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Assembly and electrical characterization of 3D-pixel modules for the ATLAS ITk Pixel detector(*)

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Summary. — To face the High-Luminosity program of the LHC, the ATLAS Inner Detector will be completely replaced with a new all-silicon tracker, the ITk. The innermost layer of the ITk pixel detector, placed at 34 mm from the beam line, will have to face an extremely high fluence that is foreseen to reach a peak value of $2 \cdot 10^{16}$ n_{eq}/cm^2 (considering a 1.5 safety factor) at the half of the High-Luminosity program when the layer is foreseen to be replaced. Due to their built-in radiation hardness, pixel sensors designed with the 3D-technology have been chosen to instrument the innermost layer of the ITk pixel detector. This paper aims to present the latest results about the ITk pre-production 3D pixel modules, focusing on the module assembly at the INFN Genova laboratory and the electrical characterization of the assembled modules. The modules met the requirement on breakdown voltage and leakage current and have provided important results to improve the quality of the interconnection between the sensor and the front-end electronics.

1. – Introduction

The High Luminosity [1] (HL) era of the Large Hadron Collider (LHC) [2] will elevate the machine's instantaneous luminosity to $7.5{\cdot}10^{34}$ cm^2 s^{-1}, with the number of proton-proton collisions per bunch crossing nearing 200. While the integrated luminosity is projected to be around 350 fb^{-1} after the LHC Run 3, it is anticipated to reach 4000 fb^{-1} after a decade of high luminosity operations. This surge in collisions will pose significant challenges in terms of radiation hardness, read-out electronics, and triggers for the experiments. The current ATLAS [3] detector's tracking system, the Inner Detector (ID), is not equipped to handle these harsher conditions. To address this, it will be completely replaced by a new all-silicon tracker, the Inner Tracker (ITk), consisting of a pixel detector [4] at a small radius, close to the beam pipe, and a large area strip detector [5] surrounding it. The involved institutes have entered the pre-production phase, transitioning the community into production mode. This paper aims to provide an overview of the hybridization qualification of ITk-Pixel bare modules, which were assembled on

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Single Chip Cards (SCC), and of the assembly and electrical characterization of ITk pixel modules, assembled at the INFN Genova laboratory, for the innermost layer of the detector.

2. – The ITk Pixel Detector

The current ATLAS Inner Detector (ID), which includes silicon pixel and strip detectors as well as a transition radiation tracker, will be replaced by the Inner Tracker (ITk). The ITk will feature 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. Compared to the current ID, the ITk's strip detectors will cover three times more surface area, and its pixel detectors will cover seven times more. The pixel detector will have a 5-layer layout, offering 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].

3. – Pixel modules for the ITk Pixel innermost layer

Due to high radiation damage in the ITk Pixel innermost layer (L0), no current pixel technology can maintain efficient operation throughout the entire high luminosity program. However, pixel sensors developed with 3D technology have emerged as strong candidates for the L0, as they can withstand a fluence of up to $2{\cdot}10^{16}$ n_{eq}/cm^2 and a Total Ionizing Dose (TID) of 1 GRad, which is about the fluence expected in the L0 after 2000 fb^{-1} when the L0 and layer 1 are planned to be replaced. Therefore, 3D-pixel sensors have been chosen to instrument the ITk Pixel L0. The sensor design consists of a single charge collection electrode at the center of the pixel cell, featuring a pixel cell size of 25x100 μm^2 for the barrel and 50x50 μm^2 for the end-caps. This dual-pitch design is chosen primarily to enhance tracking performance, driving the accuracy of the track impact parameters and, as such, the reconstruction of primary/secondary vertices, the identification of primary leptons, up to the performance of high-level objects like b-tagging and light-jet rejection. The production of ITk 3D pixel sensors will be handled by two vendors: Sintef (Stiftelsen for industriell og teknisk forskning, Norway) and FBK (Fondazione Bruno Kesseler, Italy). While the 50x50 μm^2 production will be split between the two vendors, FBK will be responsible for the entire 25x100 μm^2 production. Nearly 900 3D pixel sensor tiles will be hybridized with the ITkPix readout chip [8], implemented in 65 nm technology, to make a so-called bare module. Two hybridization vendors are currently involved in the process: the Leonardo SPA (LND, Italy) and the Fraunhofer Institute for Reliability and Microintegration (IZM, Germany). At the ITk institutes, three single bare modules will be assembled on a common flexible PCB for power and readout to make a so-called triplet module. Three different flavours of triplet modules have been designed to cover the full L0: Linear triplet modules for the barrel and Ring modules, with two different bending radii (R0/R05) for the end-caps. Four institutes are responsible for the triplet modules assembly: the Linear triplets in Barcelona, the Ring triplets R0 in Oslo, and the Ring triplets R05 in Genova and Milan.

4. – Module assembly technique at the INFN Genova laboratory

In the four assembly sites, different module assembly strategies have been developed according to the instrumentation available in each laboratory. The assembly strategy used at the INFN Genova laboratory is based on a pick&place machine. The machine allows X/Y/Z and θ movement, with a precision and repeatability of about 3 μm. It has been equipped with suction cups that allow placing the bare modules, and a high-resolution camera used for pattern recognition. The pattern recognition algorithm is based on the Yolo V5 model (You Only Look Once version 5) which is an advanced object detection model developed by Ultralytics [9], designed for real-time applications. The Yolo V5 is developed to be a pre-trained neural network architecture that can identify and locate multiple objects within a single image. The model has been trained on large datasets, allowing it to recognize a wide variety of objects with high precision, and has been adopted to recognise fiducial markers on the bare modules and on the flexible PCB of the ITk triplet modules. Moreover, dedicated measurement software has been designed and implemented in the machine. The machine is used to place and align the bare modules with respect to each other. Once the bare modules have been placed, the flexible PCB is then glued on top of them using a dedicated jig able to ensure the correct alignment with an accuracy of about 100 um, sufficient to guarantee the hermeticity of the detector and the feasibility of the wire bonding connection between the front-end electronics and the flexible PCB. As the INFN Genova will take care of half of the production of the R05 triplets, a first pre-production triplet module has been assembled, following the above procedure, in February 2024. A picture of the triplet module is presented in fig. 1.

5. – Testing results of the first pre-production module

Before moving to the production of the pixel modules, it was essential to validate the hybridization vendors, assess the electrical performance of the sensor/FE, and perform irradiation and test-beam campaigns. Therefore, several modules were assembled on SCC, primarily to deliver prompt feedback to the hybridization vendors. During the summer of 2023, FBK delivered the first 25x100 μm^2 pixel-pitch 3D sensors pre-production batch in the project. Fifteen of these sensor tiles, hybridized by LND to ITkPix v1.1 front-end electronics, have been shipped to the INFN Genova/Milan laboratory. In Genova, nine

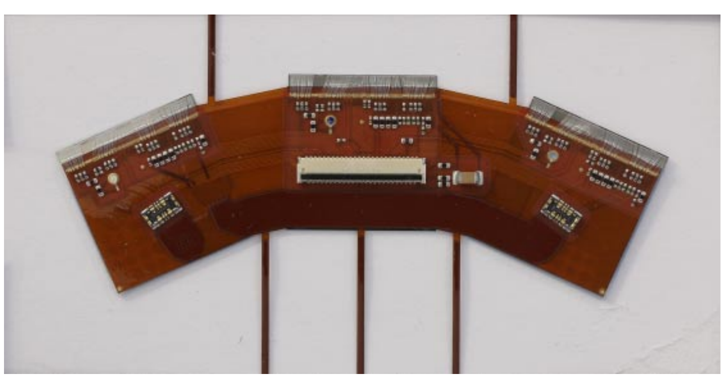

Fig. 1. – First ITk Pixel pre-production triplet module assembled at the INFN Genova.

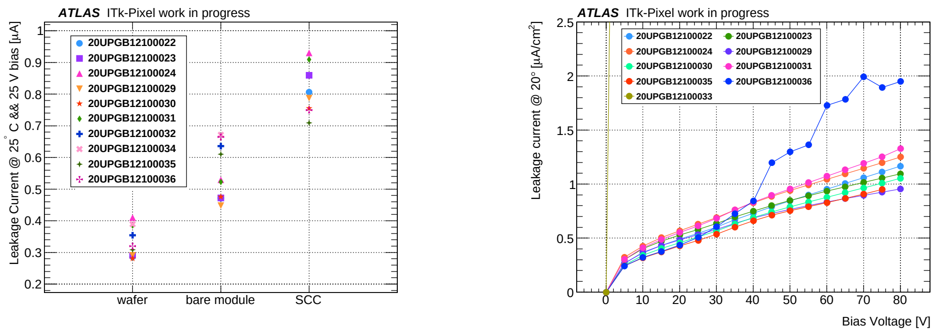

Fig. 2. – FBK 25x100 μm^2 sensors leakage current measured at 25 C$^\circ$ and 25 V bias in three different configurations: wafer level, after sensor hybridization to front-end electronics and after module assembly on single chip card (left). IV curves of FBK 25x100 μm^2 sensors measured after modules assembly on single chip cards (right).

bare modules have been mounted on SCC. Sensors performance has been verified by measuring the IV curve at the wafer level, after hybridization and after the assembly on SCC. Except for one bare module, that showed early breakdown after hybridization, the leakage current of the sensors (measured at 25V bias and 25°C) has increased by a factor less than 2 after each step, according to the ITk specs. The results are reported in fig. 2. The noise of the readout electronics can be used to verify the quality of the bump-bonding connection. The sensor input capacitance (about 50 fF for ITk 3D pixel sensors) affects the noise of the readout electronics. It can be measured as the width of the S-curve during the threshold scan (analog injection with increasing charges) of the module. The noise of the bare readout chip (or a disconnected pixel) is in the order of 40 electrons, while it raises at about 80 electrons if the readout electronics pixel is connected to a 3D pixel sensor. This technique has been adopted to check the quality of the hybridization of the LND bare modules. Despite this batch being the first 3D-batch hybridized by LND, there results were encouraging and have provided important feedback to improve the quality of the process at the LND.

In Genova a first pre-production R05 triplet module has been assembled (fig. 1) and has undergone the same set of quality control tests. This module has been assembled with spare parts to test the operation of the pick&place machine, therefore three prototype bare modules have been used: two 50x50 μm^2 pixel-pitch FBK bare modules hybridized at IZM and one 25x100 μm^2 pixel-pitch FBK bare module hybridized at LND. The two IZM bare modules showed a large area of disconnected bumps, while the LND showed excellent hybridization quality as reported in fig. 3. Hybridization problems were solved at IZM during the processing of the first pre-production modules. The electrical tests of this pre-production triplet have also contributed to improve the testing setup and the readout software.

6. – Conclusions

The ITk Pixel innermost layer will have to face extremely high fluence that is foreseen to reach a peak value of $2 \cdot 10^{16}$ n$_{eq}$/cm^2 (considering a 1.5 safety factor) at the half of the High-Luminosity program. Therefore 3D-pixel sensors have been chosen to instrument it. Fifteen 25x100 μm^2 pixel-pitch sensor tiles, produced by FBK, have been hybridized

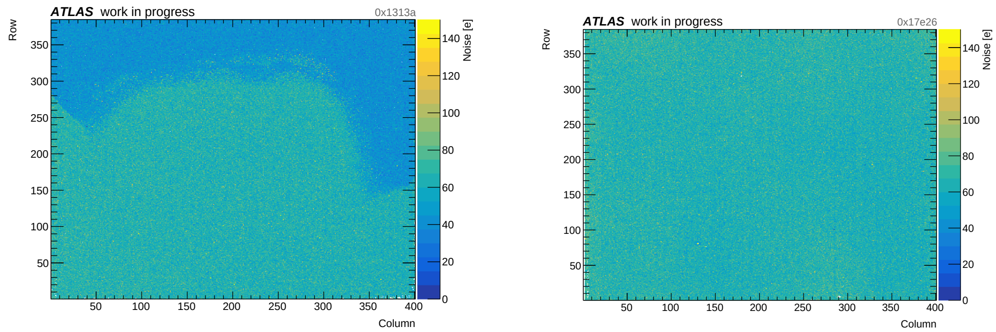

Fig. 3. – Noise map of FBK 50x50 μm^2 module hybridized at IZM: the lower noise region is a hint of a disconnected bumps area (left). Noise map of FBK 25x100 μm^2 module hybridized at LND: overall bump connectivity is excellent (right).

to ITkPix v1.1 readout chip by Leonardo SPA. Nine bare modules have been mounted on SCC at the INFN Genova laboratory for quality control evaluation. All the bare modules except one met the requirement on breakdown voltage and leakage current and have provided important results to improve the quality of the interconnection between the sensor and the front-end electronics. The ITk project is now moving to the production phase, therefore the first pre-production R05 triplet module for the innermost layer has been assembled at the INFN Genova site using a dedicated pick&place machine, showing the capability of the machine to build a triplet module within the ITk mechanical specifications and paving the way to a full-scale module production.

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