Cobalt-60 gamma irradiation of silicon test structures for high-luminosity collider experiments

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1. Overview

- Upgrade of the LHC to the HL-LHC (Fig. 1): expected integrated luminosity up to 3000 fb^{-1} [1]
- New silicon tracking detectors: improved radiation hardness required
- For HL-LHC era doses in outer layers of the trackers of the order of 10-100 kGy depending on the distance from the beam line (e.g. nominal dose for the CMS Outer Tracker: 77.5 kGy)
- Systematic program of radiation tests with neutrons and charged hadrons by the CMS and ATLAS collaborations at LHC in view of the upgrade of the experiments, in order to cope a) with the higher luminosity of the HL-LHC and b) the associated increase in pile-up events and radiation fluxes
- Complementary radiation studies with ^{60}Co gamma photons performed in which the doses are equivalent to those that the outer layers of the silicon tracker systems of the two large LHC experiments will be subjected

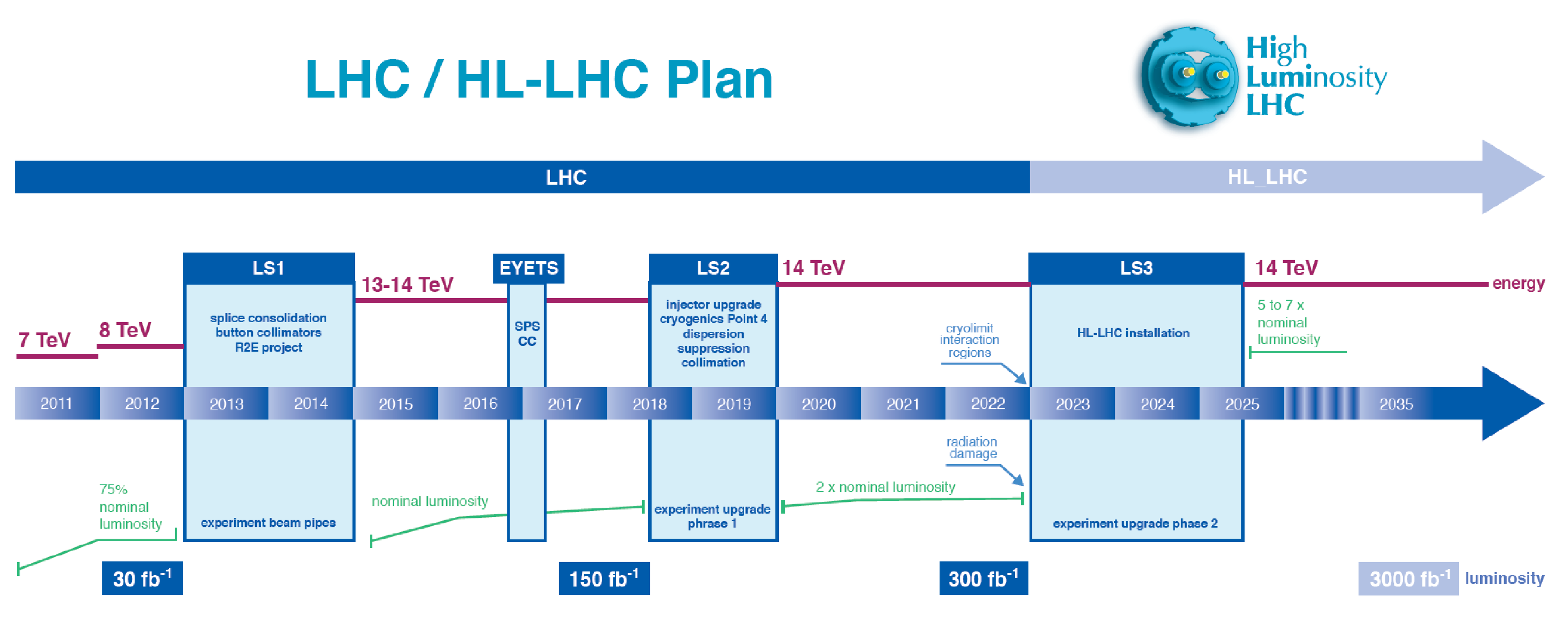

Figure 1. The HL-LHC plan for the upcoming years.

2. Samples and lab equipment

- Float zone oxygenated silicon n-in-p test structures for irradiation: Thinned 240 μm produced by Hamamatsu Photonics K.K. [2]
- Each test structure contains: 1 rectangular MOS (size = 4 mm), 2 rectangular diodes (size = 2.5 mm and size = 1.25 mm, respectively)
- ^{60}Co source: Picker therapy unit 30 TBq (March 2012) horizontal orientation (Fig. 2)
- Calculated dose rate at irradiation point (40 cm from the source): 0.96 kGy/h using FC65-P Ionization Chambers from IBA Dosimetry [3]
- Irradiation was performed in the secondary standard ionizing radiation laboratory of the Greek Atomic Energy Commission (GAEC), accredited according to ISO 17025 among others in calibration in the field of radiotherapy, and the relevant CMCs (calibration and measurement capabilities) are published in the BIPM database [4]
- Peltier element/thermoelectric cooler (at 20 °C) with glue protection to withstand radiation, fan (Fig. 3), microcontroller for stabilization of temperature, power supplies (Fig. 4)
- Charged particle equilibrium (CPE) → box of 2 mm-thick Pb and 0.8 mm of inner lining Al sheet → lead-aluminum container for absorption of low energy photons and secondary electrons [5] (Fig. 5)
- Automatic probe station (Carl Suss PA 150), equipment for electrical characterization of microelectronic devices (HP4092A, Keithley 6517A), climate test chamber (Weiss WKS 3-180/40/5)

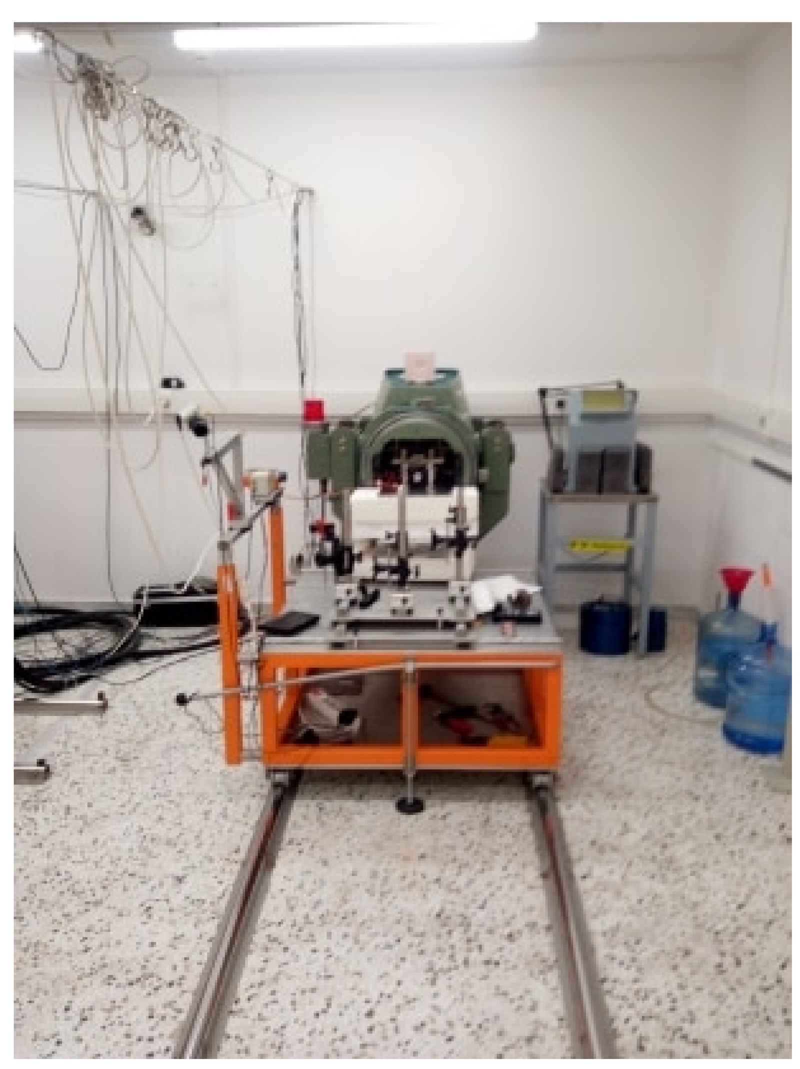

Figure 2. A cobalt-60 source: Picker therapy unit.

3. Experimental procedure/protocol

- Irradiation procedure was splitted in slots of 5 hours of irradiation
- After every 5 hours of irradiation: Annealing in the climate test chamber at 60 °C for 10 min (corresponding to 4 days of annealing at room temperature)
- Electrical tests after annealing performed using LabVIEW
- Electrical measurements:
  1) Oscillation level = 250 mV
  2) Various frequencies: 100 Hz, 1 kHz, 10 kHz, 100 kHz, 1 MHz
- Between irradiation slots: samples stored in freezer at -28 °C

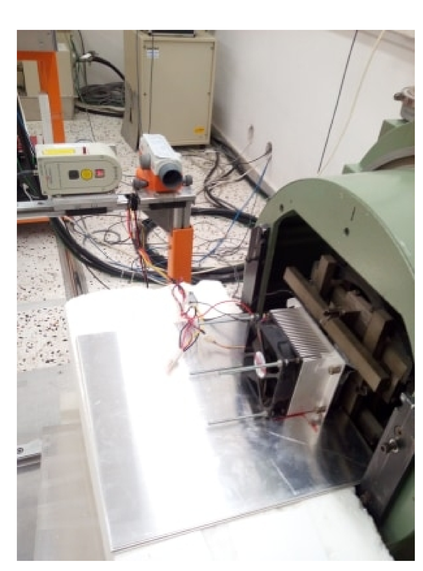

Figure 3. The container with the samples in front of the source. The fan and the thermoelectric cooler are visible.

Figure 4. The microcontroller and power supplies of the experimental setup.

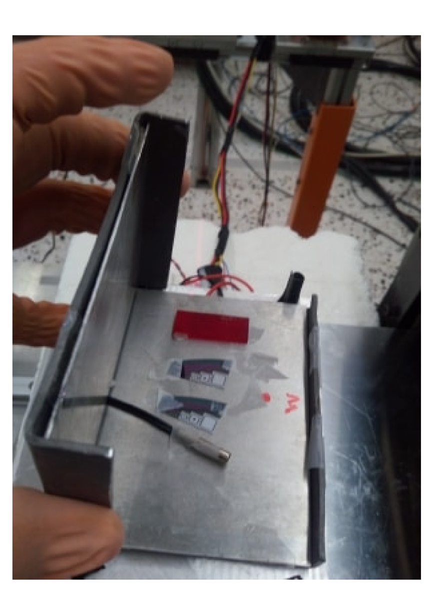

Figure 5. The lead-aluminum container for charged particle equilibrium.

4. Results from MOS (CV analysis)

- Clear evidence of positive charge induced in the oxide of the MOS structures after exposure to gamma photons (Fig. 6); various features of the MOS structure before and after irradiation summarized in Table 1 → shift of the flatband voltage (V_{fb}) to higher absolute values and increase of the dopant concentration (N_{dop}); oxide thickness remains stable because it is a geometric characteristic of the device
- Inertia effect is observed between depletion and inversion regions as a result of the delay of the carriers generation while increasing the voltage

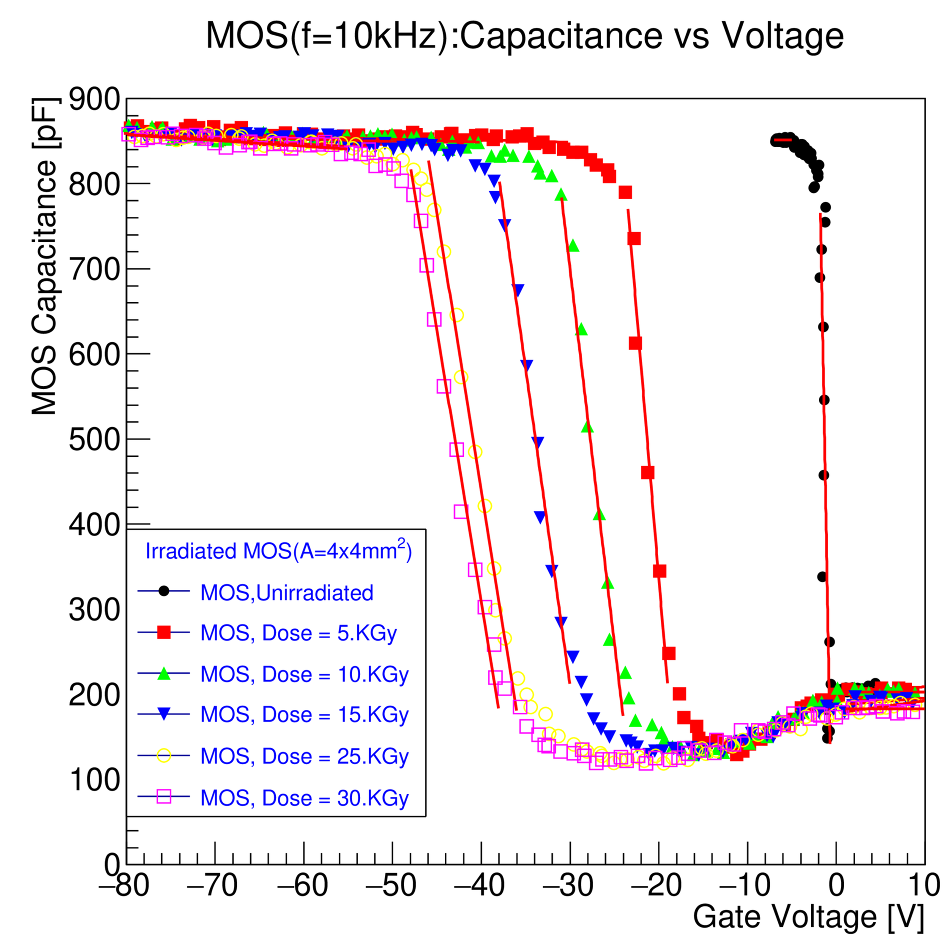

Figure 6. Capacitance-voltage curve for the MOS for various doses; f = 10 kHz.

Dose [kGy]	C_{acc} (pF)	C_{inv} (pF)	t_{ox} [μm]	V_{fb} [V]	N_{dop} [cm^{-3}]
0	851.65	203.42	0.65	-1.32	8.30×10^{12}
5	839.06	202.75	0.66	-22.80	8.37×10^{13}
10	835.72	202.75	0.66	-29.80	8.16×10^{13}
15	835.73	187.41	0.66	-36.43	9.12×10^{13}
25	811.08	178.22	0.68	-43.66	1.01×10^{14}
30	803.90	182.97	0.69	-45.71	1.03×10^{14}

Table 1. Various features of the MOS before and after irradiation; f = 10 kHz.

5. Results from 2.5 mm-size diode (IV and CV analysis)

- CV curves before and after irradiation almost identical (Fig. 7); using $1/C^2$-V plot information about depletion voltage, depletion capacitance and acceptor concentration can be obtained (Table 2); depletion voltage remains almost unchanged after irradiation (Fig. 8) as a result of the oxygen enrichment of the devices
- IV results scaled to 20 °C (Fig. 9); increase in ΔI with absorbed dose (Fig. 10)

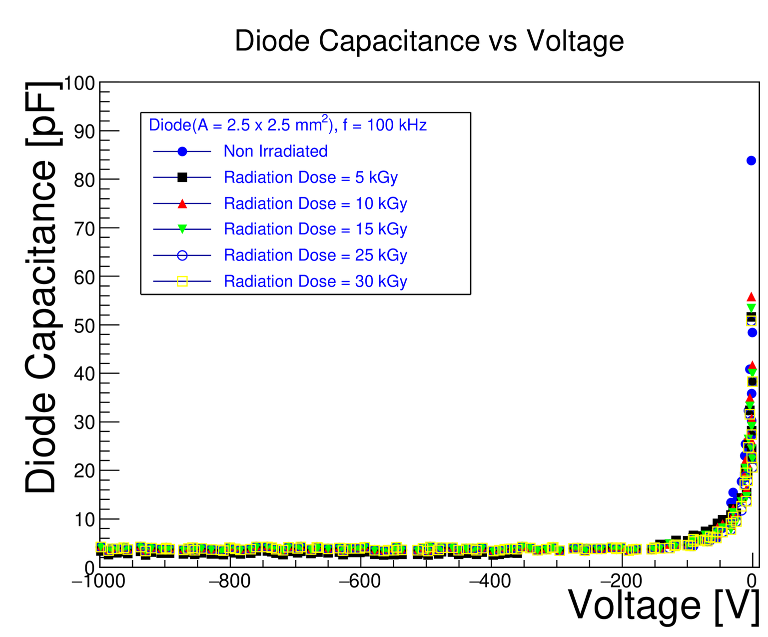

Figure 7. C-V curve for 2.5 mm-size diode for various doses; f = 100 kHz.

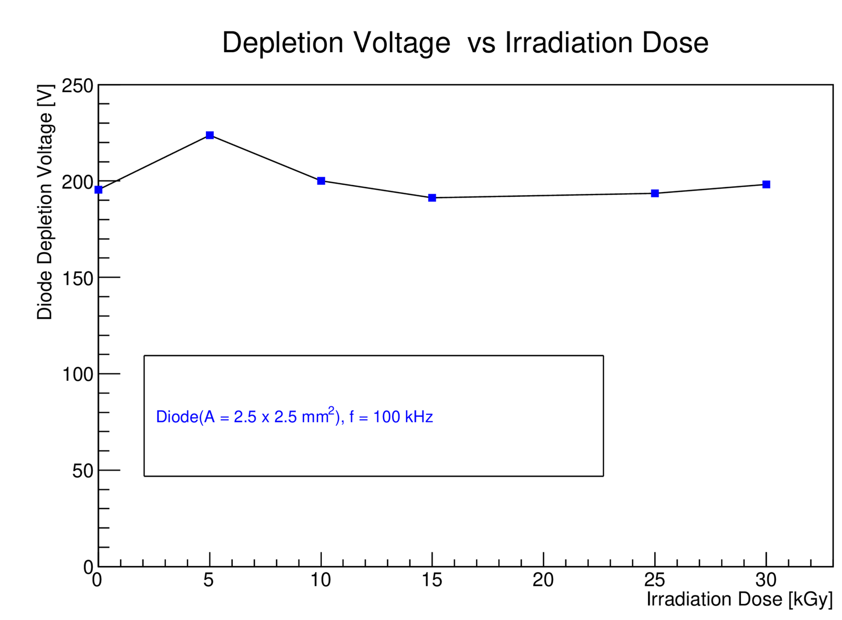

Figure 8. Depletion voltage as function of the absorbed dose for the 2.5 mm-size diode.

Dose [kGy]	0	5	10	15	25	30
V_d [V]	-195.50	-223.79	-200.05	-191.37	-193.50	-198.12
C_d [pF]	3.53	3.38	3.43	3.54	3.43	3.43
N_a [$\times10^{12}$ cm^{-3}]	7.129	7.104	6.723	6.935	6.886	7.003

Table 2. Depletion voltage, depletion corresponding capacitance and acceptor density for 2.5 mm-size diode for various doses; f = 100 kHz.

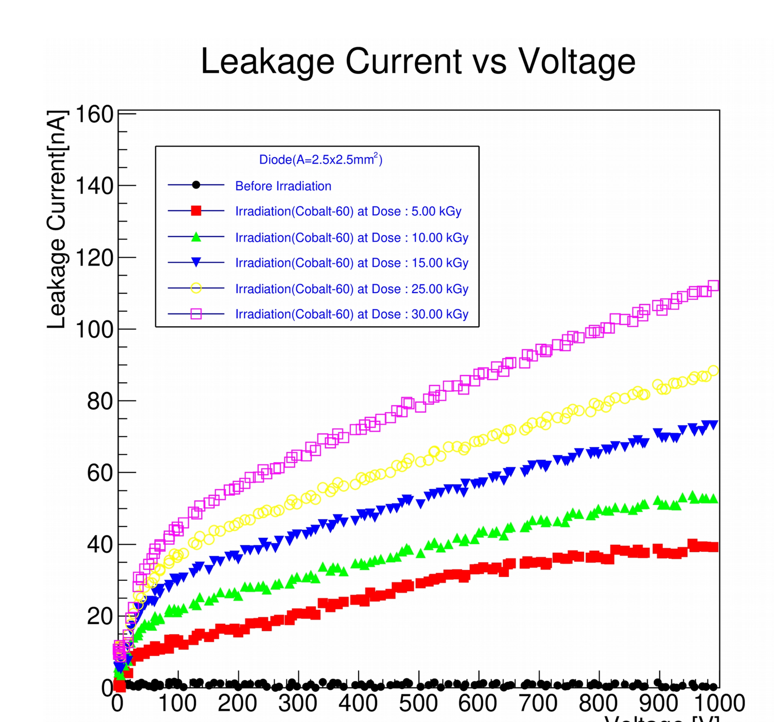

Figure 9. IV curves for the 2.5 mm-size diode for various doses.

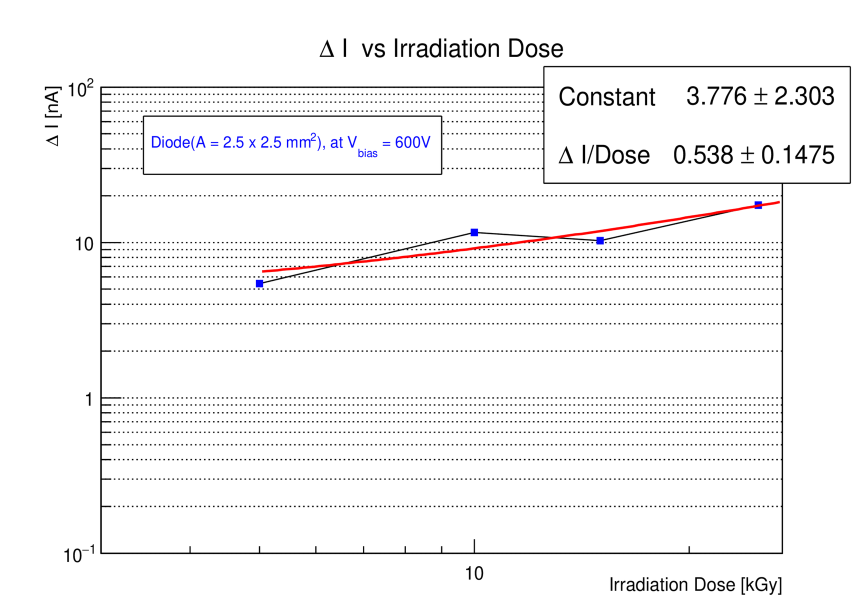

Figure 10. ΔI - dose curve at V = -600 V for the 2.5 mm-size diode; f = 100 kHz.

6. Outlook

- Silicon MOS & diodes irradiated by ^{60}Co γ; doses up to 30 kGy
- Irradiation campaign ongoing to reach even higher absorbed doses
- Even for high doses, leakage current is of the order of 10-100 nA, while depletion voltage doesn't change significantly with dose → materials and devices suitable for high-luminosity applications

References

[1] G. Apollinari et al., High-Luminosity Large Hadron Collider (HL-LHC): Technical Design Report V. 0.1, CERN Yellow Rep.Monogr. 4 (2017) 1-516 CERN-2017-007-M.
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