Study of beam induced damages to the ATLAS ITK pixel and strip detectors

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International HiRadMat Workshop: 12-July-2019

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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.

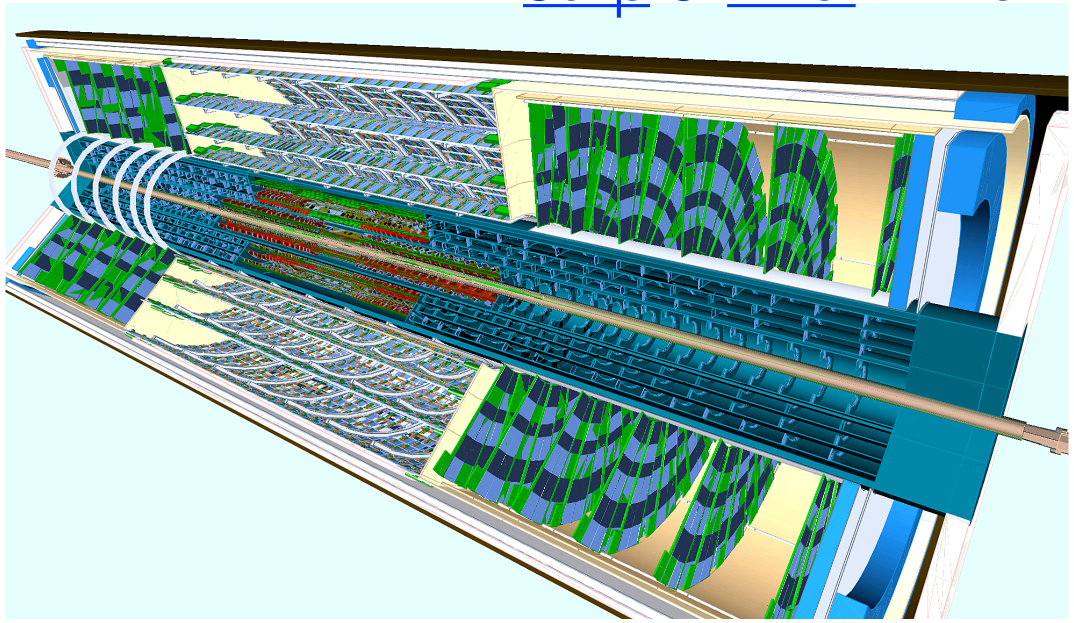
Study effects of accidental beam-loss scenarios for ATLAS tracking detector (Pixel and Strips) at HL-LHC.

- 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_{int}>7.5x10^{34} cm^{-2} s^{-1}), **ATLAS** is planning a complete **update of the detector.**

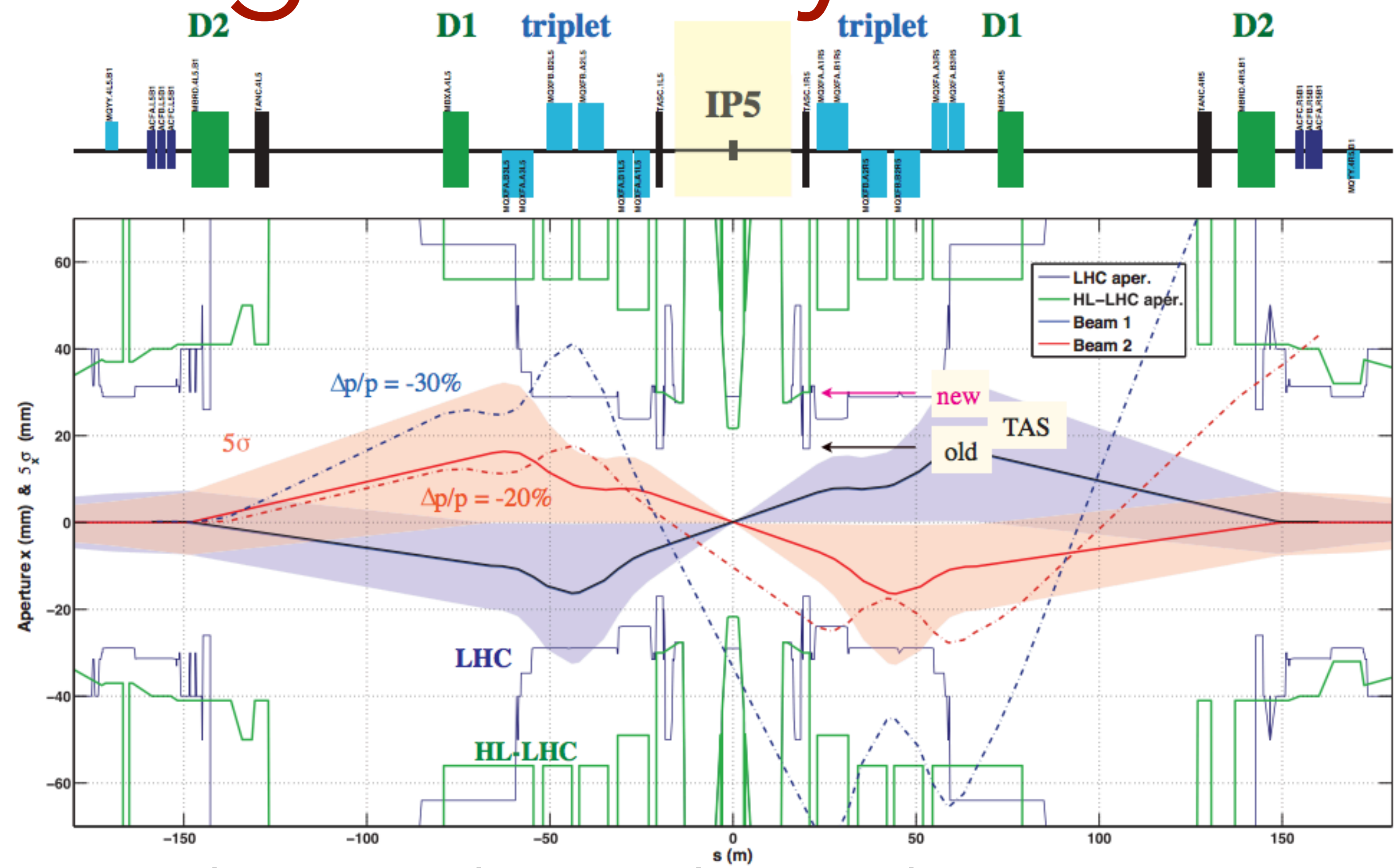
- The **new inner tracker (ITk) will be an all Si Tracker system** which will replace the current ID (Pixels, SCT + TRT)

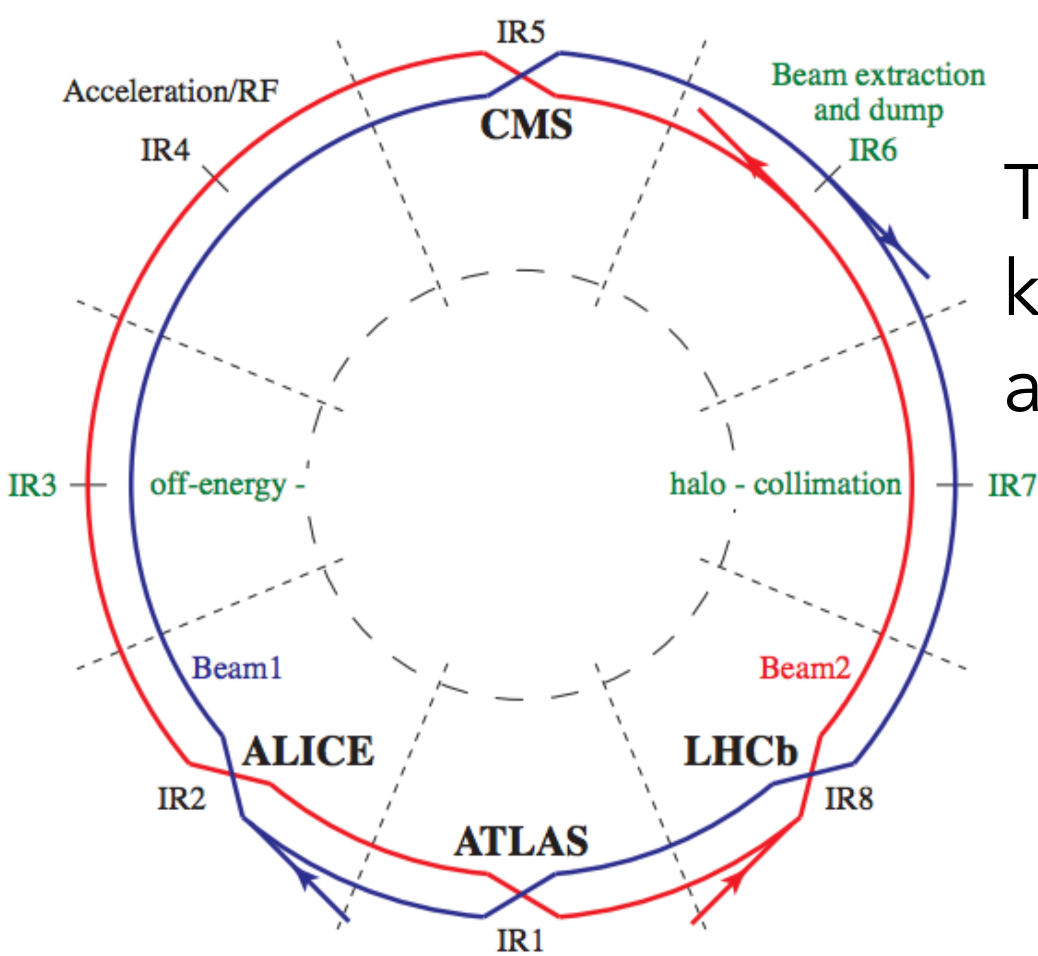
ITk Strip & Pixel TDRs



(HL-)LHC geometry [HL-LHC, IPAC'14]

- 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.



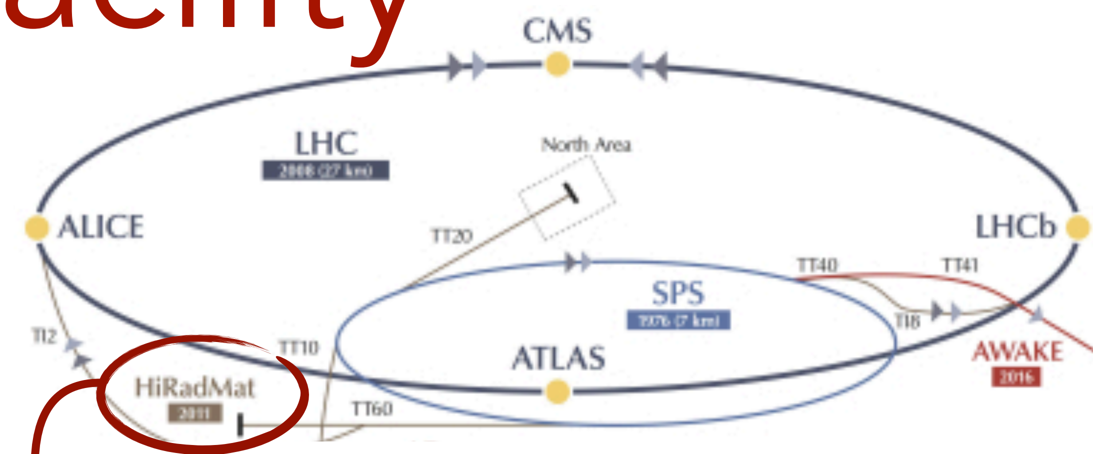


The asynchronous beam dump: the extraction kicker field switch-on is not synchronised with the abort gap [Animation].

- 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.

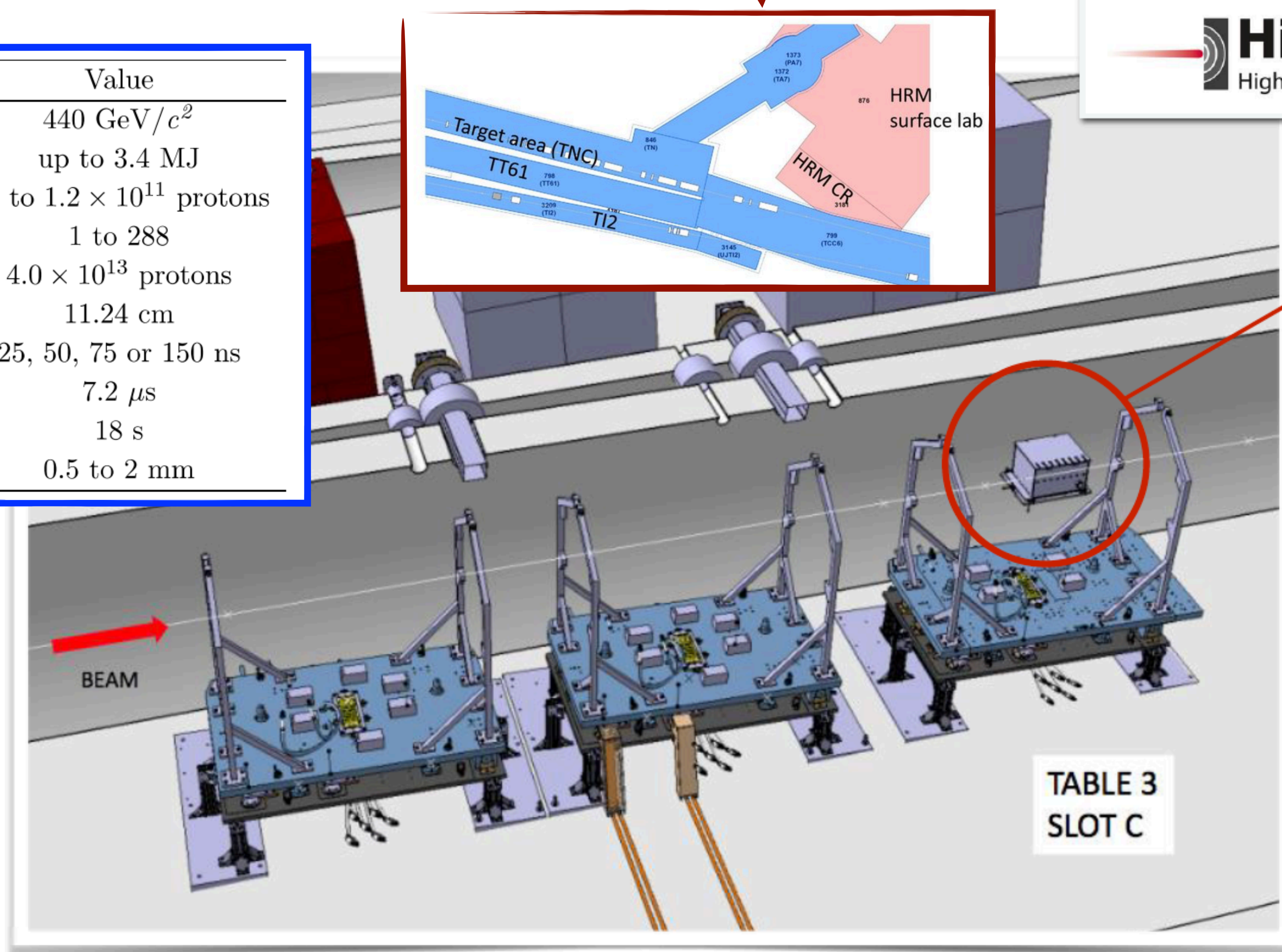
HiRadMat Facility

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



HiRadMat
High-Radiation to Materials

Proton Beam Parameters	Value
Beam Energy	440 GeV/c^2
Pulse Energy	up to 3.4 MJ
Bunch intensity	up to 1.2×10^{11} protons
Number of bunches	1 to 288
Maximum pulse intensity	4.0×10^{13} protons
Bunch length	11.24 cm
Bunch spacing	25, 50, 75 or 150 ns
Maximum pulse length	7.2 μs
Cycle length	18 s
Beam radius at target	0.5 to 2 mm



ATLAS PixRad test-box

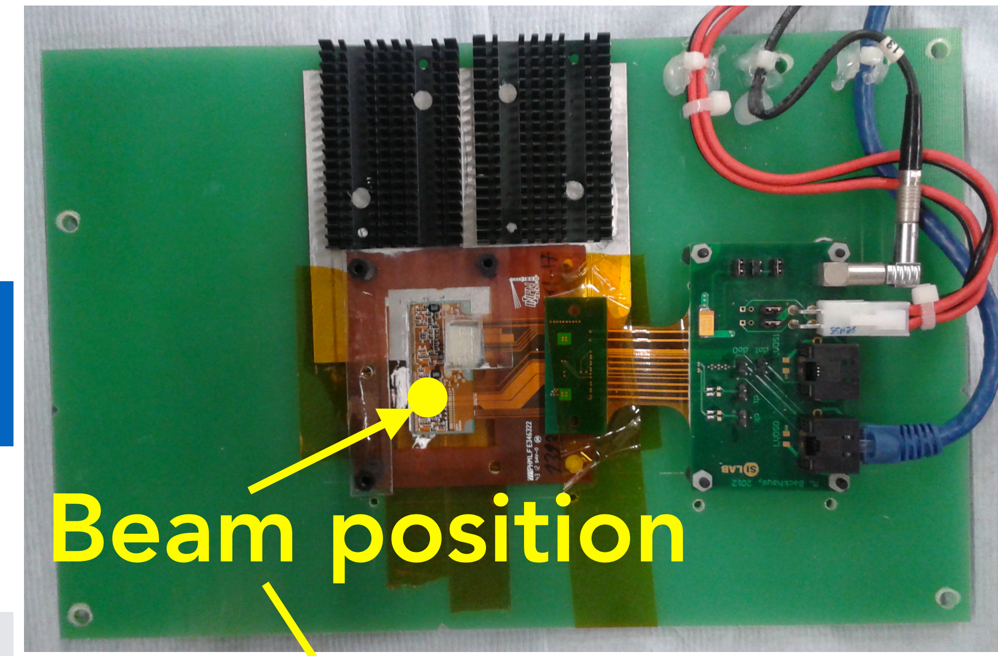
Fixed 90º impact

Beam-loss studies July 2017/8: Modules

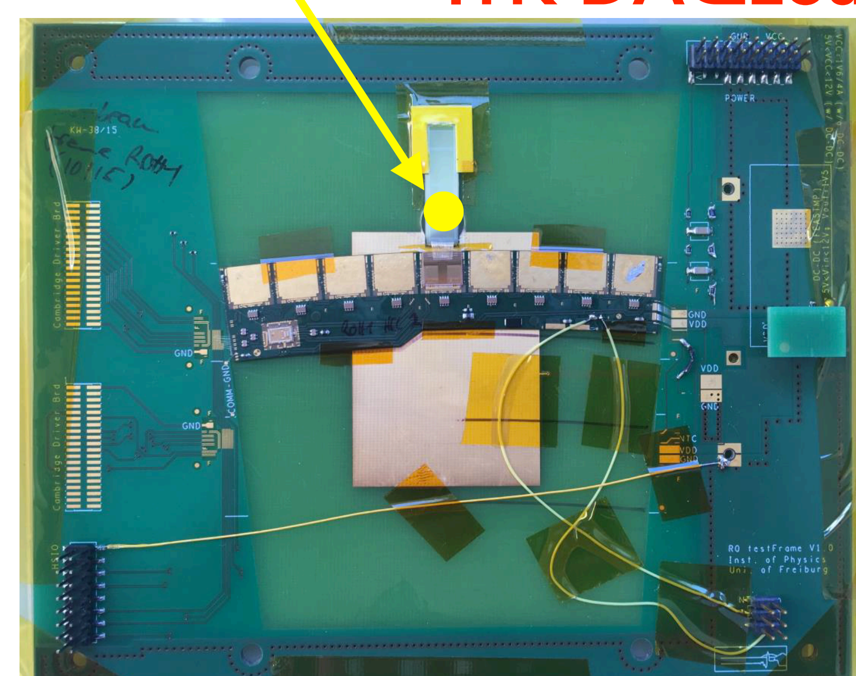
- ITk strip miniature sensor available for the beam test.
- ITk Pixel prototype with RD53A not available at that time, used most advance technology IBL
  - Improved cooling system via aluminium and dissipator: **T~36°C**

Module	IBL	IBL	ITk	ITk
Type	n^+-in-n, Planar	n^+-in-p, 3D	n^+-in-p, PTP	n^+-in-p, ATLAS12
Chip	FE-I4	FE-I4	ABC130	ABC130
Total Size	2x4 cm^2	2x2 cm^2	0.7x2.6 cm^2	1x1 cm^2
Thickness	200 µm	230 µm	310 µm	320 µm
Channel/ pitch	2x26680 (50x250	26680 (50x250	64 (77 µm)	104 (74.5 µm)
Max. Dose	250 MRad	250 MRad	35 MRad	35 MRad

IBL Planar

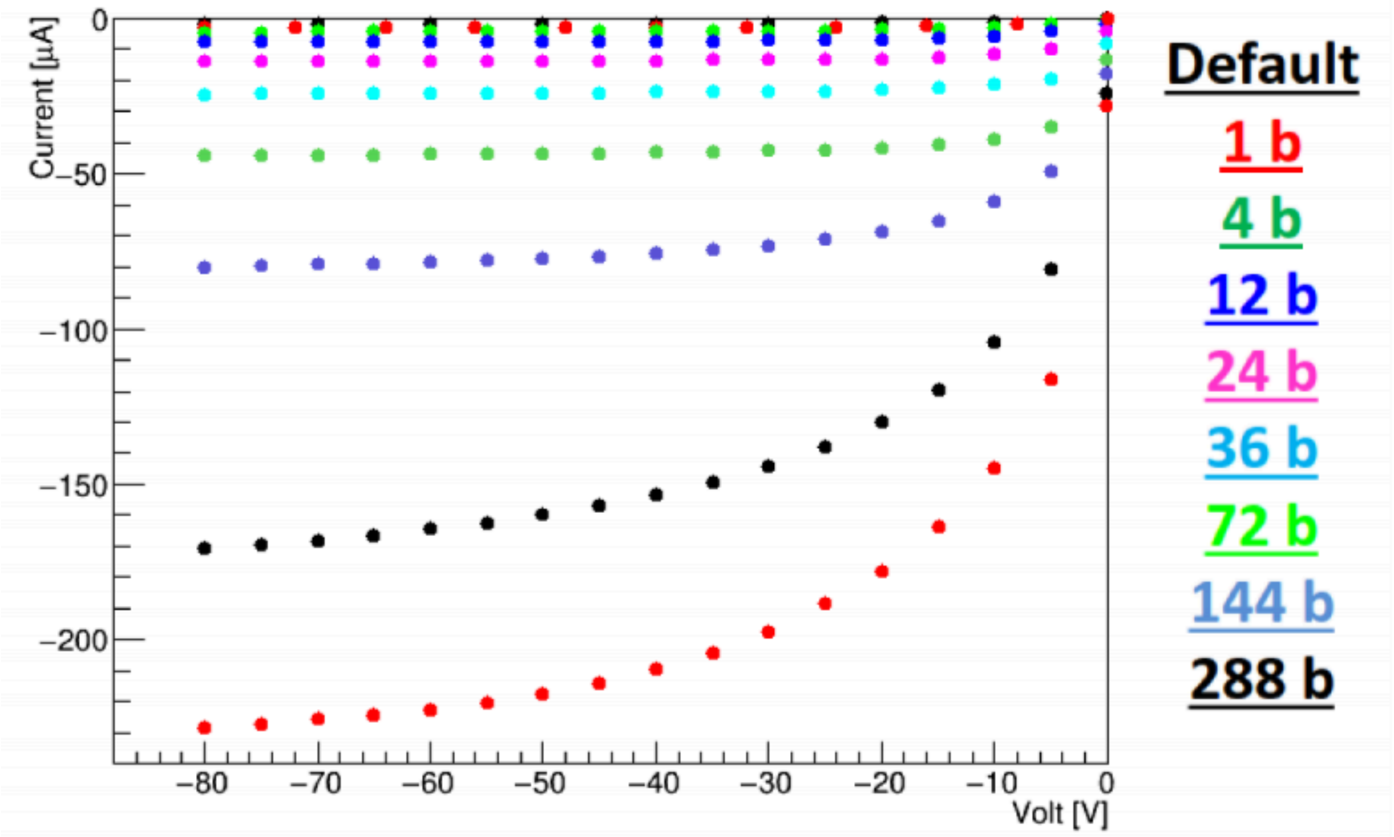


ITK DAQLoad



IBL pixel results

- 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.



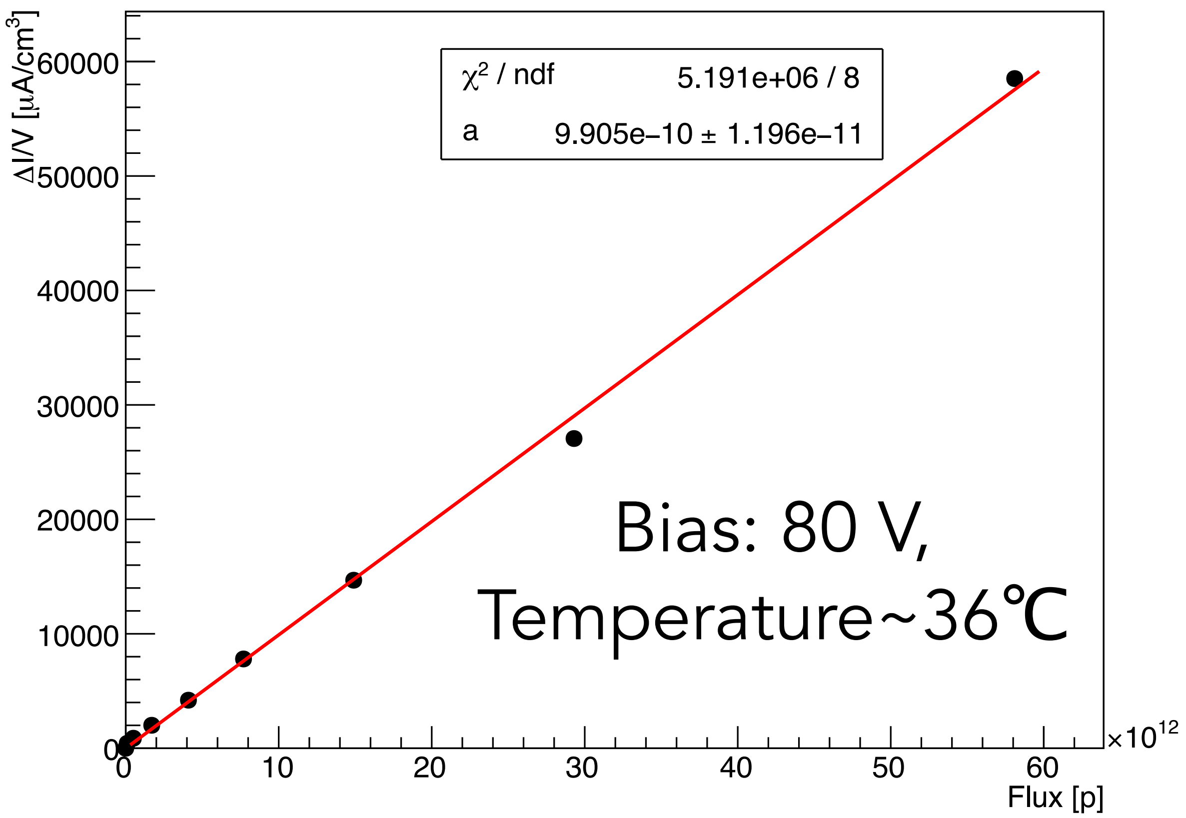
$$\Delta I \simeq \alpha \Phi V$$

ΔI: increase of leakage current before and after irradiation;

Φ: integrated proton flux ($0\text{-}288 \cdot 10^{11}$);

V: Volume= Surface x thickness (230 µm sensor);

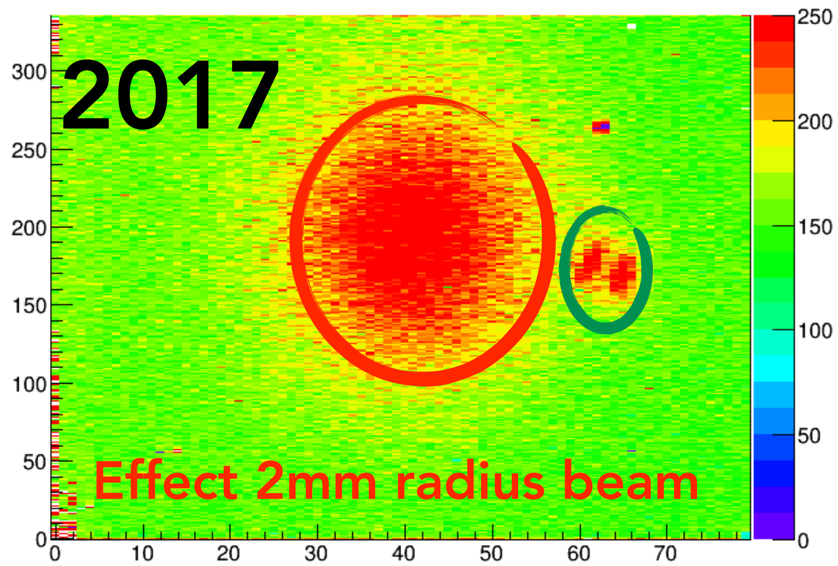
α: Current related damage rate;



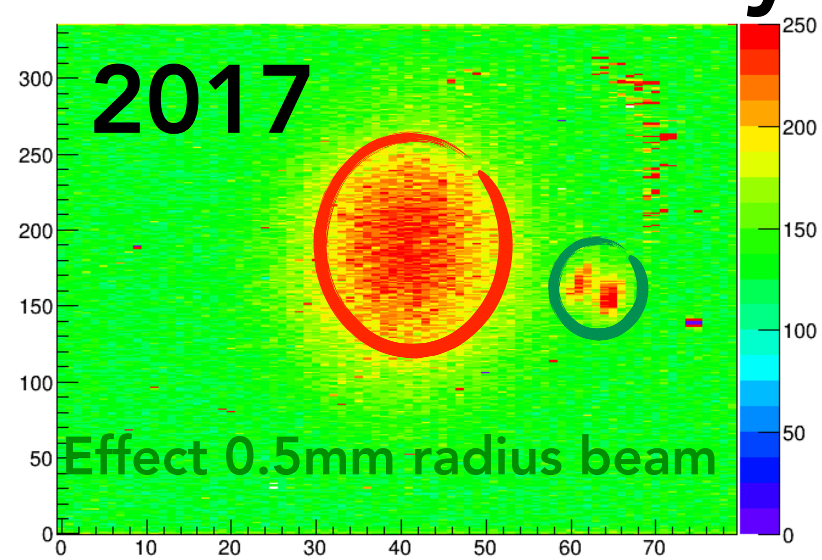
IBL pixel results

- 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.

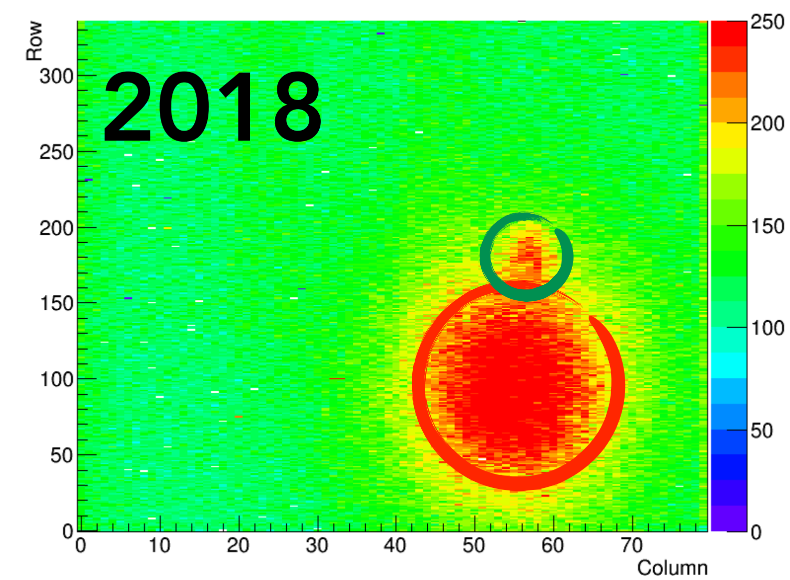
IBL 3D: stable-beam



IBL 3D: stand-by



IBL Planar

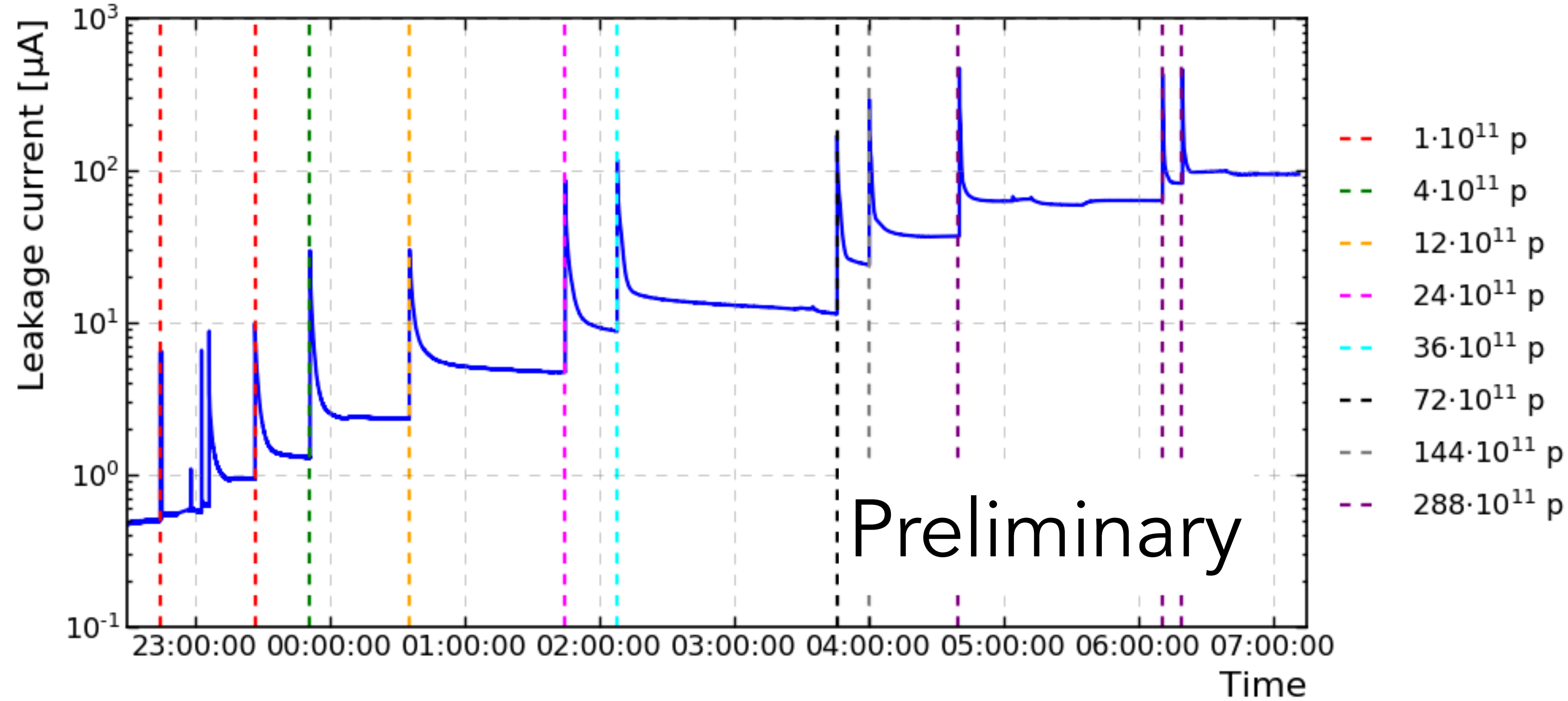


Limit on the damage threshold set to 1·10^{13} p/cm^{2} (2017/18)

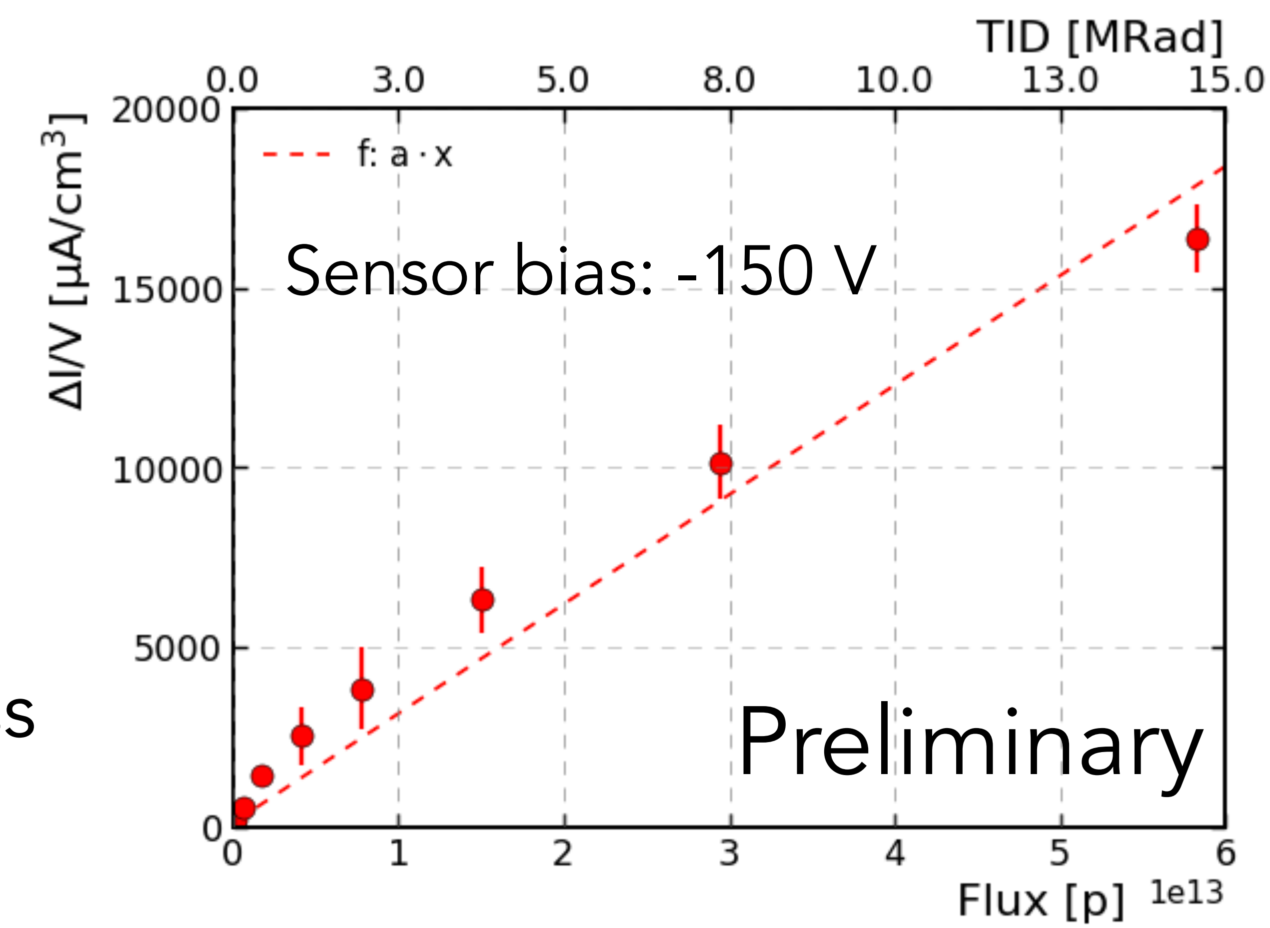
ITk strip results

Increase of the leakage current with global irradiation

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



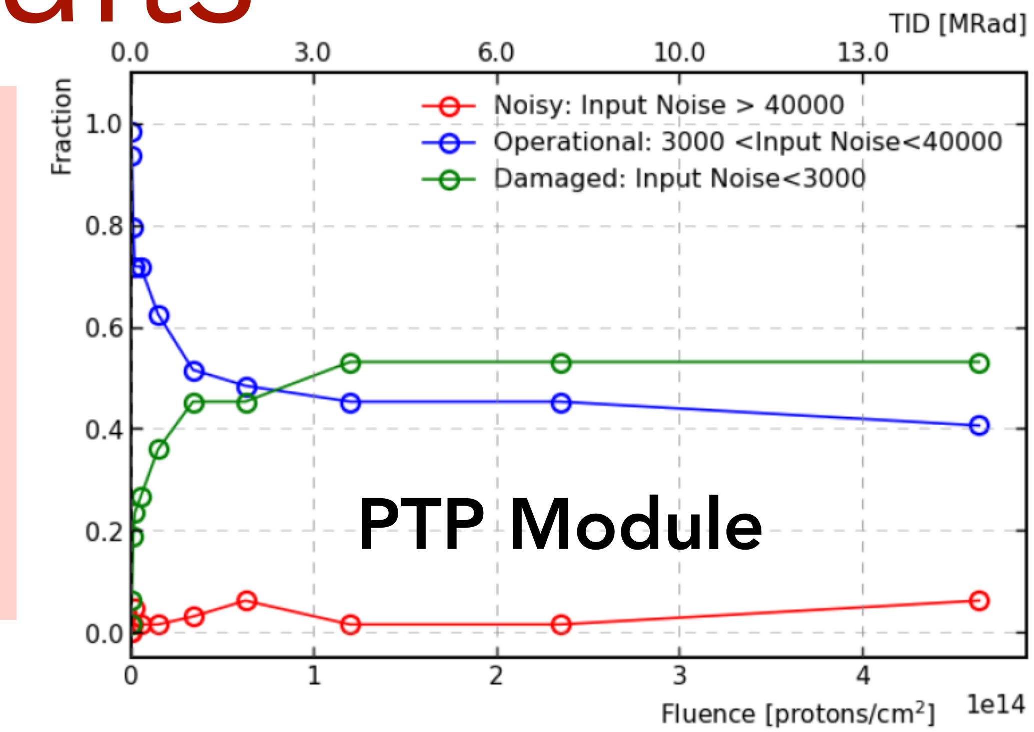
- ΔI: difference of the LC after few minutes from the shot and the original value (pre-irradiation)
- V: beam spot time sensor thickness



ITk strip results

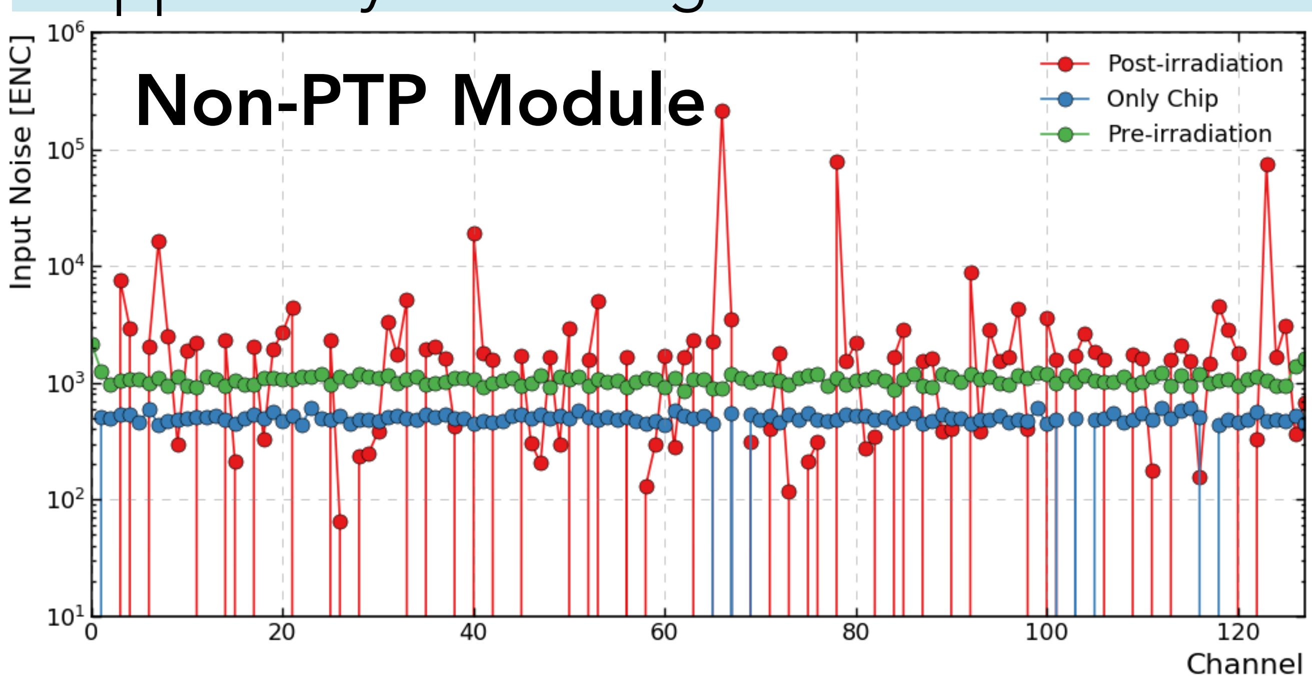
PTP Module:

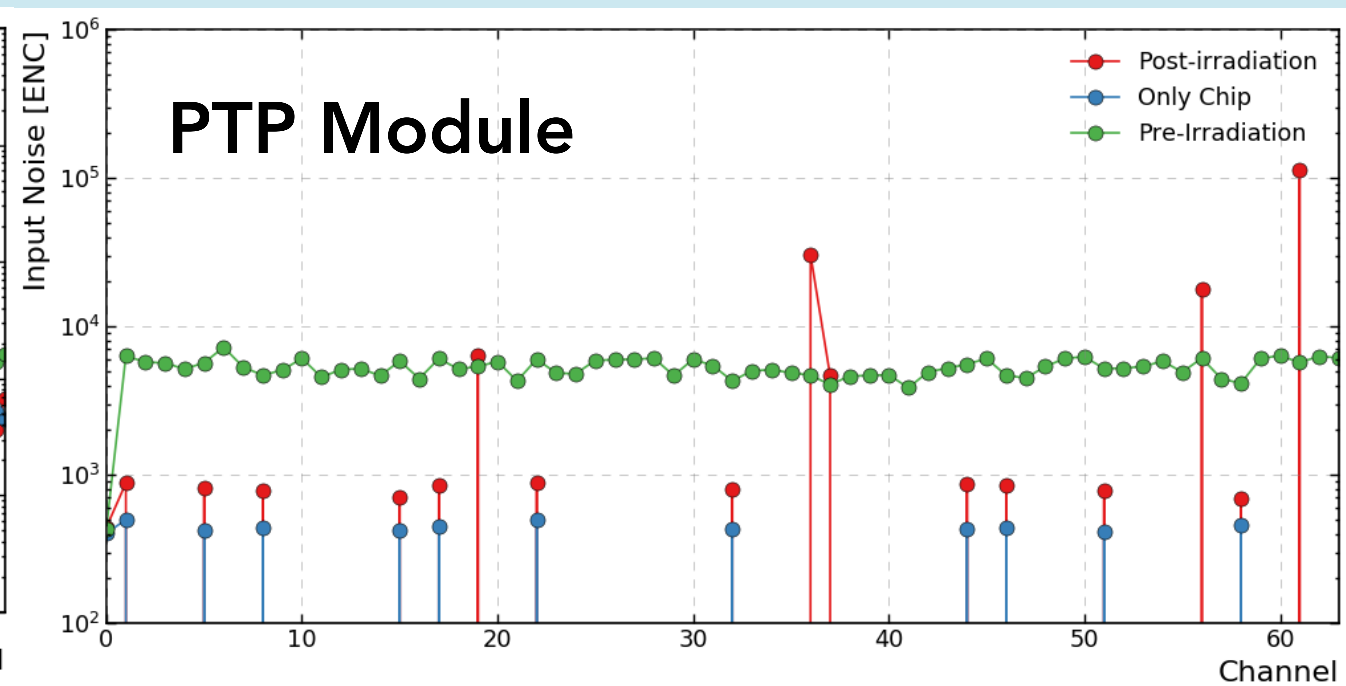
- Module noise increase concentrated in the first beam shot
- Stable behaviour before $1 \cdot 10^{13}$ proton (3 MRad)
- With increase of the proton fluence, a decreasing number of fully operating channels was observed
- After about **$6 \cdot 10^{13}$ protons (15 MRad) more than 50% of channels have been damaged for the PTP**



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





ITk strip results

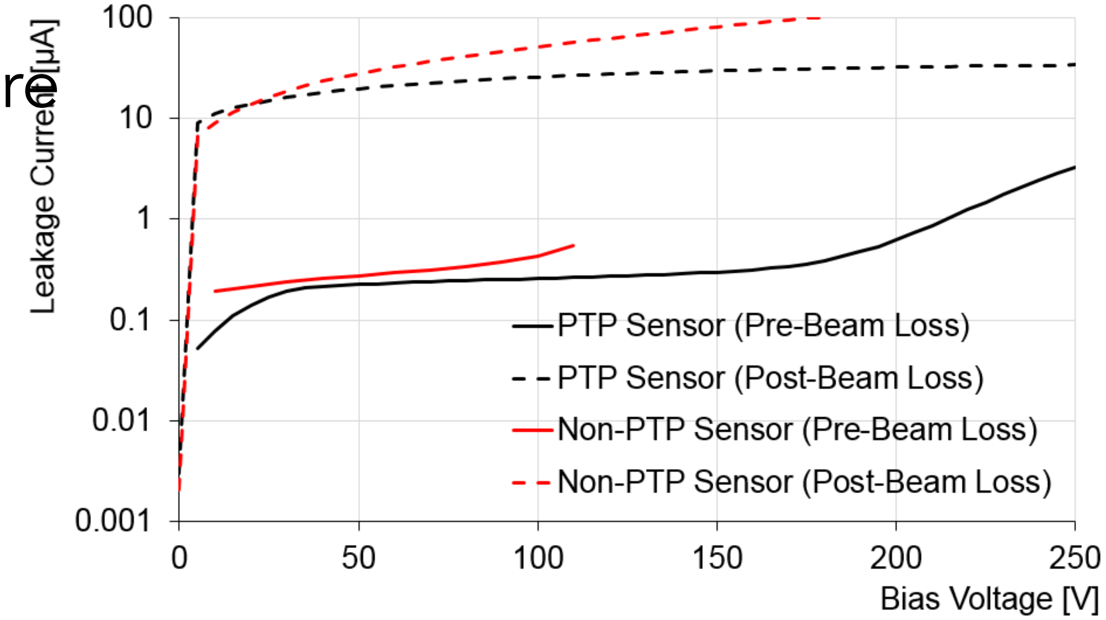
- After the beam-loss experiment, the sensors were disassembled from the testing modules and characterised
  - Typical behaviour of irradiated sensors

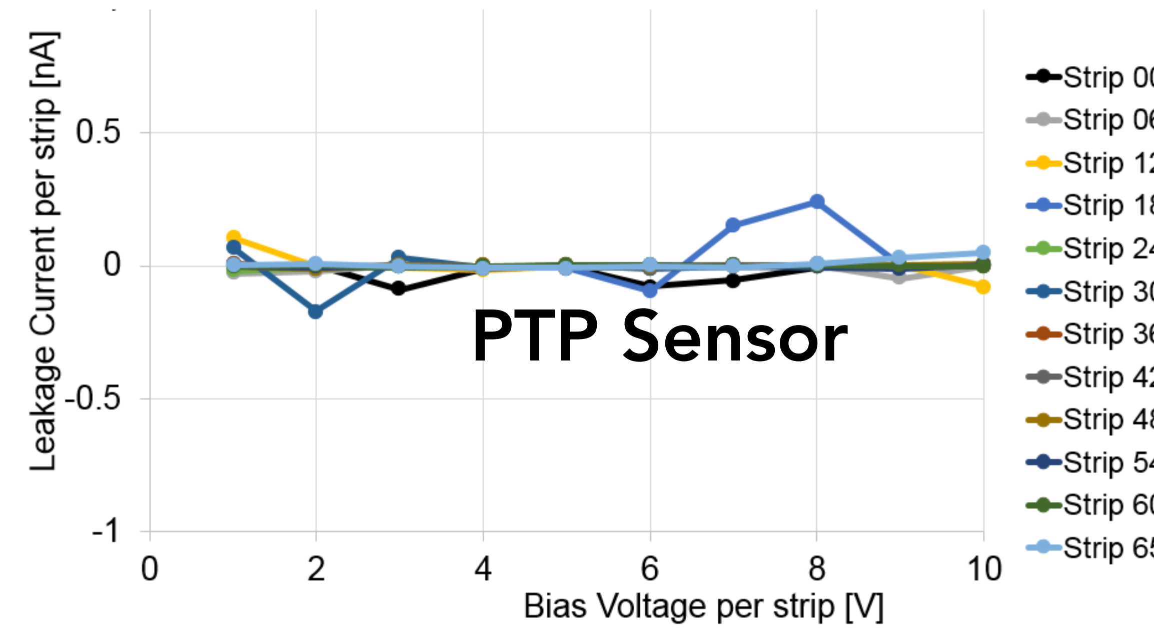
PTP Sensor:

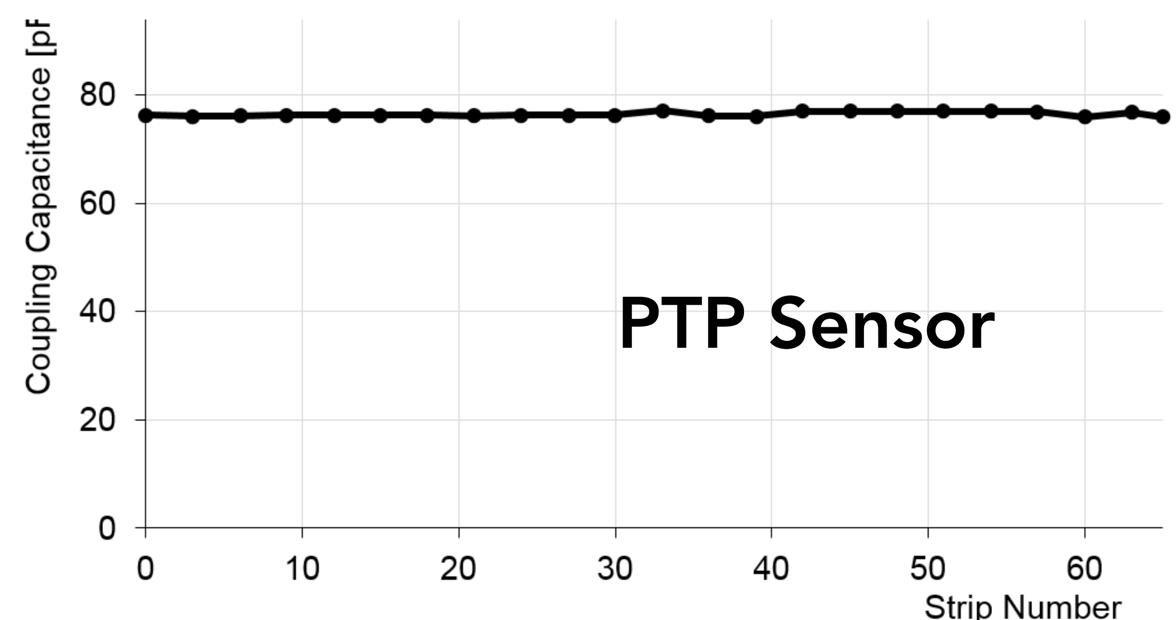
- Measured current across oxide and value of coupling capacitance:
- Strip current: OK → No electrical continuity across coupling oxide
- Coupling capacitance: OK → Expected value, no variation across the sensor

Non-PTP Sensor:

- Measurement of current across oxide showing 70% of strip coupling capacitors broken **Non-PTP strips have not survived the beam-loss experiment**







Summary

- In a beam-loss scenario, silicon strip sensors could accumulate large amounts of charges in the bulk, collapsing the electric field
  - Very large voltages through the metal/implant inter-oxide could damage the coupling capacitor
  - Strip sensors have been equipped with PTP
- Thanks to the **HiRadMat facility** it was possible to study of the damages induced by a possible beam-loss
  - Progressive number of proton bunches focused directly over the strip module with a variable beam size (0.1 - 2.0 mm)
  - Up to **288 bunches** with **$1.2*10^{11}$ protons** and **pulse length of 7.2 μs**
- Further studies needed to understand the beam-loss effect on sensor and read-out electronics

LOI

The production of ATLAS ITk modules will start before 2021

- The ITk community will, then, move from a R&D phase to an operational phase
- For safe detector operation, it is important to quantify the damage threshold of all ATLAS ITk systems (pixel, strip, BCM’), specially those dedicated to guarantee ATLAS safety (BCM’)

HiRadMat offers a unique opportunity to test the behaviour of the detectors in "extreme conditions” simulating the huge instantaneous charge release which might happen in a HL-LHC beam failure scenario

LOI

The ATLAS ITk management is in favour of the continuation of the test activities @HiRadMat with the following *minimal plan*:

- Quantify the **damage threshold** for sensor and electronic in both pixel and strip technologies
- Test the **final pixel module, only IBL module were tested in the past**
- Test the **strip sensor** with the final design
- Test the latest **strip read-out chip** (ABCStar)
  - This include a protection that should prevent damage to the chip when the sensor has PTP structure
- Test the full **ITk system: pixel, strip and BCM'**
- Perform study on previously irradiated modules

Thanks for your attention!

Acknowledgments to

ATLAS ITk

HiRadMat team

ARIES

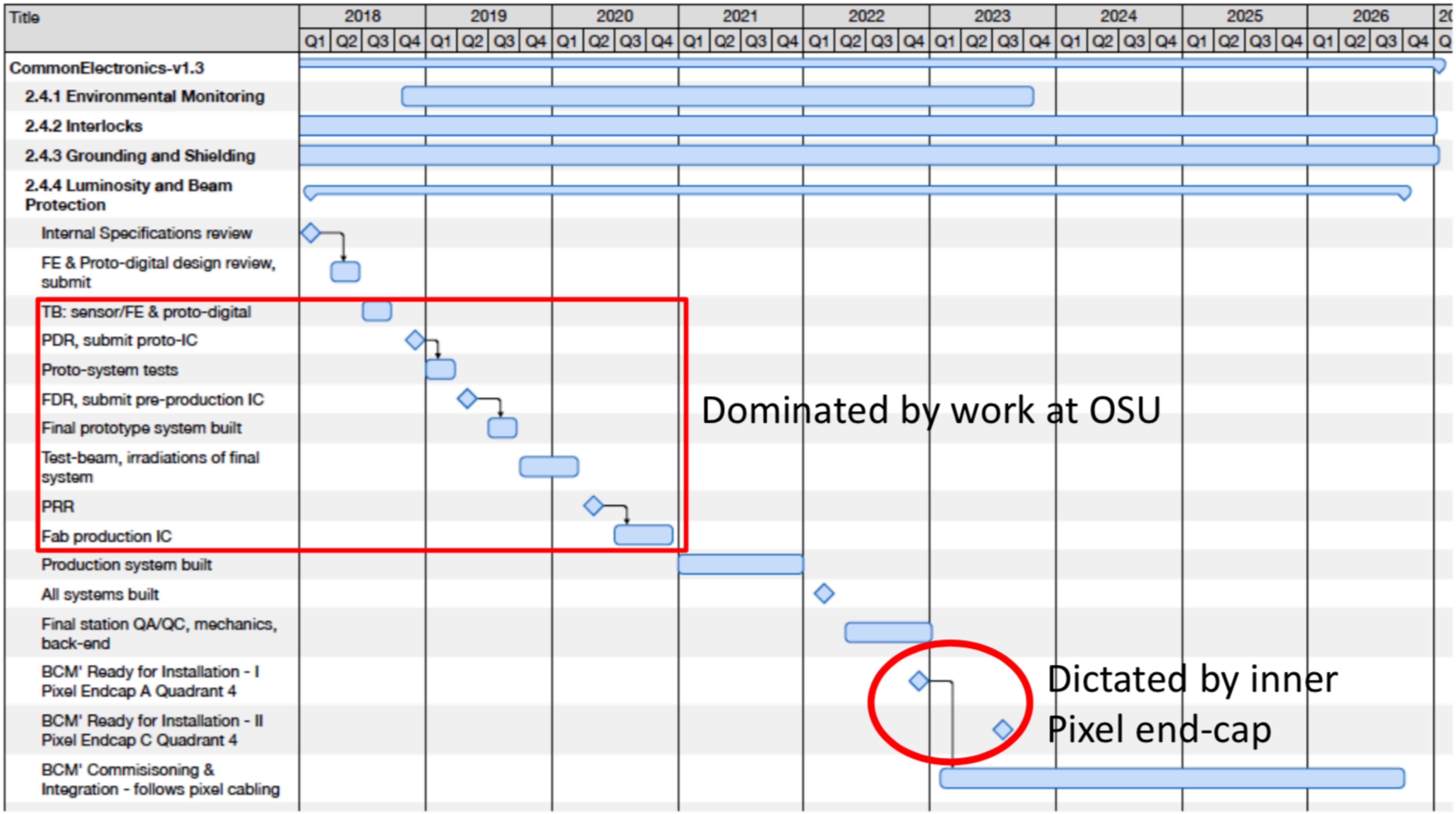
CERN FLUKA team

Beam pulse list

- 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 spot $\sigma_X = \sigma_Y$	Naming	Spacing [ns]	Num. of Bunches	Proton intensity	Total proton
	beam-test 2017				
2 mm	global irradiation	25	1,4,12,24,36,72, 144,288/288	$10^{10}/10^{11}$	$5.8 \cdot 10^{13}$
0.4 mm	local irradiation	25	1,12,72,288	10^{11}	$3.7 \cdot 10^{13}$
	beam-test 2018				
2 mm	global irradiation	25	1,4,12,24,36,72, 144,288	10^{11}	$1.16 \cdot 10^{13}$
0.5 mm	local irradiation	25	1,12	10^{11}	$2.6 \cdot 10^{12}$

BCM' schedule and installation in Its pixel system

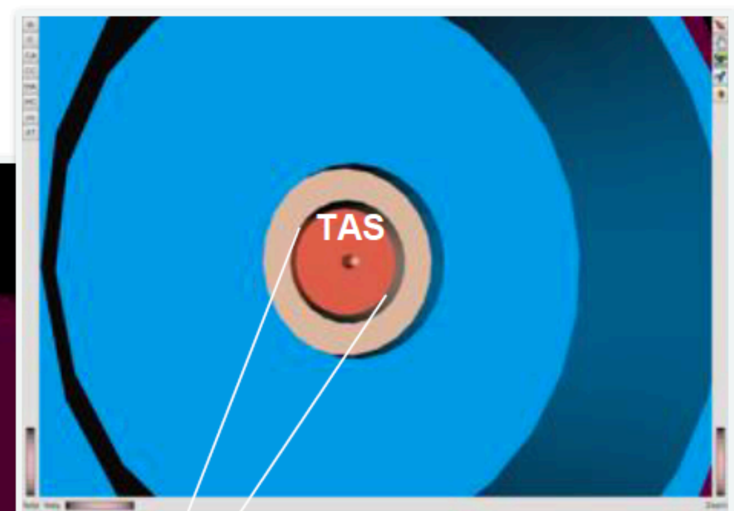


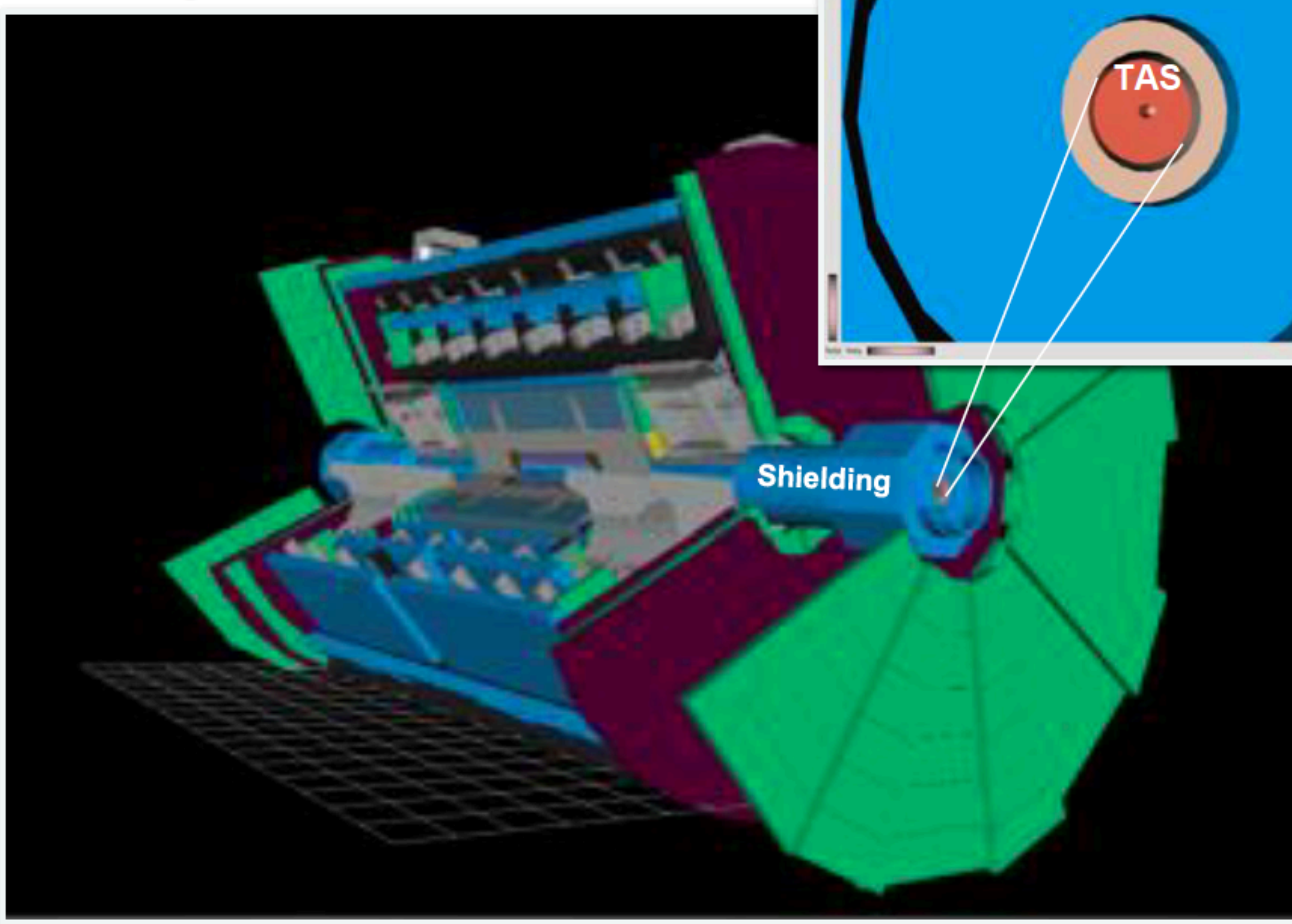
Studies done in 2006

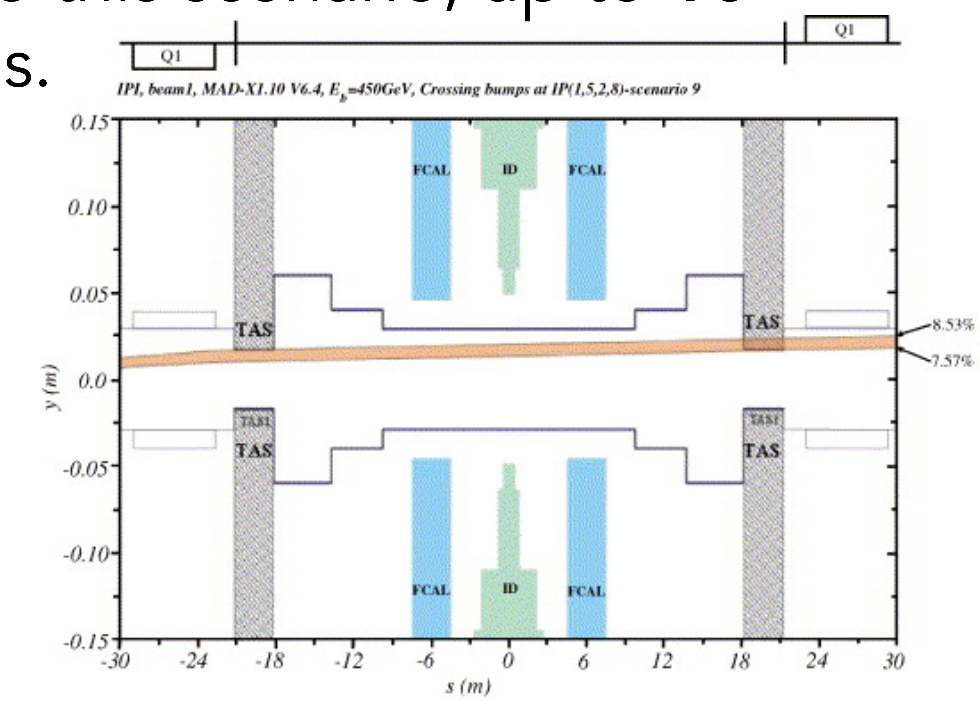
The effects of accidental beam losses were tested using a **24 GeV proton beam** at the CERN PS on, [NIM A565 (2006) 50-54](NIM A565 (2006) 50-54):

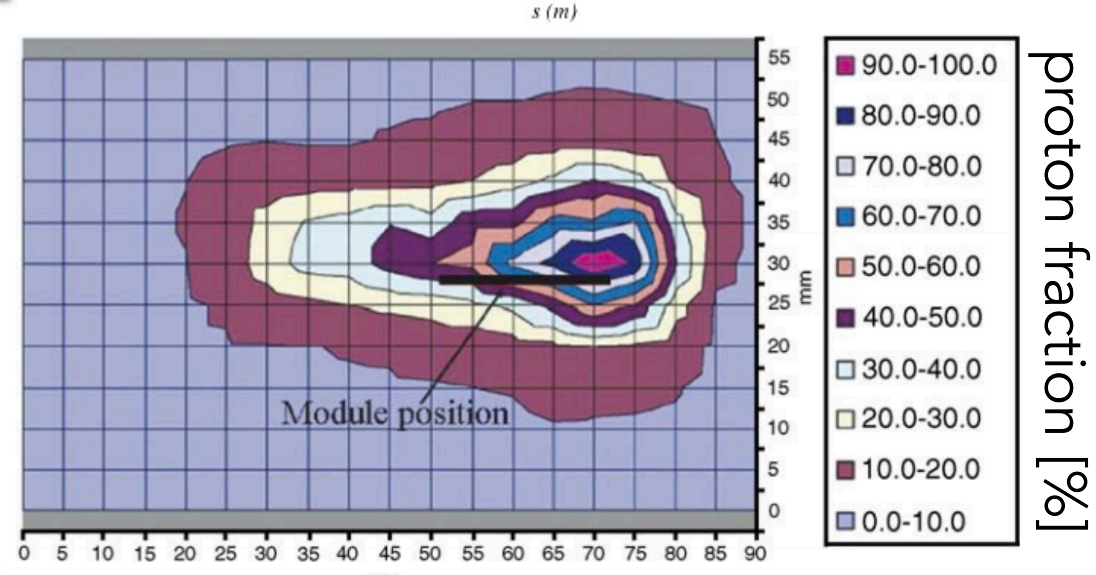
- ATLAS Pixel modules: radiation hardness up to **10^{15} n_{eq}/cm^2** with FE-I3.
- LHC worst scenario: pilot beam scraping the front quadrupole absorbers (TAS).
- Demonstrated that Pixel modules were robust to this scenario, up to **10^{10} protons/cm^2 in a single pulse** with 213 bunches.

TAS is a copper cylinder placed inside the ATLAS shielding system
1.9 m long, R = [17 mm, 250 mm], Z = 19.04 m



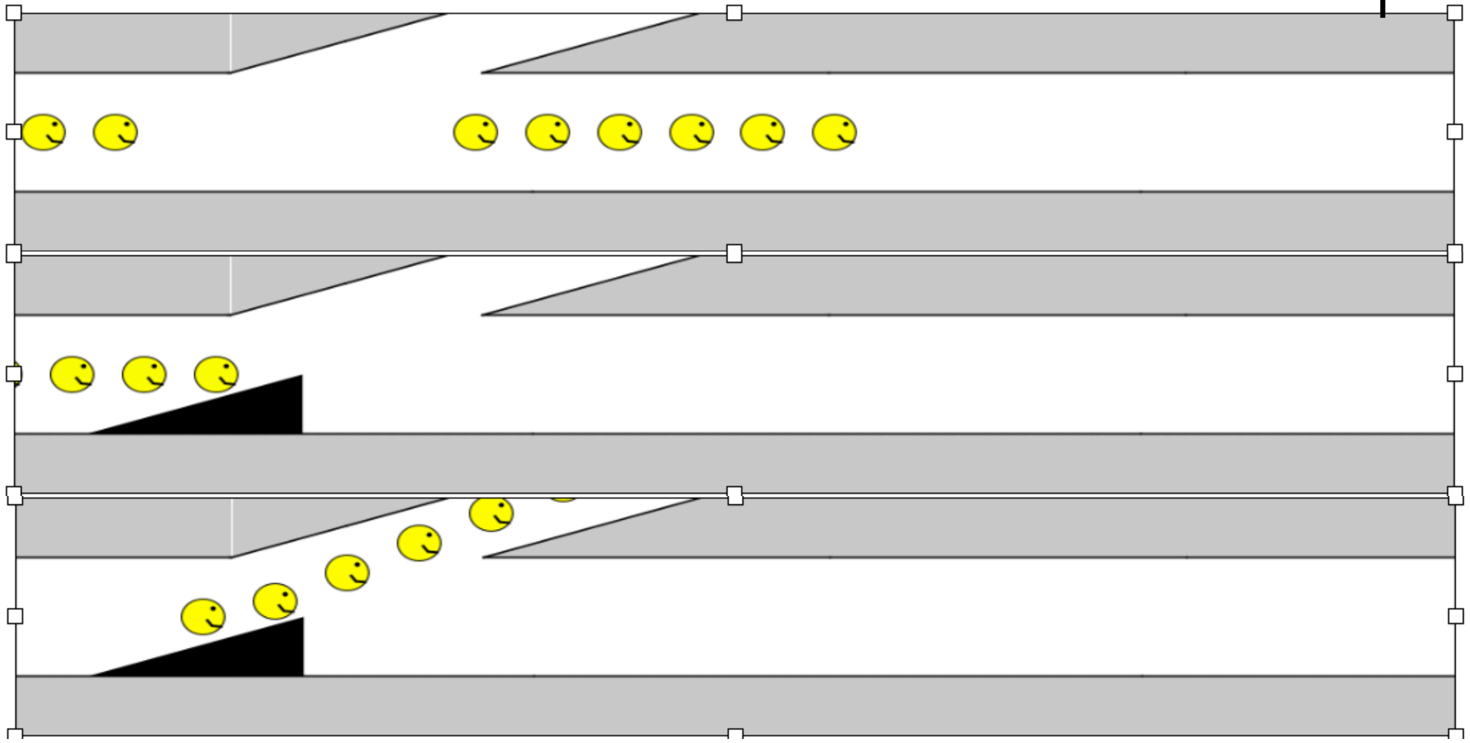




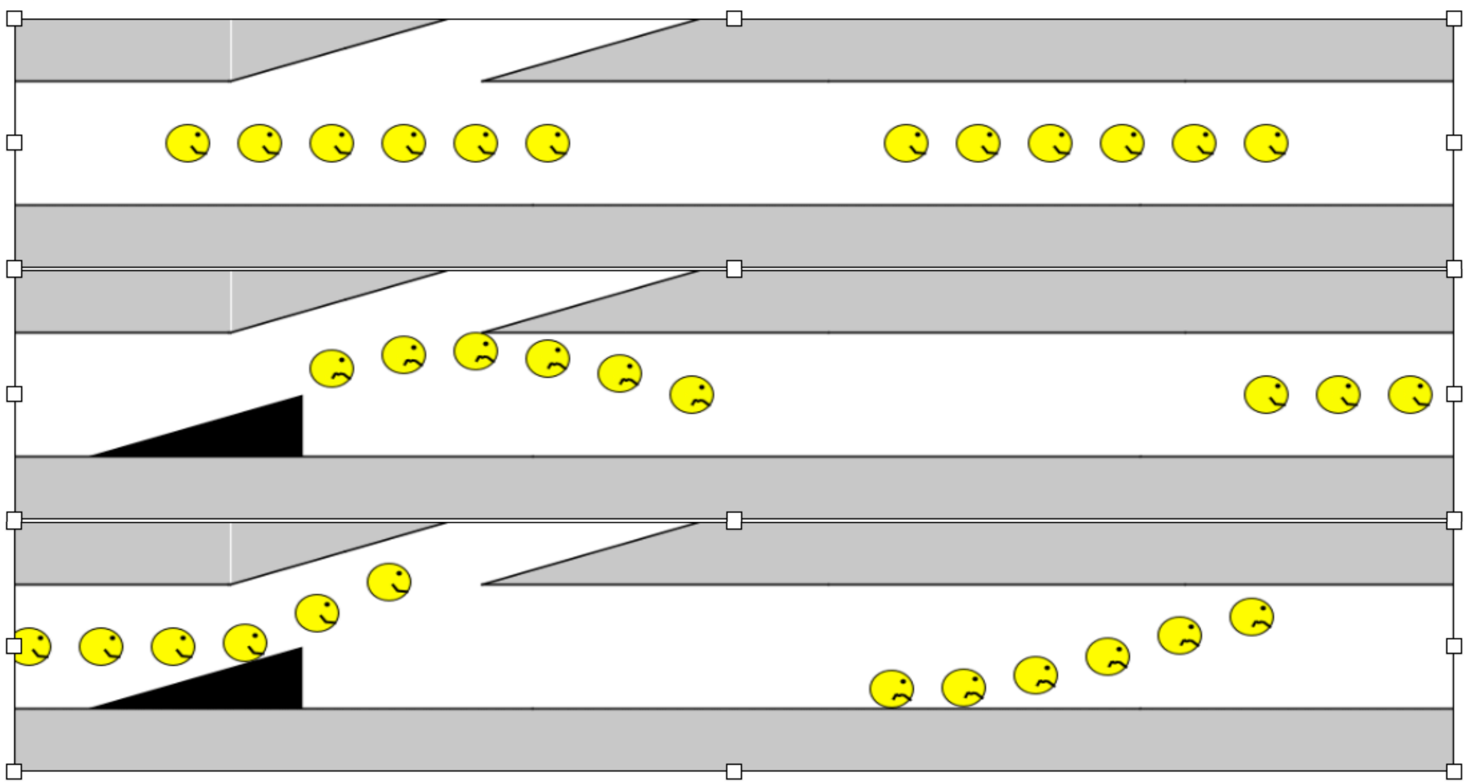


Asynchronous beam dump

Standard dump: Extraction kickers fire when no beam is passing

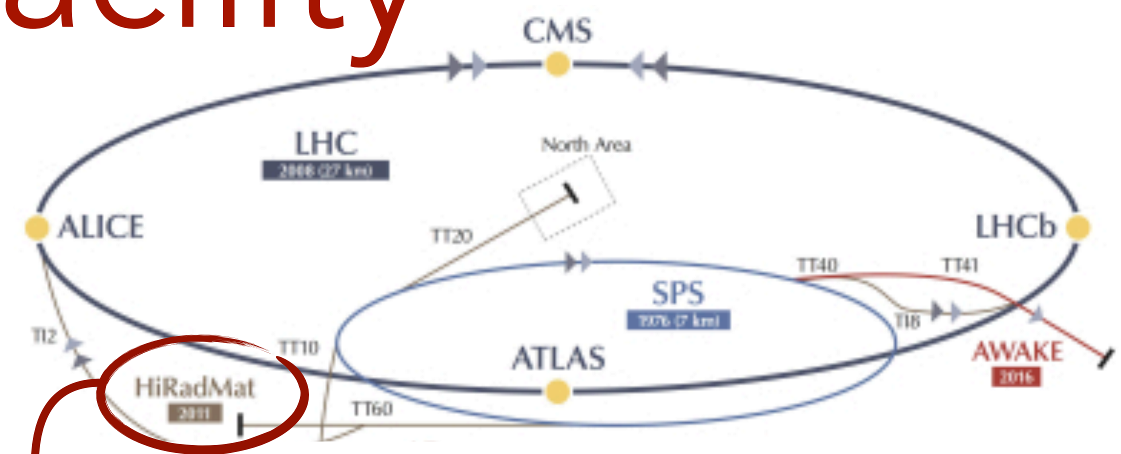


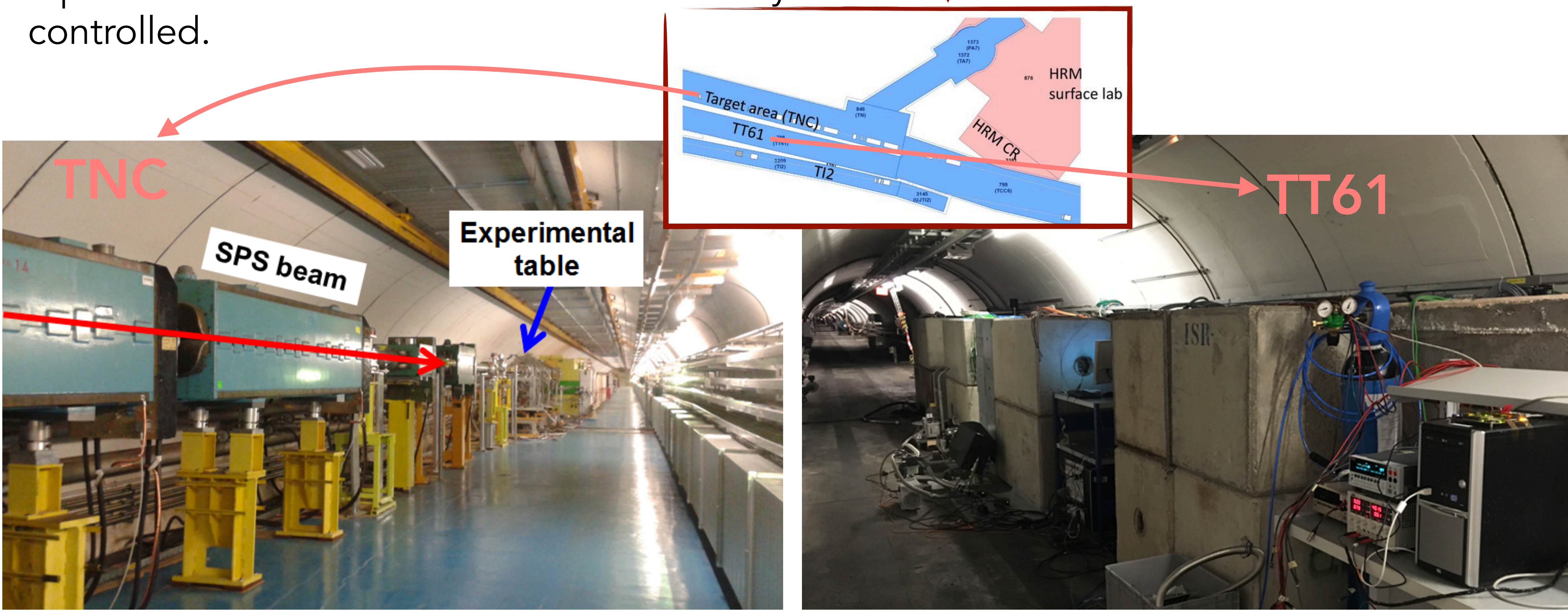
Asynchronous dump: kicker(s) fire when beam passes – kicked beam could damage sensitive equipment on the same turn



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.