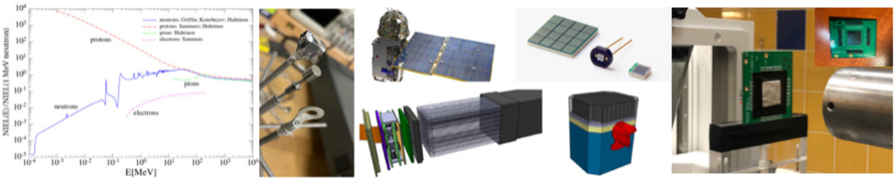

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Study of Radiation Damage on FBK SiPMs

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I. INTRODUCTION

Silicon Photomultipliers (SiPMs) are single-photon sensitive detectors that continue to attract increasing interest in several industrial and scientific applications that require fast detection speed, high sensitivity, compactness, insensitivity to magnetic fields and low noise. In some of these applications, such as high energy physics and spaceborne detectors, SiPMs can be exposed to a significant amount of radiation flux or dose that can cause damage to the detector and deterioration of their properties. For this reason, radiation tolerance is one of the main topics of research for SiPMs that has the goal of increasing their lifetime in these harsh environments and mitigating performance degradation after irradiation.

II. RADIATION SOURCES AND DEVICES

To study the effect of radiation damage on SiPMs we performed several irradiation campaigns on different technologies of FBK detectors. Sensors were irradiated using both protons and X-rays, to study the effects of Ionizing Energy Loss (IEL) and Non-Ionizing Energy Loss (NIEL) on their electrical properties, noise characteristics and photon detection efficiency. Irradiation with protons were carried out at the INFN-LNS in Catania and at the proton therapy facility in Trento for fluences up to $5\text{x}10^{14}$ and $5\text{x}10^{11}$ p/cm^2 respectively. Irradiation with X-rays was performed at TIFPA in Trento with doses up to 100 kGy. Detectors under study were chosen from several FBK technologies: near ultraviolet (NUV) and vacuum ultraviolet (VUV) sensitive detectors based on a p-on-n junction, visible light (RGB) and near-infrared (NIR) sensitive detectors based on an n-on-p junction [1]. In these irradiation campaigns, detectors with variations of process and layout parameters were tested to evaluate possible differences in their performance variation after radiation. Irradiation both with protons and X-rays were performed in steps of increasing fluence (or dose).

III. RESULTS

Protons induce mainly damages in the bulk of the detector through point or cluster dislocations, enhancing the primary dark count rate (DCR) [2-3]. The detectors performance worsening is generally visible at fluences above ˜$5\cdot10^7$ p/cm^2 depending on the starting DCR level (non-irradiated), which for FBK SiPMs is generally higher for RGB and NIR technologies than for NUV technologies. At higher fluences, where the proton damage dominates the rate of dark generation, we have not observed a significant difference in DCR between the different technologies. Between approximately 10^8 p/cm^2 and 10^{12} p/cm^2 the DCR seems to increase monotonically with the proton dose, whereas at higher fluences we see a saturation of the DCR, probably due to high cell-occupancy.
We performed functional tests (waveform analysis) on the irradiated samples, which confirmed primary DCR increment, and excluded significant variation in breakdown voltage, gain, crosstalk probability and photon detection efficiency (PDE) as a function of irradiation fluence, at least up to ˜10^{10} p/cm^2. For higher proton fluences, when the DCR of the detector becomes very high, it is generally difficult or not possible to implement the typical analysis techniques used for SiPMs, based on pulse-counting, thus the main quantities were

extrapolated from measurements of the reverse currents. Using a cryogenic version of SiPMs cooled to liquid nitrogen, however, it was possible to recover single photon counting capability and perform waveform analysis even for the samples irradiated at the highest fluences. Low temperature operation of these detectors allows to extend their lifetime under harsh radiation environments and opens new possibilities for their applications in big physics experiments.
We measured reverse current-voltage characteristics of SiPMs irradiated at different fluences and temperatures and we calculated the activation energy from the Arrhenius plot. It is observed a decrease in activation energy already at fluences of 10^8 p/cm^2 that results in a less effective reduction of DCR with cooling.
Soft/medium X-rays effect on SiPMs is mostly the creation of free charges inside the dielectrics. This produces a deterioration of the SiPMs characteristics that were observed, through reverse current-voltage measurements, starting at doses around 5 kGy. In particular, due to the modified charge in the dielectrics, the leakage current increases while the multiplied current does not change. However, at higher doses (around 20 kGy) the multiplied current also starts to increase. This increment could be explained by a local enhancement of the electric field or by a modification of the charge collection properties inside the SPAD [4]. Different technologies showed different responses to X-ray damage. In particular the NUV-HD-lowCT technology being the most sensitive one, probably due to the presence of optically insulating material inside trenches.
Finally, we studied the effect of room temperature annealing during time windows of a few days. It was observed that, although the NIR technology seems to recover faster compared to the NUV one, the relative change in current after annealing is comparable for the two technologies.

IV. CONCLUSIONS

Irradiation tests on FBK SiPMs, both with ionizing and non-ionizing radiation, showed a deterioration of the detector performance that was partially recovered through room temperature annealing. Further tests and analysis are needed to evaluate the differences between technologies and plan the next steps for the study and the improvement of radiation hardness in future productions of detectors.

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