dRICH electronics integration and SiPM

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INFN Bologna
activities involving BO, CS, CT, FE, SA, TO

incontro con referee EIC_NET
31 agosto, Bologna

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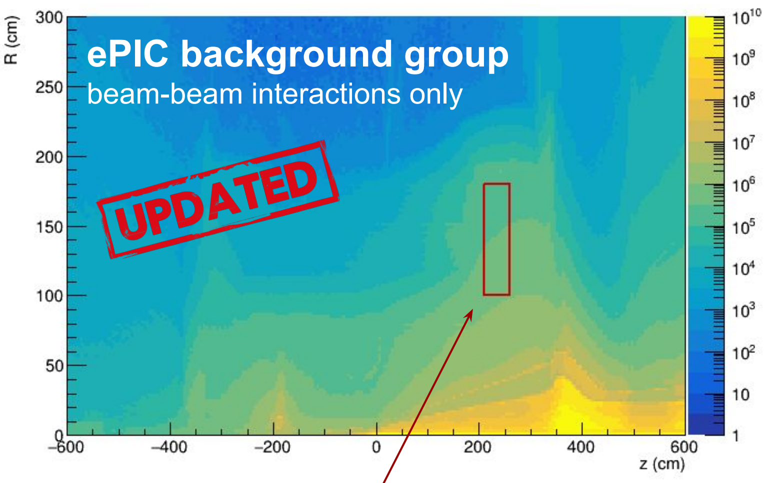
stato R&D

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}

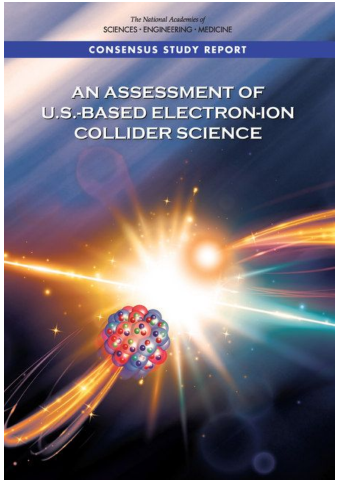
max fluence: 9.2 10^5 neq / cm^2 / fb^{-1}

- 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 $\mathcal{L}$ 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

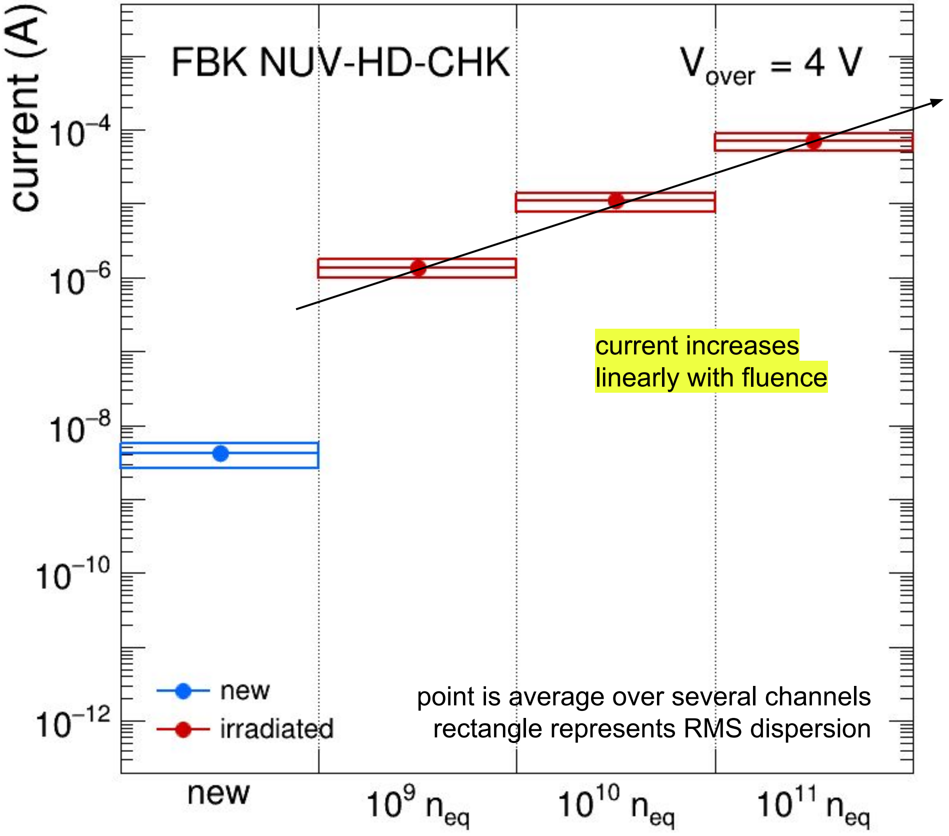
10^9 1-MeV n_{eq}/cm^2 *most of the key physics topics*

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*

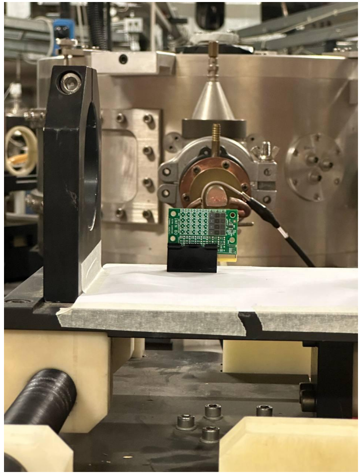
Studies of radiation damage on SiPM

in 2023 done also neutron irradiation
and variable proton energy irradiation



all results are reported at T = -30 C

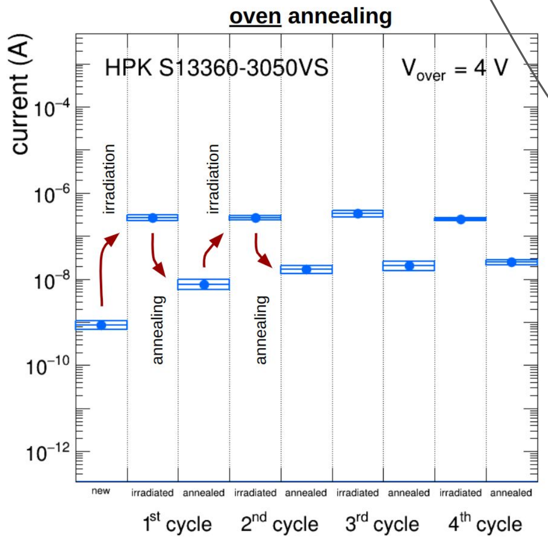
proton irradiation campaigns
in 2021, 2022 and 2023



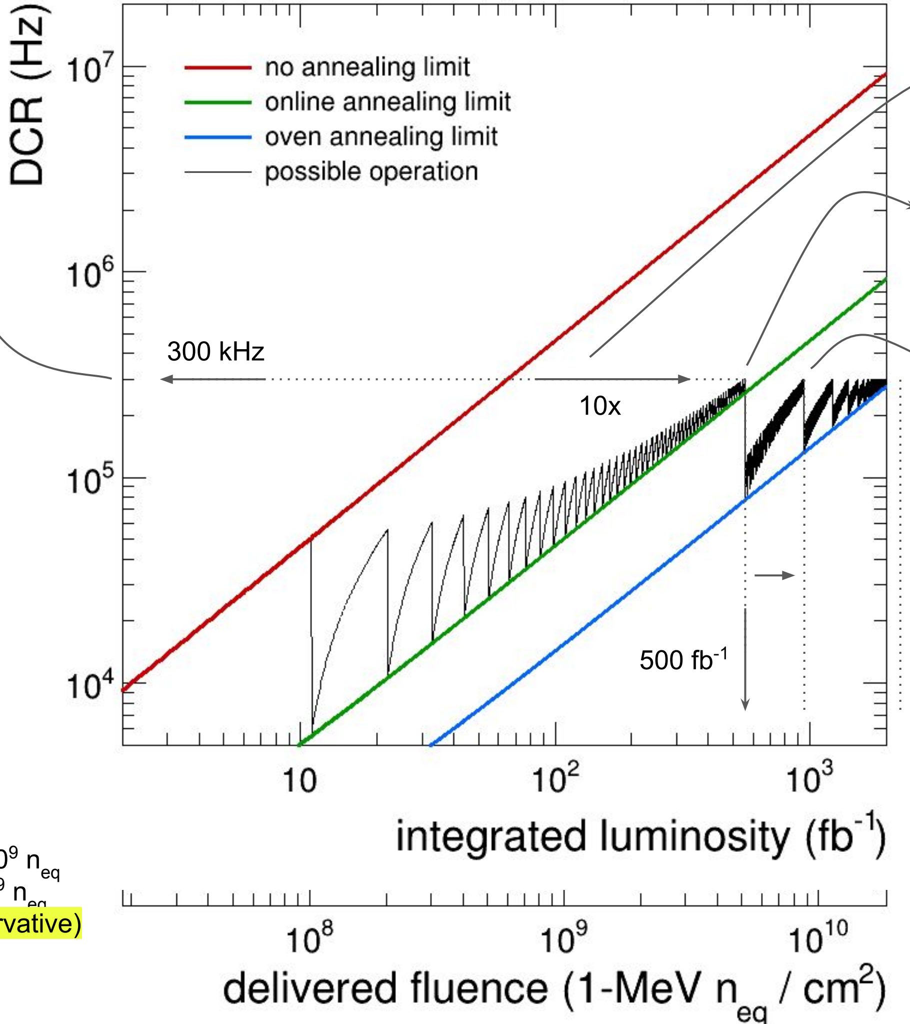
neutron irradiation
campaign in 2023

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 (up to 2022)

- 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}

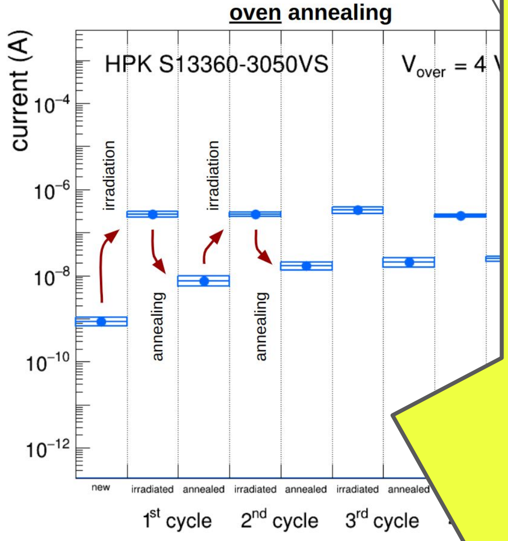
1-MeV neq fluence from background group (conservative)

- 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

Ageing model

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



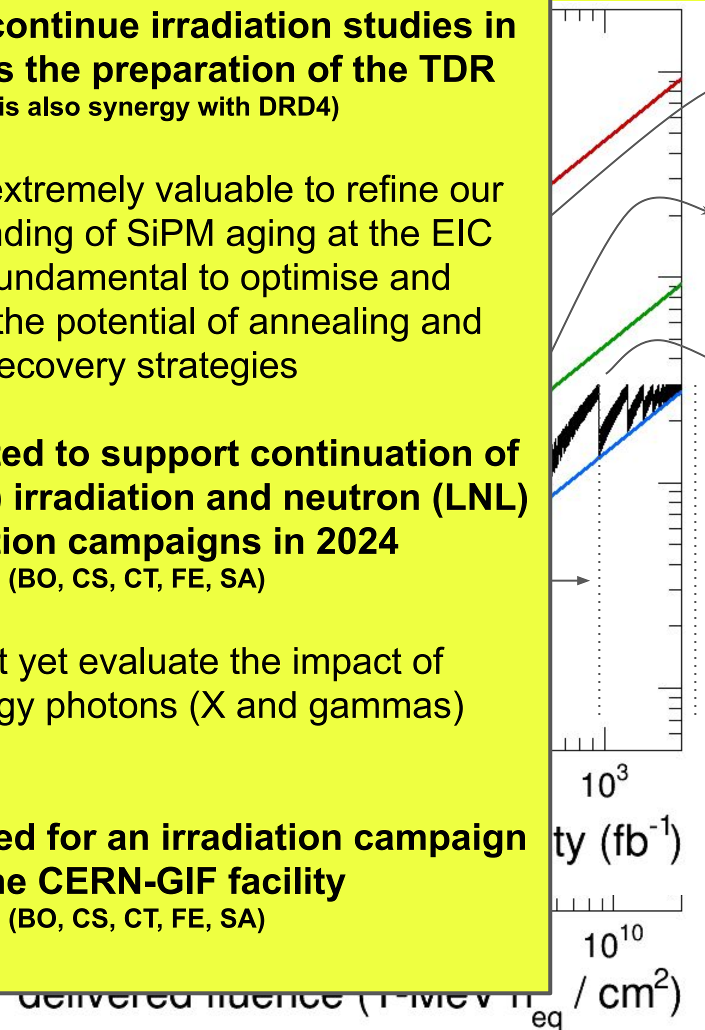
model input from R&D measurements (up to

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

1-MeV neq fluence from background group (

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

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



important to continue irradiation studies in 2024 towards the preparation of the TDR
(this is also synergy with DRD4)

- they are extremely valuable to refine our understanding of SiPM aging at the EIC
- they are fundamental to optimise and engineer the potential of annealing and damage recovery strategies

funds requested to support continuation of proton (TIFPA) irradiation and neutron (LNL) irradiation campaigns in 2024
(BO, CS, CT, FE, SA)

- we did not yet evaluate the impact of high-energy photons (X and gammas) irradiation

funds requested for an irradiation campaign at the CERN-GIF facility
(BO, CS, CT, FE, SA)

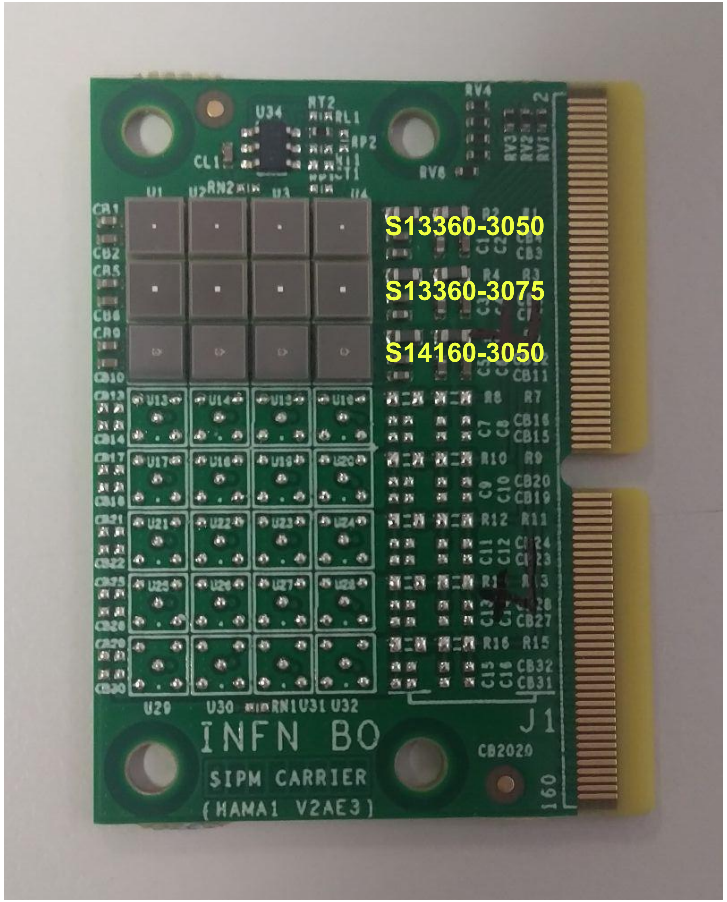
online annealing
extends SiPM
lifetime by ~ 10x

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

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

New SiPM custom boards for characterisation (2023 program)



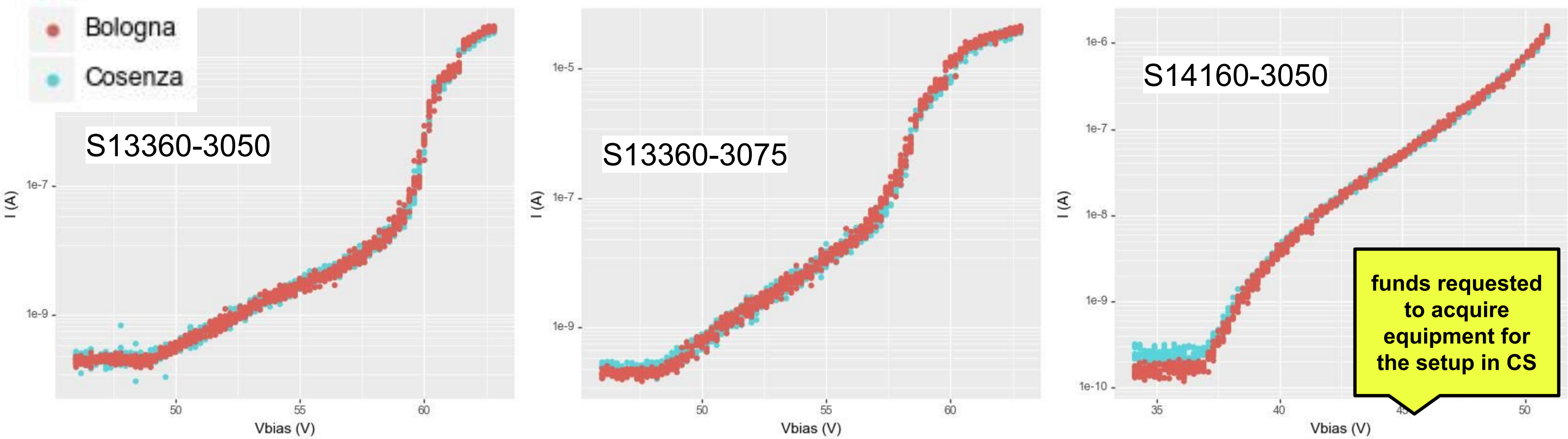
- **35 new boards have been produced**
  - same design from 2020
  - populate only 3 rows
    - 4 sensors, for minimal statistical sample
  - sensors from Hamamatsu
    - S13360-3050
    - S13360-3075
    - S14160-3050
  - replaced 50 Ω RC resistors with ferrite beads
    - allow to perform annealing
    - same components used for prototype
- **irradiation studies**
  - proton energy scan (TIFPA)
    - irradiation done in June 2023
  - neutron damage (LNL)
    - irradiation to 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

these boards will suffice to cover 2024 irradiation campaigns

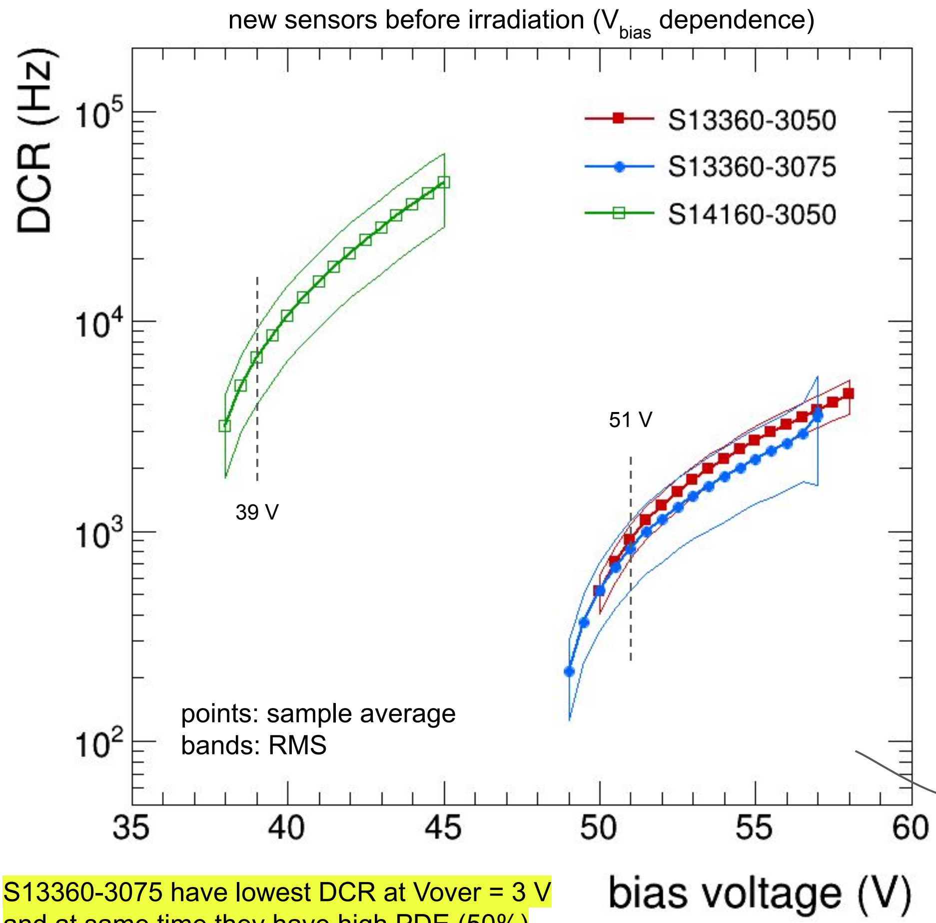
Characterisation setup in Cosenza

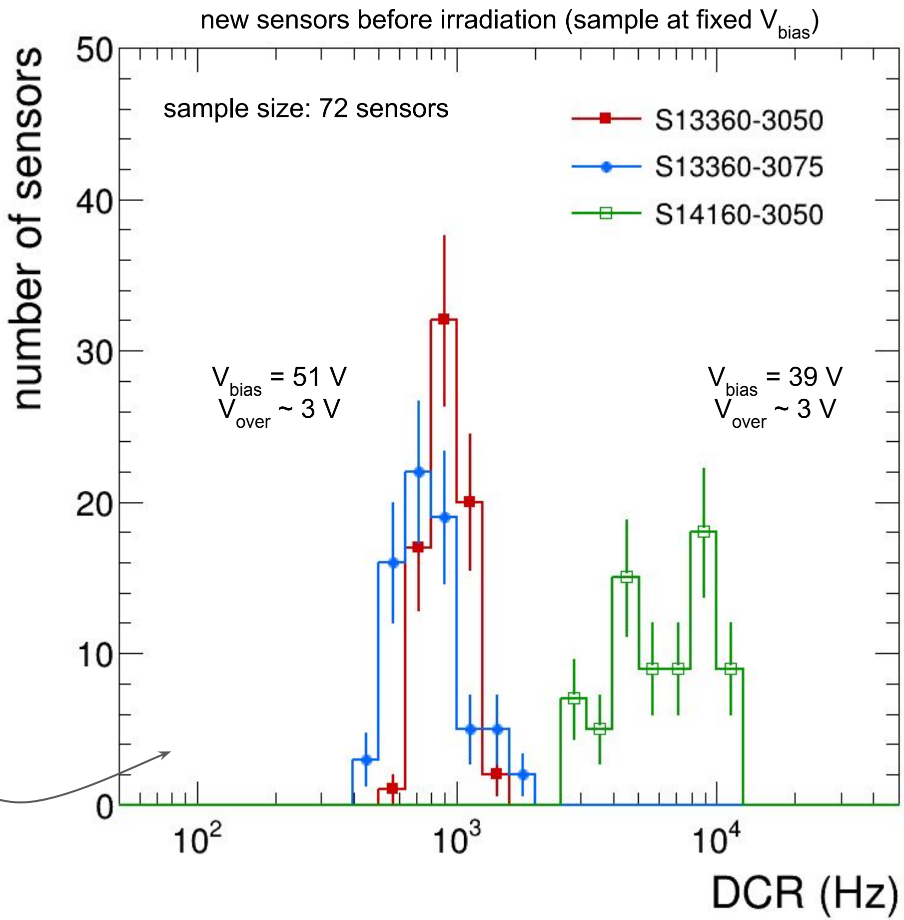
IV characteristics of 3 different SiPM types compared measured both in Bologna and Cosenza setups
- Bologna uses climatic chamber
- Cosenza uses AirBox air-cooled Peltier setup

the results are nicely compatible between the two setups
Cosenza setup is up and running to efficiently contribute to SiPM R&D and characterisation



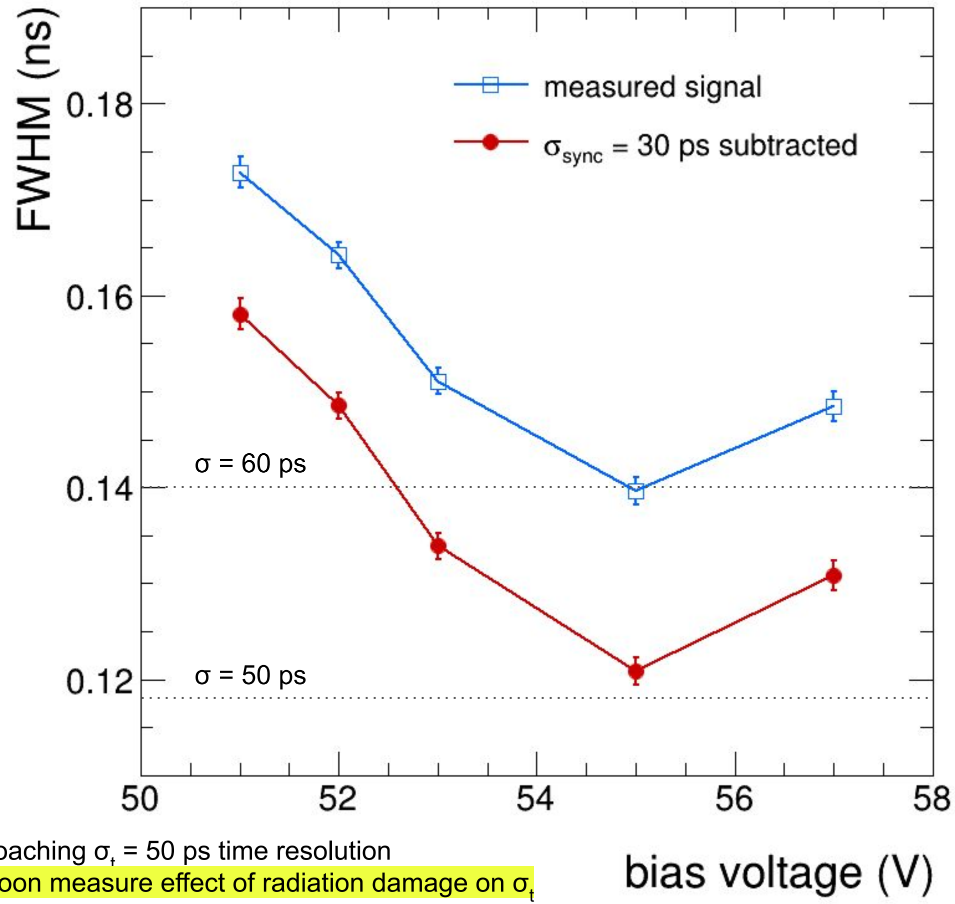
Characterisation of new SiPM boards

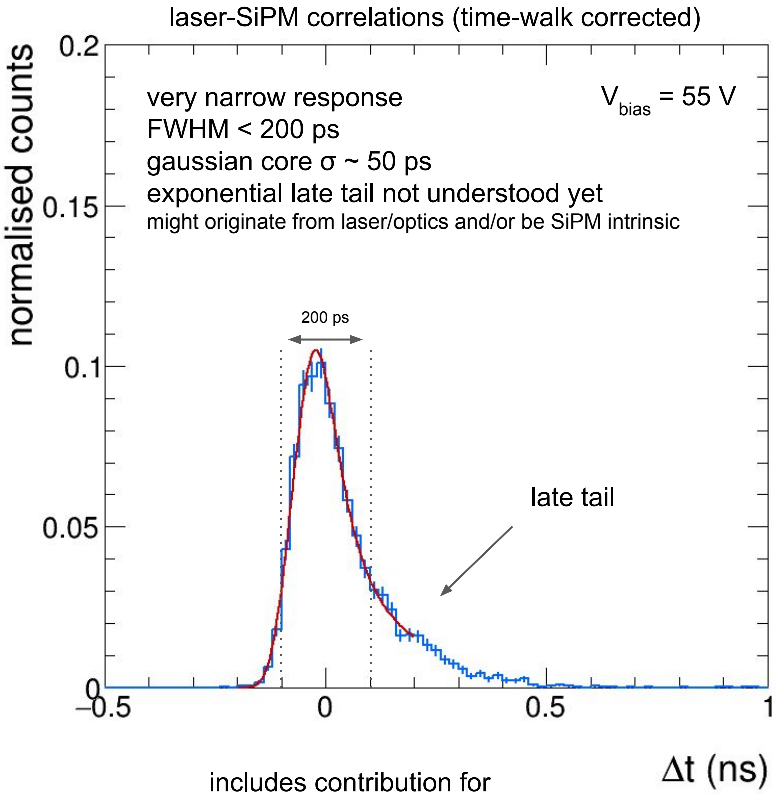




S13360-3075 have lowest DCR at Vover = 3 V
and at same time they have high PDE (50%)

Laser timing measurements with oscilloscope





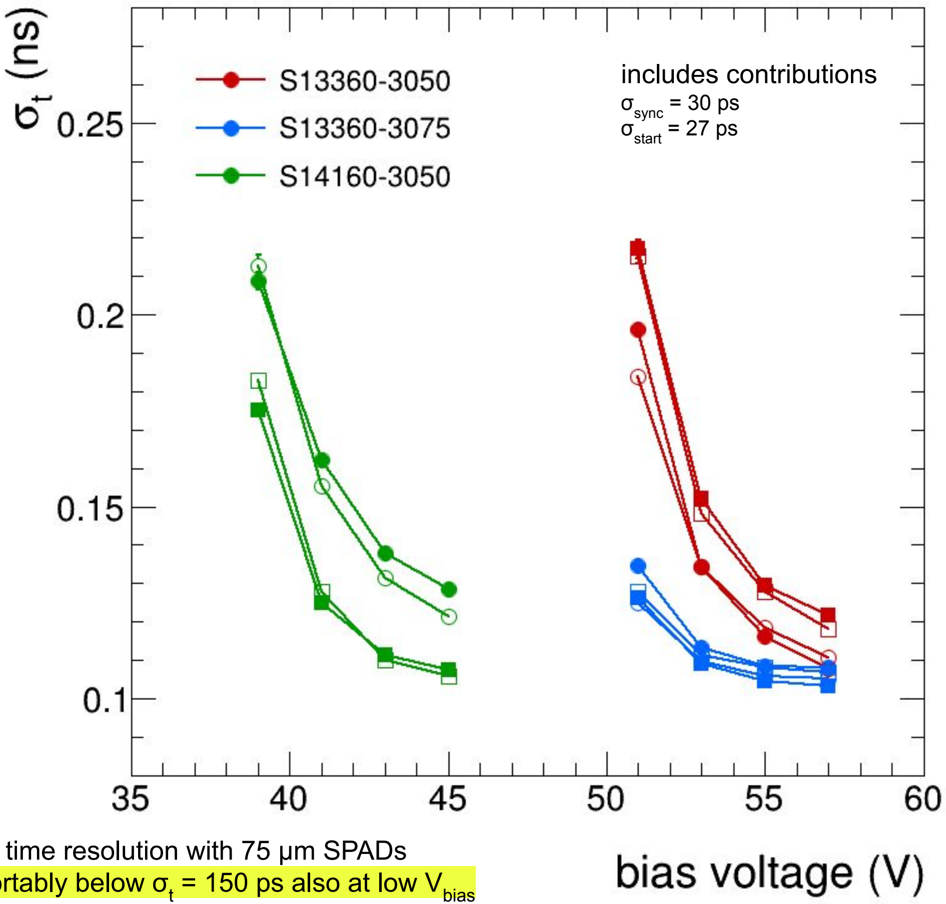
includes contribution for
laser-oscilloscope synchronization
measured to be σ_{sync} = 30 ps

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

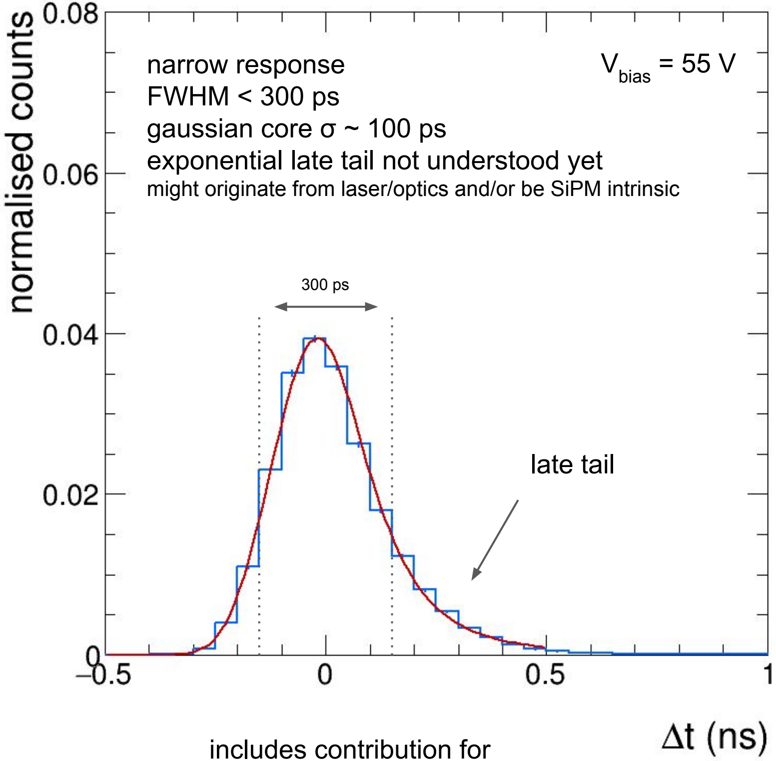
Laser timing measurements with ALCOR

Hamamatsu S13360-3075

standard ALCOR front-end bias configuration



laser-SiPM correlations (time-walk corrected)



better time resolution with 75 μm SPADs

comfortably below σ_t = 150 ps also at low V_{bias}

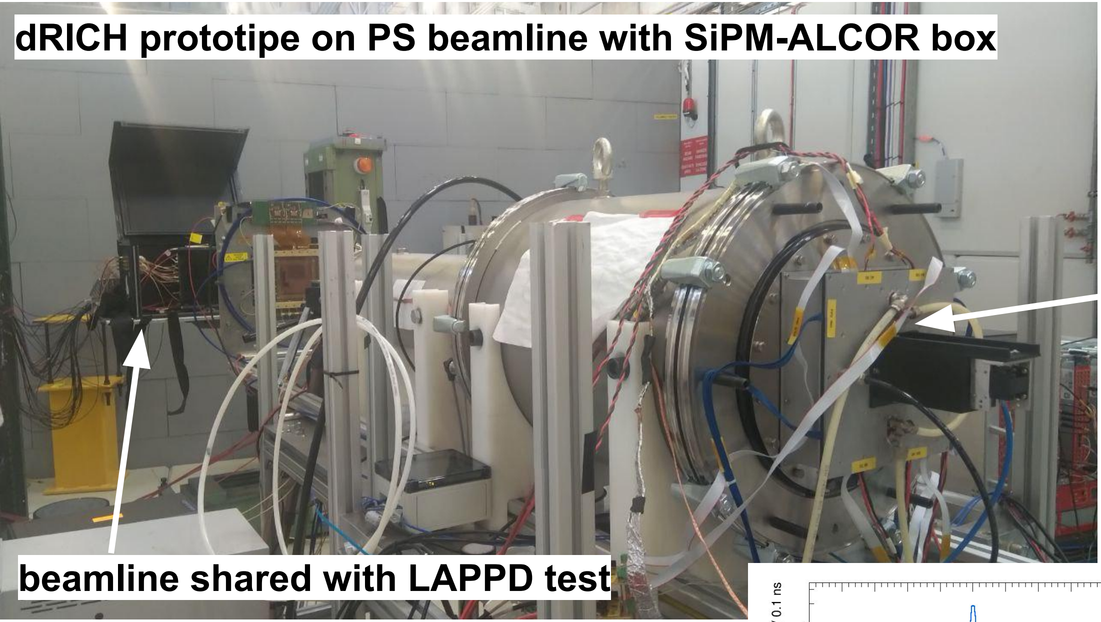
includes contribution for laser-ALCOR synchronization

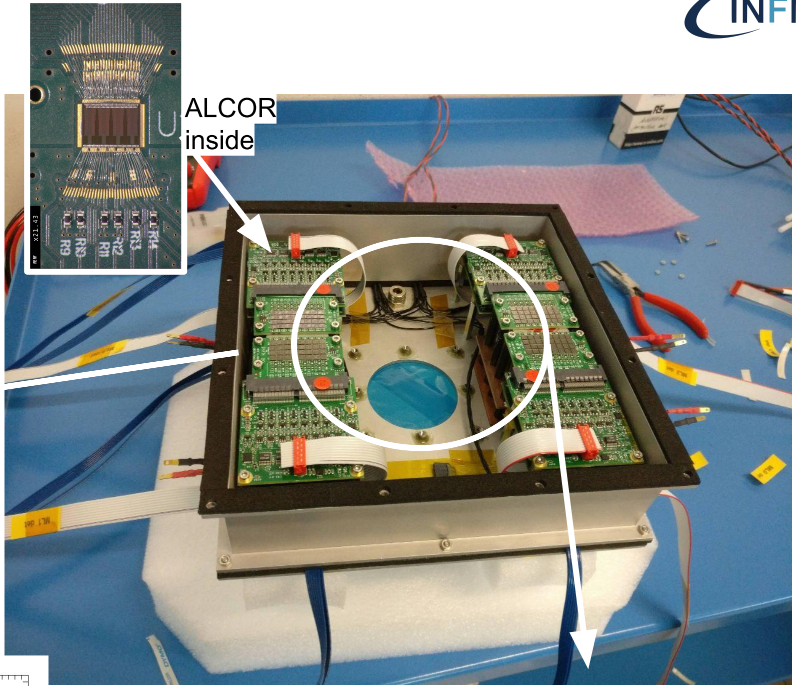
measured to be σ_{sync} = 30 ps

and reference time resolution

measured to be σ_{start} = 27 ps

2022 test beam at CERN-PS

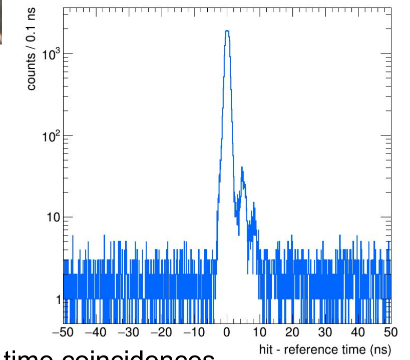




successful operation of SiPM

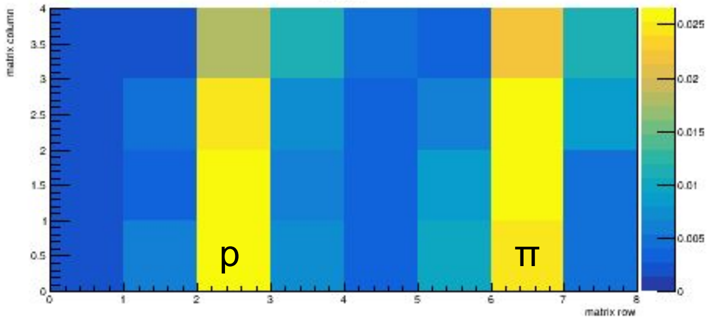
irradiated (with protons up to 10^{10})

and annealed (in oven at 150 C)

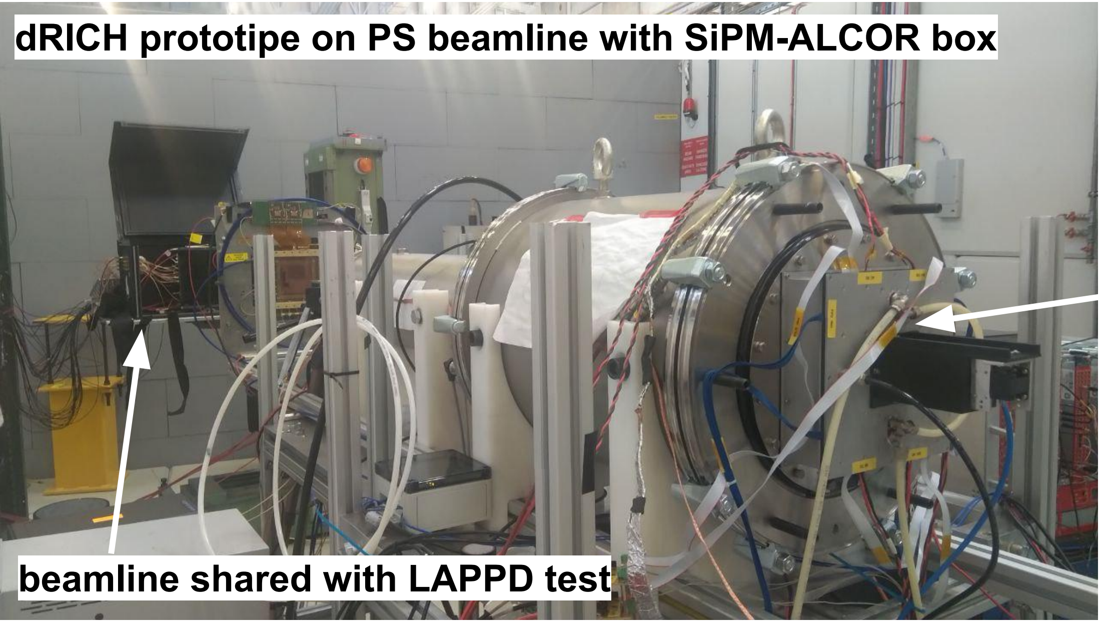


time coincidences

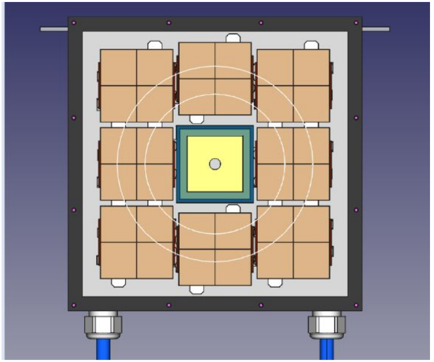
8 GeV positive beam (aerogel rings)

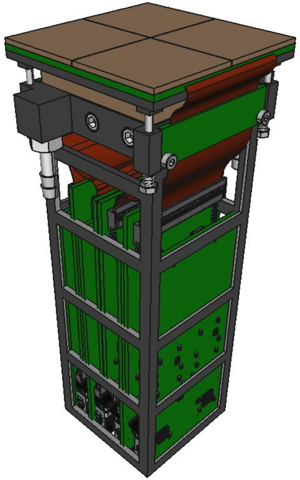


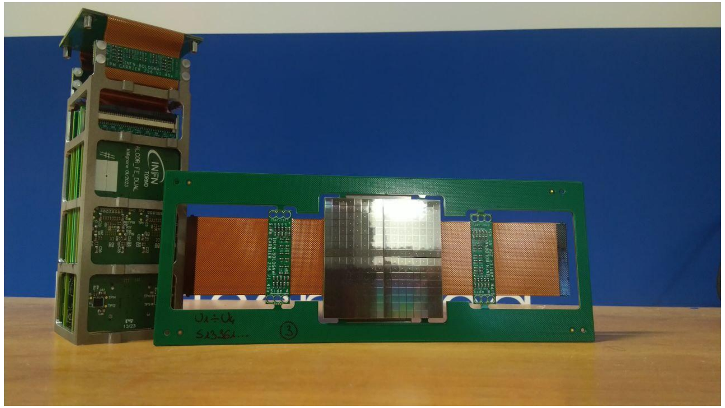
New detector plane for 2023 beam tests



prototype EIC-driven
readout unit and readout box







a few prototype photodetector units

will be assembled and tested in September

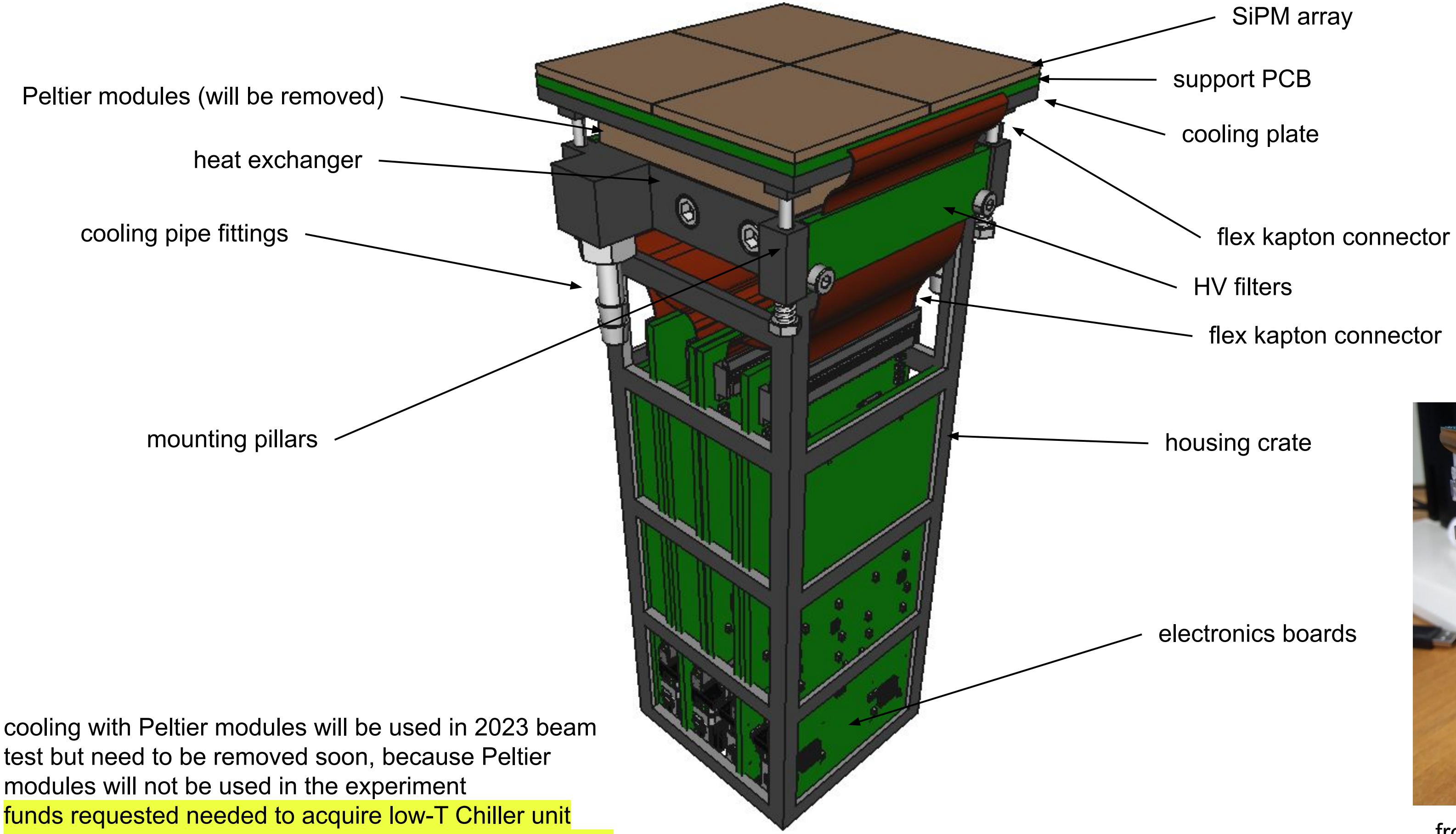
before mounting them on the dRICH detector prototype for the beam test

prototype PDU

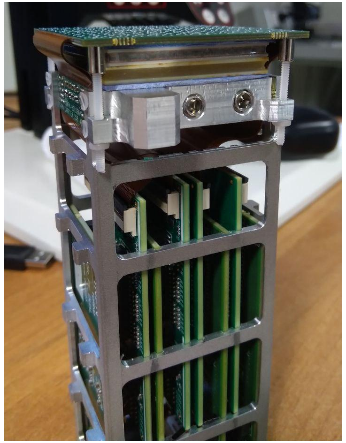
dRICH SiPM prototype photodetector unit (PDU)

- **large-area EIC-driven SiPM optical readout for the dRICH prototype**
  - based on ALCOR readout
  - milestone deadlines (eRD102 project)
    - realisation: April 2023
    - beam test: October 2023
- **SiPM sensors and layout**
  - each readout unit comprises of
    - 4 Hamamatsu 8x8 matrices
    - 256 channels
  - ~ 52 x 52 mm^2 area
- **design with layout as close as possible to needs for final experiment**
  - critical engineering exercise in view of TDR
  - place cooling and electronics on the back of the sensors
- **use as much as possible of current electronics architecture**
  - no manpower capacity to develop new FPGA board this year
  - no manpower capacity di develop new firmware this year
  - use ALCORv2 (32 channels)
- **design new electronics boards to fit the new layout configuration**
  - possibly with the same features, if all needed

Prototype photodetector unit (PDU)



cooling with Peltier modules will be used in 2023 beam test but need to be removed soon, because Peltier modules will not be used in the experiment
funds requested needed to acquire low-T Chiller unit
prototype PDU design done to allow this change in 2024

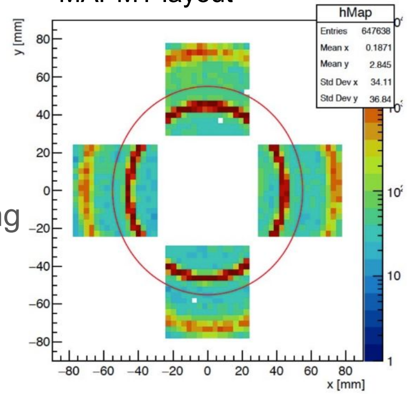


from design to assembly

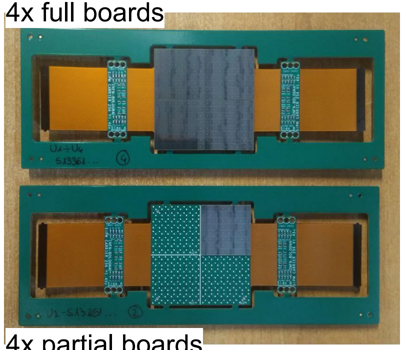
Prototype PDU status

- **acquired 20x Hamamatsu 8x8 SiPM matrix arrays**
  - eRD102 funds
  - sufficient to populate 4 full PDUs + 1 spare
  - map MAPMT readout layout
  - for 2023 beam test we eventually decided to optimise for testing
    - populated 4 full carrier boards
    - populated 4 partial carrier boards
- **produced electronic boards needed, with spares**
  - 1x carrier board / PDU
  - 4x adapter boards / PDU
  - 4x ALCOR boards / PDU
  - 8x ALCOR chips / PDU
  - 4x Masterlogic boards / PDU
- **acquired ancillary material and boards**
  - many cables
  - Peltier modules
  - FPGA boards
  - clock distribution
  - …
- **produced mechanical pieces for 10x PDUs**
  - cooling hardware
  - mini-crate for electronics
- **extend the readout to cover the full area in 2024**
  - INFN fund requests to acquire more SiPM and electronics → **produce 4 PDUs + 1 spare**

MAPMT layout



4x full boards



4x partial boards

SiPM layout (2023)

U2	U4	U2	U4	U2	U4
U1	U3	U1	U3	U1	U3
U2	U4			U2	U4
U1	U3			U1	U3
U2	U4	U2	U4	U2	U4
U1	U3	U1	U3	U1	U3

→

SiPM layout (2024)

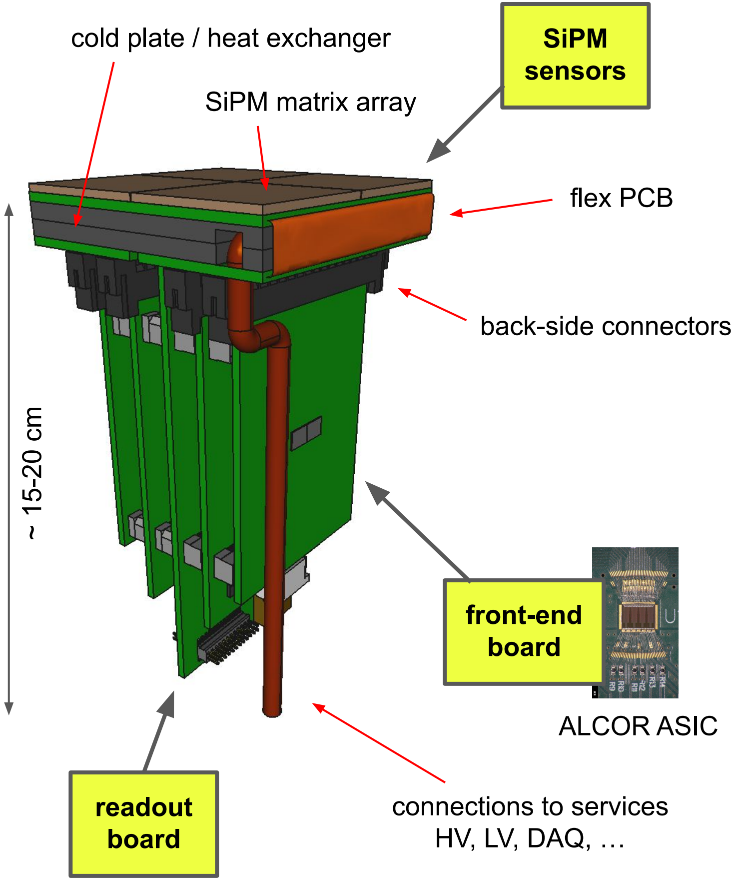
U2	U4	U2	U4	U2	U4
U1	U3	U1	U3	U1	U3
U2	U4			U2	U4
U1	U3			U1	U3
U2	U4	U2	U4	U2	U4
U1	U3	U1	U3	U1	U3

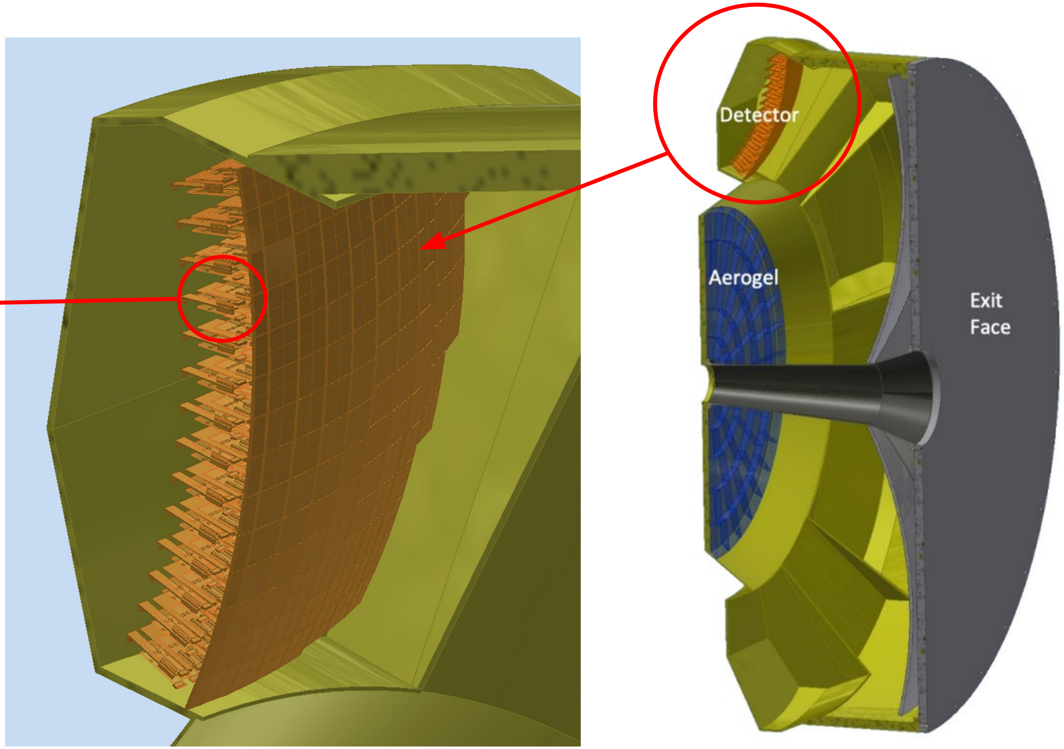
Photodetector unit

conceptual design of final layout

plans for realisation of the final prototype units

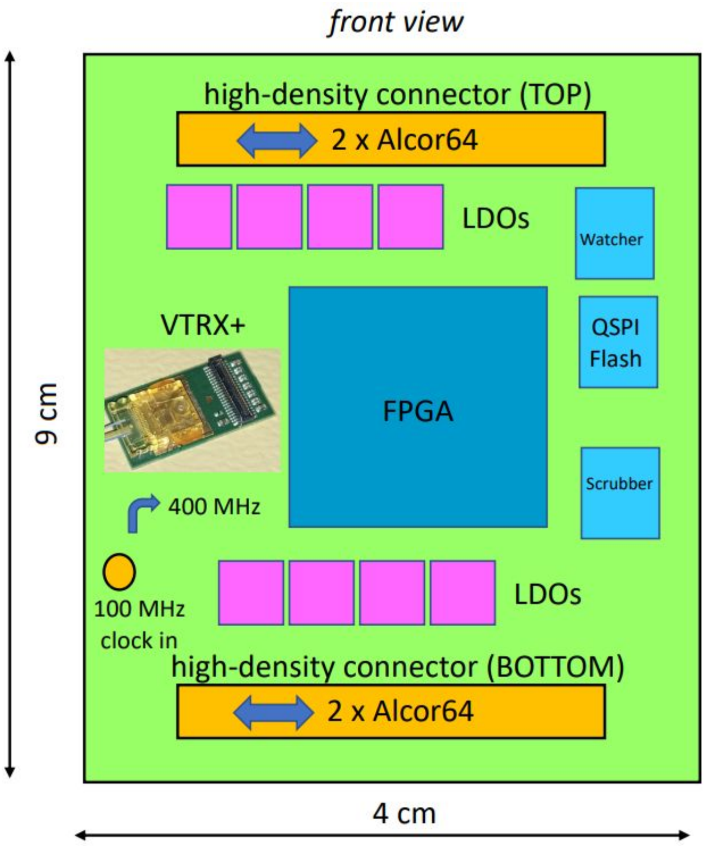
- 2024: readout board (RDO) realisation and test beam
- 2024: front-end board (FEB) with ALCOR-v3 (64ch BGA)
- 2025: final SiPM carrier realisation and test beam

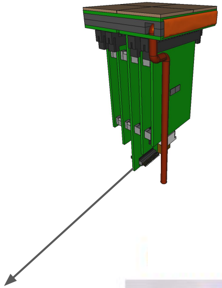




Readout board

conceptual design of RDO architecture





time to start developing custom readout boards for 2024 beam tests and TDR

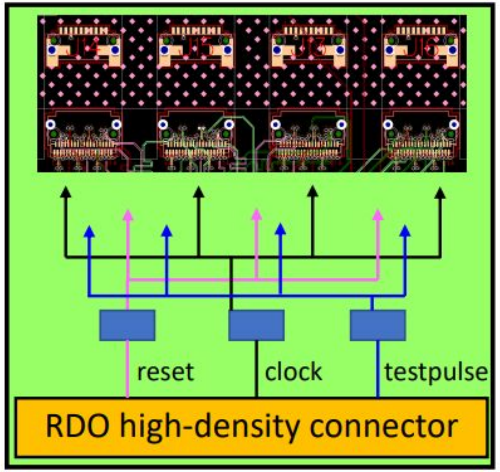
2024: design and develop 10x RDO boards

- **close to the final RDO design and PDU layout**
- **with the capability to also serve current electronics**

current breakout board

already existing (2023 test beam)

connects current ALCOR FireFly electronics to FMC connector of commercial FPGA board



new breakout board

to be made in 2024

needed to connect current ALCOR FireFly electronics to RDO high-density connector

INFN funds requested for realisation of 10x RDO boards, 10x new breakout boards, acquire FireFly cables and data aggregator DAQ system (Virtex FPGA + server)

The great management plan towards construction

	Year		2023				2024				2025			
	Quarter		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Milestone	TDR									x				
	test beam					x				x		x		x
sensors	SiPM carrier	v2												
	SiPM carrier	vF												
front-end	ALCOR	v2												
	ALCOR-FE	v2												
	ADAPTER	v2												
	MasterLogic	v2												
	ALCOR	v64												
	FEB	v64												
	packaging													
	ALCOR	vF												
	FEB	vF												
readout	KC705													
	RDO	v2												
	breakout boards	v2												
	VC709													
	felix													
	RDO	vF												

design

order

ready

important milestones

TDR in 2024:
have very high design maturity

beam tests in 2025:
test the final layout and the electronics

attività e richieste 2024

Summary

- **sviluppo prototipi readout board RDO**
  - Sviluppo e produzione di 10 schede prototipo Readout Board dRICH RDO
  - Produzione e assemblaggio di 10x schede JC23-225 Breakout board
  - Cavi interfaccia scheda-scheda SAMTEC FireFly ad alta velocità
  - KIT SVILUPPO, VIRTEX-7 FPGA
  - Server con processore aggiuntivo e 32 GB di RAM per readout RDO
- **realizzazione nuovi prototipi di photodetector units PDU**
  - Acquisto componenti, cavi e materiale per l'assemblaggio e test dei prototipi
  - Produzione e assemblaggio SiPM carrier boards per PDU prototipo
  - Matrici 8x8 SiPM Hamamatsu S13360 per prototipo dRICH
  - produzione e assemblaggio di schede ADAPTER-64
  - produzione e assemblaggio di schede ALCOR-DUAL
  - produzione e assemblaggio di schede MasterLogic-v2
- **strumentazione ed equipaggiamento per test in laboratorio e su fascio**
  - Sistema chiller con liquido di circolazione e tubazioni coibentate
  - Oscilloscopio da banco/portatile 4 ch. analogici, 16 ch. digitali, 200MHz
  - Picoamperometro da banco Keithley 6487/E, 20mA ca, Cert. LAT
  - ThinkCentre M75T Desktop con monitor e scheda di rete aggiuntiva
  - Essiccatore aria SMC IDFA11E-23
  - Compressore d'aria da laboratorio
  - Gruppo di continuità
- **collaborazione e attività di R&D su SiPM (sinergie DRD4)**
  - missioni per collaborazione tra le sezioni di BO, CS, CT, FE, SA
  - spese per fascio presso il Centro di ProtonTerapia di Trento
  - missioni per test di irraggiamento presso il TIFPA, Legnaro e il CERN

END

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

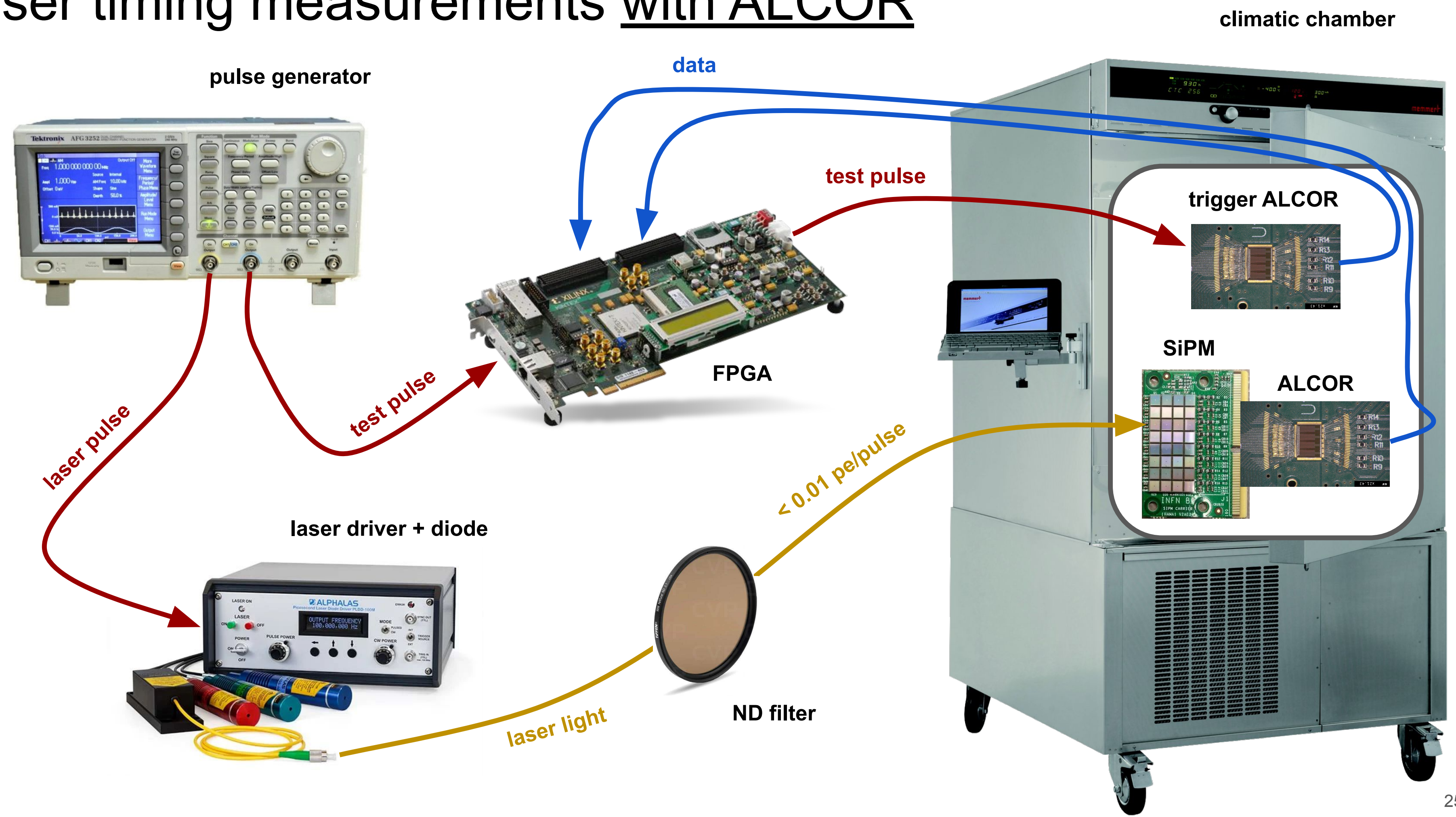
General & Temperature Control

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

Heating / cooling capacity

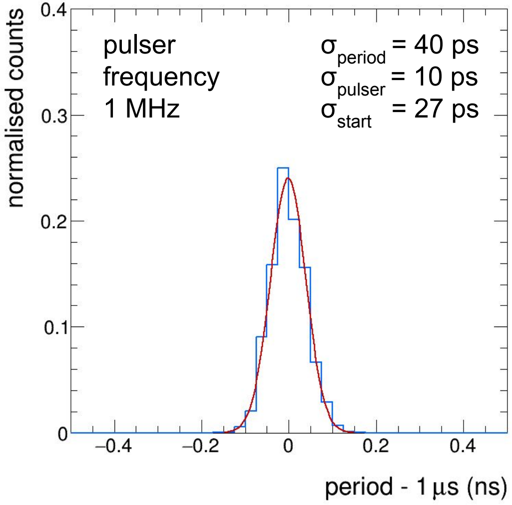
Heating capacity	6 kW								
Cooling capacity	250	200	100	20	0	-20	-40	-50	°C
	6	6	6	6	6	4,2	1,5	0,65	kW

Laser timing measurements with ALCOR

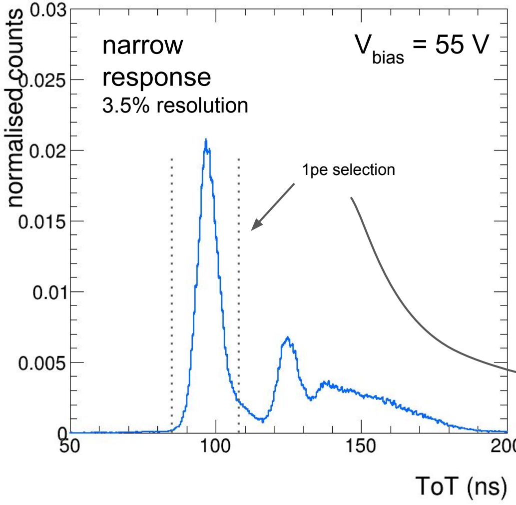


Laser timing measurements with ALCOR

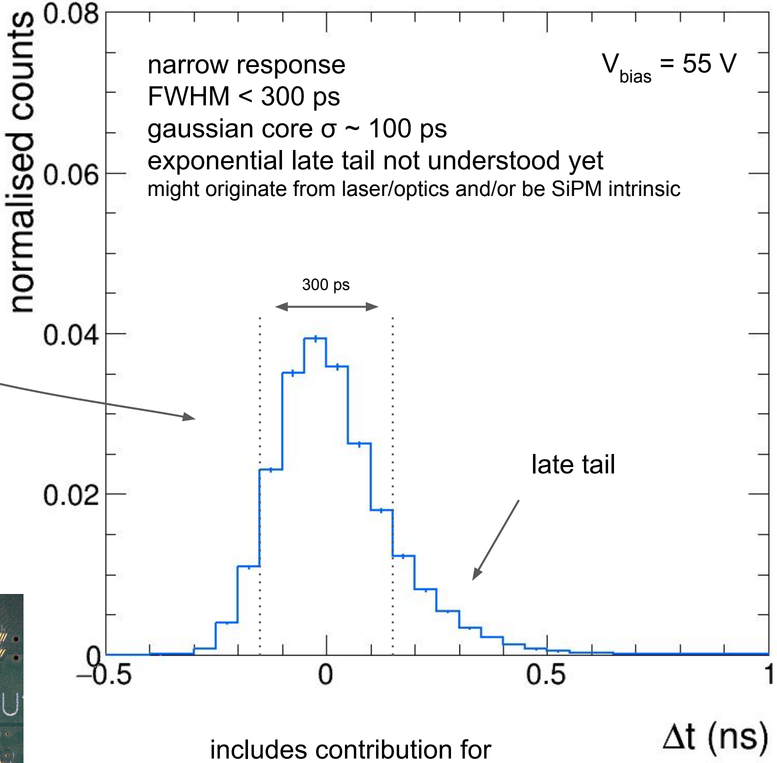
reference ALCOR pulse period



Time-over-Threshold values



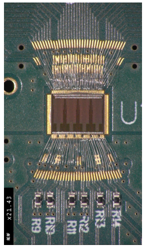
laser-SiPM correlations (time-walk corrected)



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

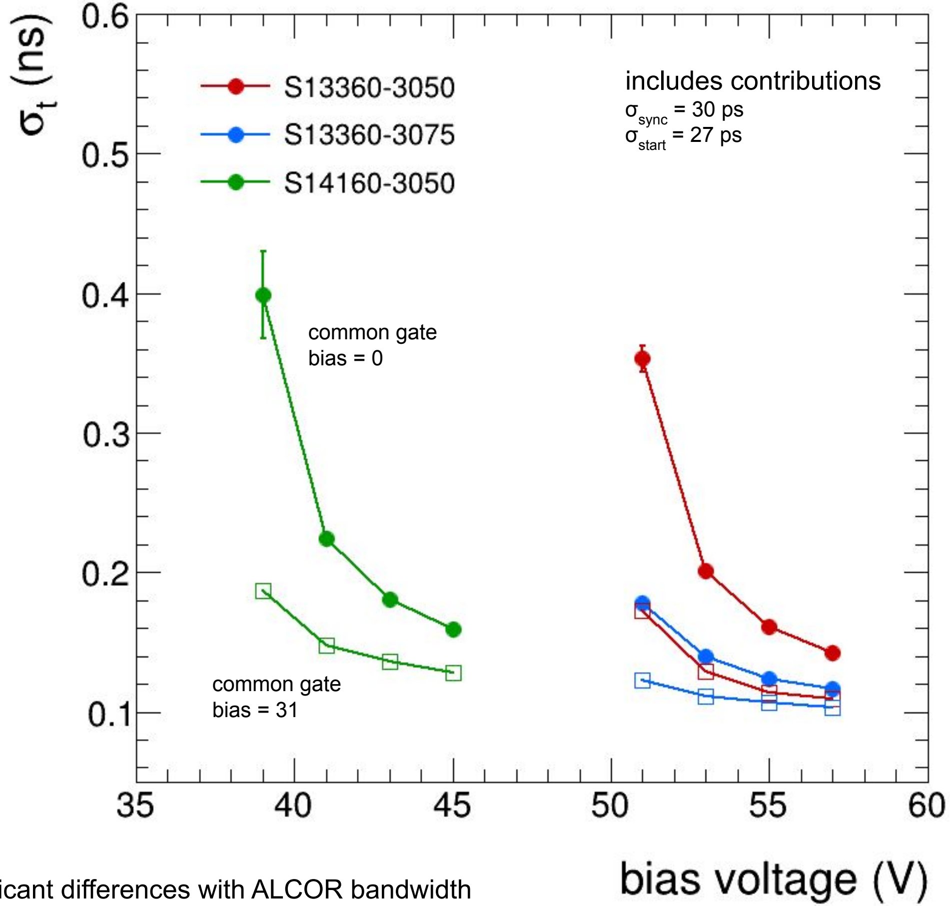
measure time coincidences Δt between reference and ALCOR reading SiPM



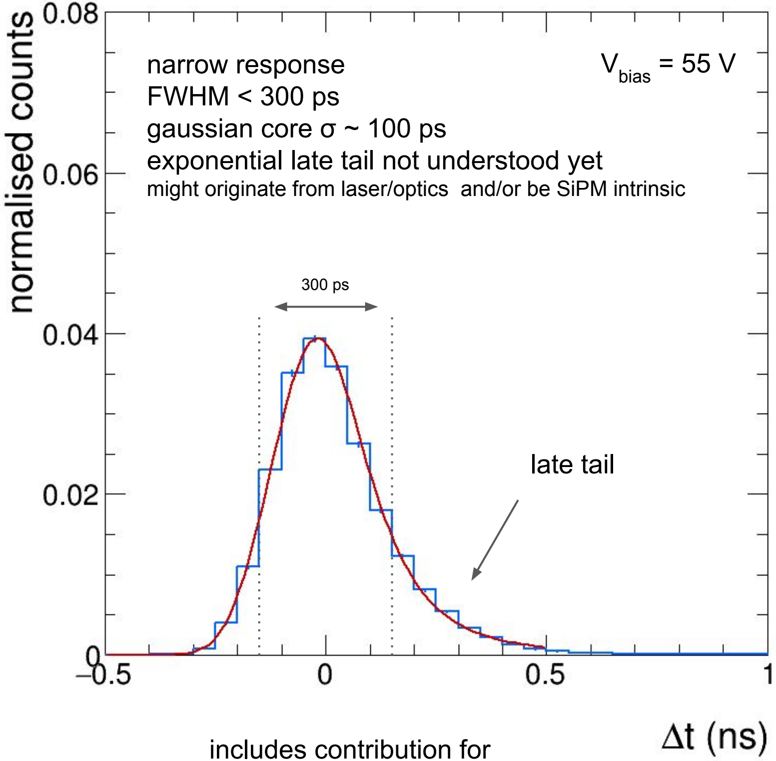
includes contribution for laser-ALCOR synchronization
measured to be σ_{sync} = 30 ps
and reference time resolution
measured to be σ_{start} = 27 ps

Laser timing measurements with ALCOR

the two extremes of ALCOR front-end bias configuration



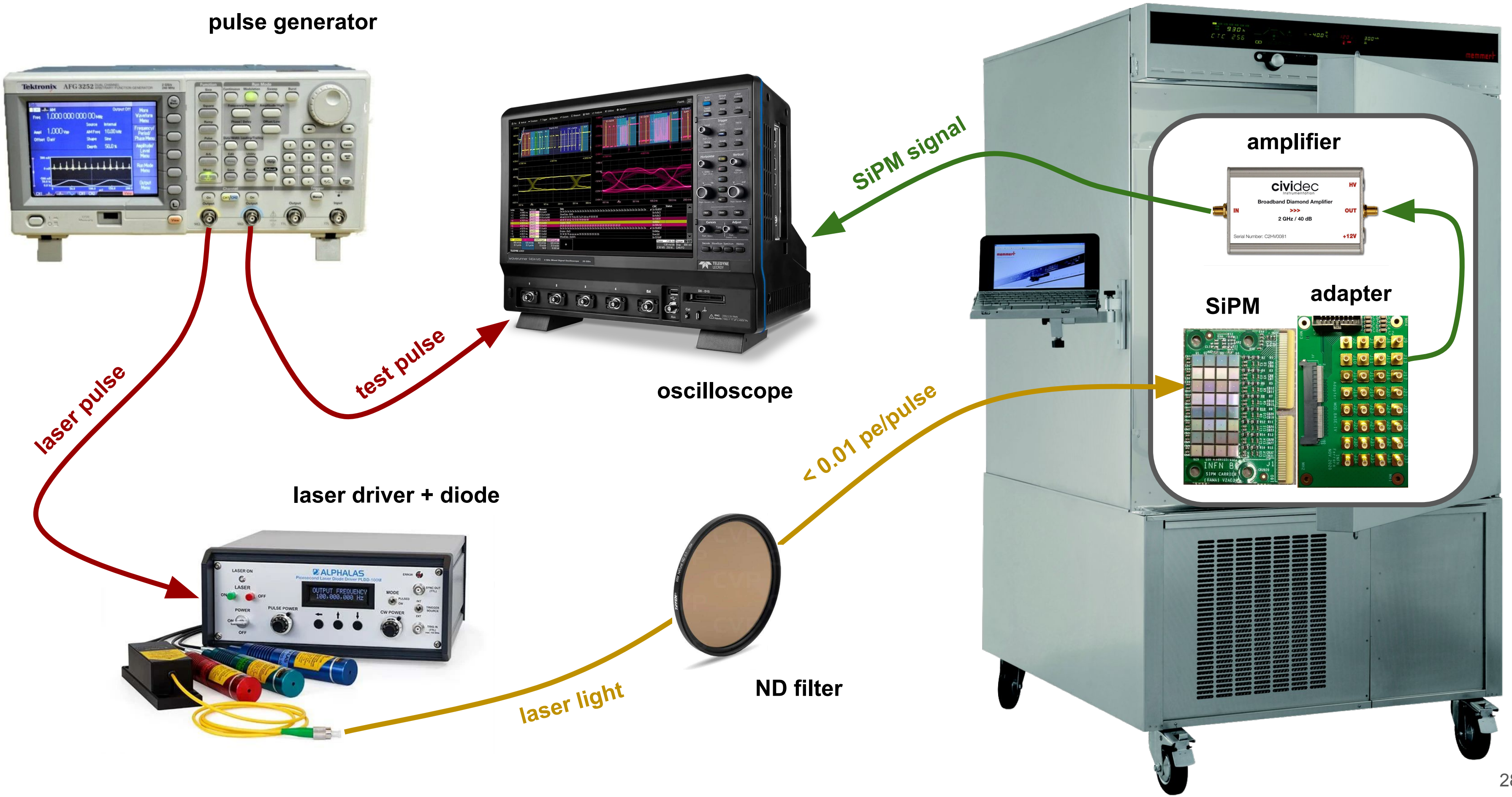
laser-SiPM correlations (time-walk corrected)



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

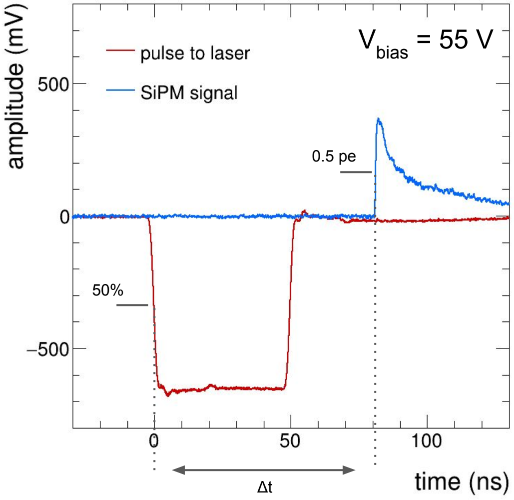
Laser timing measurements with oscilloscope



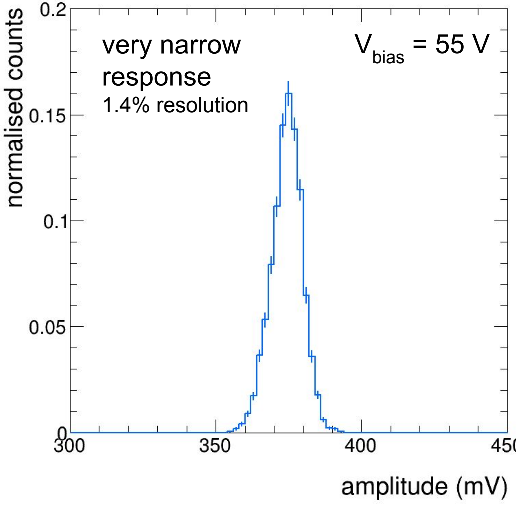
Laser timing measurements with oscilloscope

Hamamatsu S13360-3075

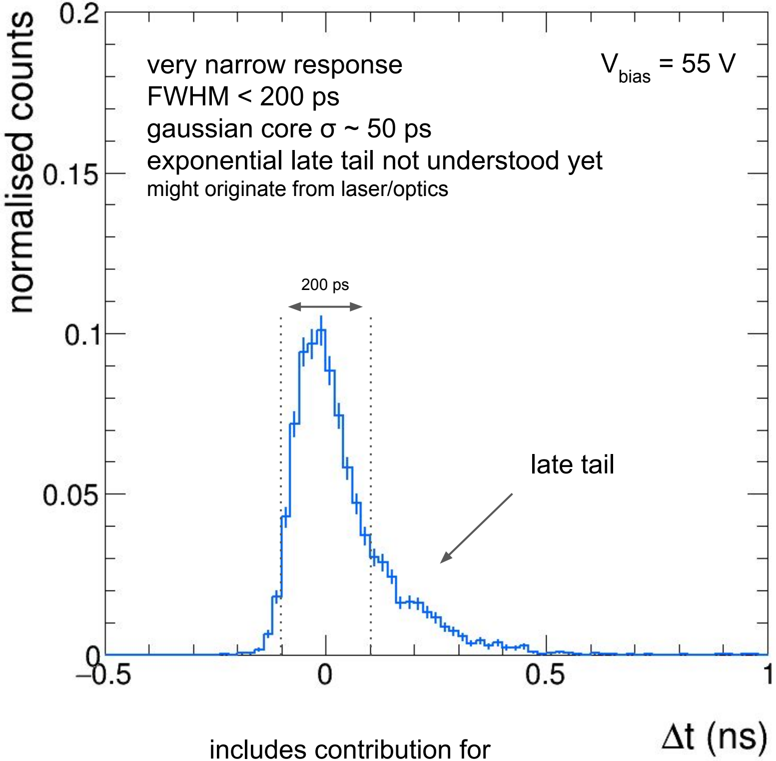
acquired oscilloscope traces



SiPM signal amplitudes (1pe)



laser-SiPM correlations (time-walk corrected)



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

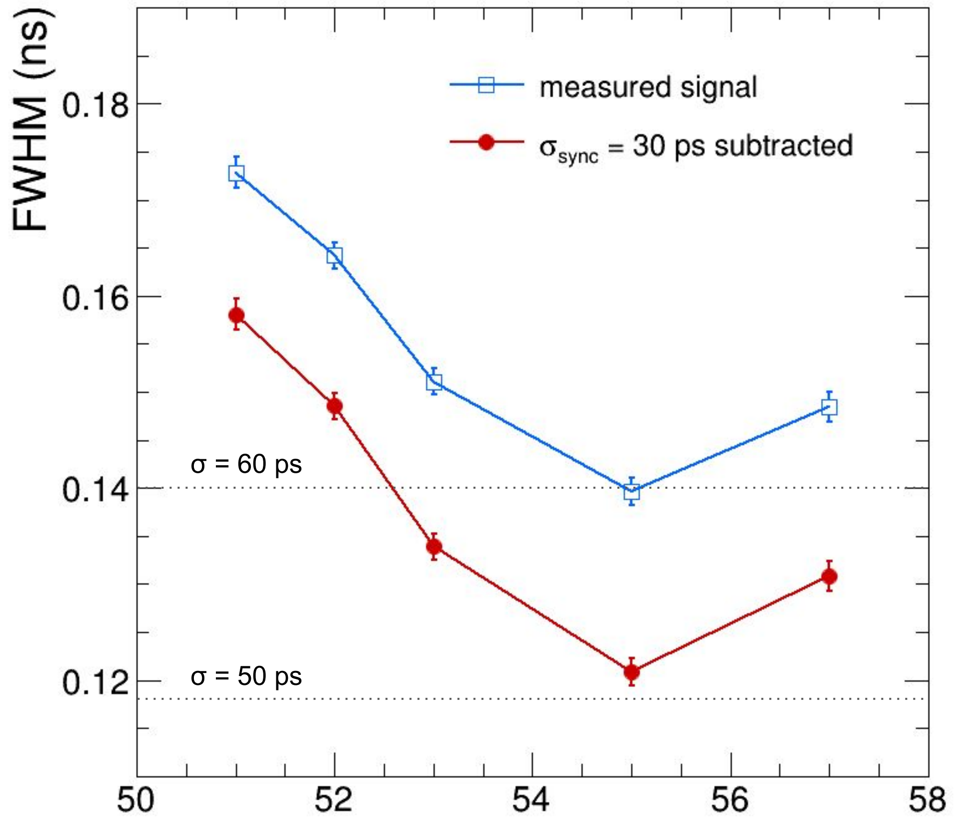
measurements performed at T = -30 C with
- Lecroy Waverunner 40186 oscilloscope
- Cividec Broadband amplifier (40 db)

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

time-amplitude correlation (walk) corrected

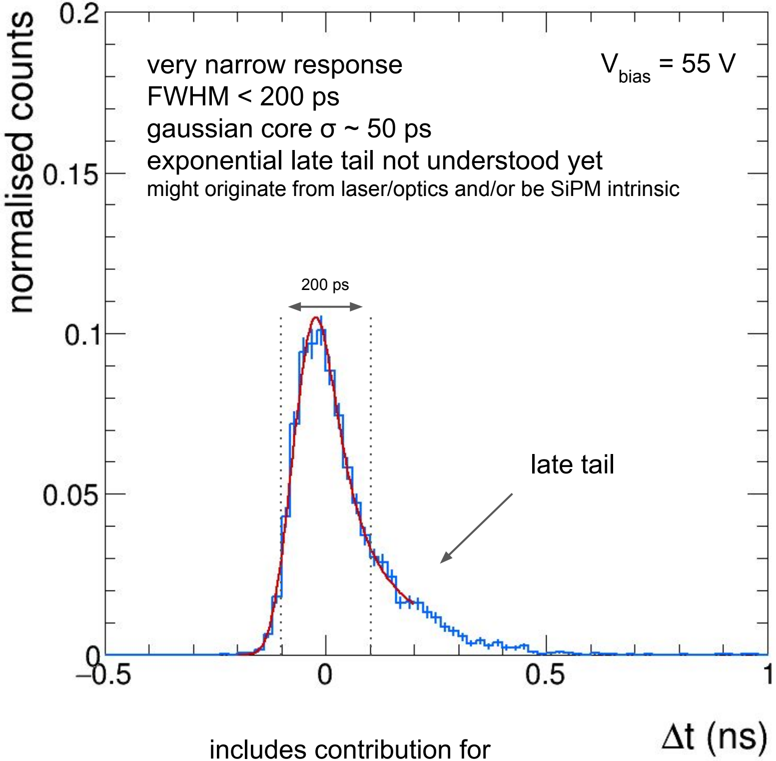
Laser timing measurements with oscilloscope

Hamamatsu S13360-3075



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

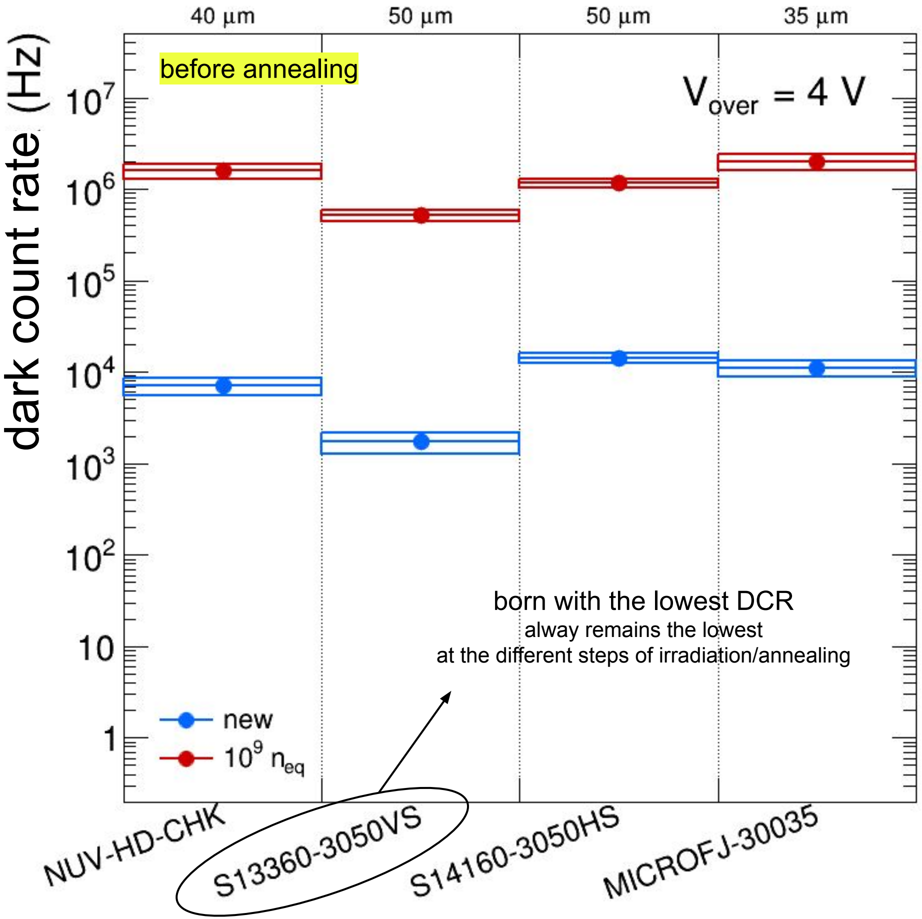
laser-SiPM correlations (time-walk corrected)

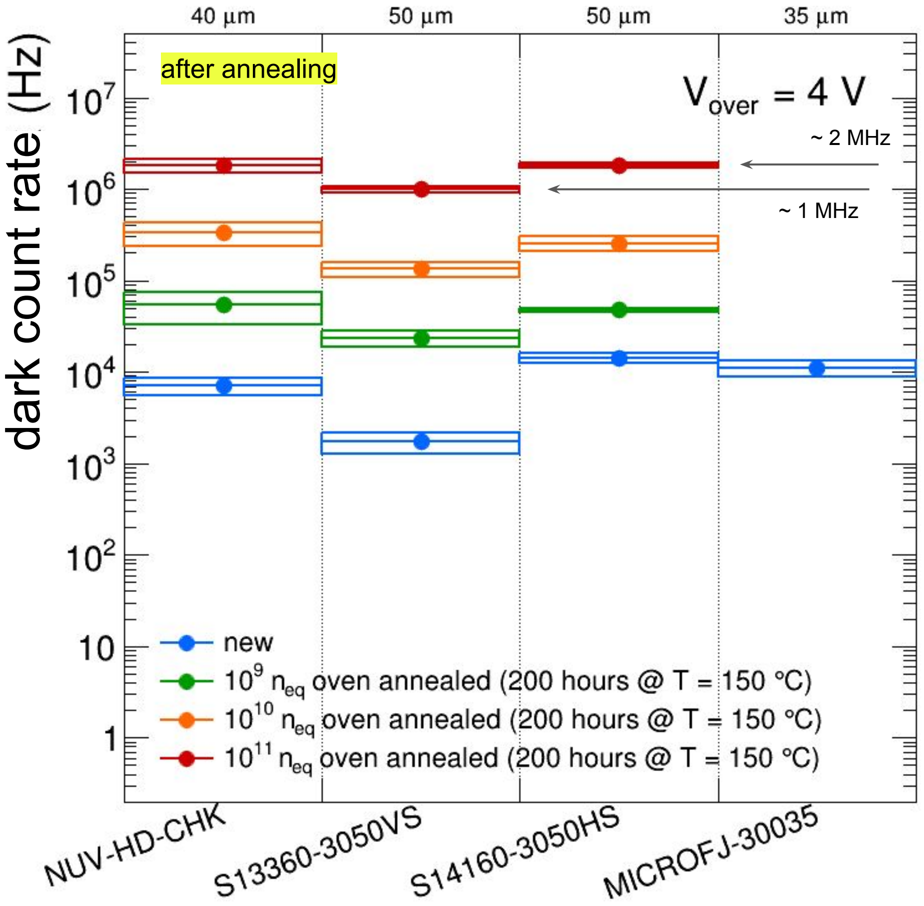


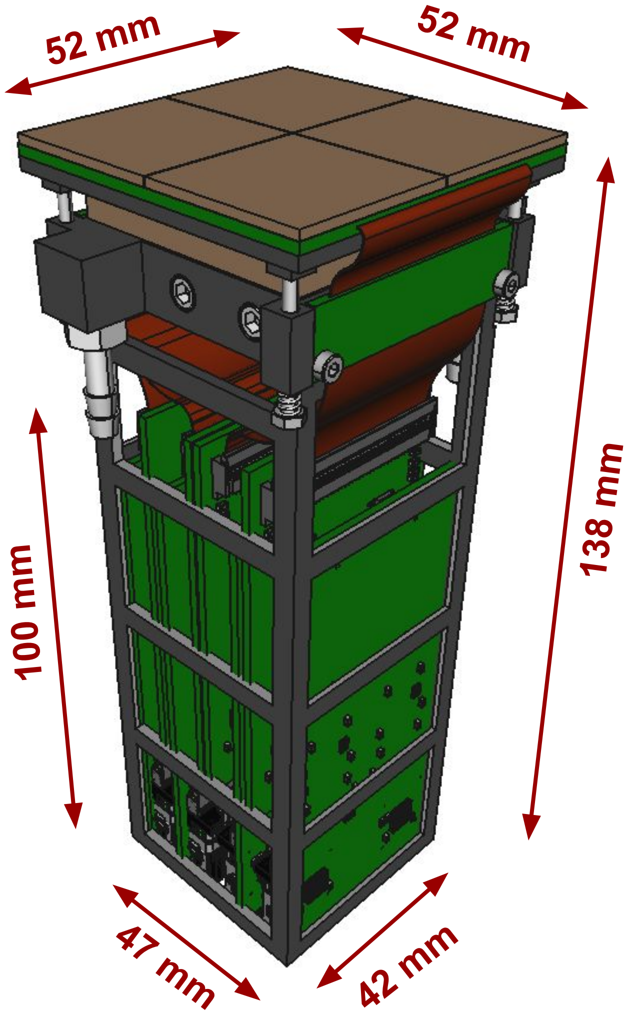
includes contribution for
laser-oscilloscope synchronization
measured to be σ_{sync} = 30 ps

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





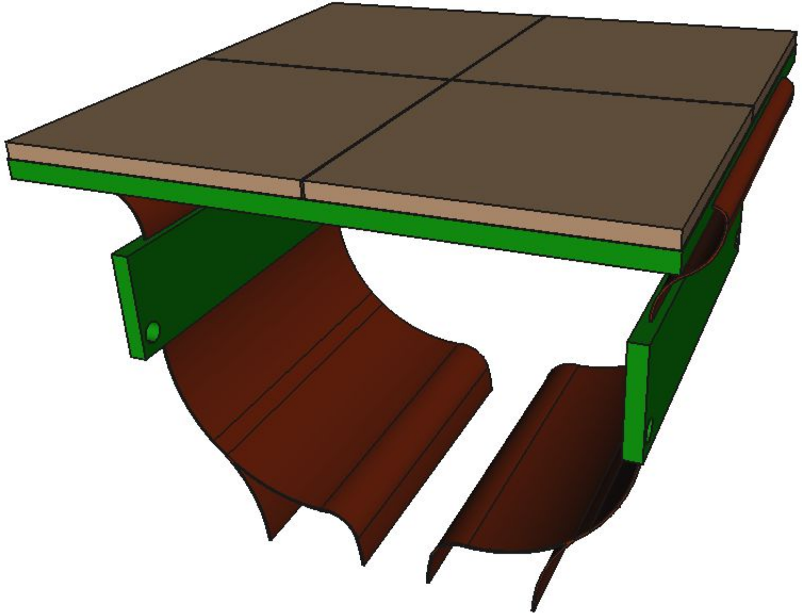

52 mm
52 mm
138 mm
100 mm
47 mm
42 mm

Carrier board V2

mounts 4x SiPM sensor matrices (256 total channels)
receives HV and sends signals via flex connectors (1 mm bending radius)
PCB-flex-PCB-flex design to host HV RC-filters
back-side temperature sensors for monitor / feedback

project completed
boards received

designed in Bologna
Casimiro Baldanza



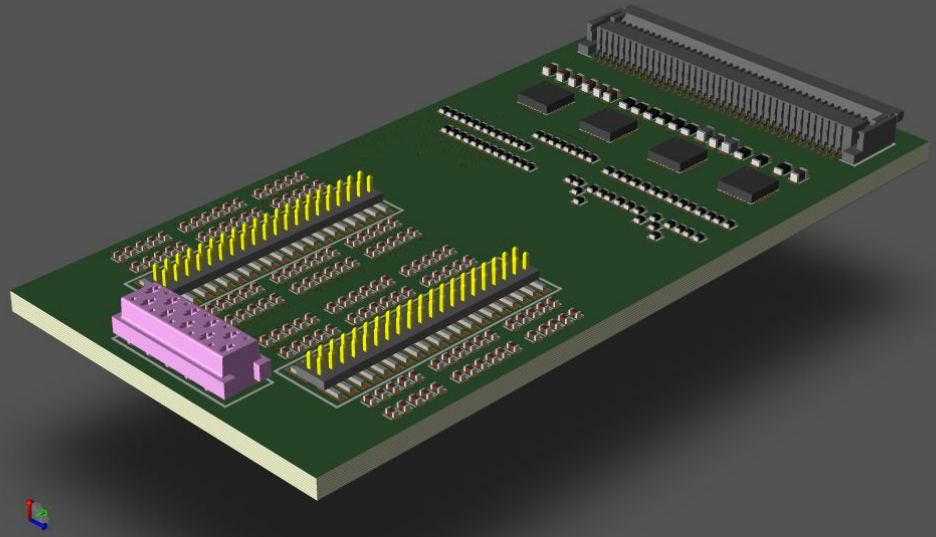
Adapter board and MasterLogic V2

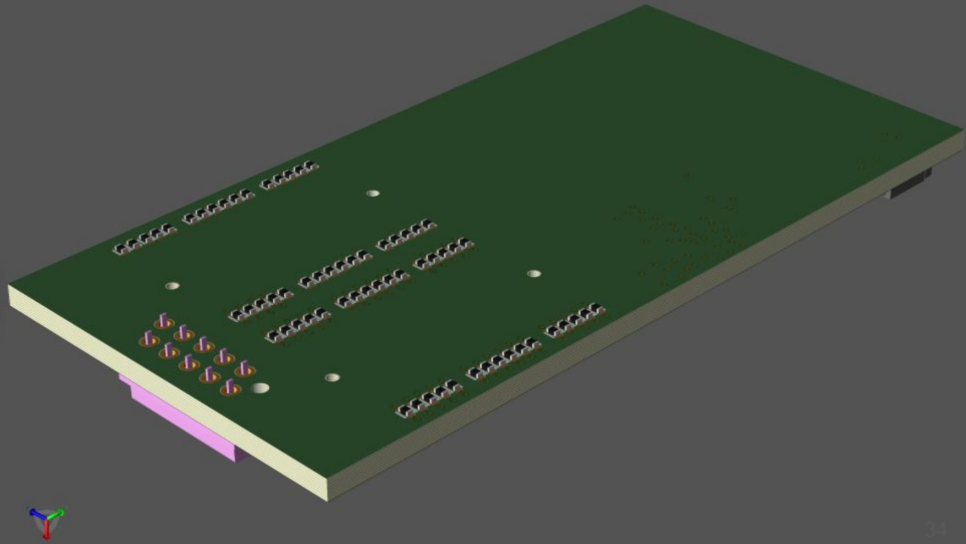
receives signals from SiPM, ships them to ALCOR
includes **complex circuitry** to

- allow HV regulation
  - 0-5 V for each channel
  - 0-80 V for groups of 8 channels
- derivate signals before ALCOR
- switch from "regular mode" to "annealing mode"

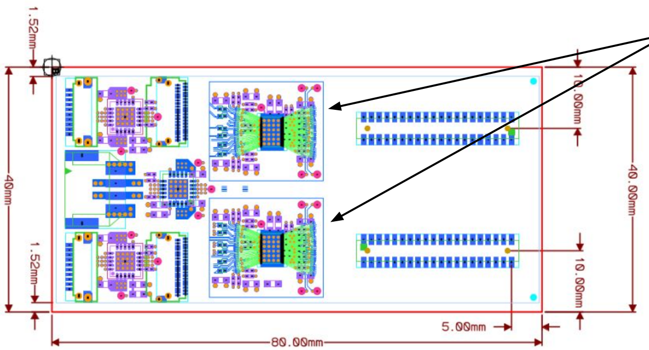
project completed
boards received

designed in Ferrara
Roberto Malaguti





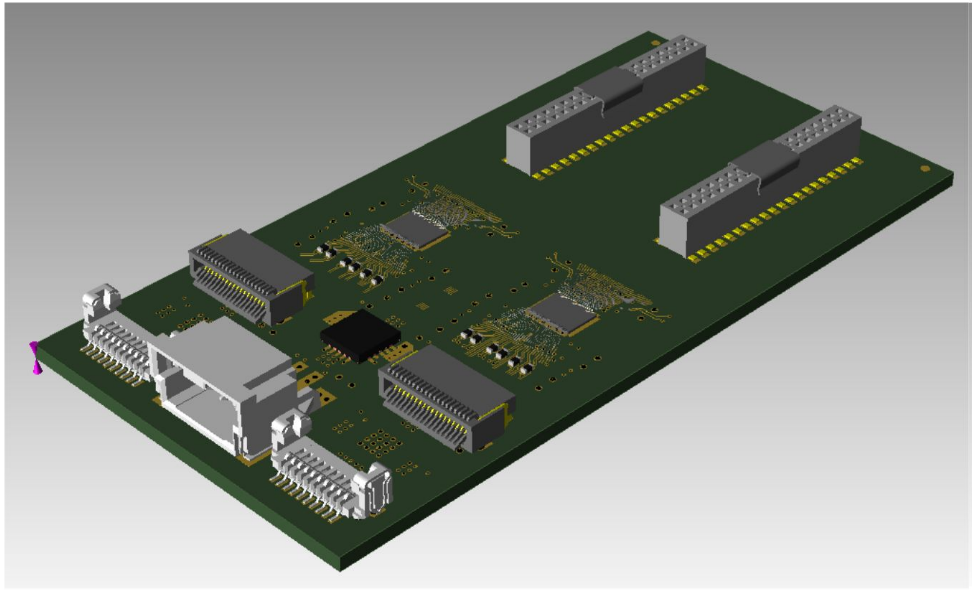
ALCOR board V2

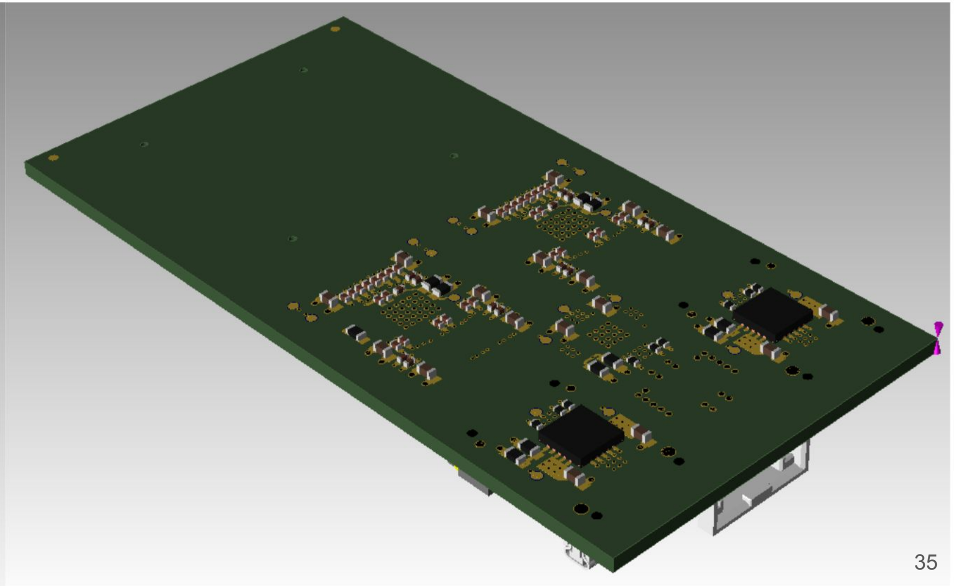


2x ALCOR-v2 ASICs (2x 32 channels)
future ALCOR-v3 will be 64 channels

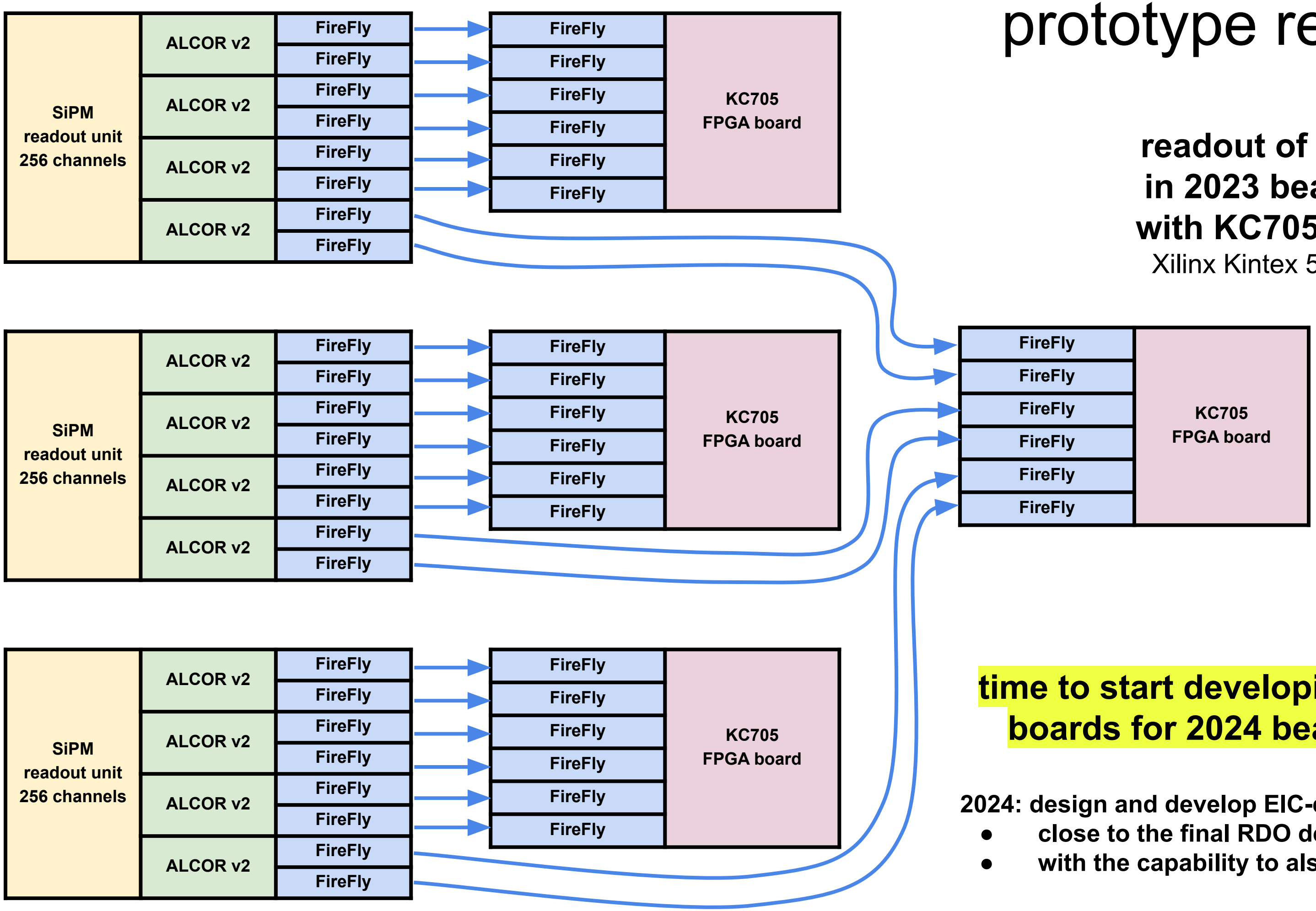
project completed
boards received

designed in Torino
Marco Mignone





prototype readout in 2023



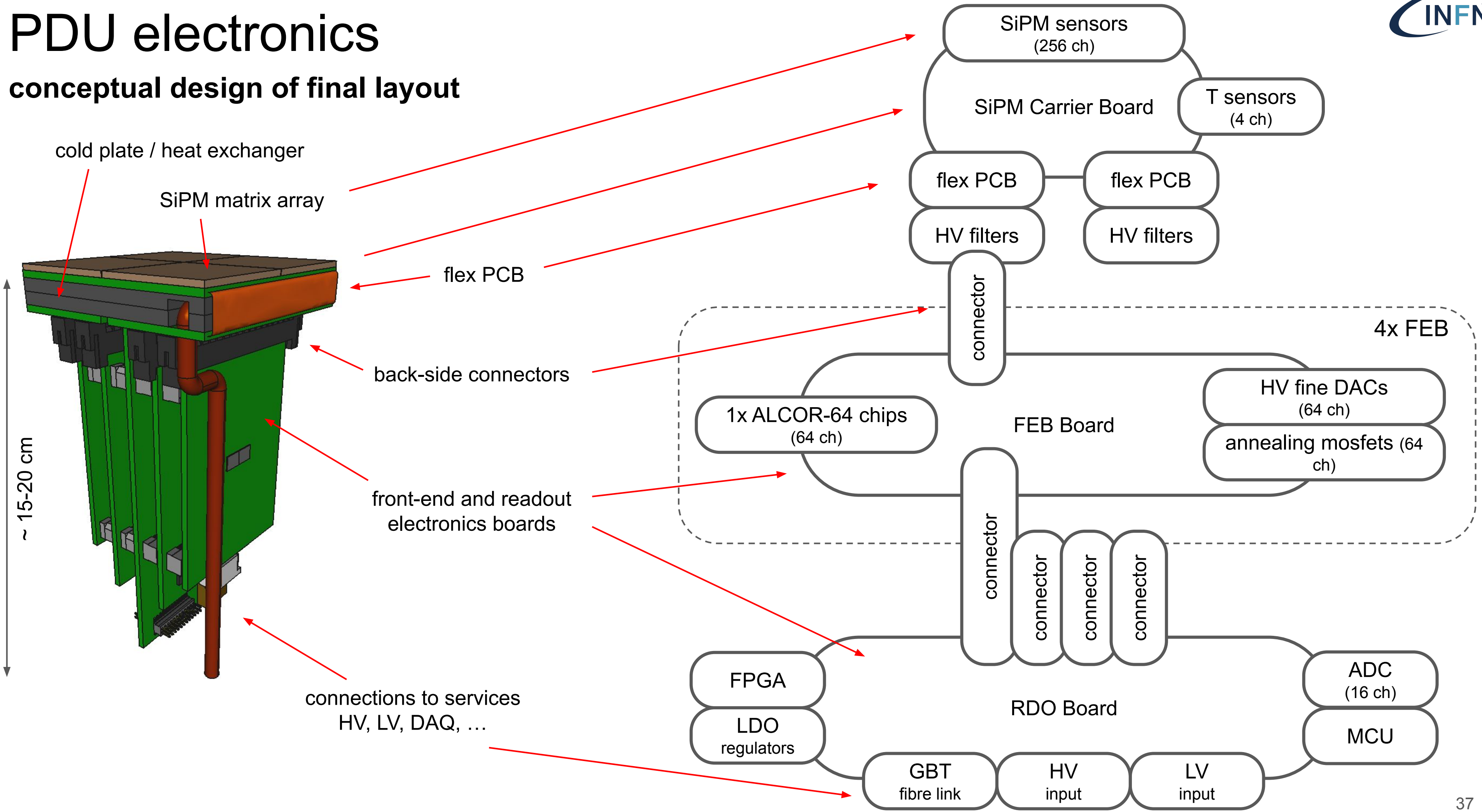
readout of photodetector units in 2023 beam test will be done with KC705 commercial boards
Xilinx Kintex 5 FPGA evaluation boards

time to start developing custom readout boards for 2024 beam tests and TDR

2024: design and develop EIC-driven readout boards (RDO)
- **close to the final RDO design and PDU layout**
- **with the capability to also serve current electronics**

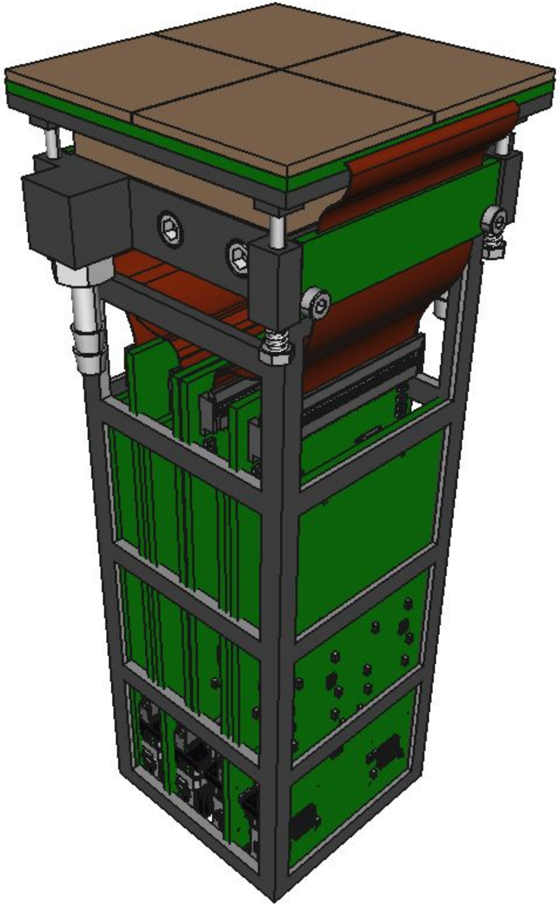
PDU electronics

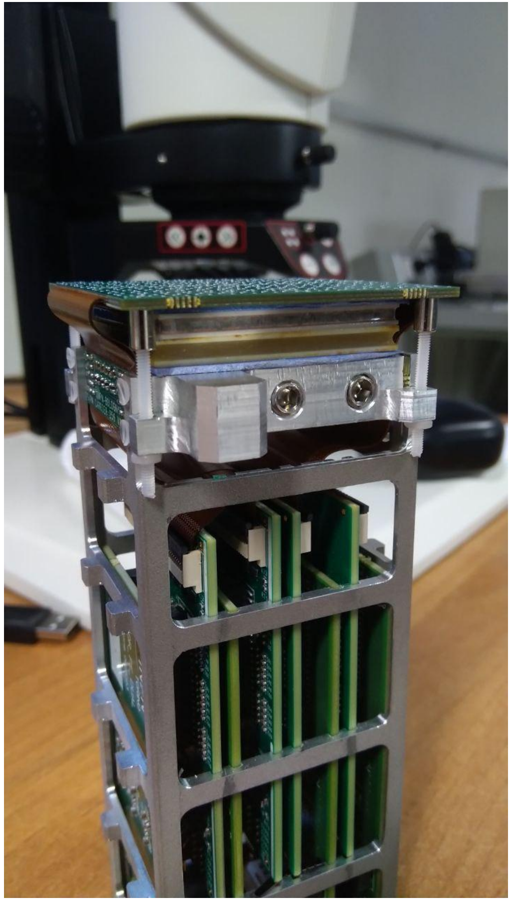
conceptual design of final layout

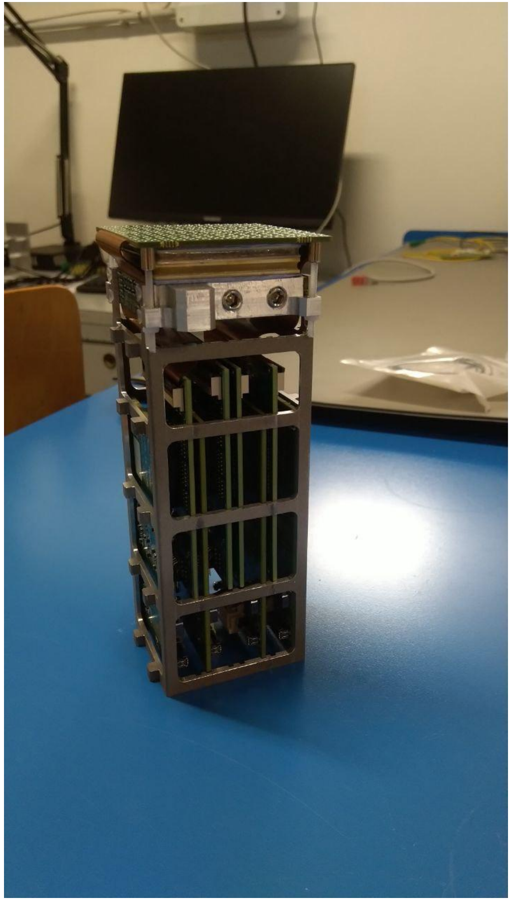


From design to assembly

dummy assembly tests with empty SiPM carriers
to check mechanical tolerances and get confidence with new electronics (come in lab to see the real piece)

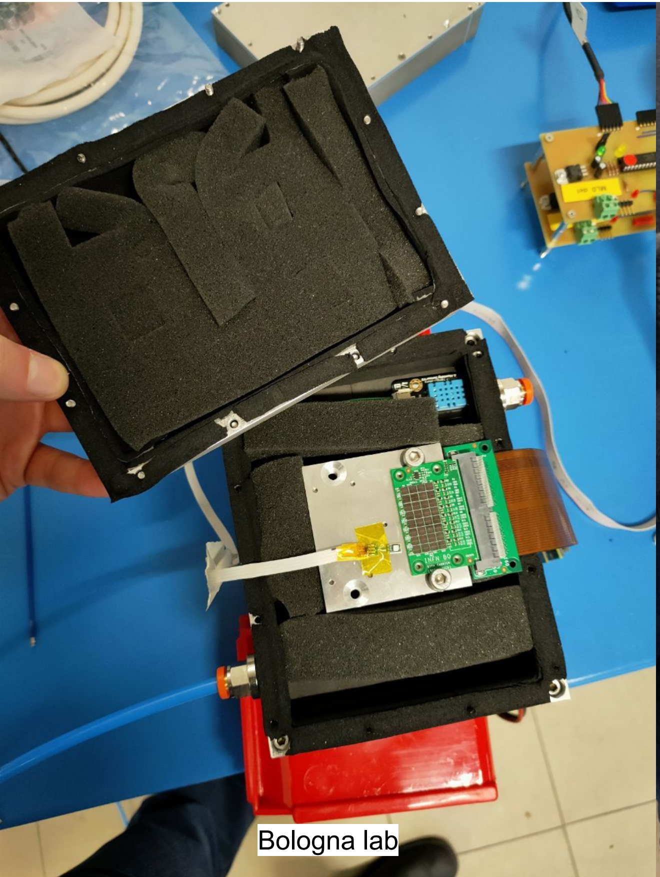




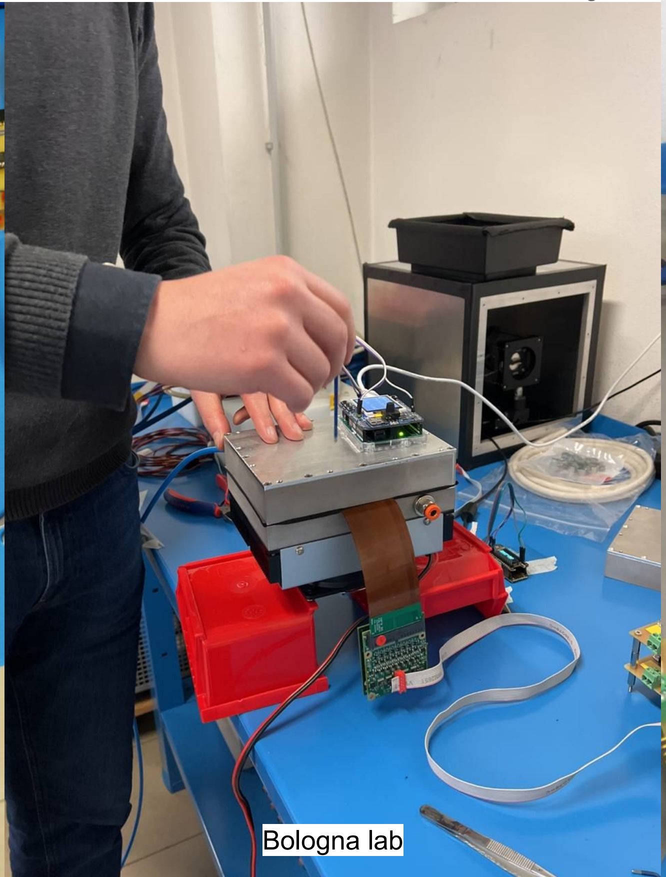


Air-cooled portable Peltier box

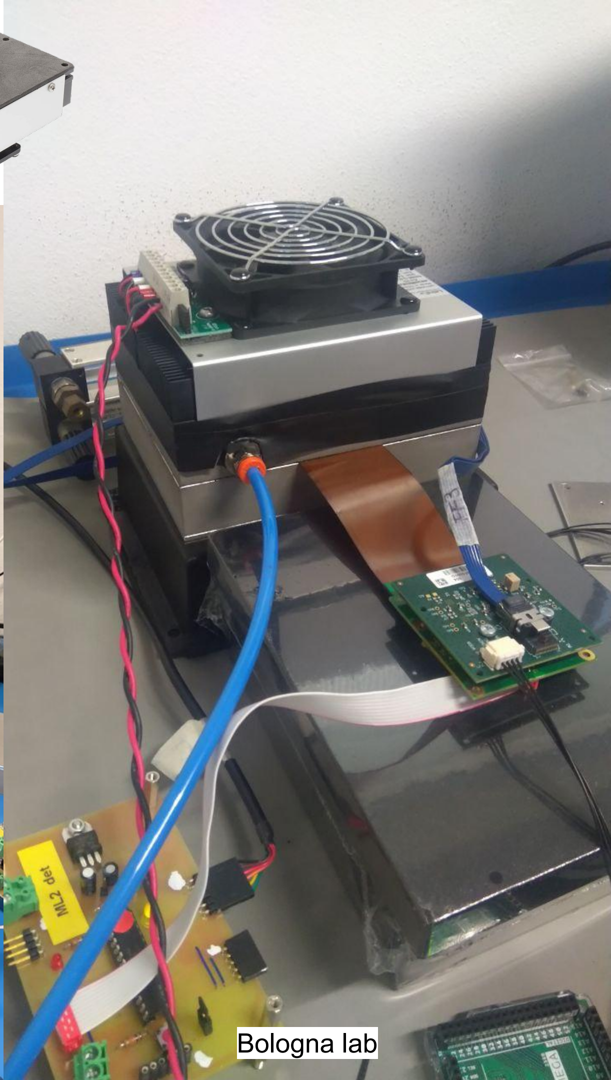
designed and realised by us based on Laird cooler assembly



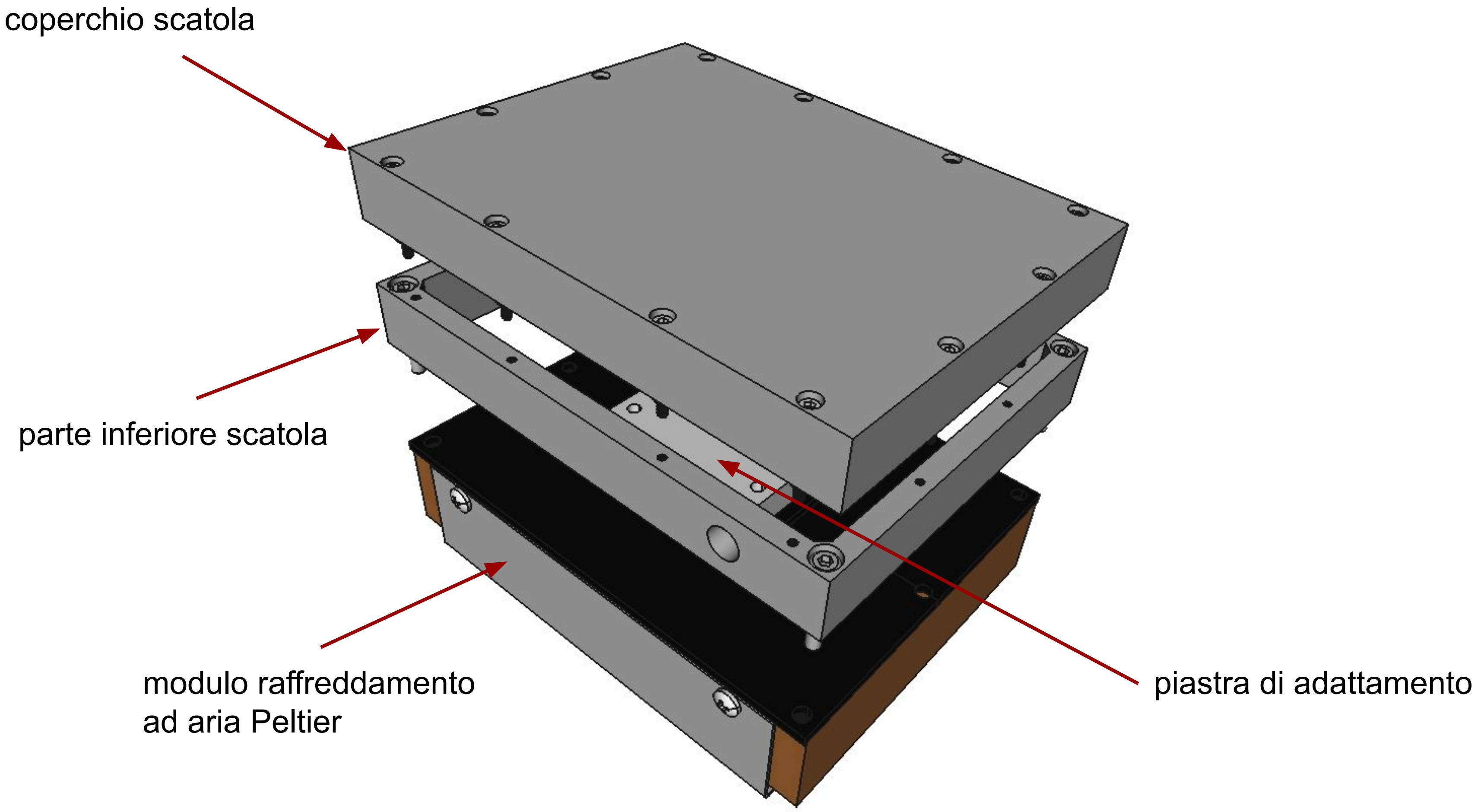
Bologna lab



Bologna lab

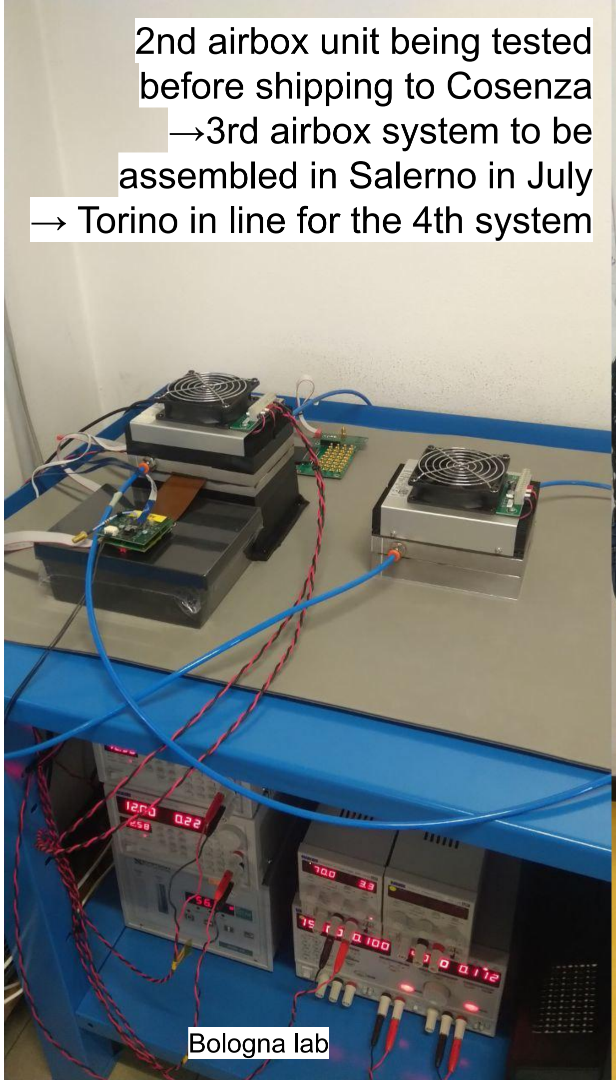


Bologna lab


coperchio scatola
parte inferiore scatola
modulo raffreddamento
ad aria Peltier
piastra di adattamento

airbox in Cosenza

- **airbox installed in Cosenza**
  - after tests in Bologna
  - shipped to Cosenza
  - system installed on 13-14 April
  - good teamwork
    - Bologna
    - Cosenza
    - Salerno
- **Cosenza ready to contribute**
  - to SiPM characterisation
  - in charge of proton-energy scan
- **3rd airbox to Salerno**
  - system will be installed in July
  - increase SiPM test capacity
- **Torino in line for 4th system**
  - for tests of ALCOR chip with SiPM at low T



2nd airbox unit being tested before shipping to Cosenza
→3rd airbox system to be assembled in Salerno in July
→ Torino in line for the 4th system

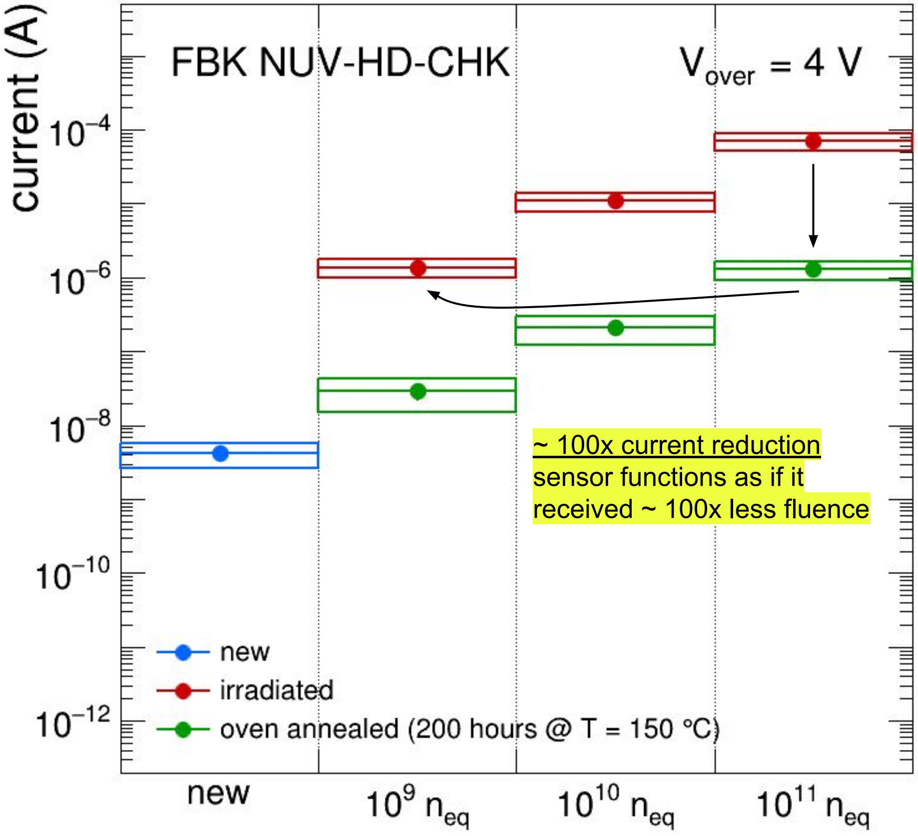
Bologna lab

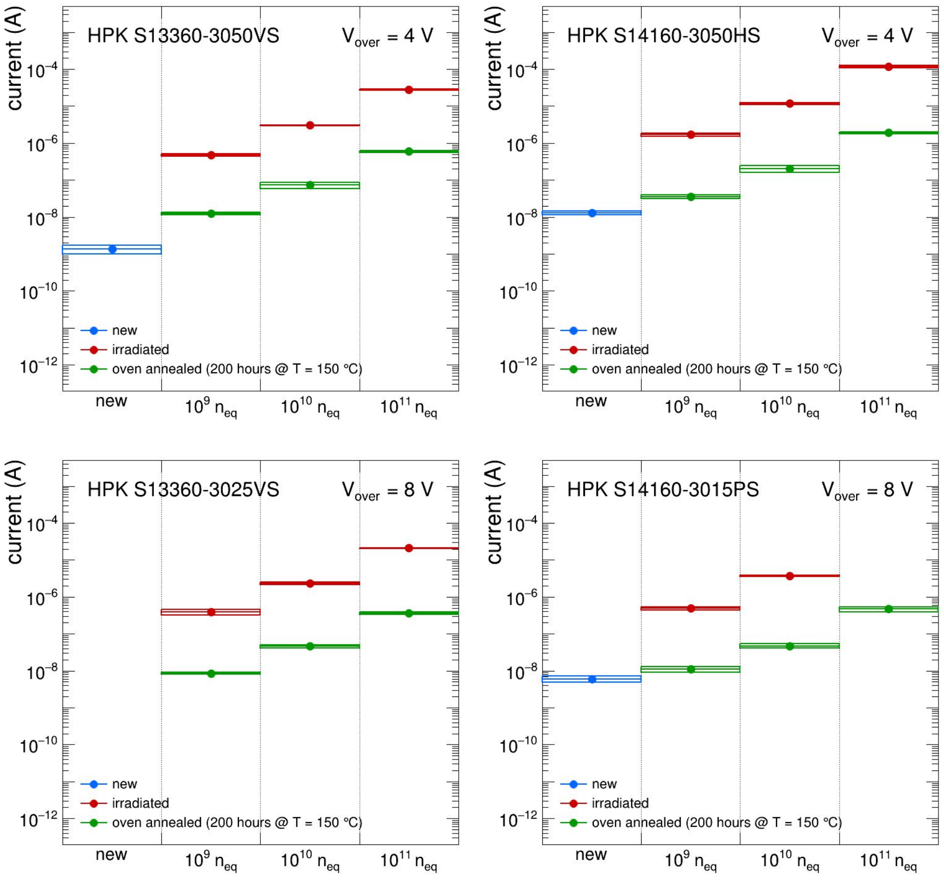
system installed on 13-14 April in Cosenza → ready to contribute to SiPM characterisation

Cosenza lab

High-temperature annealing recovery

oven annealing
~ 1 week at 150 C

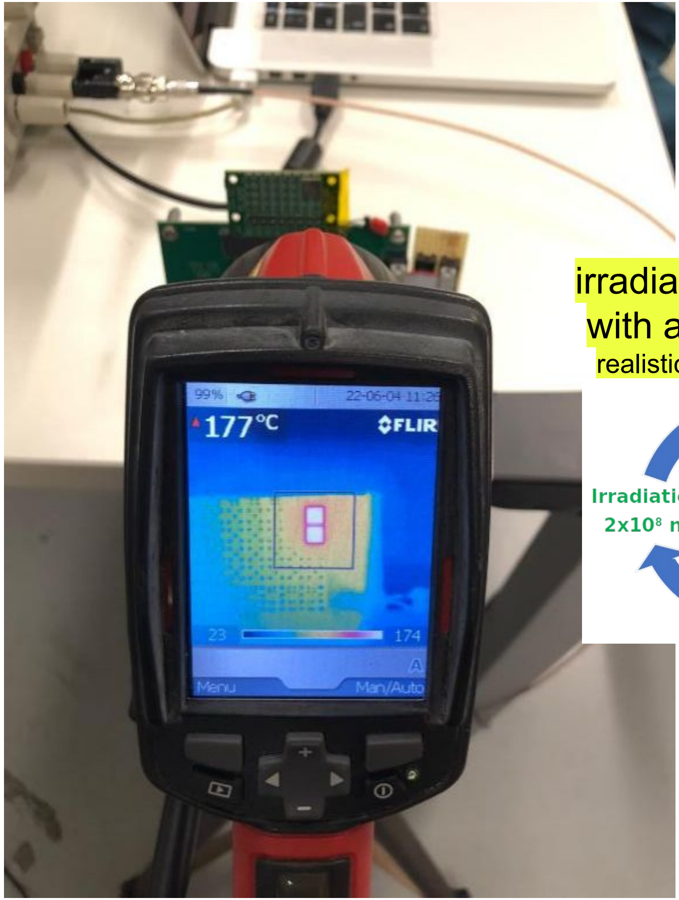




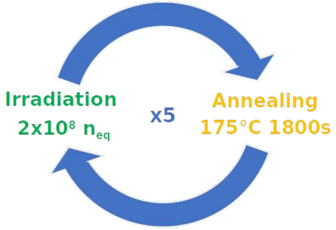
similar observation with various types of Hamamatsu sensors

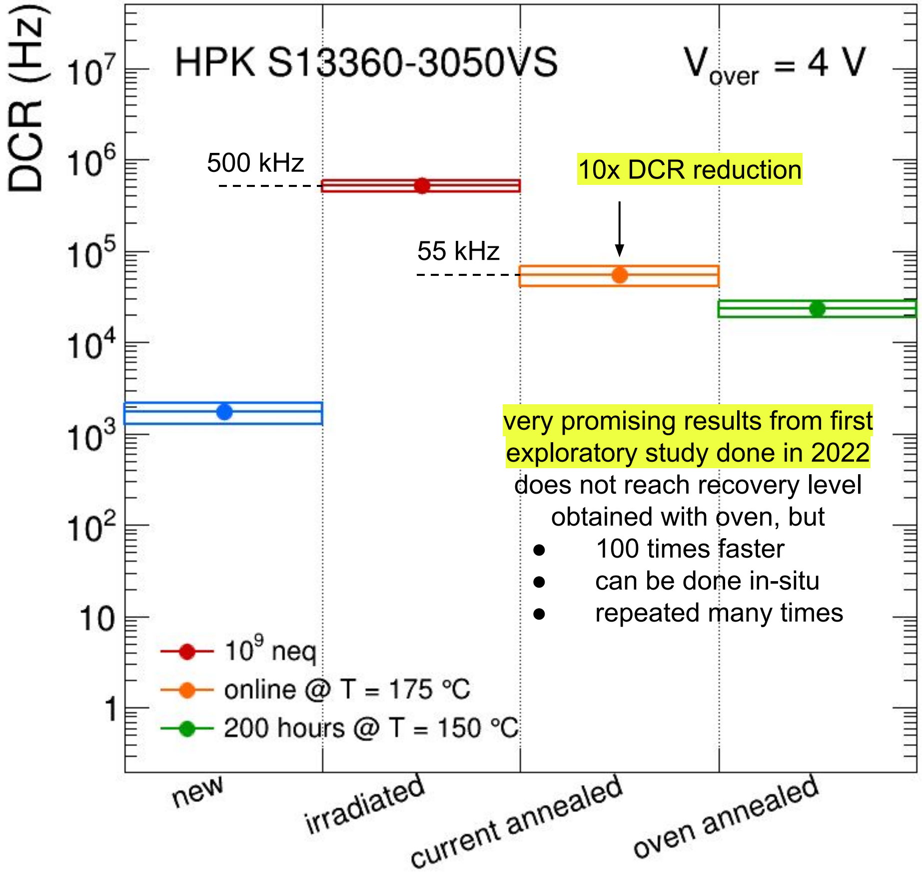
“Online” self-induced annealing

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



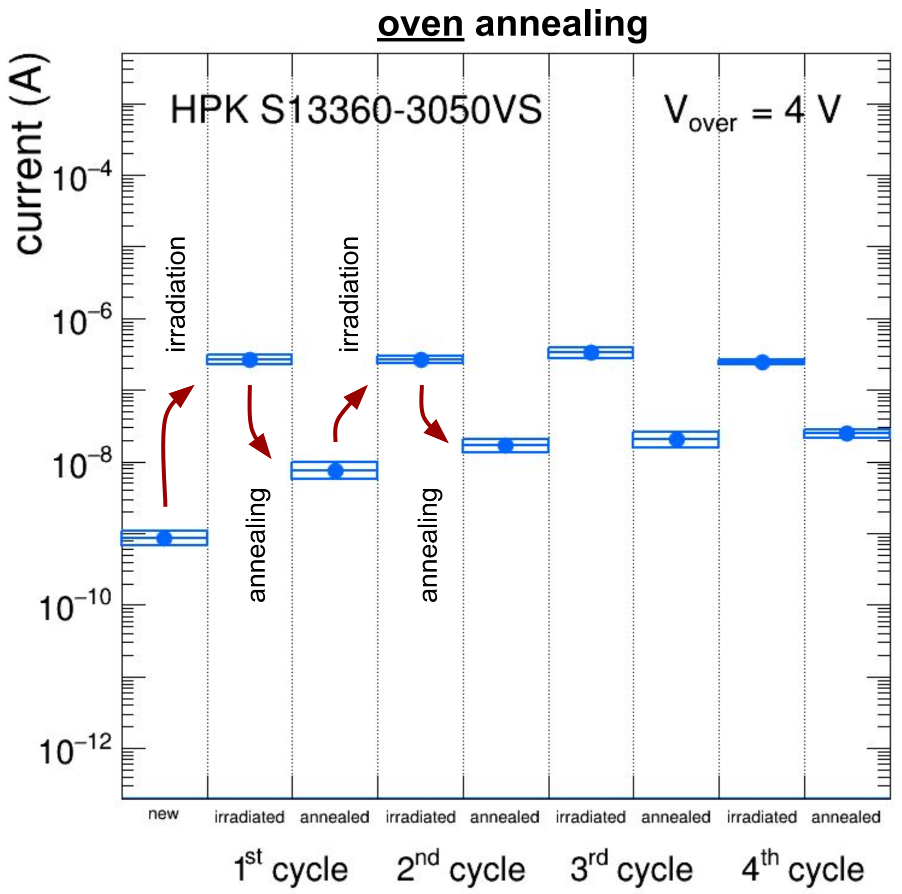
irradiation interleaved with annealing cycle
realistic experimental case





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

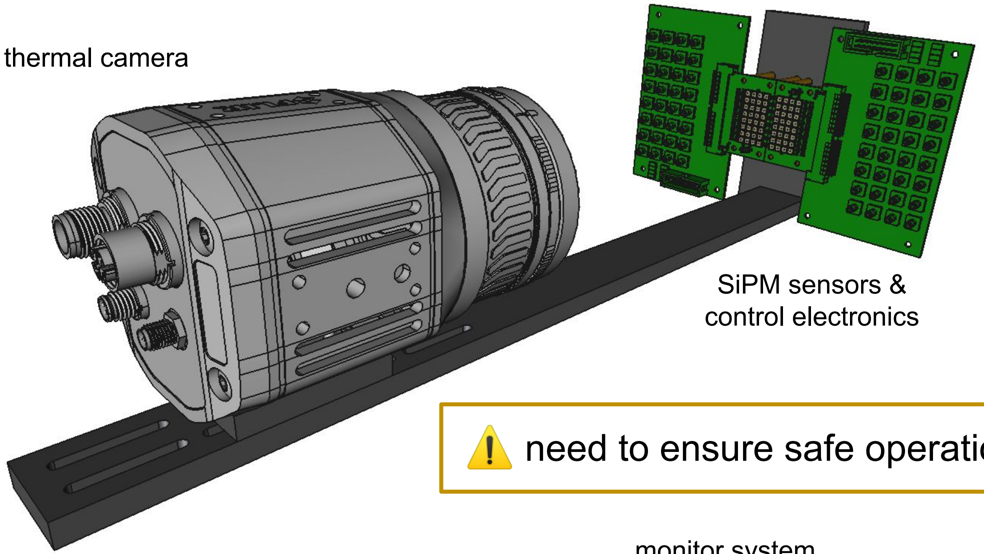
- consistent irradiation damage
  - DCR increases by ~ 500 kHz (@ Vover = 4)
  - after each shot of 10^9 n_{eq}
- consistent residual damage
  - ~ 15 kHz (@ Vover = 4) of residual DCR
  - builds up after each irradiation-annealing

annealing cures same fraction of newly-produced damage

~ 97% for HPK S13360-3050 sensors

Automated multiple SiPM online self-annealing

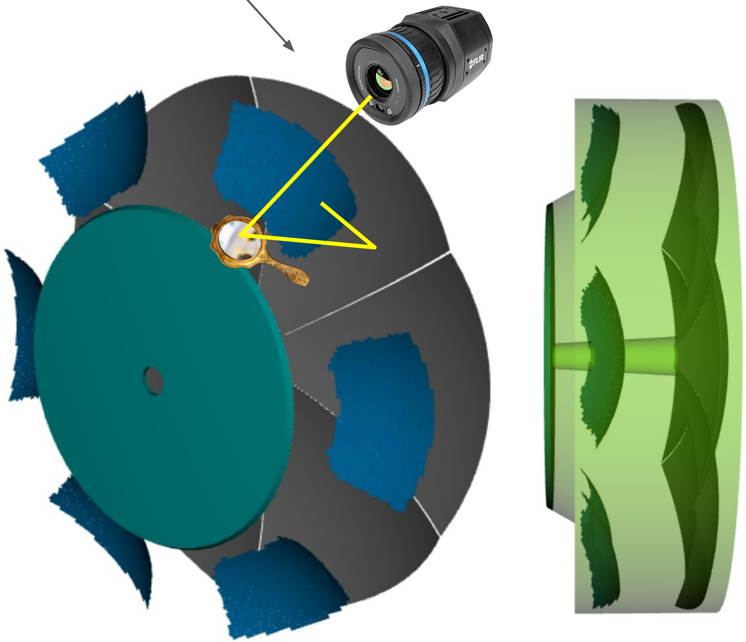
thermal camera



SiPM sensors &
control electronics

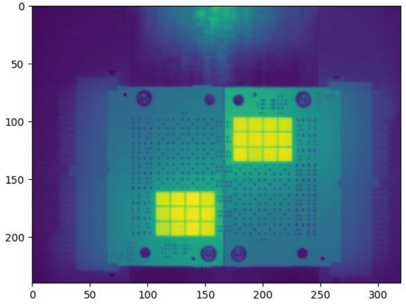
demonstrator system for online temperature monitor and control of each individual SiPM

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

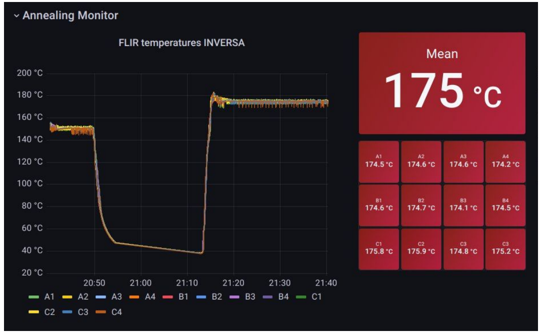


⚠️ need to ensure safe operation

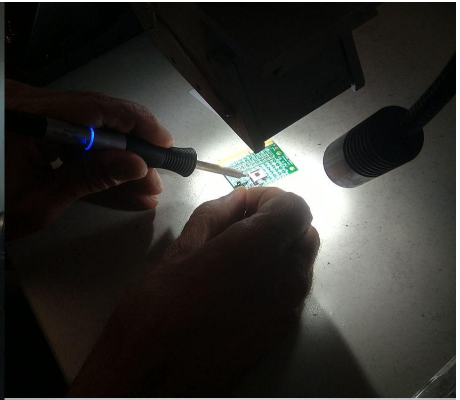
thermal image

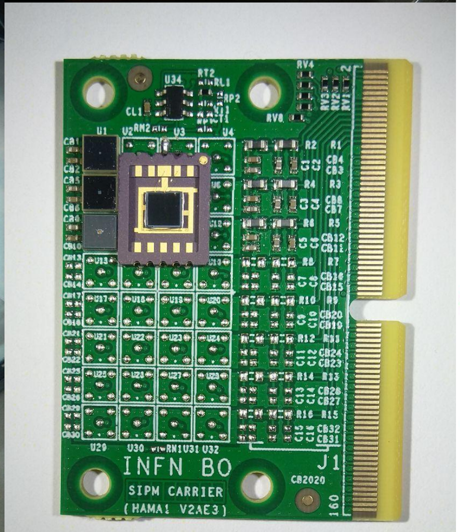


monitor system



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

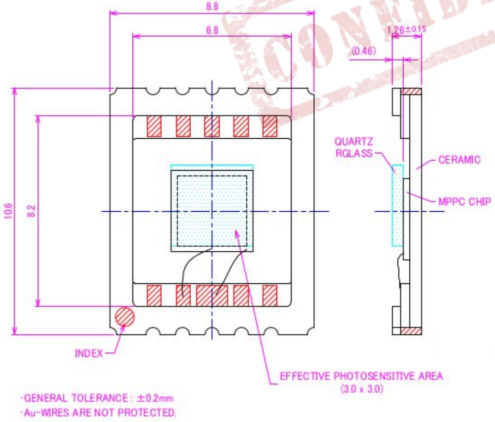
on paper they look VERY promising

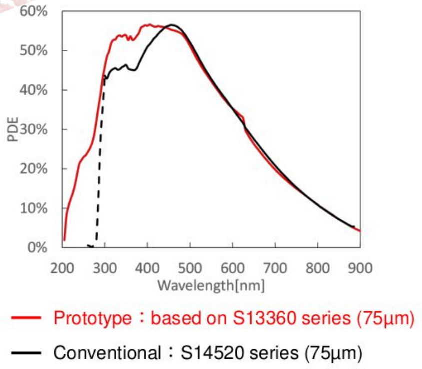
- improved NUV sensitivity
- improved signal shape
- improved recharge time

mounted on EIC SiPM test boards

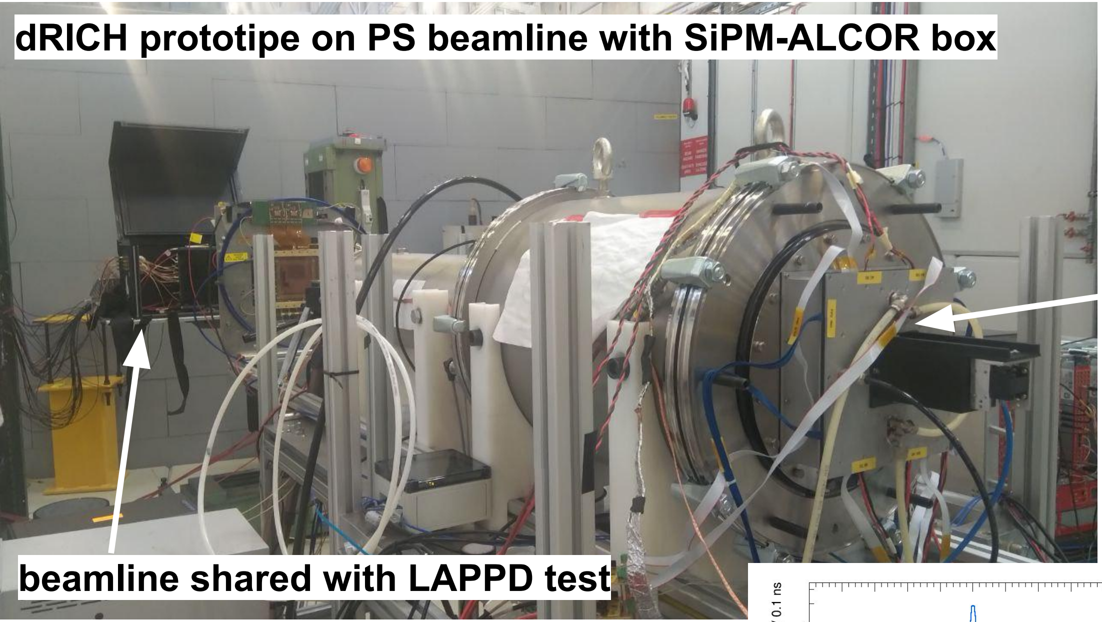
we will characterise and test them in full

irradiation, annealing, laser, …





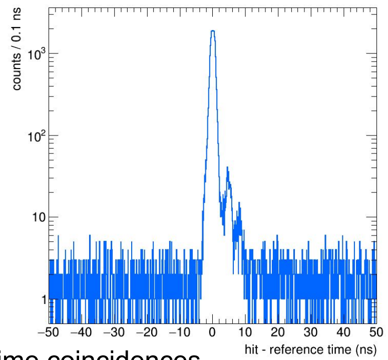
2022 test beam at CERN-PS



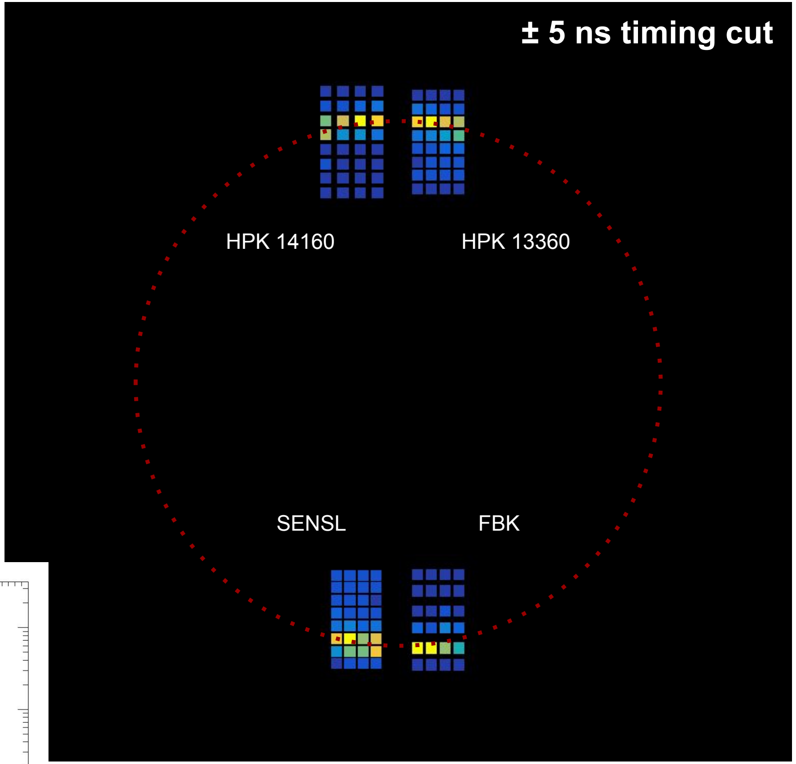
successful operation of SiPM

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

and annealed (in oven at 150 C)



time coincidences



8 GeV negative beam (aerogel rings)