SiPMs characterization

LUISA OCCHIUTO,

UNIVERSITY OF CALABRIA& INFN
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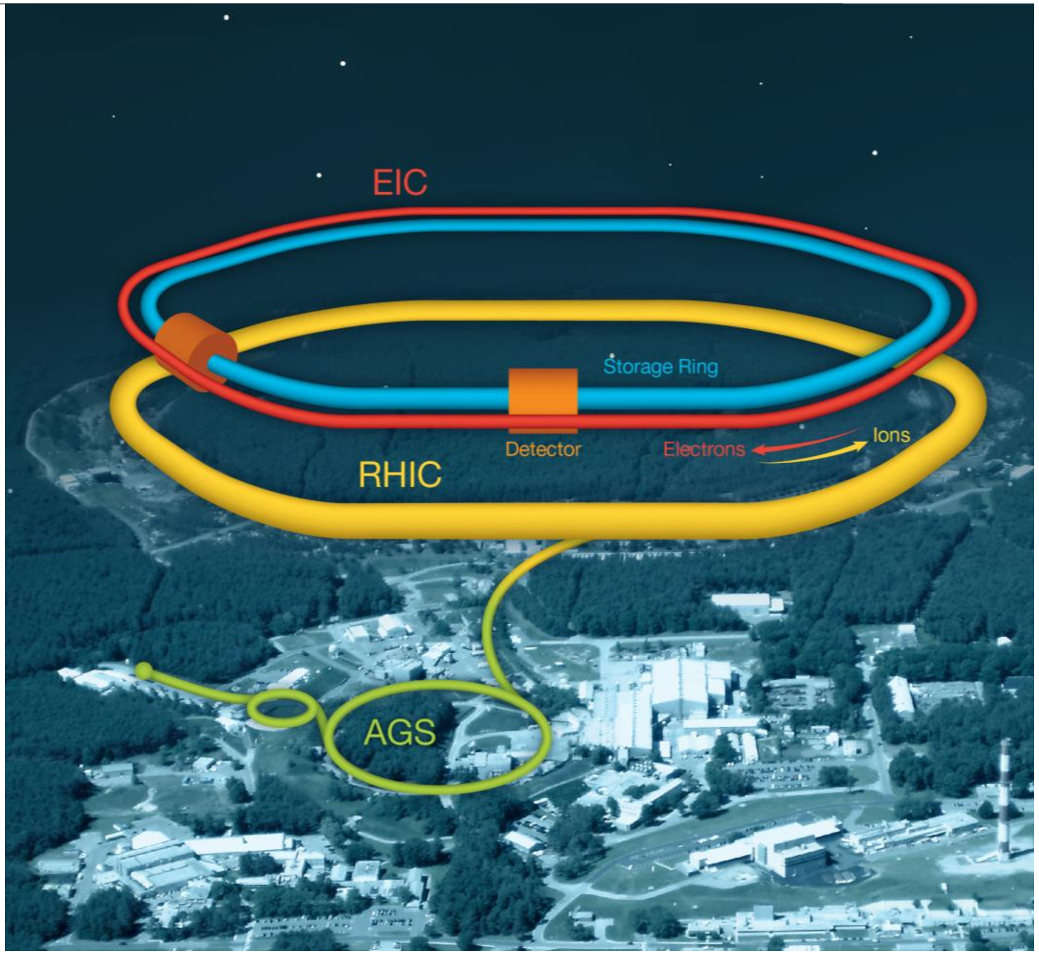
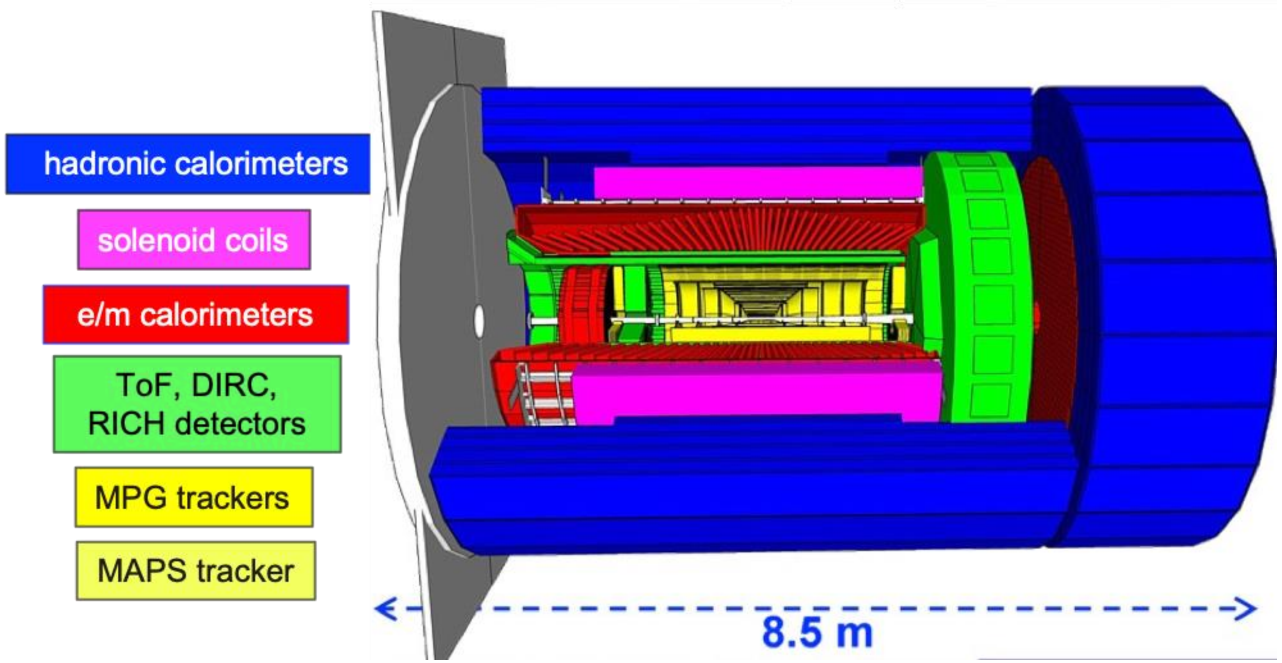
THE ELECTRON-ION COLLIDER

Its new, innovative design concept provides a cost-effective way to accelerate a highly polarized electron beam and bring it to collide with a full array of hadron beams (from highly polarized protons to light and heavy ions) at a luminosity up to $10^{34}\ interaction/cm^2 sec^1$.



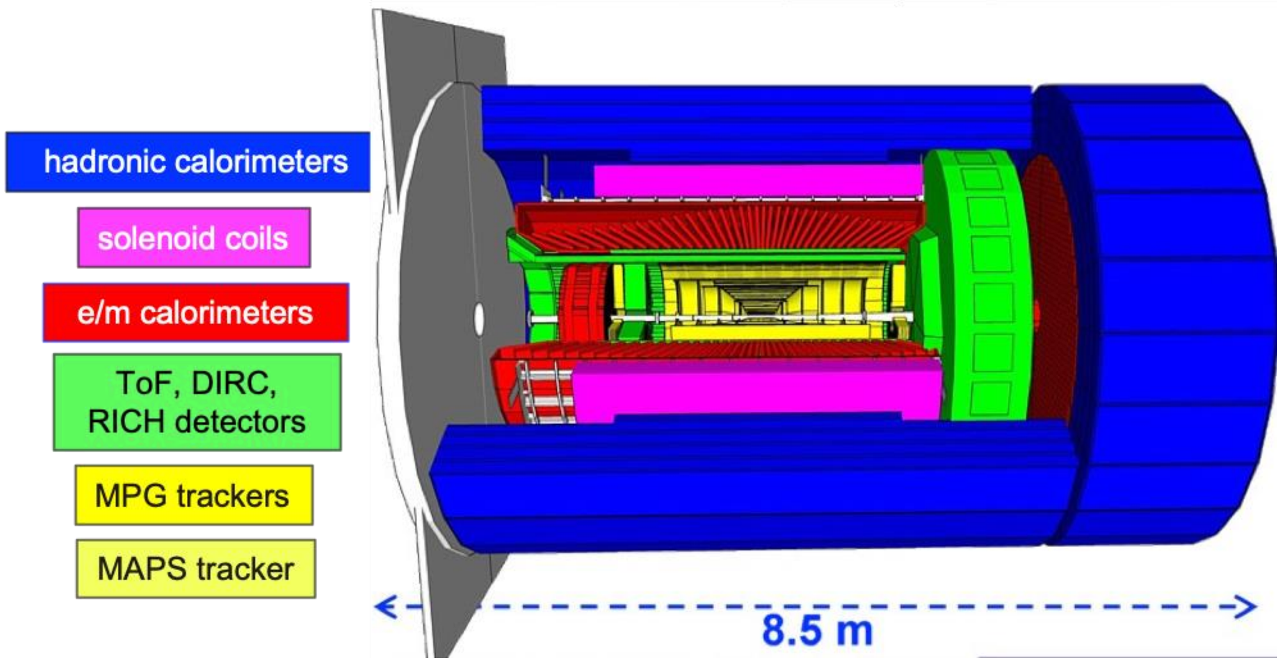
THE ePIC EXPERIMENT



After a call for proposals and several iterations, the ePIC design has emerged as general-purpose detector funded by the EIC project. The ePIC collaboration has been formed in July 2022

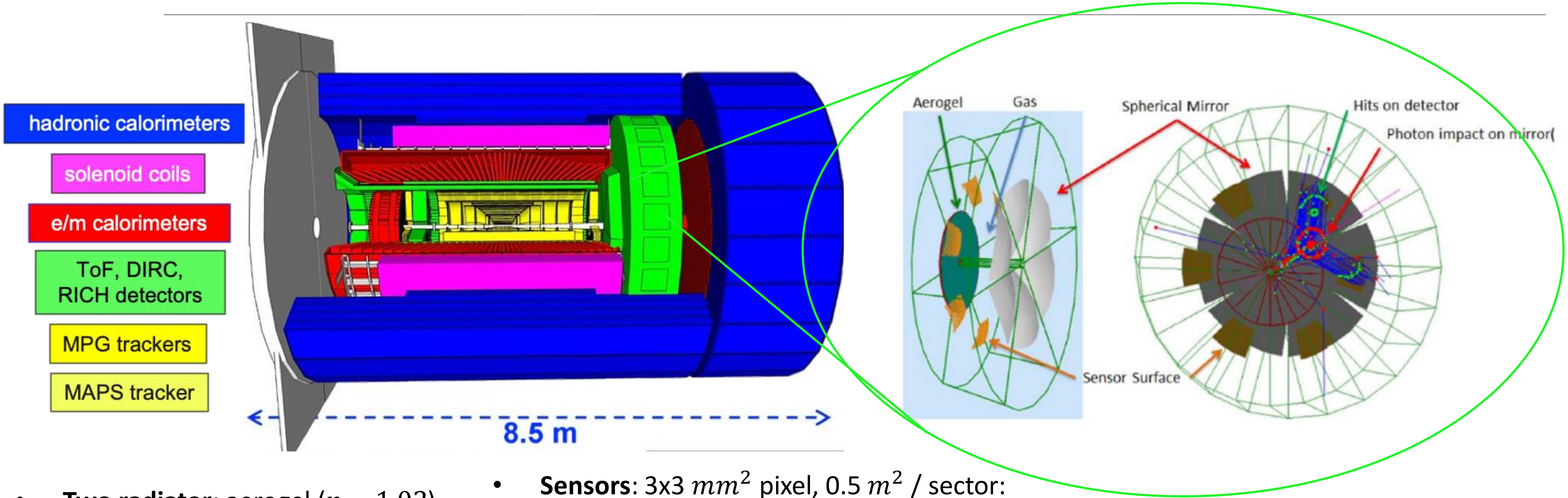
The **ePIC** detector will be located at the **IP6** interaction region, where electron and ion beams collide. **It will include many subcomponents such as tracking and vertexing systems based on silicon sensors and gaseous detectors.**

THE ePIC EXPERIMENT



- The Particles ID in the **forward region** is ensured by the **dual Ring Imaging Cerenkov detector (dRICH).**
- **A key capability of the ePIC detector is tracking and particle identification (PID), with the aim of separating electrons from pions, kaons and protons**.
- Ability to identify particles with moments starting from a few GeV/c up to about 50 GeV/c.

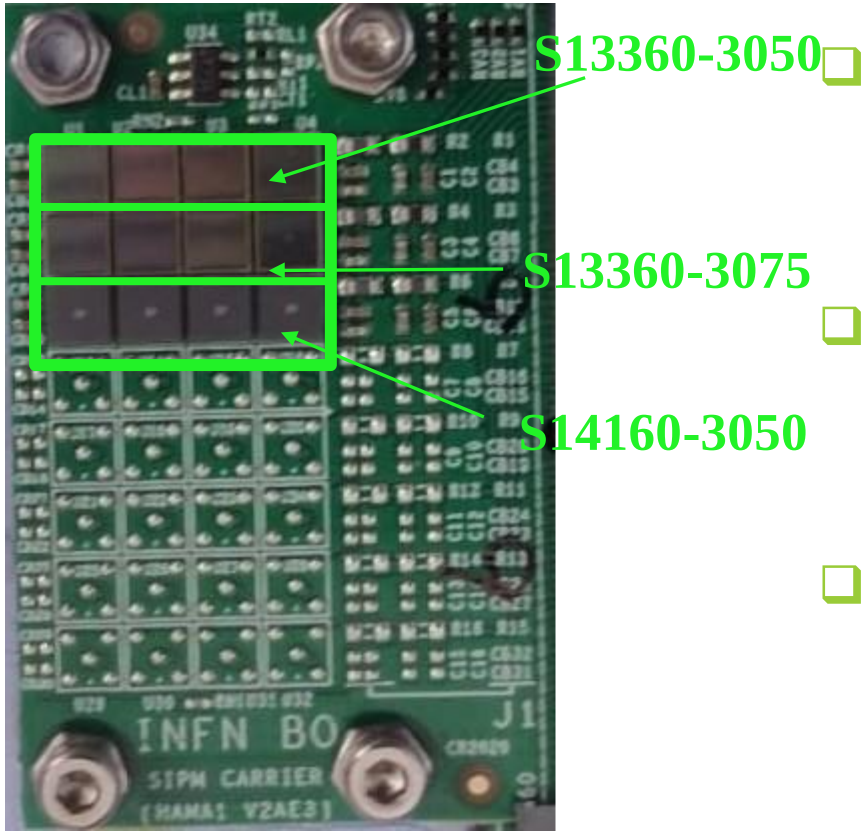
THE ePIC EXPERIMENT



- **Two radiator**: aerogel ($n \sim 1.02$), C2F6($n \sim 1.008$)
- **Mirrors:** 6 large open sectors

- **Sensors**: 3x3 mm^2 pixel, 0.5 m^2 / sector:
  1. Single photon detection;
  2. High Photon Detection Efficiency;
  3. Good time resolution;
  4. Insensitive to magnetic field;

SiPM SENSORS

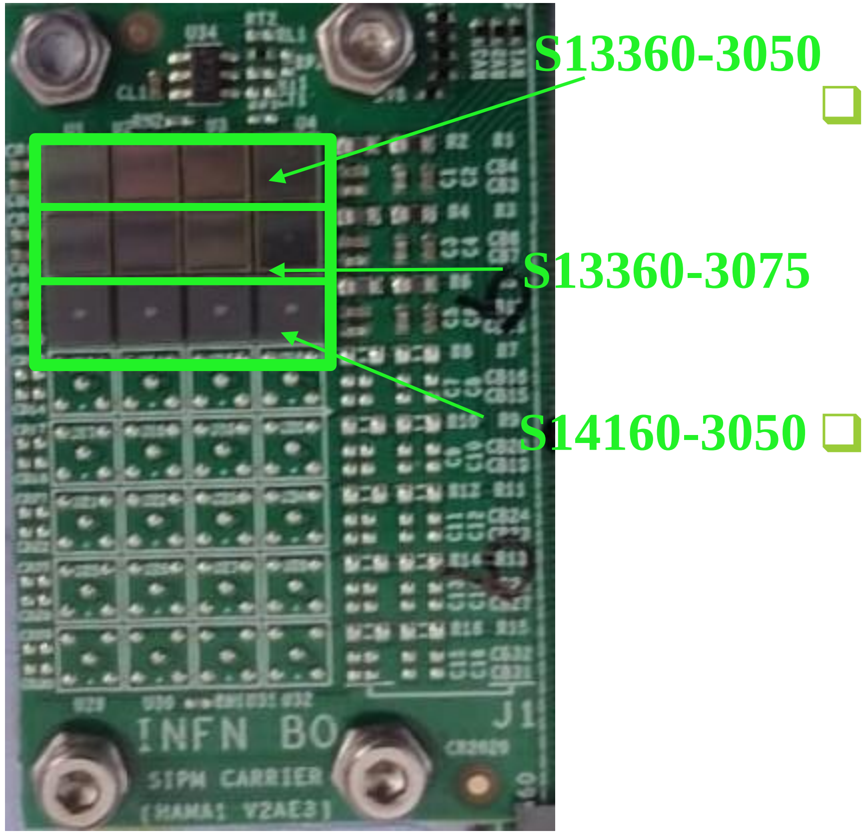


- A **silicon photomultiplier (SiPM)** consists of an array of independent SPAD (single-photon avalanche diodes) sensors, each connected to its own quenching resistor.

- SPADs (Single Photon Avalanche Diodes) are photodiodes used for detecting light at the level of individual photons, employing avalanche multiplication as an internal gain mechanism.

- Their operational mode involves **reverse biasing** at a voltage higher than the **breakdown voltage.** A device operating at a bias voltage higher than the breakdown voltage is said to **operate in Geiger mode.**

SiPM SENSORS

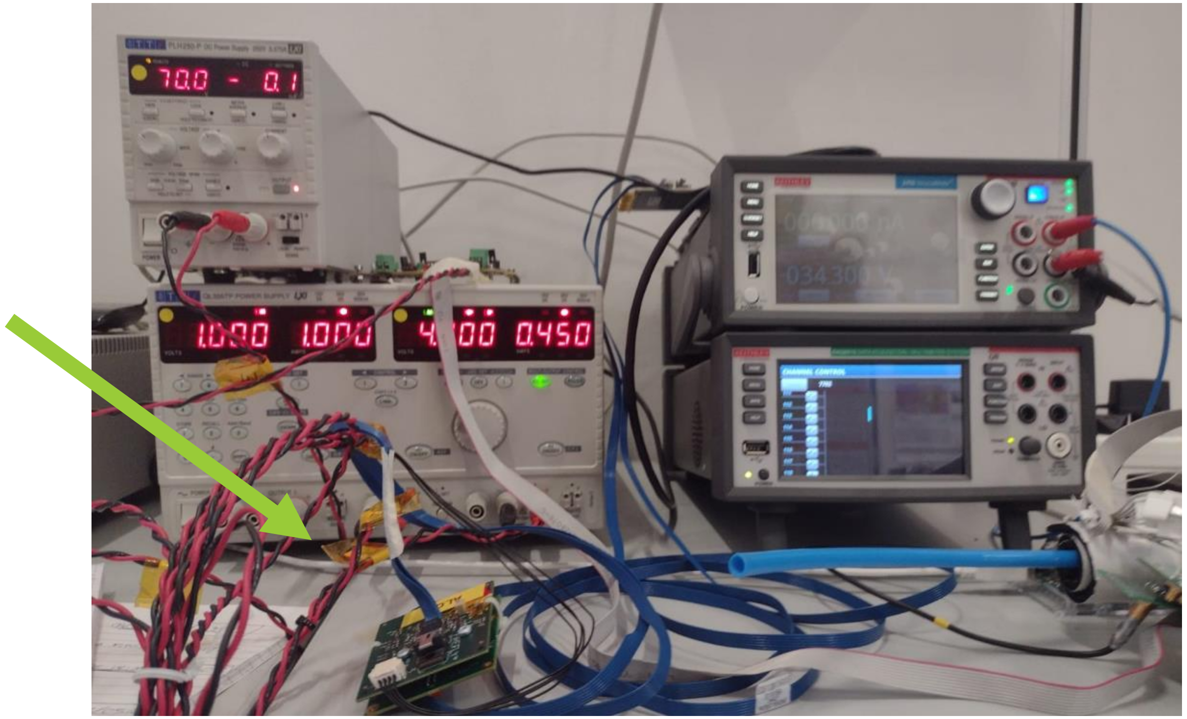


- ❑ The main source of SiPM noise is due to the **thermal generation of electron-lacuna pairs in the depletion region**, which can generate carrier avalanches. The results are a signal identical to the one produced by the incident photons.
- ❑ Since this type of signal is thermal in nature, **it can be observed in the absence of photon beam**. For this reason, their counting in the unit of time is called the dark count rate.

EXPERIMENTAL SET-UP

We take 2 types of measurements:

1. We use a setup specifically designed for measuring **dark count rate (DCR)** as a function of **reverse bias voltage**.
2. We perform measurements of **dark current** as a function of **reverse bias voltage**.



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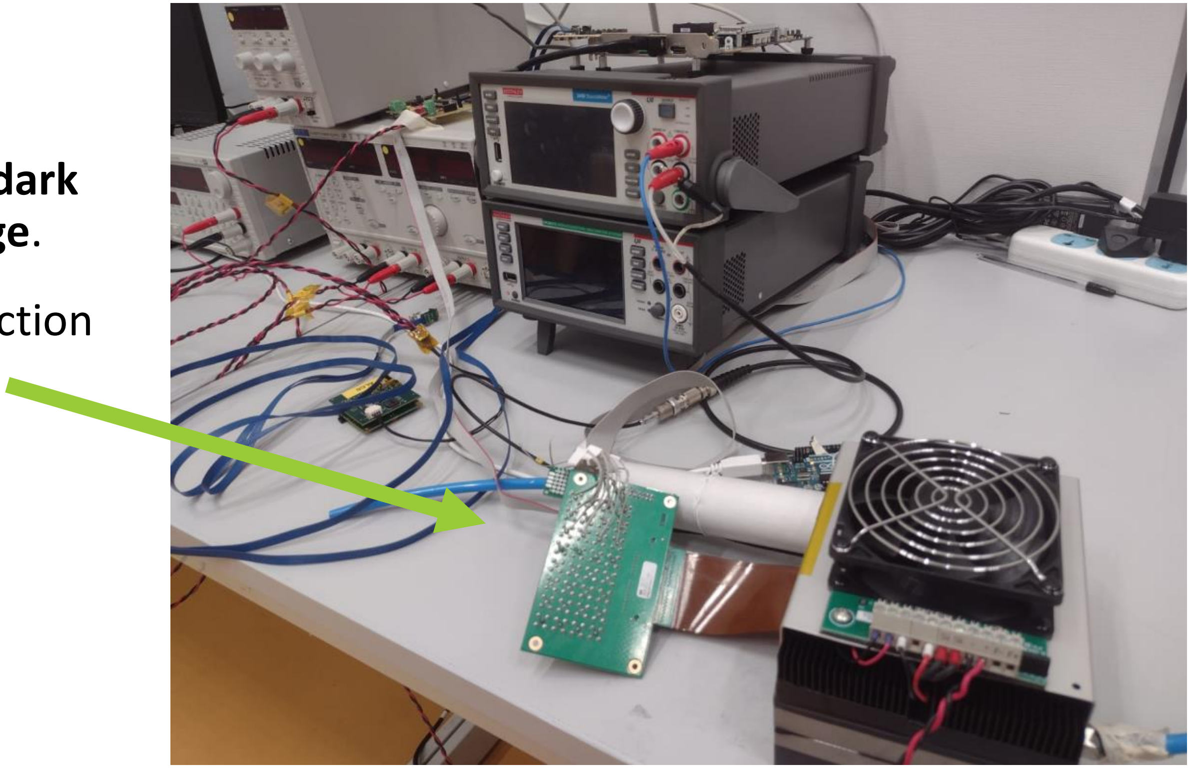
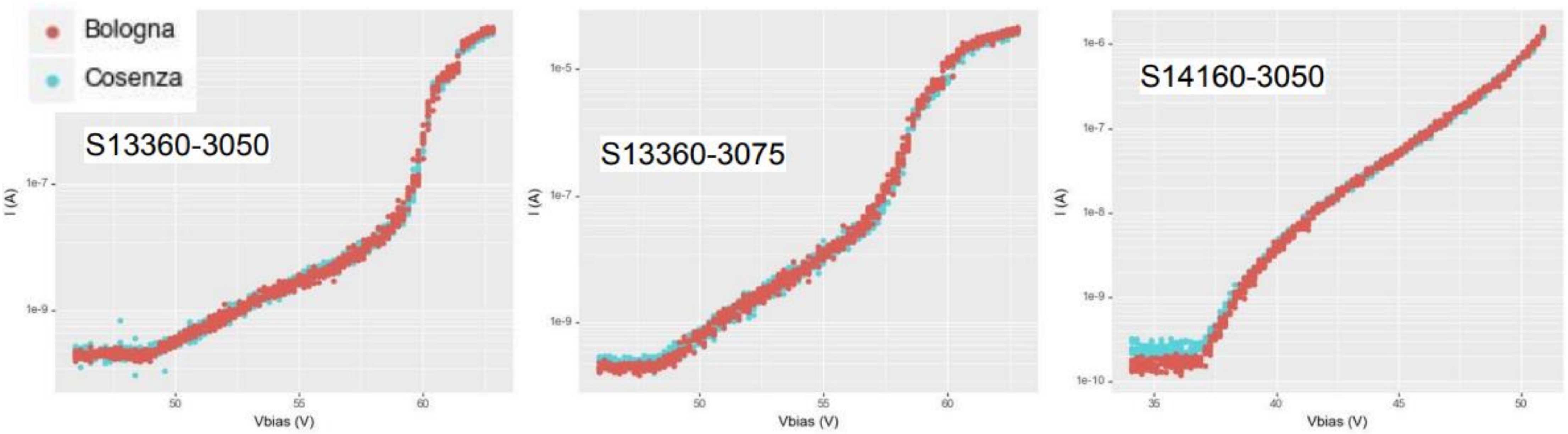


RESULTS: SANITY CHECK – COMPARISON WITH BOLOGNA

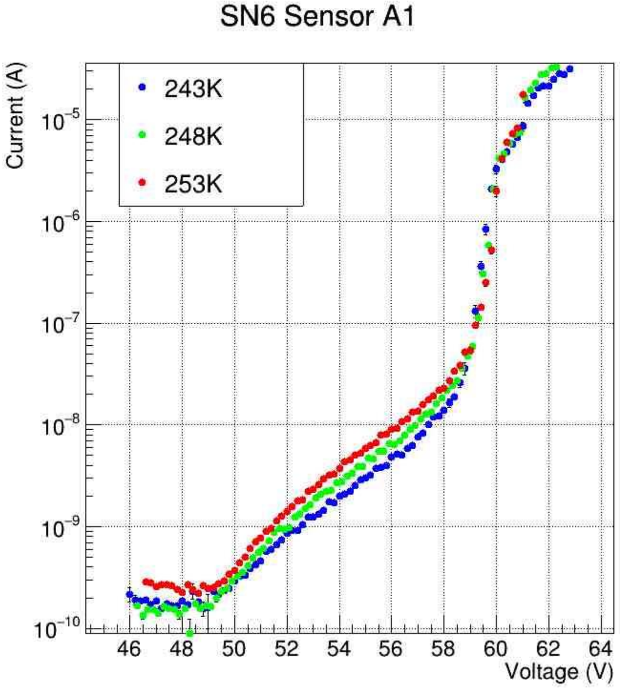
- To test our setup, we compared the I-V scan measurements with ones taken in Bologna using a climatic chamber at the same temperature. This yielded fully compatible results

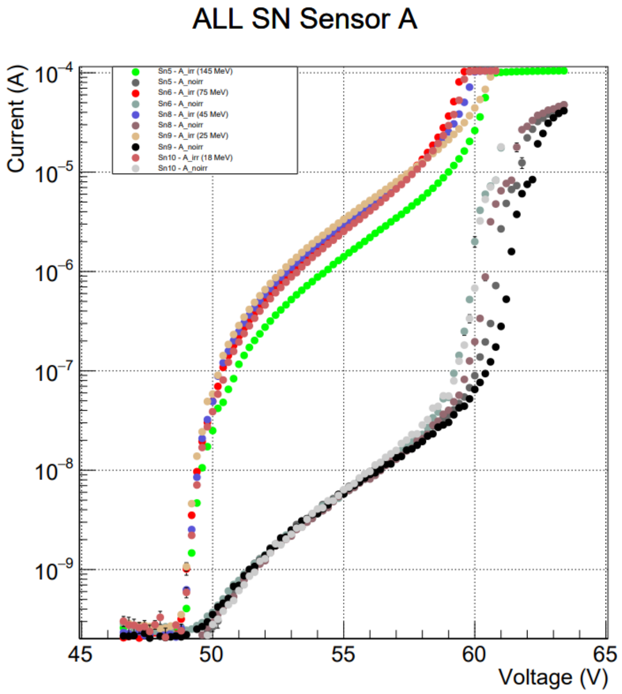


RESULTS: temperature and energy scan

- We performed several characterization measurements of SiPMs at different temperatures and after irradiating them at different energy of proton beams;

# Board	Energy scan (MeV)	Fluence cm^{-2}	K factor
5	145	$10^9 p$	1.11
6	75	$10^9 p$	1.5
8	45	$10^9 p$	2.0
9	25	$10^9 p$	2.5
10	18	$10^9 p$	3.0



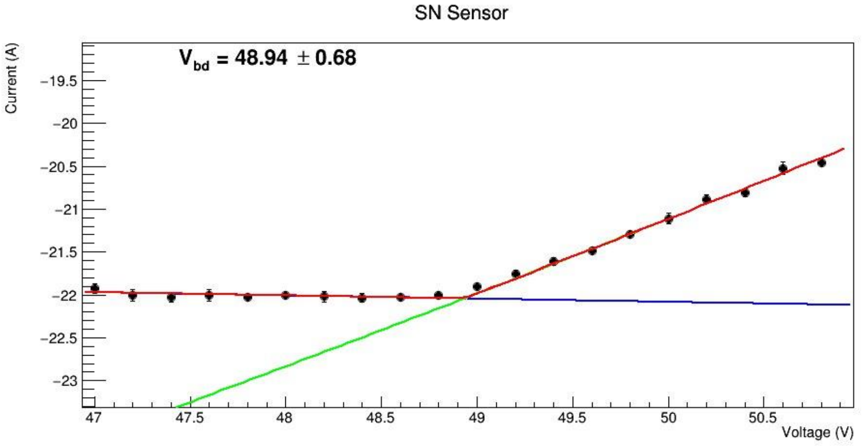


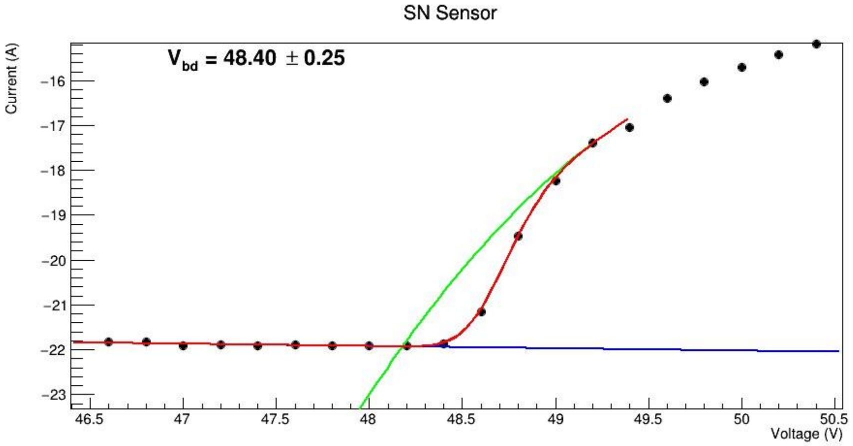
RESULTS: evaluation of Breakdown voltage

- We have calculated a **breakdown voltage** (Vbd). There are several methods to extract the value of breakdown voltage.

- In our case we use previously the one that fitted the baseline with a linear function and the curve post breakdown with a parabolic function. This result is not very useful in the case of the board not irradiated because of the shape of characteristic itself.

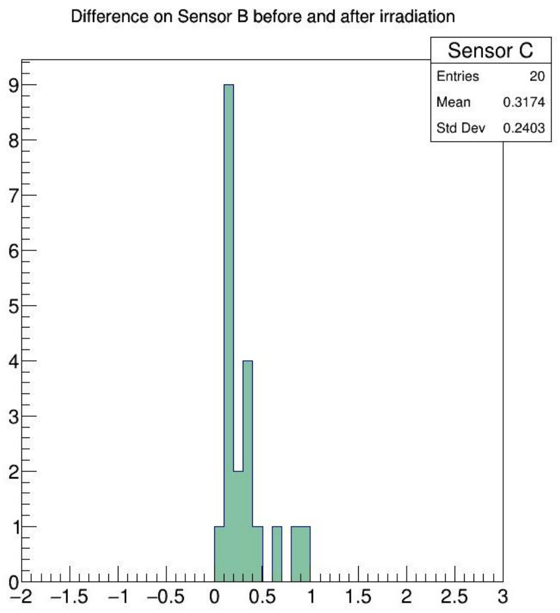
- So, the function useful to fit also the smooth part of the characteristic is a composition of polynomial function and the erf function.

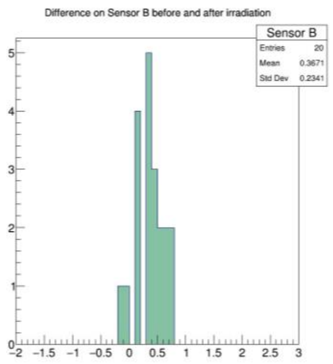


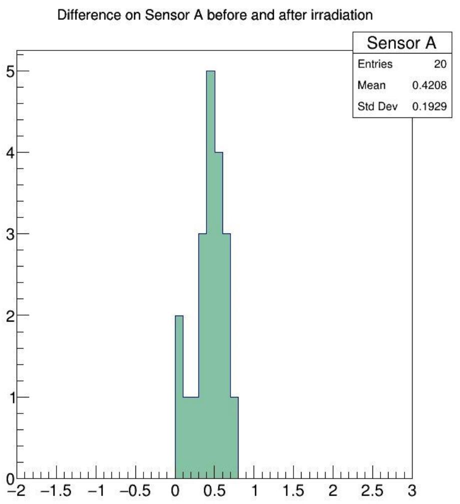


RESULTS: evaluation of Breakdown voltage

The most important study conducted at this level was to evaluate the difference between the breakdown values of individual boards for each sensor before and after irradiation. What we see from these graphs is that there is a predominant contribution around **0.5 V**.



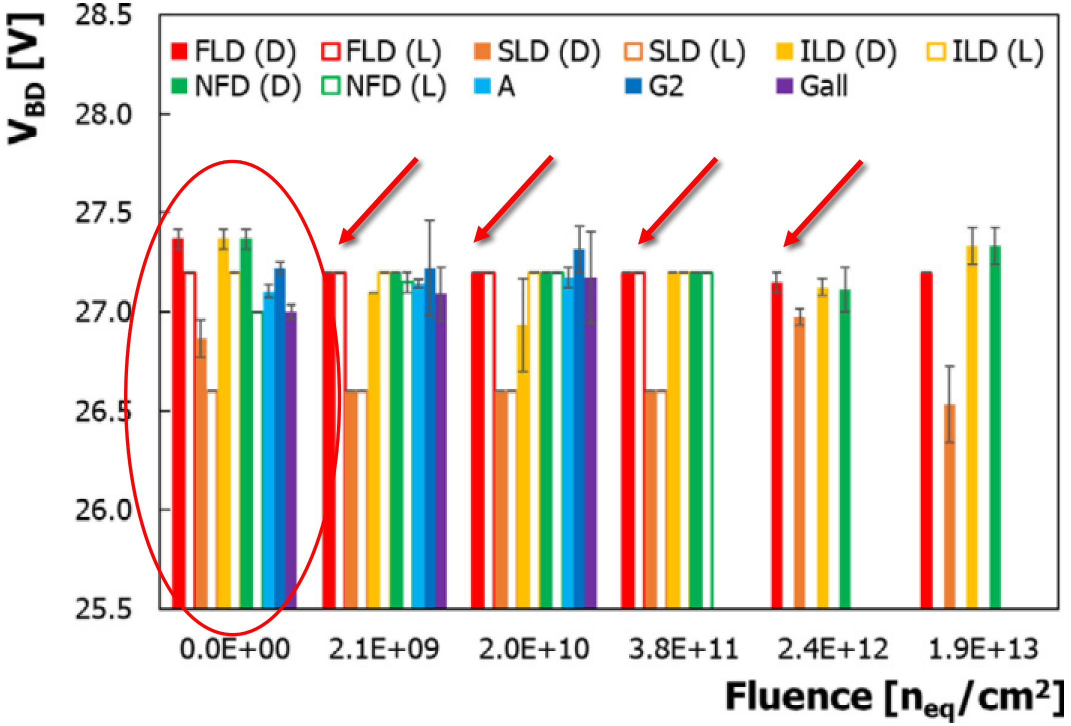




RESULTS: evaluation of Breakdown voltage

- However, at this level we did not expect to observe any kind of shift in the value of the breakdown voltage.
- Literature shows that, to have significant shifts in the breakdown voltage, it is necessary to get to an order of $\sim 10^{12} p/cm^2$, where the radiation damage becomes so high that significantly modifies the silicon structure.
- **Then, why do we observe a $\sim \mathbf{0.5}$V difference?**

Help in solving the puzzle comes from the work by **A. R. Altamura, Acerbi, et al. [NIMA 1040 (2022) 167284].**



RESULTS: evaluation of Breakdown voltage

- In the following graph: for FLD (D) and FLD (L) the breakdown value is different for fluence equal to zero (not irradiated), in 2.1E+09 instead the Breakdown value in light and in dark are equal.

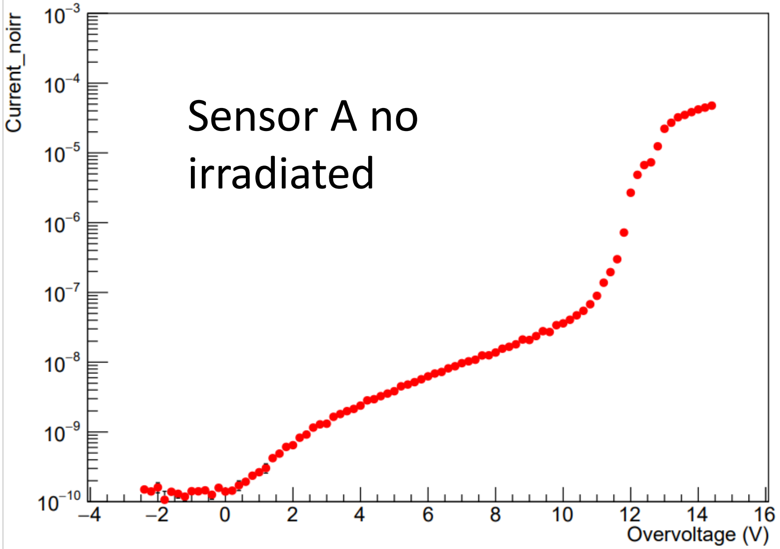
- **There is a difference between the Vbd in dark conditions and in light conditions, and this is problematic whatever method is used**.

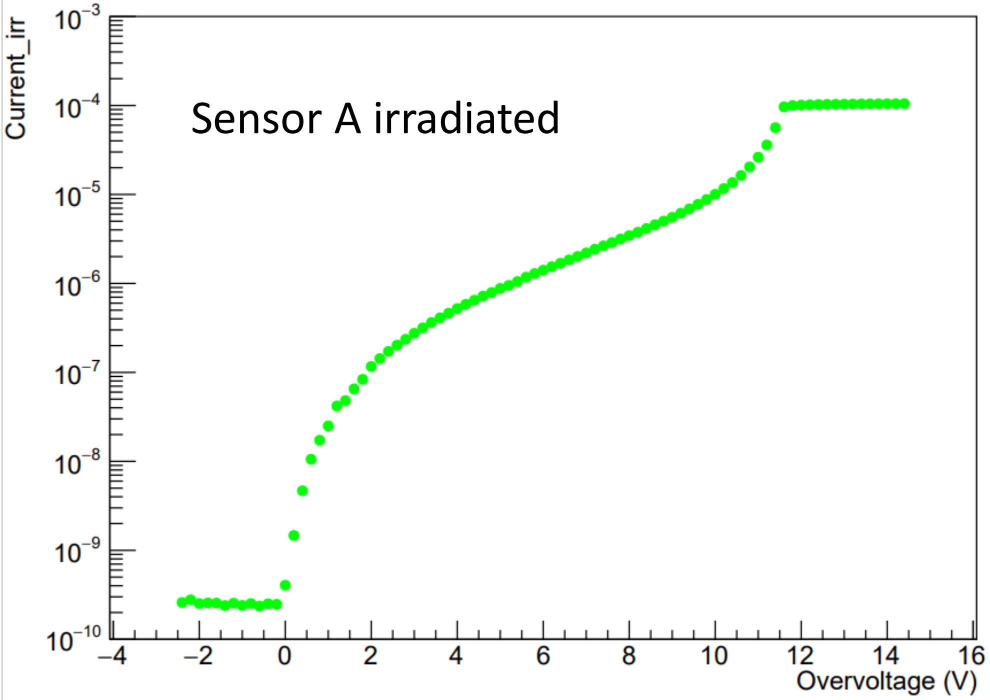
- This is due to the fact that in the dark conditions the increasing in current post Vbd is too low to have a well defined curve and, consequently, is difficult to estimate the real Vbd.

RESULTS: OVERVOLTAGE

- The next step was to determine the bias at which the SiPMs operate which is higher than the breakdown voltage, this is defined as overvoltage:

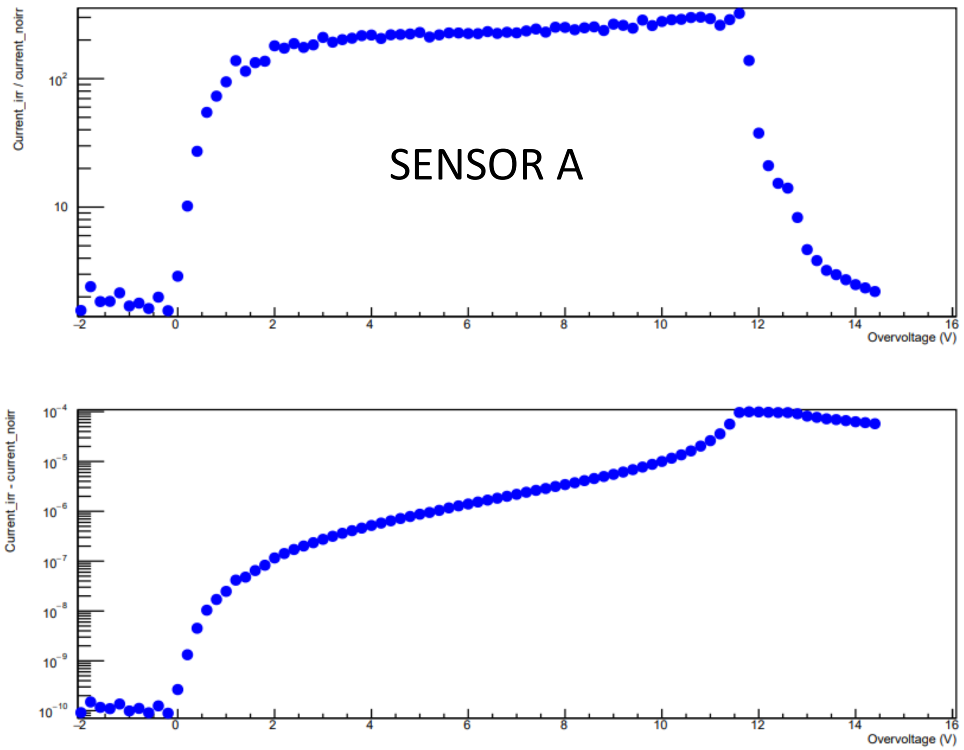
$$V_{ov} = V_{bias} - V_{bd}$$

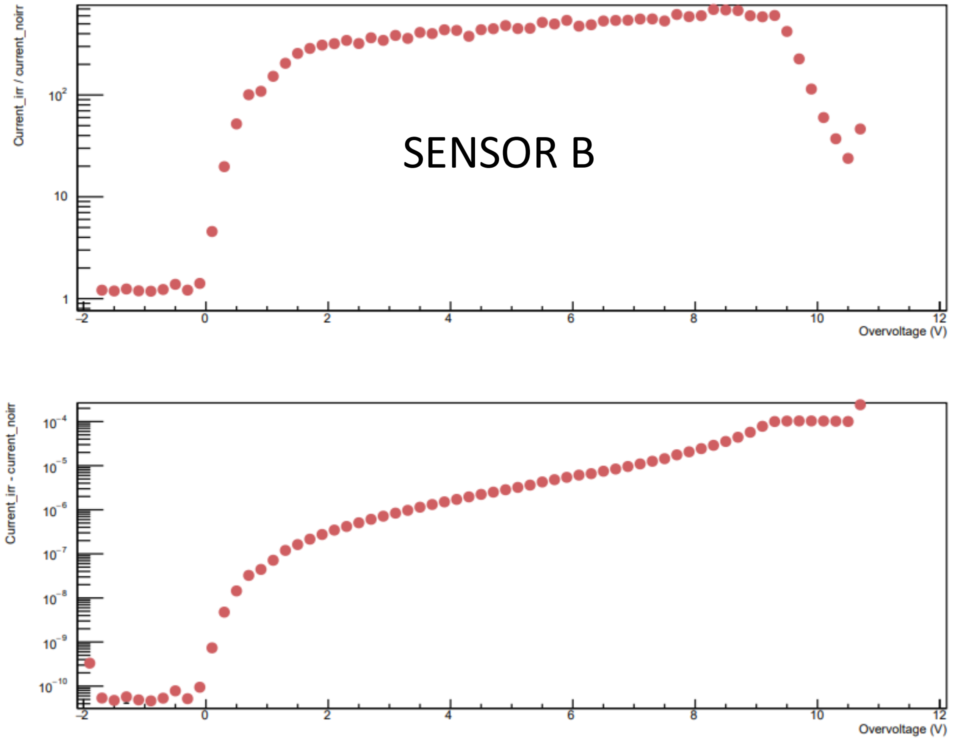




RESULTS: OVERVOLTAGE

- At this point, was calculated the ratio and difference between the currents after and before irradiation was calculated.





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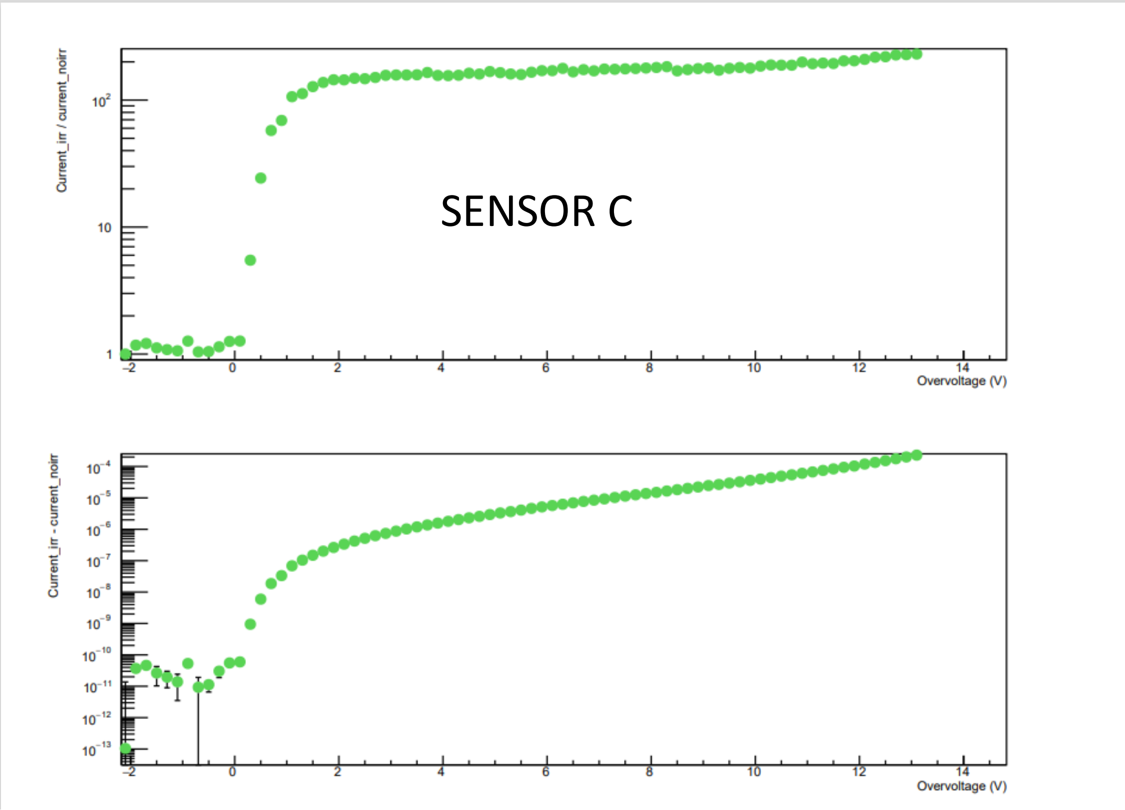
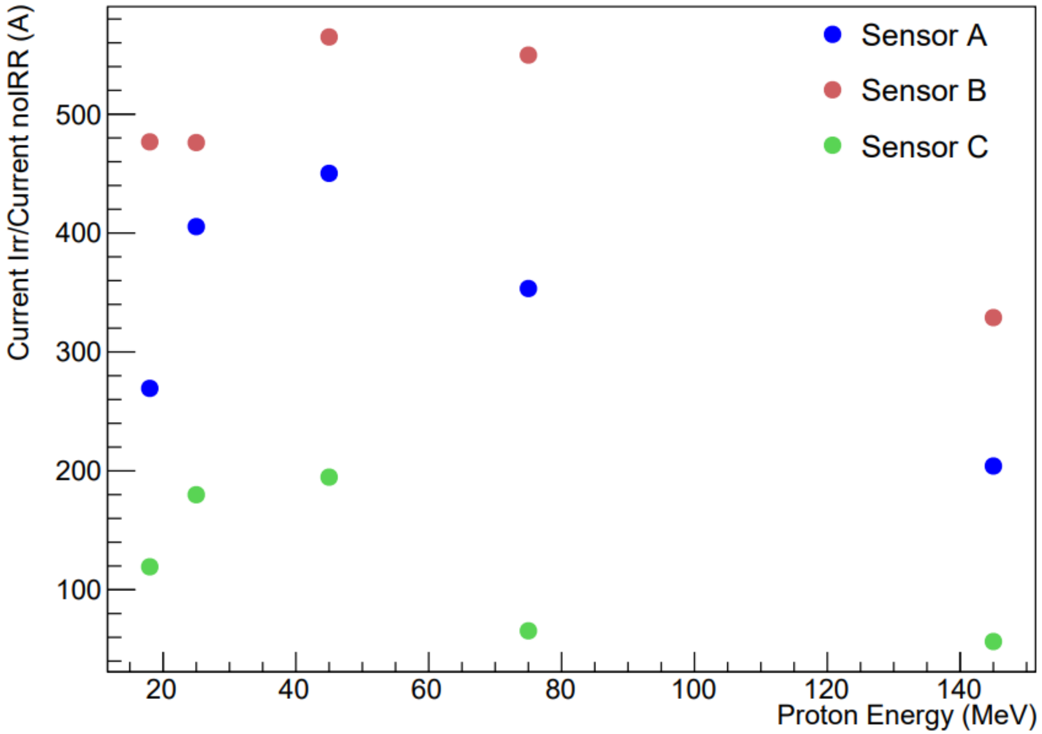


RESULTS: RATIO AFTER AND BEFORE IRRADIATION



- ☐ Subsequently, was fixed the overvoltage value at 3 and was extrapolated the relative pre- and post-irradiation current value, was made the ratio and the average for each row for each sensor for each card.
- ☐ These values were then plotted against the energy of the proton beam.
- ☐ From a first qualitative analysis, it would seem that the maximum energy release occurs around 40 MeV.

OUTLOOK

- We performed several characterization measurements of SiPMs at different temperatures and after irradiating them at different energy of proton beams;
- In order to verify the accuracy of the breakdown voltage estimate, it is necessary to carry out other studies in light conditions, from which it should therefore result that there is no significant difference between the pre- and post-irradiation breakdown estimate for a fluence of $10^9 p/cm^2$;
- Studies are now ongoing in order to investigate and understand the energy dependence of the radiation damage.
  - Data analysis of data from irradiation with protons at TIFPA (Trento) is ongoing
  - Irradiation tests using neutrons are scheduled at the Legnaro INFN facility (early August)
  - Irradiation with high energy gammas at the GIF facility (CERN) being also considered for next year

THANKS!

Backup slides: NIEL

- Many studies over the last decade have shown that device malfunctioning may occur not only as a result of the ionization induced by charged particles in the device, but also by the damage created by recoils resulting from non-ionizing energy transfer to the semiconductor lattice atoms. These effects are termed ‘non-ionizing energy losses’ (NIEL).
- The NIEL are due to the elastic scattering of the primaries (electrons, protons, a particles, neutrons) as well as of the fragments created in nuclear reactions (inelastic nuclear scattering) of the incident protons or neutrons with the device nuclei.
- Dale et al. (1989a) have shown that it would be convenient to use, for the displacement damage estimation, a quantity named NIEL which gives the portion of energy lost by a particle which leads to displacement damage.
- or the displacement damage caused by nuclear particle (protons, neutrons) induced secondaries, it is difficult to obtain the NIEL directly from the experiment, because of the short range of the recoils.

Backup slides: NIEL

- It has been shown, long ago, that at energies E > 20 MeV neutrons and protons with the same energy behave in matter in similar ways both in the elastic and inelastic scattering (Petersen, 1980). This means that neutrons-NIEL should be close to that for protons. Differences are expected at lower energies due to the Coulomb barrier.