Irradiation of ATLAS silicon detectors with fast extracted and intense proton beams

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Acknowledgments to the HiRadMat team and the CERN FLUKA team

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Introduction

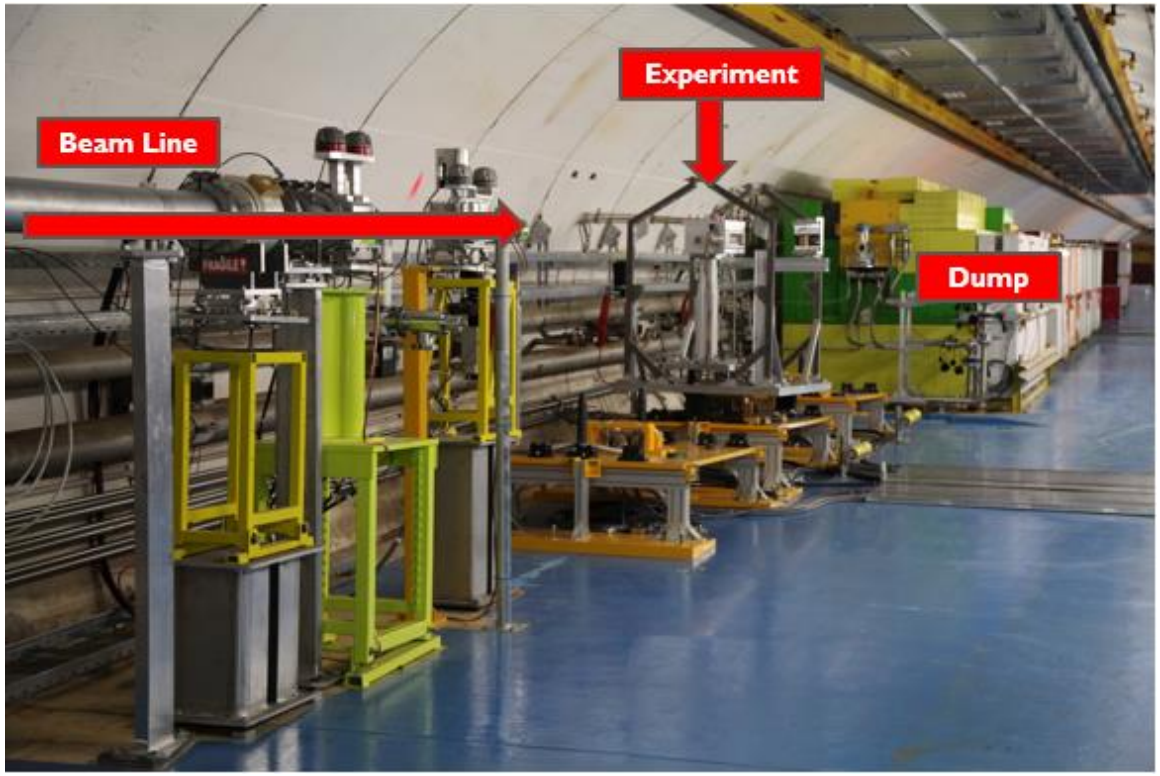
- The ATLAS silicon tracker detectors are designed to sustain high integrated dose over several years of operation. Such level of radiation hardness should also favor the survival of the detector in case of accidental beam losses.

- Measurements of the pixel detector damage threshold were performed in 2006 at the CERN Proton Synchrotron (PS) showing that pixel detectors could survive with minimal or no deterioration of the performance to a particle flux larger than 10^{10} MIPs/cm^2 [NIM A, 565 (2006) 50-54].

- The upgrade of LHC to higher luminosity (HL-LHC) calls for new tests with more intense proton beams.

- We report preliminary results of an intensive proton beam irradiation of ATLAS silicon detectors at the HiRadMat (High-Radiation to Materials) Facility of CERN Super Proton Synchrotron (SPS).

The HiRadMat facility

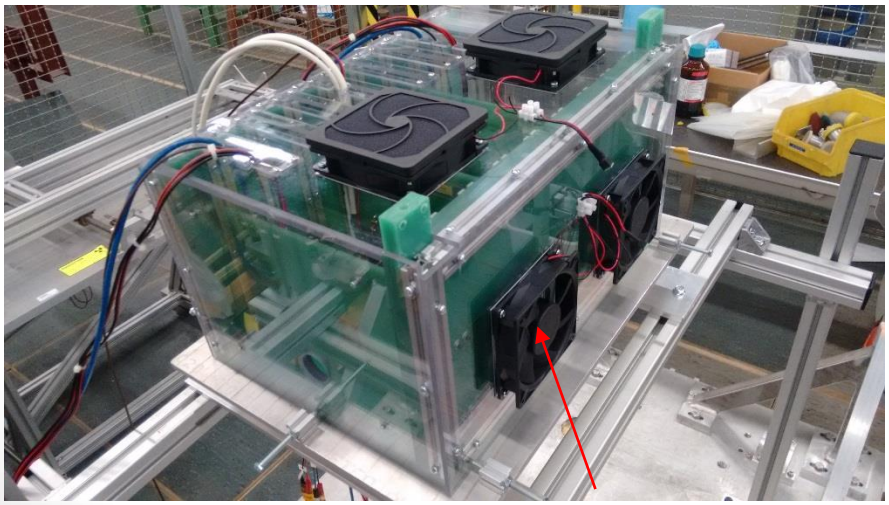


- Beam energy close to LHC injection (440 GeV).
- Single pulses with multiple bunches (1-288) -> no long term irradiation.
- Beam spot size: 0.2-2 mm.
- Beam intensity: 0.5-1.0x10^{11} protons/bunch.
- Fixed beam position over DUTs.

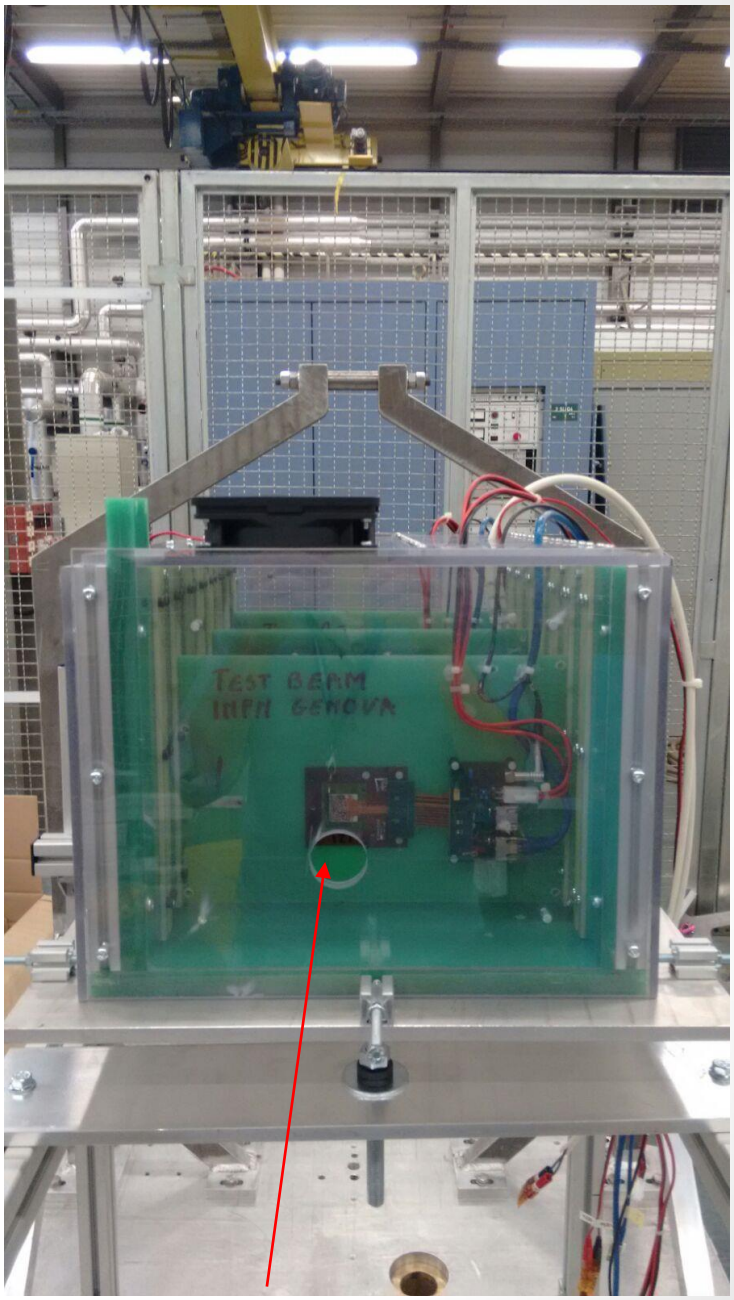
The HiRadMat facility has been used to irradiate ATLAS silicon sensors on July 2017.

The ATLAS test box

- Test-box has been designed to host up to 8 detector modules on dedicated frames.
- 3 modules loaded for the July 2017 test:
  - 2 IBL 3D pixel modules
  - 1 ITk strip module



Cooling fan



Hole for the incoming beam

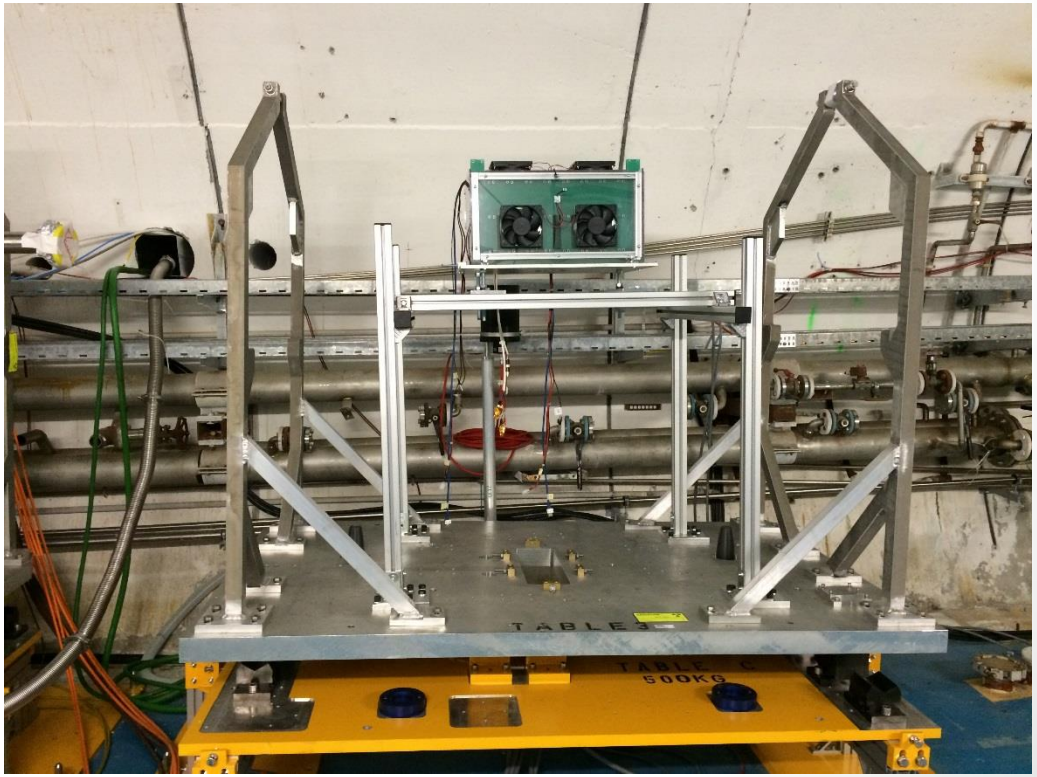
Modules under test

- Two identical IBL 3D pixel modules
  - Sensitive area: 2x2 cm^2. Pixel dimension: 250x50 μm^2. Sensor thickness: 230 µm.
  - Flex hybrid glued to the sensor and wire bonded to a FE-I4 readout chip.
  - One module in stand-by (HV off and preamplifiers off), as in unstable beam operation.
  - One module under nominal bias, as in stable beam operation.

- One ITk strip module
  - Two ATLAS12 prototype sensors [NIM A 765 (2014) 80].
  - Each sensor is bonded to a ABC130 digital read-out chip.
  - Sensitive area: 1x1 cm^2. 104 strips with a pitch of 74.5 µm. Sensor thickness: 320 µm.
  - Leakage current monitored while detector under bias (no read-out).

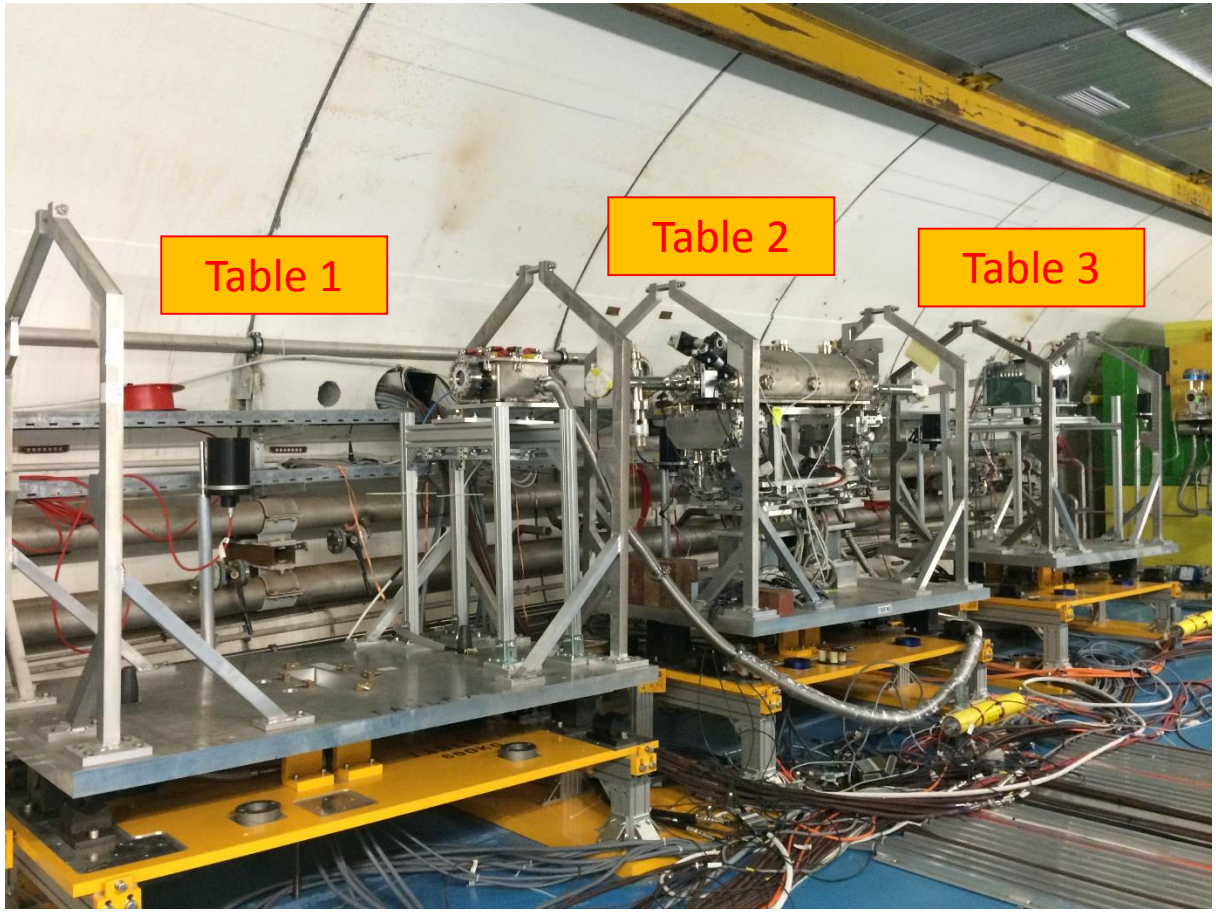
Installation on the beamline

Detectors and cables tested on surface before installing the experimental table in the tunnel.



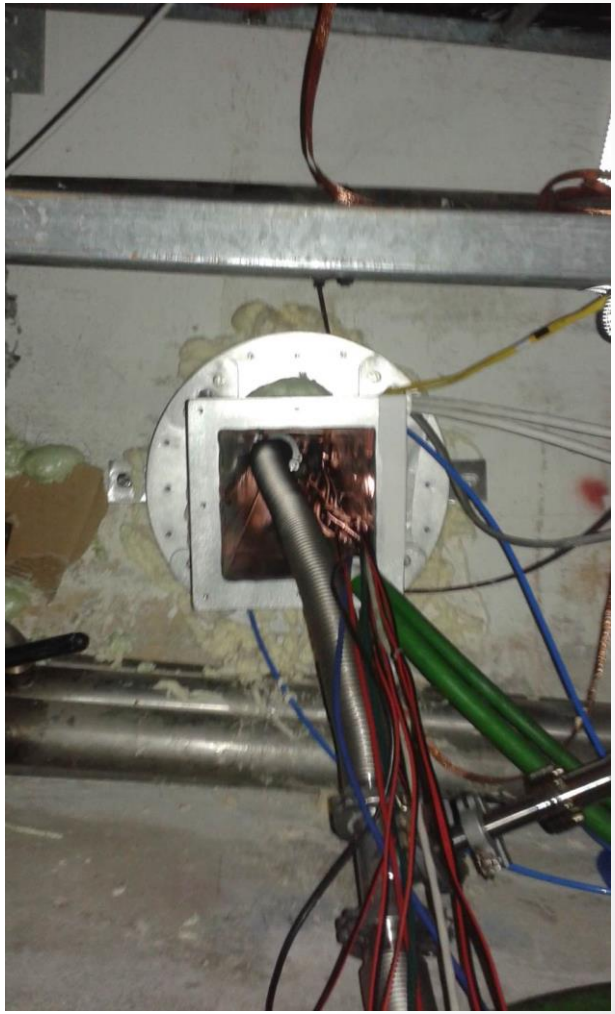
The beam line

The experimental table with the ATLAS test-box (Table 3) was installed downstream of the RotColl experiment (Table 2) for the study of HL-LHC collimator robustness.



The readout system

- The readout system was located in the TT61 tunnel, just opposite to the TNC tunnel where the experiment was installed.
- Long connecting cables (~15 m) were passing through a concrete screening wall placed between the TNC and the TT61 tunnels.



Operation

- The beam direction was perpendicular to the ATLAS detector planes.
- Expose the ATLAS detectors to proton beams of increasing particle density:
  - Experiment 1: study global effects with wide beams ($\sigma_x = \sigma_y = 2$ mm).
  - Experiment 2: study local effects with narrow beams ($\sigma_x = \sigma_y = 0.2$ mm).

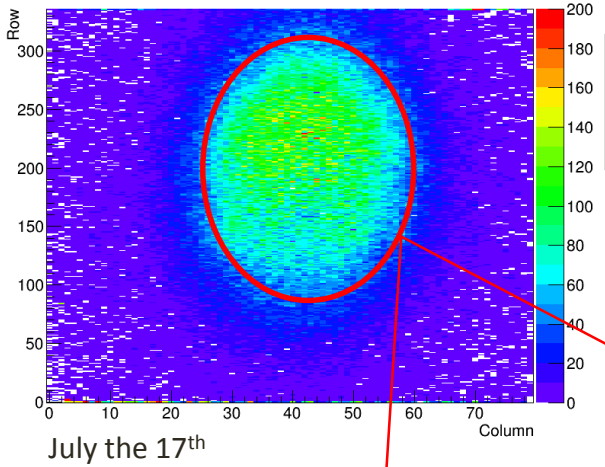
- Pixel operation:
  - Inter-pulse threshold scan.
  - Inter-pulse digital and analog scan.
  - Inter-pulse self trigger scan.
- ITk operation:
  - leakage current monitoring.
- In case of narrow beams, the local deposited energy approaches the tolerance limit measured in long term irradiation experiments.

List of pulses							
Date	Intensity			Beam spot [mm]		Bunch spacing [ns]	Pulse length [us]
	#bunches	#p/bunch	#protons	σ_x	σ_y		
Experiment 1: wide beam							
July 17th	1	5.00E+10	5.00E+10	2	2	25	0.025
July 17th	4	5.00E+10	2.00E+11	2	2	25	0.1
July 17th	12	5.00E+10	6.00E+11	2	2	25	0.3
July 17th	24	5.00E+10	1.20E+12	2	2	25	0.6
July 17th	36	5.00E+10	1.80E+12	2	2	25	0.9
July 17th	72	5.00E+10	3.60E+12	2	2	25	1.8
July 17th	144	5.00E+10	7.20E+12	2	2	25	3.6
July 17th	288	5.00E+10	1.44E+13	2	2	25	7.2
July 17th	288	1.00E+11	2.88E+13	2	2	25	7.2
Experiment 2: narrow beam							
July 17th	1	1.00E+11	1.00E+11	0.2	0.2	25	0.025
July 17th	12	1.00E+11	1.20E+12	0.2	0.2	25	0.3
1 week of RotColl operation							
July 25th	72	1.00E+11	7.20E+12	0.2	0.2	25	1.8
July 25th	288	1.00E+11	2.88E+13	0.2	0.2	25	7.2
Total #protons			9.51E+13				

Irradiation of IBL pixels

- Pixel module configuration was lost after each pulse
  - Normal detector operation recovered after reconfiguration, except for the last pulse with 288 bunches, narrow beam (short developed on the LV lines on both pixel modules).
  - Material activation visible in correspondence of the beam impact region.

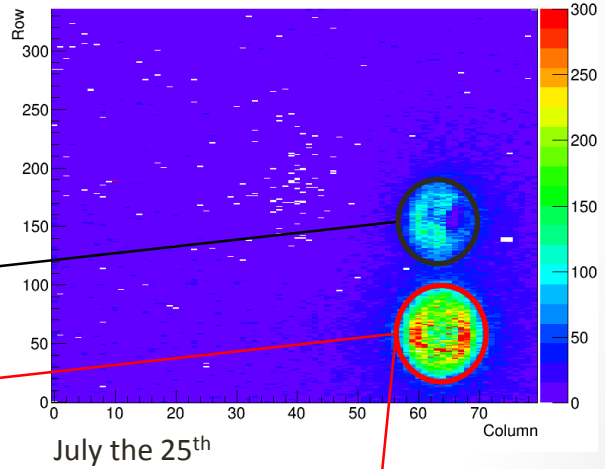
σ_{beam} = 2 mm - 288 bunches (10^{11} p/bunch)	Self trigger scans	σ_{beam} = 0.2 mm - 72 bunches (10^{11} p/bunch)



The active region recorded on July the 17th was not visible on July the 25th
→ Isotopes with $\tau_{1/2}$ < 1 week.

Activation during RotColl operation

Beam impact region

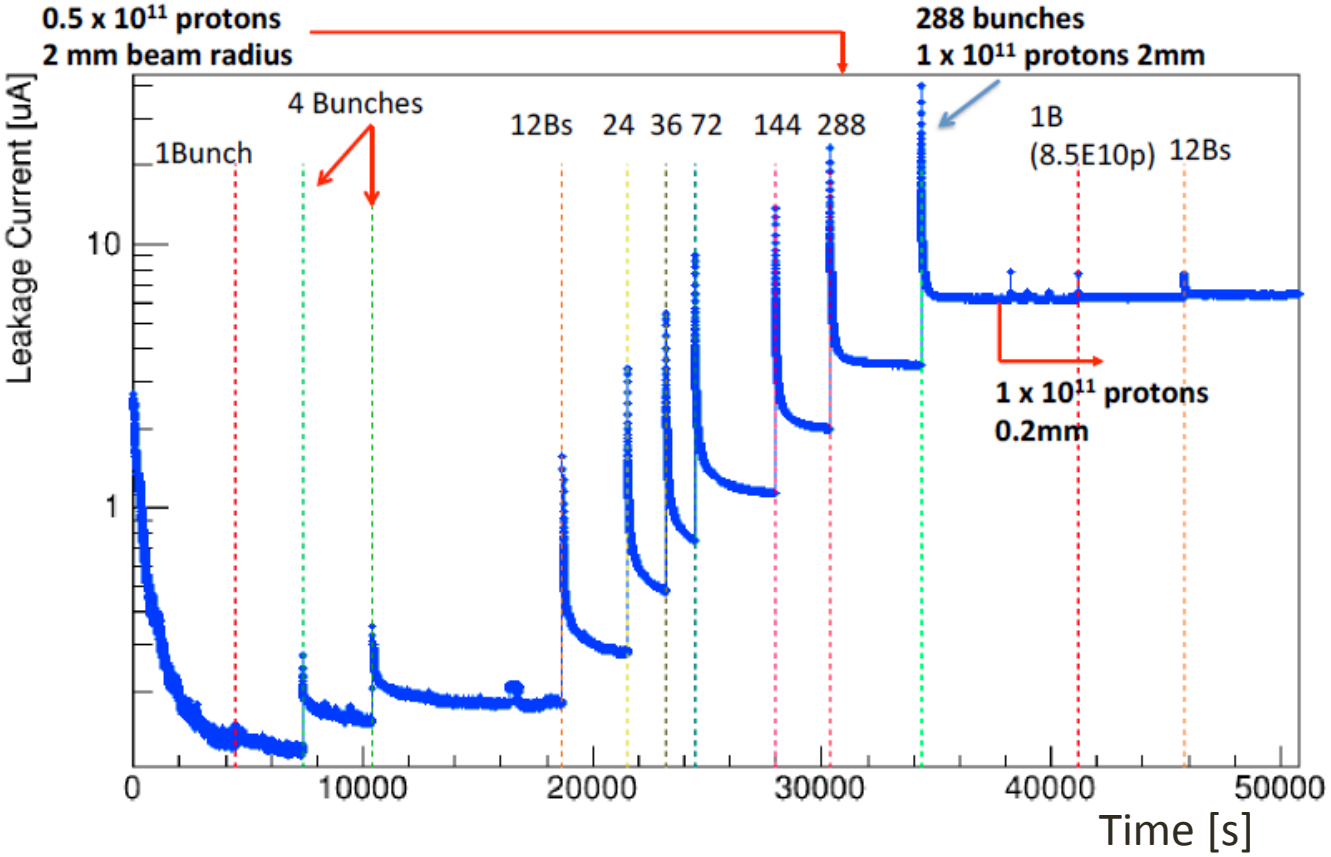


Lower limit on damage threshold [MIPs/cm^2]

$$\frac{288\ b \times 10^{11}\ MIPs/b}{4\ cm^2} \sim 10^{13}\ \frac{MIPs}{cm^2}$$

Irradiation with narrow beams shows that the damage threshold is potentially higher than 10^{13} MIPs/cm^2.

Irradiation of ITk strips



- Wide beam (σ_{beam} = 2 mm):
  - No drift of leakage current, even after 288 bunches (10^{11} protons/bunch).
  - The increment of the leakage current follows the increase of the beam intensity.

Conclusions and future plans

- Preliminary results of the test beam performed at the HiRadMat facility show that the damage threshold of the IBL 3D pixel detector is at least 10^{13} MIPs/cm^2.
  - Pixel modules are currently under investigation to understand the origin of the short.
  - Main concern: high temperature on the modules (up to 60° C).
  - The damage threshold results substantially higher than the lower limit published in 2006 (10^{10} MIPs/cm^2). At such high particle fluxes, many others aspects have to be taken into account before claiming that the ATLAS detector is safe.
- ITk sensors are able to drain the charge density generated in the bulk without evident radiation damages at least up to 10^{13} MIPs/cm^2.
  - To be repeated with a system to monitor readout signals.

- New test foreseen in 2018.
  - Improve test-box cooling with heat sinks.
  - Add a motorized system to move the test-box in and out of the beam.
  - Explore the possibility of adding Al foils for post-processing dose measurements.
  - Add one SCT module currently operating in ATLAS.
  - Add two ITk prototype sensors with different strip resistivities for punch-through protection studies.