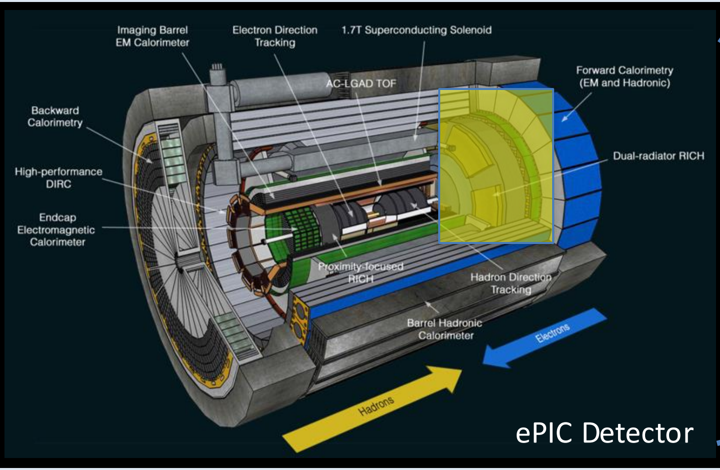
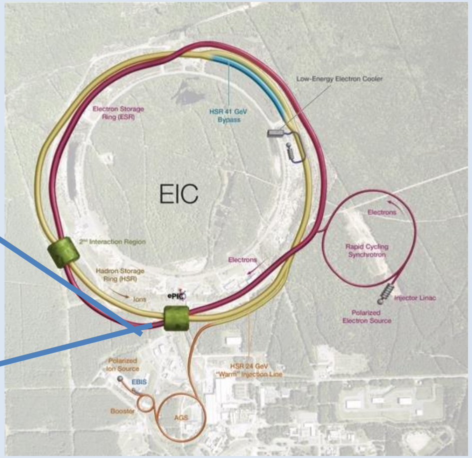
The ePIC Dual-Radiator RICH Detector





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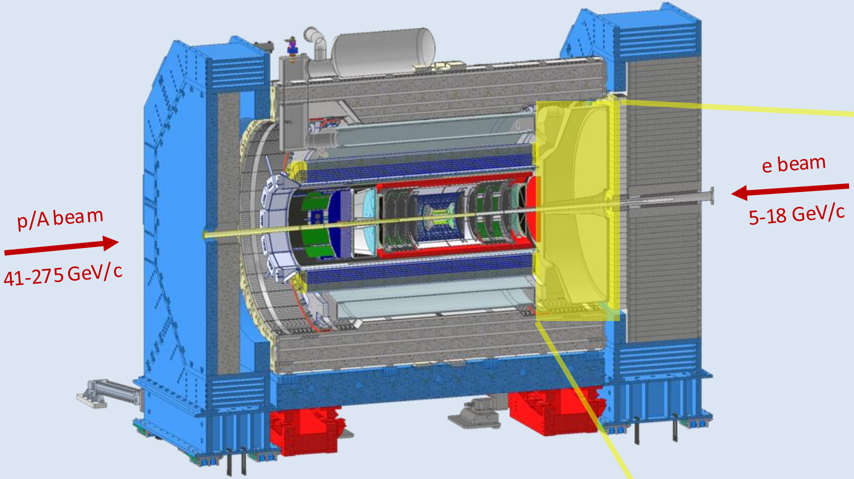
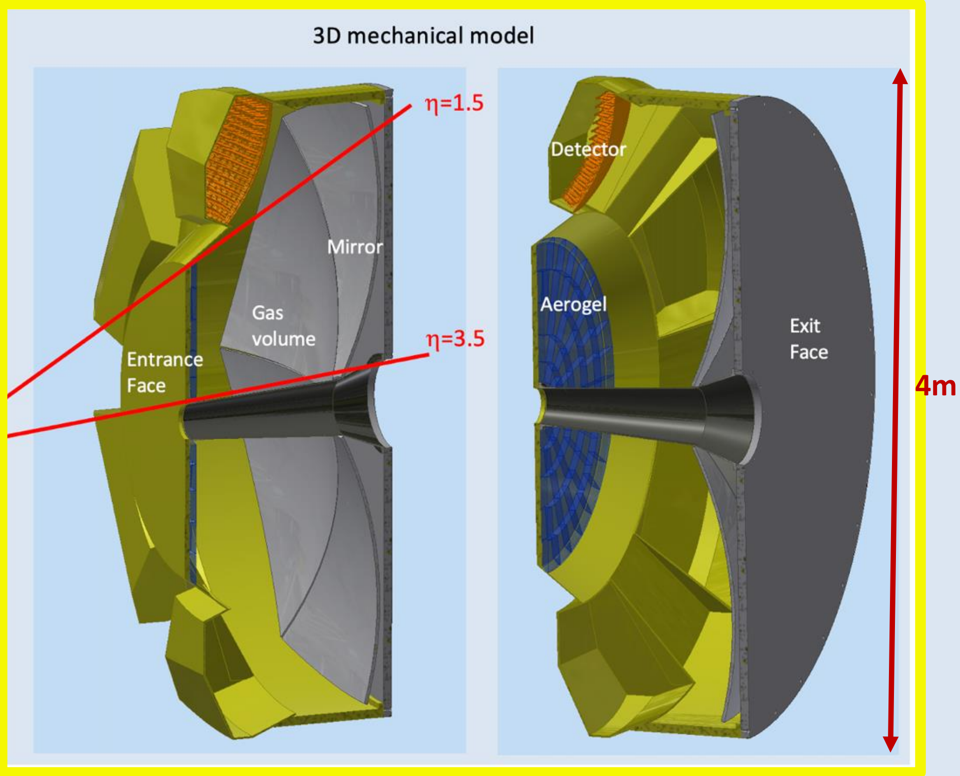
M. Contalbrigo – INFN Ferrara

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

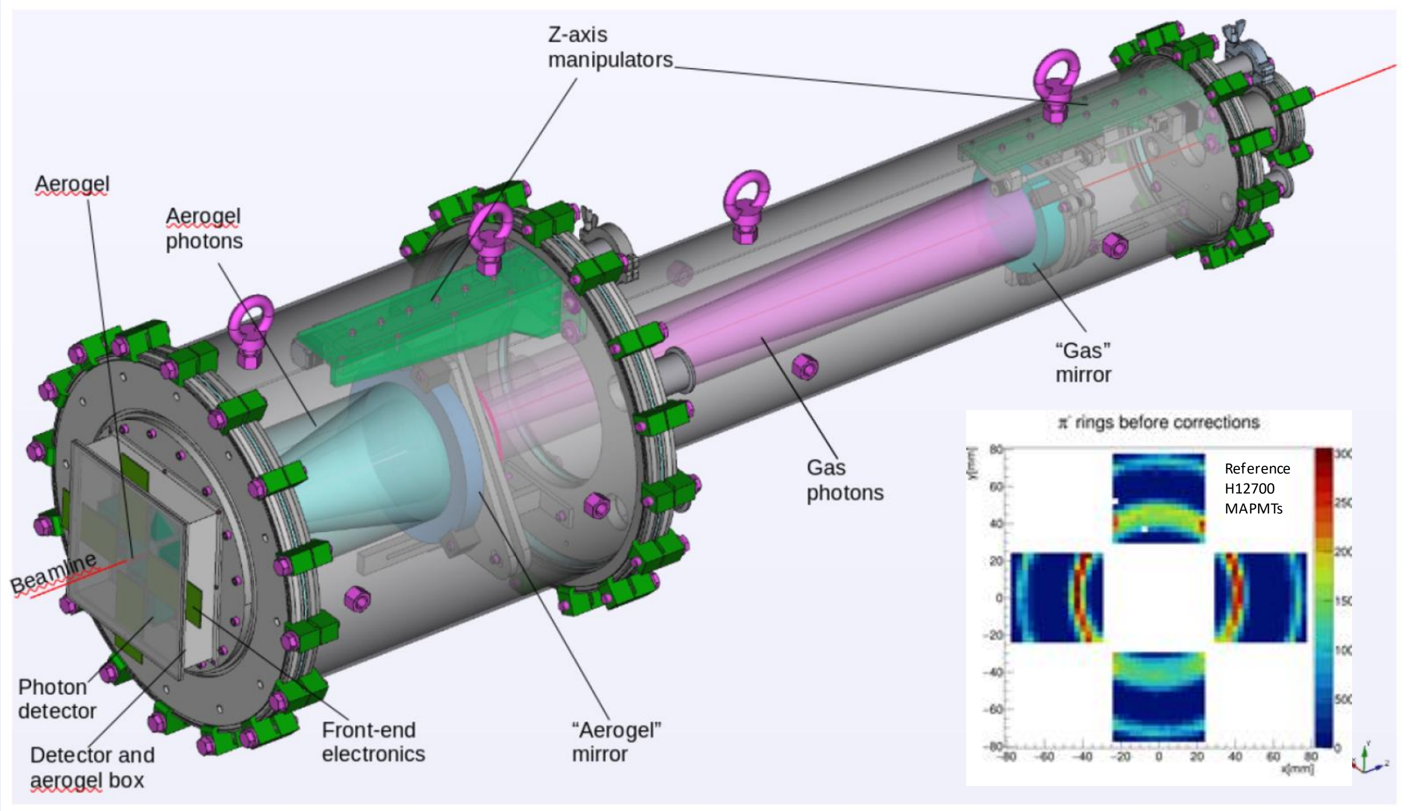
Design Status

	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** $dn/d\lambda = 6\ 10^{-6}\ nm^{-1}$ 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 $dn/d\lambda = 0.2\ 10^{-6}\ nm^{-1}$ 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

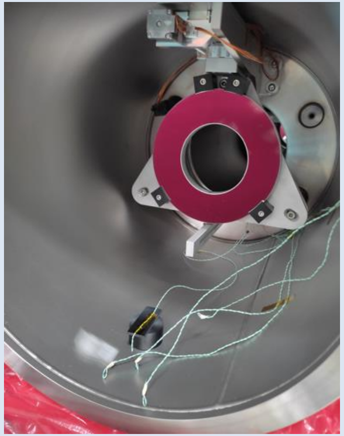
dRICH Prototype

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

Vacuum technology & recovery system for efficient gas exchange



1st chamber

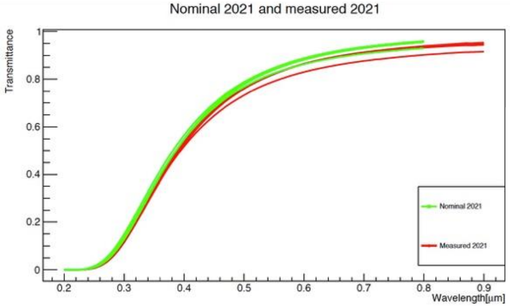


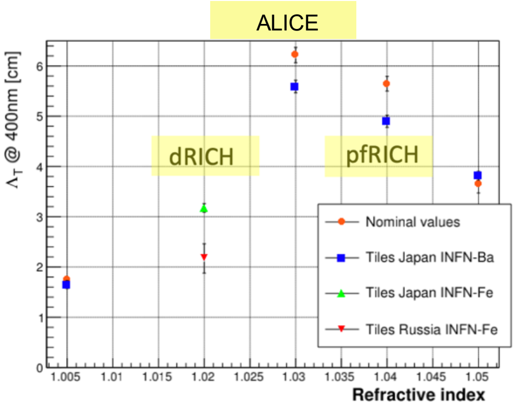
Gas recovery system

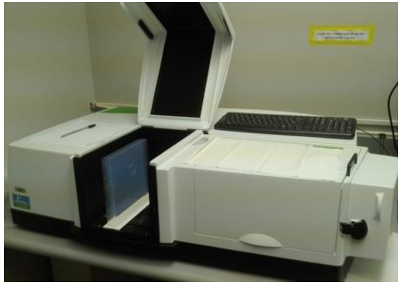
Aerogel Radiator

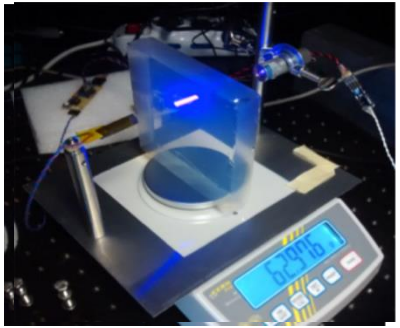
Aerogel Factory (BELLE-II)
Initial evaluation & Reproducibility
on small samples in sinergy with ALICE

Transmittance & Transflectance

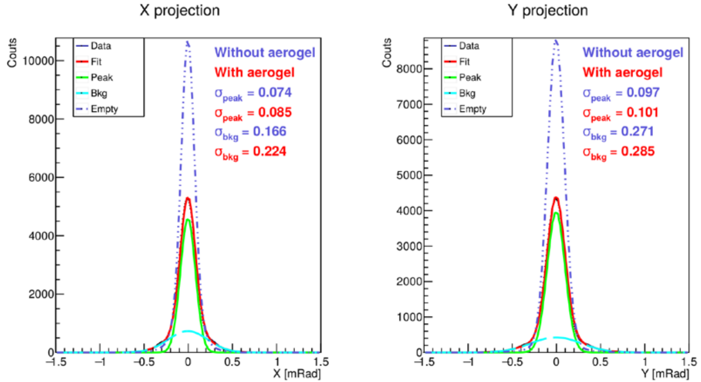






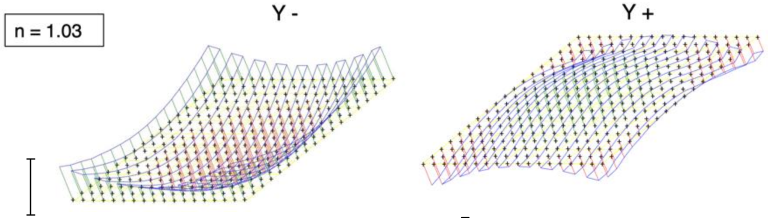


Laser spot broadening with 3 x 2 cm aerogel



Touch Probe: planarity and thickness

10x10x2 cm^3 tile
(from ALICE)



G. Volpe (poster)

Aerogel Technical Performance

Aerogel with n=1.026 validated with lab and prototype tests

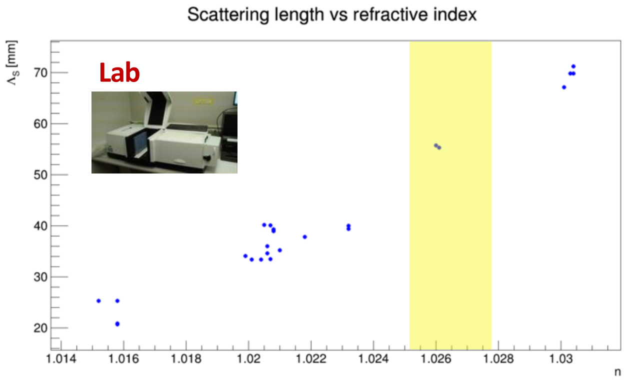
* meet SPE resolution expectations

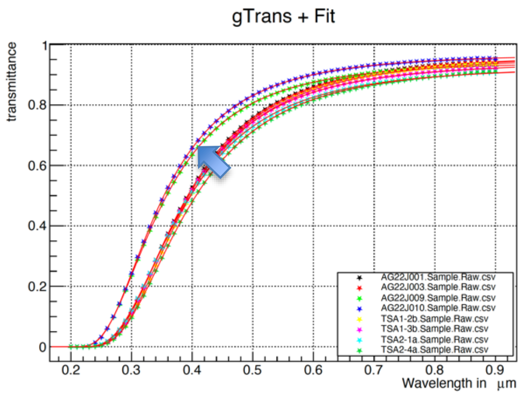
* scattering length > 50 mm

* match with TOF end point (2.5 GeV/c)

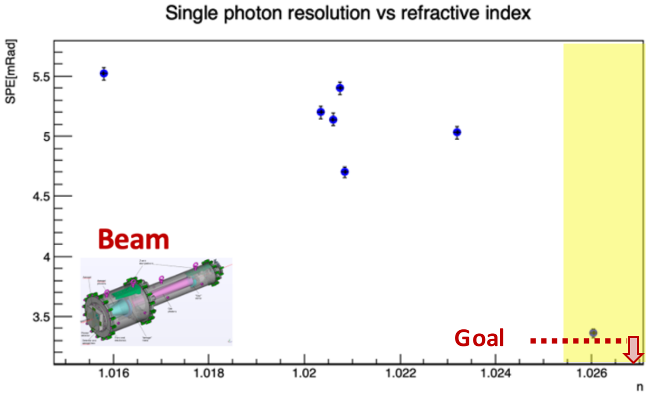
* overlap with gas (> 12 GeV/c)

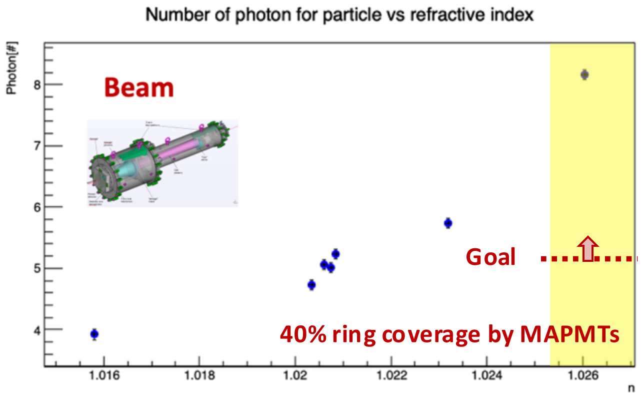
* photon yield > 10 per particle with MAPMTs





Various samples from Aerogel Factory





Aerogel Pre-Production

First large aerogel tile demonstrators delivered

based on dRICH baseline specifications

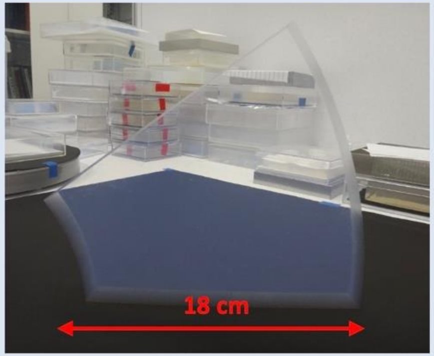
An effort should be pursued by the vendor to keep the aerogel quality parameters as close as possible or better than the following reference values.

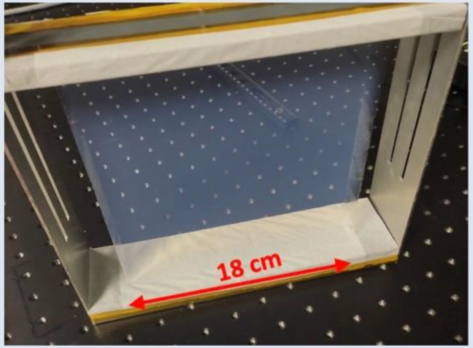
General specifications:

- 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

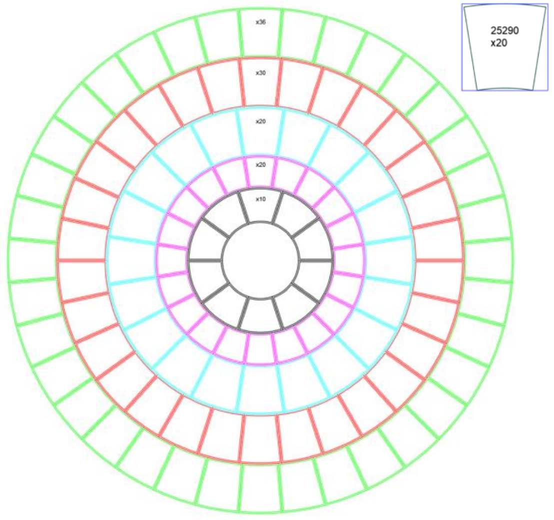
* optimize area vs number of tiles

* minimize the waste of material

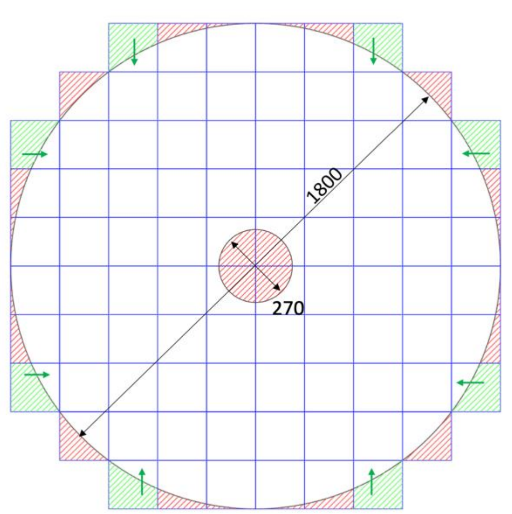
* minimize the dead/low-efficiency gaps

* optimize thickness:

  - photon yield vs resolution
  - planarity



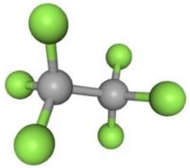
Active Area = 21605 cm^2
Dead Ara = 3269 cm^2 (13%)
Wasted Area = 9112 cm^2 (27 %)



Active Area = 21368 cm^2
Dead Ara = 3506 cm^2 (14%)
Wasted Area = 1868 cm^2 (7 %)

Gas Radiator Technical Performance

Baseline Hexsafluoroethane validated with lab and beam tests



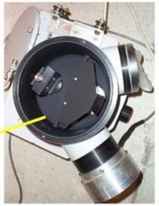
1 covalent + 6 hydrogen bonds

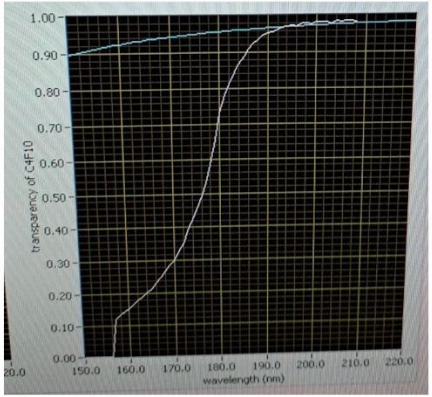
C_2F_6 molecular weight: 138.01 g/mol
boiling point: -78.1 °C
melting point: -100.6 °C
density: 5.734 kg/m³ at 24 °C
density: 16.08 kg/m³ at -78 °C

Gas	Npe(π/K)	θ_π	θ_K	σ_π	σ_K	N_σ	ρ = Δθ/θ (λ = 300 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 %

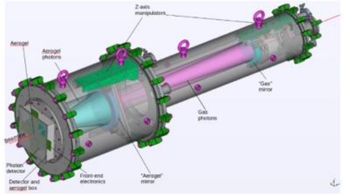
Deuterium UV lamp, Monochromator system, 1.6 m column for gas transparency measurement

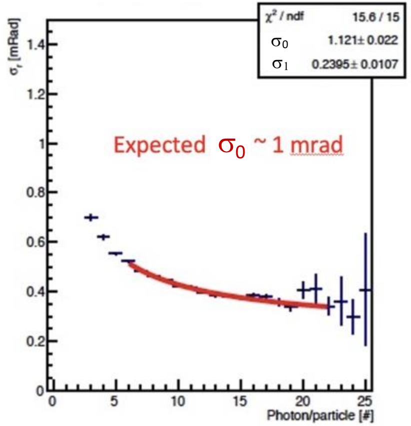




Measured 139.7 m/s speed of sound confirms negligible contaminants after few year in bottle

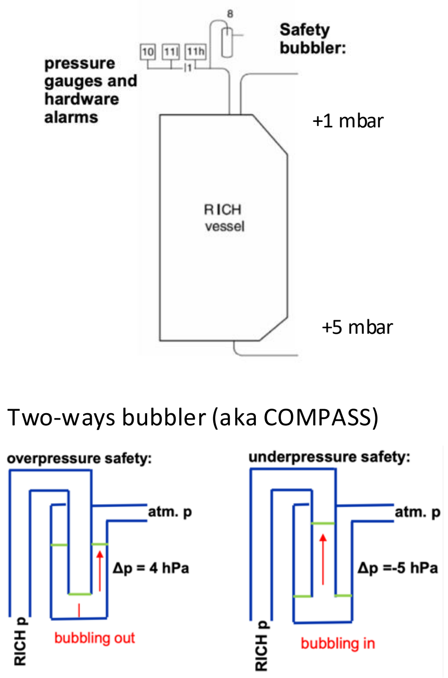
Expected performance obtained with dRICH prototype



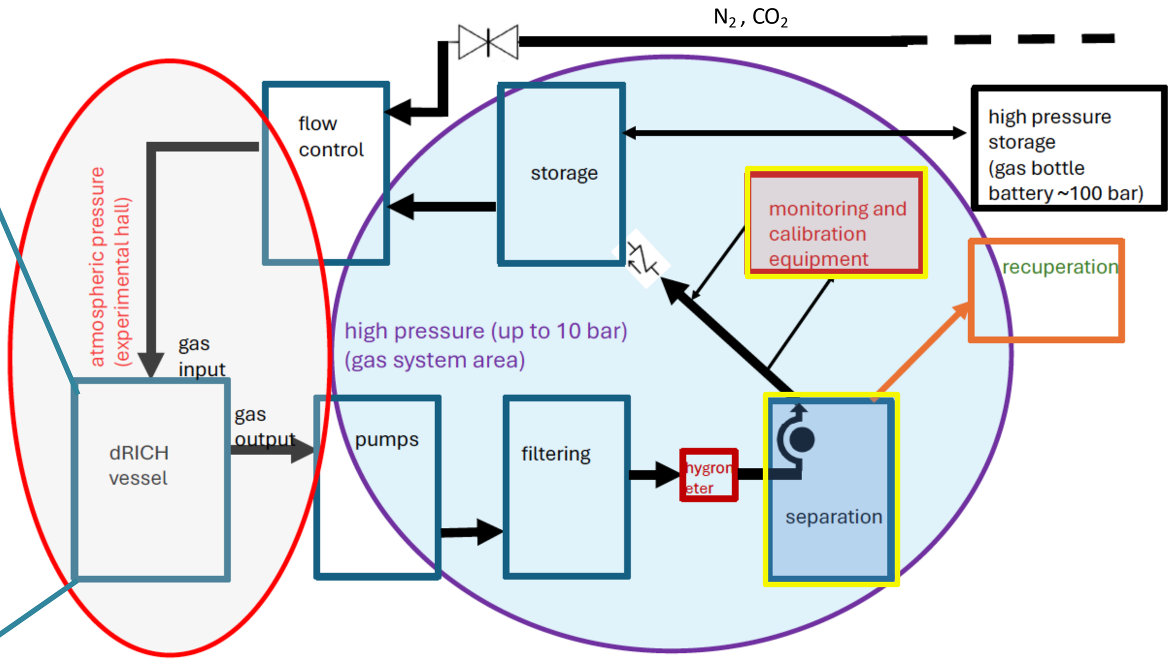


Adaptation from realizations at CERN with focus on separation/monitor expected by 2026
Realization at BNL in compliance with DOE safety standards

dRICH vessel



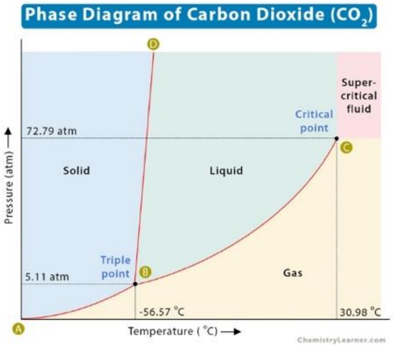
dRICH gas system

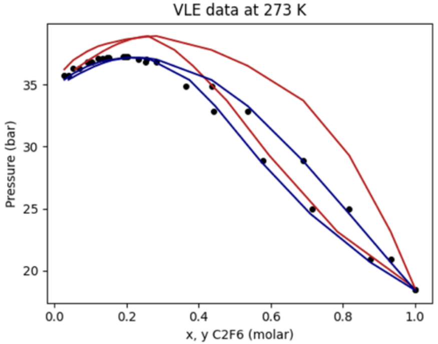


Development of gas separation protocols expected by 2026

Purging via liquefaction of stand-by gas

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

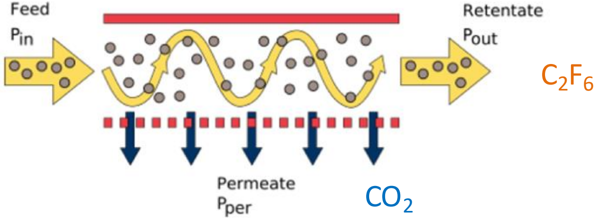


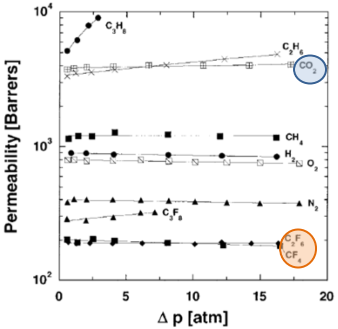


F. Tessarotto (talk)

Purging via membranes

Effective separation of CF_4 and CO_2 demostrated in LHCb
hpps://edms.cern.ch/document/2816490/1

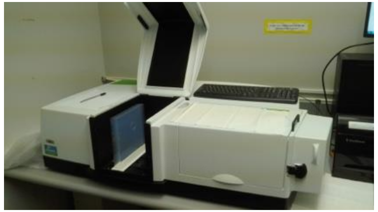


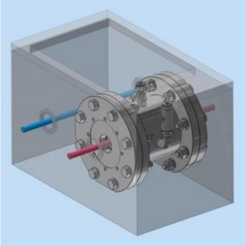


Design of online purity monitors expected by 2026

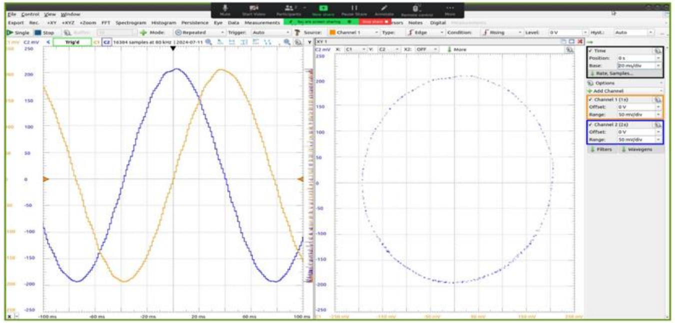
Sonar to measure speed of sound

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 $dn/d\lambda = 6\ 10^{-6}\ nm^{-1}$ 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 $dn/d\lambda = 0.2\ 10^{-6}\ nm^{-1}$ 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

Photon Detector

Steadly progress of photodetector towards integrated design completion in 2026

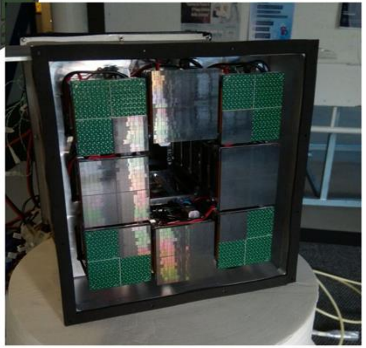
towards construction

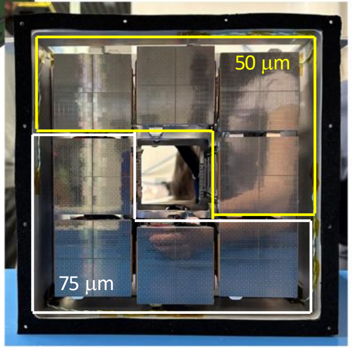
2022
electronics v1

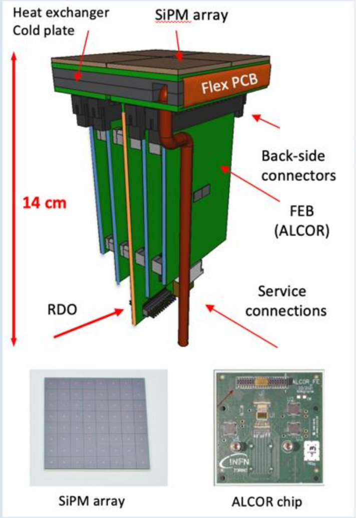
2023
electronics v2

2024
electronics v2.1
Operated at -37°

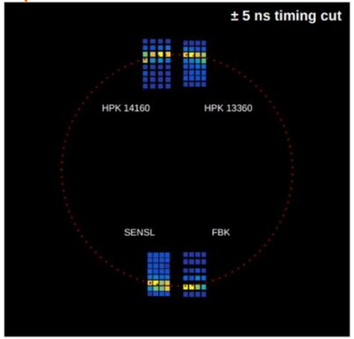
2025/26
electronics v3
final prototype

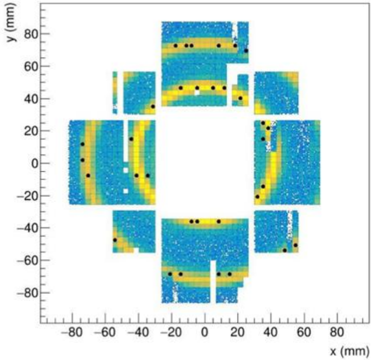


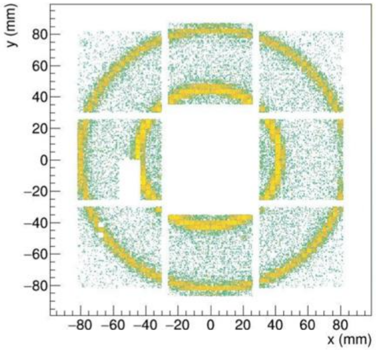




ALCOR 32 ch



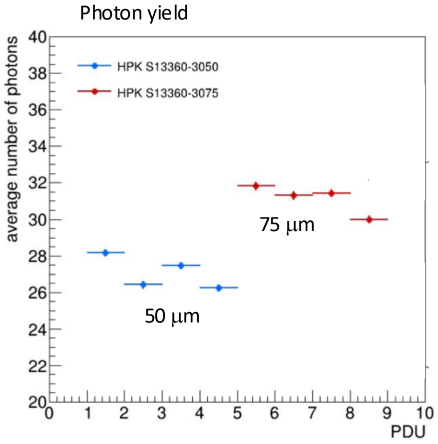




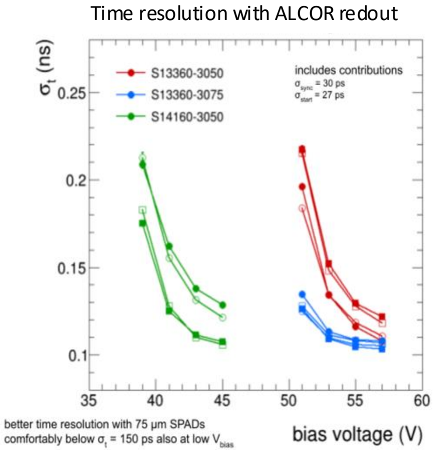
2025
+ SiPM carrierv3
+ RDO

2026
+ ALCOR 64ch
+ FEB 64

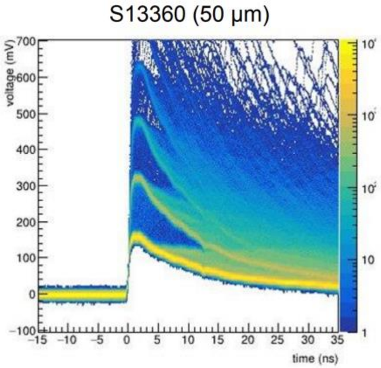
Baseline specs defined, flnalization of the engineering of the SiPM optimized layout ongoing

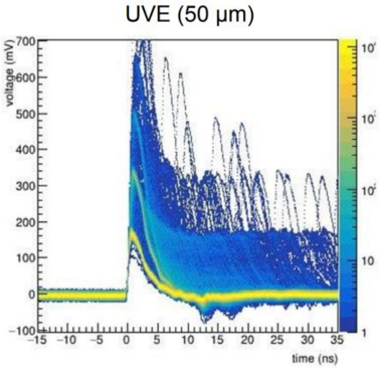


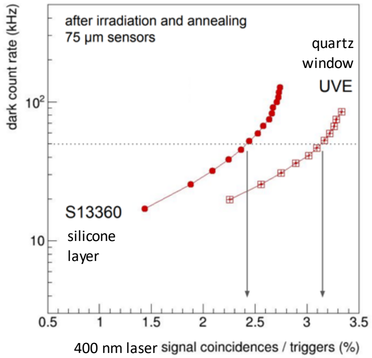
SPAD size

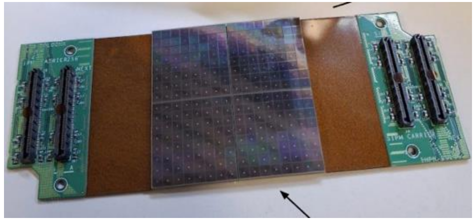


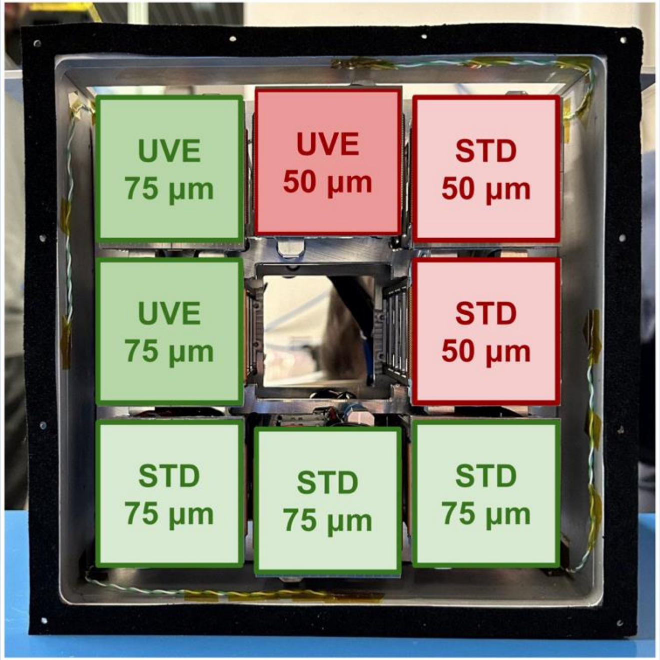
Novel HPK UVE fast SiPM



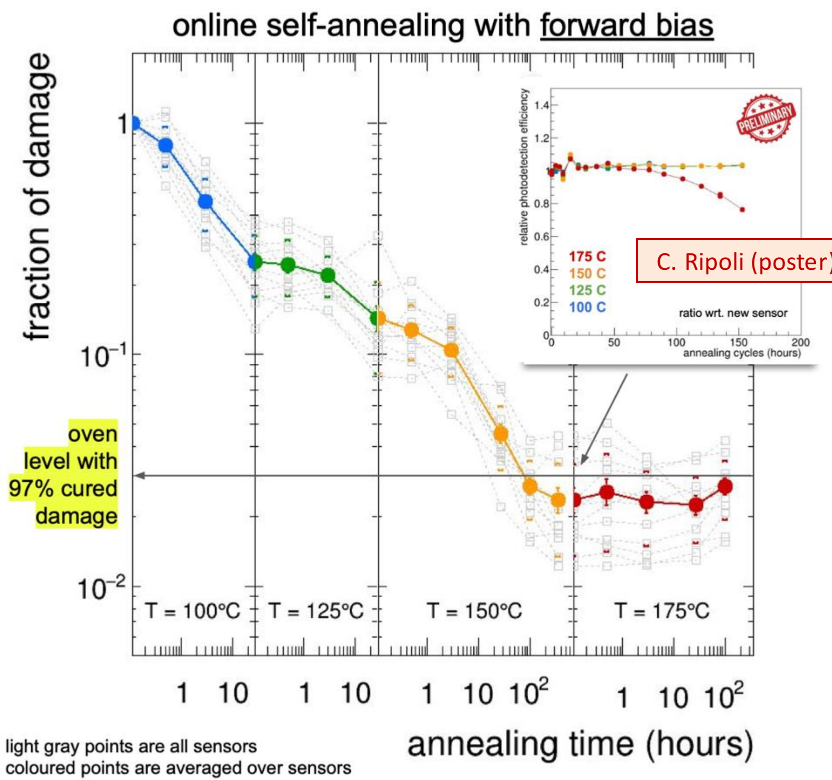








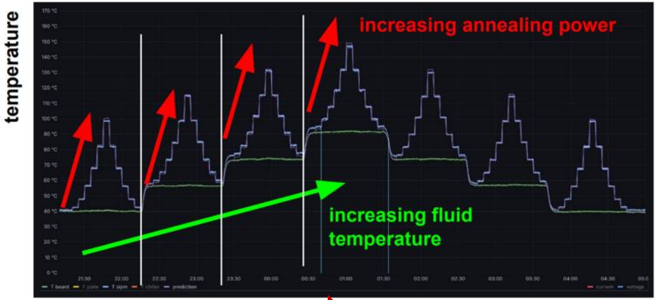
Completion of engineering of the SiPM optimized layout and temperature treatments expected by 2026



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

C. Ripoli (poster)

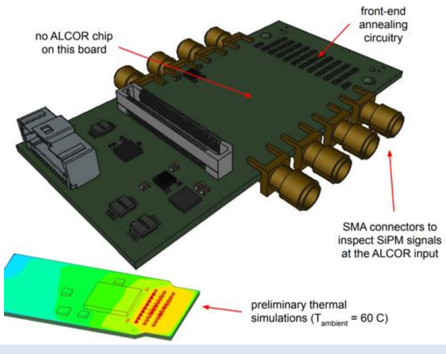
Details of in-situ annealing protocol based on Joule-effect

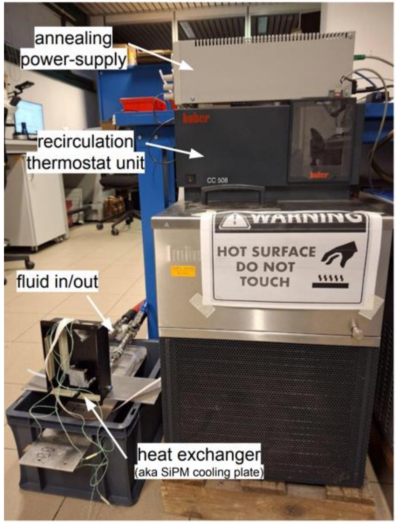


N. Rubini (talk)

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



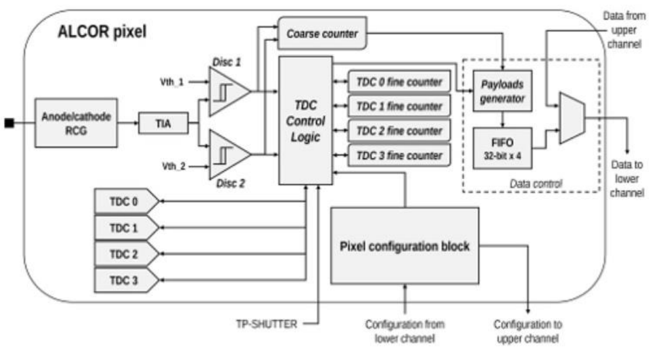


ALCOR Readout Chip

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

MPW run in March '25

ALCOR block diagram

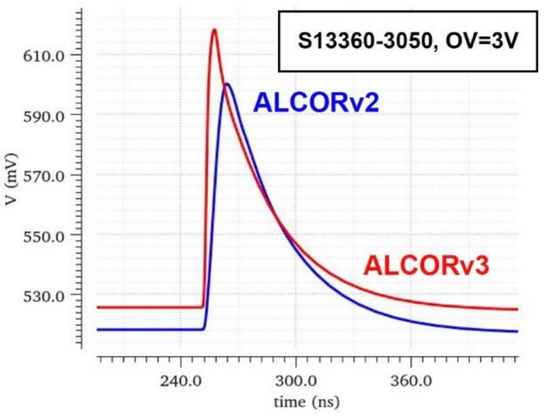


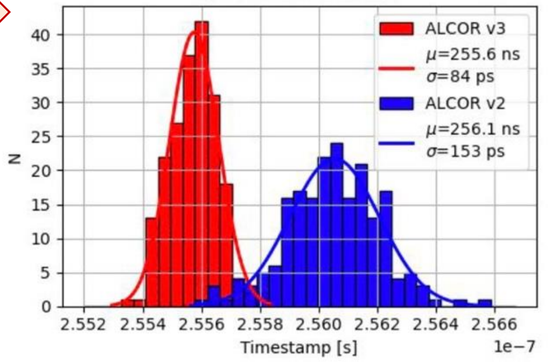
R. Preghenella (poster)

ALCOR key specifications

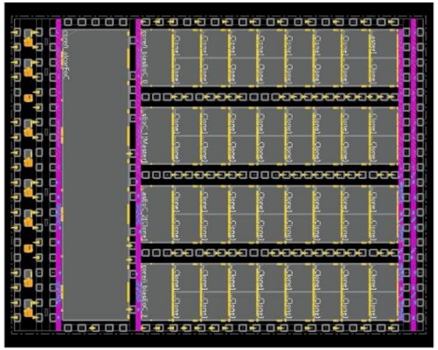
Function	Digitization from SiPMs with 1 p.e. sensitivity
Mode	Single-photon tagging or time and charge
Tech Node	110 nm CMOS
Channels	64 (8x8), dual polarity
Cdin	<1 nF
Digitization	20-40 ps TDCs, TOA + TOT; Timing <150 ps
Shutter	Width: 2–3 ns, programmable latency
Input Rate	<2.4 MHz (up to 5 MHz on 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

Improved timing and digital shutter

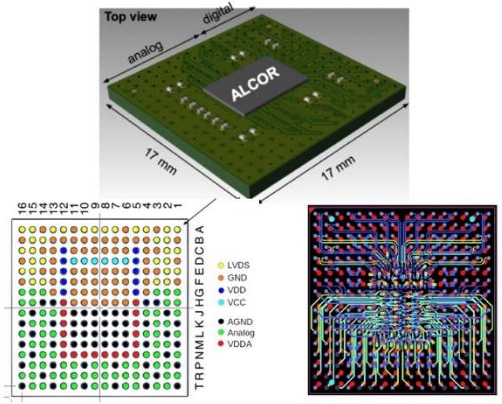




Silicon die layout



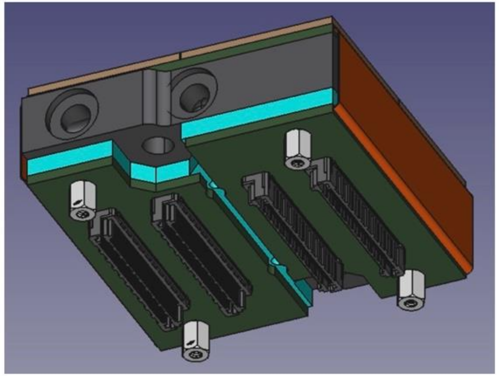
Compact ball-grid array (BGA) package with interposer

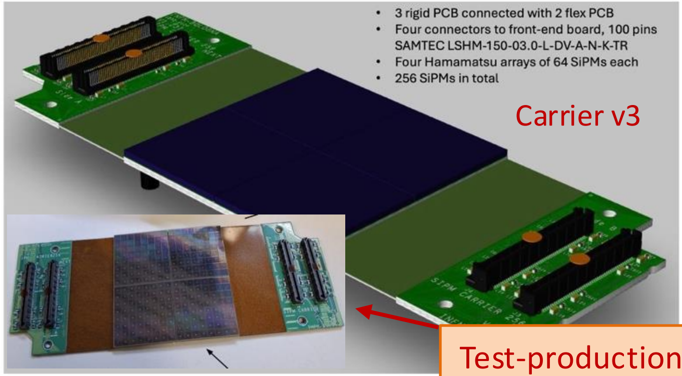


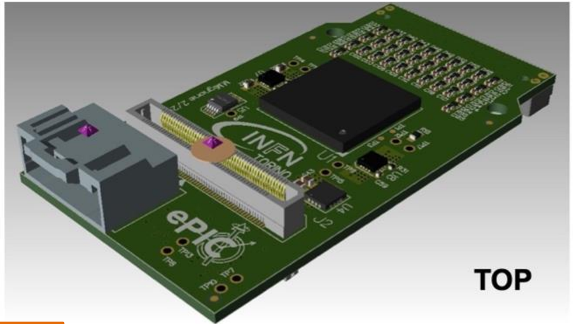
Design of the readout electronics in the "final" ePIC layout version is ready for test production.

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

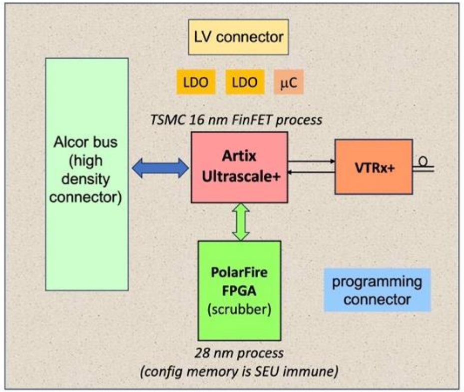




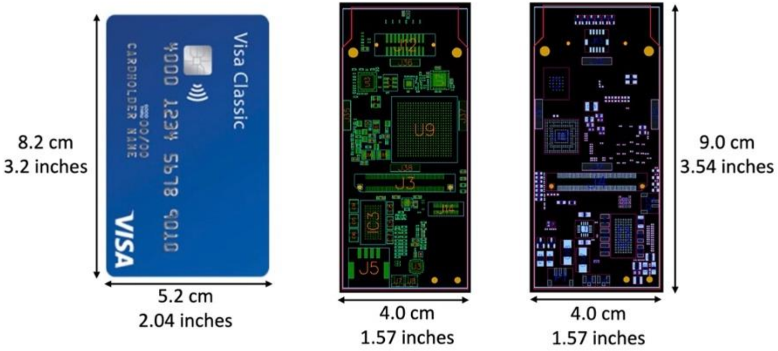


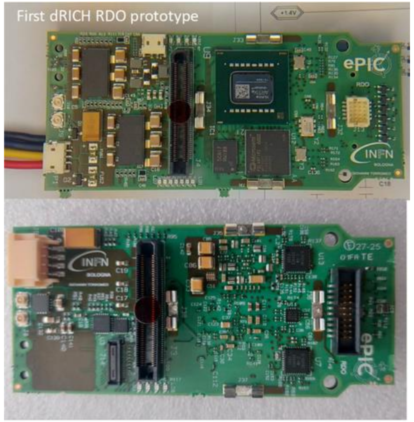
Front-End Board (FEB)

Test-production ongoing



Readout Board (RDO)





Readout Irradiation Tests

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

Regular irradiation campaign ongoing:

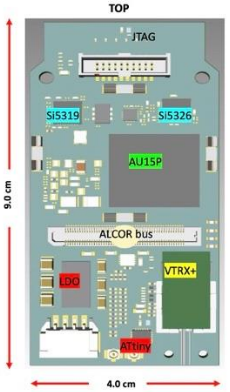
Neutron irradiation campaign at LNL-CN (9-11 October 24)

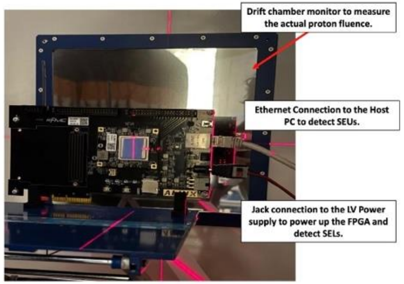
Gamma irradiation campaign at CERN-GIF (14-16 October 24)

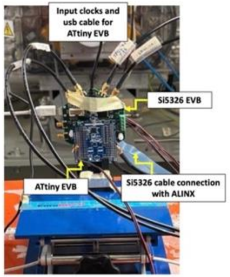
Proton irradiation campaign at TIFPA (12-14 December 24)

$\mathrm{TID}_5 \cong 2.3$ krad
(for 1000 fb^{-1})

RDO radiation tolerance



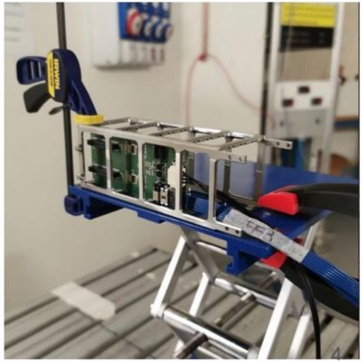




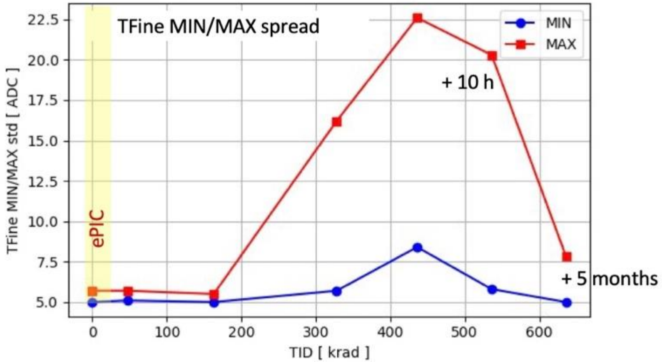
	Measured	Mean SEU time @ ePIC
Si5326 (clock)	$\sigma_{SEU} = (3.89 \pm 0.54) \cdot 10^{-14} \frac{\mathrm{cm}^2}{\mathrm{bit}}$	4 h
Attiny (power)	$\sigma_{SEU} = (2.11 \pm 0.50) \cdot 10^{-14} \frac{\mathrm{cm}^2}{\mathrm{bit}}$	3.8 h
AU15P (FPGA)	see table below	2 min

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

ALCOR radiation tolerance



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

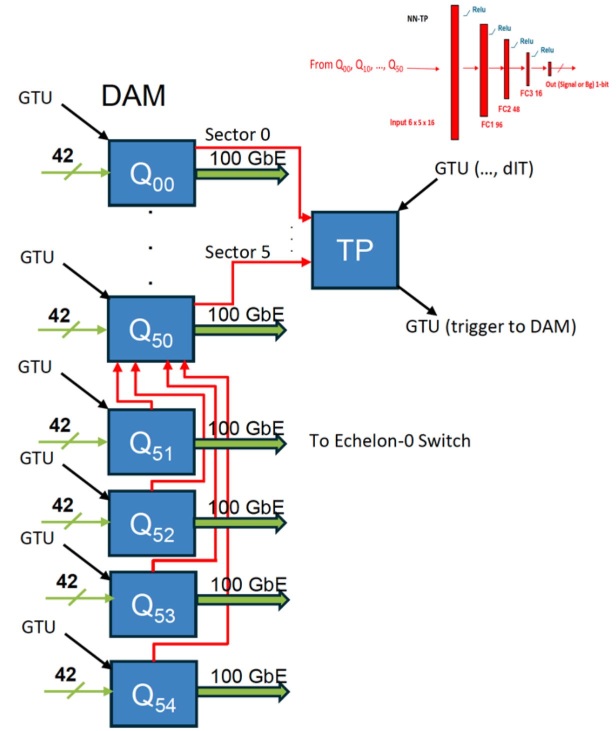


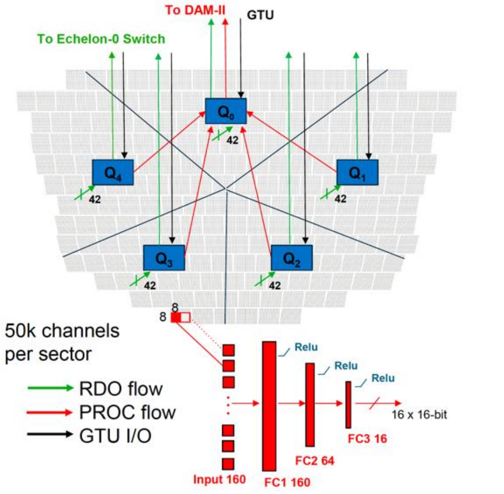
dRICH Online Filtering

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

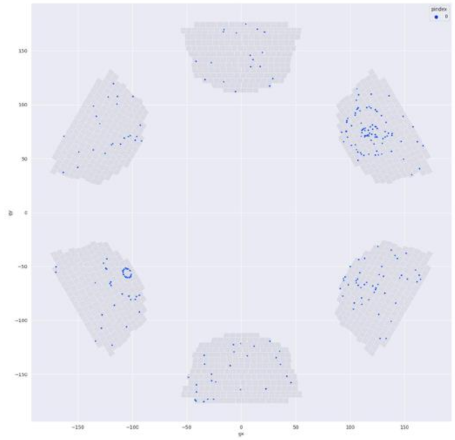
Scheme based on ePIC DAM (Felix) & APEIRON communication network (INFN)

sub-sector integrated analysis | detector integrated analysis





Phys Signal+Phys Background+Noise

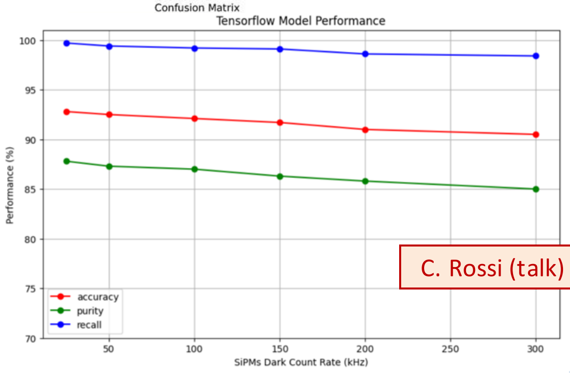


Promising preliminary tests

➔ 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 $dn/d\lambda = 6\ 10^{-6}\ nm^{-1}$ 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 $dn/d\lambda = 0.2\ 10^{-6}\ nm^{-1}$ 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

Mirror Technical Performance

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

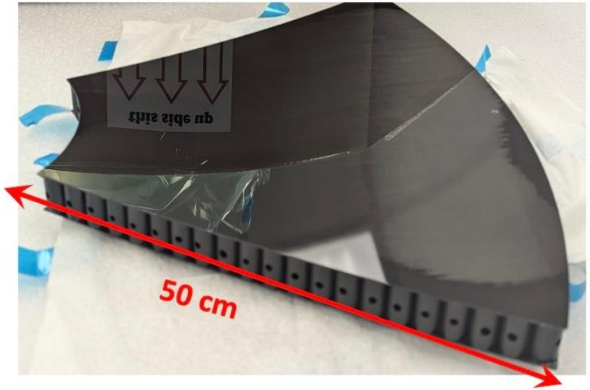
Annex C. Technical Requisite

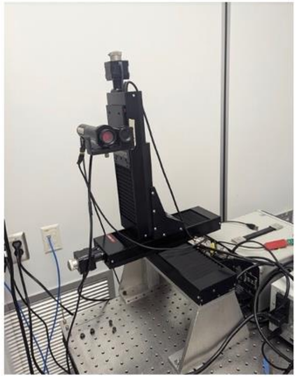
Each spherical mirror is supplied with

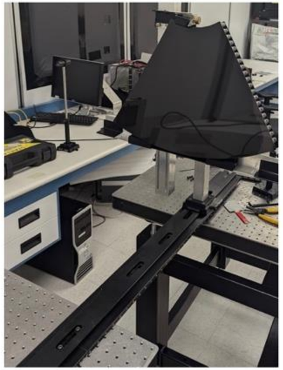
- a spot-size measurement,
- a report on dimensions,
- no reflective coating.

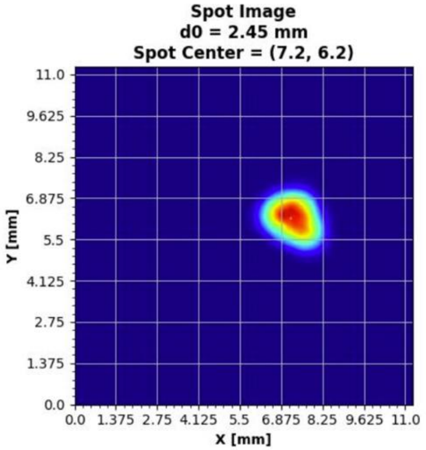
The spherical mirrors are replicated from the same mandrel. The latter is realized with the novel cost-effective technology that reduces the mandrel total mass and cost. Each mirror fulfills the following optical quality specification:

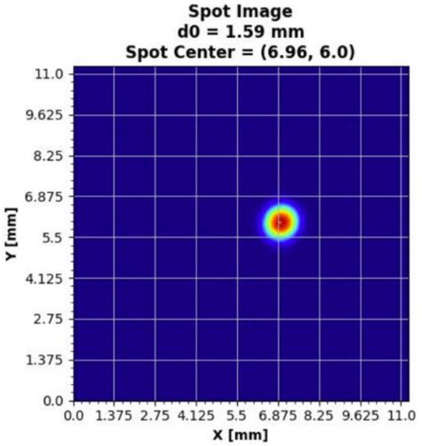
- Radius within 1% of nominal RoC value (the nominal RoC values is defined by the customer before production in the range 2000 mm +/- 10%),
- Roughness < 2 nm,
- Pointlike image spot size D0 < 2.5 mm,
- Compatibility with fluorocarbon gases (C_2F_6),
- Compatibility with SiO_2 reflecting coating.



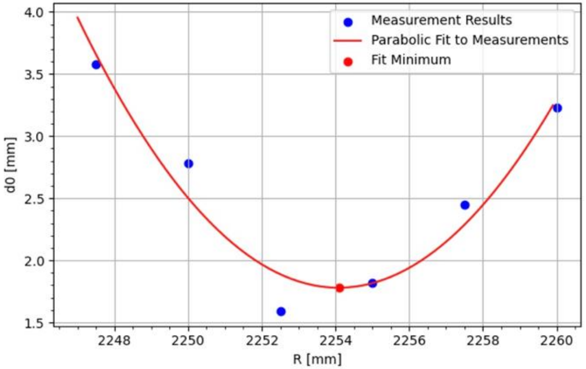






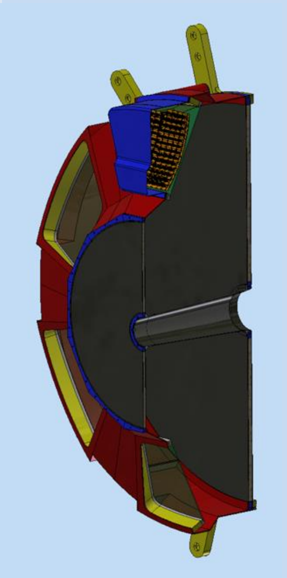


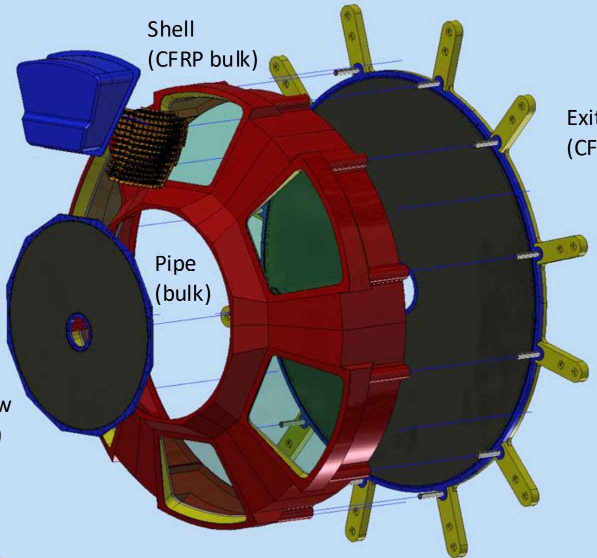
✓ D0 < 2.5 mm ✓ R = 2200 +/- 1%



General Layout

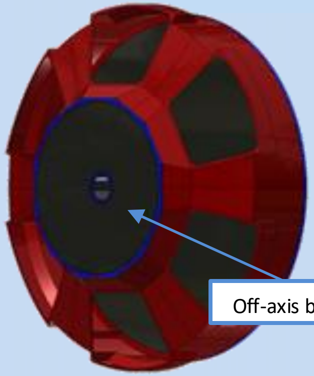
A detailed mechanical model of the single-vessel detector is outlined with composite materials

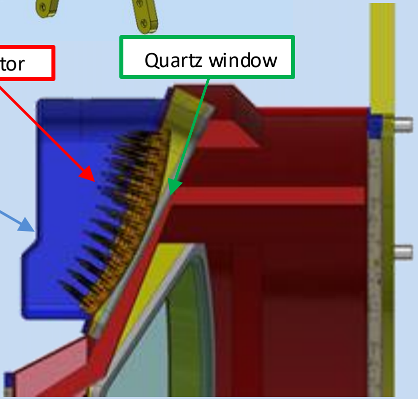




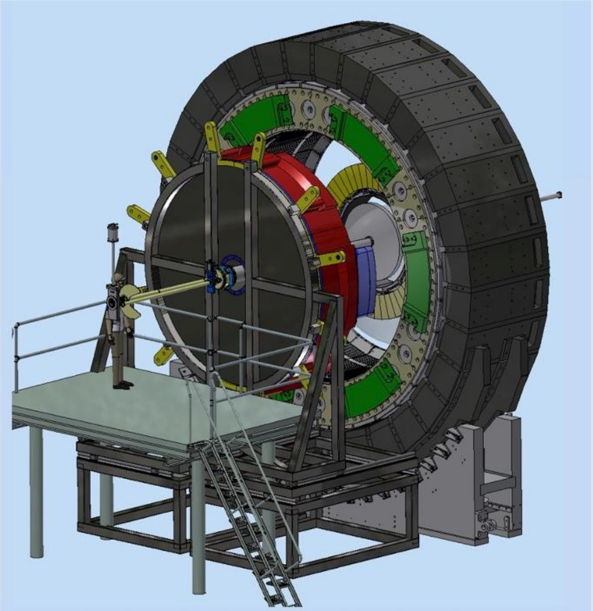
Composite materials

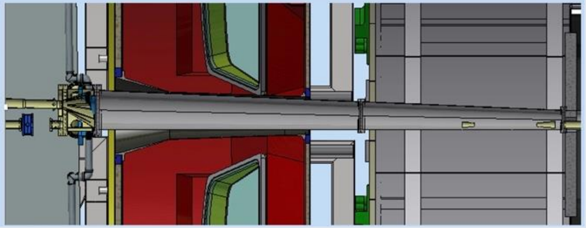
Total wieght: ~ 2 ton





On-site maintenance access
without breaking the beam vacuum





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

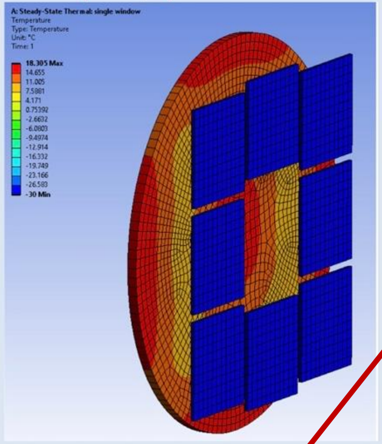
Ongoing study with ANSYS workbench simulations

Benchmarked by dRICH prototype

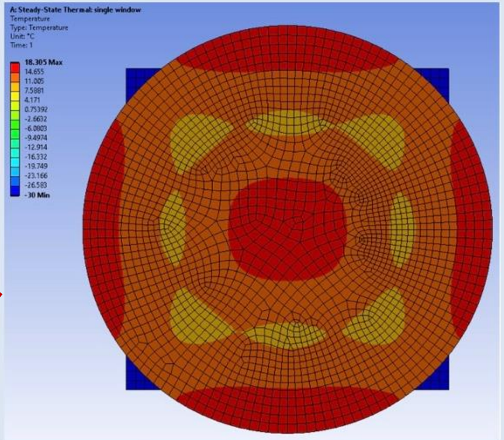
Gradients are largely mitigated by

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

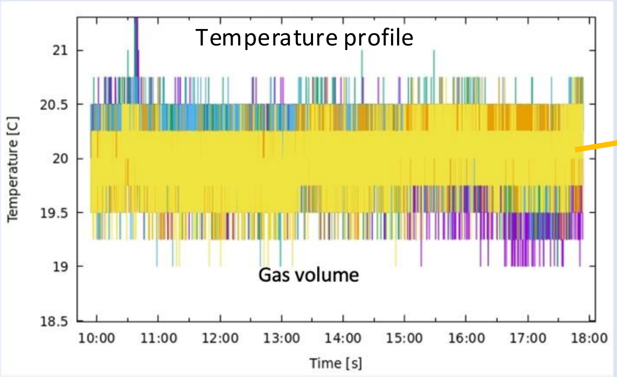
SiPM plane, cycled from 22º to -30º

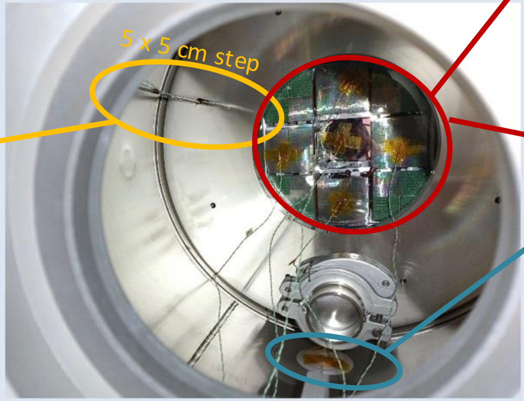


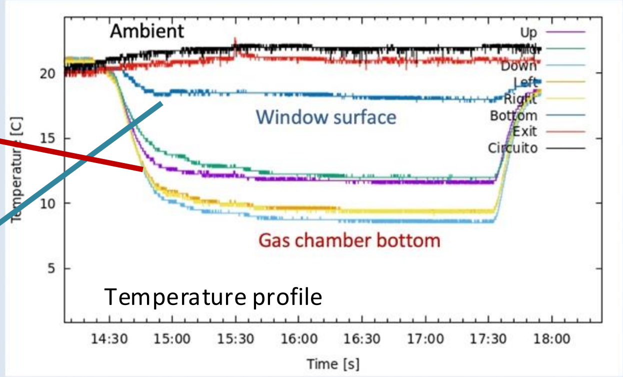
3 mm lucite window



Gas volume with thermocouples



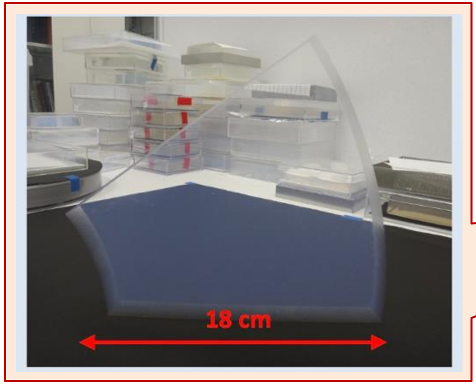


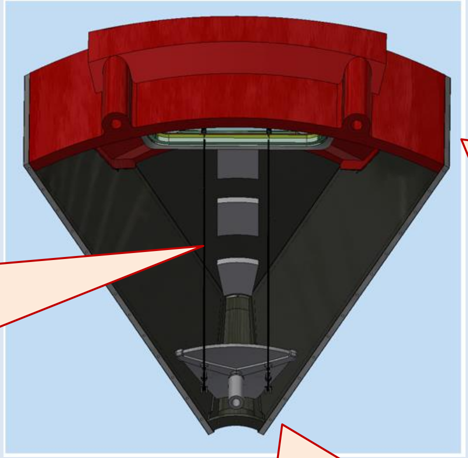


Real Scale Prototype

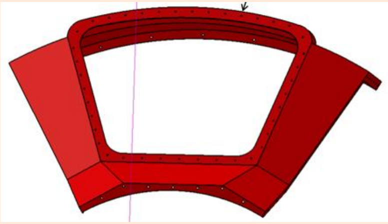
Engineering of all the mechanical details pursued with the real-scale prototype now expected by mid-October

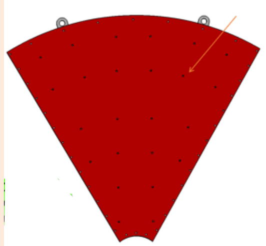
Aerogel demonstrator

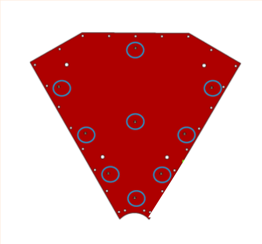


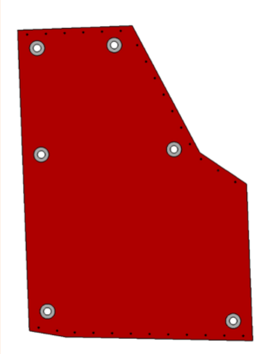


Under Construction



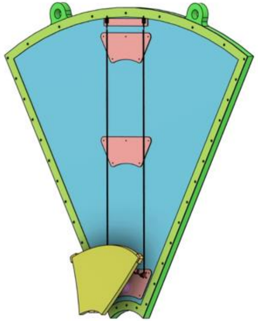


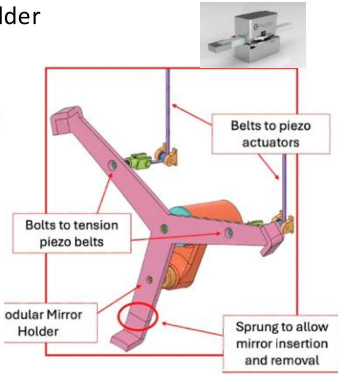




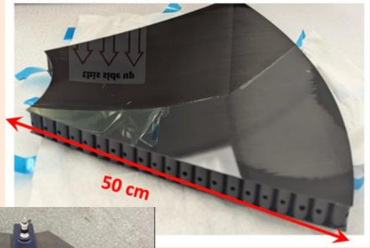
CFRP layer samples

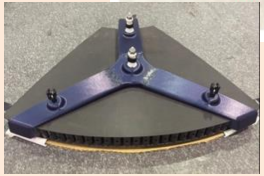
Mirror mounting and holder





JLab





Previous validations:

Dual-radiator concept

C_2F_6 radiator gas performance

Aerogel rafractive index

SiPM-ALCOR readout chain

EIC-drive readout plane

Induced temperature gradients

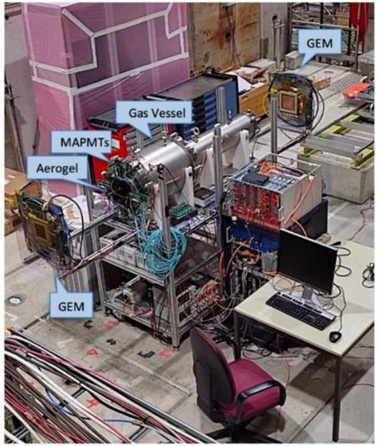
2025 main goals:

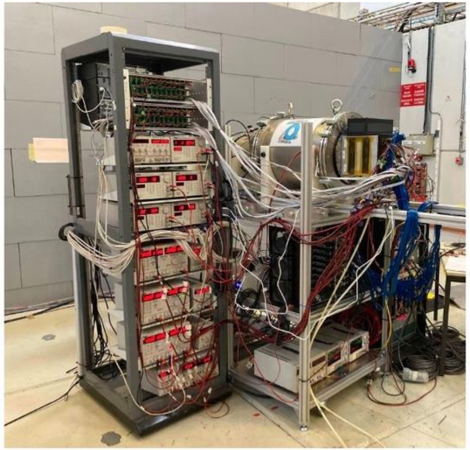
UVE Sensors

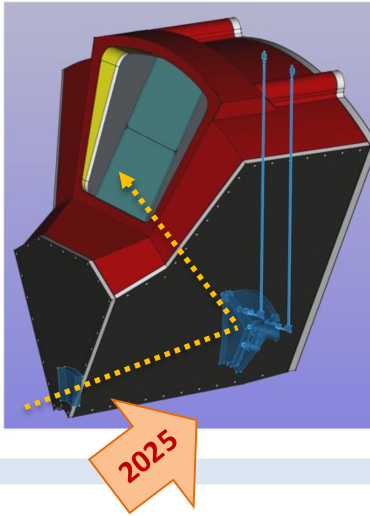
ALCOR readout with RDO

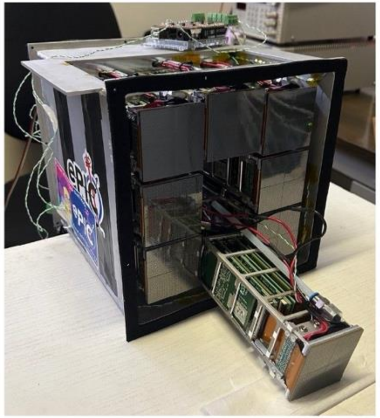
Real scale 1-sector prototype
with demo components

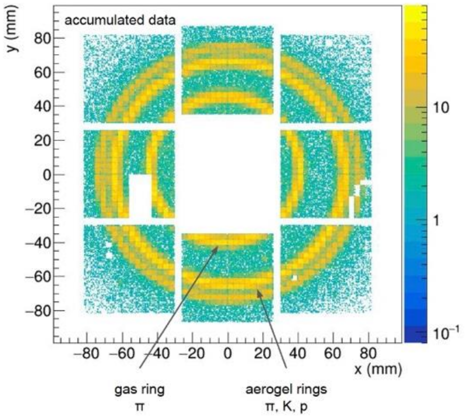
Slot at SPS H8 in November

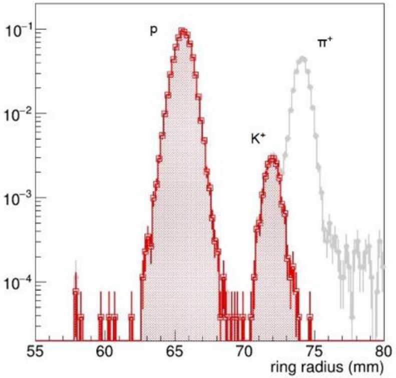








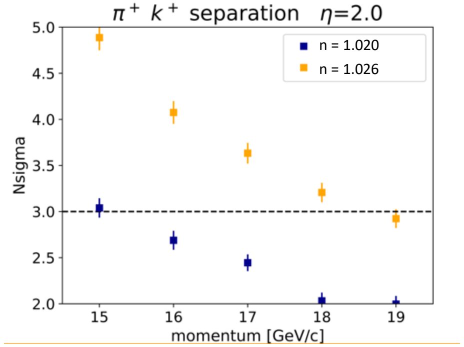




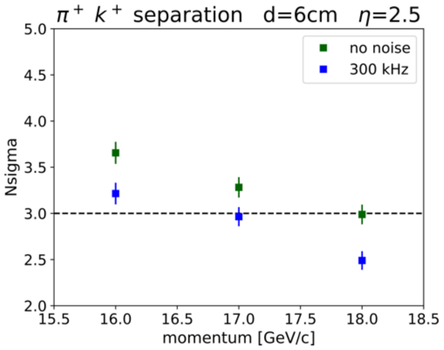
Simulation within ePIC dd4hep framework accounts for tracking, material budget and magnetic bending.

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

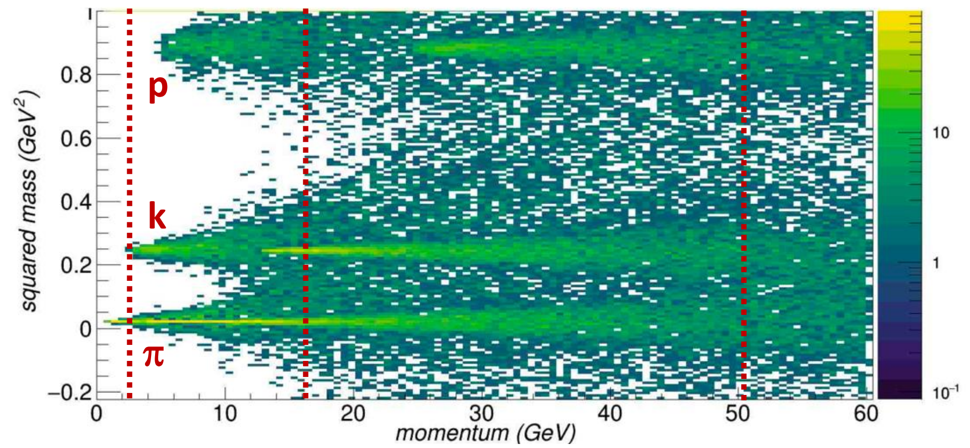
Aerogel specs

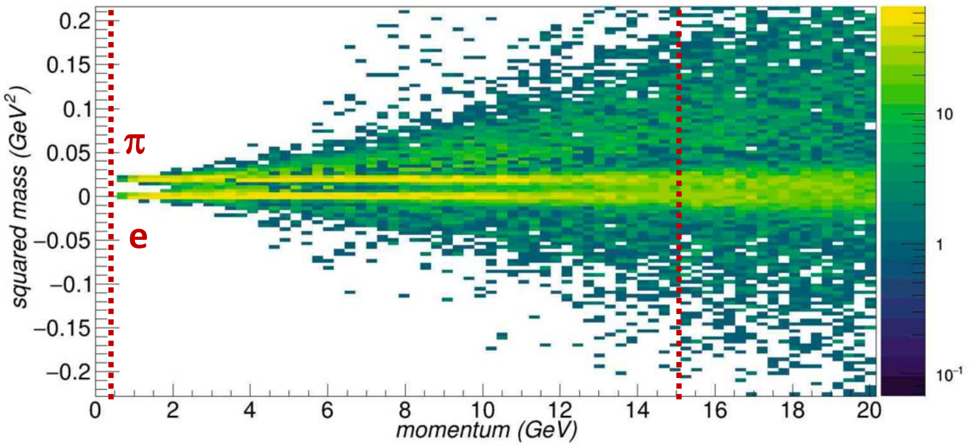


SiPM Dark-counts



T. Boasso (poster)





Conclusions

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 fom 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