A SiPM-based optical readout for the EIC dual-radiator RICH

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on behalf of the dRICH Collaboration

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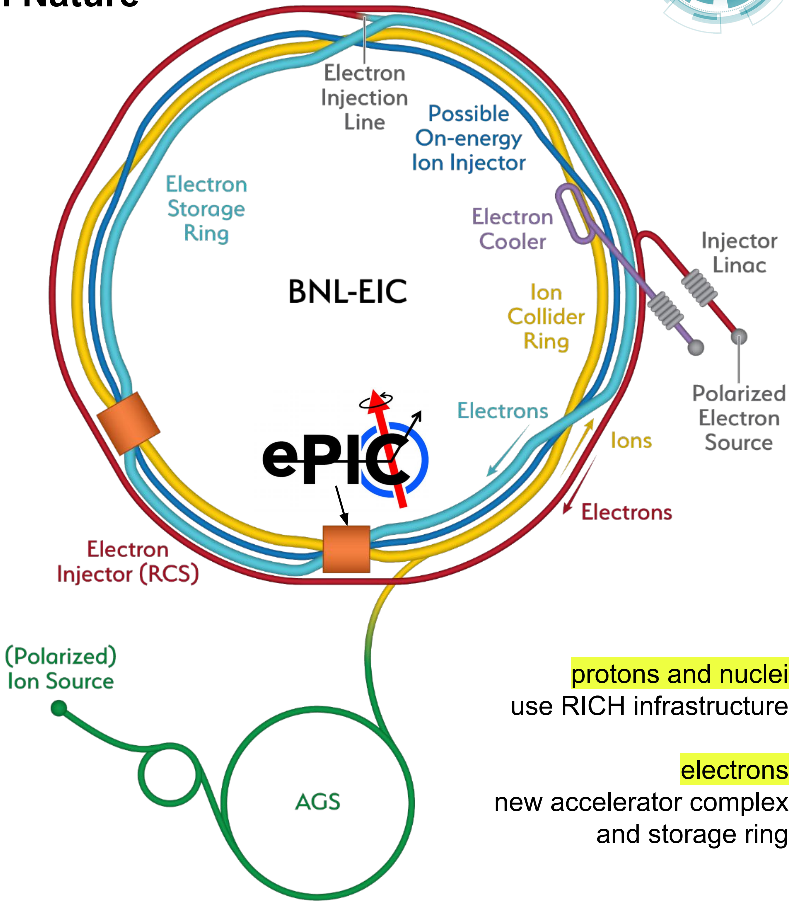
The Electron-Ion Collider

a machine that will unlock the secrets of the strongest force in Nature
is a future electron-proton and electron-ion collider at BNL (USA)
foreseen to start operation in early 2030's

- **the major US project in the field of nuclear physics**
  - one of the most important scientific facilities for the future of nuclear and subnuclear physics
- **the world's first collider for**
  - polarised electron-proton (and light ions)
  - electron-nucleus collisions
- **will allow to explore the secrets of QCD**
  - understand origin of mass & spin of the nucleons
  - extraordinary 3D images of the nuclear structure



protons and nuclei
use RICH infrastructure

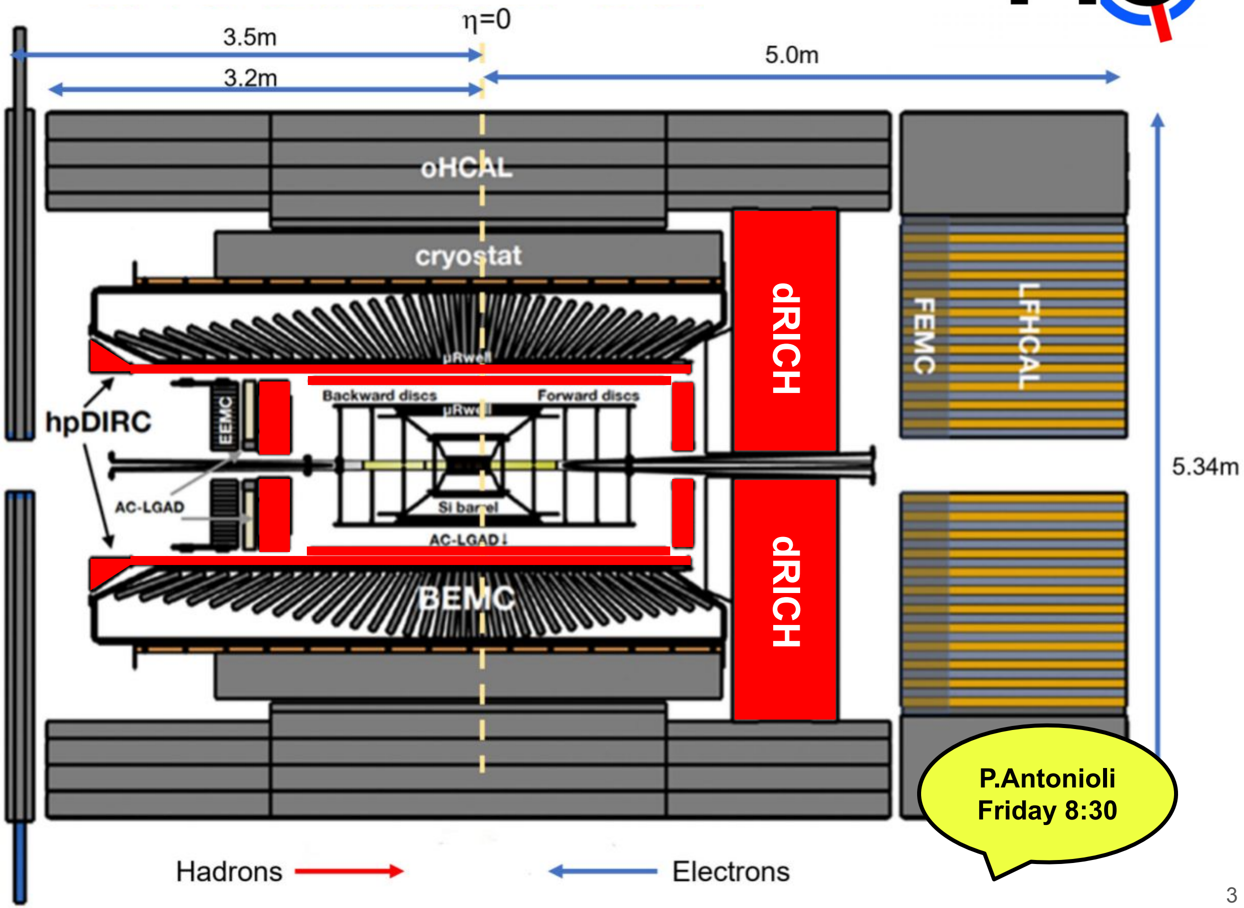
electrons
new accelerator complex and storage ring

www.bnl.gov/eic

The ePIC experiment

layout of the barrel detector

- **tracking**
  - new 1.7 T magnet
  - Si-MAPS + MPGDs
- **calorimetry**
  - e-side: $PbWO_4$ EMCal
  - barrel: imaging EMCal
  - h-side: finely segmented
  - outer barrel HCal
- **particle ID**
  - AC-LGAD TOF
  - pfRICH
  - hpDIRC
  - dRICH



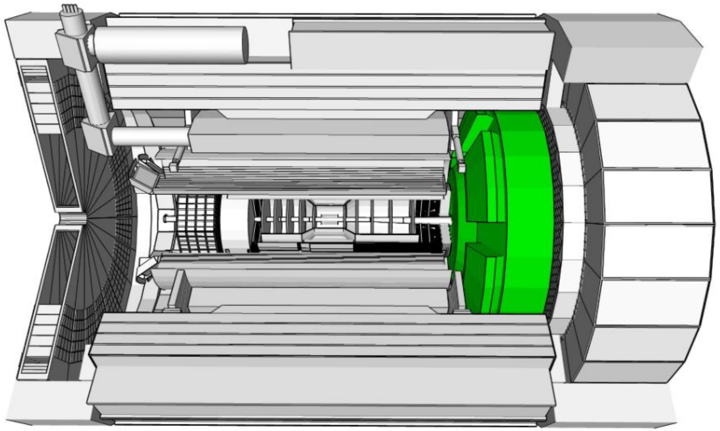
P.Antonioli
Friday 8:30

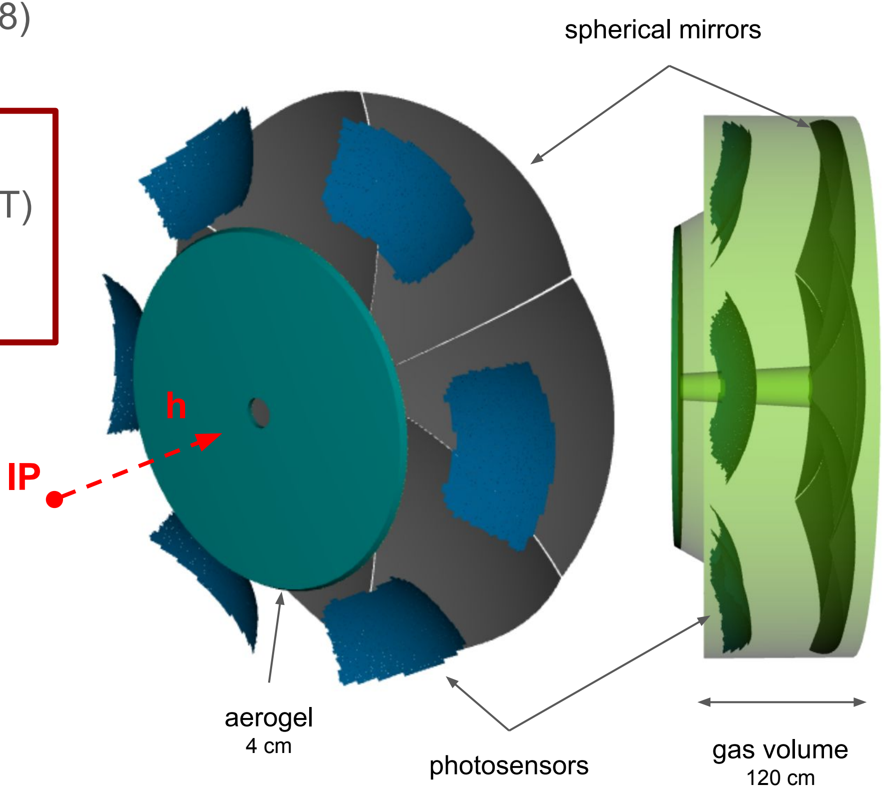
The dual-radiator (dRICH) for forward PID at EIC

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

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





SiPM option and requirements for RICH optical readout

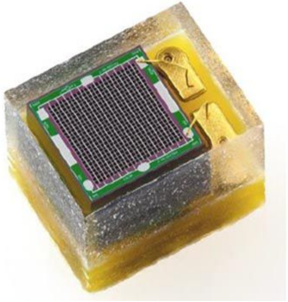
- **pros**
  - cheap
  - high photon efficiency
    requirement
  - excellent time resolution
    requirement
  - insensitive to magnetic field
    requirement

- **cons**

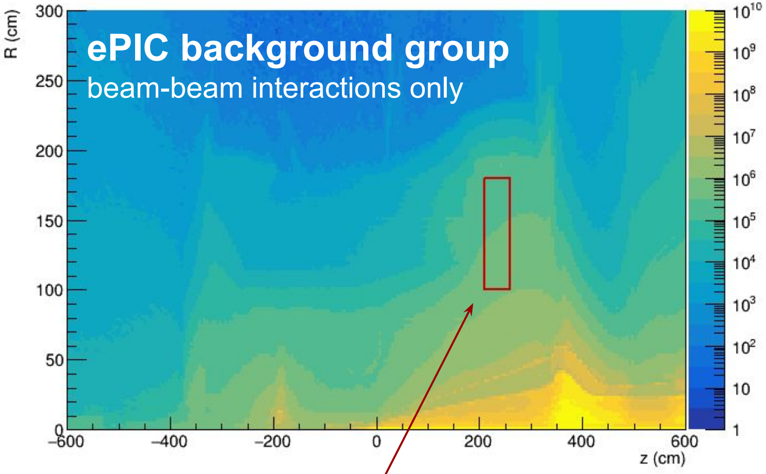
large dark count rates
not radiation tolerant

technical solutions and mitigation strategies

🐧 cooling
⌚ timing
🔥 annealing



Neutron fluxes at the dRICH photosensor surface



location of dRICH photosensors

mean fluence: 3.9 10^5 neq / cm^2 / fb^{-1}

max fluence: 9.2 10^5 neq / cm^2 / fb^{-1}

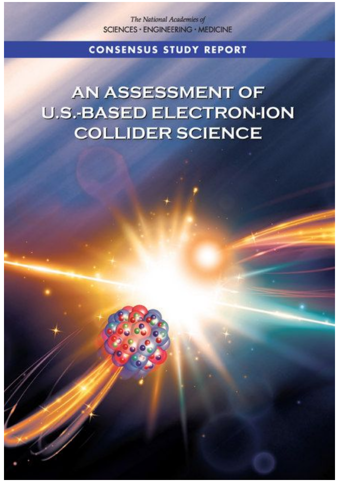
- radiation level is moderate

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

conservatively assume max fluence and 10x safety factor

Most of the key Physics goals defined by the NAS require an integrated luminosity of 10 fb^{-1} per center of mass energy and polarization setting

The nucleon imaging programme is more luminosity hungry and **requires 100 fb^{-1} per center of mass energy and polarization setting**



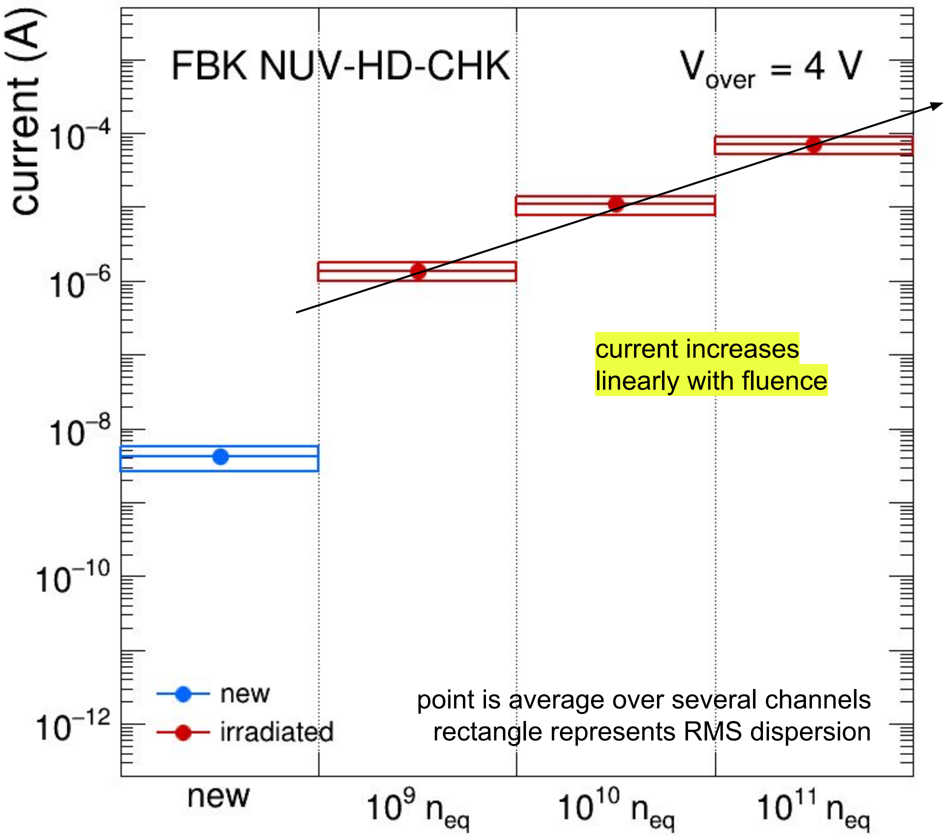
in 10-12 years the EIC will accumulate 1000 fb^{-1} integrated $\mathcal{L}$ corresponding to an integrated fluence of ~ 10^{10} n_{eq}/cm^2

study the SiPM usability for single-photon Cherenkov imaging applications in moderate radiation environment

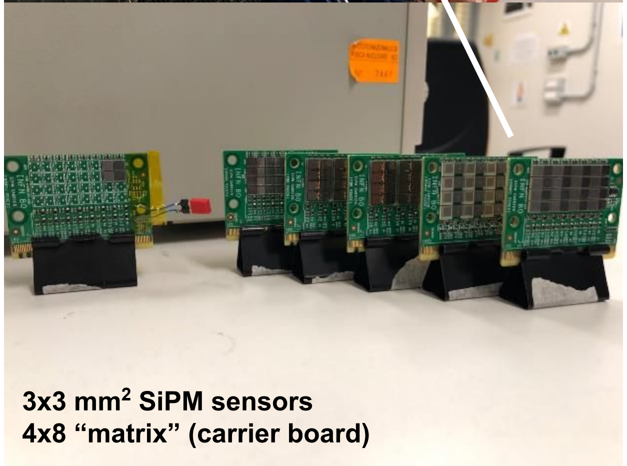
→ radiation damage studied in steps of radiation load

10^9 1-MeV n_{eq}/cm^2	*most of the key physics topics*
10^{10} 1-MeV n_{eq}/cm^2	*should cover most demanding measurements*
10^{11} 1-MeV n_{eq}/cm^2	*might never be reached*

Studies of radiation damage on SiPM

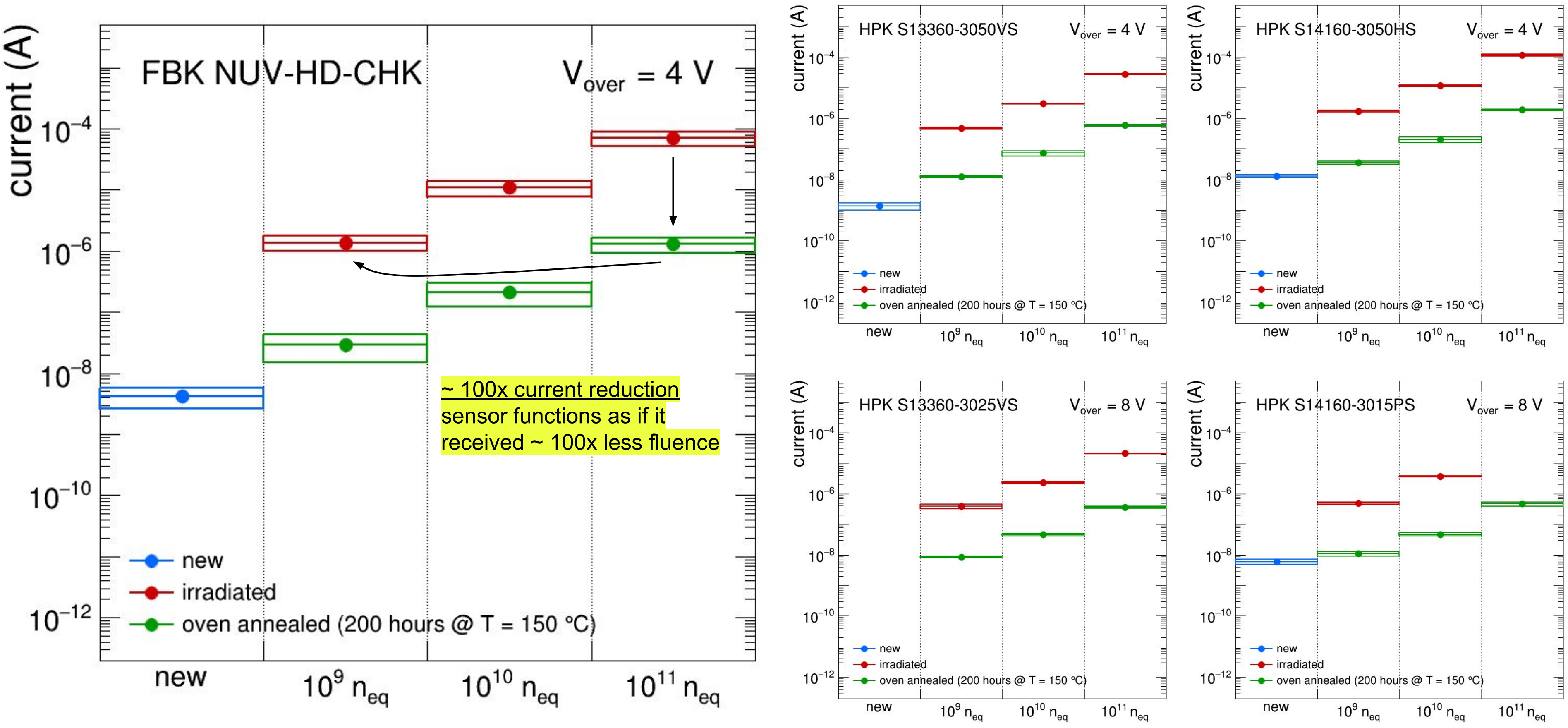


all results are reported at T = -30 C



High-temperature annealing recovery

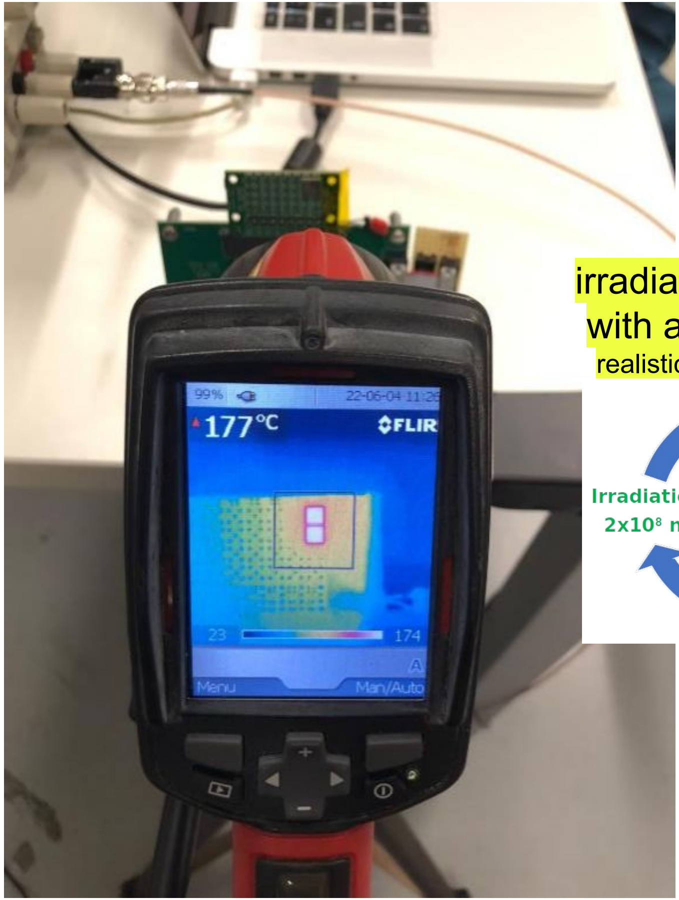
oven annealing
~ 1 week at 150 C



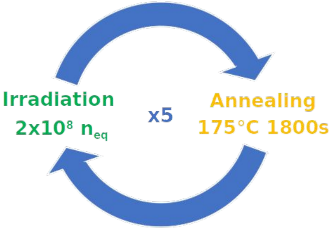
similar observation with various types of Hamamatsu sensors

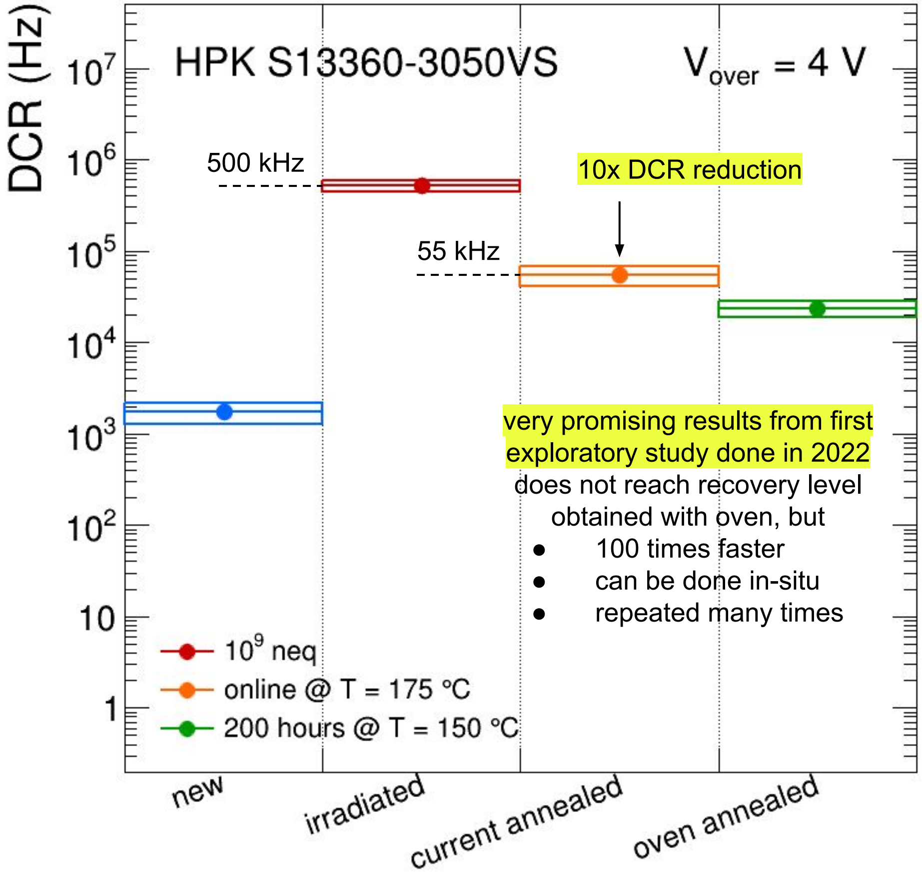
“Online” self-induced annealing

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



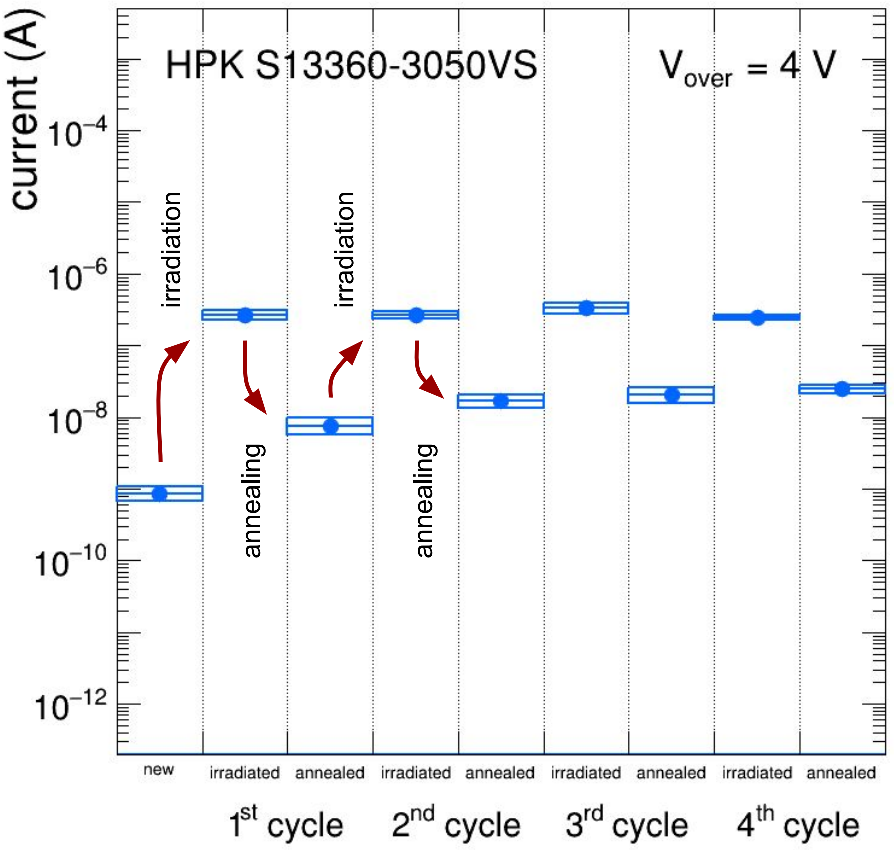


10x DCR reduction

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

Repeated irradiation-annealing cycles

oven annealing



test reproducibility of repeated irradiation-annealing cycles

simulate a realistic experimental situation

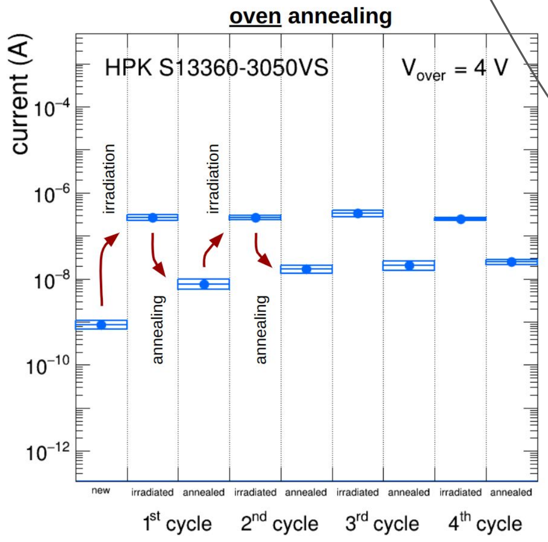
- consistent irradiation damage
  - DCR increases by ~ 500 kHz (@ Vover = 4)
  - after each shot of 10^9 n_{eq}
- consistent residual damage
  - ~ 15 kHz (@ Vover = 4) of residual DCR
  - builds up after each irradiation-annealing

annealing cures same fraction of newly-produced damage

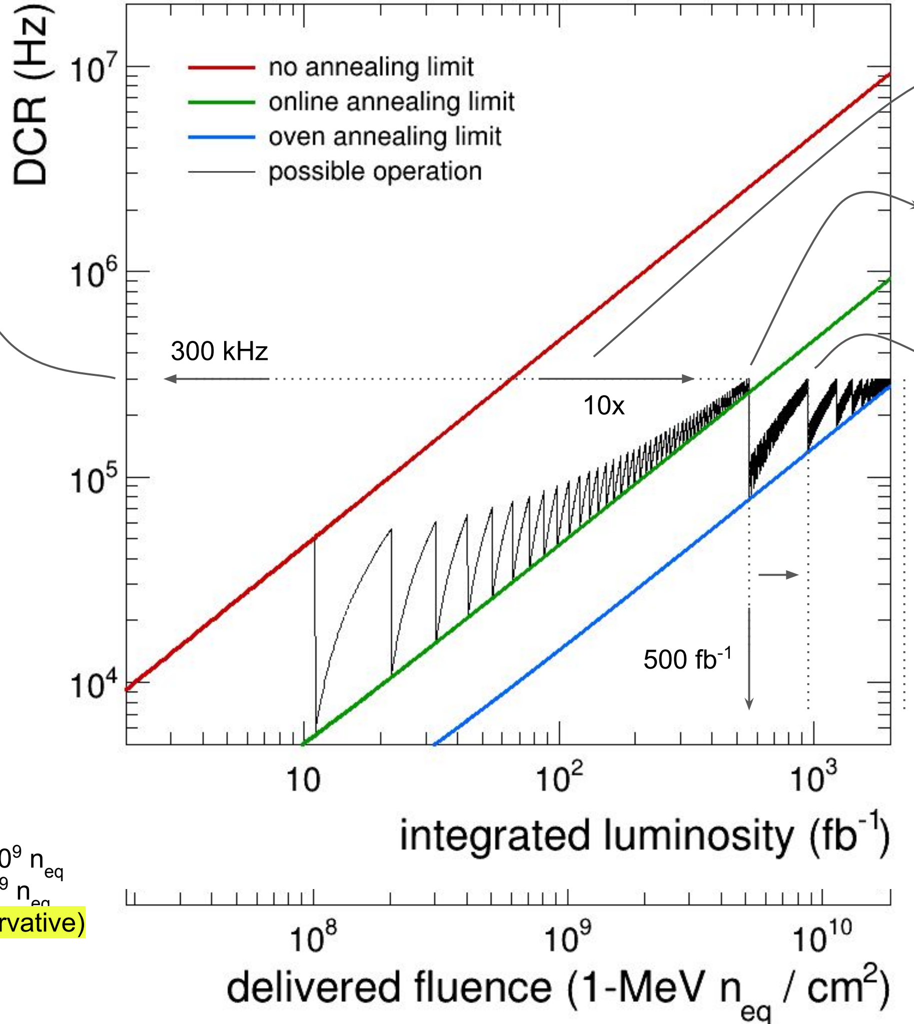
~ 97% for HPK S13360-3050 sensors

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 need to unmount SiPM (oven)

up to 1000 fb^{-1} with only one oven annealing cycle
optimisation of online annealing protocol could reach beyond that

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}

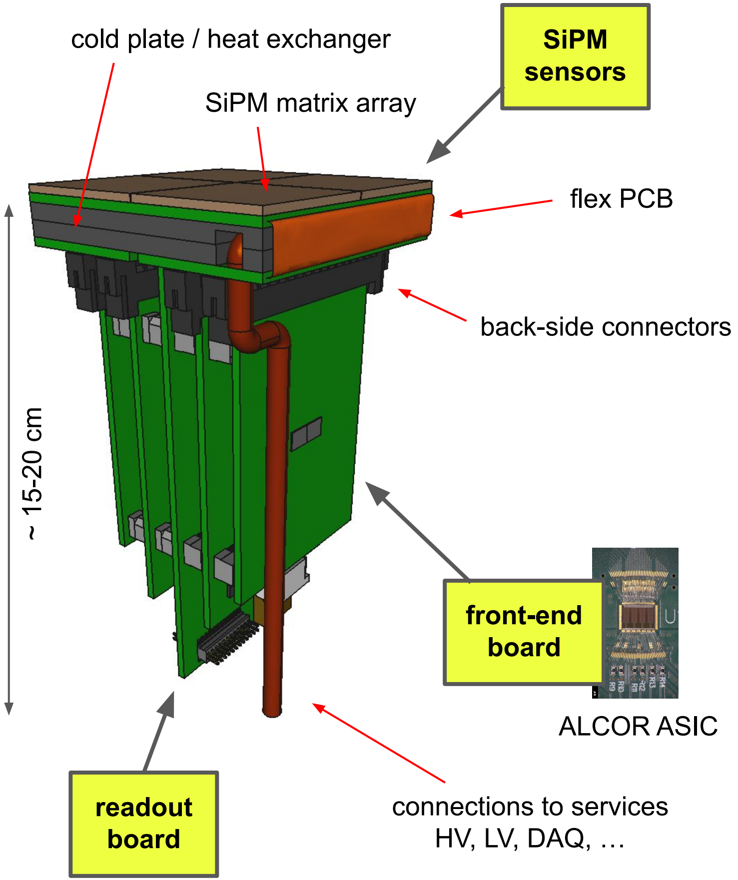
1-MeV neq fluence from background group (conservative)

- 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

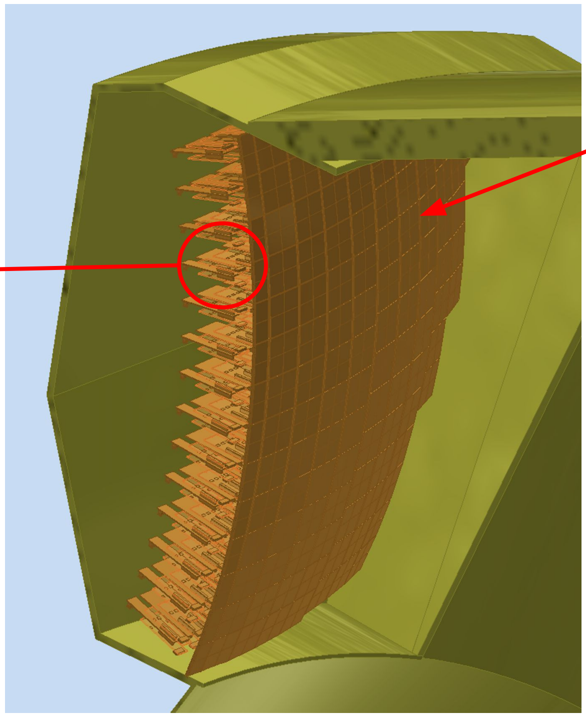
Photodetector unit

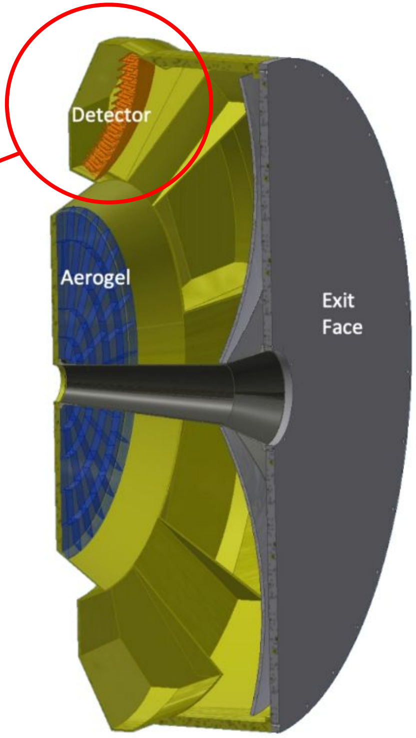
conceptual design



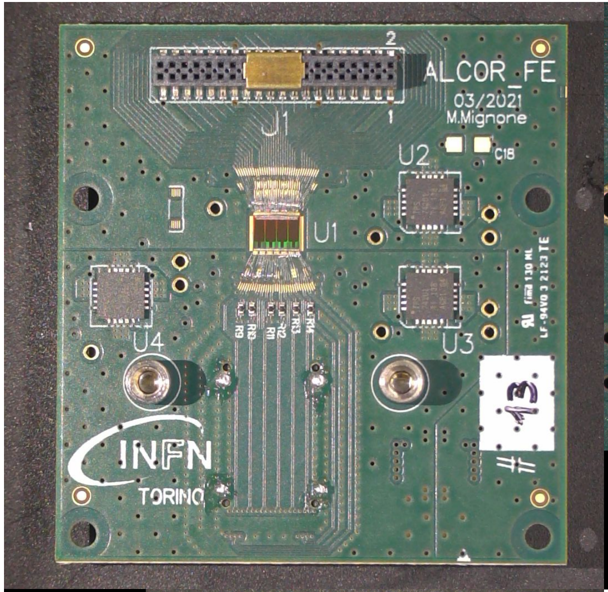
compact solution to minimise space

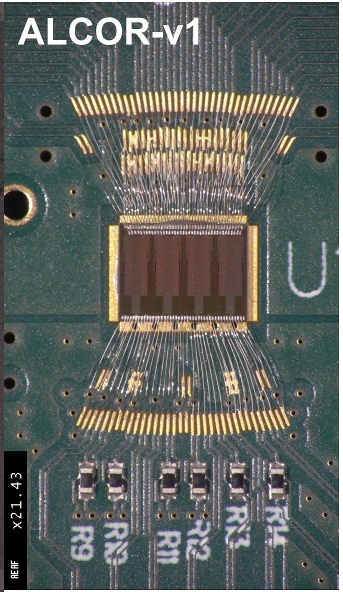
- cold plate “sandwich” with flex-PCB circuit
- all electronics and services on the back side
- uniform sensor cooling with no loss of active area

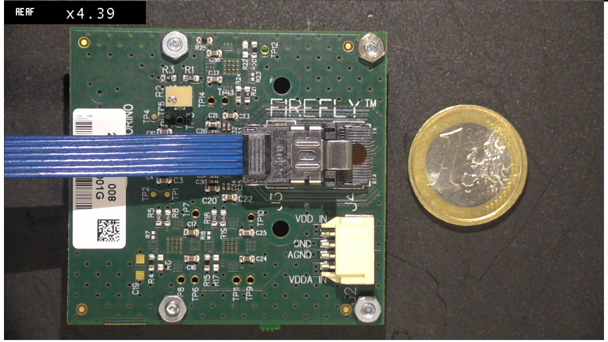


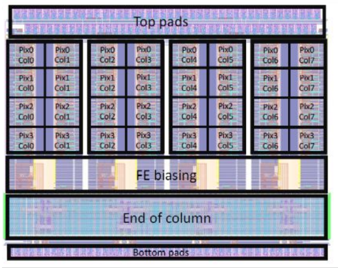


ALCOR ASIC: integrated front-end and TDC









developed by INFN-TO

64-pixel matrix mixed-signal ASIC

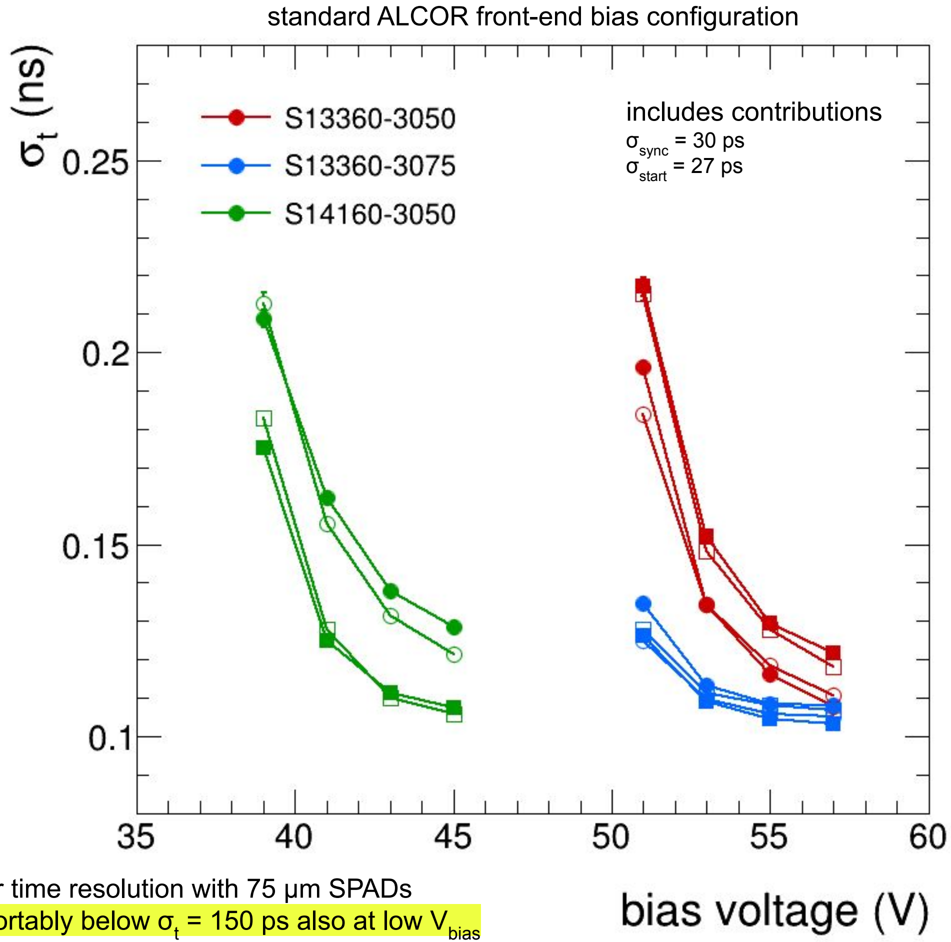
current versions (v1,v2) have 32 channels, wirebonded

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

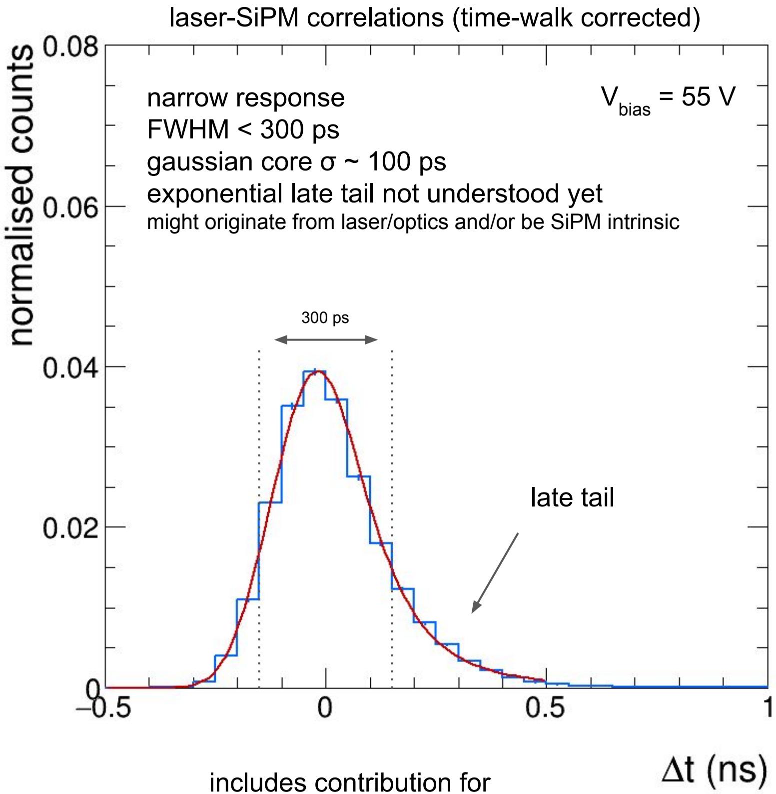
- **the chip performs**
  - signal amplification
  - conditioning and event digitisation
- **each pixel features**
  - 2 leading-edge discriminators
  - 4 TDCs based on analogue interpolation
    - 20 or 40 ps LSB (@ 394 MHz)
  - digital shutter to enable TDC digitisation
    - suppress out-of-gate DCR 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

Hamamatsu S13360-3075

Laser timing measurements with ALCOR

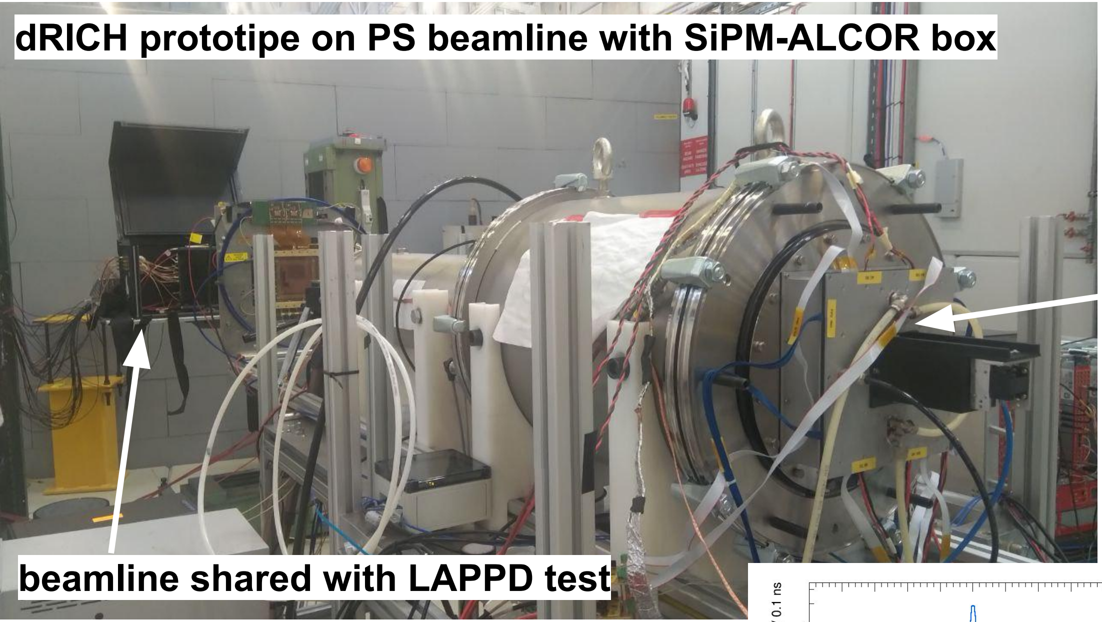


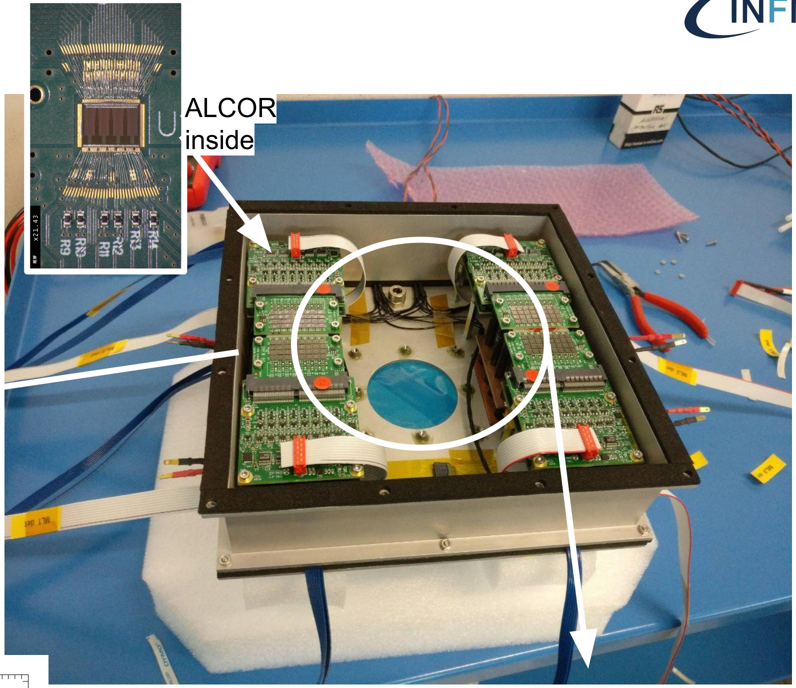
better time resolution with 75 μm SPADs
comfortably below σ_t = 150 ps also at low V_{bias}



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

2022 test beam at CERN-PS

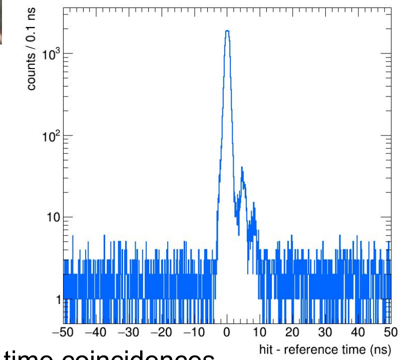




successful operation of SiPM

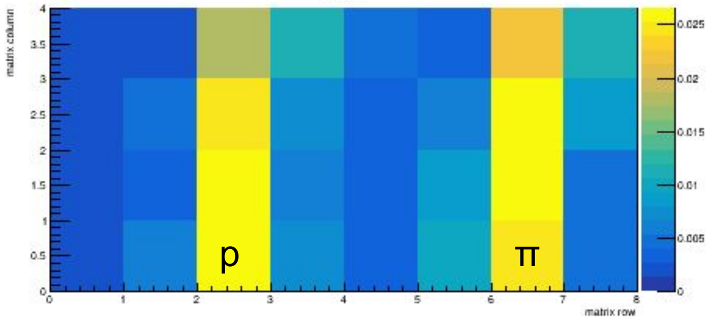
irradiated (with protons up to 10^{10})

and annealed (in oven at 150 C)



time coincidences

8 GeV positive beam (aerogel rings)



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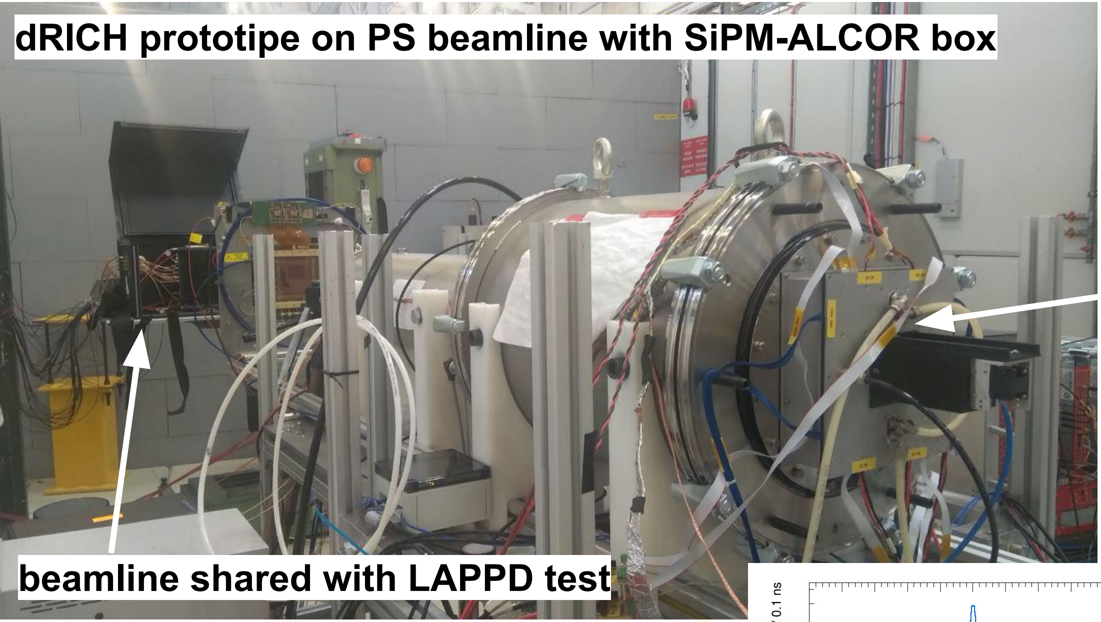
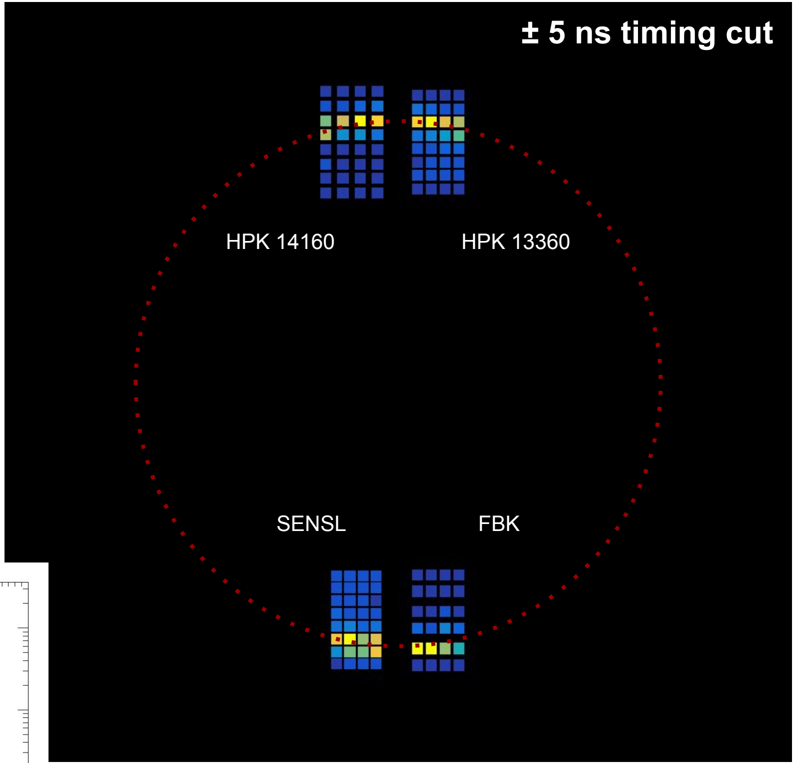


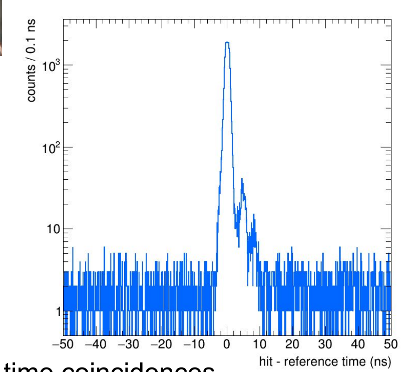


8 GeV negative beam (aerogel rings)

successful operation of SiPM

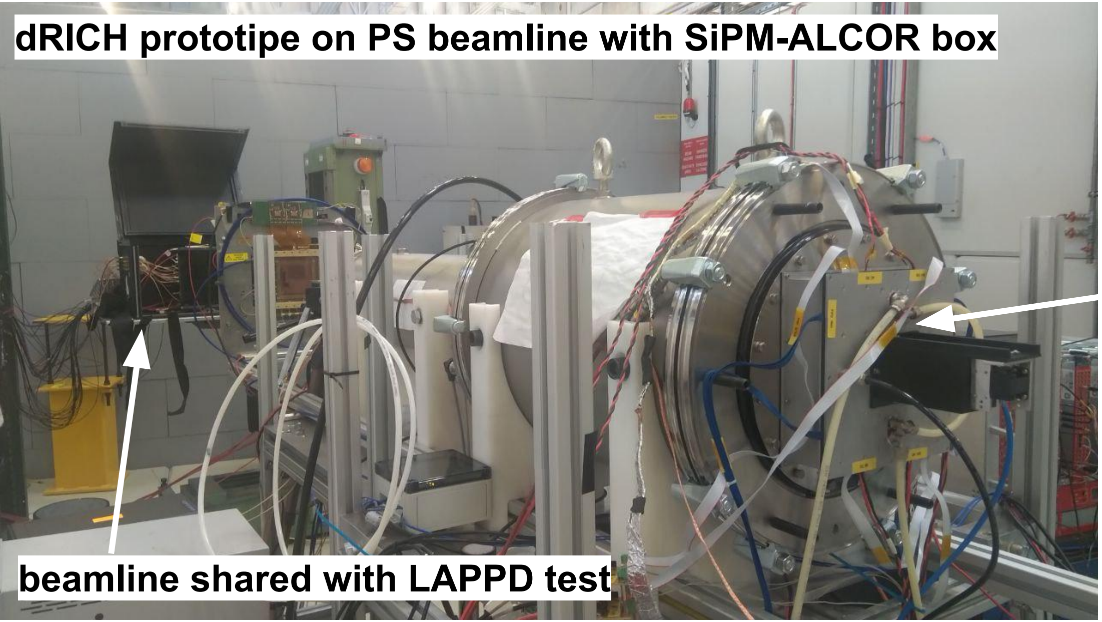
irradiated (with protons up to 10^{10})

and annealed (in oven at 150 C)

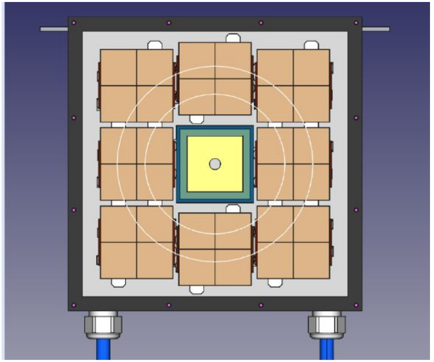


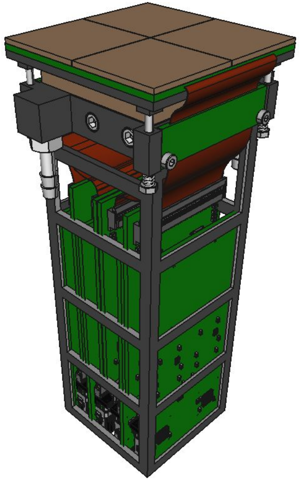
time coincidences

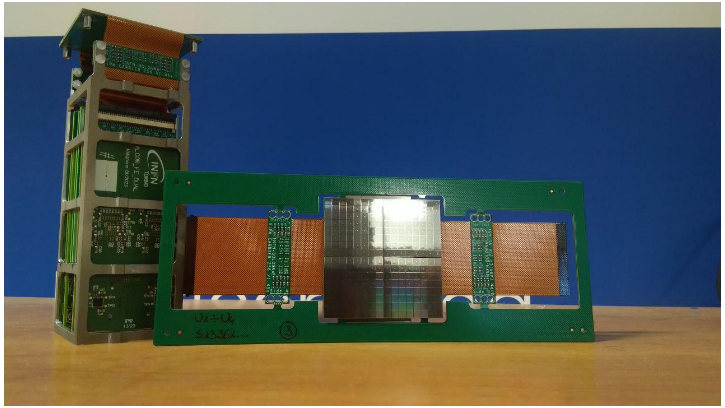
New detector plane for 2023 beam tests



prototype EIC-driven
readout unit and readout box







a few prototype photodetector units

will be assembled and tested in September

before mounting them on the dRICH detector prototype for the beam test

Summary

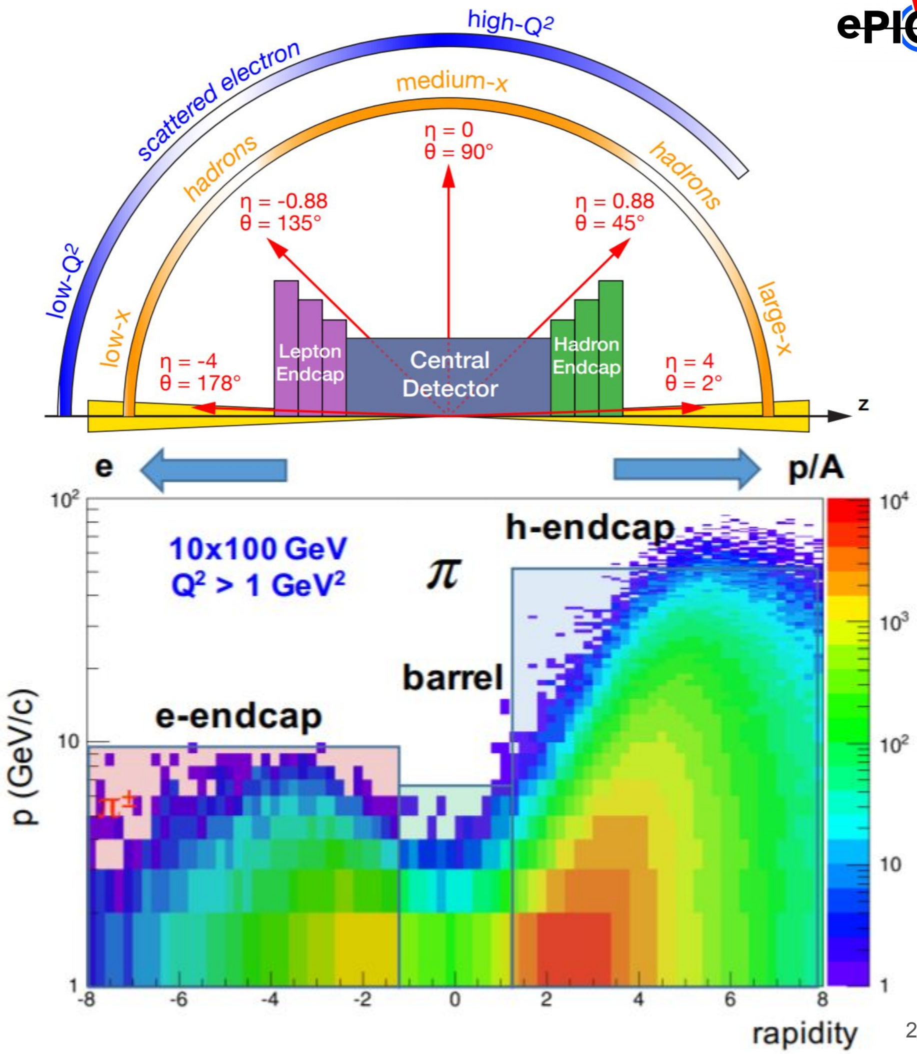
- **SiPM option fulfills requirements for the forward RICH at the EIC**
  - magnetic field limitations
  - excellent timing and efficiency
- **technical solutions to mitigate radiation damage**
  - low temperature operation
  - online “in-situ” self-annealing
  - extend lifetime of good detector performance for Physics
    - present solutions can be optimised/improved to extend it further
- **SiPM readout with full electronics chain**
  - based on ALCOR ASIC
  - successful beam test at CERN-PS in 2022
  - overall 1-pe time resolution approaching 100 ps
- **clear path for development and optimisations towards TDR**
  - EIC-driven prototype readout units to be tested soon
  - developments for the first prototype readout boards
  - final optimisations and packaging of the ALCOR ASIC chip

END

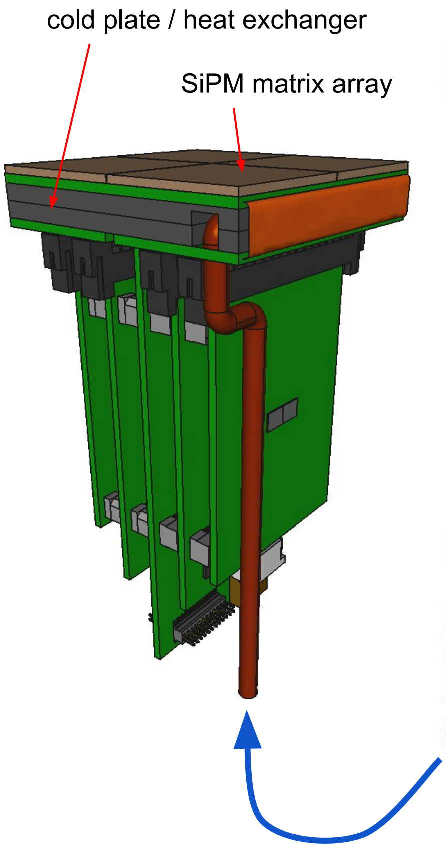
Particle identification at the EIC

one of the major challenges for the detector

- **physics requirements**
  - pion, kaon and proton ID
  - over a wide range $|\eta| \leq 3.5$
  - with better than 3σ separation
  - significant pion/electron suppression
- **momentum-rapidity coverage**
  - forward: up to 50 GeV/c
  - central: up to 6 GeV/c
  - backward: up to 10 GeV/c
- **demands different technologies**



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

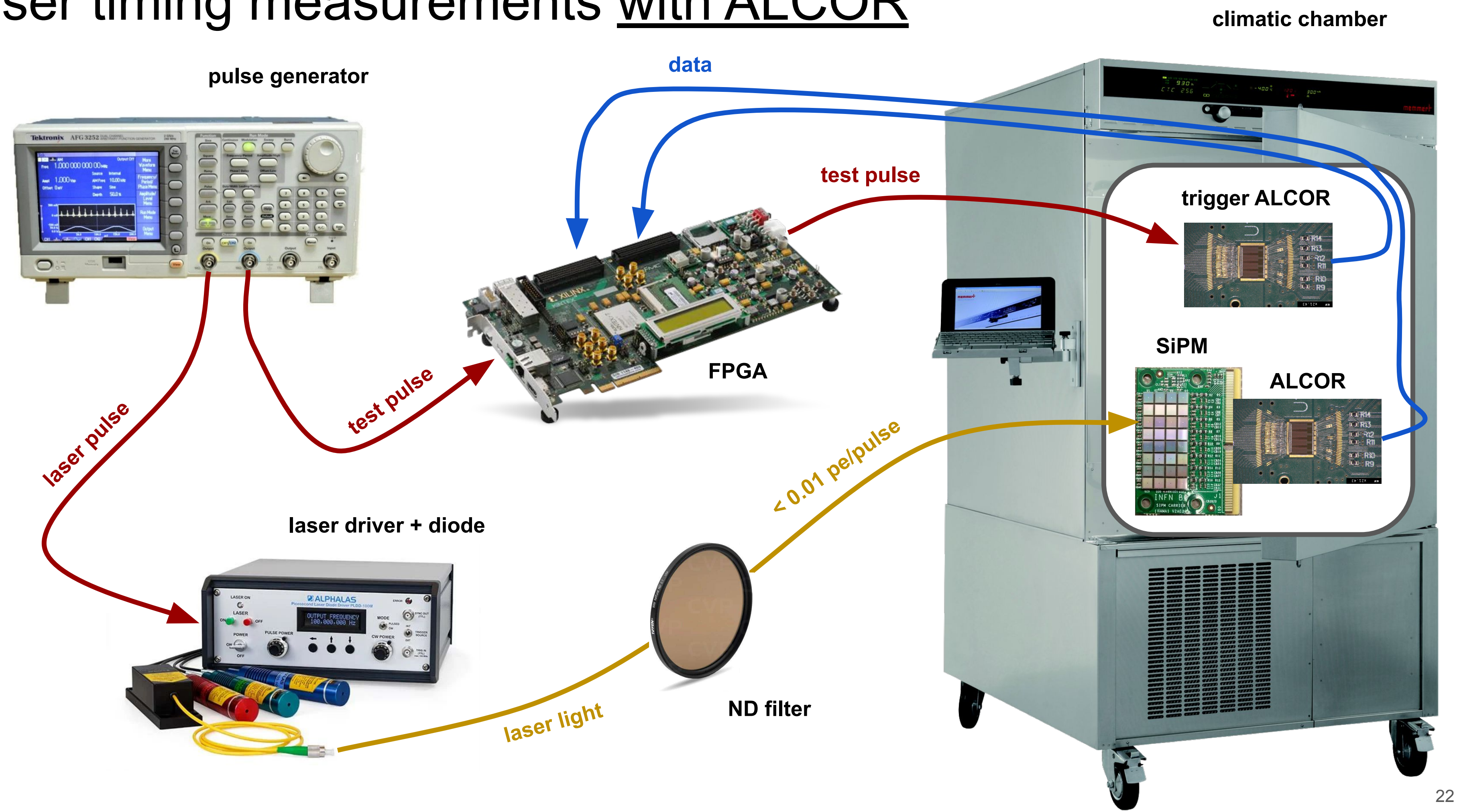
Temperature range	-55...250 °C
Temperature stability	±0,01 K

Heating / cooling capacity

Heating capacity	6 kW

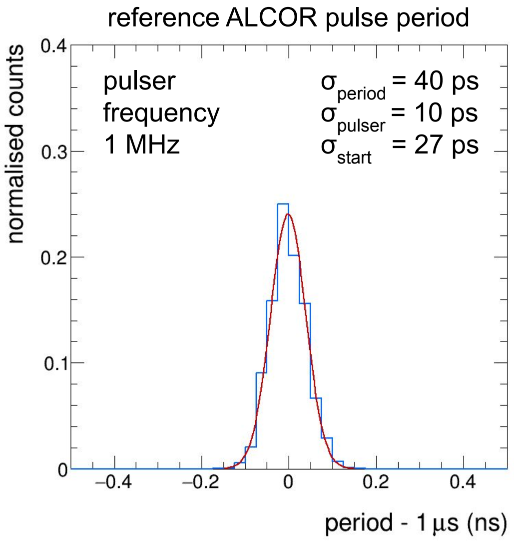
Cooling capacity	250	200	100	20	0	-20	-40	-50	°C
	6	6	6	6	6	4,2	1,5	0,65	kW

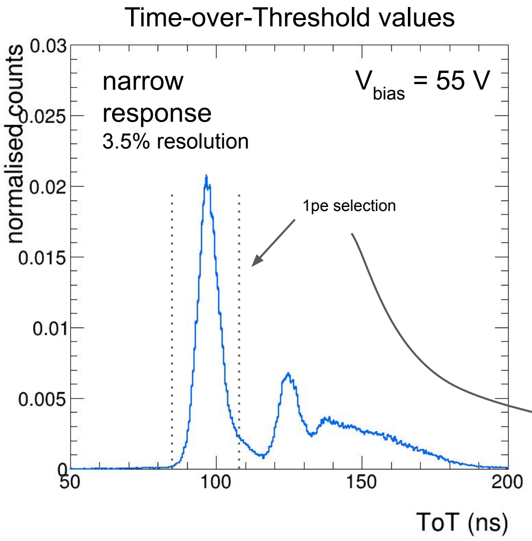
Laser timing measurements with ALCOR

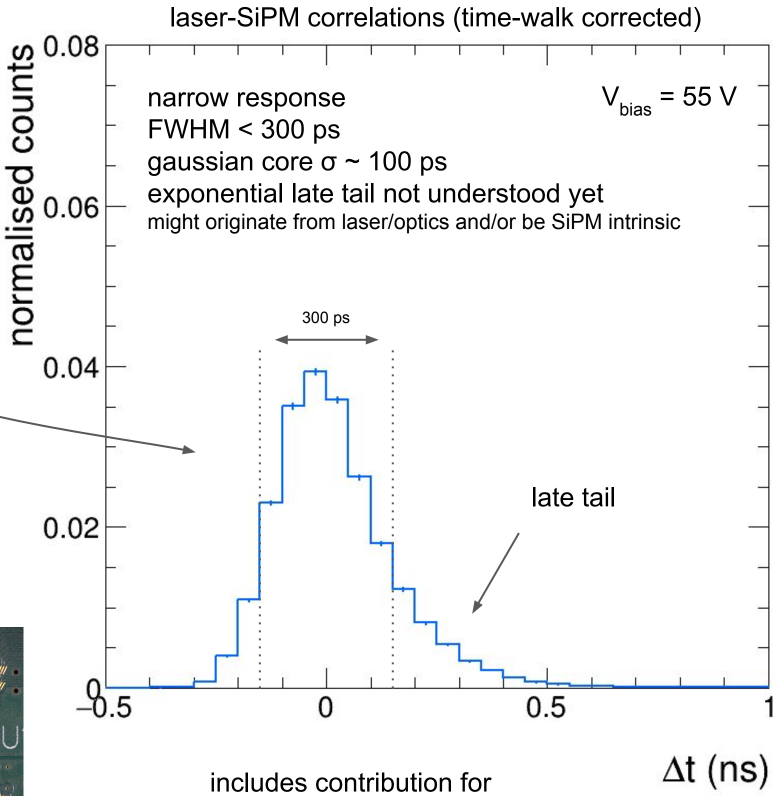


Laser timing measurements with ALCOR

Hamamatsu S13360-3075



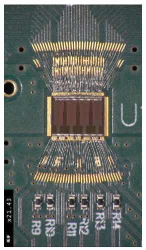




laser-SiPM signal synchronisation by sending test pulse to reference ALCOR

- to measure laser pulse t_{start}
- with 50 ps LSB TDC
- in synch with ALCOR readout

measure time coincidences Δt between reference and ALCOR reading SiPM



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

Laser timing measurements with ALCOR

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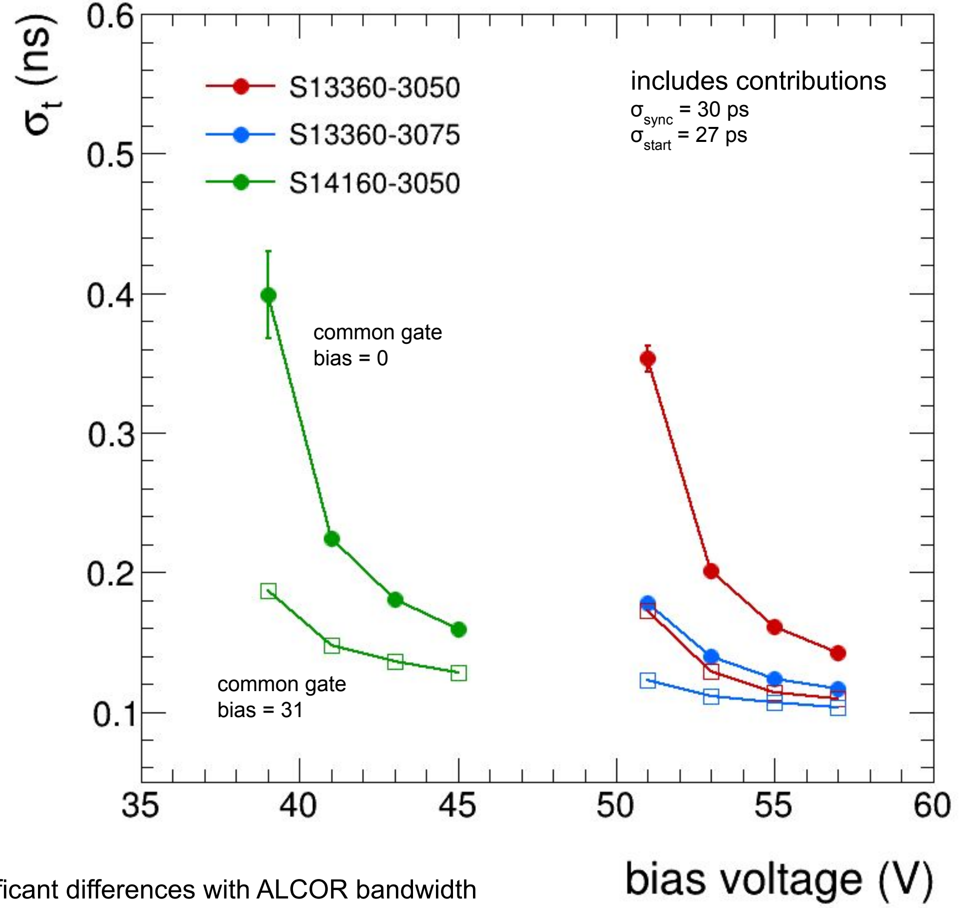
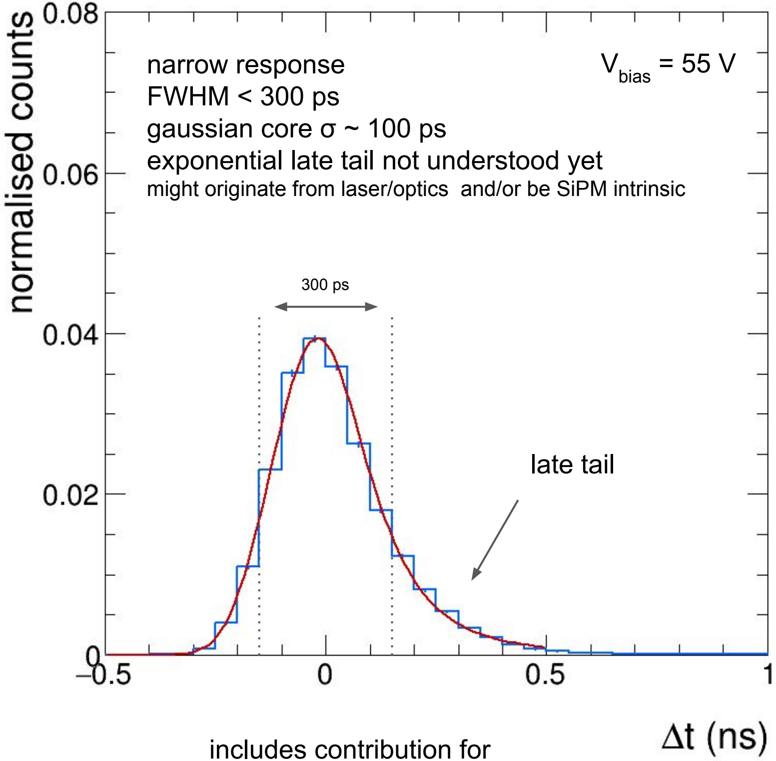
the two extremes of ALCOR front-end bias configuration



laser-SiPM correlations (time-walk corrected)



significant differences with ALCOR bandwidth

includes contribution for laser-ALCOR synchronization
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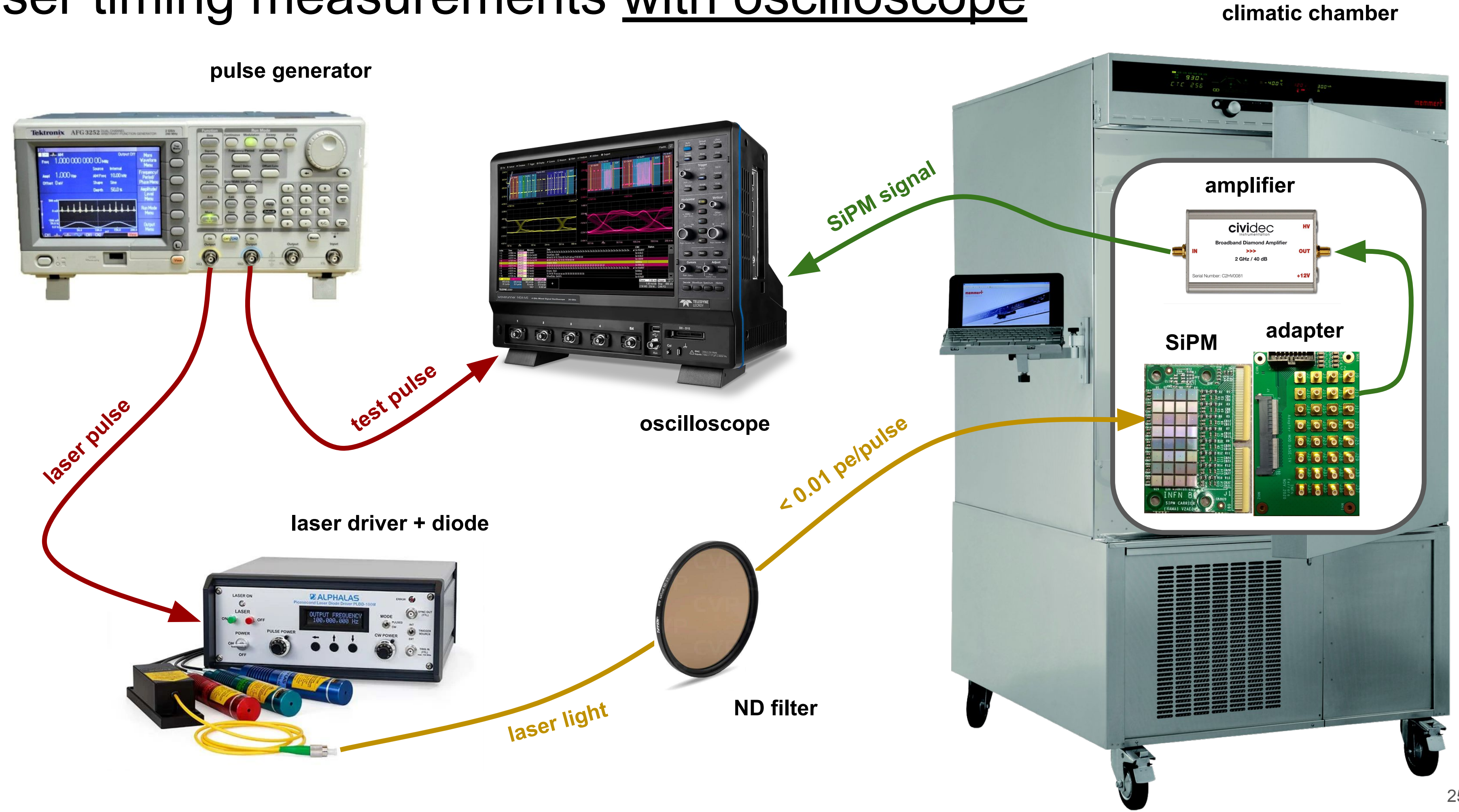
Laser timing measurements with oscilloscope



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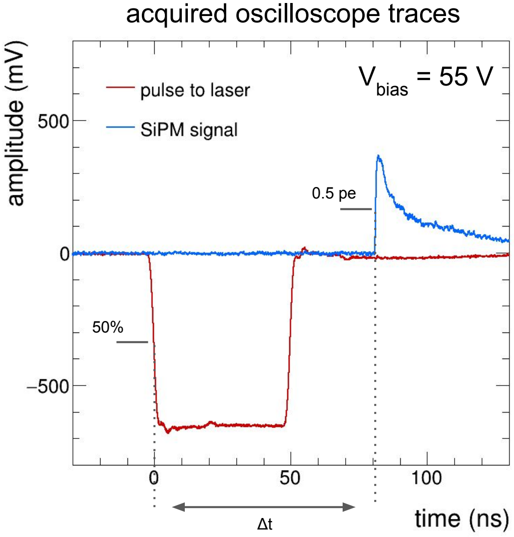
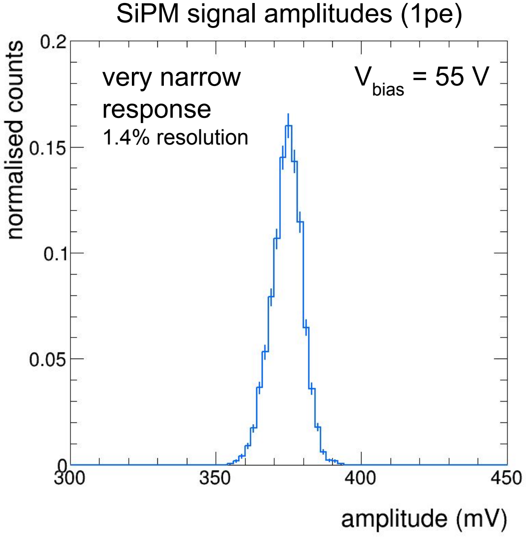
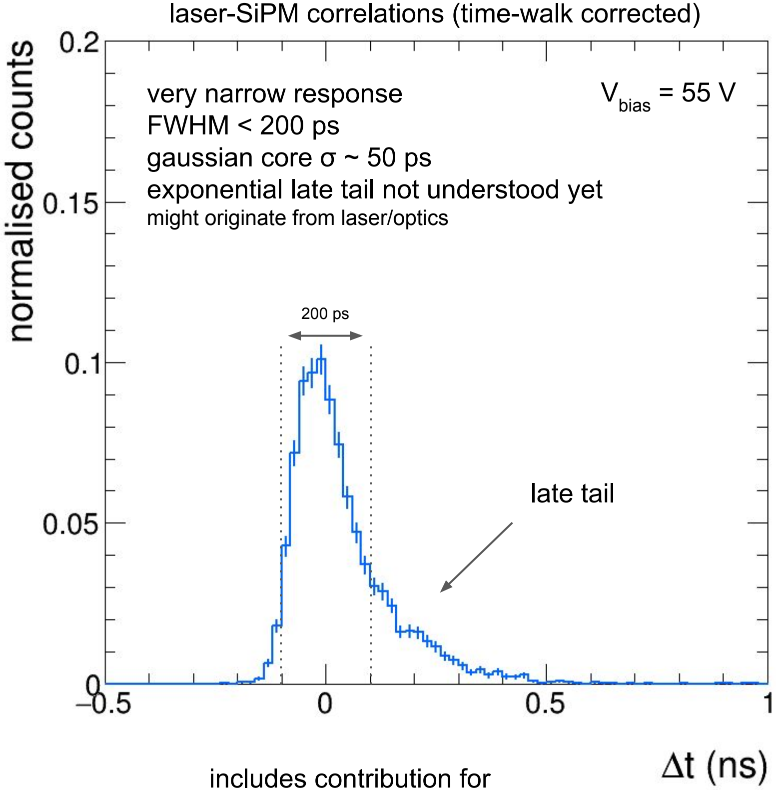






includes contribution for laser-oscilloscope synchronization
measured to be σ_{sync} = 30 ps

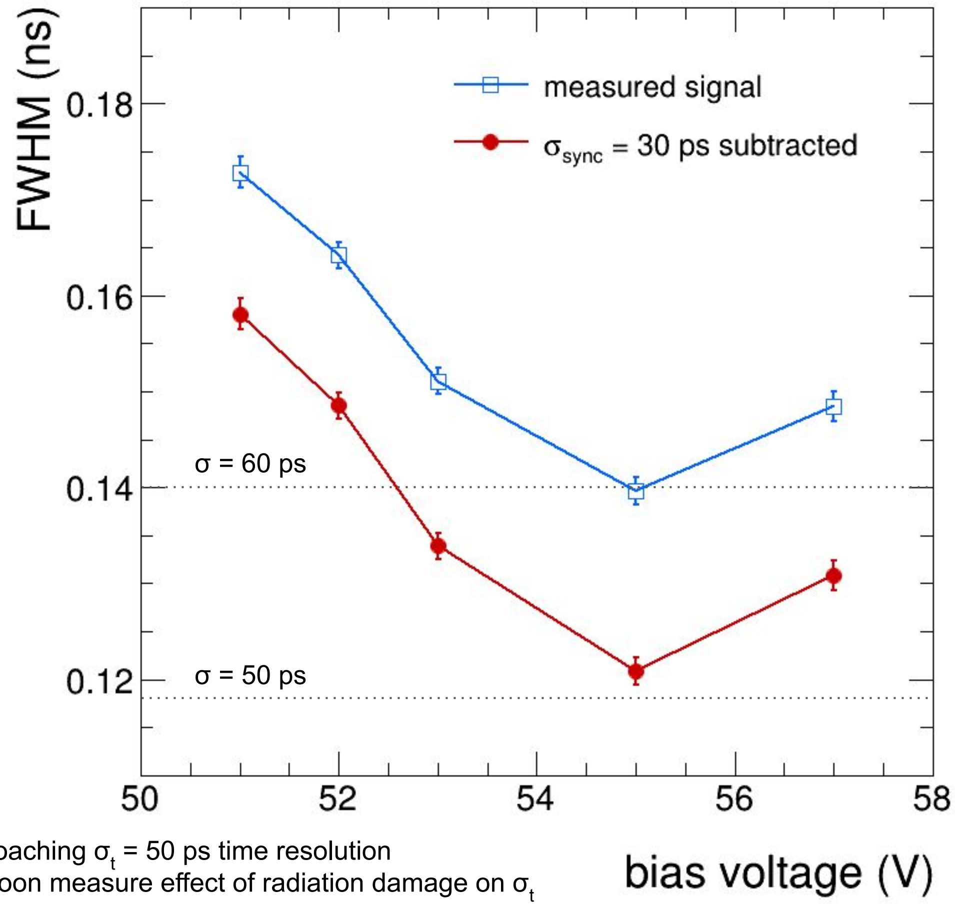
measurements performed at T = -30 C with
- Lecroy Waverunner 40186 oscilloscope
- Cividec Broadband amplifier (40 db)

timing defined with fixed thresholds
- laser pulse at 50% of signal
- SiPM signal at 0.5 pe (average amplitude)

time-amplitude correlation (walk) corrected

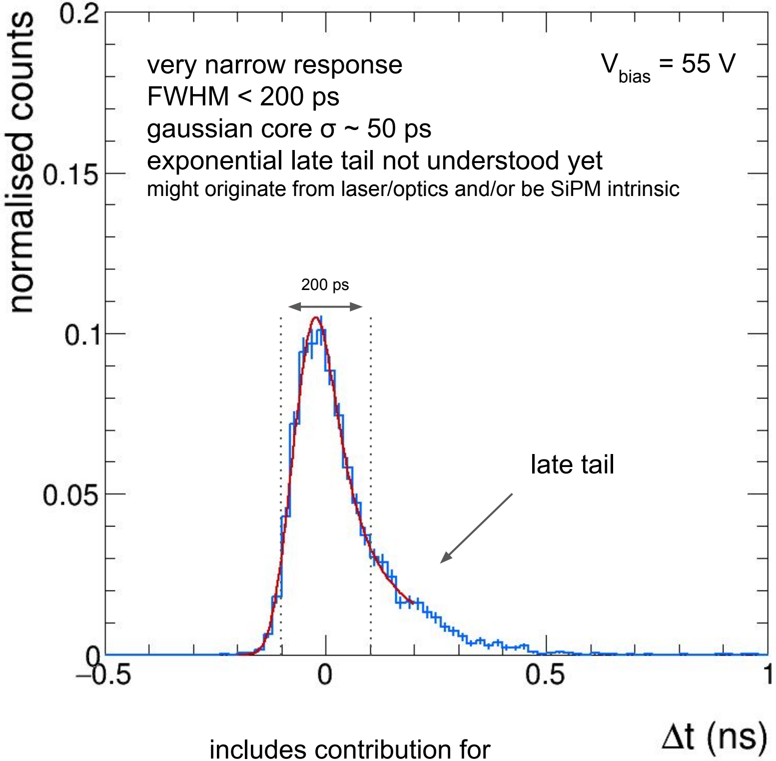
Hamamatsu S13360-3075

Laser timing measurements with oscilloscope



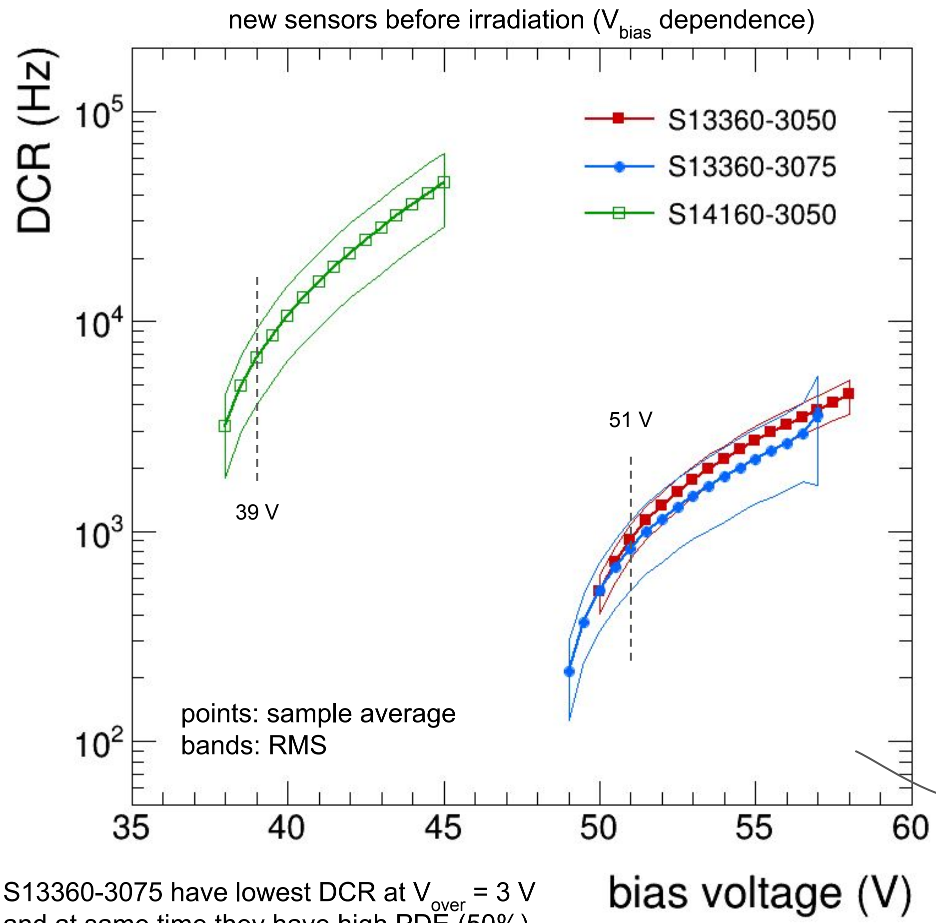
approaching σ_t = 50 ps time resolution
will soon measure effect of radiation damage on σ_t

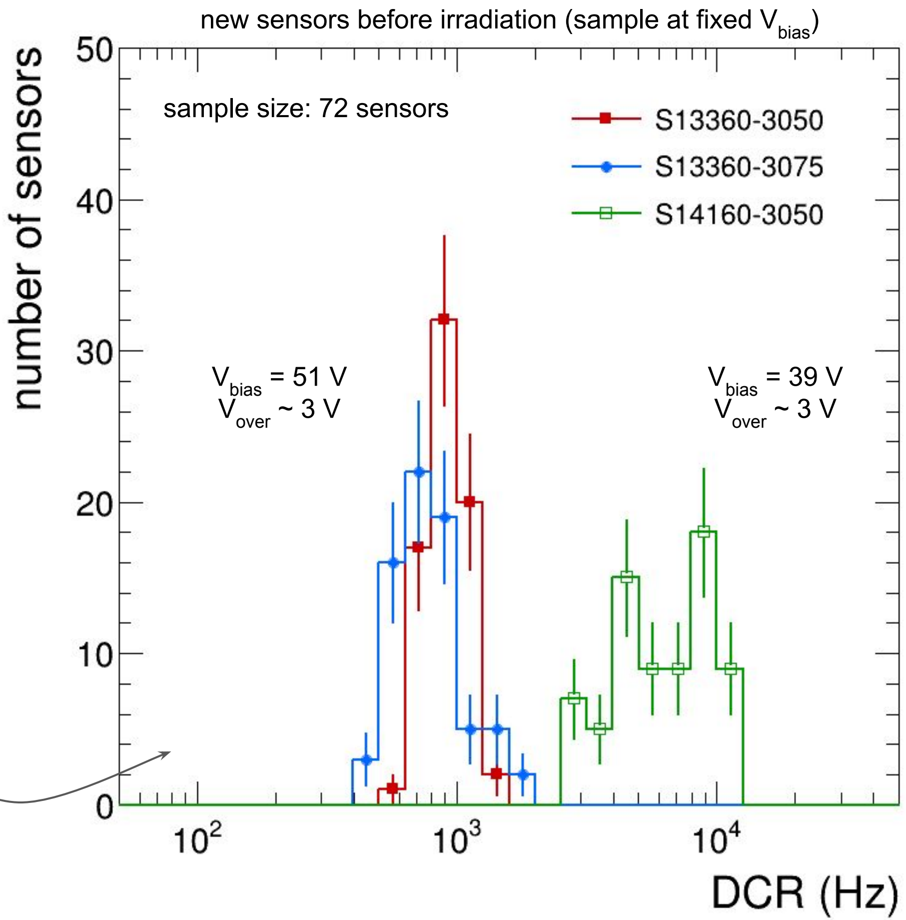
laser-SiPM correlations (time-walk corrected)



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

Characterisation of new SiPM boards



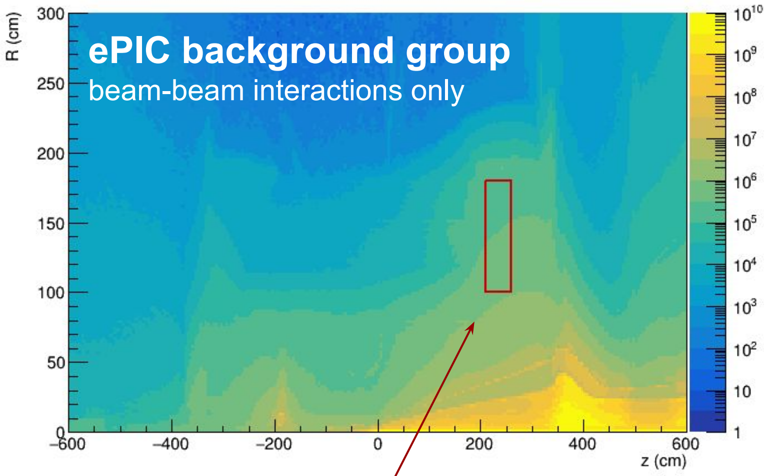


S13360-3075 have lowest DCR at V_{over} = 3 V
and at same time they have high PDE (50%)

Environment

recently updated radiation damage estimates

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



location of dRICH photosensors

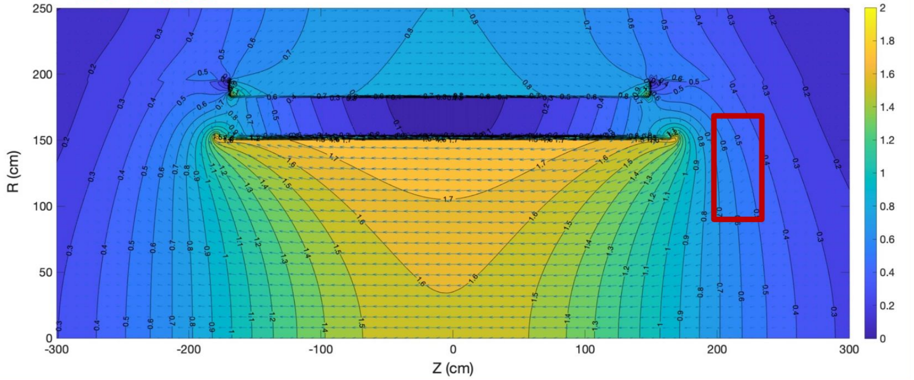
assume fluence: ~ 10^7neq / cm^2 / fb^{-1}

conservatively assume max fluence and 10x safety factor

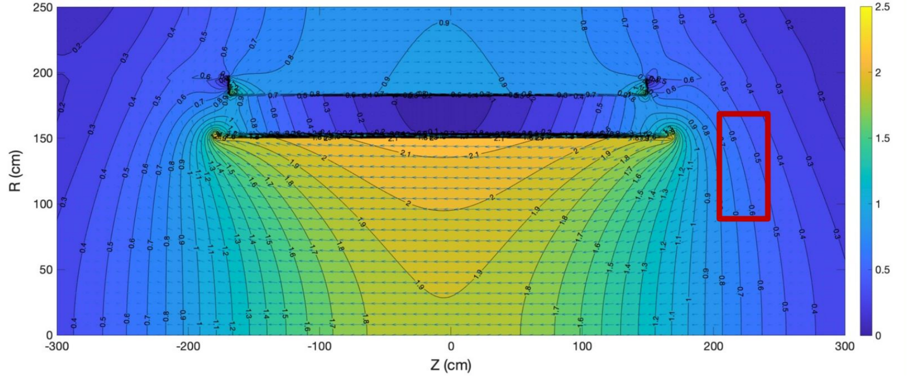
moderate radiation, 1000 fb^{-1} integrated $\mathcal{L}$ corresponds to ~ 10^{10} n_{eq}/cm^2

MARCO magnetic field maps

1.7 T field



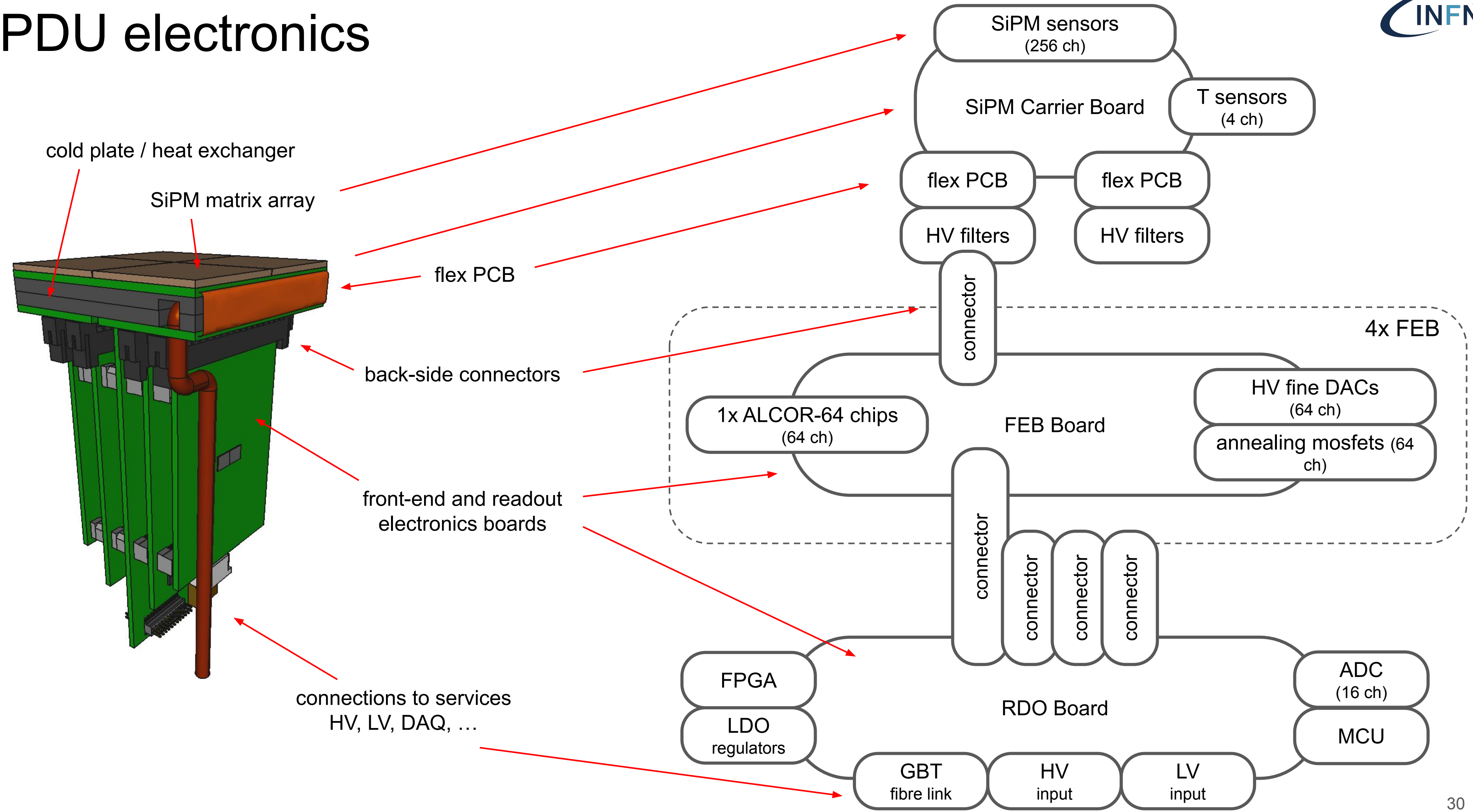
2.0 T field



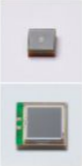
non-uniform, strong magnetic field ~ 0.7 T

field lines ~ parallel to photodetector surface

PDU electronics



Commercial SiPM sensors and FBK prototypes

	board	sensor	uCell (µm)	V_{bd} (V)	PDE (%)	DCR (kHz/mm^2)	window	notes
	HAMA1	S13360 3050VS	50	53	40	55	silicone	legacy model Calvi et. al
	HAMA1	S13360 3025VS	25	53	25	44	silicone	legacy model smaller SPAD
	HAMA2	S14160 3050HS	50	38	50		silicone	newer model lower V_{bd}
	HAMA2	S14160 3015PS	15	38	32	78	silicone	smaller SPADs radiation hardness
	SENSL	MICROFJ 30035	35	24.5	38	50	glass	different producer and lower V_{bd}
	SENSL	MICROFJ 30020	20	24.5	30	50	glass	the smaller SPAD version
	BCOM	AFBR S4N33C013	30	27	43	111	glass	commercially available FBK-NUVHD

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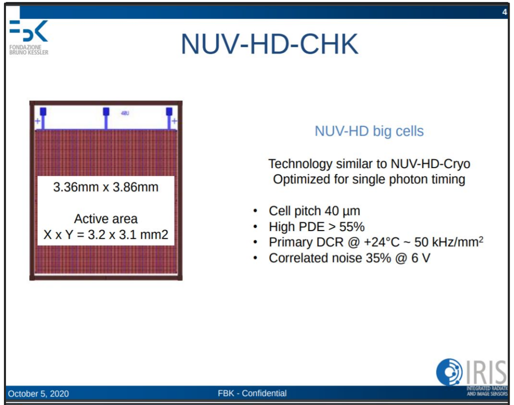
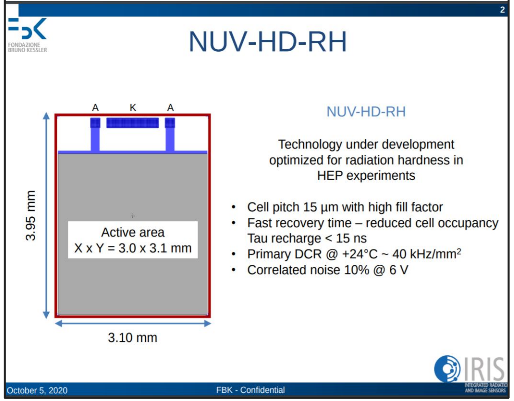
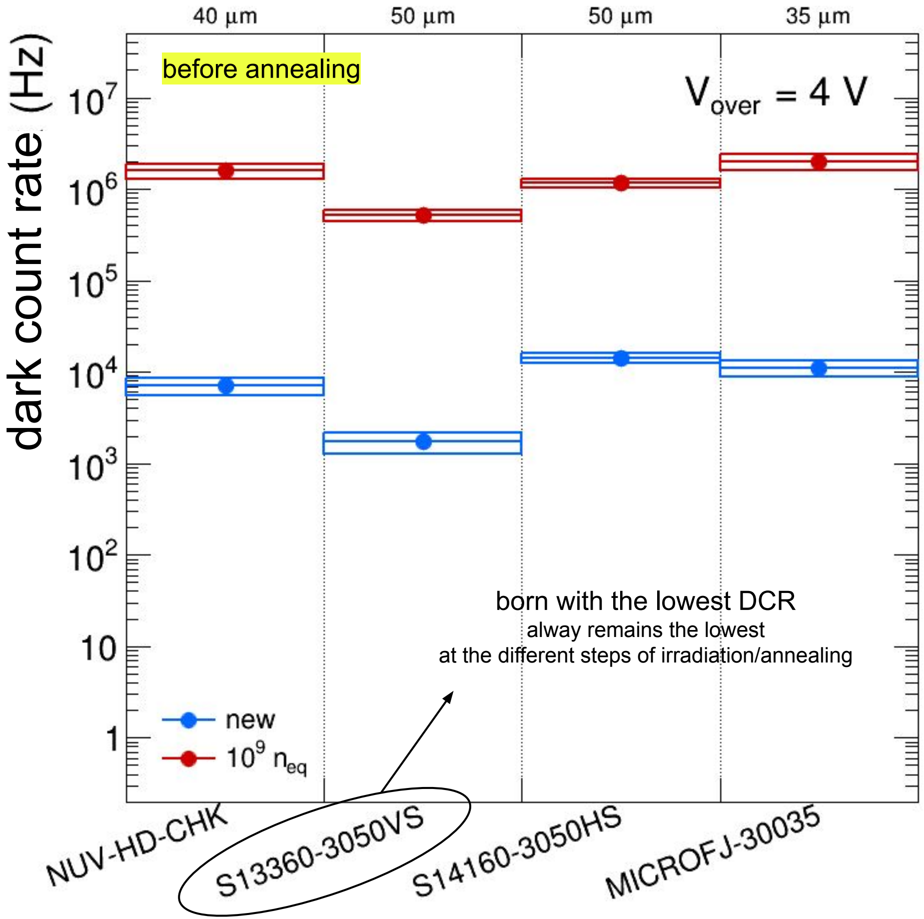


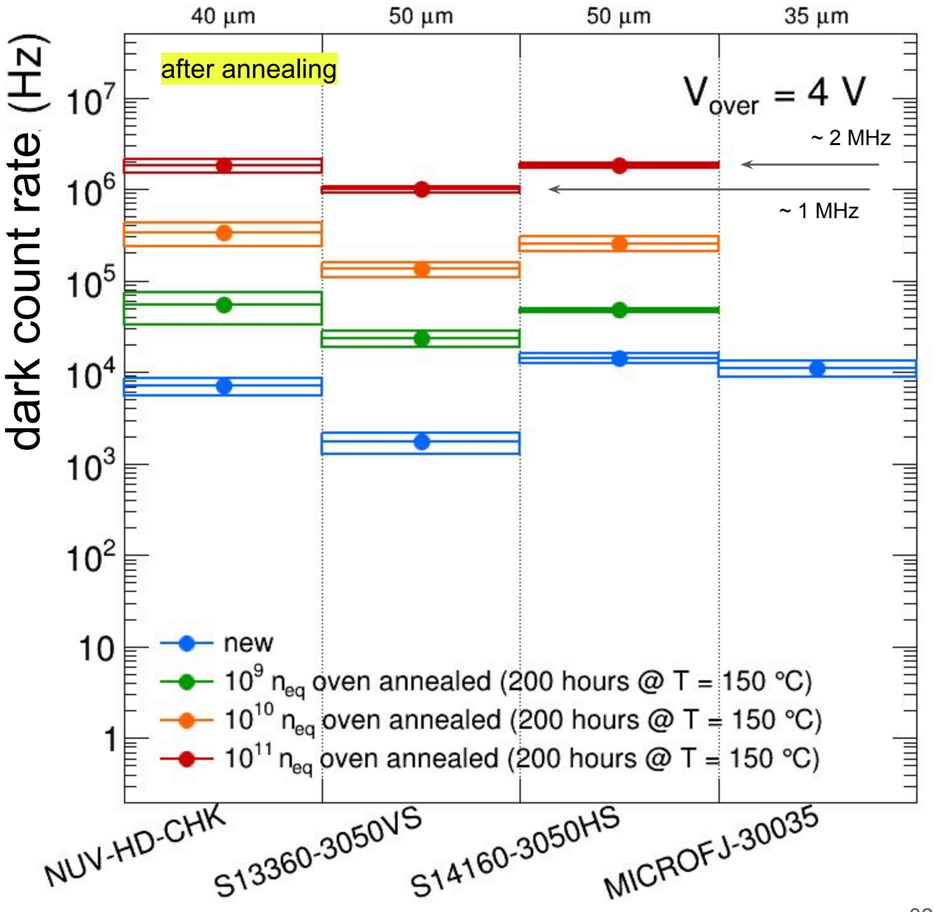


multiple producers: different technologies, SPAD dimensions, V_{bd}, electric field …

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

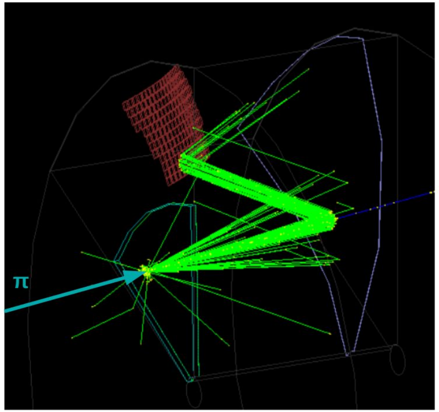


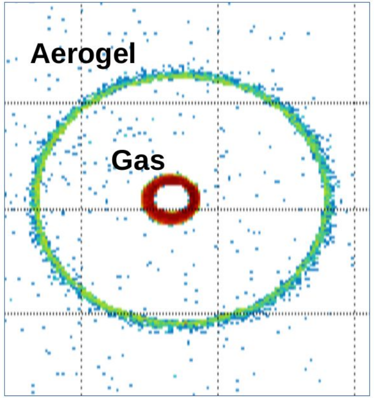


The dual-radiator (dRICH) for forward PID at EIC

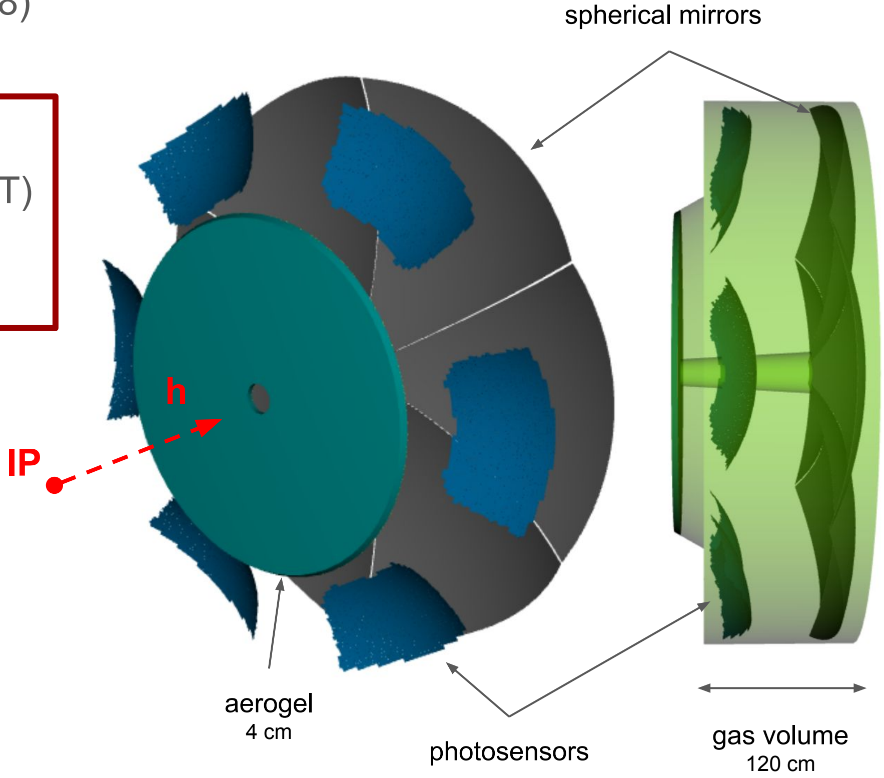
compact and cost-effective solution for broad momentum coverage at forward rapidity

- **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
  - best candidate: SiPM option



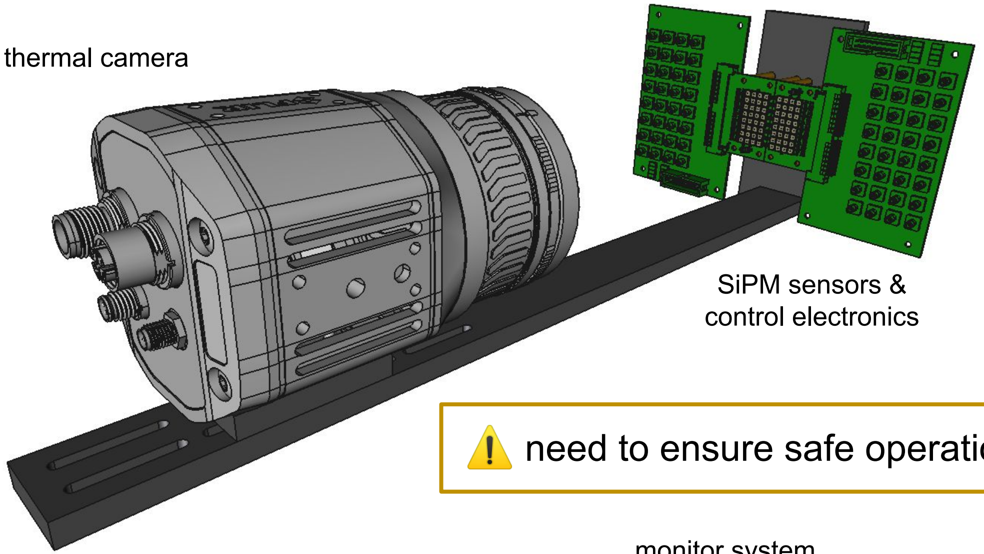


example event (accumulated hits)



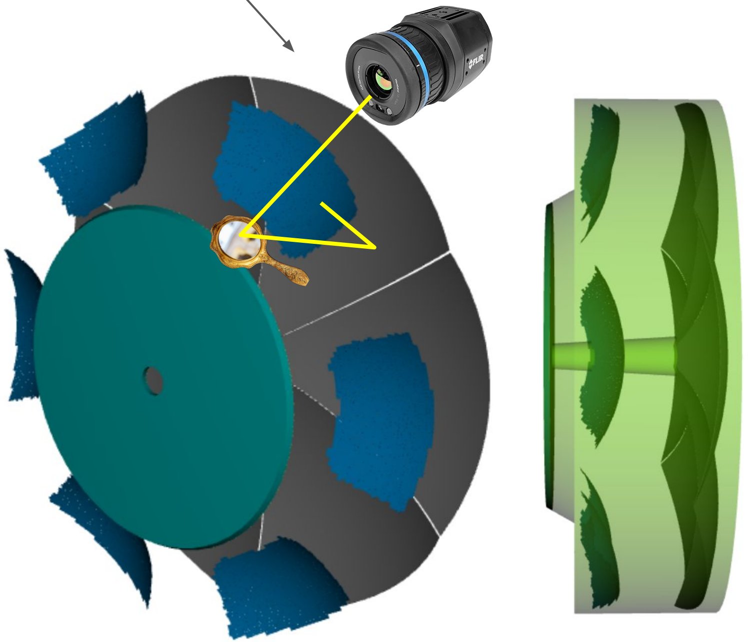
Automated multiple SiPM online self-annealing

thermal camera



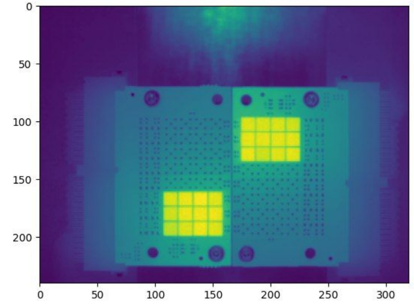
demonstrator system for online temperature monitor and control of each individual SiPM

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

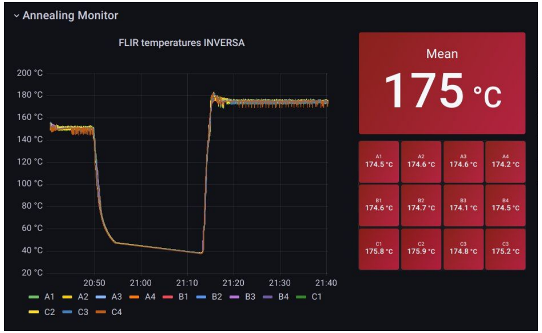


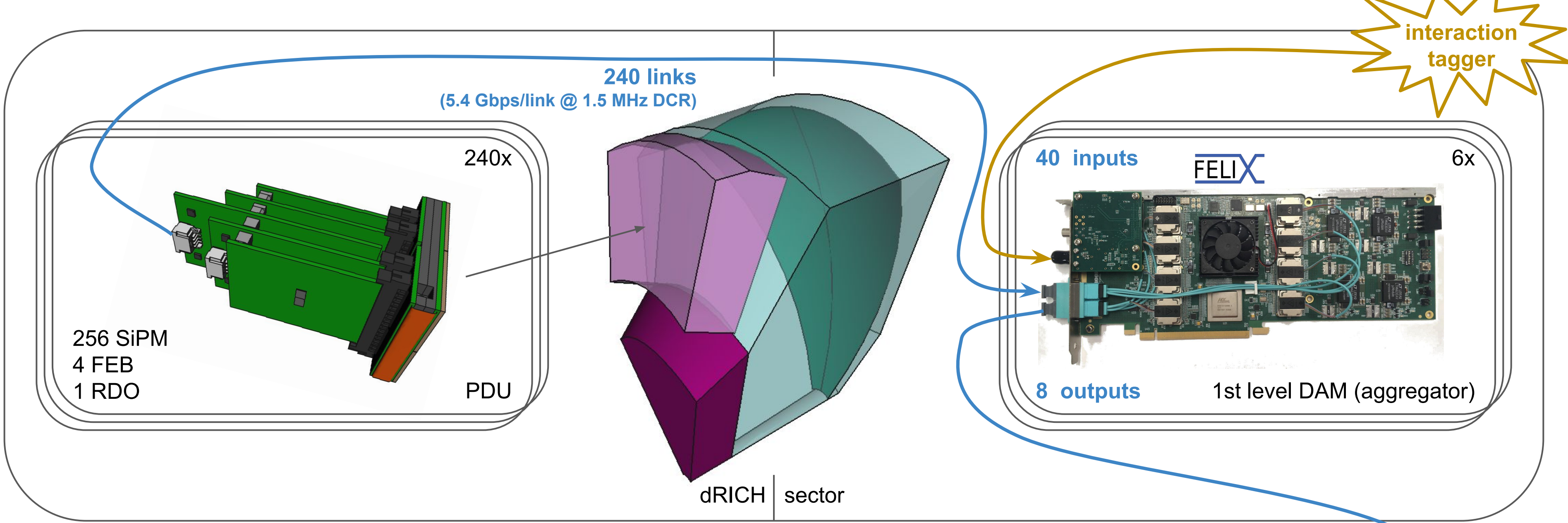
⚠️ need to ensure safe operation

thermal image



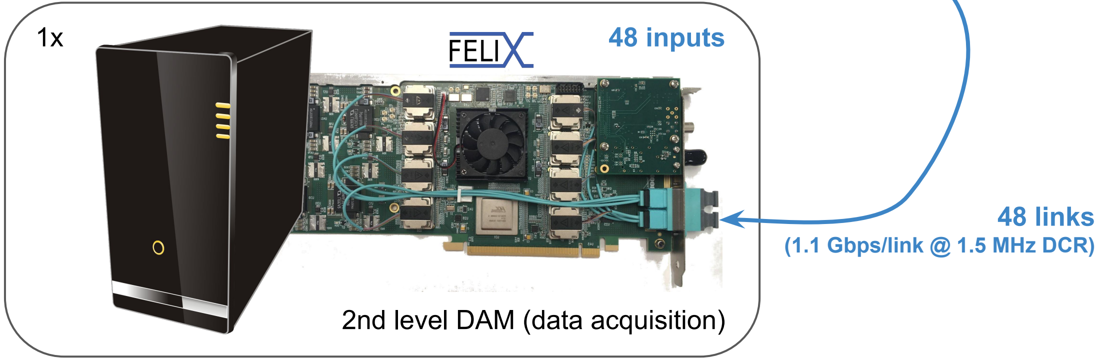
monitor system





one dRICH sector, up to

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

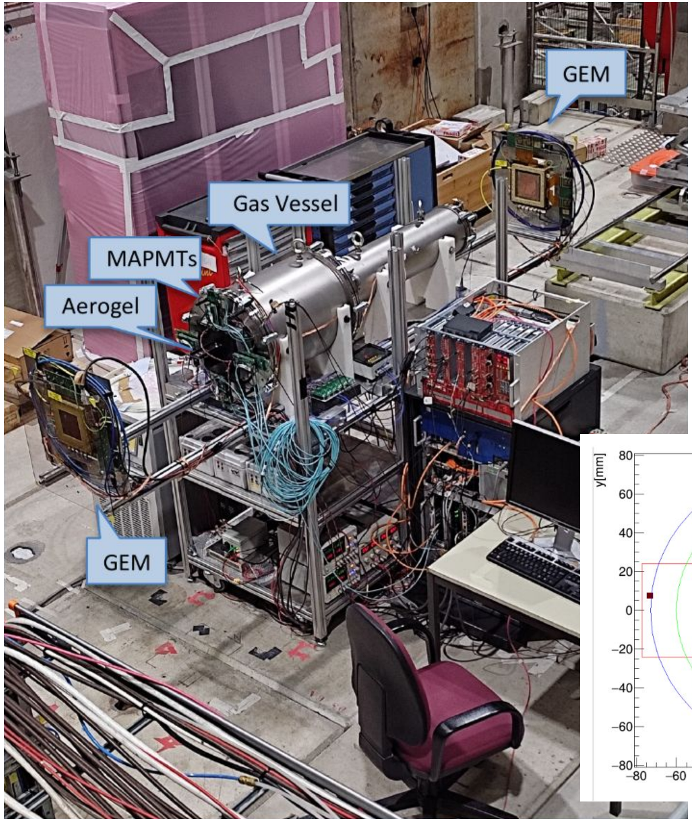


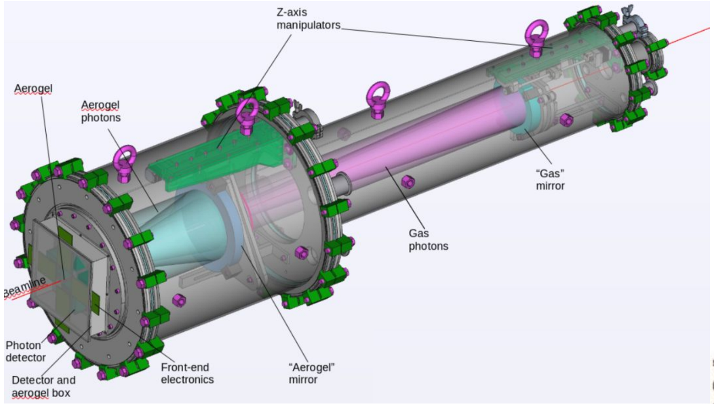
Readout model

dRICH prototype

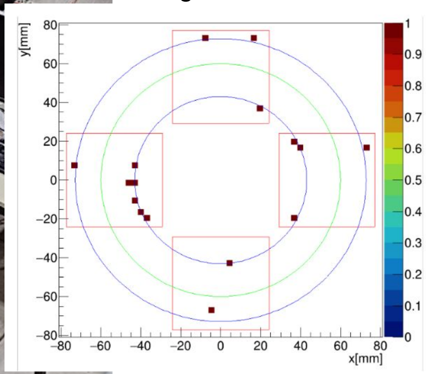
dRICH prototype operative
and commissioned in beam tests
double ring imaging achieved

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





single event



accumulated data