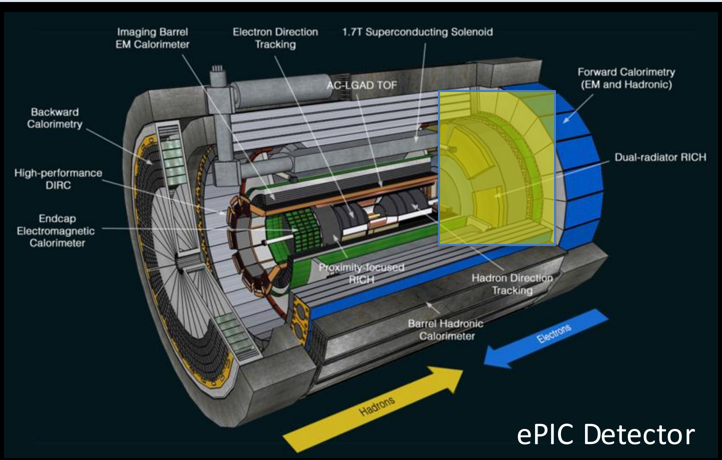
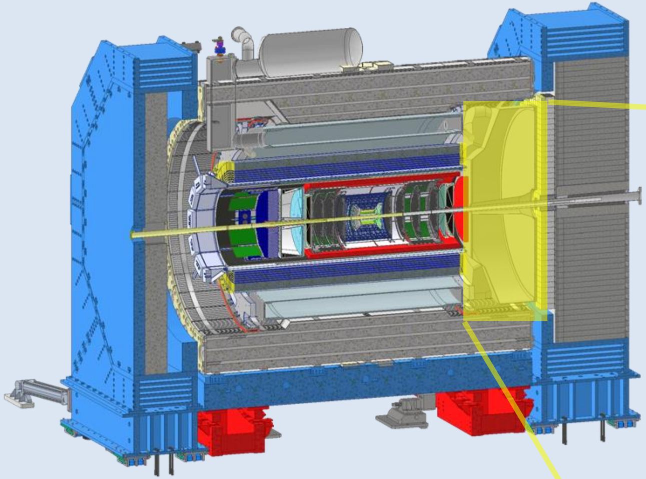
eRD102 - dRICH



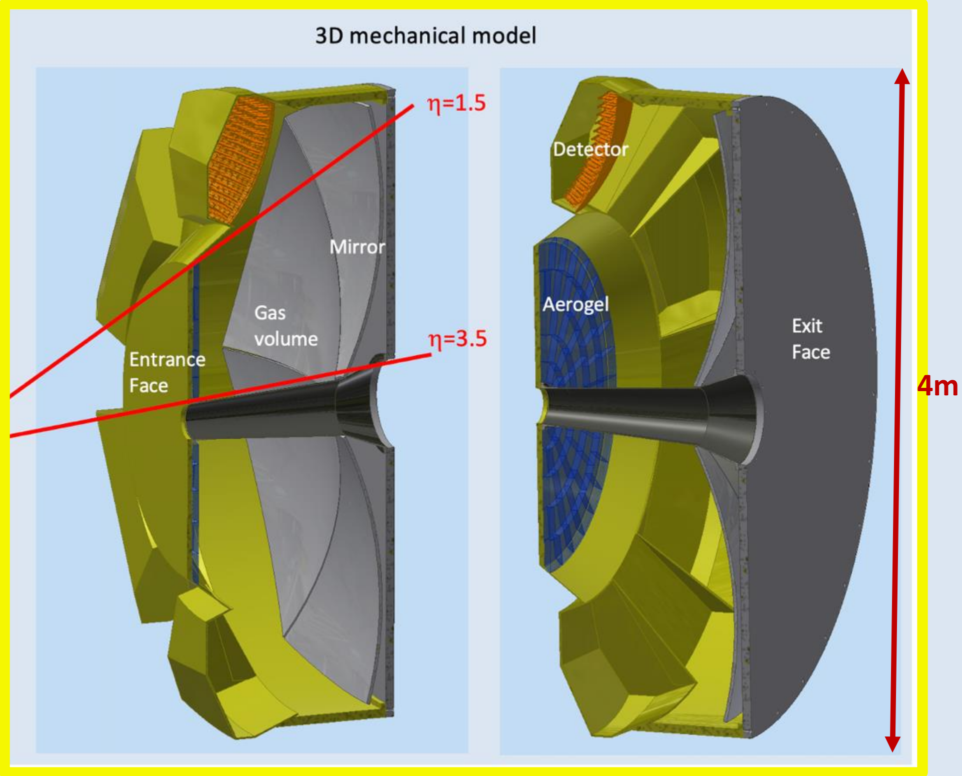
M. Contalbrigo – INFN Ferrara - DSCL

ePIC / EIC Project Detector R&D Day – April 16th and 17th, 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

Technical Performance Requirements

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
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
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 Reflectivity $\gtrsim$ 90 %
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
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 Digital programmable shutter
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

Aerogel with n=1.026 validated with lab and prototype tests

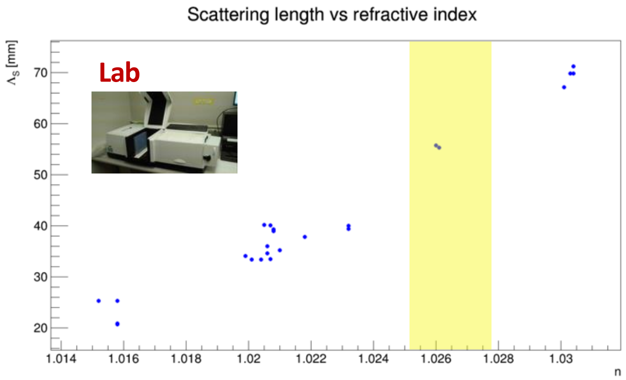
* meet SPE resolution expectations

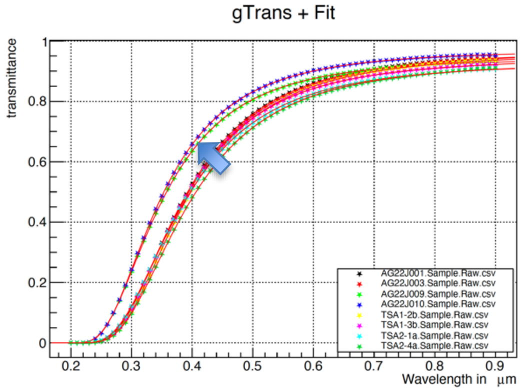
* scattering length > 50 mm

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

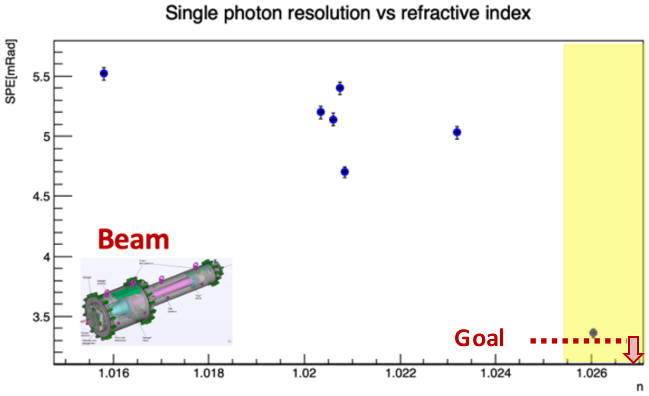
* overlap with gas (> 12 GeV/c)

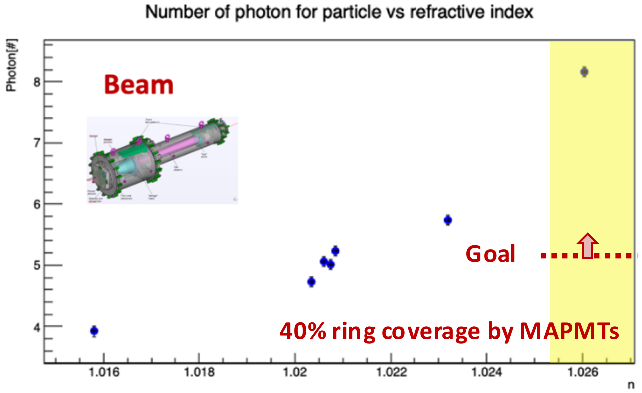
* photon yield > 10 per particle with MAPMTs





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

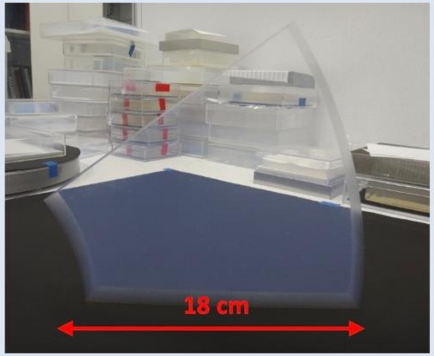
* optimize area vs number of tiles

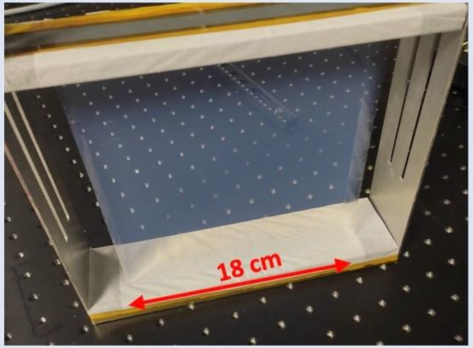
* minimize the waste of material

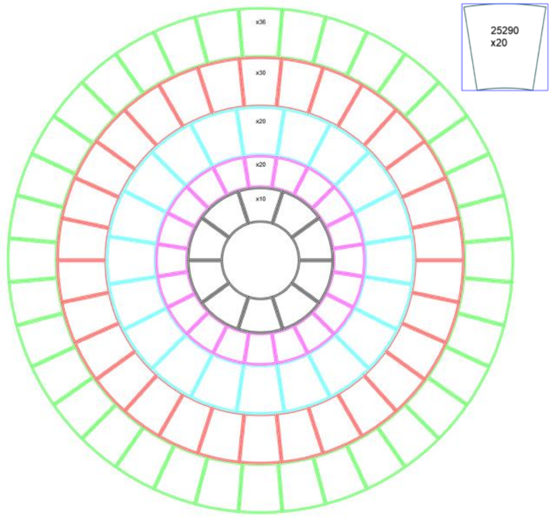
* minimize the dead/low-efficiency gaps

* optimize thickness:

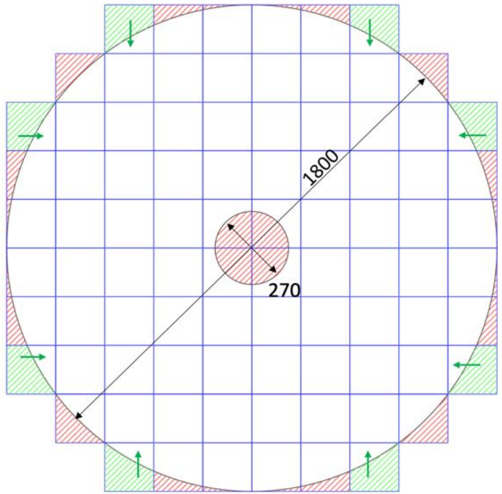
  - photon yield vs resolution
  - planarity







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 %)

Technical Performance Requirements

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
Gas:	Momentum reach above 50 GeV/c at pseudorapidity > 2.5 More than 20 detected photons from 1 m depth Single photon resolution approaching1 mrad	C_2F_6	with n = 1.00086 $dn/d\lambda = 0.2\ 10^{-6}\ nm^{-1}$ absorption length > 100 m
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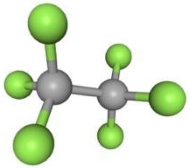
Mechanics:	Acceptance maximized in 1.5 – 3.5 pseudorapidity range Material budget minimized in acceptance Compatibility with barrel maintenance at IP6		Composite materials Single open volume Detector in the barrel shadow

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

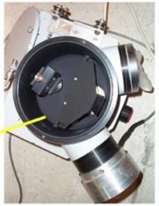
density: 5.734 kg/m³ at 24 °C

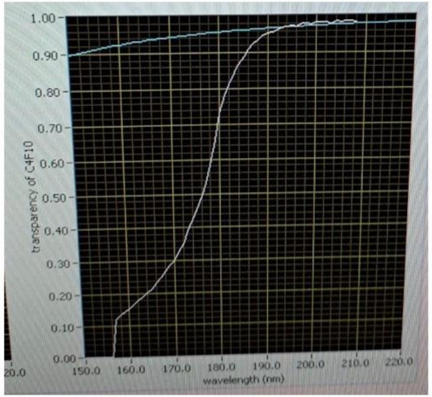
density: 16.08 kg/m³ at -78 °C

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 %

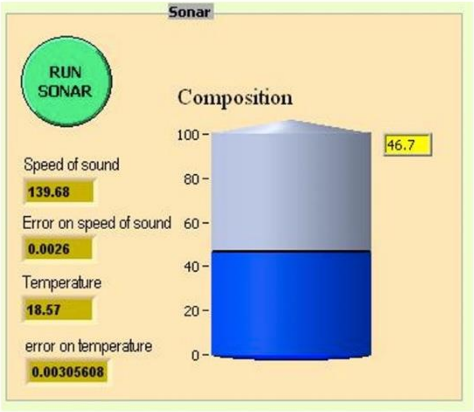
Transmission in UV range > 98 %

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

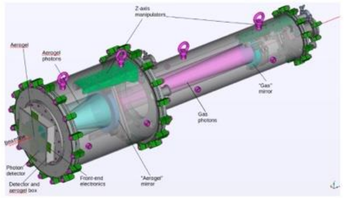


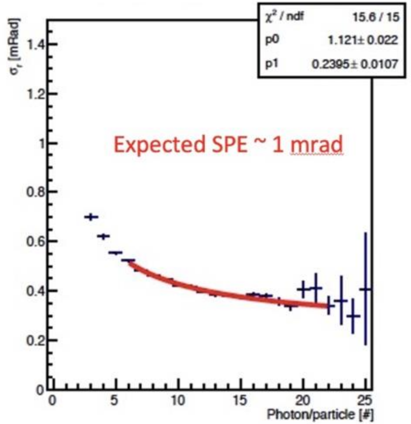


Measured 139.7 m/s speed of sound confirms negligible contaminants after few year in bottle



Expected performance obtained with dRICH prototype



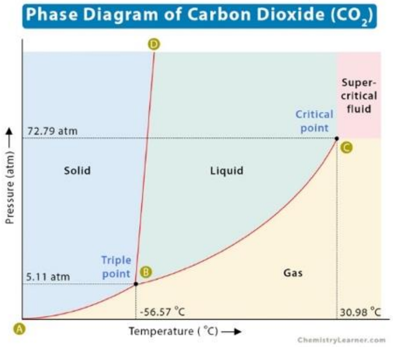


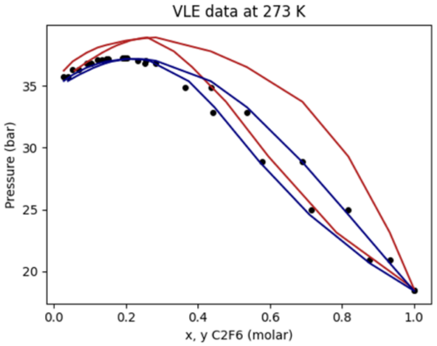
Gas Separation and Purging

Development of gas separation protocols expected by 2026

Purging via liquefaction of unwanted gas

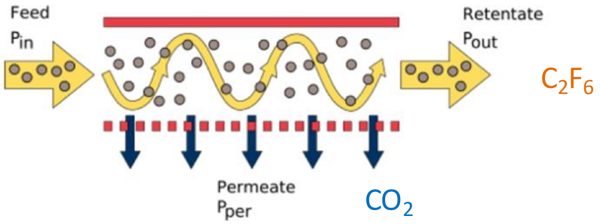
Updated vapor-liquid equilibrium C_2F_6-CO_2 model, test in preparation at CERN

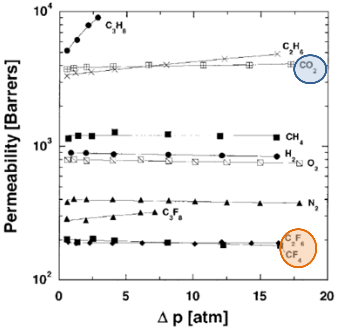




Purging via membranes

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

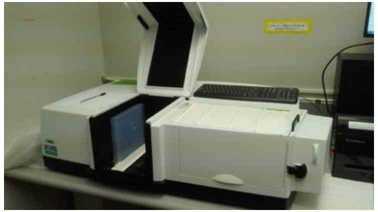


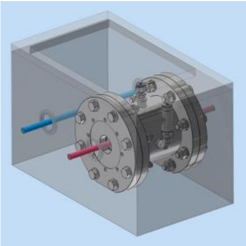


Design of online purity monitors expected by 2026

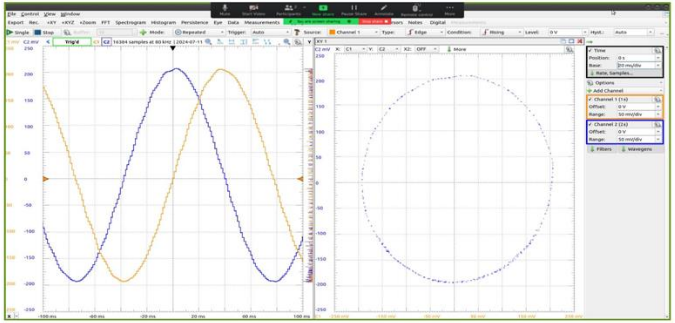
Sonar to measure speed of sound

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

Technical Performance Requirements

	Requirements		Solution
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
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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

Mirror Technical Performance

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

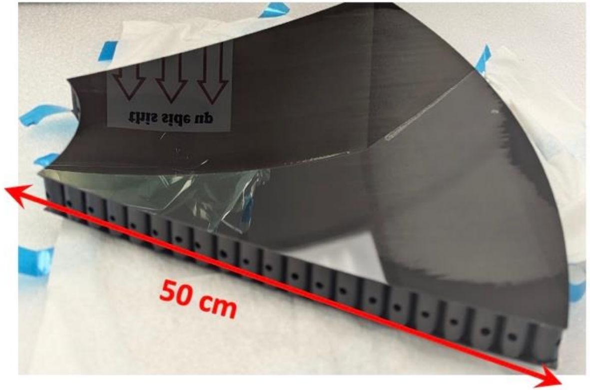
Annex C. Technical Requisite

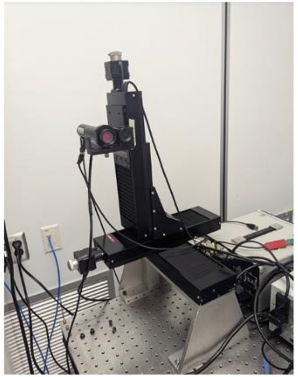
Each spherical mirror is supplied with

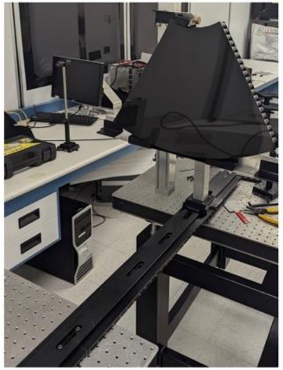
- a spot-size measurement,
- a report on dimensions,
- no reflective coating.

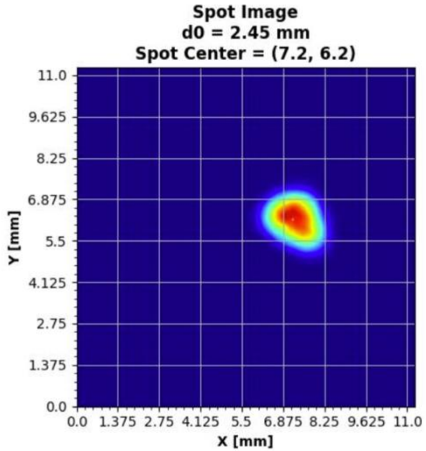
The spherical mirrors are replicated from the same mandrel. The latter is realized with the novel cost-effective technology that reduces the mandrel total mass and cost. Each mirror fulfills the following optical quality specification:

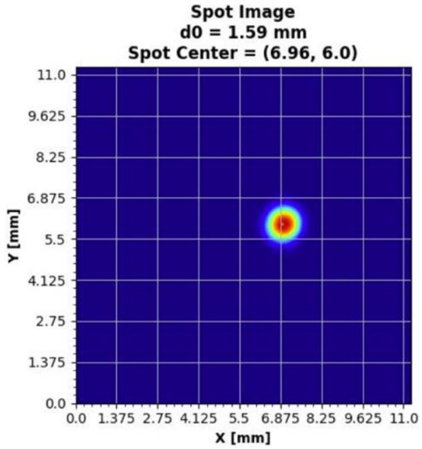
- Radius within 1% of nominal RoC value (the nominal RoC values is defined by the customer before production in the range 2000 mm +/- 10%),
- Roughness < 2 nm,
- Pointlike image spot size D0 < 2.5 mm,
- Compatibility with fluorocarbon gases (C_2F_6),
- Compatibility with SiO_2 reflecting coating.



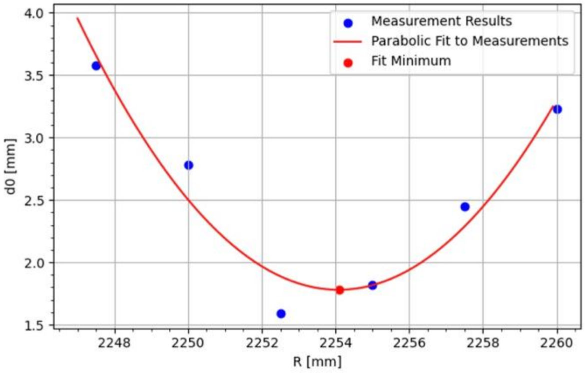






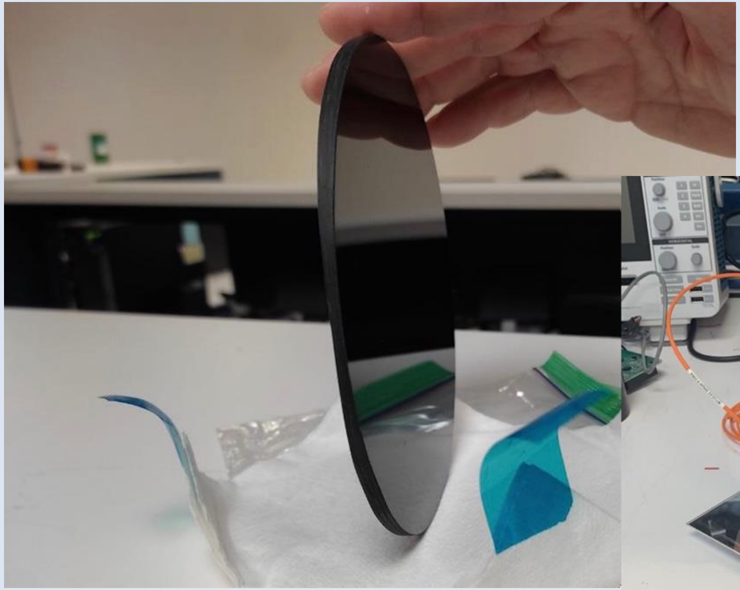


✓ D0 < 2.5 mm ✓ R = 2200 +/- 1%



Ongoing activities with possible synergies with pfRICH to be completed by 2026

Studying special material (ultra-low degassing)



Developing portable reflectivity test beanch

Testing coating (SBU) on dRICH samples

Technical Performance Requirements

Component	Requirements		Choice	Specifications
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
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
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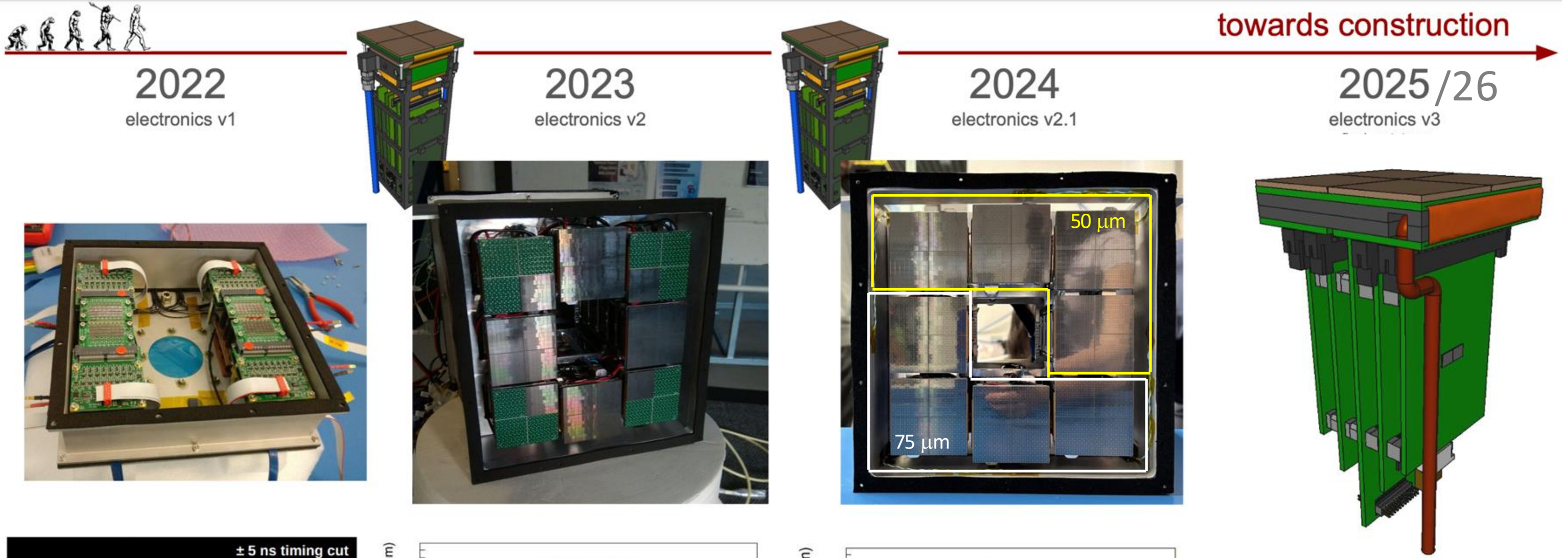
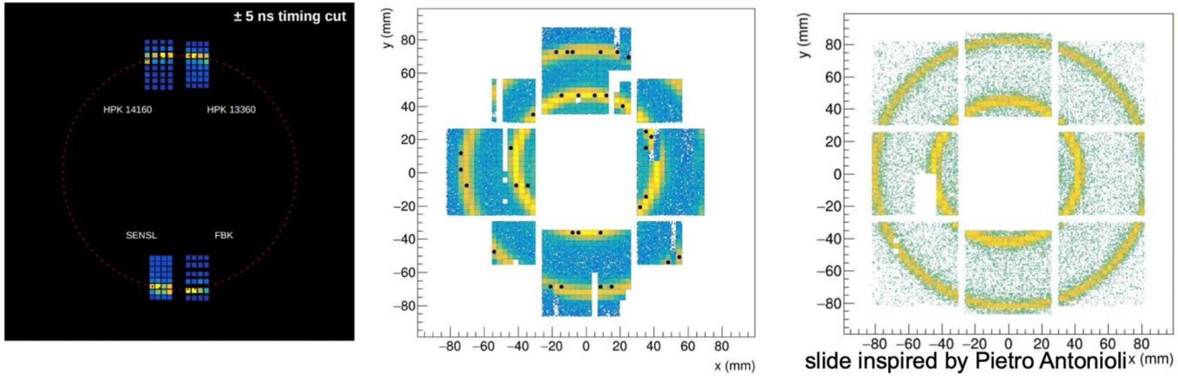
Steadly progress of photodetector towards integrated design completion in 2026





Full size engineering test article

2025
+ SiPM carrierv3
+ RDO

2026
+ ALCOR 64ch
+ FEB 64

Baseline specs defined at the SiPM LLP Rewiew in fall 2023 after several tests on a variety of sensors

SiPM technical specs

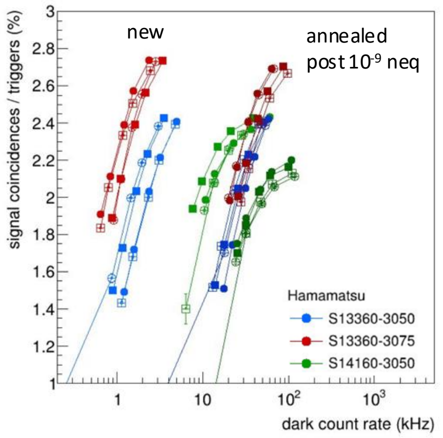
baseline sensor device
64 (8x8) channel SiPM array
3x3 mm^2 / channel

Parameters	Value	Notes (all parameters at the recommended operating voltage and T = 25 C, unless specified)
Device type	SiPM array	
Number of channels	64	8 x 8 matrix
Active Area	3 x 3 mm²	active area of one channel, total active area is 64 x 3 x 3 mm²
Device Area	< 28 x 28 mm²	device area should be small such as to have > 75% fraction of active area over device total area
Pixel Size	40 - 80 um	pitch of the microcell SPAD
Package Type	surface mount	
Operating voltage	< 64 V	
Peak Sensitivity	400 - 450 nm	
PDE	> 35%	at peak sensitivity wavelength
Gain	> 1.5 10⁶	
DCR	< 1.5 MHz	
Temperature coefficient of Vop	< 60 mV / C	
Direct crosstalk probability	< 10%	
Terminal capacity	< 600 pF	
Packing granularity		
Vop variation within a tray	< 300 mV	Vop variation between channels in one device
Recharge Time	< 100 ns	ctau recharge time constant
Fill Factor	> 70%	
Protective Layer	silicone resin (n = 1.5 - 1.6)	radiation resistant, heat resistant (up to T = 180 C)
DCR at low temperature	< 10 kHz	at T = -30 C
DCR increase with radiation damage	< 1 MHz / 10⁹ neq	at T = -30 C, after a radiation damage corresponding to 10⁹ 1-MeV neutron equivalent / cm² (neq)
Residual DCR after annealing	< 25 kHz / 10⁹ neq	at T = -30 C, after a radiation damage of 10⁹ neq and a 150 hours annealing cycle at T = 150 C
Single photon time resolution	< 200 ps FWHM	corresponding to < 85 ps RMS

we will evaluate as part of QA, testing sensor samples in received batches

8

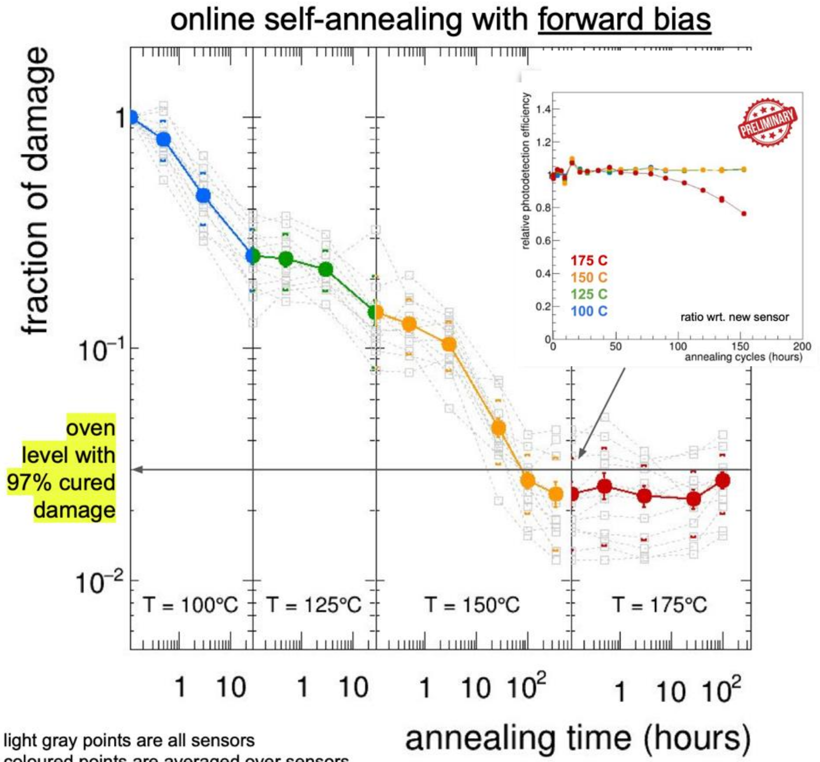
Based on PDE vs DCR studies over a variety of SiPM



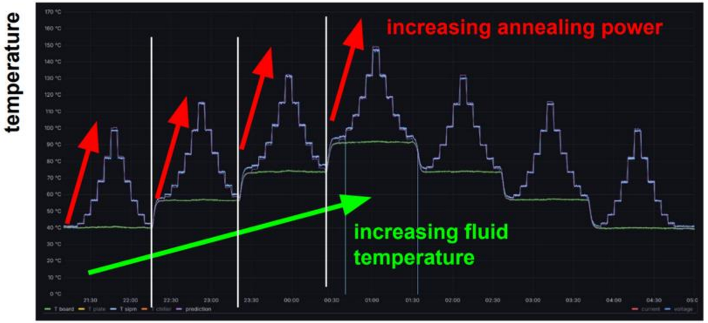
PED funds

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

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

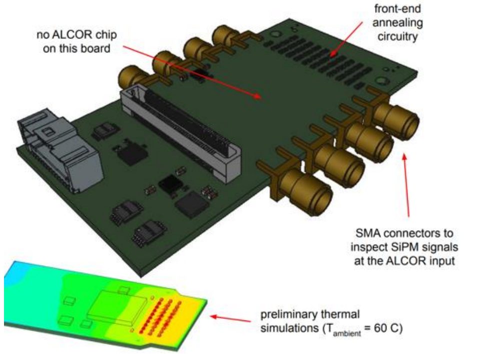


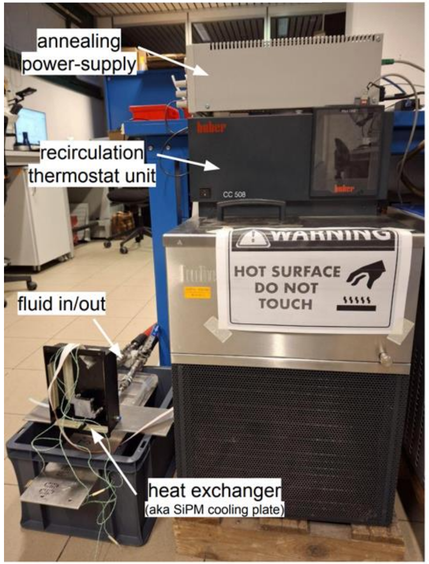
light gray points are all sensors
coloured points are averaged over sensors
coloured brackets is the RMS



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

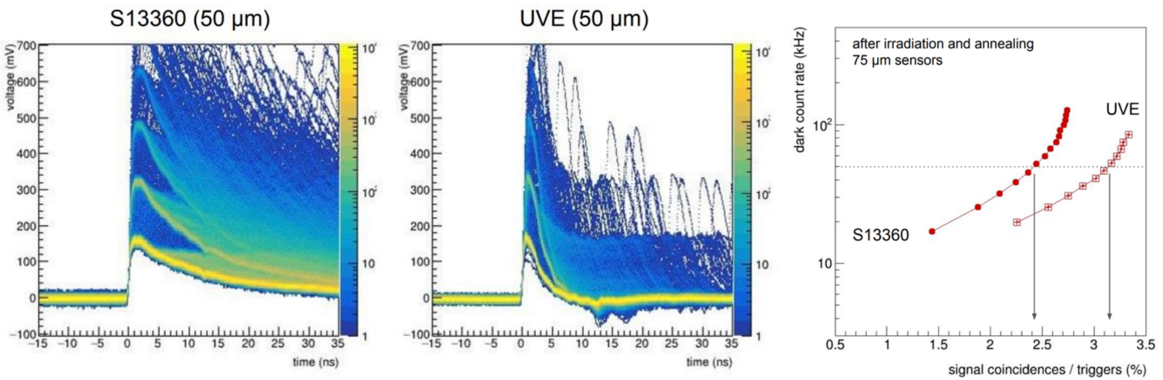
goals
- test realistic dRICH annealing electronics
- study/engineering of annealing process details



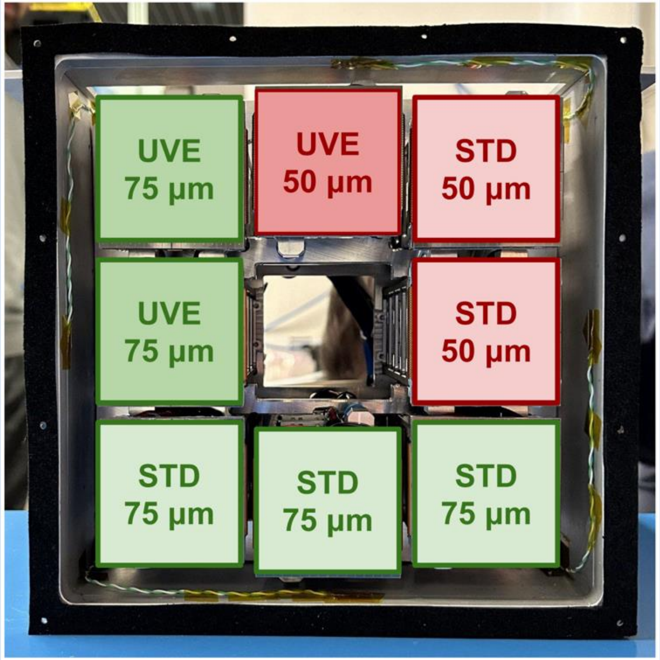


Sensor Layout Engineering

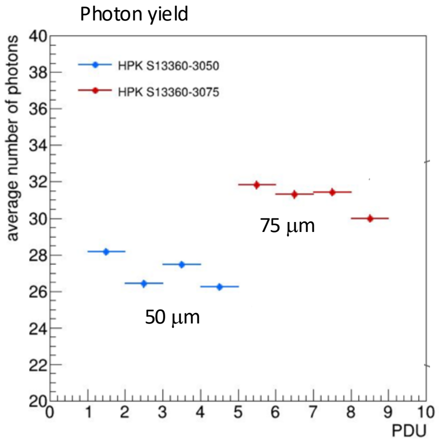
Novel UVE fast SiPM

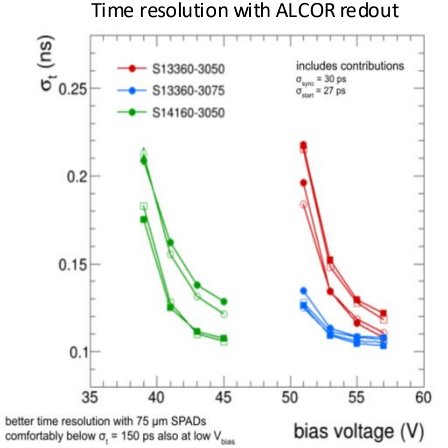


- **purchased and received**
  - 4x matrices with 50 µm SPADs
  - 12x matrices with 75 µm SPADs
  - several single-SiPM sensors
- **goal**
  - assemble few new PDUs
  - use them in the next beam test
  - evaluate expected PDE improvement



SPAD size





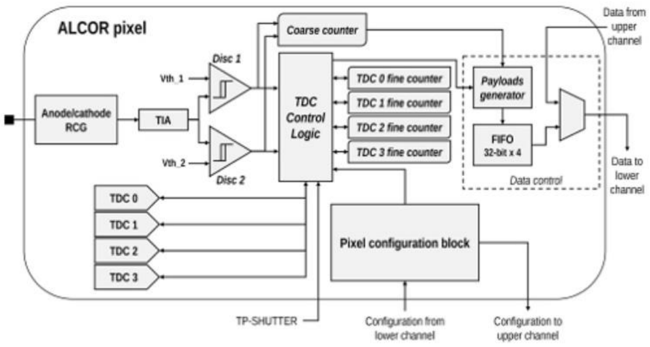
Technical Performance Requirements

	Requirements		Choice	Specifications
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
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
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 Reflectivity $\gtrsim$ 90 %
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
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 Digital programmable shutter
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

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

MPW run in March '25

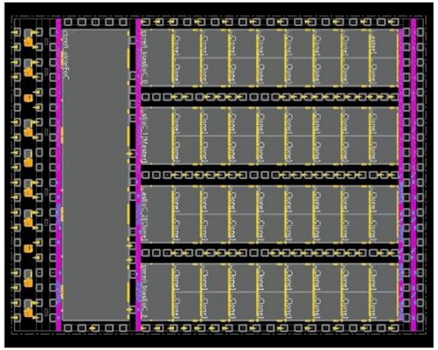
ALCOR block diagram



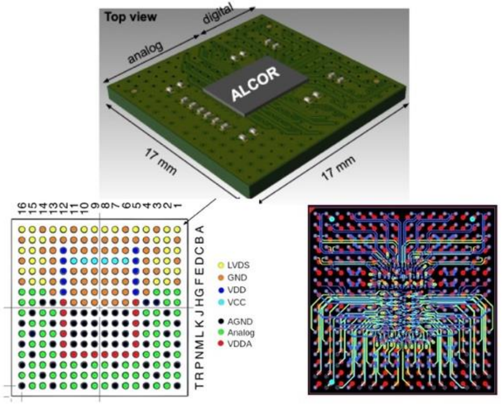
ALCOR key specifications

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
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

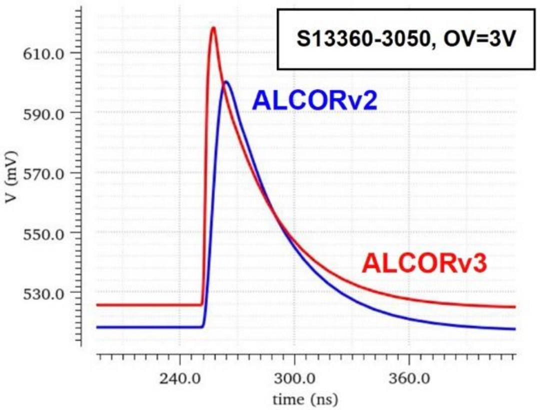
Silicon die layout

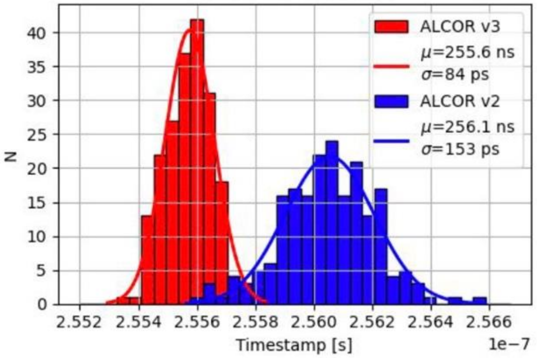


Compact ball-grid array (BGA) package with interposer

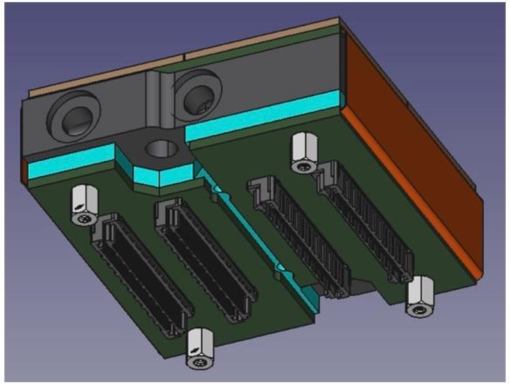


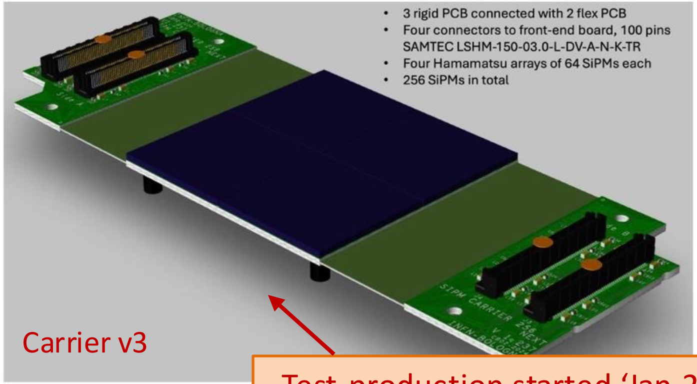
Improved timing and digital shutter



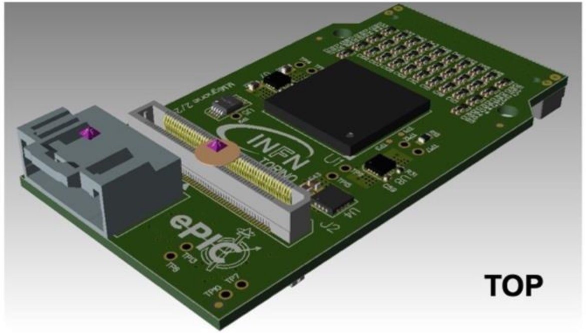


Design of the readout electronics in the “final” ePIC layout version is ready for test production.



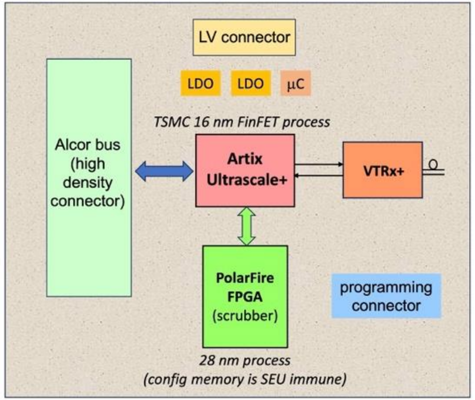


Carrier v3

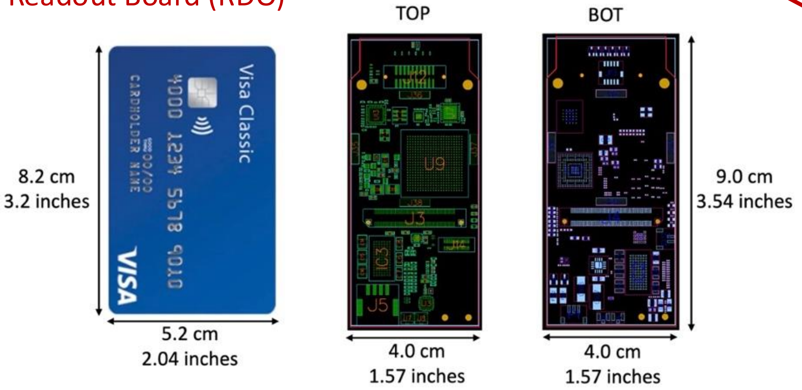


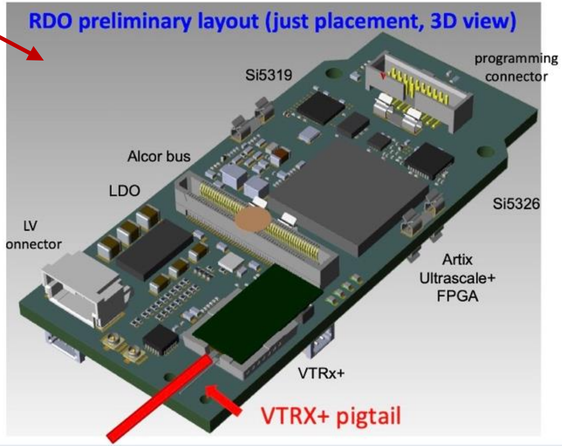
Front-End Board (FEB)

Test-production started ‘Jan 25



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:

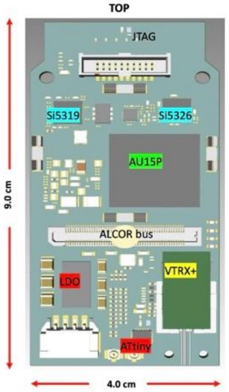
Neutron irradiation campaign at LNL-CN (9-11 October 24)

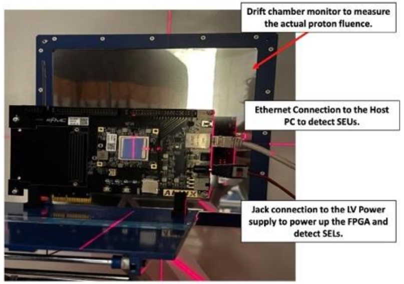
Gamma irradiation campaign at CERN-GIF (14-16 October 24)

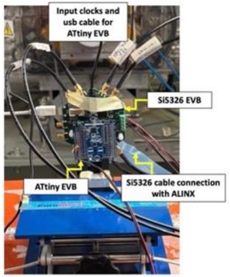
Proton irradiation campaign at TIFPA (12-14 December 24)

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

RDO radiation tolerance



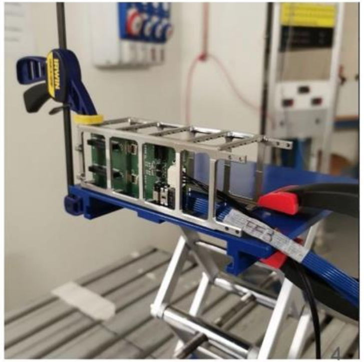




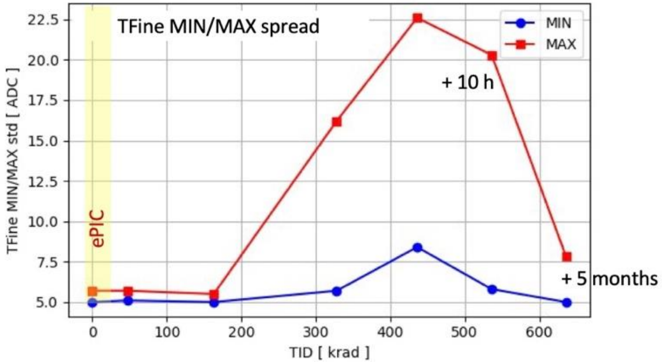
	Measured	Mean SEU time @ ePIC
Si5326 (clock)	$\sigma_{SEU} = (3.89 \pm 0.54) \cdot 10^{-14} \frac{cm^2}{bit}$	4 h
Attiny (power)	$\sigma_{SEU} = (2.11 \pm 0.50) \cdot 10^{-14} \frac{cm^2}{bit}$	3.8 h
AU15P (FPGA)	see table below	2 min

Our estimates	$\sigma_{SEU} \left(\frac{cm^2}{bit}\right)$
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



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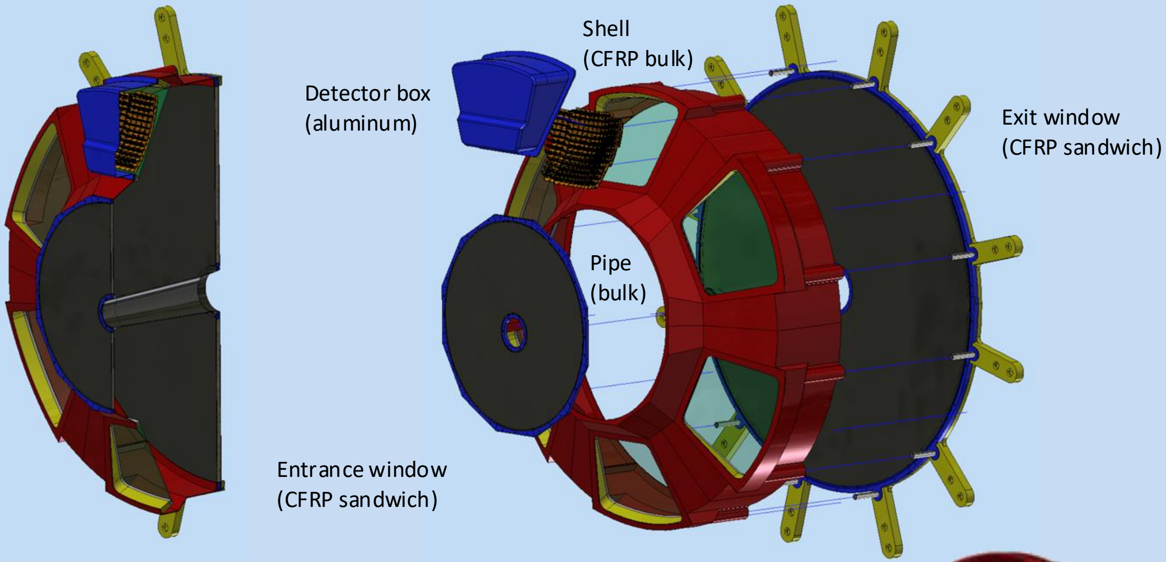
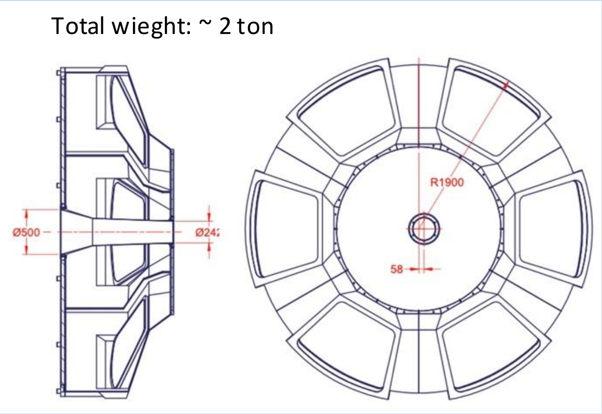
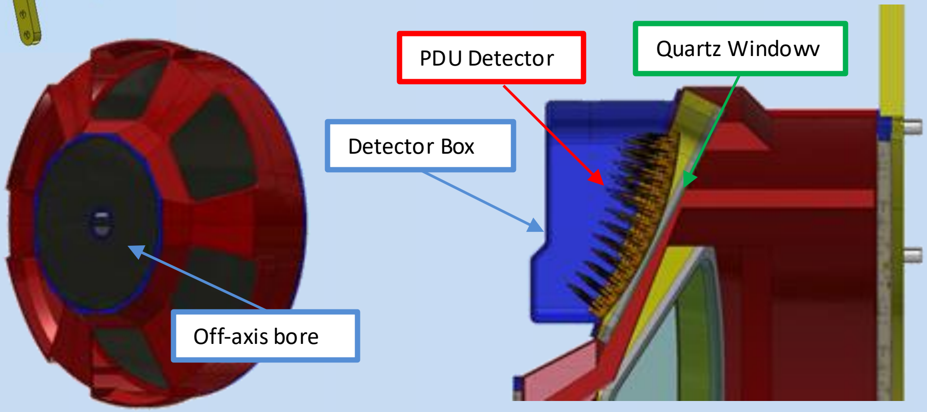
Mechanics:	Acceptance maximized in 1.5 – 3.5 pseudorapidity range Material budget minimized in acceptance Compatibility with barrel maintenance at IP6	⇨		Composite materials Single open volume Detector in the barrel shadow

General Layout

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







New assigned workforce

Cooling: **Carlo Mingioni (engineer, TO)**
Marco Nenni (engineer, TO)

Detector Box: **Michele Melchiorri (engineer, FE)**

Prototype: **Antonio Grmek (LNS)**
Giuseppe Laudani (PhD, LNS)

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

Recommendation: Perform a thermal simulation of the dRICH SiPM array considering different operating temperatures and impact on the quartz window and gas radiator.

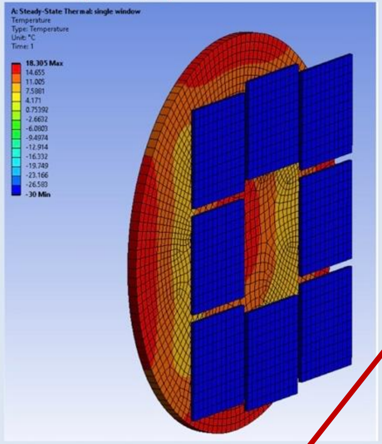
Ongoing study with ANSYS workbench simulations

Benchmarked by dRICH prototype

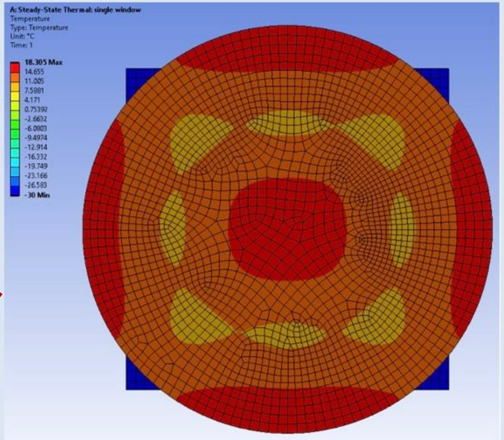
Gradients are largely mitigated by

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

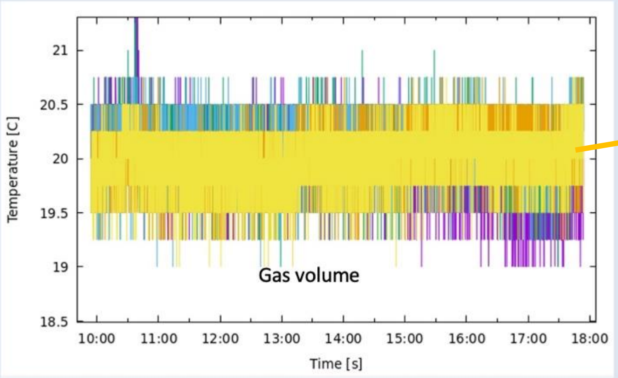
SiPM plane, cycled from 22º to -30º



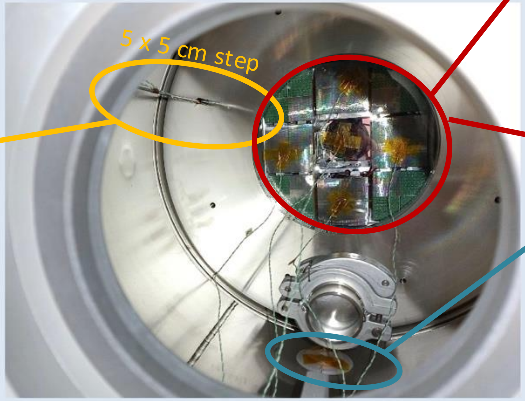
3 mm lucite window



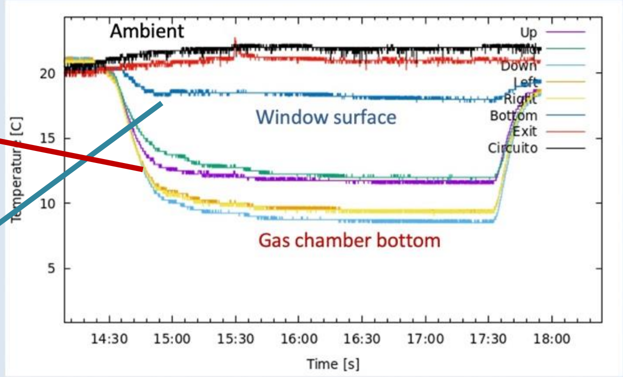
Temperature profile



Gas volume with thermocouples



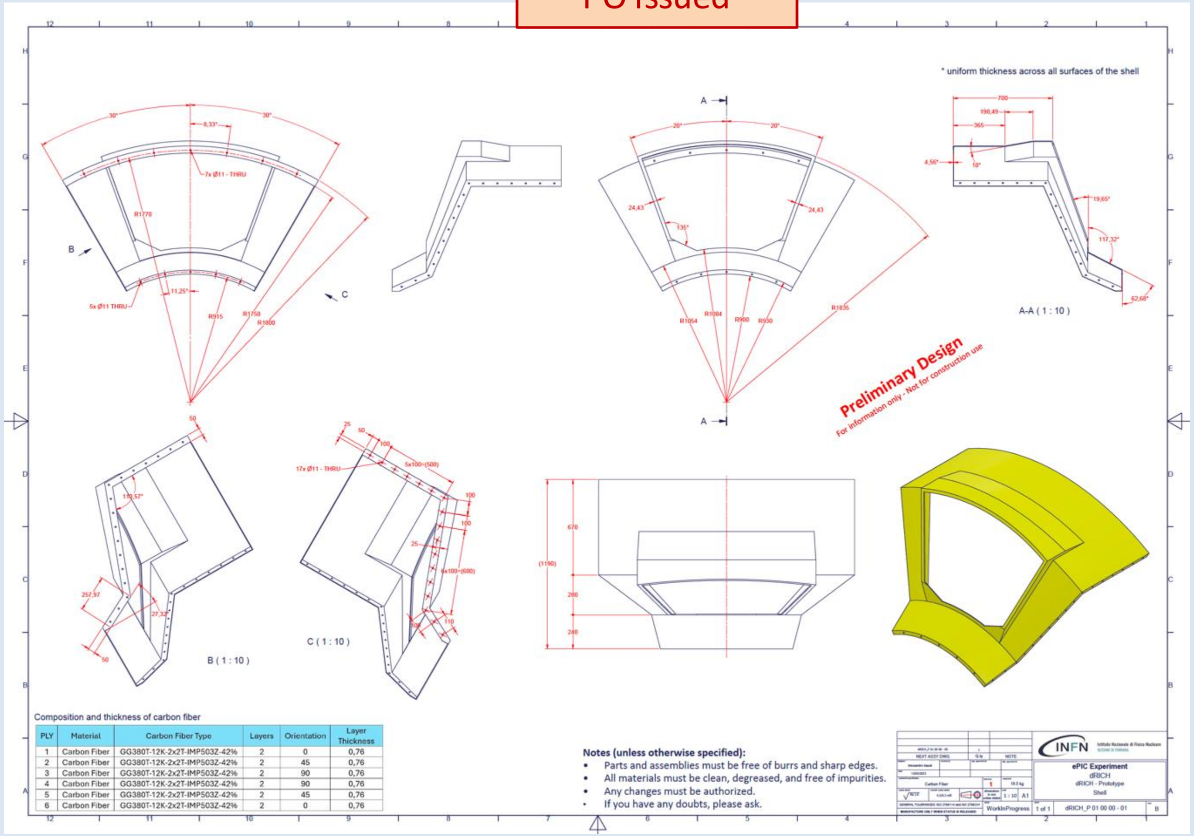
Temperature profile



Real-scale Prototype

Engineering of all the mechanical details pursued with the real-scale prototype being realized in 2025

PO issued

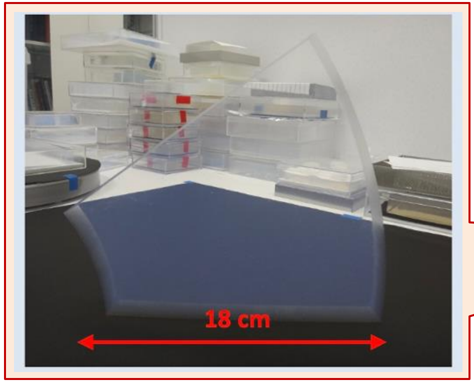


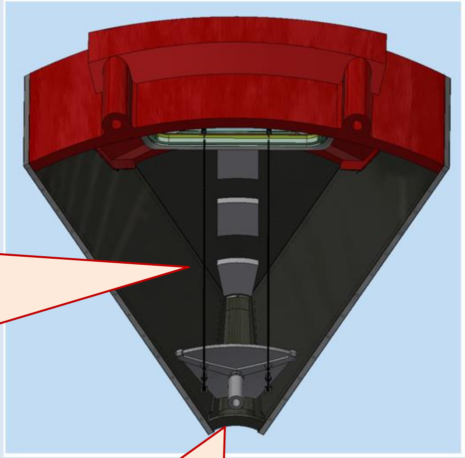
Composition and thickness of carbon fiber

PLY	Material	Carbon Fiber Type	Layers	Orientation	Layer Thickness
1	Carbon Fiber	GG380T-12K-2x2T-IMP503Z-42%	2	0	0,76
2	Carbon Fiber	GG380T-12K-2x2T-IMP503Z-42%	2	45	0,76
3	Carbon Fiber	GG380T-12K-2x2T-IMP503Z-42%	2	90	0,76
4	Carbon Fiber	GG380T-12K-2x2T-IMP503Z-42%	2	90	0,76
5	Carbon Fiber	GG380T-12K-2x2T-IMP503Z-42%	2	45	0,76
6	Carbon Fiber	GG380T-12K-2x2T-IMP503Z-42%	2	0	0,76

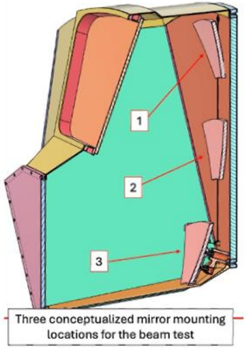
CFRP Layer composition

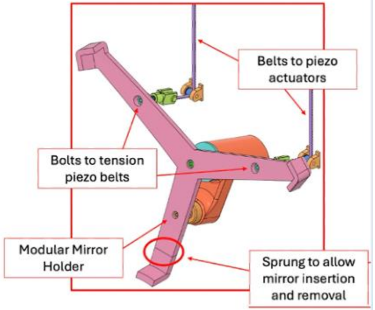
Aerogel support

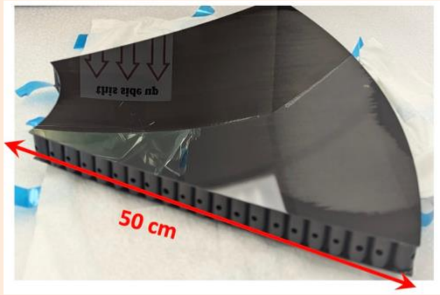




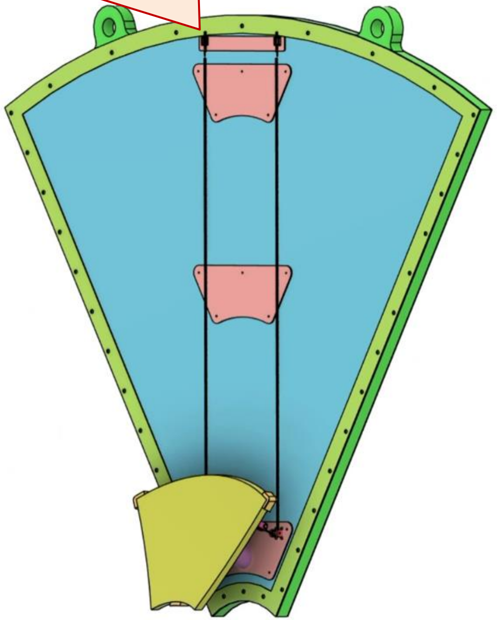
Mirror mounting and alignment (aka NA62)





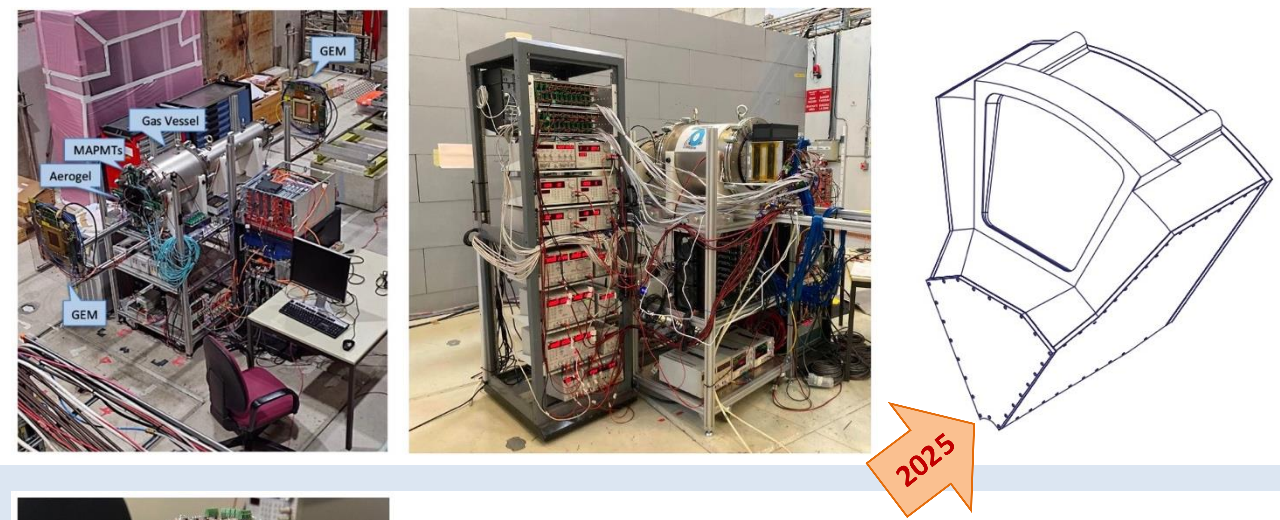


Piezo-electric translator



Previous validations:

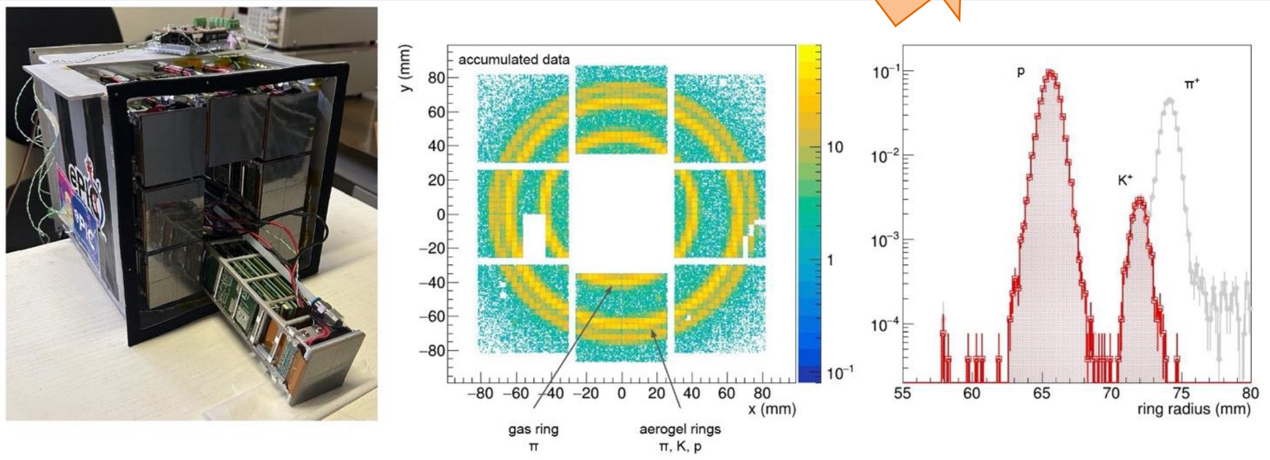
- Dual-radiator concept
- C_2F_6 radiator gas performance
- Aerogel rafractive index
- SiPM-ALCOR readout chain
- EIC-drive readout plane
- Temperature gradients



2025 main goals:

- Real scale 1-sector prototype with demo components
- ALCOR redout with RDO

Slot at SPS H8 in November



dRICH technological choices are supported by a structured performance and simulations activity

Essential to guide technological choices

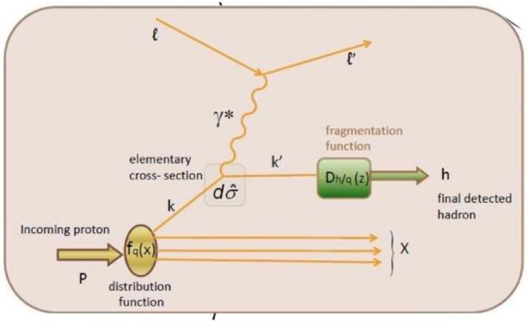
Effective entry-point for new collaborators

New performance study group being initiated

Focussed on SIDIS physics

Experience in Spin Physics and Nucelon Structure gained at HERMES (DESY), CLAS12 (JLab) and COMPASS (CERN)

INFN FE-BO-PV-TO-SA-LNS-TS (7 staff, 5 student/postdoc)

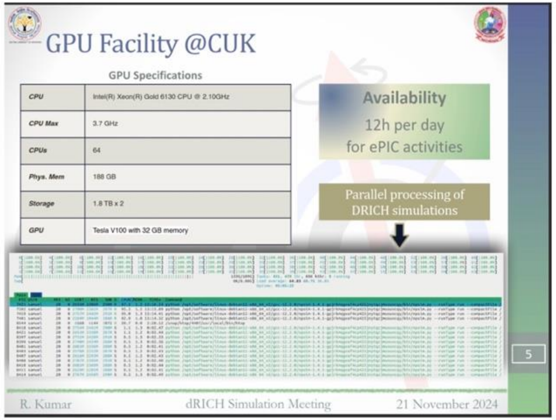


Close collaboration with Theory groups already active in inpact studies on (un-)polarized TMDs

INFN PV-TO (4 staff, 1 student/postdoc)

Significant reinforcement of the simulation group

- New group also provided resources to perform many new simulation - 12h/day allocation for ePIC
  - Substantial use of GPUs
- Simulations and Reconstruction in EICrecon



INFN TS-CS
U. of Salerno
Duke U.
Central U. of Karnataka
Central U. of Haryana
Ramaiah U. of Applied Science

(5 staff, 11 student/postdoc)

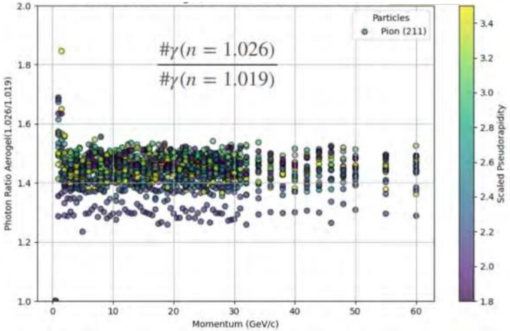
Simulation within ePIC dd4hep framework accounts for tracking, material budget and magnetic bending.

Recommendation: Capture the bi-directional interface between tracking and PID detectors: e.g., translation between position and angular resolution requirements for PID detectors

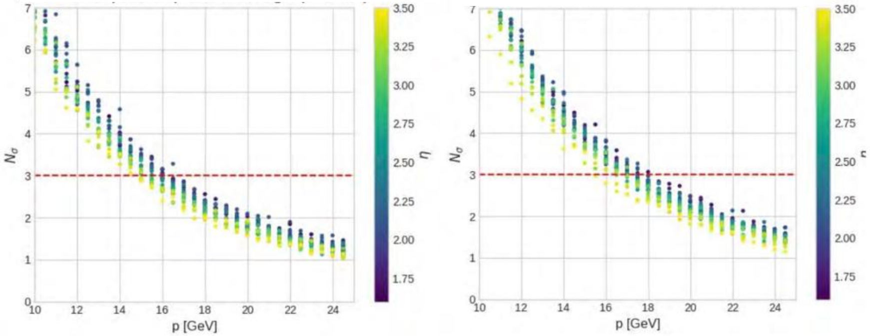
Model bases on lab characterization and test-beam data of components

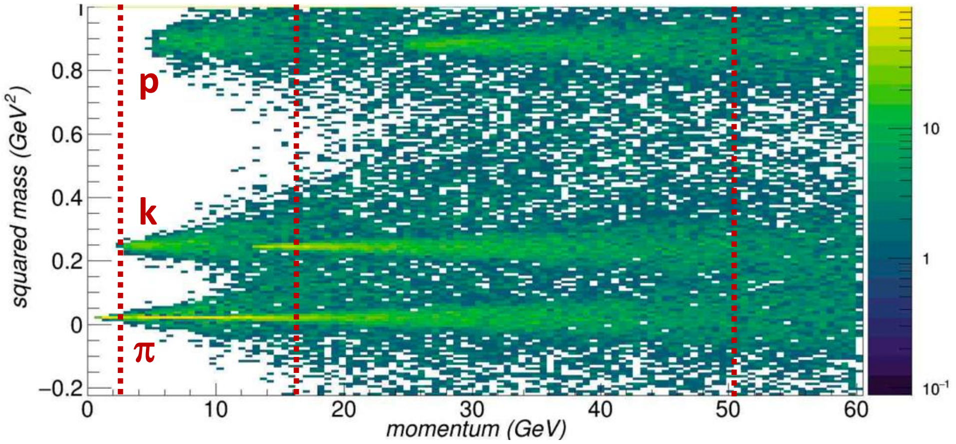
e.g. impact of optimized refractive index

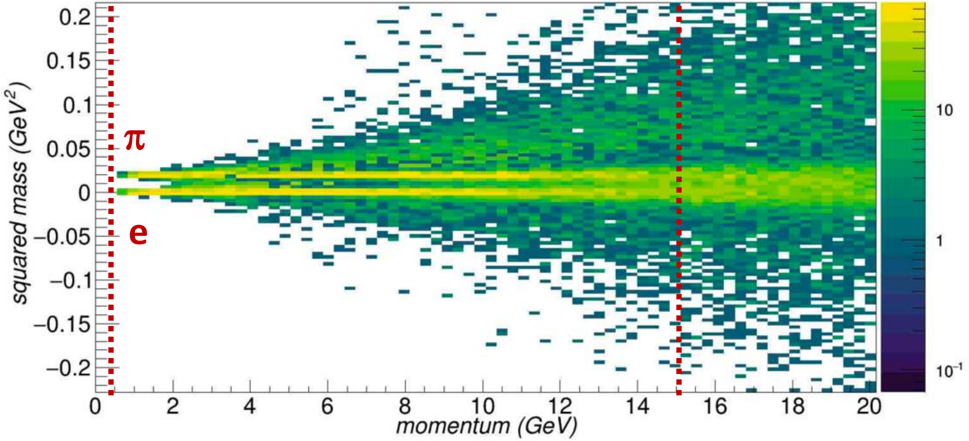
Photon yield



K^+ - π^+ Separation power







Conclusions

dRICH Design Status is documented in pre-TDR:

Essential technical performance has been detailed 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 achievements expected in 2025 (real-scale prototype, RDO, ALCOR64)

On track for Final Design completion in January 2027 as for P6

Milestones FY24:

✓ Preliminary definition of the technical specifications of all the dRICH components (April ’24);

✓ Complete mechanical design of the dRICH structure (June ’24);

✓ Integration of the readout and optical component developments in a real-scale prototype (October ’24).

Milestones FY25:

✓ Validation of dRICH production readiness with the real-scale prototype and realistic com-ponent demonstrators (July ’25).