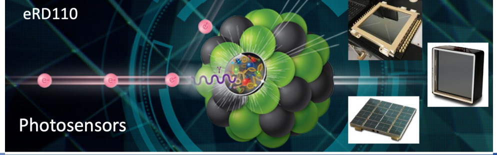


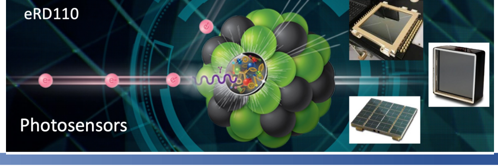
ePIC Collaboration meeting
9-11 January 2023

Cherenkov PID: photosensors

P. Antonioli – INFN Bologna

on behalf of the ePIC Cherenkov PID Working Group
(and special thanks to A. Kiselev, R. Preghenella and J. Schwiening)

photosensors for Cerenkov PID



*"The objective of the R&D effort presented here is to **mitigate technical, cost, and schedule risk related to readout sensors of EIC Cherenkov detectors and Calorimeters.** The call for this proposal requests that this R&D effort comes to a clear and well-informed decision for a baseline sensor solution for each PID detector in FY22. <u>Our common consensus is that R&D effort beyond FY22 is absolutely necessary</u> in order to be able to form a decision that capitalizes on all state-of-the-art technologies to mitigate all of the risks specified above".*

from eRD110 proposal

ePIC Cherenkov PID photosensors as of Jan 2023

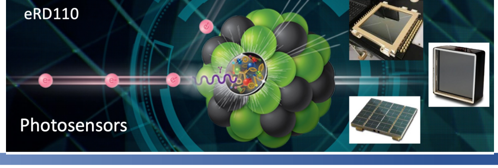
backward RICH	hpDIRC	dRICH
LAPPD/HRPPD	MCP-PMT (→ HRPPD?)	SiPM

LAPPD (20x20 cm): Large Area Picosecond Photon Detector
HRPPD (10x20 cm): High Rate Picosecond Photon Detector
strip/pixelated readout
SIPM: Silicon Photo Multipliers / Multi-Pixel Photon Counter → MPPC arrays ("SiPMs tile")

<u>Disclaimer:</u>
- no discussion about electronics
- no discussion about MCP-PMT for DIRC (no recent R&D)

"what happened since last ePIC meeting?"

the candidates table (June 2022)



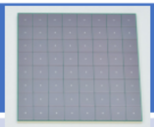
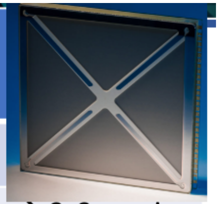
eRD110 presentation shown at "From RICH to EIC" / AGS/RHIC user meeting – June 2022

B-field (LAPPD)

Radiation (SiPM))

commercially available (ex.: Planacon XP85122) with (< 100 ps time resolution are ok. Problem is price tag (hpDIRC)

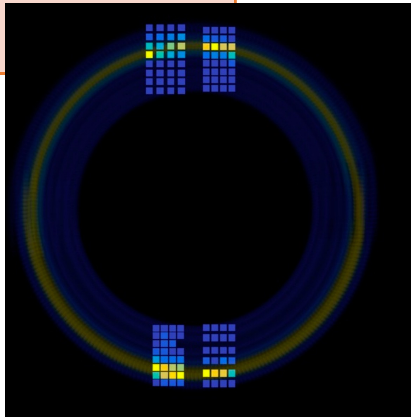
move from prototypes to "production" (LAPPD)

	MCP-PMT/Planacon 	SiPM 	LAPPD 
Area	5x5 cm^2	Tiles available 5.76 cm^2	20x20 cm^2
Pixel		3x3 mm^2	25 x 25 mm available → 3x3 mm in future?
Magnetic field	Seen drop in collection efficiency at angle > 10 deg	insensitive	0.7 T on 20 μm MC seems ok, depending orientation. Smaller MCP's for larger field
Radiation	insensitive	neeeds test + assess mitigation protocol (annealing)	No data, but reasonable to expect not a problem
Availabteyility	In stock*	In stock*	"In-stock" for 20 μm
Manufacturers	Photonis/Photek	many (HPK, OnSemi, FBK/L-Foundry, Ketek/Boradcom)	Incom
Price	$ 15-20 k$ each (few units)	1 k$ /(8x8 tile 3x3 mm)	$25-50K each LAPPD (20x20 cm^2 or 10x10 cm^2 similar price)
Unit price	16 k$/25 cm^2 = 600 $/cm^2	≈50-100 $/cm^2	62.5-500 $/cm^2
Concerns	cost	DCR increase with radiation	Cross talk, integration, availability
Risks	None	None if mitigation of DCR increase "manageable"	Achievable with risk, time schedule challenging

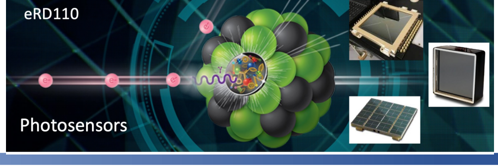
SiPM: the R&D program so far (an outline)

sensor	• SiPM selection by manufacturer, Vbd, SPAD cell • R&D with FBK
electronics	SiPM carriers/adapters – readout cards for ALCOR ASIC
irradiation	• with proton beams (140 MeV) • fluences from 10^9 to 10^{11} 1 MeV-n_{eq}/cm^2
annealing	• High-temperature cycles (oven) • electrically induced annealing
characterization	I-V, DCR, LED pulse in climatic chamber
test beams	test on dRICH prototy (aerogel only) using irradiated & annealed sensors

SIPM never used so far for Cerenkov detectors (retain single photon sensitivity). DCR increase with radiation well known risk.



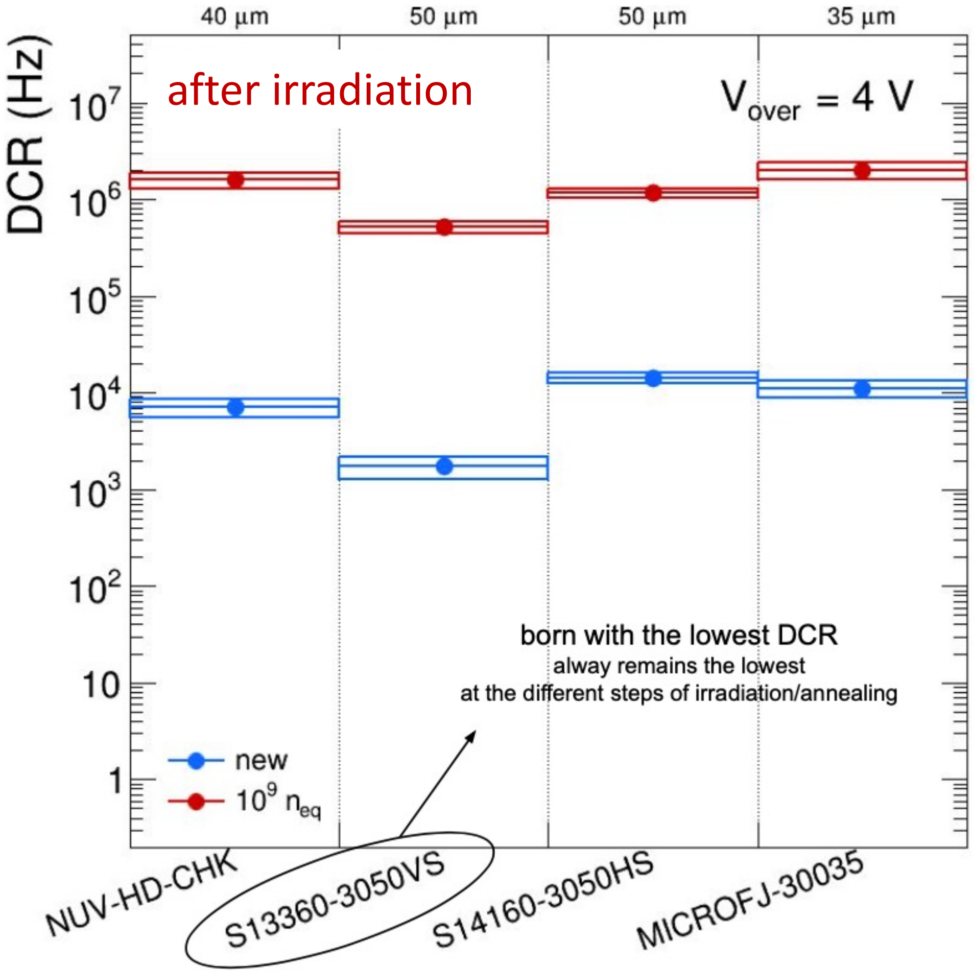
DCR: after irradiation and post-annealing

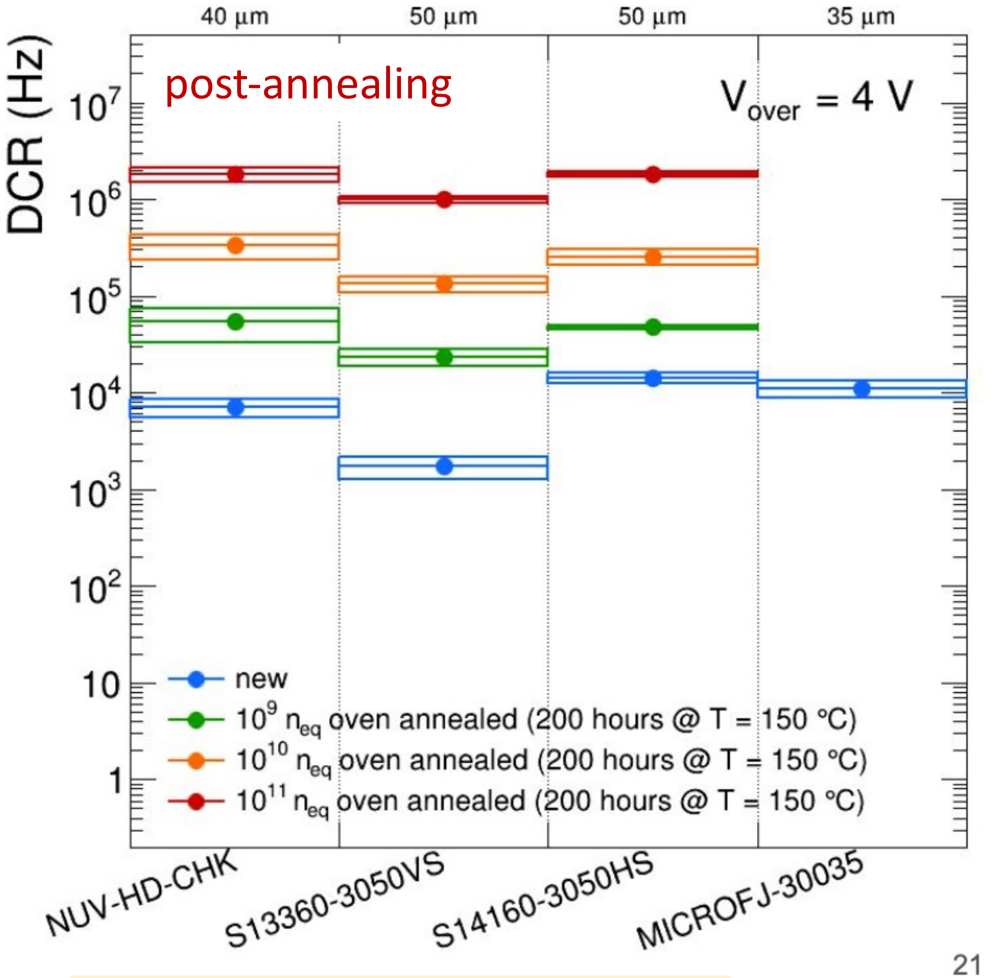


INFN BO-FE-TO

-30 °C

150 °C

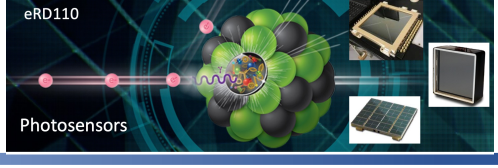




O(100) DCR increase after 10^{11} n_{eq}

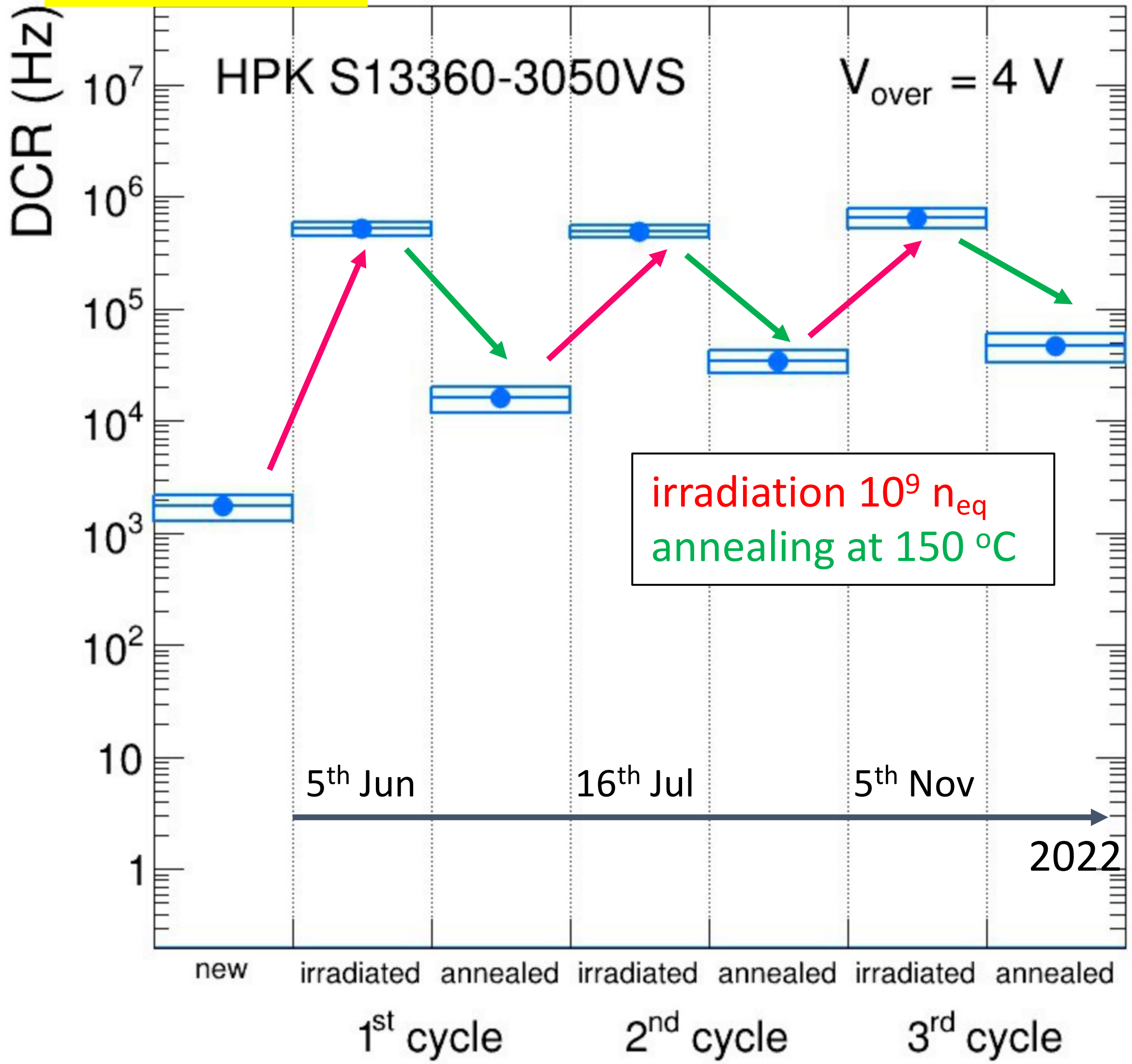
O(10) DCR recovery post-annealing

Much more results discussed/presented at RICH2022 and CPAD2022 conferences.



2022 campaign: irradiation + annealing cycles

INFN BO-FE-TO



"getting closer to the experimental setup"

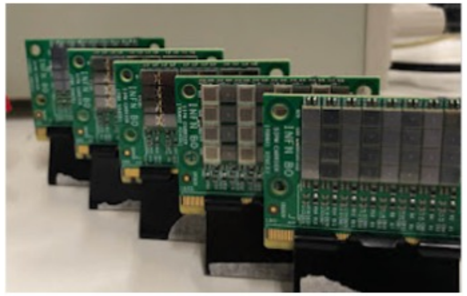
- test reproducibility of repeated irradiated/annealing cycles on the same sensors. Last shot 3rd December.
- each shot is 10^9 n_{eq} (remember: 0.2/1 year EIC at max lumi)
- extract parameters (<u>sensor and V_{over} specific</u>!) to shape annealing cycles in the experiment:
  - f_d : every 10^9 n_{eq} increases by 500 kHz DCR pixel rate (3x3 mm^2)
  - f_a : each annealing leaves 15 kHz of additional DCR rate

$$DCR_r(k) = DCR_0 + f_d + (k-1)f_a$$

DCR after k irradiation and k-1 annealing cycles

- damage and recovery remain additive
- annealing repairs f_a/f_d of a given sensor (97% here)

Total of 134 sensors under test



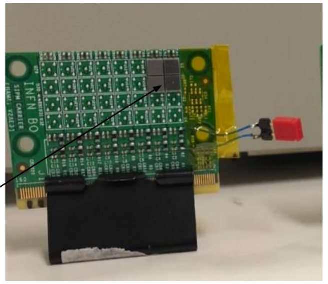
*Take home message

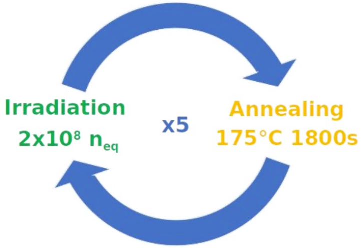
radiation damage and its recovery measured & parameterized

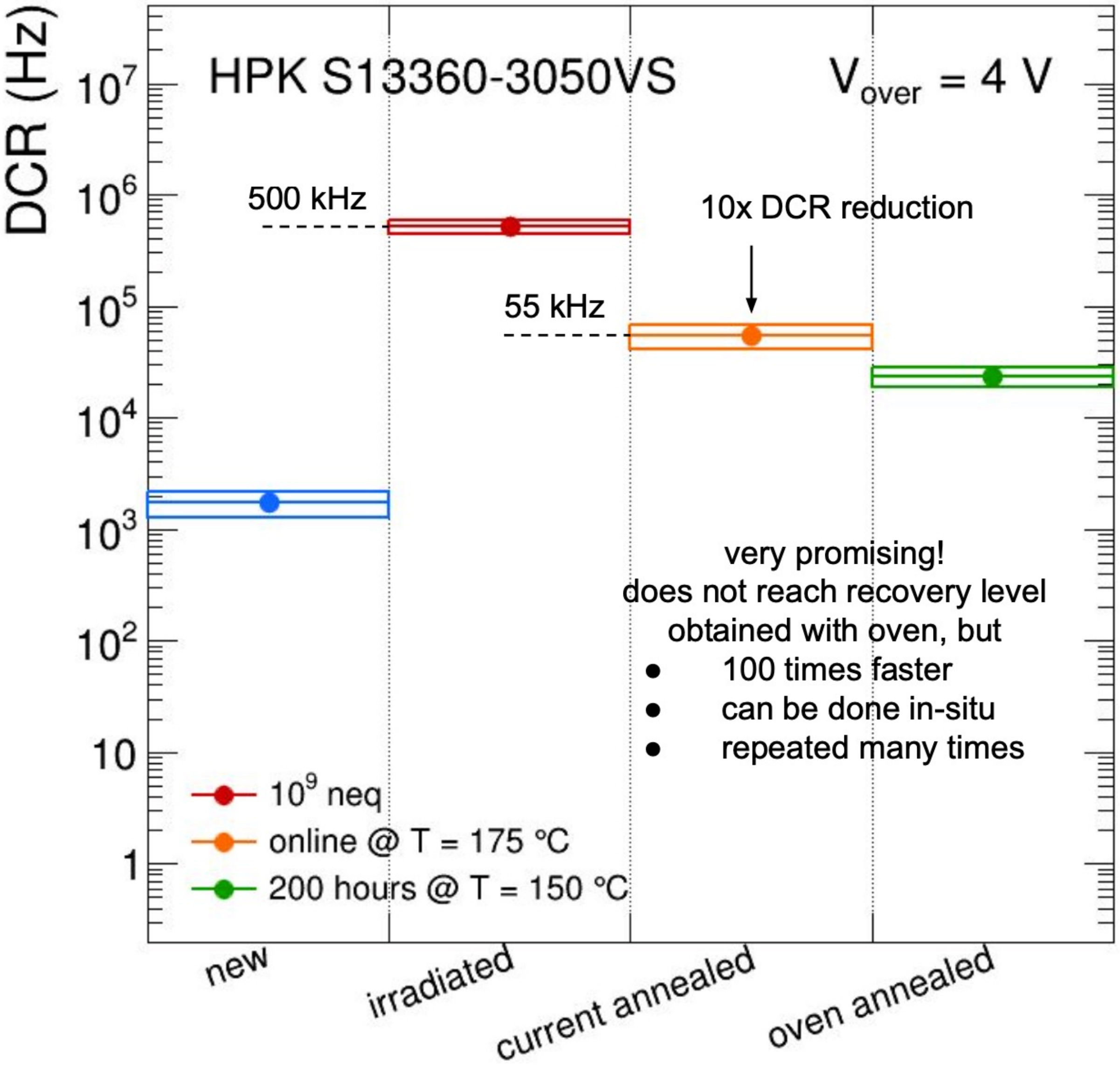
"Getting closer to the experimental setup"

testing online annealing solutions ("in situ")

INFN BO-FE-TO



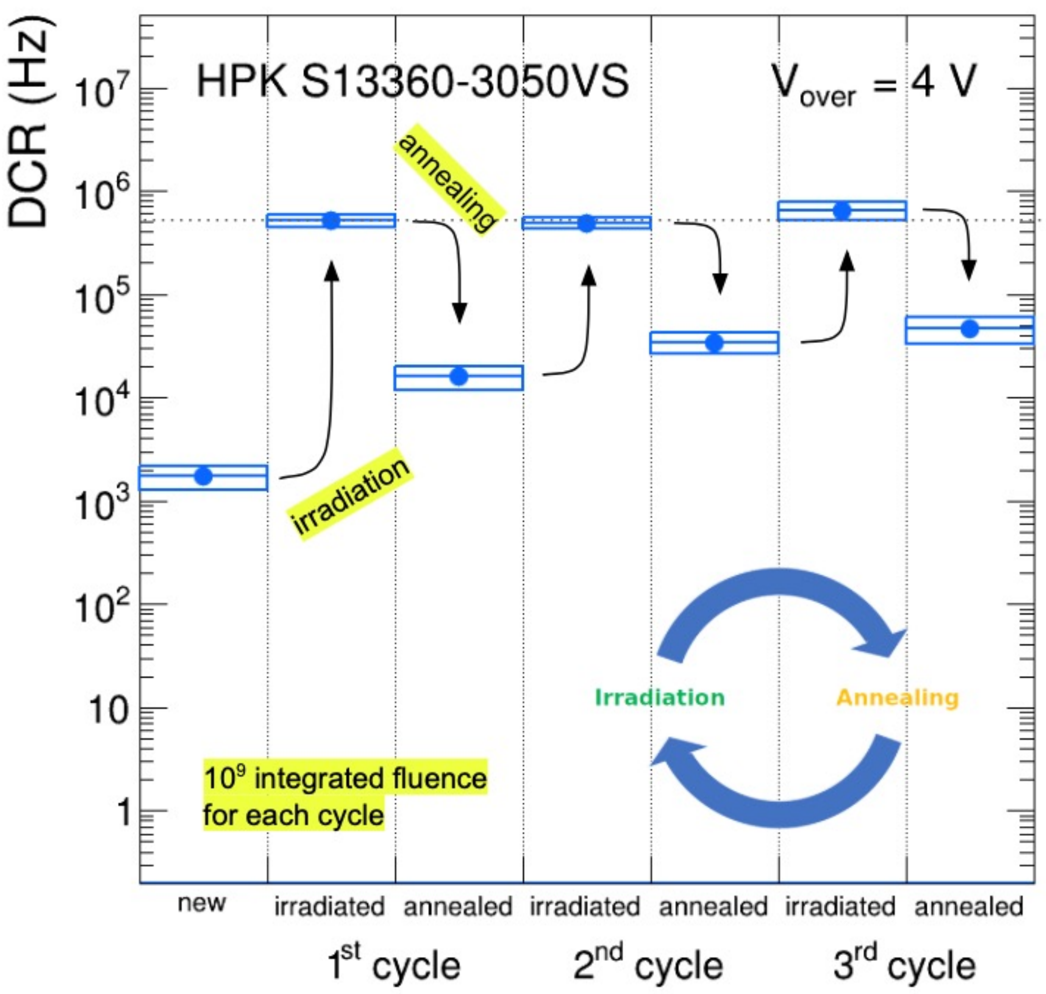


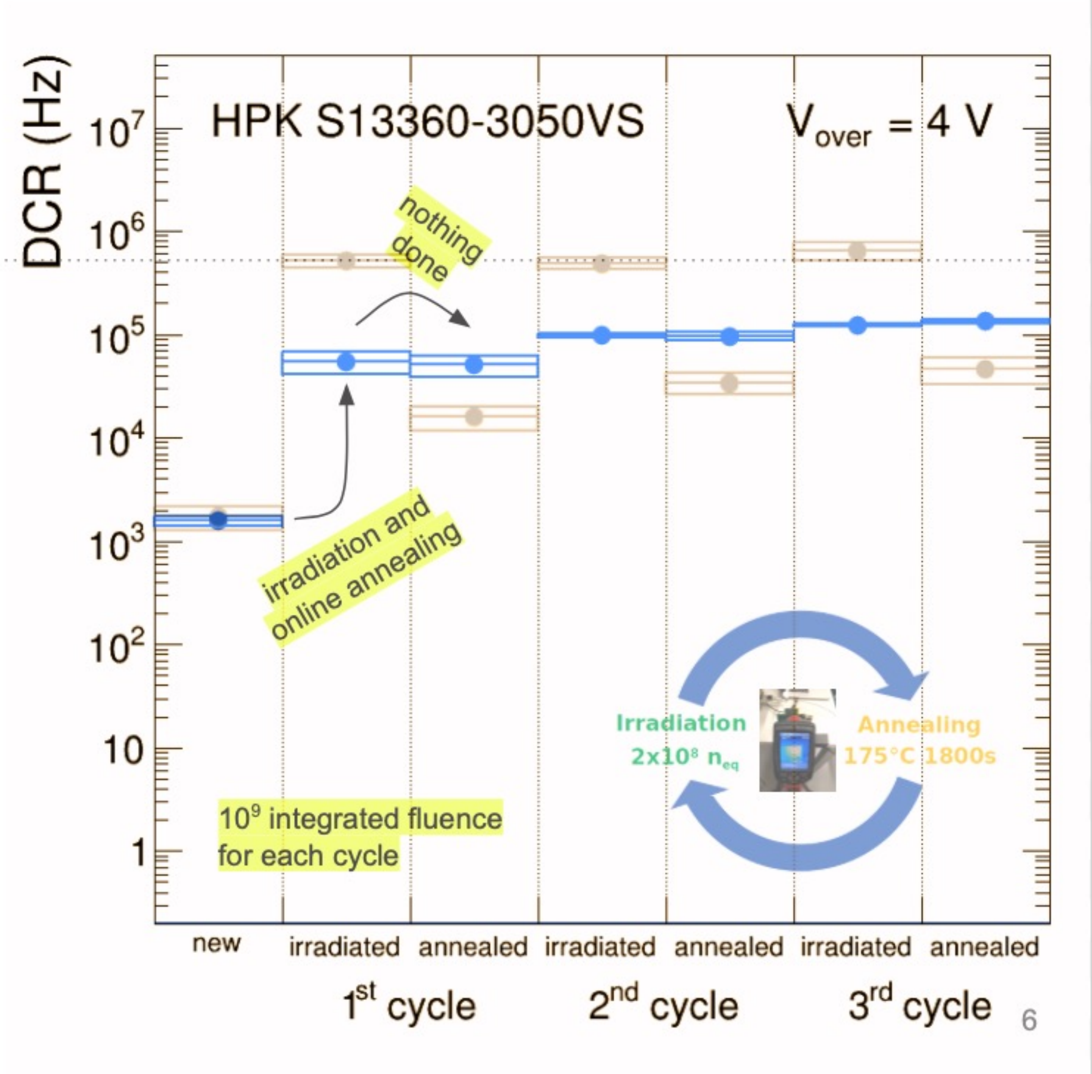


M. Cordelli *et al* 2021 *JINST* **16** T12012 results on HPK and SensL (OnSemi) sensors, both forward and inverse bias

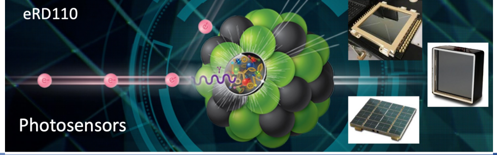
- preliminary test on electrical annealing techniques
- forward bias + Joule effect: ~ 1 W / sensor → T = 175 °C
- could pave the way to more frequent (and without dismounting sensors) annealing cycles
- irradiation fluence (10^9 n_{eq}) split in five shots, interleaved by 30 minutes annealing

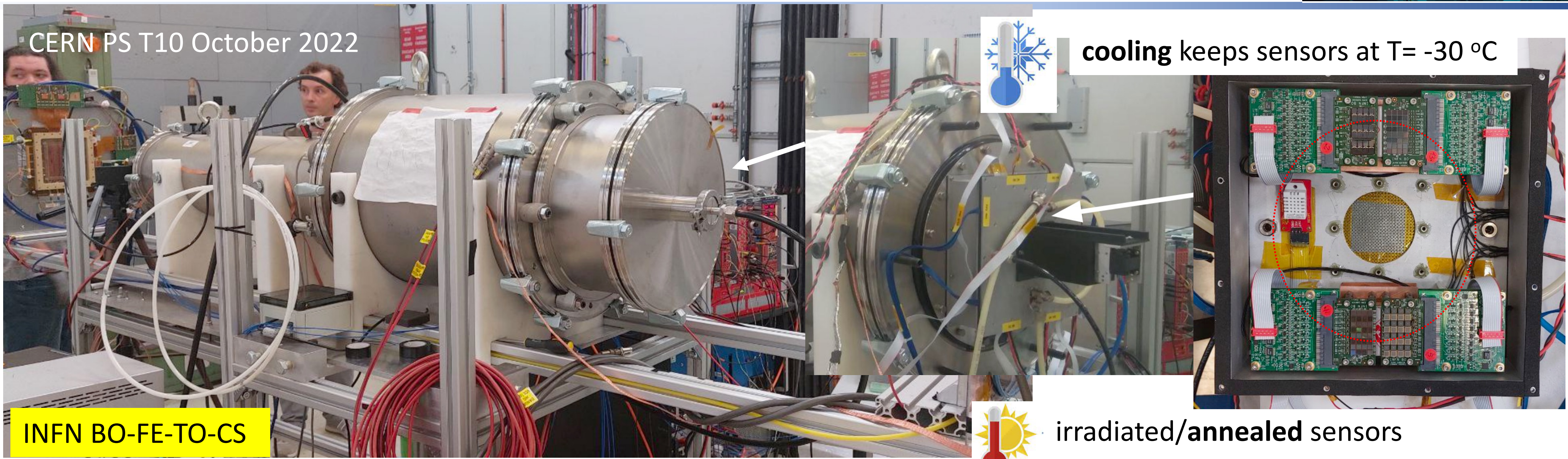
online annealing keeps DCR lower





Bringing irradiated sensors on a dRICH (prototype)



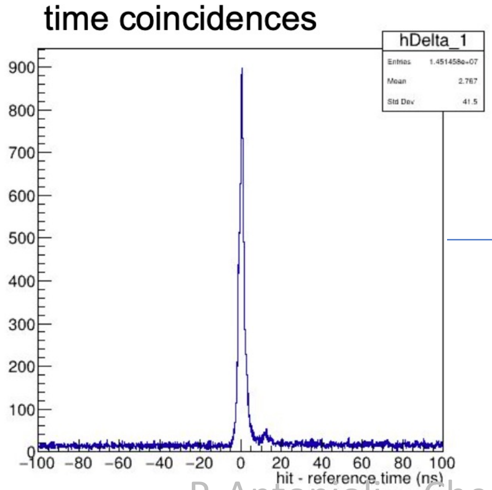


cooling keeps sensors at T= -30 ^{o}C

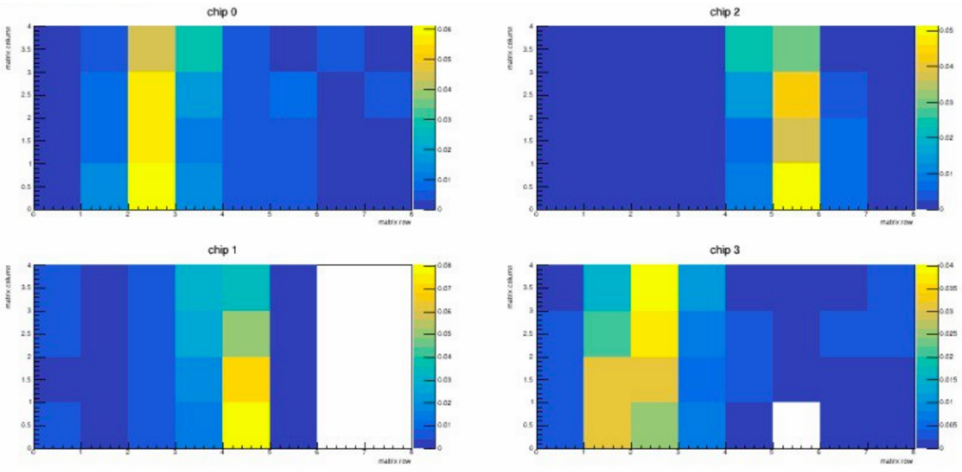
irradiated/**annealed** sensors

timing

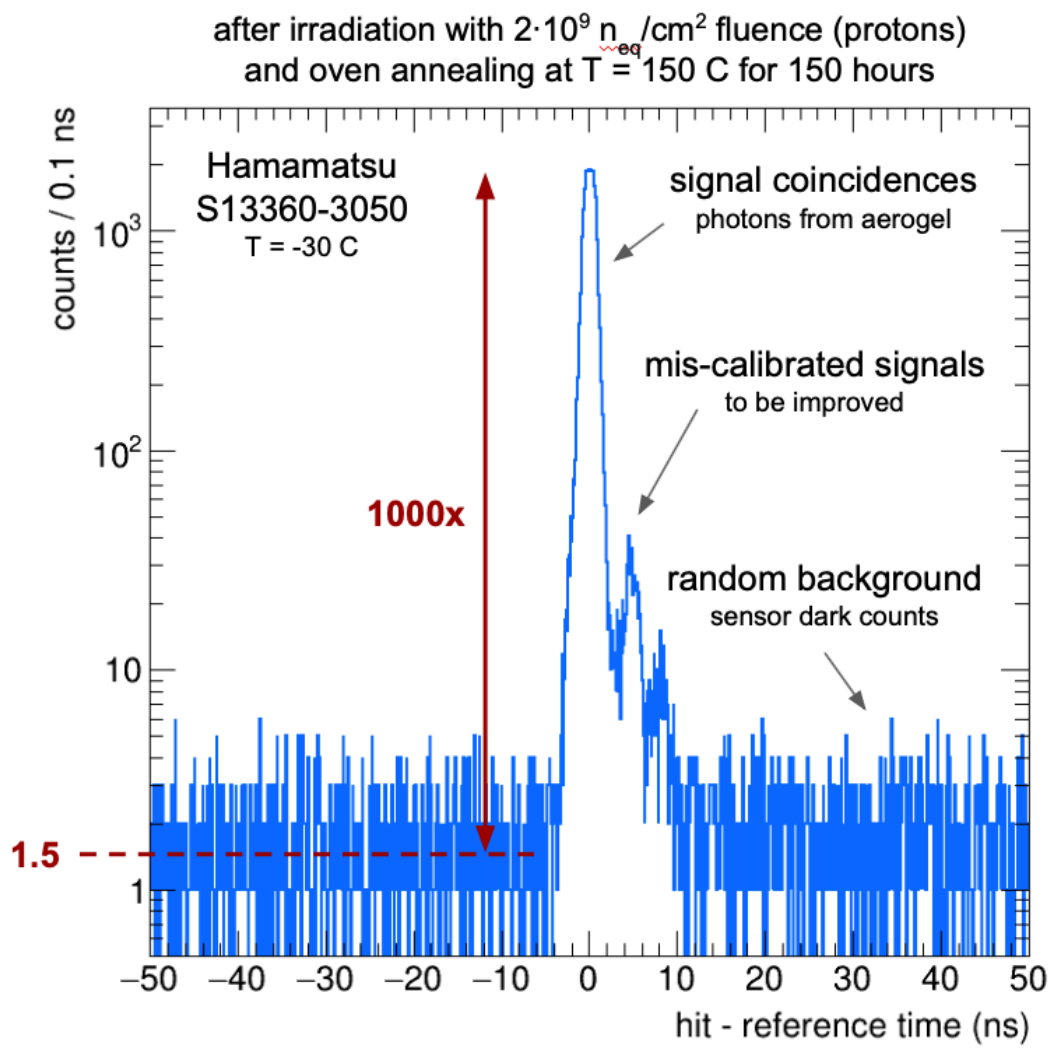
ALCOR streaming readout
time tagger with scintillators

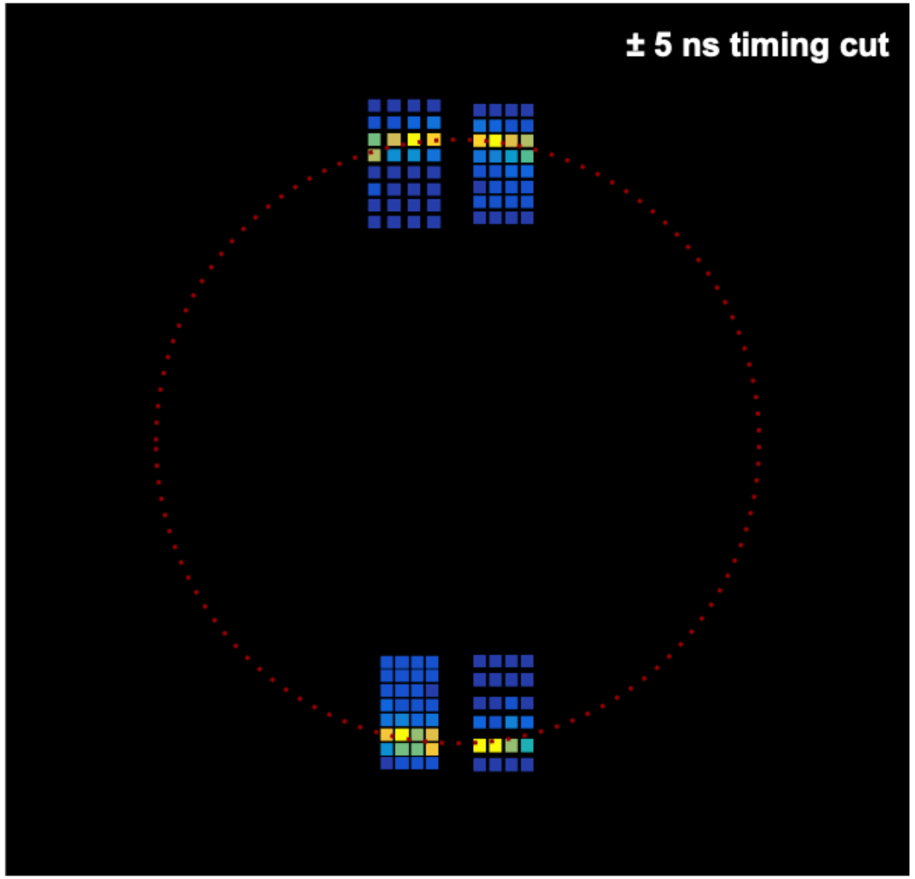


Cherenkov photons visible!



Irradiated sensors on test beam/dRICH prototype (II)

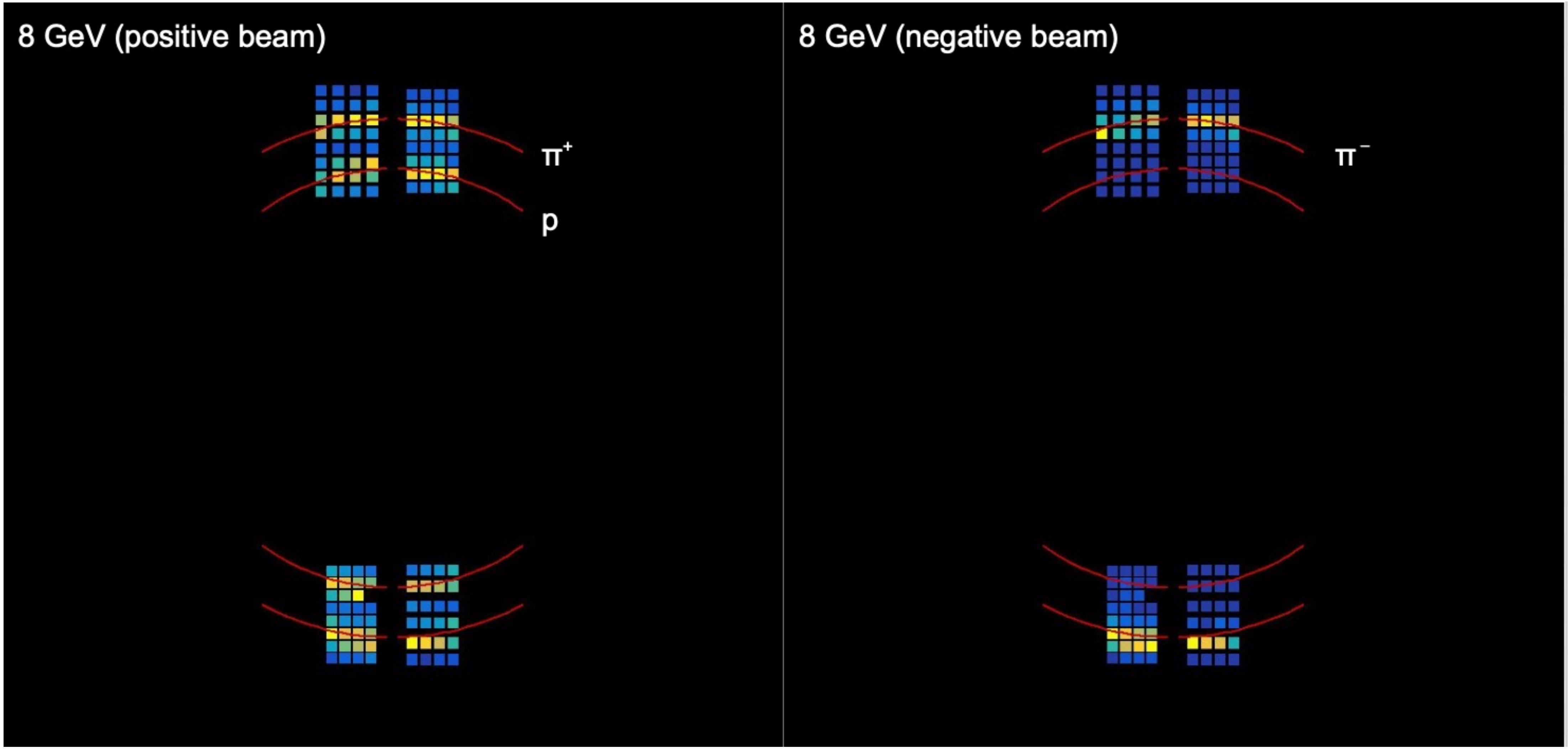




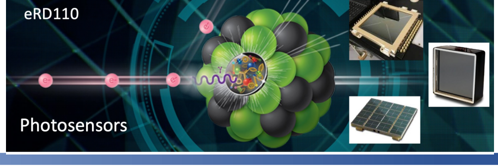
*Take home message

irradiated/annealed sensors (repeatedly) operated successfully at test beam
S/N ratio very promising

Ring patterns



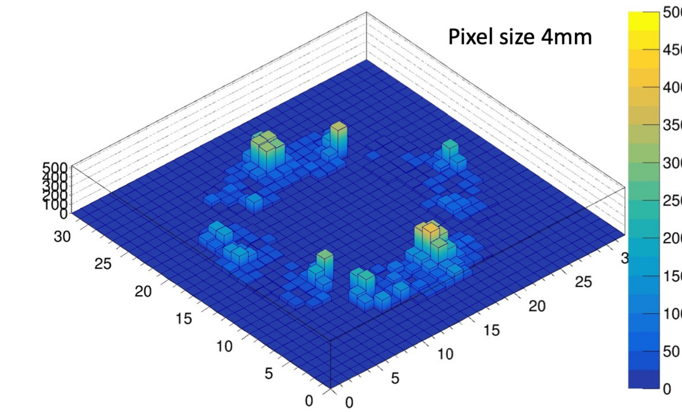
LAPPD: the R&D program so far (an outline)



sensor	increased partnership with Incom: capacitively-coupled LAPPD received, progresses on 10/20 μm pore and development of 10x10 cm^2 HRPDD
B-field	characterisation at Argonne up to 1.4 T tested effects of different B-field orientations
networking	two LAPPD workshops well attended by the potential users community (beyond EIC)
test beams	• test with aspheric lens (CERN & Fermilab) • preliminary evaluation of timing performance
sensor for EIC	• pixelization of HRPPD • QE optimization • make it more "tileable" (cit)

INCOM BRIGHT IDEAS

LAPPD ("large area MCP") never used so far in HEP/NP applications. Sensor at prototype level by one company.



Workshop #1 (March 2022) : https://indico.bnl.gov/event/15059/

Workshop #2 (October 2022): https://indico.bnl.gov/event/17475/

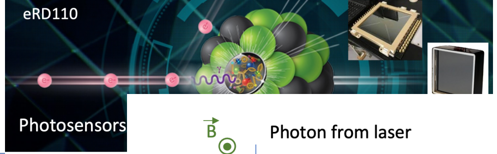
Description Organizers: Silvia Dalla Torre (INFN), Alexander Kiselev (BNL), Simona Malace (JLab), Deb Sankar Bhattacharya (INFN), Junqi Xie (ANL)

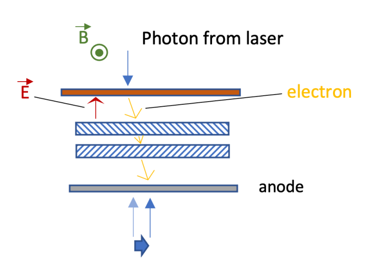
Hosted by CFNS: https://stonybrook.zoom.us/j/97182934798?pwd=TGJ2dkNwdUlqYS9Yc2owUVVTd05iUT09

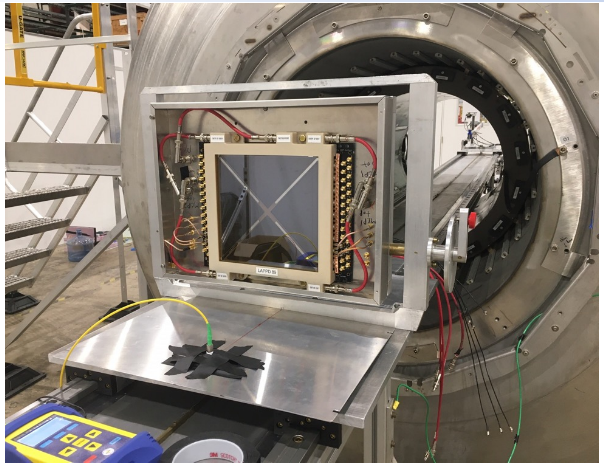
Argonne NATIONAL LABORATORY · Brookhaven National Laboratory · INFN · Center for Frontiers in Nuclear Science · Jefferson Lab

magnetic field measurements

Argonne



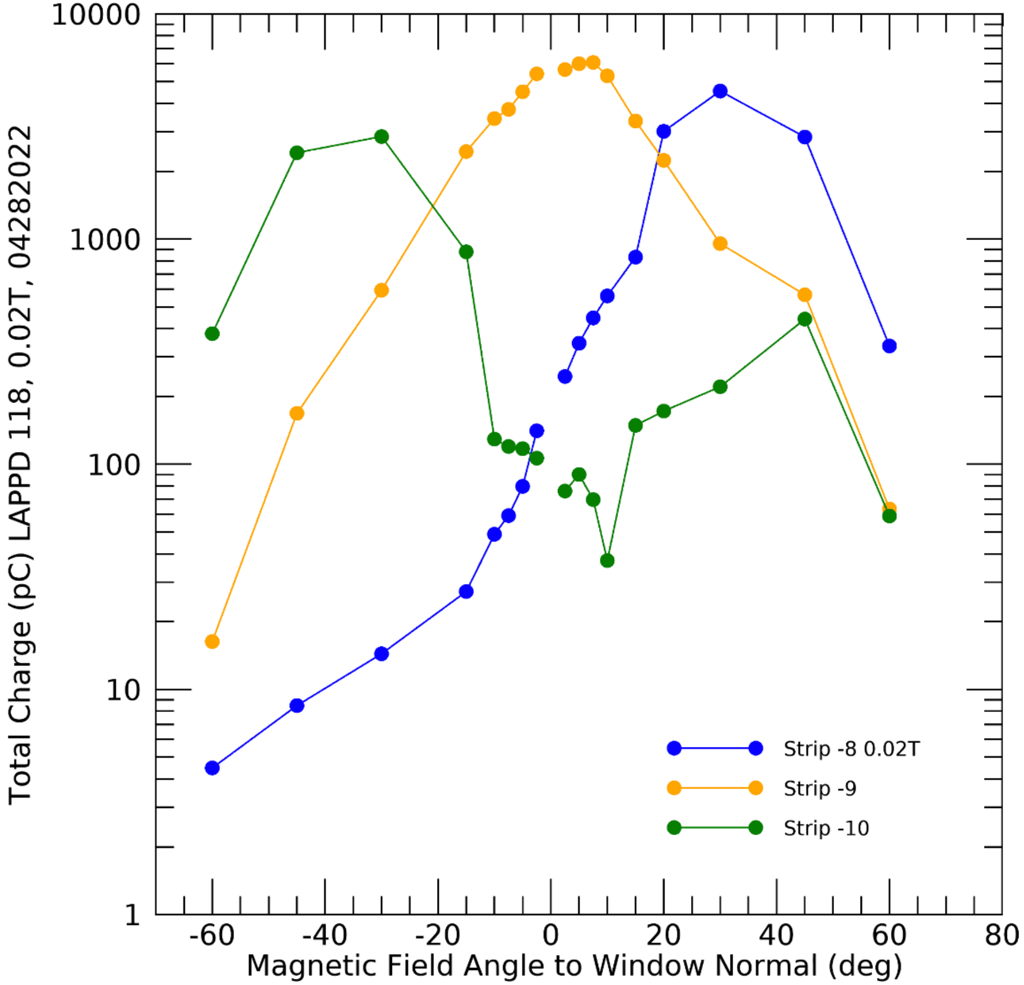




B=0.02 to 1.4 T
Two **stripline** LAPPDs tested:
118, 20 um MCP pore size
89, 10 um

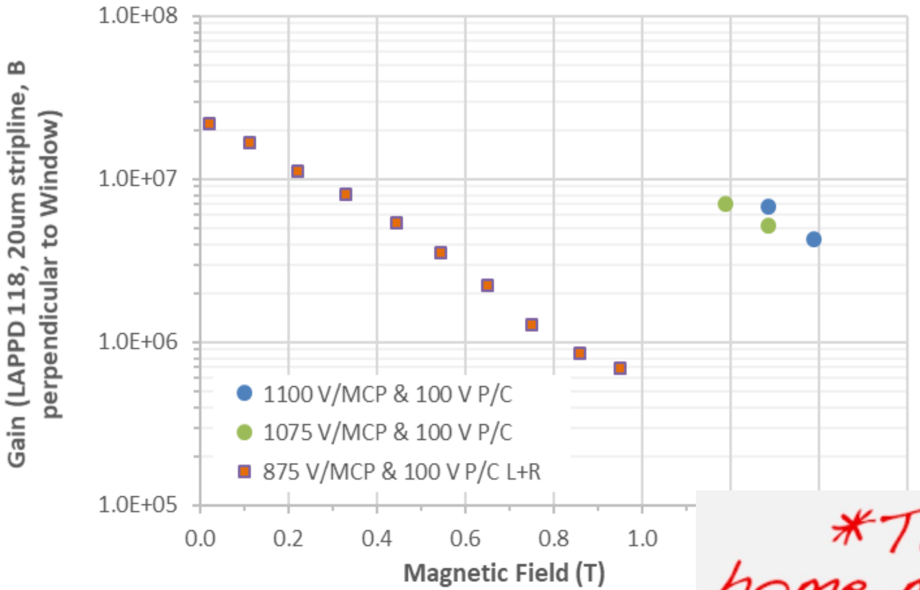
B tilted w.r.t. electron motion
- small field

Gain vs rotation in small field



B normal to the tile surface – large field

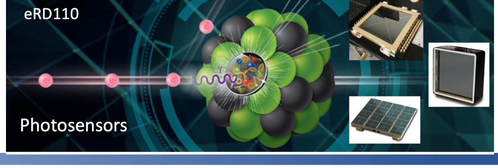
Gain decreases from 10^7 down to below 10^6
Can be recovered (partially) increasing MCP voltage



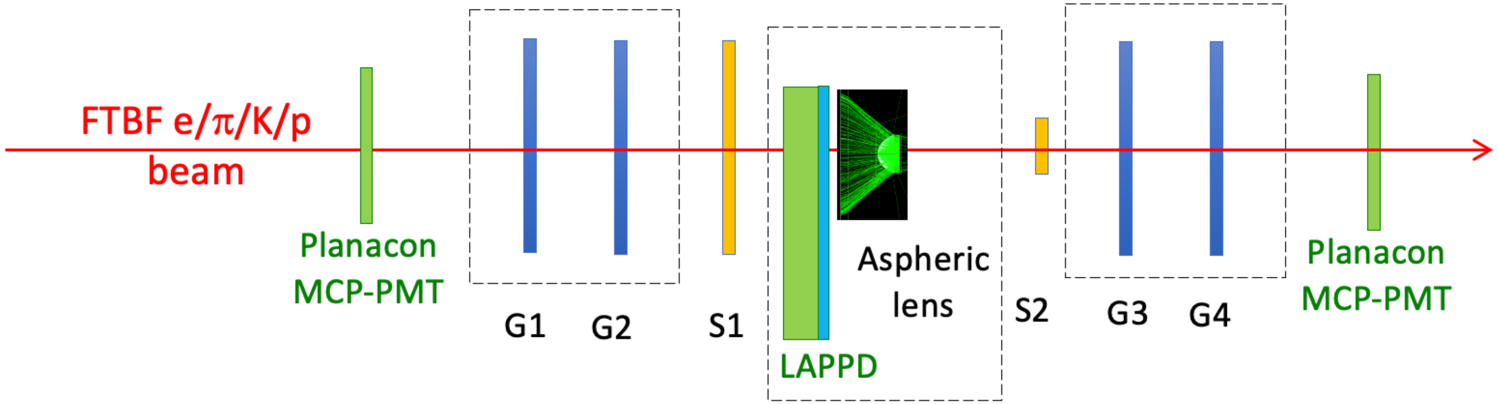
*Take home message

we can manage B-field, further measurements needed

test beam at Fermilab

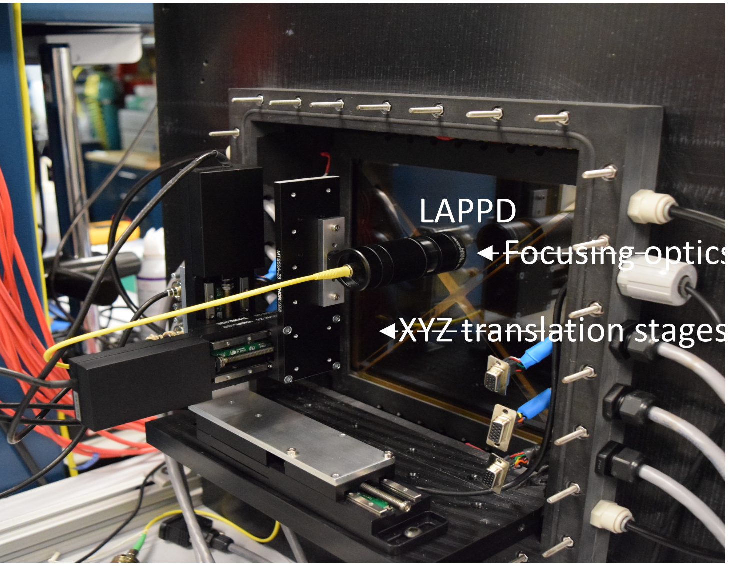


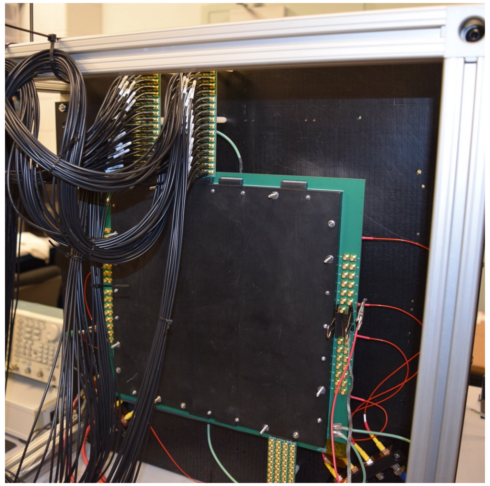
- G1 .. G4 – COMPASS GEM reference tracker
- S1 .. S2 – trigger scintillator counters



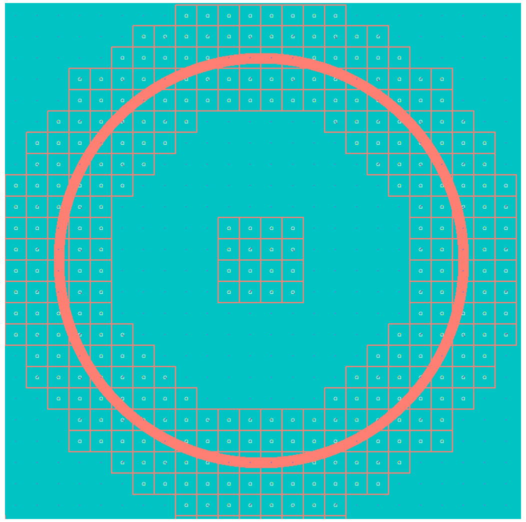
Argonne, BNL, Incom Inc., NFN Trieste, MSU

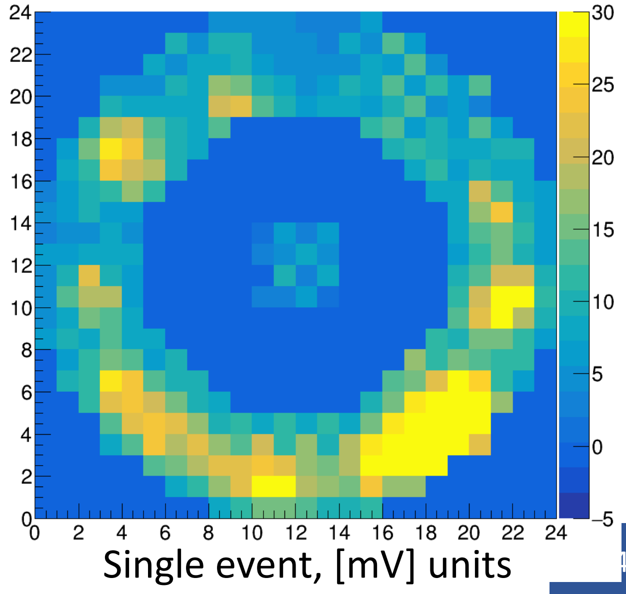
- A new 20 cm Gen II LAPPD tile #136: 10 μm pore MCPs
- New set of the pixelated readout boards





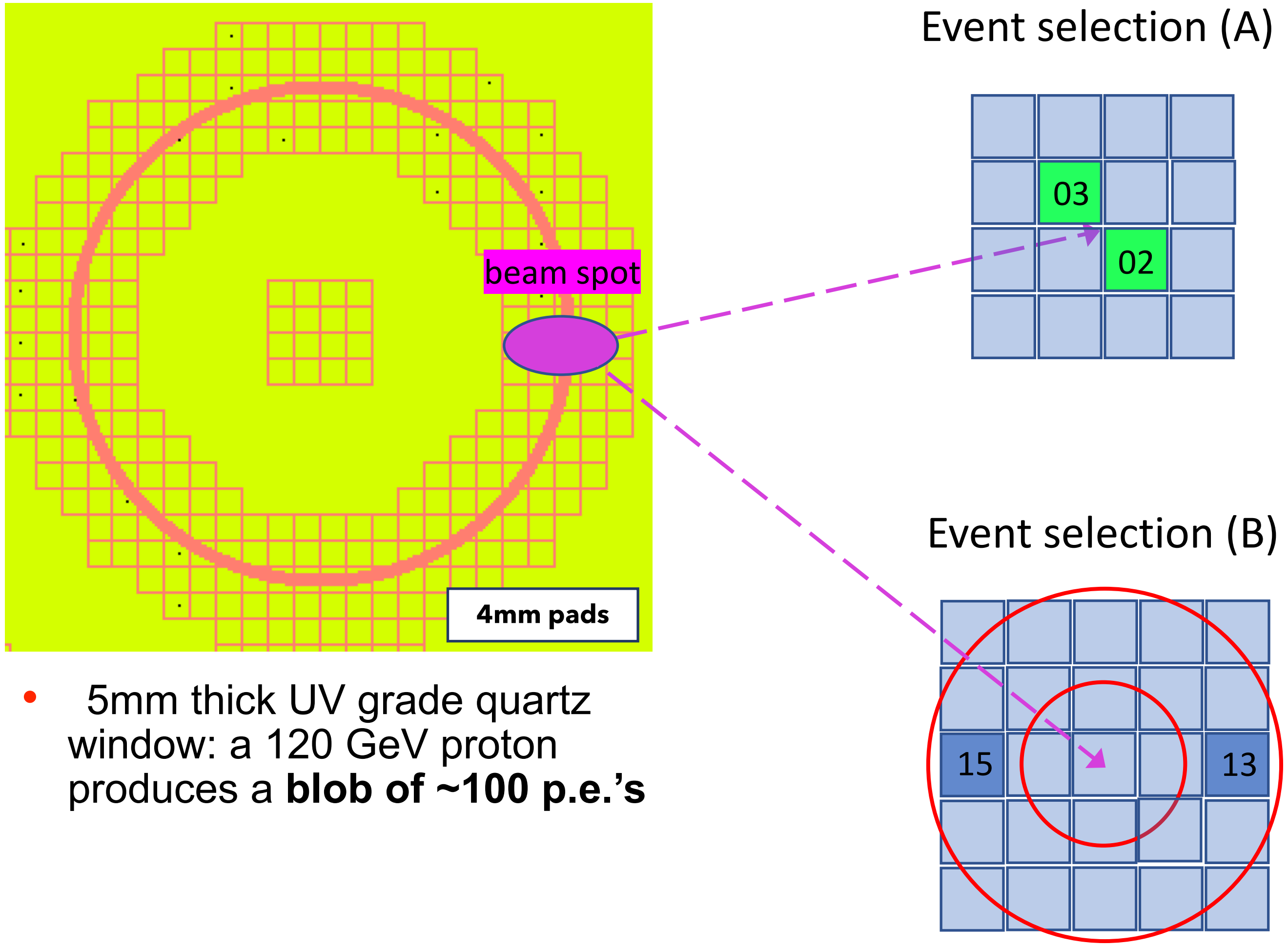
Aspheric lens as a source of coherent Cherenkov photons





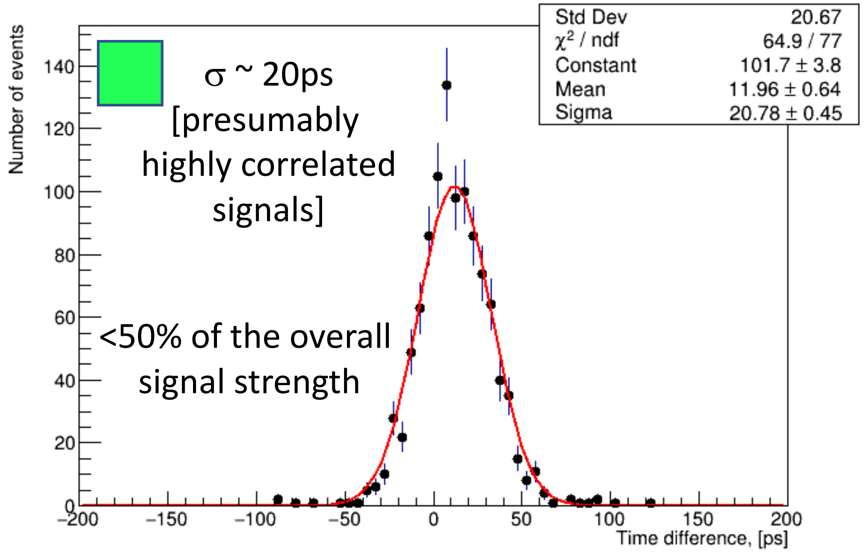
timing performance (preliminary)

LAPPD quartz window as a Cherenkov radiator

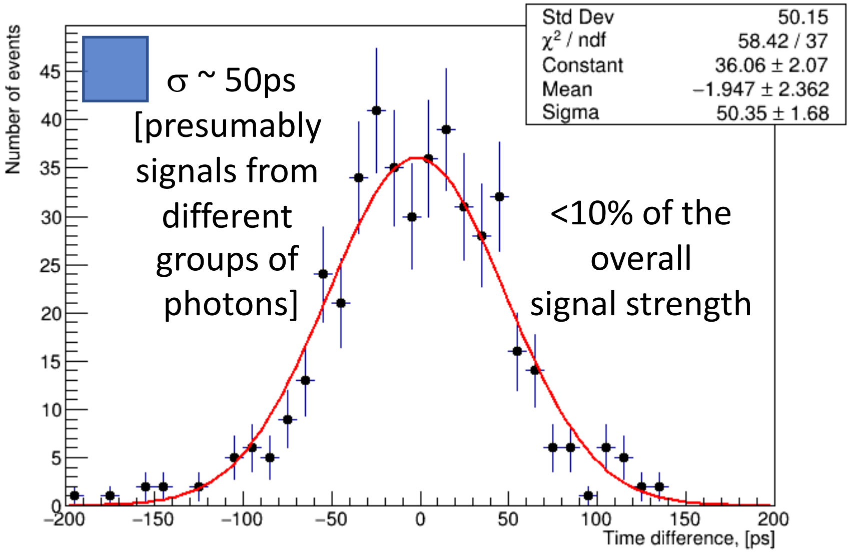


- 5mm thick UV grade quartz window: a 120 GeV proton produces a **blob of ~100 p.e.'s**

Due to the total internal reflection, photons only hit the PC in a radial band ~[5.5 .. 12.0] mm



DRS4 chip#0: time(ch#03) – time(ch#02)

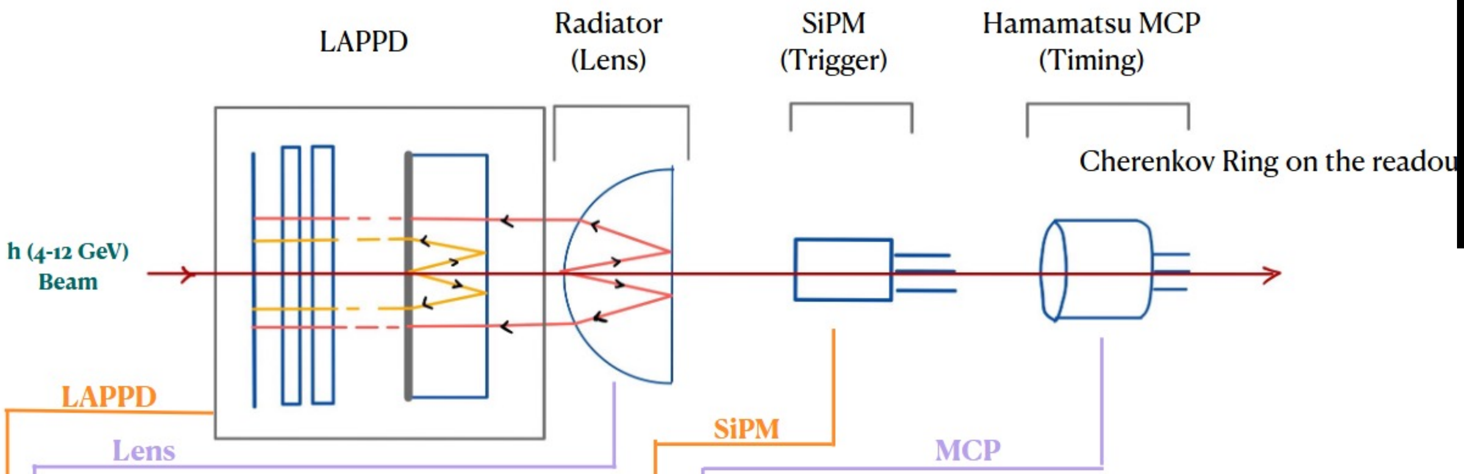


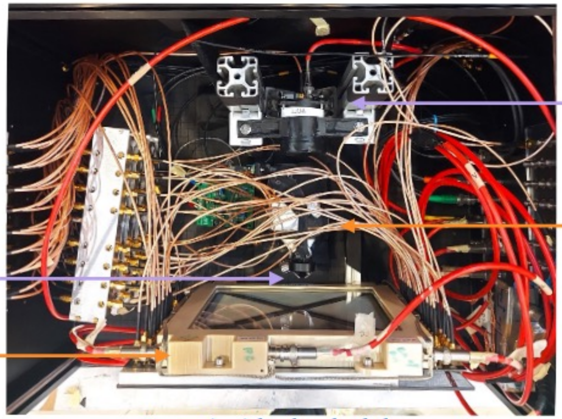
DRS4 chip#1: time(ch#15) – time(ch#13)

CERN test-beam (October 2022)

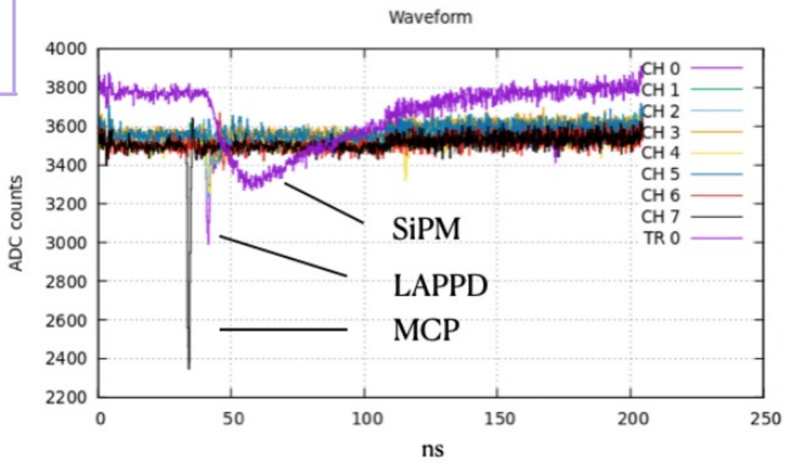
Goal: **Measuring the Single Photoelectron time resolution of the LAPPD**

Overview of the Test beam setup





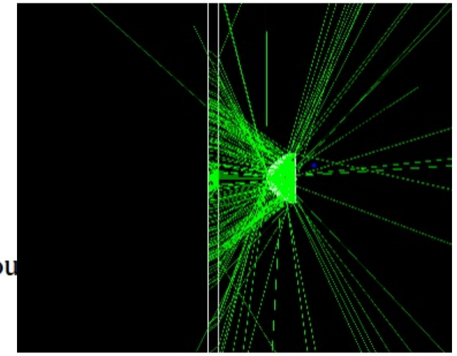
Setup inside the dark-box



Online Signals

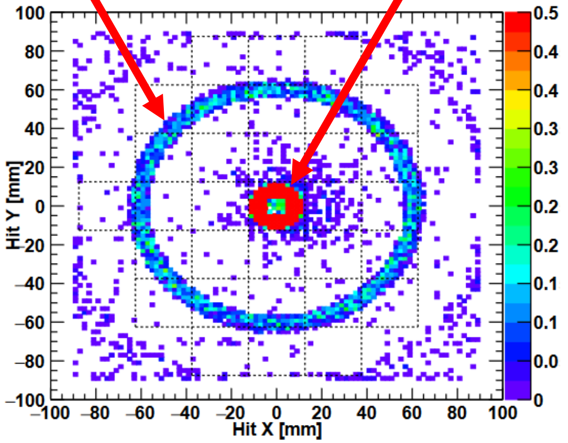
EIC_DAC, 21 Oct 2022

backward reflection

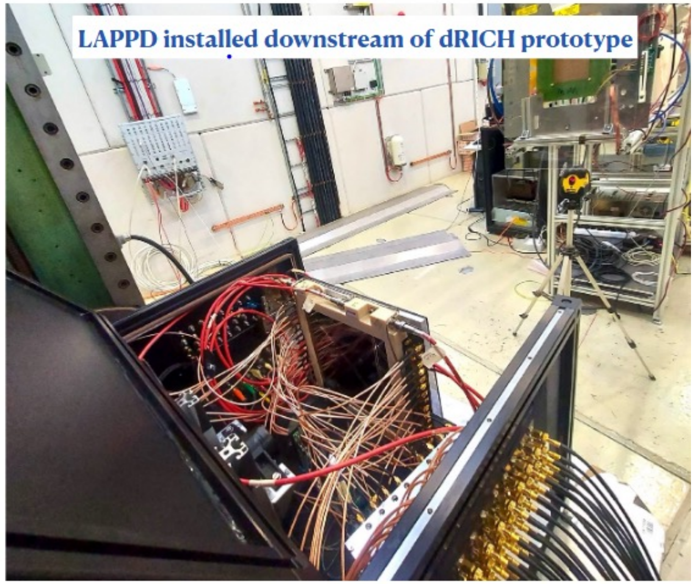


radiatoir Č ph.s

beam Č ph.s

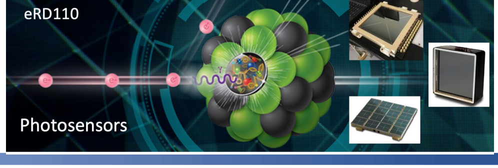


Geant4 simulatons

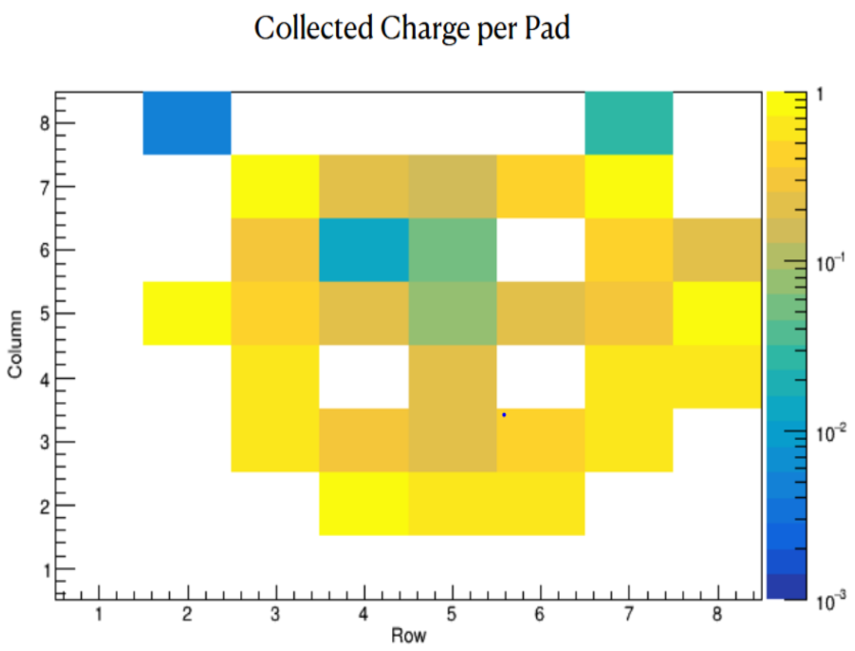


BNL, Incom Inc., NFN TS GE

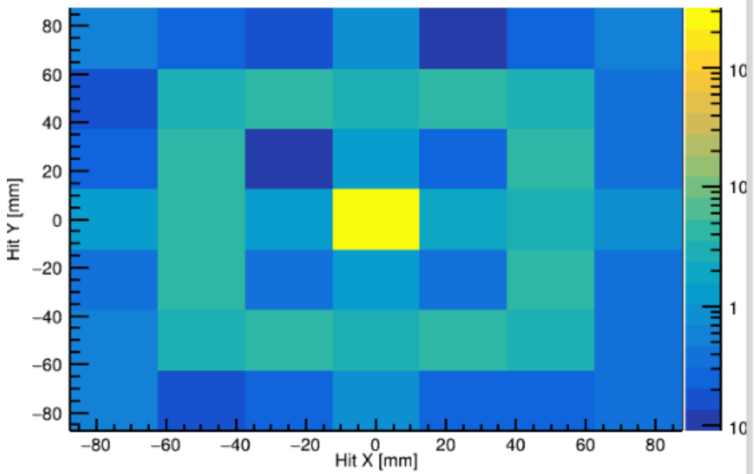
CERN test beam preliminary results



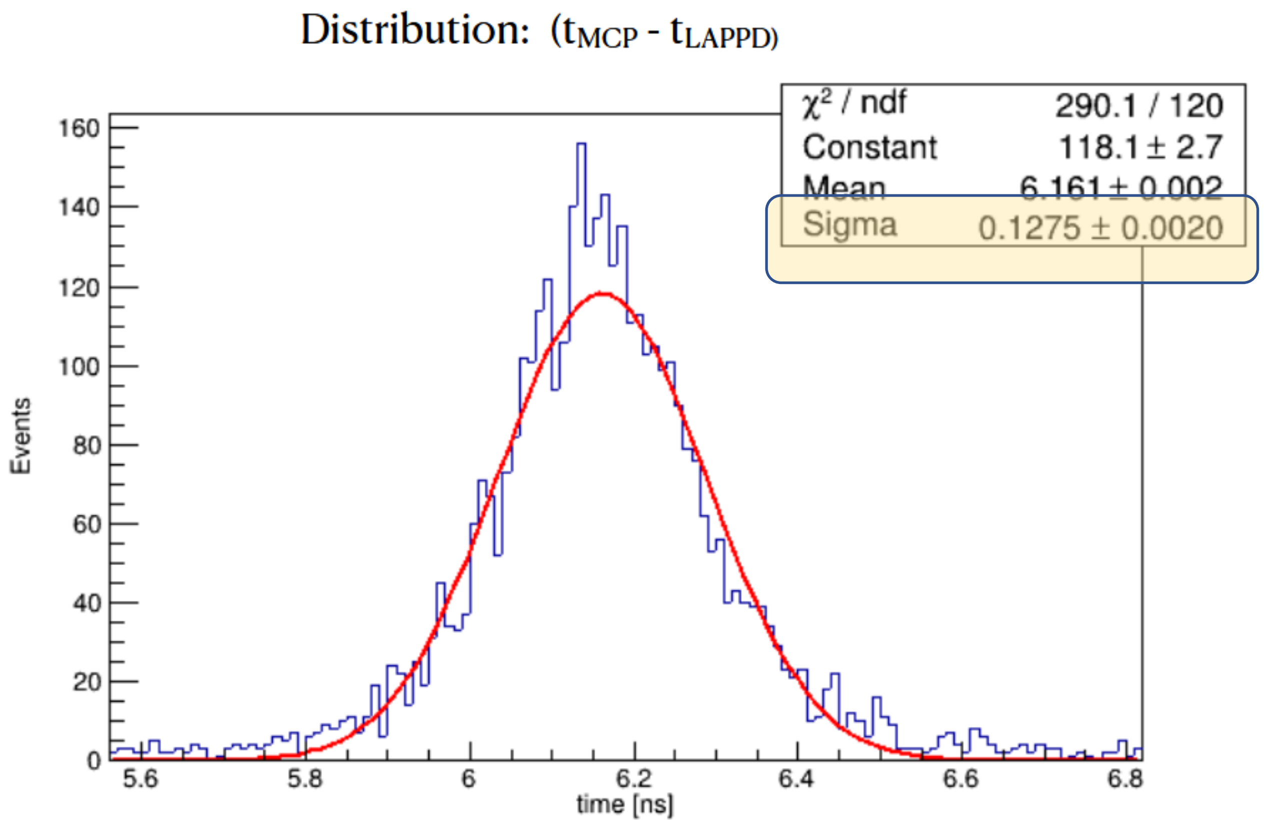
Data



Simulation

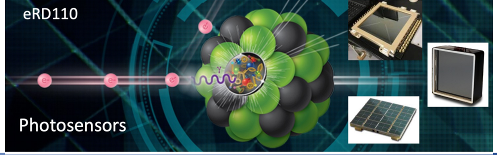


Hit map of a Cherenkov ring from GEANT4 simulation



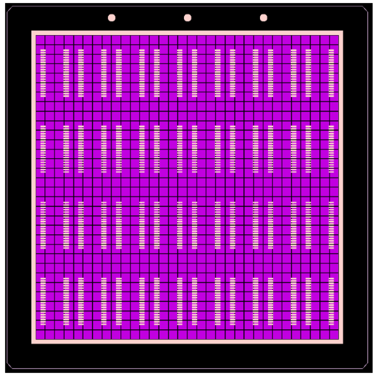
- The standard INCOM readout board is not optimized for multi-hit measurements (also 25mm pad size is too coarse)
- Time resolution spectrum is very preliminary (raw data shown)
- A novel DRS4 calibration procedure is being developed
- Detailed data analysis is required (test beam ended on 10/19, 2022)

HRPPD prototype → "HRPPD for EIC"

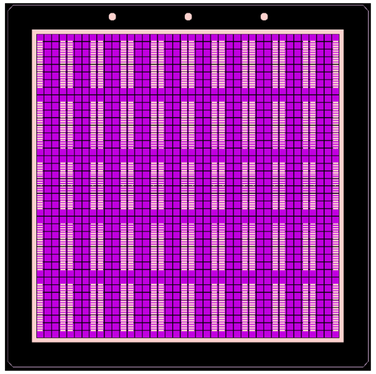


HRPPD re-design effort for EIC

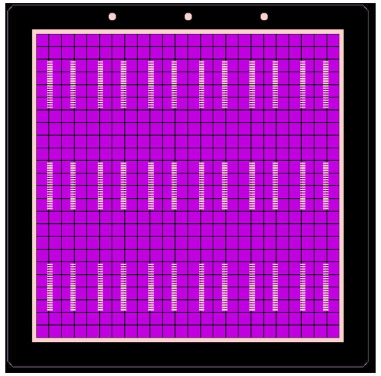
Variety of HRPPD anode base plate pixellation, with 40-pin Samtec connector footprints on the outer side



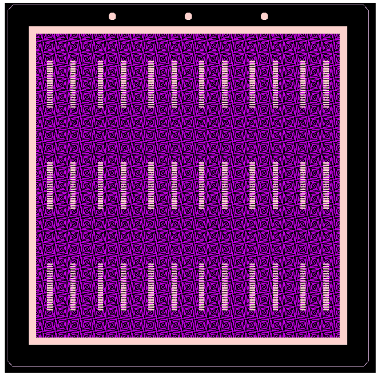
32 x 32 square pads (present layout)



40 x 40 square pads (DIRC)



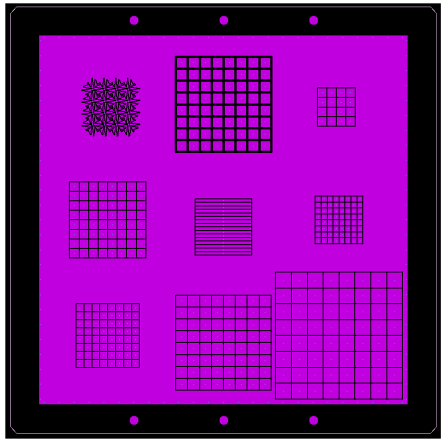
24 x 24 square pads (pfRICH)



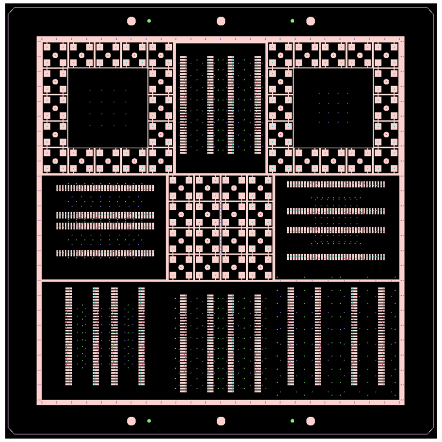
24 x 24 charge sharing pads (pfRICH)

- Polish ceramic manufacturer (Techtra) claims they can produce such layouts in house
- First iteration will be a test bench HRPPD tile with a mixed layout, to test them all at once

pad (inner) size



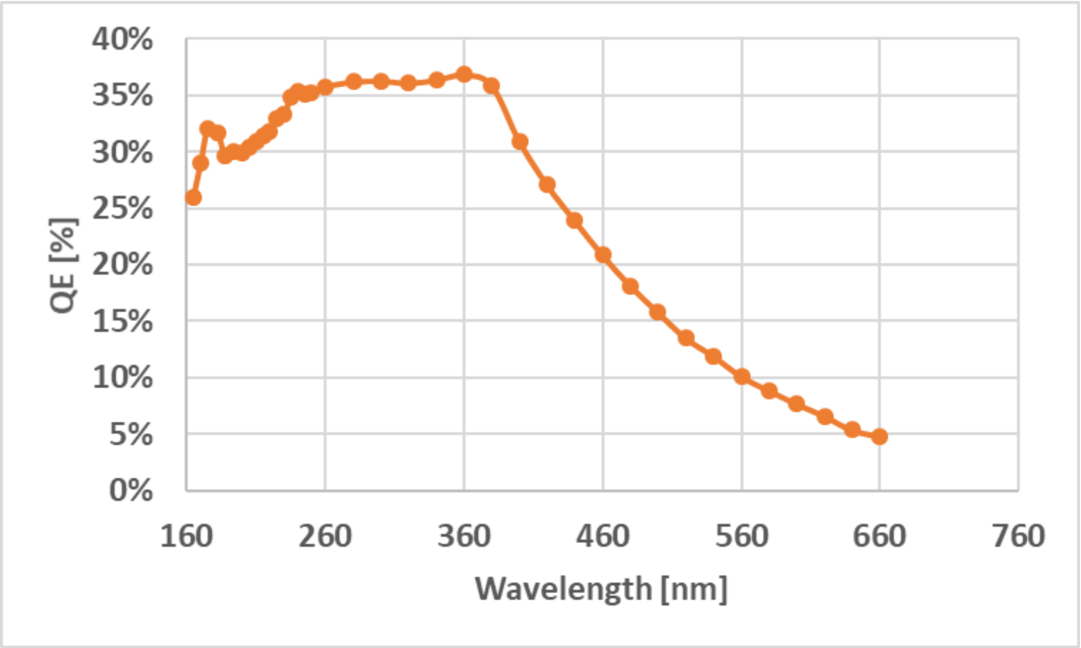
connector (outer) side

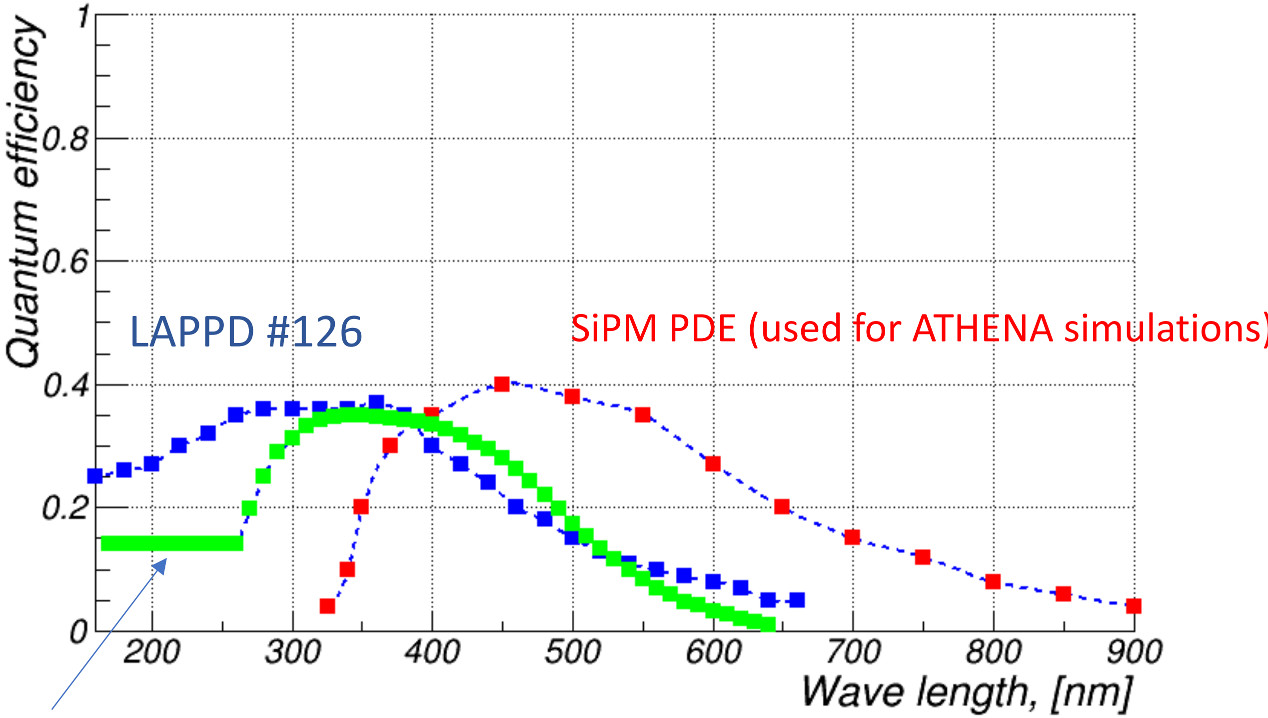


*Take home message different pixelization schemes to be tested

LAPPD QE and aerogel

LAPPD #126 - QE

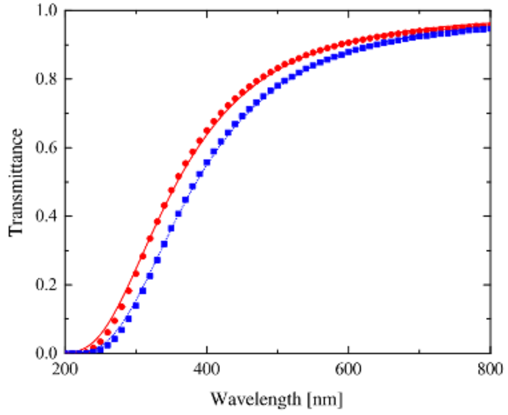




Belle II HAPD for aerogel RICH

QE of LAPPD and SiPM quite different
caveat: this is QE of just the photocatode!

Belle II aerogel transmittance



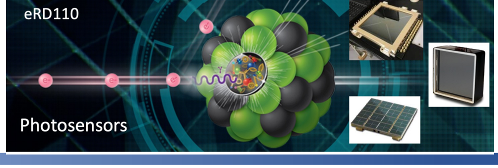
*Take home message

optimization toward HRPPD "EIC" tile under way
QE/PDE to be carefully investigared

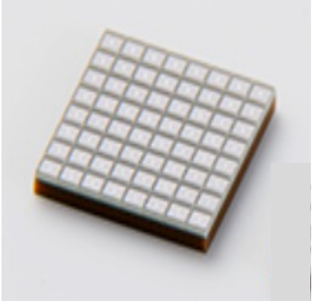
the baseline table as of Jan 2023...

	SiPM	LAPPD
Area	Tiles available 8x8 (3x3 mm^2): 5.76 cm^2	20x20 cm^2 and 10x10 cm^2
Pixel	3x3 mm^2	Finely pixelated schemes tested (capacity coupled LAPPD)
Magnetic field	insensitive	proper HV settings can recover gain at 6 10^6 as for MCP, B-field not oorthogal to tile difficult to manage
Radiation	irradiation/annealing cycles done. Tested	No data, but reasonable to expect not a problem
Availability	In stock. dRICH prototype SiPM plan will use HPK 13360. Exploratory run with FBK to improve NUV-HD	"In-stock" for 20 μm
Manufacturers	Many. Current focus on HPK and FBK/L-Foundry	Incom Inc
Price	1 k$ /(8x8 tile 3x3 mm)	price per unit expected to drop at 20-30 k$
Unit price	$\approx$50-100 $/$cm^2$	52 $/$cm^2$
Concerns	DCR increase with radiation management	Cross talk, integration (dead-space, QE, pixelation, ...)
Risks	None if mitigation of DCR increase "manageable"	Sensor must be brought to production level, time schedule challenging

Conclusions and outlook/what next in 2023



- EPIC DIRC, bRICH, dRICH have chosen "baseline" photosensors
- 2023 will be critical year **to consolidate** respective baseline choices



- validate proton irradiation results with neutron irradiations
- time resolution & irradiation/annealing
- check residual DCR is "manageable" (reconstruction) → annealing frequency

- [ALCOR (electronics): EIC-branch: integration (64 ch) + shutter implementation
- [dRICH prototype: fully equipped with SiPM]
- [dRICH prototype: "cooling & annealing-in-situ" integration]

- have final result on B-field studies
- assess LAPPD performance (PDE + spatial resolution + timing) with "aerogel photons"
- toward EIC "LAPPD/HRPPD" tile

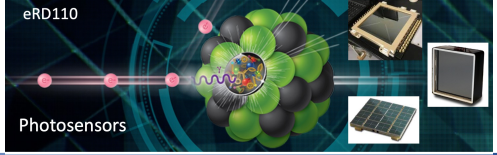
- [electronics: need to define it must cope with timing requirements

hpDIRC looks with interest at HRPPD result. Could be (cheaper) alternative to MCP-PMT

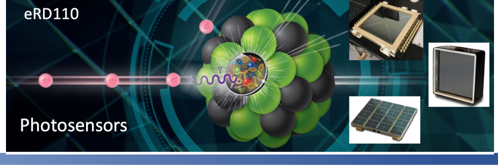
A final comment

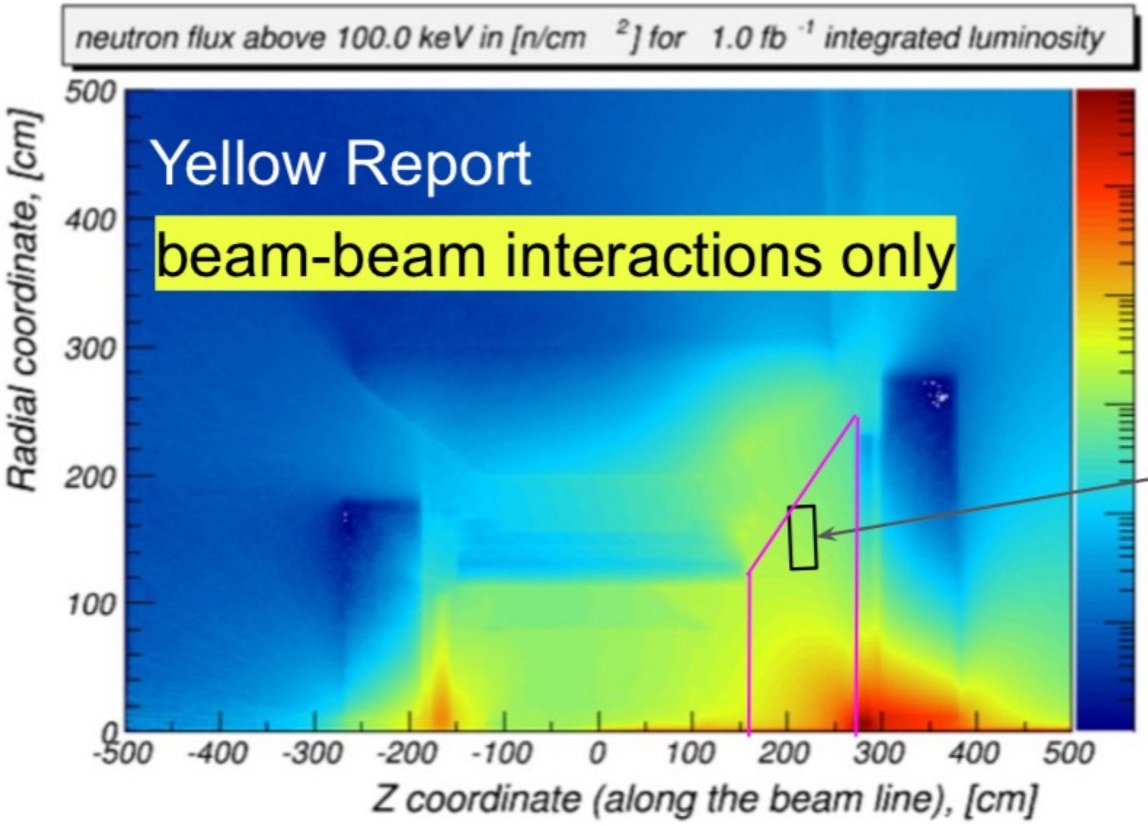
The current baseline photosensors choices for bRICH , DIRC and dRICH are in a very different R&D space due to the different "design maturity" and "known issues" to be managed of the respective photosensors.

Backup



How much radiation?





potential location of photosensors:
≈ **1-5 10^7 n/cm² every 1 fb^{-1}**

10^{11} n/cm² 1-MeV n_{eq} is a "true maximum"

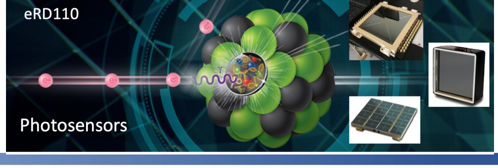
- 30 weeks @ 10^{34} cm^{-2} s^{-1}= 100 fb^{-1} → 1-5 10^9 n/cm²
- 10^{11} n/cm² would be reached in O(10+) years at full $\mathcal{L}$!

A moderately hostile environment:

10^9 1-MeV n_{eq}/cm² → most of the key physics topics
10^{10} 1-MeV n_{eq}/cm² → GPD and more statistically eager topics
10^{11} 1-MeV n_{eq}/cm² → may be we will never go here…

Can we use SiPM for a Cherenkov detector up to 10^{11} 1-MeV n_{eq} /cm² fluence?

How to mitigate the SiPM DCR? (II)



cooling

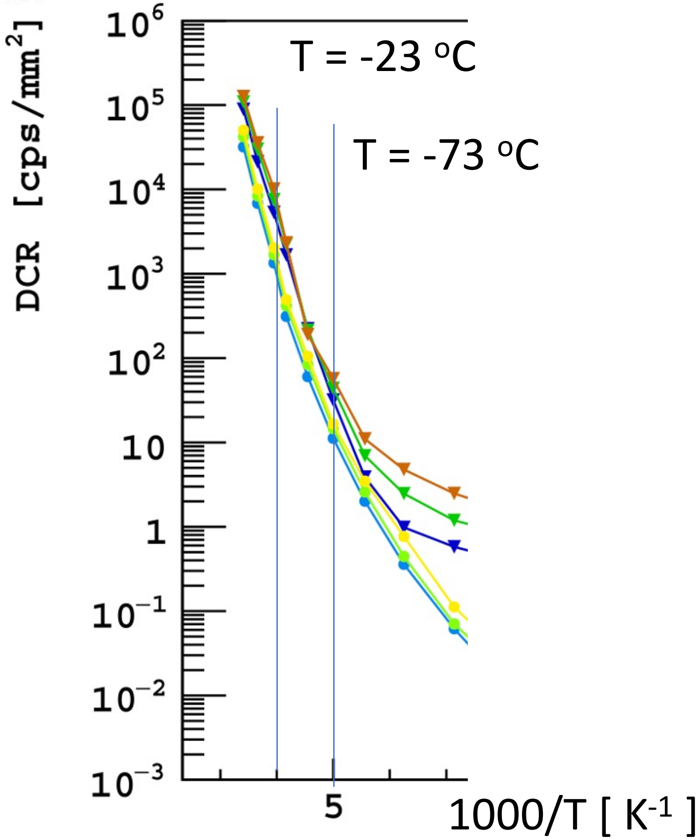
"DCR decreases by a factor 2-2.5 every 10 degrees"

annealing

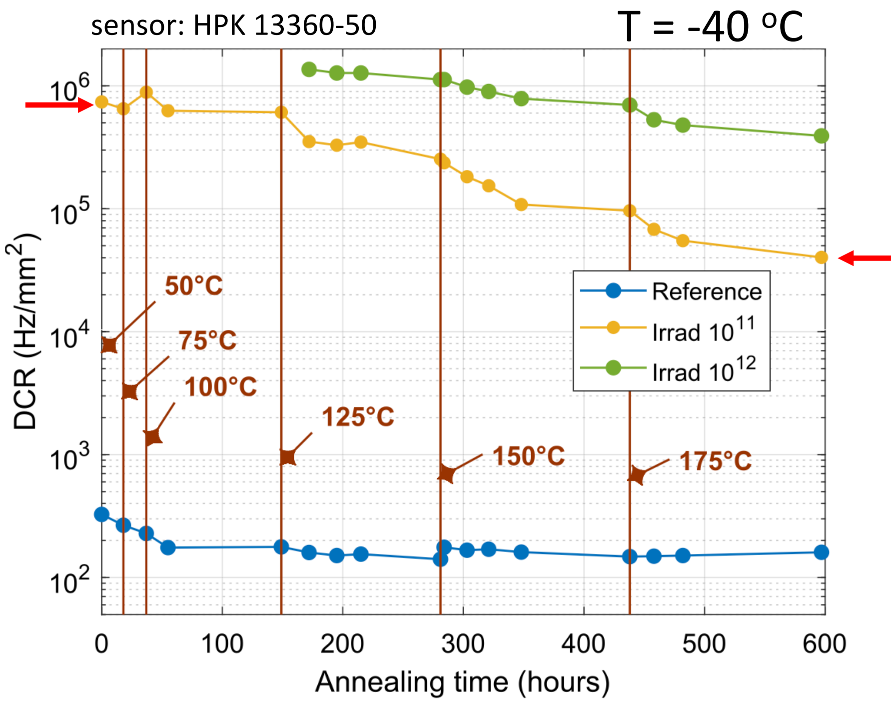
"DCR decreases by a **factor 20** after an annealing cycle up to 175 °C"

timing

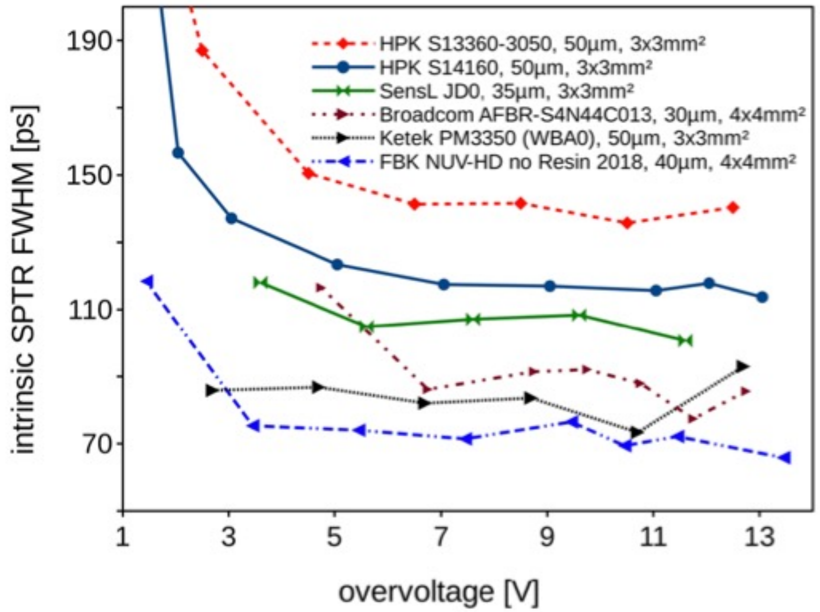
- Timing resolution below 100 ps are nowadays achieved by SiPM
- A 3σ cut based on interaction time will further reduce DCR in a RICH



[Acerbi F. et al., IEEE Trans. On El. Devices 64 (2017) 521]

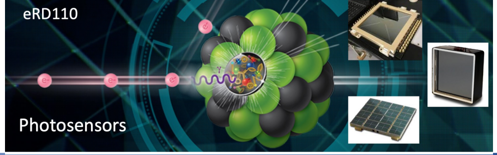


[M. Calvi et al., NIMA 922 (2019) 243]



[S. Gundacker et al., Phys. Med. Biol. **65** (2020) 025001]

SiPM under test

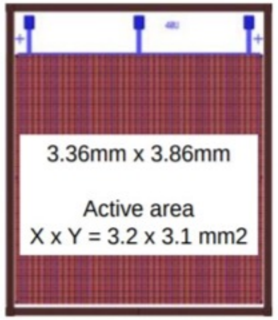


Commercial:

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

Prototypes

NUV-HD-CHK

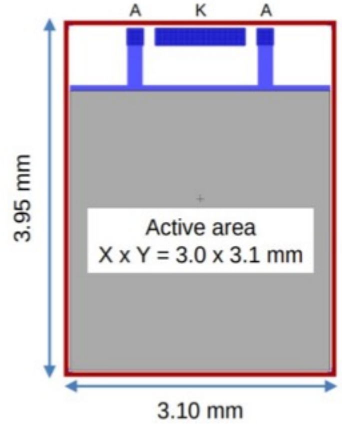


NUV-HD big cells

Technology similar to NUV-HD-Cryo
Optimized for single photon timing

- Cell pitch 40 µm
- High PDE > 55%
- Primary DCR @ +24°C ~ 50 kHz/mm^2
- Correlated noise 35% @ 6 V

NUV-HD-RH



NUV-HD-RH

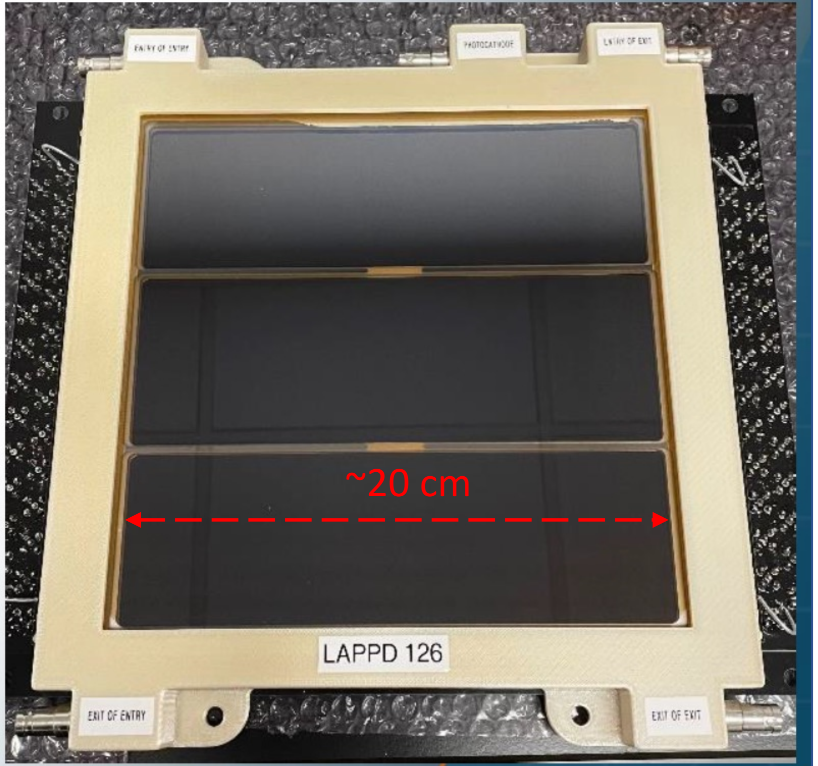
Technology under development optimized for radiation hardness in HEP experiments

- Cell pitch 15 µm with high fill factor
- Fast recovery time – reduced cell occupancy Tau recharge < 15 ns
- Primary DCR @ +24°C ~ 40 kHz/mm^2
- Correlated noise 10% @ 6 V

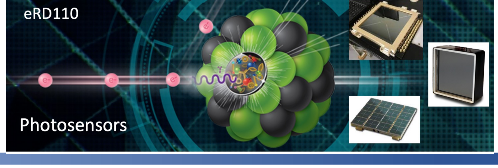
LAPPD/HRPPD notation & history

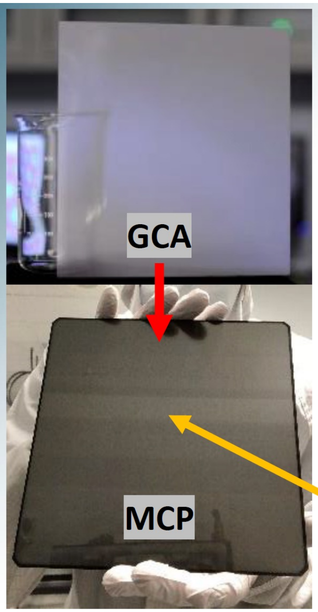
LAPPD (20cm): Large Area Picosecond Photon Detector
HRPPD (10cm): High Rate Picosecond Photon Detector

- **2009**: LAPPD Collaboration founded by Prof. Henry Frisch (U Chicago)
  - Motivation: Low cost, large detection coverage with picosecond timing
- **2015**: Early commissioning trials at Incom, Inc.
- **2018**: Demonstrated pilot production of LAPPDs
- **2022**:
  - 141 LAPPDs starts all time
  - 6 HRPPDs starts in 2022
  - Current capability of 36 LAPPDs / year
  - Current max capacity of 96 LAPPDs / year
- **Future**:
  - Improved performance
  - Commercial production



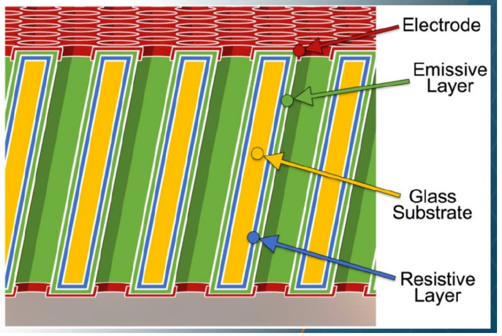
LAPPDs / HRPPDs by Incom Inc.

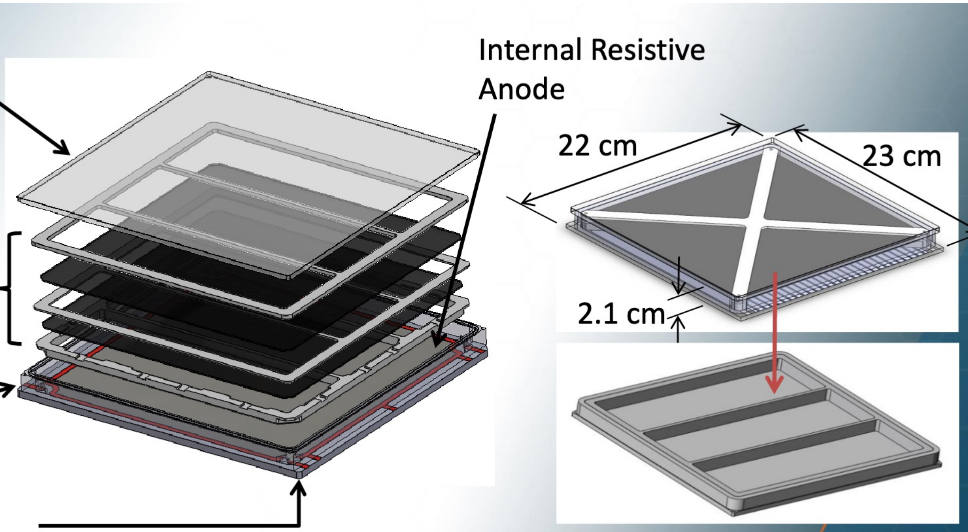




- *Hollow core* **Glass Capillary Array** (GCA) substrate
  - Borosilicate glass (AKA Pyrex)
    - Little radioactive ^{40}K
  - *No etching necessary! Already hollow*
- **Atomic Layer Deposition** (ALD) is a thin-film deposition technique used to functionalize GCAs
  - **GCA + ALD = MCP**
- Flexible adjustment of film composition and resistivity

Open Area Ratio (OAR) **up to 74%**

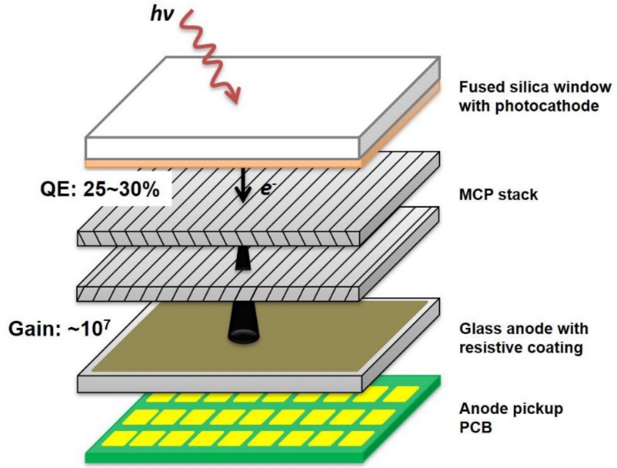




- **No wall or anode penetrations**
- **Active area: 195 mm x 195 mm**
  - **X → Grid Spacer**
  - **350 cm² (92%) → 373 cm² (97%)**

- An affordable large area (finely pixelated) vacuum photosensor
- 10x10 cm^2 or 20x20 cm^2 active area
- DC- (Gen I) or capacitively (Gen II) coupled species
- DC-coupled 1D strips or 2D pixellation
- Expected to be (very) cost efficient in mass production
- Quantum efficiency above 30% and uniform high gain up to ~10^7
- Sub-mm spatial resolution for finely pixelated tiles
- Single-photon timing resolution on a ~50ps level or higher

Gen II variety

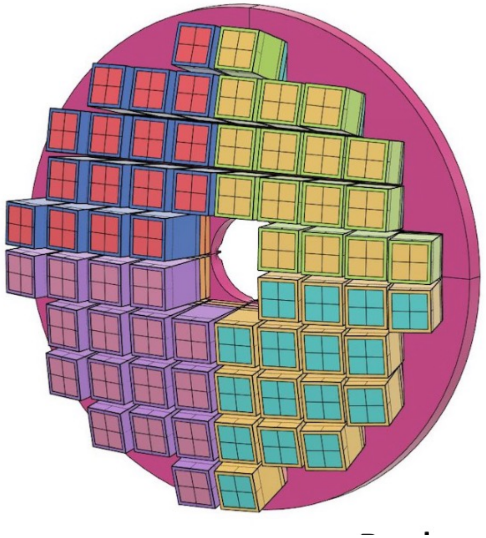


Possible HRPPD applications for the ePIC detector

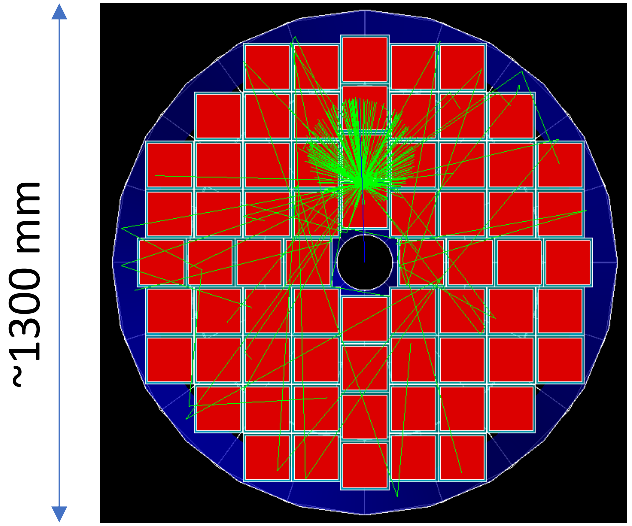
- mRICH / pfRICH: low dark noise, Time of Flight capability (vs SiPMs)
- DIRC: expected to be more cost-efficient (vs other MCP-PMTs)
- dRICH: problematic, because of the magnetic field orientation
- Preferred variety:

mRICH	either DC-coupled or Gen II
pfRICH	either DC-coupled or Gen II
DIRC	DC-coupled

electron-going endcap

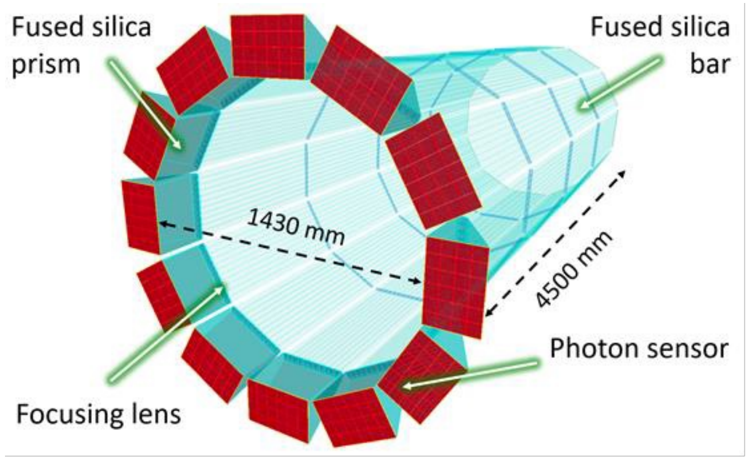


mRICH: 64 modules



pfRICH sensor plane: 68 tiles

barrel



DIRC: 12*3*2 = 72 tiles