Studio della lettura di fotoni Cerenkov in un RICH con SiPM

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R&D needed for SiPM:

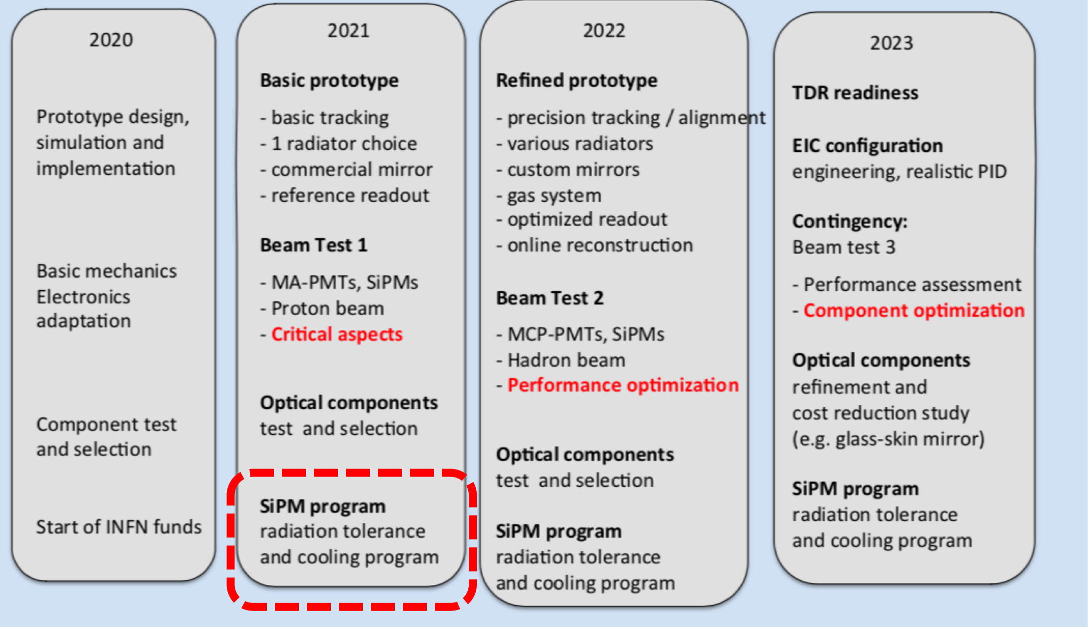
1. Proof of "feasibility": DCR & operating conditions, single photon detection etc.
2. Readout electronics: ASIC (+ streaming readout)
3. Radiation tolerance

Note these three R&D items are deeply interlinked!

Groups involved: Fe, LNF, RM1, CT, Bo, To, Ts

- "dRICH based" for test beams and parameters selection, but expected R&D outcome might extend beyond

dalle slides di Marco



dRICH and SiPM: "an option to be explored"

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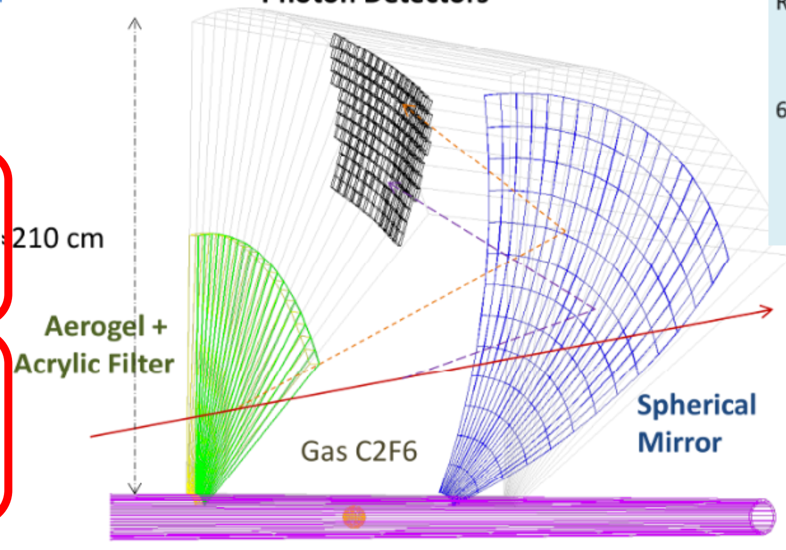
dRICH Key Hardware Components 2/2

Component	Function	Specs/ Requirements	Risk	Mitigation
Photon Detector	Single photon spatial detection	Magnetic field tolerant and radiation hardness; ~ few mm spatial resolution	MCP-PMT is likely duable, but expensive. Need to find alternatives	LAPPD may represent an alternative. **R&D on SiPM:** a promising, quicky improving, wordwide pursued, and cheap technology.
Electronics	Amplify and shape single photon analog signal, convert to digital, transfer to DAQ nodes	Low noise Time res. ~ 0.5 ns μs signal latency; High density	No major risk but need to be tailored to photon sensors	MAROC3 based readout available for prototyping; final choice will depend on sensor. **ASIC development for optimised streaming readout (discrimination vs sampling)**

EIC R&D committee explicitly asked for such a program



Radiators:
- Aerogel: 4 cm, $n_{(400nm)}$~1.02 + 3 mm acrylic filter
- Gas: 1.6m (1.1m ePHENIX), n_{C2F6}~1.0008

6 Identical Open Sectors (Petals):
- Large Focusing Mirror with R ~2.9m (~2.0m ePHENIX)
- Optical sensor elements: ~4500 cm²/sector, 3 mm pixel size, UV sensitive, out of charged particles acceptance

- 6 x 4500 cm² = **O(3 m²)** active sensors
- **3x3 mmxmm pixel size**

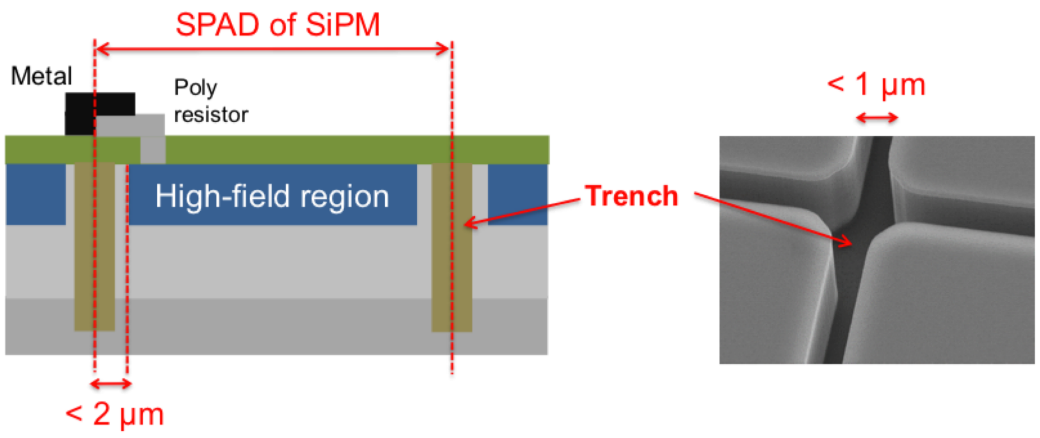
In-depth EIC R&D Review Report (11/25/2019): *"An important remaining issue is the SiPM noise rate after irradiation which should be clarified. We expect that it will take 2-3 years to fully understand if SiPMs can be used in RICH detectors at EIC".*

18th EIC R&D Meeting Report (01/30/2020): *"The committee again recommends the group to re-examine options that do not rely on waveform sampling, e.g., a TOT-based design like the TOPFET2 ASIC, which is radiation hard, has low power consumption and has achieved a very good resolution per single photon with SiPMs."*

→ Single Photon Detection (**PDE** ↑)
→ **Temperature** vs DCR ("not cryogenic")
→ Use **timing** to help filter DCR
→ **Radiation** tolerance
→ Sampling vs **discrim. + TOT**

NUV-HD technology from FBK with SPTR could be an interesting candidate (peak PE@400 nm)

NUV-HD: technology



- p-on-n junction → higher Pt for UV light
- Narrow dead border region → Higher Fill Factor
- Trenches between cells → Lower Cross-Talk
- Make it simple: 9 lithographic steps

TABLE II
NUV-HD CELL SIZES

Cell pitch (μm)	Cells/mm^2	Fill factor (%)
15	4500	55
20	2500	65
25	1600	72
30	1100	77

PDE

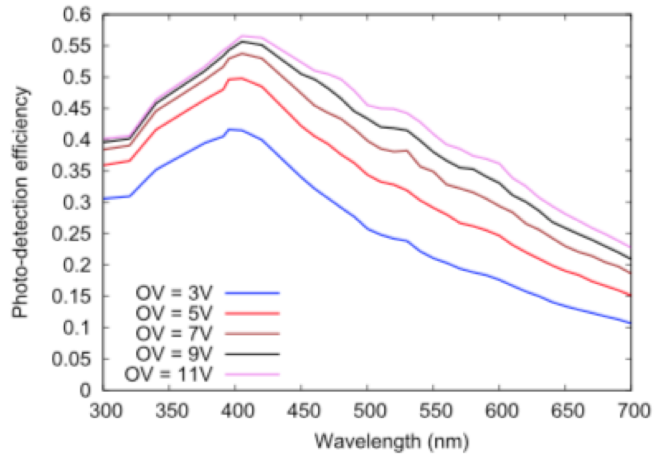


Fig. 2. PDE spectrum of the 30 × 30 μm^2 cell (78% FF) at different overvoltages. The measurement error is estimated to be 4%.

In this paper, we presented the main technological characteristics as well as the performance of the novel NUV-HD SiPM technology. It features a very high FF at the cell level, which allows production of devices with a high dynamic range while retaining the same PDE as other devices with lower cell densities. The electro-optical performance improved significantly from the previous FBK NUV technology: for a 30 × 30 μm^2 cell pitch, the PDE exceeds 50% with an optical CT of ~25% and a DCR of ~200 kHz/mm^2 (at 20 °C). These features have a direct impact on the perfor-

Ref: NUV-HD FBK technology
C. Piemonte et al., IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 63, NO. 3, MARCH **2016**

FBK as a potential SiPM supplier for EIC (II)

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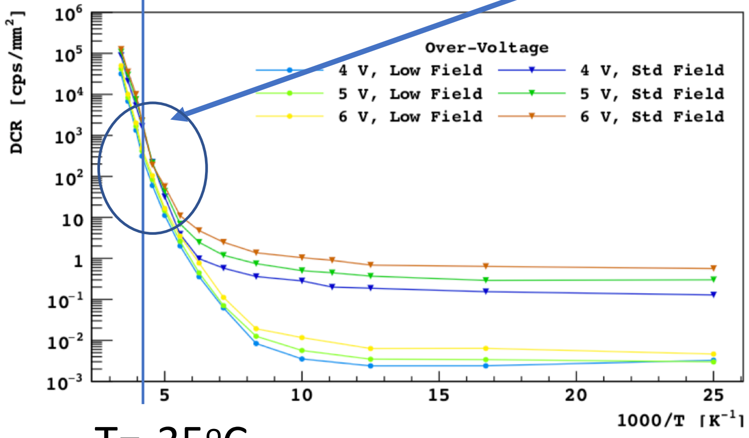
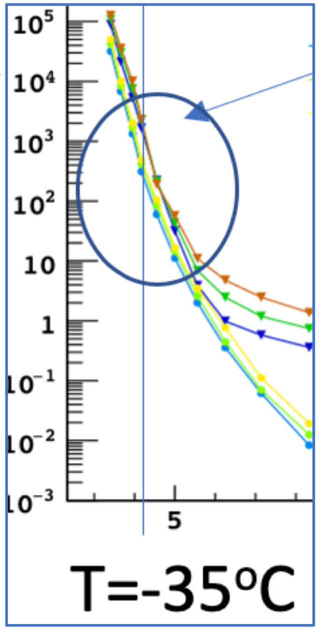
NUV-HD technology from FBK with SPTR could be an interesting candidate (peak PE@400 nm)

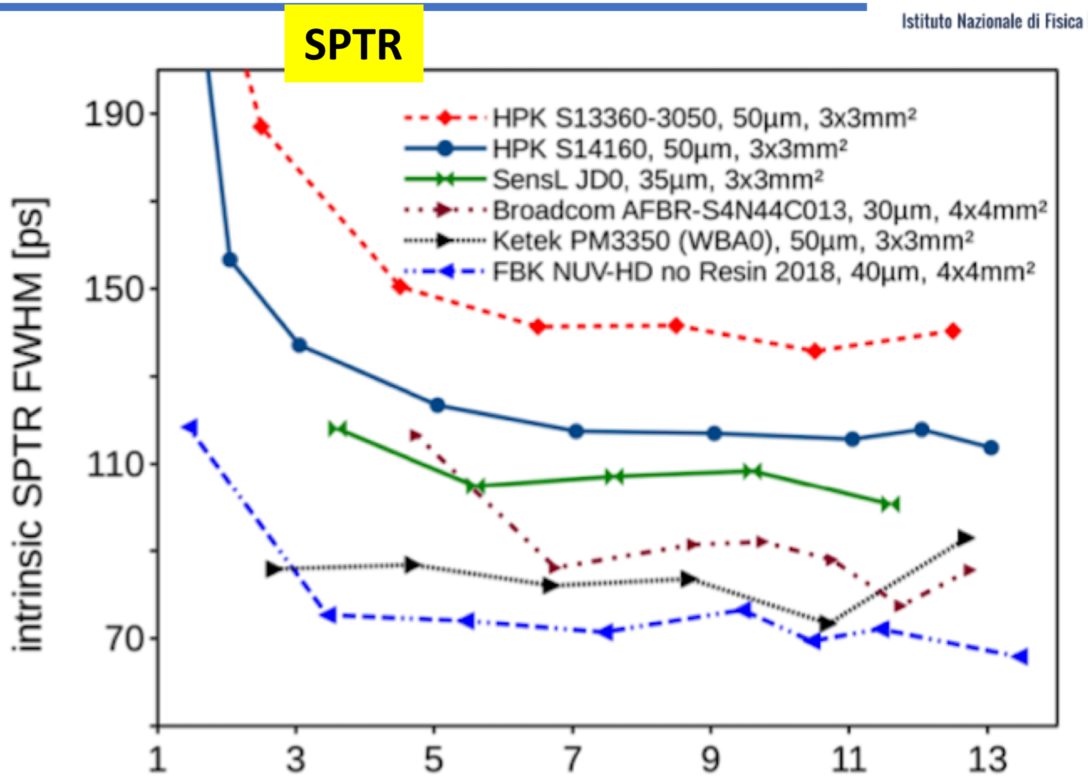
Cell size 3x3 mm^2

DCR



T=-35°C





S. Gundacker *et al* 2020 *Phys. Med. Biol.* **65** 025001

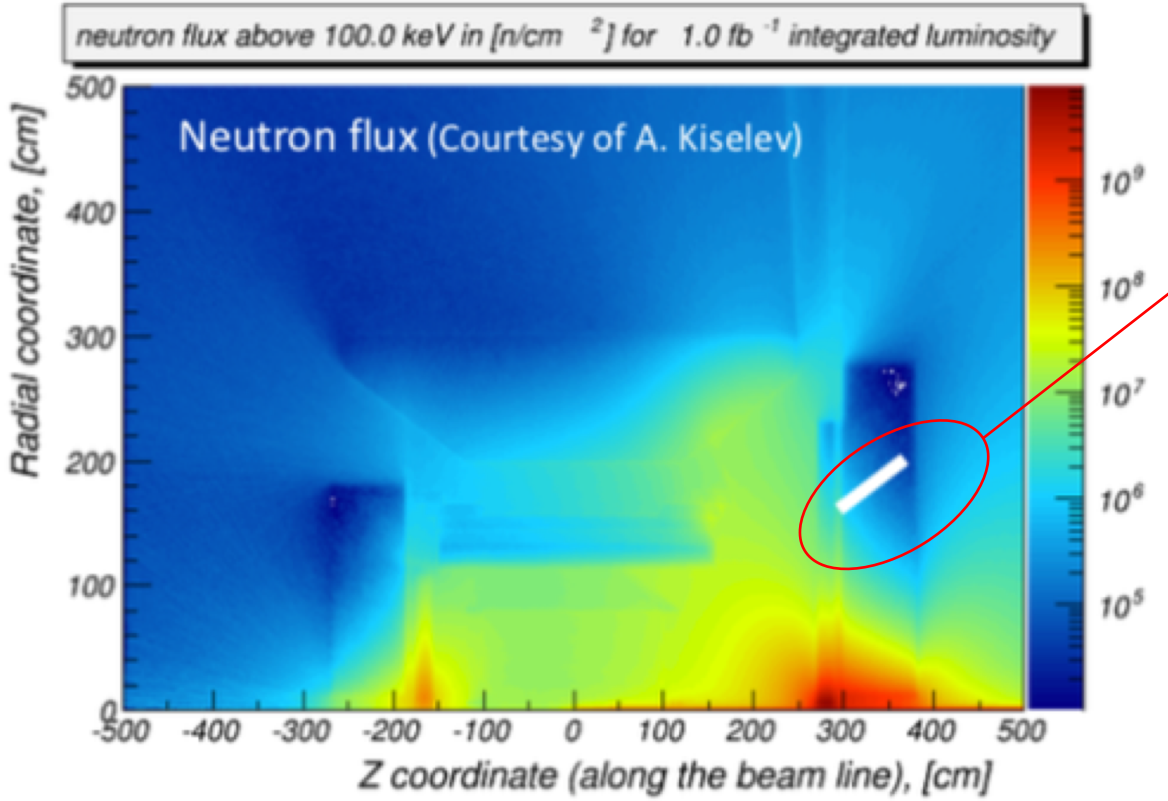
With 3x10^2 Hz/mm^2 -→ 2.7 KHz/sensor → 15 GHz/sector (comparable to Hamamatsu S13360-1350CS)

Note with PMT estimated for dRICH 10^5 Gbit/s (@1MHz DCR/sensor and 0.5 ns sampling). Assuming 64-bit word/hit this brings to **10^3 Gbit/s /sector**

Ref:
Alberto Gola
https://agenda.infn.it/event/15508/contributions/30188/attachments/21368/24347/GSSI_2018_-_Alberto_Gola_-_FBK_custom_SiPMs_technologies.pdf

Radiation levels @ EIC

Radiation tolerance



- Likely position of RICH sensors
- Values to be confirmed by further simulations when BNL will design more precisely IP
- Reference value ~ **10^{11} neq/cm^2** "for several years at max lumi (10^{34} /s/cm^2)"

We are Interested for a R&D program to check:

1) radiation tolerance (DCR degradation and loss of baseline as result of irradiation + SPTR)
2) annealing procedure to recover baseline + mitigate DCR degradation

- Bologna has experience of irradiation campaigns @TIFPA (200 MeV protons) (Centro di Protonterapia), Ferrara and Frascati irradiated already SiPM (Hamamatsu 12572 and 13360) @ENEA.
- Devoted ASIC might be part of the solution for a "rad tolerant SiPM" (add high-pass filter)

SiPM and radiation damages

Radiation tolerance

Some relevant literature:
E. Garutti and Y. Musienko, NIM, A 926 (2019) 69-84 Review of SiPM radiation damages

- T. Tsang et al., (Phenix) JINST (2016) 11 P12002, one of first publications reporting "recovery" after annealing at high temperatures for SiPM
- I. Balossino et al. (CLAS12), NIMA 876 (2017) 89
- M. Calvi et al. (Mi Bicocca/CMS-BTL), NIM, A 922 (2019) 243–249 CMS-BTL R&D for 10^{14} n_{eq}/cm^2 fluences. Annealing @ 175°C

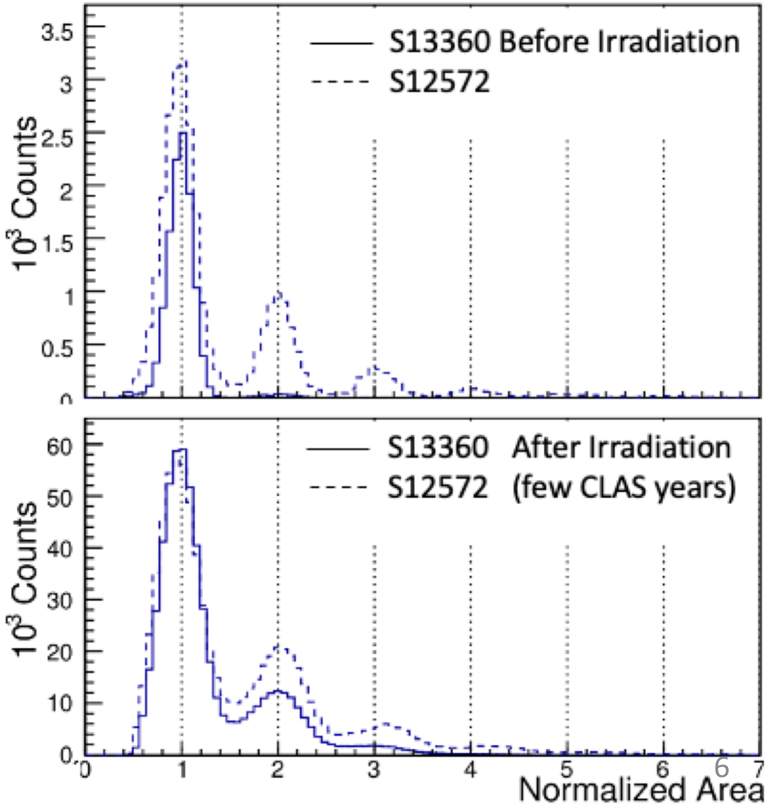
Neutrons produced isotropically through
d(230keV) t → n α
α particles measured to monitor the intensity
- max flux 10^{11} s^{-1} in 4π
- max neutron energy 14.6 MeV

Hamamatsu

S12572 standard technology
S13360 trench technology

10^9

@ 0° C



Radiation damages and recovering via annealing (@175 °C)

Radiation tolerance

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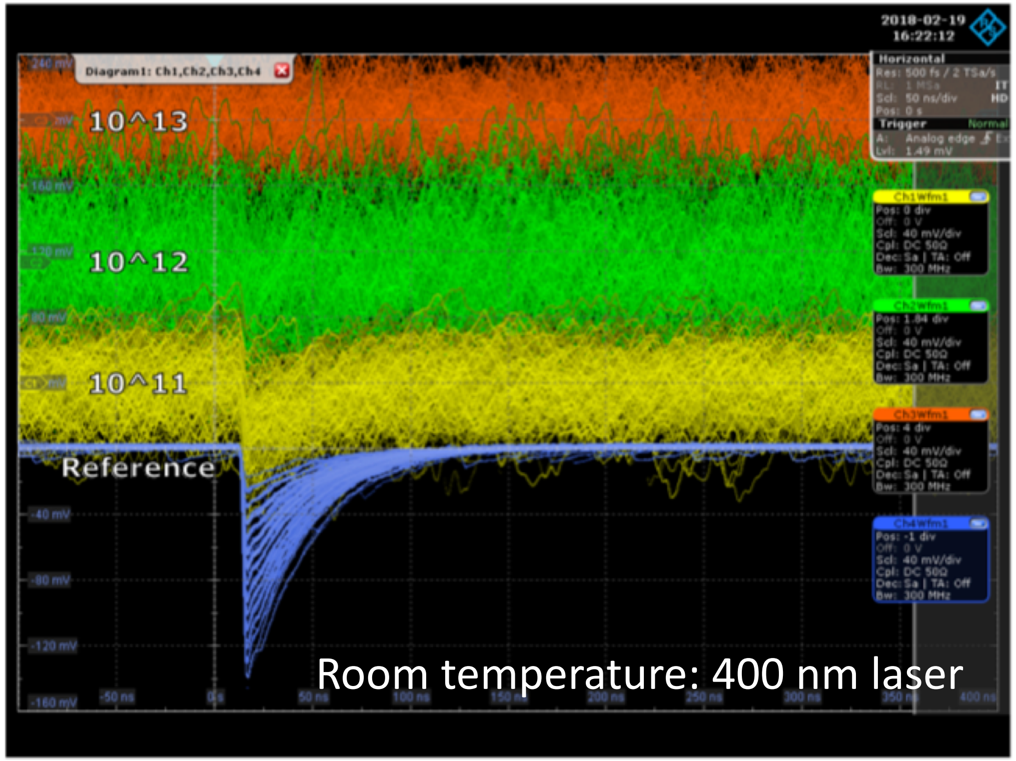

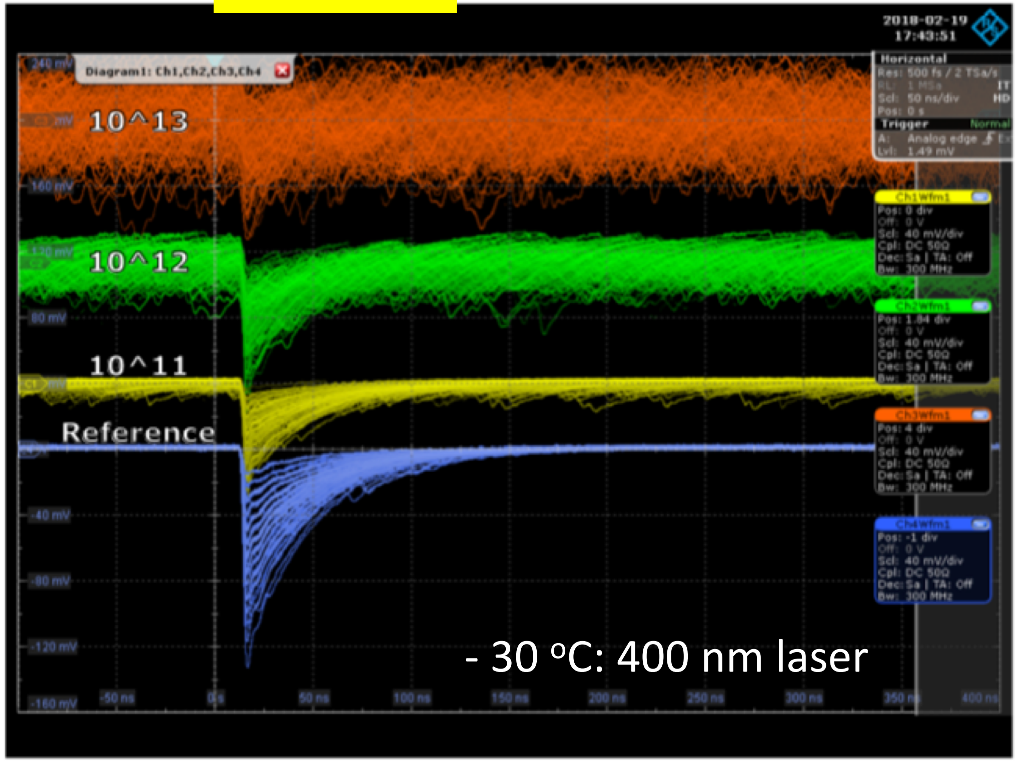

Hamamatsu S13360-1325CS (1.3x1.3 mm^2 – 25 μm)
Hamamatsu S13360-1350CS (1.3x1.3 mm^2 – 50 μm)

Effect of radiation (10^{11} 10^{12} 10^{13}):
- loss of baseline
- room temperature not an option

Ref:
M. Calvi et al.
Nuclear Inst. and Methods in Physics Research, A 922 (2019) 243–249

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journal homepage: www.elsevier.com/locate/nima

Single photon detection with SiPMs irradiated up to 10^{14} cm^{-2} 1-MeV-equivalent neutron fluence

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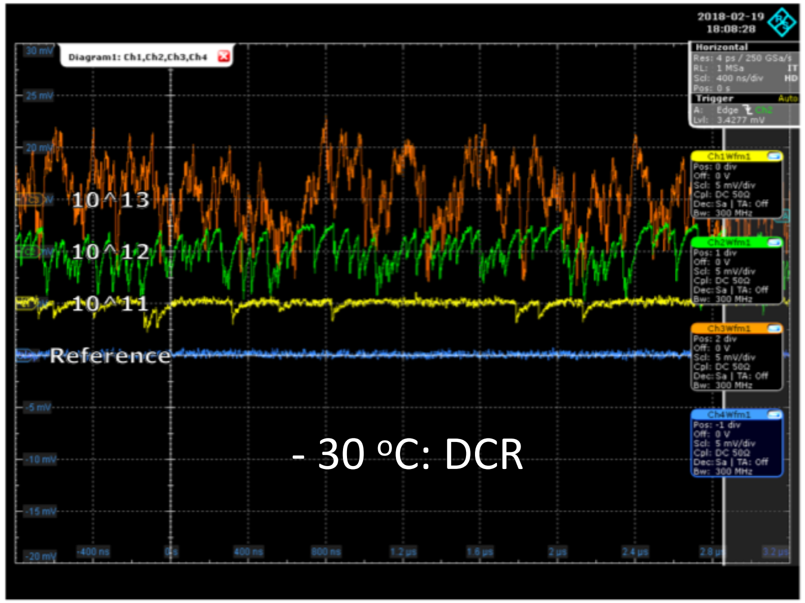
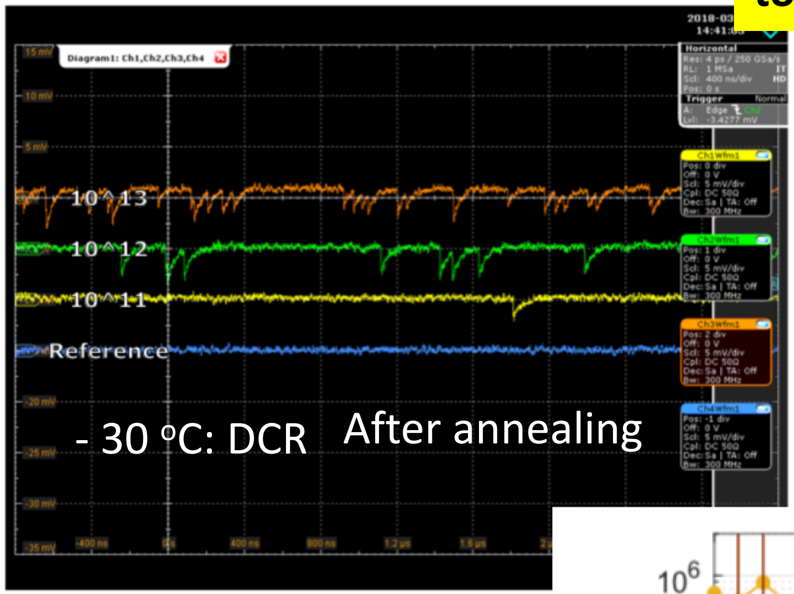
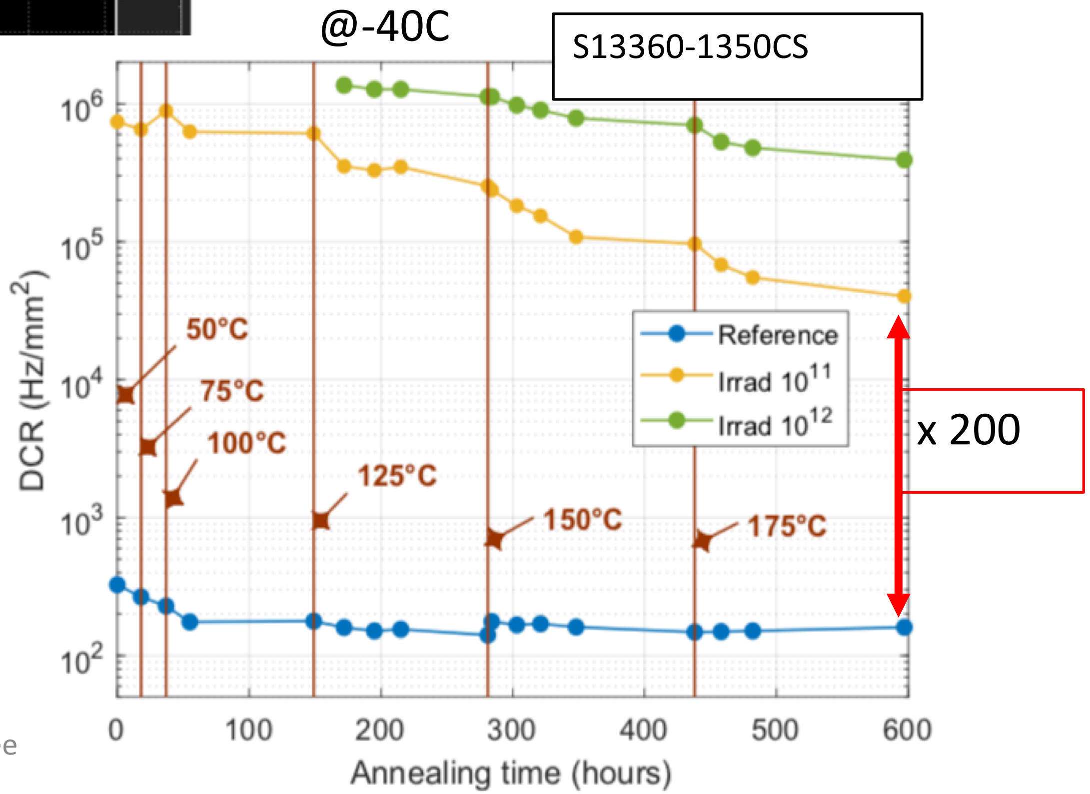
Radiation damages and recovering via annealing (@175 °C)

Radiation tolerance





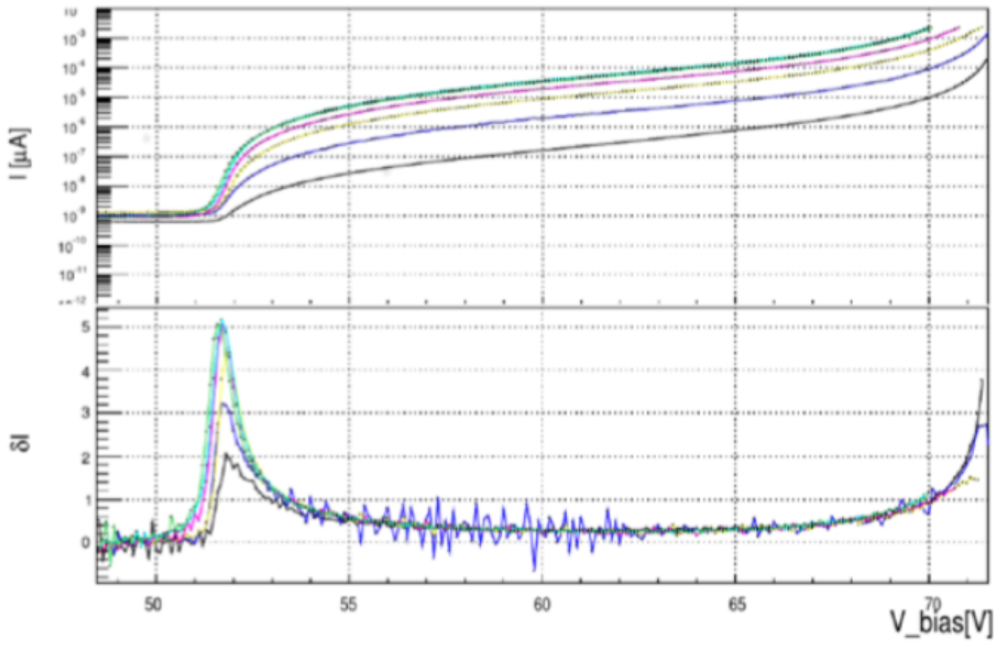


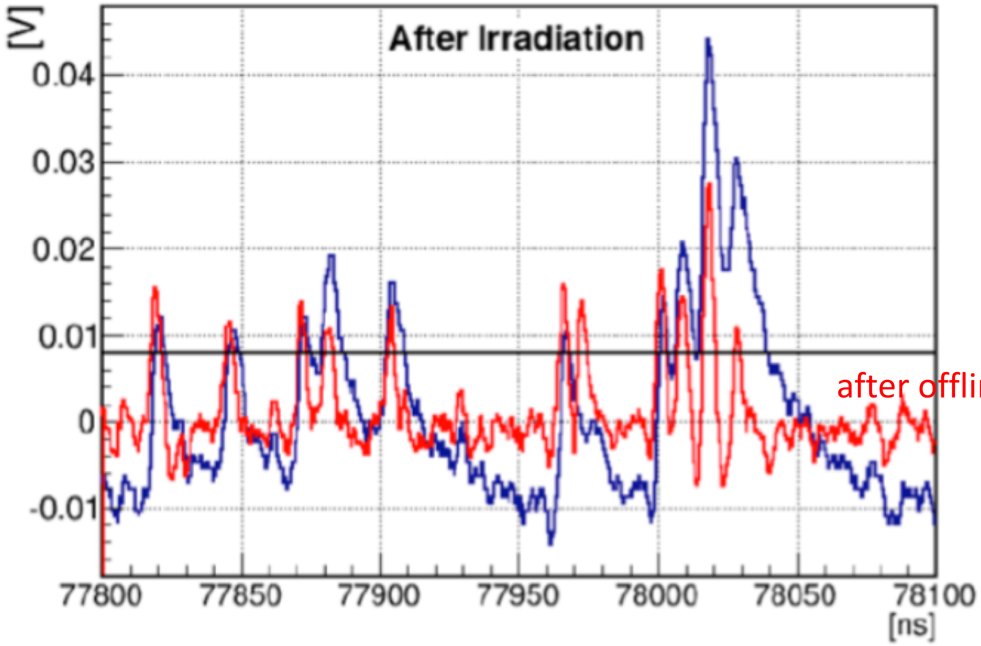
- SPD looks possible at -30°C/-40°C after annealing!
- 10^{11} seems a manageable fluence for annealing
- DCR penalty factor (pre-irradiation – post-annealing)@10^{11}: **200**
- Further lowering temperature is another option to explore
- Note, however, that with a 200 penalty factor we would have a $2 \cdot 10^5$ Gbit/sector throughput, still manageable... (and close to what "declared" @Temple)

Ref:
M. Calvi et al.
Nuclear Inst. and Methods in Physics Research, A 922 (2019) 243–249

caratterizzazione sensori

metodologia già utilizzata da gruppo Ferrara
caratterizzazione I-V e valutazione restore baseline per ricupero single photon counting + DCR

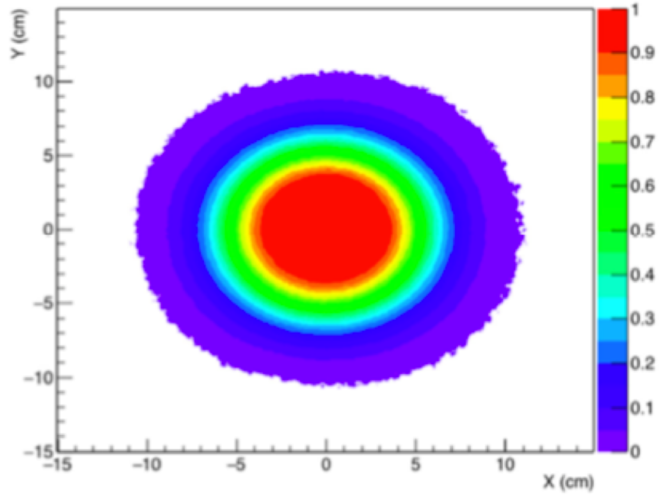


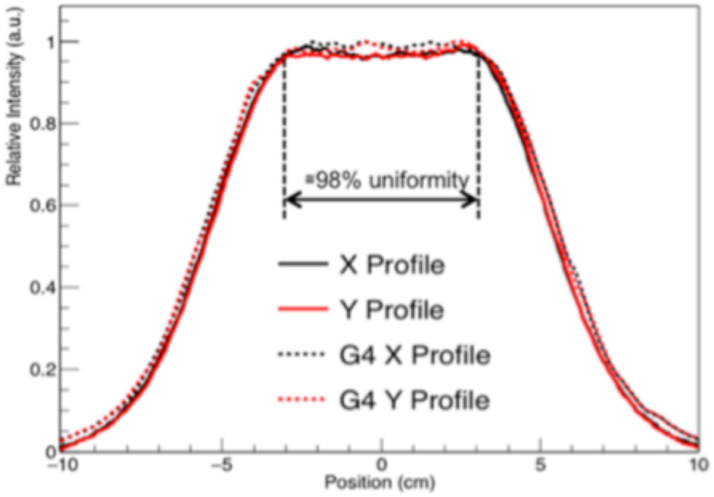


after offline software filter

- misure saranno effettuate pre-irraggiamento, post-irraggiamento e post-annealing (vedi Calvi et al.)
- read-out ALCOR based (quando operiamo a T=-30 °C)

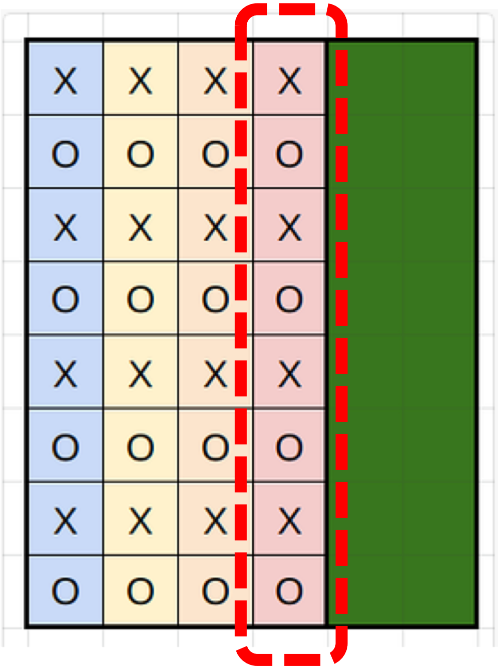
irraggiamento





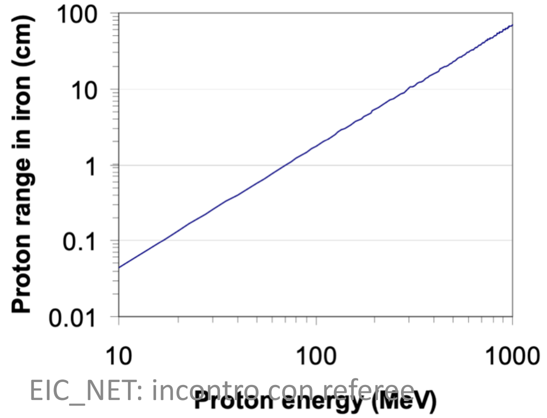
Centro di protonterapia @Trento via TIFPA
beam fino a 200 MeV proton

- 6 matrici
- 3 produttori SiPM
- 2 tipologie sensori per matrice



6x6 cm x cm "uniform area"
Otherwise beam can be with Gaussian sigma ~ 0.58 cm **or 1.12 cm**
Irraggiamento con schermi opportuni e finestra 2.4 cm x 3 mm

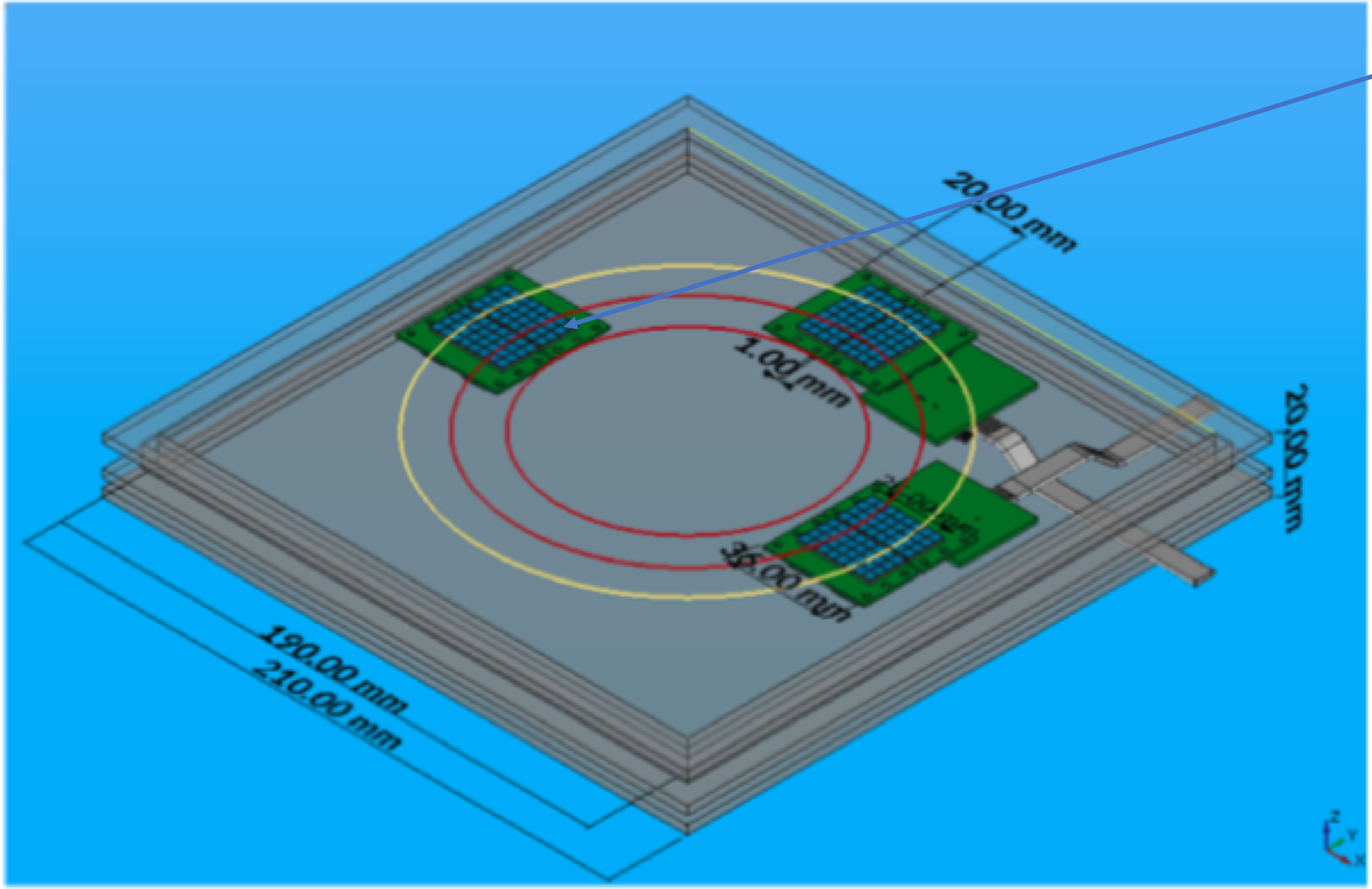
- Domanda sottomessa a PAC TIFPA il 20/7
- Richiesta per 10 h (gio-ven-sab)
- Febbraio-Marzo 2021



X-O: "diversa microcella"
colori: "diverso irraggiamento"
3 matrici NON irraggiate

irradiation	0	e9	e10	e11

post-irraggiamento e test beam setup



minimal sensor unit:
4x8 matrix

- 6 matrici
- 3 produttori SiPM
- 2 tipologie sensori per matrice

X	X	X	X	
O	O	O	O	
X	X	X	X	
O	O	O	O	
X	X	X	X	
O	O	O	O	
X	X	X	X	
O	O	O	O	

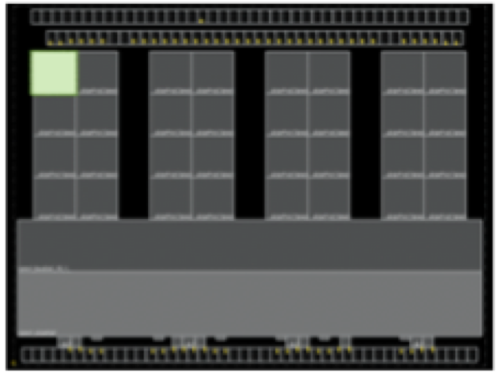
irradiation	0	e9	e10	e11

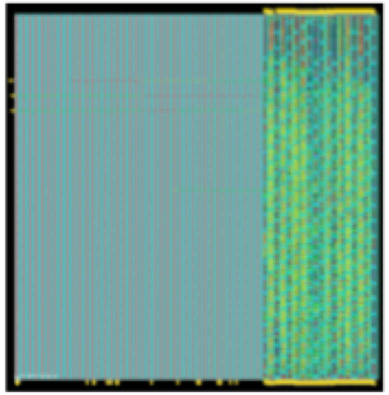
X-O: "diversa microcella"
colori: "diverso irraggiamento"
3 matrici NON irraggiate

SiPM ASIC readout: ALCOR (I)

ASIC+readout

ALCOR - A Low Power Chip for Optical Sensor Readout





- 32-pixel matrix mixed signal ASIC
- the chip performs amplification, signal conditioning and event digitisation, and features fully digital I/O.
- each pixel reads an SiPM (up to 1 cm^2, compatible with smaller pixels)
- Pixel hosts SiPM VFE, leading-edge discriminator, 4 TDCs, charge integrator, digital control and interface
- Single-photon time tagging mode or time and charge measurement
- 64-bit (32-bit on time tagging mode) event and status data is generated on-pixel and propagated down the column
- Up to 4 LVDS TX data links used, SPI configuration
- operation from 10 MHz up to 320 MHz (TDC binning down to 50 ps)
- 10 MHz clock, 500 ps r.m.s. time resolution on single photon

Manuel Da Rocha Rolo (INFN Torino) | Integrated FEE for Low-Background LAr DM | FEE2018 Jouvence 21 / 23

ALCOR:

- Developed by INFN Torino originally for a Darkside application
- Optimized for cryo operation
- First samples received from foundry, first qualification with carrier board starting literally these days!

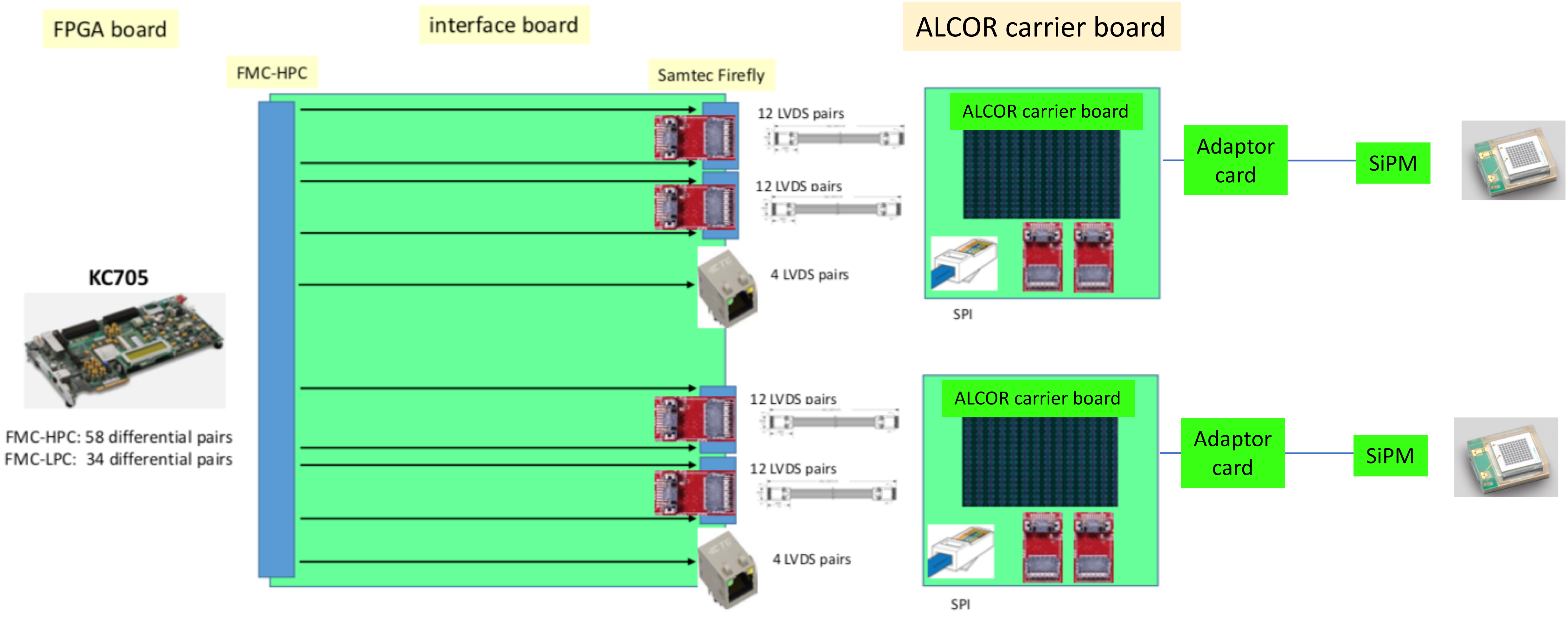
- Specs would match – at first order – requirements for EIC, but an ALCOR++ optimised for RICH application will be next step
- INFN Torino → characterization with a FBK SiPM sensor
- INFN Bologna → development of readout card FPGA-based (connected to ASIC carrier via fast serial links)

- Test of the ASIC expected to end by ~2020
- Based on 2020 results and coupling with SiPM → 2022 for an ALCOR v2.0 better tailored for EIC requirements

Good synergies with respect to other on-going collaborations between INFN Torino & Bologna (on microelectronics + readout, ALCOR, ARCADIA, DUNE, DarkSide)

R. Kugathasan, "A Low-Power Mixed-Signal ASIC for SiPM Readout at Low Temperature," *2019 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC)*, Manchester, United Kingdom, 2019, pp. 1-3.

Readout scheme



- Similar scheme under development between TO-BO for other chip (ARCADIA, Gruppo5)
- Can be scaled up to provide readout to SiPM matrix in test beam
- Supports for simple DAQ (UDP) or optical links: "streaming readout ready"

- testare pre/post irraggiamento e poi su test beam varie tipologie di SiPM
  - selezione SiPM
  - montaggio su matrici (8x4 vedi talk Marco)
  - caratterizzazione pre-irraggiamento
  - irraggiamento a Centro di Protonterapia (**Trento**, sala gestita da TIFPA)
- effettuare su **test beam** lettura con ASIC ALCOR matrice SiPM
  - cooling
  - matrici vs irraggiamento
  - readout (6 matrici: 192 canali acquisiti con "streaming readout")

Struttura	missioni		consumo		altri_cons		trasporti	
BA.DTZ	14.00		2.00					
BO.DTZ	9.00	2.00	23.00					
CT.DTZ	7.00	2.00						
FE.DTZ	3.50	2.00	17.00					2.00
GE.DTZ	6.50	2.00	6.00					
LNF.DTZ	1.00							
LNS.DTZ	2.50							
PD.DTZ	2.50							
RM1.DTZ	3.50							
RM2.DTZ	5.00							
TO.DTZ	6.00	2.00						
TS.DTZ	36.00	2.00	14.50					
Totali	96.50	12.00	62.50					2.00

3 KEU accesso TIFPA (10 h)
5 KEU schede ALCOR (To)
3 KEU break-out boards Firefly (Bo)
4 KEU SiPM sensors (Broadcom/OnSemi)
8 KEU SiPM carrierboards
23 KEU

2 KEU SiPM sensors (Hamamatsu)
4 KEU SiPM carrierboards
6 KEU

Selezione sensori

È stata fatta ricerca estesa su mercato tra principali produttori in preparazione preventivi

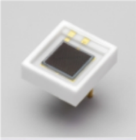
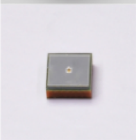
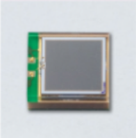
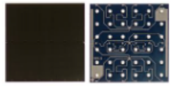
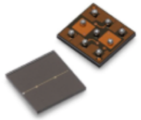
supplier	model	vendor	price [10 pcs,matrix] (EUR)	type	pixel (mm)	cell (um)	mount / connector	window	PDE (%) peak	DCR (kHz/mm2)	PDE / sqrt(DCR)	package fill factor (%)	x-talk (%)	after-pulse (%)	Vop (V)	CTR (ps)	rise time (ps)
Ketek	PM3325-WB-D0	self	159	single	3	25	smt	glass	45	125	4.02	82	26	5	30	70	110
Ketek	PM3315-WB-C0	self	159	single	3	15	smt	glass	31	125	2.77	82	18	5	30		630
Ketek	PA3325-WB-0404	self	310	4x4	3	25	Samtec	glass	45	125	4.02	80	26	5	30		110
Hamamatsu	S13360-3025CS	self		single	3	25	ceramic	silicone	25	45	3.73	23	1		60		
Hamamatsu	S13360-3025PE	self		single	3	25	smt	epoxy	25	45	3.73	54	1		60		
Hamamatsu	S13360-3050CS	self		single	3	50	ceramic	silicone	40	55	5.39	23	3		60		
Hamamatsu	S13360-3025PE	self		single	3	50	smt	epoxy	40	55	5.39	54	3		60		
Hamamatsu	S13360-3050VE	self		single	3	50	smt	epoxy	40	55	5.39	78	3		60		
Hamamatsu	S13361-3050NE-04	self		4x4	3	50	smt	epoxy	40	55	5.39	85	3		60		
Hamamatsu	S14160-3050HS	self	290	single	3	50	smt	silicone	50	165	3.89	78	7		40	60	
Hamamatsu	S14161-3050HS-04	self		4x4	3	50	smt	silicone	50	165	3.89	85	7		40	60	
Hamamatsu	S14520-3050VS	self	320	single	3	50	smt	silicone	49	133	4.25	78	5		41		
Hamamatsu	S14160-3015PS	self	480	single	3	15	smt	silicone	32	78	3.62	54	< 1		45		
Hamamatsu	S13362-3050DG	self		single	3	50	metal	glass	40	25	8.00	4	3		55		
SensL	C-Series 30050			single	3	50	smt	compound	35	33	6.09	56	10	0.6	25		600
SensL	ARRAYC-30035-16P-PCB			4x4	3	35	Hirose	compound	31	33	5.40	56	7	0.2	25		600
SensL	MICROFJ-30035-TSV-TR	Mouser	211	single	3	35	smt	glass	38	50	5.37	94	8	0.75	25		90
SensL	MICROFJ-30035-TSV-TR1	Mouser	523														
SensL	MICROFJ-30020-TSV-TR1	Mouser	475	single	3	20	smt	glass	30	50	4.24						
SensL	ARRAYJ-30035-16P-PCB			4x4	3	35	Hirose	glass	38	50	5.37	86	8	0.75	25		90
AdvanSid	ASD-NUV3S-P				3	40		epoxy	43	100	4.30	65		4	26		
Broadcom	AFBR-S4N44P163	Mouser	312	4x4	3	30	smt	glass	55	255	3.44	92		1	10		
Broadcom	AFBR-S4N33C013	Mouser		single	3	30	smt	glass	54	255	3.38	91					
Broadcom	AFBR-S4N44C013	Mouser	202	single	3.72	30	smt	glass	55	270	3.35	92					

Guidelines:

dimensions and packages
- single pixel sensors
- 3x3 mm^2 active area
- high active/device area
- surface mount

SPAD size and PDE
- PDE is surely a very important parameter vs usability as photosensor after radiation is more important (DCR, baseline)
- progress in smaller SPADs with larger PDE (worth trying them, PDE might improve further)

multiple manufacturers
- differences in architecture, V_{bd} and electric fields
- keep Hamamatsu, leading producer of photosensors
- keep Broadcom, possible future R&D within FBK-INFN collaboration agreement
- choose between Ketek (25/15 μm, cheaper) and SensL (30/20 μm, timing)

model	uCell (μm)	V_{bd} (V)	PDE (%)	DCR (kHz/mm^2)	window	notes
S13360 3050CS	50	53	40	55	silicone	legacy model Calvi et. al not for beam
S14160 3050HS	50	38	50		silicone	newer model lower V_{bd}
S14160 3015PS	15	38	32	78	silicone	smaller SPADs radiation hardness
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
AFBR S4N33C013	30	27	43	111	glass	commercially available FBK-NUVHD

HAMAMATSU PHOTON IS OUR BUSINESS — 2000 EU

ON Semiconductor — 3000 EU

BROADCOM — 1000 EU

+ FBK prototype (small uCell 15 μm: NUV-HD-RH)

Conclusioni

INFN
Istituto Nazionale di Fisica Nucleare

R&D needed for SiPM:

1. Proof of "feasibility": DCR & operating conditions, single photon detection etc.
2. Readout electronics: ASIC (+ streaming readout)
3. Radiation tolerance (& annealing)

Note these three R&D items are deeply interlinked!

il programma proposto e' intenso ma permette di fornire una importante "proof of principle" con l'insieme dati da irraggiamento, annealing, readout e test beam per l'uso SiPM per readout per dRICH (e piu' in generale per RICH-based detector a EIC, almeno fino alle fluenze di radiazione studiate)

Backup

SiPM as candidate for a RICH detector

https://doi.org/10.1016/j.nima.2020.163804

7. Summary

Semiconductor sensors for single photons, in particular SiPMs, are a novel device for RICH. Their advantages, operation in the magnetic field, high quantum efficiency, low supply voltage, fast response, flexible granularity, make them an almost ideal sensor for ring imaging Cherenkov detectors. The main challenge, a high occupancy due to dark counts, can be overcome by a narrow time window and by using light collecting elements to increase the ratio of the light collection area and the SiPM sensor area. The remaining issue for operation in experimental environments with high radiation exposure, in particular by neutrons, is under intense study for the next generation of experiments.

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Solid state single photon sensors for the RICH application

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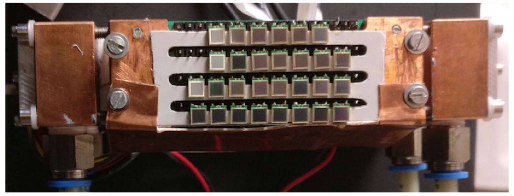
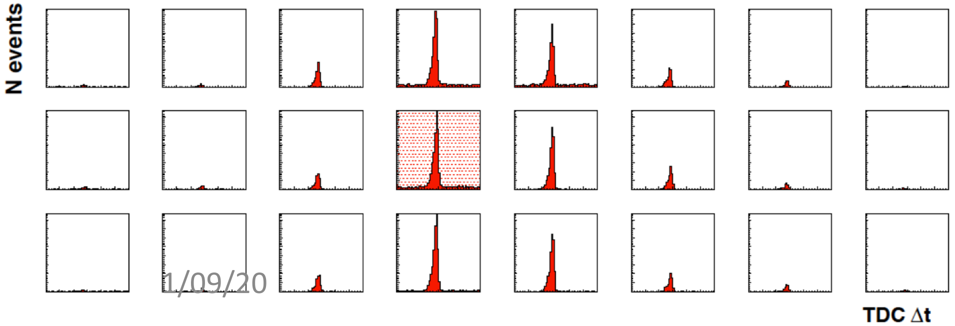
ABSTRACT
Silicon photomultipliers, arrays of avalanche photodiodes operated in the Geiger mode, are exciting novel light sensors for RICH detectors. In the present review, we discuss the motivation for employing solid-state single-photon sensors, describe their principles of operation and challenges of their use. We review the current state of development and the progress made with semiconductor sensors. We also discuss applications in ongoing and planned future experiments.

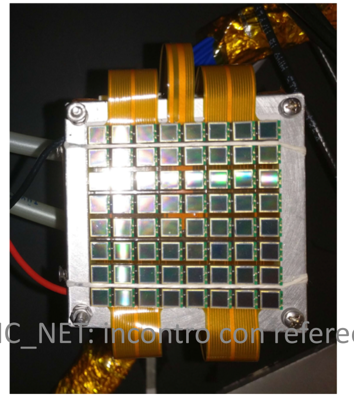
Interesting review, also quoting recent results presented by mRICH at INSTR20
https://indico.inp.nsk.su/event/20/session/6/contribution/153/material/slides/0.pdf

And don't forget CLAS12 testing also SiPM option back in 2014!

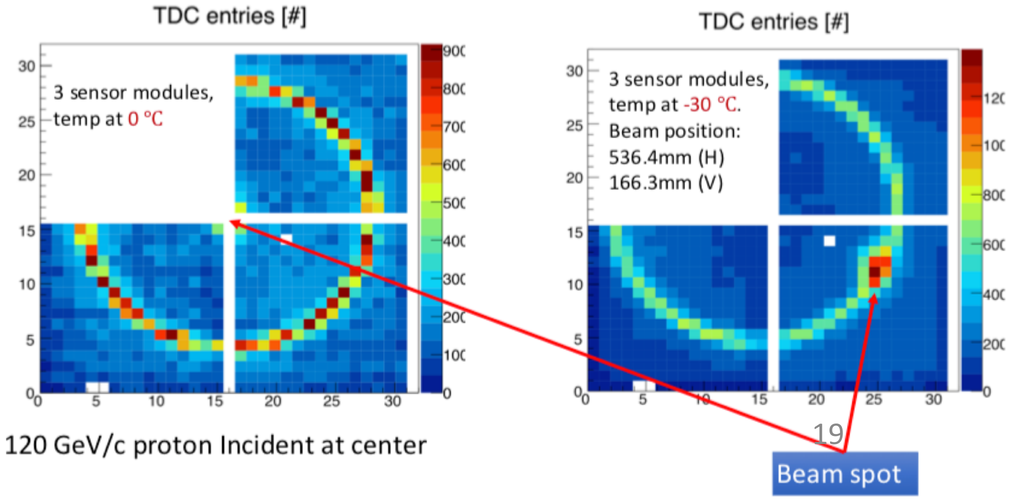


M. Contalbrigo et al., NIM A766 (2014) 22



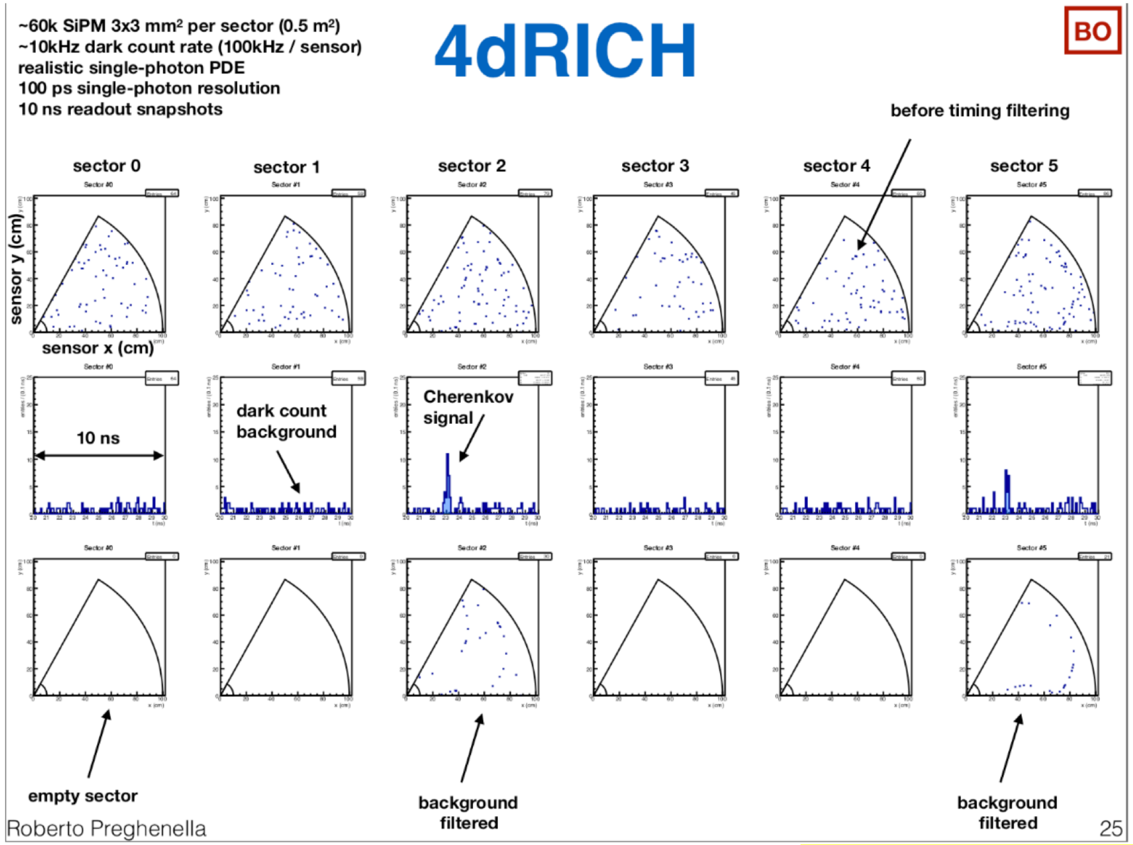


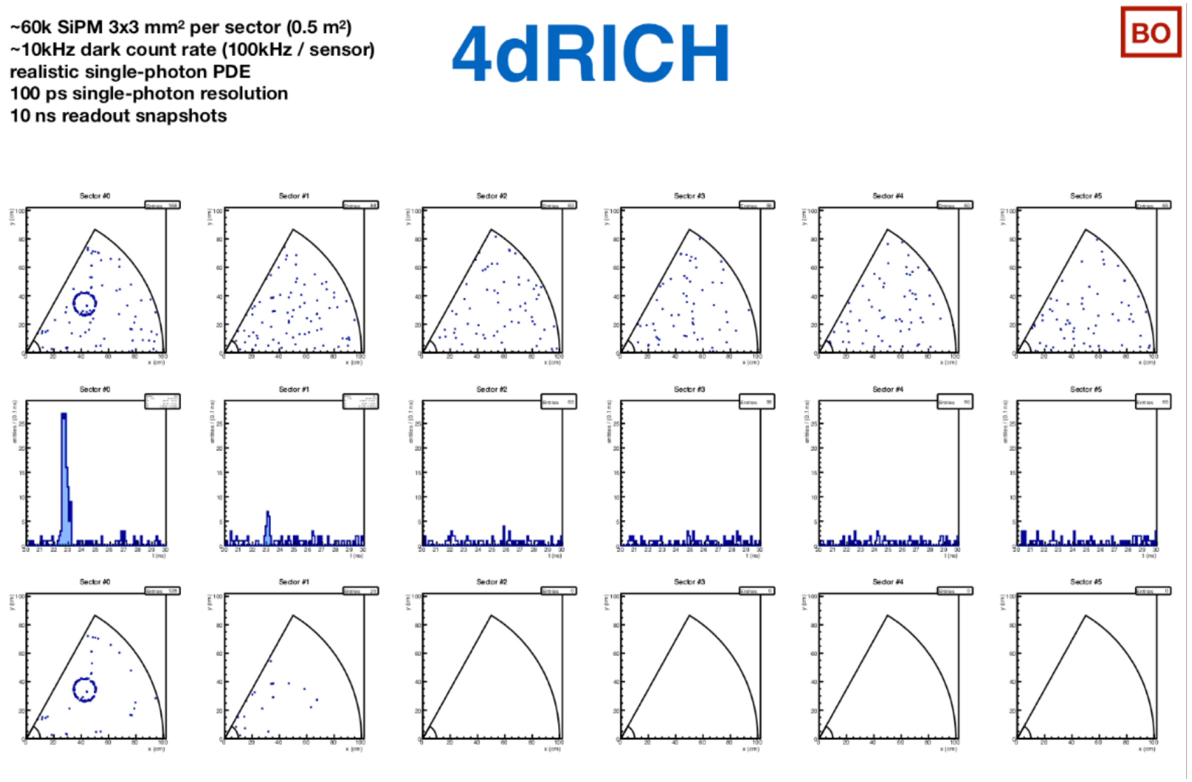
mRICH readout with SiPM matrix sensors



Use SPTR to reduce DCR ("narrow time window")

DCR ⟷ **SPTR**





How much narrow? Initial studies on dRICH reconstruction performance: no degradation with a 150 ps time resolution sensor with up to 20 kHz/mm² DCR
And: σ = 150 ps conservative, better resolution -> sustain higher noise rates"

Ref:
RobertoPreghenella@EIC meeting/Bari
https://agenda.infn.it/event/20360/contributions/103553/attachments/68342/84348/eicnetBari.pdf