A SiPM R&D program towards a forward RICH proposal for EIC

Istituto Nazionale di Fisica Nucleare

R&D needed for SiPM:

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

Note these three R&D items are deeply interlinked!

Ferrara: M. Contalbrigo et al.
LNF: M. Mirazita et al.
Roma1: E. Cisbani et al.
Catania: C. Tuvé et al.
} dRICH group
Bologna: P. Antonioli, D. Falchieri, F. Noferini, R. Preghenella
Torino: M. Alekseev, M. Chiosso, M. Da Rocha Rolo, D. Panzieri, M. Ruspa

Caveat & info:

- "dRICH based" for test beams and parameters selection, but generic for R&D towards a forward RICH
- some literature collection effort + we report recent direct contacts with FBK (Bologna/Torino)

dRICH and SiPM: "an option to be explored"

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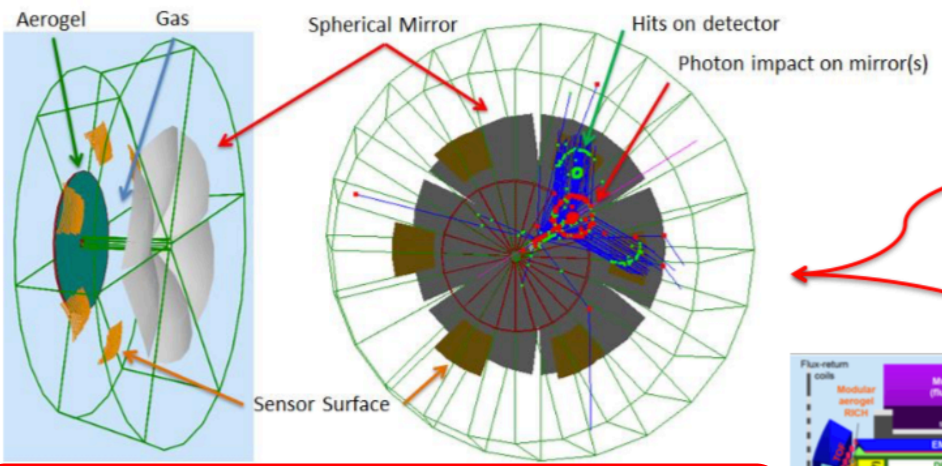
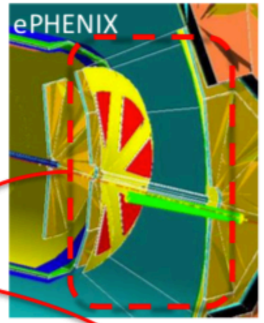
dRICH Key Hardware Components 2/2

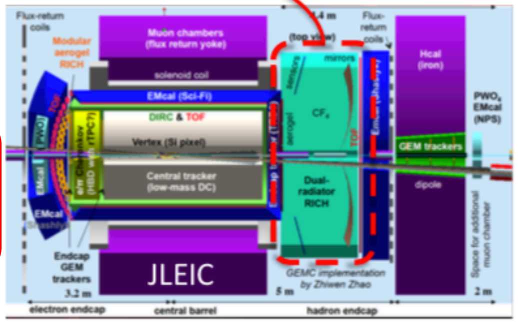
Component	Function	Specs/ Requirements	Risk	Mitigation
Photon Detector	Single photon spatial detection	Magnetic field tolerant and radiation hardness; ~ few mm spatial resolution	MCP-PMT is likely duable, but expensive. Need to find alternatives	LAPPD may represent an alternative. **R&D on SiPM:** a 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

Dual Radiator – Focusing – RICH in EIC Hadron-endcap







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 cm^2/sector, 3 mm pixel size, UV sensitive, out of charged particles acceptance

Optimized for JLEIC, preliminary implementation in ePHENIX

Phase Space:
- Polar angle: 5-25 deg
- Momentum: 3-50 GeV/c

20/Mar/2020 E.Cisbani, M.Contalbrigo - dRICH status 4

dRICH (E. Cisbani) @Temple
https://indico.bnl.gov/event/7449/contributions/35908/
And last dRICH @PID meeting 15th April
https://indico.bnl.gov/event/8297/contributions/36712/attachments/27616/42317/drich_toward_yr_v0.4.pdf

Notes:
- 6 x 4500 cm^2 = **O(3 m^2)** active sensors
- **3x3 mmxmm pixel size**

Intermezzo: this paper is out these days quite timely

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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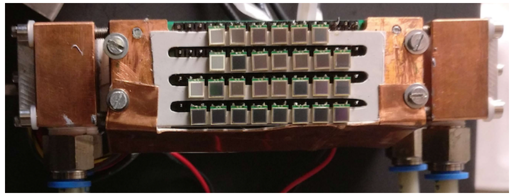
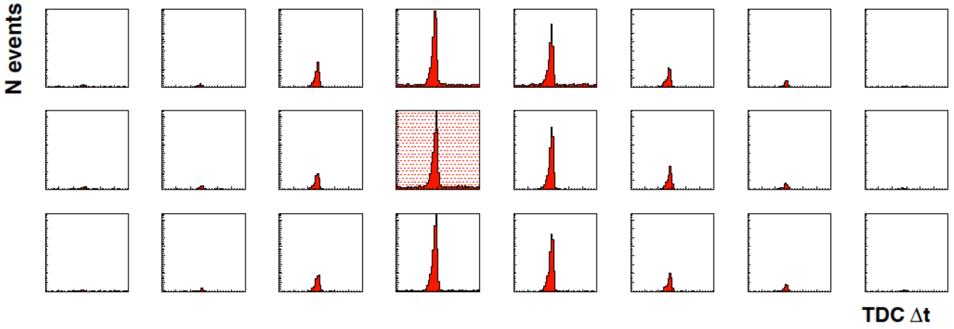
ABSTRACT
Silicon photomultipliers, arrays of avalanche photodiodes operated in the Geiger mode, are exciting novel light sensors for RICH detectors. In the present review, we discuss the motivation for employing solid-state single-photon sensors, describe their principles of operation and challenges 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.

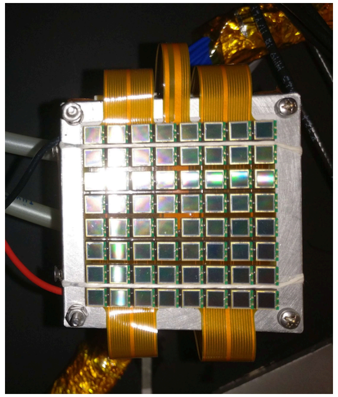
Interesting review, also quoting recent results presented by mRICH at INSTR20
https://indico.inp.nsk.su/event/20/session/6/contribution/153/material/slides/0.pdf

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

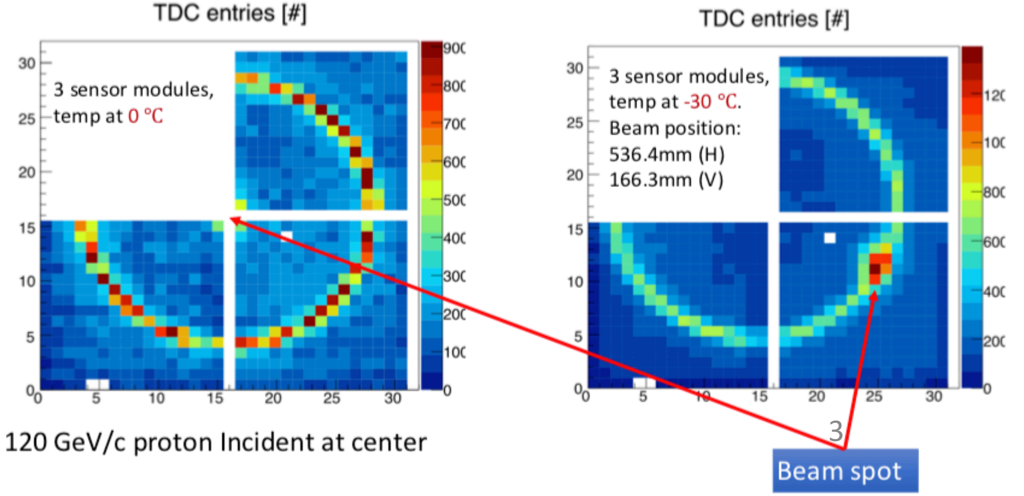


M. Contalbrigo et al., NIM A766 (2014) 22





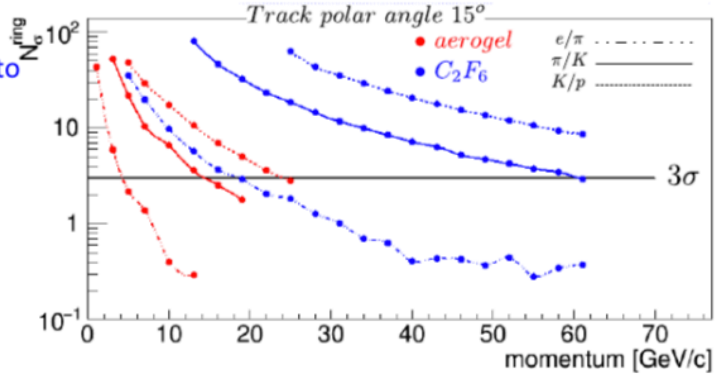
mRICH readout with SiPM matrix sensors



R&D on SiPM@EIC: assess requirements using dRICH case

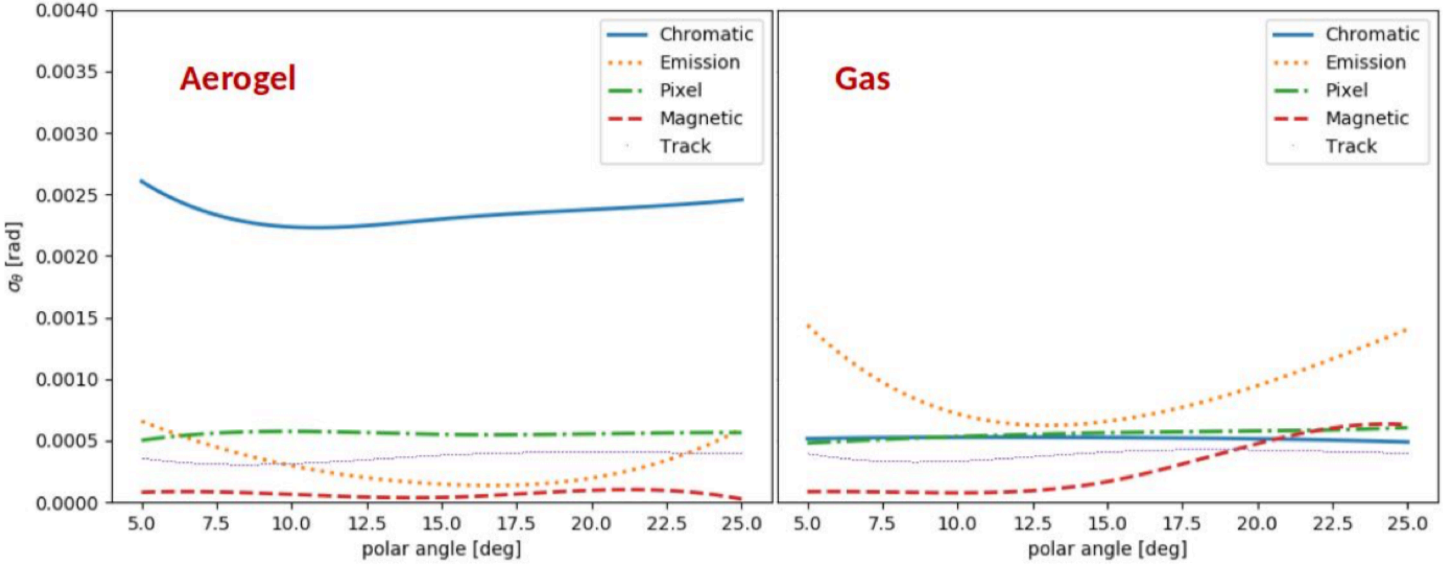
dRICH MonteCarlo Expected Performance

- Montecarlo: GEMC (Geant4)
- Acrylic Filter (<300nm) after the aerogel to minimize Rayleigh scattering
- Aerogel and mirror quality from CLAS12/RICH
- PMT 3x3 mm pixel; QE from real CLAS12/RICH/PMT data (200-500 nm)
- Tracking accuracy 0.5 mrad
- Include 3T central magnetic field
- Cherenkov Angle reconstruction based on Inverse Ray Tracing



Hadron identification (π/K/p): provides better than 3 sigma from ~3 up to ~50 GeV/c for π/K

Single Photon Angular resolution



So far used "baseline option" with MCP-PMT plus "old" electronics

We want to explore SiPM feasibility as photon sensors + devoted electronics:

<u>Requirements:</u>

→ mainly **UV band** (due to Cerenkov spectra + chromaticity)

aerogel: 300-650 nm

gas: 180-650 nm

→ dimension: **3x3 mm²** can be flexible? How?

→ Single Photon Detection (PE: "highest as possible")

→ Temperature vs DCR ("not cryogenic") (not below -50°C?)

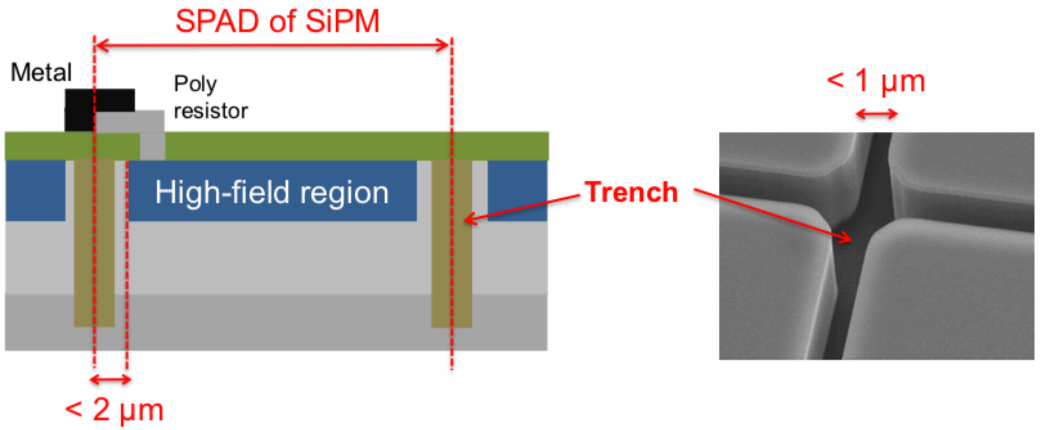
→ SPTR: (how much good? **200 ps** would be enough?) to filter DCR

→ Radiation tolerance (**10^{11} n_{eq}/cm²** so far as "sensible" number – "after *some* years assuming max luminosity")

FBK as a potential SiPM supplier for dRICH (or let's say "a full Italian RICH@EIC") (I)

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

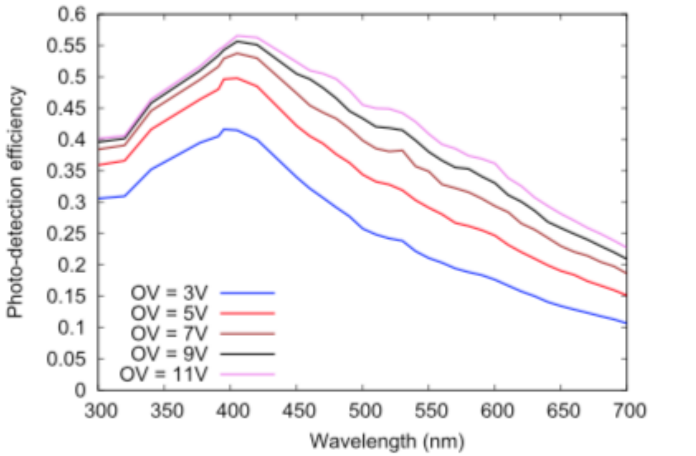


Fig. 2. PDE spectrum of the 30 × 30 μm^2 cell (78% FF) at different overvoltages. The measurement error is estimated to be 4%.

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 dRICH (or let's say "a full Italian RICH@EIC") (II)

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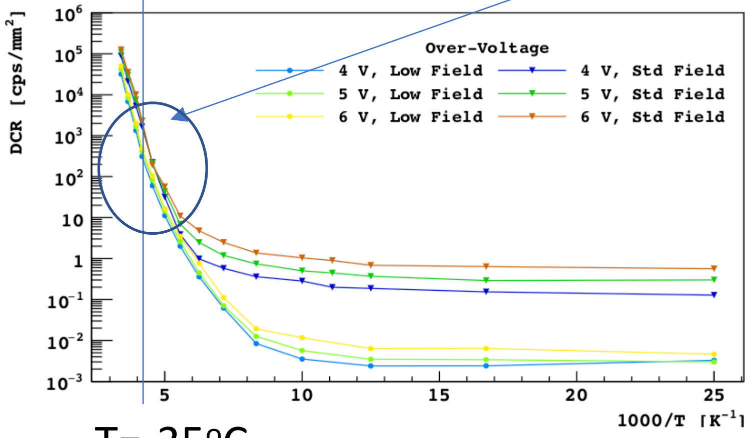
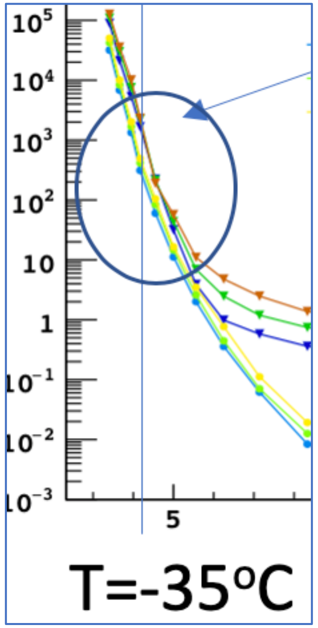
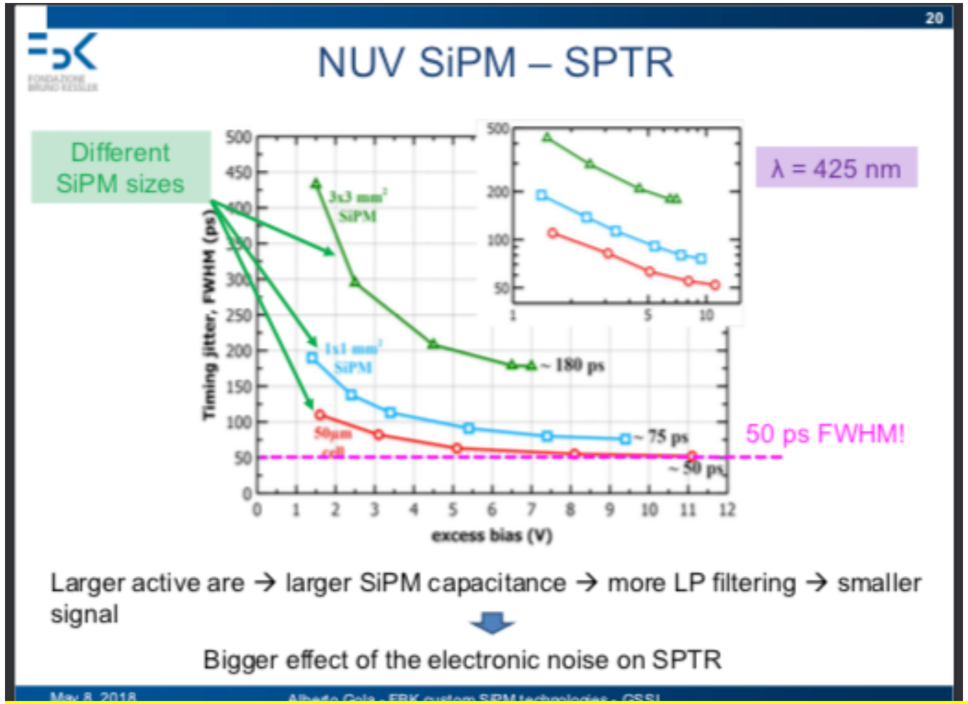
NUV-HD technology from FBK with SPTR could be an interesting candidate (peak PE@400 nm)

Cell size 3x3 mm^2



T=-35°C





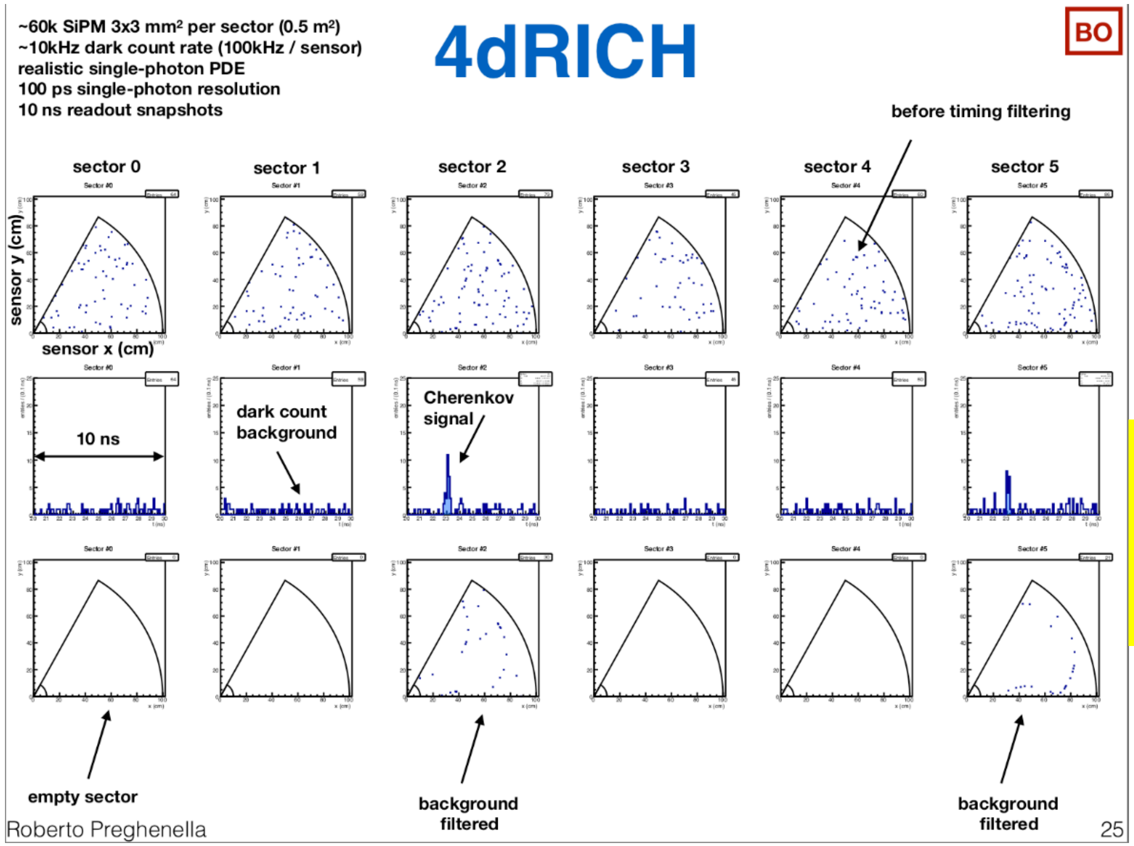
Note: FBK says they have now updated (and better) results with devoted electronics for SPTR

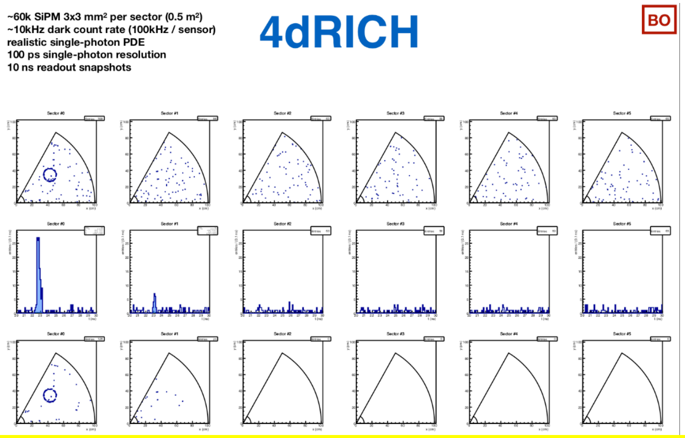
With 3x10^2 Hz/mm^2 -→ 2.7 KHz/pixel → 15 GHz/sector (comparable to Hamamatsu S13360-1350CS)

Note with PMT estimated 10^5 Gbit/s (@1MHz DCR/pixel and 0.5 ns sampling) see Evaristo@Temple. 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

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



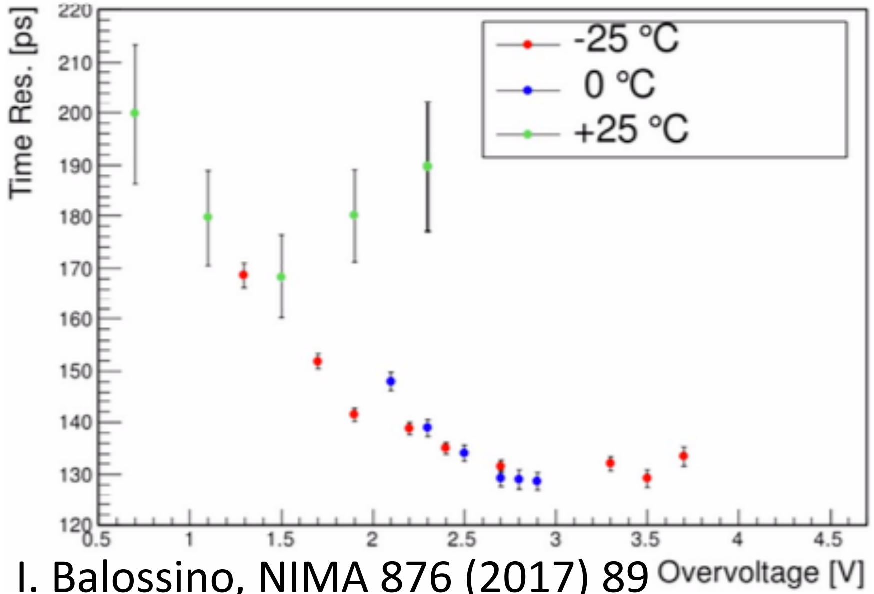


How much narrow?

For the moment we set σ_t=150 ps →1 ns 99%

(note FBK results are reported as FWHM and CLAS12 result with SiPM below)

→ σ_t=150 ps is conservative assumption



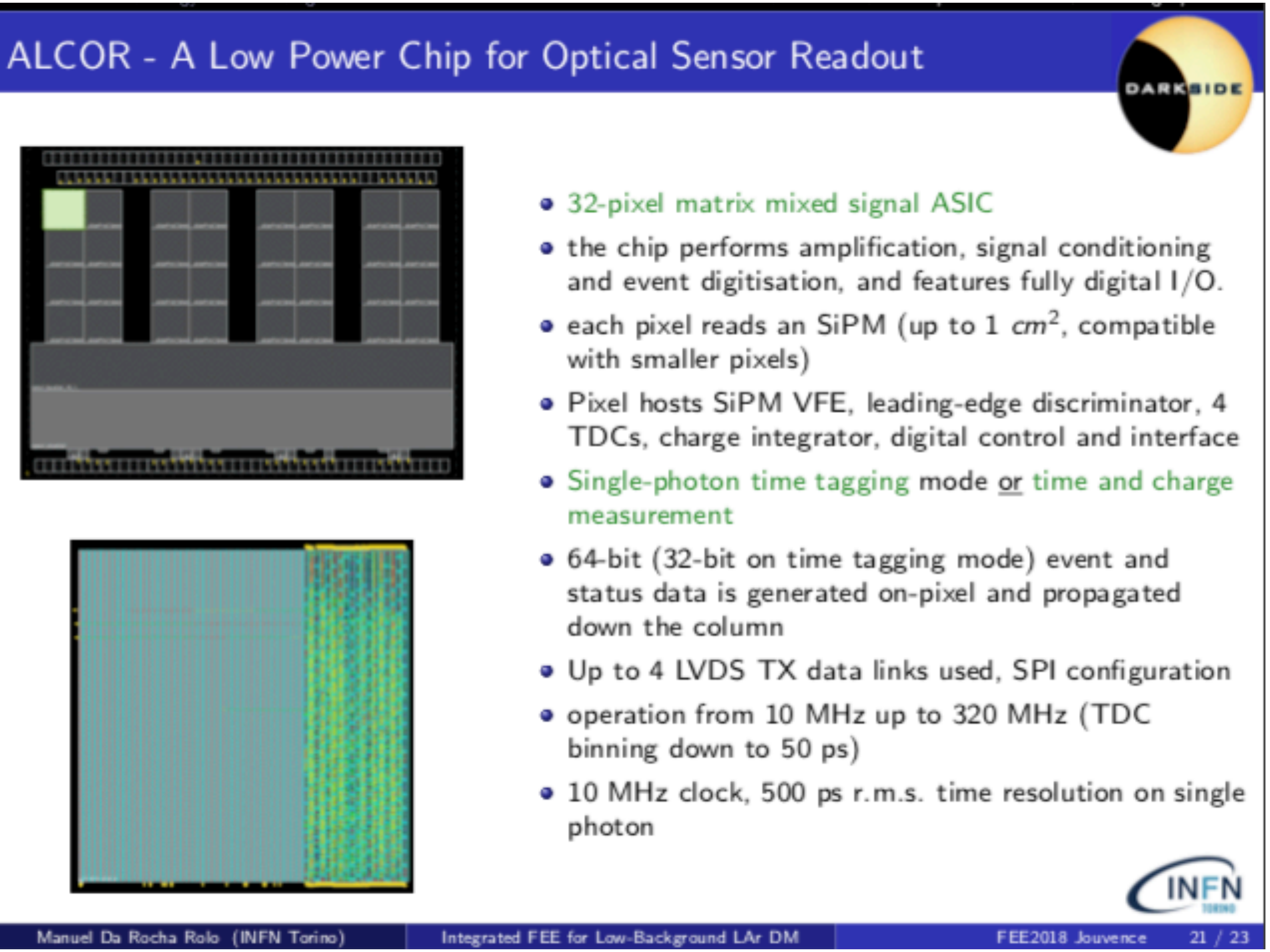
I. Balossino, NIMA 876 (2017) 89

Ref:

Roberto@EIC meeting/Bari

https://agenda.infn.it/event/20360/contributions/103553/attachments/68342/84348/eicnetBari.pdf

SiPM ASIC readout: ALCOR (I)



ALCOR:

- Developed by INFN Torino originally for a Darkside application
- Optimized for cryo operation
- First samples just received from foundry, carrier board under development

- 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 start 06.2020 with the goal to be ended by ~2020
- Based on 2020 results → 2021 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.

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To address the main challenges of the measurement taking advantage of the state of the art developments at INFN sez. Torino, we would investigate:

- ➢ The possibility to further adapt as a next revision the newly developed ASIC ALCOR to the foreseen EIC challenges

- ➢ Evaluation of the existing solutions to be the base for a modification of the FE design

Already fulfilled

- ❑ Magnetic field >= 1T/m
- ❑ Rates per channel of ~50 kHz
- ❑ Strong space and as following cooling size constraints
- ❑ Charge and time measurement
- ❑ Trigger less DAQ

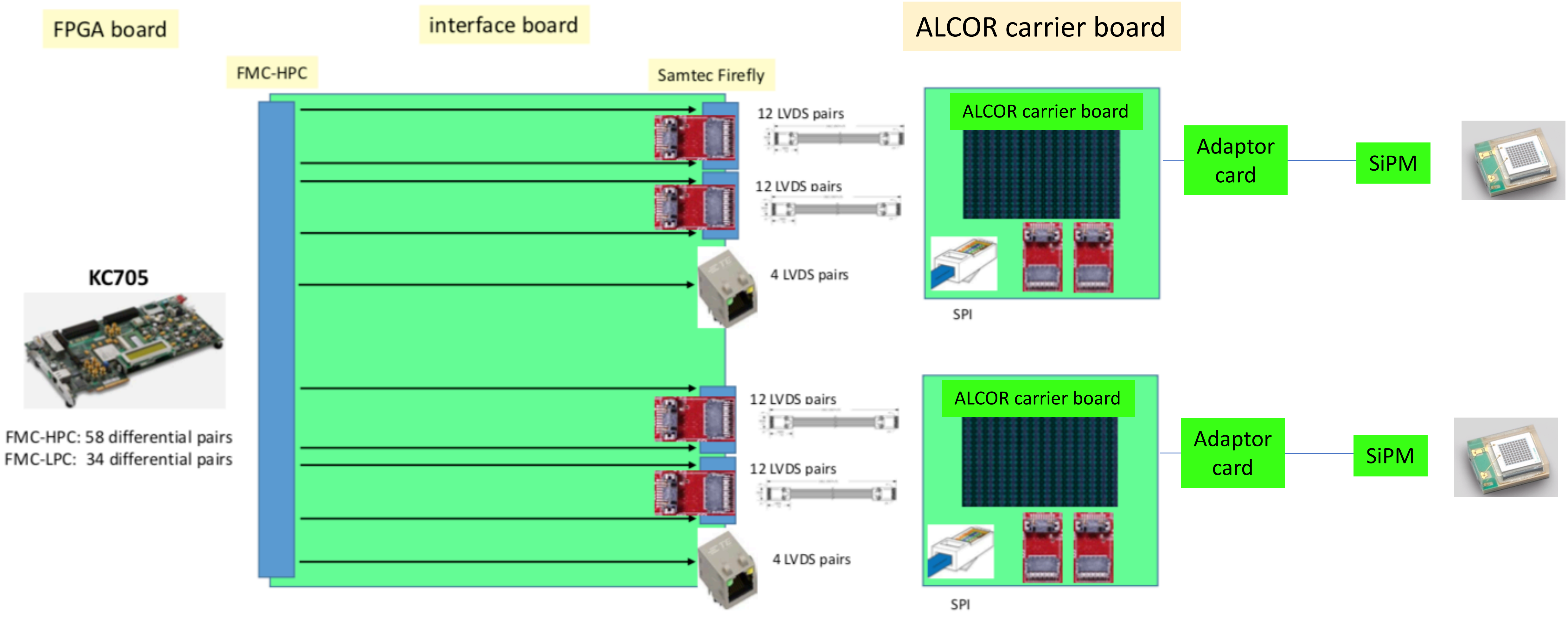
Depends on the targeted dose and the SiPM sensor performance

- ❑ Necessity to guarantee single photon counting
- ❑ 10^{11} n_{eq}/cm^2 radiation dose that degrade the SiPM performance

In case the present ASIC + SiPM are underperforming

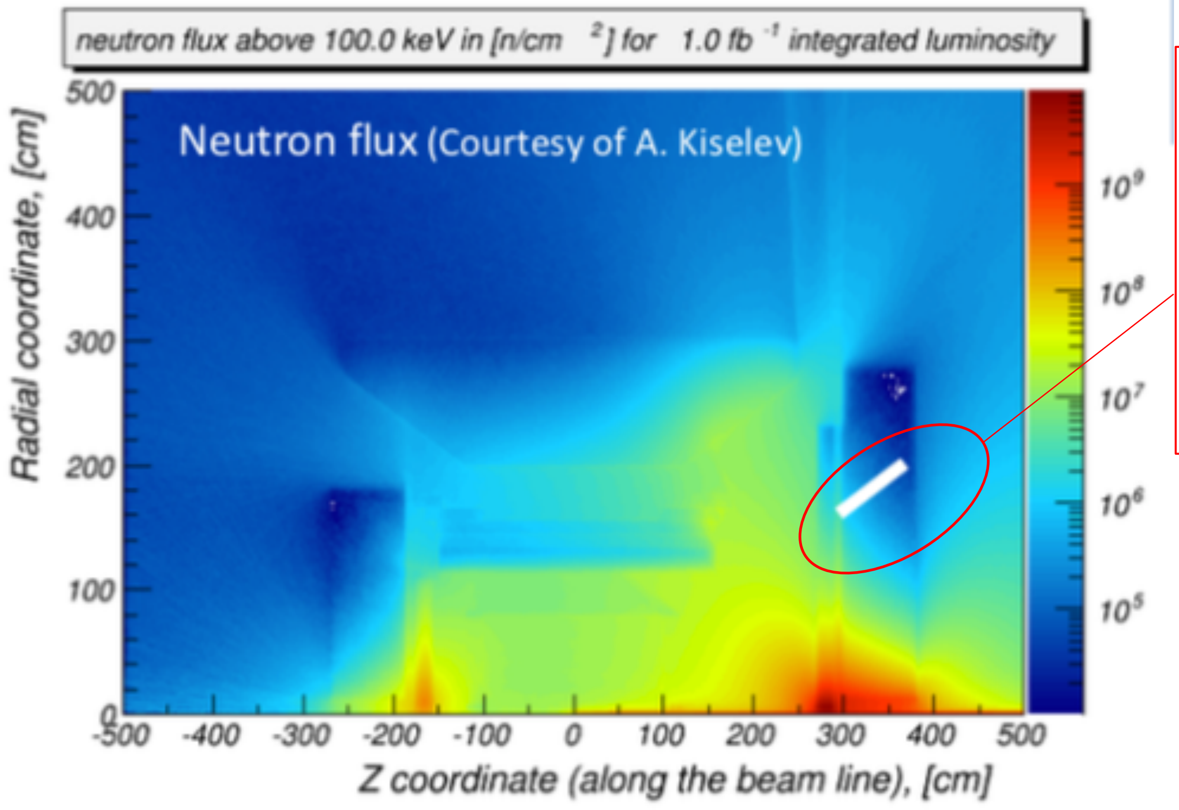
See later in this presentation about this number

Possible readout scheme



- Similar scheme under development between TO-BO for other chip
- Can be scaled up to provide readout to SiPM matrix in test beam in addition to irradiation campaigns
- Supports for simple DAQ (UDP) or optical links (lpGBTX could be final link of choice for DAQ@EIC): "streaming readout ready"

Radiation levels @ EIC



- Likely position of RICH sensors
- Values to be confirmed by further simulations when BNL will design more precisely IP
- Reference value ~ **10^{11} neq/cm²**
  "for several years at max lumi (10^{34} /s/cm²)"

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

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

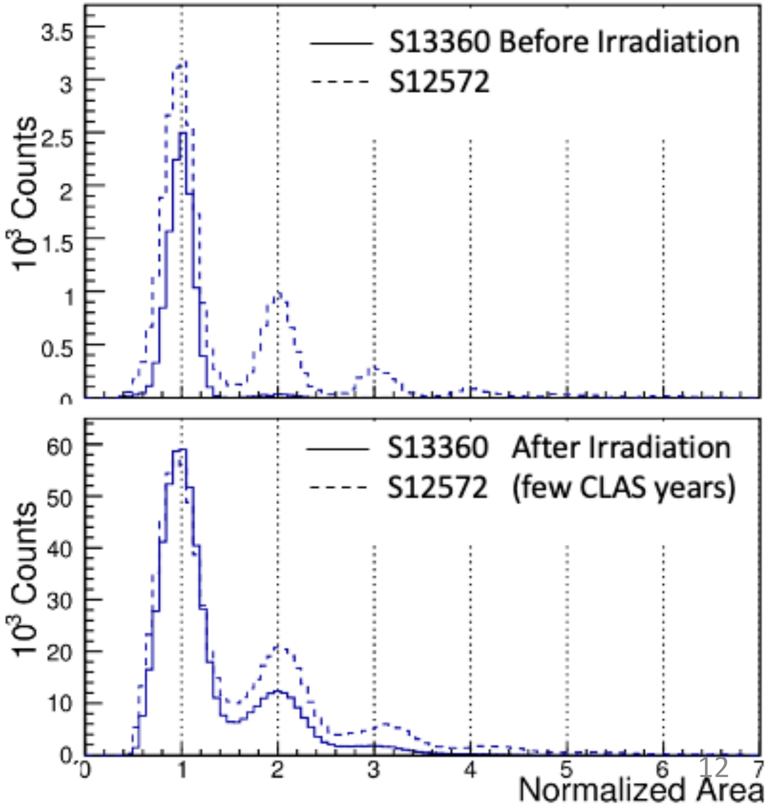
- T. Tsang et al., (Phenix) JINST (2016) 11 P12002, one of first publications reporting "recovery" after annealing at high temperatures for SiPM
- I. Balossino et al. (CLAS12), NIMA 876 (2017) 89
- M. Calvi et al. (Mi Bicocca/CMS-BTL), NIM, A 922 (2019) 243–249 CMS-BTL R&D for 10^{14} n_{eq}/cm^2 fluences.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

Hamamatsu

S12572 standard technology
S13360 trench technology

10^9

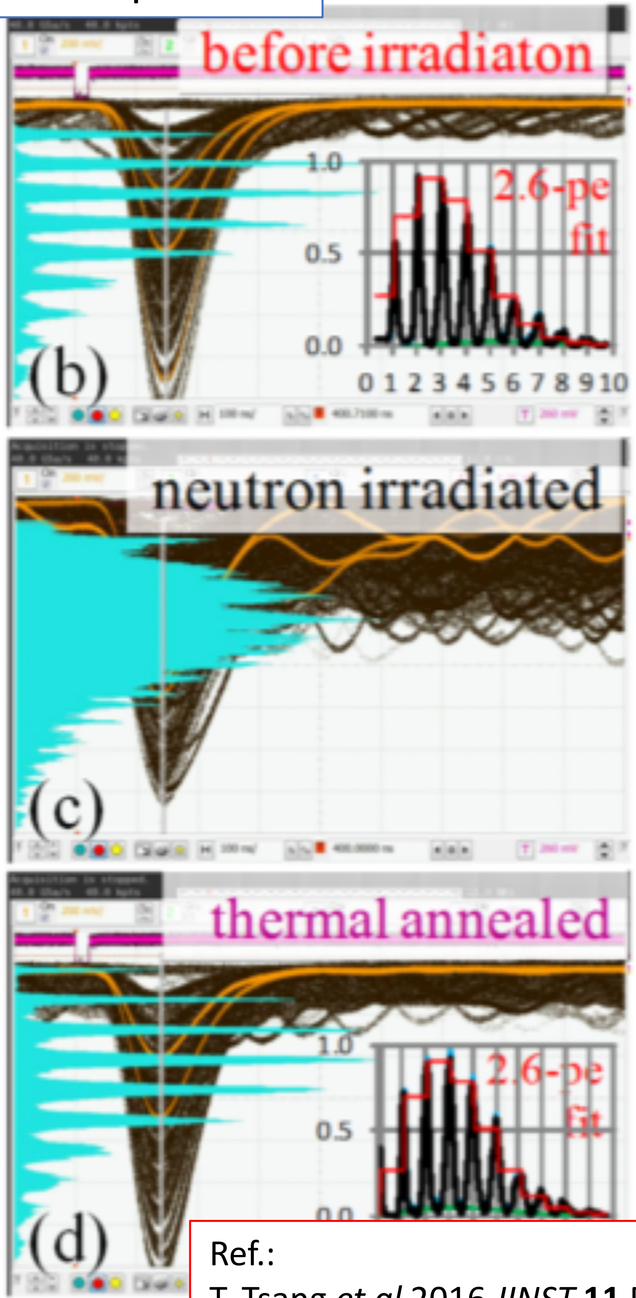
@ 0° C



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

Radiation damages and recovering via annealing (@250°C)

Room Temperature



Ref.:
T. Tsang *et al* 2016 *JINST* **11** P12002
doi:10.1088/1748-0221/11/12/P12002

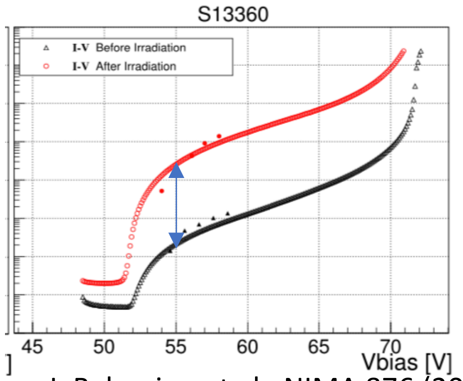
Hamamatsu SiPMs S12572/S13360 (both 3x3 mm^2)

Results

- After 10^9 fluence and annealing observed very good recovery with DCR increase by a factor 10 and single photon peaks back visible
- Note: for 10^{12} the paper is not fully documented even it says they irradiated up to that fluence

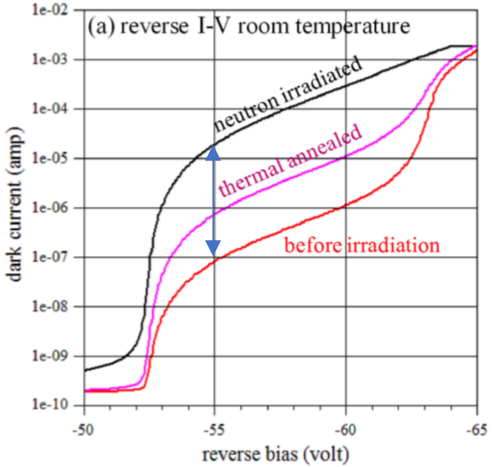
Questions

- Optimal annealing temp?
- Damages to epoxy resin window to be considered (relevant for Hamamatsu not for FBK)

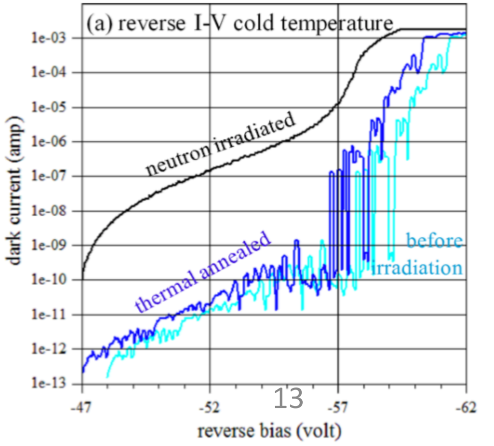


I. Balossino et al., NIMA 876 (2017) 89

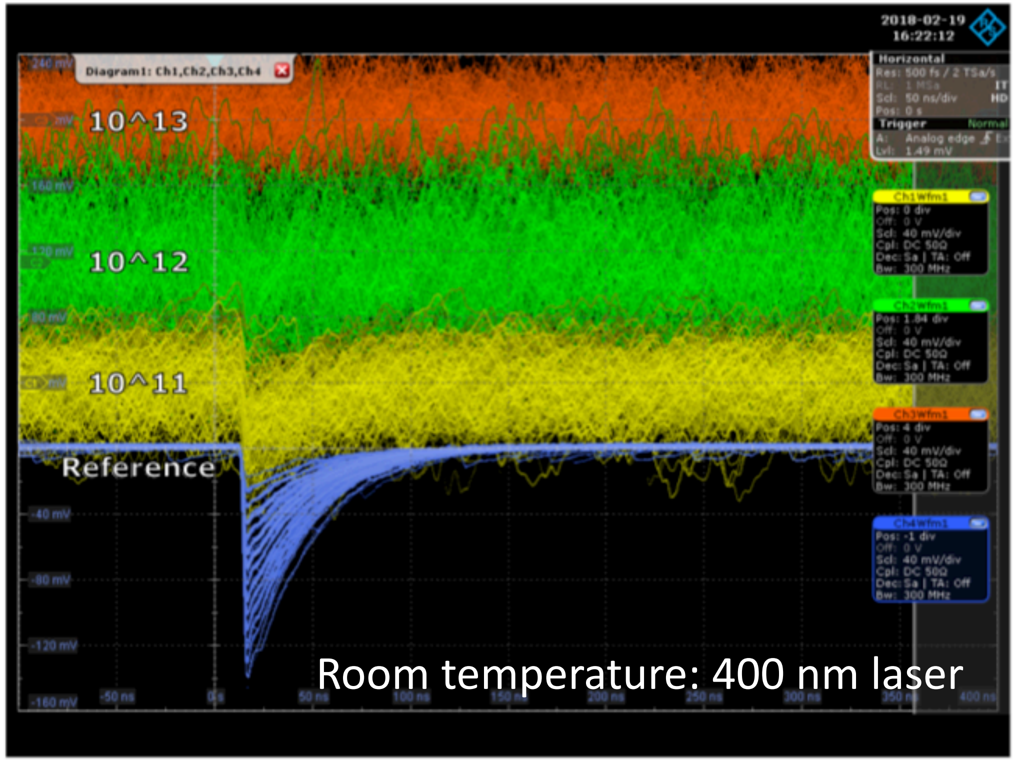
300 K 10^9

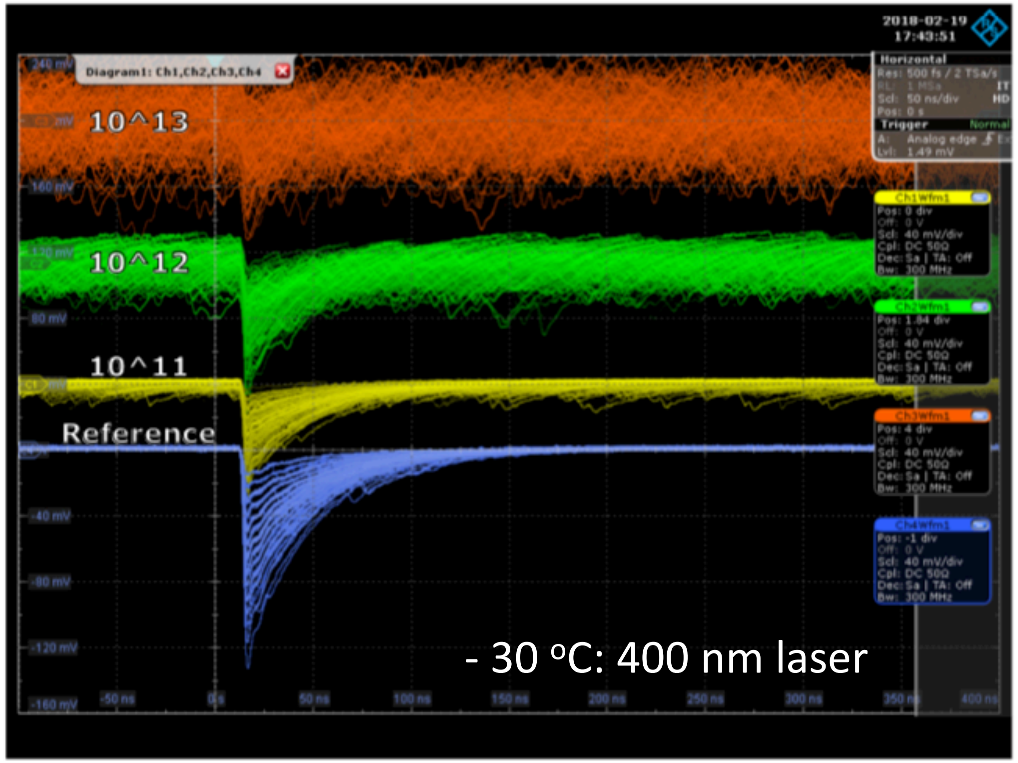


82 K 10^9



Radiation damages and recovering via annealing (@175 ^oC)





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

Nuclear Inst. and Methods in Physics Research, A 922 (2019) 243–249
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Single photon detection with SiPMs irradiated up to 10^{14} cm^{-2} 1-MeV-equivalent neutron fluence

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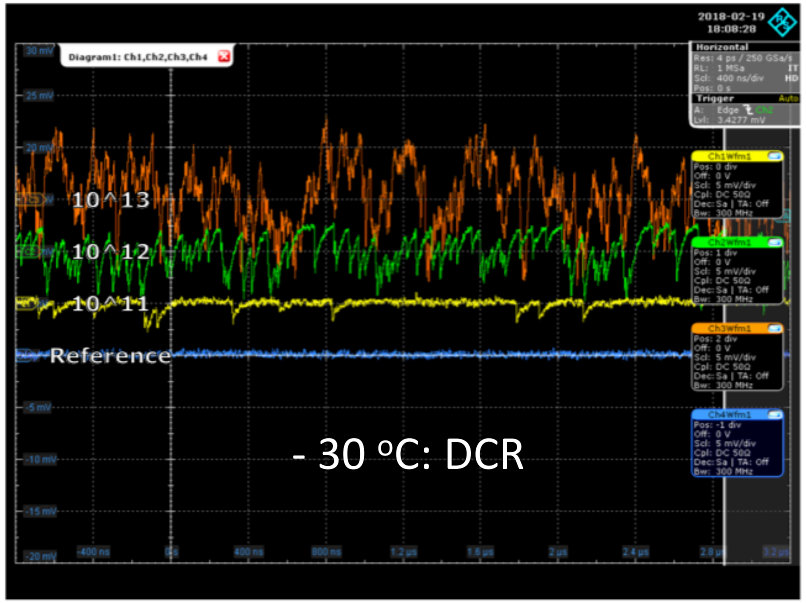
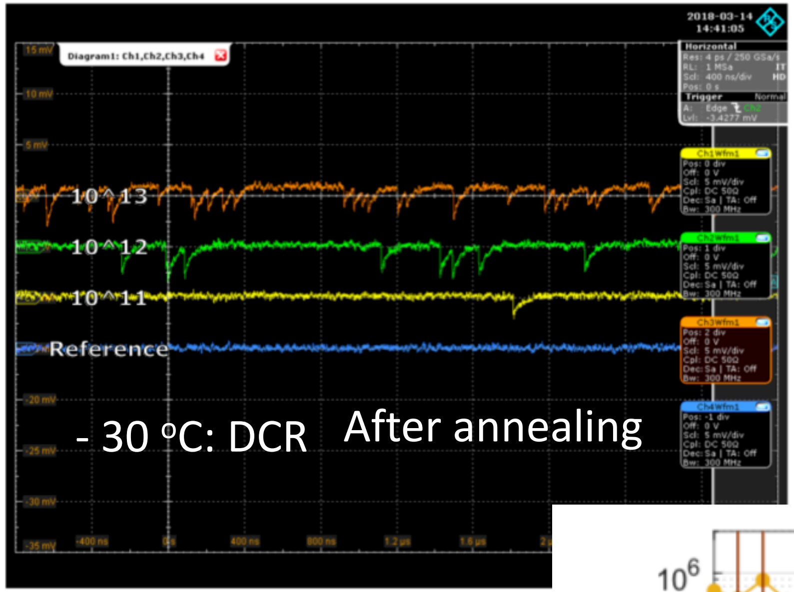
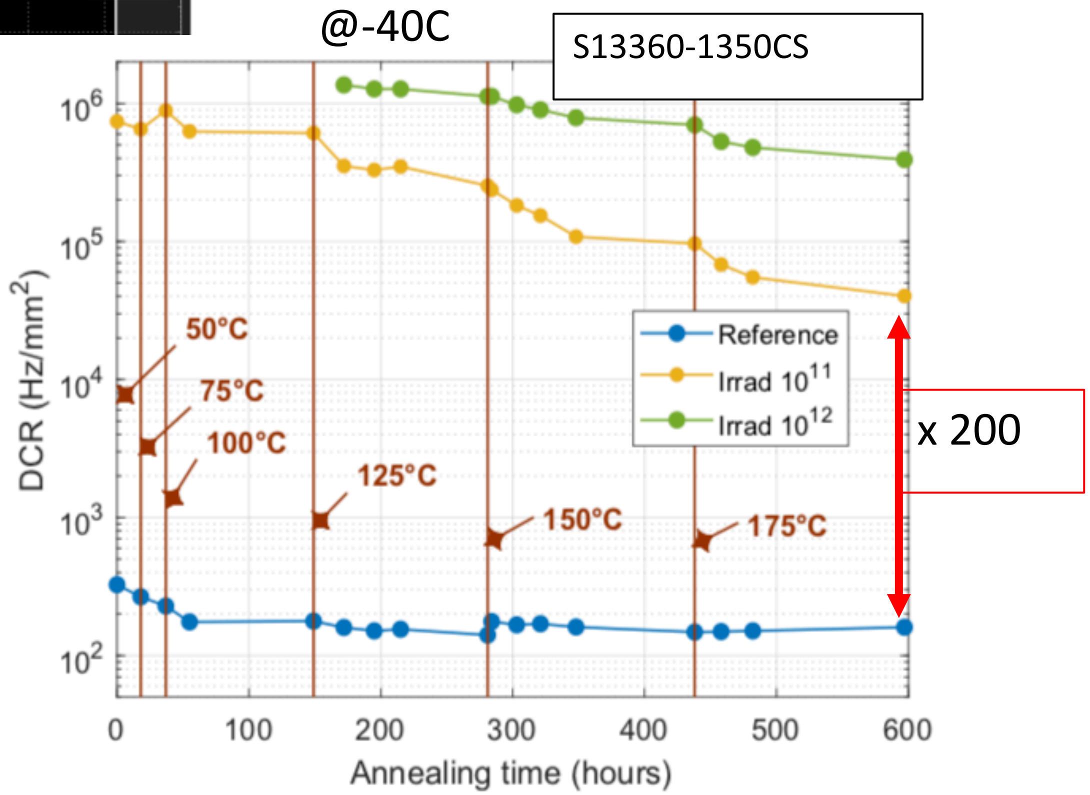
Radiation damages and recovering via annealing (@175 °C)







- 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

Feedback from FBK

- Very interested on a joint INFN-FBK R&D project to explore SiPM application for a EIC RICH (3 m^2 SiPM is attractive business ;-))
- Available to provide us samples subject to a NDA + INFN-FBK agreement ("convenzione") already in place
- Keen to know better our "requirements phase space" (PDE vs area vs FF vs op.temp. vs SPTR vs DCR etc.)
- Active project they have with Milano (CMS-BTL) has different (and shorter) time scale, but lessons learned there would be certainly useful. Also CMS group aims to avoid cryo temperatures post-annealing
- Current trend to improve radiation tolerance points towards reducing microcell size (the SPAD) from 30x30 $\mu m \times \mu m$ to 15x15 $\mu m \times \mu m$ → implies improving PDE + design ASIC to "aggregate" (at sytem readout level) the number

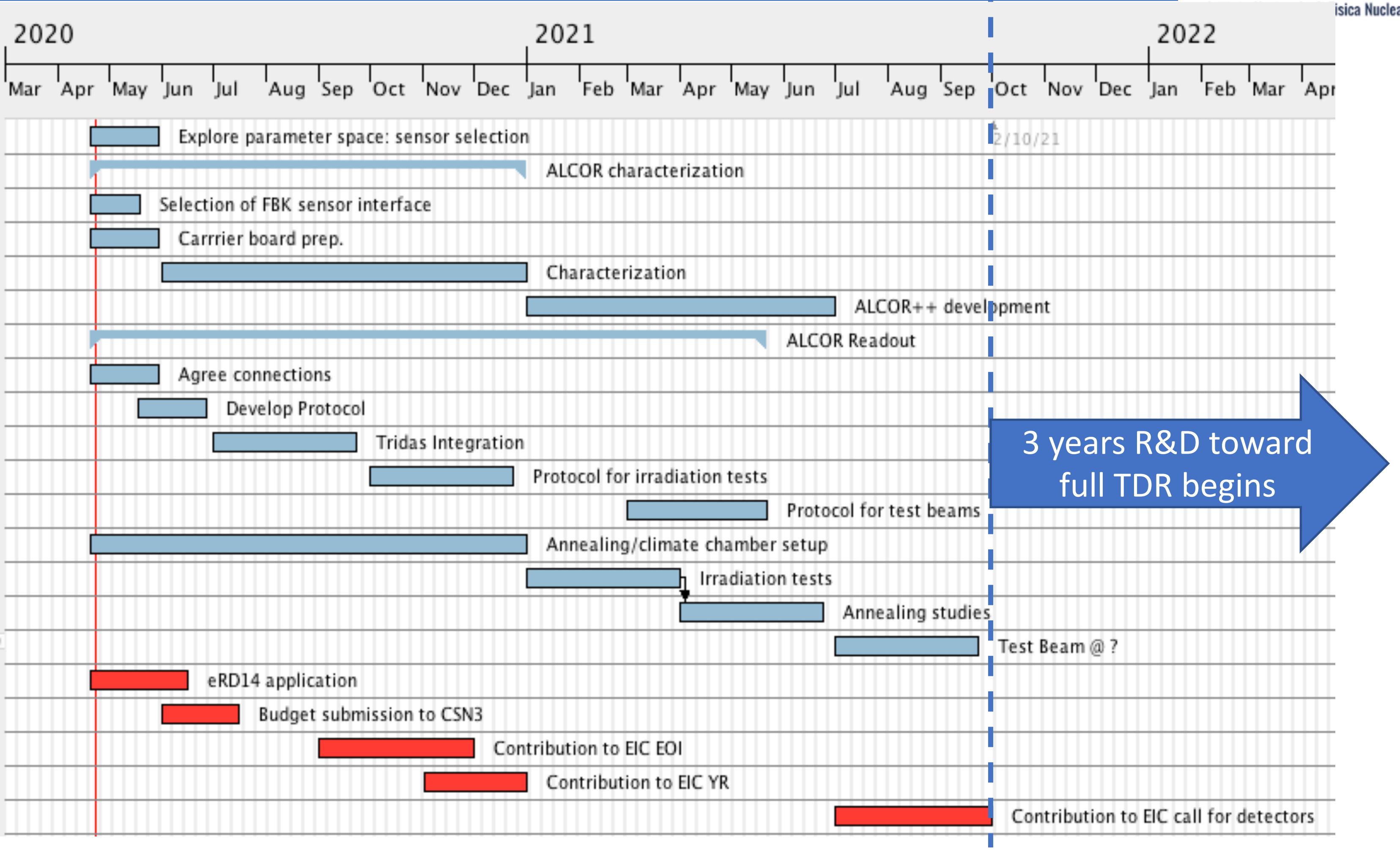
- As first step FBK to provide samples to INFN Torino to ease ALCOR characterization (with real device)

- We made clear we will try to check also competitors (Hamamatsu and SensL typically), but obviously agreed "common interest" to build possibly an Italian production chain (with devoted microelectronics developed by INFN with Torino leadership)

Timeline (under preparation)

This is just a 18 months timeline assuming EIC call for detectors deadline as "horizon"

Name	Begin date	End date
Explore parameter space: sensor ...	20/4/20	29/5/20
ALCOR characterization	20/4/20	31/12/20
Selection of FBK sensor interface	20/4/20	18/5/20
Carrrier board prep.	20/4/20	29/5/20
Characterization	1/6/20	31/12/20
ALCOR++ development	1/1/21	30/6/21
ALCOR Readout	20/4/20	21/5/21
Agree connections	20/4/20	29/5/20
Develop Protocol	18/5/20	26/6/20
Tridas Integration	1/7/20	22/9/20
Protocol for irradiation tests	1/10/20	23/12/20
Protocol for test beams	1/3/21	21/5/21
Annealing/climate chamber setup	20/4/20	31/12/20
Irradiation tests	1/1/21	31/3/21
Annealing studies	1/4/21	23/6/21
Test Beam @ ?	1/7/21	22/9/21
eRD14 application	20/4/20	15/6/20
Budget submission to CSN3	1/6/20	15/7/20
Contribution to EIC EOI	1/9/20	30/11/20
Contribution to EIC YR	2/11/20	31/12/20
Contribution to EIC call for detectors	1/7/21	30/9/21



- Microelectronics: Torino
- Readout: Bologna
- Sensor characterization: ALL (climatic chamber in BO/FE, oven for annealing likely in BO, see backup)
- Irradiation tests: ALL + BO to help for "TIFPA setup"
- Test beam: ALL (dRICH group →**detector!**): CERN, FERMILAB and JLAB are options considered

Conclusions & outlook

- ✓ SiPM a very interesting option to explore as photon sensors for a forward RICH @EIC
- ✓ Good synergies among INFN groups + existing resources (namely FBK, but not only)

- ➢ During next weeks careful budgeting work needed
- ➢ Next steps toward EIC_NET (INFN preventivi, referees etc.)
- ➢ Next steps toward wider EIC community (PID group YR, Pavia, eRD14, Miami EICUG...)

18 months program to be prepared for:

- meaningful contribution for EIC call for detectors
- devise a full-fledged R&D program (3 years) toward a TDR

Miscellanea backup

Annealing: climate chamber in Bologna

Modello MKFT 115 richiedere ›

Modello 115

Vantaggi

- Condizioni omogenee del clima grazie alla camera di preriscaldamento APT.line™
- Gestione automatica dell'acqua e dell'acqua di scarico
- Umidificazione a vapore reattiva
- Programmazione e rilevamento dei dati completi
- Grande finestra di controllo riscaldata

Caratteristiche importanti

- Intervallo di temperatura: da -70 °C fino a 180 °C
- Intervallo di umidità: dal 10 % u.r. fino al 98 % u.r.
- Serbatoio di accumulo d'acqua integrato da 20 L
- 4 contatti a relè a potenziale zero
- Tecnologia con camera di preriscaldamento APT.line™
- Protezione anticondensa programmabile per i campioni
- Controller touch-screen intuitivo con programmazione in tempo reale e per fasce orarie
- Data logger interno, valori di misurazione in formato aperto leggibili via USB
- Finestra di controllo riscaldata con illuminazione del vano interno a LED
- Regolazione dell'umidità con sensore di umidità capacitivo e umidificazione a vapore
- BINDER Multi Management Software APT-COM™ Basic Edition
- Sistema diagnostico con allarme acustico e visivo
- Dispositivo di sicurezza di temperatura indipendente regolabile classe 2 (DIN 12880) con allarme visivo
- Foro di accesso con tappo in silicone 50 mm, a sinistra
- 4 rotelle, due con freno di stazionamento
- Interfaccia per computer: Ethernet

- "reserved" to ATLAS-ITK for 2 years, but they are open for sharing
- Dry-air system to be still fully commissioned to avoid condensation
- Available for cold measures, likely not for long annealing cycles O(1 month)
- @INFN-BO we are looking for a oven: currently exploring options from Memmert and Fischer) but director available to consider "second climate chamber"

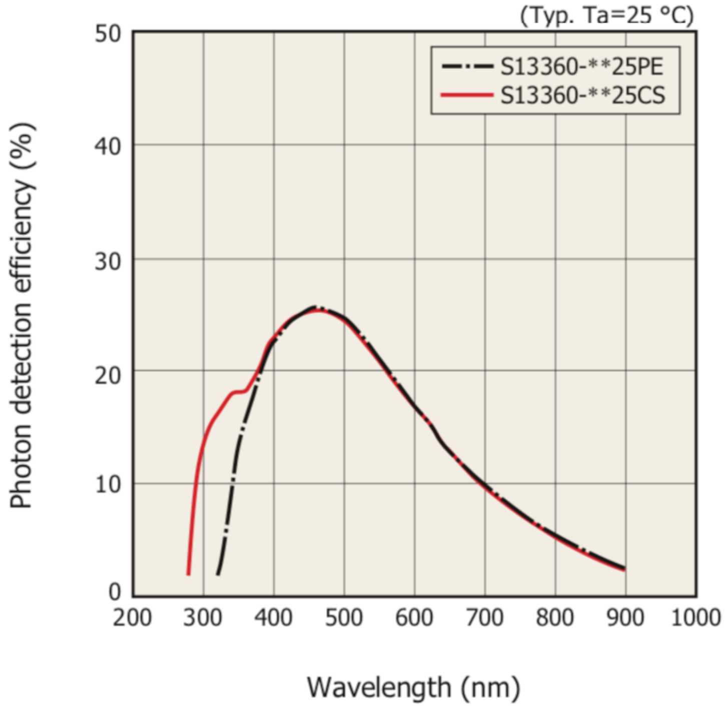
https://www.binder-world.com/it/prodotti/camere-climatiche-di-simulazione-ambientale/serie-mkft/mkft-115

Hamamatsu and SensL potential sensors

HAMAMATSU
PHOTON IS OUR BUSINESS

S13360 series

Pixel pitch: 25 μm



Type no.	Pixel pitch (μm)	Effective photosensitive area (mm)	Number of pixels	Package	Fill factor (%)
S13360-1325CS	25	1.3 × 1.3	2668	Ceramic	47
S13360-1325PE				Surface mount type	
S13360-3025CS		3.0 × 3.0	14400	Ceramic	
S13360-3025PE				Surface mount type	
S13360-6025CS		6.0 × 6.0	57600	Ceramic	
S13360-6025PE				Surface mount type	

ON Semiconductor®

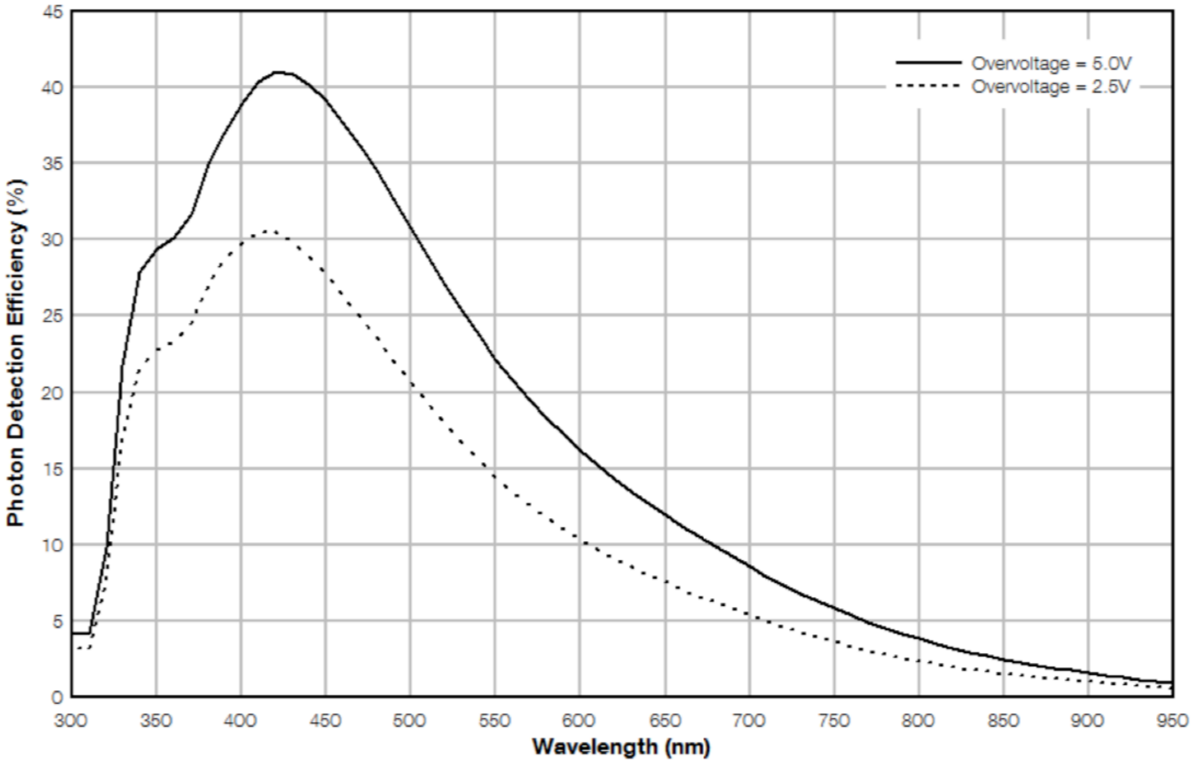
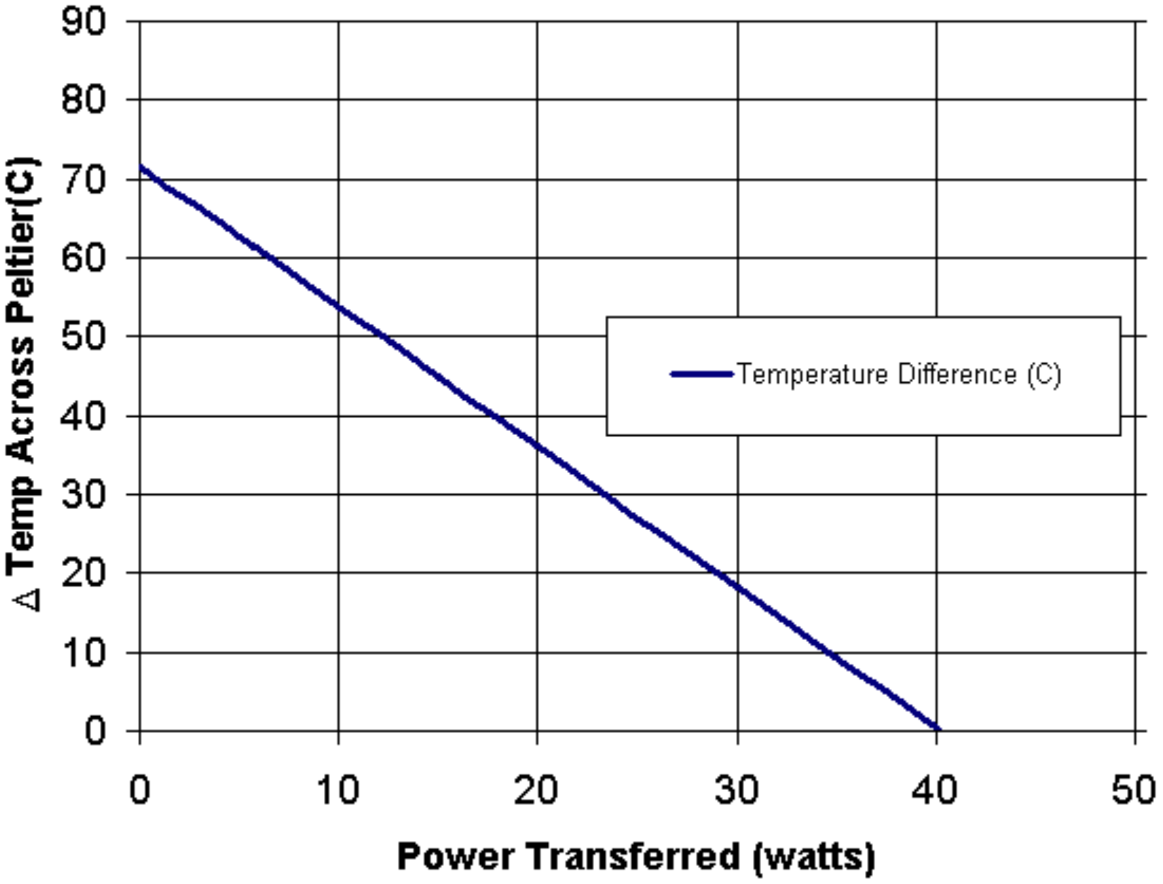


Figure 3. PDE versus Wavelength
(MicroFC–30035–SMT)

										(KHz/mm)	
ARRAYC-30020-16P-PCB		Pb-free Halide free	Active	Array		3 mm x 3 mm per pixel	20	420	31	30	ARRAYC-300XX-16P-PCB



http://www.heatsink-guide.com/peltier.htm

Task	Deliverable	By when	Comment
Explore parametric space available for photon sensors	Pixel size variation Wavelength (?)	June 2020	This should be out naturally out of on-going MC efforts (see last YR PID meeting)
SiPM requirements for TB		June 2020	How many sensors (area) we need? Probably 5x10 matrix is enough
Select sensors for TB and radiation	FBK: NUV-HD variants SensL C-series? Hamamatsu S13360-3025CS	June 2020	Include budgets! Aim for samples of at least 5 DUT for each irradiation. More samples with FBK, use SensL and Hamamatsu as reference? (S13360 tested both by Tsang and Calvi, but we could use 3x3 mm^2 cell)
eRD14 application		Jun 2020	Money for people & hardware
CSN3 2021 preventivi		Jul 2020	Note: Covid-19 crisis might make available already fresh money in Sep2020 Money for hardware
EoI - dRICH	contribute to EoI for dRICH	Nov 2020	This assumes EoI for a dRICH variant should have also the SiPM option listed.
Characterization of ALCOR	modifications needed / requirements for RICH applications identified	Dec 2020	Card will use a Samtec (FBK compatibile) connector but we plan interface cards towoards SensL and Hamamatsu (and likely FBK itself to test front-end opt.)
Common readout card to achieve SiPM		Jan 2021	Should be possibly used both in rad. test (and post annealing) and during test beam to optimize all chain. Uses serial link to achieve ALCOR data
Irradiation up to 10^{11} p/cm^2	Irradiation test @ TIFPA	March 2021	Important in situ monitoring in step of some 10^9 n_{eq}/cm^2
Annealing	DCR vs I-V, SPD, SPTR etc.: characterization	June 2021	The annealing program must be carefully planned, probably step of 48 hours would be enough.
Prepare detector setup (including SiPM readout, cooling etc) but also the detector for test beam.	Test beam @?	July 2021	Before it would be much better to be in line with foreseen timeline for Call for proposals (that is Sep. 2021), but all very difficult. CERN-PS availability TBC! TB@JLAB could be also an option as well as FERMILAB (T. Hemmick contact) Requirements to be detailed.
EIC - Call for detectors deadline	Show R&D work on SiPM	Sep 2021	

Note: during 2021 we should also aim for an "ALCOR++" better suited for RICH/not-cryo and consequent tests