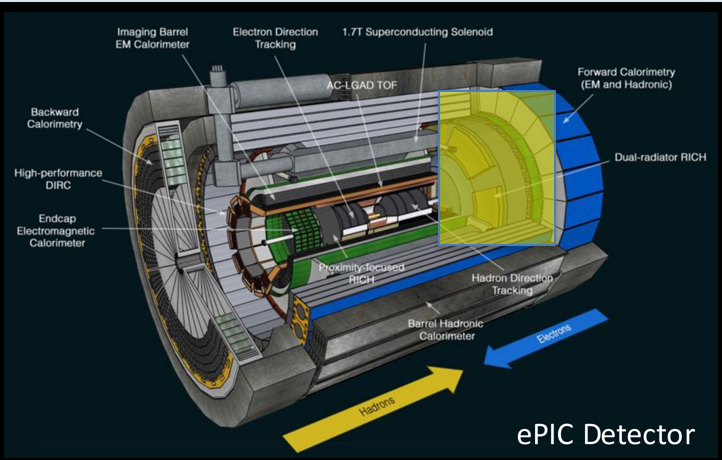
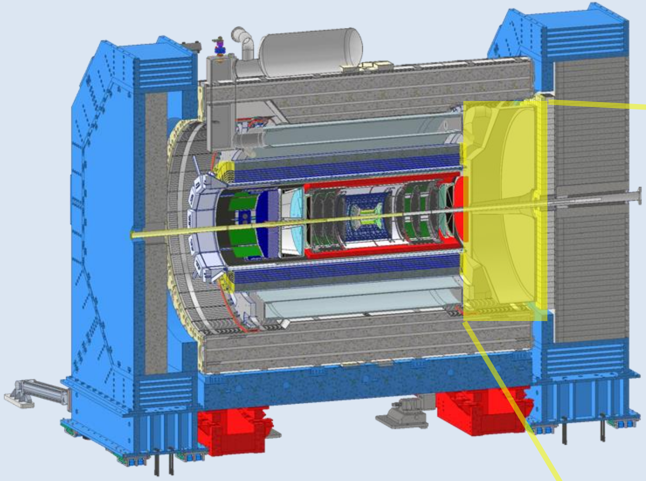
dRICH Project Update



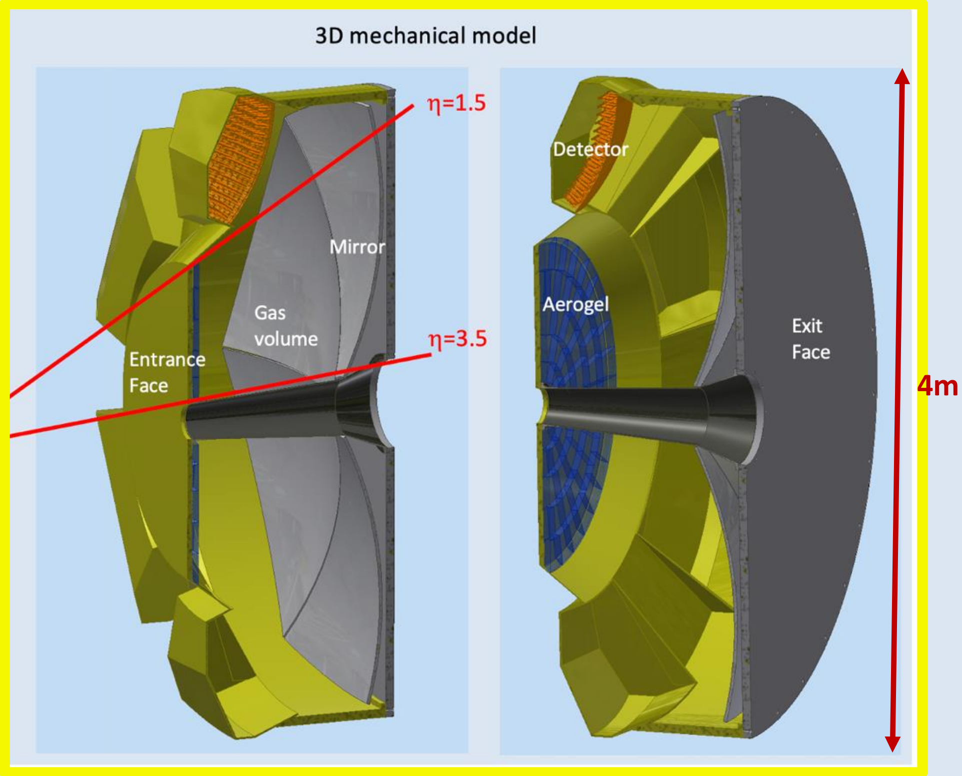
M. Contalbrigo – INFN Ferrara - DSCL

ePIC Italia, Padova, June 16th - 18th, 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

April 1-2 Incremental Preliminary Design and Safety Review of pfRICH, dRICH and hpDIRC
"60% Preliminary Design Review"

PASSED

April 16 EIC Project Detector R&D Day

June 11-13 10th EIC Detector Advisory Committee Meeting

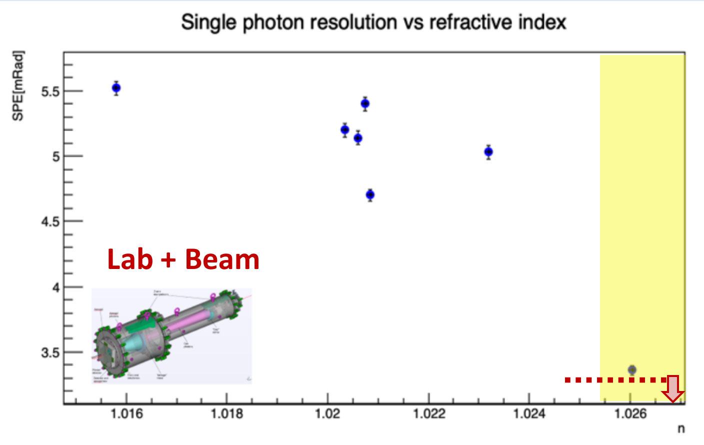
- (dRICH) The chromatic error is dominating the overall performance of the aerogel. It is recommended to study the optimization between (a) loss of photon yield and (b) reduction in chromatic error, using a possible optical filter installed after the aerogel tiles. — *Simulations*
- (dRICH/DAQ) High level filtering of interactions through the GTU is being built into the DAQ design, with the specific example of the dRICH filtering provided. As this is developed the ePIC collaboration should work to understand the dependence between detectors this may introduce and prioritize the external inputs for this online filtering for different detectors. — *DAQ*
- (dRICH) In order to optimise the ALCOR time gate, a simulated distribution of the time-of-arrival of the photon signal (and background) on the photon detector plane would be required, together with an evaluation of the main front-end electronics contributions (if any) before the application of the time gate. — *Simulations*
- (dRICH) Preliminary results from studies of the SiPM array optical window after annealing were shown. A more detailed evaluation of the effect of high-temperature annealing on the shape integrity and optical properties of the resin layer is advised. — *Annealing*

Global services (cables, cooling, etc.) through the endcaps have been identified, including their impact on the hpDIRC and dRICH positioning. These should continue to be monitored to allow reasonable overhead for packing and inevitable increases as additional services are identified. — *Cooling*

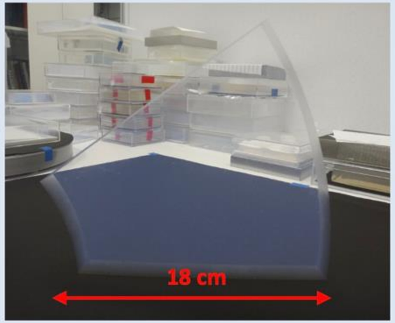
Design Status

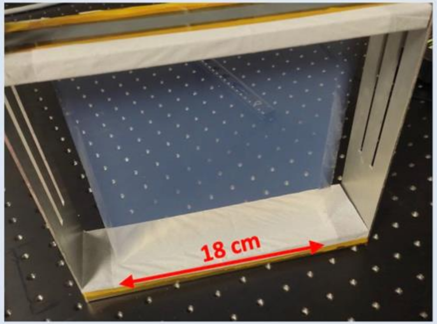
	Technical requirements			Validated technical solutions		Before CD-2
Aerogel:	Momentum reach above 15 GeV/c to overlap with gas More than 10 detected photons from 4 cm thickness Single photon resolution approaching 2 mrad	⇒		n = 1.026 $dn/d\lambda = 6\ 10^{-6}\ nm^{-1}$ scattering length > 50 mm	⇒	Dimensions
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

Aerogel with n=1.026 validated with lab and prototype tests



Details on Backup 26





First large aerogel tile demonstrators delivered

Engineering of the aerogel wall expected by 2026

dRICH baseline specifications

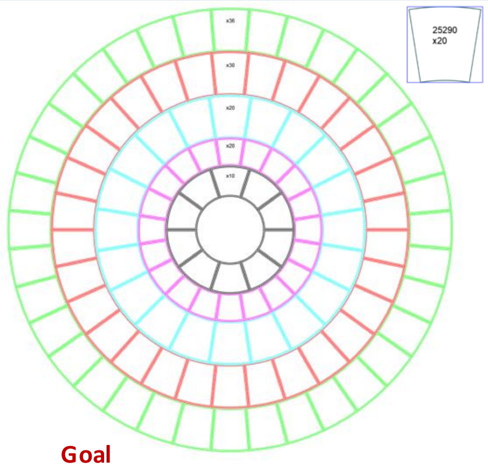
An effort should be pursued by the vendor to keep the aerogel quality parameters as close as possible or better than the following reference values.

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.

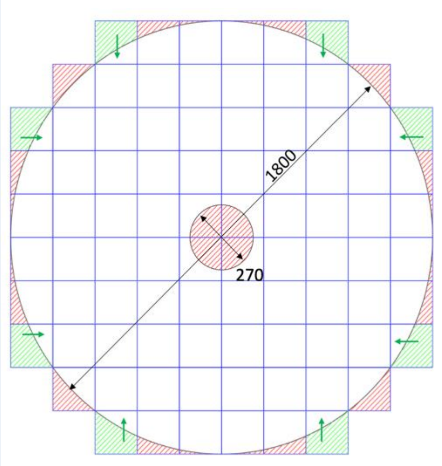
Technical specifications:

- 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.



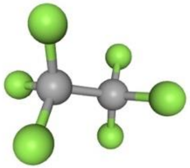
Goal

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



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

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

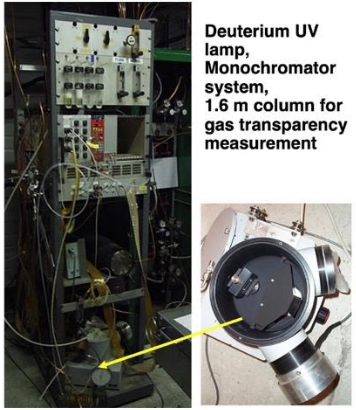
melting point: -100.6 °C

density: 5.734 kg/m³ at 24 °C

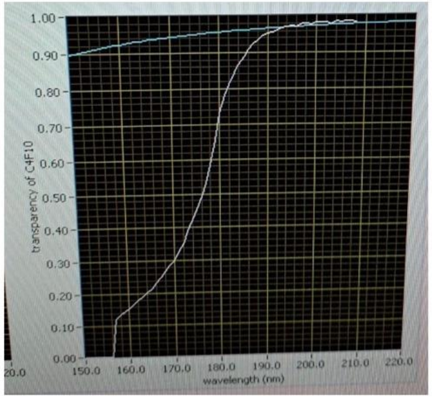
density: 16.08 kg/m³ at -78 °C

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 %

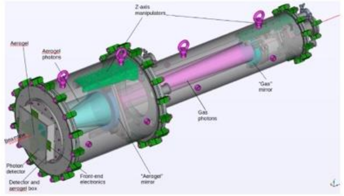


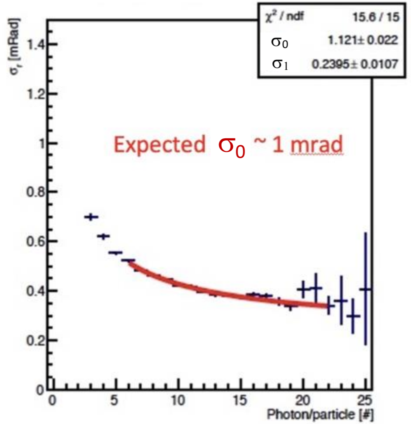
Deuterium UV lamp, Monochromator system, 1.6 m column for gas transparency measurement



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

Expected performance obtained with dRICH prototype



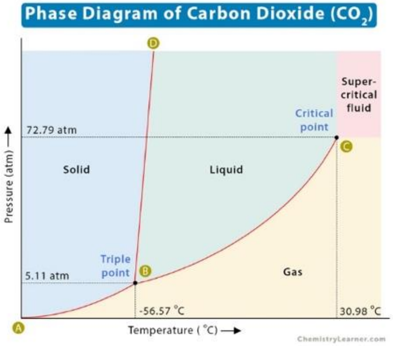


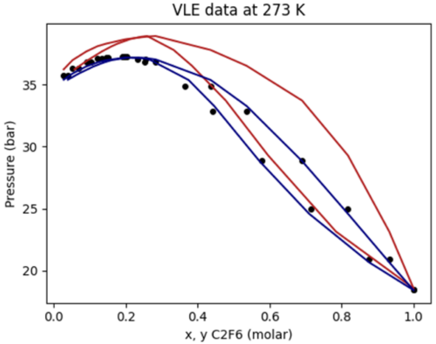
Gas Separation and Purging

Development of gas separation protocols expected by 2026

Purging via liquefaction of stand-by gas

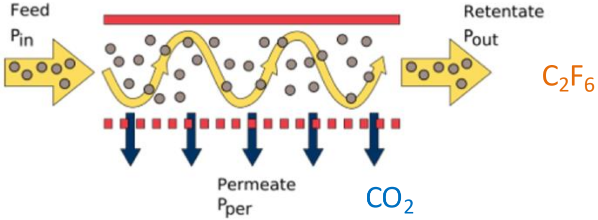
Updated vapor-liquid equilibrium C_2F_6-CO_2 model, test in preparation at CERN

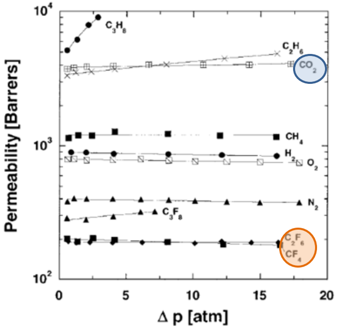




Purging via membranes

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

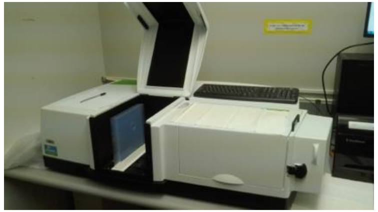


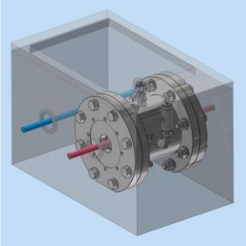


Design of online purity monitors expected by 2026

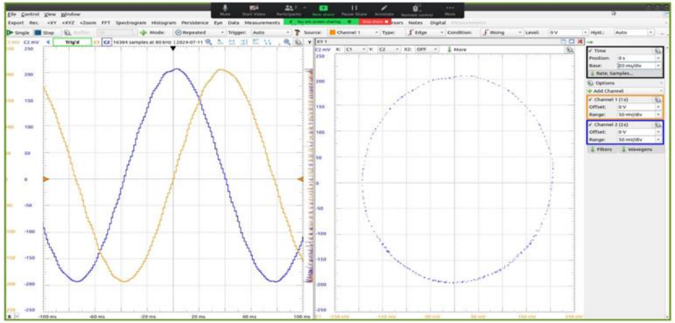
Sonar to measure speed of sound

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

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

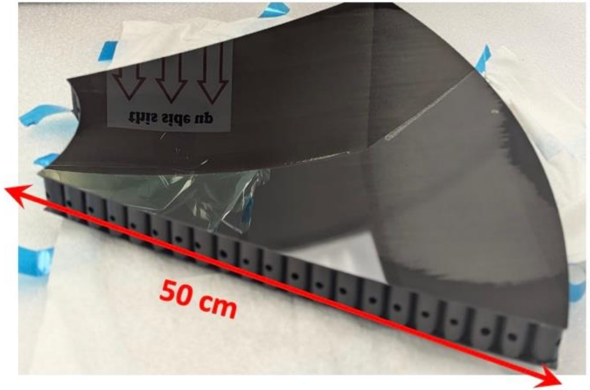
Annex C. Technical Requisite

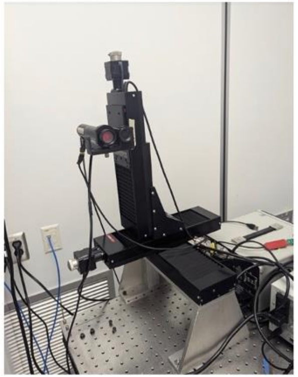
Each spherical mirror is supplied with

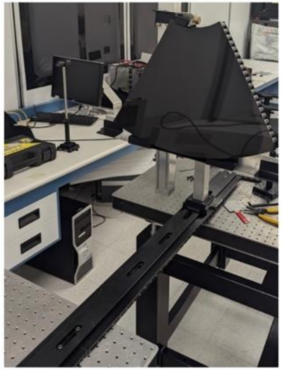
- a spot-size measurement,
- a report on dimensions,
- no reflective coating.

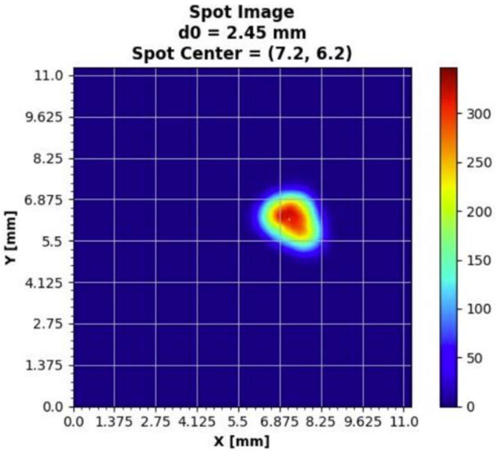
The spherical mirrors are replicated from the same mandrel. The latter is realized with the novel cost-effective technology that reduces the mandrel total mass and cost. Each mirror fulfills the following optical quality specification:

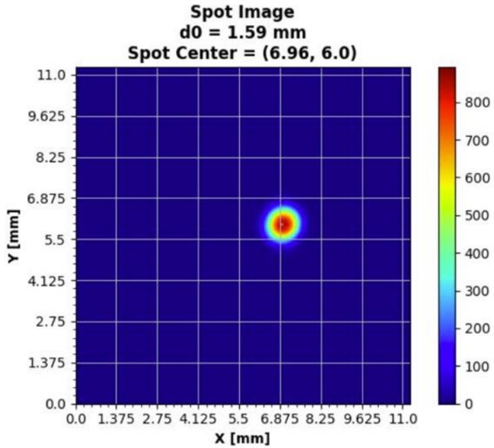
- Radius within 1% of nominal RoC value (the nominal RoC values is defined by the customer before production in the range 2000 mm +/- 10%),
- Roughness < 2 nm,
- Pointlike image spot size D0 < 2.5 mm,
- Compatibility with fluorocarbon gases (C_2F_6),
- Compatibility with SiO_2 reflecting coating.



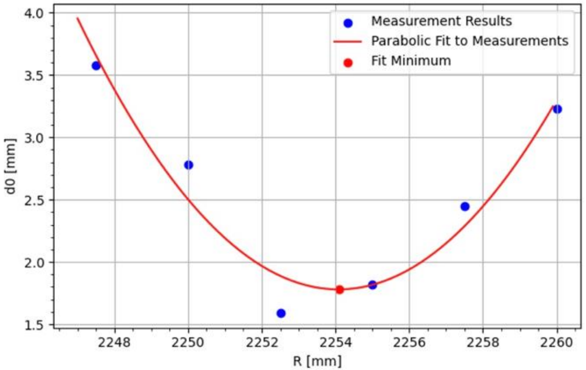




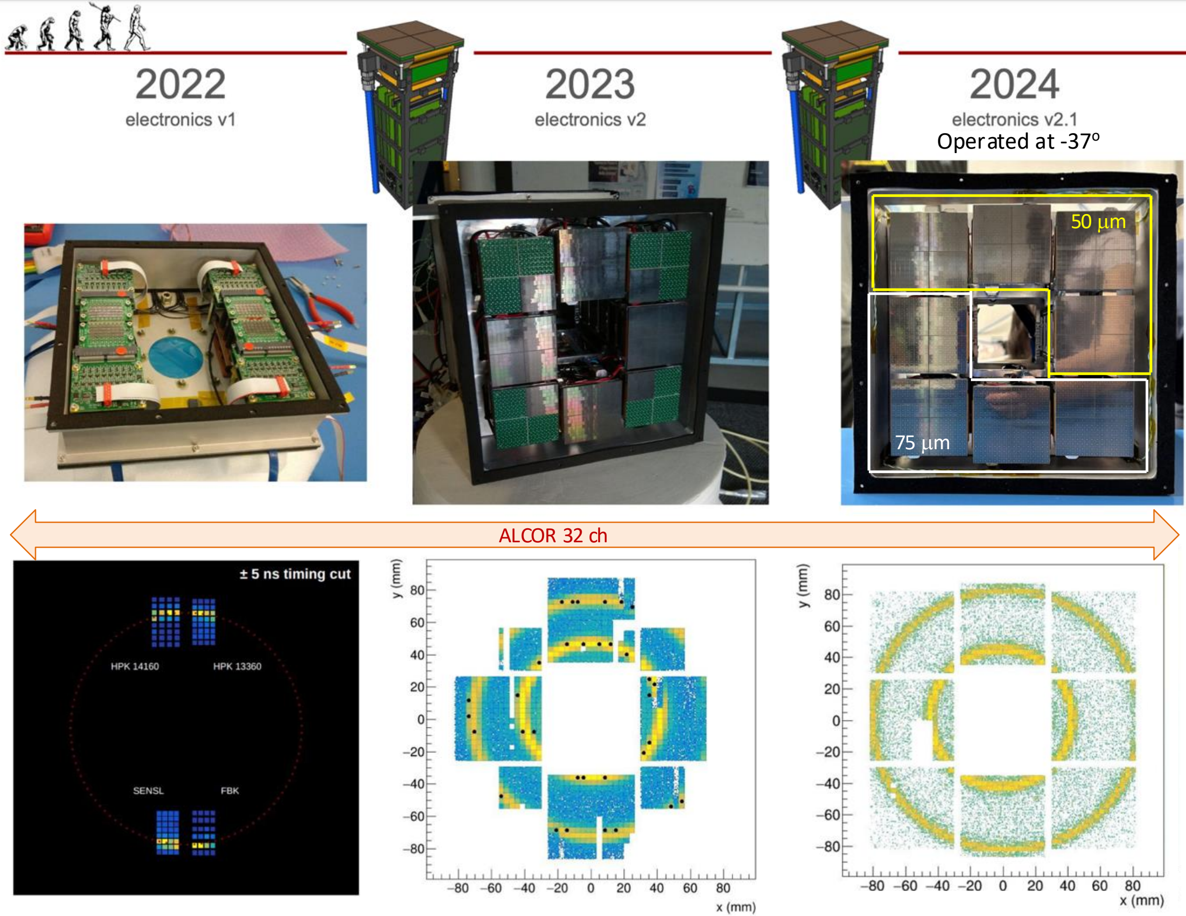


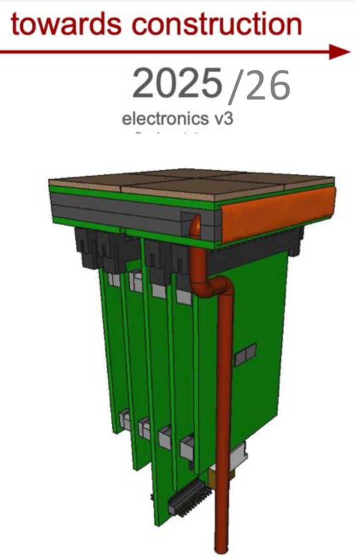


✓ D0 < 2.5 mm ✓ R = 2200 +/- 1%



Steadly progress of photodetector towards integrated design completion in 2026





Full size engineering test article

2025	+ SiPM carrierv3 + RDO
2026	+ ALCOR 64ch + FEB 64

dRICH Readout Electronic

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

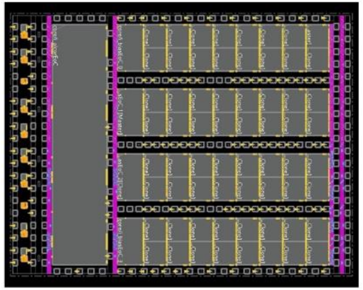
F. Cossio

P. Antonioli

Proton irradiation campaigns for ALCOR-32 and key RDO components showed SEU rate is within the expected manageable levels

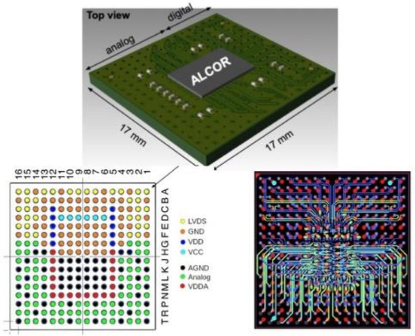
ALCOR v3 – 64 channels

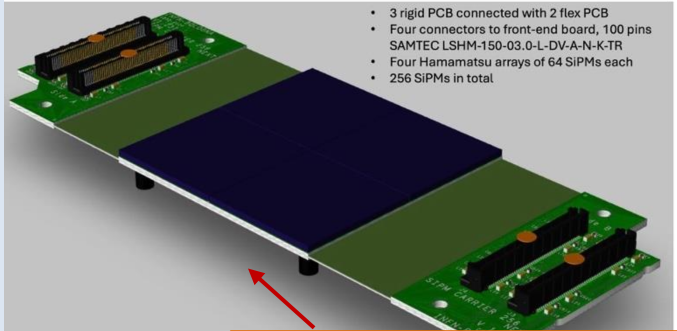
MPW run in March ‘25



Silicon die layout

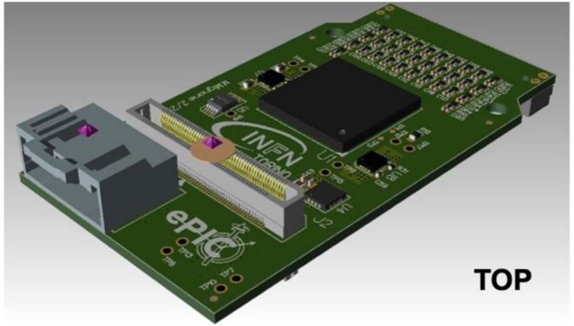
Compact ball-grid array (BGA) package with interposer





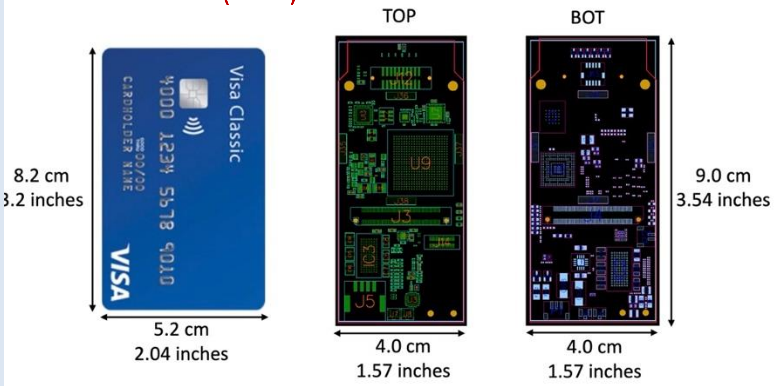
Carrier v3

Test-production started ‘Jan 25

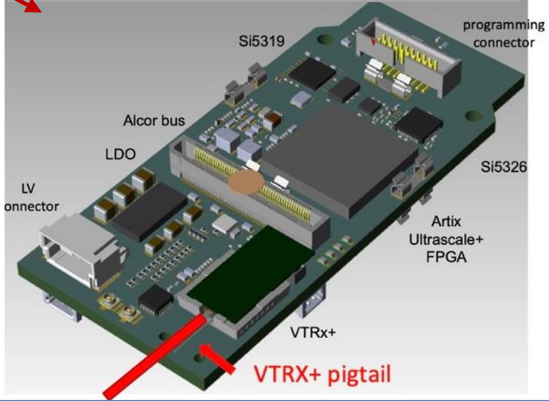


Front-End Board (FEB)

Readout Board (RDO)

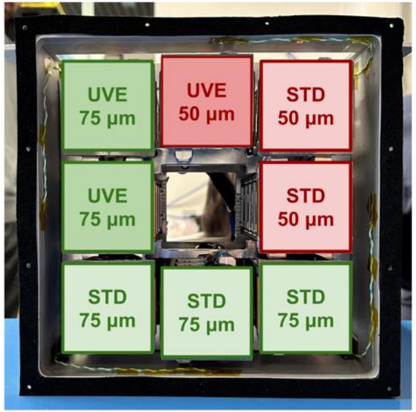


Delivery imminent

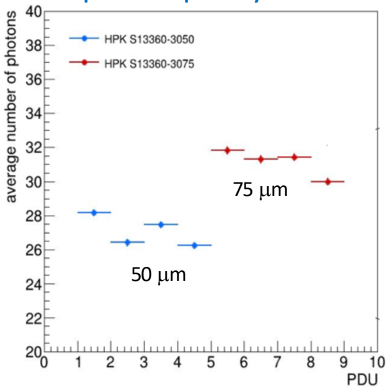


FInalization of the engineering of the SiPM optimized layout and temperature treatments ongoing

D. De Gruttola

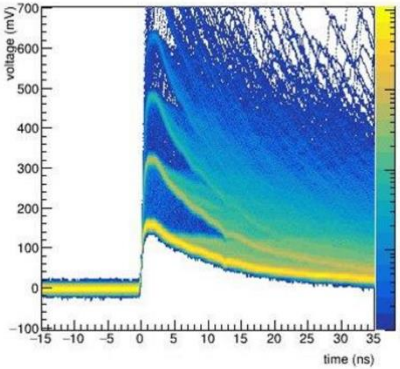


Spad size vs photon yield

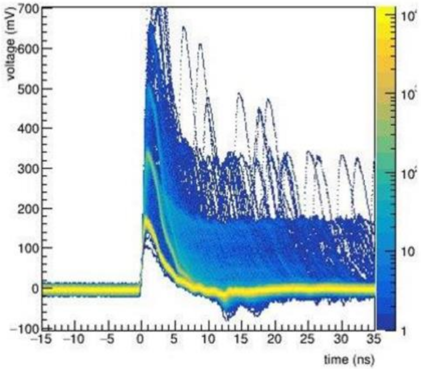


UV enhanced with fast signal

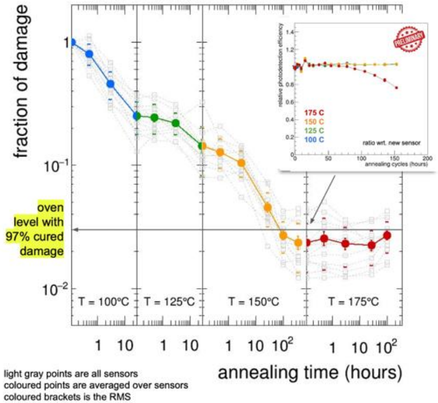
S13360 (50 µm)

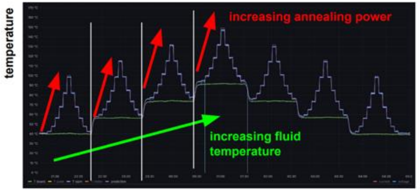


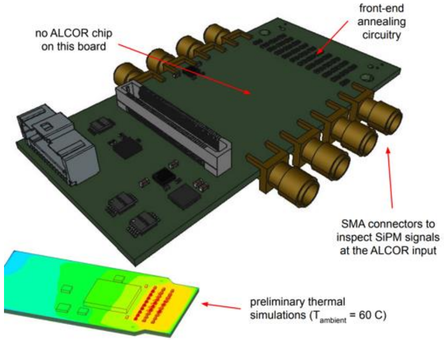
UVE (50 µm)

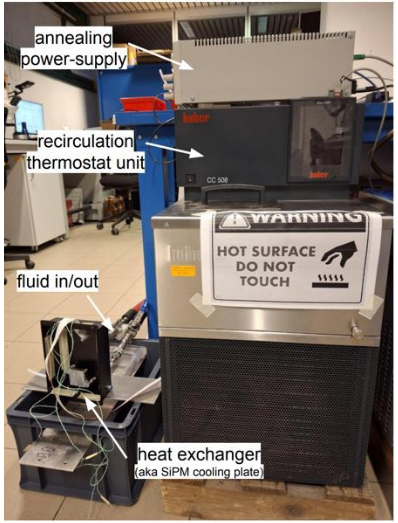


Details of in-situ annealing protocol based on Joule-effect







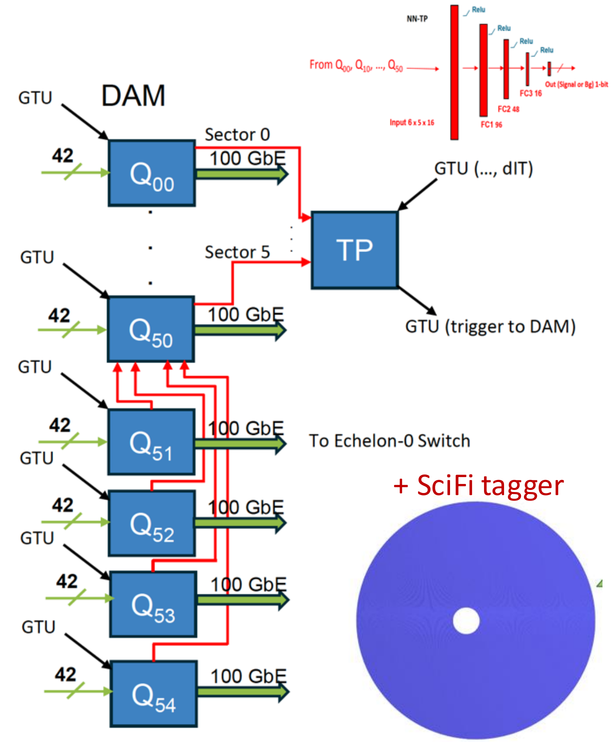


A working DAQ scheme has been identified to support ML online data filtering at sub-detector level against pure dark-count event

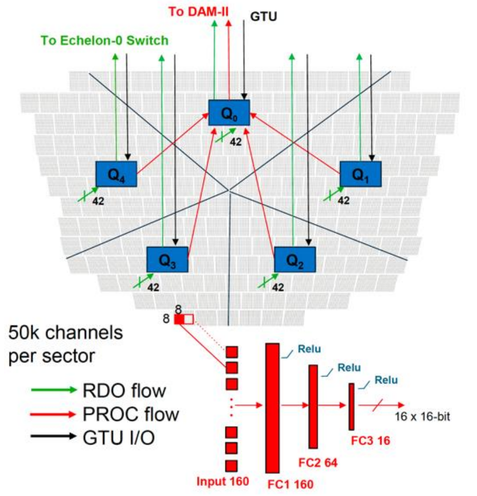
Scheme based on ePIC DAM (Felix) &
APEIRON communication network (INFN)

sub-sector integrated analysis

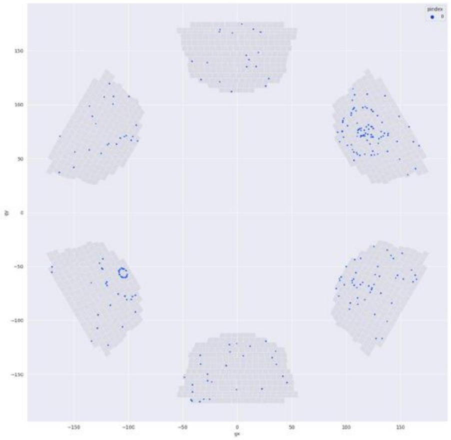
detector integrated analysis



+ SciFi tagger



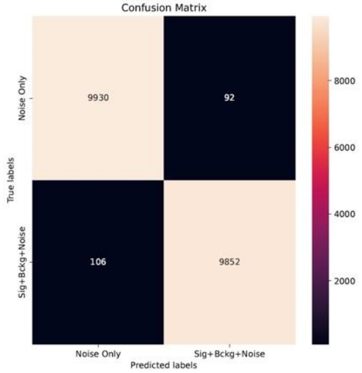
Phys Signal+Phys Background+Noise



Promising preliminary tests

- Accuracy = (TP+TN)/(TP+TN+FP+FN) = 0.990
- Precision = TP/(TP+FP) = 0.989
- Recall = TP/(TP+FN) = 0.991

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



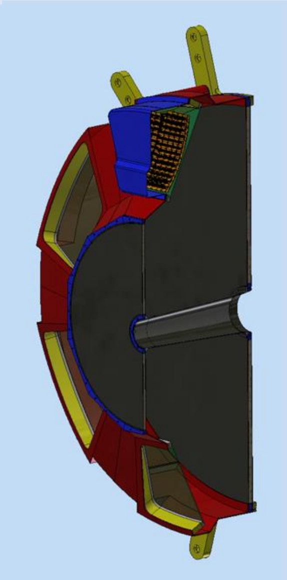
A. Lonardo

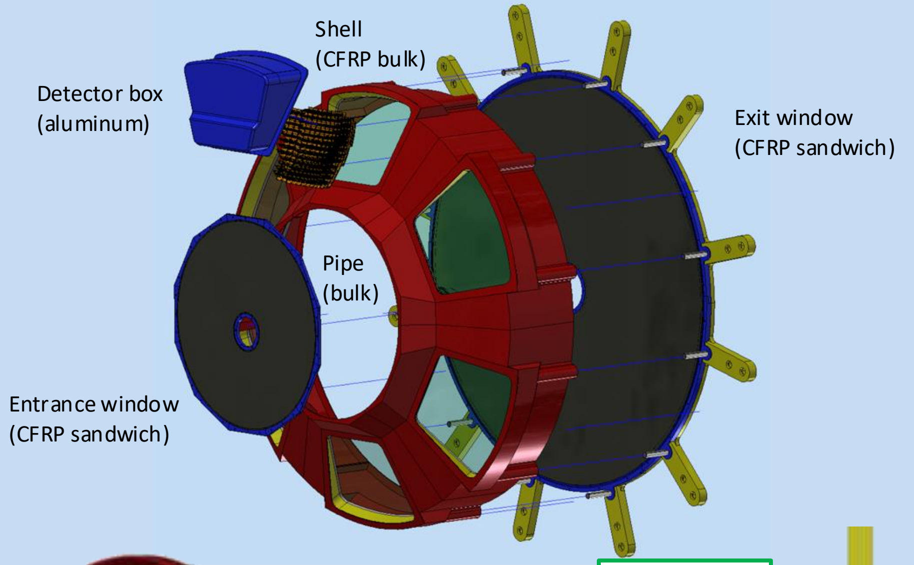
C. Rossi

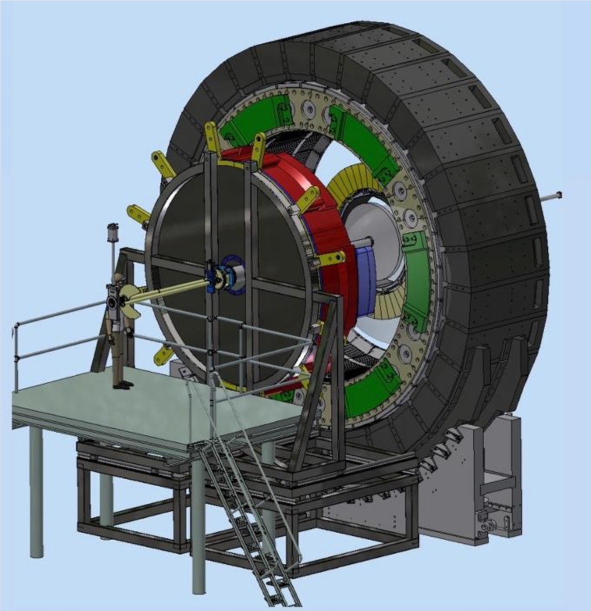
S. Vallarino

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

A. Saputi

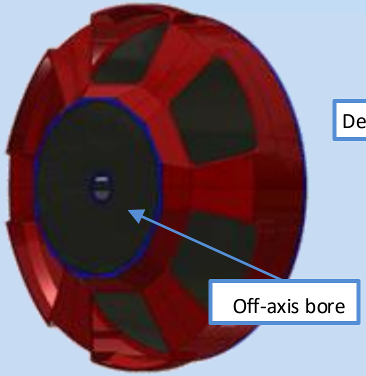


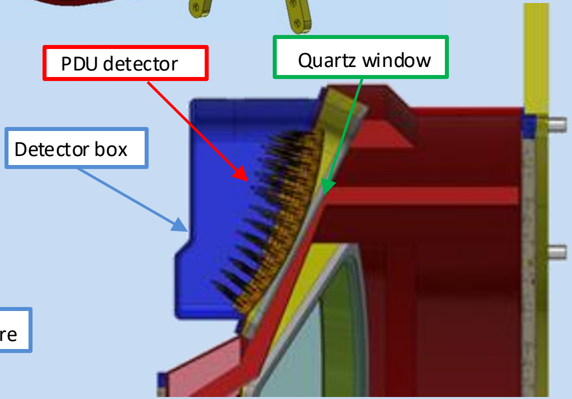


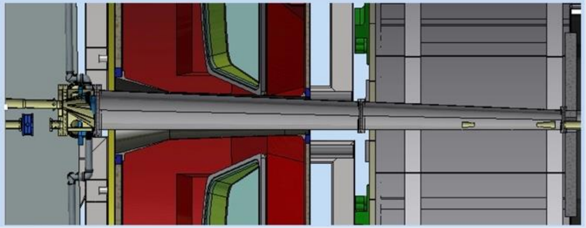


Composite materials

Total wieght: ~ 2 ton



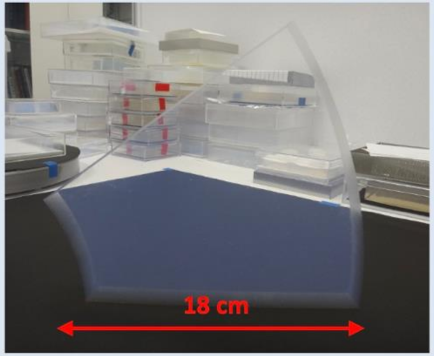


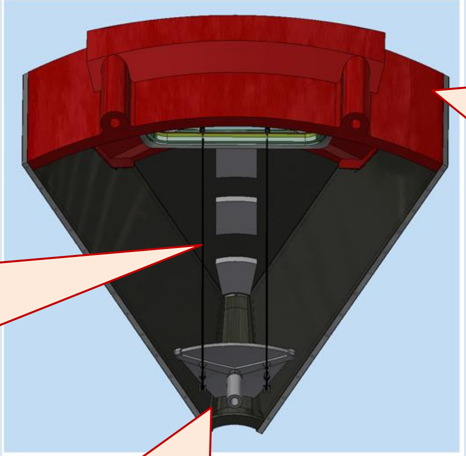


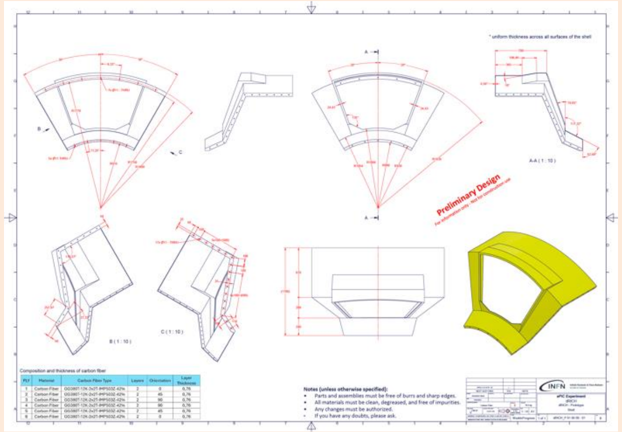
Realistic Components

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

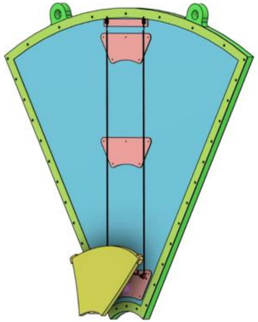
Aerogel support

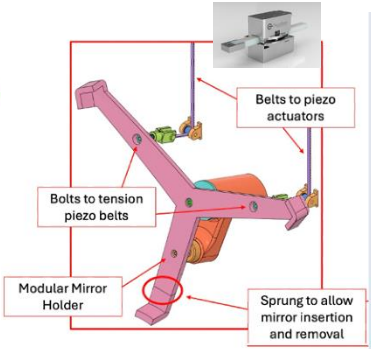


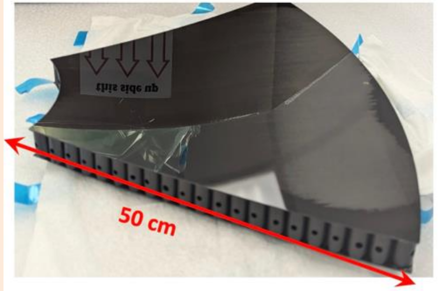




Mirror mounting and alignment (aka NA62)







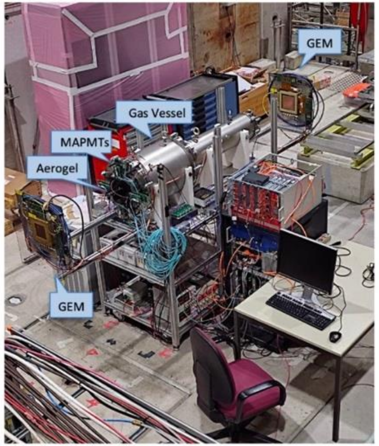
Vessel

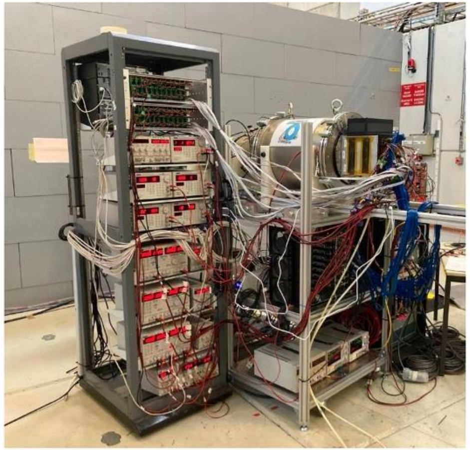
PO issued

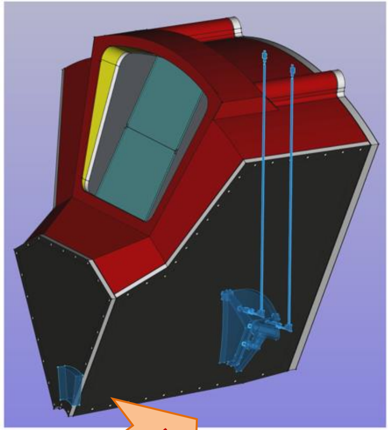
CFRP Layer composition

Previous validations:

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





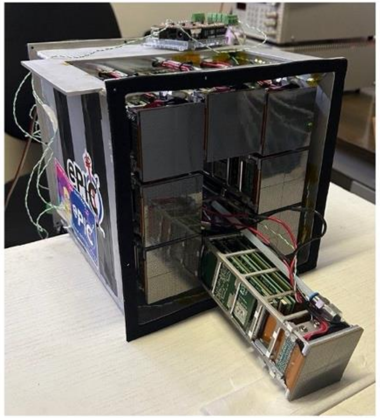


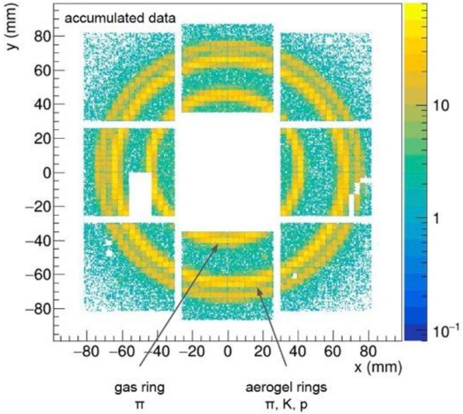
2025

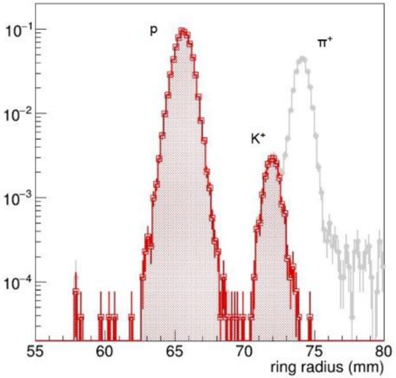
2025 main goals:

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

Slot at SPS H8 in November



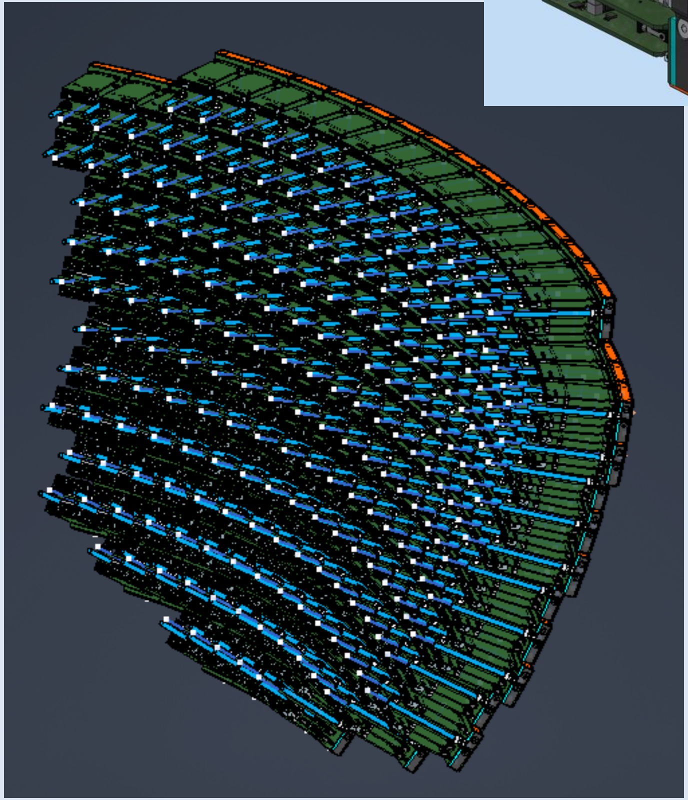


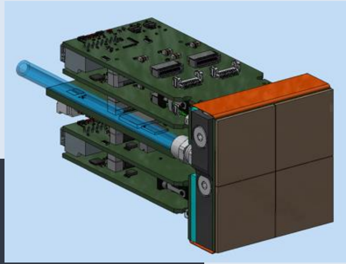


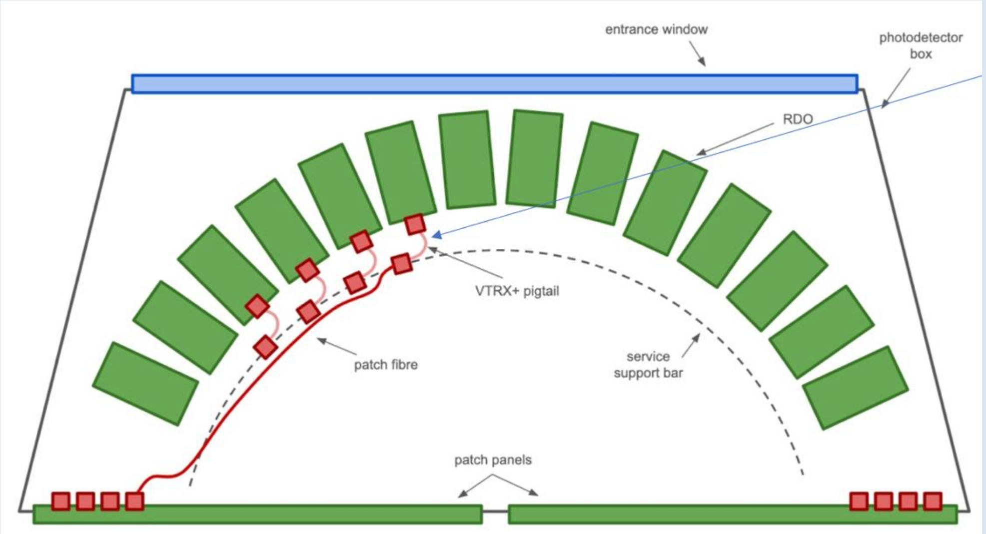
Detector Box

Engineering of detector box planned in 2026

Michele Melchiorri (INFN FE)

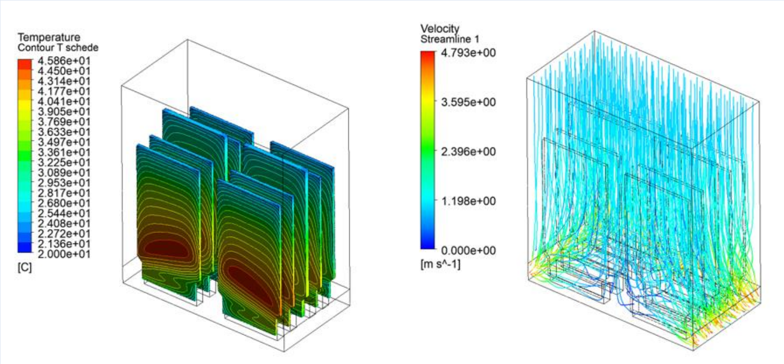






Preliminary CFD (Computational Fluid Dynamics) Simulation

Marco Nenni
Carlo Mingioni
(INFN TO)



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

Recomm. (DAC): Investigate whether windows are necessary to separate regions at different temperatures (gas radiator and the photon detector), and if needed, whether they impact performance significantly.

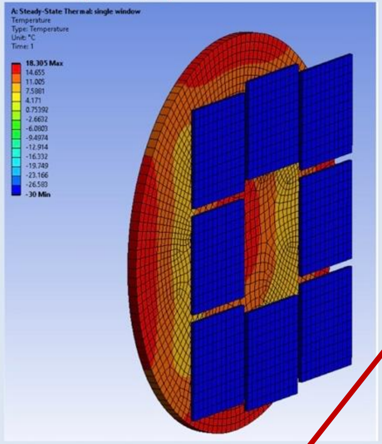
Ongoing study with ANSYS workbench simulations

Benchmarked by dRICH prototype

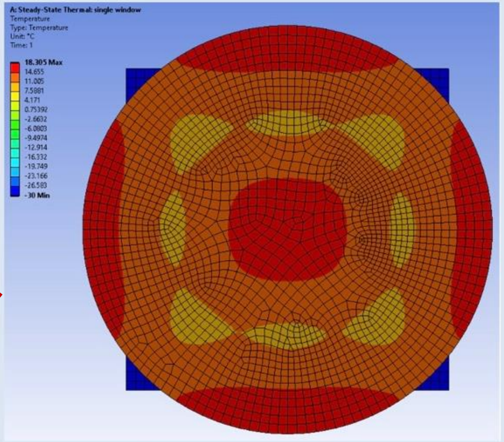
Gradients are largely mitigated by

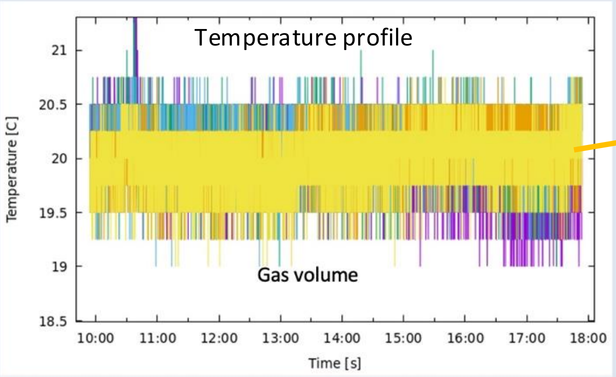
- double lucite window (with air gap) x 0.5
- 8 mm thick quartz window
- inner gas recirculation x 0.1

SiPM plane, cycled from 22º to -30º

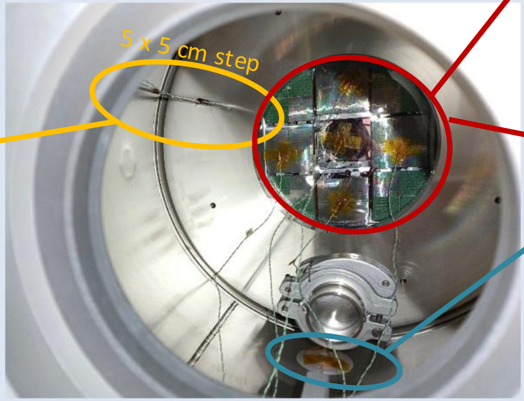


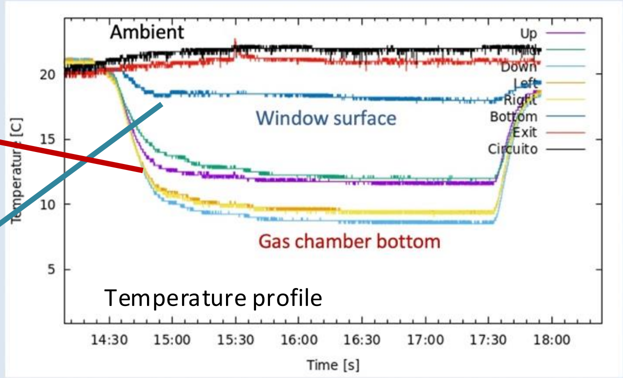
3 mm lucite window





Gas volume with thermocouples

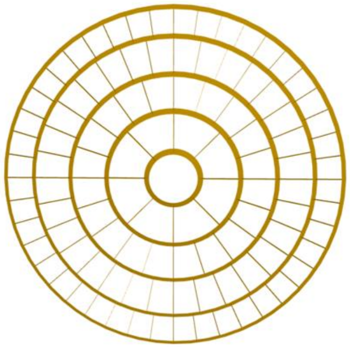


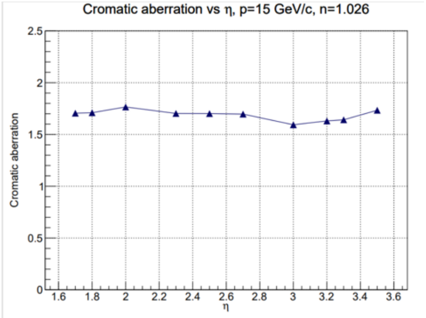


Simulation within ePIC dd4hep framework accounts for tracking, material budget and magnetic bending.

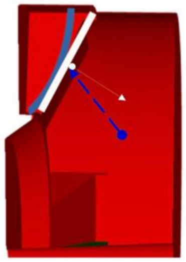
Model bases on lab characterization and test-beam data of components

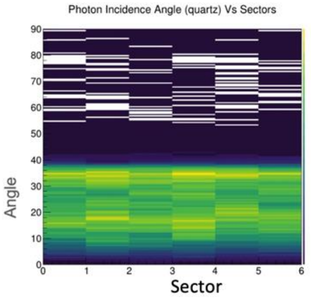
Aerogel tiling and chromatic aberration

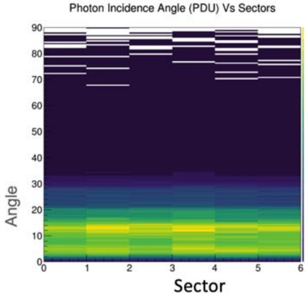




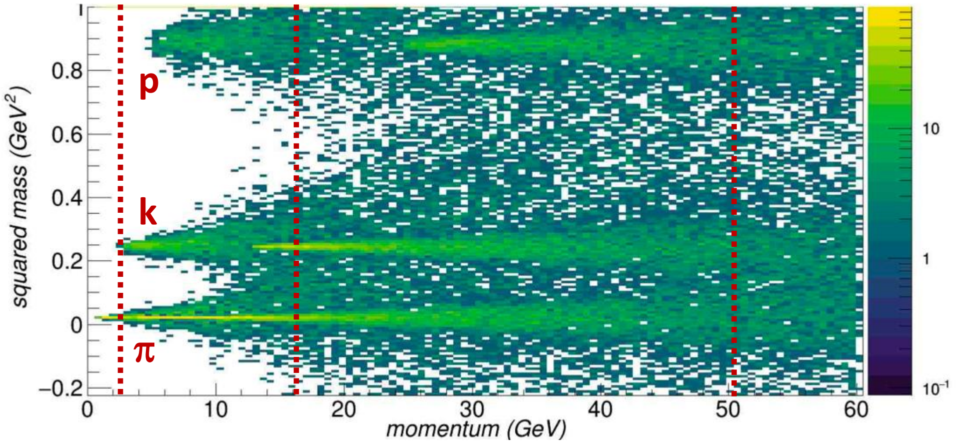
Photons impinging angles and transmission probability

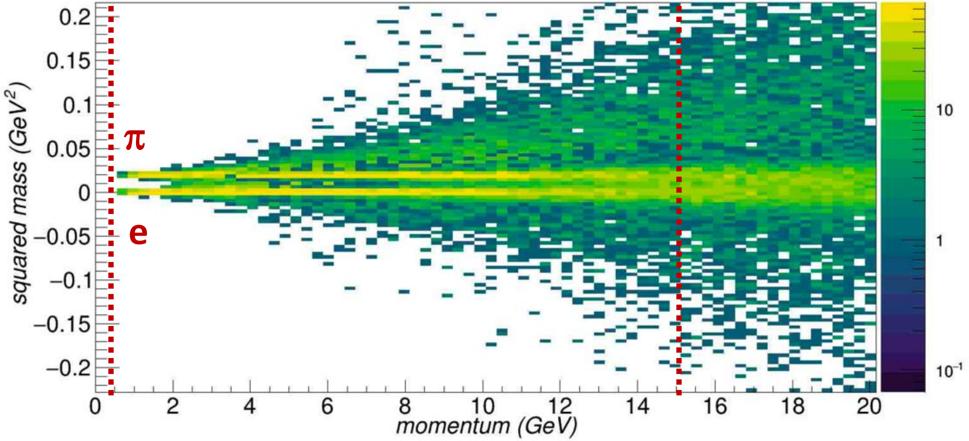






L. Occhiuto





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

Essential to guide technological choices

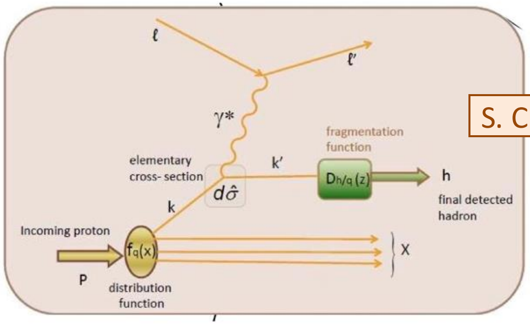
Effective entry-point for new collaborators

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-GE-LNS-PV-SA-TO-TS (7 staff, 5 student/postdoc)



S. Costanza

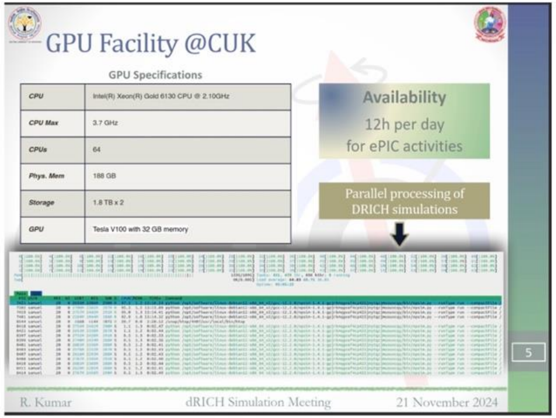
Close collaboration with Theory groups already active in inpact studies on (un-)polarized TMDs

INFN LE-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

C. Chatterjee



INFN TS-CS-GE-LNS
U. Salerno, U. Calabria
Duke U.
Central U. of Karnataka
Central U. of Haryana
Ramaiah U. of Applied Science

(5 staff, 11 student/postdoc)

dRICH Workforce

Preliminary commitments for the construction phase are defined

Institution	Nation	Activity	
INFN-FE	Italy	Mechanics, detecor box and control panels	24 staff 18 postdocs/ students 18 technicians/ engineers
INFN-BO	Italy	Photosensors, photodetection unit PDU and readout board RDO	
INFN-TO	Italy	ALCOR and front-end board FEB	
INFN-BA	Italy	Aerogel radiator	
INFN-CS-SA-CT	Italy	SiPM quality assurance	
INFN-GE	Italy	dRICH tagger	
INFN-LNS	Italy	Mechanical design	
INFN-RM1-RM-TV	Italy	Online data reduction	
INFN-TS	Italy	Radiator gas, gas system and software, SiPM quality assurance	
Duke-U.	USA	Mirror	8 staff 2 postdocs/ students 2 technicians/ engineers
JLab	USA	Mechanical design and mirror characterization	
BNL	USA	Mechanical design, integration, infrasctructure	
Temple U.	USA	Aeorgel quality assurance	
M.S. Ramaiah U.	India	Simualtions and performance study	8 staff 2 postdocs/ students
NISER	India	Performance study	
Central U. of Haryana	India	Performance study	
Central U. of Karnataka	India	Performance study	

Many groups have committed to the construction phase of the above items

QA stations are of common interest: best performance with co-funded equipment & shared workforce

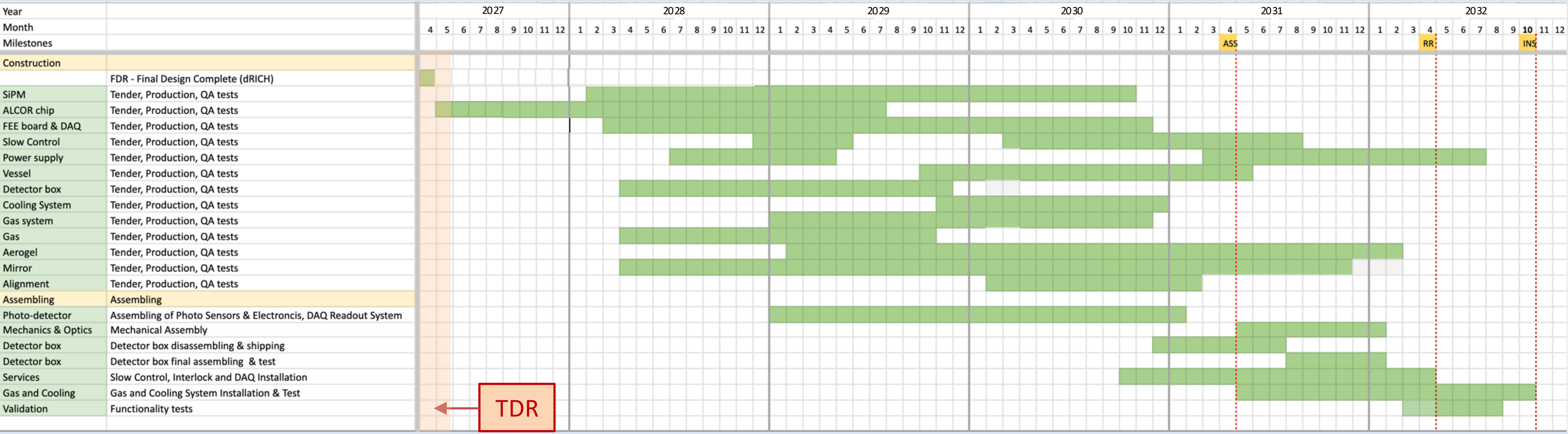
open to collaborators: opportunity for secondments and students traning

Construction Plan

60% Preliminary Design Review passed. A construction and QA plan is outlined accounting for lead, assembling and commissioning time

Recomm. (DAC): Present at least a vague timeline for the project at the next DAC review.

Details on Backup 31-32



CD-2: Validate ALCOR-64 & RDO design
Validate real-scale prototype mechanics
Study detector box engineering
Define baseline integration and maintenance plan
Work out a baseline cooling & gas sytem

CD-3: Optimize component performance
Complete component integration
Finalize cooling & gas system
Detail detector integration and maintenance

Stage 1: Procurement for the PDU components (asics, SiPM, carrier, FEB, RDO…)
Anticipate mirror and gas procurement to reduce risk

Stage 2 : Central 2-3 year for the detector box assembling before delivery to BNL
Aerogel production after engineering optimization
Gas system realization after BNL authority approval

Stage 3: Mechanical structures
Assembling and completion of services
6 months of contingency and functionality tests

QA is organized to allow essential acceptance tests on 100% of components plus in-depth sample characterization

QA stations organized in order to

- Be close to the assembling site
- Ensure adequate personnel training
- Provide redundancy & investment synergy
- Support specific in-deep characterization studies

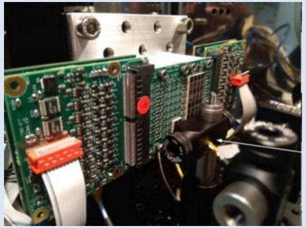
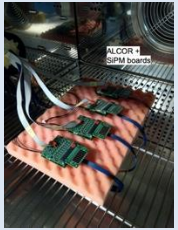
Aerogel: Integrity, defects, transmittance, refractive index, dimensions, planarity

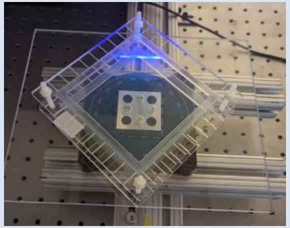
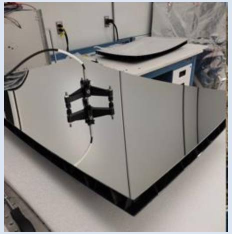
Mirror: Dimensions, shape accuracy, radius, reflectivity

Sensors: Electrical connections, quench resistor, I-V characteristics, DCR, relative PDE

Readout: Electrical connections, bias levels, threshold and gain scans, time jitter, DAQ rate

Gas: Refractive index, transparency, sound speed, leakage rate

Component	QA station 1	QA station 2	QA detail and backup	QA Acceptance	In-depth
Aerogel	Temple U.	BNL	INFN-BA	100 %	5%
Gas	BNL		INFN-TS	2 %	2%
Mirror	JLab	Duke U.		100 %	10%
Sensor (SiPM)	INFN CS-SA-CT	INFN-TS	INFN-BO	100 %	1%
Readout	INFN-BO	INFN-FE	INFN-TO	100 %	1%

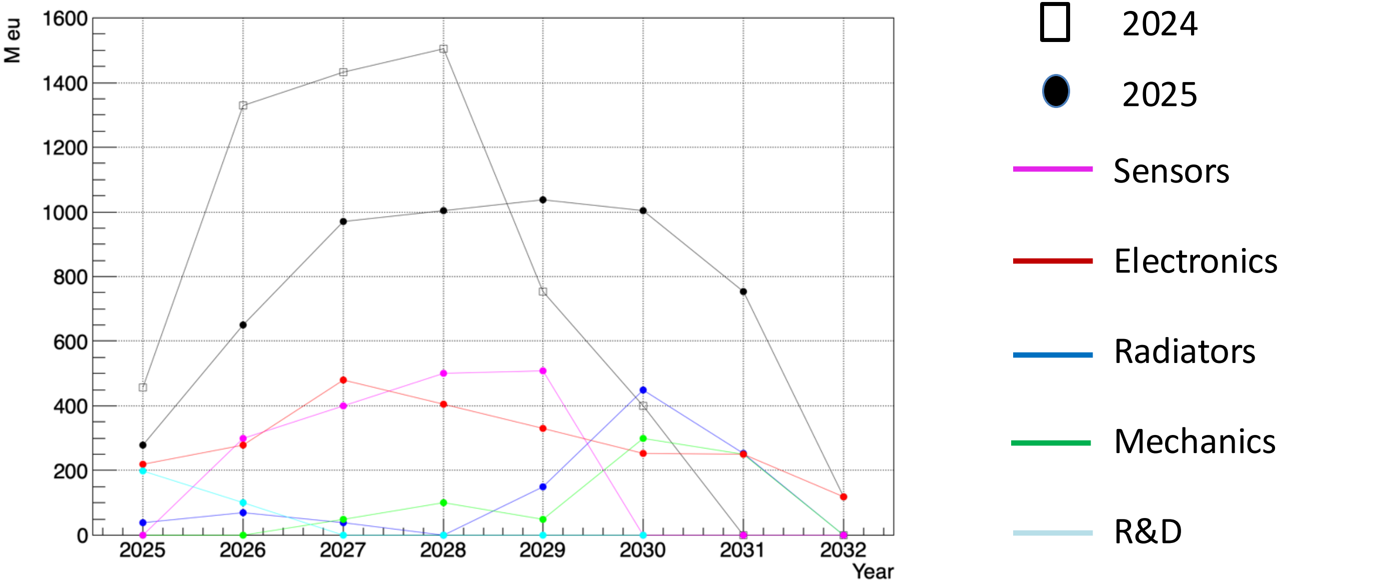
INFN Funding Profile

60% Preliminary Design Review passed. A construction and QA plan is outlined accounting for lead, assembling and commissioning time

Assumptions: - Installation in 2032
- possibility to split the major procurements in batches/years

Potential risk: - sub-optimal spreading of vendor effort for SiPM
- late investment on aerogel

Peak investment being mitigated with respect 2024 anticipation



Conclusions

dRICH Design Status is documented in the pre-TDR

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 phase to PED

On track for CD-2 in 2026 and Final Design completion (TDR) in 2027

Readout Irradiation Tests

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

Regular irradiation campaign ongoing:

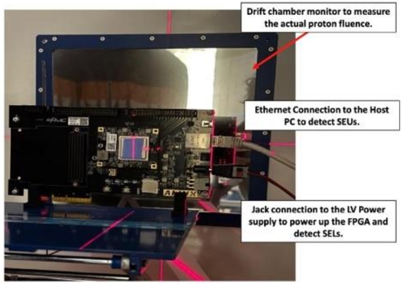
Neutron irradiation campaign at LNL-CN (9-11 October 24)

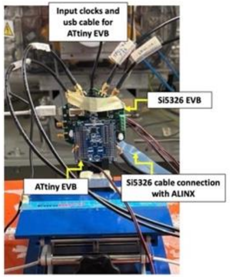
Gamma irradiation campaign at CERN-GIF (14-16 October 24)

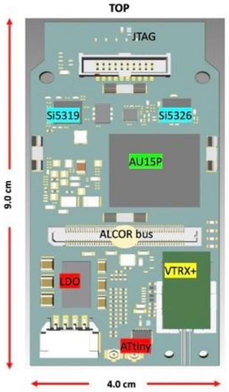
Proton irradiation campaign at TIFPA (12-14 December 24)

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

RDO radiation tolerance



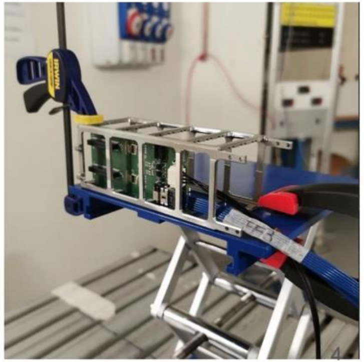




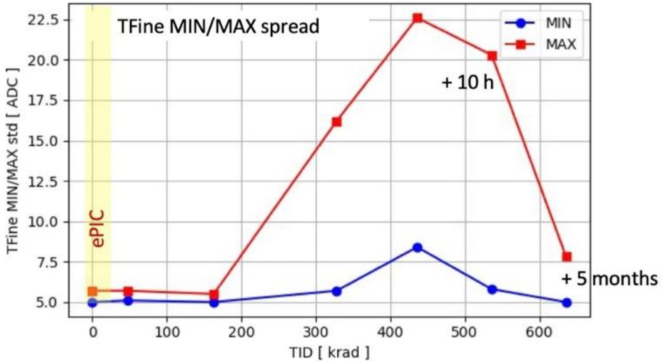
	Measured	Mean SEU time @ ePIC
Si5326 (clock)	$\sigma_{SEU} = (3.89 \pm 0.54) \cdot 10^{-14} \frac{cm^2}{bit}$	4 h
Attiny (power)	$\sigma_{SEU} = (2.11 \pm 0.50) \cdot 10^{-14} \frac{cm^2}{bit}$	3.8 h
AU15P (FPGA)		2 min

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

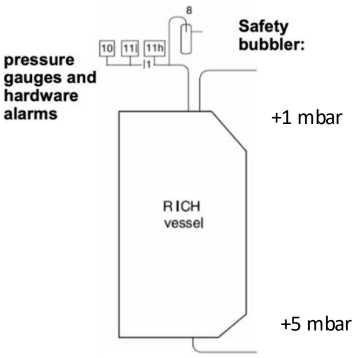


- ECCR $\sigma = 9.8 \cdot 10^{-14}$ cm^2/bit periphery register → no TMR in ALCOR v2.1
- BCR $\sigma = 6.1 \cdot 10^{-14}$ cm^2/bit periphery register → no TMR in ALCOR v2.1
- PCR **no SEU detected** re-written every 10 seconds to mimick TMR

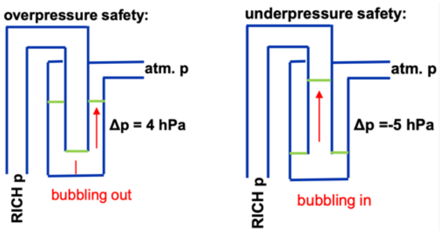


Adaptation from realizations at CERN with focus on separation/monitor expected by 2026
Realization at BNL in compliance with DOE safety standards

dRICH vessel



Two-ways bubbler (aka COMPASS)



dRICH gas system