5.3 Devices

Figure 5.2: Planar (double chip) and 3D (single chip) IBL modules.

The IBL read-out chip, FE-I4, was designed in 130 nm CMOS technology to cope with higher radiation levels (250 MRad) and larger occupancies. It has a total size of 20.2×18.8 mm² (5 times larger than the FE-I3, Figure 5.3) and consists of 26880 pixel cells organized in a matrix of 80 columns (50 µm pitch) by 336 rows (250 µm pitch).

Figure 5.3: Comparison of the FE-I4 and FE-I3.

5.3.2 ITk strip

The ITk strip modules used in 2017 and 2018 tests are made by strip silicon sensors (ATLAS12) wire-bonded to ABC130 readout chip [49] and placed on a DAQLoad test board, from which LV, HV and data transfer is provided. In 2017 a single module with 104 strips was used, while in 2018 two different modules were tested, with (64 strips) and without (128 strips) the Punch-Through Protection structure (PTP). In particular, one of the sensors was a standard strip sensor with standard PTP design (typically ∼20 µm distance from the implant to the bias ring) while
the second sensor had virtually no PTP (with an unusual long distance from the implant to the bias ring of 70 \( \mu \text{m} \)). In a beam-loss scenario, silicon strip sensors could accumulate large amounts of charges in the bulk, collapsing the electric field, and producing high voltages in the strip implants. In order to prevent this situation, ITk strip sensors have been equipped with PTP for each strip, reducing the distance between the strip implant and the bias rail. One of the goal of this test is to check the effectiveness of the PTP structure in order to contribute to the choice of a proper PTP design for the ITk strip detectors.

## 5.4 Setup

The ATLAS silicon modules were mounted on frames, hosted in a dedicated box placed on the experimental table 3 (slot C) in the TNC tunnel (Figure 5.4). The supporting table (aluminum), provided by the HiRadMat facility, was fixed with respect to the beam position. A detailed description of the box and its components is available in the following Sections.

![Figure 5.4: ATLAS test box placed on the experimental table 3 in the TNC tunnel.](image)

### 5.4.1 Box and frames

The test box (epoxy fiber glass, makrolon and aluminum) was designed to host up to 8 modules on dedicated frames. The modules are loaded on fiber glass frames within the test box (Figure 5.7), aligned perpendicularly to the beam, with the beam spot centered on the modules. The same box was used in 2017 and 2018 tests: thanks to the gained experience, several improvements were introduced in the experimental setup in 2018.
5.4 Setup

In 2017, the modules were not in a fully dark environment because the box was partly built with glass walls and it was not possible to completely switch off the tunnel lights. Therefore, before the 2018 test beam, the box was covered with aluminum tape in order to have a completely dark environment for the modules, beneficial for the operations (better tuning, reduced noise).

During the 2017 test, the modules received secondary radiation from the RotColl experiment placed in the upstream table. In 2018, it was decided to mount the box on a remotely-controlled motorized system (Figure 5.6), in order to move the box out of the beam in case of spurious beam shots or shots dedicated to other experiments in order to better monitor the received dose.

5.4.2 Cooling

Due to the high radiation environment, the material of the modules would heat up after the beam impact. To keep the temperature below the damage threshold (i.e. avoid the melting of the silicon), the box was equipped with a simple cooling system: four 12×12 cm² fans (Figure 5.5), two for injecting air inside the box and
two for ejecting air outside it. The fans were equipped with filters to avoid dust and any other possible particle to enter or exit the box because of the air flow. This was required especially to avoid radioactive contamination in case of melting of the silicon detectors during the experiment.

During the 2017 test, the temperature raised up to 60°C on the IBL modules\(^2\). For the 2018 test, the dissipation was improved for the IBL module. The IBL planar module is made by two FE-I4 chips: it was decided to use only one chip for the irradiation experiment, while the other one served as a metallic contact to transfer the heat to an aluminum foil connected to two aluminum heat sinks (Figure 5.8). Additionally, a heat transfer compound (RS 503-357) was spread between the module, the aluminum foil and the heat sinks, in order to improve the thermal conductivity. The performance of this setup was proved in laboratory with a thermal camera: thanks to the improved dissipation, the operational temperature of the device has decreased from 52°C to 34°C. The chip used as a metallic contact was not powered in order to further reduce the heat production, removing the wire-bonding lines that supply sensors and electronics. The operational temperature of the IBL module was monitored during the 2018 experiment, the value was constant at about 36.5°C.

### 5.4.3 Dose measurement

As already mentioned, during the 2017 test, the modules received a certain amount of secondary radiation from the beam pulses hitting the RotColl experiment. It was not possible to estimate the amount of radiation received during the week of RotColl operation.

In order to have a direct estimate of the particle fluence deposited in the ATLAS modules during the 2018 test, a separate system to measure the dose was developed (visible in Figure 5.5 and 5.6): two additional insertable and easily removable frames were mounted on the front and on the back of the test box. Each frame supported a passive aluminum foil over the windows where the beam enters or exits the box.\(^2\)

\(^2\)The temperature was monitored with NTC thermistors embedded in the IBL modules.
Figure 5.8: Planar IBL module (2018) loaded on the frame, with improved heat dissipation.

The aluminum foil is divided in 100 squares (with a 10×10 grid); the squares are properly numbered in order to know their exact position with respect to the beam and the modules, once singled out for dose measurement. During the irradiation, the aluminum nuclei are activated through the process $\text{Al}^{27} (p, X) \text{Na}^{22}$. Once the experiment is completed, the activity of the $\text{Na}^{22}$ isotope is measured on each aluminum square using germanium spectrometers at the CERN IRRAD facility. From the front and rear direct measurements, it is possible to interpolate the fluence measurements and to extrapolate the value to the different modules.

5.5 IBL measurements

Differently from the standard HiRadMat experiments, which are performed on passive materials (such as collimators, targets, magnets), the ATLAS setup was made of active sensors. Therefore, the live monitoring of the state of these modules involved the powering and the readout of the signals. Several power supplies were used: low voltage supplies for the front-end electronics, the read-out boards, the fans; high voltage supplies for the bias of the silicon sensors. The whole system was connected to PCs and remotely controlled (see Figure 5.9).

In this Section, the measurements performed on IBL modules are described. The IBL modules were controlled through the USBpix setup [65], via the STControl software. The hardware consists of a Multi-IO board connected to an adapter card (see Figure 5.10). The Multi-IO board, developed at SiLab in Bonn University, is interfaced to the PC with a micro USB controller. The adapter card, dependent to the FE used, receives the signal from the module via ethernet cable and is powered by a low voltage supply. STcontrol, a C++ and ROOT based software application

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3 Gamma spectroscopy, $\text{Na}^{22}$ peak: 1274.53 KeV.
5.5 IBL measurements

Figure 5.9: PCs, power supplies and readout boards installed in the TT61 tunnel for the 2018 experiment.

based on the ATLAS PixLib package, is used to perform scans. Additional C++ software was used to remotely control the power supplies and to perform IV scans. The IBL modules were configured to specific operational parameters\(^4\) sent through the USBPix setup.

Figure 5.10: USBPix hardware: readout board used for IBL modules during 2017 and 2018 experiments.

The tests on IBL modules were performed between two shots, because the FE was deconfigured after the beam transit. Several different scans were performed:

- digital and analog scan: check the FE analog and digital functionality;
- threshold scan: measure the occupancy at different injected charges for a fixed threshold;

\(^4\)Tuning values: threshold at 3000 electrons, TOT at 10 bunch crossing at 10000 electrons.
5.5 IBL measurements

Figure 5.11: Threshold and relative noise distribution for each pixel of 2018 IBL module after tuning to 3000 electrons in a dark environment.

Figure 5.12: Noise measurement from Threshold scans performed before (left) and after (right) the beam: the noise increases in correspondence of the irradiated region.

- self-triggering scan: measure the material activation after irradiation;
- IV scan: measure the leakage current at different bias voltages.

The basic functionality of the IBL module was quickly checked after the beam transit, performing digital or analog scans. In case these scans were not responsive, the supplies were power-cycled and a reconfiguration of the module was performed.

Threshold scans have been performed, with HV on, to measure the noise increase due to the beam irradiation. The response curve of the threshold scan may be fitted with a gauss error function of sigmoid shape. The width of the corresponding gaussian can be identified as the noise. For a non irradiated module, the noise value corresponds to about 130 electrons (ENC): 30 electrons from sensor leakage current and bulk capacitance and 100 from the electronics. After the beam irradiation, the noise increases in correspondence of the irradiated region up to 300 electrons (see Figure 5.12).

The self-triggering scan (also referred to as source scan) is usually performed in laboratory to check the full functionality of the module. A trigger signal is generated with a Hitbus formed by the outputs of the individual pixel comparators ORed together. During the quality assurance, a radioactive source (i.e. Am$^{241}$) is
placed on top of the module and the signal produced by the gamma rays cascade is registered thanks to the self-triggering.

During the 2017 HiRadMat experiment, a self-triggering scan was performed after the beam: it was noticed that the part of the detector crossed by the beam has become itself a source of radiation, because of the material activation. The hit occupancy per pixel is shown in Figure 5.13: the two spots corresponding to the 2 mm and the 0.5 mm radius beams are visible.

![Material activation of the 2017 IBL module in terms of hit occupancy after the 2 mm (central big spot) and 0.5 mm (small spot on the right side) beam operations.](image)

The leakage current was measured as a function of the sensor bias voltage (IV characteristic) during the test. During laboratory tests, a current limit of 10 $\mu$A is used to protect the modules. After the beam irradiation, the leakage current increases and therefore it is necessary to increase the current limit in order to achieve the full depletion of the sensor (see Figure 5.14).

### 5.6 IBL results

The first and main result of the experiments performed with IBL modules is the survival of the module after the 288 bunches at 2 mm beam radius, with $10^{11}$ protons per bunch. Both IBL 3D modules survived to this level of radiation in 2017, as well as the IBL planar module in 2018.

Therefore a lower limit on the damage threshold of IBL modules can be conservatively set at $1 \cdot 10^{13}$ protons/cm$^2$. The limit is calculated taking into account $288 \cdot 10^{11}$ protons delivered in a single pulse of 7.2 $\mu$s over an effective irradiated region (square) of 0.5×0.5 cm$^2$. 
5.6 IBL results

Figure 5.14: IV scans performed on IBL module during 2018 test: the leakage current increases after irradiation, reaching the current limit (set to 10 μA) after 24 bunches.

The new limit is three orders of magnitude larger than the previous limit [56], however it should be noted that, despite the number of protons and the delivered energy per pixel are higher in the 2017/2018 tests with respect to the 2006 experiment, the total energy deposited in the module is similar in the two tests.\(^5\)

During 2017, the modules were tested as well with 0.5 mm radius beam pulses, increasing the intensity up to 288 bunches. After the last shot with 288 bunches, the FE-I4 was irreparably damaged on both IBL modules. Although a small bump on the Flex-Hybrid is visible under a microscope in correspondence of the spot where the last 288 bunches 0.5 mm beam shot was delivered, the electrical lines of the Flex-Hybrid circuitry are working. Detailed post processing inspections seem to indicate the presence of a short circuit between ground and analog voltage in the read-out chip. Because of this issue, it was not possible to supply the modules anymore, inhibiting any post-experiment measurement.

In order to keep safe the 2018 IBL module for post-experiment measurements, after completing the wide beam tests, it was decided to stop the narrow beam tests at 12 bunches. The IBL module survived and it is now in ATLAS Genoa laboratory for post-experiment measurements.

The damage suffered by the silicon detectors during beam irradiation is well known and studied. Because of the bulk and surface radiation damage, the leakage current increases linearly with the fluence [66]. During the 2018 experiment, the leakage current of the IBL module was systematically measured after each pulse. The full series of measurements is visible in Figure 5.15: the leakage current increases after irradiation, reaching 170 μA at 80 V after 228 bunches.

\(^5\)The beam is perpendicular to the modules in 2017/2018 tests, while it goes through the whole module in 2006 experiment (beam parallel with respect to the module).
Figure 5.15: IV scans performed on IBL module after the beam irradiation: the leakage current increases after irradiation, reaching 170 \( \mu \text{A} \) after 228 bunches.

The linear relation between the leakage current increase and the fluence is summarized by the relation:

\[ \Delta I = \alpha \Phi V, \]  \hspace{1cm} (5.1)

where \( \Delta I \) is the increase of the current measured before and after the irradiation, \( \alpha \) is the linear coefficient, \( \Phi \) is the proton fluence and \( V \) is the volume. The linear relation between the leakage current, normalized over the sensor volume, and the fluence is verified (see Figure 5.16), taking into account the measurements performed on the 2018 IBL module at 80 V bias and at a constant temperature of about 36.5\(^\circ\)C, after each beam pulse.

A detailed analysis was performed to correlate the degradation of the performance of the modules to the proton fluence received. The performance was measured for each pixel in terms of increase of the noise, extracted from threshold scans. The proton fluence per pixel was simulated taking into account the position of the beam, the X and Y width of the beam, assuming a bidimensional gaussian profile, the number of bunches and the number of protons per bunch. The estimated fluence in terms of number of protons per pixel reaches \( 13 \cdot 10^9 \) in the center of the beam spot (see Figure 5.17, left), after the whole series of 2 mm beam pulses, during the 2018 experiment. In the irradiated region, the noise reaches values up to 300 electrons (see Figure 5.17, right), while on the top and left corners the noise remains stable at about 120 electrons. The full series of noise measurements, along with the corresponding simulated proton fluences, is reported in the Appendix 12.

There is a clear correlation between the proton fluence and the noise increase, as can be seen in the distribution in Figure 5.18: each point corresponds to a pixel,