Beam-Loss Damage Experiment on ATLAS-like Silicon Strip Modules Using an Intense Proton Beam

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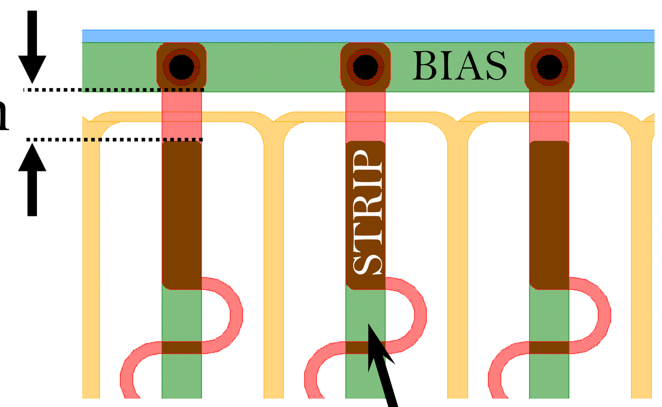
Abstract

The ATLAS detector community is entering in the final stages of sensor development for the future upgrade of the Large Hadron Collider (LHC). An increase by an order of magnitude of the LHC luminosity of the present experiment, up to 10^{35} cm^{-2}s^{-1}, will lead to an increased radiation dose delivered to the detector, especially for the devices located in the Inner Tracker (ITk)[1]. In 2018, an experimental study of the damages induced by a possible beam-loss over Silicon Strip Detectors (SSD) was done in the High-Radiation to Materials (HiRadMat) facility at CERN. A progressive number of proton bunches was extracted from the CERN Super Proton Synchrotron (SPS), and focused directly over the strip sensor with a variable beam radius (0.5 - 2.0 mm), in order to simulate the large amount of charges typically generated in a beam-loss failure.

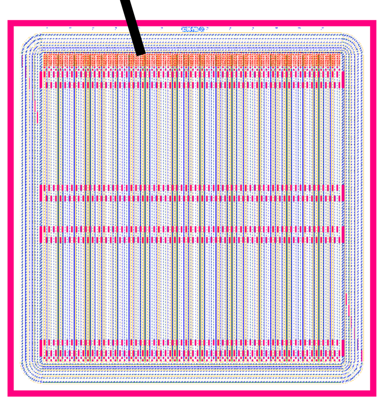
This work presents the relevant results obtained during this experiment, showing that Punch-Through Protection (PTP) effectively protects the AC-coupling capacitors of the silicon sensors from large charge accumulation, but still this could induce damages on the read-out electronics.

Punch-Through Protection (PTP)



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 AC-coupled SSD, very large voltages through the metal/implant inter-oxide could damage the coupling capacitor[2].



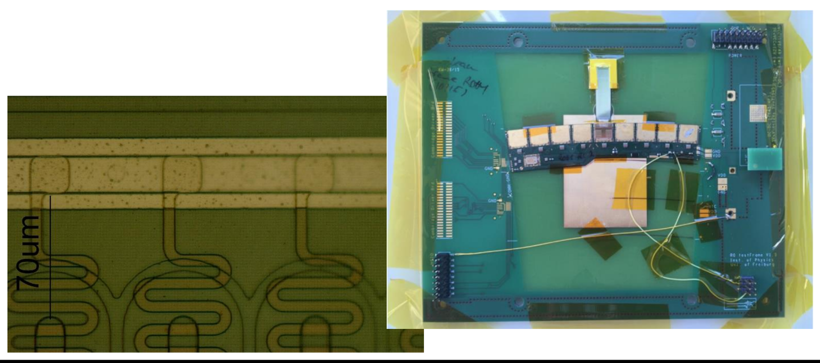
In order to prevent this situation, future High Luminosity-LHC (HL-LHC) strip sensors have been equipped with PTP for each strip, reducing the distance between the strip implant and the bias rail. Several studies[3] conclude that 20 µm is the optimal strip-to-bias separation to effectively discharge the excess of charges through the grounded bias line.

Devices Under Test

In order to compare the effectiveness of the PTP during a beam-loss, two ATLAS-like IMB-CNM strip sensors with different strip-to-bias distances have been tested. Sensors were wire-bonded to ABC130 data read-out chips, and assembled in two different ITk strip miniature modules.

Module	Sensor Size	Sensor Type	Sensor Thickness	Readout Chip	Channel (Pitch)	Strip-to-Bias Distance
PTP	0.7 x 2.6 cm²	n⁺-in-p	300 µm	ABC130	64 (77 µm)	20 µm
Non-PTP	1 x 1 cm²				128 (74.5 µm)	70 µm

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 end of structure electronics.



Beam-Loss Experiment

Bunch intensity	0.5-1·10¹¹ protons
Number of bunches	1-288
Max. Bunch length	11.24 cm
Bunch spacing	25 ns
Max. Pulse length	7.2 µs
Beam size at target	From 0.1 to 2.0 mm

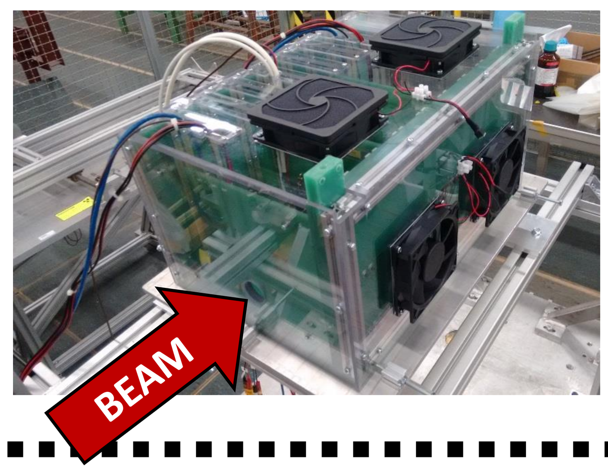
HiRadMat is a users facility at CERN, designed to provide high-intensity pulsed beams to an irradiation area where material samples can be tested.

The facility uses a 440 GeV proton beam extracted from the CERN SPS with a maximum pulse length of 7.2 µs, to a maximum pulse energy of 3.4 MJ.

HiRadMat
High-Radiation to Materials

Testbox

- Designed to host a maximum of 8 detector modules
- Cooling system: 4 fans (12x12 cm²) with filters
- Thin layer of aluminum, at the entry point, for beam positioning



- Proton beam perpendicular to silicon strip sensor miniature modules
- Two irradiation schemes: Global (2mm radius) and Local (0.5 mm radius)
- Increase of number of bunches step-by-step
- More details in Ref.[4]

Test Routine

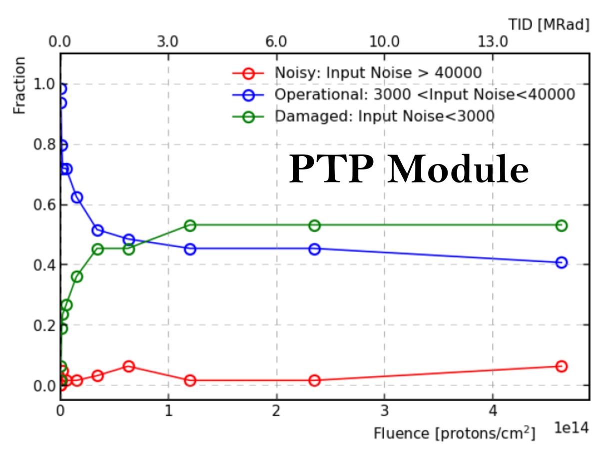
Target	Beam radius	Spacing	Bunches	Proton intensity	Total protons
Global Irradiation	2 mm	25 ns	1, 4, 12, 24, 36, 72, 144, 288	10^{11}	$1.16\cdot10^{13}$
Local Irradiation	0.5 mm		1, 12		$2.6\cdot10^{12}$

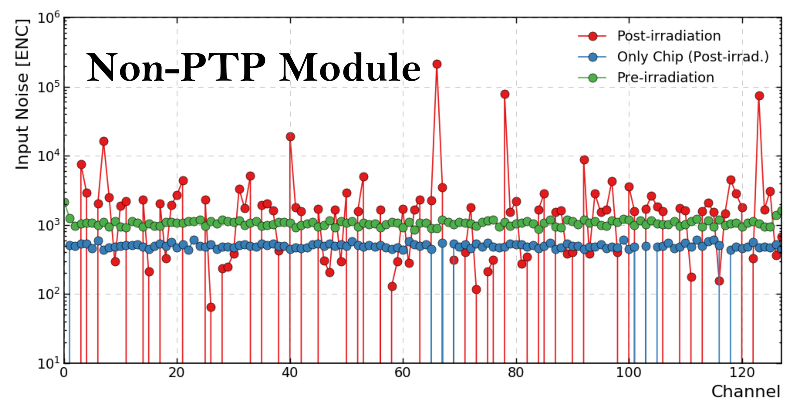
Preliminary Results

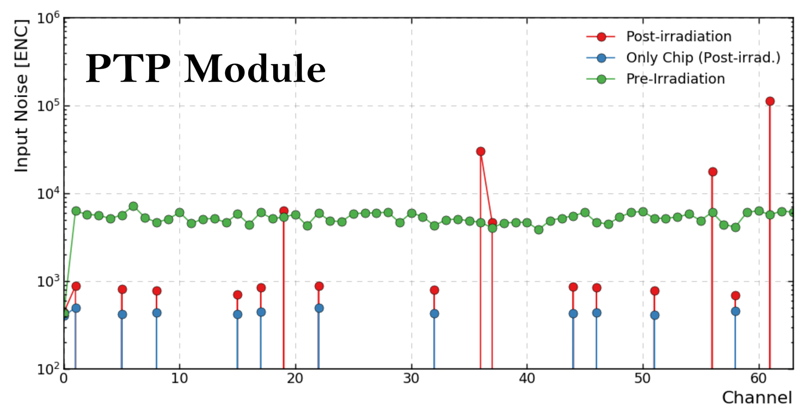
Influence on Read-out Electronics

PTP Module:

- Module noise increase concentrated in the first beam shot
- Stable behavior before $1\cdot10^{13}$ protons (3 MRad)
- With increase of the proton fluence, a decreasing number of fully operating channels was observed
- **After about $6\cdot10^{13}$ protons (15 MRad) more than 50% of channels have been damaged for the PTP module**





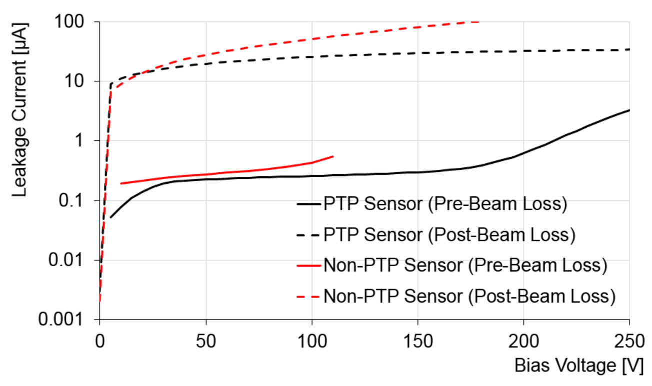


Non-PTP Module:

- Unfortunately, due to connectivity problems during the experiment, the on-line monitoring of this sensor was not possible
- Noise and gain measurements before and after the beam-loss experiment showing typical values for silicon strip modules
- **Apparently no damage of beam-loss on the read-out channels for the non-PTP module**

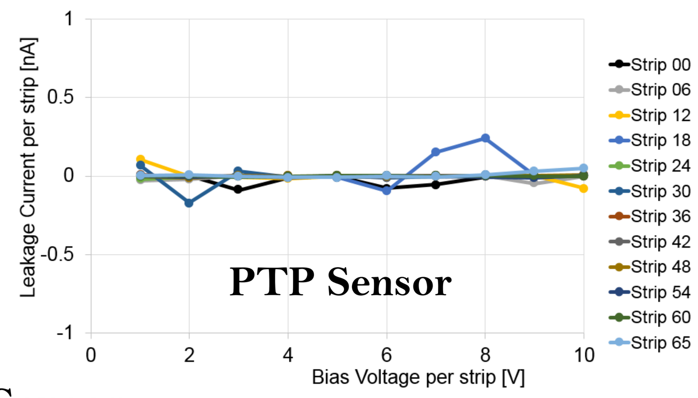
Influence on Silicon Strip Sensors

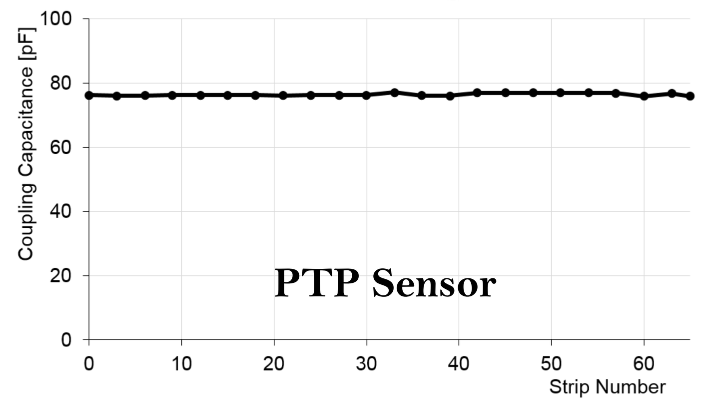
- After the beam-loss experiment, the sensors were disassembled from the testing modules and characterized
- Increase of leakage current and full depletion voltage, showing typical behavior of irradiated sensors



PTP Sensor:

- Measured current across oxide and value of coupling capacitance:
  - ✓ Strip current: OK → No electrical continuity across coupling oxide
  - ✓ Coupling capacitance: OK → Expected value, no variation across the sensor
- **Noisy behavior seen in module cannot be attributed to broken strips in the PTP sensor**





Non-PTP Sensor:

- Measurement of current across oxide showing 70% of strip coupling capacitors broken (i.e. short-circuit between AC pad and strip implant)
- **Non-PTP strips have not survived the beam-loss experiment**

Module	Read-out	Sensor
PTP	DEAD	ALIVE
Non-PTP	ALIVE	DEAD

Conclusions

- After beam-loss experiment, IMB-CNM strip sensors show typical leakage current and depletion voltage for proton irradiated sensors
- **PTP effectively protects strip sensors from large amount of charge induced by a beam-loss, but the read-out electronics still might be damaged**
- Further studies needed to understand the beam-loss effect on read-out electronics for the PTP module

References

[1] ATLAS-TDR-025, CERN, 2017.
[2] H.F.-W. Sadrozinski, et al. NIMA 699 (2013) 31-35.
[3] Y. Unno, et al., NIMA 636 (2011) S24-S30.
[4] C. Bertella, et al., VERTEX 2018. To be published in PoS.

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