dRICH status

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on behalf of the dRICH Collaboration

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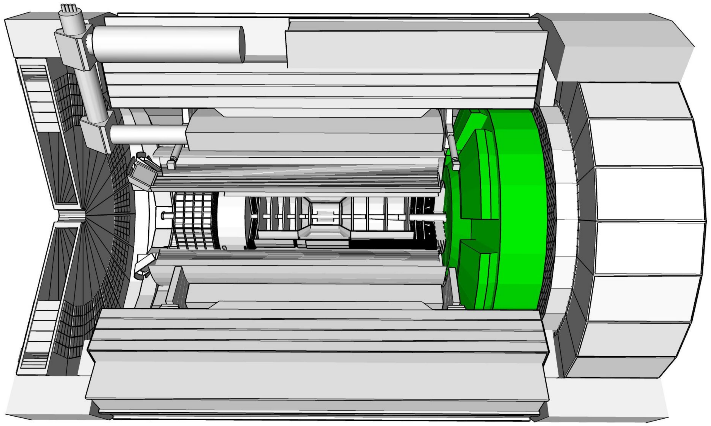
ePIC Collaboration Meeting, 28 July 2023

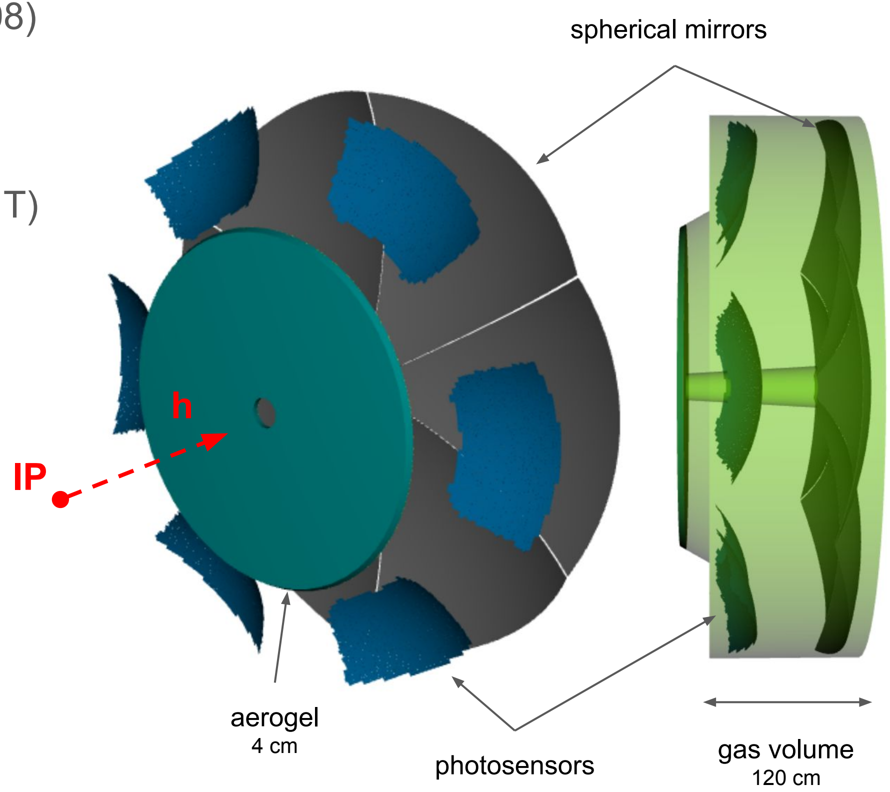
The dual-radiator (dRICH) for forward PID at EIC

compact and cost-effective solution for broad momentum coverage at forward rapidity
essential for SIDIS physics

p = [3.0, 50] GeV/c
η = [1.5, 3.5]
e-ID up to 15 GeV/c

- **radiators:** aerogel (n ~ 1.02) and C_2F_6 (n ~ 1.0008)
- **mirrors:** large outward-reflecting, 6 open sectors
- **sensors:** 3x3 mm^2 pixel, 0.5 m^2 / sector
  - single-photon detection inside high B field (~ 1 T)
  - outside of acceptance, reduced constraints
  - SiPM optical readout





Collaboration

INFN

BA, BO, CS, CT
FE, GE, LNF, LNS
RM1, RM2, SA, TO, TS

Duke University

NISER

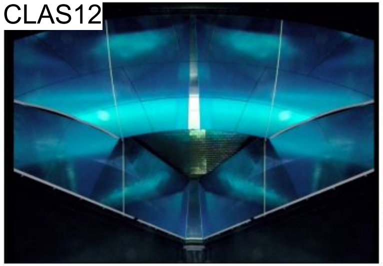
Jefferson Lab

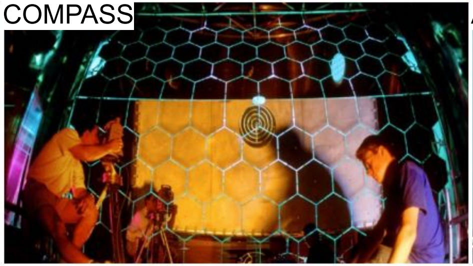
further collaboration within the EIC RICH Consortium

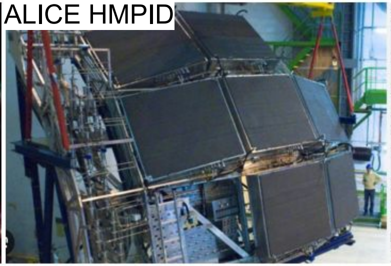
Brookhaven National Laboratory

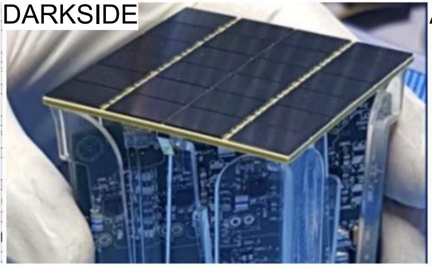
Stony Brook University

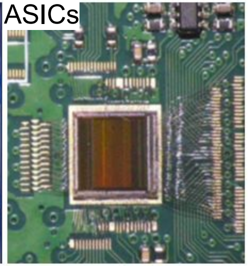
University of Ljubljana


CLAS12


COMPASS


ALICE HMPID


DARKSIDE


ASICs

extensive background expertise from the groups involved

Organisation

DSC Leader

Technical Coordinator

Marco Contalbrigo

work packages, leaders and contributing institutions

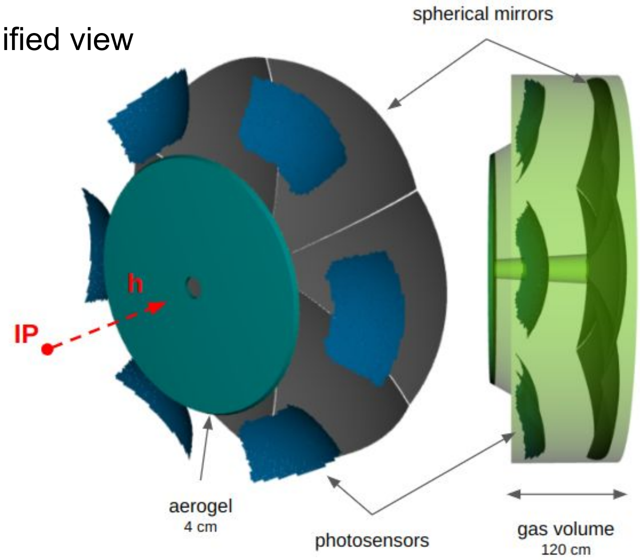
Work package	Leader and contributing institutions
photodetector	**Roberto Preghenella** INFN BO, FE, CS, SA, LNF, CT, NISER
front-end ASIC	**Fabio Cossio** INFN TO, BO
data acquisition	**Pietro Antonioli** INFN BO, FE
mechanics	**Alessandro Saputi** INFN FE, CT, GE, JLAB, BNL
gas radiator	**Fulvio Tessarotto** INFN TS, BNL
mirrors	**Anselm Vossen** DUKE, INFN FE
aerogel radiator	**Giacomo Volpe** INFN BA, FE, RICH Consortium
simulation	**Chandradoy Chatterjee** INFN TS, DUKE, FE

work packages not yet active

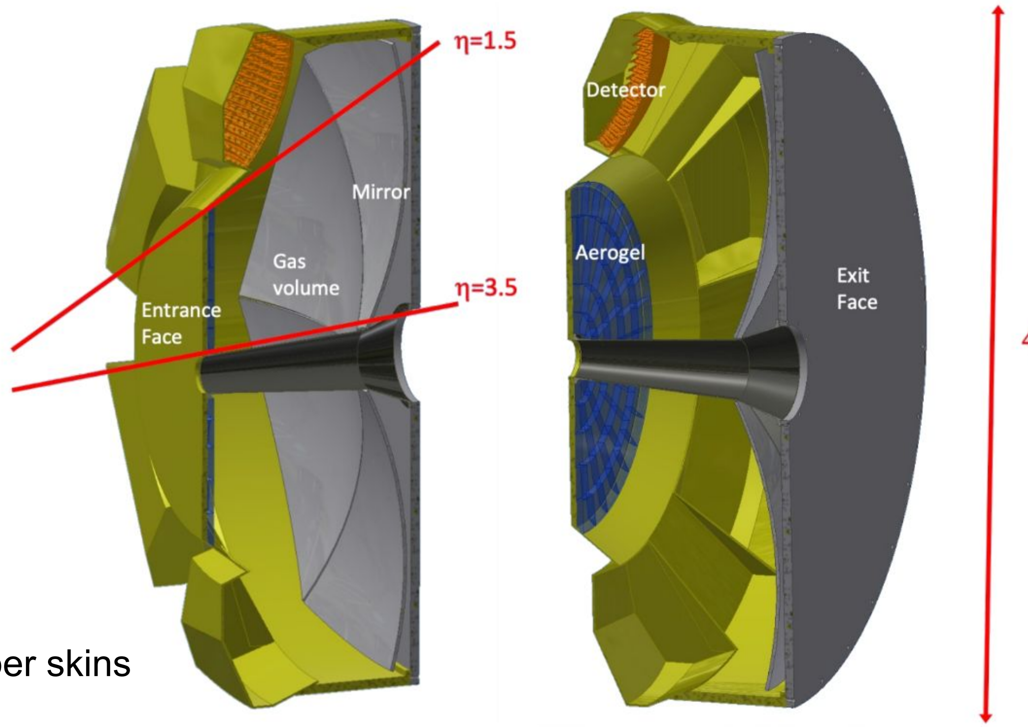
- interlock
- slow control
- cooling
- vessel
- detector box
- mirror alignment
- power supply

Mechanical Layout

simplified view



3D mechanical model



entrance / exit windows (~ 1% X_0)

- sandwich panel made of two ~ 1 mm carbon fiber skins
- separated by 30 mm of foam or Al honeycomb

inner / outer shells (~ 4% X_0)

- 3 mm (inner) to 8 mm (outer)
- thick carbon fiber epoxy composite

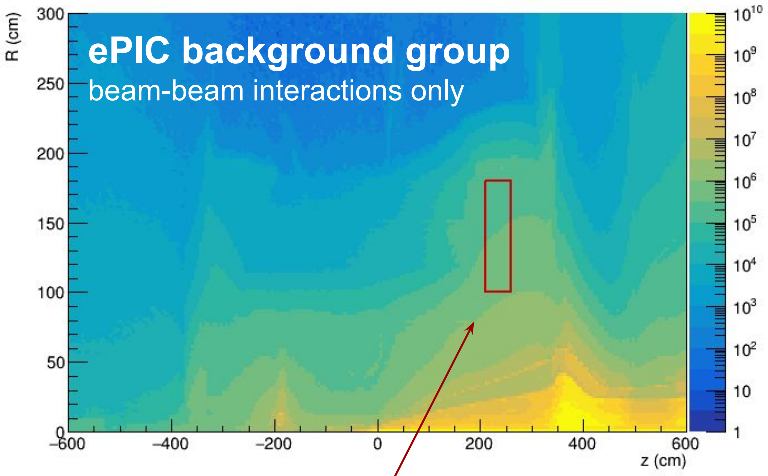
in close interaction with project engineers
working on integration and solving interferences

Skins formed with two layers of balanced weave laminate with fibers at 0^o/90^o and +/- 45^o for uniform stiffness

Environment

recently updated radiation damage estimates

1-MeV neutron equivalent fluence (1 fb^{-1} ep running)



location of dRICH photosensors

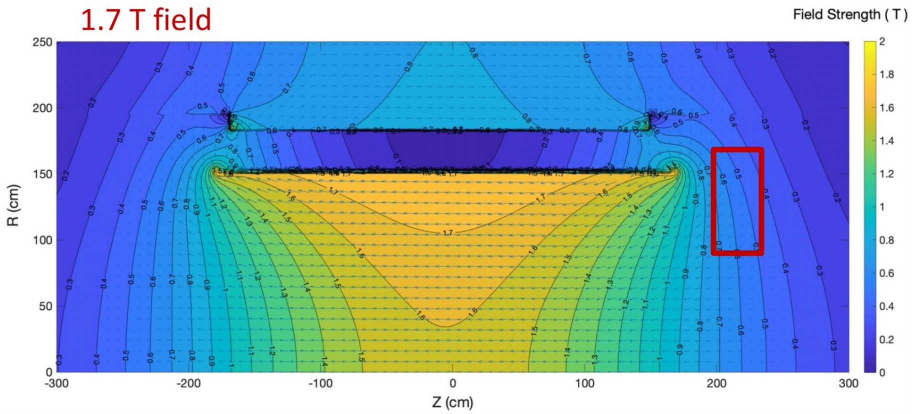
assume fluence: ~ 10^7neq / cm^2 / fb^{-1}

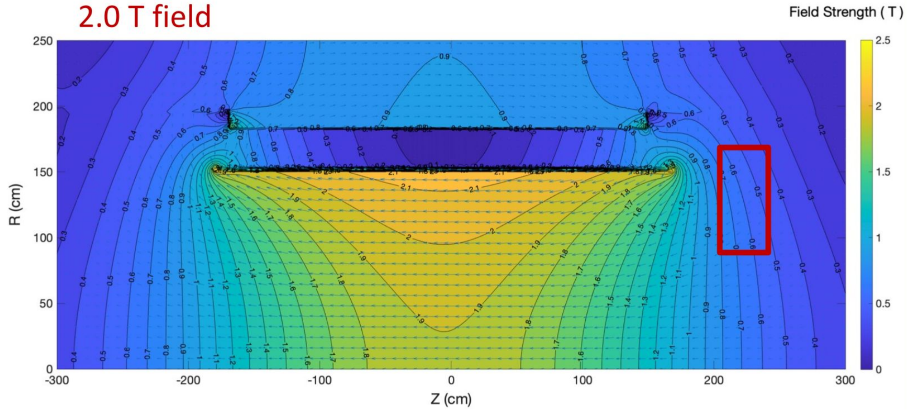
conservatively assume max fluence and 10x safety factor

moderate radiation, 1000 fb^{-1} integrated $\mathcal{L}$ corresponds to ~ 10^{10} n_{eq}/cm^2

MARCO magnetic field maps

ePIC

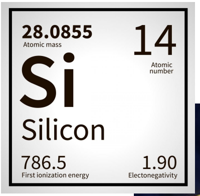




non-uniform, strong magnetic field ~ 0.7 T
field lines ~ parallel to photodetector surface

SiPM optical readout

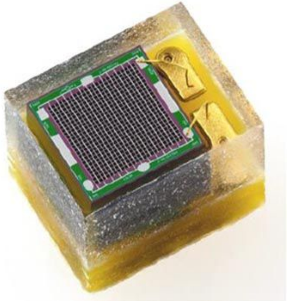
- **pros**
  - cheap
  - high photon efficiency
    requirement ☑
  - excellent time resolution
    requirement ☑
  - insensitive to magnetic field
    requirement ☑



- **cons**

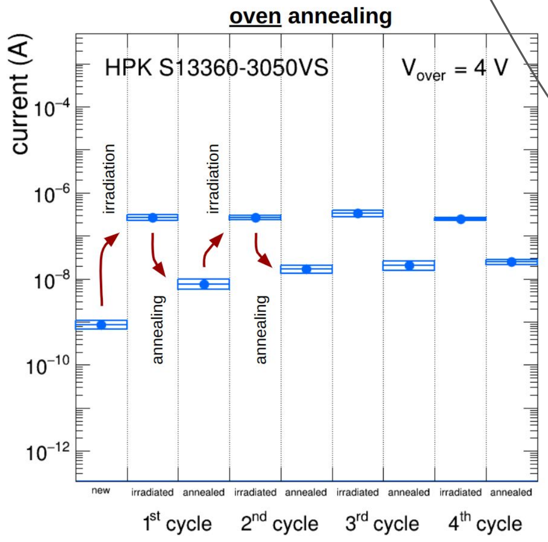
large dark count rates
not radiation tolerant

technical solutions and mitigation strategies
🐧 cooling
⏱ timing
🔥 annealing

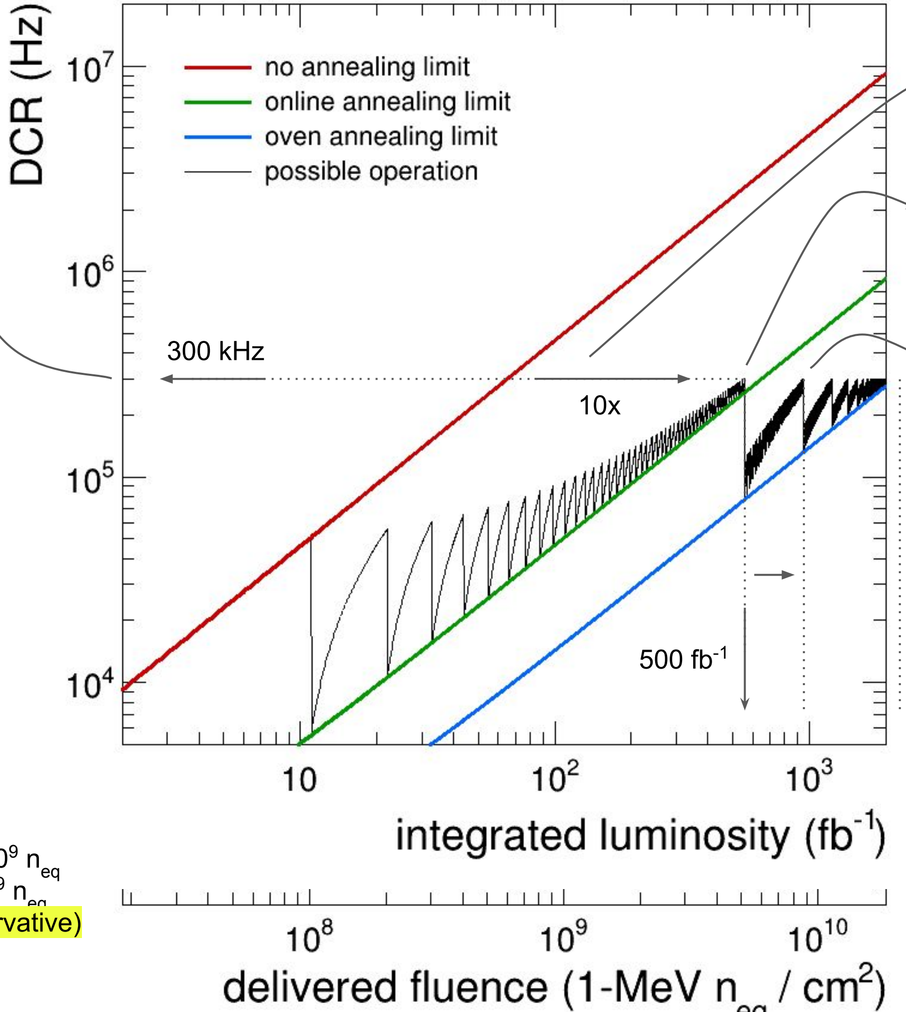


Ageing model

max acceptable DCR for
Physics performance
~ 10 noise hits / sector within 500 ps



Hamamatsu S131360-3050 @ Vover = 4 V, T = -30 C



online annealing
extends SiPM
lifetime by ~ 10x

more aggressive
annealing needed here
might want to unmount/replace SiPM

up to 1000 fb^{-1} and beyond
with optimisation of online
annealing protocol

model input from R&D measurements

- DCR increase: 500 kHz/10^9 n_{eq}
- residual DCR (online annealing): 50 kHz/10^9 n_{eq}
- residual DCR (oven annealing): 15 kHz/10^9 n_{eq}

1-MeV neq fluence from background group (conservative)

- 9 10^6 n_{eq} / fb^{-1}
- includes 10x safety factor

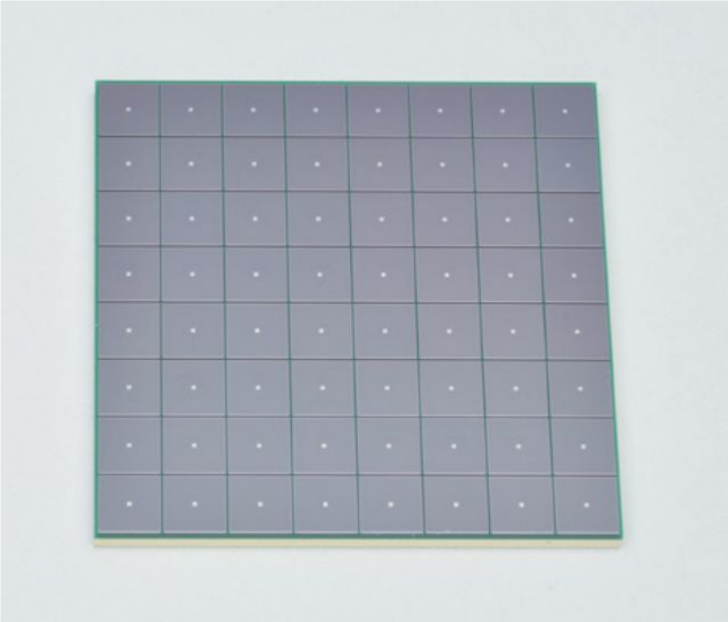
these predictions are according to
present knowledge / tested solutions
there are more handles to
further mitigate DCR
lower Vover, 3V
lover T operation -40 C or below

SiPM technical specs

baseline sensor device

64 (8x8) channel SiPM array

3x3 mm^2 / channel



SiPM are Long Lead Procurement items

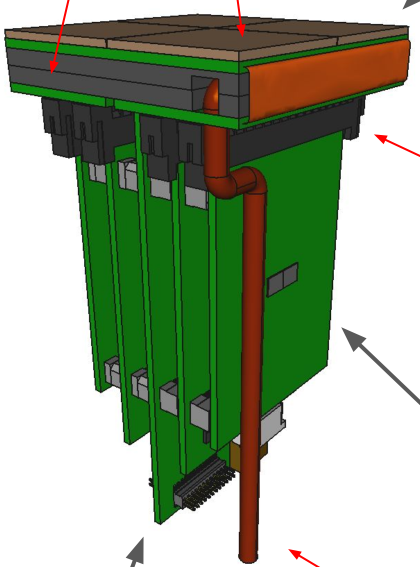
under review in the coming weeks

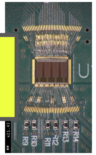
Parameters (at Vop, T = 25 C, unless specified)	Symbol	Value	Notes
Package type		SiPM array	
Mounting technology		surface mount	wire bonding also acceptable
Number of channels		64 (8 x 8)	8 (2 x 4) also acceptable
Effective photosensitive area / channel		3 x 3 mm^2	
Package dimension		< 26 x 26 mm^2	
Fraction of active area in package		> 85 %	
Microcell pitch		50 or 75 um	
Number of microcells	Nspad	> 1500	
Protective window material		Silicone resin	radiation / heat resistant
Protective window refractive index		1.55 - 1.57	
Spectral response range		300 to 900 nm	
Peak sensitivity wavelength	Lambda	400 - 450 nm	
Photon detection efficiency at Lambda		> 40%	
Breakdown voltage	Vbreak	< 60 V	
Operating overvoltage	Vover	< 5 V	
Operating voltage	Vop	Vbd + Vover	
Max Vop variation between channels		< 100 mV	at T = -30 C
Dark count rate	DCR	< 500 kHz	
DCR at T = -30 C		< 5 kHz	at T = -30 C
DCR increase with radiation damage		< 500 kHz / 10^9 neq	at T = -30 C
Residual DCR after annealing		< 50 kHz / 10^9 neq	at T = -30 C
Terminal capacitance		< 500 pF	
Gain		> 1.5 10^6	
Recharge time constant	Tau	< 100 ns	
Crosstalk	CT	< 5%	
Afterpulsing	AP	< 5%	
Operating temperature range		-40 C to 25 C	
Single photon time resolution	SPTR	< 200 ps FWHM	

Photodetector unit

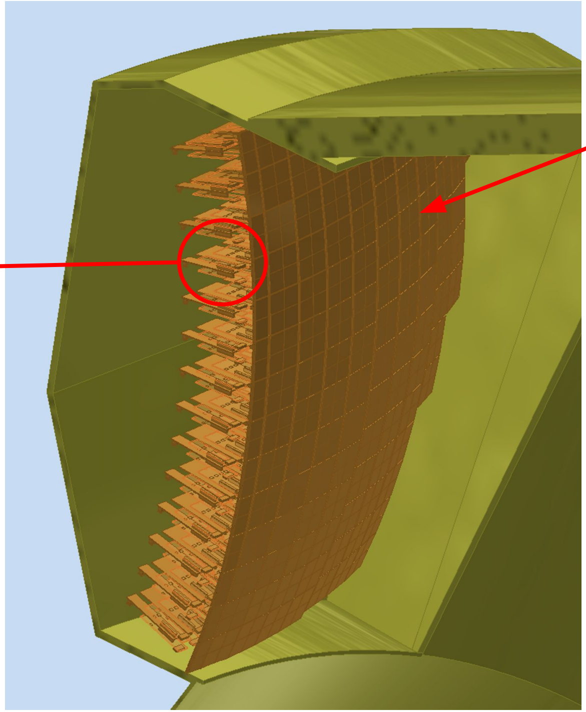
compact solution to minimise space

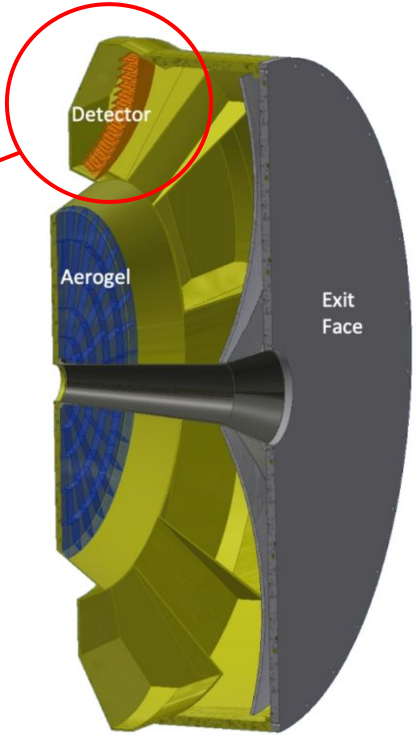
- cold plate and flex-PCB circuit
- uniform sensor cooling with no loss of active area
- all electronics and services on the back side



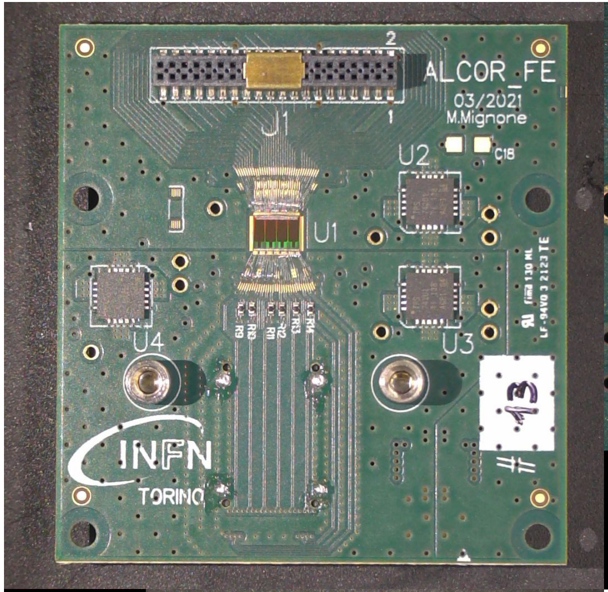


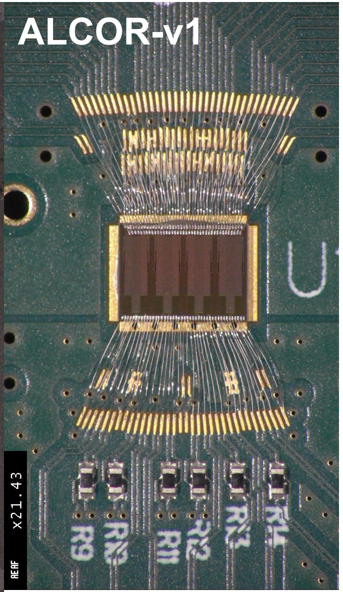
ALCOR ASIC

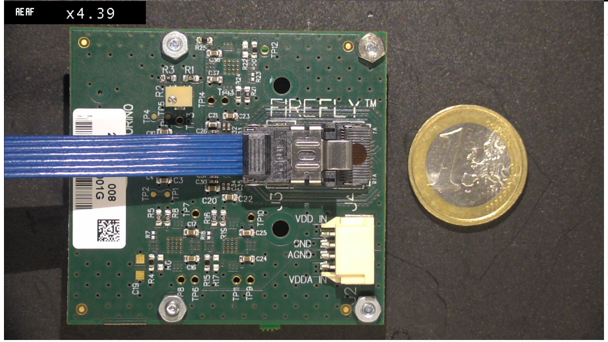


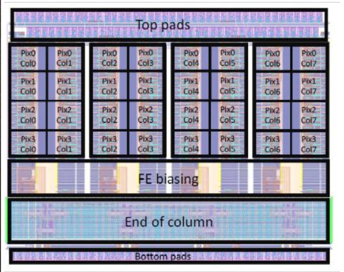


ALCOR ASIC: integrated front-end and TDC









developed by INFN-TO

64-pixel matrix mixed-signal ASIC

current versions (v1,v2) have 32 channels, wirebonded

final version will have 64 channels, BGA package, 394.08 MHz clock

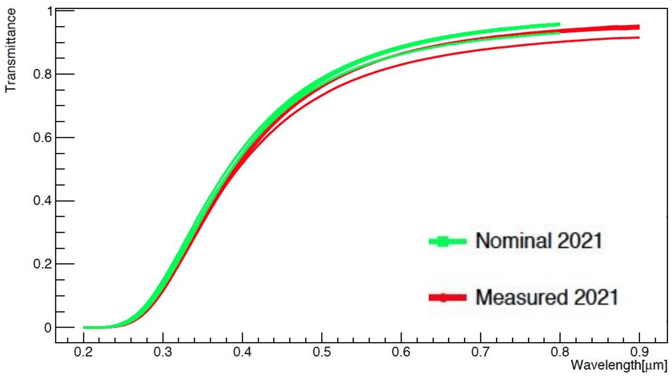
- **the chip performs**
  - signal amplification
  - conditioning and event digitisation
- **each pixel features**
  - 2 leading-edge discriminators
  - 4 TDCs based on analogue interpolation
    - 20 or 40 ps LSB (@ 394 MHz)
  - digital shutter to enable TDC digitisation
    - suppress out-of-gate DCR hits
    - 1-2 ns timing window
    - programmable delay, sub ns accuracy
- **single-photon time-tagging mode**
  - continuous readout
  - also with Time-Over-Threshold
- **fully digital output**
  - 8 LVDS TX data links

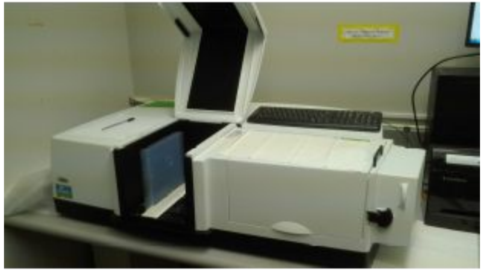
Aerogel and gas radiators

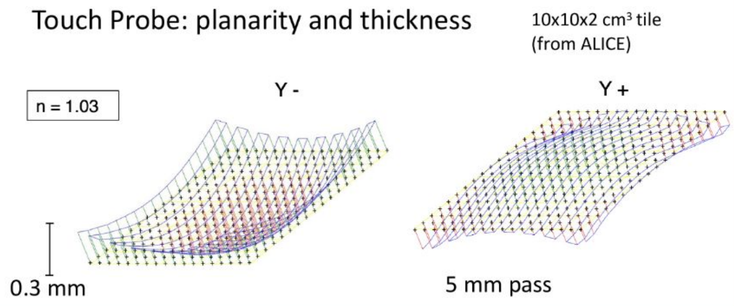
Aerogel Factory (BELLE-2)

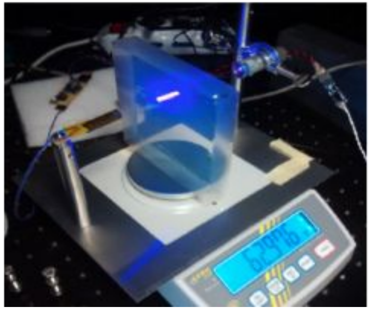
initial evaluation and characterisation of small samples (synergy with ALICE3)

nominal and measured transmittance compared



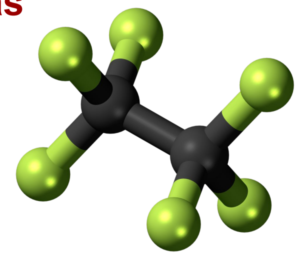






baseline gas

C_2F_6



comes with environmental and potential procurement issues

needs proper recirculation and purging system

evaluation of yearly leaks

difficult to estimate with precision

filling and recovery operations: 6%

filtering and maintenance: 3%

leaks: 10%

sampling, analysis, etc: 2%

dRICH volume: 20 m^2

C_2F_6 density: 5.73 kg/m^3

estimated emission of 30 kg/year

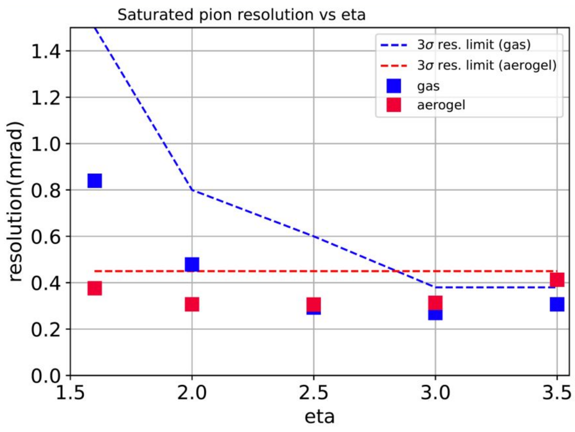
equivalent to 300 tons CO_2/year

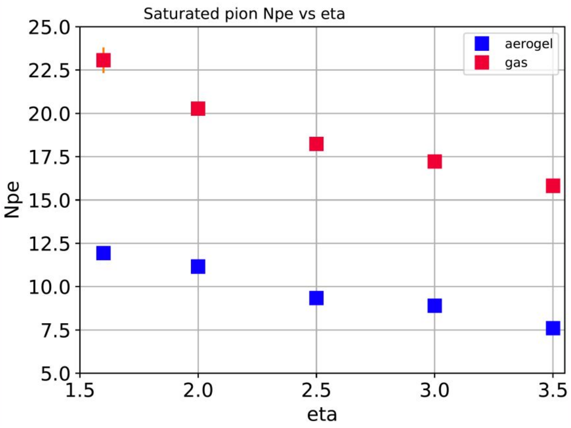
comparable to one intercontinental flight

Performance simulation

preliminary optimisation of dRICH optics within ePIC simulation framework

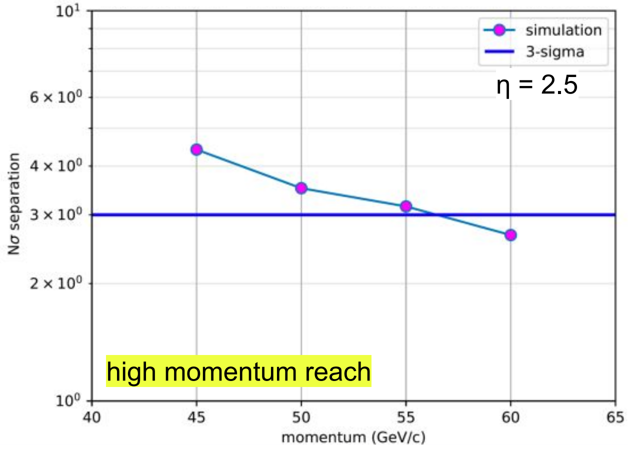
- single mirror configuration
- optimise focus in the most demanding region, 2.5 < η < 3.5
- target resolution of ~ 0.3 mrad



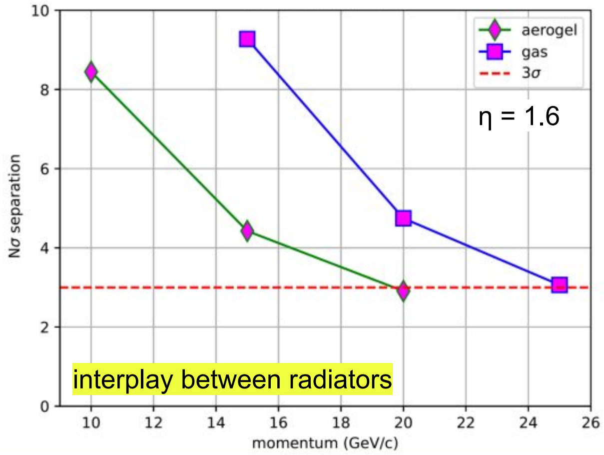


> 3σ continuous separation in the desired momentum range

π/K separation



3σ

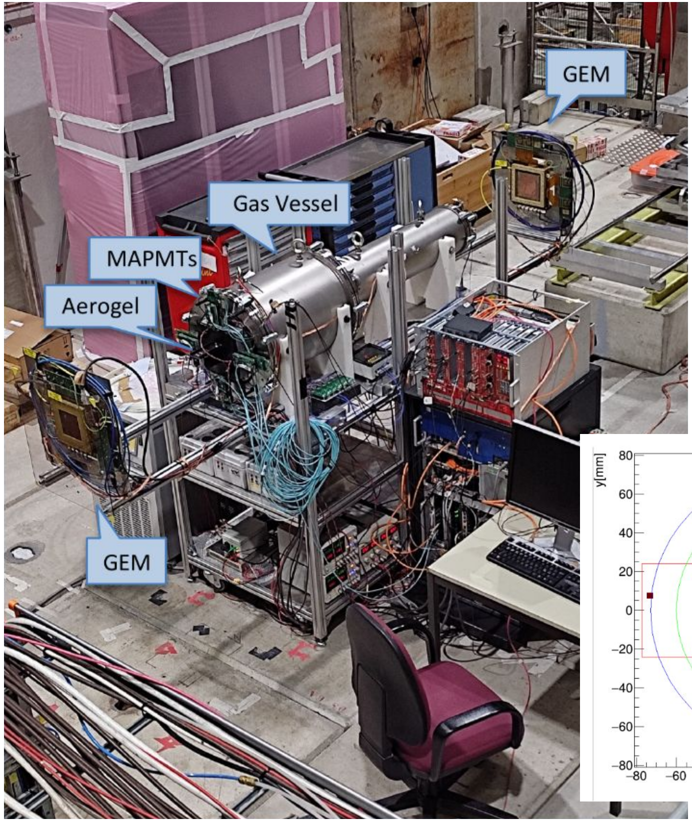


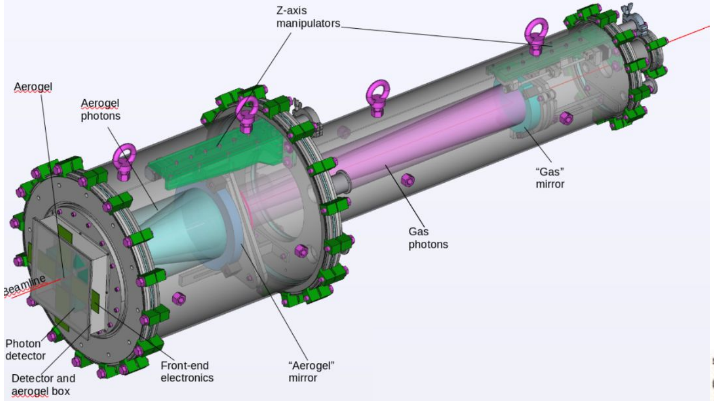
3σ

R&D status

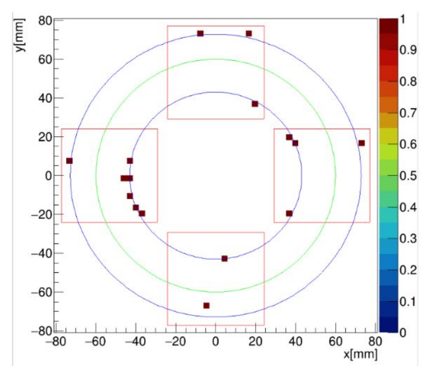
dRICH prototype operative
and commissioned in beam tests
double ring imaging achieved

performance in line with expectations
except for aerogel single-photon
angular resolution (worse by a factor ~ 1.5)

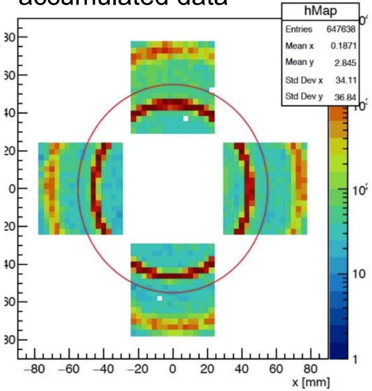


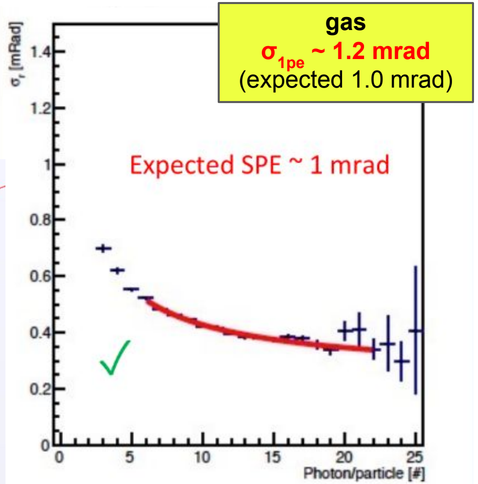


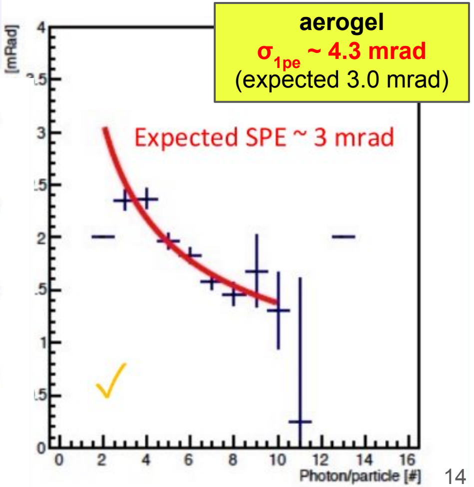
single event



accumulated data

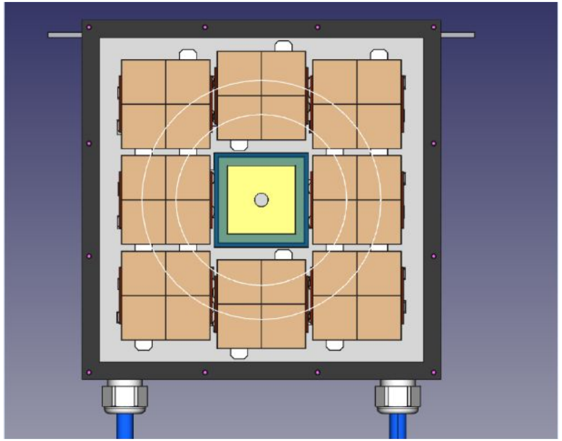


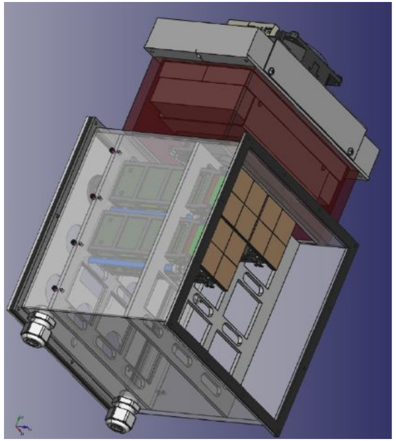




R&D milestones

new EIC-driven detector plane and readout box for 2023 beam tests



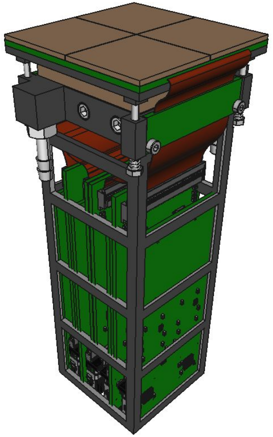


2023: EIC-driven detector plane
test beams planned in August and October

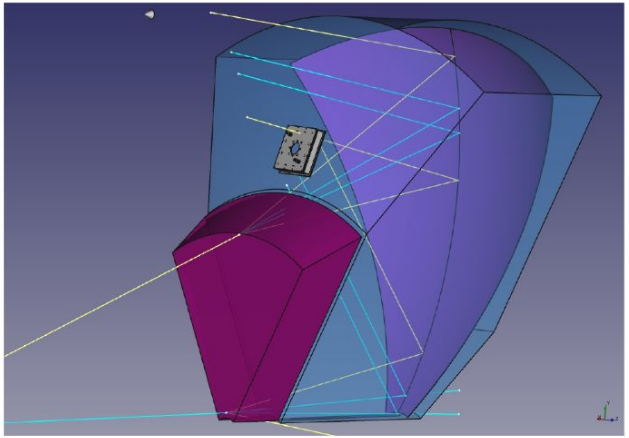
- initial characterization of realistic aerogel and mirror components (23/04)
- projected performance of the baseline detector as integrated into EPIC (23/06)
- assessment of the dRICH prototype performance with the EIC-driven detection plane (23/10)

2024: real-scale prototype for TDR (1 sector)

- mechanical structure
- realistic optics (off-axis)
- prototype RDO board
- aerogel and mirror demonstrator



new EIC-driven readout unit



full-scale dRICH sector prototype

Reviews

ePIC

PID Review, 5-6 July 2023

- Forward Region: dual RICH (Marco Contalbrigo)
- Readout and Sensor Status SiPM (Roberto Preghenella)

generally positive outcome: comments and a few recommendations
specifically for the dRICH

point of attention: quartz window to separate the photodetector box from the gas radiator
recommendation: perform thermal simulation

SiPM annealing and lower temperature operation
consider option of SiPM replacement
sensor performance after annealing
check tolerance of materials to annealing
precautions to avoid damage to ASIC

from the closeout report

- The quartz window to separate the photodetector box from the gas radiator was identified as a point of attention. A thermal simulation is required with the SiPM array at the foreseen operating temperature of -30 C and the approach to avoid condensation or convection of the C2F6 gas radiator should be described. The reviewers fully recognise the importance of the foreseen small-scale system tests in the SPS testbeam facility later this year.

- We recommend to perform a thermal simulation of the dRICH SiPM array considering different operating temperatures and impact on the quartz window and gas radiator.

- The reviewers suggest to consider also the option of replacing the SiPM array once during the experiment lifetime as an alternative to the "oven" annealing process.
- To reduce dark current, heavy annealing is planned. It is required to check that the charge collection efficiency is not reduced due to over-annealing. The reviewers understand that this is part of the ongoing R&D campaign and that encouraging first results have been obtained.
- For online self-annealing, all materials including glue, PCB etc have to be checked to see if these are tolerant to the high temperature and if the thermal cycling does not affect the components due to CTE mismatch.
- We advise exploring the operation of SiPMs at a lower temperature (for example -40C) to guarantee a low level of DCR.

- The online annealing procedure requires forward biasing of the sensors creating local heat generation and large current flows close to the front-end electronics. Precautions will have to be taken to avoid damage to the ASIC. It was understood that this is a part of the R&D effort, for example through the use of MOSFETs to protect the readout.

Long Lead Procurement (LLP) SiPM review, upcoming

Summary

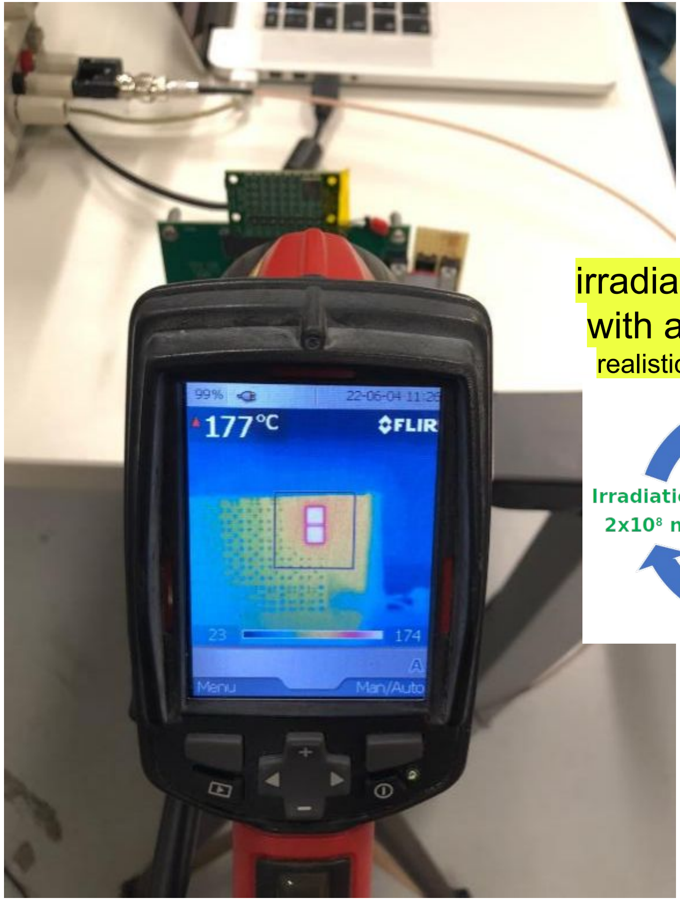
dRICH is a compact and cost-effective solution for broad momentum coverage at forward rapidity

- **baseline configuration and technology identified**
  - fulfills the EIC requirements
  - 3σ K/π separation up to p = 50 GeV/c and up to $\eta = 3.5$
- **dRICH collaboration is setting up**
  - executive office engaged
  - several active work packages
  - welcome new collaborators to join
- **R&D is on track**
  - will deliver the anticipated milestones
  - work progress towards the TDR
    - consolidation of the baseline design
    - further optimization of the components

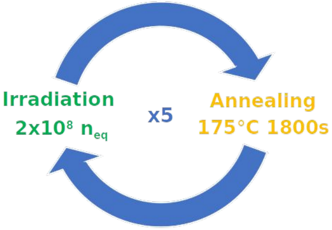
END

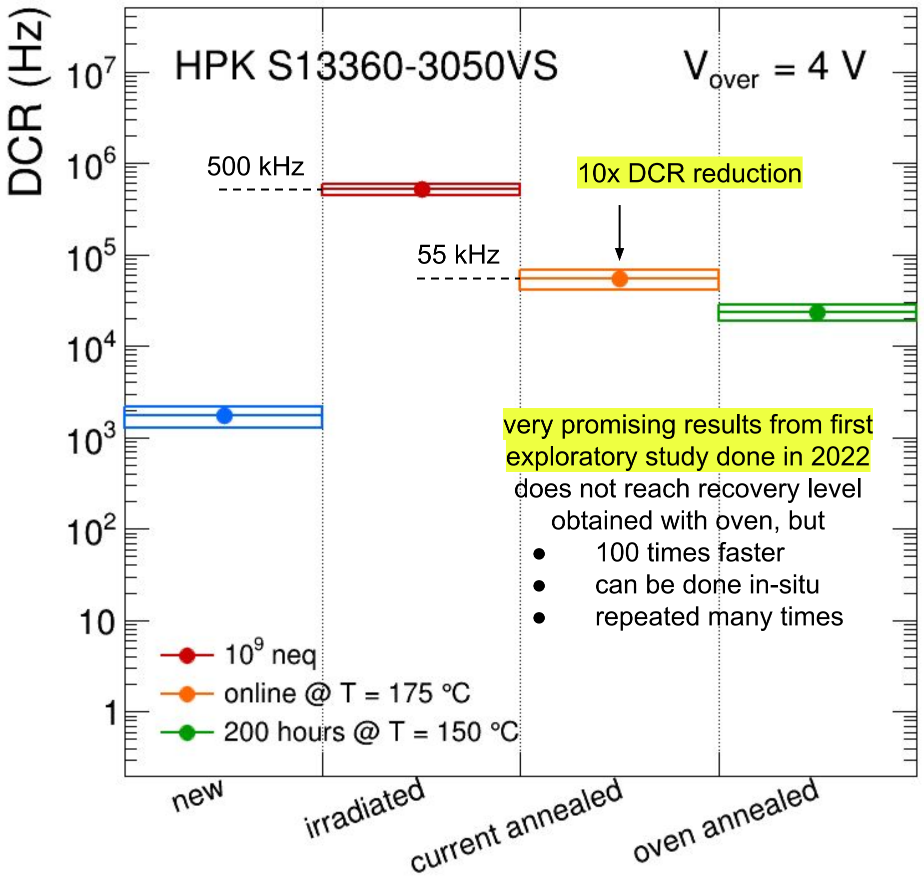
“Online” self-induced annealing

studies for “in-situ” SiPM recovery
multiple cycles: 30 minutes at 175 C
~ 1 W power/sensor delivered with forward bias voltage



irradiation interleaved with annealing cycle
realistic experimental case



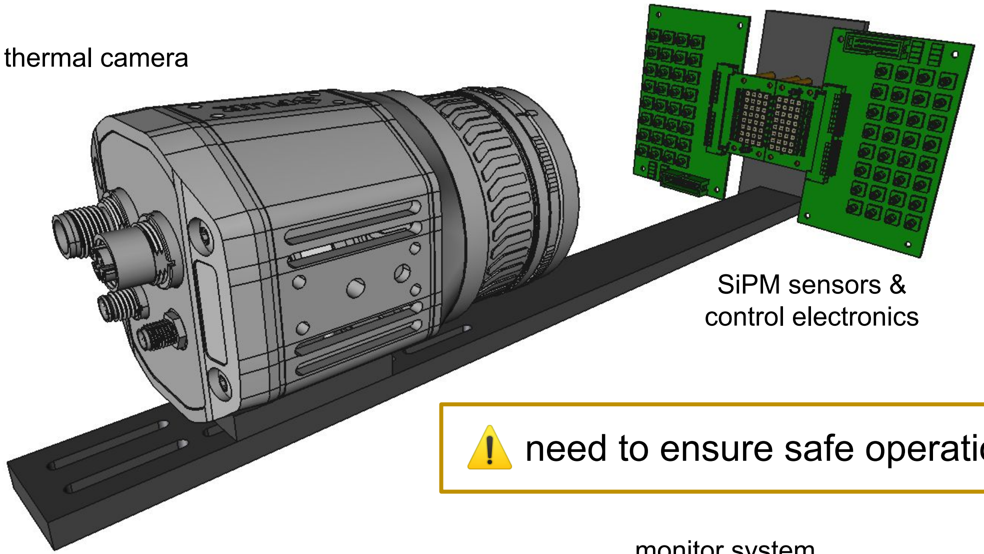


very promising results from first exploratory study done in 2022
does not reach recovery level obtained with oven, but
- 100 times faster
- can be done in-situ
- repeated many times

Automated multiple SiPM online self-annealing

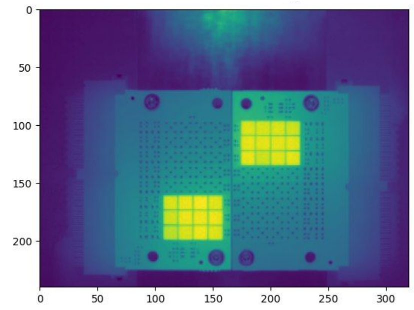
demonstrator system for online temperature monitor and control of each individual SiPM

technical feasibility and implementation in the experimental environment to be studied in details

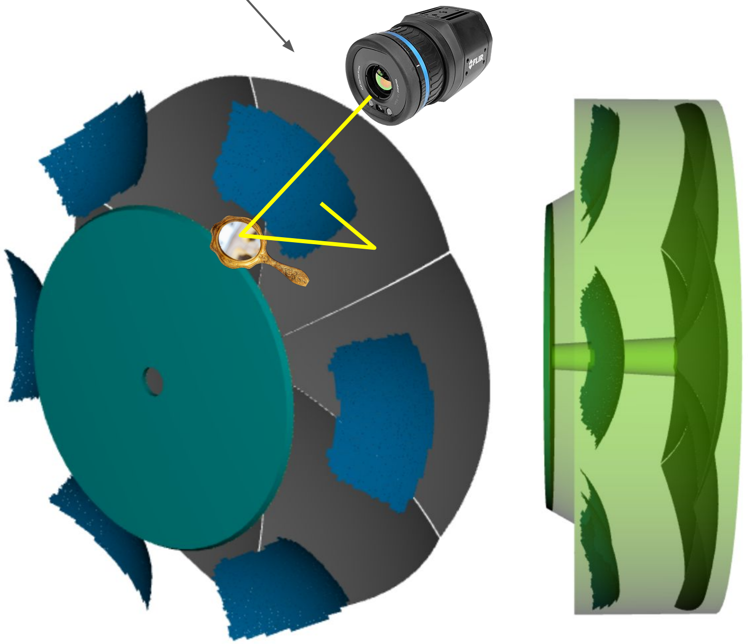


⚠️ need to ensure safe operation

thermal image



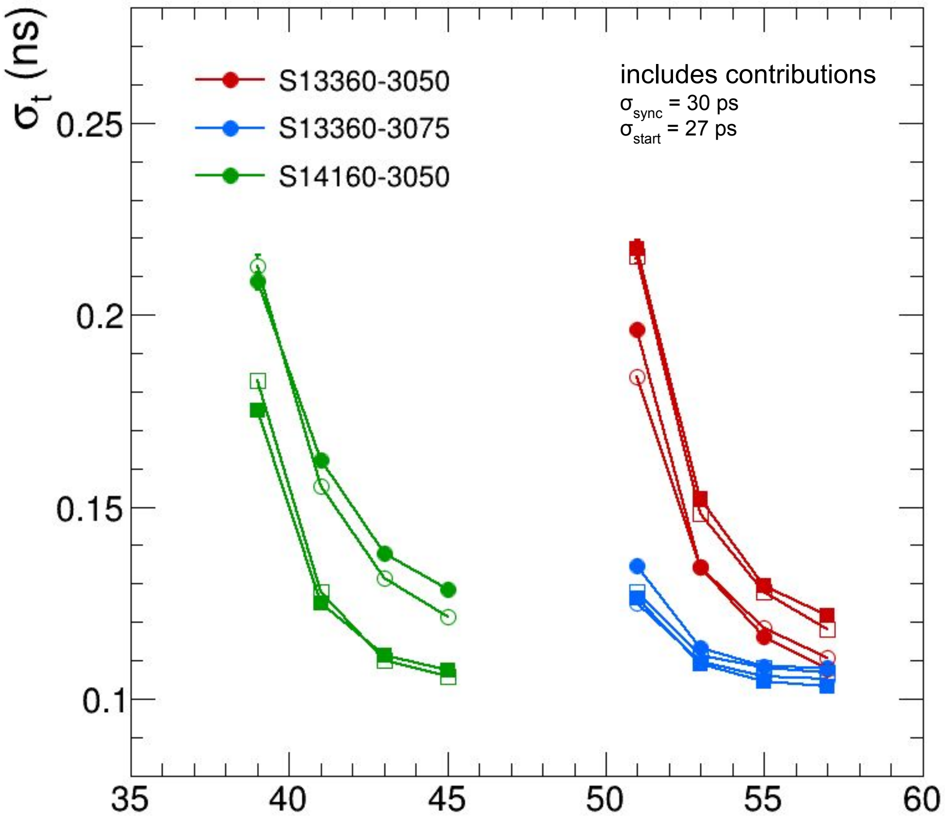
monitor system



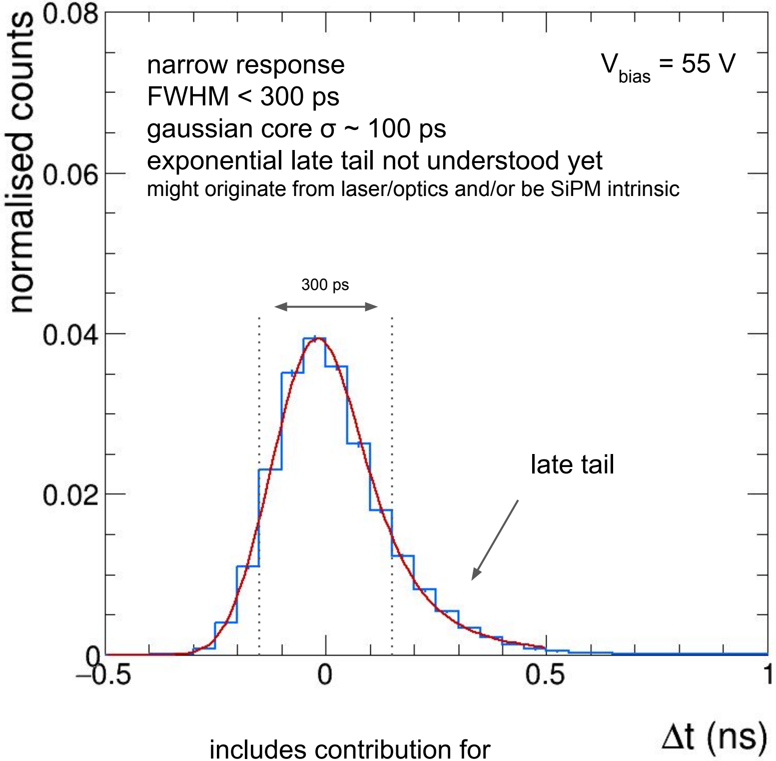
Laser timing measurements with ALCOR

Hamamatsu S13360-3075

standard ALCOR front-end bias configuration



laser-SiPM correlations (time-walk corrected)

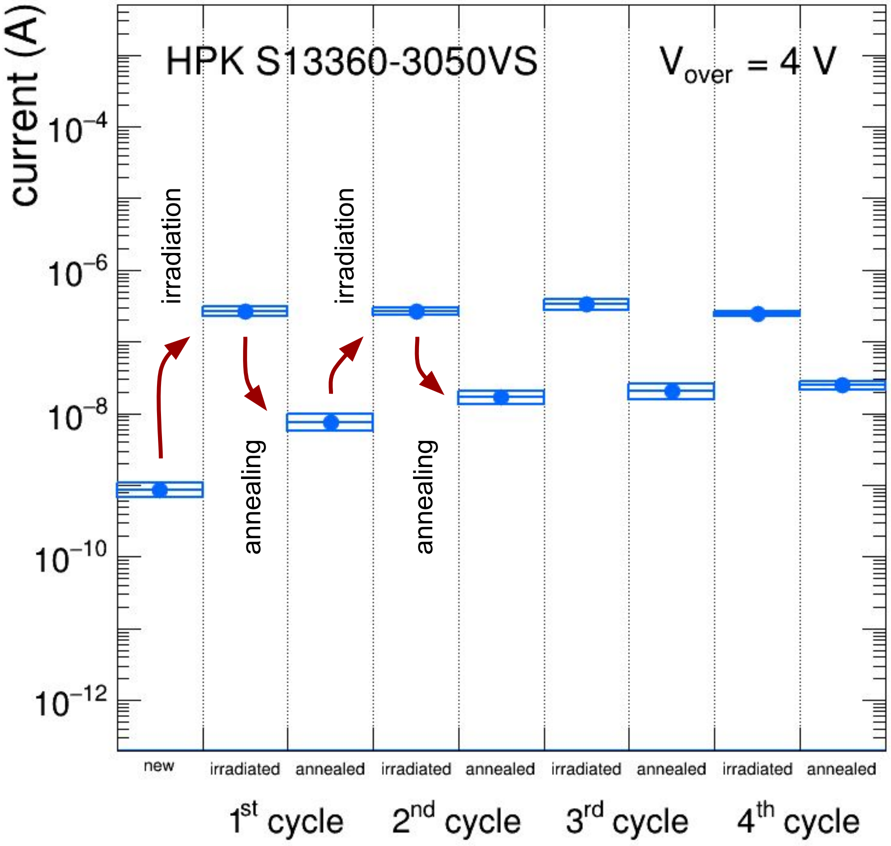


better time resolution with 75 μm SPADs
comfortably below σ_t = 150 ps also at low V_{bias}

includes contribution for
laser-ALCOR synchronization
measured to be σ_{sync} = 30 ps
and reference time resolution
measured to be σ_{start} = 27 ps

Repeated irradiation-annealing cycles

<u>oven</u> annealing



test reproducibility of repeated irradiation-annealing <u>cycles</u>

simulate a realistic experimental situation

- consistent irradiation damage
  - DCR increases by ~ 500 kHz (@ Vover = 4)
  - after each shot of 10^9 n_{eq}
- consistent residual damage
  - ~ 15 kHz (@ Vover = 4) of residual DCR
  - builds up after each irradiation-annealing

annealing cures same fraction of newly-produced damage

~ 97% for HPK S13360-3050 sensors

SiPM cooling for low-temperature operation (−30 °C or lower)

external chiller with fluid recirculation (ie. siliconic oil)

the chiller here one is just a commercial example

cooling and heating capacity

could use heating capability for annealing? must be demonstrated to be feasible

cooling capacity at -40 C is large (1.5 kW)

huber

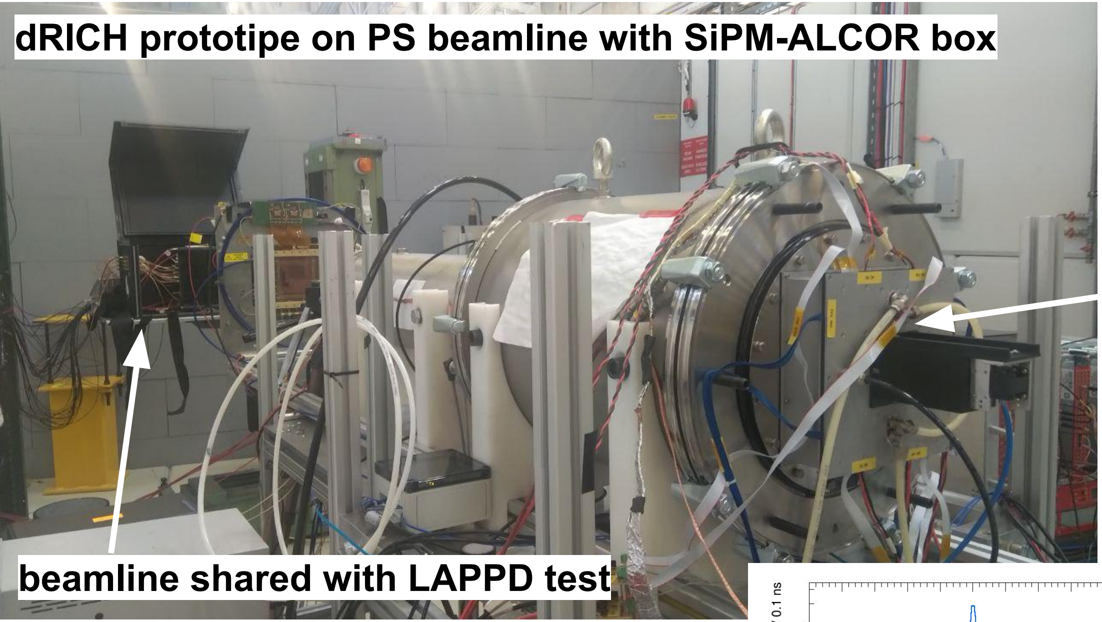
General & Temperature Control

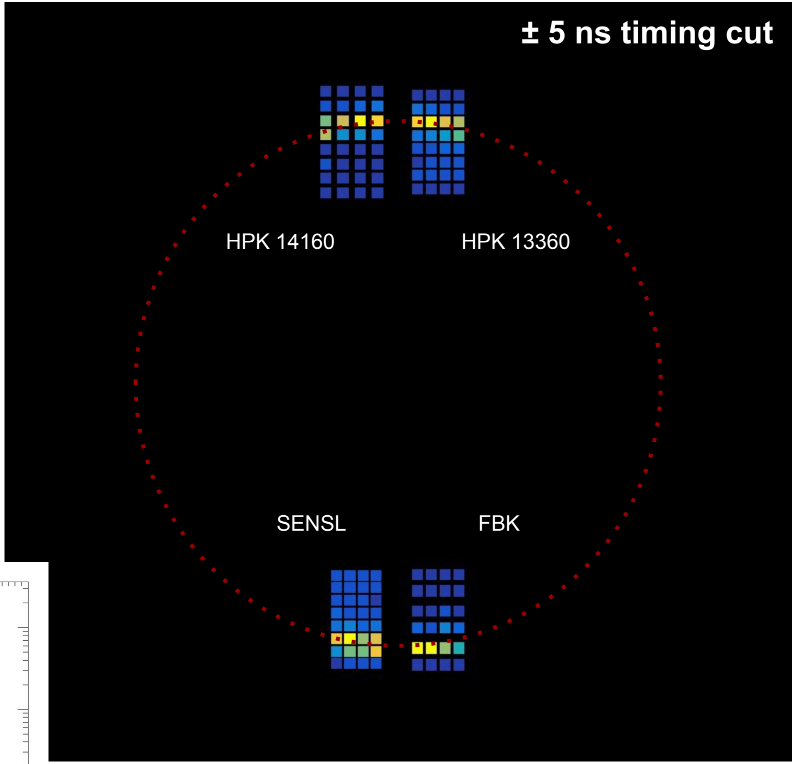
Temperature range	-55...250 °C
Temperature stability	±0,01 K

Heating / cooling capacity

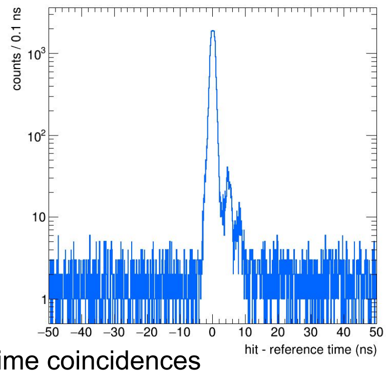
Heating capacity	6 kW								
Cooling capacity	250	200	100	20	0	-20	-40	-50	°C
	6	6	6	6	6	4,2	1,5	0,65	kW

2022 test beam at CERN-PS





8 GeV negative beam (aerogel rings)



time coincidences

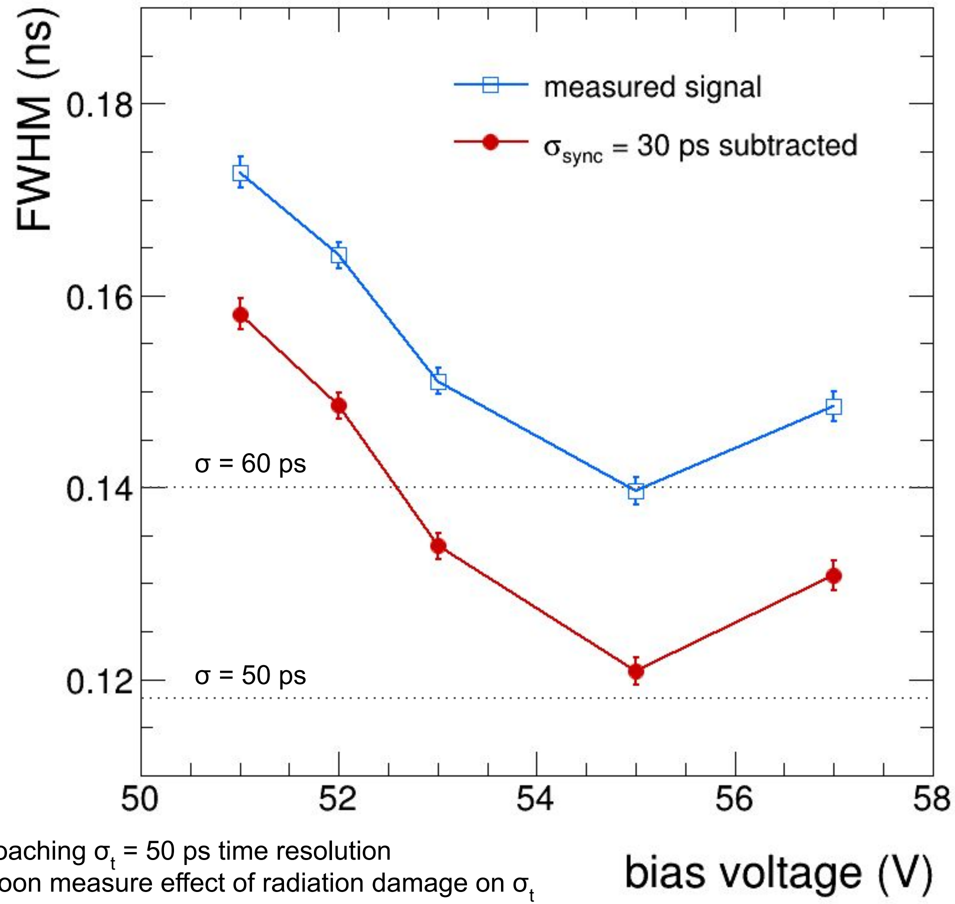
successful operation of SiPM

irradiated (with protons up to 10^{10})

and annealed (in oven at 150 C)

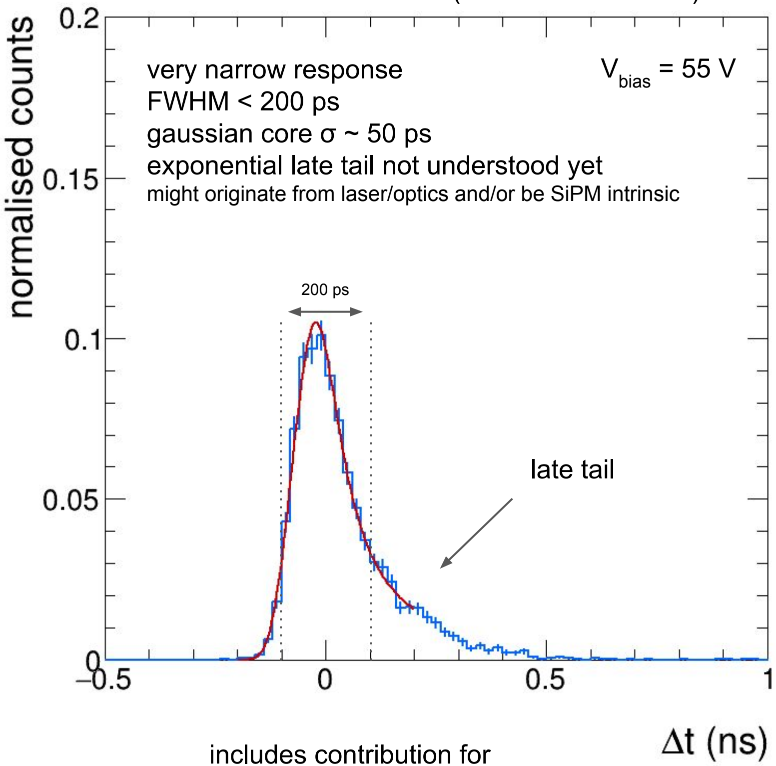
Laser timing measurements with oscilloscope

Hamamatsu S13360-3075

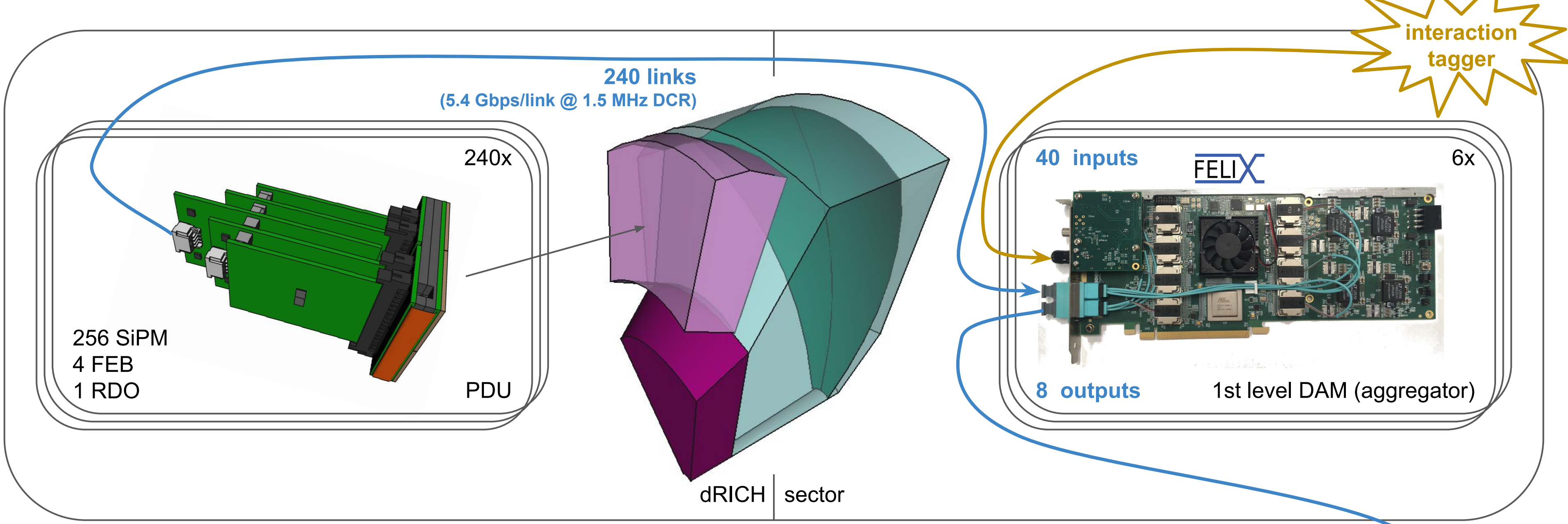


approaching σ_t = 50 ps time resolution
will soon measure effect of radiation damage on σ_t

laser-SiPM correlations (time-walk corrected)

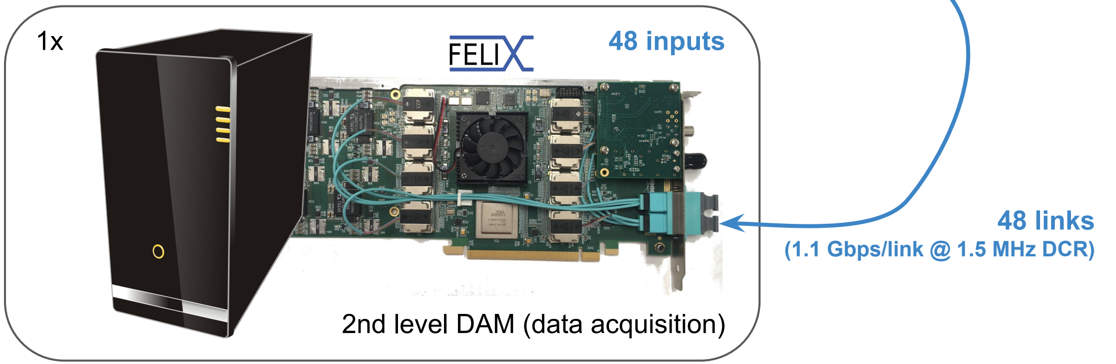


includes contribution for
laser-oscilloscope synchronization
measured to be σ_{sync} = 30 ps



one dRICH sector, up to

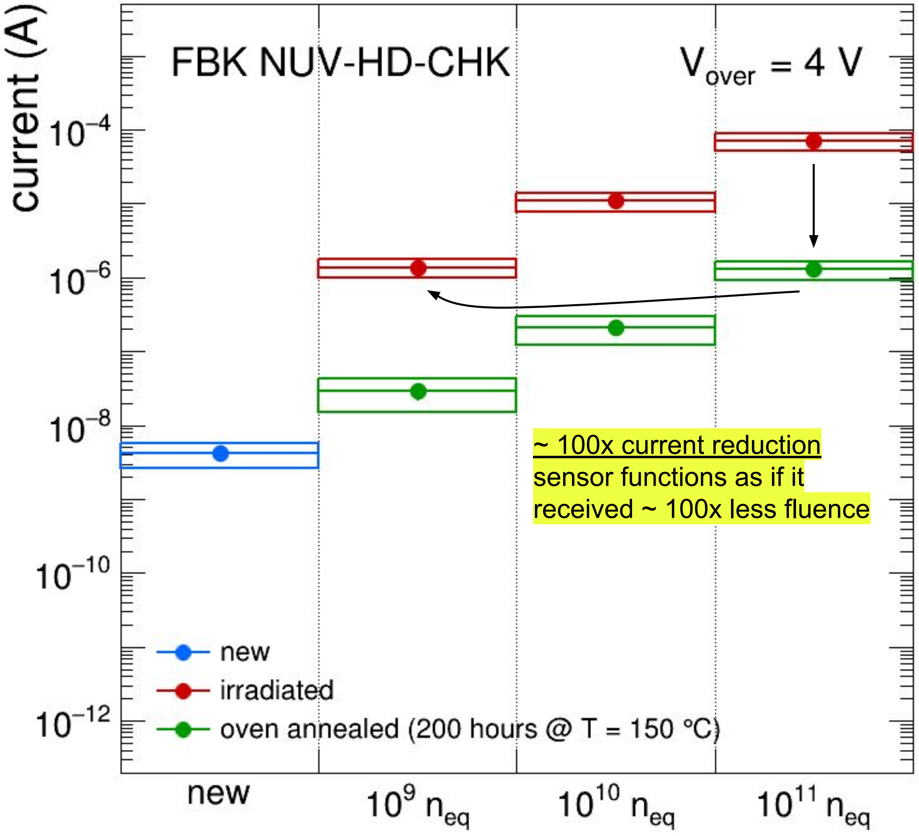
- 59040 channels
- 960 FEBs
- 240 RDOs
- 6 1st level DAMs
- 1 2nd level DAM



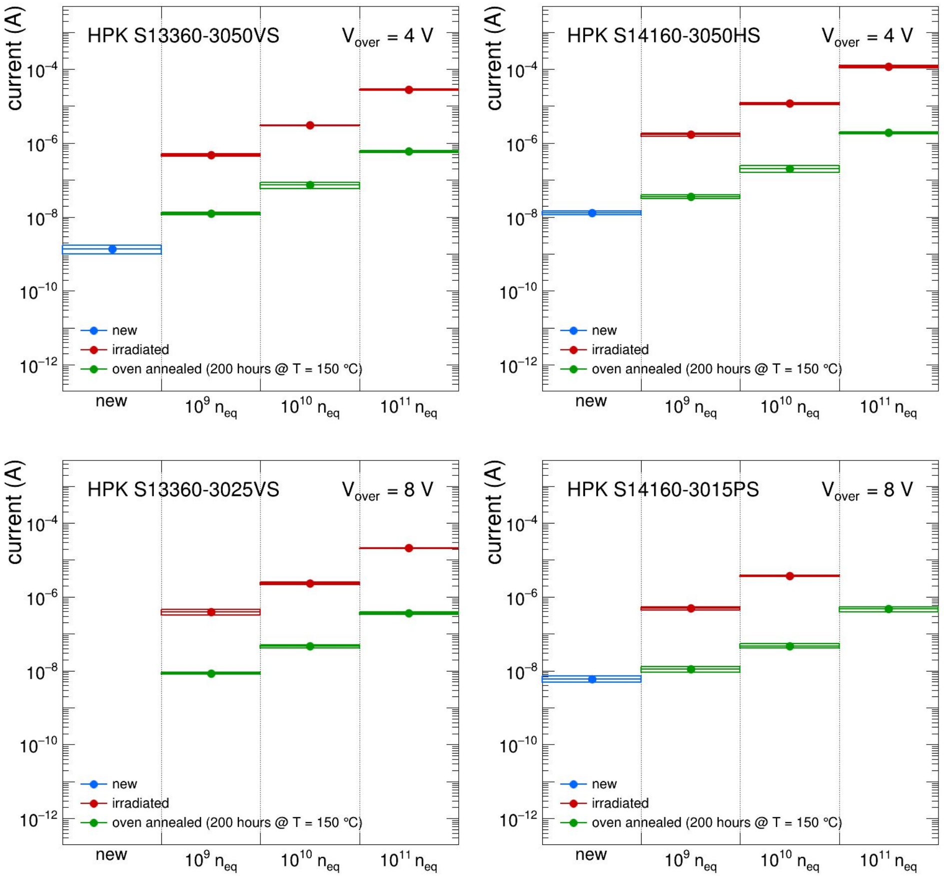
PDU readout model

High-temperature annealing recovery

oven annealing
~ 1 week at 150 C



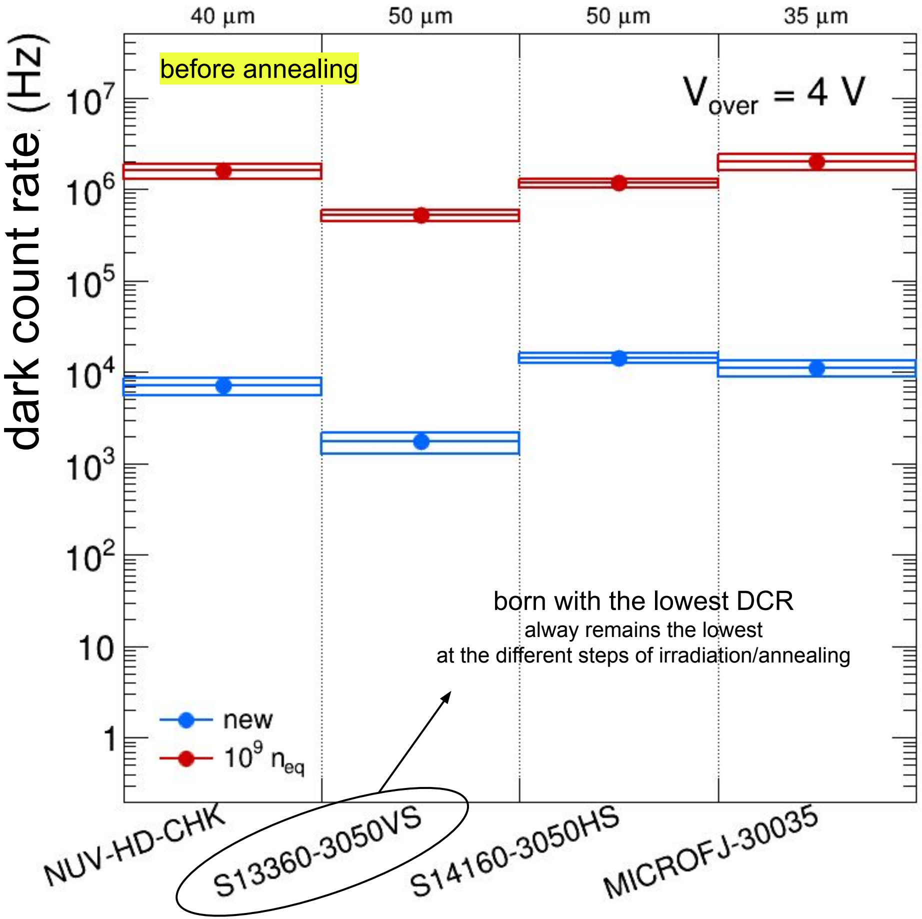
~ 100x current reduction
sensor functions as if it
received ~ 100x less fluence

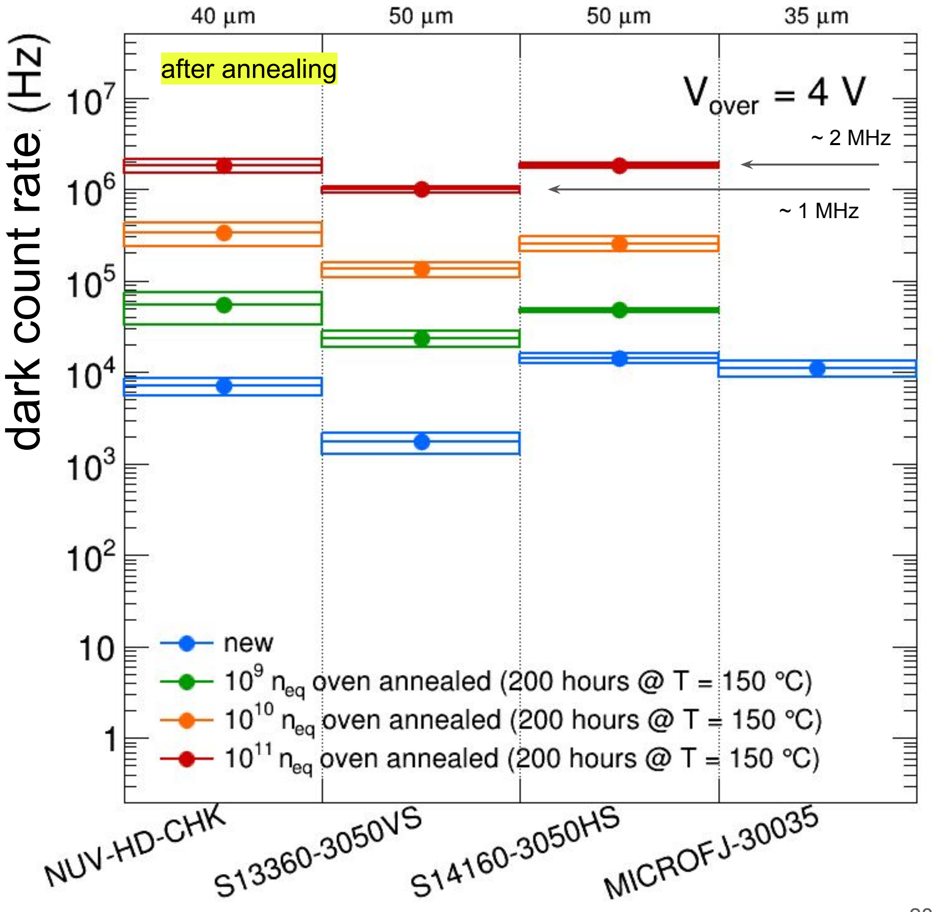


similar observation with various types of Hamamatsu sensors

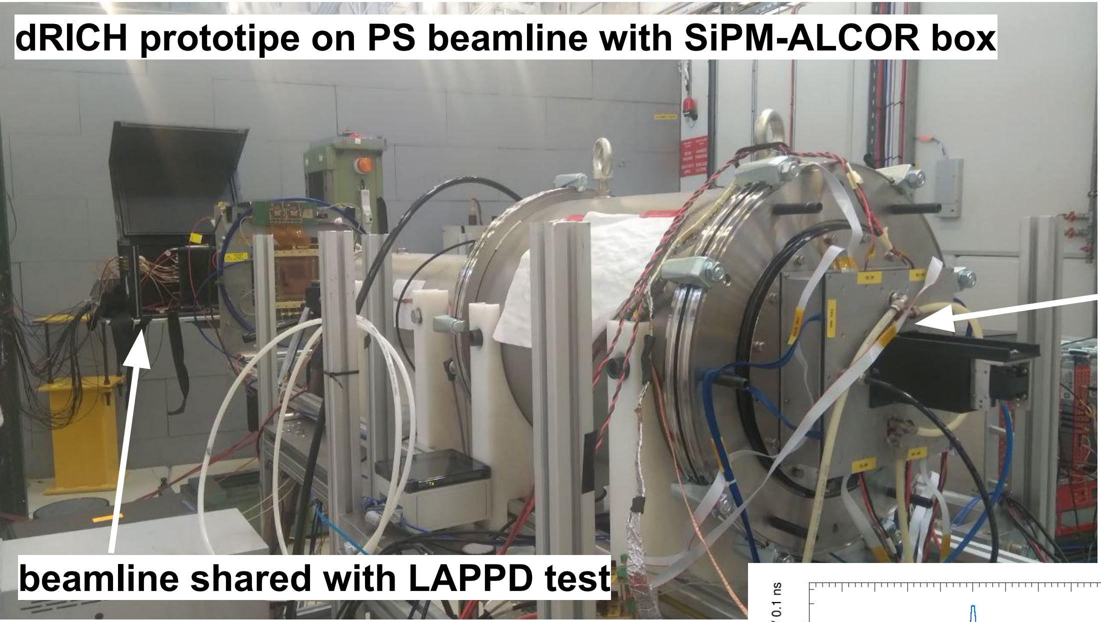
Comparison between different sensors

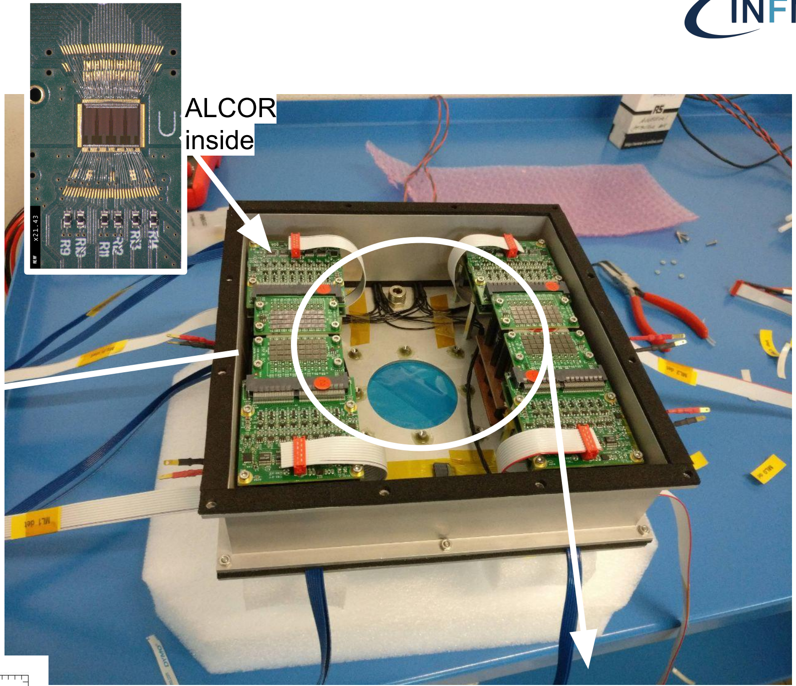
comparison at same Vover not totally fair
important to consider PDE (and SPTR) → SNR ~ PDE / DCR
unlikely 2x larger DCR is matched by 2x larger PDE





2022 test beam at CERN-PS

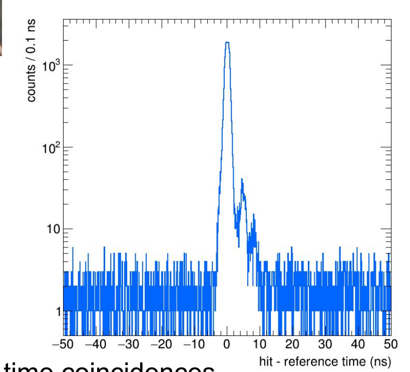




successful operation of SiPM

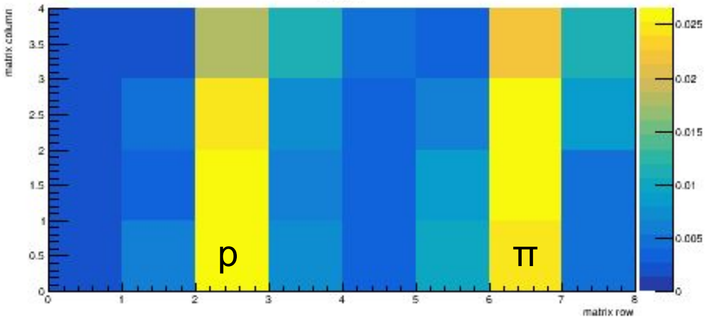
irradiated (with protons up to 10^{10})

and annealed (in oven at 150 C)



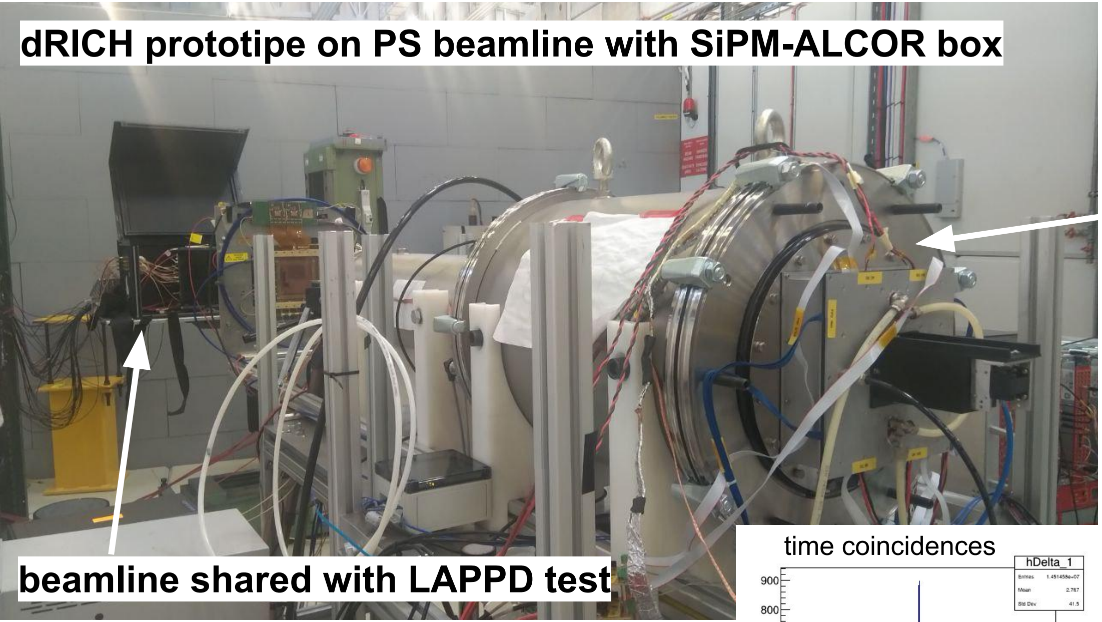
time coincidences

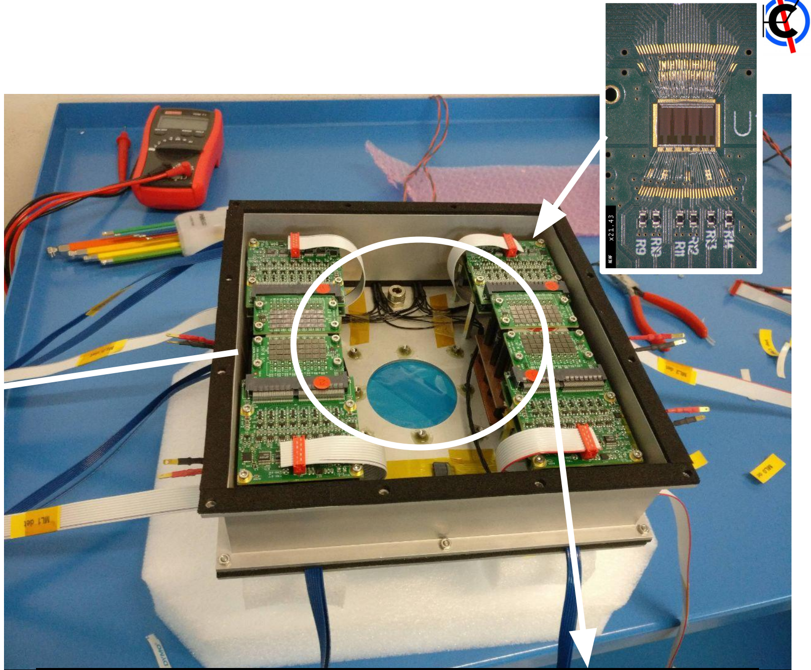
8 GeV positive beam (aerogel rings)



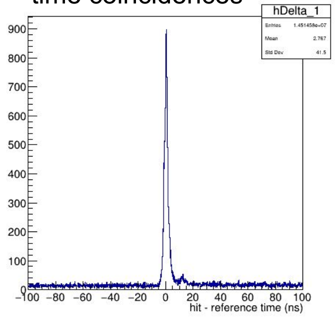
R&D status

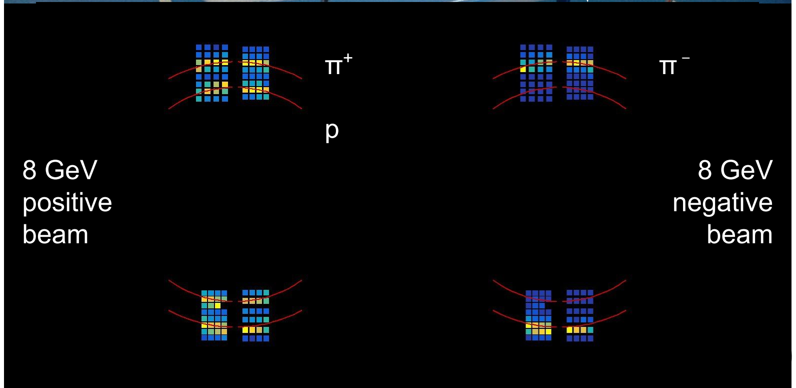
successful operation of SiPM with complete readout chain





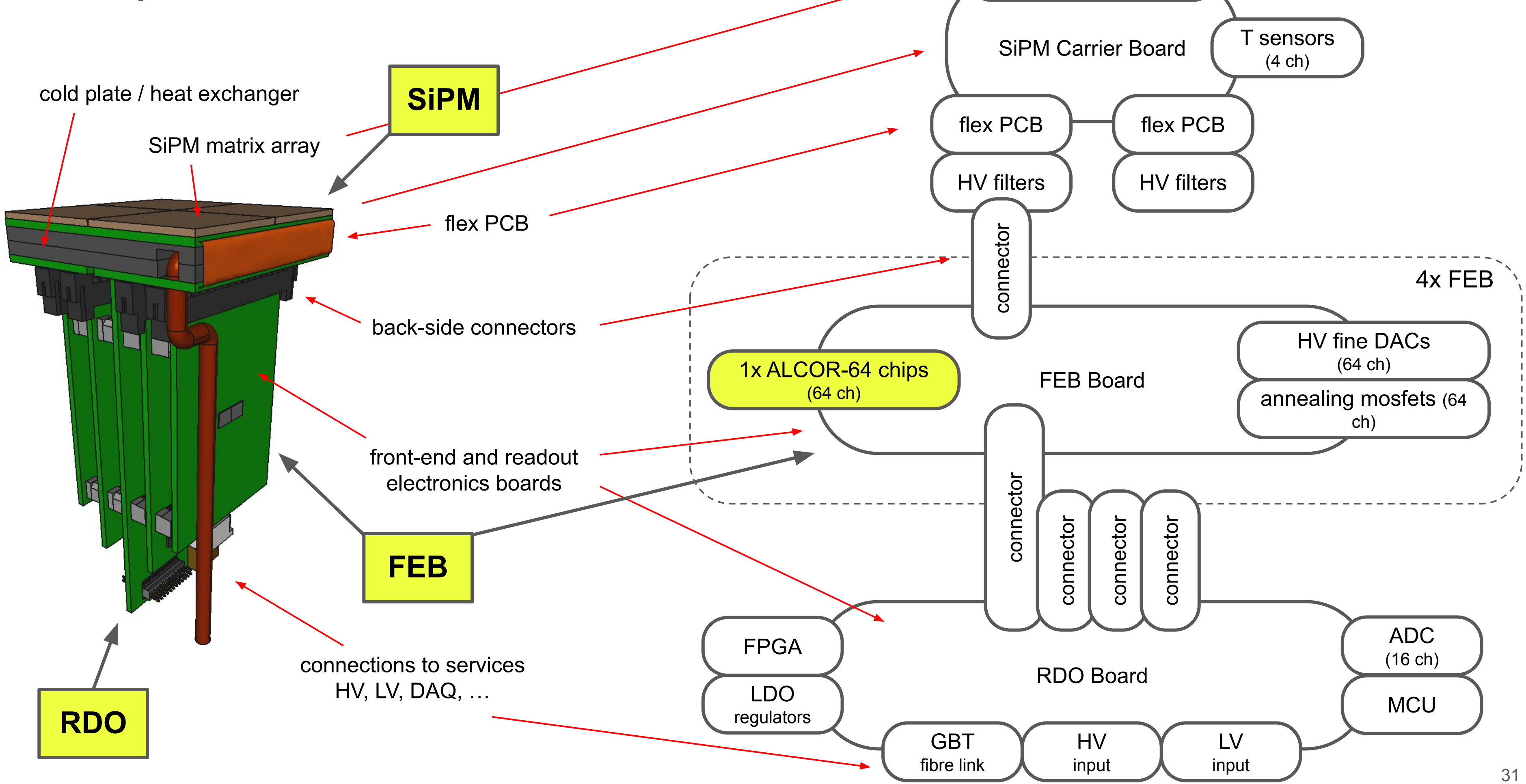
time coincidences





SiPM sensors were **irradiated** (up to 10^{10}) and **annealed** (150 hours at T = 150 C)

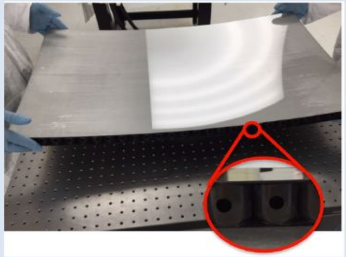
SiPM photodetector unit

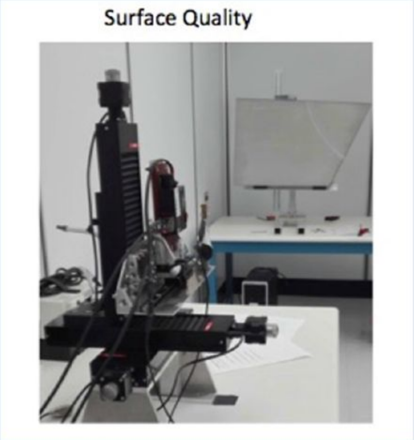


CMA Carbon fiber mirrors (HERMES, AMS, LHCb, CLAS12)

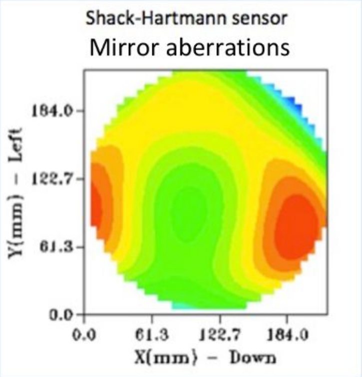
cost-effective light & stiff solution:

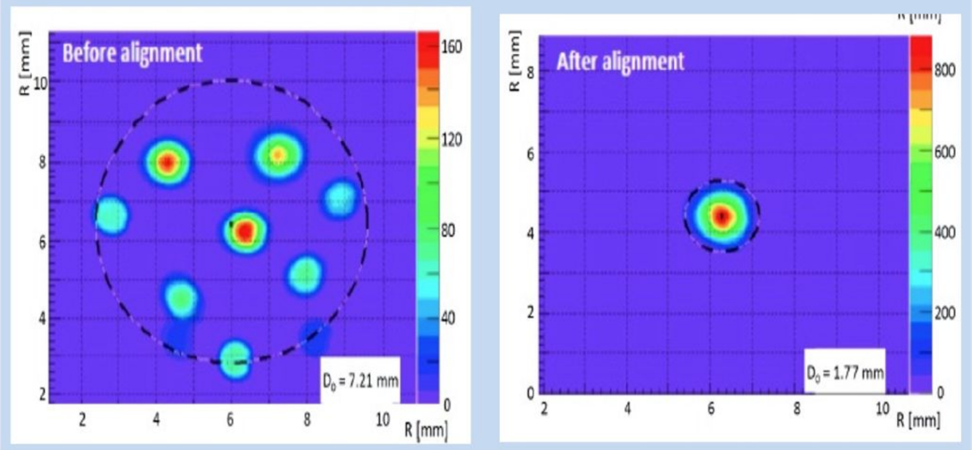
- roughness driven by mandrel 1-2 nm rms
- surface accuracy better than 0.2 mrad
- radius reproducibility better than 1 %





CLAS12 RICH QA laboratory @ JLab being refurnished





Optimization and Risk Mitigation

Component	Baseline	Optimization	Possible improvement
SiPM	Hamamatsu H13361-3050HS	75 μm cell FBK sensor	Larger PDE Better time resolution
Aerogel radiator	Aerogel Factory n=1.02	Refractive index Tile dimensions Tsinghua aerogel	Increase photon yield Reduce edge effects Risk reduction for single vendor
Gas radiator	SIAD C_2F_6	Gas mixture Early procurement	Reduced environment impact (global warming) Limit dependence on market & regulations
Mechanics	Tecnavan Carbon fiber composite	Al composite	Cost reduction
Mirrors	CMA Carbon fiber composite	Mold material Different core strucuture Tessellation	Better shape quality vs cost
Cooling	Al plate	Carbon foam plate	Reduce material budget

Commercial Examples:

Power supply

Cooling plants

General & Temperature Control	
Temperature range	-55...250 °C
Temperature stability	±0,01 K

Heating / cooling capacity									
Heating capacity	6 kW								
Cooling capacity	250	200	100	20	0	-20	-40	-50	°C
	6	6	6	6	6	4,2	1,5	0,65	kW

Existing systems & standards:

COMPASS C_4F_{10} recirculating and purgingn system