dRICH photosensors and electronics

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Outline

Slides for the PID review talk on dRICH photosensors and electronics
https://docs.google.com/presentation/d/16ryHWn-_nRFSmFvSAPw3c9DlefwNzhGCVsBjL56-Tb8

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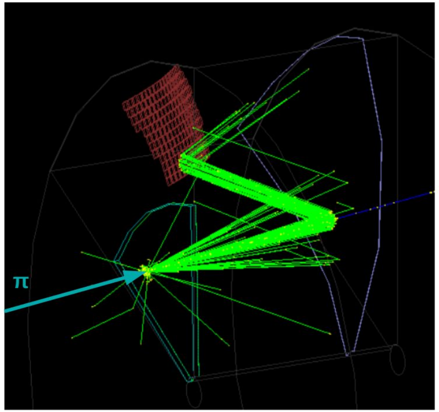
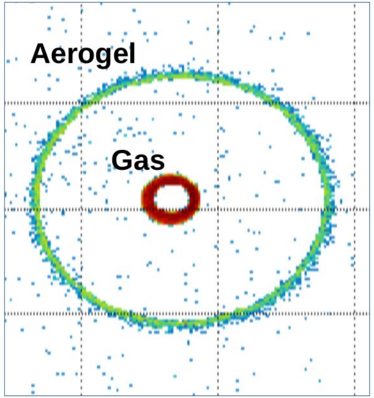
The dual-radiator (dRICH) for forward PID at EIC

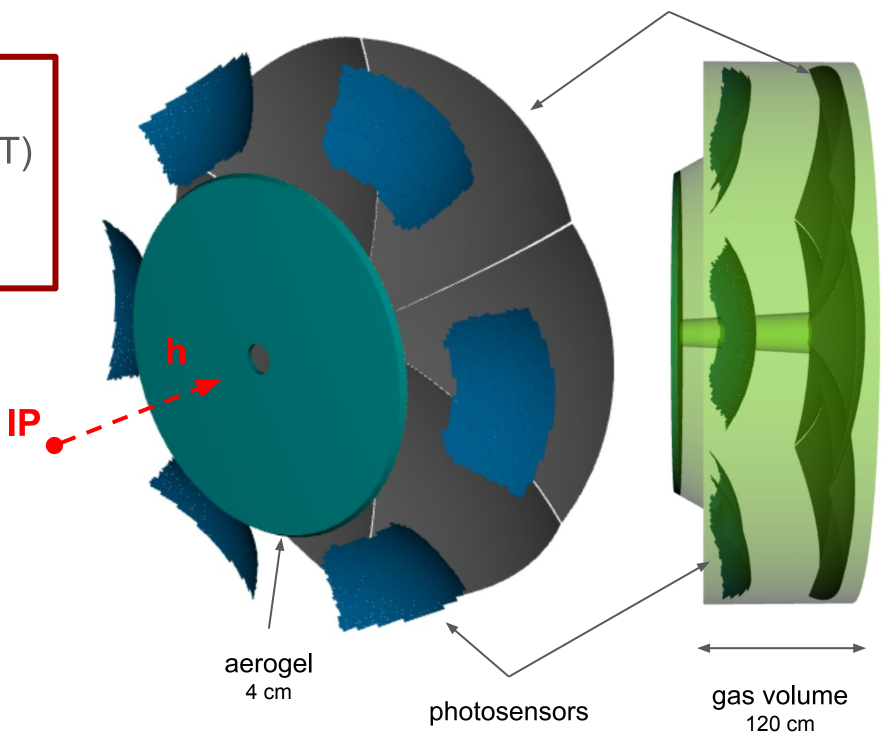
compact and cost-effective solution for broad momentum coverage at forward rapidity

- **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



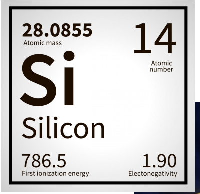
example event (accumulated hits)





SiPM option and requirements for RICH optical readout

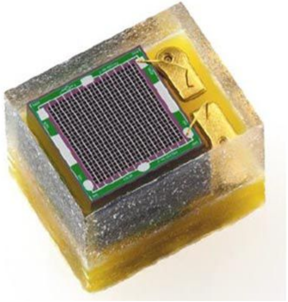
- **pros**
  - cheap
  - high photon efficiency
    requirement
  - excellent time resolution
    requirement
  - insensitive to magnetic field
    requirement



- **cons**

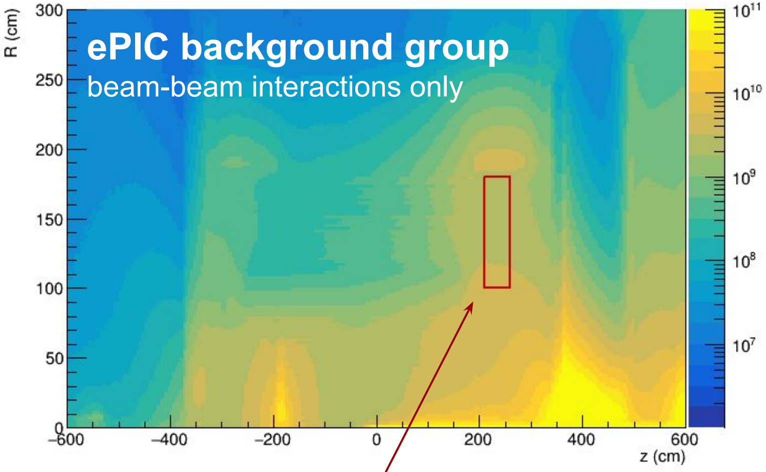
large dark count rates
not radiation tolerant

technical solutions and mitigation strategies
🐧 cooling
⌚ timing
🔥 annealing



Neutron fluxes at the dRICH photosensor surface

neutron (> 100 keV) fluence for 6 months at 500 kHz



location of dRICH photosensors

mean fluence: 1.75 10^7 n / cm^2 / fb^{-1}

max fluence: 2.25 10^7 n / cm^2 / fb^{-1}

(> 100 keV neutron ~ 1 MeV n_{eq})

- radiation level is moderate

assume fluence: 4.5 10^7 n / cm^2 / fb^{-1}

conservatively assume max fluence and 2x safety factor

Most of the key physics topics discussed in the EIC White Paper [2] are achievable with an integrated luminosity of 10 fb^{-1} corresponding to 30 weeks of operations. One notable exception is studying the spatial distributions of quarks and gluons in the proton with polarized beams. These measurements require an integrated luminosity of up to 100 fb^{-1} and would therefore benefit from an increased luminosity of $10^{34} cm^{-2} sec^{-1}$.

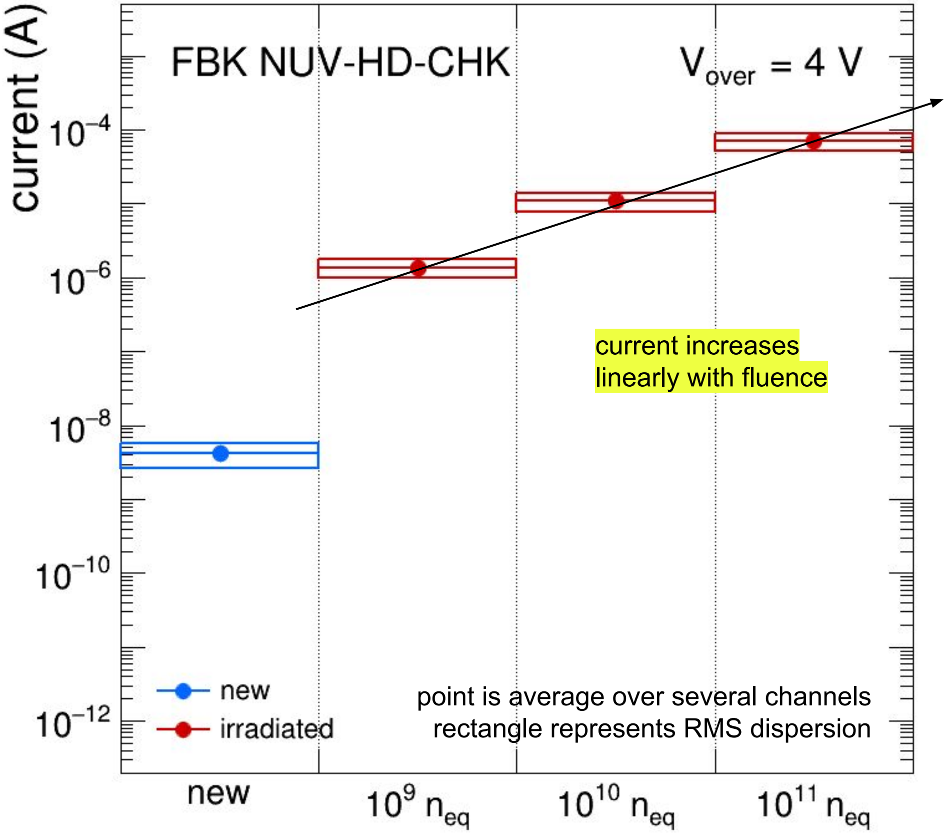
R&D on SiPM as potential photodetector for dRICH, main goal **study SiPM usability for Cherenkov up to 10^{11} 1-MeV n_{eq}/cm^2**

notice that 10^{11} neq/cm^2 would correspond to 2000 fb^{-1} integrated $\mathcal{L}$
it would be 12 years of 6-months/year (160 fb^{-1}/year) running at top lumi $\mathcal{L} = 10^{34}\ s^{-1}\ cm^{-2}$
quite a long time of EIC running before we reach there, if ever

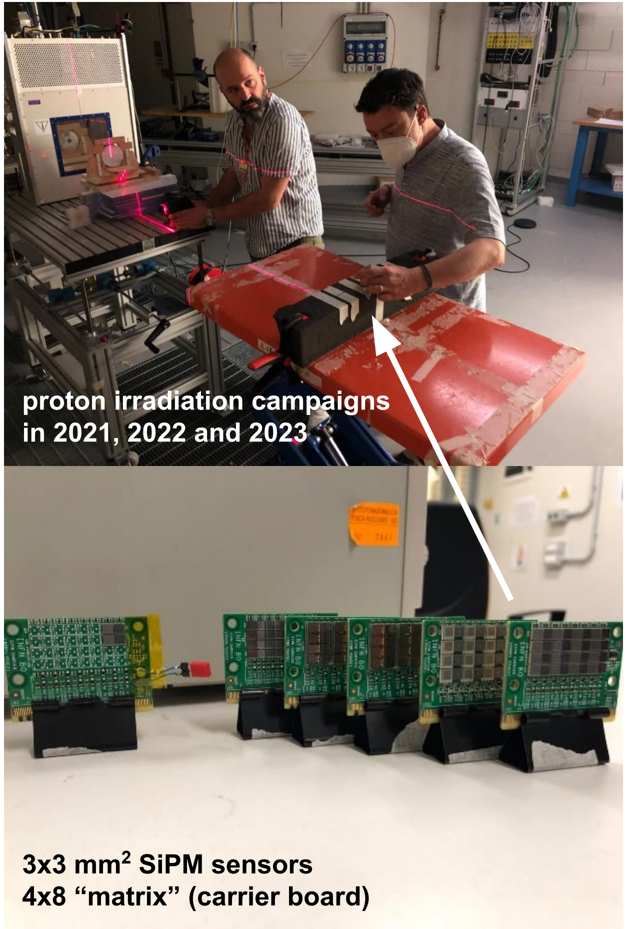
→ radiation damage studied in smaller steps of radiation load

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

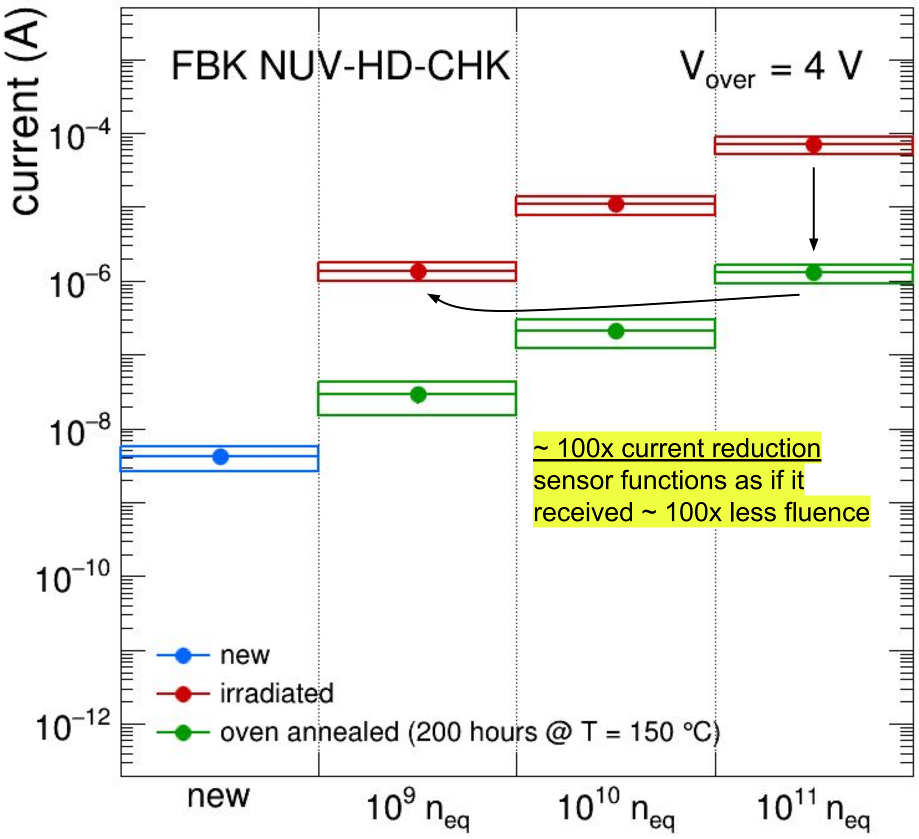


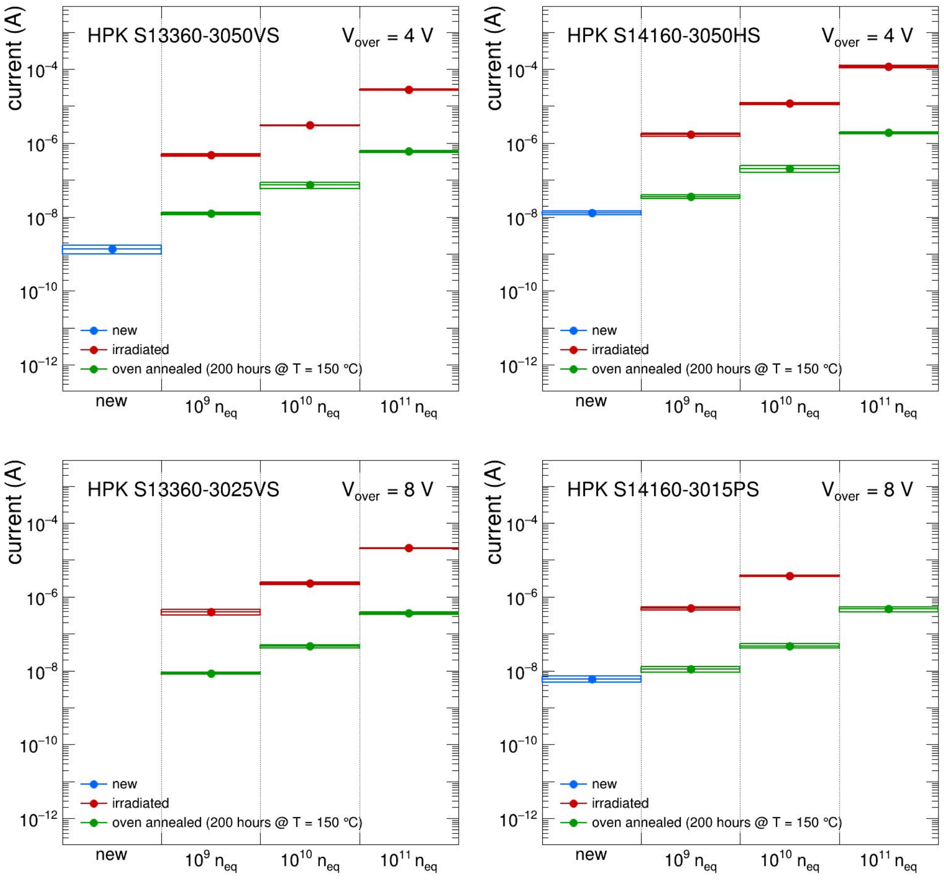
all results are reported at T = -30 C



High-temperature annealing recovery

oven annealing
~ 1 week at 150 C

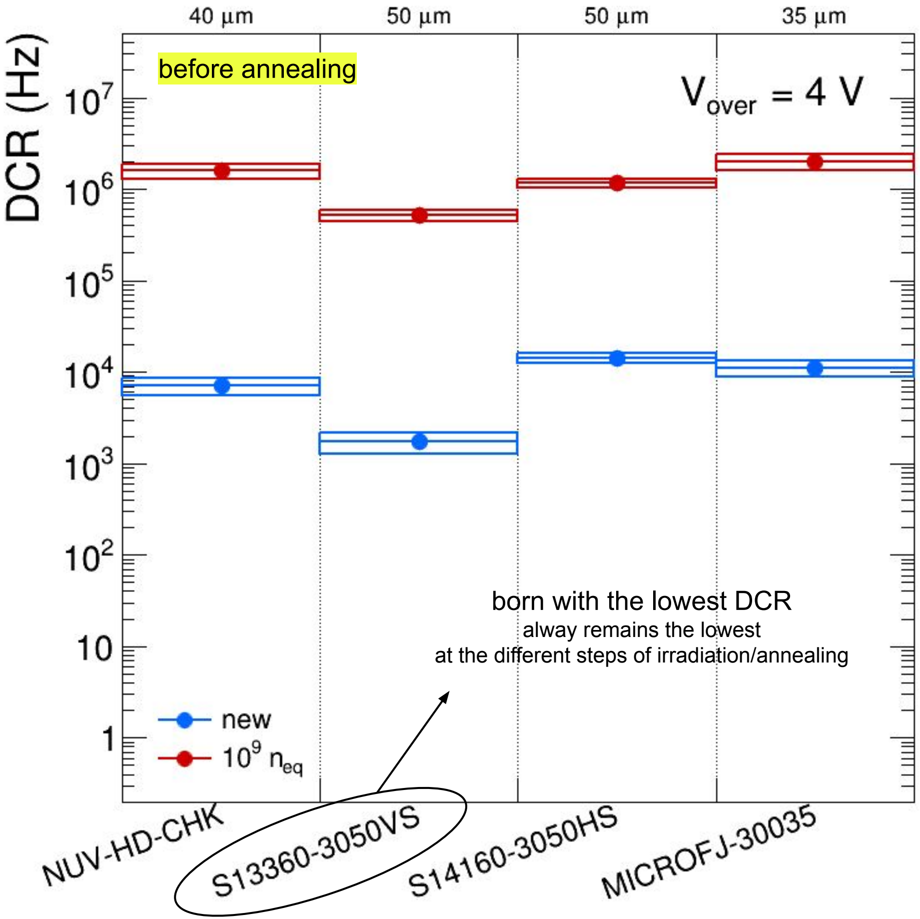


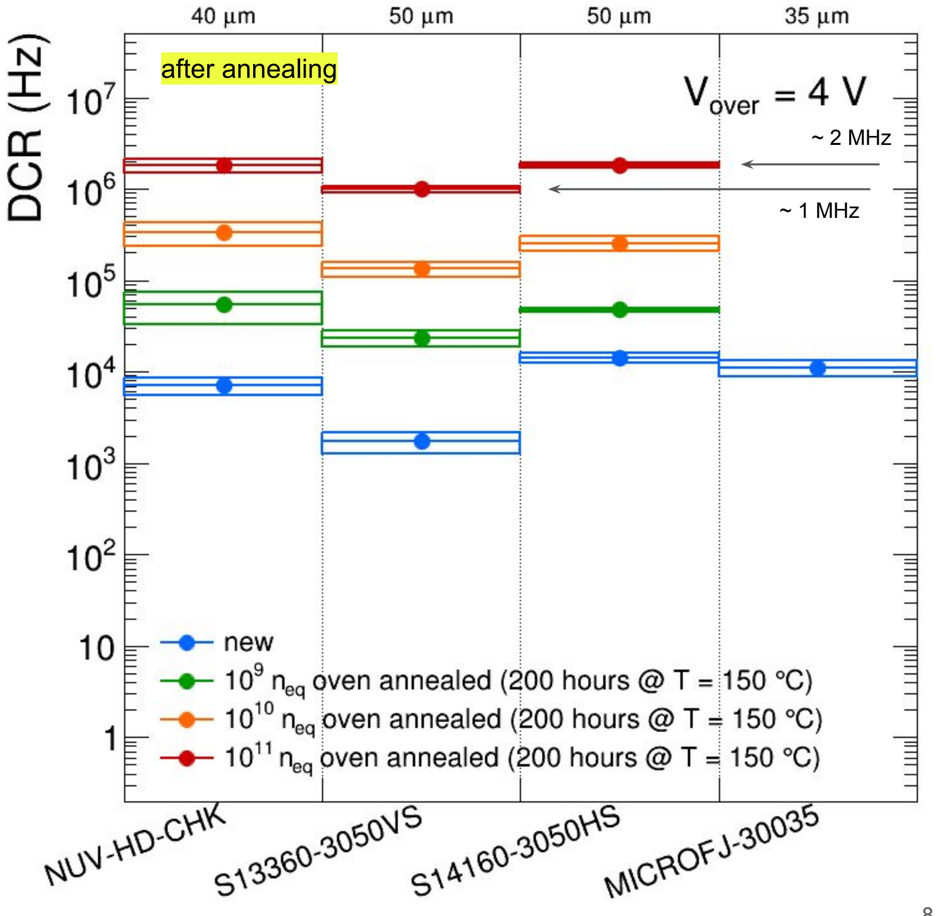


similar observation with various types of Hamamatsu sensors

Comparison between different sensors

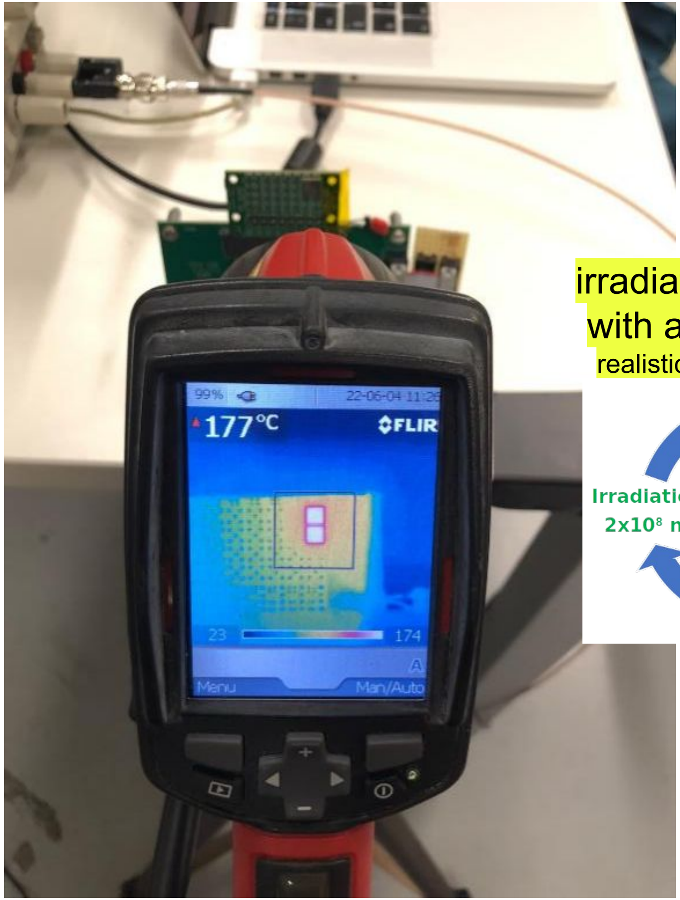
comparison at same Vover not totally fair
important to consider PDE (and SPTR) → SNR ~ PDE / DCR
unlikely 2x larger DCR is matched by 2x larger PDE



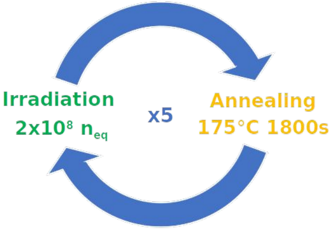


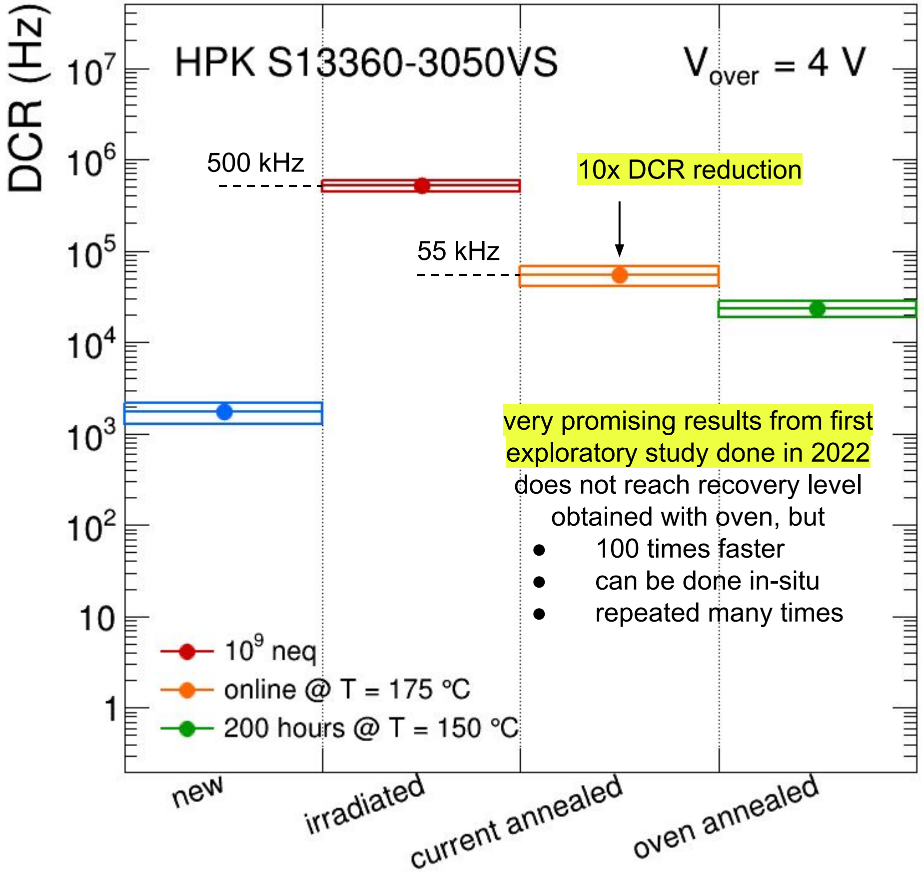
“Online” self-induced annealing

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



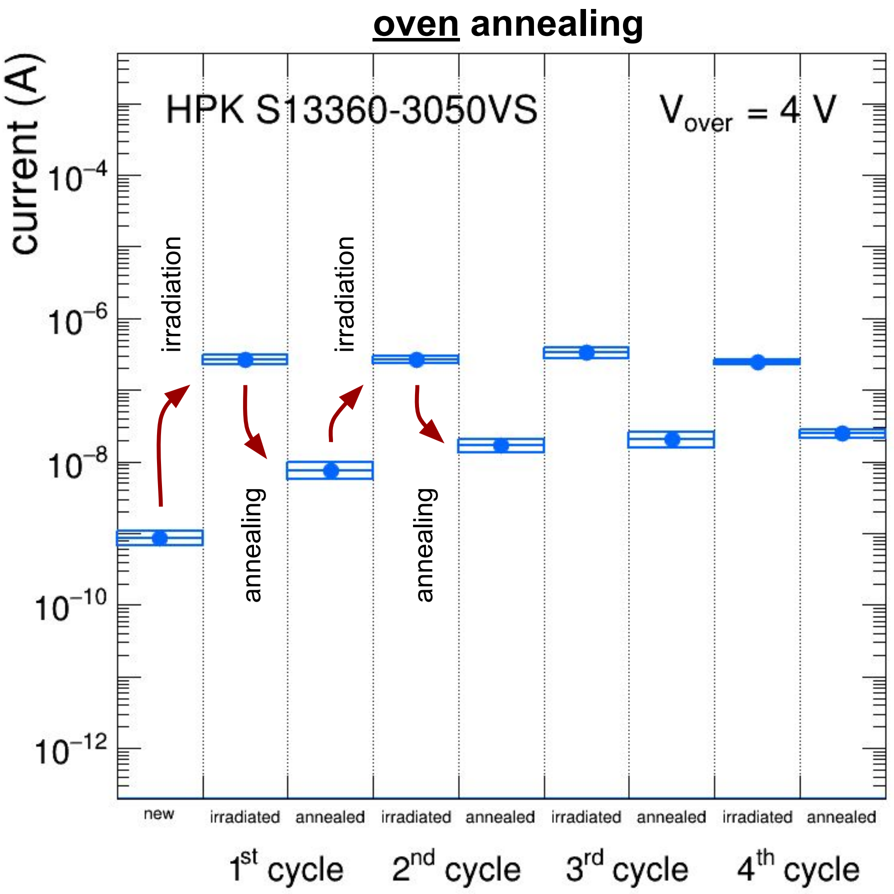
irradiation interleaved with annealing cycle
realistic experimental case





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

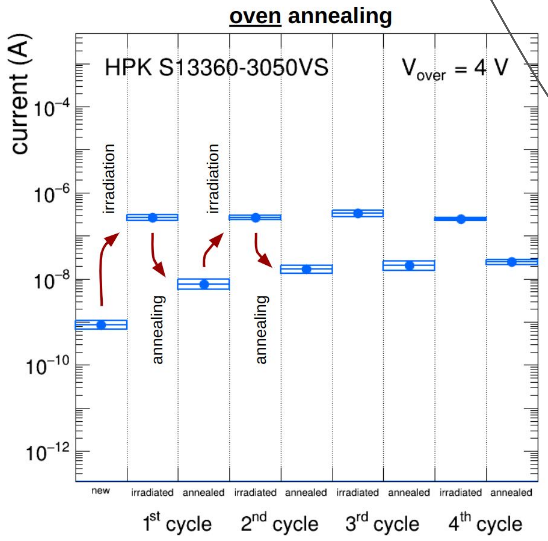
- consistent irradiation damage
  - DCR increases by ~ 500 kHz (@ Vover = 4)
  - after each shot of 10^9 n_{eq}
- consistent residual damage
  - ~ 15 kHz (@ Vover = 4) of residual DCR
  - builds up after each irradiation-annealing

annealing cures same fraction of newly-produced damage

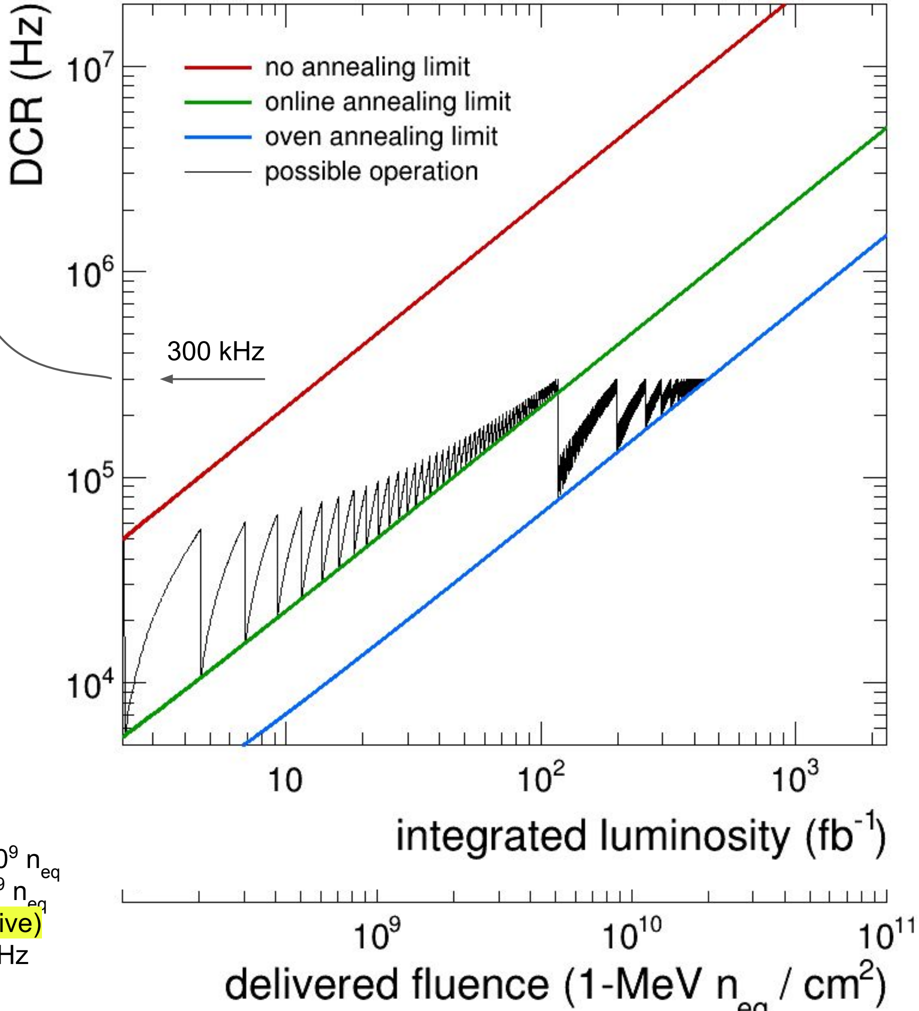
~ 97% for HPK S13360-3050 sensors

Ageing model

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



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



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}

neutron fluence from background group (conservative)

- 7 10^9 1-MeV n_{eq}/cm^2 for 6 months at 500 kHz
- corresponds to 4.5 10^7 n_{eq} / fb^{-1}

Ageing model

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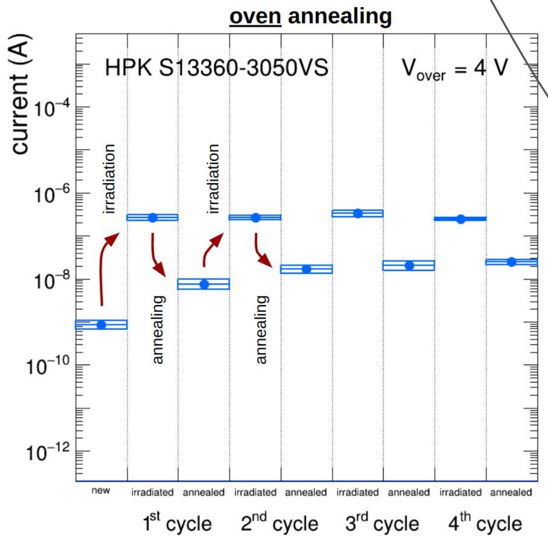

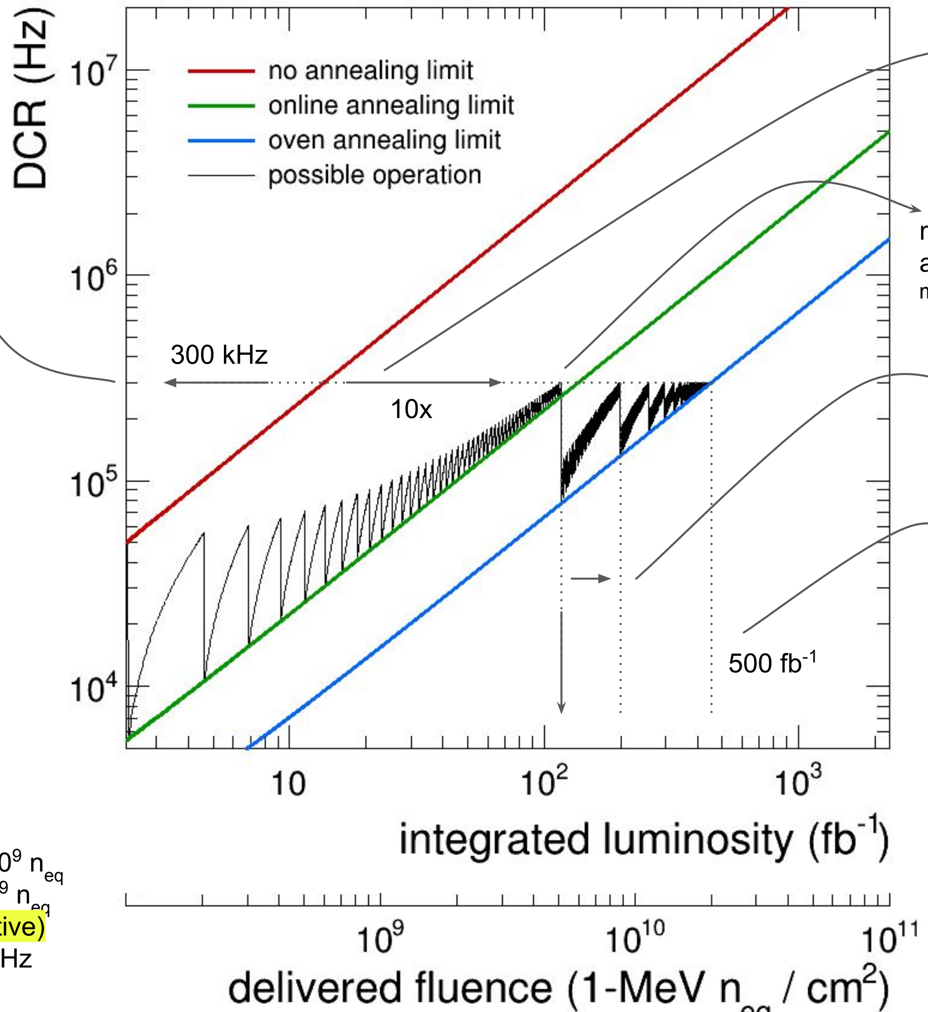

online annealing extends SiPM lifetime by ~ 10x

more aggressive annealing needed here
might need to unmount SiPM (oven)

up to 200 fb^{-1} with only one oven annealing cycle

could reach 500 fb^{-1} with optimisation of online annealing protocol
to approach oven performance

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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

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} cm^{-2} sec^{-1}
6 months/year of running at 50% duty cycle = 15 full months

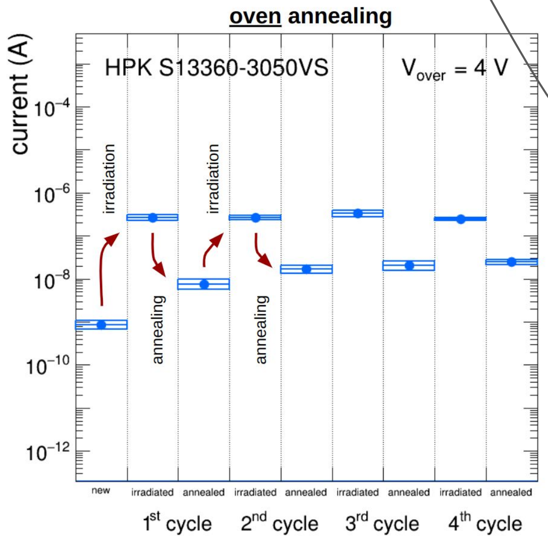
Table 3.4: EIC beam parameters for different center-of-mass energies $\sqrt{s}$, with strong hadron cooling. High acceptance configuration.

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}cm^{-2}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)
in line with Abhay's view

Ageing model

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



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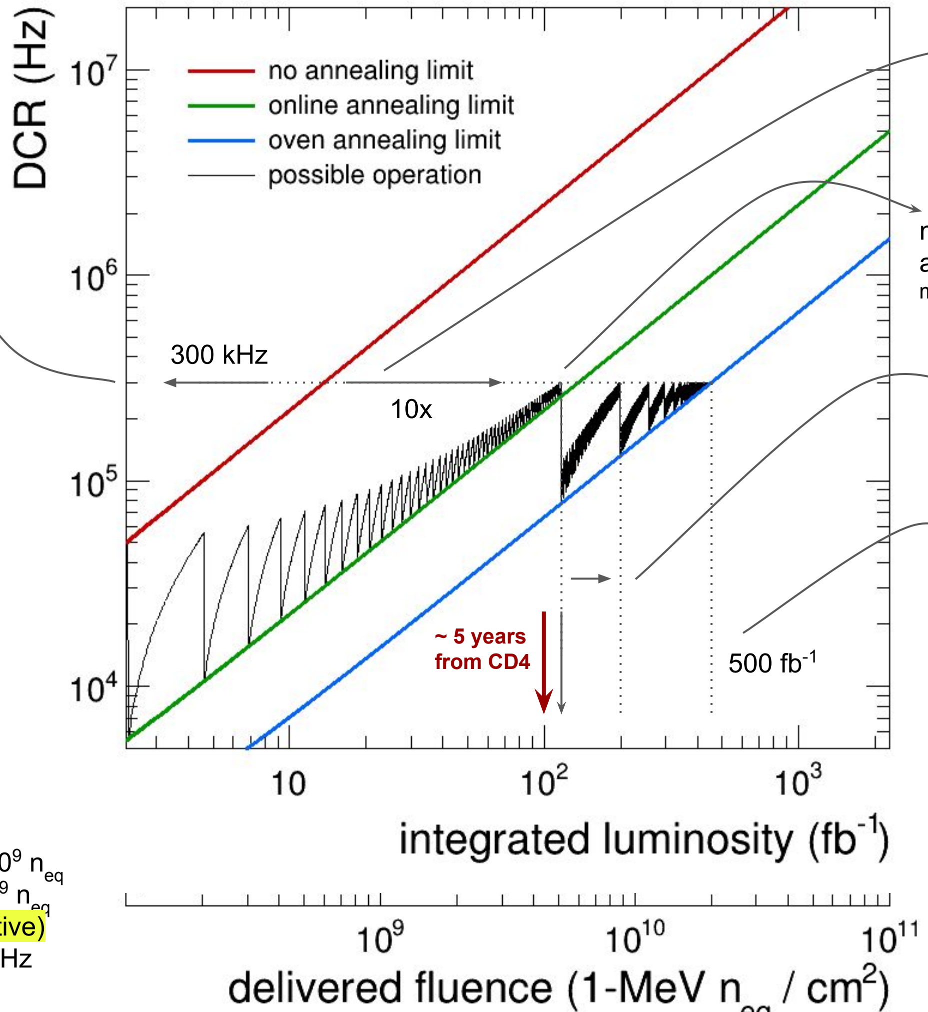

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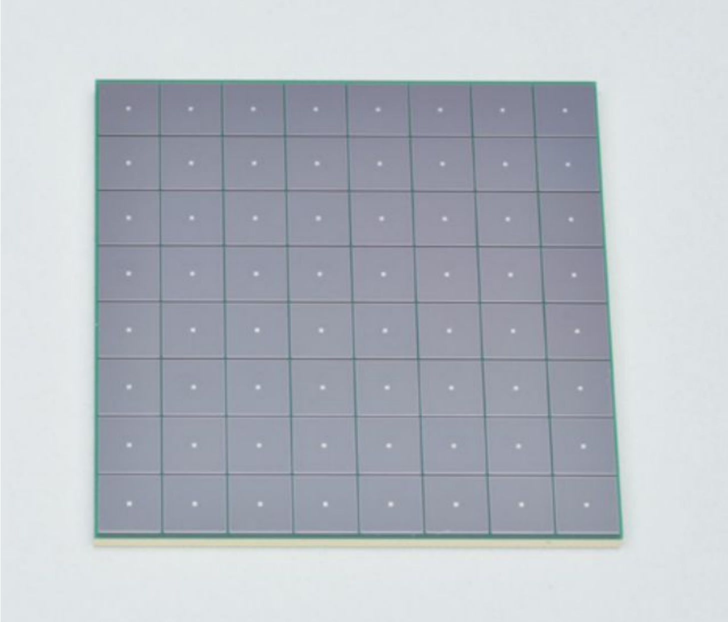
lover T operation -40 C or below

SiPM technical specs

baseline sensor device

64 (8x8) channel SiPM array

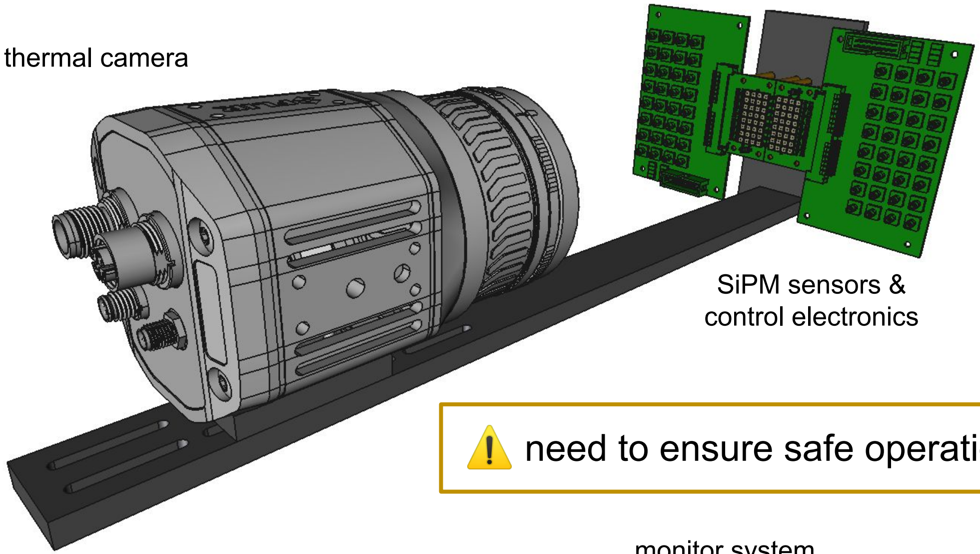
3x3 mm^2 / channel



Parameters (at Vop, T = 25 C, unless specified)	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	

Automated multiple SiPM online self-annealing

thermal camera



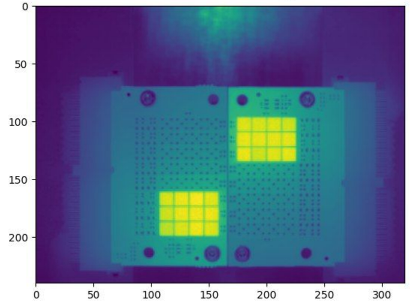
SiPM sensors &
control electronics

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

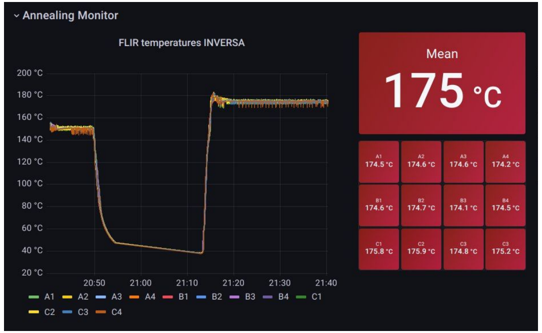
technical feasibility and implementation in the experimental environment to be studied in details

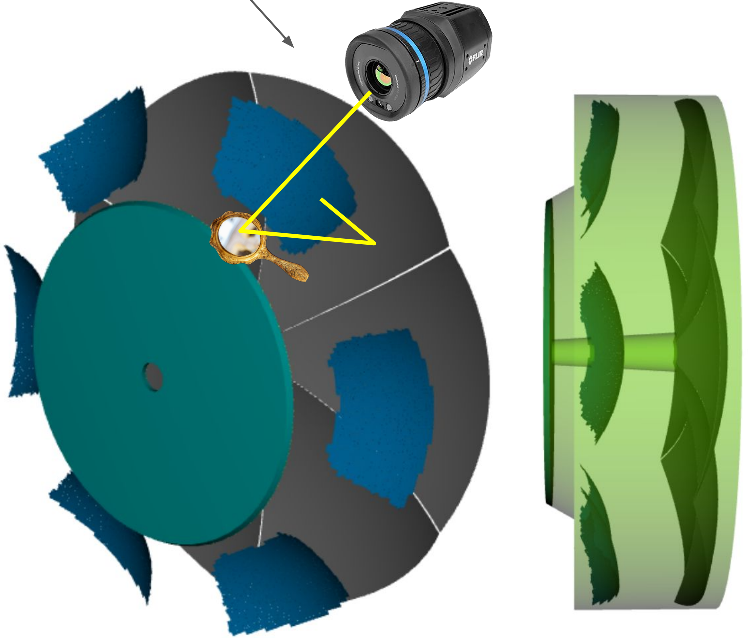
⚠️ need to ensure safe operation

thermal image



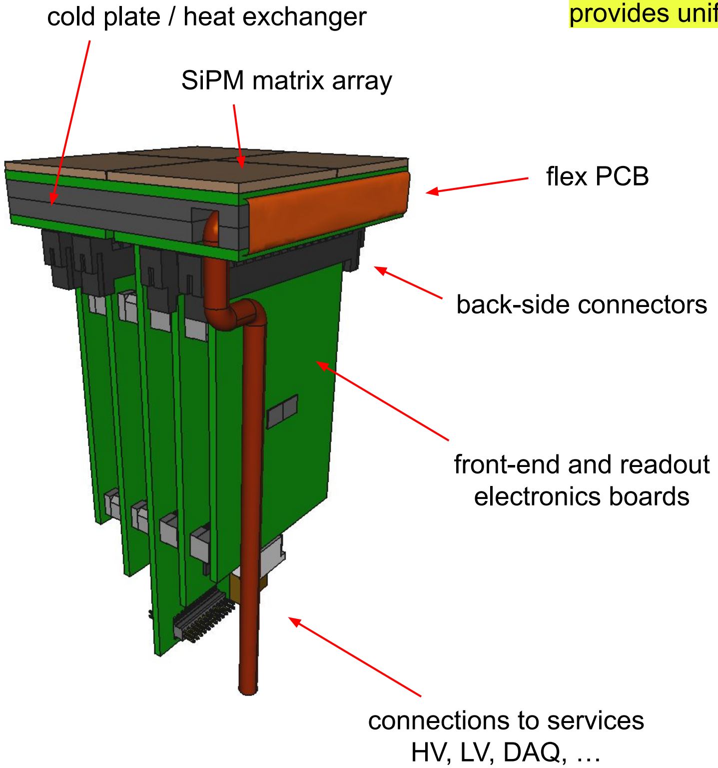
monitor system

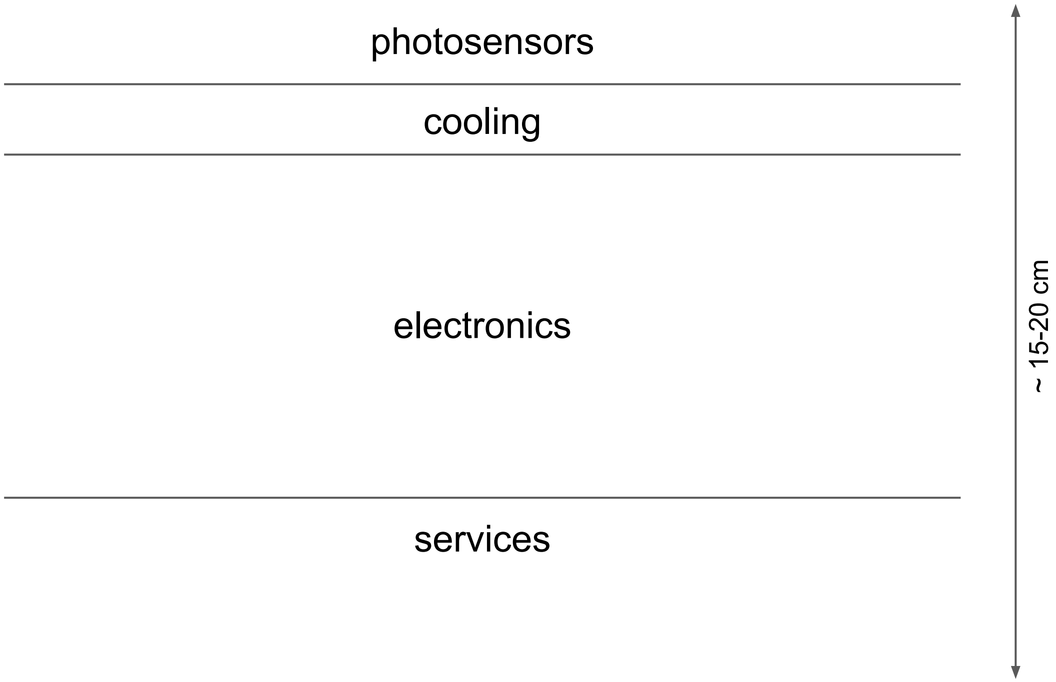




SiPM photodetector unit – PDU

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

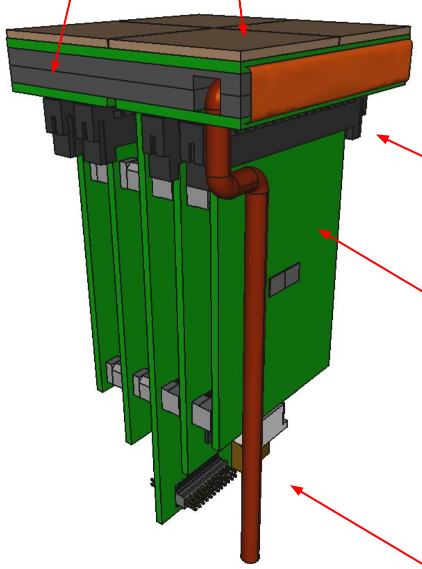
General & Temperature Control

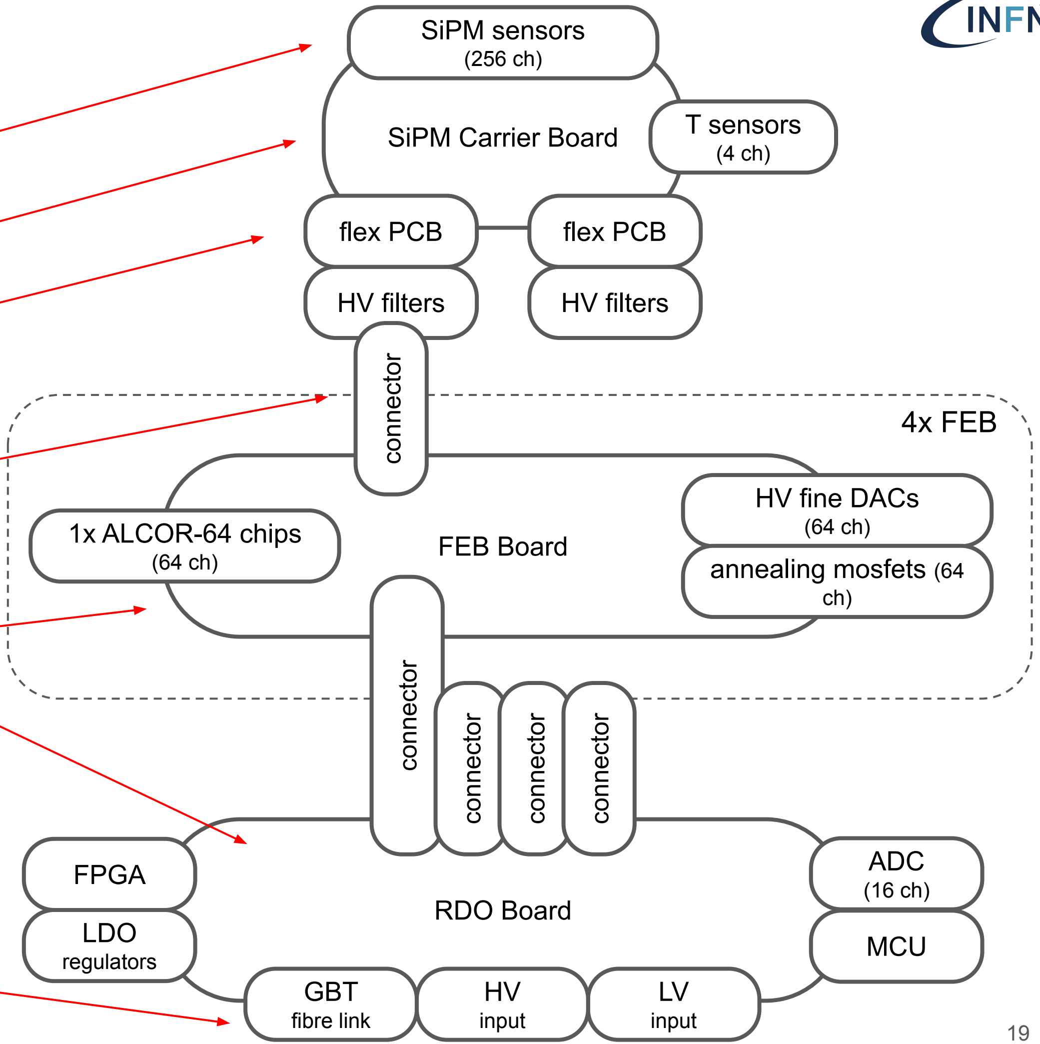
Temperature range	-55...250 °C
Temperature stability	±0,01 K

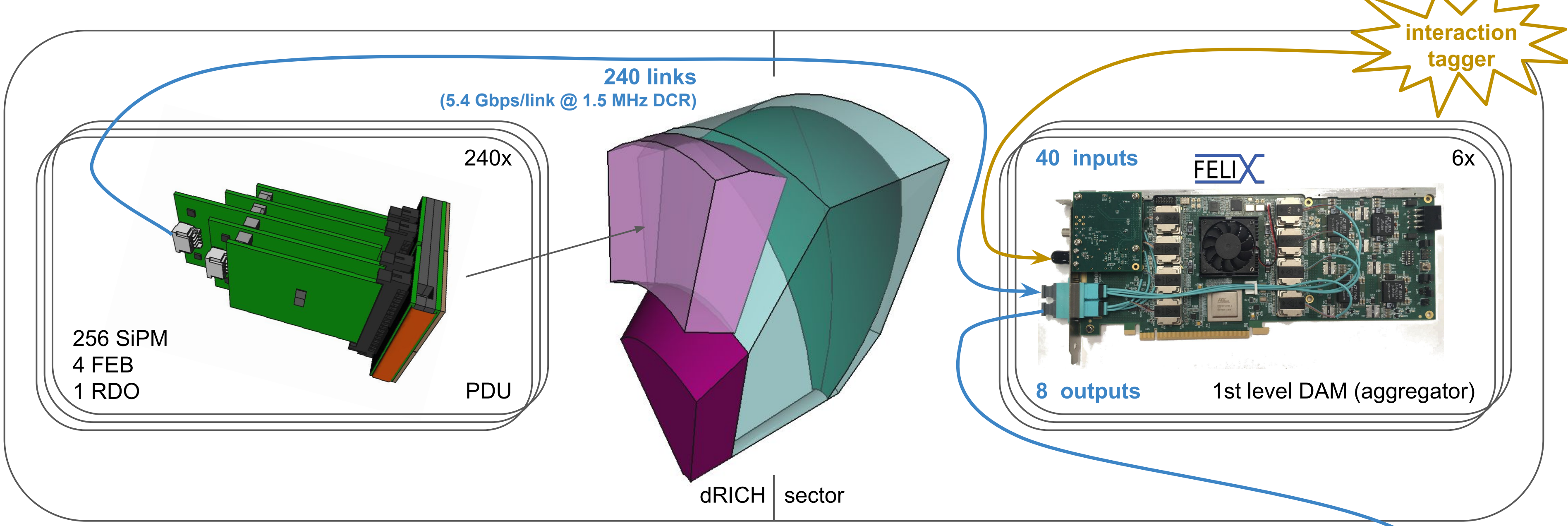
Heating / cooling capacity

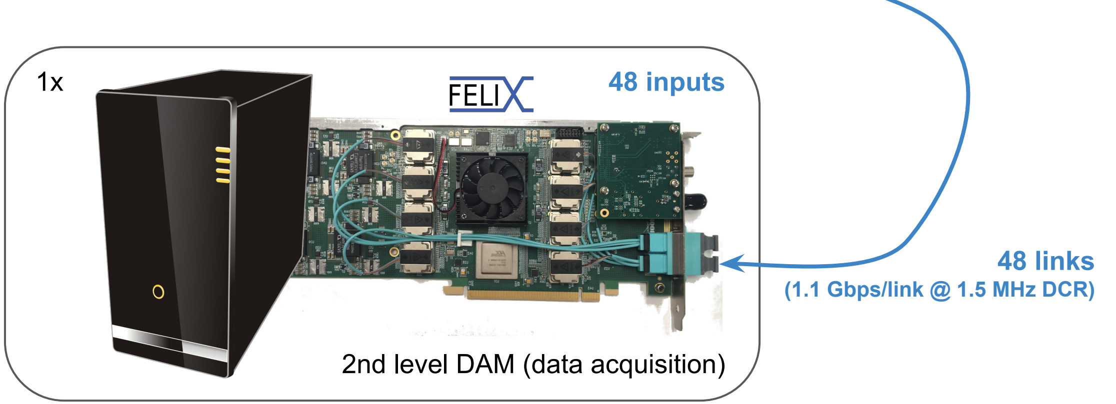
Heating capacity	6 kW								
Cooling capacity	250	200	100	20	0	-20	-40	-50	°C
	6	6	6	6	6	4,2	1,5	0,65	kW

PDU electronics







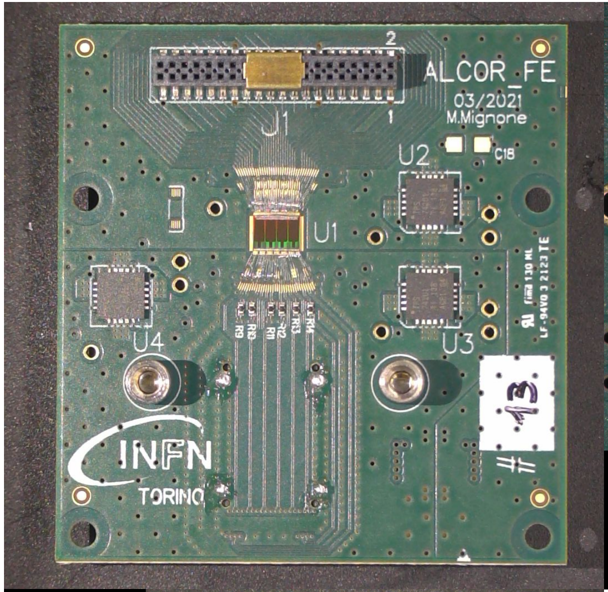


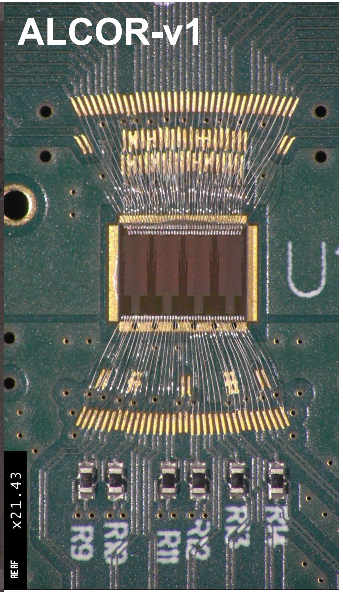
one dRICH sector, up to

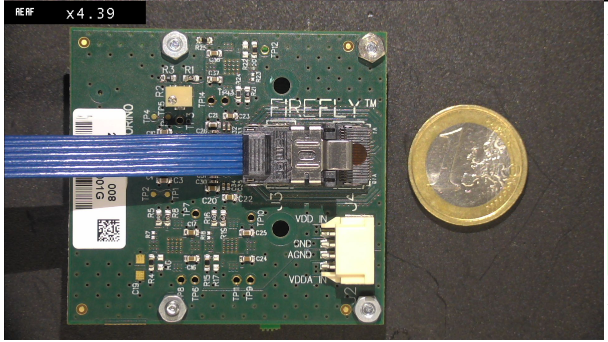
- 59040 channels
- 960 FEBs
- 240 RDOs
- 6 1st level DAMs
- 1 2nd level DAM

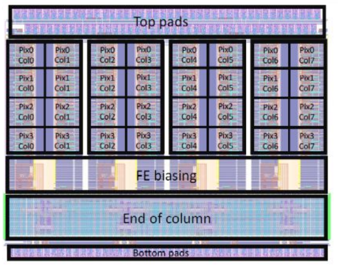
PDU readout model

ALCOR ASIC: integrated front-end and TDC









developed by INFN-TO

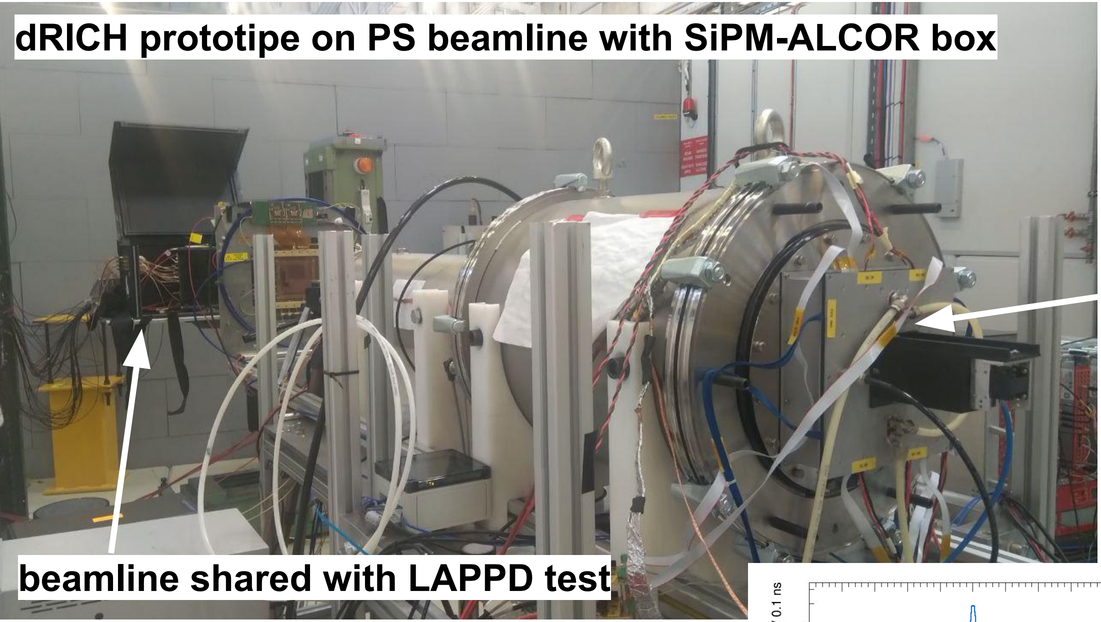
64-pixel matrix mixed-signal ASIC

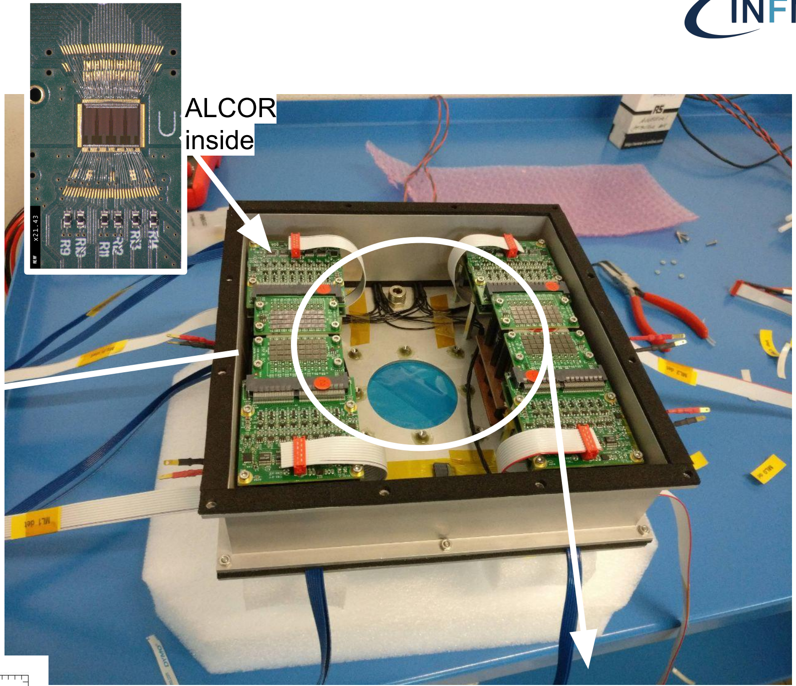
current versions (v1,v2) have 32 channels, wirebonded

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

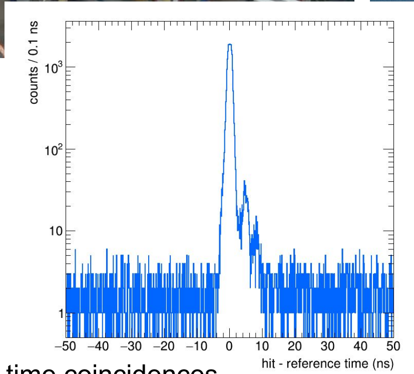




successful operation of SiPM

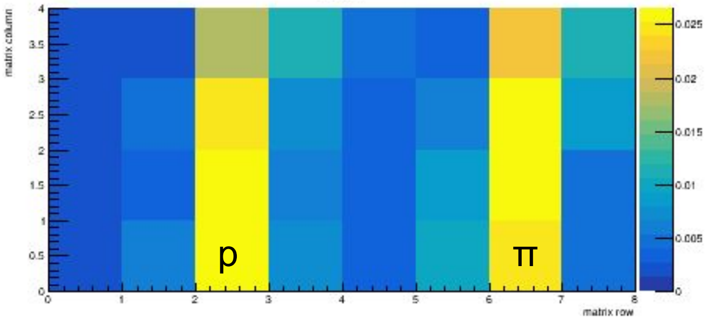
irradiated (with protons up to 10^{10})

and annealed (in oven at 150 C)

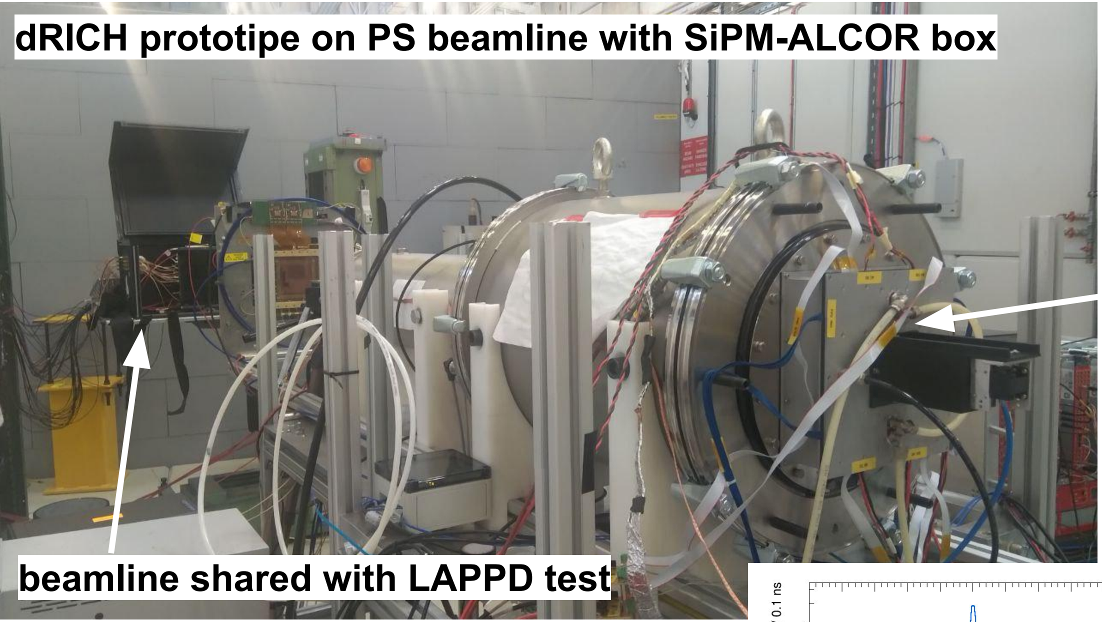


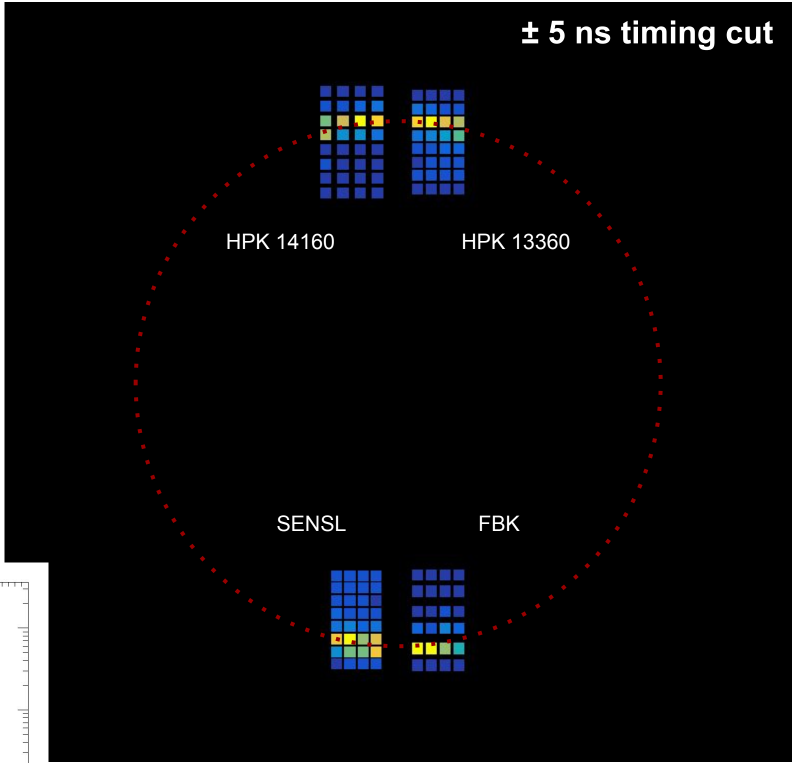
time coincidences

8 GeV positive beam (aerogel rings)



2022 test beam at CERN-PS



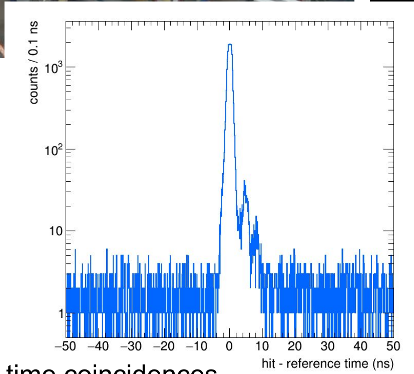


8 GeV negative beam (aerogel rings)

successful operation of SiPM

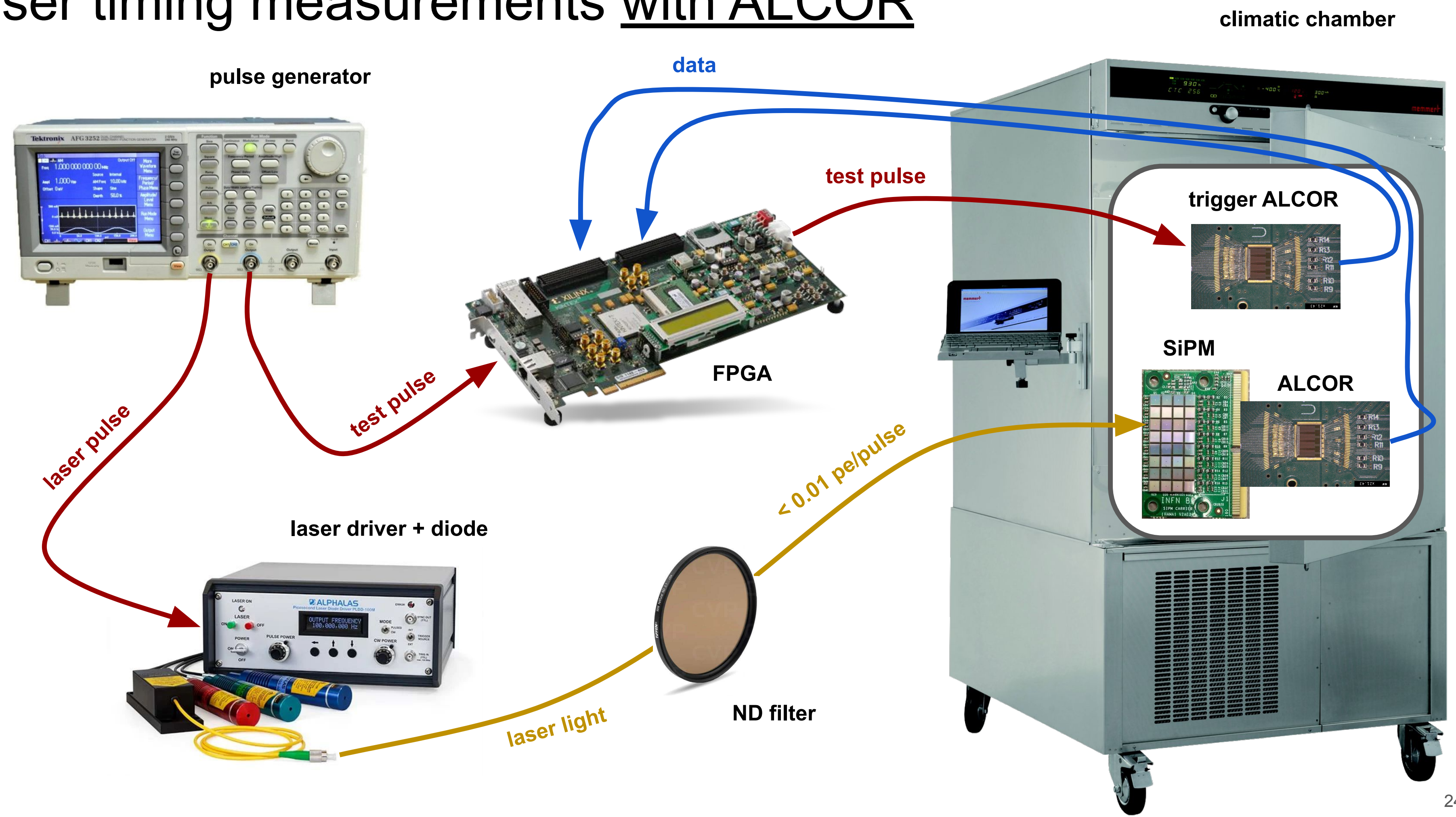
irradiated (with protons up to 10^{10})

and annealed (in oven at 150 C)



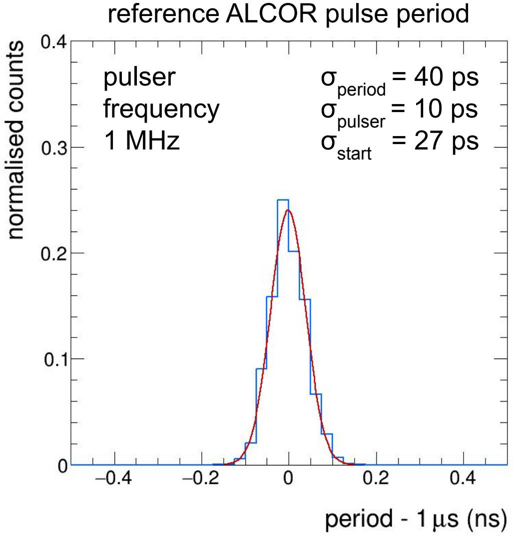
time coincidences

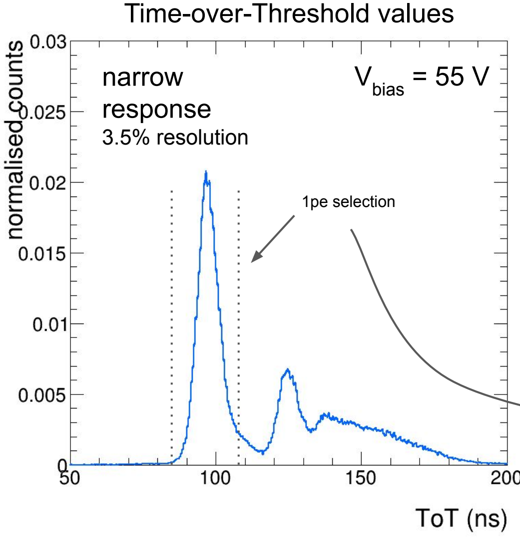
Laser timing measurements with ALCOR

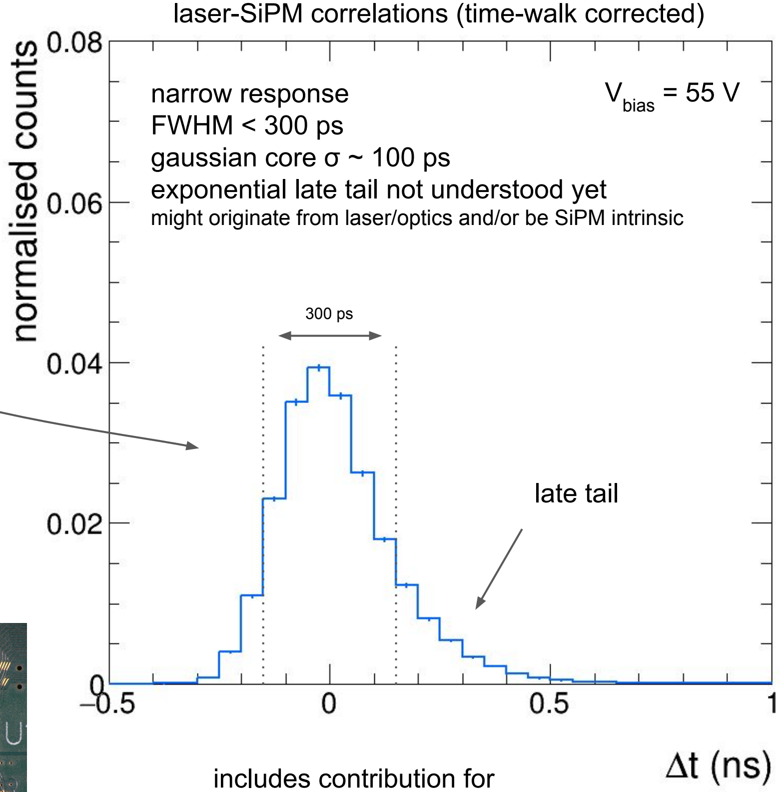


Laser timing measurements with ALCOR

Hamamatsu S13360-3075



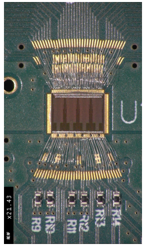




laser-SiPM signal synchronisation by sending test pulse to reference ALCOR

- 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

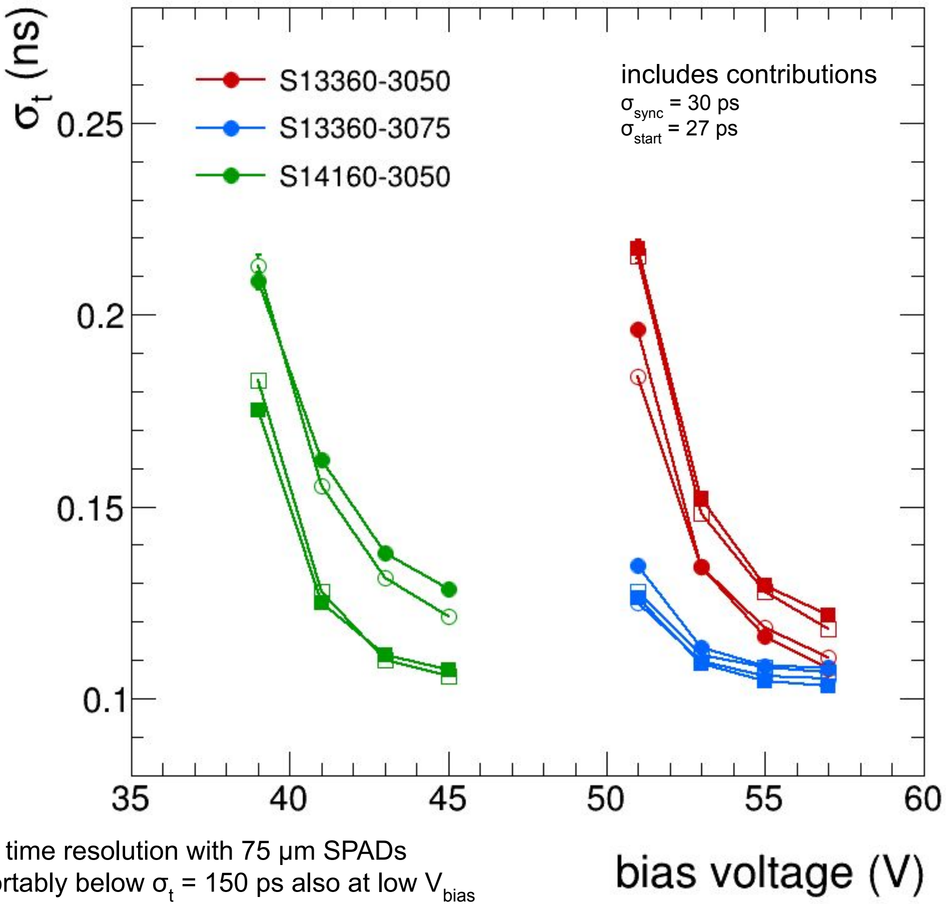


includes contribution for laser-ALCOR synchronization
measured to be σ_{sync} = 30 ps
and reference time resolution
measured to be σ_{start} = 27 ps

Laser timing measurements with ALCOR

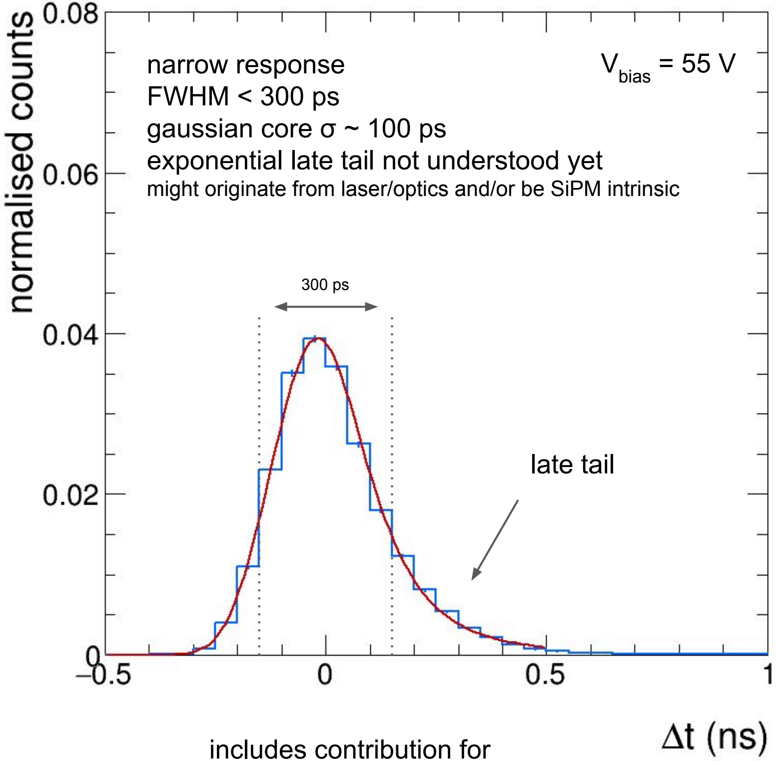
Hamamatsu S13360-3075

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)

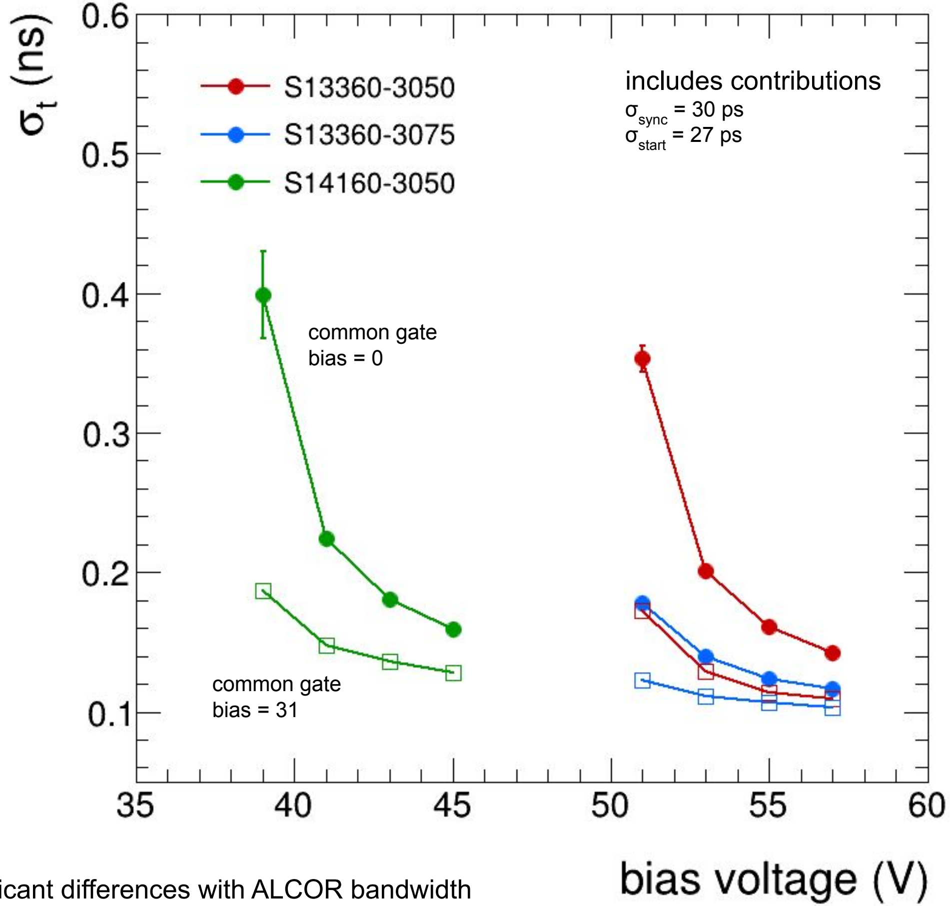


includes contribution for
laser-ALCOR synchronization
measured to be σ_{sync} = 30 ps
and reference time resolution
measured to be σ_{start} = 27 ps

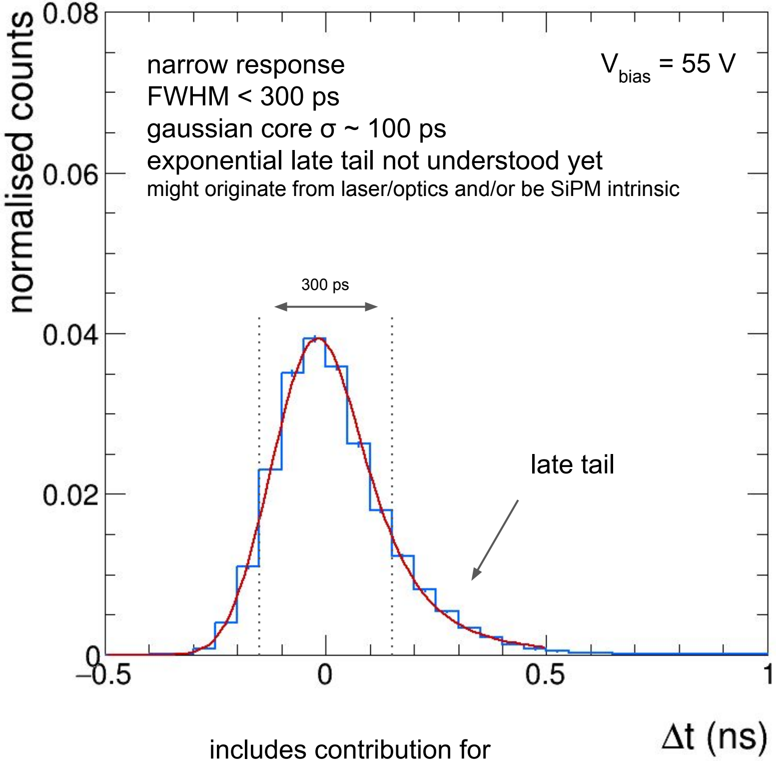
Laser timing measurements with ALCOR

Hamamatsu S13360-3075

the two extremes of ALCOR front-end bias configuration



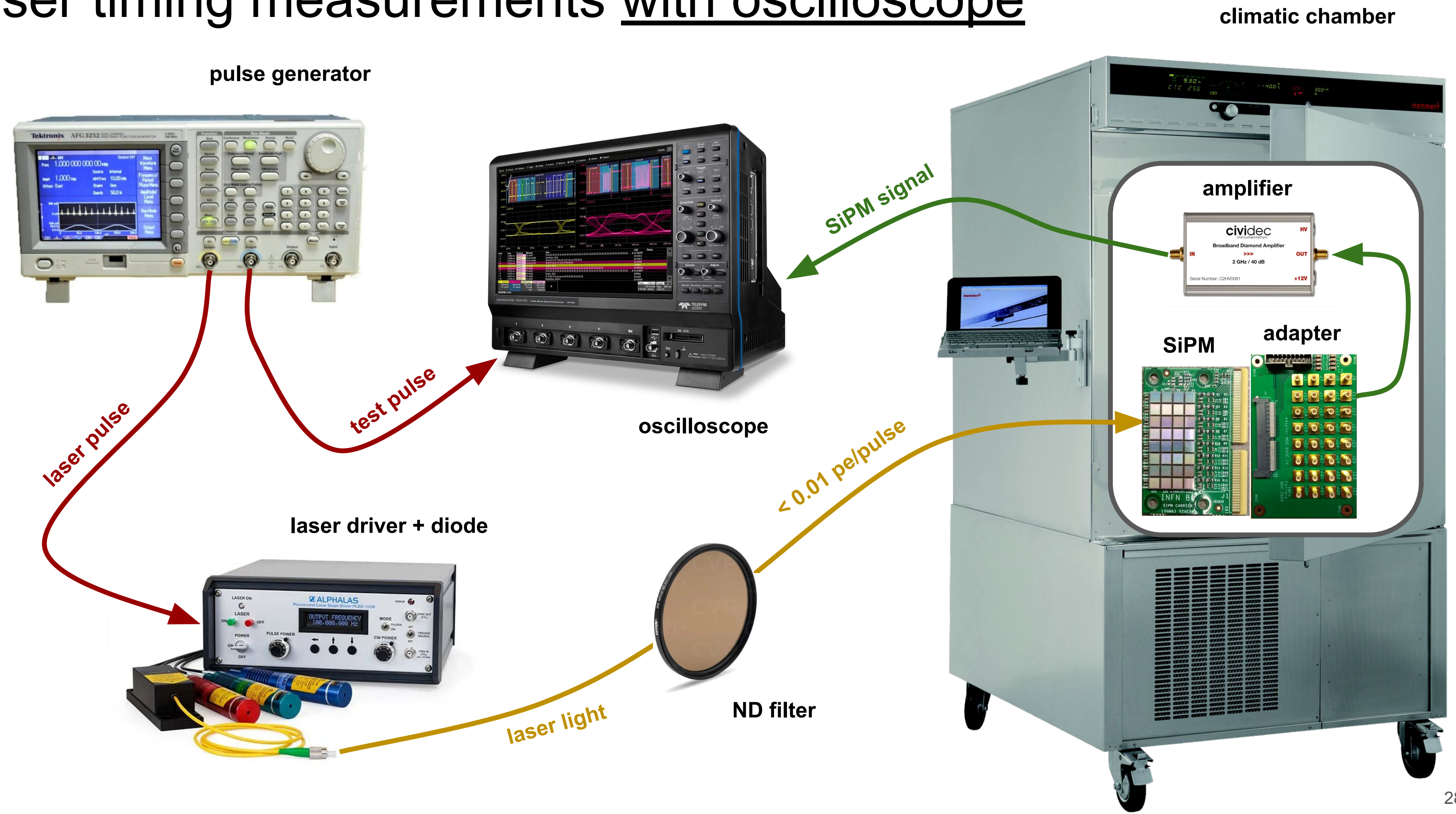
laser-SiPM correlations (time-walk corrected)



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

significant differences with ALCOR bandwidth

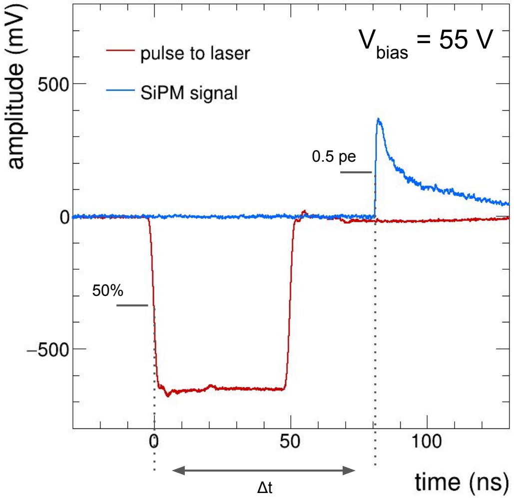
Laser timing measurements with oscilloscope



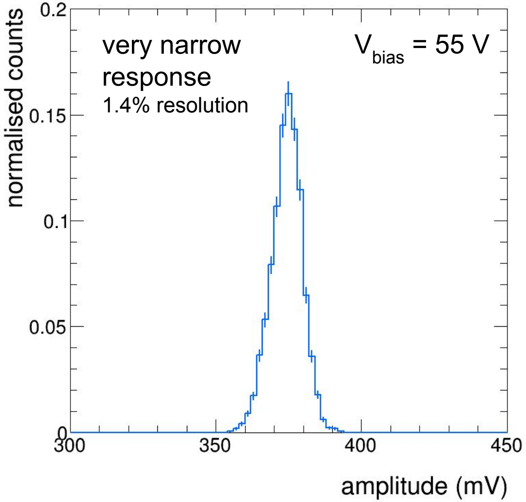
Laser timing measurements with oscilloscope

Hamamatsu S13360-3075

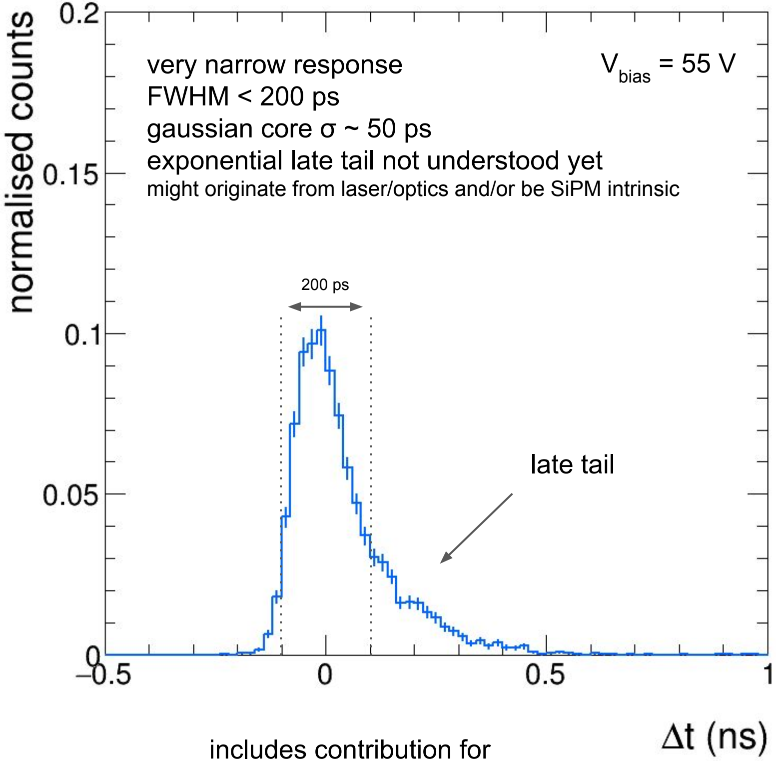
acquired oscilloscope traces



SiPM signal amplitudes (1pe)



laser-SiPM correlations (time-walk corrected)



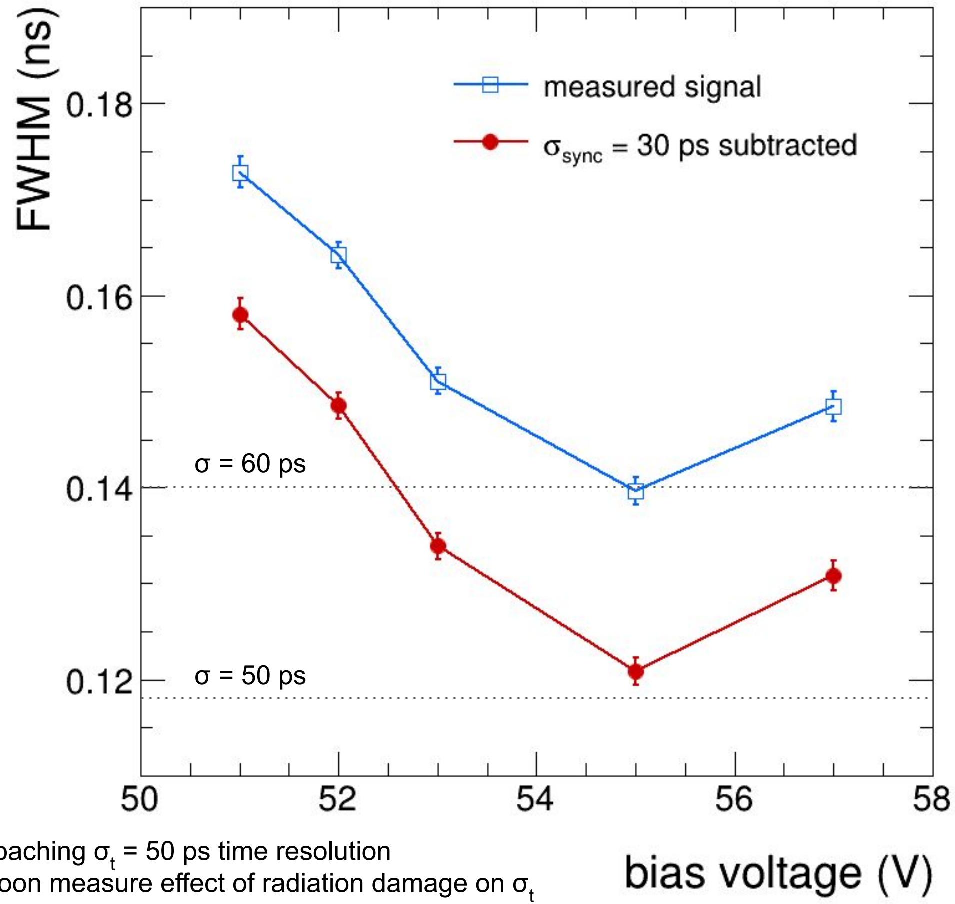
measurements performed at T = -30 C with
- Lecroy Waverunner 40186 oscilloscope
- Cividec Broadband amplifier (40 db)

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

time-amplitude correlation (walk) corrected

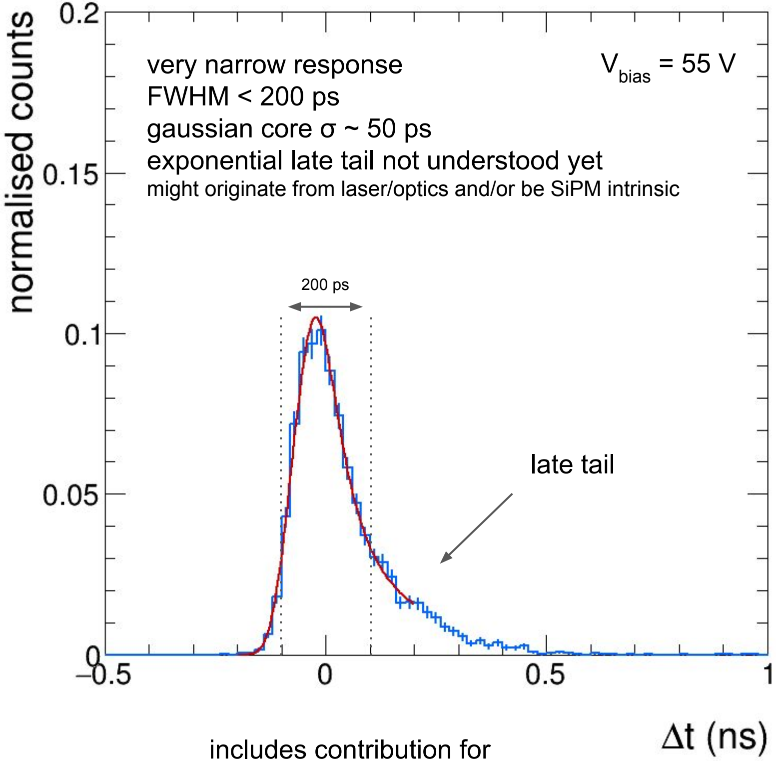
includes contribution for
laser-oscilloscope synchronization
measured to be σ_{sync} = 30 ps

Laser timing measurements with oscilloscope



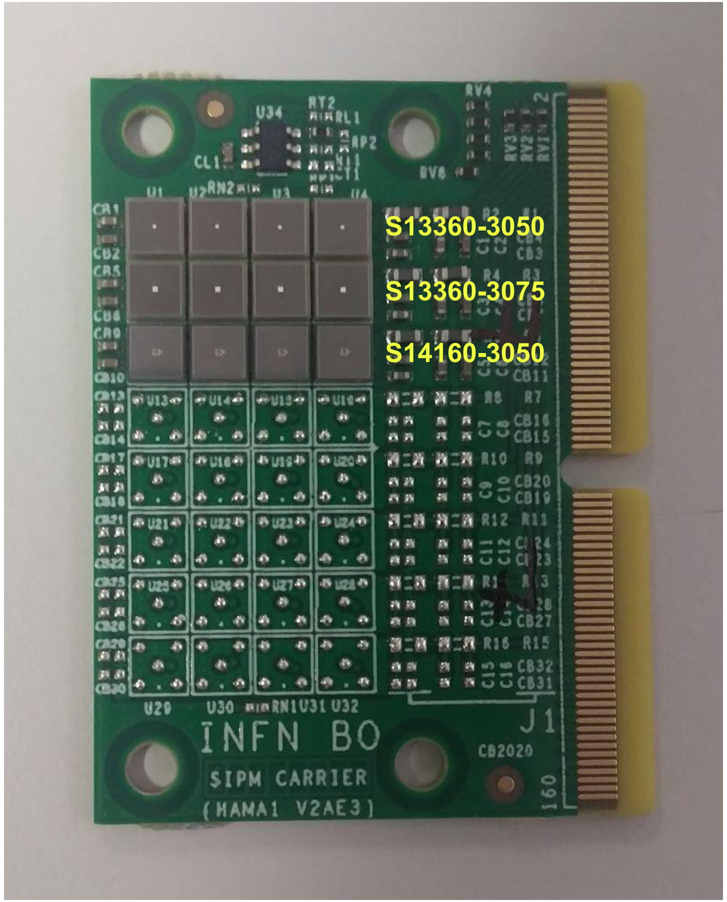
approaching σ_t = 50 ps time resolution
will soon measure effect of radiation damage on σ_t

laser-SiPM correlations (time-walk corrected)



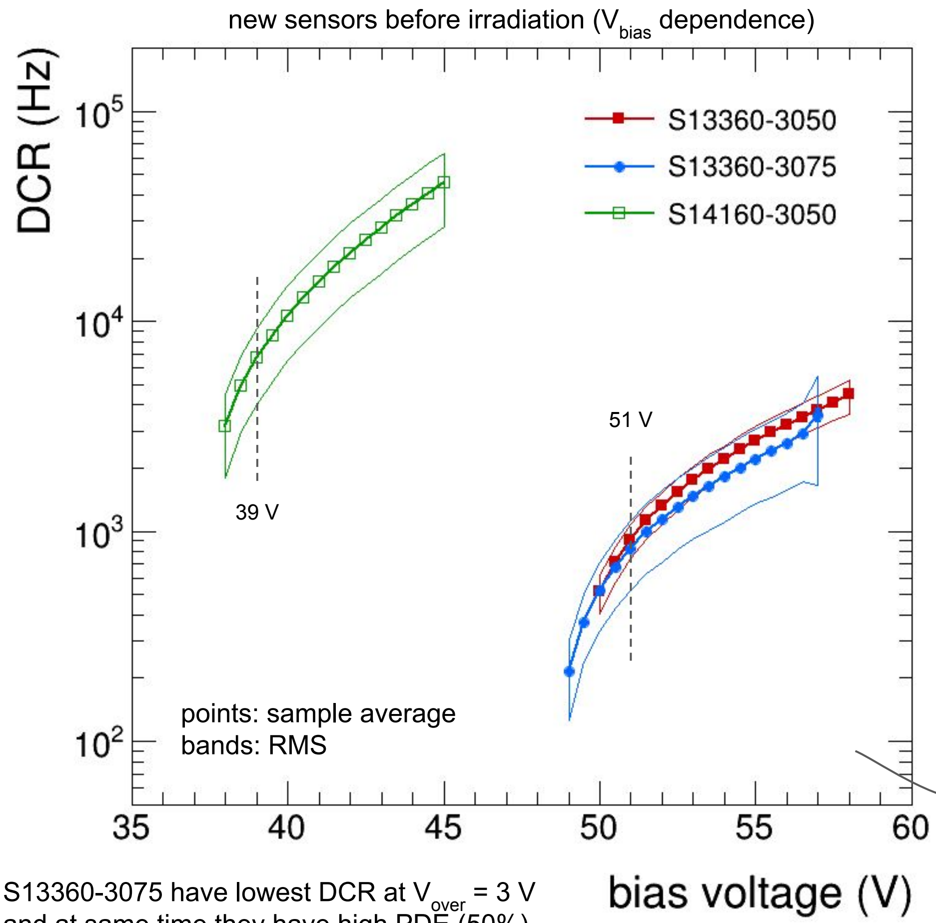
includes contribution for
laser-oscilloscope synchronization
measured to be σ_{sync} = 30 ps

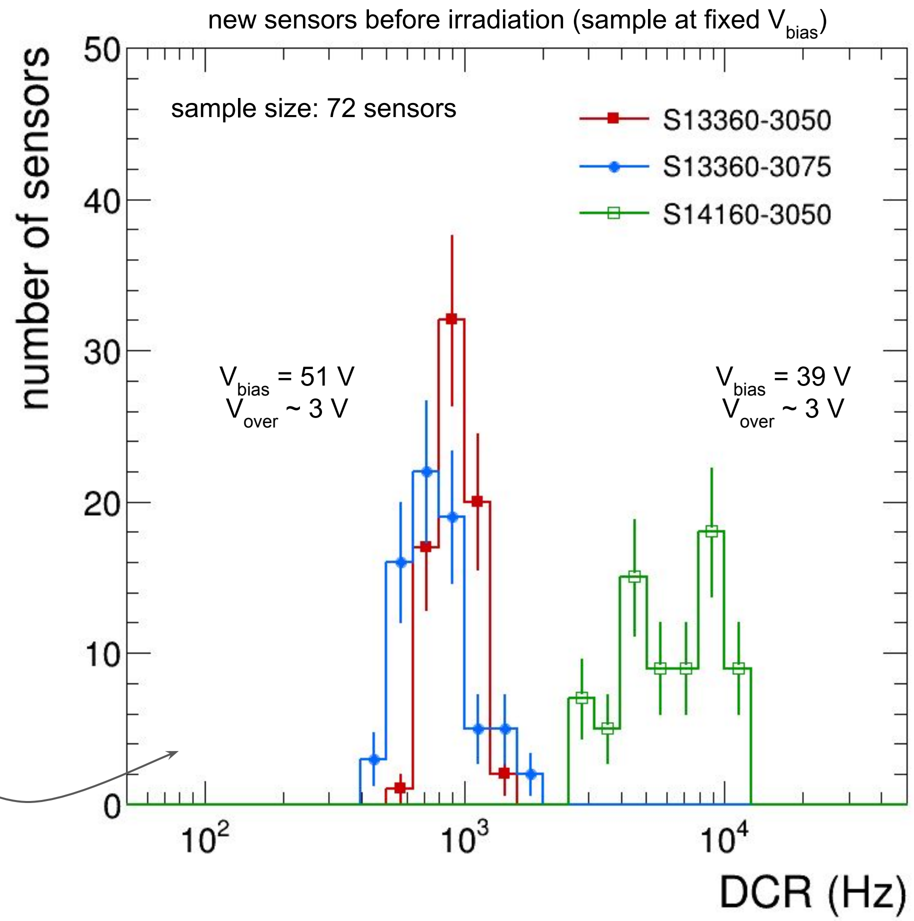
New SiPM custom boards for characterisation (2023 program)



- **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

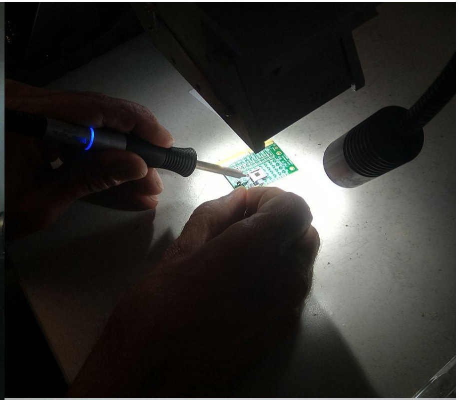
Characterisation of new SiPM boards

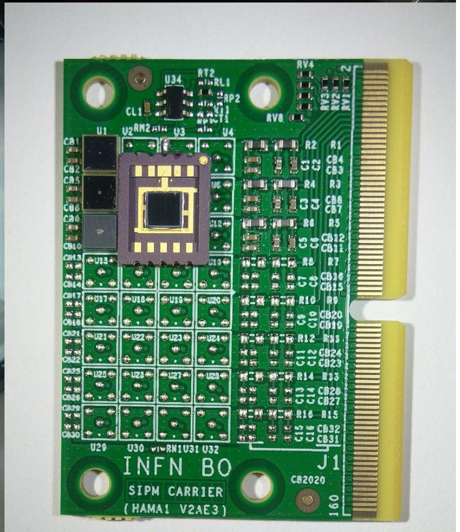




S13360-3075 have lowest DCR at V_{over} = 3 V
and at same time they have high PDE (50%)

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

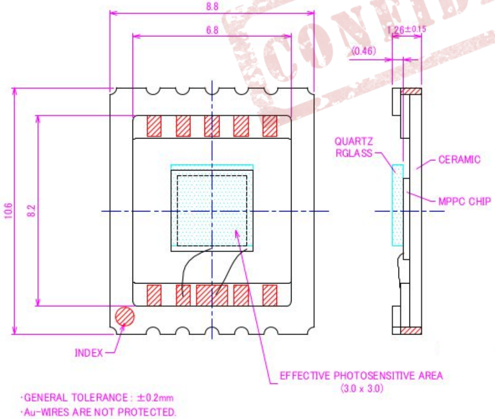
on paper they look VERY promising

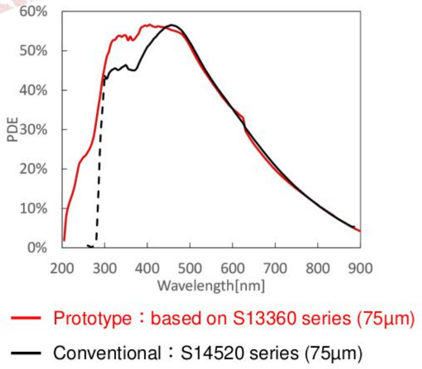
- improved NUV sensitivity
- improved signal shape
- improved recharge time

mounted on EIC SiPM test boards

we will characterise and test them in full

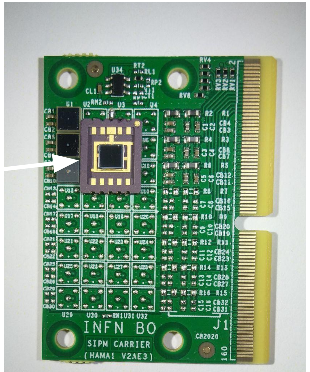
irradiation, annealing, laser, …





Current & future plans: 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)

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 improved ASIC (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 final ASIC version (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
    - other electronics
  - measure SEU rates
    - and latch-ups
    - verify monitor watchdogs are effective to protect

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

EIC luminosity

L_{int} [fb^{-1}] 10^{15} / ($\mathscr{L}$ [10^{33} cm^{-2} s^{-1}] 10^{33} 10^{-24}) / (3600 * 24 * 365 / 12) = Time [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 [$10^{33}cm^{-2}s^{-1}$]	0.32		3.14		3.14		2.92		0.44	
months to reach 100 fb^{-1}	**119**		**12**		**12**		**13**		**86**	

EIC luminosity

without hadron cooling peak luminosities reach up to $\mathcal{L}$ = 4.3 10^{33} cm^{-2} sec^{-1}

Table 3.3: EIC beam parameters for different center-of-mass energies $\sqrt{s}$, with strong hadron cooling. High divergence 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}]	19.1	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]	5.2/0.47	845/71	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]	18/1.6	24/2.0	11.3/1.0	20/1.3	30/2.7	20/1.3	26/2.3	20/1.8	44/10	20/3.5
β^*, h/v [cm]]	80/7.1	59/5.7	80/7.2	45/5.6	63/5.7	96/12	61/5.5	78/7.1	90/7.1	196/21.0
IP RMS beam size, h/v [μm]	119/11		95/8.5		138/12		125/11		198/27	
K_x	11.1		11.1		11.1		11.1		7.3	
RMS $\Delta\theta$, h/v [μrad]	150/150	202/187	119/119	211/152	220/220	145/105	206/206	160/160	220/380	101/129
BB parameter, h/v [10^{-3}]	3/3	93/100	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]	6.3	2.1	7.9	2.4	6.3	1.8	7.0	2.0	4.2	1.1
Long. IBS time [h]	2.0		2.9		2.5		3.1		3.8	
Transv. IBS time [h]	2.0		2		2.0/4.0		2.0/4.0		3.4/2.1	
Hourglass factor H	0.91		0.94		0.90		0.88		0.93	
Luminosity [10^{33}cm^{-2}s^{-1}]	1.54		10.00		4.48		3.68		0.44	
months to reach 100 fb^{-1}	**24.7**		**3.8**		**8.5**		**10.3**		**86.5**	

EIC luminosity

Table 3.5: EIC beam parameters for e-Au operation for different center-of-mass energies $\sqrt{s}$, with strong hadron cooling.

Species	Au ion	electron	Au ion	electron	Au ion	electron	Au ion	electron
Energy [GeV]	110	18	110	10	110	5	41	5
CM energy [GeV]	89.0		66.3		46.9		28.6	
Bunch intensity [10^{10}]	0.08	6.2	0.05	17.2	0.05	17.2	0.036	17.2
No. of bunches	290		1160		1160		1160	
Beam current [A]	0.23	0.227	0.57	2.50	0.57	2.50	0.41	2.50
RMS norm. emit., h/v [μm]	5.1/0.7	705/20	5.0/0.4	391/20	5.0/0.4	196/20	3.0/0.3	196/20
RMS emittance, h/v [nm]	43.2/5.8	20.0/0.6	42.3/3.0	20.0/1.0	42.3/3.0	20.0/2.0	68.1/5.7	20.0/2.0
β^*, h/v [cm]]	91/4	196/41	91/4	193/12	91/4	193/6	90/4	307/11
IP RMS beam size, h/v [μm]	198/15		196/11		197/11		248/15	
K_x	0.077		0.057		0.056		0.061	
RMS $\Delta\theta$, h/v [μrad]	218/379	101/37	216/274	102/92	215/275	102/185	275/377	81/136
BB parameter, h/v [10^{-3}]	1/1	37/100	3/3	43/47	3/2	86/47	5/4	61/37
RMS long. emittance [10^{-3}, eV·s]	16		16		16		16	
RMS bunch length [cm]	7	0.9	7	0.7	7	0.7	11.6	0.7
RMS $\Delta p/p$ [10^{-4}]	6.2	10.9	6.2	5.8	6.2	6.8	10	6.8
Max. space charge	0.007	neglig.	0.008	neglig.	0.008	neglig.	0.038	neglig.
Piwinski angle [rad]	4.4	1.1	4.5	1.2	4.5	1.5	5.8	1.2
Long. IBS time [h]	0.33		0.36		0.36		0.85	
Transv. IBS time [h]	0.81		0.89		0.89		0.16	
Hourglass factor H	0.85		0.85		0.85		0.71	
Luminosity [10^{33}cm^{-2}s^{-1}]	0.52		4.76		4.77		1.67	

months to reach 100 fb^{-1} 73.2 8.0 8.0 22.8