dRICH photosensors and electronics

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on behalf of the dRICH Collaboration

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Charges

The committee is asked to respond to the following charge questions

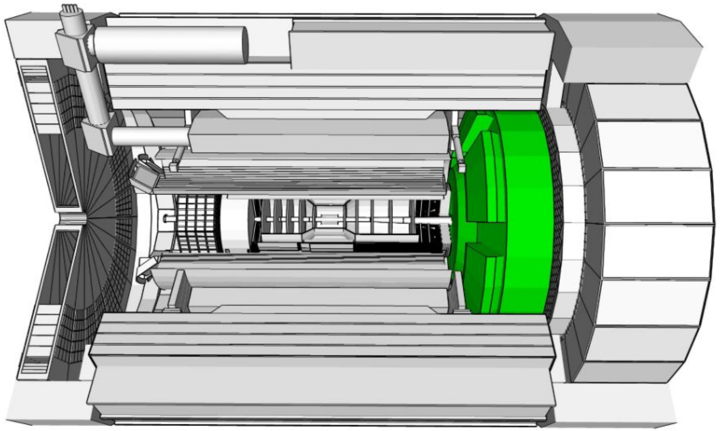
1. Are the technical performance requirements complete for all detector systems that employ SiPMs, documented, and understood?
2. Are the plans for achieving detector performance and construction sufficiently developed and documented for the present phase of the project? (ie., are they commensurate with the initiation of the SiPM procurement?)
3. Do the present detector system designs and the resulting SiPM specifications meet the performance requirements with a low risk of cost increases, schedule delays, and technical problems?
4. Are the fabrication and assembly plans for the detector systems consistent with the overall project and detector schedule and sufficiently developed to initiate the SiPM procurement?
5. Are the plans for detector integration in the EIC detector appropriately developed to initiate the SiPM procurement?
6. Have previous review recommendations been adequately addressed to initiate the SiPM procurement?
7. Have ES&H and QA considerations been adequately incorporated in the SiPM procurement planning? (This includes a quality assurance plan for receipt of material meeting specifications.)
8. Is the procurement approach sound and the procurement schedule credible?

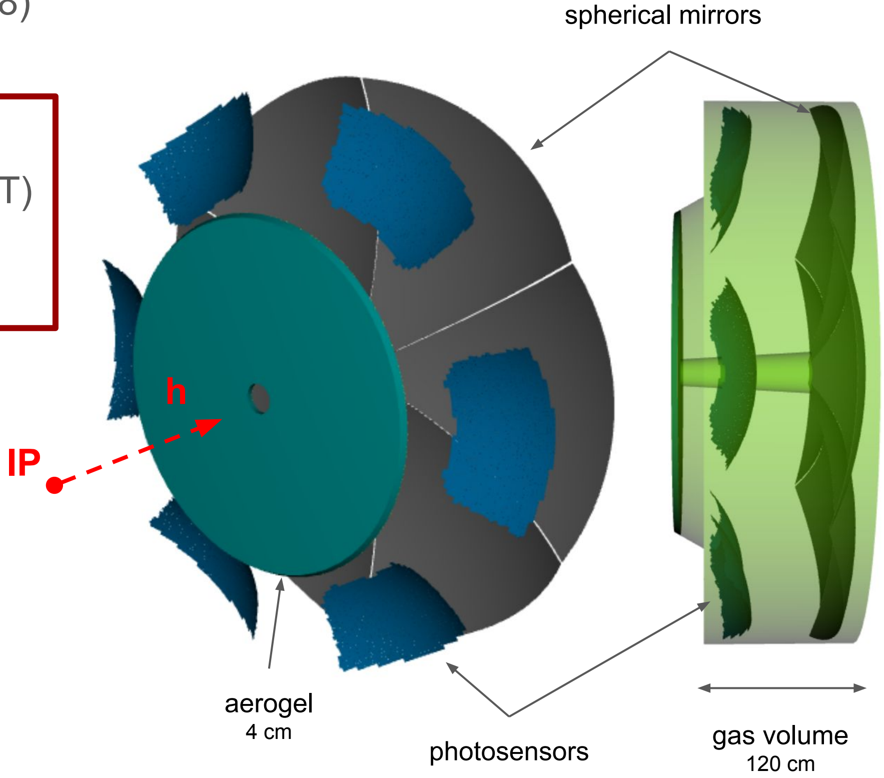
The dual-radiator (dRICH) for forward PID at EIC

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

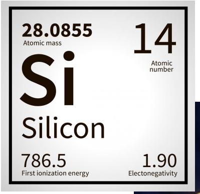
- **radiators:** aerogel (n ~ 1.02) and C_2F_6 (n ~ 1.0008)
- **mirrors:** large outward-reflecting, 6 open sectors
- **sensors:** 3x3 mm^2 pixel, 0.5 m^2 / sector
  - single-photon detection inside high B field (~ 1 T)
  - outside of acceptance, reduced constraints
  - SiPM optical readout





SiPM option and requirements for RICH optical readout

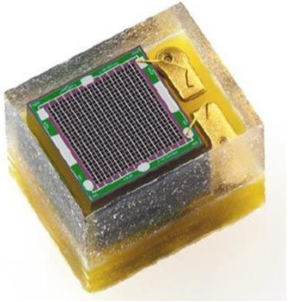
- **pros**
  - cheap
  - high photon efficiency
    requirement
  - excellent time resolution
    requirement
  - insensitive to magnetic field
    requirement



- **cons**

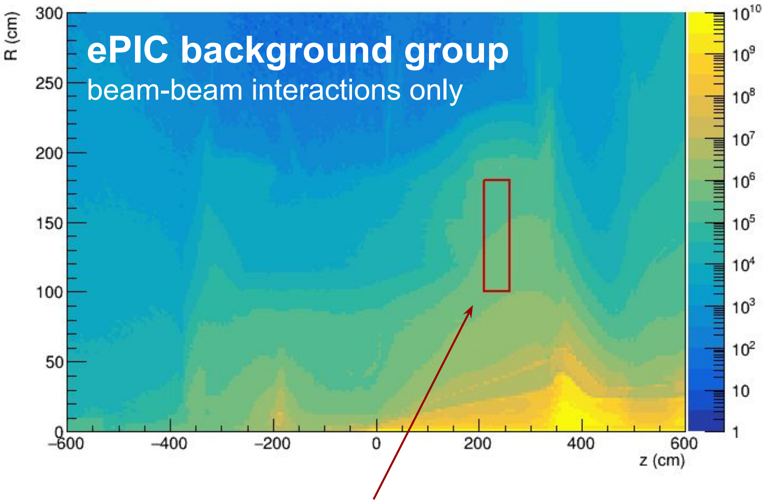
large dark count rates
not radiation tolerant

technical solutions and mitigation strategies
🐧 cooling
⏱ timing
🔥 annealing



Neutron fluxes at the dRICH photosensor surface

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



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}

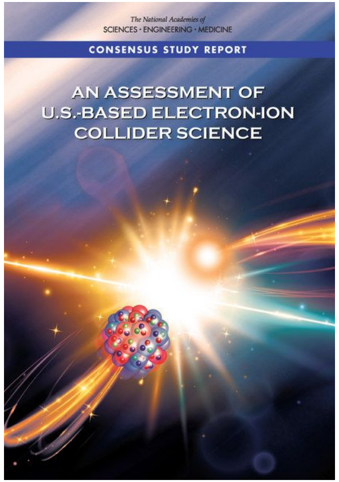
- radiation level is moderate

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 $\mathscr{L}$ 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

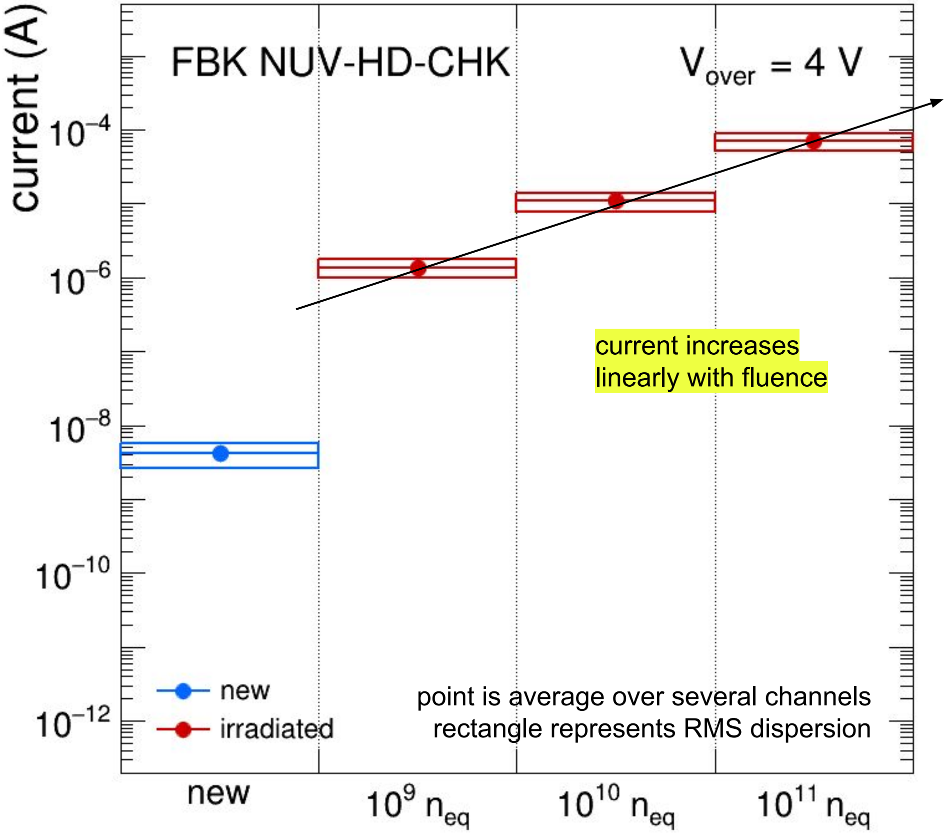
→ radiation damage studied in steps of radiation load

10^9 1-MeV n_{eq}/cm^2 *most of the key physics topics*

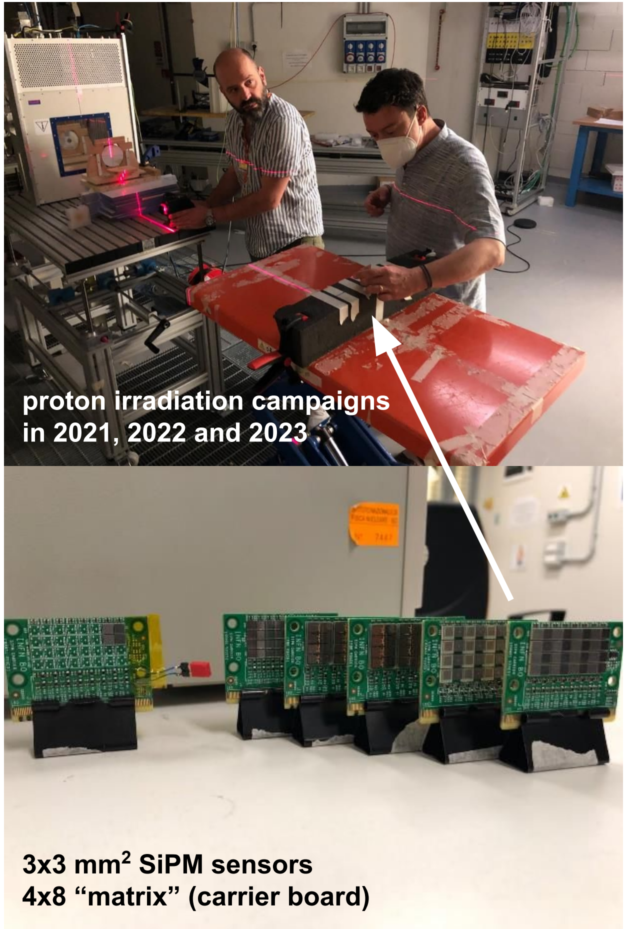
10^{10} 1-MeV n_{eq}/cm^2 *should cover most demanding measurements*

10^{11} 1-MeV n_{eq}/cm^2 *might never be reached*

Studies of radiation damage on SiPM

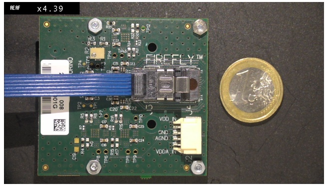


all results are reported at T = -30 C

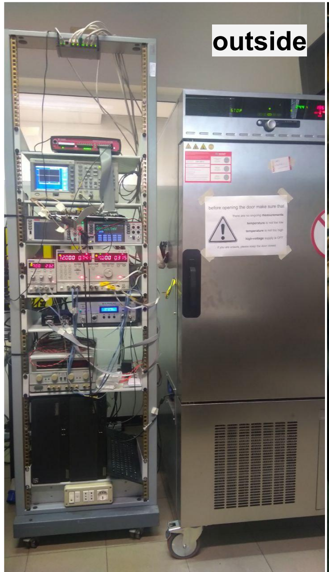


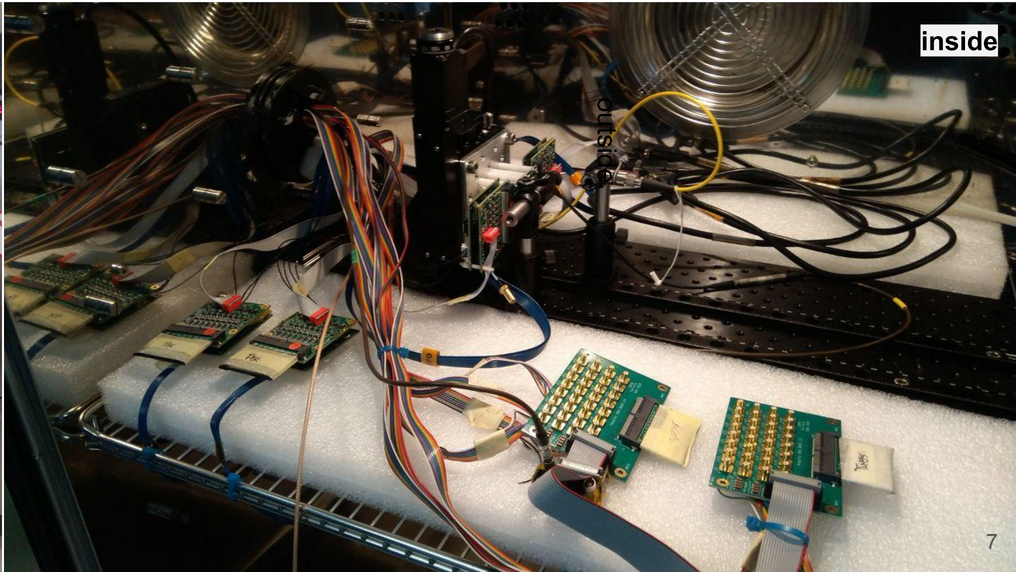
Characterisation setup

- **climatic chamber**
  large volume low-temperature operation
- **source meter & multiplexers**
  automatic IV characterisation of 80 SiPM channels
- **picosecond pulsed laser**
- **complete readout chain**
  automatic DCR and full readout of 128 channels

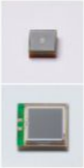


characterisation setup to be expanded for QA testing ~ 300 SiPM / day (25% of production over 2 years)
more setups (2-3) to be deployed (reach ~ 100%)





Commercial SiPM sensors and FBK prototypes

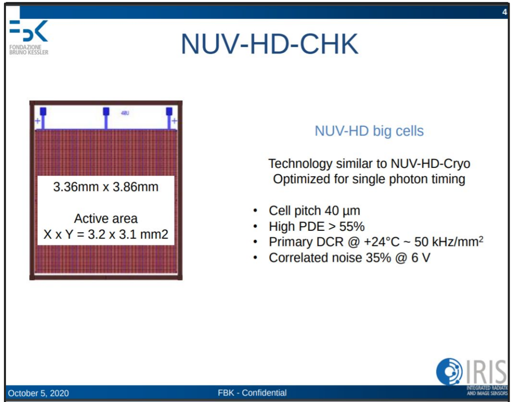



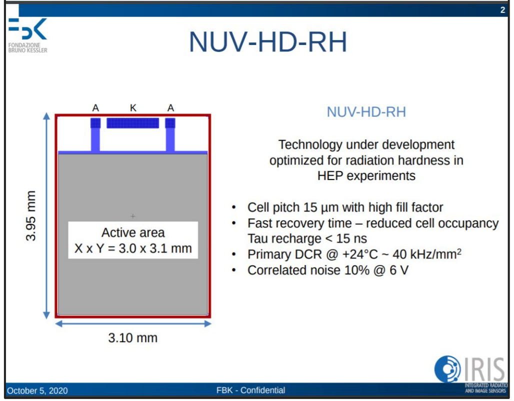
board	sensor	uCell (µm)	V_{bd} (V)	PDE (%)	DCR (kHz/mm^2)	window	notes
HAMA1	S13360 3050VS	50	53	40	55	silicone	legacy model Calvi et. al
	S13360 3025VS	25	53	25	44	silicone	legacy model smaller SPAD
HAMA2	S14160 3050HS	50	38	50		silicone	newer model lower V_{bd}
	S14160 3015PS	15	38	32	78	silicone	smaller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

HAMAMATSU PHOTON IS OUR BUSINESS

ON Semiconductor

BROADCOM

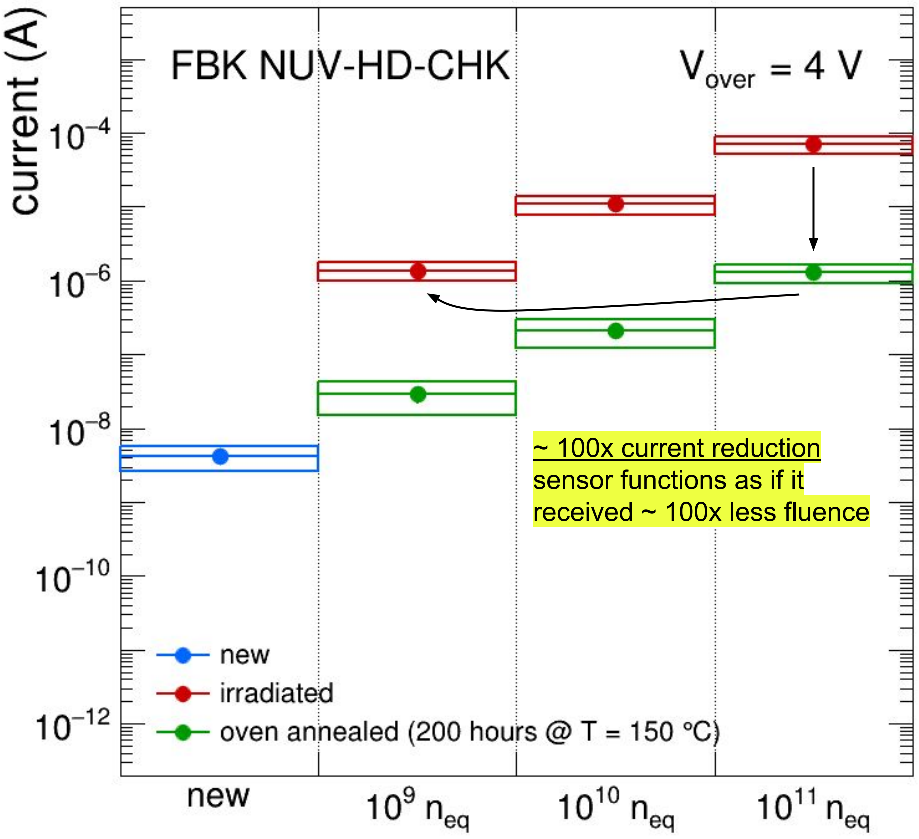




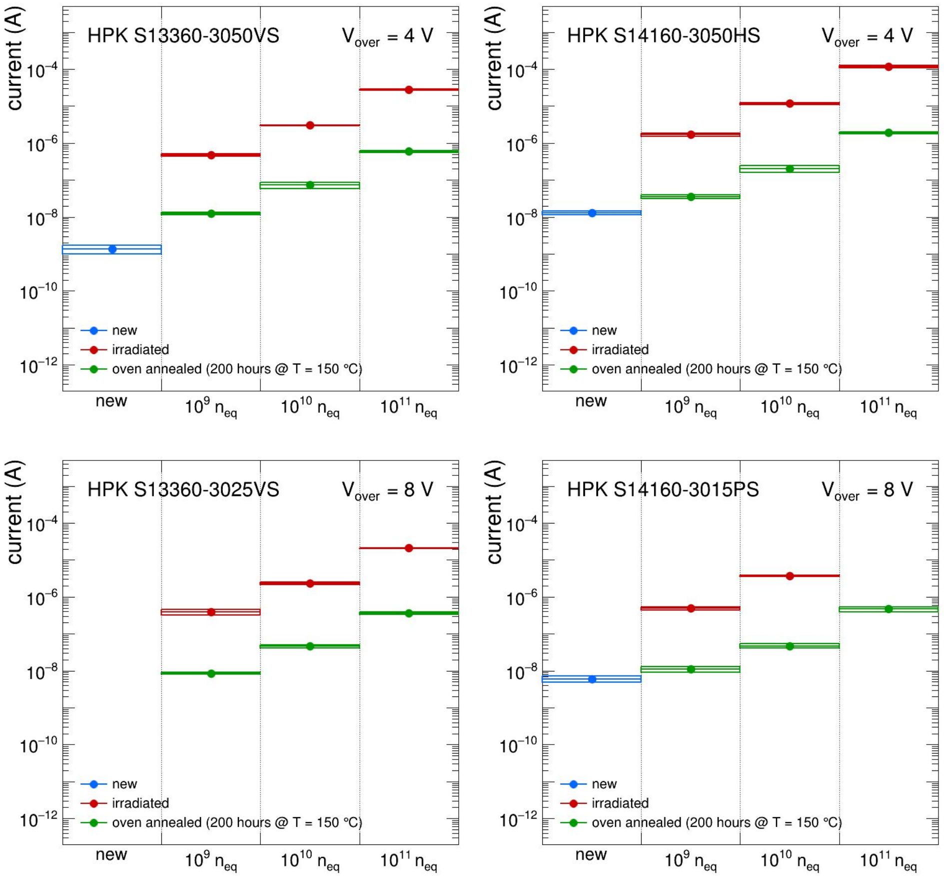
multiple producers: different technologies, SPAD dimensions, V_{bd}, electric field …

High-temperature annealing recovery

oven annealing
~ 1 week at 150 C



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



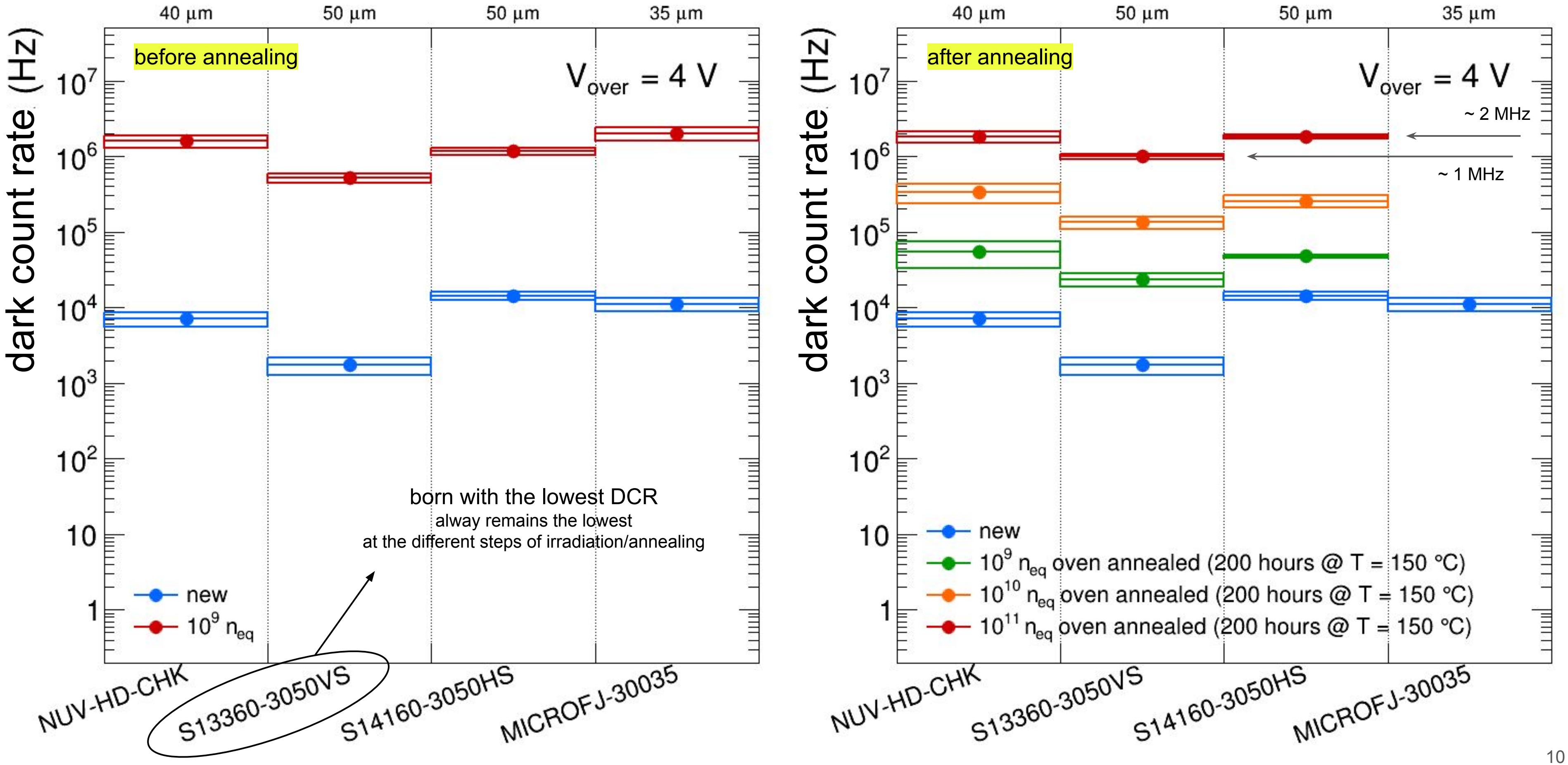
similar observation with various types of Hamamatsu sensors

Comparison between different sensors

comparison at same Vover not totally fair

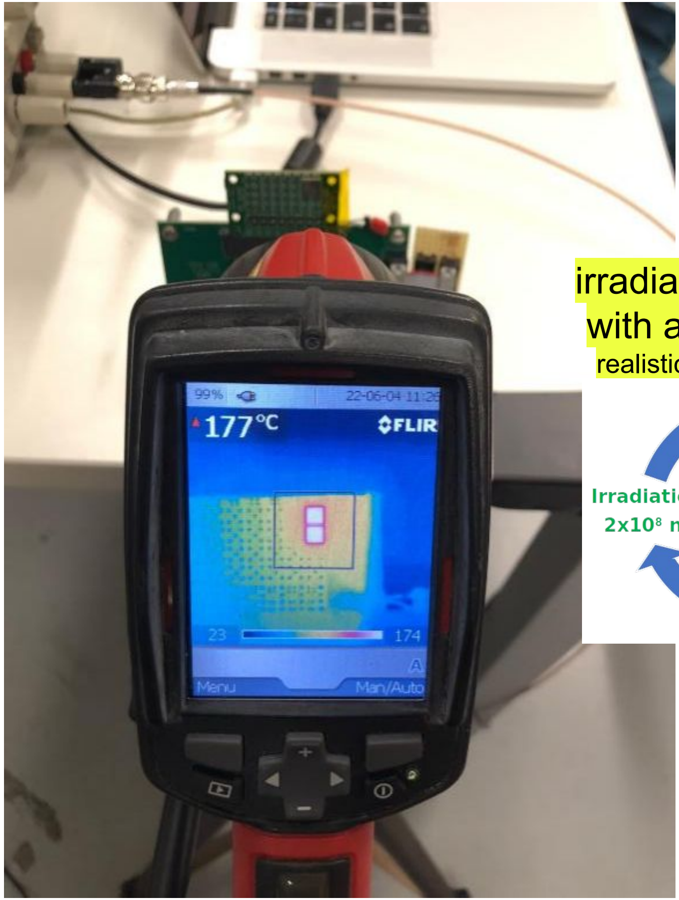
important to consider PDE (and SPTR) → SNR ~ PDE / DCR

unlikely 2x larger DCR is matched by 2x larger PDE

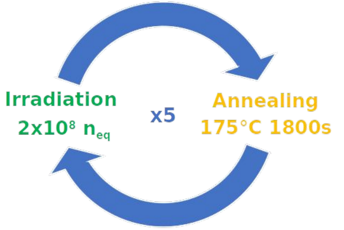


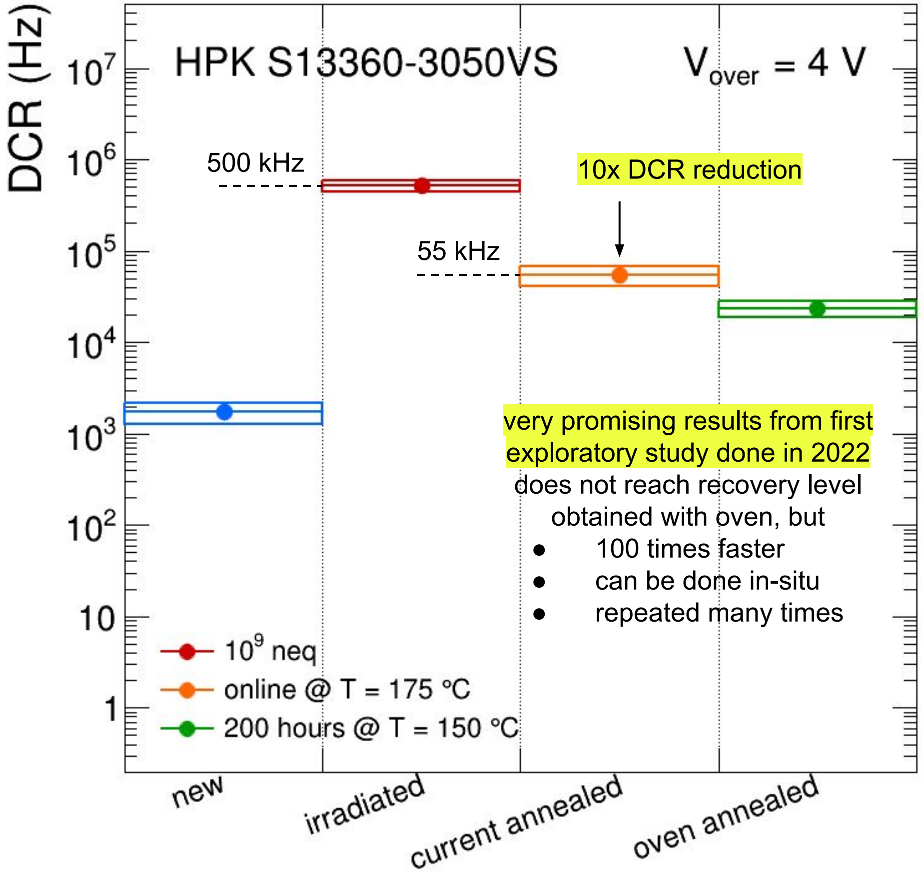
"Online" self-induced annealing

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



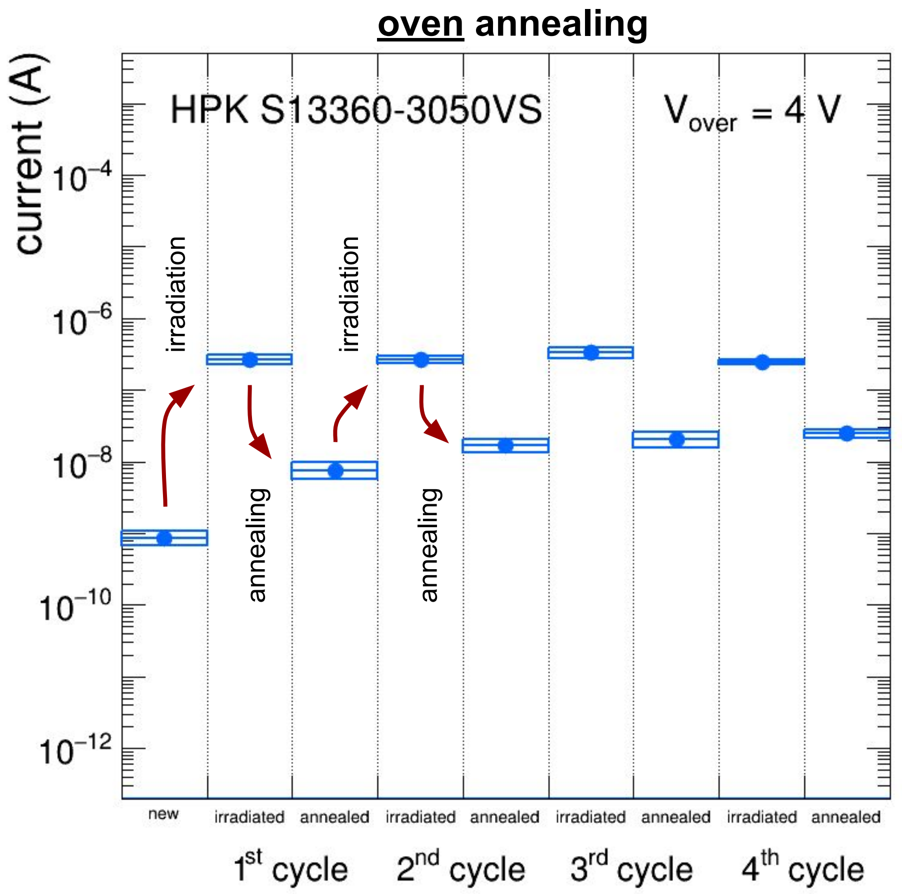
irradiation interleaved with annealing cycle
realistic experimental case





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

Repeated irradiation-annealing cycles



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

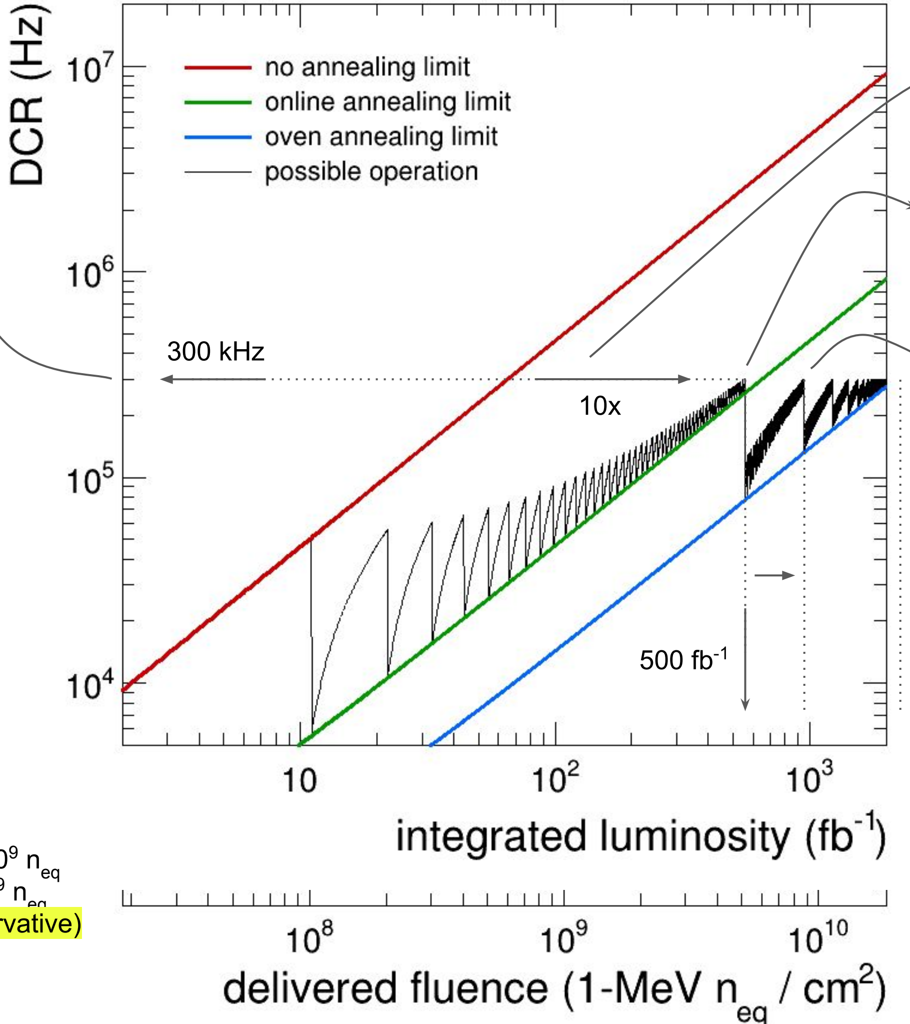
annealing cures same fraction of newly-produced damage

~ 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}

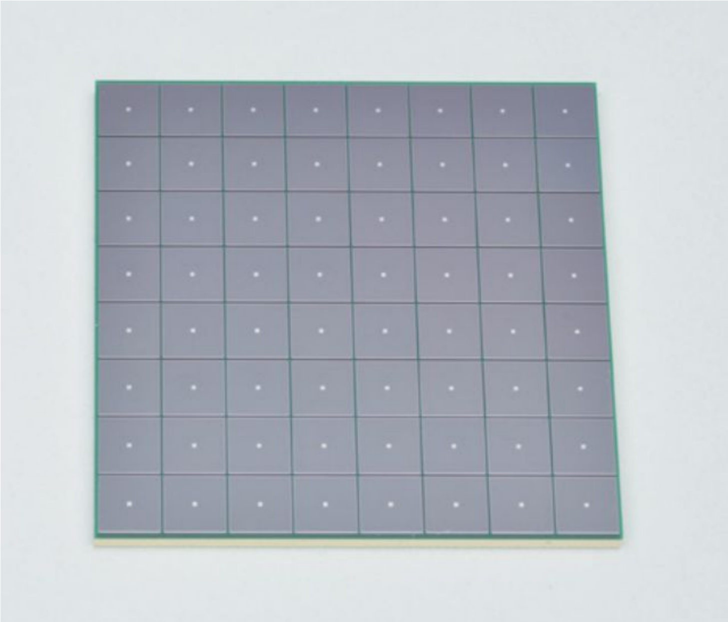
1-MeV neq fluence from background group (conservative)

- 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

SiPM technical specs

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



Parameters (at Vop, T = 25 C, unless specified)	Value	Notes
Device type	SiPM array	
Number of channels	64	8 x 8 matrix
Active Area	3 x 3 mm^2	active area of one channel, total active area is 64 x 3 x 3 mm^2
Device Area	< 28 x 28 mm^2	device area should be small such as to have > 75% fraction of active area over device total area
Pixel Size	40 - 80 um	pitch of the microcell SPAD
Package Type	surface mount	
Operating voltage	< 64 V	
Peak Sensitivity	400 - 450 nm	
PDE	> 35%	at peak sensitivity wavelength
Gain	> 1.5 10^6	
DCR	< 1.5 MHz	questo è il max DCR indicato su datasheet serie 13
DCR at low temperature	< 10 kHz	at T = -30 C
DCR increase with radiation damage	< 1 MHz / 10^9 neq	at T = -30 C, after a radiation damage corresponding to 10^9 1-MeV neutron equivalent / cm^2 (neq)
Residual DCR after annealing	< 25 kHz / 10^9 neq	at T = -30 C, after a radiation damage of 10^9 neq and a 150 hours annealing cycle at T = 150 C
Temperature coefficient of Vop	< 60 mV / C	
Direct crosstalk probability	< 10%	
Terminal capacity	< 600 pF	
Packing granularity		
Vop variation within a tray	< 300 mV	Vop variation between channels in one device
Recharge Time	< 100 ns	ctau recharge time constant
Fill Factor	> 70%	
Protective Layer	silicone resin (n = 1.5 - 1.6)	radiation resistant, heat resistant (up to T = 180 C)
Single photon time resolution	< 200 ps FWHM	corresponding to < 85 ps RMS

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Protective Layer	silicone resin (n = 1.5 - 1.6)	radiation resistant, heat resistant (up to T = 180 C)
Single photon time resolution	< 200 ps FWHM	corresponding to < 85 ps RMS

specs that might not be in the vendor's standard "menu", but that we should require

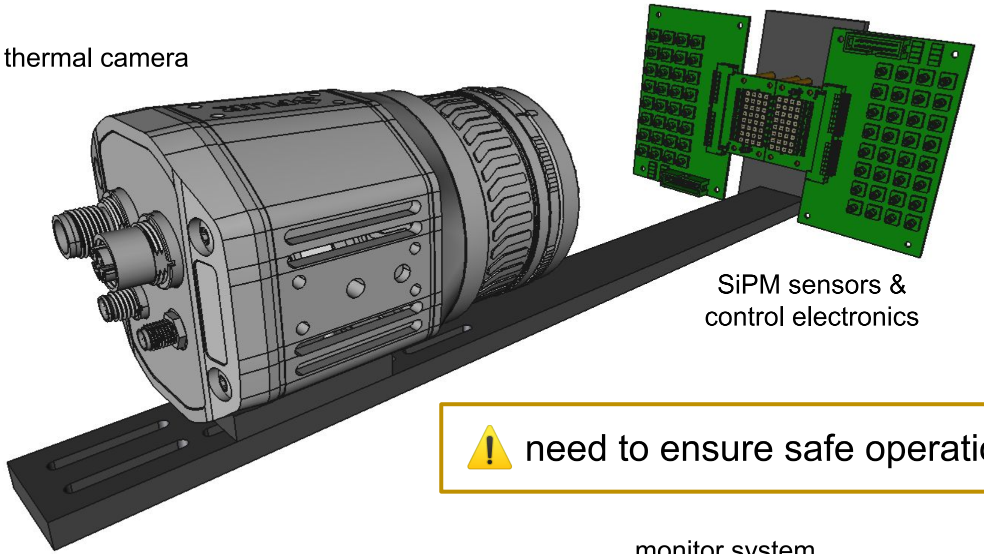
we will qualify vendors/sensors ourselves and deep test samples from each batch to ensure they are met throughout production

Automated multiple SiPM online self-annealing

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

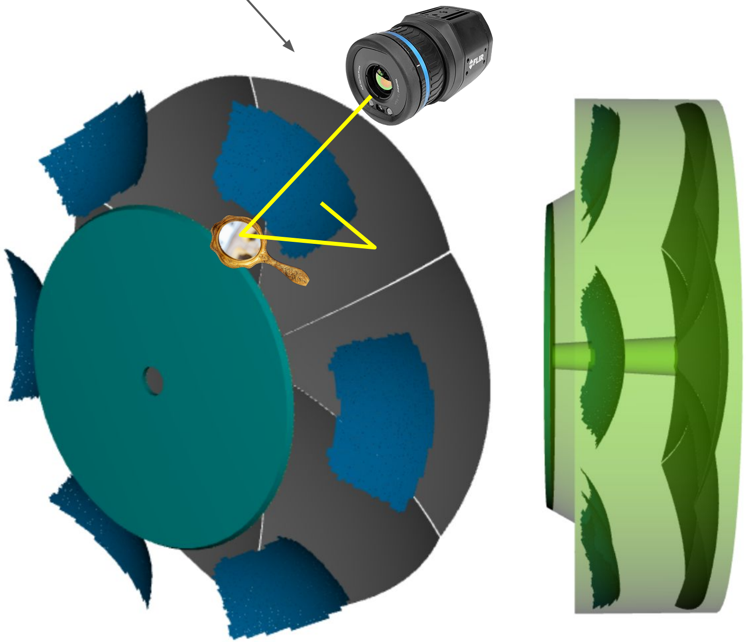
technical feasibility and implementation in the experimental environment to be studied in details

thermal camera

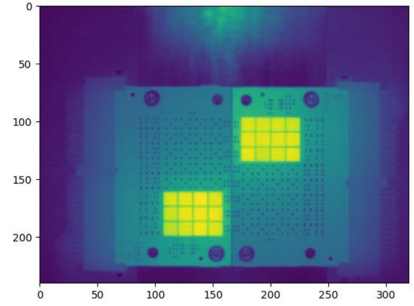


SiPM sensors & control electronics

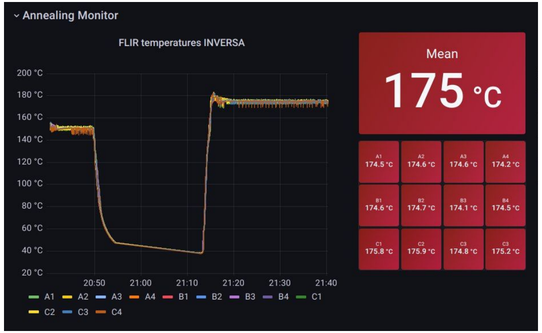
⚠️ need to ensure safe operation



thermal image

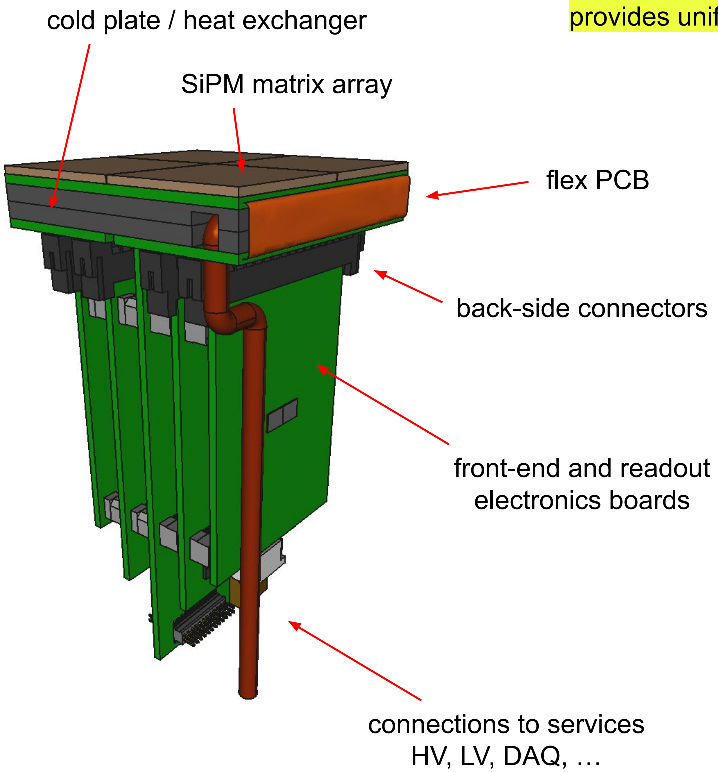


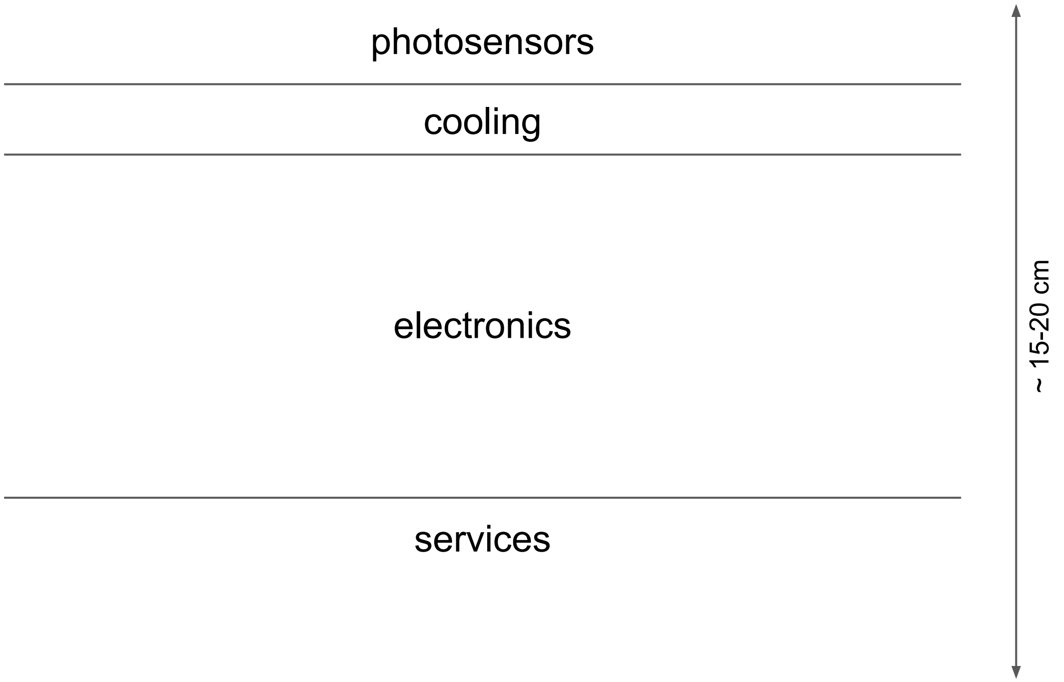
monitor system



SiPM photodetector unit – PDU

technical solution using cold plate and flex-PCB circuit
provides uniform sensor cooling with no loss of active area





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

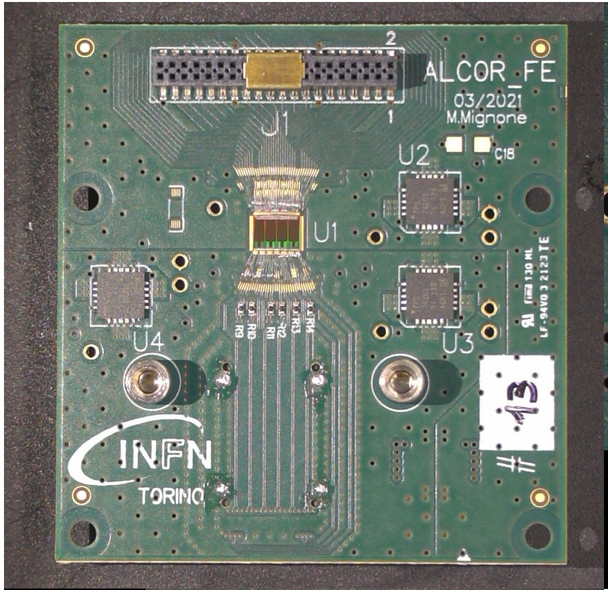
General & Temperature Control

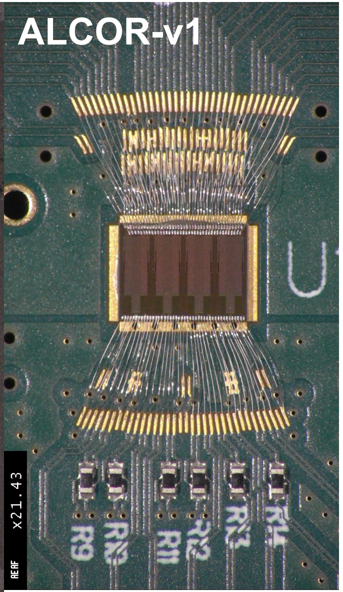
Temperature range	-55...250 °C
Temperature stability	±0,01 K

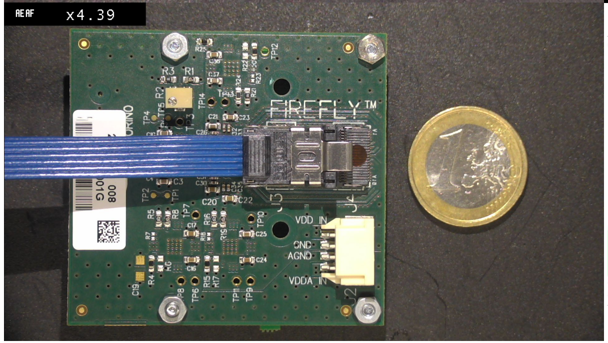
Heating / cooling capacity

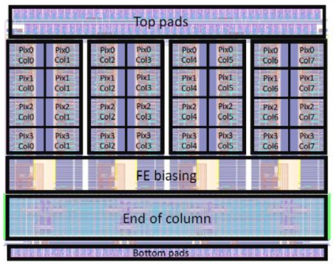
Heating capacity	6 kW								
Cooling capacity	250	200	100	20	0	-20	-40	-50	°C
	6	6	6	6	6	4,2	1,5	0,65	kW

ALCOR ASIC: integrated front-end and TDC









developed by INFN-TO

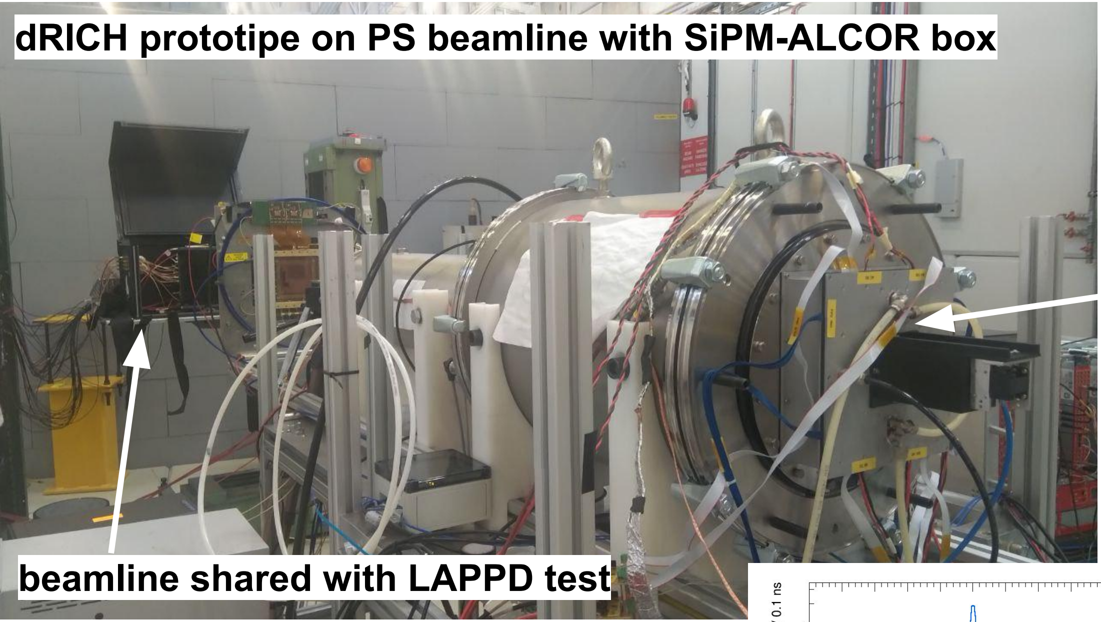
64-pixel matrix mixed-signal ASIC

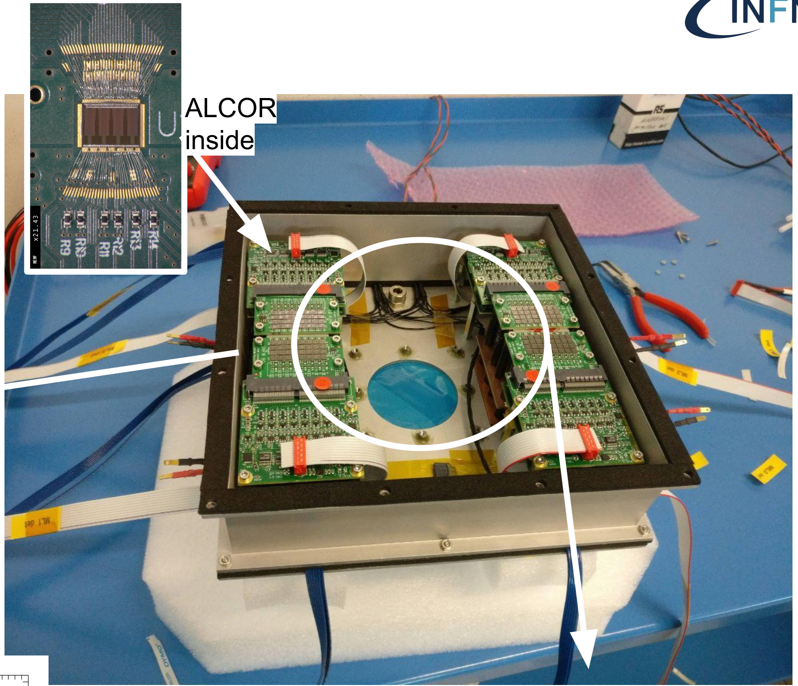
current versions (v1,v2) have 32 channels, wirebonded

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

2022 test beam at CERN-PS

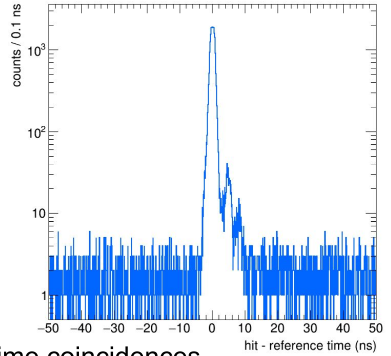




successful operation of SiPM

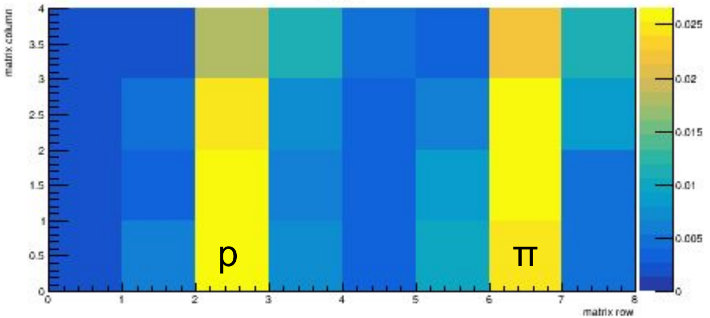
irradiated (with protons up to 10^{10})

and annealed (in oven at 150 C)

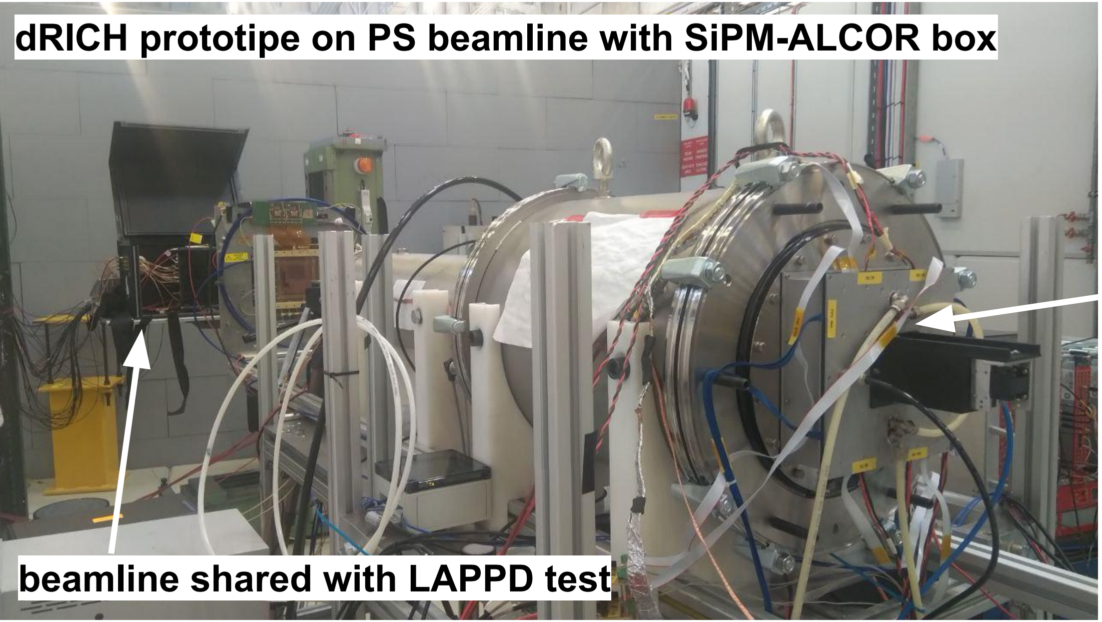


time coincidences

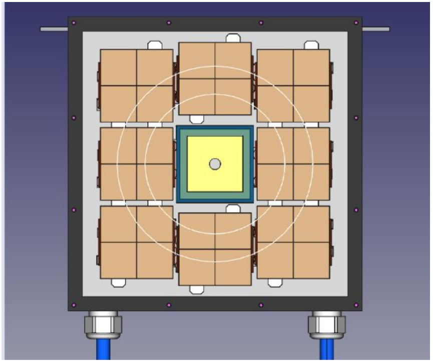
8 GeV positive beam (aerogel rings)

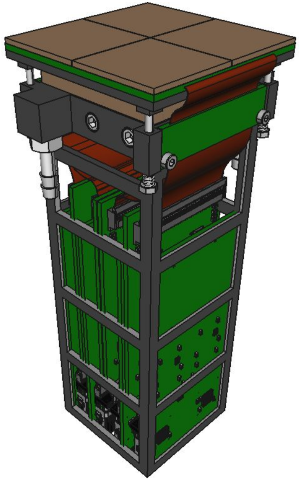


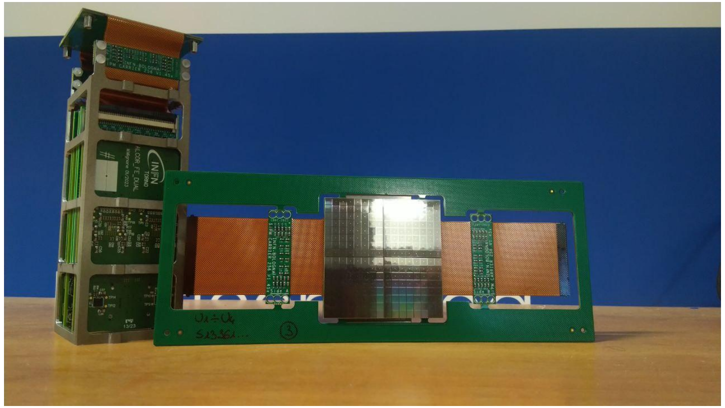
New detector plane for 2023 beam tests



prototype EIC-driven
readout unit and readout box







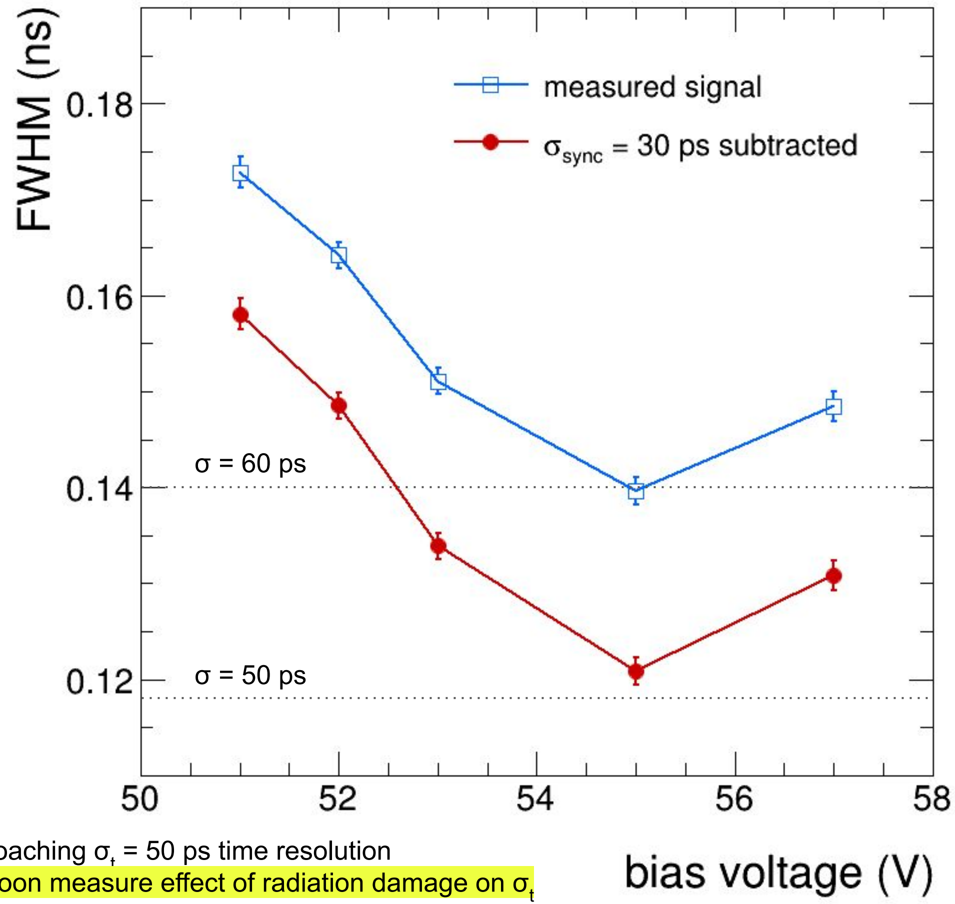
a few prototype photodetector units

will be assembled and tested in September

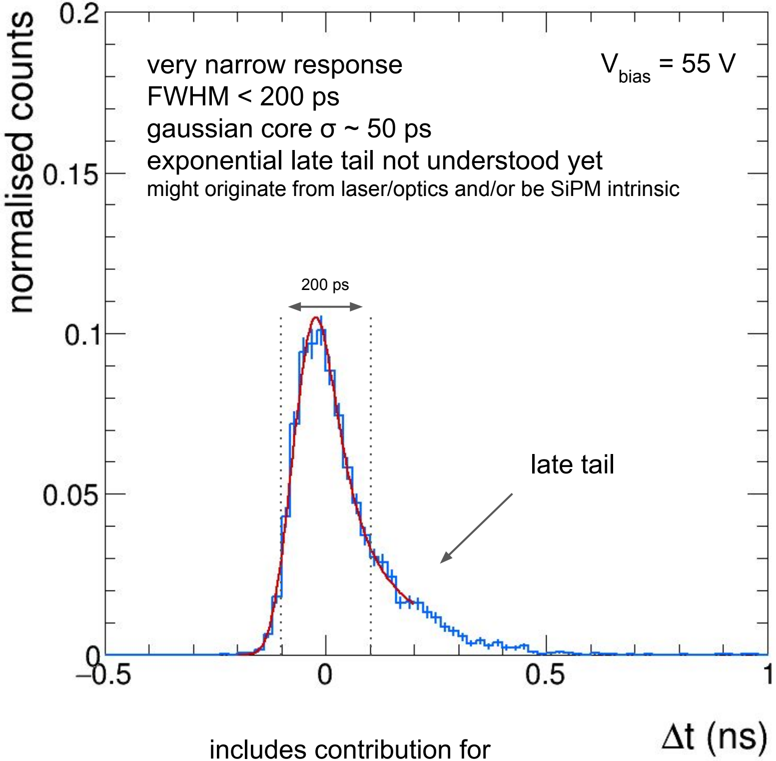
before mounting them on the dRICH detector prototype for the beam test

Laser timing measurements with oscilloscope

Hamamatsu S13360-3075



laser-SiPM correlations (time-walk corrected)



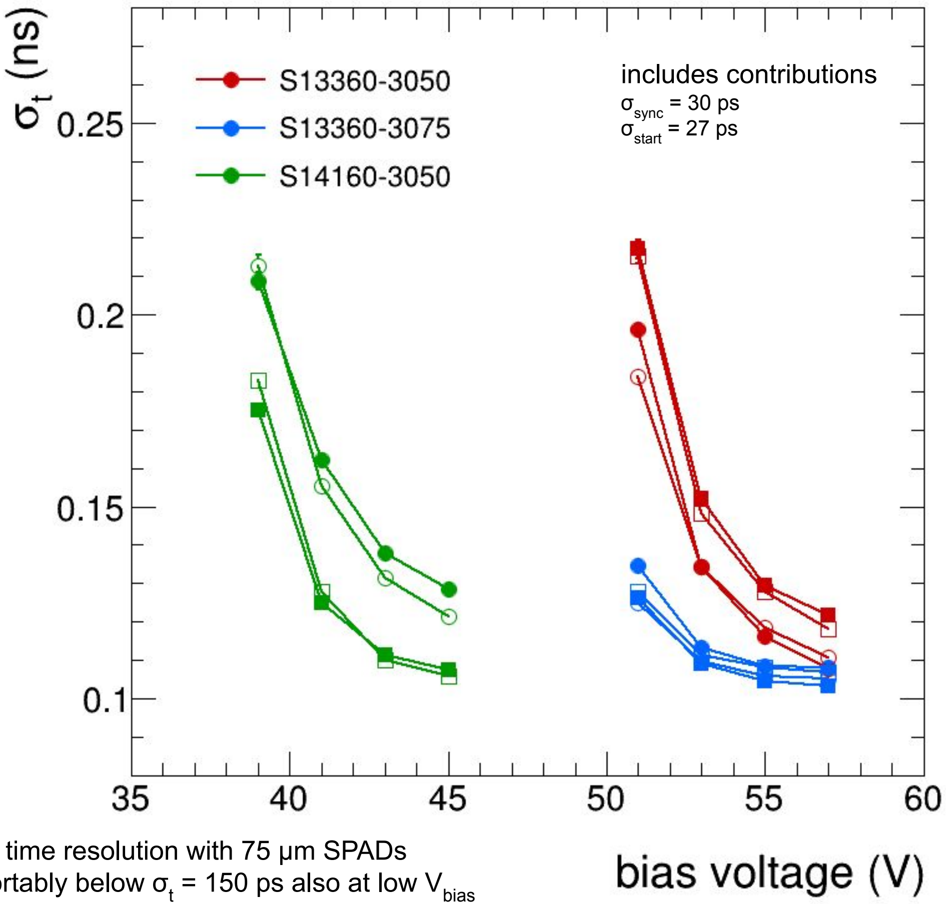
includes contribution for laser-oscilloscope synchronization
measured to be σ_{sync} = 30 ps

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

Laser timing measurements with ALCOR

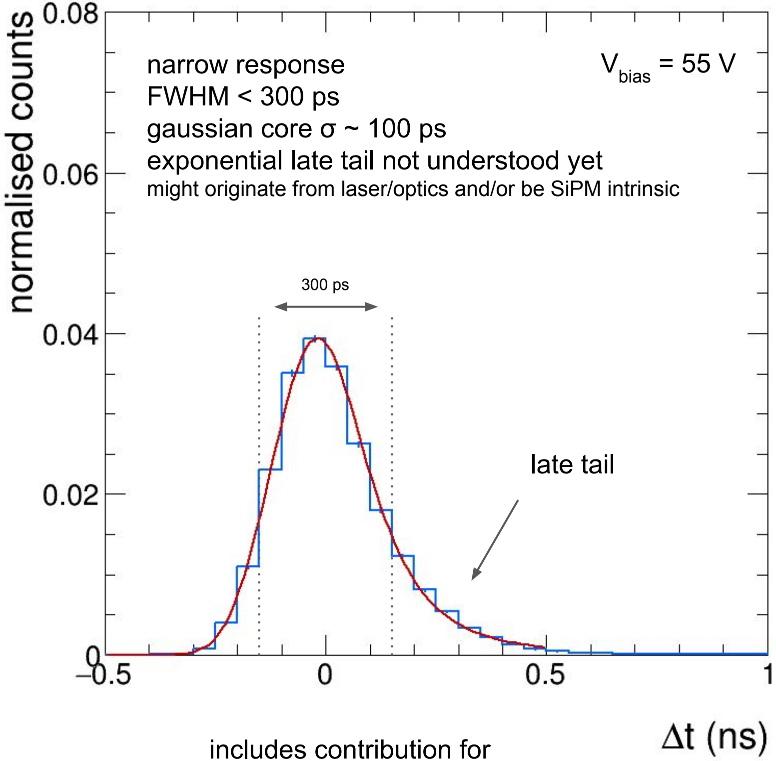
Hamamatsu S13360-3075

standard ALCOR front-end bias configuration



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

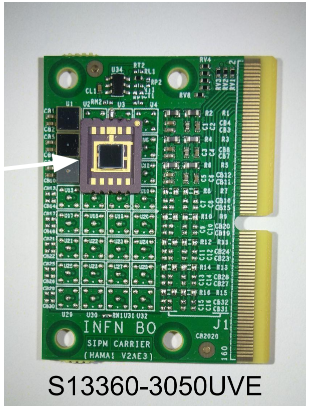
laser-SiPM correlations (time-walk corrected)



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

Current & future plans: sensor optimisation and risk mitigation

This list is not exhaustive and only contains the most important items and steps towards the TDR



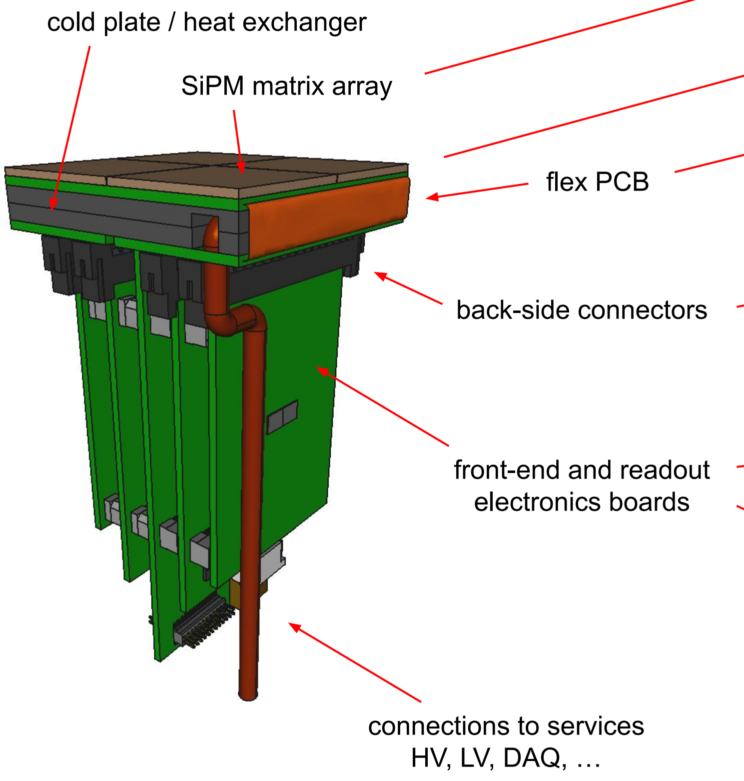
- **characterisation measurements**
    - measurements of time resolution after irradiation and annealing
    - define SiPM performance and comparisons based on SNR (DCR, PDE, SPTR)
    - full evaluation of 75 μm SPAD sensors (ie. Hamamatsu S13360-3075)
        - PDE is larger than 50 μm, SPTR is better, DCR is similar
    - full evaluation of new Hamamatsu SiPM prototypes (based on S13360 technology)
        - improved NUV sensitivity, improved signal shape and recharge time
        - already received 50 μm and 75 μm samples
- **operation and annealing**
    - test low-temperature (down to T = -40 C) operation with fluid-based chiller
        - evaluate possibility of using the system in heating mode for annealing
    - study the details of "in-situ" online self-induced annealing
        - forward (safer, but larger currents) vs. reverse (less safe, lower currents) bias operation
        - recovery vs. annealing temperature and time
        - refine technical solutions (and electronics) for monitor and control in the experiment
- **engineering run with FBK**
    - optimisations for the EIC of the already-mature NUV-HD technology (lower field / shaping to improve DCR)
    - development of single-die multi-channel SiPM sensor (achieve high fraction of active area with a low-cost process)

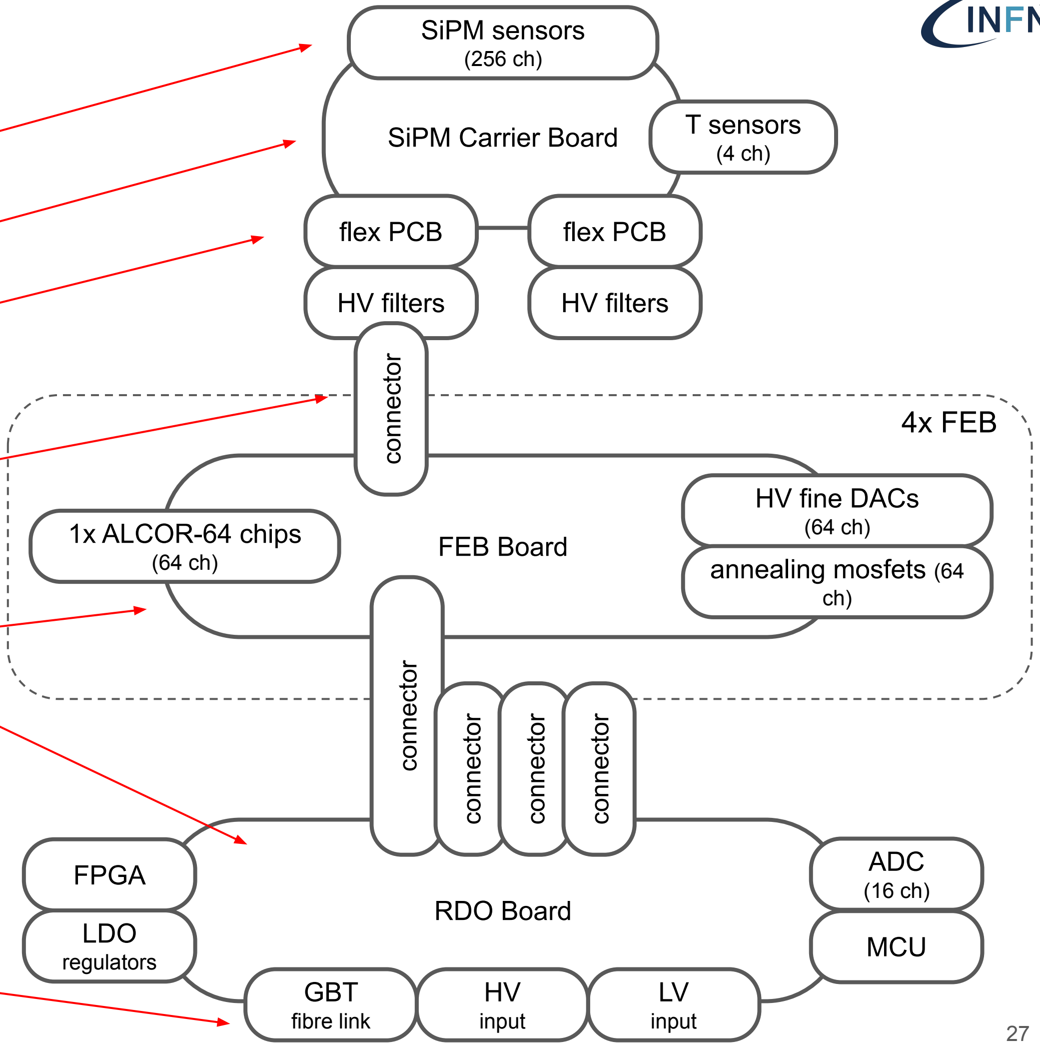
Summary

- **dRICH SiPM option fulfills dRICH requirements**
  - 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 optimisation towards TDR**
  - good feeling on 75 μm SPAD sensors
  - new Hamamatsu prototypes and FBK developments
  - development of RDO
  - ALCOR-v3, optimisation and final packaging

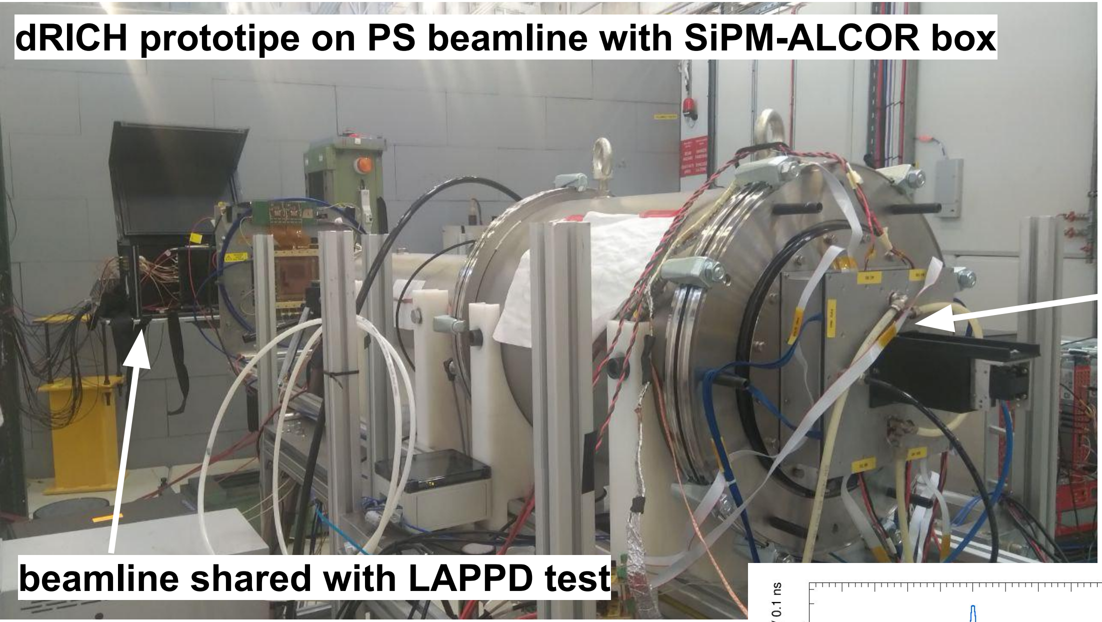
END

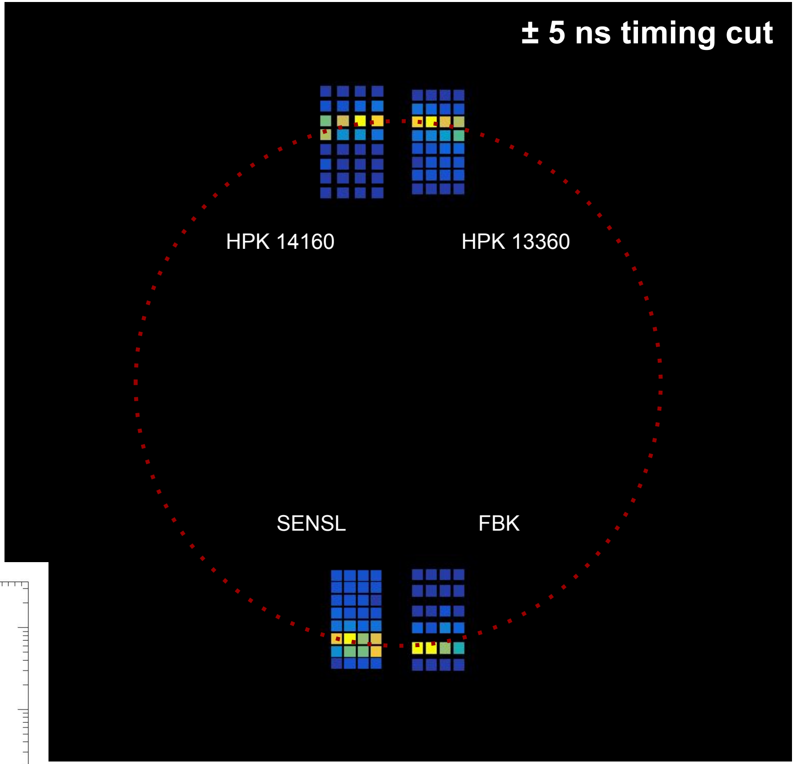
PDU electronics



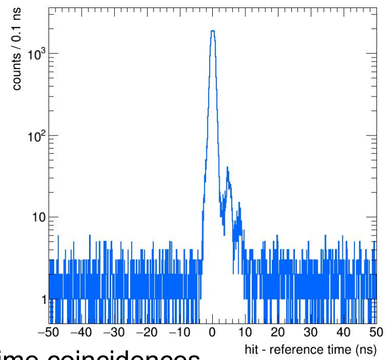


2022 test beam at CERN-PS





8 GeV negative beam (aerogel rings)



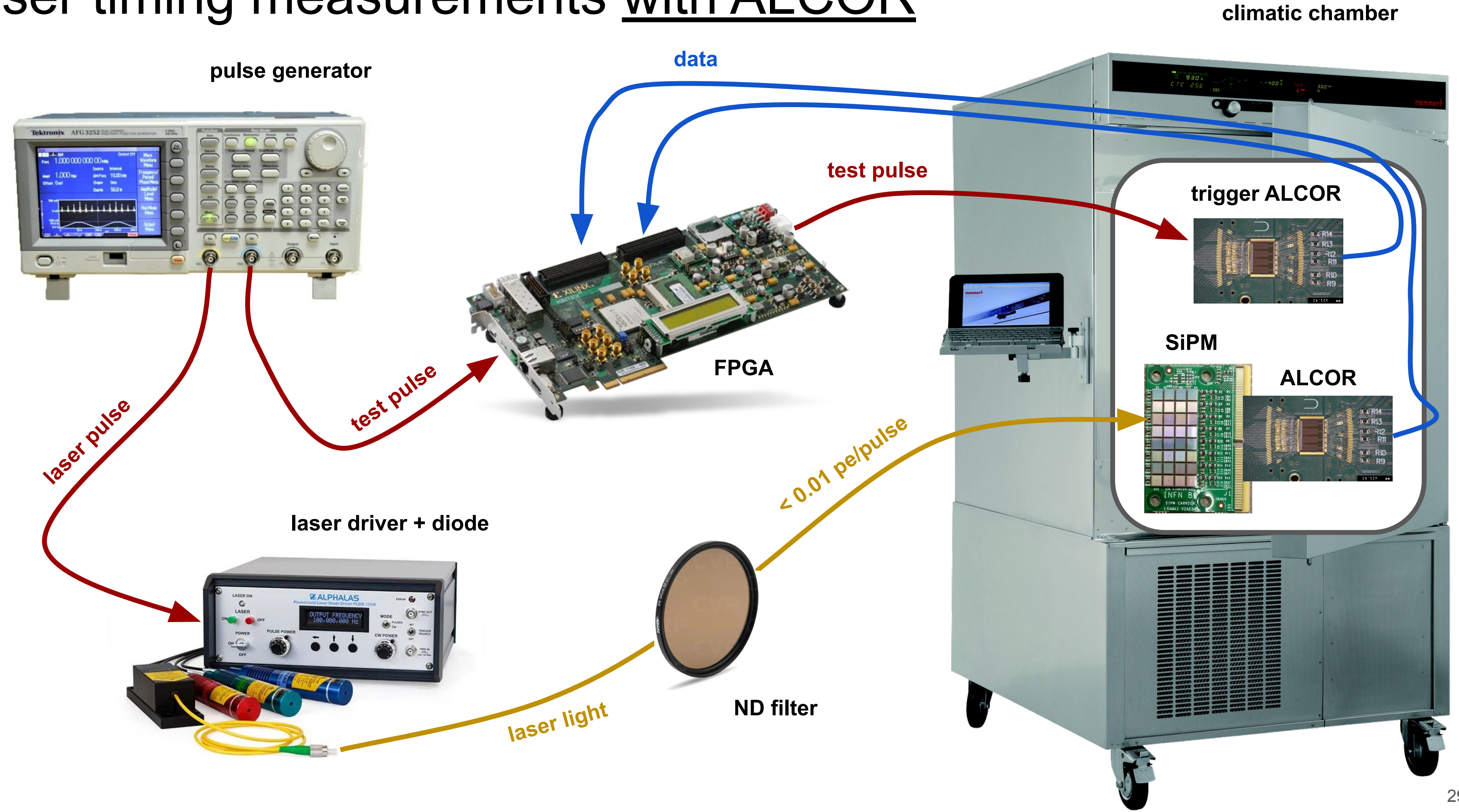
time coincidences

successful operation of SiPM

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

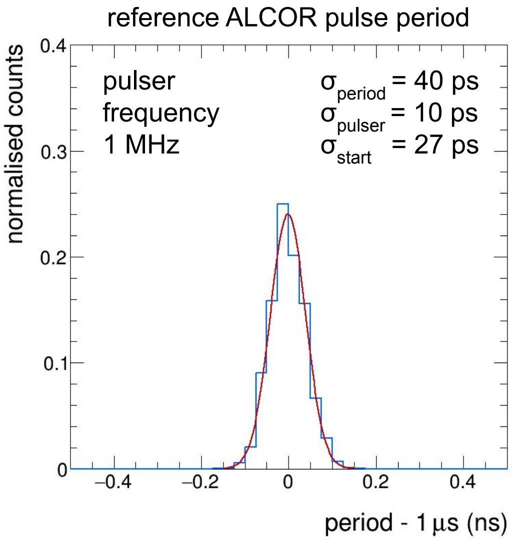
and annealed (in oven at 150 C)

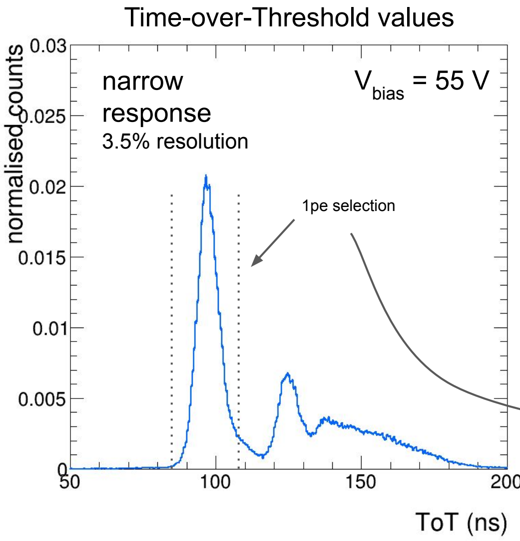
Laser timing measurements with ALCOR

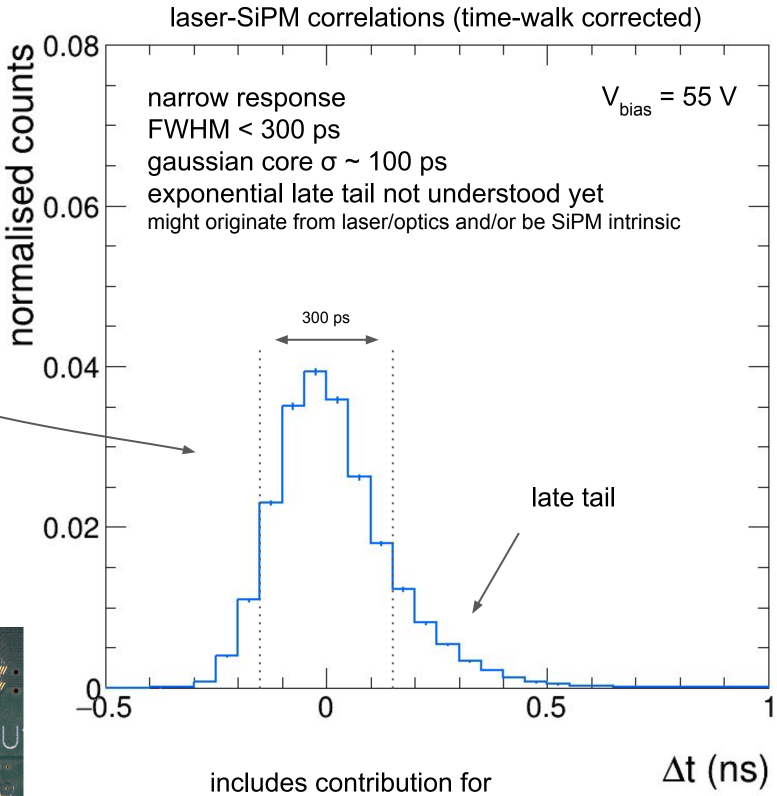


Laser timing measurements with ALCOR

Hamamatsu S13360-3075



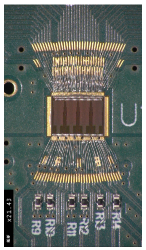




laser-SiPM signal synchronisation by sending test pulse to reference ALCOR

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

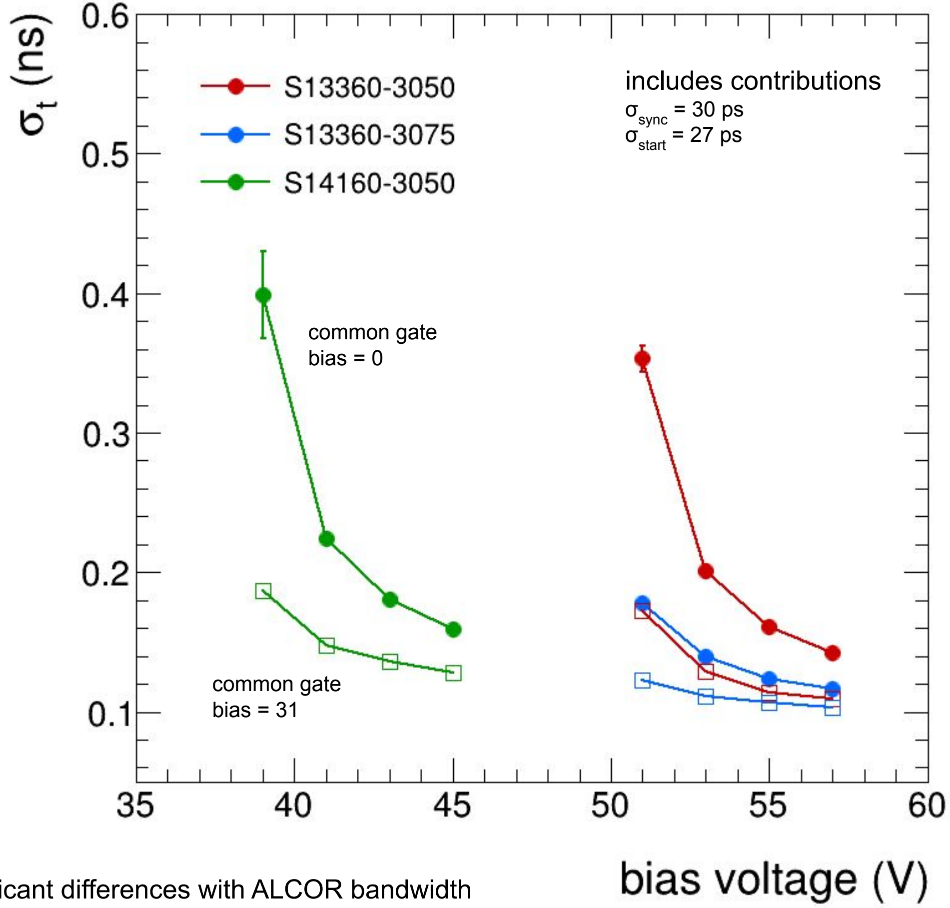
measure time coincidences Δt between reference and ALCOR reading SiPM



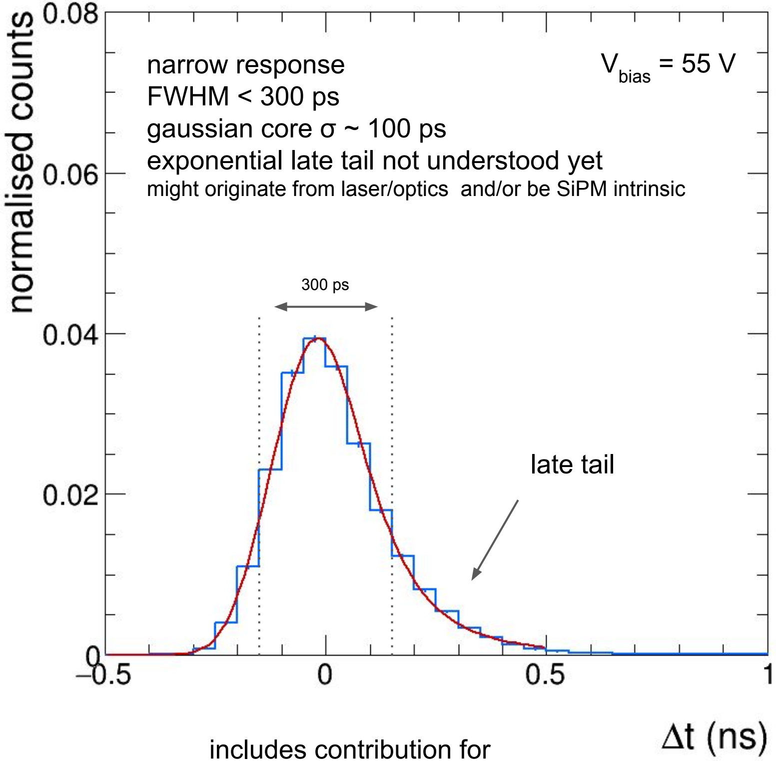
includes contribution for laser-ALCOR synchronization
measured to be σ_{sync} = 30 ps
and reference time resolution
measured to be σ_{start} = 27 ps

Laser timing measurements with ALCOR

the two extremes of ALCOR front-end bias configuration



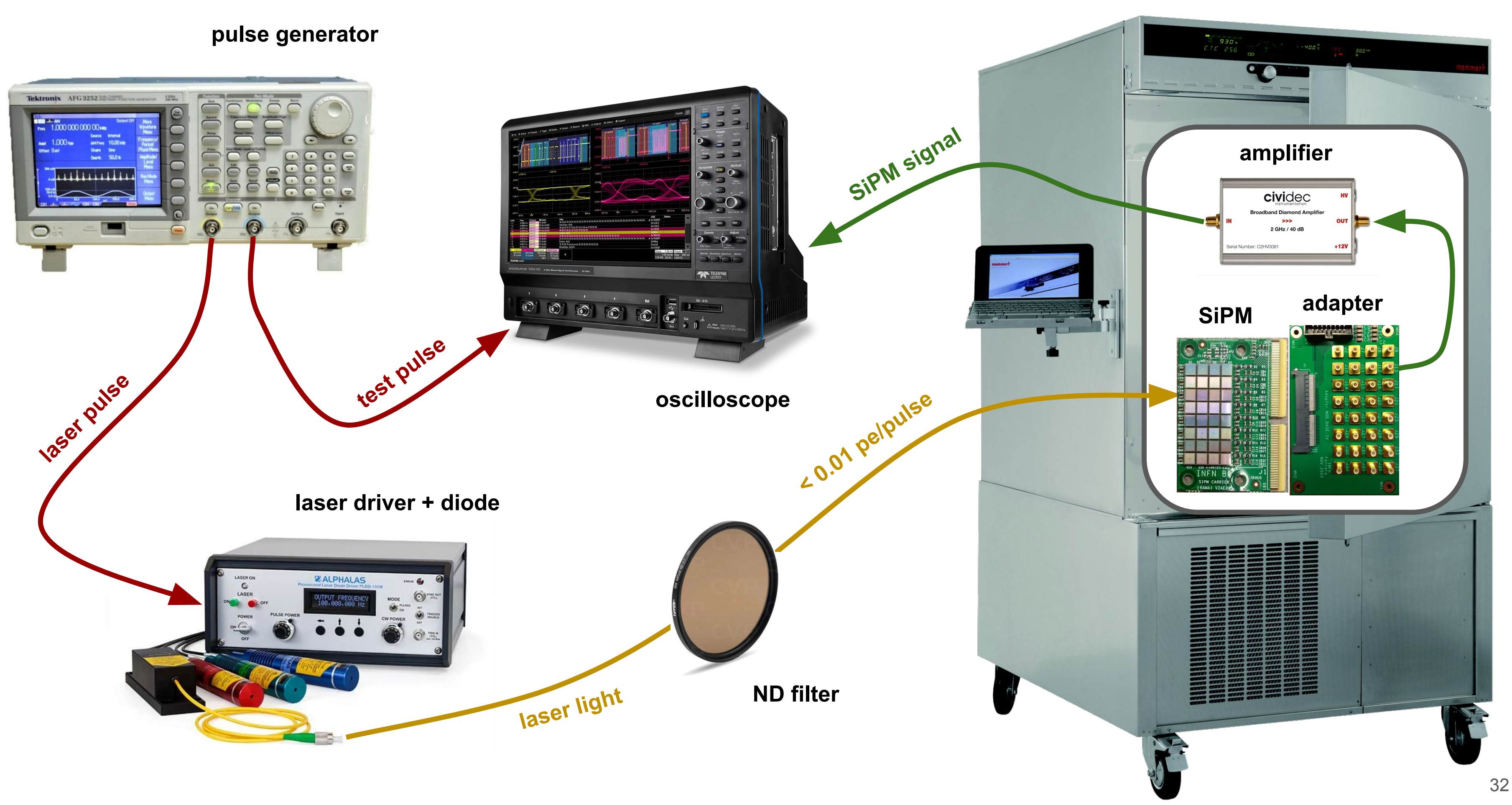
laser-SiPM correlations (time-walk corrected)



significant differences with ALCOR bandwidth

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

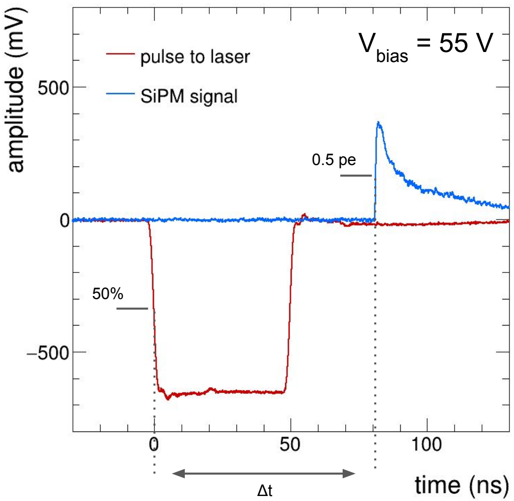
Laser timing measurements with oscilloscope



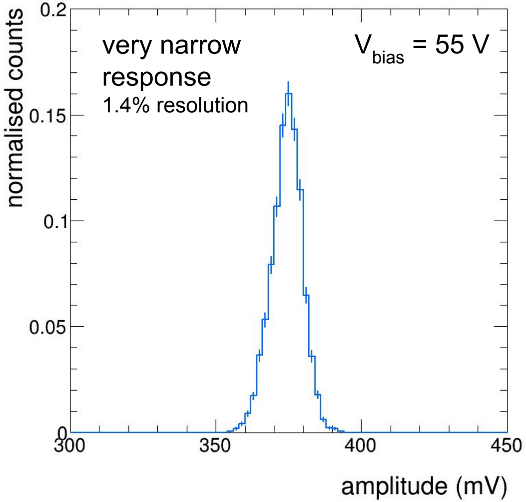
Laser timing measurements with oscilloscope

Hamamatsu S13360-3075

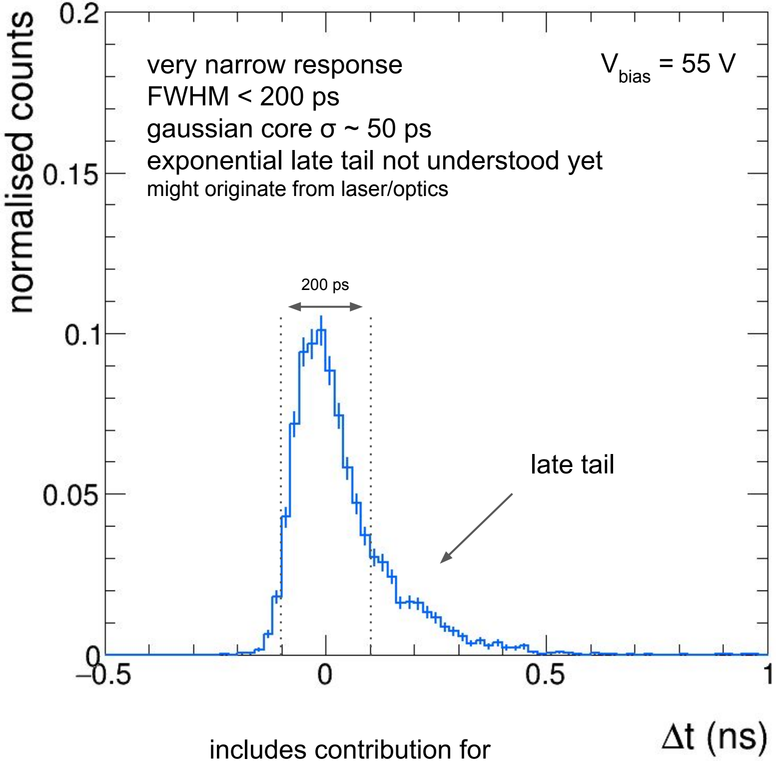
acquired oscilloscope traces



SiPM signal amplitudes (1pe)



laser-SiPM correlations (time-walk corrected)



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)

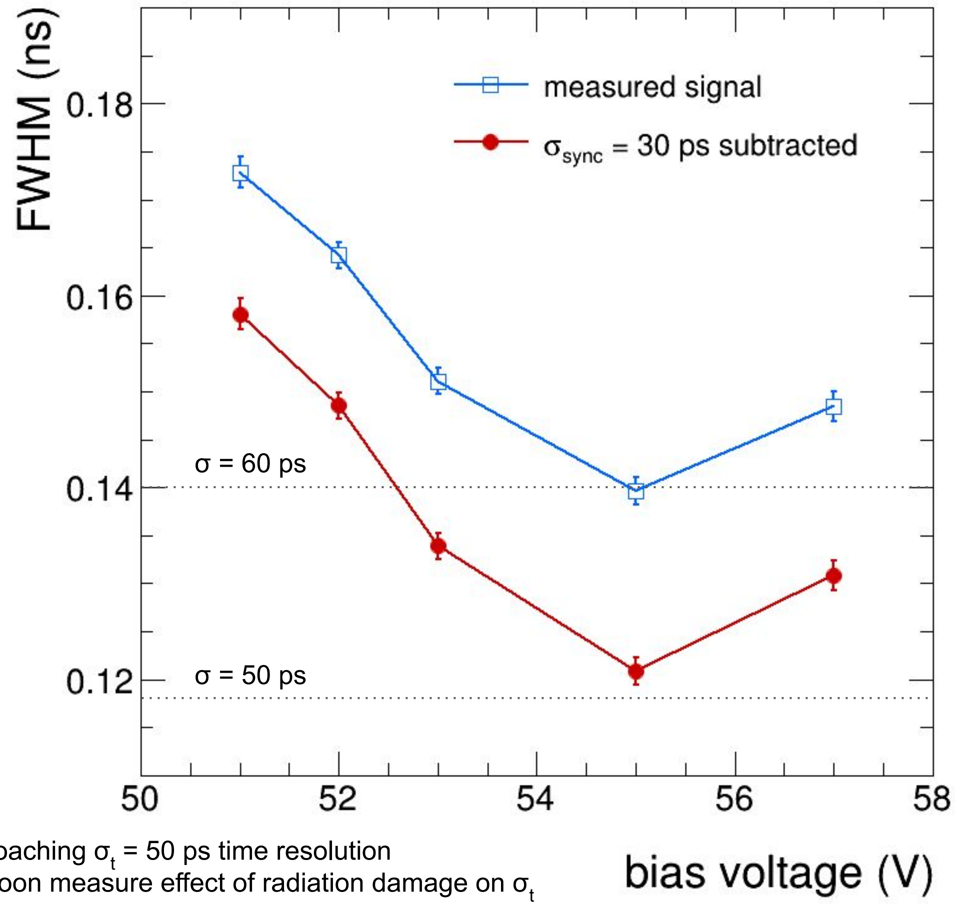
timing defined with fixed thresholds

- laser pulse at 50% of signal
- SiPM signal at 0.5 pe (average amplitude)

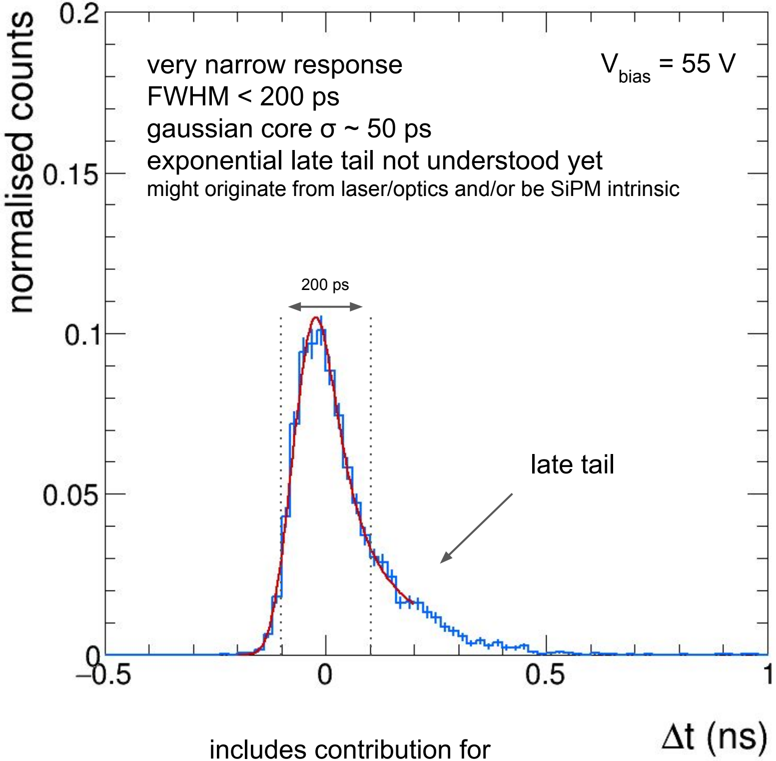
time-amplitude correlation (walk) corrected

Laser timing measurements with oscilloscope

Hamamatsu S13360-3075



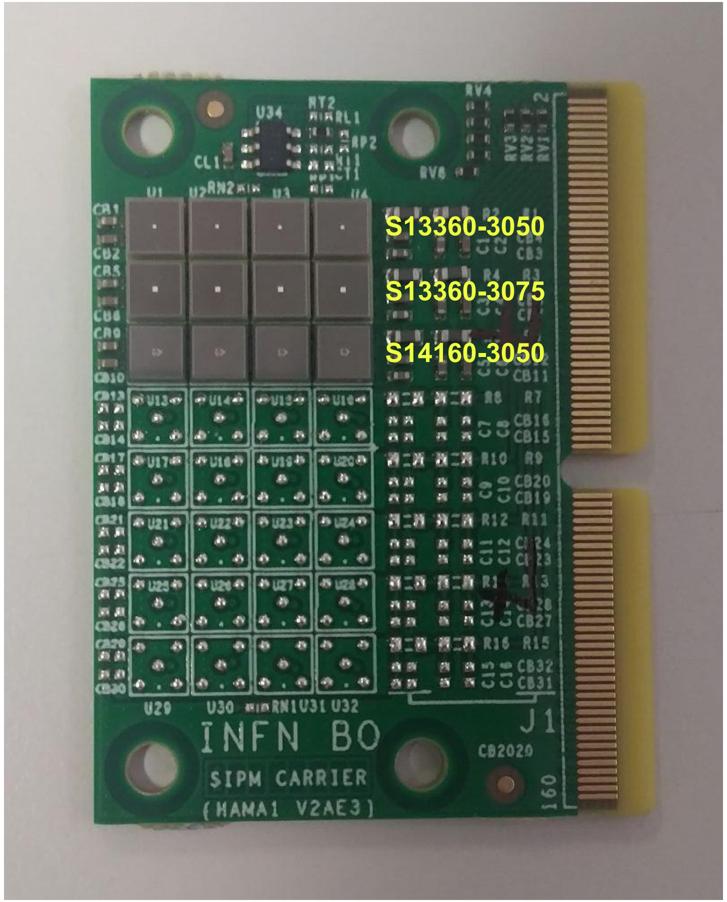
laser-SiPM correlations (time-walk corrected)



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

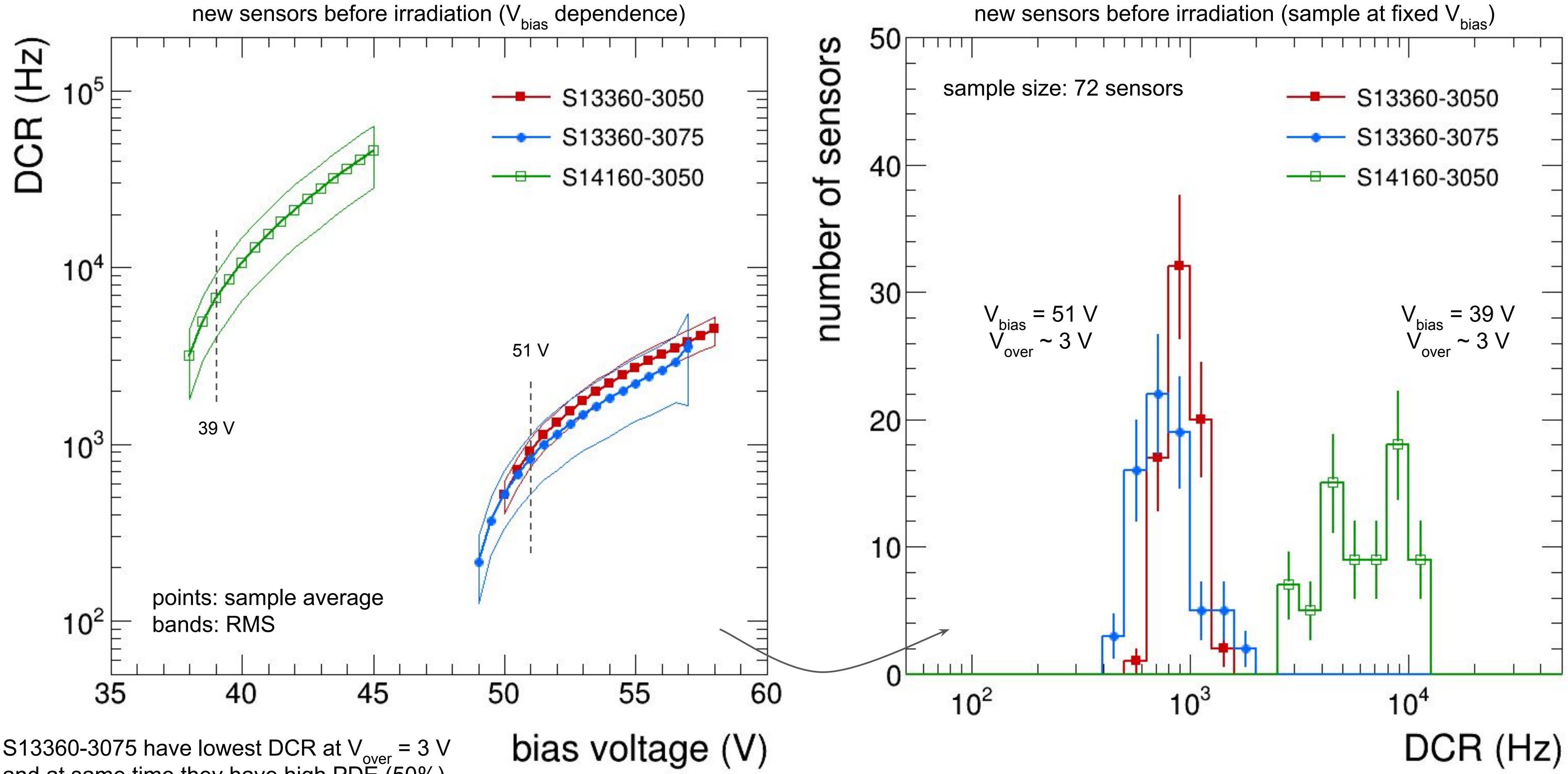
approaching σ_t = 50 ps time resolution
will soon measure effect of radiation damage on σ_t

New SiPM custom boards for characterisation (2023 program)



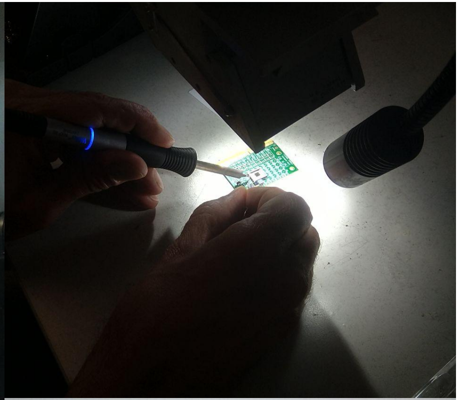
- **35 new boards have been produced**
  - same design from 2020
  - populate only 3 rows
    - 4 sensors, for minimal statistical sample
  - sensors from Hamamatsu
    - S13360-3050
    - S13360-3075
    - S14160-3050
  - replaced 50 Ω RC resistors with ferrite beads
    - allow to perform annealing
    - same components used for prototype
- **irradiation studies**
  - proton energy scan (TIFPA)
    - irradiation done in June 2023
  - neutron damage (LNL)
    - irradiation to be done in August 2023
  - more proton irradiation (TIFPA)
    - November - December 2023
- **annealing studies**
  - online annealing
    - forward and reverse bias
  - detailed studies of annealing techniques
    - time and temperature dependence
    - comparison of different techniques

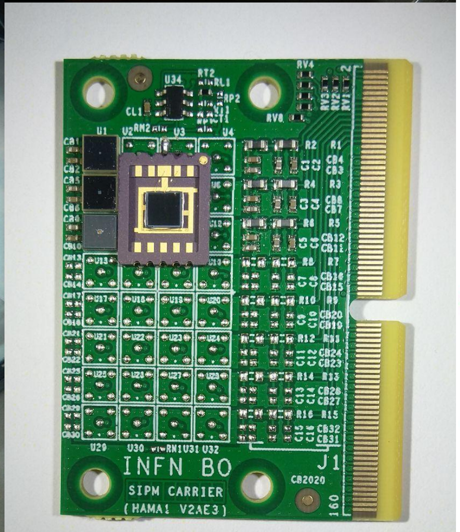
Characterisation of new SiPM boards



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

New Hamamatsu SiPM prototypes





S13360-3050UVE

newly-developed Hamamatsu SiPM sensors

based on S13360 series

few samples of 50 μm and 75 μm SPAD sensors

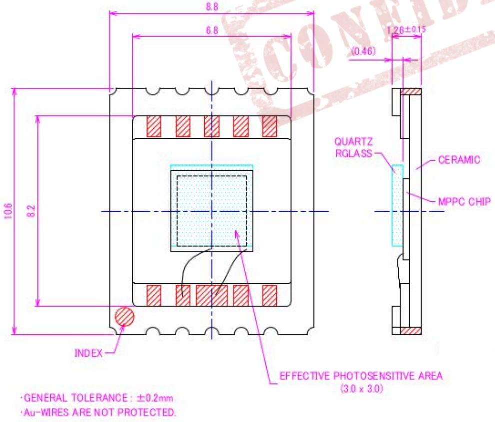
on paper they look VERY promising

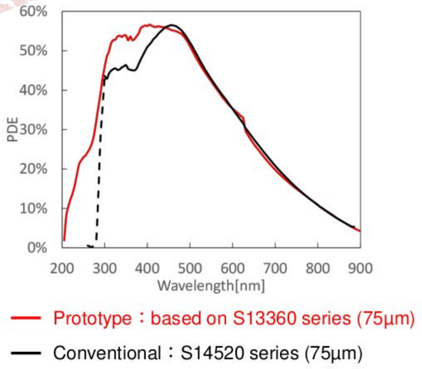
- improved NUV sensitivity
- improved signal shape
- improved recharge time

mounted on EIC SiPM test boards

we will characterise and test them in full

irradiation, annealing, laser, …





Current & future plans: electronics

This list is not exhaustive and only contains the most important items and steps towards the TDR

- **front-end electronics**
  - full test and evaluation of <u>improved ASIC</u> (ALCOR-v2, 32-channels, wirebonded)
    - recently received chips from MPW production
    - will be mounted on electronics for beam test of dRICH prototype (October 2023)
  - developments toward <u>final ASIC version</u> (ALCOR-v3, 64-channels, BGA package)
    - upgrade front-end to improve time resolution
    - include digital shutter, hysteresis to discriminator and other optimisations
    - optimise chip layout for “flip-chip” BGA packaging
- **readout electronics**
  - design and develop first prototype RDO
    - target is a beam test in 2024
- **radiation tolerance**
  - measure radiation damage / tolerance of susceptible components
    - ALCOR
    - FPGA
  - measure SEU rates
    - and latch-ups
    - verify monitor watchdogs are effective to protect

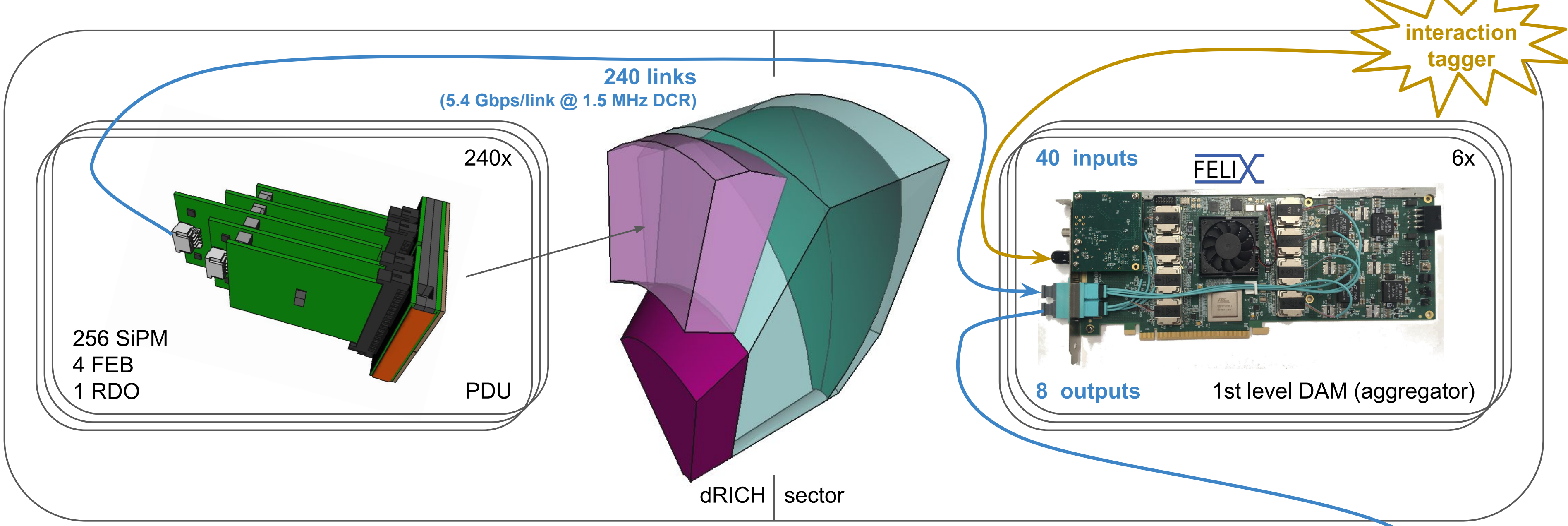
EIC luminosity in first 5 years

possible scenario for first 5 years from CD4 (luminosity ramp-up)
average luminosity $\mathcal{L} = 3.14\ 10^{33}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$
6 months/year of running at 50% duty cycle = 15 full months

Table 3.4: EIC beam parameters for different center-of-mass energies $\sqrt{s}$, with strong hadron cooling. High acceptance configuration.

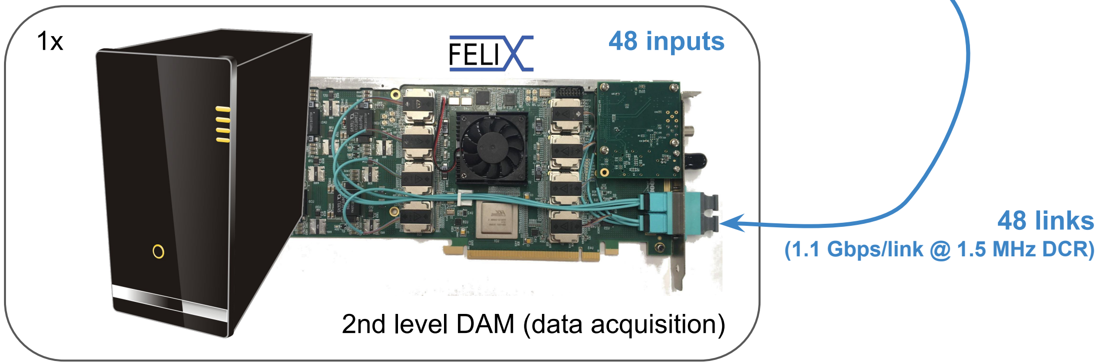
Species	proton	electron	proton	electron	proton	electron	proton	electron	proton	electron
Energy [GeV]	275	18	275	10	100	10	100	5	41	5
CM energy [GeV]	140.7		104.9		63.2		44.7		28.6	
Bunch intensity $[10^{10}]$	18.9	6.2	6.9	17.2	6.9	17.2	4.8	17.2	2.6	13.3
No. of bunches	290		1160		1160		1160		1160	
Beam current [A]	0.69	0.227	1	2.5	1	2.5	0.69	2.5	0.38	1.93
RMS norm. emit., h/v [μm]	5.2/0.46	845/70	3.3/0.3	391/26	3.2/0.29	391/26	2.7/0.25	196/18	1.9/0.45	196/34
RMS emittance, h/v [nm]	17.6/1.6	24.0/2.0	11/1.0	20/1.3	30/2.7	20/1.3	26/2.3	20/1.8	44/10	20/3.5
β^*, h/v [cm]]	417/38	306/30	265/24	149/19	94/8.5	143/18	80/7.2	103/9.2	90/7.1	196/21
IP RMS beam size, h/v [μm]	271/24		172/16		169/15		143/13		198/27	
K_x	11.1		11.1		11.1		11.1		7.3	
RMS $\Delta\theta$, h/v [μrad]	65/65	89/82	65/65	116/84	180/180	118/86	180/180	140/140	220/380	101/129
BB parameter, h/v $[10^{-3}]$	3/3	92/100	12/12	72/100	12/12	72/100	14/14	100/100	15/9	53/42
RMS long. emittance $[10^{-3}$, eV·s]	36		36		21		21		11	
RMS bunch length [cm]	6	0.9	6	0.7	7	0.7	7	0.7	7.5	0.7
RMS $\Delta p/p$ $[10^{-4}]$	6.8	10.9	6.8	5.8	9.7	5.8	9.7	6.8	10.3	6.8
Max. space charge	0.007	neglig.	0.004	neglig.	0.026	neglig.	0.021	neglig.	0.05	neglig.
Piwinski angle [rad]	2.8	0.9	4.3	1.4	5.2	1.5	6.1	1.7	4.2	1.1
Long. IBS time [h]	2.0		3.2		2.5		3.1		3.8	
Transv. IBS time [h]	2.0		2.0		2.0/4.0		2.0/4.0		3.4/2.1	
Hourglass factor H	0.99		0.98		0.94		0.91		0.93	
Luminosity $[10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	0.32		3.14		3.14		2.92		0.44	
months to reach 100 fb^{-1}	**119**		**12**		**12**		**13**		**86**	

~ 100 fb^{-1}
in first 5 years
after CD4 (2034)



one dRICH sector, up to

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



PDU readout model