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Determination of the Charge Collection Efficiency in Neutron Irradiated Silicon Detectors

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***Abstract*—The charge collected from p-type silicon strip sensors irradiated to SuperLHC fluences has been determined with a beta source using fast front-end electronics. The bias voltage dependence of the collected charge and the hit detection efficiency have been measured before and after accelerated annealing. Predictions of the performance at the SuperLHC are derived.**

***Index Terms*—Silicon, radiation damage, detectors, high-energy physics.**

I. INTRODUCTION

THE proposed ten-fold luminosity upgrade of the Large Hadron Collider (LHC) [1] is motivating intense studies into upgrades of the trackers of the LHC detectors [2], which will require sensors capable of operating up to particle fluences of 10^{16}/cm^2 (pixel sensors), or 10^{15}/cm^2 (short strip detectors) [3]. The expected radial fluence distribution for ATLAS is shown in Fig. 1 for an expected integrated luminosity of 3000 fb^{-1}. The fluences of different particle species are normalized to the radiation effects of 1 MeV neutrons according to the Non-ionizing Energy Loss (NIEL) procedure [4] resulting in neutron equivalent fluences [neq/cm^2]. A fit to the radial dependence of the total fluence ϕ in [3] gives the "RTF" formula:

$$\Phi = 1.3\times10^{17}/r^2 + 4.8\times10^{15}/r + 9.9\times10^{13} - 3.6\times10^{11}r \ \ [\text{neq/cm}^2] \qquad (1)$$

for 3000 fb-1 and r in cm. The vertical bars signify the location of the different sensor types: pixels (R <30 cm), short strips (35 cm < R < 65 cm), long strips (70 cm < R < 100 cm) in a layout, which satisfies the requirement that the occupancy is less than 2% [5]. In order to come up with target fluences for the design and testing of the ATLAS sensors, an engineering margin of a factor of 2 is attached, which results in the fluences and total doses at fixed radii shown in Table I.

For short and long strips, radiation tolerance to fluences close to 10^{15} neq/cm^2 will be required.

The CERN-RD50 project, "Development of Radiation Hard Semiconductor Devices for Very High Luminosity Collider," has been formed to explore detector technologies that will allow device operation up to, or beyond, these limits [6]. This includes the study of new silicon materials (e.g. Magnetic Czochralski (MCz) [7] and p-type wafers), new structures (e.g. 3D detectors [8]) or changing strip implantation to collect electrons instead of holes.

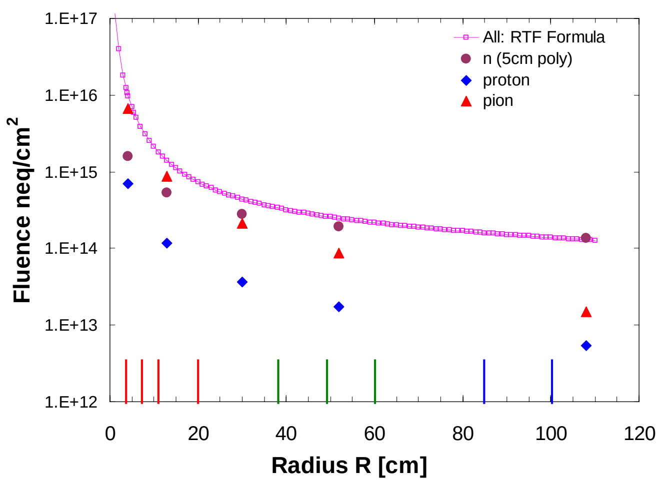

Fig. 1. Expected radial distribution of the particle fluences for ATLAS at the LHC upgrade for an expected integrated luminosity of 3000 fb^{-1}, separated into pions, protons, neutrons and the sum, all expressed in terms of 1MeV neutron equivalent fluences [3].

To characterize the performance of the irradiated detectors, the charge collection efficiency and the signal to noise ratio is measured as a function of bias voltage. Thus the data reflect the different effects influencing the charge collection of irradiated silicon sensors: wafer type and initial doping density (n- or p-type, Float Zone (FZ) or MCz), fluence dependence of the depletion voltage, and trapping of charges during collection (electrons vs. holes). A parallel study measured the fluence dependence of the depletion voltage on these sensors [9], while trapping has been investigated in Ref [10]. To summarize the findings for high fluences: one expects MCz to have higher initial depletion voltage, but with lower fluence dependence, than FZ; that n-type has lower

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depletion voltage than p-type since it first has to go through "inversion"; and that electron collection is better than hole collection since the trapping is reduced due to higher mobility. One needs to read out the charge at the main junction to be able to operate the sensor at partial depletion at high fluences, favoring n-on-n and n-on-p over p-on-n. Thinner p-on-n sensors would allow depletion even at high fluences, while there seems to be no reason for thinning p-type sensors except to reduce the radiation length.

In addition, the annealing behavior of the charge collection is measured. This is important since the annealing behavior of the FZ n-on-p sensors used in the ATLAS SCT [11] requires keeping the irradiated sensors cold even when not operating.

TABLE I
EXPECTED FLUENCE ϕ AND DOSE IN THE ATLAS UPGRADE
(3000 FB^{-1}, INCLUDES FACTOR 2 SAFETY)

Radius [cm]	System	Φ [neq/cm^2]	Dose [Mrad]
3.7	B-Layer	2.5×10^{16}	1140
7	2nd Inner Pixel Layer	7.8×10^{15}	420
11	1st Outer Pixel Layer	3.6×10^{15}	207
38	Short Strips	6.8×10^{14}	30
85	Long Strips	3.2×10^{14}	8.4

II. SILICON STRIP DETECTORS

For this paper, we study silicon strip detectors (SSD) from two sources: SMART and Micron Semiconductor. The AC-coupled sensors have a length between 3 cm and 4.5 cm, and 64 strips with pitch between 50 and 100 µm. The SMART detectors were processed by IRST, Trento within the frame of the SMART INFN project [12] on 4" n- and p-type 300 µm thick Magnetic Czochralski (MCz), 200 µm thick p-type Float Zone (FZ) and Epitaxial (Epi) n-type layer 150 µm thick wafers. In the figures and tables they are identified by a two or three digit wafer number followed by a detector number running from one to ten.

The Micron Semiconductor detectors were produced and processed in Sussex, UK on 6" 300 µm thick MCz and FZ Si wafers with crystal orientation <100> as part of a fabrication run organized by RD50. They are identified by four digit wafer numbers between 2550 and 2555, and/or by the label "Micron". The characteristics of the wafers including starting resistivity and depletion voltage (V_{FD}) are shown in Table II.

TABLE II
PROPERTIES OF THE WAFERS IN THE MICRON FABRICATION

	MCz (n-p)	MCz (n-n), (p-n)	Fz (n-p)	Fz (n-n), (p-n)
V_{FD} [V]	520	220	75	95
Resistivity [kΩ·cm]	1.9	1.4	13	3.3

The irradiations with neutrons were performed at the spallation source in Louvain [13] (average energy 20 MeV) and the TRIGA reactor in Ljubljana [14] at room temperature, and then kept cold until the annealing started. To shorten the annealing time, it was performed at 60°C, which is estimated to be ~1/700 of that at room temperature, i.e. 1000 min at 60°C corresponds to 486 days at room temperature. The fluences were measured to better than 10%.

III. CHARGE COLLECTION SYSTEM AT UCSC

To measure the collected charge as a function of bias voltage (CC(*V*)), we use the Embedded Particle Tracking Silicon Microscope, or EPTSM [15] (Fig. 2). Electrons from a ^{90}Sr source (max energy 2.28 MeV) traverse the device under test before being counted in the scintillation counter. The Si readout system allows for a binary readout from 64 AC-coupled detector channels with a 100 ns shaping time. The system uses the XILINX ML410 board and is an upgrade of the previous system at UCSC, PTSM [16].

The binary system measures the efficiency directly by counting the rate above a threshold, which represents the integral of the pulse height above that threshold. It also permits one to determine in threshold scans the median charge (50% efficiency point) and the peak charge (peak in the derivative of the threshold scan), as described in detail in Ref. [17]. Charge collection measurements were performed at lowered temperature between -20 °C and -30 °C inside of a freezer. In addition, C-V measurements were done for a few sensors at several temperatures, but less systematic than in Ref. [9]. The system is electronically calibrated during every run to better than 2%, and repeated runs have shown reproducibility of the system to better than 5%.

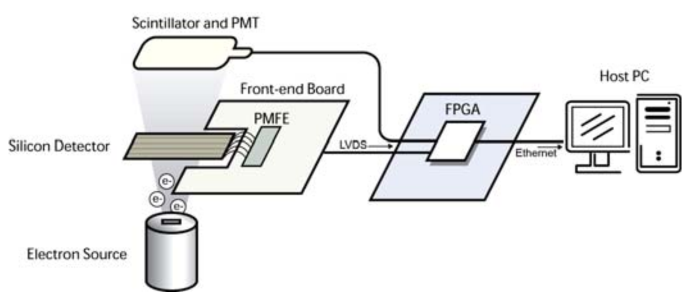


Fig. 2. Block diagram of the Embedded Particle Tracking Silicon Microscope EPTSM) [15], making use of the XILINX ML410 FPGA board. Note that the data connection from the FPGA board to the host computer consists of a single Ethernet cable.

IV. COLLECTED CHARGE VS. BIAS VOLTAGE

The performance of the sensors were measured with the bias dependence of the collected charge. Fig. 3a shows a comparison of the median charge vs. bias for FZ sensors, and Fig. 3b for MCz sensors, respectively, before and after neutron irradiation to fluences close to those shown for strips in Fig. 1 and Table I. The pre-rad voltage dependence of the charge collection reflects the initial doping concentration of the wafers shown in Table II. It is interesting to note the difference in pre-rad charge collected between FZ (23 ke$^-$, as expected from 300 µm thick Si sensor) and MCz (20 ke$^-$), which is outside the reproducibility of the apparatus (~5%) and the agreement of the wafer thickness (~3%).

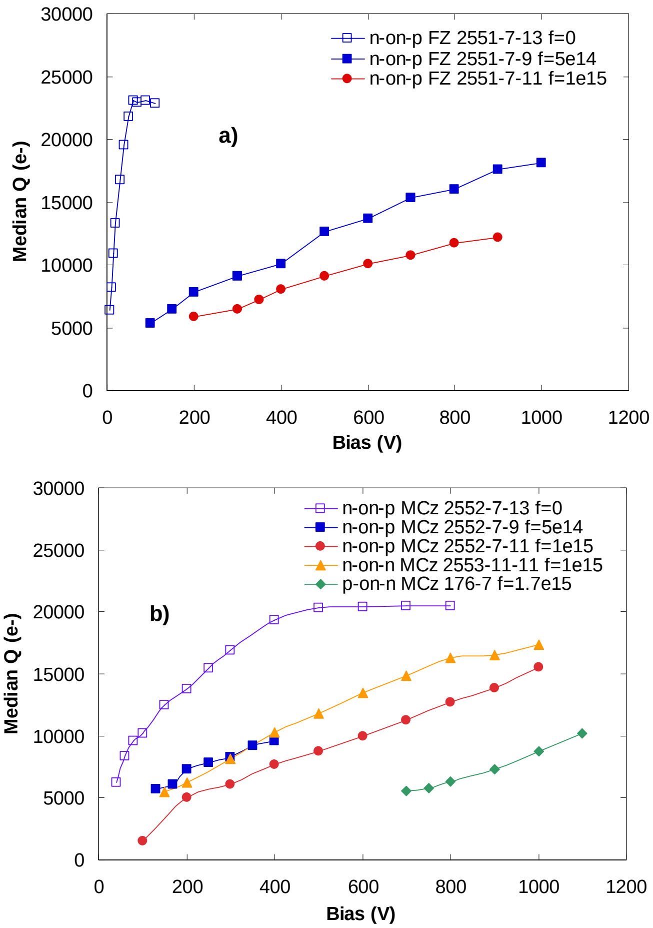


Fig. 3. Median collected charge vs. bias voltage for (a) n-on-p FZ detectors and (b) MCz detectors before and after neutron irradiation (before annealing).

Fig. 4 shows the collected charge vs. bias for all neutron irradiated sensors after annealing at 60°C for 80 min. For both fluences of $5x10^{14}$ and $1x10^{15}$ n/cm^2, the charge collection in p-type FZ and MCz is about the same. For FZ, at 500V bias, about 14 ke$^-$ are collected after $5x10^{14}$ n/cm^2, and at 800V bias, about 13 ke$^-$ are collected after $1x10^{15}$ n/cm^2. The n-on-n MCz sensor performs best after neutron irradiation, yielding as much charge after $1x10^{15}$ n/cm^2 as the n-on-p after $5x10^{14}$ n/cm^2. Since the charge in n-on-n appears to saturate at high bias, and the n-on-p sensors don't, the n-type MCz must be close to depletion at the highest bias voltages. The p-on-n MCz (although at higher fluence) seems to be less efficient than the sensors which collect electrons.

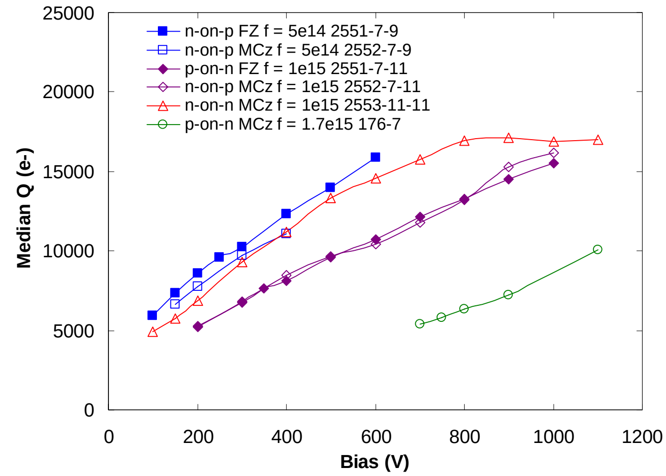


Fig. 4. Median collected charge for neutron irradiated detectors vs. bias after annealing for 80 min at 60°C.

The bias dependence of the median charge after several anneal steps at 60 °C is quite different for n-on-p FZ (Fig. 5a) and for n-on-n MCz (Fig. 5b), respectively: while the p-type FZ anneals beneficially, the n-type MCz annealing leads first to increased, but after large times to decreased, collected charges. In addition, the apparent saturation of the collected charge for large bias in n-on-n mentioned above disappears during long-term annealing, presumably due to an increase in the depletion voltage.

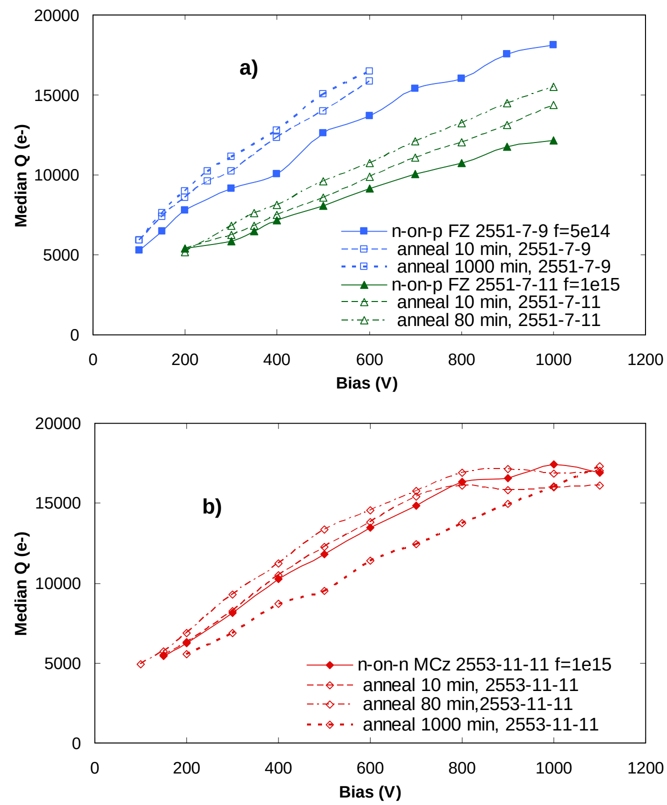
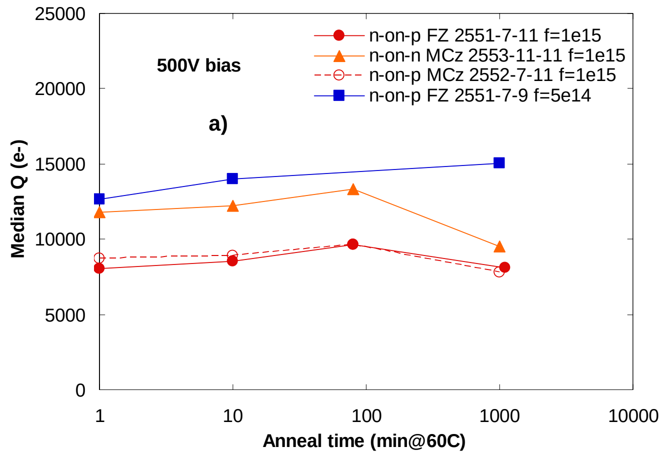


Fig. 5. Median collected charge vs. bias voltage in neutron irradiated Micron sensors for different annealing times at 60°C: a) n-on-p FZ, b) n-on-n MCz.

The anneal trends of the different sensors are highlighted in Fig. 6, where the charge collected during annealing at a bias voltage of 500V (Fig. 6a) and 800V (Fig. 6b) are shown. (The interest in the performance at 500V is the anticipation that the rating of existing cables will limit the bias voltage of the silicon sensors in an upgraded ATLAS inner detector.) Basically, the charge collection in irradiated p-type sensors (both FZ and MCz) improves or stays constant during annealing, while the one of n-type MCz sensors deteriorates slightly, but much less than in n-type FZ [11].



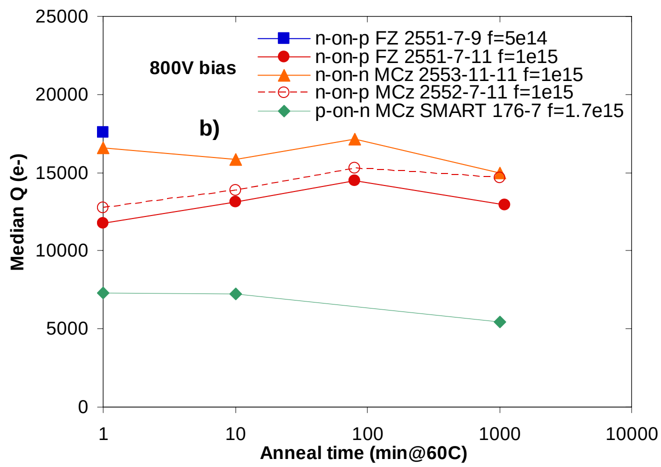


Fig. 6. Median collected charge for neutron irradiated detectors as a function of anneal time at 60°C a) at 500V bias and b) at 800V bias. Sensor 2551-7-9 did not reach 800V during annealing.

V. Signal / Noise in Irradiated SMART Sensors with CMS Electronics

Using the analog CMS data acquisition system with 50 ns shaping time in peak mode [18], charge collection measurements were performed on SMART sensors irradiated with neutrons at Ljubljana [14]. Since the sensors are 4.5 cm long, the measured signal-to-noise ratio (S/N) is representative of applications in short strips at the LHC upgrade. The bias of the sensors was typically 600 V (500 V for Epi).

The measured S/N and the collected charge are shown in Table III for both un-irradiated and irradiated detectors. The signal collected in un- irradiated sensors scales with the active thickness. After neutron irradiation the MCz p-on-n sensor shows the strongest deterioration of the collected charge at high fluence, while Epi p-on-n and FZ n-on-p show good charge collection efficiency (CCE). The two materials seem suitable for this fluence range.

It is interesting to compare the measured S/N on FZ p-type to the predicted one in Fig. 9 of Ref. [2]. Although the absolute normalization differ due to different assumptions of operating conditions and noise performance of the future tracker at the LHC upgrade, the agreement is good.

TABLE III
CCE Comparison of Irradiated and Un-Irradiated SMART Micro-Strip Sensors.

Sensor material/ ID	Thickness (μm)	Φ (neq/cm^2)	S/N	Signal (ke-)	CCE (%)
Epi(p-on-n)					
13-s3	150	not-irr	15.9	11.2	
12-s4	150	$2.55x10^{15}$	8.6	7.6	67.7
MCz(p-on-n)					
160-s7	300	not-irr	35.9	23.2	
127-s4	300	$1.70x10^{15}$	5.6	4.6	19.9
FZ(n-on-p)					
14-s7 lps	200	not-irr	23.1	15.7	
24-s2 lps	200	$8.50x10^{14}$	19.1	12.8	81.3

The comparison of all our neutron data with proton [19] and neutron [20] data of the Liverpool group at 800V bias are shown in Fig. 7. While the binary readout gives the median of the distribution of the highest single-strip pulse heights, the analog readout measures the most probable value of the cluster charge distribution. Pre-rad measurements indicate that the binary median charge is as much as 15% lower than the expected most probable cluster charge. Our data are shown after 80 min annealing at 60°C to approximate the conditions of the data of ref. [19] and [20]. Within these caveats, agreement between values from electron collection in FZ and MCz sensors is reasonably good. The disadvantage of the thick planar p-on-n type is evident, as well the advantage of collecting electrons. The thin n-type epitaxial sensors collect less charge than the 300 μm n-on-p FZ sensors, both pre-rad and post-rad.

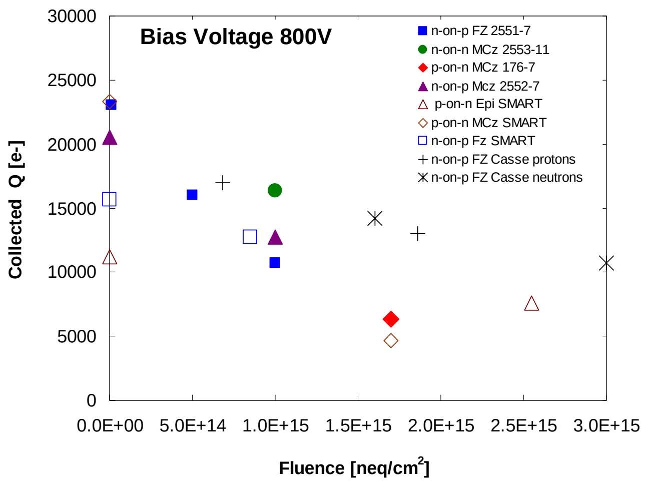


Fig. 7. Charge collected at 800V bias vs. particle fluence after 80 min annealing at 60°C. The data labeled SMART, Casse proton [19] and Casse neutron [20]) are most probable values taken with analog electronics, all others median values taken with binary electronics.

VI. Efficiency vs. Charge Collection (CCE)

For tracking sensors with binary readout, the figure of merit is not the collected charge, but the hit detection efficiency. Fig. 8 shows both the median collected charge and the efficiency as a function of the bias voltage for n-on-p sensors irradiated to two neutron fluences, $5x10^{14}$ and $1x10^{15}$ cm^{-2}, respectively. For the lower fluence, the efficiency reaches 100% at the threshold of 1 fC = 6400 e^- at a signal-to-noise ratio of S/N ≈ 10. For long strips (where the design fluence will be $5x10^{14}$ cm^{-2}) with a signal of about $14ke^-$, the usual threshold of 1fC = 6400 e^- can be used. For short strips with design fluence of $1x10^{15}$ cm^{-2} and with a signal of about 8ke, the threshold needs to be reduced to about 4500 e^-. Thus, in order to have a threshold/noise ratio > 4, i.e. noise occupancy of about 10^{-4}, the electronics must be designed for a noise of ~ 1000 e^- .

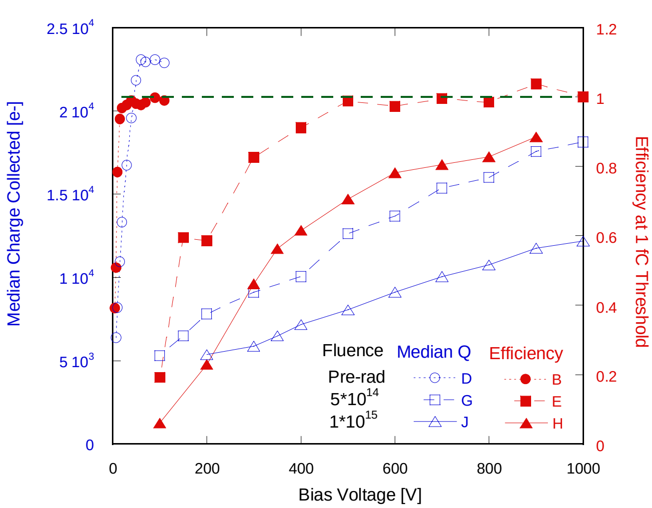


Fig. 8. Median collected charge (open symbols) and efficiency (closed symbols) of three n-on-p FZ SSD: pre-rad and after neutron irradiation with fluence of $5x10^{14}$ and $1x10^{15}neq/cm^2$, respectively. The threshold is 1fC.

VII. Conclusions

We have investigated the charge collection in neutron irradiated silicon sensors fabricated on a variety of different wafer types. In the range of neutron fluences expected for the strip sensors in the LHC upgrade trackers, n-on-p sensors fabricated on FZ and MCz wafers show satisfactory charge collection, while the n-on-n MCz performs best and planar p-on-n MCz shows stronger deterioration with increased fluence. Thin sensors, either 200 µm p-type FZ or 150 µm p-on-n epi, perform reasonably well at high fluences, but seem to exhibit no advantage over the customary 300 µm thick wafers. The annealing in both FZ and MCz p-type sensors and in n-type MCz sensors is moderate.

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