Study of damages induced on ATLAS silicon by fast extracted and intense proton beam irradiation

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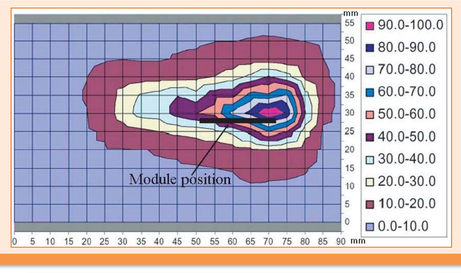
C. Bertella[1], C. Escobar[2], A. Gaudiello[3], G. Gariano[3], C. Gemme[3], S. Katunin[4], A. Lapertosa[3,5], M. Miñano[2], A. Rovani[3], E. Ruscino[3], A. Sbrizzi[6]

[1] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
[2] Instituto de Fisica Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Spain
[3] INFN Sezione di Genova , Genova, Italy
[4] Petersburg Nuclear Physics Institute, St. Petersburg, Russia
[5] Università degli Studi di Genova, Genova, Italy
[6] INFN Sezione di Bologna, Bologna, Italy

Abstract

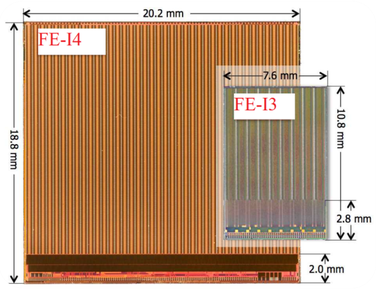


The ATLAS silicon tracker detectors are designed to sustain high dose integrated over several years of operation. The radiation hardness should also favour the survival of the detector in case of accidental beam losses. In 2006, measurements [NIM A, 565 (2006) 50-54] were published for the ATLAS Pixel detector modules (silicon planars hybridly coupled with FE-I3 electronics), confirming that they could survive to beam losses (1.5×10^{10} protons/cm^2 in a single bunch) with minimal or no deterioration of performance. In this poster, preliminary results are shown, reporting the effect of a very intensive proton beam releasing a high instantaneous dose in two Insertable B-Layer (IBL) pixel and one Inner Tracker (ITk) strip module detectors at High-Radiation to Materials (HiRadMat) Facility of CERN Super Proton Synchrotron (SPS).

Devices Under Test

For this test a new generation of ATLAS pixel modules have been used. The new modules were developed for the new layer IBL and inserted inside the pixel detector in 2014. They are at least a factor 5 more radiation-hard than the modules used in the previous test.

The two modules have **FE-I4 front-end electronics (total area ~2 x 2 cm^2)** coupled with a 3D silicon sensor. A module has 26680 pixels (50x250 μm^2 pitch).



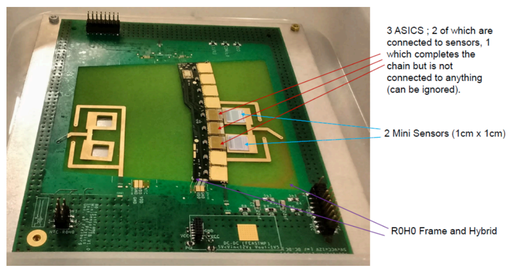
Parameter	FE-I4	FE-I3
Number of Pixels	26880	2880
Pixel Unite Size	250×50 μm^2	50×400 μm^2
Nominal Analog Voltage/Current	1.4 V/12 μV	1.6 V/16 μV
Nominal Digital Voltage/Current	1.2 V/6 μV	2.0 V/10 μV
Nominal Clock Input Frequency	40 MHz	40 MHz
Nominal Data Output	160 Mb/s	140 Mb/s

FE-I4

- Produced by **IBM** 130 nm technology to cope with higher radiation levels (750 Mrad) and larger occupancies
- 70 Million transistors
- 89% active area
- Lower noise than FE-I3 (~150 e$^-$ with sensor)
- Local hit storage (four pixel region) supports higher occupancies without saturation

ITk Strip Module for HL-LHC

It consists of two 1 x 1cm^2 silicon strip sensor (ATLAS12) wire-bonded to a readout chip (ABC130)



Front-End: ABC130

- Fabricated in the 8RF **IBM** 130 nm CMOS
- Data readout at a rate of 80 MHz

Sensor: ATLAS12

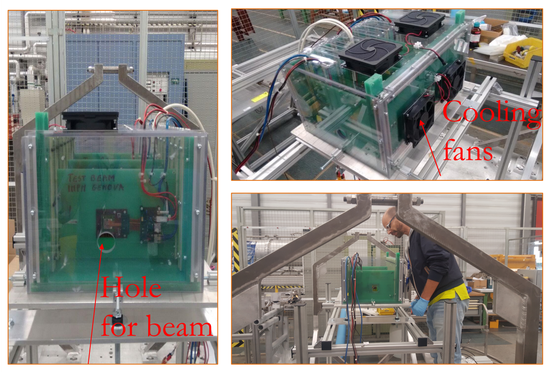
- Consisted of 104 strips (74.5 μm pitch in 2 rows) with punch through protection (PTP) structures
- All data were multiplexed through the hybrid control chip (HCC), and routed via a custom designed PCB along with HV and LV connections.
- The HCC interfaces the ABC130 ASICs on the hybrid to the to end of structure electronics.

The HiRadMat Facility at CERN

HiRadMat is a users facility at CERN, designed to provide high-intensity pulsed beams to an irradiation area where material samples can be tested.

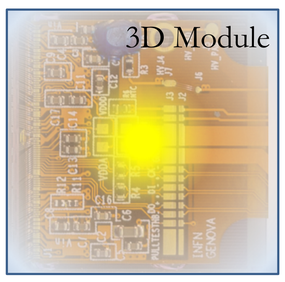
The facility uses a 440 GeV proton beam extracted from the CERN SPS with a pulse length of 7.2 μs, to a maximum pulse energy of 3.4 MJ. In addition to protons, ion beams with an energy of 173.5 GeV/nucleon and a total pulse energy of 21 kJ can be used.

Installation and Performed Tests

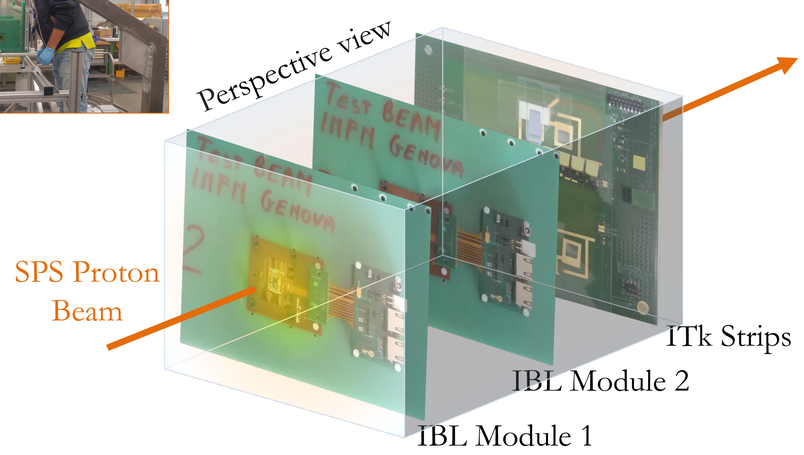


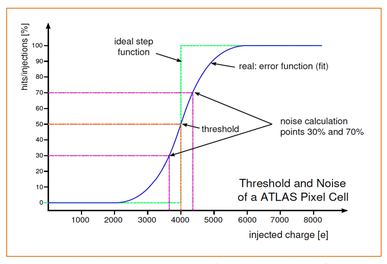
The test box can host up to 8 modules on dedicated frames

Due to the high radiation environment the box is equipped with only a cooling system which consists in four fans, but it allows to keep the temperature at ~ 40 °C



Front View





The typical outcome of a threshold scan: an S-curve for each pixel

The tests on IBL Modules were performed during beam inter-fill to avoid loosing the FE configuration during the shots.

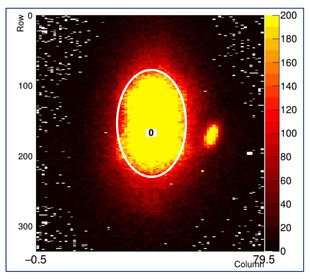
Performed Scans:

- **Digital and Analog:** Check the FE analog and digital part functionality
- **Threshold:** It measures the occupancy at different injected charges for a fixed threshold (2500 e). In the pixels the response curve may be fitted with a sigmoid curve, where the slope is a characteristic of the noise. In not irradiated modules it corresponds to about 30 electrons equivalent from leakage current and sensor capacitance and about 100 electron equivalents from the electronic (FE) noise.
- **Self-triggering:** In this modality the outputs of the individual pixel comparators are ORed together to form a Hitbus that is used as a trigger signal.

Unfortunately the communication with the ITk readout chip was not possible, for this reason only the leakage current of the strip sensor was continuously monitored.

The detectors have been irradiated with an increasing proton density

Beam spot $\sigma_x = \sigma_y$	Spacing	#protons (x10^{11})	Pulse lenght [μs]
2 mm	25 ns	0.3, 3, 6, 12, 18, 24, 20, 36, 72, 288	0.025, 0.15,0.3, 0.6, 0.9, 1.2, 1.5, 1.8, 3.6, 7.2, 7.2
0.2 mm	25 ns	0.5 (x4), 30, 60, 120, 180, 360, 740,1440	0.025 (x4), 0.15, 0.3, 0.6, 0.9, 1.8, 3.6, 7.2



Two IBL modules configurations were used in 2 different configurations:

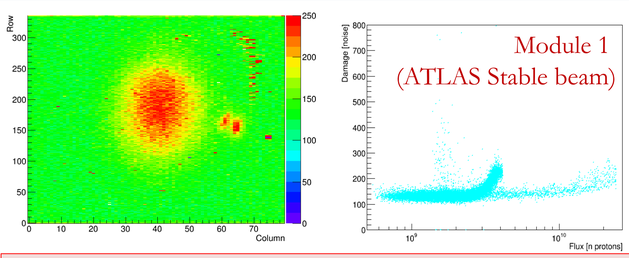
- ATLAS in Standby: sensor bias and FE preamplifiers off, this configuration is used in unstable beam conditions to avoid local shorts in the sensors, or damages in FE electronics due to heavily ionizing particles (e.g. gate rupture in CMOS transistors)
- ATLAS in Stable beam operation: sensor bias and FE amplifiers on

On the left the effect of the 2 mm and 0.2 mm optics are visible after the shot using the self-trigger scan of the FE-I4 due to material activation.

Preliminary Results

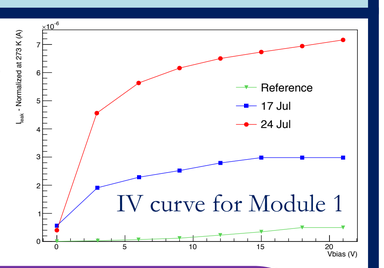
In the inter-fill, Threshold scans have been performed with HV on. Results are shown on the left (top and bottom for the two modules). On the left panels the noise maps, where it is shown that the noise increases in correspondence of the beam spot.

On the right the correlation between the noise and the proton flux of one shot is shown.

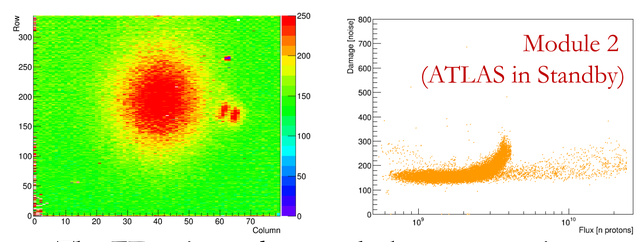


The variation of leakage current of the sensor, normalized at 273 K, for different days. Also here the current follows the beam intensity.

The noise of the first amplification stage of FE-I4 is strictly dependent from that.

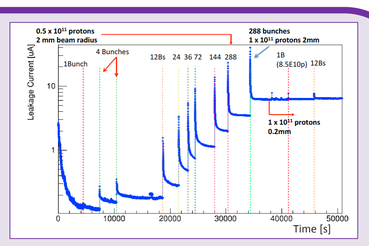


Both modules have been tested with sensor V_{bias} on



The FE noise and sensor leakage current increased constantly after each shot. The last 288 bunches shot with 2 mm optics caused a short in FE at pixel level.

ITk strip Module Results



Increase of the leakage current with global irradiation (2 mm optics)

The increment of leakage current follows the increase of the beam intensity

Conclusions

The ITk sensors are able to drain the charge density generated in the bulk without evident radiation damages. The test has to be repeated with a system to monitor readout signals.

After the last shot the FE-I4 was damaged irremediably. The problem seems to be a short between ground and analog voltage in the incident beam region at pixel level.

The lower limit for IBL modules on radiation damage has been evaluated at ~10^{13} mips/cm^2 for 288 bunches case at large beam spot.

Further investigations are currently ongoing and new tests are planned for 2018.