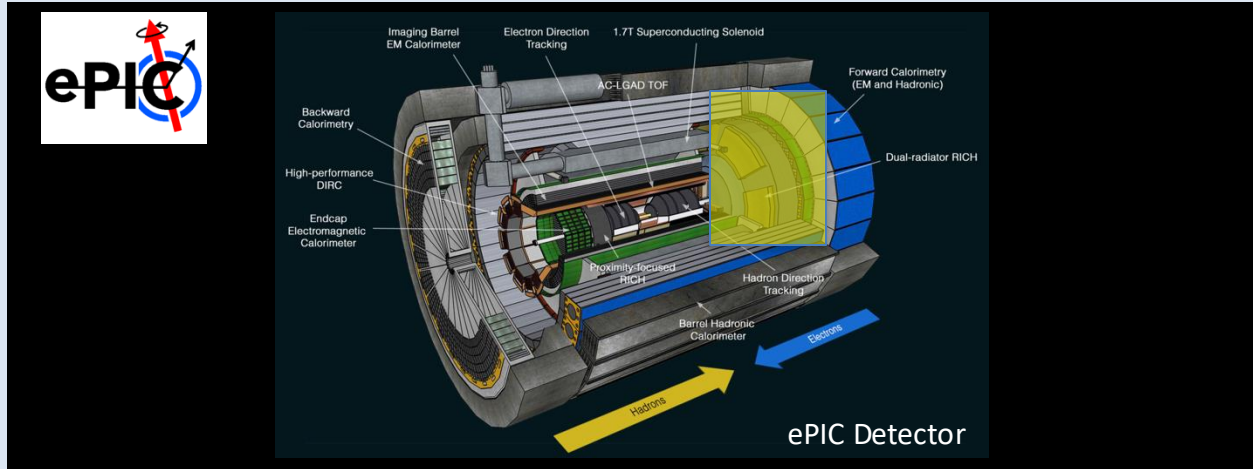


The ePIC Dual-Radiator RICH Detector

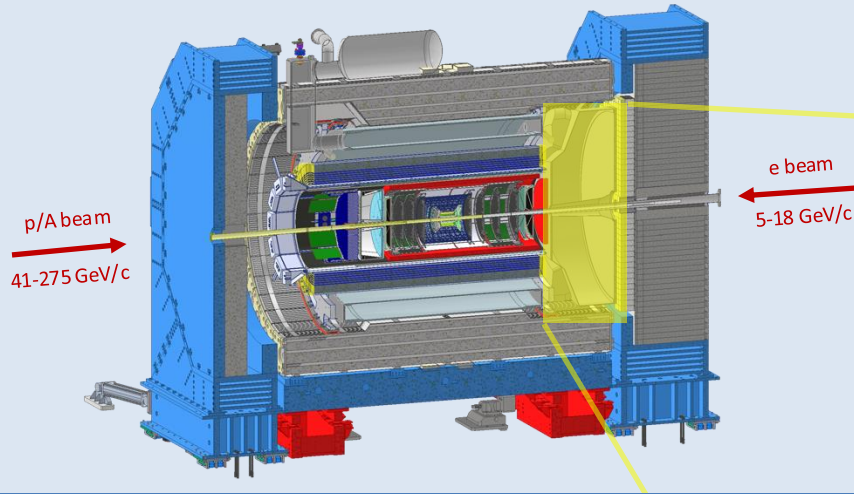


M. Contalbrigo – INFN Ferrara

RICH 2025, Mainz, September 15th - 19th, 2025

Dual-radiator Ring-imaging Cherenkov Detector (dRICH)

Essential to access flavor information

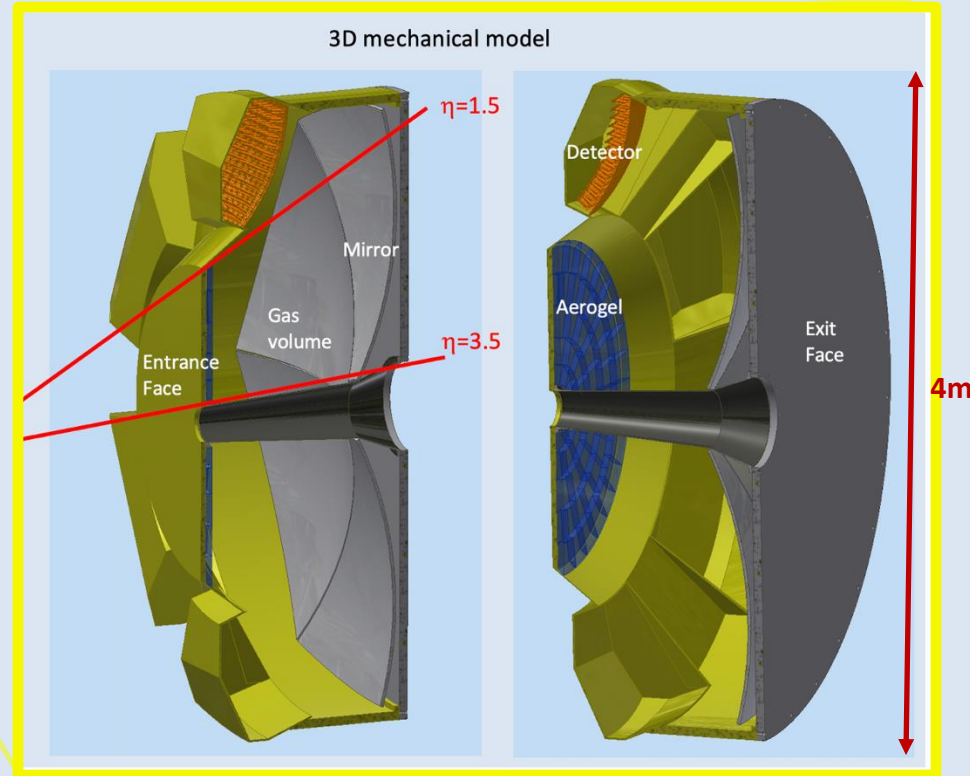


Goals:

Hadron 3σ -separation between 3 - 50 GeV/c
 Complement electron ID below 15 GeV/c
 Cover forward pseudorapidity 1.5 (barrel) - 3.5 (b. pipe)

dRICH Features:

Extended 3-50 GeV/c momentum range --> **Dual radiator**
 Single-photon detection in high Bfield --> **SiPM**
 Limited space --> **Compact optics with curved detector**

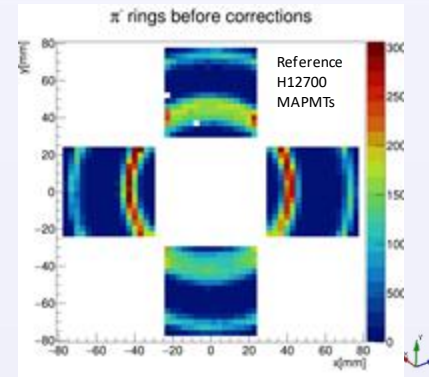
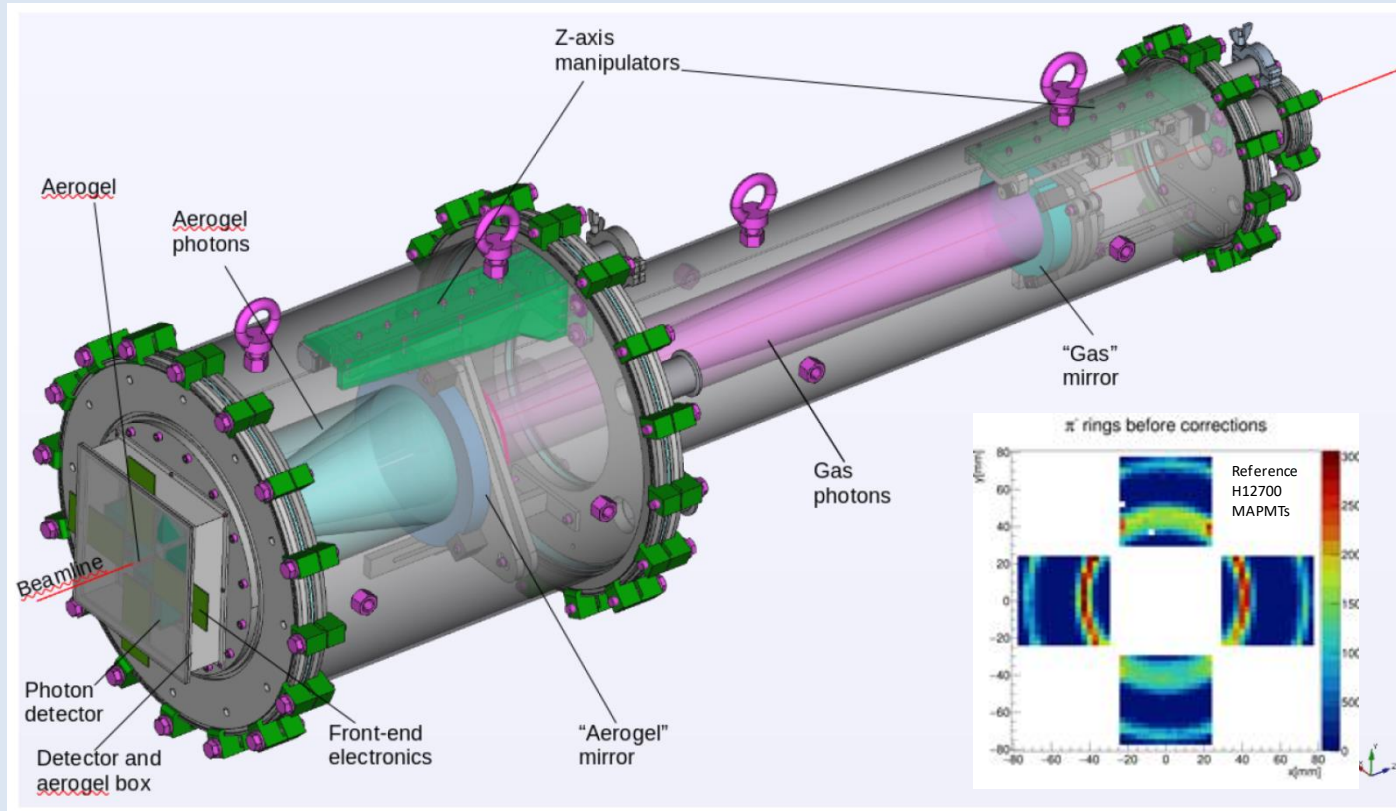


Design Status

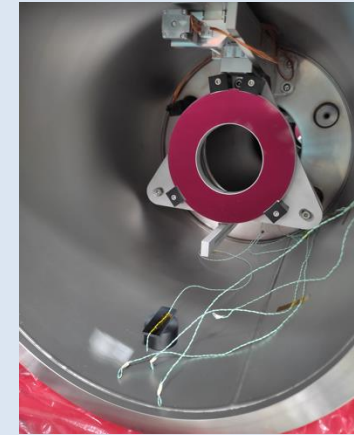
	Technical requirements		Baseline technical solutions	Ongoing
Aerogel:	Momentum reach above 15 GeV/c to overlap with gas More than 10 detected photons from 4 cm thickness Single photon resolution approaching 2 mrad	➡	n = 1.026 $dn/d\lambda = 6 \cdot 10^{-6} \text{ nm}^{-1}$ scattering length > 50 mm	➡ Dimensions
Gas:	Momentum reach above 50 GeV/c at pseudorapidity > 2.5 More than 20 detected photons from 1 m depth Single photon resolution approaching 1 mrad	➡	C₂F₆ with n = 1.00086 $dn/d\lambda = 0.2 \cdot 10^{-6} \text{ nm}^{-1}$ absorption length > 100 m	➡ Purging
Mirror:	Focalization of Cherenkov light onto the detector surface Preservation of the Cherenkov information Material budget limited to O(2 %) of radiation length	➡	Carbon fiber material Roughness of few nm Angular precision < 0.3 mrad	➡ Coating
Sensors:	Single photon detection capability in highly non-uniform magnetic field Excellent PDE in the visible range to cope with aerogel Marginal contribution to the angular resolution Preserve prompt Cherenkov information Tolerance to few 10^{10} 1-MeV neutron equivalent fluence	➡	SiPM Spatial resolution of 3 x 3 mm ² Time resolution O(100 ps) Operation at < -30 degrees Annealing curing cycles	➡ Layout Annealing
Readout:	Below 1 p.e. signal threshold capability Preserve sensor time resolution to cope with dark counts and accidentals More than 300 kHz/ch rate capability Streaming readout with suppression of no-interaction frames	➡	ALCOR ALCOR chip (ToT architecture) Time resolution < 200 ps Rate > 300 kHz/ch	➡ ALCOR 64ch RDO
Mechanics:	Acceptance maximized in 1.5 – 3.5 pseudorapidity range Material budget minimized in acceptance Compatibility with barrel maintenance at IP6	➡	Composite materials Single open volume Detector in the barrel shadow	➡ Real-scale prototype Cooling

On axis optics to minimize the active area, single or double radiator imaging

Vacuum technology & recovery system for efficient gas exchange



1st chamber

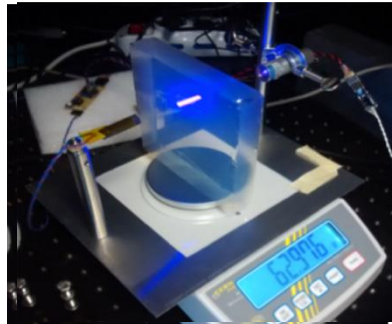
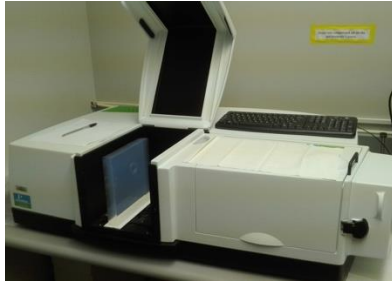
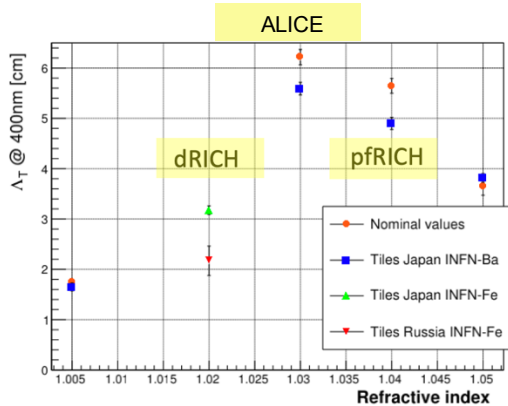
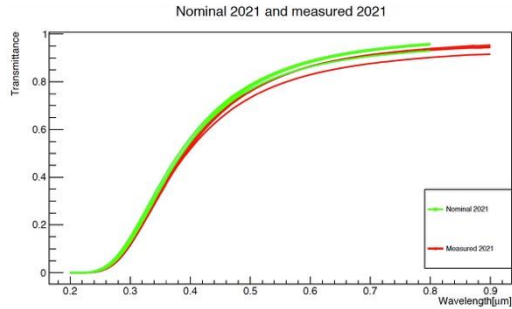


Gas recovery system

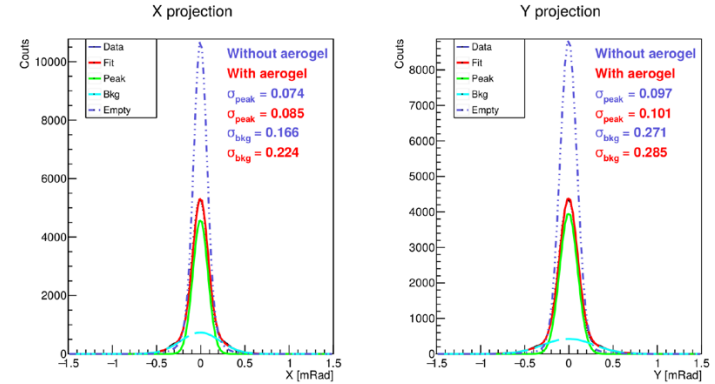


Aerogel Factory (BELLE-II) Initial evaluation & Reproducibility on small samples in synergy with ALICE

Transmittance & Transflectance

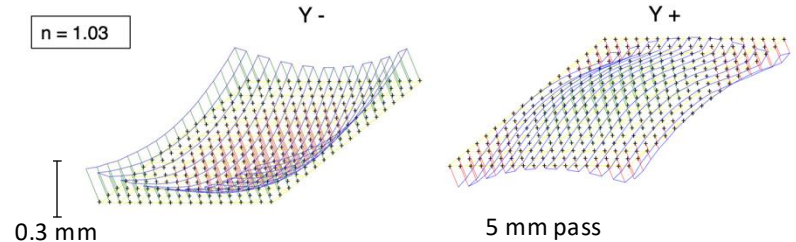


Laser spot broadening with 3 x 2 cm aerogel



Touch Probe: planarity and thickness

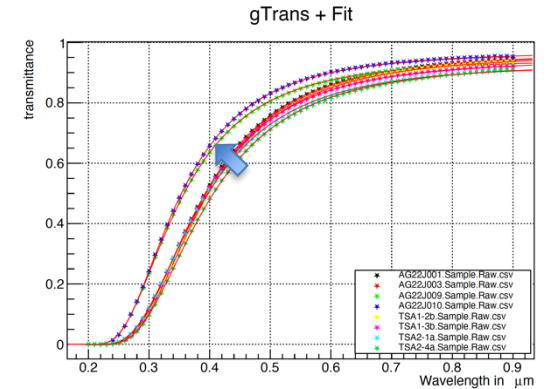
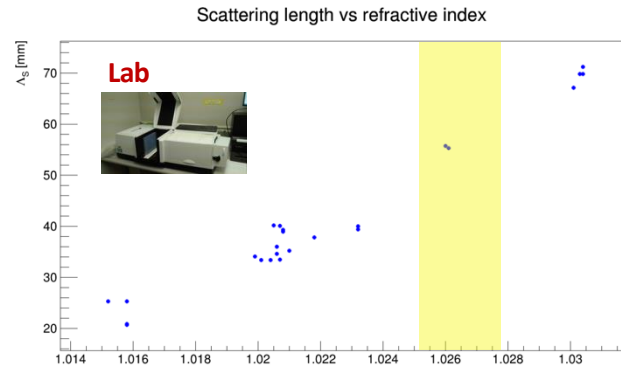
10x10x2 cm³ tile
(from ALICE)



G. Volpe (poster)

Aerogel with $n=1.026$ validated with lab and prototype tests

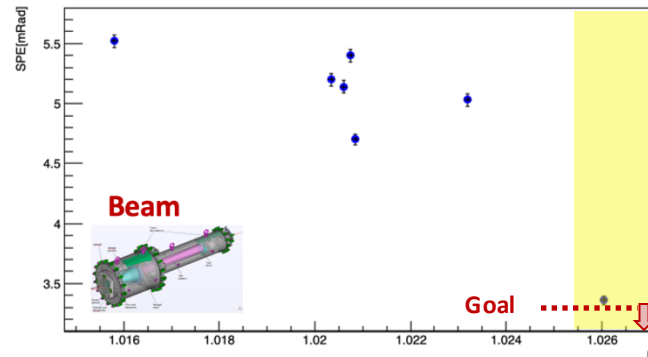
- * meet SPE resolution expectations
- * scattering length > 50 mm
- * match with TOF end point (2.5 GeV/c)
- * overlap with gas (> 12 GeV/c)
- * photon yield > 10 per particle with MAPMTs



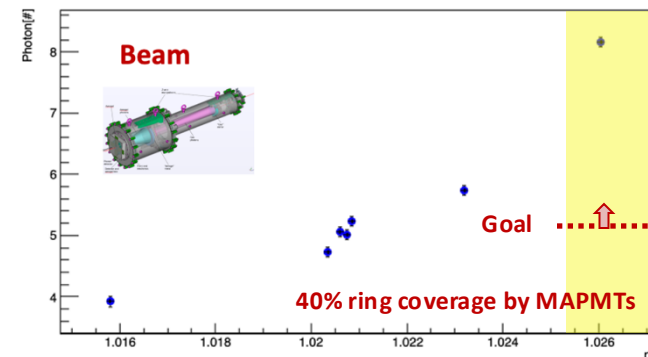
Various samples from Aerogel Factory



Single photon resolution vs refractive index



Number of photon for particle vs refractive index



First large aerogel tile demonstrators delivered

based on dRICH baseline specifications

An effort should be pursued by the vendor to keep the aerogel quality parameters as close as possible or better than the following reference values.

General specifications:

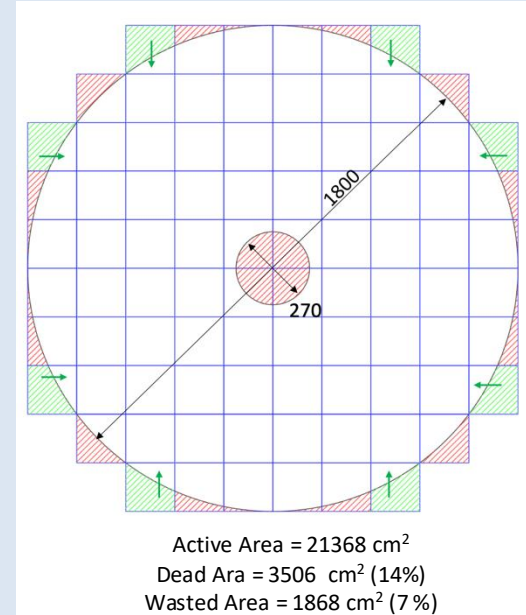
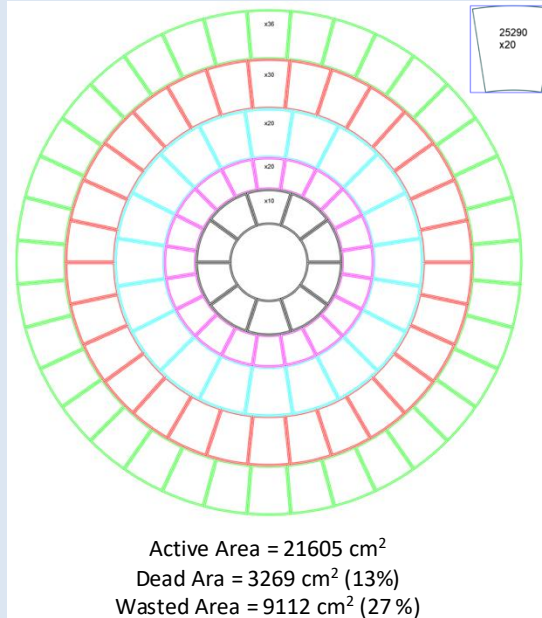
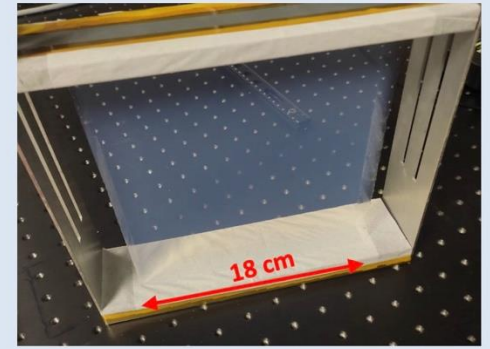
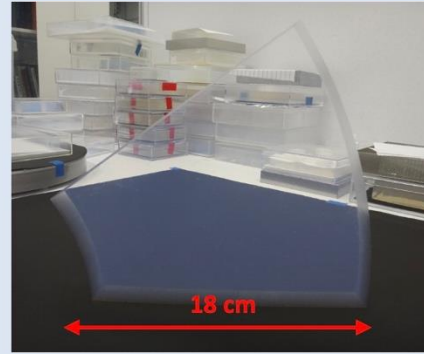
- No cracks or bubbles inside the block. Single spallings which decrease its area no more than 0.25 % are acceptable on the top surface;
- Lateral dimension tolerance within 0.25 mm;
- No evident disuniformity inside the tile volume.

Technical specifications:

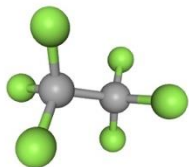
- Refractive index, to be chosen by the customer, in the range from 1.025 to 1.030, with a maximum tile-to-tile variation of ± 0.002 ;
- Tolerance on thickness ± 1 mm, being the error intended as the maximum tile-to-tile variation;
- Absorption coefficient, defined as the constant term of the Hunt parameterization of the aerogel transmission, bigger than 0.95;
- Scattering length wavelength bigger than 45 mm at 400 nm;
- Planarity of the transmission surface, defined as the maximum peak to valley variation, does not exceed 1.5 % of the lateral dimensions.

Engineering of the aerogel wall expected by 2026

- * optimize area vs number of tiles
- * minimize the waste of material
- * minimize the dead/low-efficiency gaps
- * optimize thickness:
 - photon yield vs resolution
 - planarity



Baseline Hexafluoroethane validated with lab and beam tests



C_2F_6 molecular weight: 138.01 g/mol

boiling point: $-78.1\text{ }^\circ\text{C}$

melting point: $-100.6\text{ }^\circ\text{C}$

density: 5.734 kg/m^3 at $24\text{ }^\circ\text{C}$

density: 16.08 kg/m^3 at $-78\text{ }^\circ\text{C}$

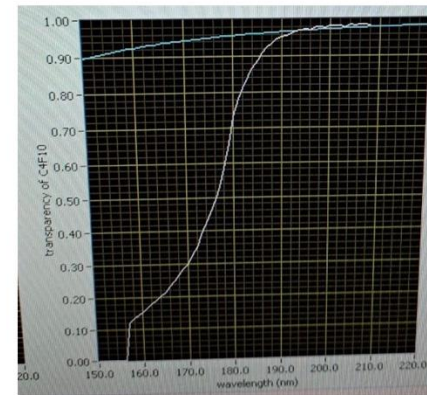
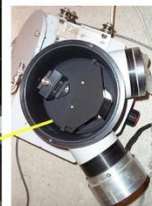
1 covalent + 6 hydrogen bonds

Gas	Npe(π/K)	θ_π	θ_K	σ_π	σ_K	N $_\sigma$	$\rho = \Delta\theta/\theta$ ($\lambda = 300\text{ nm}$)
C_2F_6	16.0/14.9	36.8	35.7	0.32	0.33	3.5	1.8 %
C_4F_{10}	24.8/23.8	48.6	47.8	0.29	0.30	2.8	2.4 %

Transmission in UV range $> 98\%$



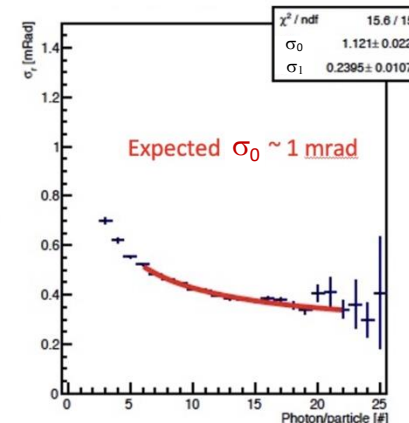
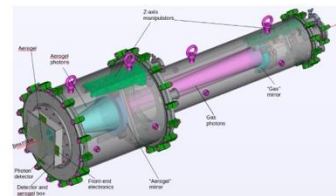
Deuterium UV lamp, Monochromator system, 1.6 m column for gas transparency measurement



Measured 139.7 m/s speed of sound confirms negligible contaminants after few year in bottle

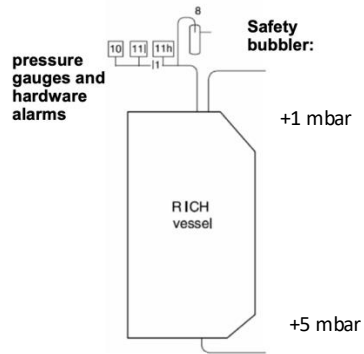


Expected performance obtained with dRICH prototype

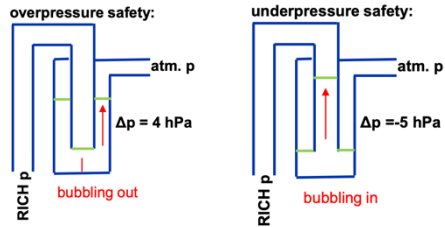


Adaptation from realizations at CERN with focus on separation/monitor expected by 2026
Realization at BNL in compliance with DOE safety standards

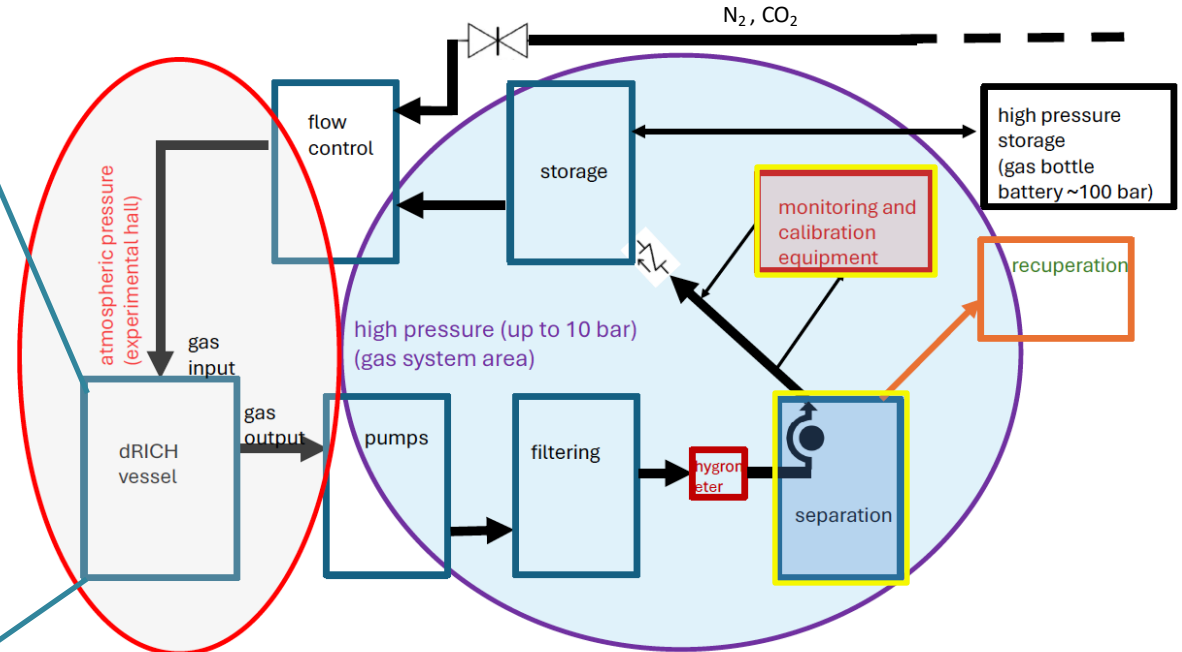
dRICH vessel



Two-ways bubbler (aka COMPASS)



dRICH gas system

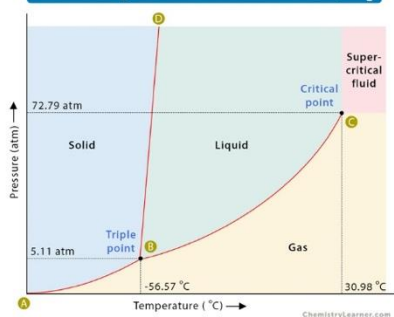


Development of gas separation protocols expected by 2026

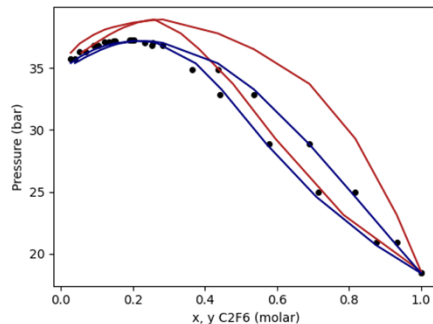
Purging via liquefaction of stand-by gas

Updated vapor-liquid equilibrium C_2F_6 - CO_2 model, test in preparation at CERN

Phase Diagram of Carbon Dioxide (CO_2)

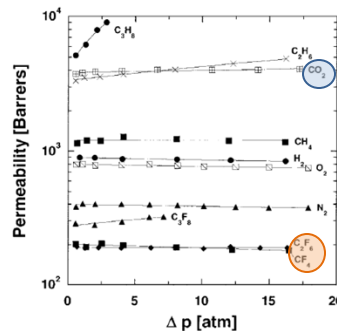
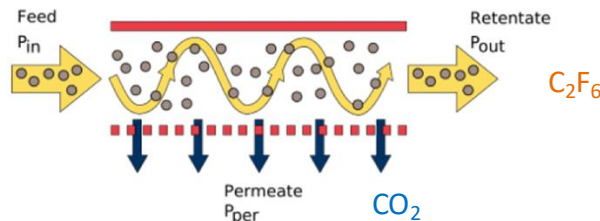


VLE data at 273 K



Purging via membranes

Effective separation of CF_4 and CO_2 demonstrated in LHCb
<https://edms.cern.ch/document/2816490/1>

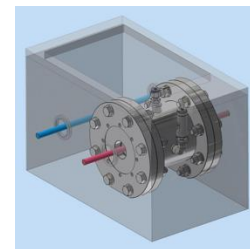
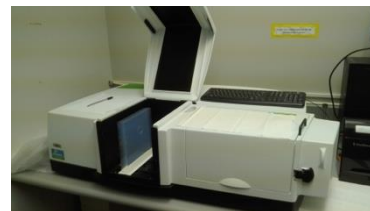


F. Tessarotto (talk)

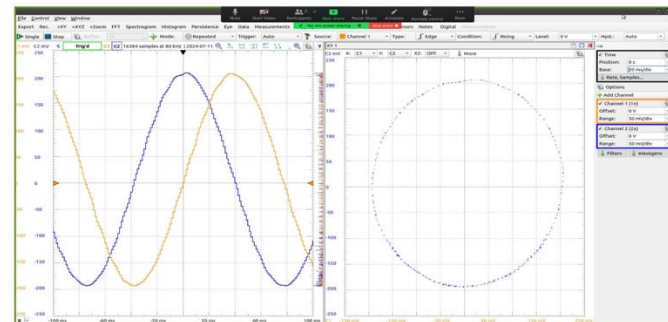
Design of online purity monitors expected by 2026

Sonar to measure speed of sound

10 bar chamber + specrophotometer to measure light transmission in the visible range



Jamin interferometer for precise n determination



Nominal sensitivity down to 10 ppm of refractive index

Design Status

	Technical requirements		Baseline technical solutions	Ongoing
Aerogel:	Momentum reach above 15 GeV/c to overlap with gas More than 10 detected photons from 4 cm thickness Single photon resolution approaching 2 mrad	→	$n = 1.026$ $dn/d\lambda = 6 \cdot 10^{-6} \text{ nm}^{-1}$ scattering length > 50 mm	→ Dimensions
Gas:	Momentum reach above 50 GeV/c at pseudorapidity > 2.5 More than 20 detected photons from 1 m depth Single photon resolution approaching 1 mrad	→	C_2F_6 with $n = 1.00086$ $dn/d\lambda = 0.2 \cdot 10^{-6} \text{ nm}^{-1}$ absorption length > 100 m	→ Purging
Mirror:	Focalization of Cherenkov light onto the detector surface Preservation of the Cherenkov information Material budget limited to O(2 %) of radiation length	→	Carbon fiber material Roughness of few nm Angular precision < 0.3 mrad	→ Coating
Sensors:	Single photon detection capability in highly non-uniform magnetic field Excellent PDE in the visible range to cope with aerogel Marginal contribution to the angular resolution Preserve prompt Cherenkov information Tolerance to few 10^{10} 1-MeV neutron equivalent fluence	→	SiPM Spatial resolution of $3 \times 3 \text{ mm}^2$ Time resolution O(100 ps) Operation at < -30 degrees Annealing curing cycles	→ Layout Annealing
Readout:	Below 1 p.e. signal threshold capability Preserve sensor time resolution to cope with dark counts and accidentals More than 300 kHz/ch rate capability Streaming readout with suppression of no-interaction frames	→	ALCOR ALCOR chip (ToT architecture) Time resolution < 200 ps Rate > 300 kHz/ch	→ ALCOR 64ch RDO
Mechanics:	Acceptance maximized in 1.5 – 3.5 pseudorapidity range Material budget minimized in acceptance Compatibility with barrel maintenance at IP6	→	Composite materials Single open volume Detector in the barrel shadow	→ Real-scale prototype Cooling

Steady progress of photodetector towards integrated design completion in 2026

towards construction →



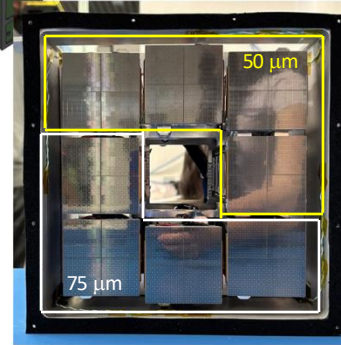
2022
electronics v1



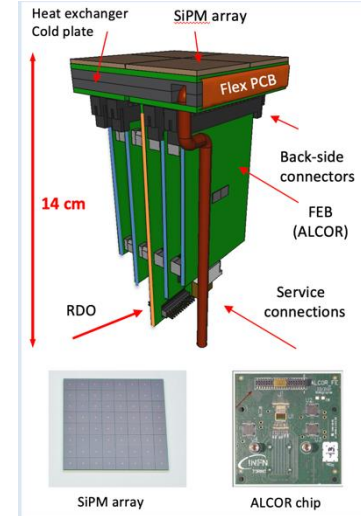
2023
electronics v2



2024
electronics v2.1
Operated at -37°



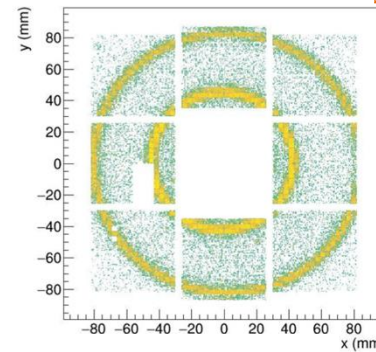
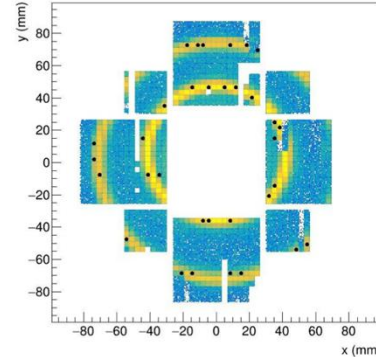
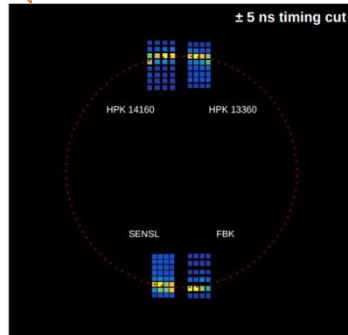
2025/26
electronics v3
final prototype



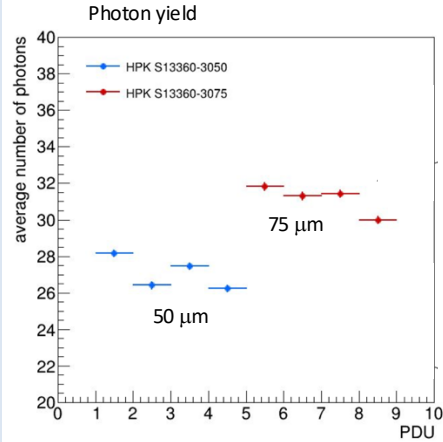
2025 + SiPM carrier v3
+ RDO

2026 + ALCOR 64ch
+ FEB 64

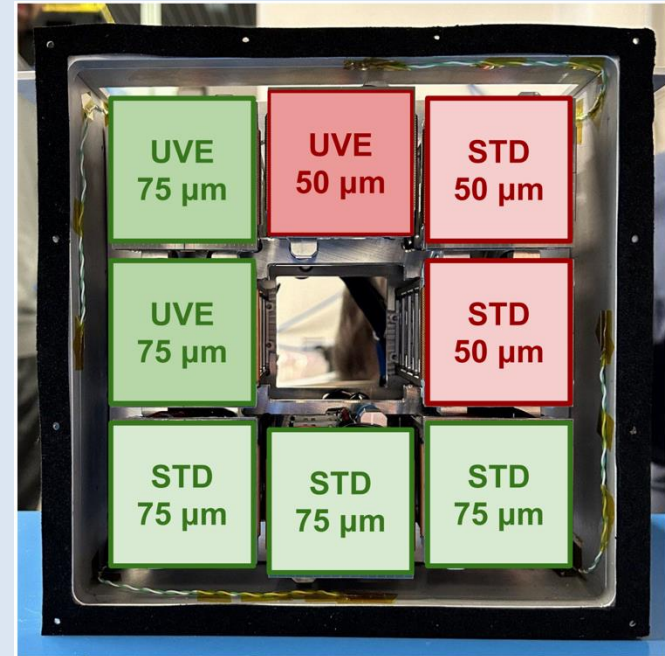
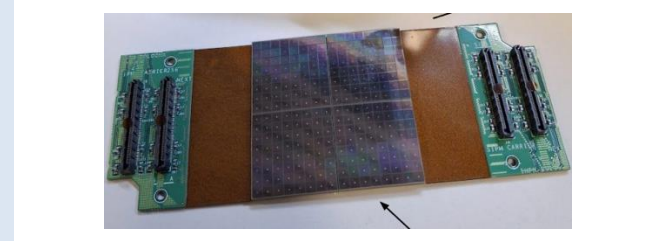
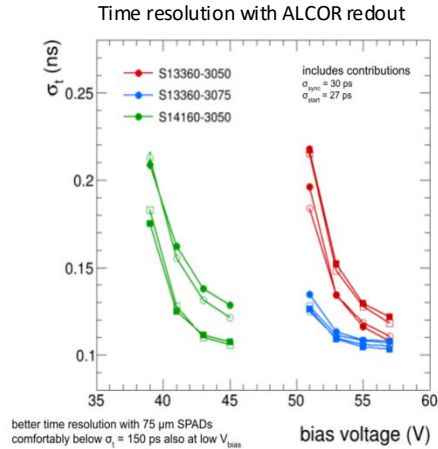
ALCOR 32 ch



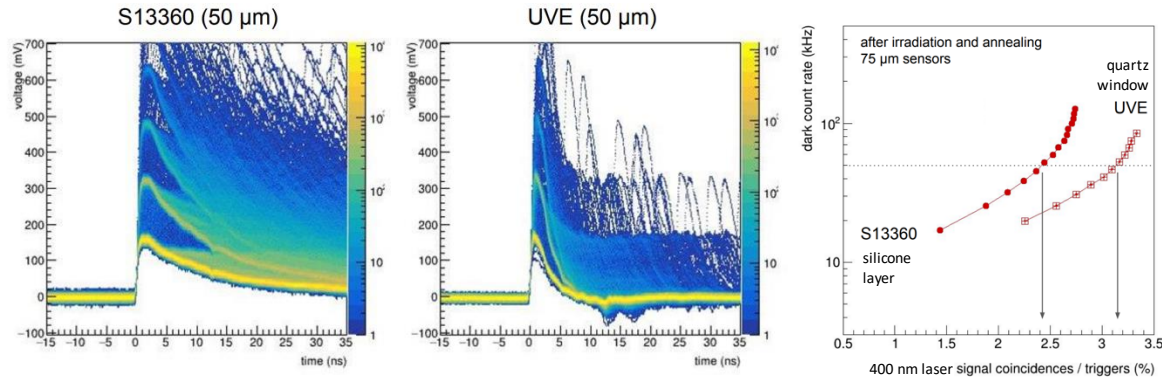
Baseline specs defined, finalization of the engineering of the SiPM optimized layout ongoing



SPAD size

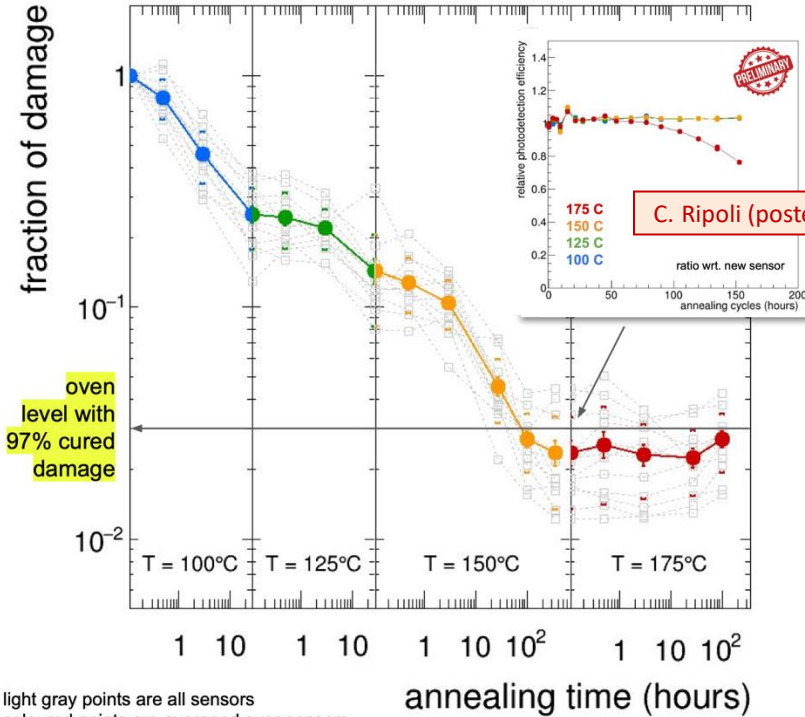


Novel HPK UVE fast SiPM



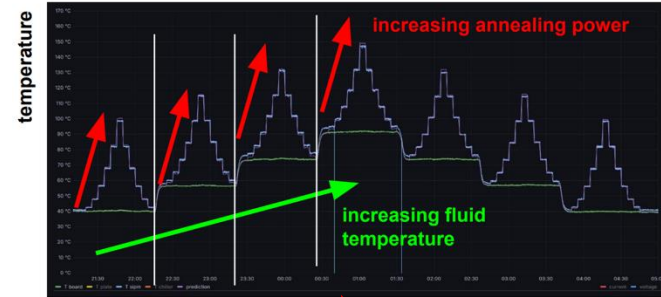
Completion of engineering of the SiPM optimized layout and temperature treatments expected by 2026

online self-annealing with forward bias



light gray points are all sensors
coloured points are averaged over sensors
coloured brackets is the RMS

Details of in-situ annealing protocol based on Joule-effect



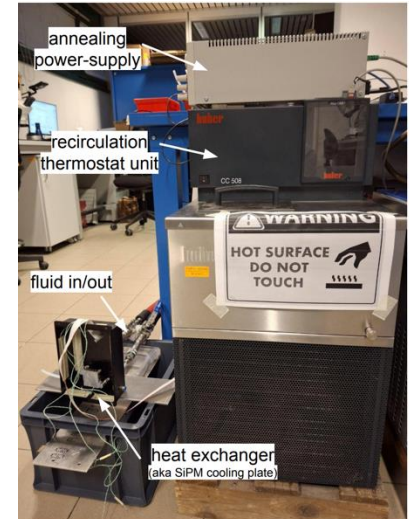
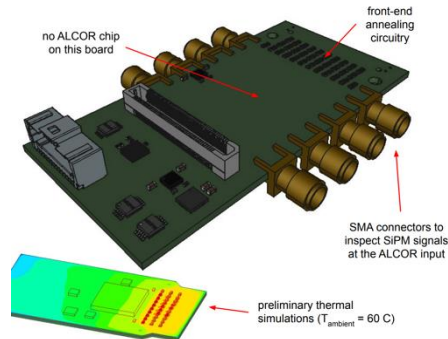
N. Rubini (talk)

features

- like a final FEB with all annealing circuitry
- SMA connectors to inspect SiPM signals on scope

goals

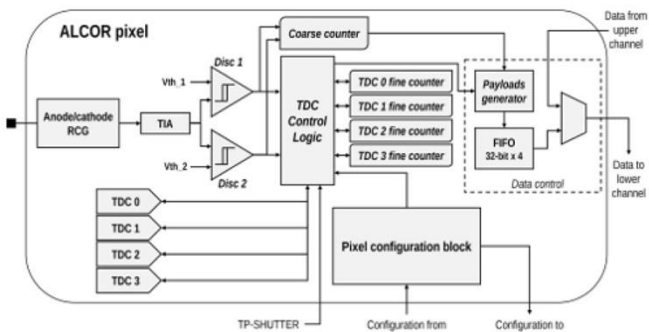
- test realistic dRICH annealing electronics
- study/engineering of annealing process details



ALCOR specs defined with years of lab + beam tests with the 32 channel version - ALCORv64 pilot production ongoing

MPW run in March '25

ALCOR block diagram

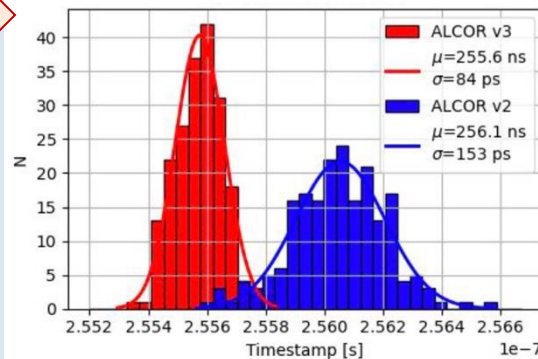
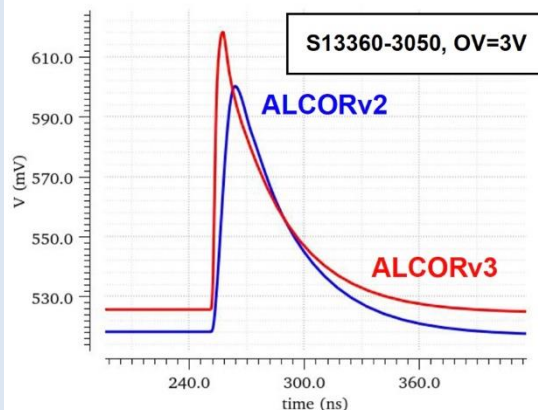


ALCOR key specifications

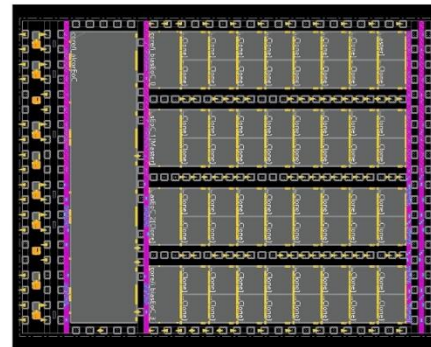
Function	Digitization from SiPMs with 1 p.e. sensitivity
Mode	Single-photon tagging or time and charge
Tech Node	110 nm CMOS
Channels	64 (8x8), dual polarity
C _{din}	<1 nF
Digitization	20-40 ps TDCs, TOA + TOT; Timing <150 ps
Shutter	Width: 2-3 ns, programmable latency
Input Rate	<2.4 MHz (up to 5 MHz on single channel)
Clock	394.08 MHz operation from BX 98.5 MHz
Links	788 Mbps LVDS, SPI configuration
Power	12 mW/ch
Package	BGA
Rad Tolerance	Radiation hard

R. Preghenella (poster)

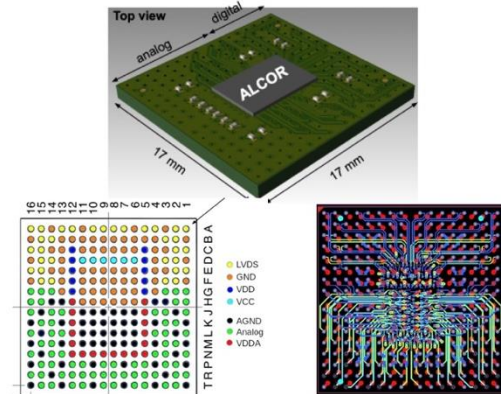
Improved timing and digital shutter



Silicon die layout

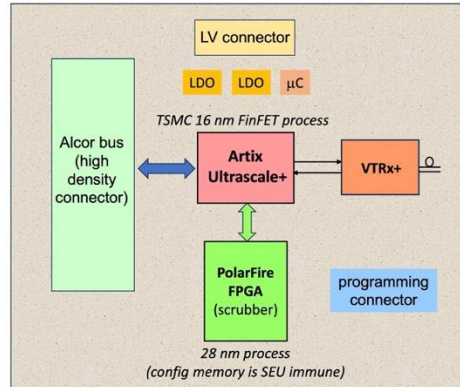
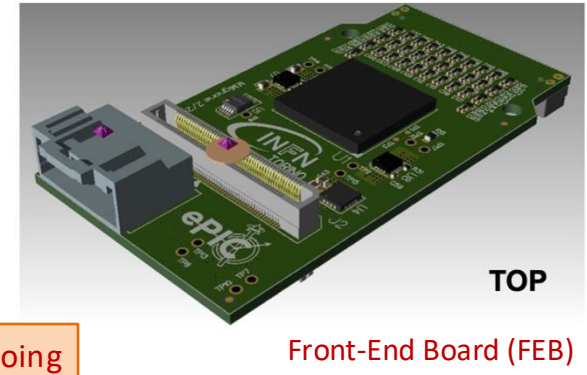
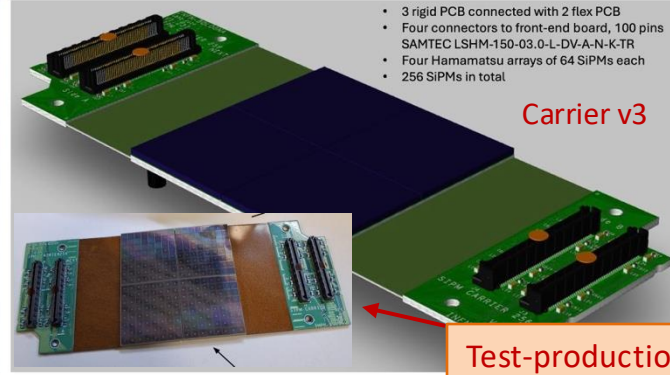
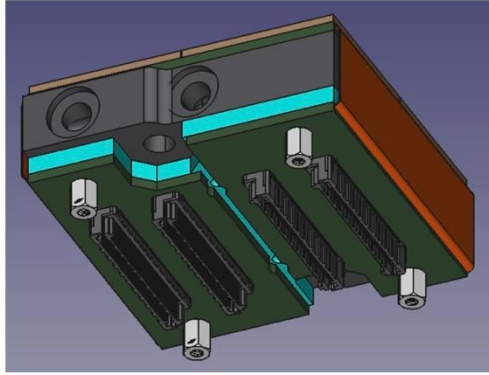


Compact ball-grid array (BGA) package with interposer

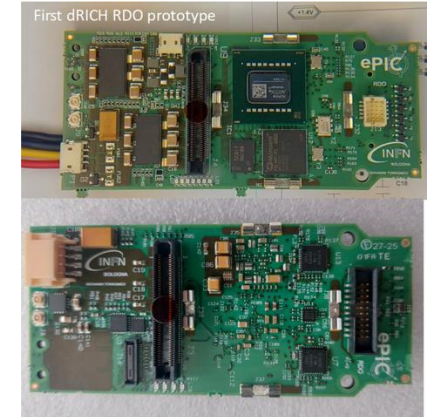
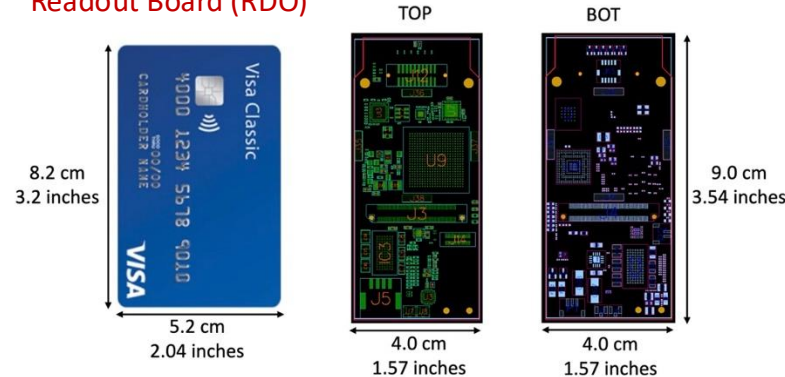


Design of the readout electronics in the “final” ePIC layout version is ready for test production.

Proton irradiation campaigns for ALCOR-32 and key RDO components showed SEU rate is within the expected manageable levels
A working DAQ scheme has been identified to support ML online data filtering at sub-detector level against pure dark-count event



Readout Board (RDO)



Singe-event upset (SEU) rate of dRICH electronics is manageable with standard firmware redundancy and resets features

Regular irradiation campaign ongoing:

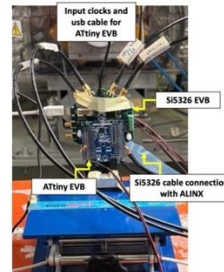
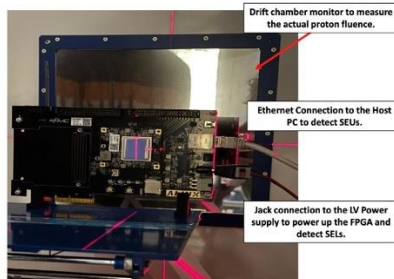
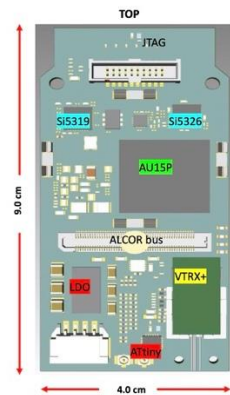
Neutron irradiation campaign at LNL-CN (9-11 October 24)

Gamma irradiation campaign at CERN-GIF (14-16 October 24)

Proton irradiation campaign at TIFPA (12-14 December 24)

$$TID_5 \cong 2.3 \text{ krad} \text{ (for } 1000 \text{ fb}^{-1} \text{)}$$

RDO radiation tolerance



Measured

Mean SEU time @ ePIC

Si5326 (clock)

$$\sigma_{\text{SEU}} = (3.89 \pm 0.54) \cdot 10^{-14} \frac{\text{cm}^2}{\text{bit}}$$

4 h

Attiny (power)

$$\sigma_{\text{SEU}} = (2.11 \pm 0.50) \cdot 10^{-14} \frac{\text{cm}^2}{\text{bit}}$$

3.8 h

AU15P (FPGA)

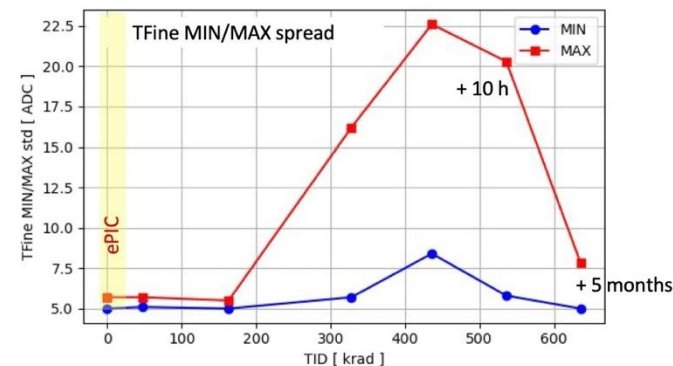
Our estimates	$\sigma_{\text{SEU}} \left(\frac{\text{cm}^2}{\text{bit}} \right)$
BRAM	$(1.78 \pm 0.23) \cdot 10^{-15}$
CRAM	$(2.30 \pm 0.28) \cdot 10^{-16}$

2 min

ALCOR radiation tolerance



- ECCR $\sigma = 9.8 \cdot 10^{-14} \text{ cm}^2/\text{bit}$ periphery register $\rightarrow$ no TMR in ALCOR v2.1
- BCR $\sigma = 6.1 \cdot 10^{-14} \text{ cm}^2/\text{bit}$ periphery register $\rightarrow$ no TMR in ALCOR v2.1
- PCR **no SEU detected** re-written every 10 seconds to mimic TMR

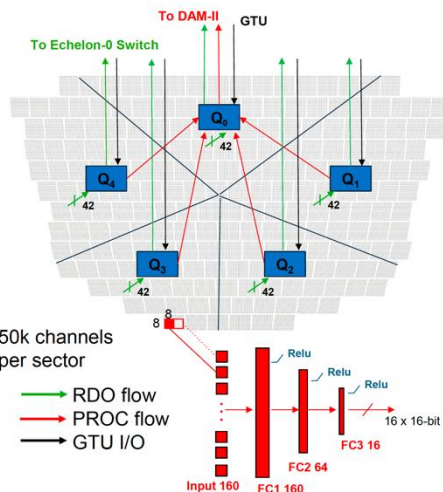
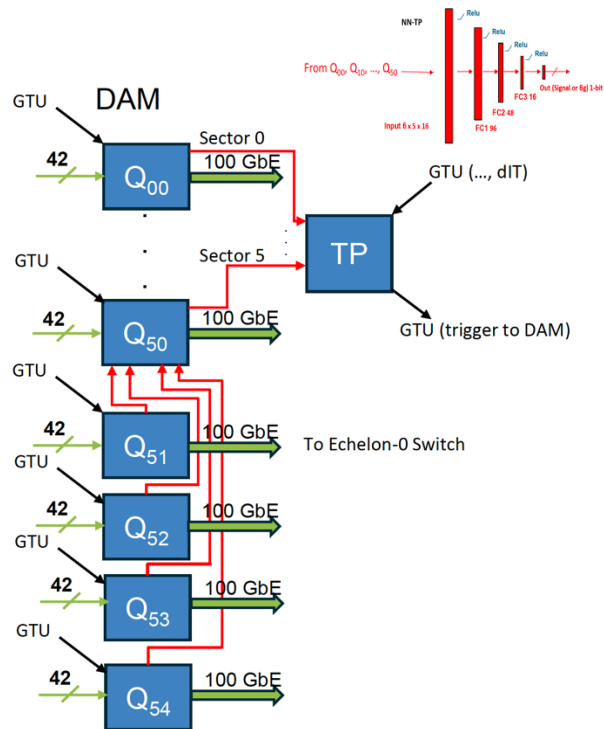


A working DAQ scheme has been identified to support ML online data filtering at sub-detector level against (1:5) pure dark-count event

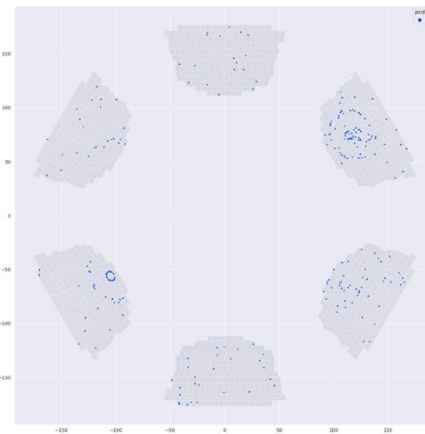
Scheme based on ePIC DAM (Felix) & APEIRON communication network (INFN)

sub-sector integrated analysis

detector integrated analysis



Phys Signal+Phys Background+Noise

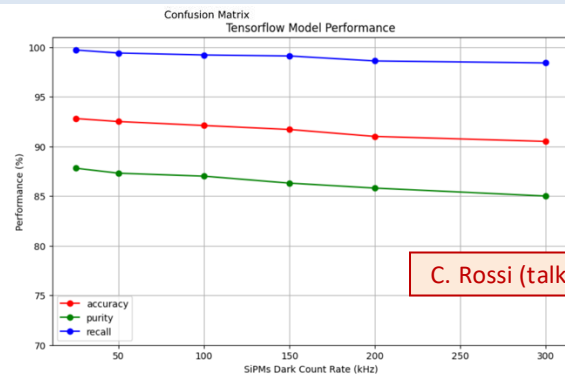


Promising preliminary tests

Through **quantization**, we defined:
quantized fixed point<16,6> inputs
quantized fixed point<8,1> weights
quantized fixed point<8,1> biases

@ 100 kHz & 10 ns:

- Accuracy = $(TP+TN)/(TP+TN+FP+FN) = 0.906$
- Purity = $TP/(TP+FP) = 0.858$
- Recall = $TP/(TP+FN) = 0.977$



C. Rossi (talk)

Design Status

	Technical requirements		Baseline technical solutions		Ongoing
Aerogel:	Momentum reach above 15 GeV/c to overlap with gas More than 10 detected photons from 4 cm thickness Single photon resolution approaching 2 mrad	➡	$n = 1.026$ $dn/d\lambda = 6 \cdot 10^{-6} \text{ nm}^{-1}$ scattering length > 50 mm	➡	Dimensions
Gas:	Momentum reach above 50 GeV/c at pseudorapidity > 2.5 More than 20 detected photons from 1 m depth Single photon resolution approaching 1 mrad	➡	C_2F_6 with $n = 1.00086$ $dn/d\lambda = 0.2 \cdot 10^{-6} \text{ nm}^{-1}$ absorption length > 100 m	➡	Purging
Mirror:	Focalization of Cherenkov light onto the detector surface Preservation of the Cherenkov information Material budget limited to O(2 %) of radiation length	➡	Carbon fiber material Roughness of few nm Angular precision < 0.3 mrad	➡	Coating
Sensors:	Single photon detection capability in highly non-uniform magnetic field Excellent PDE in the visible range to cope with aerogel Marginal contribution to the angular resolution Preserve prompt Cherenkov information Tolerance to few 10^{10} 1-MeV neutron equivalent fluence	➡	SiPM Spatial resolution of $3 \times 3 \text{ mm}^2$ Time resolution O(100 ps) Operation at < -30 degrees Annealing curing cycles	➡	Layout Annealing
Readout:	Below 1 p.e. signal threshold capability Preserve sensor time resolution to cope with dark counts and accidentals More than 300 kHz/ch rate capability Streaming readout with suppression of no-interaction frames	➡	ALCOR ALCOR chip (ToT architecture) Time resolution < 200 ps Rate > 300 kHz/ch	➡	ALCOR 64ch RDO
Mechanics:	Acceptance maximized in 1.5 – 3.5 pseudorapidity range Material budget minimized in acceptance Compatibility with barrel maintenance at IP6	➡	Composite materials Single open volume Detector in the barrel shadow	➡	Real-scale prototype Cooling

CFRP substrate mid-size (~50 cm side) demonstrator validated with lab tests before coating

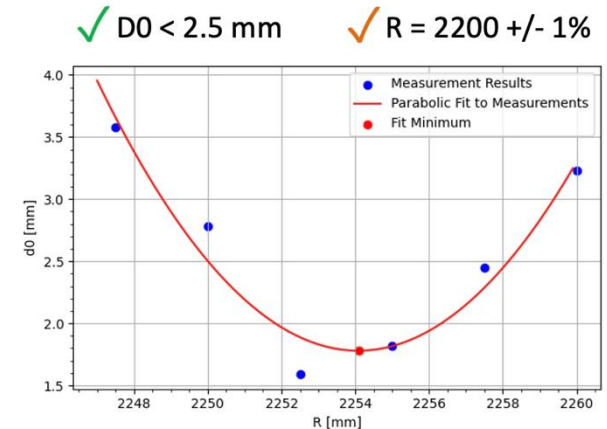
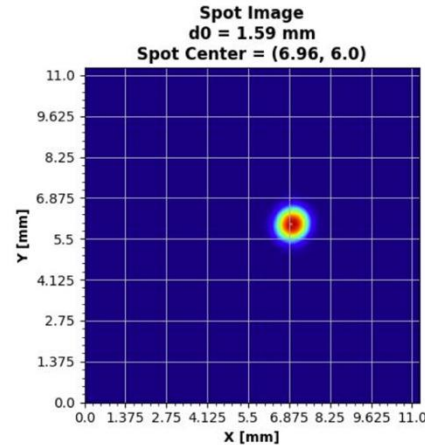
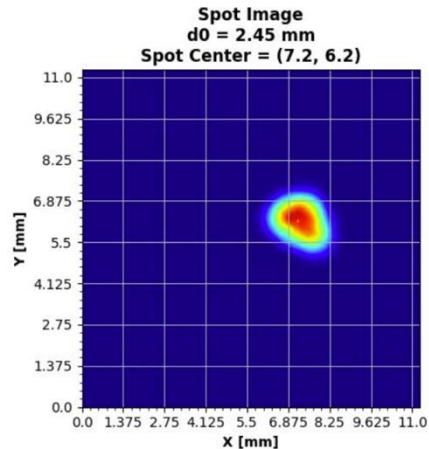
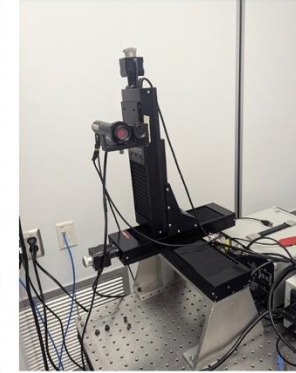
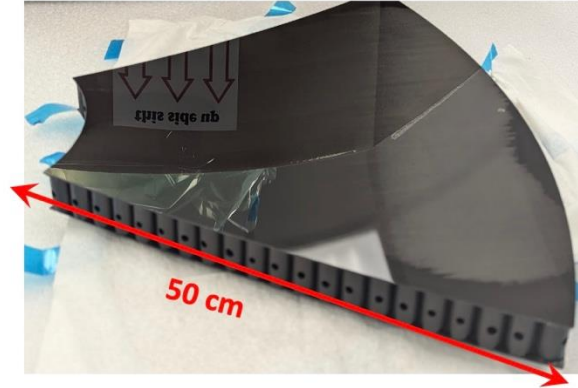
Annex C. Technical Requisite

Each spherical mirror is supplied with

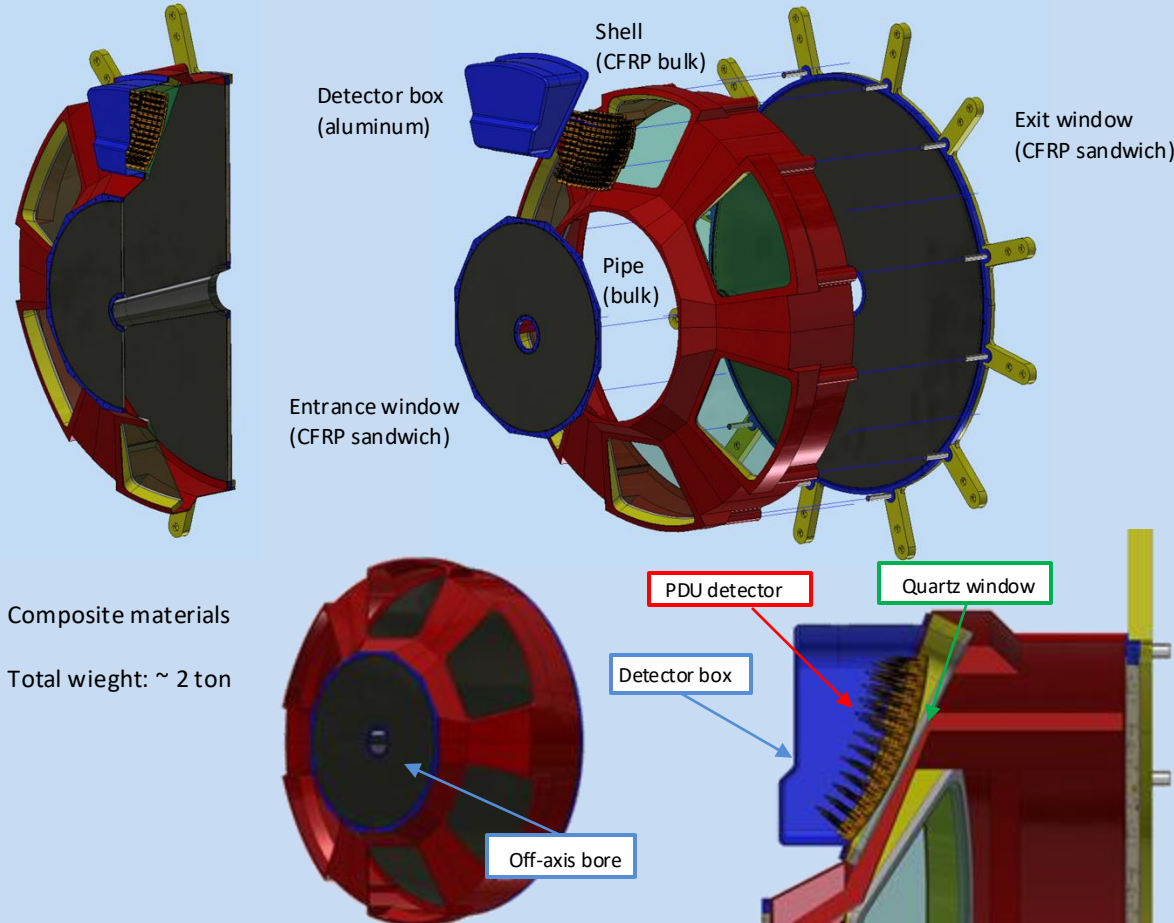
- a spot-size measurement,
- a report on dimensions,
- no reflective coating.

The spherical mirrors are replicated from the same mandrel. The latter is realized with the novel cost-effective technology that reduces the mandrel total mass and cost. Each mirror fulfills the following optical quality specification:

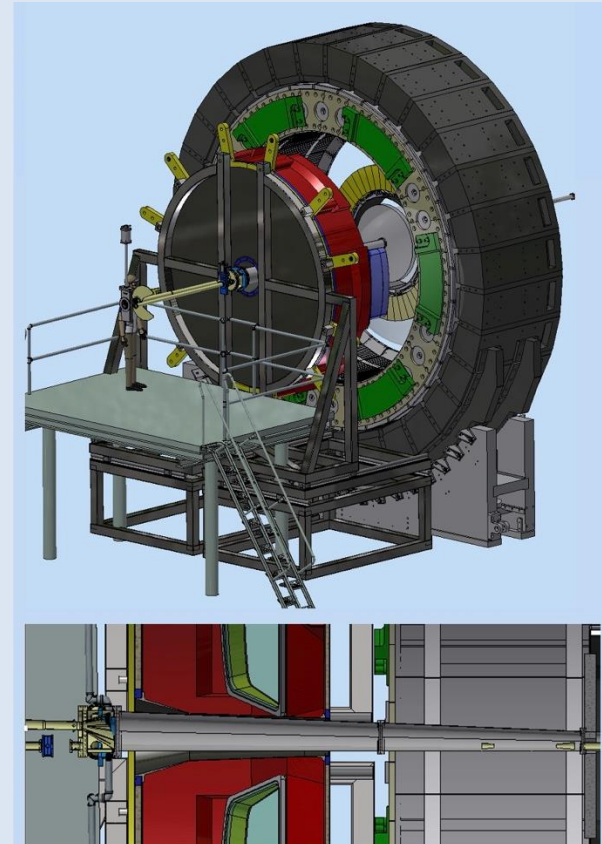
- Radius within 1% of nominal RoC value
(the nominal RoC values is defined by the customer before production in the range 2000 mm $\pm$ 10%),
- Roughness < 2 nm,
- Pointlike image spot size $D0 < 2.5$ mm,
- Compatibility with fluorocarbon gases (C_2F_6),
- Compatibility with SiO_2 reflecting coating.



A detailed mechanical model of the single-vessel detector is outlined with composite materials



On-site maintenance access without breaking the beam vacuum



Ongoing comparative simulation vs prototype thermal study expected to be completed by mid 2026

SiPM plane, cycled from 22° to -30°

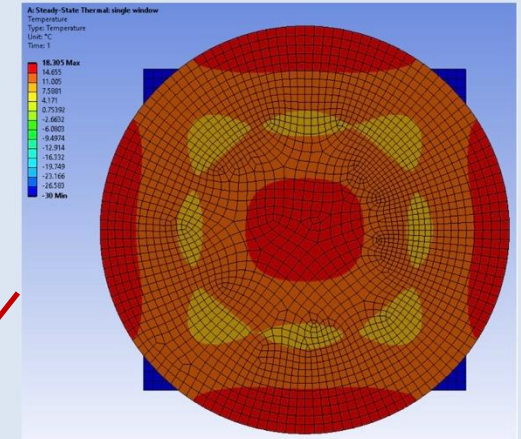
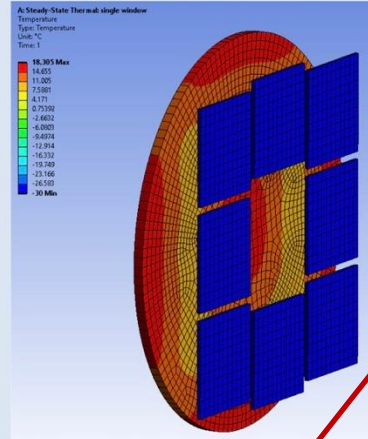
3 mm lucite window

Ongoing study with ANSYS workbench simulations

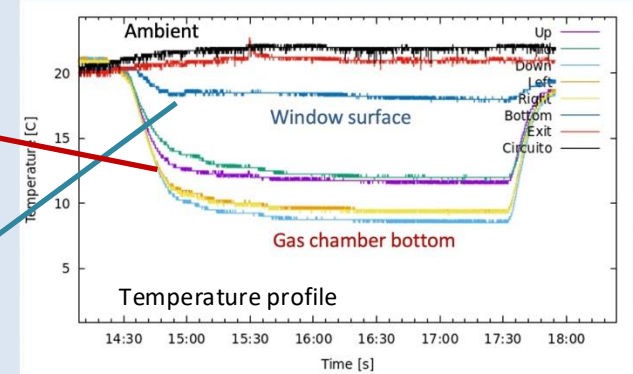
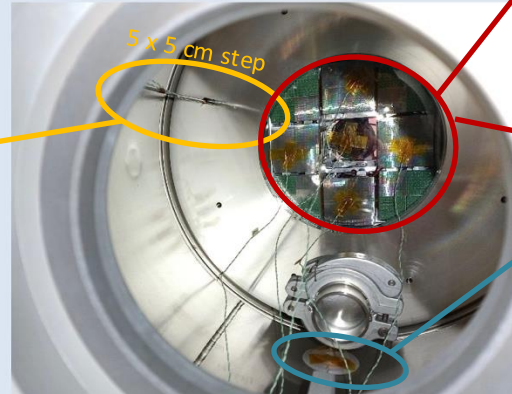
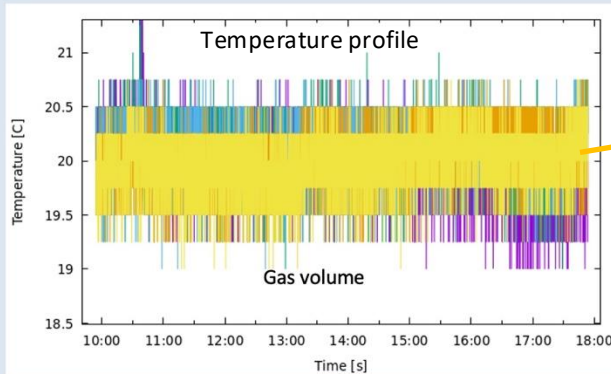
Benchmarked by dRICH prototype

Gradients are largely mitigated by

- double lucite window (with air gap) x 0.5
- 8 mm thick quartz window
- inner gas recirculation x 0.1

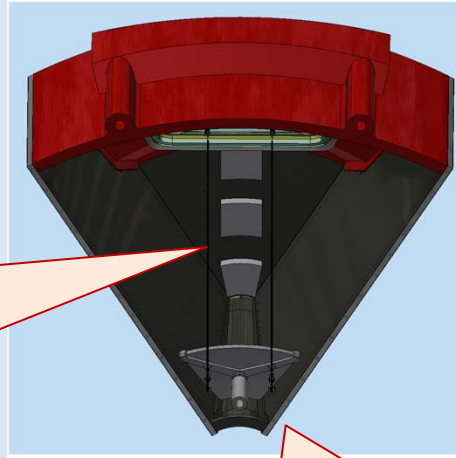
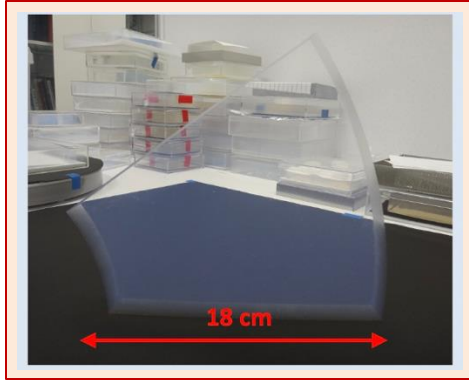


Gas volume with thermocouples

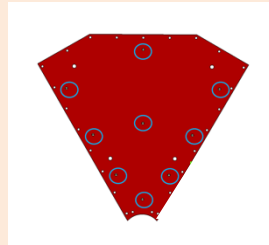
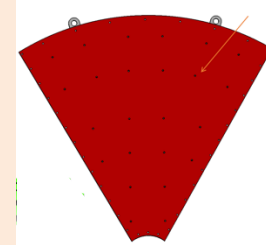
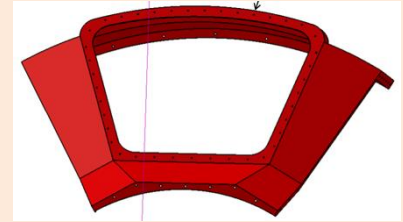


Engineering of all the mechanical details pursued with the real-scale prototype now expected by mid-October

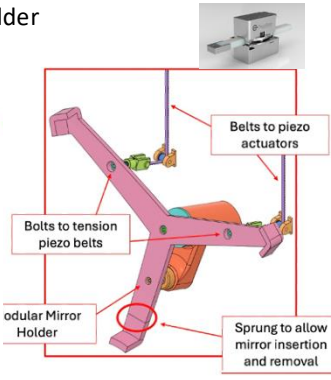
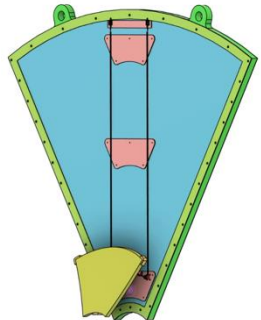
Aerogel demonstrator



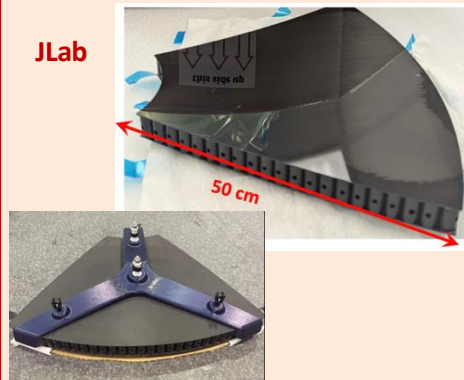
Under Construction



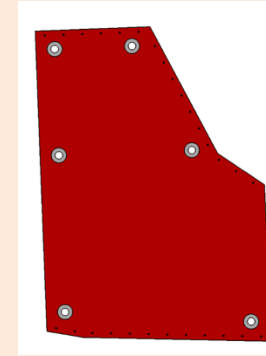
Mirror mounting and holder



JLab

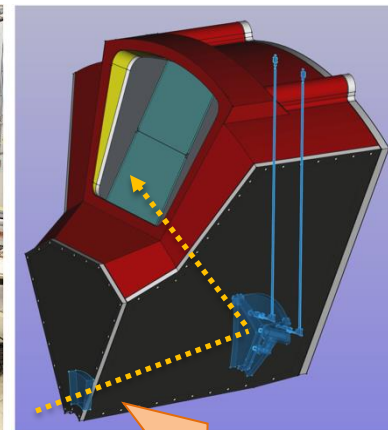
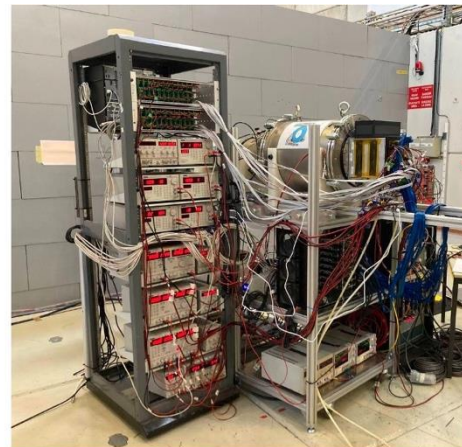
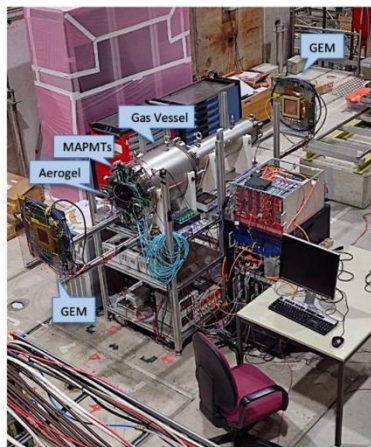


CFRP layer samples



Previous validations:

- Dual-radiator concept
- C_2F_6 radiator gas performance
- Aerogel refractive index
- SiPM-ALCOR readout chain
- EIC-drive readout plane
- Induced temperature gradients

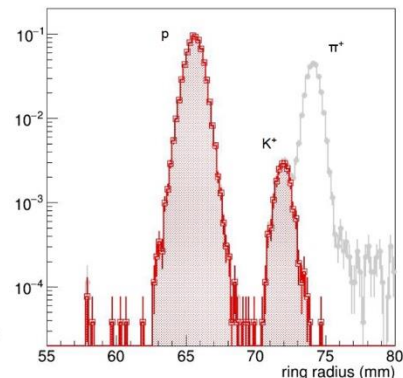
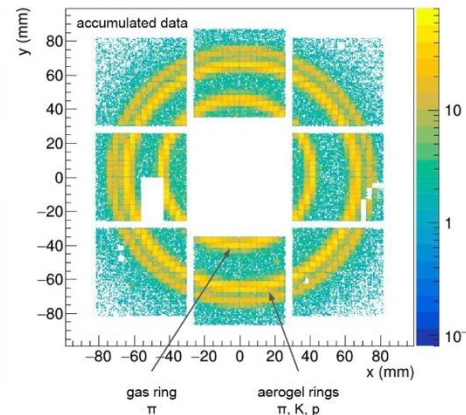
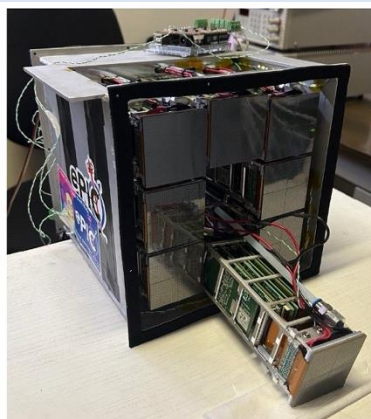


2025

2025 main goals:

- UVE Sensors
- ALCOR readout with RDO
- Real scale 1-sector prototype with demo components

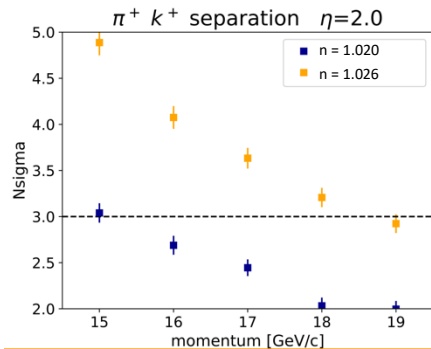
Slot at SPS H8 in November



Simulation within ePIC dd4hep framework accounts for tracking, material budget and magnetic bending.

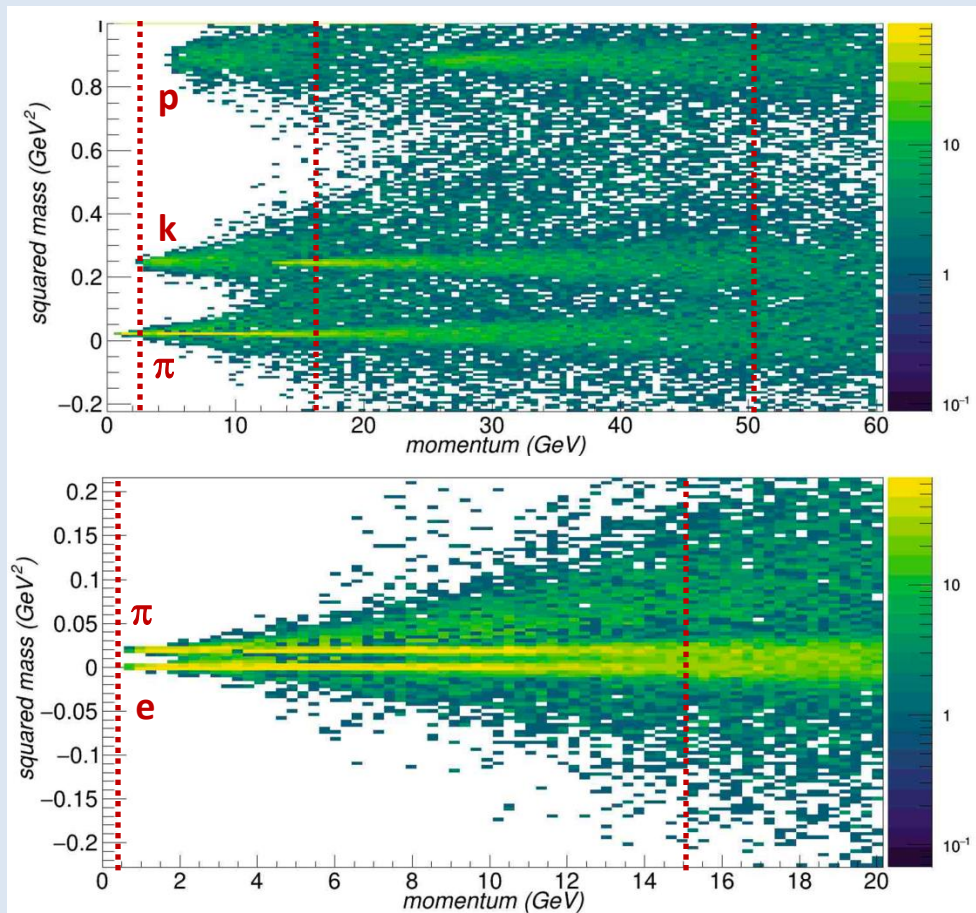
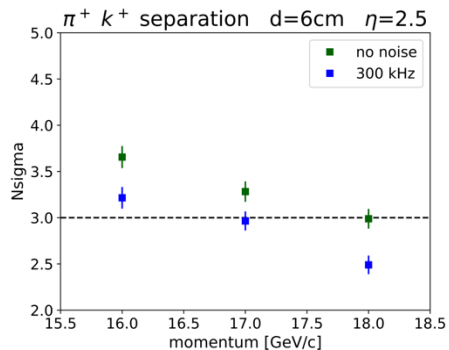
Model bases on lab characterization and test-beam data of components

Aerogel
specs



T. Boasso (poster)

SiPM
Dark-counts



dRICH aims for a compact and cost-effective solution for forward PID at ePIC

hadron identification in the 2.5 GeV/c – 50 GeV/c momentum range

electron identification from few hundred of MeV/c up to ~15 GeV/c

Design Status is being documented in the ePIC pre-TDR under preparation

dRICH passed 60% Preliminary Design Review on April 1-2, 2025

Essential technical performance has been validated for each dRICH component

Engineering is ongoing with pre-productions for performance vs cost optimization

Workforce is increasing, with focus in simulations and engineering

Ultimate R&D achievements expected in 2025 (real-scale prototype, RDO, ALCOR64)

Moving from R&D to engineering phase