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

Introduction

The ATLAS silicon tracker detectors are designed to sustain high integrated dose over several years of operation at the LHC. Such level of radiation hardness should also favour the survival of the detector in case of accidental beam losses.

The upgrade of LHC to higher luminosity (HL-LHC) calls for new tests. **Study effects of accidental beam-loss scenarios for ATLAS tracking detector (Pixel and Strips) at HL-LHC.**

- Provide a realistic estimate of the damage threshold for sensors and electronics.
- Evaluate the performance degradation due to the radiation damage.
- HL-LHC failure scenarios: asynchronous beam dump or wrong injection settings.

To cope with the future accelerator ($L_{\text{int}} > 7.5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$), ATLAS is planning a complete update of the detector.

- The **new inner tracker (ITk) will be an all Si Tracker system** which will replace the current ID (Pixels, SCT + TRT)
Studies done in 2006

The effects of accidental beam losses were tested using a 24 GeV proton beam at the CERN PS on, NIM A565 (2006) 50-54:

• ATLAS Pixel modules: radiation hardness up to $10^{15} \text{n}_{\text{eq}}/\text{cm}^2$ with FE-I3.
• LHC worst scenario: pilot beam scraping the front quadrupole absorbers (TAS).
• Demonstrated that Pixel modules were robust to this scenario, up to $10^{10}$ protons/cm$^2$ in a single pulse with 213 bunches.

TAS is a copper cylinder placed inside the ATLAS shielding system 1.9 m long, $R = [17 \text{ mm}, 250 \text{ mm}]$, $Z = 19.04 \text{ m}$.
The beam pipe will not be in the shadow of the TAS at HL-LHC.

The beam will be much more focused at the IP.

The asynchronous beam dump: the extraction kicker field switch-on is not synchronised with the abort gap [Animation].

- Unlikely off-orbit protons hit directly the experiments.
- Possible scenario: protons hit the TCT4 collimators (120 m away from the IP) and shower into the experiments.
HiRadMat Facility

- Facility at CERN providing high-intensity pulsed beam.
- 440 GeV proton beam extracted from CERN SPS.
- 3 experimental test stands.

**Proton Beam Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy</td>
<td>440 GeV/c^2</td>
</tr>
<tr>
<td>Pulse Energy</td>
<td>up to 3.4 MJ</td>
</tr>
<tr>
<td>Bunch intensity</td>
<td>up to $1.2 \times 10^{11}$ protons</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>1 to 288</td>
</tr>
<tr>
<td>Maximum pulse intensity</td>
<td>$4.0 \times 10^{13}$ protons</td>
</tr>
<tr>
<td>Bunch length</td>
<td>11.24 cm</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>25, 50, 75 or 150 ns</td>
</tr>
<tr>
<td>Maximum pulse length</td>
<td>7.2 μs</td>
</tr>
<tr>
<td>Cycle length</td>
<td>18 s</td>
</tr>
<tr>
<td>Beam radius at target</td>
<td>0.5 to 2 mm</td>
</tr>
</tbody>
</table>

**Fixed 90° impact**
HiRadMat Facility

- Two separated tunnels: beam line with experimental tables (TNC), and powering/read-out system (TT61).
- Long cables pass through a concrete wall connect the experimental setup to powering, and read-out.
- Operation on the modules must be remotely controlled.
Text Box

Design and construction of the test-box:

- Material: epoxy fiber glass, makrolon and aluminium.
- Designed to host a maximum of 8 detector modules mounted on dedicated frames: module frames separated by 5 cm.
- Cooling system: 4 fans (12x12 cm) with filters.
  - In 2017: important temperature variation affected modules performance
  - Aluminium plane and dissipator added in 2018 to stabilise the temperature for IBL module.
Beam-loss studies July 2017: Modules

- ITk strip miniature sensor available for the beam test.
- ITk Pixel prototype with RD53A not available at that time, used most advance technology IBL.
  - Not proper cooling system, no constant temperature: \( T \sim [30, 60] ^\circ C \)

<table>
<thead>
<tr>
<th>Module</th>
<th>IBL</th>
<th>ITk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>n(^+)-in-p, 3D</td>
<td>n(^+)-in-p, ATLAS12</td>
</tr>
<tr>
<td>Chip</td>
<td>FE-I4</td>
<td>ABC130</td>
</tr>
<tr>
<td>Total Size</td>
<td>2x2 cm(^2)</td>
<td>1x1 cm(^2)</td>
</tr>
<tr>
<td>Thickness</td>
<td>230 ( \mu )m</td>
<td>320 ( \mu )m</td>
</tr>
<tr>
<td>Channel/pitch</td>
<td>26680 (50x250 ( \mu )m(^2))</td>
<td>104 (74.5 ( \mu )m)</td>
</tr>
<tr>
<td>Max. Dose</td>
<td>250 MRad</td>
<td>35 MRad</td>
</tr>
</tbody>
</table>
Beam-loss studies July 2018: Modules

- ITk strip miniature sensor available for the beam test.
- ITk Pixel prototype with RD53A not available at that time, used most advance technology IBL
  - Improved cooling system via aluminium and dissipator: $T \sim 36^\circ C$

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<th>ITk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>$n^+\text{-in-n}$, Planar $n^+\text{-in-p}$, Low-R</td>
<td></td>
</tr>
<tr>
<td>Chip</td>
<td>FE-I4</td>
<td>ABC130</td>
</tr>
<tr>
<td>Total Size</td>
<td>2x4 cm$^2$</td>
<td>0.7x2.6 cm$^2$</td>
</tr>
<tr>
<td>Thickness</td>
<td>200 $\mu$m</td>
<td>310 $\mu$m</td>
</tr>
<tr>
<td>Channel/ pitch</td>
<td>2x26680 (50x250 $\mu$m$^2$)</td>
<td>64 (77 $\mu$m)</td>
</tr>
<tr>
<td>Max. Dose</td>
<td>250 MRad</td>
<td>35 MRad</td>
</tr>
</tbody>
</table>

- Improved cooling system via aluminium and dissipator: $T \sim 36^\circ C$
Detector irradiated with an increasing proton density with pulse length, 25 ns x Num. of bunches.

- Number of proton per bunch is $10^{11}$.
- Fixed step in number of bunches provided by SPS.
- Two beam spots used: global/local irradiation.

### Beam pulse list

<table>
<thead>
<tr>
<th>Beam spot $\sigma_X = \sigma_Y$</th>
<th>Naming</th>
<th>Spacing [ns]</th>
<th>Num. of Bunches</th>
<th>Proton intensity</th>
<th>Total proton</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>beam-test 2017</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 mm</td>
<td>global irradiation</td>
<td>25</td>
<td>1,4,12,24,36,7 2,144,288/288</td>
<td>$10^{10}/10^{11}$</td>
<td>$5.8 \cdot 10^{13}$</td>
</tr>
<tr>
<td>0.4 mm</td>
<td>local irradiation</td>
<td>25</td>
<td>1,12,72,288</td>
<td>$10^{11}$</td>
<td>$3.7 \cdot 10^{13}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>beam-test 2018</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 mm</td>
<td>global irradiation</td>
<td>25</td>
<td>1,4,12,24,36,7 2,144,288</td>
<td>$10^{11}$</td>
<td>$1.16 \cdot 10^{13}$</td>
</tr>
<tr>
<td>0.5 mm</td>
<td>local irradiation</td>
<td>25</td>
<td>1,12</td>
<td>$10^{11}$</td>
<td>$2.6 \cdot 10^{12}$</td>
</tr>
</tbody>
</table>
Beam-test 2017
Two IBL modules configurations were used in 2 different configurations.

- **ATLAS in Standby**: sensor bias and FE preamplifiers off.

- **ATLAS in Stable beam operation**: sensor bias and FE amplifiers on.

In the inter-fill, tests **were performed with sensor bias on for both modules**.

- **Threshold scan** measures the occupancy at different injected charges for a fixed threshold (2500 e\(^{-}\)).

- **Response curve** fitted with a sigmoid curve, where the **slope is a characteristic of the noise**.
Two IBL modules configurations were used in 2 different configurations:

- **ATLAS in Stand-by**: sensor bias off and FE preamplifiers off.
- **ATLAS in Stable beam** operation: sensor bias on and FE amplifiers on.

Correlation between performance degradation and proton fluence

- Noise increase per pixel used as figure of merit.
- Proton beam simulated to take into account beam position.

**Noise level**: Pre-Irr 130 e⁻ → Post-Irr 300 e⁻

**NB**: Results updated wrt Hiroshima2017
IBL 3D: Material Activation

- **Source scan:** In this modality the outputs of the individual pixel comparators are ORed together to form a Hitbus that is used as a trigger signal (Self-Triggering).

- **Self-Triggering** scan shows that the sensor is acting as a radiation source due to material activation.

- Two spots corresponding to the two beam positions are visible.
The variation of leakage current of the sensor, normalised at 273 K, for different days.

- Temperature not under control: $T \sim [30, 60] ^\circ C$
- Leakage current follows the beam intensity.
- Noise of the first amplification stage of FE-I4 is strictly dependent from that.

Leakage current measured as function of the sensor bias voltage.

- The FE noise and sensor leakage current increased constantly after each shot.
  - Higher limit allowed to reach full depletion.
Local Irradiation: 0.4 mm beam.

- Detector dead after 288 bunches.
  - FE supply in short.
- Small bump on the Flex-Hybrid visible under microscope, caused by a short between ground and analog voltage.

Global irradiation: 2 mm beam.

- Beam spot due to material activation (after glow).
- The intensity of the spot was increasing after each shot.
- The intensity of the spot was decreasing with time.

Limit on the damage threshold with large beam spot: $1 \cdot 10^{13}$ p/cm$^2$

- Radius of damage: 15 pixels ~0.38 cm

IBL 3D: 2017 summary
ITk: Global and Local irradiation

**ITk strip (Global irradiation)**

Increase of the leakage current with global irradiation (2 mm optics).
The increment of leakage current is approximately linear with the beam intensity.

Detector still alive after 288 bunches ($10^{11}$ protons).

**ITk strip (Local irradiation)**

- Shots of bunches with $1 \times 10^{11}$ p/bunch and 0.3 mm beam + Beam-based alignment runs with $0.5 \times 10^{11}$ p and ~0.4 mm beam

- Shots of bunches with $1 \times 10^{11}$ p/bunch and 0.4 mm beam

Probably detector died after 288 bunches.
IBL Planar: IV scan

- Module tested in Stable beam configuration.
- Bulk and surface damage post-irradiation, cause a linear increase of the leakage current with the fluence.
- Monitoring of leakage current after each shot.
  - Increase after irradiation: ~230 μA at 80 V.

\[ \Delta I \approx \alpha \Phi V \]

- \( \Delta I \): increase of leakage current before and after irradiation;
- \( \Phi \): integrated proton flux (0-288 \cdot 10^{11})
- \( V \): Volume= Surface x thickness (230 μm sensor);
- \( \alpha \): Current related damage rate;

Bias: 80 V, Temperature~36°C
Correlation between performance degradation and proton fluence

- Noise increase per pixel used as figure of merit
- Proton beam simulated to take into account beam position
- Estimated fluence at beam centre: $13 \cdot 10^9$ p

Noise increasing starts after 4 bunches, and constantly increases after each pulse following a specific trend.

Beam simulation:
- $288 \cdot 10^{11}$ p
- Noise ~ 300 e
- Noise ~ 120 e
ITk strip: Leakage current evolution

Increase of the leakage current with global irradiation

The increment of leakage current is approximately linear with the beam intensity.

- $\Delta I$: difference of the LC after few minutes from the shot and the original value (pre-irradiation)
- $V$: beam spot time sensor thickness

Preliminary Sensor bias: -150 V

Preliminary
The threshold scan is performed by injecting a constant charge and varying the threshold value of the discriminator from zero to its maximum.

- At each threshold level several charge injections are performed.
- Measured average hit rate versus threshold —> S-curve

Extract Vt50 and sigma for different input charges —> the gain and input noise.

For each injected charge the Vt50 point is plotted as a function of the charge —> Response Curve.

- By fitting the RC the gain [mV/fC] of the input stage is obtained.
- Equivalent Noise Charge (e− ENC) can be obtained.

\[
ENC = \frac{\sigma [mV]}{\text{gain}[mV/fC]}, \quad 1fC = 6241e^-
\]
Monitoring the 64 channels with each beam shot.

Gain and Noise displayed for few beam shots.

Used those variables to define the sensor performance.
Initial values:

- Noise: 5200 e⁻.
  - High nominal noise associated to temperature and circuit.
- Gain: 77 mV/fC.
- Level of Noise or Gain used to characterise the strip behaviour.
- ~40% of the strip shows good performance.

Noisy: noise > 40000 e⁻
Damaged: noise < 3000 e⁻
OK: 3000 e⁻ < noise < 40000 e⁻
Channel behaviour: around the beam

Sensor slices to study behaviour near(far away) the beam centre.

- **[0, 1] mm**: 26 strips
- **[1, 2] mm**: 24 strips
- **[2, rest] mm**: 14 strips

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**C. Bertella**

23-October-2018
Conclusion: IBL

- Three IBL modules were tested with different configurations with SPS beam @HiRadMat facility.
- Two configurations used to reproduce ATLAS standard operation status when LHC deliver stable or non-stable beams.
- Two different IBL structure tested: 3D and Planar.
- Noise increases around the beam spot in a similar way for the three modules.

IBL 3D: stable-beam

2017

Effect 2mm radius beam

IBL 3D: stand-by

2017

Effect 0.5mm radius beam

IBL Planar

2018

Limit on the damage threshold from $300 \cdot 10^{10}$ p/cm$^2$ (2006) to $1 \cdot 10^{13}$ p/cm$^2$ (2017/18)
Conclusion: ITk

- Increase in leakage current follows the increase of beam intensity.
- Noise level increases as a function of the proton flux, while gain decreases.
- Fraction of fully working channels decrease with the increase of the dose received.
  - Large effect observed around the beam centre.
- Sensors presents an acceptable damage when exposed to $1 \cdot 10^{11}$ p with 2 mm beam radius.
  - Limit on the damage threshold $8 \cdot 10^{11}$ p/cm$^2$ (2018).
- Not macroscopic or physics damages on sensor and chip are visible even at the instantaneous change density of $288 \cdot 10^{11}$ p.
  - On-going investigation of sensor oxide, checking possible break/failure in sensor structure.
Thanks for your attention!

Acknowledgments to

ATLAS ITk

HiRadMat team

ARIES

CERN FLUKA team
Initial condition: noise and gain

\[ \mu = 76.91, \sigma = 6.74 \]

\[ \mu = 5238.0, \sigma = 919.11 \]
**Analog Test**
Each pixel contains test hit injection circuitries. Analog test signals are injected using a voltage step defined by the calibration voltage ($V_{cal}$) and two test charge injection capacitances ($C_{in j1/2}$), which can be selected independently.

**Digital Test** detects failures in the global and pixel registers that may affect the proper configuration of the module. It also tests the readout chain and detects defective channels.

1. for each pixel, 200 pulses are fed at low frequency to the output of the discriminator, simulating the discriminator signal when a preamplifier pulse triggers the discriminator. This part of the test checks the readout chain from the pixel cell down to the data LVDS transmitter of the chip.

4. for each pixel, 5 short pulses are injected at high frequency to the output of the discriminator, simulating the discriminator signal when a preamplifier pulse triggers the discriminator. This test checks the functionality of the five ToT buffers for each pixel as well as the proper operation of the five LVL1 counters of each four pixel digital region.
**IBL test routine**

**Threshold Scan** performs a measurement of the threshold and noise of each pixel and is the central part of the calibration task.

- A voltage pulse $V_{cal}$ is injected on the calibration capacitance $C_{inj}$ of each pixel.
- It generates a signal at the input of the preamplifier equivalent to the one generated by a charge $Q = V_{cal} \cdot C_{inj}$.
- A set of 200 pulses is generated for different value of the injected charge (from 0 to ~10000: electrons, in ~50 electrons steps).
- The number of collected hits for each injected charge is recorded and at the end of the scan an S-Curve is fitted.
- The 50% efficiency on the S-curve defines the threshold value.
- The steepness of the transition from no detected hits to full efficiency is inversely proportional to the noise, which can be so calculated.

**Source Scan** identifies pixels that are not answering to ionisation because of either bumps defects (disconnected, merged) or read-out defects (badly tuned).

- The whole module should be exposed to the source until the number of events (hits) exceeds the target event number of e.g. 2 million hits in order to have an average occupancy of ~75 hits per pixel.
- The FE chip has a **self triggering mode**, in fact whenever a pixel comparator is high a convenient signal is generated. The comparator of each pixel in a column is ORed together to form a HitBus.
IBL Initial condition

Threshold tuning 3000e

Mean 2990
Sigma 41.27

Noise

Mean 120.6
Sigma 9.025
IBL Noise

Pre-Irradiation

After-Irradiation

Noise increases in correspondence of irradiated region
Channel behaviour

- Level of Noise or Gain used to characterise the strip behaviour.
- ~40% of the strip shows good performance.
Channel behaviour: around the beam

Sensor slices to study behaviour near (far away) the beam centre.

- [0, 1] mm: 26 strips
- [1, 2] mm: 24 strips
- [2, rest] mm: 14 strips

“High-gain level”: Gain > 100
Damaged: Gain < 40
OK: 40 < Gain < 100

Total size: 6.59 mm
Active size: 4.99 mm

Preliminary
Leakage current 2017
Beam-loss studies May 2018: Improvement

• Re-use existing material (test-box, frames, cables, readout system, etc…)

• Add heat dispersion system in Pixel modules (aluminium heatsinks)

• System to control remotely (by software) the test-box cooling fans.

• System to estimate/measure the fluence and dose deposited in the modules based on passive aluminium foils and post-irradiation gamma spectroscopy analysis (similarly to irradiations at IRRAD).

• System to control remotely the position of test-box (motorised table).

• Darken the test-box to minimise the (electromagnetic) noise due to the residual light of the tunnel.

**MOTION CONTROL**

Status: STOP Speed: -2

ON

OFF

SET PARK POSITION 0293563 SET BEAM POSITION
Beam-loss studies May 2018: Modules

Plans for IBL Pixel in May 2018

- 1x Pixel Double Chip (IBL Planar sensor + FE-I4 chip):
- 1x chip centered on beam axis
- 1x chip used as metallic contact to Al heatsinks

IBL DC module on frame + cooling
Beam-loss studies May 2018: Modules
ITk DAQloads, CNM provided p-type sensors

**DAQload from Valencia**
- 1x sensor without PTP
  - mini petalet: barrel
  - embedded: 6271_w06
- 1x ABC130

**DAQload from Freiburg**
- 1x sensor with PTP
  - LowR: 6958_w08_s1c
  - gated PTP structure
    - d=20µm / p=4µm / s=8µm
  - p-stop width = 4 µm
- 1x ABC130

CNM sensor (6271_w06)  
CNM sensor (6958_w08_s1c)
Beam-loss studies May 2018: Module

CNM provided p-type sensors

DAQload from Freiburg

- 1x sensor with PTP
  - LowR: 6958_w08_s1c
  - gated PTP structure
    - \(d=20\mu\text{m} / p=4\mu\text{m} / s=8\mu\text{m}\)
    - p-stop width = 4 \(\mu\text{m}\)
  - 1x ABC130

CNM sensor (6958_w08_s1c)

- **Size:**
  - Active part: 4.99 \(\times\) 23.960 mm\(^2\)
  - Full x-size: 6.59 mm
- Thickness: 310 \(\mu\text{m}\)
- Strip pitch: \(~77\ \mu\text{m}\)
- Num strip: 64
ITk Read-out: 2018

NB:

• Note 2 Modules installed
• Connection with Petalet module lost after installation in the tunnel
IBL modules

Single Chip (July 2017) vs Double Chip (May 2018)

2017: 1x Pixel Single Chip (IBL 3D sensor + FE-IF chip):
  - chip centered on beam axis

2018: 1x Pixel Double Chip (IBL Planar sensor + FE-I4 chip):
  - 1x chip centered on beam axis
  - 1x chip used as metallic contact to Al heat sinks

IBL SC module (3D)  IBL DC module (Planar)
IBL Read-out

Read-out board
IBL damage

Damaged IBL Pixel in July 2017

IBL module with 80x336 pixels (250x50 μm each)

<table>
<thead>
<tr>
<th></th>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>72b damage position</td>
<td>63</td>
<td>280</td>
</tr>
<tr>
<td>(Pixel)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>288b beam position</td>
<td>4.25</td>
<td>2.8</td>
</tr>
<tr>
<td>extrapolation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visible damage</td>
<td>4.28</td>
<td>2.77</td>
</tr>
<tr>
<td>position</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Both Pixel Modules
damaged by
288 bunches (0.3 mm)

Overlapping of 288b expected beam position and visible damage position
- Same damage visible both IBL pixel modules
- Flex contacts tested, working properly
- FE could be damaged instead
Axis definition

\[
Flux[p] = \sum_{i \in [1, 288]} n_{b\text{uch}}^i \cdot n_p = \sum_{i \in [1, 288]} n_{b\text{uch}}^i \cdot 10^{11}p
\]

\[
TID_{1p} = \frac{E_{\text{ionisation}}[J]}{M[Kg]} = \frac{dE}{\rho dx \cdot dS}
\]

\[
= \frac{2 \cdot MeVg^{-1}cm^2}{\pi \cdot 0.2^2 \cdot cm^2} = \frac{2 \cdot 10^6 \cdot 1.610^{-19}}{\pi \cdot 4 \cdot 10^{-2} \cdot 10^{-3}} \cdot \left[ \frac{J}{kg} \right]
\]

\[
= 25.5 \cdot 10^{-10}Gy = 25.5 \cdot 10^{-8}Rad
\]

\[
TID_{\text{Total}} = TID_{1p} \cdot Flux
\]
Beam-loss studies: Setup

Design and construction of the test-box:

- Material: epoxy fiber glass, makrolon and aluminium.
- Designed to host a maximum of 8 detector modules mounted on dedicated frames: module frames separated by 5 cm
- Cooling system: 4 fans (12x12 cm) with filters.

![Diagram of the test-box with dimensions and cooling system]

read-out, power cables
Asynchronous beam dump

Standard dump: Extraction kickers fire when no beam is passing

Asynchronous dump: kicker(s) fire when beam passes – kicked beam could damage sensitive equipment on the same turn
Asynchronous beam dump

Standard dump: Extraction kickers fire when no beam is passing

Asynchronous dump: kicker(s) fire when beam passes – kicked beam could damage sensitive equipment on the same turn