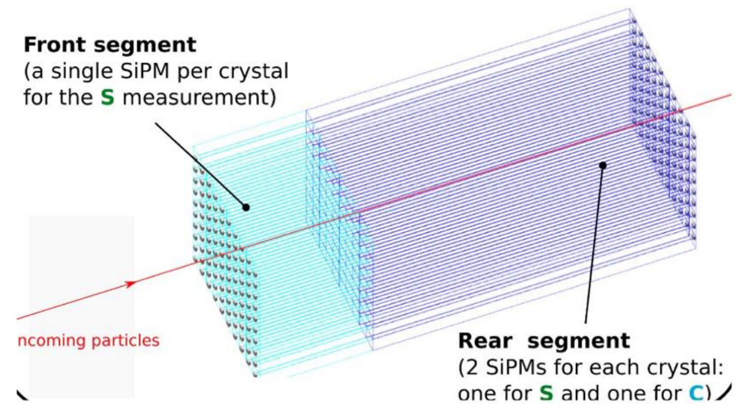
MAXICC: Maximum Information Crystal Calorimetry for future e+e- colliders

- Evaluate the potential and the feasibility of integrating a cost-effective homogeneous dual-readout segmented crystal EM calorimeter in the IDEA detector
  - First studies and concept descriptions in:
    - 2020 JINST 15 P11005
    - 2022 JINST 17 P06008
- Activity at 360 degrees:
  - Simulation studies (from standalone to full sim)
  - R&D on technology and proof-of-principle
  - Prototyping of a calorimetric module
- Two full containment prototypes with different crystals to qualified on beam in the next years



R. Hirosky and M. Lucchini





MAXICC TB plans: towards a multi-channel prototype

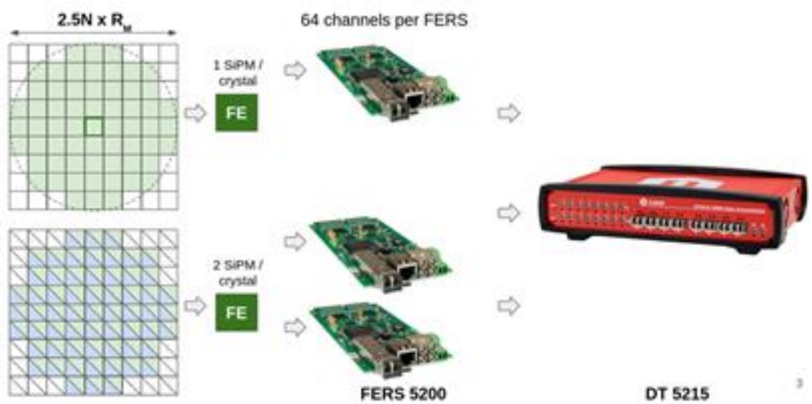
- 2024 lab and beam test results on single calorimeter cells will inform the choice of a baseline technology for **a full containment EM calorimeter prototype (~200 channels)**

- Procurement of electronics completed (FERS-5200), procurement of crystals (PWO/BSO) and SiPMs in early 2025, mechanics and front-end design about to start
  - Coordinated/funded by PRIN2022 (MAXICC) and INFN RD_FCC

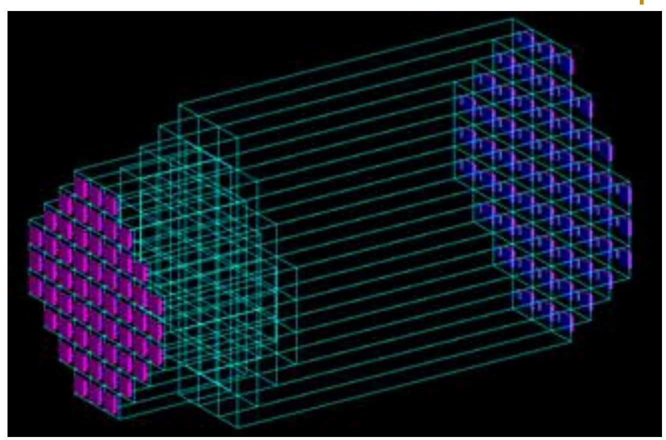
- **2 weeks of test beam at CERN SPS (H6) requested for late September 2025**

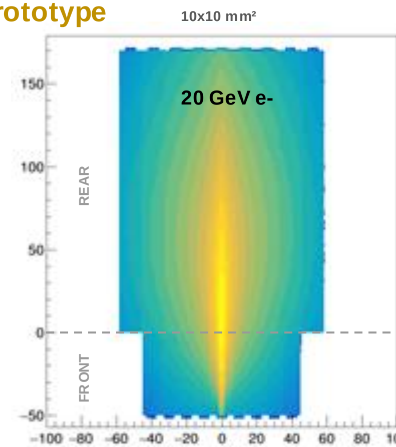
- Possible joint test with HIDRA fiber calorimeter prototype from 2026

Prototype readout schematics



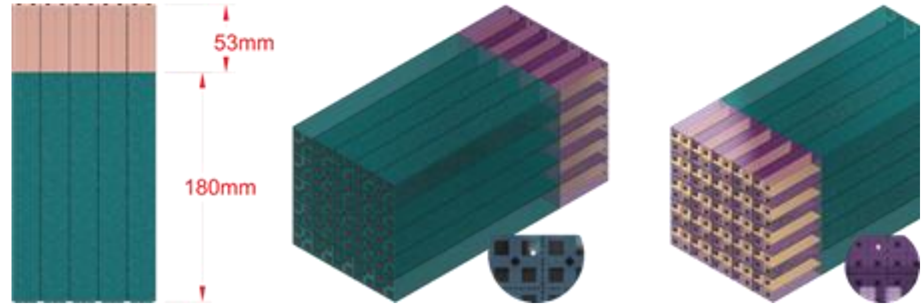
Geant4 simulation of prototype



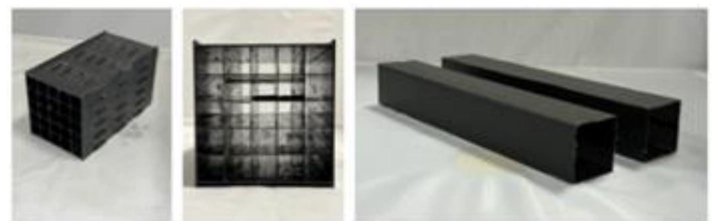


Complementary matrix plan for beam tests in 2025

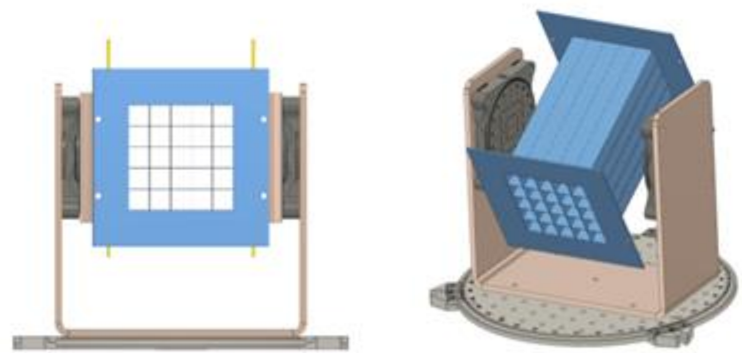
- **Alternative full containment prototype using a BGO crystal** matrix: $22X_0$ deep, $5X_0$ x $5X_0$ lateral with $1X_0$ and $\frac{1}{4}X_0$ lateral granularity
  - Crystal purchase in progress - expected to arrive and complete testing in spring
  - Coordinated/supported/funded by **US Calvision**



- **Carbon fibre alveolar, mechanic support, and cooling options, R&D in progress**



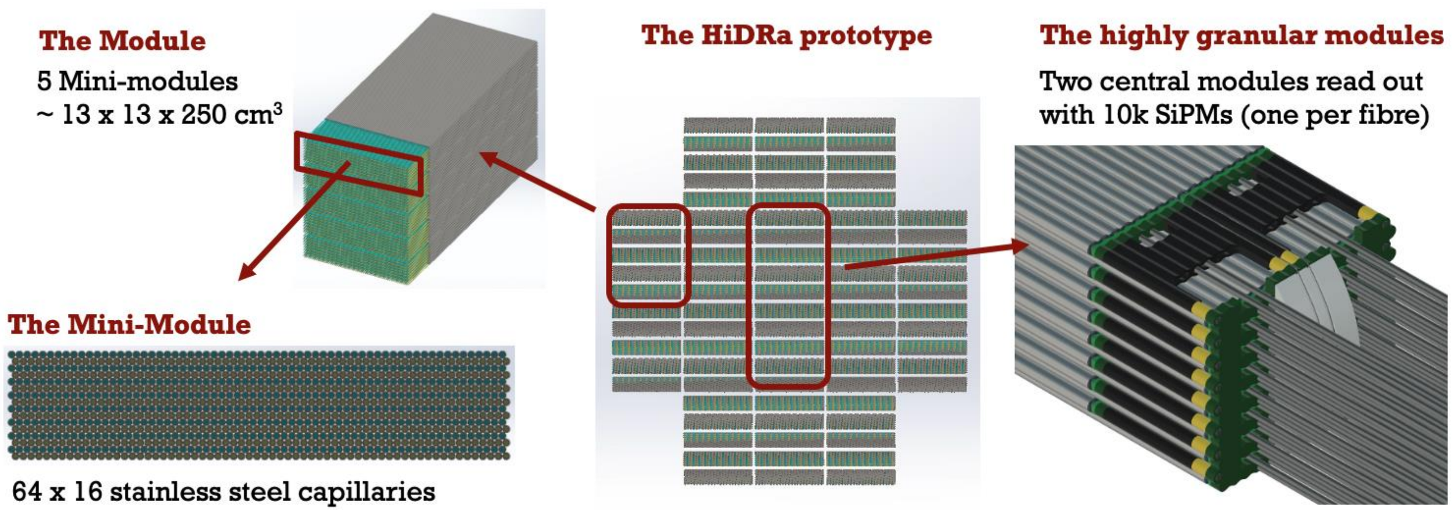
- **Studies to improve electronics (e.g. linearity) over next 6-8 months**
  - Similar readout w/ FERs 5200 for front section, most likely DRS or NALU HDSoc for rear section



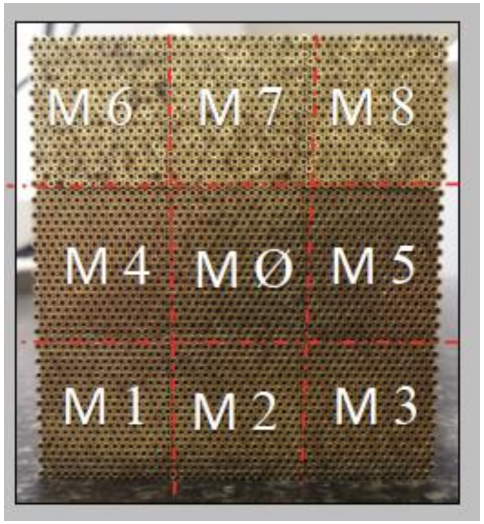
- Form factors and mechanics of electronics for EM containment scale will be challenging

HiDRa: High-Resolution Highly Granular Dual-Readout Demonstrator

- R&D aiming at building and qualifying the hadronic response of a dual-readout calorimeter partially equipped with highly granular modules
  - supported by INFN grant
- In recent years, prototypes of increasing complexity have been built and qualified on beam
  - 1st prototype: EM-size with a highly granular core
  - 2nd prototype: built with part of the HiDRa minimodules

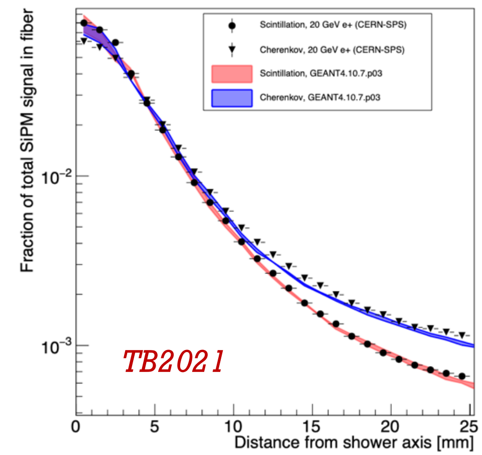


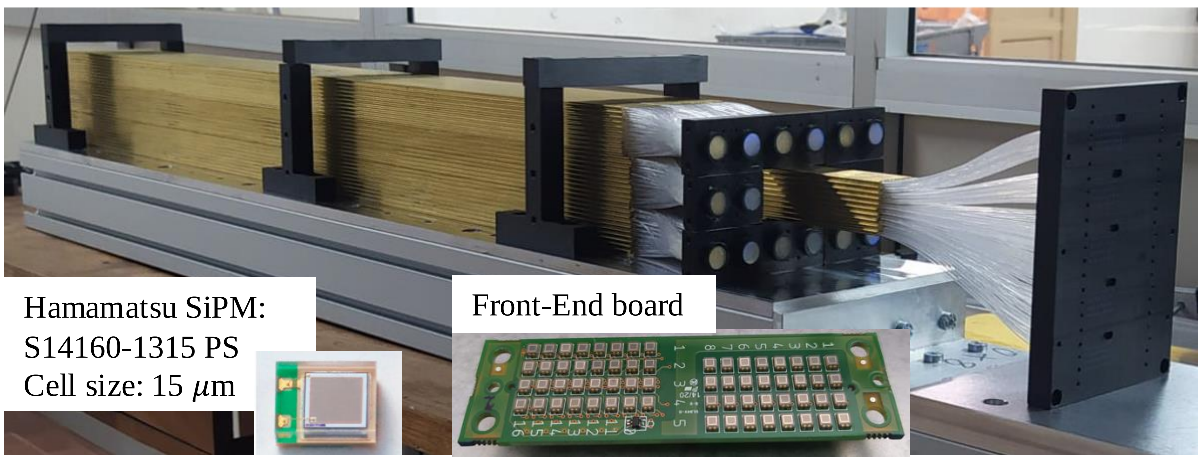
The EM-size prototype (TB2021-2023)

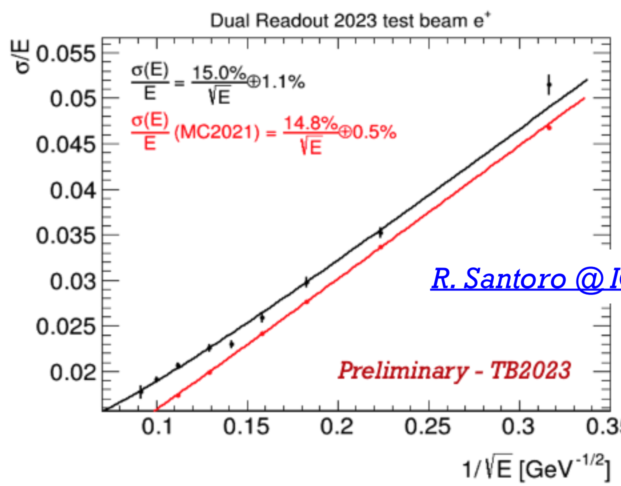


- EM-size prototype (10x10x100 cm^3)
  - 9 modules made of 16 x 20 capillaries (160 C and 160 Sc)
- Readout
  - Highly granular readout: Each fibre is connected to a SiPM (central module)
  - Standard readout: each module equipped with 1 PMT for C and 1 PMT for Sc fibres (8 surrounding modules)
- Different beam test to qualify the performances with electrons and to tune the Montecarlo simulation

N. Ampilogov et al 2023 JINST 18 P09021







R. Santoro @ ICHEP2024

Prototype with HiDRa minimodules (TB2024)

Only modules readout with PMTs

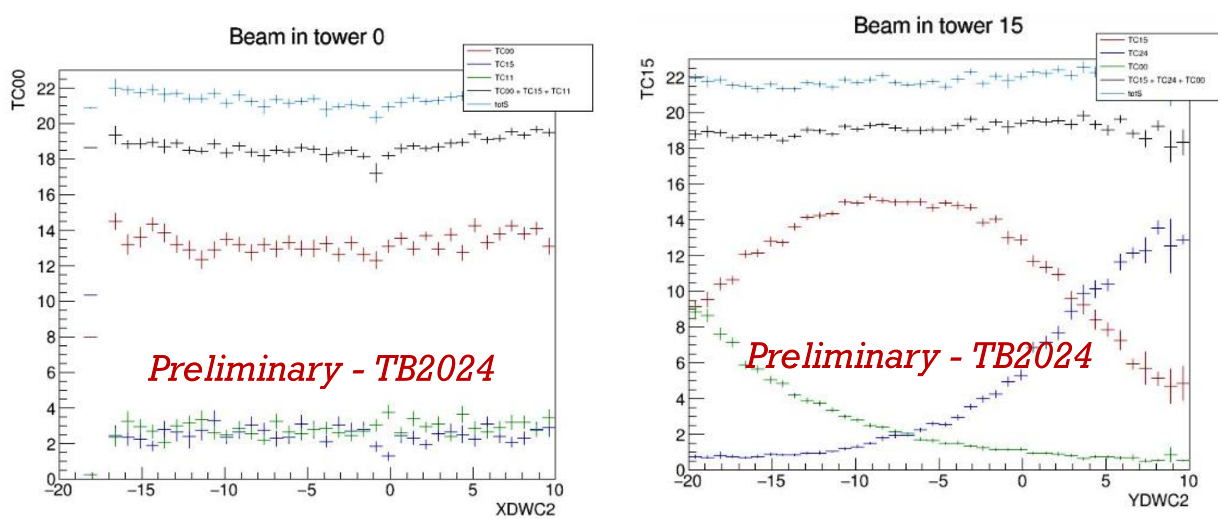
Main Goals of TB2024:

- Test the calibration and equalisation procedure
- EM resolution
- Uniformity response
- Tuning of G4 simulation
- Attenuation length measurement

$3 \times 128\ mm^2 = 384\ mm^2$

TS55	TC55	TS54	TC54	TS53	TC53
TS45	TC45	TS44	TC44	TS43	TC43
TS35	TC35	TS34	TC34	TS33	TC33
TS25	TC25	TS24	TC24	TS23	TC23
TS16	TC16	TS15	TC15	TS14	TC14
TS17	TC17	TS00	TC00	TS13	TC13
TS10	TC10	TS11	TC11	TS12	TC12
TS20	TC20	TS21	TC21	TS22	TC22
TS30	TC30	TS31	TC31	TS32	TC32
TS40	TC40	TS41	TC41	TS42	TC42
TS50	TC50	TS51	TC51	TS52	TC52
TS60	TC60	TS61	TC61	TS62	TC62

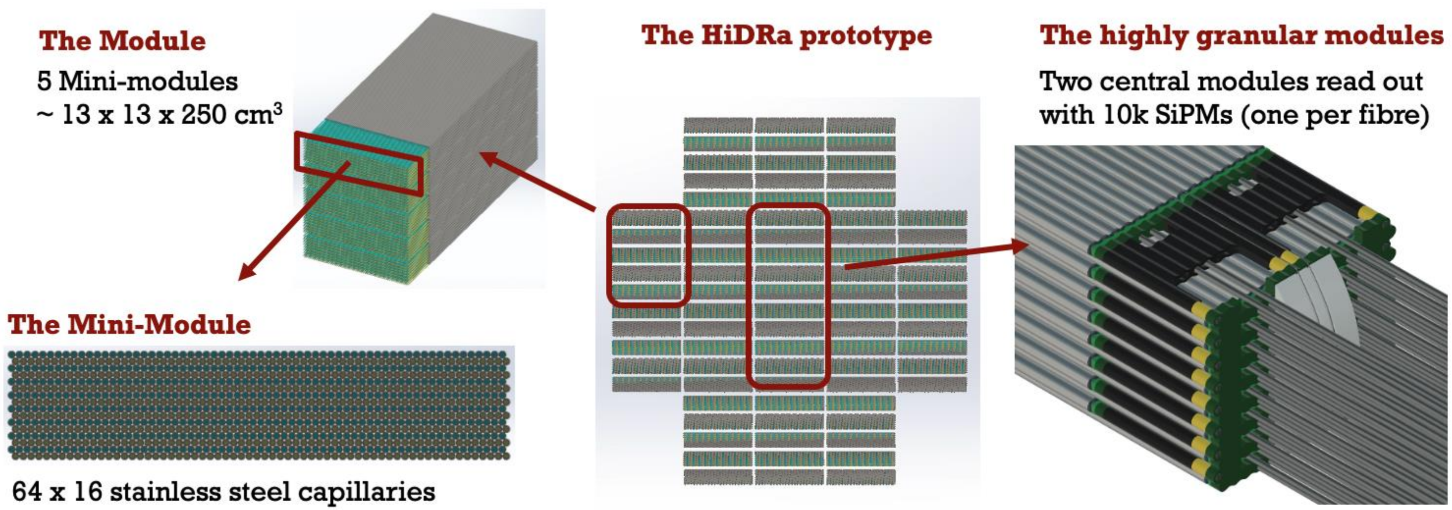
$12 \times 28.3\ mm^2 = 339\ mm^2$



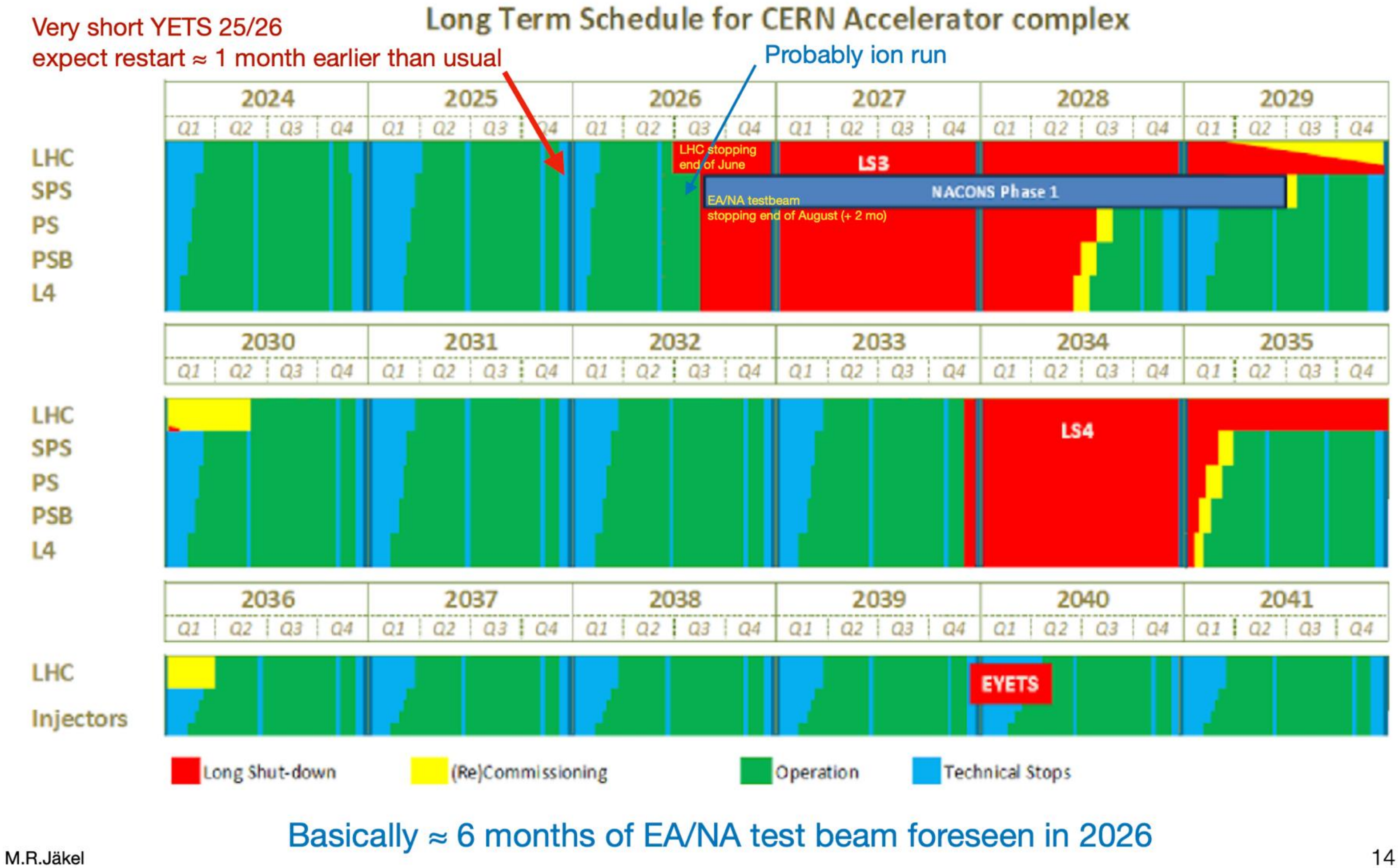
Energy shared between minimodules versus impact points of 20 GeV electrons (calibration to be finalised, analysis still ongoing)

TB schedule for 2025 and beyond

- Asked two weeks @ CERN SPS in 2025:
  - Full HiDRa demonstrator (highly granular modules included)
  - Demonstrate the equalization and calibration procedure
  - Assess the calorimetric performances with electrons and hadrons
- In future, we are considering a joint test beam with crystal dual-readout in front



CERN Long Term Schedule (as of Oct. 2024)



International Overview

- CERN dates updated with current schedule
- Dates for Fermilab currently uncertain, might start shutdown in summer 2025 (same end date)

Possible synergies and common needs

- Sharing beam time could be an interesting option to assess combined performance and to increase the probability of having allocated beam time (parasitic)
  - Tracking systems (vertex, wire chambers, μ-RWELL)
  - ECAL + HCAL + tracking
  - Dual Readout (crystal + fibres) + tracking

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  - Tracking systems (vertex, wire chambers, μ-RWELL)
  - ECAL + HCAL + tracking
  - Dual Readout (crystal + fibres) + tracking
- Test beam with the slice of a detector concept: it is probably too early, but it could help to strengthen collaboration and to prepare the infrastructure
  - Shared electronics and DAQ
  - Analysis techniques
  - Simulation Framework

My personal viewpoint

- Almost all R&D programs are included in CERN DRDs. A good opportunity to share ideas and needs, and to identify synergies for new collaborations
- Cross-contamination between detector technologies (in DRDs) and between different DRDs is also important

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  - Newcomers who are incidentally necessary: we are discussing something that will happen in $\approx$ 20 years from now