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Qualification of irradiated 3D pixel sensors produced by FBK for the pre-production of the ATLAS ITk detector

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To be ready for the challenging conditions of the High Luminosity phase of the LHC accelerator at CERN, the ATLAS Inner Detector will be completely replaced with a new all-silicon Inner Tracker, the ITk. Sensors in the innermost layer will be exposed to a fluence up to $1.9{\cdot}10^{16}$ n_{eq}/cm^2 (considering a safety factor of 1.5) at the half of the HL-LHC program, after which it is scheduled to be replaced together will the full innermost system. Pixel sensors with 3D technology have been chosen to instrument it due to their radiation hardness. Sensors with 25x100 μm^2 pixel pitch will be used in the central region of the innermost layer (barrel) while sensors with a pitch of 50x50 μm^2 will instrument its two side regions (end-caps). The Fondazione Bruno Kessler (FBK) has been chosen as one of the two vendors for the production of these sensors. This paper will present the performance of 3D pre-production sensors with both pixel pitches produced by FBK measured in test beams with devices irradiated up to and beyond the sensors end-of-life fluence.

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1. Introduction

The Large Hadron Collider (LHC) [1] High Luminosity (HL) program is going to start in 2029 bringing the instantaneous luminosity of the machine up to the nominal (ultimate) value of $5 \cdot 10^{34}$ cm^{-2} s^{-1} ($7.5 \cdot 10^{34}$ cm^{-2} s^{-1}) and the average number of inelastic proton-proton collisions per bunch-crossing close to 140 (200) [2]. The HL scenario will push the ATLAS detector [3] to operate in an extremely challenging environment, well beyond the one for which it was designed. The ATLAS detector has been upgraded in stages to be ready for the HL phase: calorimeters, muons spectrometer and the trigger and DAQ system have been improved during the Phase-I upgrades, while the ATLAS Inner Detector (ID) is going to be completely replaced with a new all-silicon Inner Tracker (ITk) [4, 5] during the LS3 of the LHC in the context of the Phase-II upgrades. Phase-II upgrades will also include improvements in the ATLAS hardware trigger increasing the total trigger accept rate from 100k to 1MHz and minimising the latency time. The new technologies involved will allow the ITk to survive an unprecedented level of radiation and to guarantee performance close to the current ID with extended coverage.
In section 2 the ITk detector is briefly present, section 3 describes the novel 3D technology of the ITk innermost layer pixel sensors, while sections 4 and 5 are devoted to the irradiations results and beam tests performance of pre-production 3D pixel sensors.

2. ATLAS ITk overview

The current ATLAS ID, consisting of silicon pixel, silicon strip detectors and transition radiation tracker is going to be replaced with the ITk. The ITk will consist of 13 m^2 of pixel detectors with 5 billion read-out channels and 160 m^2 of strip detectors with 50 million read-out channels. With respect to the current ID, the two sub-detectors have three times and seven times larger surfaces for Strip and Pixel, respectively. The 5-layer layout of the pixel detector provides extended coverage up to $|\eta| <4$. It minimizes multiple scattering effects by reducing the material budget compared to the current ID. This is achieved primarily by using DC-DC powering and data transmission with optical links and lpGBT in Strip; thinner modules serial powering and inclined sections in Pixel [6]. The pixel detector is organised into three mechanically independent sub-systems. The Inner System (IS) includes the first two innermost pixel layers (Layer 0, 1), the Outer Barrel (OB) and the Outer Endcap (EC) (Layer 2, 3, 4) with the three outermost pixel layers of flat staves, inclined sections, and rings [7]. Currently, no pixel technology can sustain efficient operation for the entire duration of the high luminosity program due to the high radiation damage. However, pixel sensors developed using 3D technology have been identified as good candidates for the L0 since they can sustain a fluence up to $1.9{\cdot}10^{16}$ n_{eq}/cm^2 and Total Ionising dose (TID) of 1 GRad which is close to the fluence received by the L0 after 2000 fb^{-1}, when the IS is foreseen to be replaced. Almost 900 pixel 3D sensor tiles will be hybridized each with the ITkPix readout chip [8] which is implemented in 65 nm technology. Three each of the resulting bare modules will be placed on a common flexible PCB for powering and readout forming a triplet module. Sensors with a single charge collection electrode in the centre of the pixel cell will instrument the ITk L0: a pixel cell of 25x100 μm^2 is used for the barrel and a 50x50 μm^2 layout in the end-caps. The choice of the two pitches is mainly driven by the tracking performance to improve the effect of the impact parameter d_0 on high-level objects. For example, with a 25x100 μm^2 pixel pitch barrel, the light-jets rejection improves of 10-20% to an all 50x50 μm^2 scenario. Two vendors will deliver the entire production of the ITk 3D pixel sensors: Sintef (Stiftelsen for industriell og teknisk forskning) and FBK (Fondazione Bruno Kesseler). The production of the 50x50 μm^2 layout is split between the two vendors while FBK will take care of the complete 25x100 μm^2 layout production.

3. Pixel sensors 3D-technology

The increased pileup of the HL-LHC will require a small granular pixel design, with small inter-electrode distances in the order of 50 µm or less. These values can be reached with the 3D technology, consisting of direct drilling of the electrodes in the silicon substrate, which allows the sensor thickness to be decoupled from the inter-electrode distance and makes it possible to realize extremely radiation-hard pixel detectors. With such a small pitch design, the dead area due to the 3D electrodes is potentially a concern for the detector efficiency. Several processing technologies have been explored for FBK 3D Si sensors [9]. A small electrode diameter of about 5 µm has been implemented at FBK using a state-of-the-art Deep Reactive Ion-Etching (DRIE) process to address this issue, reducing the ReadOut Chip (ROC) input capacitance. Sensors are realized at FBK in 6-inches wafers using a single-side approach. This simplified production process assures mechanical integrity, a lower risk of high wafer bow, and bump-bonding complexity [10]. The charge collection electrode is drilled in the 150 µm thickness active material up to a safety distance of about 35 µm from the handle wafer (100 µm thickness) to avoid early breakdown.

4. Irradiations

During 2022 and 2023 several pre-production single sensor tiles delivered by FBK have been hybridised by IZM (The Fraunhofer Institute for Reliability and Microintegration) and LND (Leonardo SpA) with pre-production ITkPix v1.1 front-end chips. In total 16 modules including the two different sensors layout 50x50 μm^2 (8) and 25x100 μm^2 (8) were mounted on Single Chip Card (SCC) to validate the pre-production. All the modules have been tested in the Genova laboratory following a standard quality control (QC) procedure including Front-End (FE) tuning and X-ray scans for the bump-bonding validation. It has been decided to irradiate 8 sensors, 4 per sensor layout, at different irradiation facilities. Half of the modules have been irradiated in Bonn and KIT (Karlsruhe Institute of Technology) with low energy protons beam (13-23 MeV) up to a uniform fluence of $1{\cdot}10^{16}$ n_{eq}/cm^2, and half at the CERN IRRAD facility up to higher fluence close to $2.4{\cdot}10^{16}$ n_{eq}/cm^2. The IRRAD facility, contrary to the first two, can not deliver uniform irradiation over the entire sensor surface given the beam size and despite a scan on the horizontal axes. The local fluence received by the sensor is reconstructed starting from an Aluminum dosimeter placed on the back of the sensor during the whole irradiation. The reconstruction is then refined by the information on the noise and efficiency of the device that respectively grows and decreases as a function of the fluence received. An example of a reconstructed fluence map is shown in picture 1.

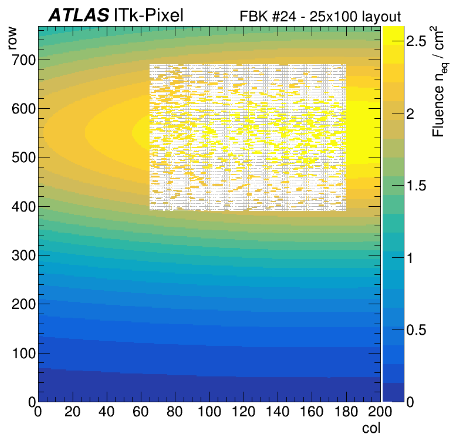

Figure 1: Reconstructed irradiation profile of FBK 25x100 μm^2 pixel pitch irradiated at CERN IRRAD facility. The coloured area is the fluence profile, while the white halo is the area where test-beam performance was evaluated [13].

5. Beam test performance

Irradiated modules have been tested on the H6A SPS 120 GeV pion beamline during 2022-2023 in several test beam campaigns. The same setup was used for all test beam campaigns mentioned in this report [11]. It includes an ACONITE telescope with six MIMOSA26 planes and an FE-I4 single chip module as a timing reference plane, two scintillators at the two ends of the setup whose coincidence triggers the signal readout via a Trigger Logic Unit (TLU) and a data acquisition system based on YARR and EUDAQ. The resulting position resolution delivered by the beam telescope on the surface of the Devices Under Test (DUTs) is ~2μm. Test beam data were analysed with the C++ based framework Corryvreckan. In particular, reconstructed particle tracks passing through disabled or masked pixels on DUTs or through neighbouring pixels are not used in the efficiency calculation. Hence the resulting efficiency applies to pixels not masked or disabled [12]. Particular attention was paid to the study of the efficiency of sensors and the number of pixels disabled. The ITk requirements for excellent particle tracking ask for modules with the 96% (97%) efficiency at normal (inclined) incidence reached with at most the 3% of masked pixels, even after irradiation. Modules including both pixel pitches, have been irradiated close to $1{\cdot}10^{16}$ n_{eq}/cm^2 showing similar performance. The efficiency is close to 97% at 40 V (60 V) for the 50x50 μm^2 (25x100 μm^2) in normal incidence conditions and it reaches 99% when modules are inclined with an angle of 15° to the beam, as shown in figure 2 (left). In both cases, the number of noisy pixels is lower than the 0.1%. Modules with the 50x50 μm^2 layout, irradiated up to the IS end-of-life fluence ($1.9{\cdot}10^{16}$ n_{eq}/cm^2), showed excellent performance with the 96% efficiency (normal incidence) reached at 100 V bias with the 3% of masked pixels. Due to the not uniform irradiation in IRRAD, 25x100 μm^2 modules have been irradiated with a peak fluence far behind the sensor end-of-life fluence, reaching a peak fluence close to $2.4{\cdot}10^{16}$ n_{eq}/cm^2, as described in section 3. Test beam performance has been evaluated in two fiducial areas on the modules, that received a different mean fluence. In the first area, the mean fluence is close to $2.3{\cdot}10^{16}$ n_{eq}/cm^2: efficiency reaches 96% (97%) at normal (inclined) incidence with a bias of 160 V (150 V) although 5% of the pixels are disabled; while

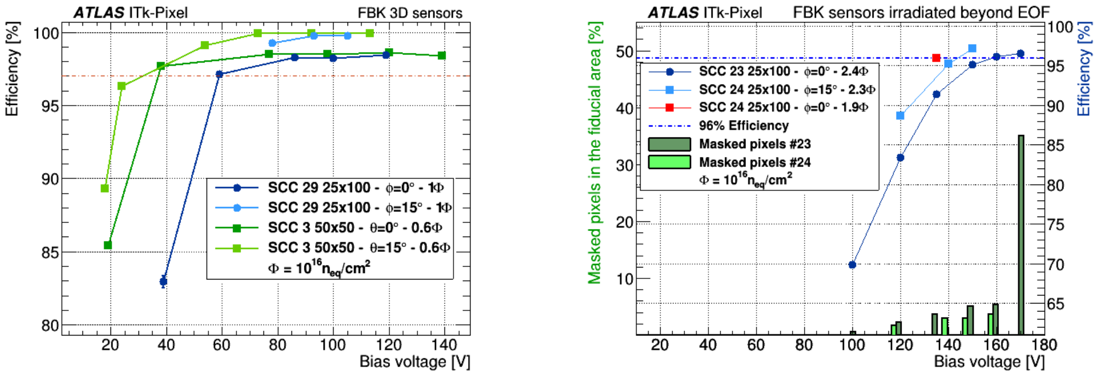

Figure 2: Left: Test beam performance of FBK 50x50 μm^2 and 25x100 μm^2 irradiated at a fluence close to $1{\cdot}10^{16}$ n$_{eq}$/cm^2. Right: Test beam performance of FBK 25x100 μm^2 irradiated beyond the sensors end-of-life fluence, the number of noisy pixels per each bias is reported in the histogram [13].

in the second area, the mean fluence is about $1.9{\cdot}10^{16}$ n$_{eq}$/cm^2 and the efficiency is close to 97% (inclined incidence) with 3% of disabled pixels thus fulfilling the requirements. The number is under control up to a bias of 120 V where it stays below 3% and grows up to 35% at 170 V bias. Results are shown in figure 2 (right).

6. Conclusions

FBK has delivered the pre-production of the 3D pixel sensors during 2022-2023, including both sensor layouts: 50x50 μm^2 and 25x100 μm^2. Sensors, hybridised with ITkPix v1.1 pre-production FEs, have been irradiated at different fluence in several facilities. Modules meet the ITk requirements in terms of efficiency and disabled pixels even after irradiation up to the sensor's end-of-life fluence. Pixel sensors with 3D technology could be confirmed as the viable choice for the ITk L0. These results contributed to the positive outcome of the review and allowed to launch of the full production of the FBK 3D sensors for ITk.

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