15th Topical Seminar on Innovative Particle and Radiation Detectors

October 14-17 2019, Siena

Radiation induced degradation in a 150-nm CMOS SPADs device

(M. Campajola, F. Di Capua, D. Fiore, L. Gasperini, E. Sarnelli)

Marcello Campajola (University of Naples 'Federico II' and INFN)

marcello.campajola@na.infn.it

Università degli Studi di Napoli Federico II

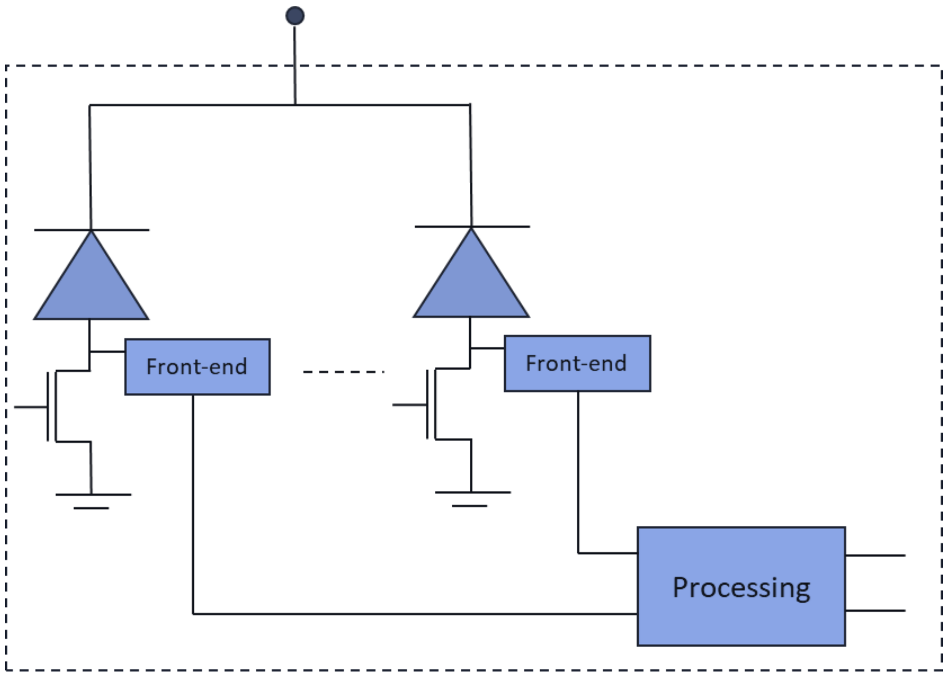
INFN Istituto Nazionale di Fisica Nucleare

Single-Photon Avalanche Diodes

➢ CMOS SPAD

- Single-Photon Avalanche Diodes (SPADs) are photodiode biased above the breakdown voltage.
- SPADs have sensitivity at the single-photon level with no need for amplification.
- First implementation of SPAD in CMOS technological process has been achieved in 2003, since them many improvements have been obtained

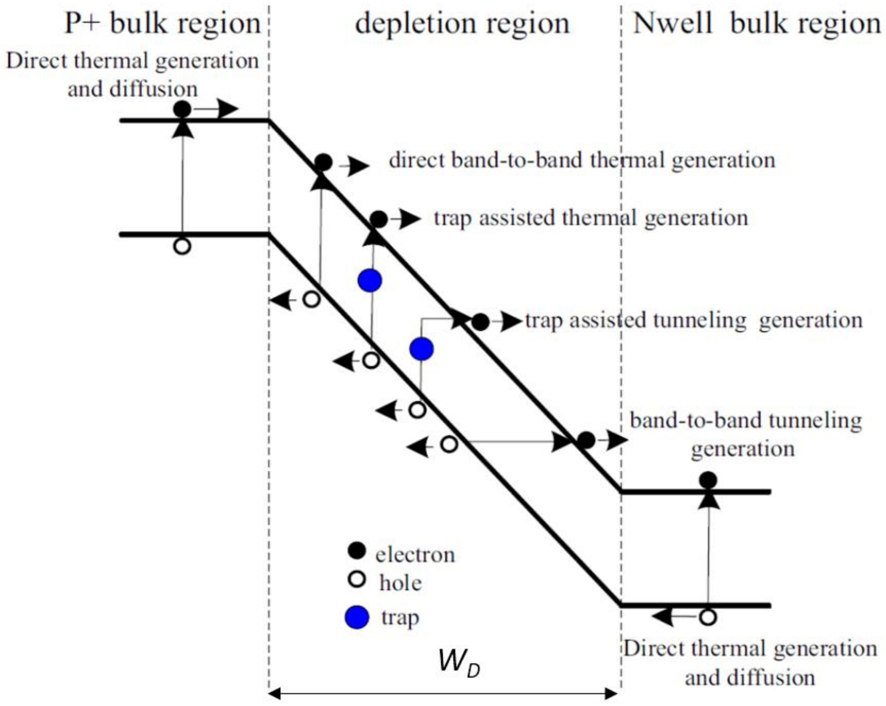
- **CMOS SPADs**
  - Excellent timing resolution;
  - Position sensitive device;
  - Addressing the output of a single SPAD pixel;
  - Post-processing circuits integrated on chip;
  - High DCR wrt custom processes;



Single-Photon Avalanche Diodes

➢ Radiation Effects

- Several possible applications (**HEP tracker, PET, Spectroscopy, LIDAR, 3D camera, space communication, etc**.).
- Many of them require the detector to be utilized in radiation environment; It is fundamental to understand the radiation induced effects on CMOS SPADs.
- A critical issue is related to the Dark Count Rate (DCR). It is due to:
  - Fabrication process: impurities and crystal defects;
  - Radiation environments effects:
    - Displacement Damage: it is the result of energetic particles displacing atoms from their lattice structure;
      As a consequence of DD, new energy level are introduced in the mid-gap. Mid-gap levels lead to an increased rate of dark count rate according several mechanisms;

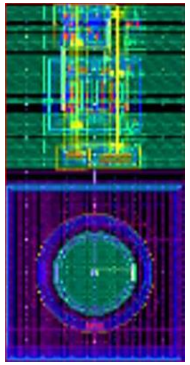


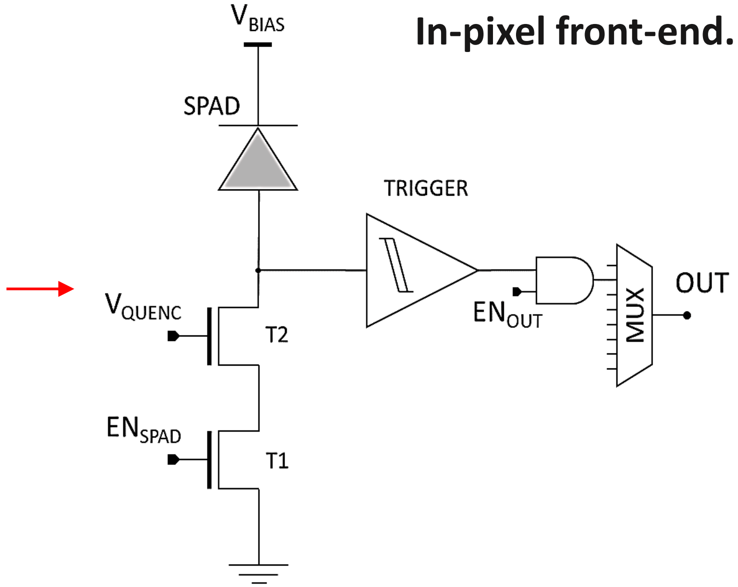
Devices Under Test

➢ Test chip architecture

"Low-noise Single Photon Avalanche Diodes in 0.15 μm CMOS Technology", L. Pancheri, D. Stoppa.

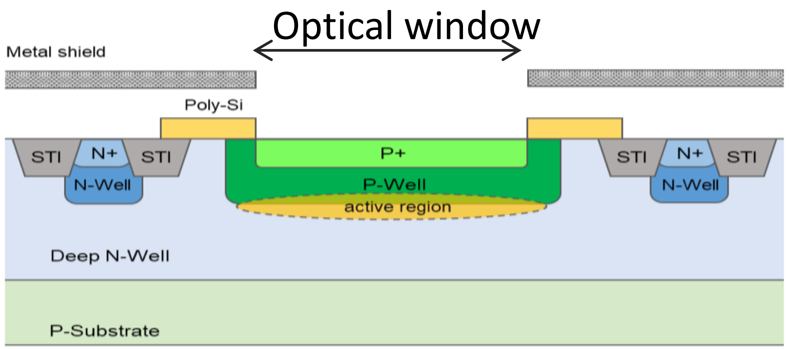
- Devices designed by Fondazione Bruno Kessler (FBK), Italy.
- SPADs implemented in a 150-nm CMOS process (LFoundry).
- Two junction layouts;
- Several dimensions (5, 10, 15, 20 μm);
- Each SPADs is implemented with its front-end electronics:
  - A trigger to digitalize the pulse;
  - MUX to select one pixel at the time;



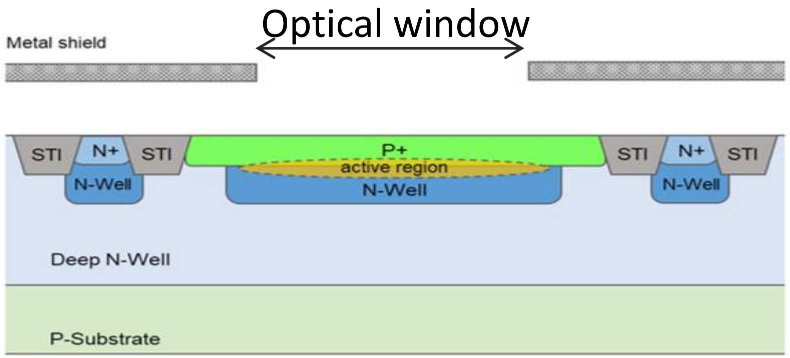


In-pixel front-end.

PWNISO layout



PNWELL layout

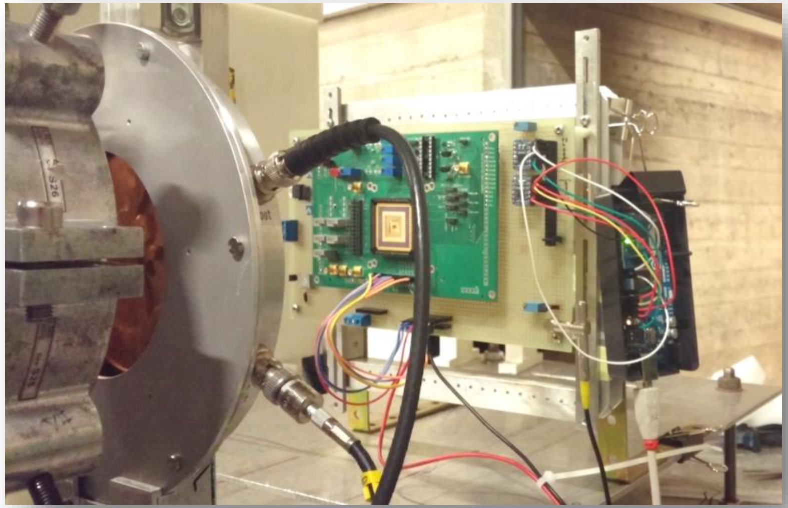


Irradiation Test

➢ **Proton and electron Irradiations**

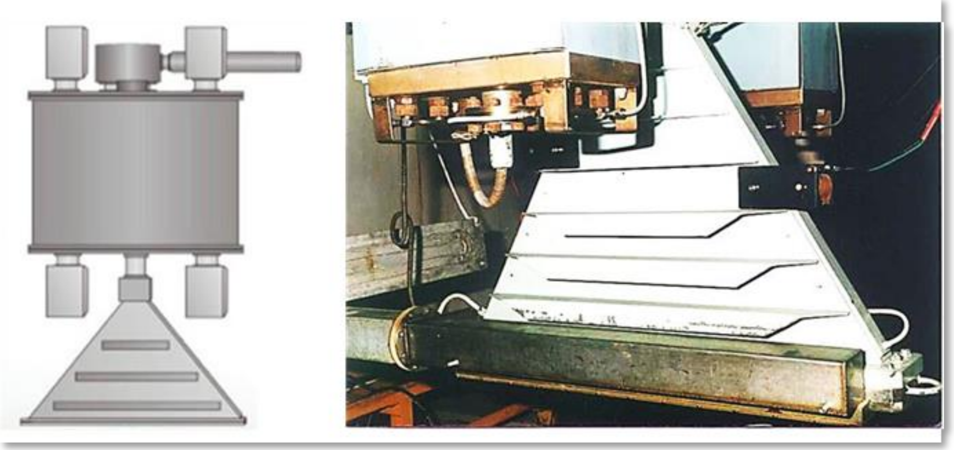
- Proton test performed at INFN-LNS in Catania (Italy) using:
  - 21 and 16 MeV proton beam;
  - Delivered fluences: 10^{10} - 10^{11} p/cm^2
  - Displacement Damage Dose (DDD) up to 600 TeV/g

Test at Tandem Accelerator line @ LNS



- Electron test performed at ILU-6 accelerator at the Warsaw Institute of Chemistry and Nuclear Technology
  - 2 MeV electron beam;
  - Delivered fluences: 10^{12} e/cm^2
  - Displacement Damage Dose (DDD) up to 300 TeV/g

Test at ILU-6 accelerator @ ICNT



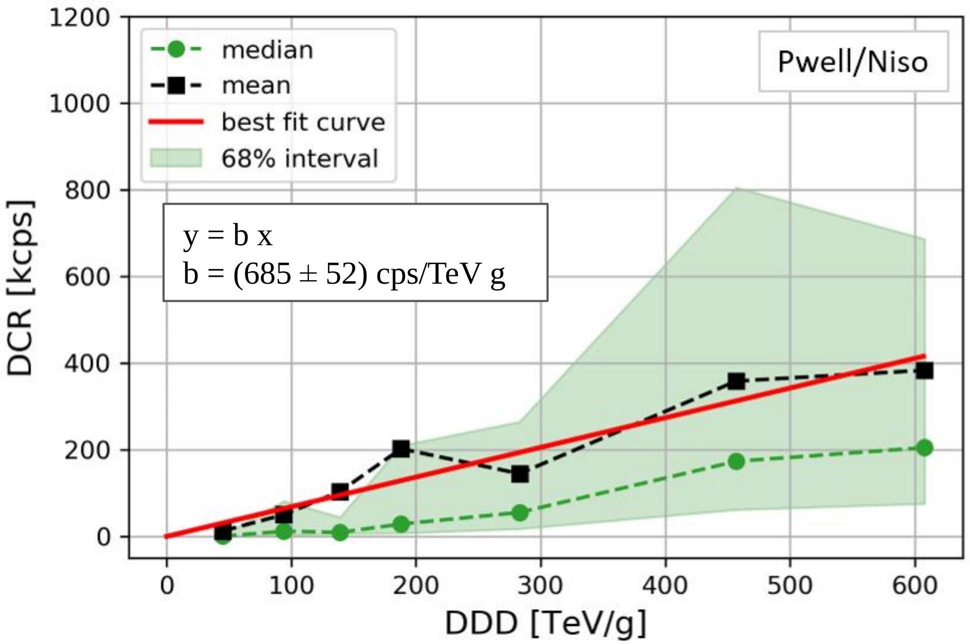
DCR Induced Degradation

"Proton induced dark count rate degradation in 150-nm CMOS single-photon avalanche diodes", *M. Campajola et al.*

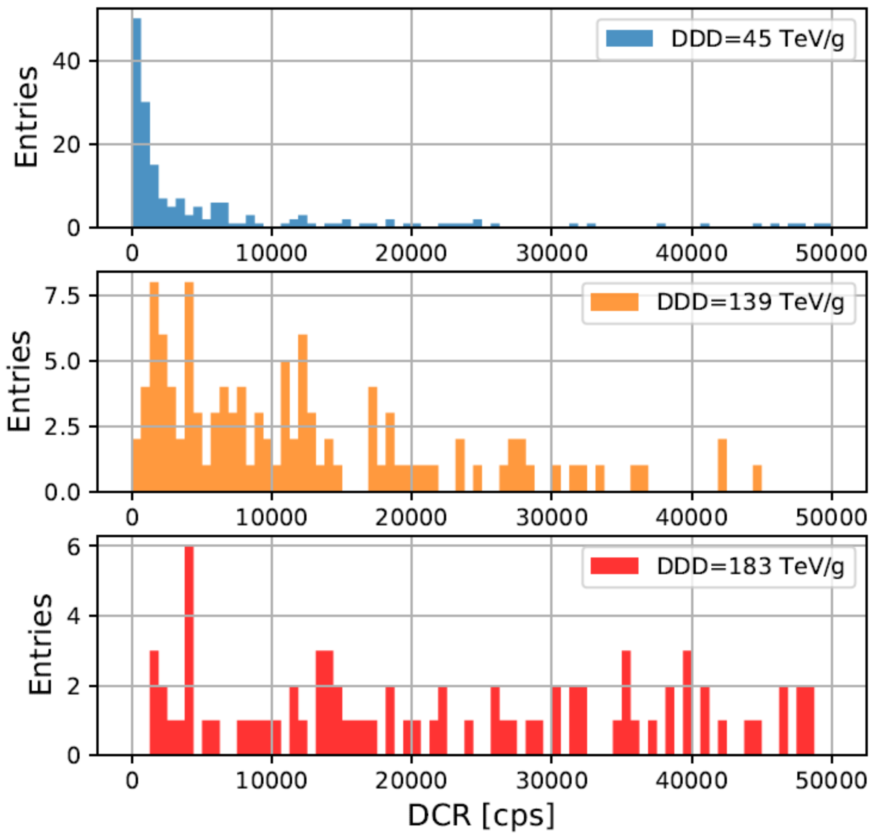
➢ **Proton irradiation**

- High susceptibility to the DCR increase as a function of the dose: mean DCR increases up to two order of magnitude at maximum dose delivered;
- No significative changes in the breakdown voltage.

Mean DCR increase as a function of the dose



DCR distribution after irradiation steps

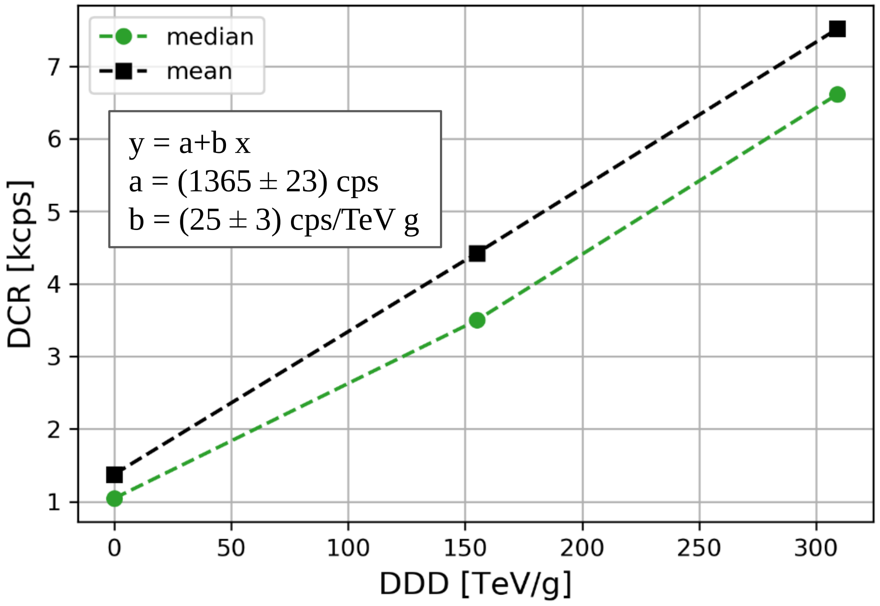


DCR Induced Degradation

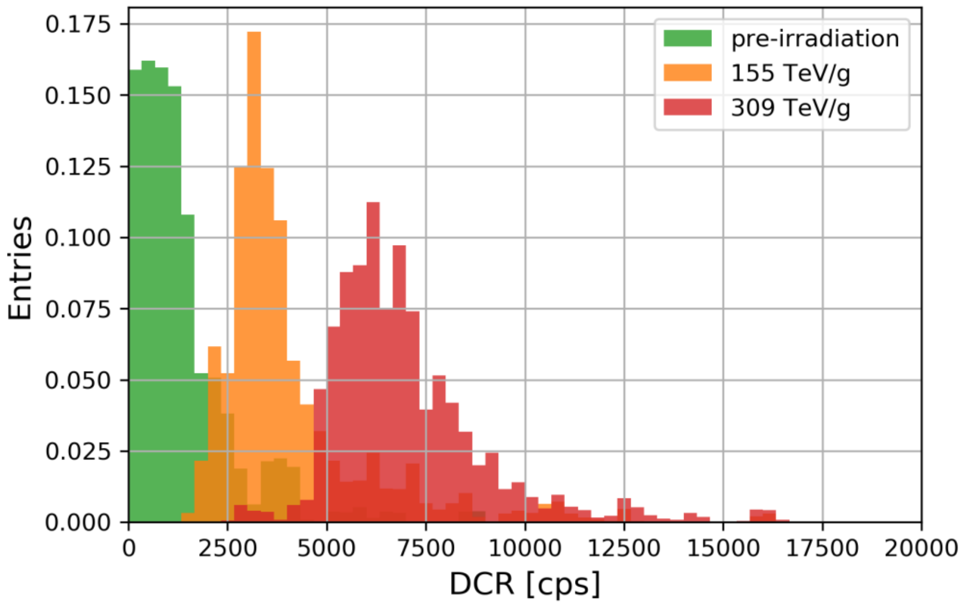
➢ Electron irradiation

- Defects induced by protons may be produced relatively close together and form a local region of disorder (defect cluster or disordered region).
- Electrons with energy less than about 2 MeV, produce relatively isolated defects (point-like defects).

Mean DCR increase as a function of the dose



DCR distribution after irradiation steps



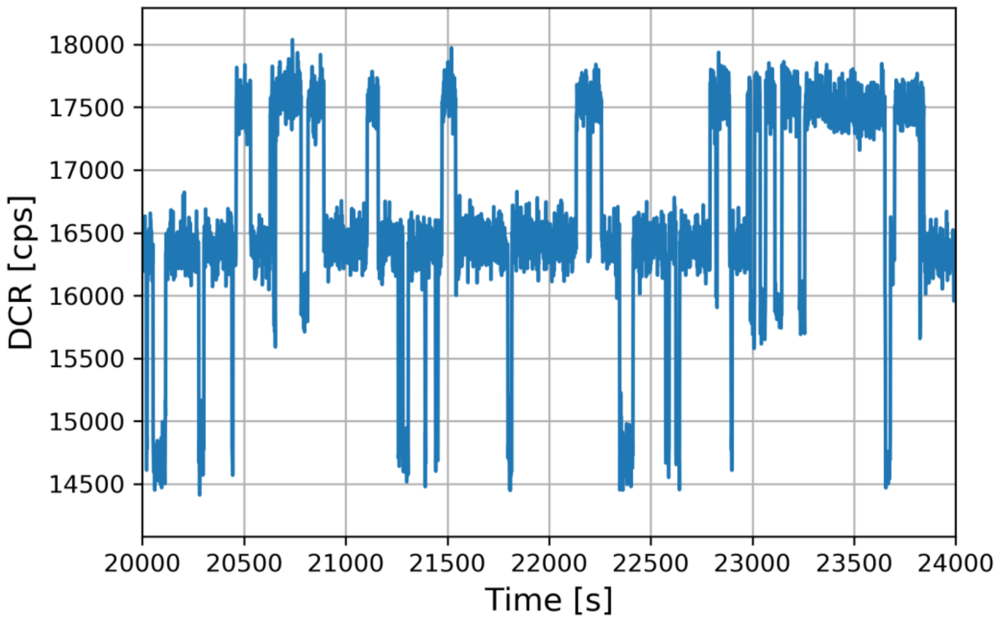
DCR Induced Degradation

"Random Telegraph Signal in Proton Irradiated Single-Photon Avalanche Diodes", *F. Di Capua et al.*

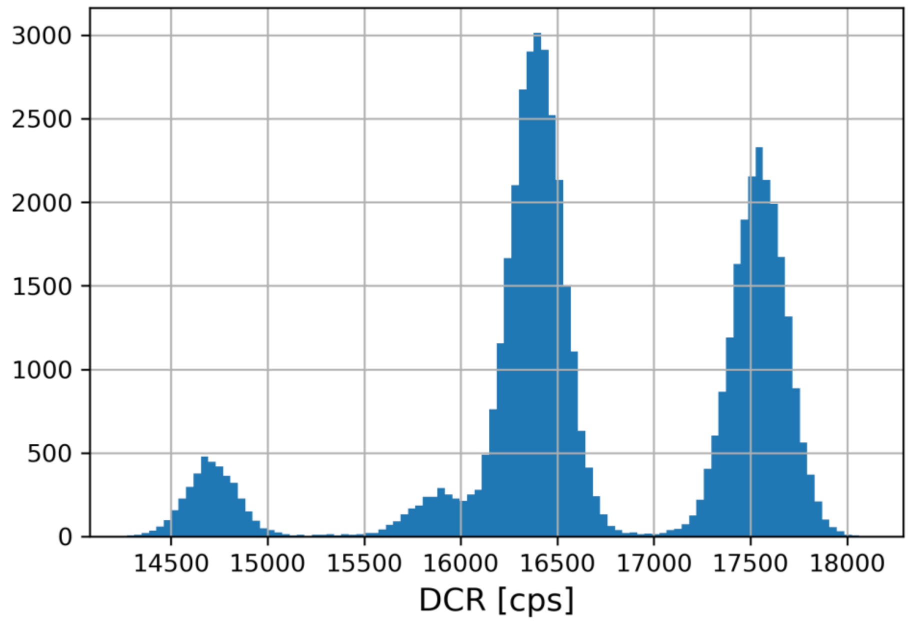
➢ Random Telegraph Signal Noise

- After proton irradiation discrete fluctuation between two or more levels have been observed;
- This phenomenon is known as Random Telegraph Signal Noise;
- Its occurrence increases with the DDD.

DCR vs observation time



DCR distribution

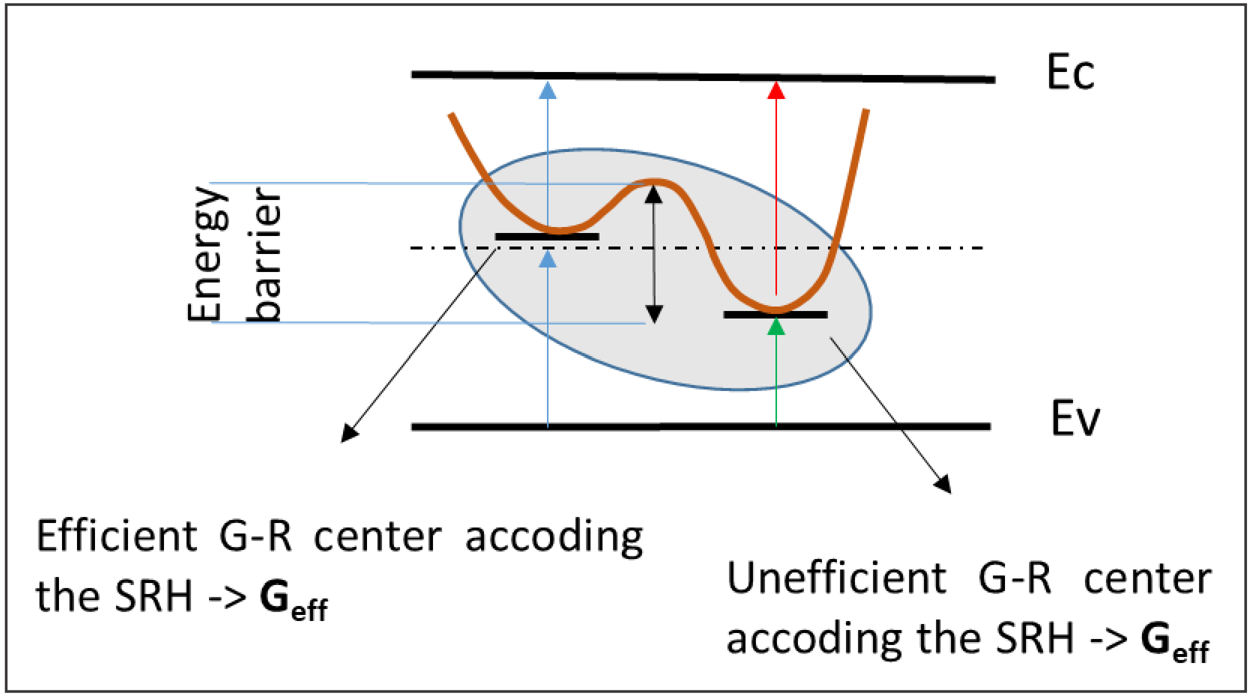


Random Telegraph Noise

➢ **A possible explanation**

- In photon devices RTS is due to Displacement Damage Dose effects. Induced defects introduced by proton irradiation can exist in two or more stable configurations.

Bi-stable complex defect schematization



- Metastable defects can randomly change their configuration.
- As a consequence the *e-h* generation rate can change, resulting a ‘jump’ in the level of DCR: RTS.
- An energy barrier must be overcome to switch from one configuration to another: for this reason the RTS switching frequency is expected to depend on the temperature.

Random Telegraph Noise

➢ A possible explanation

- Phosphorus-Vacancy (P-V) defects can be generated in doped silicon devices. It can be formed at any of four Si-atoms around the P-atom.
- P-V center has a dipole structure. The dipole axis can change with the vacancy position and may induce RTS.
- Calculation on kinetics of reorientation predicts 0.9 eV for activation energy. [G. D. Watkins and J. W. Corbett, 1964; H. Hopkins, G.R. Hopkinson, 1995, T. Nuns, 2007]

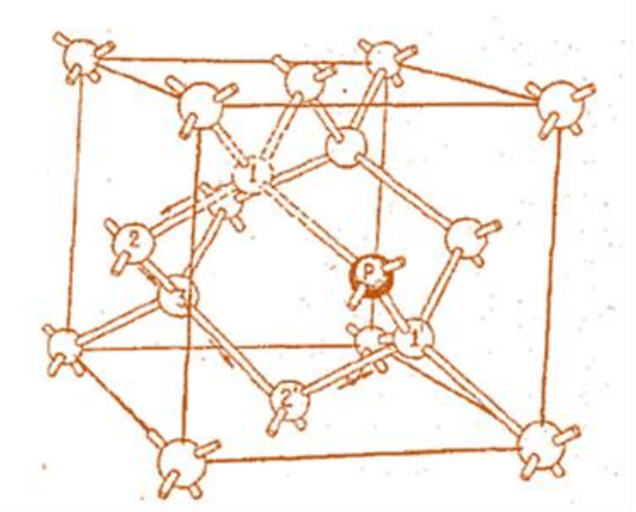


Figure from Watkins & Corbett (1964)

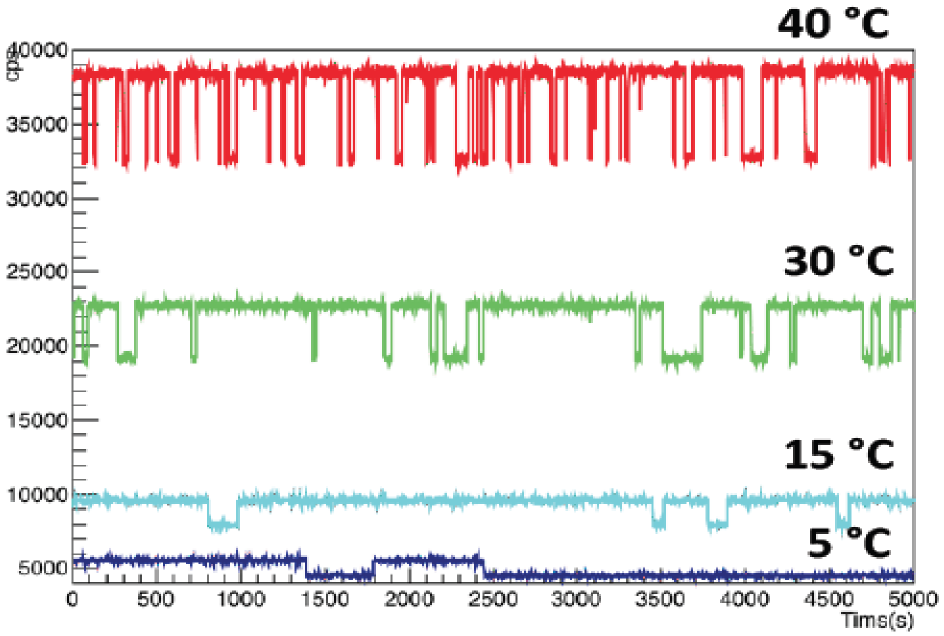
- Di-Vacancies cluster: these defects have three energy levels and four charge states (+,0,-,2-).
- The interaction of neutral di-vacancies (the most probable state) can produce a reaction called “Inter-center transfer” which has the effect to increase the generation rate.
- The rearrangement of defects can create configuration in which inter-center transfer is possible and in other no, giving rise to RTS.

Random Telegraph Noise

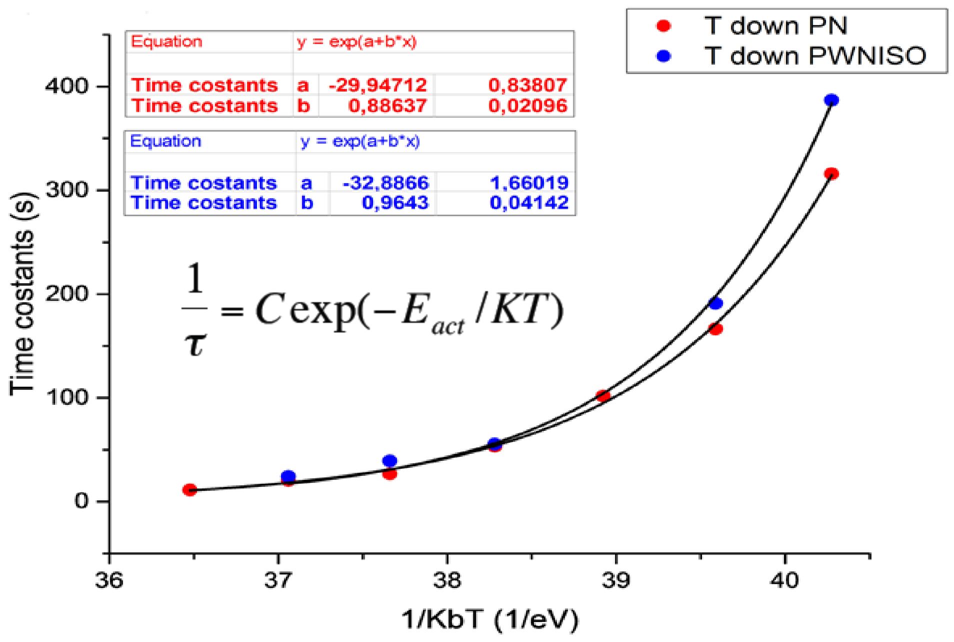
➢ Temperature dependence

- RTS amplitude has been found to increase with temperature;
- Also the switching probability increases with temperature, following an exponential dependence.

RTS as a function on Temperature



RTS time constant vs. Temperature

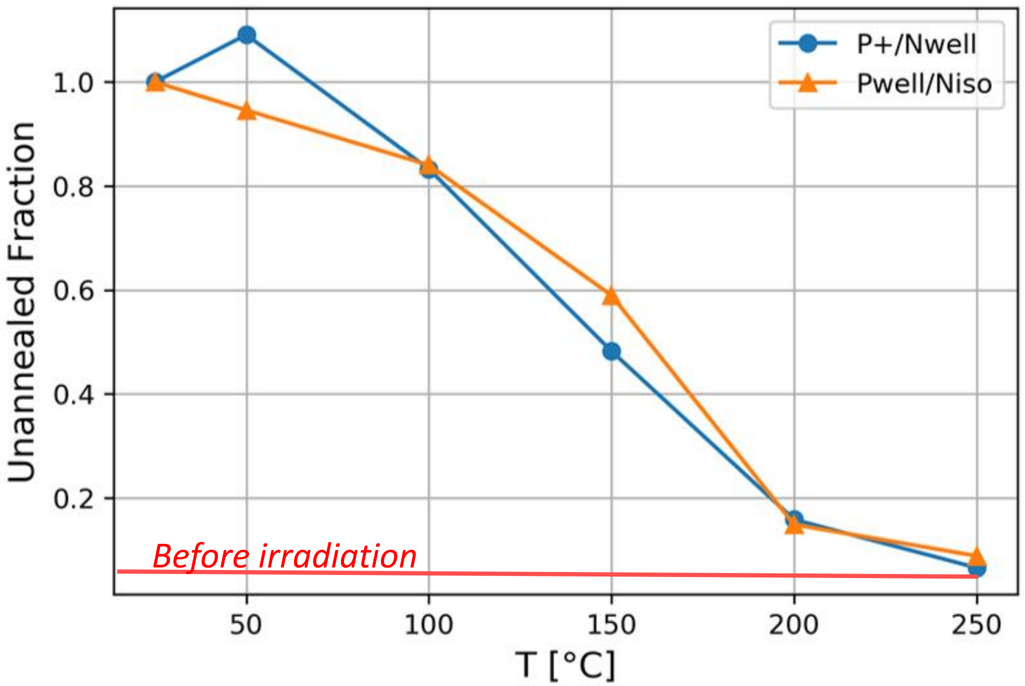


Isochronal Annealing

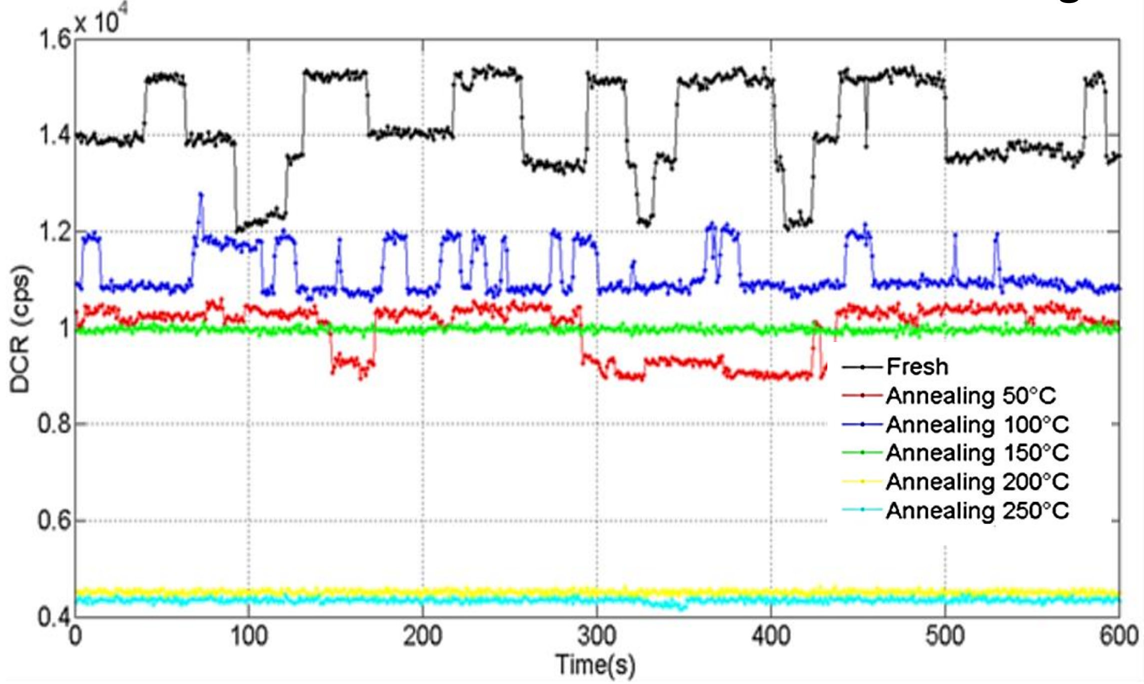
➢ DCR and RTS characterization

- DCR of irradiated SPAD has been measured after different annealing steps between 50°C and 250°C.
- After annealing the mean DCR recovered its initial value, while multi-level RTS transformed into lower level and less frequent RTS, before completely disappear.

Mean DCR vs annealing step



Evolution of DCR vs Time as a function of Annealing



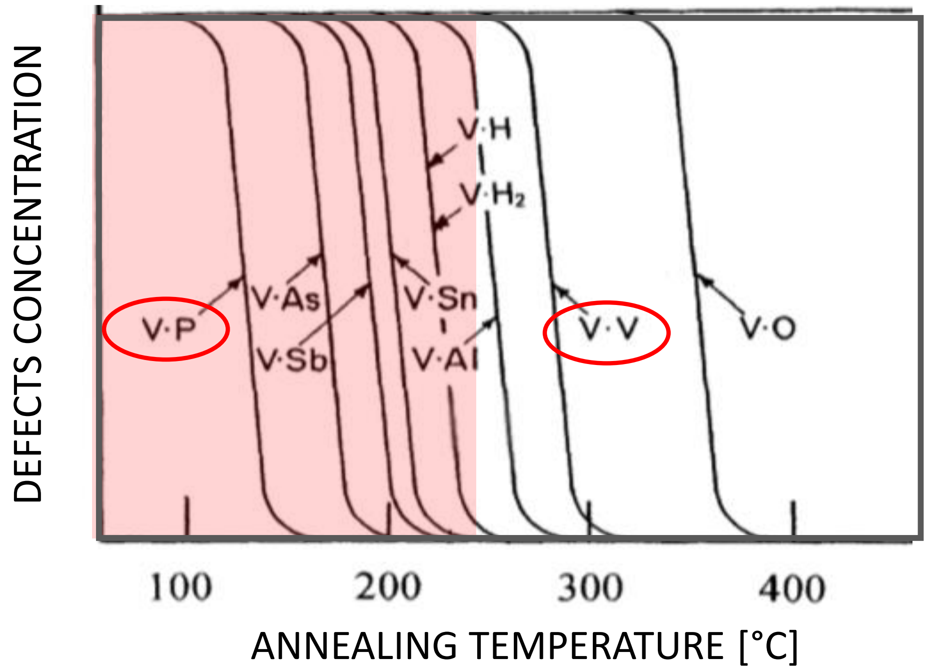
Isochronal Annealing

➢ Working principle

- The annealing procedure is an useful tool to investigate the defects responsible for DCR and RTS.
- Different bound energy of the defects results in different annealing temperature:
    - P-V centers anneal at about 130°C
    - Di-Vacancies anneal at 270°C

Our results suggest the P-V complex defects as a candidate responsible for DCR increase and Random Telegraph Signal behaviour.

Schematic of vacancy-defect annealing *



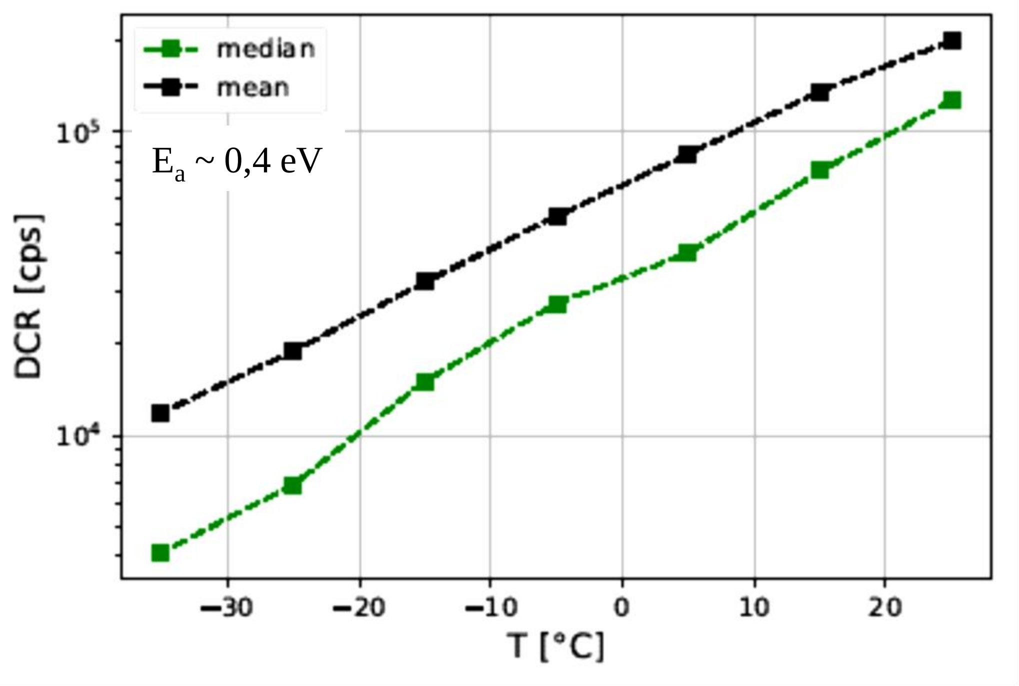
***"Annealing of Proton-Induced Random Telegraph Signal in CCDs" ,** T. Nuns et al.

DCR increase mitigation

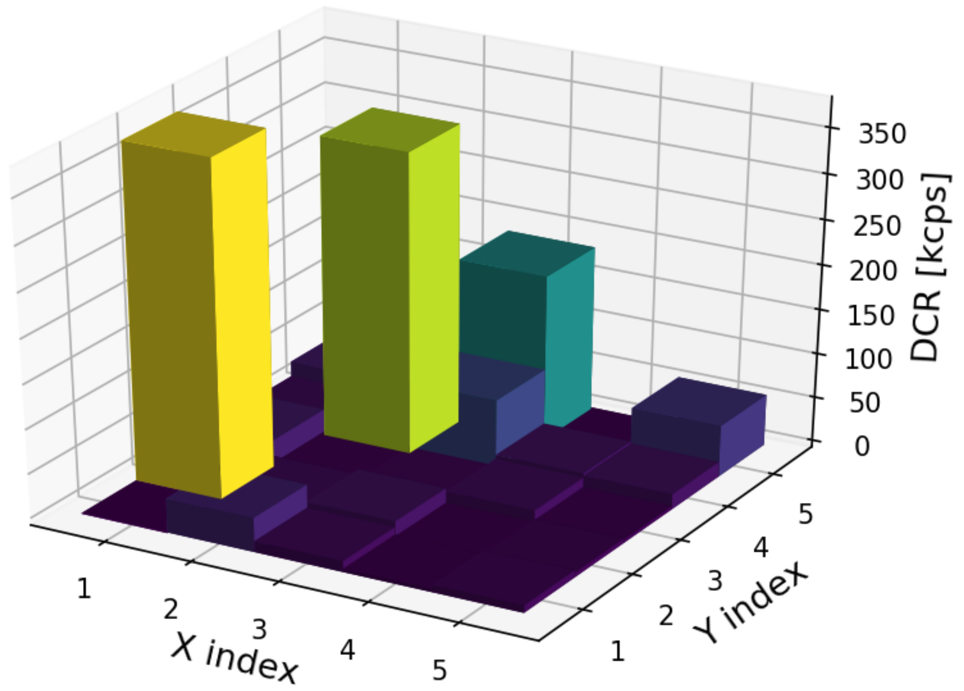
➢ Cooling, Coincidence

- High DCR level require some efficient mitigation method to allow SPADs operation.
- Many possibility: thermal annealing, cooling, hot pixel masking, coincidence (adjacent pixels or vertical coincidence)

DCR vs Temperature



DCR maps of 5x5 matrix



Conclusion

- We analysed the dark count behaviour of proton and electron irradiated CMOS SPADs.
- DCR has been found to depend heavily on proton-induced displacement damage.
- A less marked dependence was found in electron-irradiated devices. Requires further study.
- Long term measurements of DCRs also showed Random Telegraph Signal behaviour in the DCR level after proton irradiation.
- RTS characterization and annealing procedure indicate the P-V complex defect as a possible responsible for RTS.
- We investigated cooling and annealing, as possible methods of mitigation.

Contact:

Marcello Campajola (University of Naples ‘Federico II’ and INFN)

marcello.campajola@na.infn.it

Università degli Studi di Napoli Federico II

INFN Istituto Nazionale di Fisica Nucleare

Spare

➢ Space environment simulation

Proton irradiation test summary.

Chip	Fluence [p/cm^2]	Energy [MeV]	TID [krad]	DDD [TeV/g]
1	6.7 $\times 10^9$	16.4	2.3	45
2	1.4 $\times 10^{10}$	16.4	4.8	94
3	2.0 $\times 10^{10}$	16.4	7.1	139
4	2.8 $\times 10^{10}$	16.4	9.6	188
5	4.1 $\times 10^{10}$	16.4	14.5	283
6	6.7 $\times 10^{10}$	16.4	23.5	457
7	9.1 $\times 10^{10}$	21.1	30.5	608

Electron irradiation test summary.

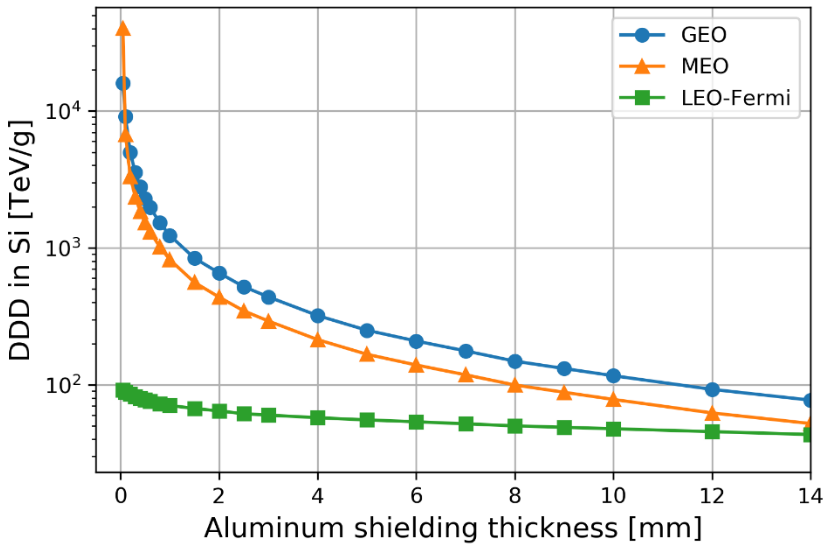
Fluence (e/cm2)	Dose (krad)	DDD (TeV/g)
6,92E+12	202,2	308,8
3,48E+12	101,6	155,2

Spare

➢ Space environment simulation

- The expected radiation doses for several space environment case-studies have been investigated.
- Low orbits can be considered safe enough for long lifetime space missions: only a slight DCR increase is expected. On the contrary, results showed a significant increase in DCR at a proton fluence corresponding to long-lifetime, high altitude missions.
- This could be an issue for using SPADs in most of the applications in long life GEO mission, requiring the implementation of an efficient on-mission mitigation procedure

DDD simulation



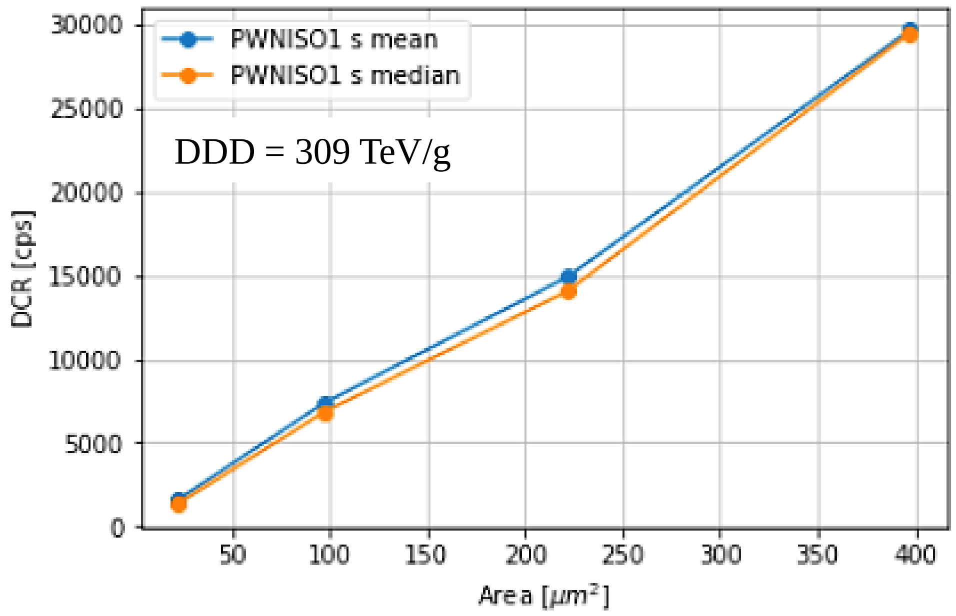
Expected ionizing and non-ionizing dose for different orbits, calculated for a 10-year mission lifetime and variable aluminum shielding.

Orbit Type	Mean Altitude [km]	Inclination [deg.]	Al Shield [mm]	TID [krad]	DDD [TeV/g]
LEO-ISS	400	51.6°	2	3.7	19.6
LEO-FERMI	560	26°	2	3.0	64.3
MEO	20000	56.2°	3	2196	292
GEO	36000	0°	3	355	438

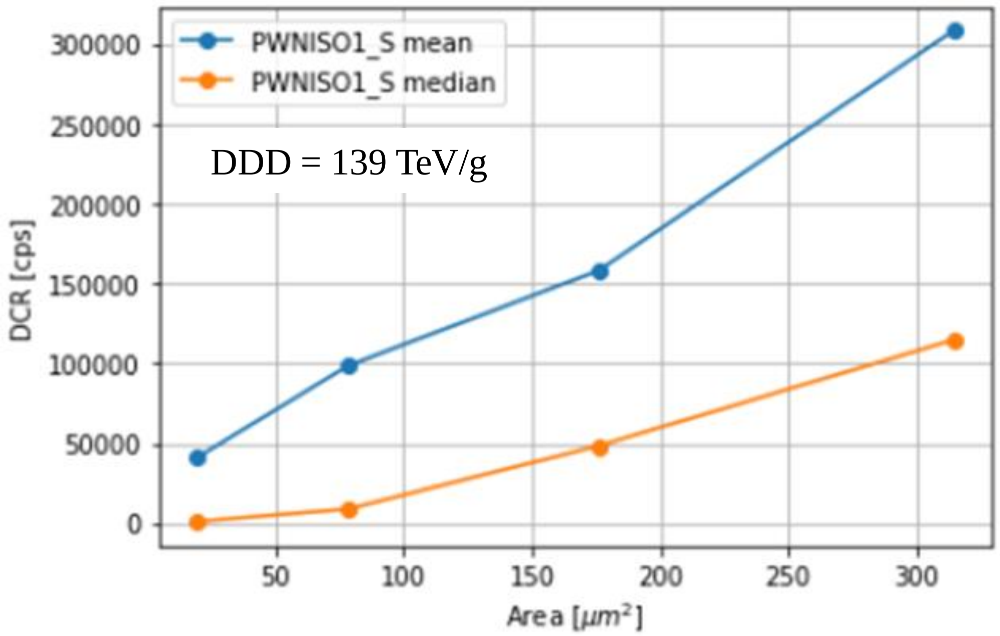
Spare

- DCR scaling

DCR vs Active Area in electron irradiated SPAD



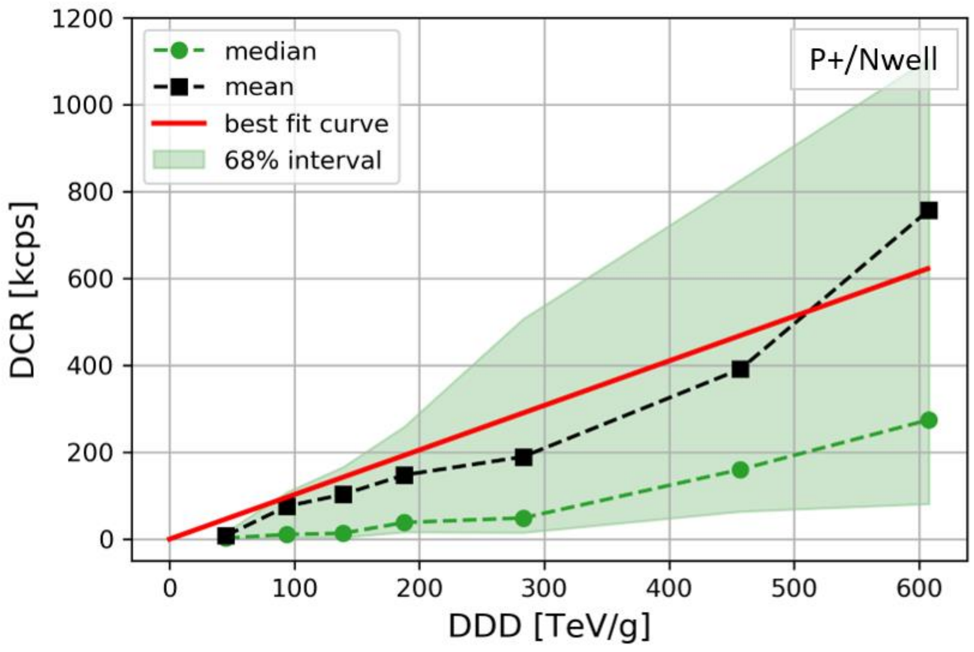
DCR vs Active Area in proton irradiated SPAD



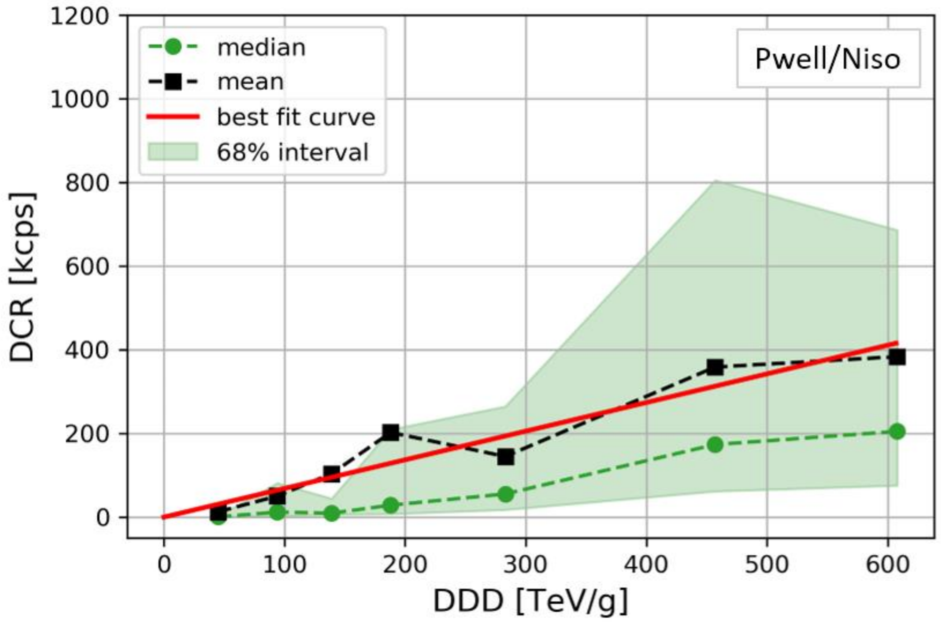
Spare

- Figure of merits

1025.5179549504705 +- 95.58042252554048



684.5802755379023 +- 51.61677421939295



Spare

➢ Figure of merits

- Higher doping concentration in PN junction results in a more peaked electric field inside the junction.

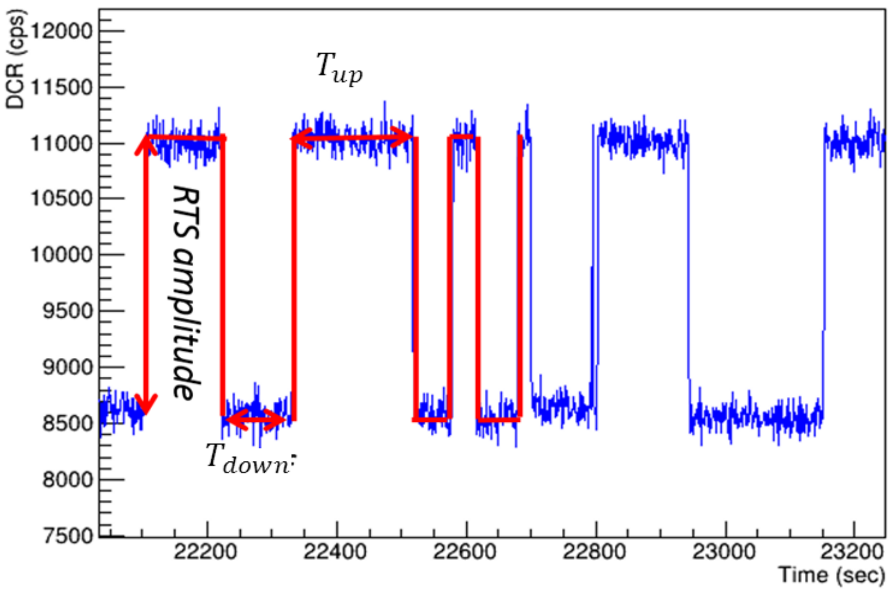
Layout	Analysed SPADs	RTS pixels	2 levels	3 levels	4 levels	≥5 levels	RTS fraction	DDD (TeV/g)
PN	118	65	18	10	10	27	55%	115
PN	124	80	31	11	5	33	65%	304
PN	139	118	17	11	8	82	85%	376
PWNISO	334	131	34	9	13	75	39%	115
PWNISO	334	190	51	19	16	104	57%	304
PWNISO	321	186	34	15	8	129	58%	376

Spare

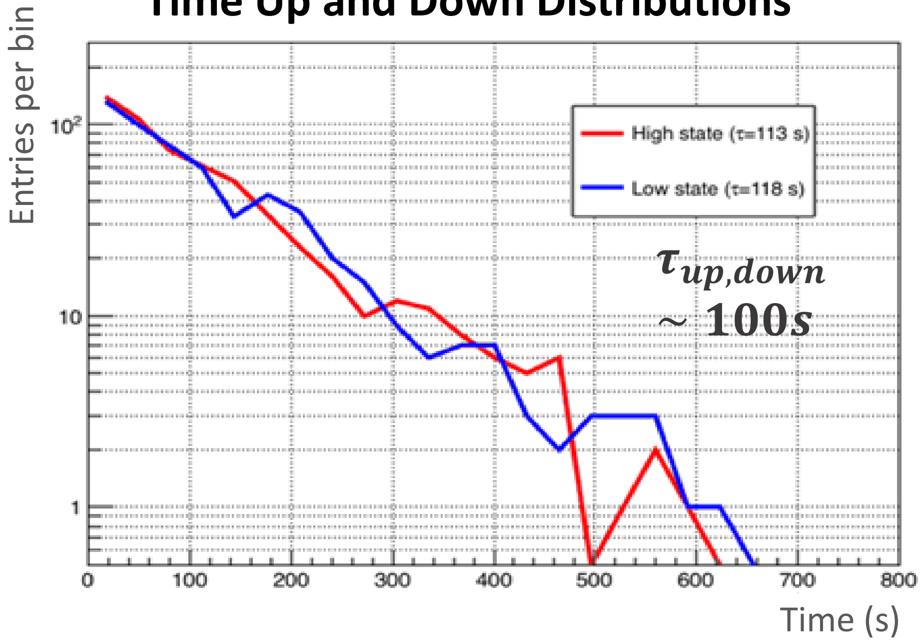
➢ RTS behaviours

- RTS characterized by an amplitude, and The number of DCR switching in a fixed time interval follows a Poisson distribution for random switching events.
- As a consequence times between RTS transitions are exponentially distributed $P_{switch}(t) = \frac{1}{\tau}\exp(-t/\tau)$

DCR vs observation time



Time Up and Down Distributions

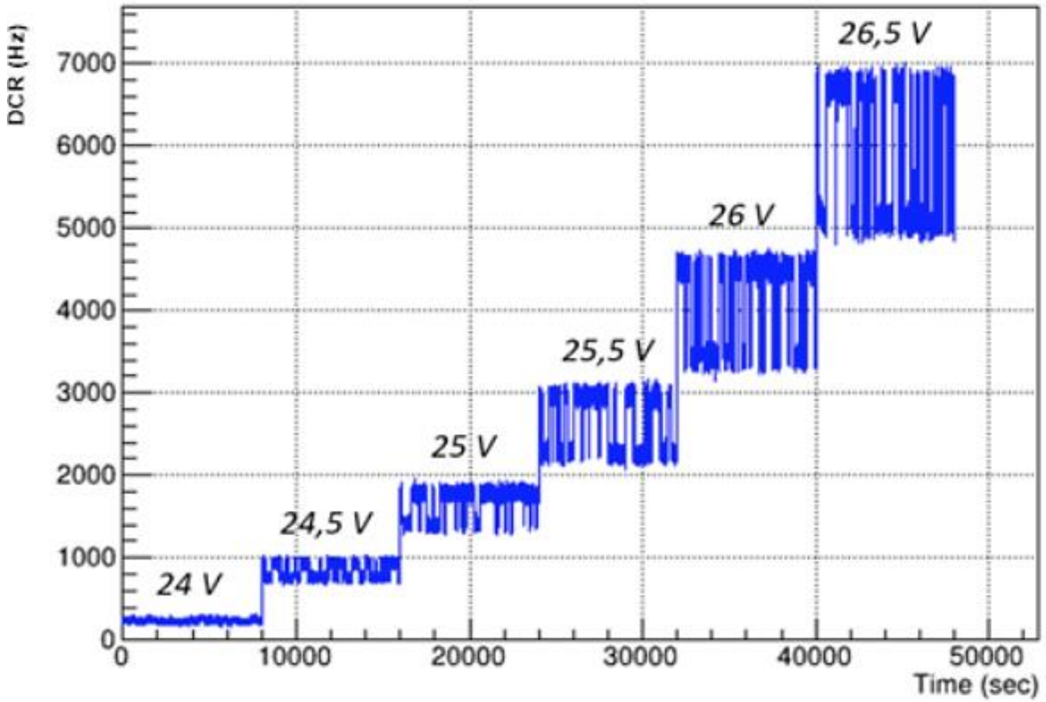


Spare

➢ RTS behaviours

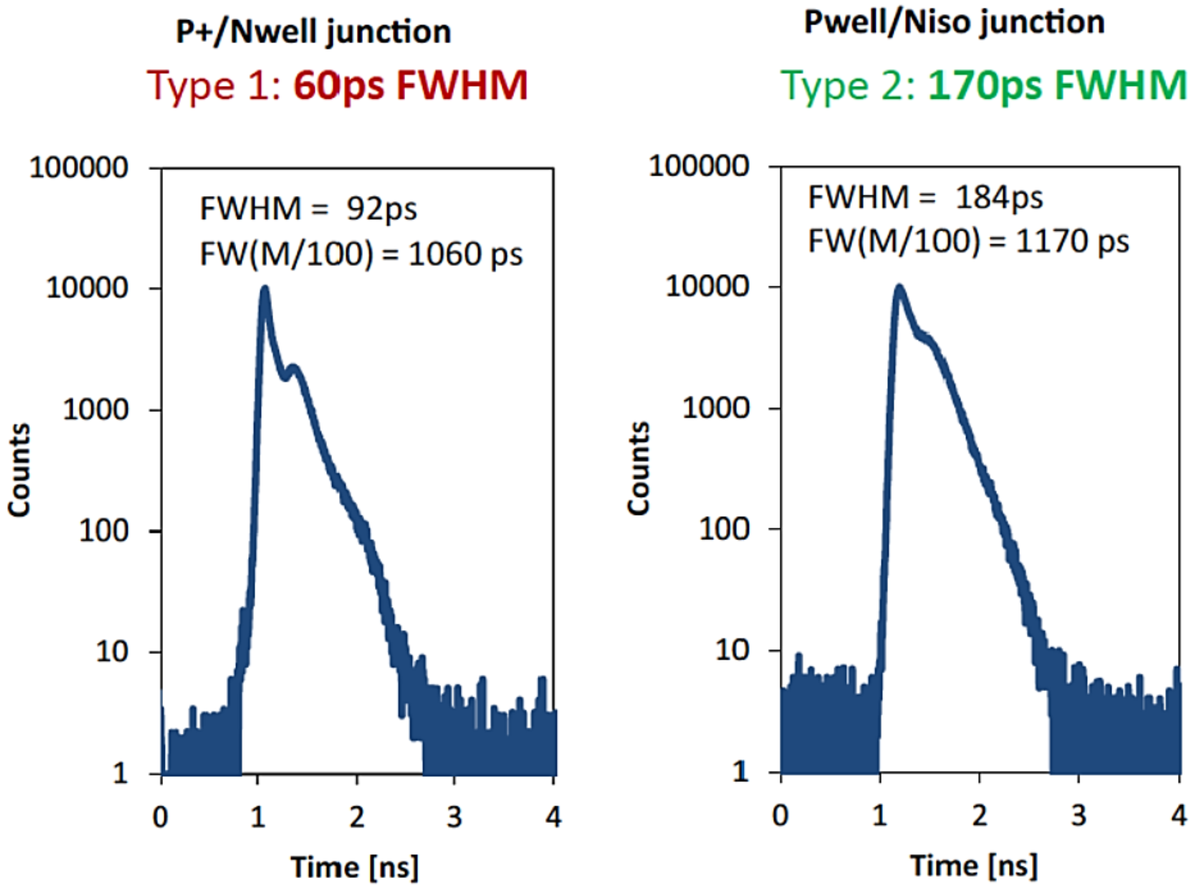
- RTS amplitude increase with the overvoltage

RTS amplitude vs overvoltage



Spare

➢ Figure of merits

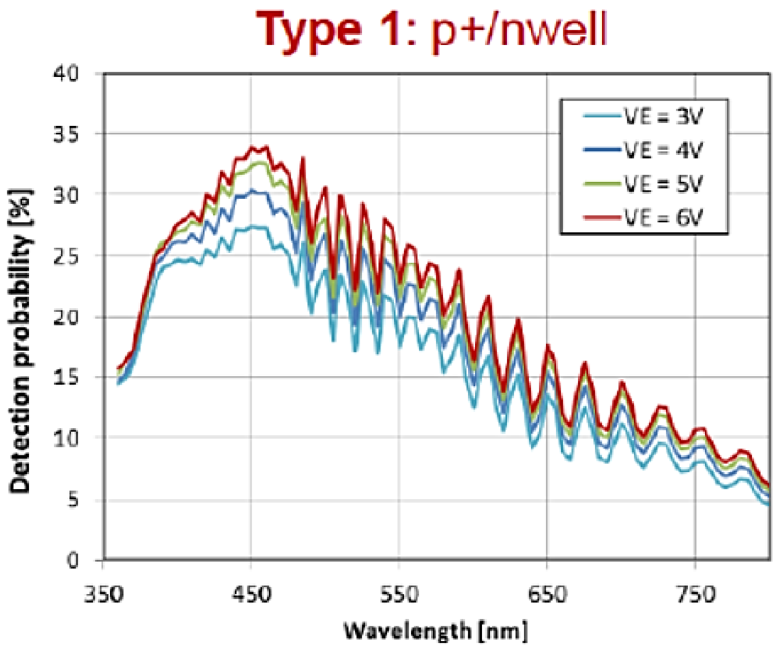


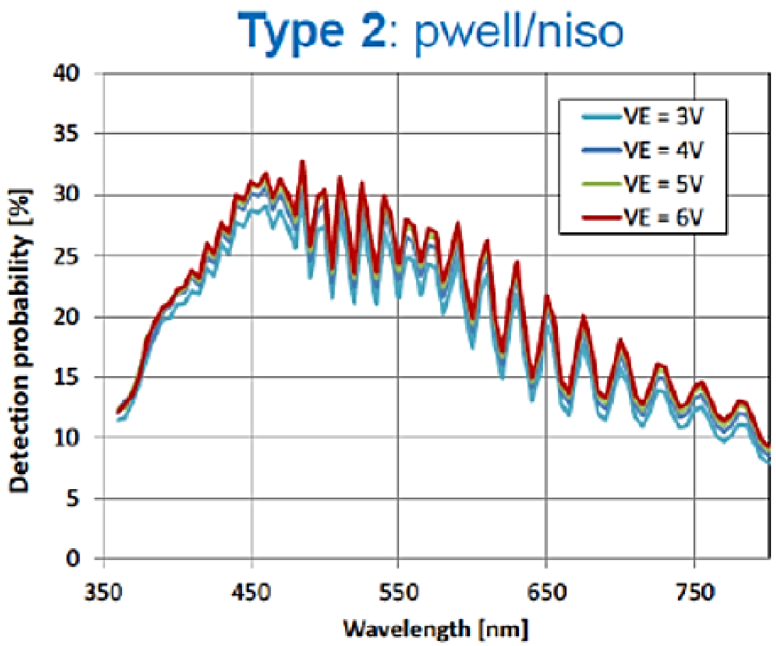
"Low-noise Single Photon Avalanche Diodes in 0.15 µm CMOS Technology", *L Pancheri, D Stoppa*

Spare

➢ Figure of merits

Photon detection probability;



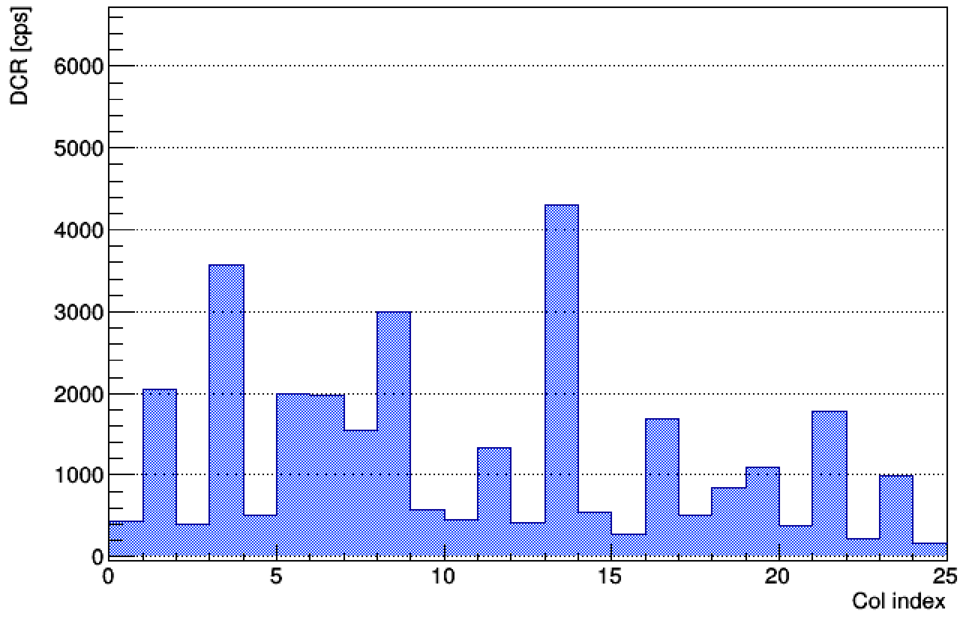


"Solid-state single-photon Detectors and CMOS Readaout Circuits for Positron Emission Tomography Applications", *Hesong Xu, et. Al.*

Spare

- Figure of merits

DCR vs. pixel index



DCR Cumulative Distribution