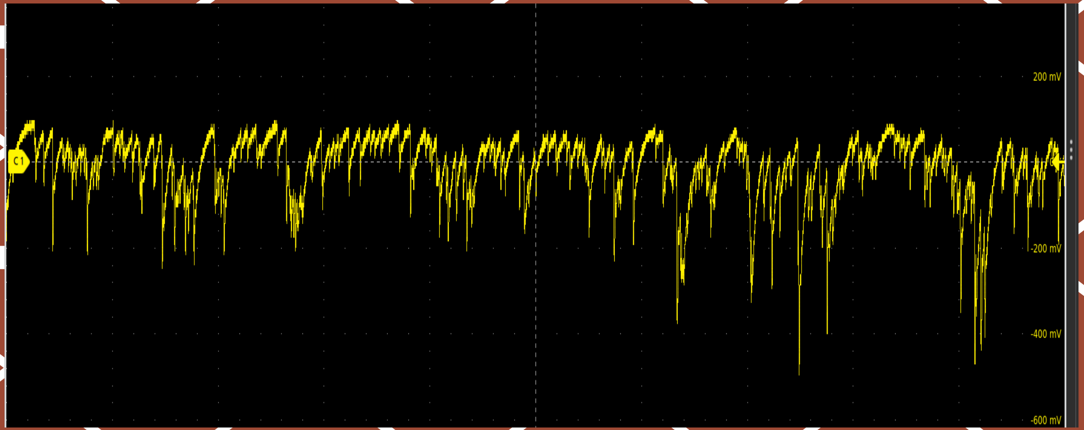
XII International Workshop on Ring Imaging Cherenkov Detectors - RICH2025

- Radiation damage mechanisms in SiPMs
- Experimental results
- Mitigation startegies



SIPM RADIATION HARDNESS AND PERSPECTIVES FOR NEW DEVELOPMENTS

Rok Pestotnik
Jožef Stefan Institute, Ljubljana, Slovenia
Jožef Stefan Institute

SILICON PHOTOMULTIPLIERS

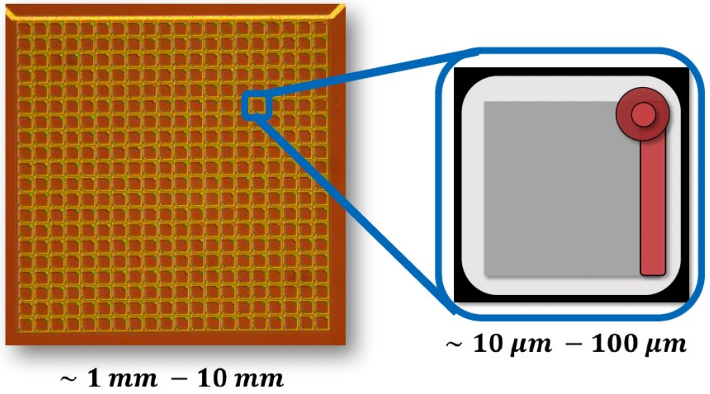
An array of **Single Photon Avalanche Diodes (SPADs)** connected in parallel.

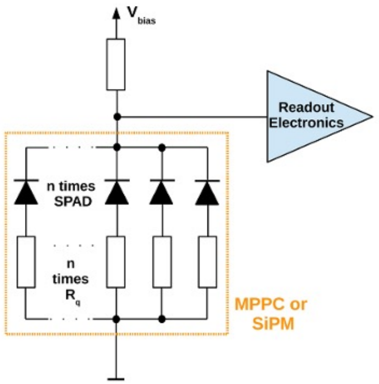
A photon is absorbed in the depletion region, generating an **electron–hole pair**. If the electric field exceeds the breakdown voltage (negative bias), this initiates a **Geiger avalanche.**

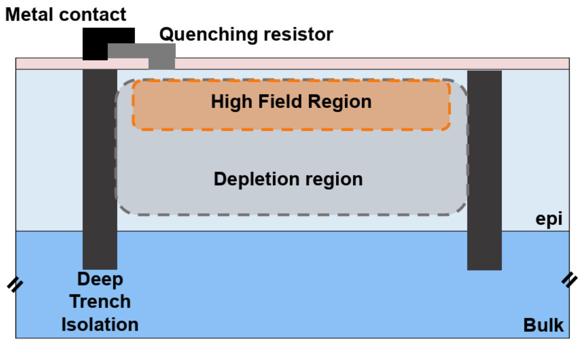
The avalanche discharges the junction until it is stopped by the **quenching resistor,** after which the cell requires a short **recovery time (dead time)** before it can fire again.

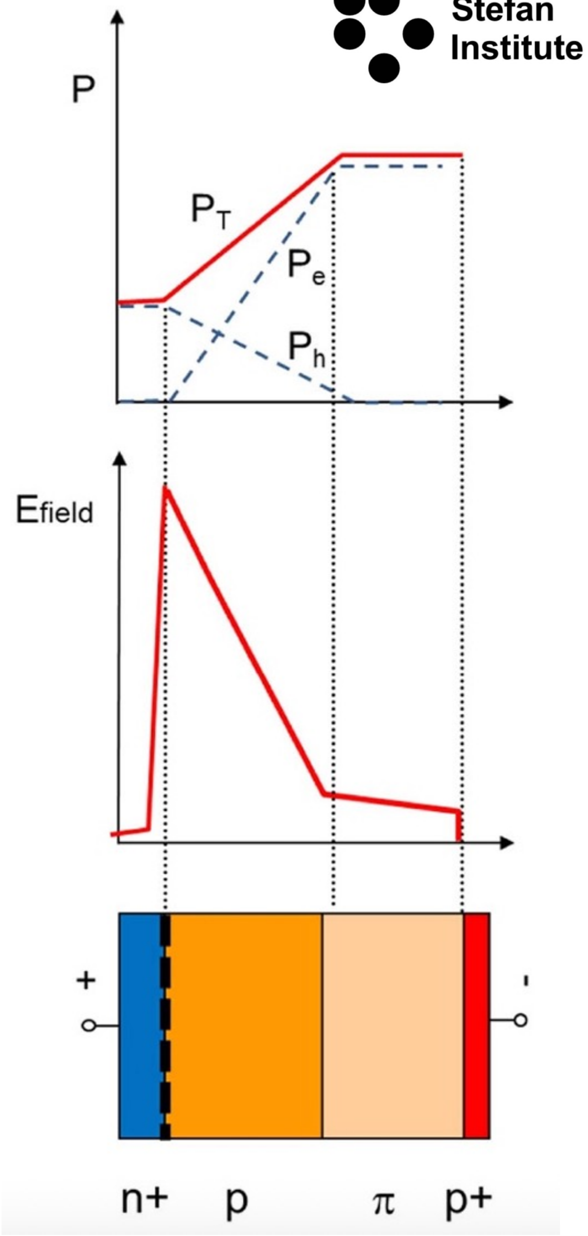
Key design parameters: **fill factor, SPAD size, and layout**

directly affect the **photon detection efficiency (PDE), gain, and noise performance.**







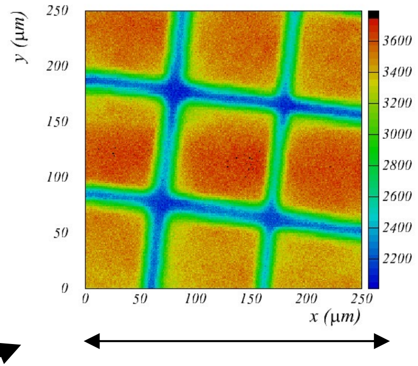


Piemonte, Gola 2019

M. Penna TREDI2024

USE OF SIPMS

Becoming widely adopted in high-energy physics (HEP), space instrumentation, nuclear facilities, and medical imaging.

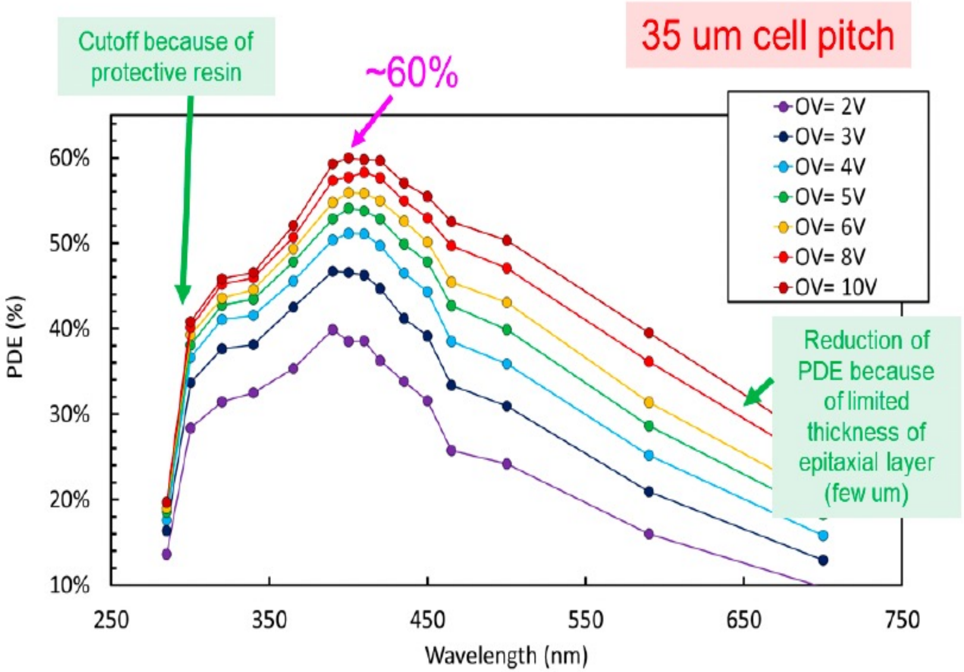


Advantages with respect to vacuum sensors (PMTs):

- Low operation voltage~ 20-100 V
- High gain ~ 10^6
- Peak PDE up to 65% @400nm PDE = QE x ε_{geiger} x ε_{geo}
  - ε_{geo} – dead space between the SPADs
  - ε_{geiger} – Geiger discharge probability
- Intrinsic timing resolution ~ 100ps
- Very compact size, can be combined in larger modules
- Operate in the magnetic field

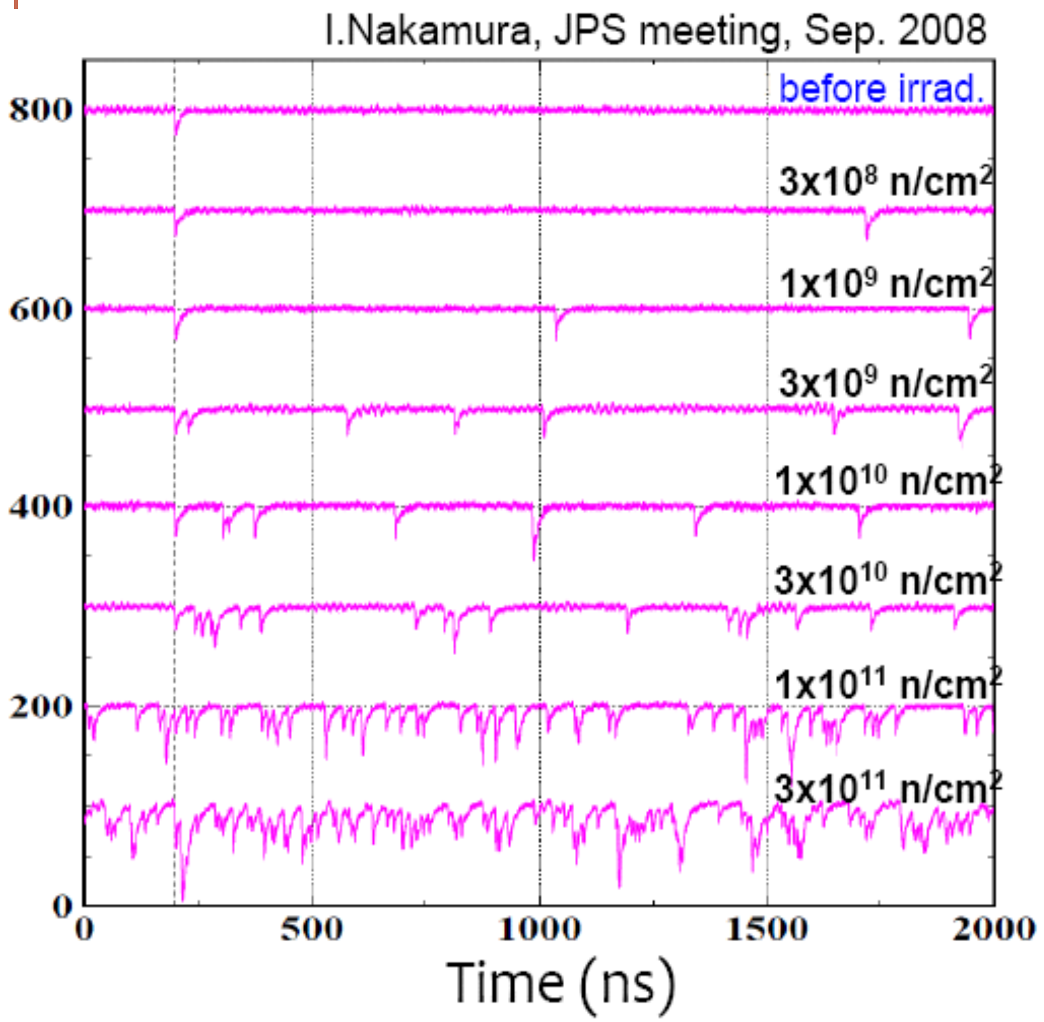
Disadvantages:

- Gain variation with temperature
- Limited energy linearity, finite number of SPADs
- Dark counts ~ a few 100 kHz/mm^2
- Radiation damage (p,n) - The main limiting factor for deploying SiPMs in extreme environments.



Gola, A et al. (2019). "NUV-Sensitive Silicon Photomultiplier Technologies Developed at Fondazione Bruno Kessler." *Sensors*, *19*(2), 308.

NEUTRON DAMAGE IN SIPMS



Time evolution of a SiPM signal after neutron irradiation

Degradation of the signal baseline

Radiation leads to:

- higher noise,
- reduced PDE,
- detector failure.

Can SiPMs be used as an efficient detector of single photons for RICH application in highly irradiated areas?

APPLICATION AREAS

Application	Dose (Ionizing)	Fluence (n_{eq}/cm^2)	Comment
CMS/ATLAS Calorimetry	10–100 kGy	10^{13}–10^{14}	Cooling mandatory
Space Missions	~ 10 Gy/ year	10^{9}–10^{11} per year	Shielding/annealing
PET/MRI	<10 Gy/year	negligible	Lifetime stability issue
Nuclear Facilities	up to kGy	10^{11}–10^{13}	Harsh local conditions
TOF & RICH Detectors	1–10 kGy	10^{12}–10^{13}	Sensor lifetime critical

SPECIFICATIONS FOR SEVERAL FUTURE RICH DETECTORS

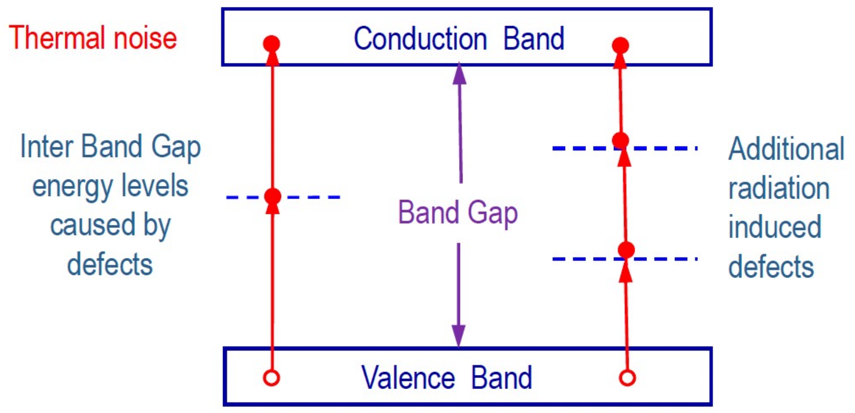
Application / Property	Unit	dRICH ePIC@EIC	TOP @ Belle II	Aerogel RICH @ Belle II	RICH @ LHCb
Sensor size	mm2	3x3	6x6 (to keep the current 8192 channels)	3x3	1x1 - - 3x3
Smallest acceptable Sensor size	mm2	3x3	1x1 / 3x3 (depending to electronic solution)	1.5x1.5	0.5x0.5 ? Depending on the density of el. channels
Single photon sensitivity (PDE)	%	> 40	Required	> 40	Required
Acceptable DCR at the working voltage	kHz/mm2	< 30 (after cooling, radiation and annealing)		< 100	<1 MHz
Required Peak PDE		Blue	Blue	Blue	Green
Expected SPTR (sigma)	ps	50	50	100	100
Acceptable range of Operating temperatures	°C	-50 to -20	20	-50 to 20	-200 - -50
Light focusing (micro or micro lensing, light concentrators)		No	No	Yes	Yes
Photon incident angle range	°	0-45	0-90	0-45	0-10
Thermal coupling to		dry nitrogen	quartz bar radiator	air/nitrogen gas	dry air (nitrogen)
Expected Photon Sensitive Area	m2	3	0.4	4.5 m2	1m2/9m2
Expected Fluence 1MeV neq	n/cm2	10**10	10**11	10**12	3x10**13
Expected TID	Gy		5 Gy/year	1000	
Trigger rate	MHz	triggerless, 98 MHz bunch-crossing	0.3	0.3	40
Expected Project timeline					
Conceptual design report		2021	2030	2030	2025
End of R&D		already concluded	2031	2031	2026
Start of Operation		2031	2035	2035	2033

LIMITING OPERATION FACTORS: NOISE IN SIPMS

SiPMs are noisy devices due to thermal noise.

Defects in the silicon lattice create energy levels within the band gap, enabling electrons to be thermally excited from the valence band to the conduction band, thereby generating dark current.

Radiation creates additional defect states in the band gap, facilitating electron transitions to the conduction band and leading to increased noise.



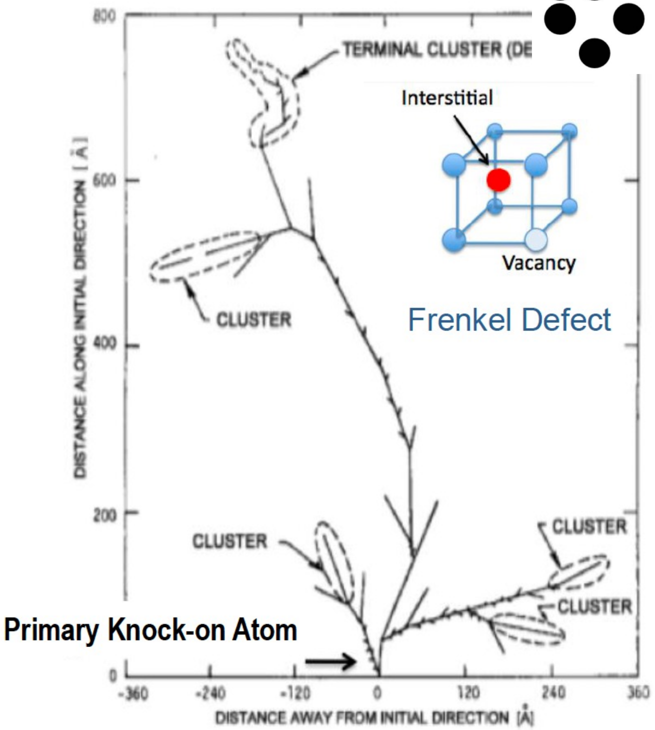
Band gap in Si: 1.12 eV @300 K

C.Woody, CPAD 2016

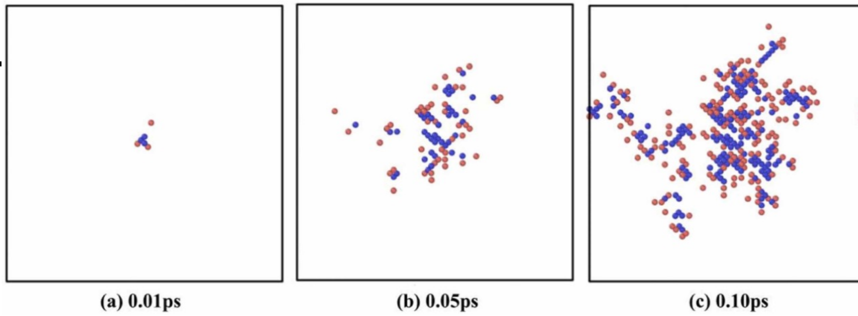
BULK DAMAGE IN SILICON

Damage caused by high-energy heavy particles (e.g., n or p with E ~ few MeV or higher)

- **Bulk damage in silicon** arises from the displacement of atoms in the crystal lattice.
- **An incoming particle** transfers part of its kinetic energy to a lattice atom.
- If this energy exceeds the silicon displacement threshold (~190 eV), the atom is knocked from its site, creating a vacancy and moving to an interstitial position.
- The resulting Primary Knock-on Atom (PKA) may generate isolated point defects or clusters of defects along its track.
- Such defect formation is primarily associated with Non-Ionizing Energy Loss (NIEL).
- The number of defects is proportional to the Non-Ionizing Energy Loss (NIEL) – which depends on the incoming particle type and its energy.
- Defect clusters act as generation–recombination centers, increasing leakage current and DCR.



G. Cibinetto, ANIMMA 2013
IEEE Conference Proceedings

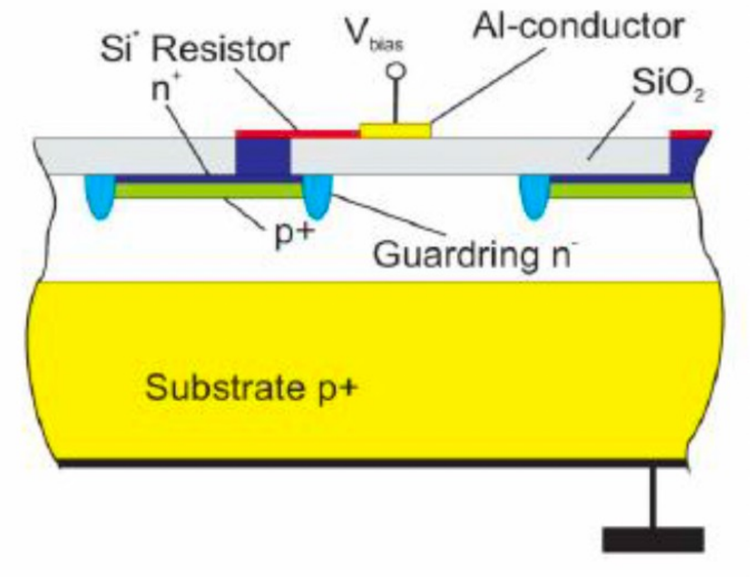


Qingyang Li, Materials 2024

SURFACE DAMAGE

- **Low-energy X-rays** predominantly damage surface layers, especially the **SiO_2 passivation**, leading to increased surface leakage currents.
- **Charge build-up** in oxide and interface regions alters the **internal electric fields**, shifting breakdown voltage and reducing stability.
- **Ionization-induced optical absorption** in the entrance window reduces the number of photons reaching the active area, lowering PDE.

Trapped charge in SiO_2

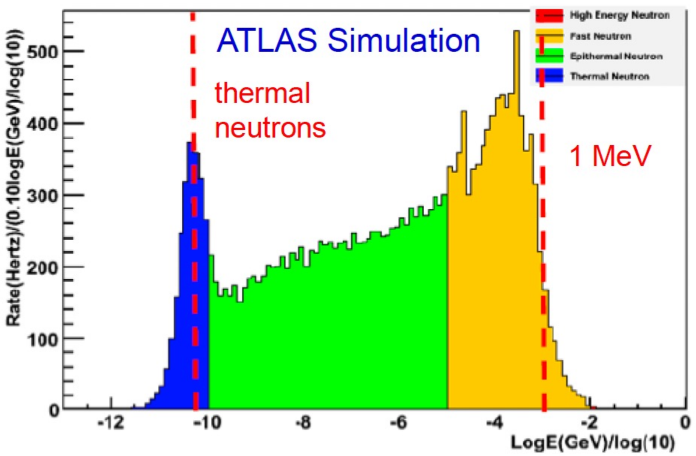


DAMAGE FROM THERMAL NEUTRONS

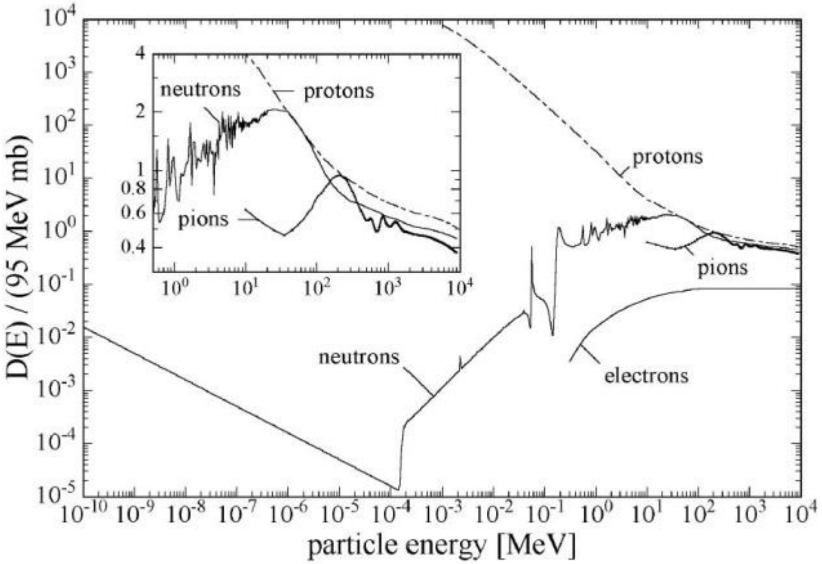
Capture of thermal neutrons may alter the nucleus, transforming it into another isotope or element.

$$^{30}Si + n \rightarrow {}^{31}Si \rightarrow {}^{31}P + \beta^-$$

Each absorbed neutron typically generates a few isolated defects (~2–5 per event) neutrons (neq/cm²)



Thermal neutrons are created when fast neutron from particle collisions lose energy through successive interactions and slow down.



M. Moll,, Ph.D.,1999

Radiation damage depends on particle energy

Commonly normalized to the equivalent damage caused by 1 MeV n

EFFECTS OF RADIATION IN SILICON PHOTODETECTORS

Jožef Stefan Institute

Non-Ionizing Energy Loss (NIEL) – Displacement Damage

- These defects act as **generation–recombination centers** in the depletion region.
- Effect: **increased leakage current and dark count rate (DCR)**, reduced carrier lifetime → overall **increased noise.**

Ionizing Energy Loss (IEL) – Ionization Dose Effects

- create **trapped charges (+ in SiO_2) and interface states.**
- Consequences: **shift of breakdown voltage,** higher surface leakage, reduced stability of gain, and PDE degradation.

Single Event Effects (SEE)

- Heavy ions or high-energy protons produce localized dense ionization tracks.
- These can cause **transients, logic upsets, or even catastrophic failures (ruptures)** in the device.
- In SiPMs, this may appear as large transient noise pulses or permanent damage to microcells.

Transmission loss in the optical window

→ reduced light reaching the active area.

Impact:
The operational consequences for SiPMs for RICH experiments strongly depend on the accumulated **dose levels** and radiation environment.

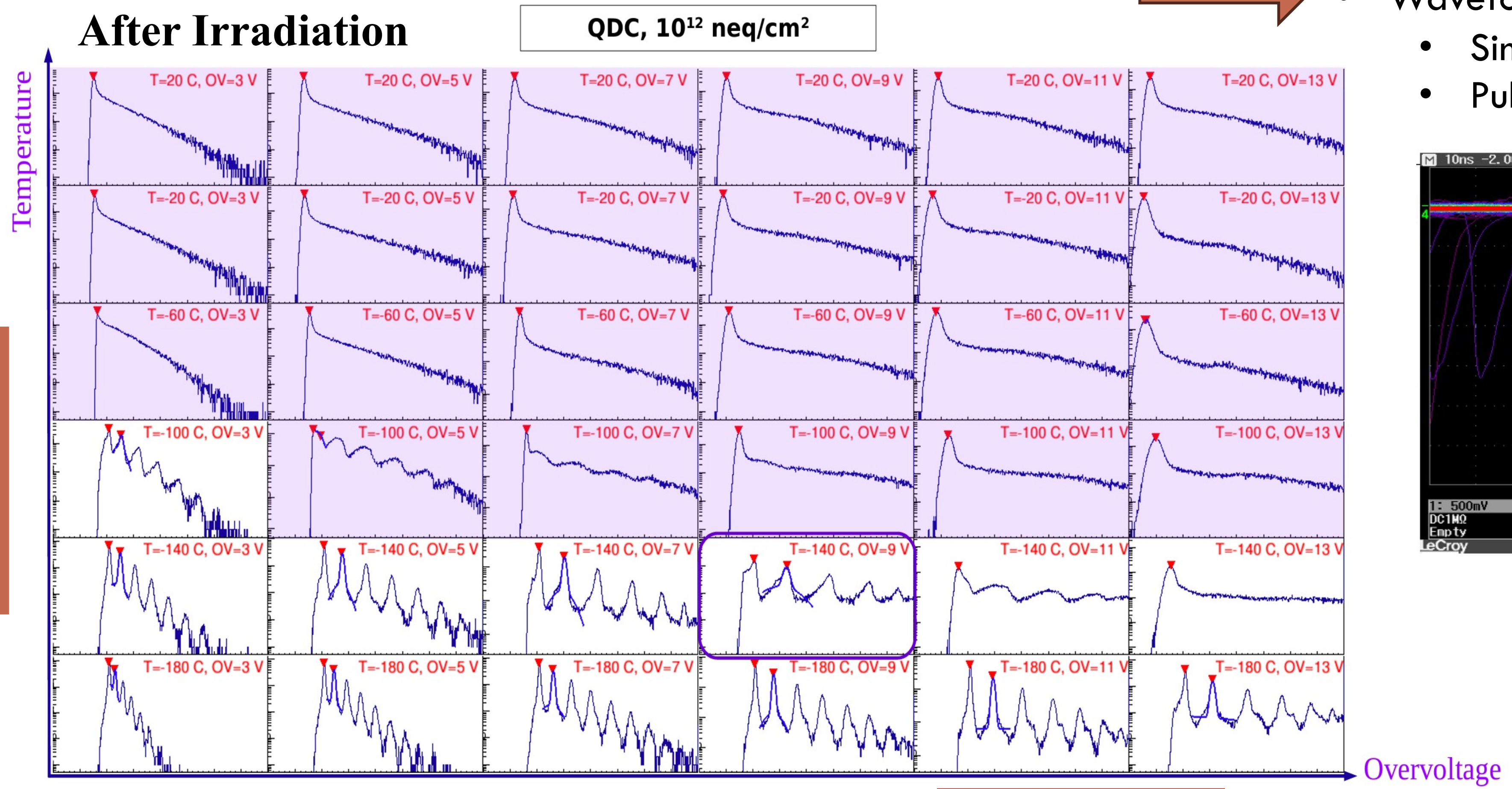
For RICH applications where single photon detection is needed, the limiting factor is SiPM sensitivity to neutrons.

CHARACTERISATION OF SIPMS BEFORE AND AFTER THE NEUTRON IRRADIATION

Characterization of irradiated SiPMs at different temperatures

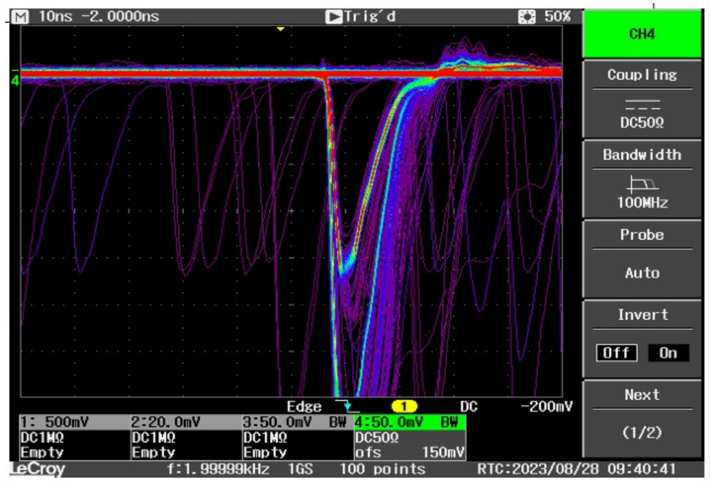
Pulse height distributions for different temperatures and overvoltages

- I-V dependance
- Dark Count Rate (DCR)
- Waveform acquisition:
  - Single Photon Time Resolution (SPTR)
  - Pulse height distributions



Temperature

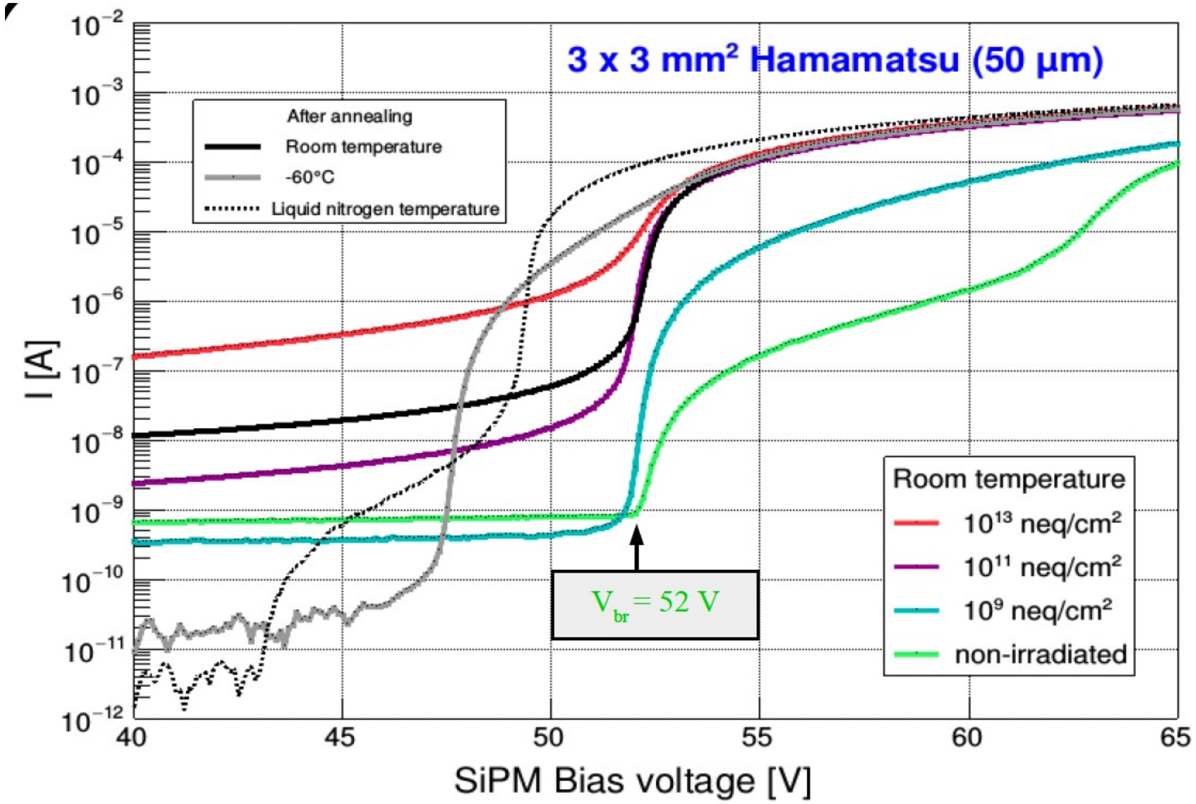
OverVoltage

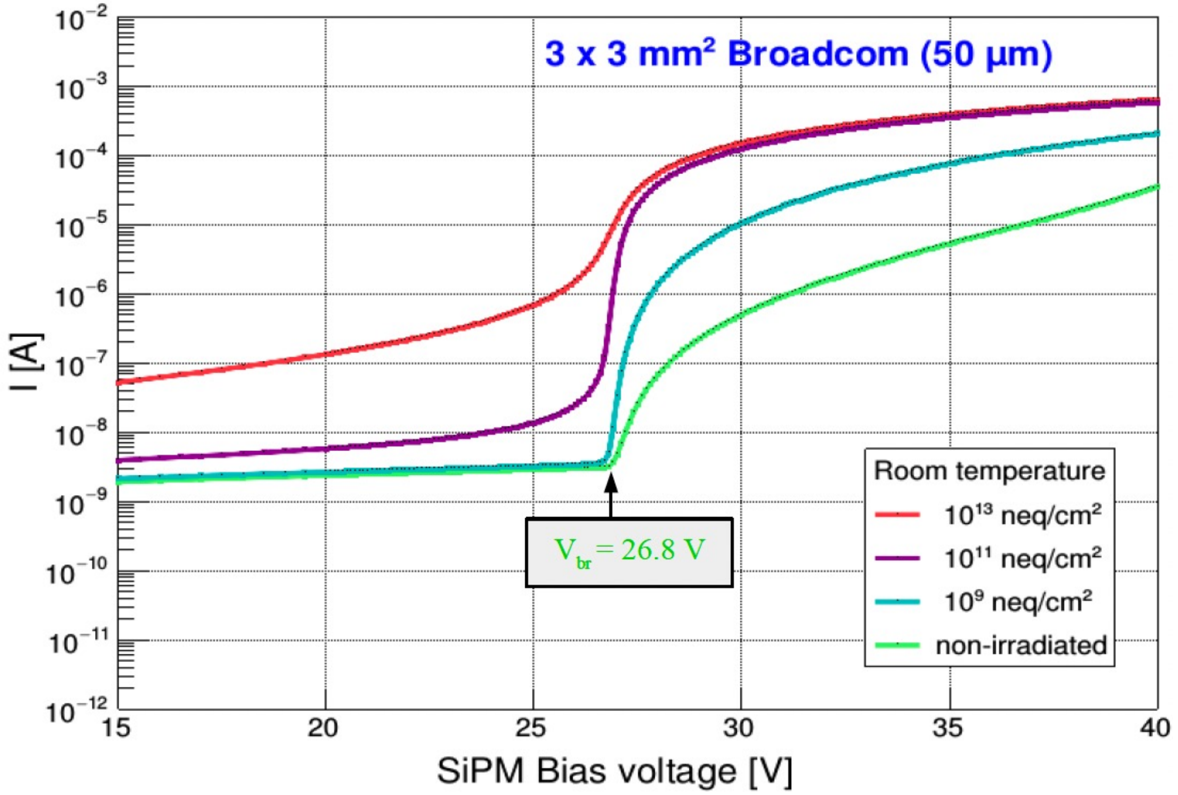


IMPACT OF NEUTRON IRRADIATION ON I-V

Defect-induced leakage depends strongly on temperature. Approximate doubling of leakage current every 7–10 °C rise.

Similar behavior of different technologies and different producers.

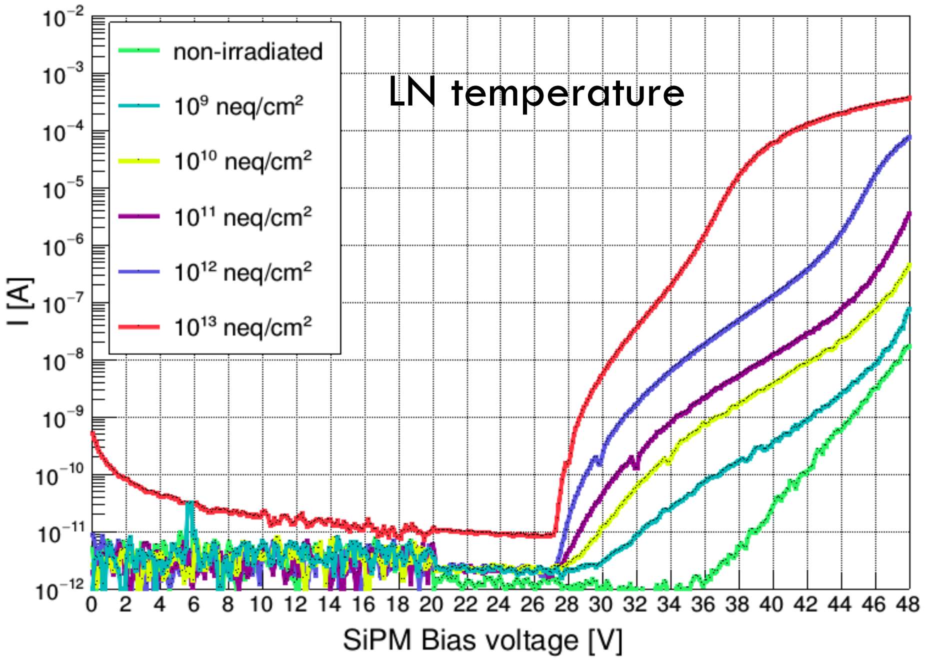




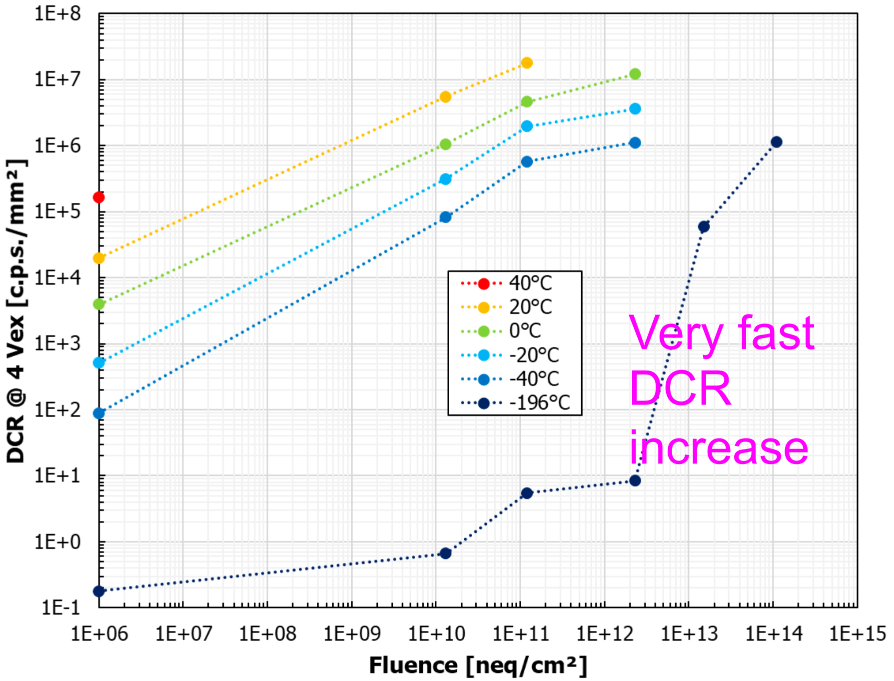
I-V AND DCR AT LIQUID NITROGEN TEMPERATURE

1x1 mm2 FBK NUV-HD-RH -
Damage visible already at LN

I-V at LN after irradiation



DCR at LN after irradiation



A. Gola: RICH 2022

Cooling is *extremely effective in reducing Idark & DCR after irradiation up to ~1·10^{12}neq/cm2*

What happens at the higher doses (~10**13 n/cm2) is still not resolved:

Further investigations needed

RADIATION DAMAGE MITIGATION STRATEGIES

To enable the operation of SiPMs in the single photon regime:

- Shielding of the sensors

Change of operation parameters:

- Operation at low temperatures
- Operation at lower bias:
  - Working at a lower bias decreases the DCR, but the PDE also drops
- Annealing (in the oven / with forward bias?)

Design changes of the detector:

- Smaller sensor size:
  - smaller active volume, lower C, smaller DCR
- light collection – focus photons on a smaller sensitive area

Change of internal design of SiPMs to reduce the active volume:

- Incremental changes in the electric field
  - Faster increase of PDE vs. bias allows using lower over-voltage.
- reduction of cross-talk and after-pulsing
- Smaller cells: More cells and faster recharge: lower PDE loss and better baseline integrity
- Back Side Illuminated SiPMs
- Use of new materials

Electronics:

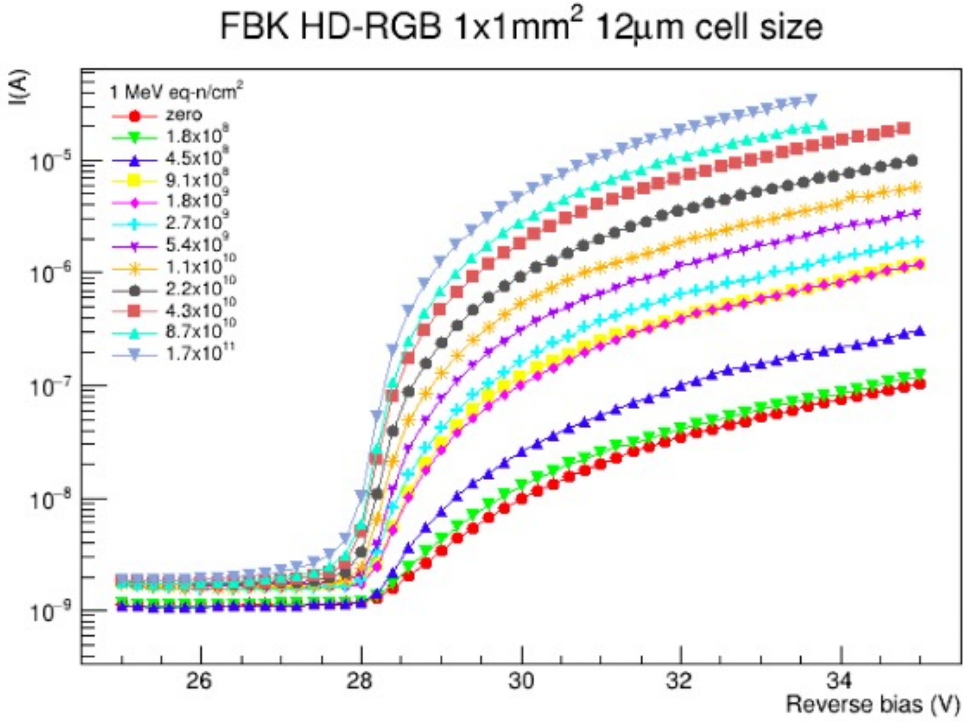
- Gating to limit the acquisition to a narrow time window
- Use of fast/integrated electronics

COLLABORATION ON THE RESEARCH AND DEVELOPMENT FOR PHOTON DETECTORS AND PARTICLE IDENTIFICATION TECHNIQUES

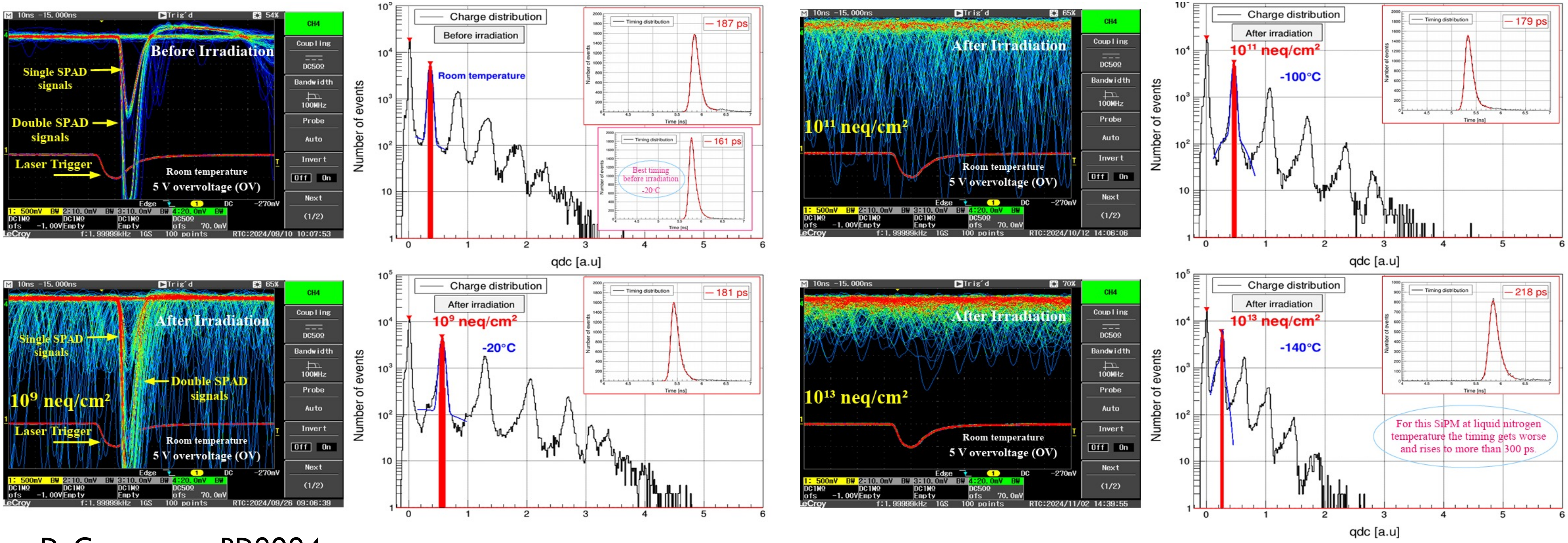
https://drd4.web.cern.ch/

Task 4.3 - Fast radiation hard SiPMs

- **Standardize procedures for quantification** of radiation effects.
- **Characterize the irradiated SiPMs** in a wide range of temperatures down to -200 deg..
- **Study of annealing**.
- **Study and quantify other measures** enabling the use of SiPM in highly irradiated areas:
    - smaller SiPMs
    - macro- and micro-light collectors

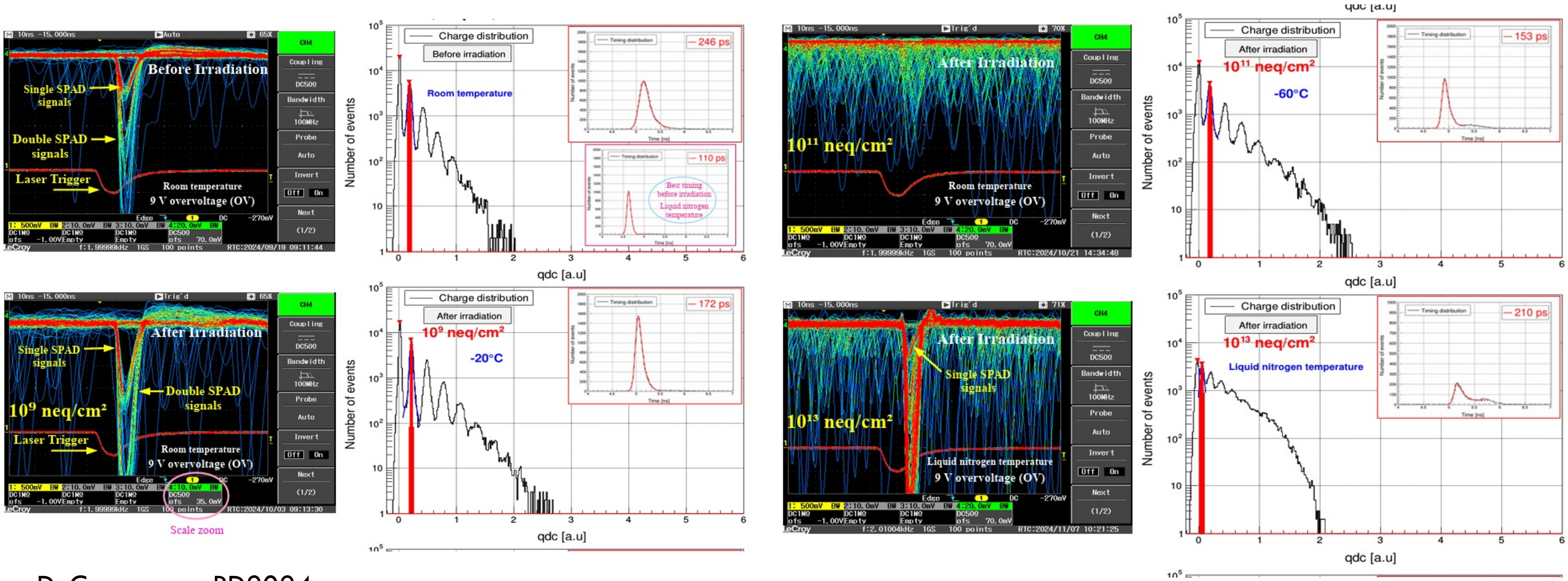


HAMAMATSU 3X3 MM2 – 50 UM



D. Consuegra, PD2024

SENSL 1X1MM2 – 35 UM



D. Consuegra, PD2024

CHARACTERISATION OF NEUTRON IRRADIATED SIPMS

AidaInnova has received funding from the EU Horizon 2020 RIA programme under Grant No 101004761
EU grant n.822070
Jennifer 2 is an MSCA-RISE project funded by EU under grant n.822070

Jožef Stefan Institute

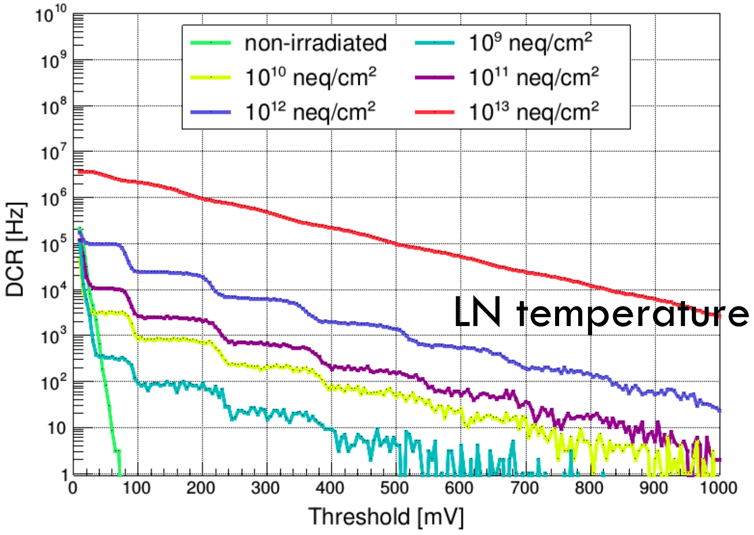
1x1 mm2 FBK NUV-HD-RH

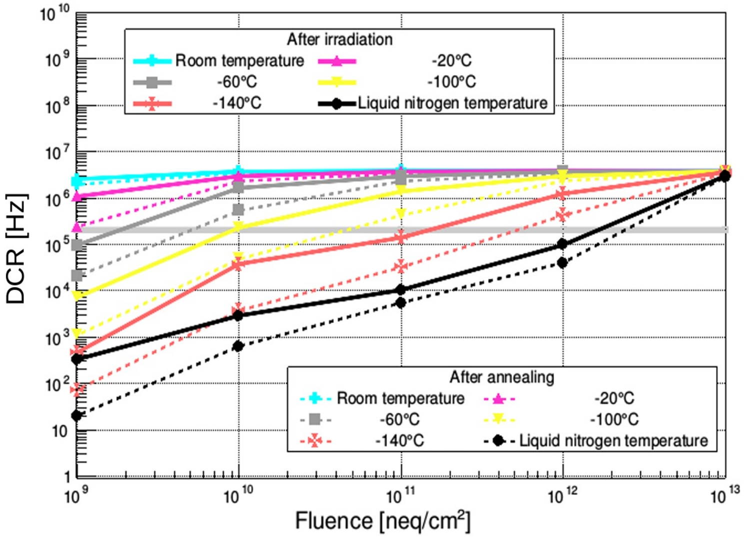
Irradiated with neutrons: 10^9 … 10^{13} n_{eq}/cm^2

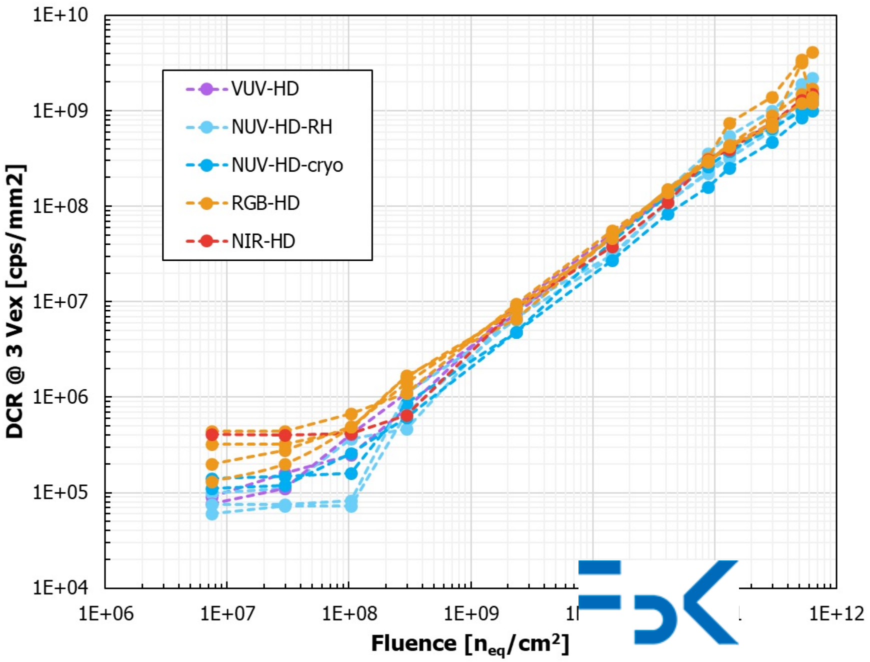
and later annealed at 80 deg. for 24h

A. Gola, RICH2022

Dark count rate







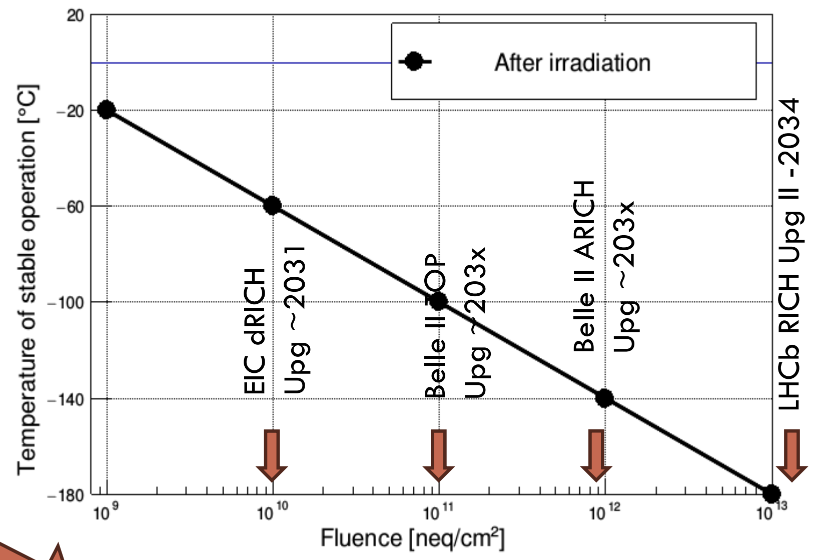
Different technologies converge towards similar values

Independence of bulk damage from contaminants in the SiPM starting material?

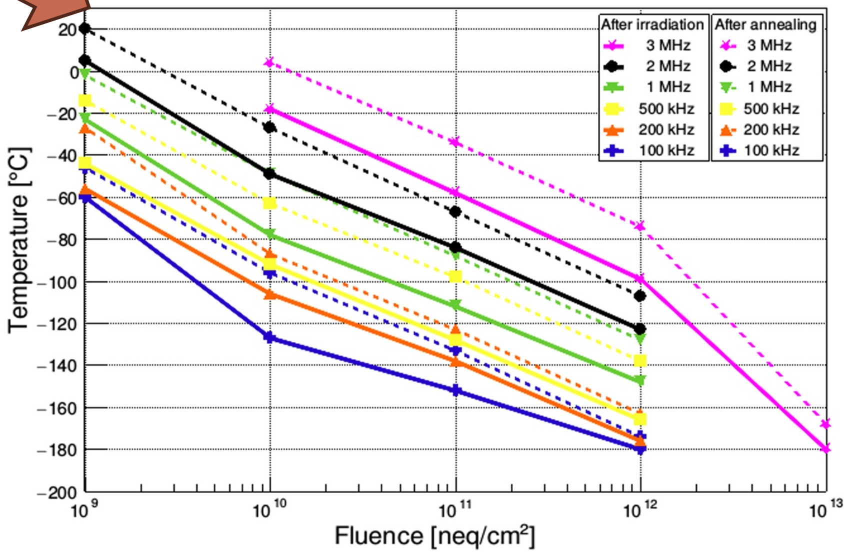
TEMPERATURE OF STABLE OPERATION

Jožef Stefan Institute

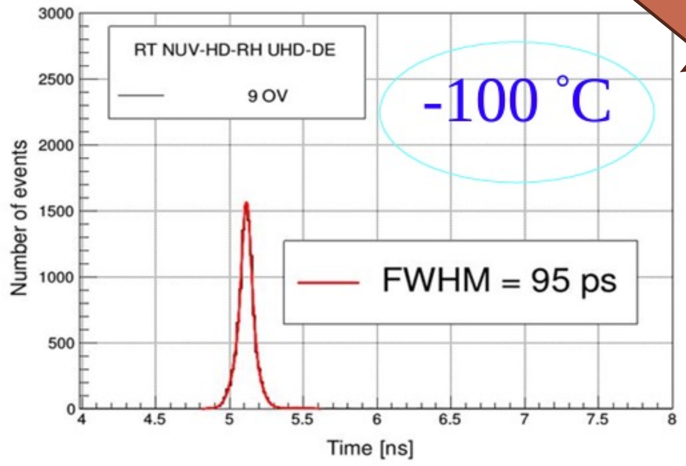
- The temperature at which the SiPMs are "usable", i.e., where the single photo electron peak @ certain OV (e.g.,9V) is separated from the background.

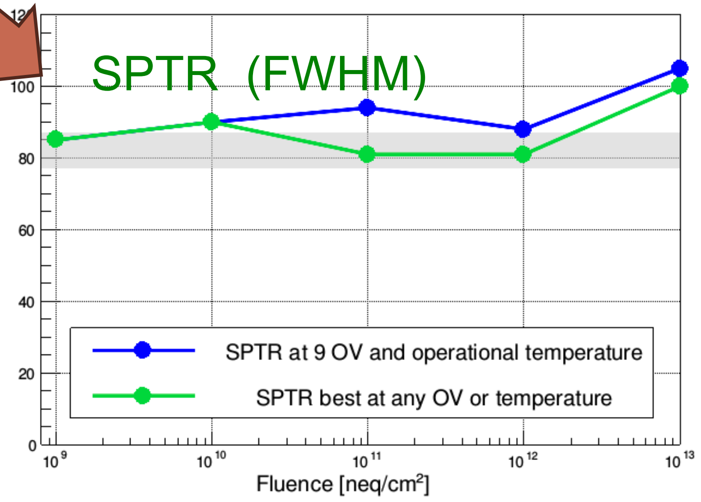


- The temperature below which the DCR falls below a particular value.



- SPTR as a function fluence –no significant degradation





OPTICAL CROSSTALK AND AFTERPULSES

Avalanche light emission: SPAD avalanches generate secondary photons in the sensitive volume of the SPAD.

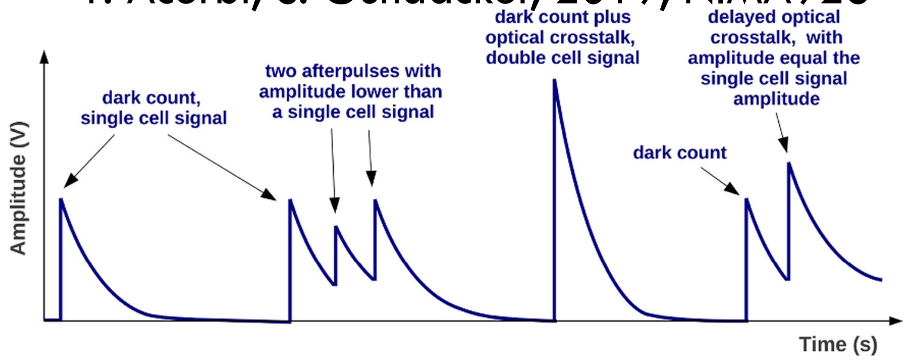
Noise avalanches: Secondary photons can trigger spurious avalanches in neighboring pixels.

Internal crosstalk: occurs between pixels within the same SiPM

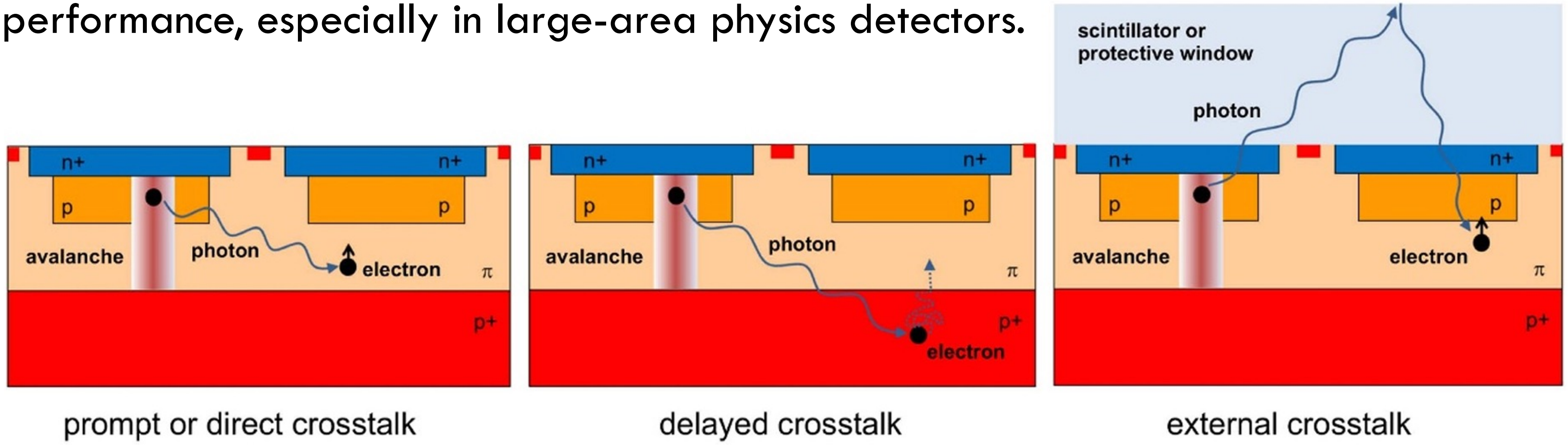
External crosstalk: occurs between adjacent SiPMs in large detector arrays.

Impact: correlated avalanches increase noise and degrade performance, especially in large-area physics detectors.

F. Acerbi, S. Gundacker, 2019, NIMA926

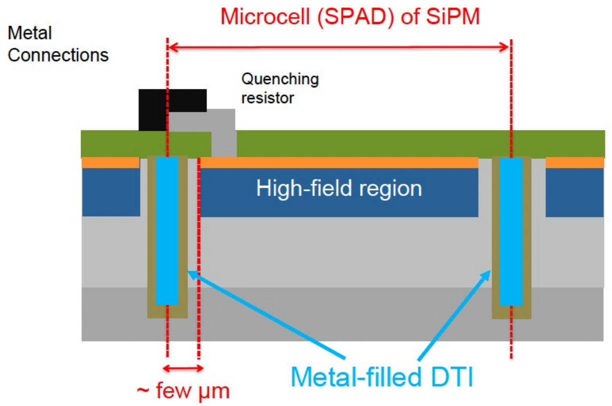


After-pulses (APs): occur when avalanche carriers are trapped and later released, triggering a secondary avalanche during or after recovery.



Piemonte, Gola, 2019, NIMA926

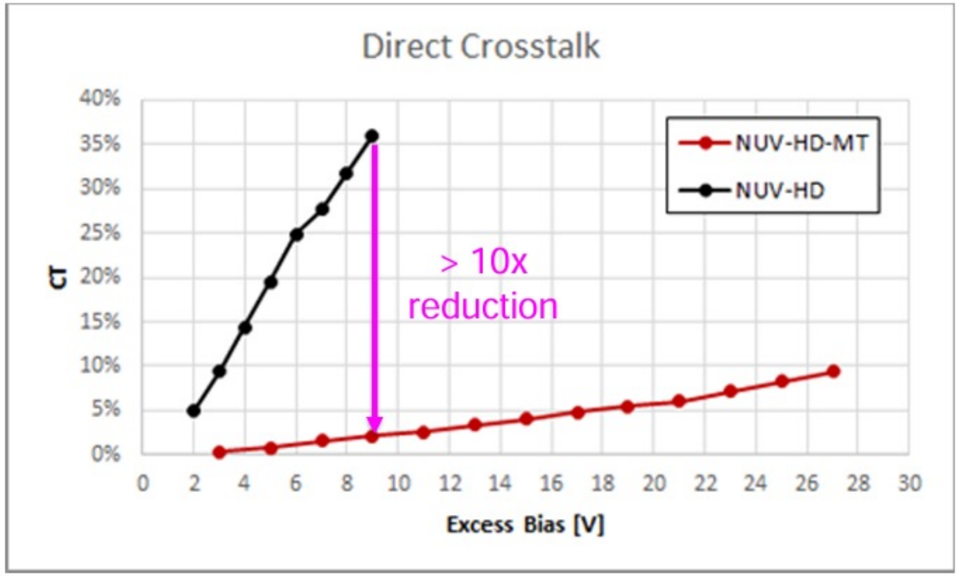
REDUCTION OF OPTICAL CROSSTALK



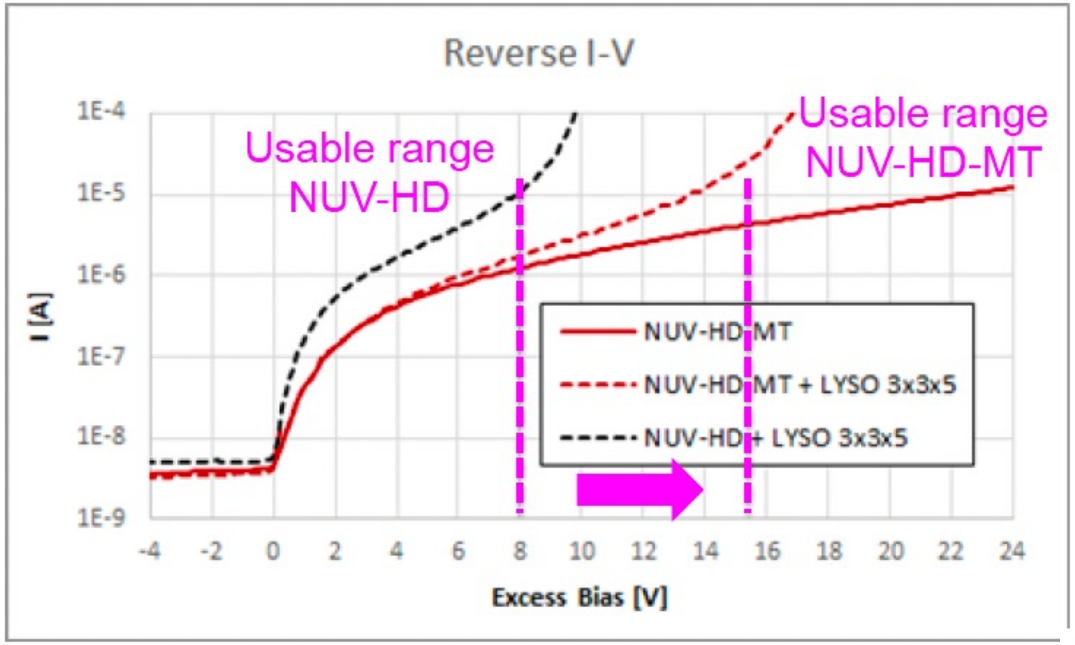
Conceptual drawing of the NUV-HD-MT, with the addition of metal-filled Deep Trench Isolation.

,FBK and Broadcom: new NUV-HD-MT technology with metal-filled Deep Trench Isolation

Reduction of c-talk *increases the maximum usable excess bias of the SiPM*



Reduction of optical crosstalk probability in NUV-HD-MT, compared to the "standard" NUV-HD. Measurement without encapsulation resin, i.e. *only considering internal crosstalk probability*.



Reverse IV measured on a 4x4 mm^2 NUV-HD-MT SiPM with 45 um cell pitch under different conditions.

A.Gola, RICH 2022

DESIGN CHANGES AND CHALLENGES

- Long development cycles: O(year) - Processing of the sensing layer + postprocessing
- High price of the developments, depending on the design complexity: several 10-100 kEUR
- Several iterations are needed to optimize the technology.

FUTURE STUDIES - AIDAINNOVA RUN @ FBK

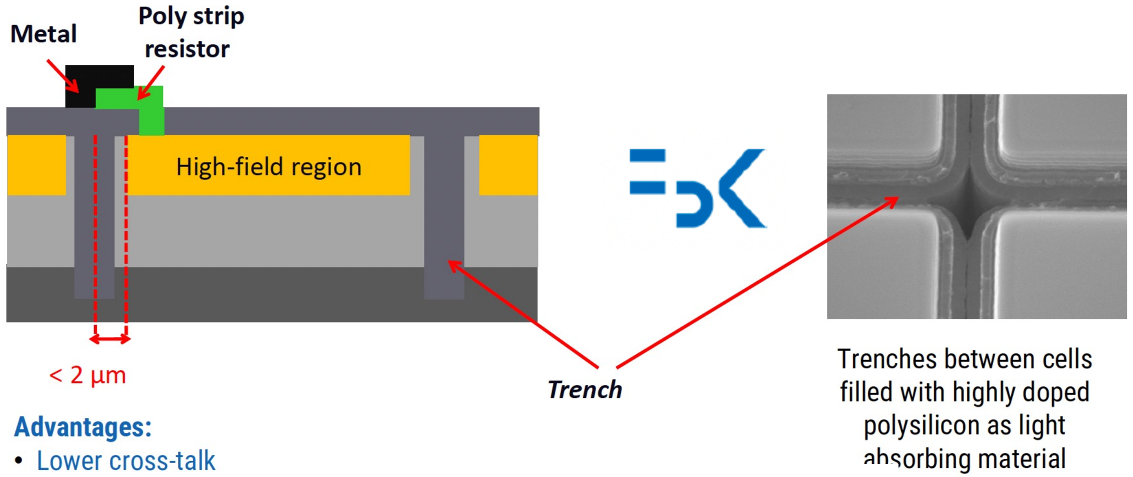
Experimental structures for a better understanding of the radiation effects

Incremental changes in the technology:

- **Low electric field & Ultra-low electric field**
- **Poly-silicon trenches**

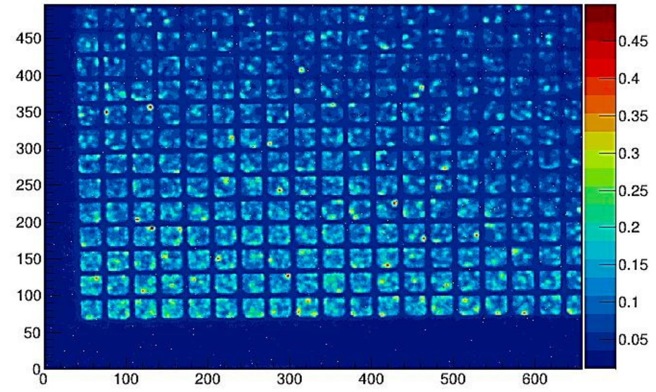
Status 9.2025: characterisation of the produced wafers.

NUV-HD for AIDAInnova



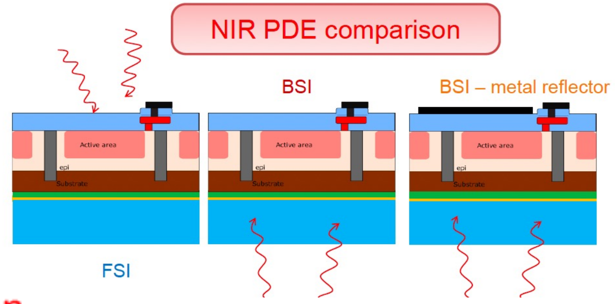
2x2 array of 1x1 mm^2 and mini-SiPM, die size 3.15mmx3.15 mm

Variants of 2x2 arrays:
1) 2x2 array of SiPM 1x1mm2 with 15um-25um-40um-75um cell size
2) 2x2 array of SiPM 0.75x0.75mm2 with 15um-25um-40um-75um
3) 2x2 array of SiPM 0.5x0.5mm2 with 15um-25um-40um-75um
4) 2x2 array of SiPM 0.25x0.25mm2 with 15um-25um-40um-75um
5) 2x1 array of SiPM 1.5x1.5mm2 with 15um+25um
6) 2x1 array of SiPM 1.5x1.5mm2 with 40um+75um
7) single SiPM 2x2mm2 with 15um, 40 um
8) Arrays of single SPADs



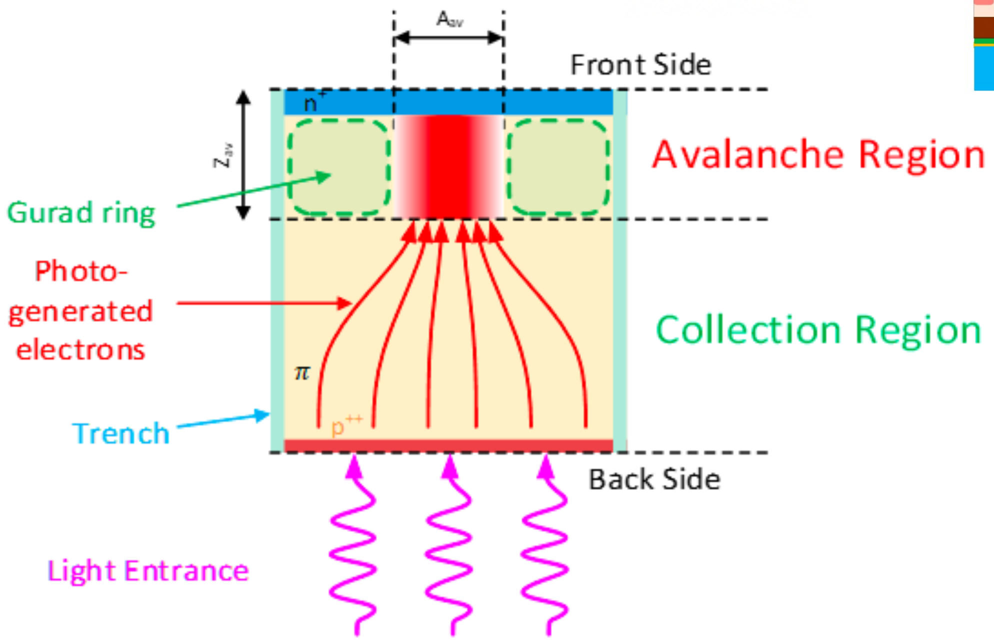
Localization of defects:
-Are there any critical areas in the irradiated SiPM?

BACKSIDE ILLUMINATED SIPMS



Potential Advantages

- ~100% fill factor, even at small pitch
- Interconnection density < 15 µm
- High speed, wide dynamic range
- Lower gain, reduced crosstalk
- Uniform backside entrance window (VUV-ready)
- Option for integrated, ultra-fast low-power electronics



Development Risks:

- Charge collection time jitter
- Low Gain might impact SPTR
- Effectiveness of the new entrance window

Radiation hardness:
Assuming the primary source of DCR is field-enhanced generation (or tunneling). ->

The area sensitive to radiation damage is much smaller than the light-sensitive area

First results from IBIS Run:

The nominal gain: 10x smaller than standard FBK technology : 1.5 x 10^5 – 3.5 x 10^5
Develop low-noise electronics!

A.Gola, RICH 2022

INCREASE OF S/B RATIO: MACRO LENSES

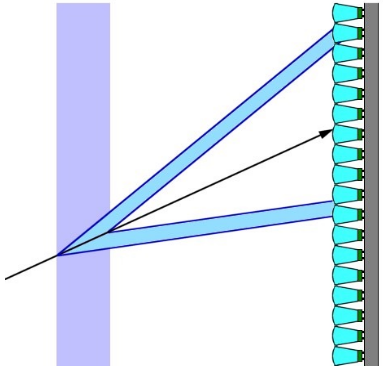
8x8 array of 1mm2 SiPMs at 2.54 mm pitch

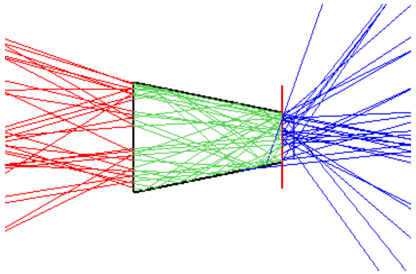
Expected number of background hits
Depends on
- Ring area
- Dark count rate
- Coincidence window

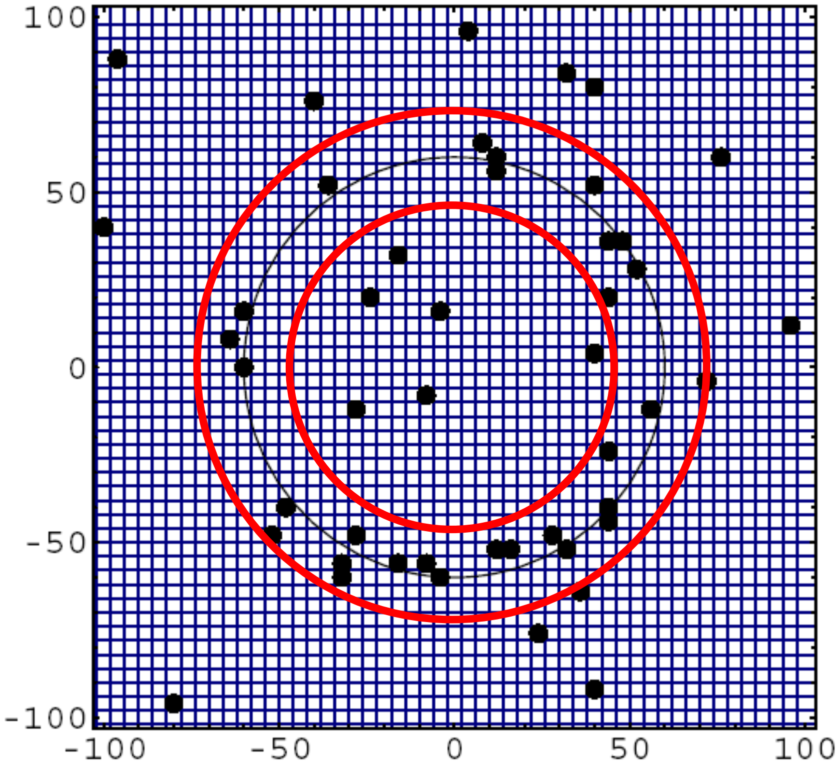
e.g.: N_{dark} ~ 6 → N_{ph}/N_{dark} ~ 3.3

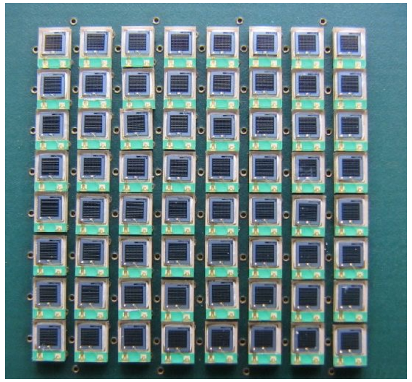
Ratio can be increased by:

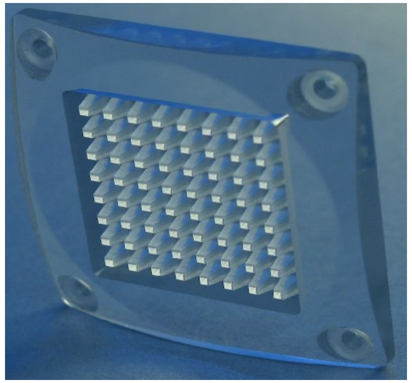
- **Smaller ring image area**
- **Narrower time window**
- **Use of a light collection system to increase the effective area of the sensor**

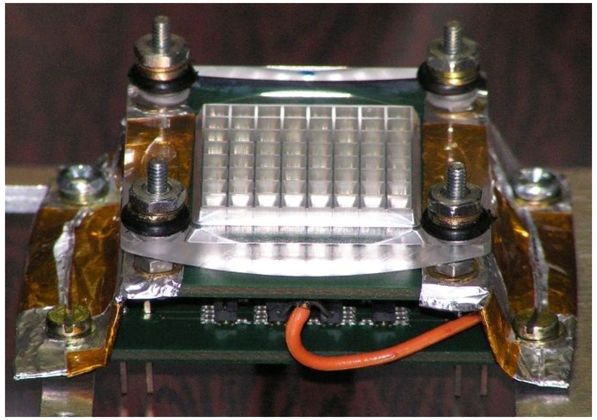








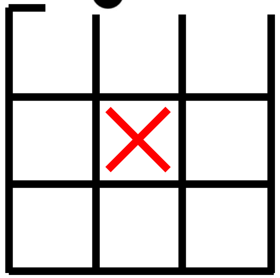




Korpar, 2009, NIMA

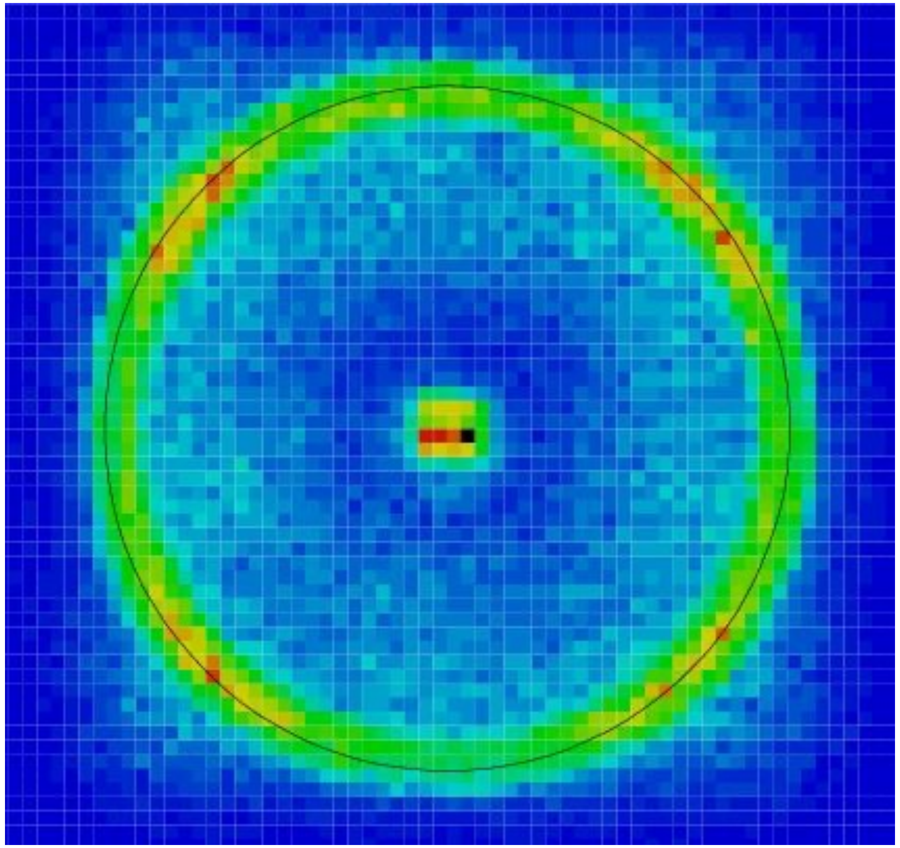
EFFECT OF LIGHT COLLECTION: TEST BEAM RING IMAGES

Jožef Stefan Institute

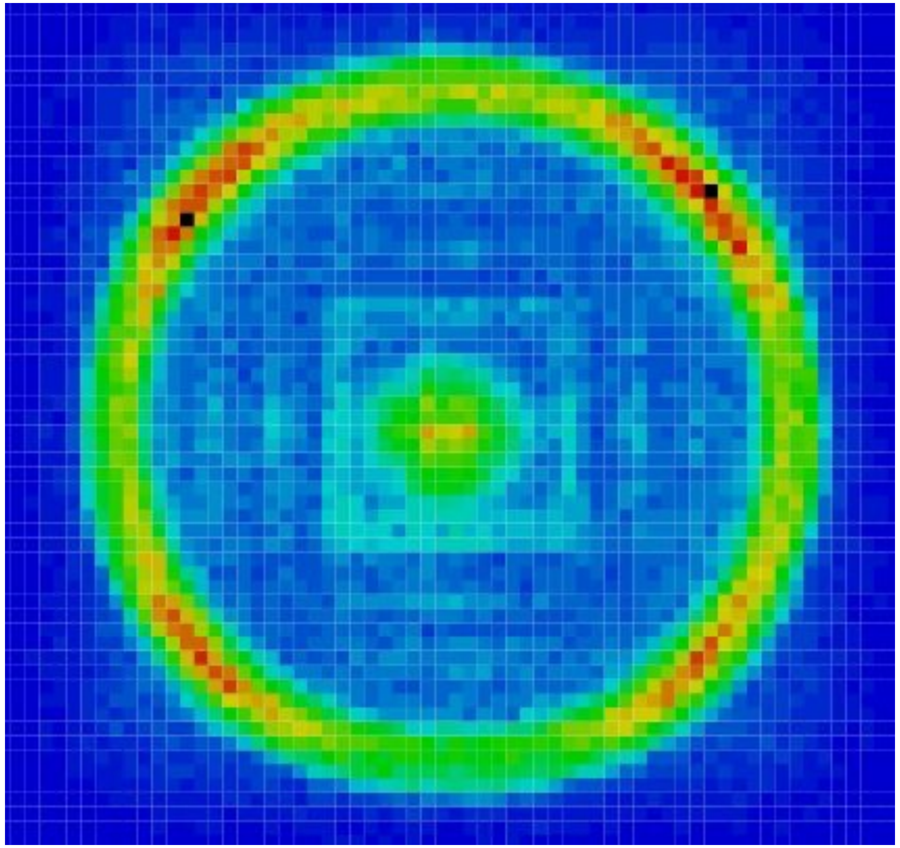


Measured yield: setup with aerogel tiles in a pion beam
w/o LG ~ 16
w/ LG ~ 37

w/o light guides



w/ light guides

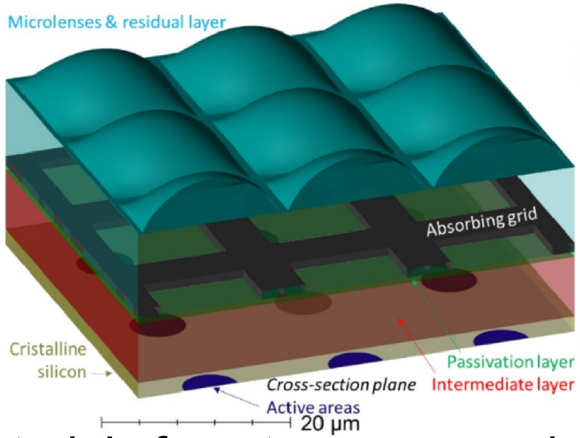


Korpar, 2009, NIMA

INCREASE OF S/B : MICROLENSES ON SPADS

- For high occupancies, macroscopic light collectors don't work if you don't measure the number of detected photons.
- Decrease fill factor – increase distance between SPADs + μLens
- Can potentially concentrate light by factors as high as 20

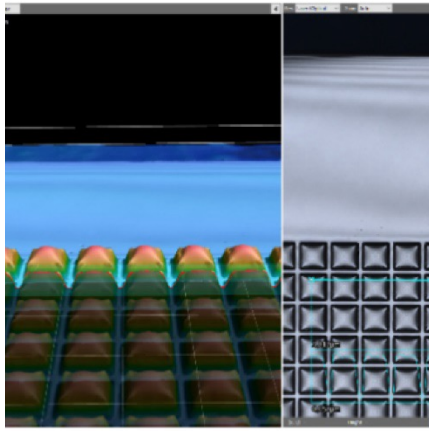
G. Haefeli, 2025, 3.DRD4 CM



A μLens is placed on top of every SPAD cell

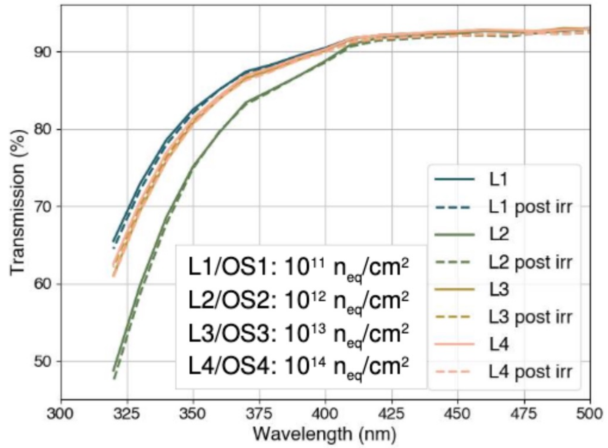
Development risks:

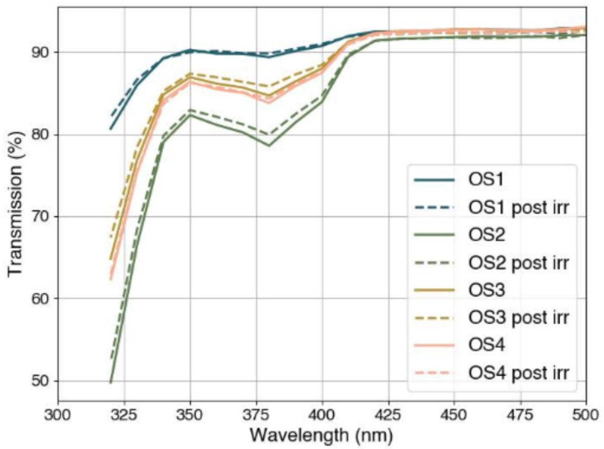
- Critical to reach a minimal distance between lenses,
- The substrates can be sensitive to radiation damage as well
- An additional step in the fabrication



C. Bruschini, et al," Opt. Express 31, 21935-21953 (2023).

Irradiation of two materials from two commercial suppliers:
Lumogen – L, d=120 μm and Ormostamp – OS, d=500 μm
No observable difference was seen even for 10^{14} n_{eq}/cm2





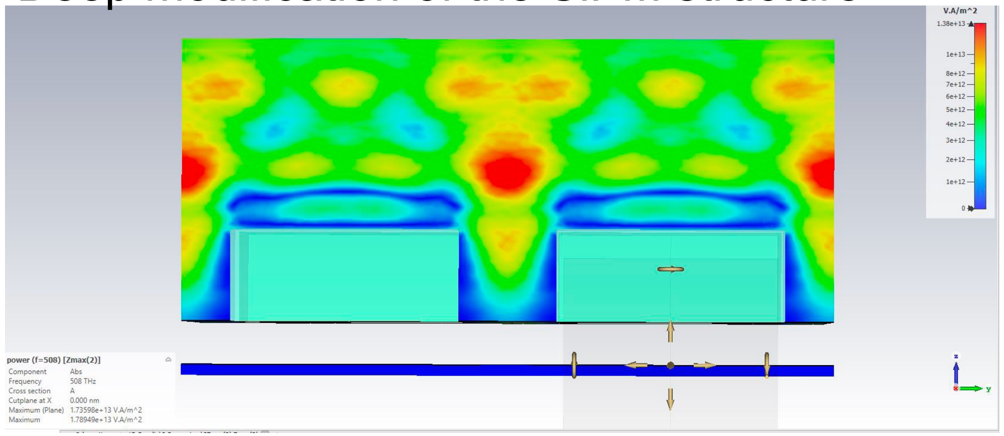
R. Dolenec, poster at this conference

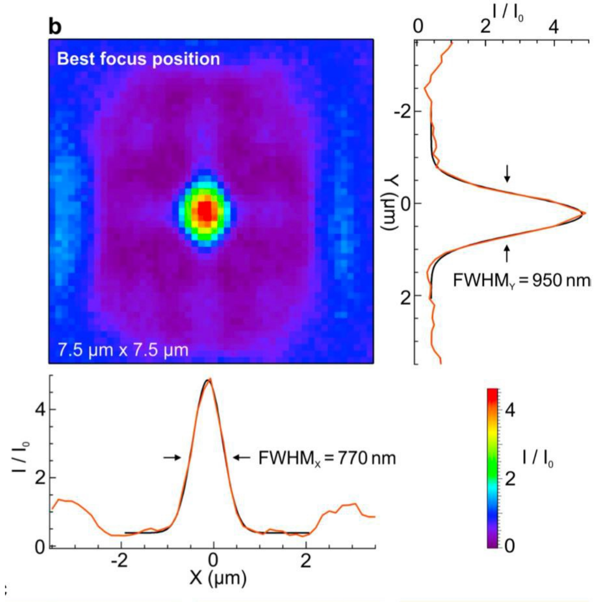
INCREASE OF S/B : METALENS-BASED LIGHT CONCENTRATORS

Metalens-based light concentrators can work similarly to microlenses

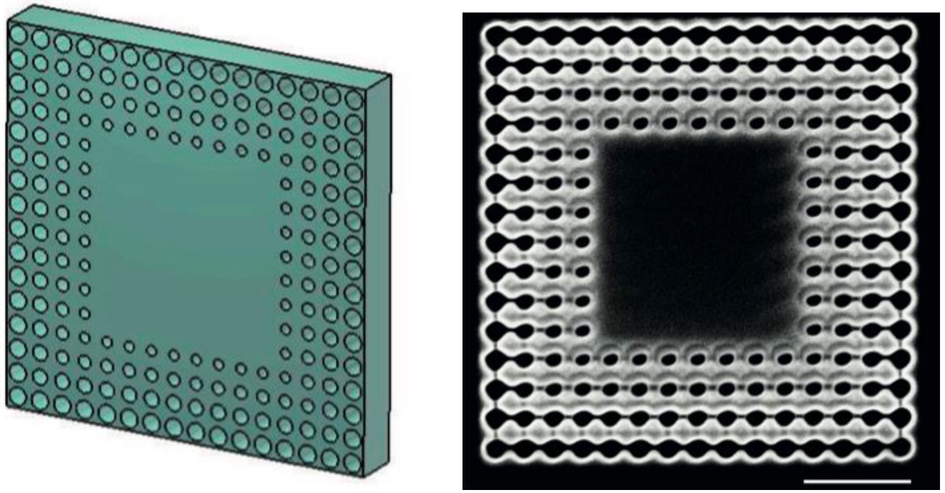
PHOTOQUANT ATTRACT project

Deep modification of the SiPM structure





Fabrication of a 4x4 mm Nb_2O_5 metalens with a refractive index gradient introduced by holes of varying diameter (joint ATTRACT project CERN, FBK, Institut Fresnel).



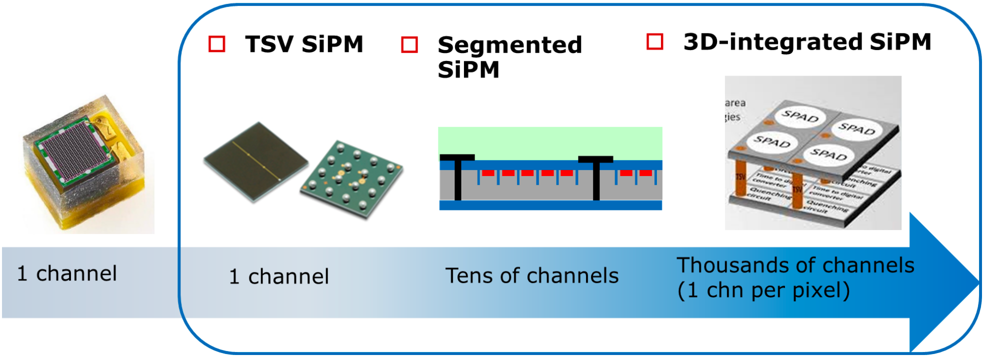
E. Mikheevaet al., CMOS-compatible all-dielectric metalens for improving pixel photodetector arrays, APL Photonics

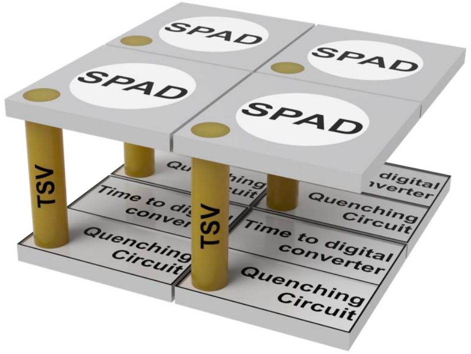
INTEGRATION : ENABLING TSV TECHNOLOGY

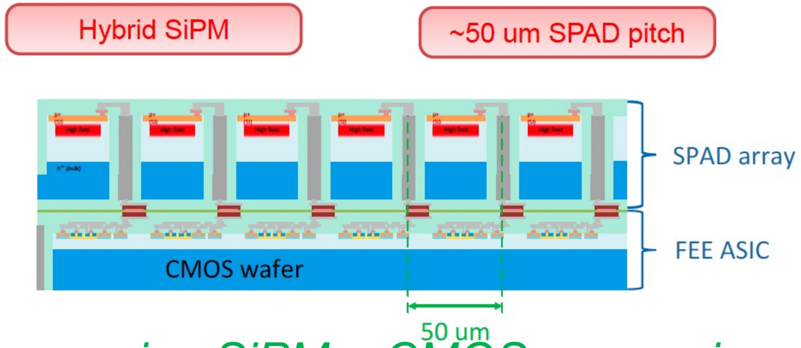
Jožef Stefan Institute

Allows for high-density interconnections to the front-end and high-segmentation.

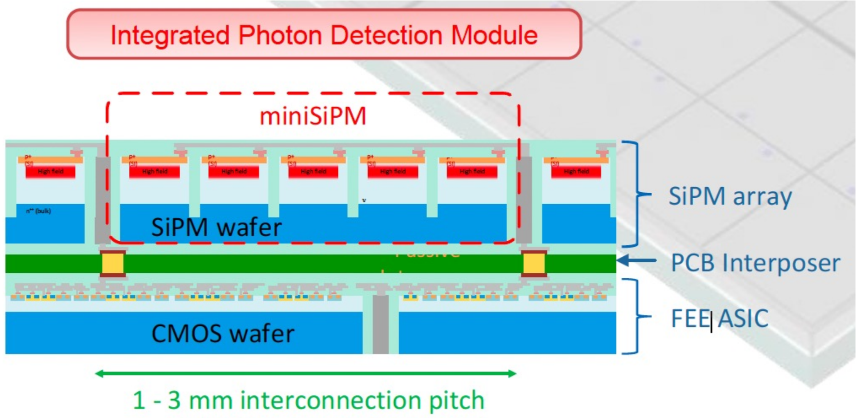
Technological advancements in the SiPM production at various levels are necessary.





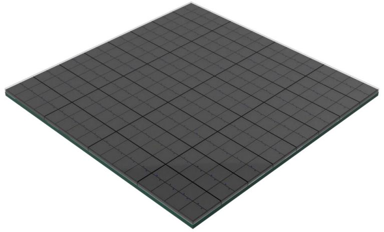


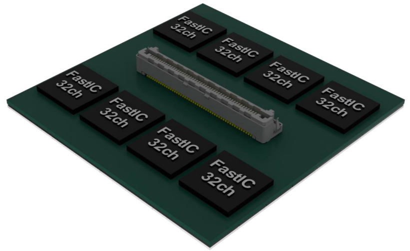
Hybrid SiPM: Custom sensing SiPM + CMOS processing layer, exploit optimal segmentation – Digilog project



The 2.5D integrated PDM (50x50 mm2) development by EIC Pathfinder project PetVision (8 partners, FBK, JSI, I3M, Yale, CERN, Oncovision, ICCUB, TUM-MED) – mainly for medical TOF-PET applications

PET VISION

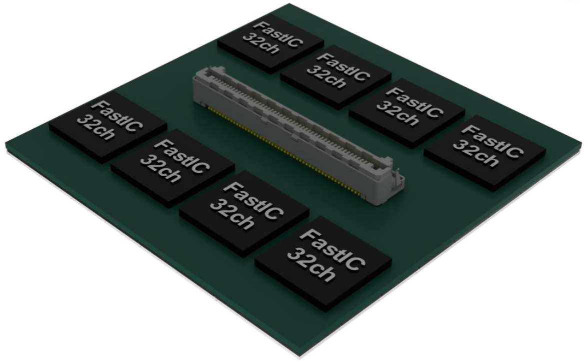




INTEGRATION OF SIPM AND ELECTRONICS

Preserve signal integrity

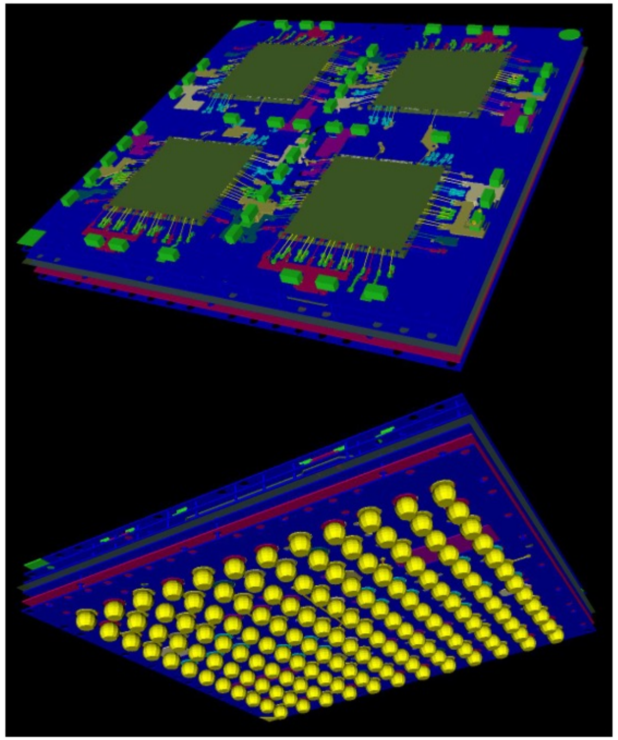
Ultra-fast SiPM with optimized readout electronics



Institut de Ciències del Cosmos UNIVERSITAT DE BARCELONA

Proof of Concept prototype:

- FastIC+ BGA (32 channels)
- 11x11 mm2 Package with 12x12 pads (144 balls)
- balls of 0.3/0.35mm and pitch of 0.8mm-
- 4x FastIC+ (3x3mm2) ASICs
- Wire Bonding
- Additional passive components(C, R, ...)
- First samples in October 2025



Otello (AidaInnoova succesor) proposal: Integration of BSI and front-end electronics

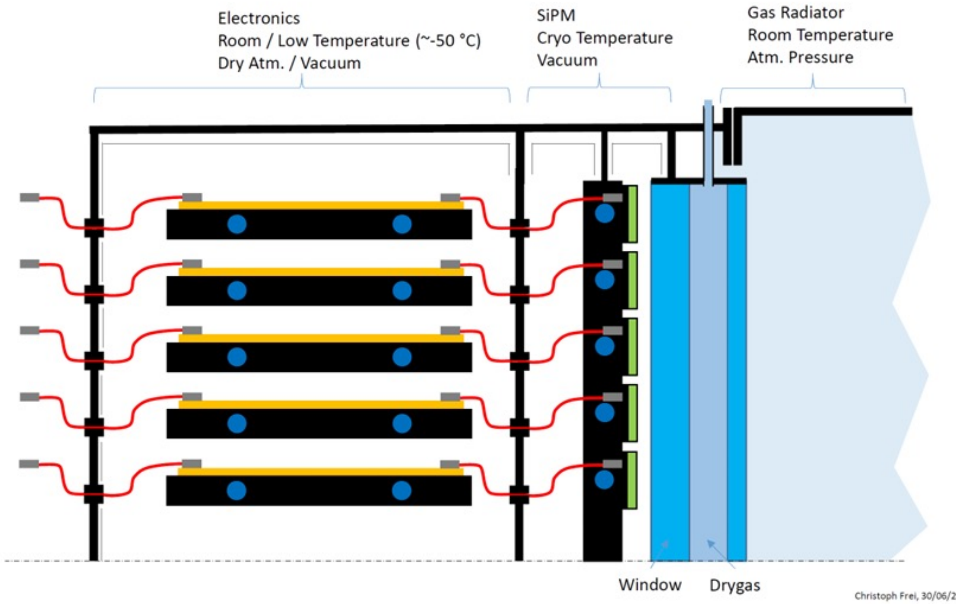
CRYOGENIC COOLING OF PHOTO DETECTORS

R&D into compact vessel structures has started and several meetings held with the cryogenics experts at CERN (TE-CRG-CI).

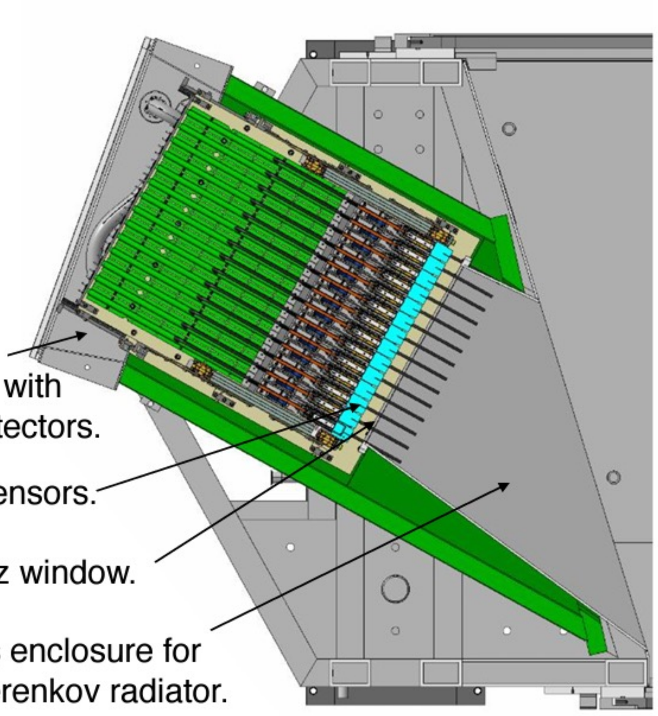
- One of the ideas could be to use two specially-coated quartz windows separated by a vacuum.
- Exploring synergies with other LHCb sub-detectors (Velo, SciFi).

RICH – Cooling the Photodetectors at Low Temperature

First Thought on Implementation of SiPMs



Christoph Frei, 30/06/2021, 9



https://indico.cern.ch/event/1175130/

11.01.23 LHCb RICH R&D - F.Keizer 6

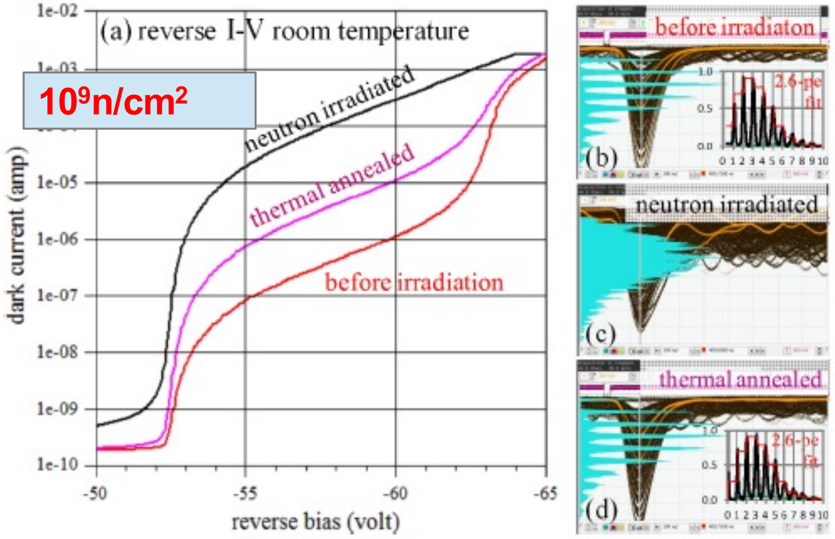
ANNEALING

Jožef Stefan Institute

T,Tsang et al., 2016 JINST 11 P12002:

Annealing 3days at high temperature 250 C
To accelerate: a forward bias of 8mA applied

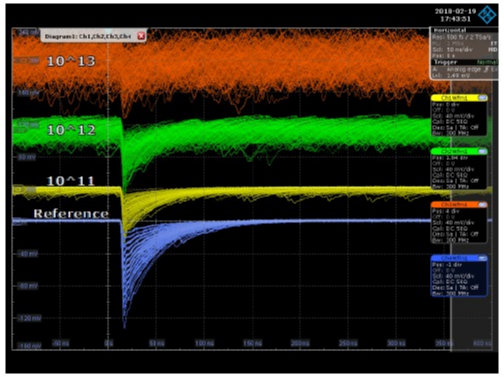
10^9n/cm^2

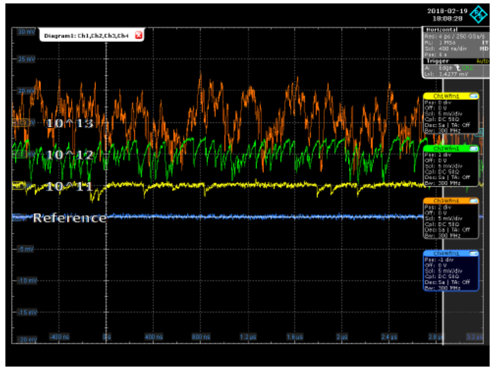


Single photons are resolved after annealing

M. Calvi et al., arXiv:1805.07154v1:

Annealing several weeks above 175 C





10^{11}n/cm^2
10^{12}n/cm^2
10^{13}n/cm^2

Drop of DCR after annealing

Not irradiated
< 100 kHz/cm^2

10^{11} n_{eq} cm^{-2}
200 → 20 MHz/cm^2

10^{12} n_{eq} cm^{-2}
2 → 0.2 GHz/cm^2

10^{13} n_{eq} cm^{-2}
? (20) → 0.5 GHz/cm^2

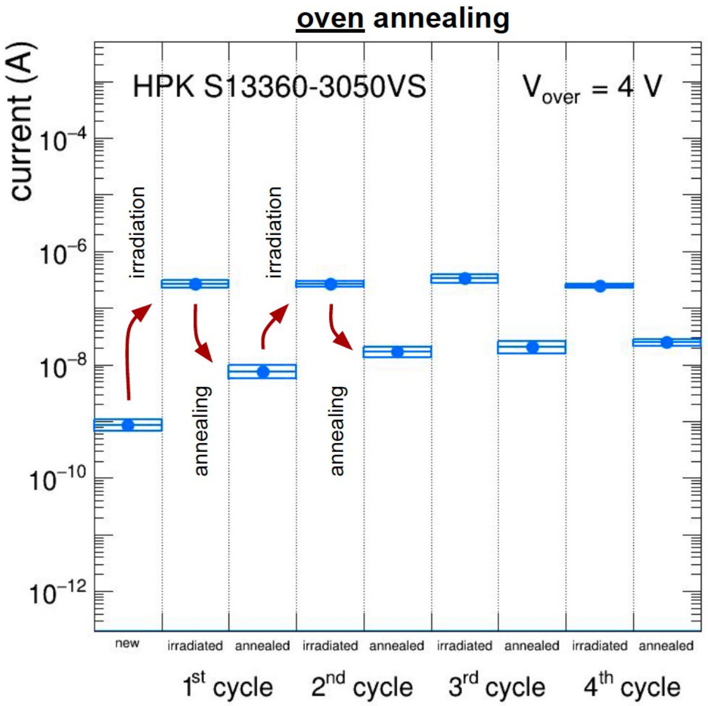
REPEATED IRRADIATION & ANNEALING

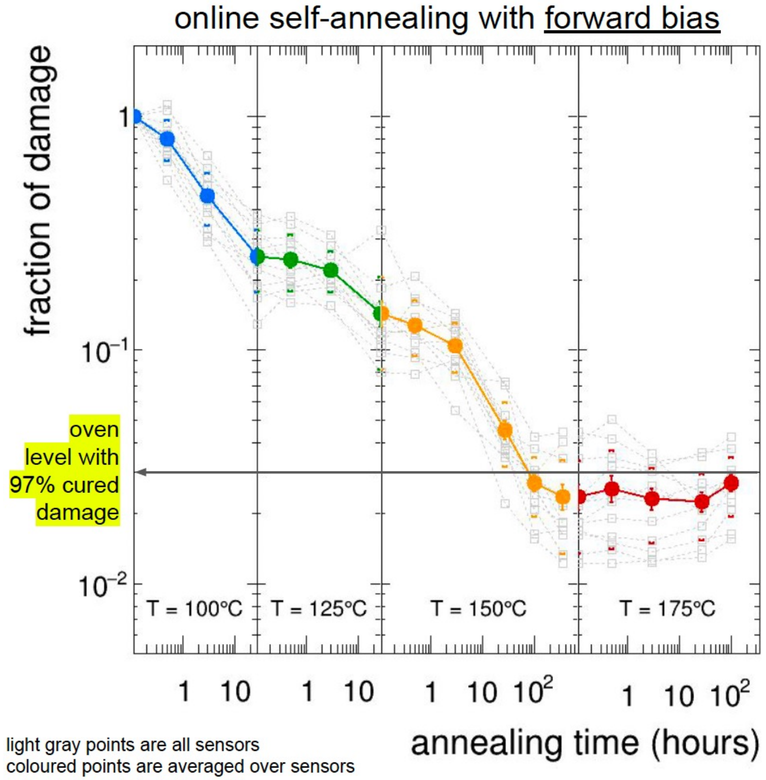
What annealing method should be applied during SiPM characterization?

Can an optimized procedure improve performance in a given experimental setup?

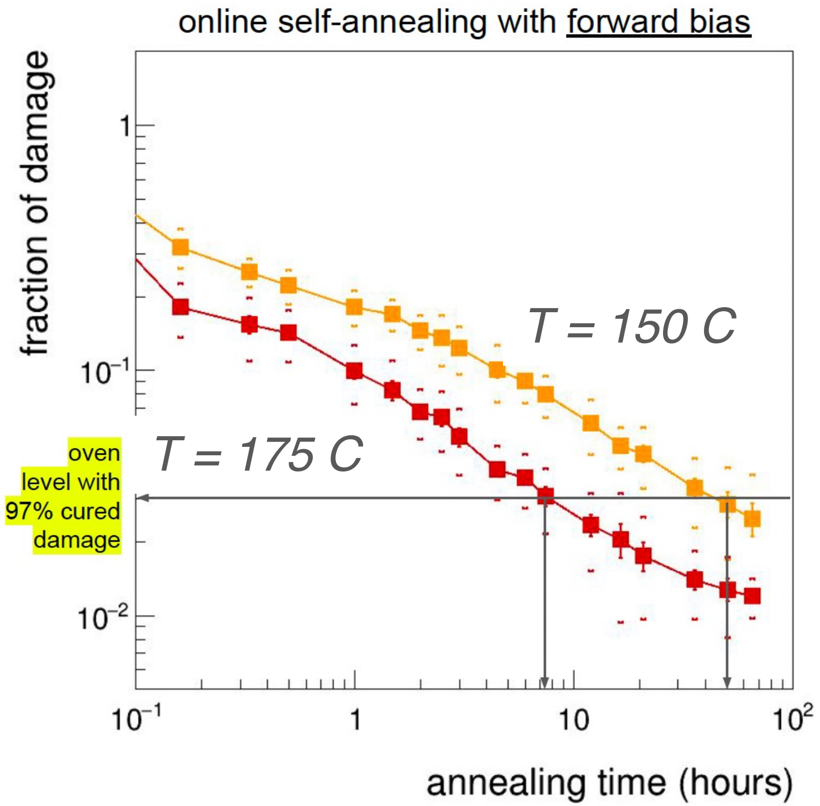
- *irradiation fluence / cycle : 10^9 neq*
- *annealing in oven :150 hours at 150 °C*

In-situ annealing with forward bias- how much damage is cured as a function of temperature and time





light gray points are all sensors
coloured points are averaged over sensors
coloured brackets is the RMS



faster "sudden" cure followed by a similar reduction with time

R. Preghenella, 2 DRD4 CM, 2024

NEW MATERIALS

Very early stage of development:

Studies of potential new materials for light detection, e.g., SiC, GeC, and investigation of InGaAs, GaAs technology for photon detectors:

Colour centers in SiC have recently emerged as one of the most promising emitters for bright single-photon emitting diodes.

The precise properties of GeC, such as its band gap and electrical conductivity, would depend on its crystal structure and specific composition. As it could be integrated into semiconductor devices, its properties may offer advantages in SSPDs.

Band Gaps (eV @ 300 K)

Si	1.12
GaAs	1.42
GaInP	1.90

Larger Band Gap

⇒ • Lower thermal noise
• Better radiation resistance

SUMMARY & OUTLOOK

Radiation damage in SiPMs is intrinsic to the silicon lattice, making it difficult to prevent entirely.

Material quality: Reducing the density of crystal defects in the substrate can improve tolerance.

Device design and other mitigation measures: Modifying structures (e.g. smaller depletion regions, optimized pixel geometry) may limit the impact of damage and make the SiPM usable for harsh environments.

Alternative materials: Wider bandgap semiconductors (e.g. GaAs, GaN, GaInP, SiC) may exhibit lower intrinsic noise and reduced degradation after irradiation.

Community & industry partnership: Progress requires joint efforts with (not so many) manufacturers