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

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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.

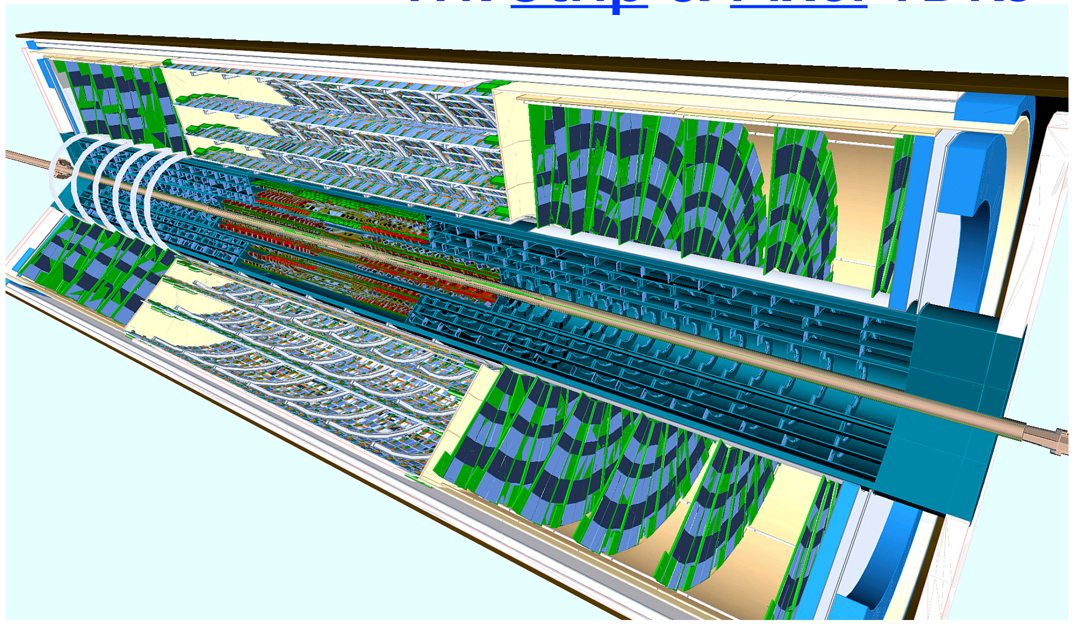
Study effects of accidental beam-loss scenarios for ATLAS tracking detector (Pixel and Strips) at HL-LHC.

- Provide a realistic estimate of the damage threshold for sensors and electronics.
- Evaluate the performance degradation due to the radiation damage.

To cope with the future accelerator (L_{int}>7.5x10^{34} cm^{-2} s^{-1}), **ATLAS** is planning a complete **update of the detector.**

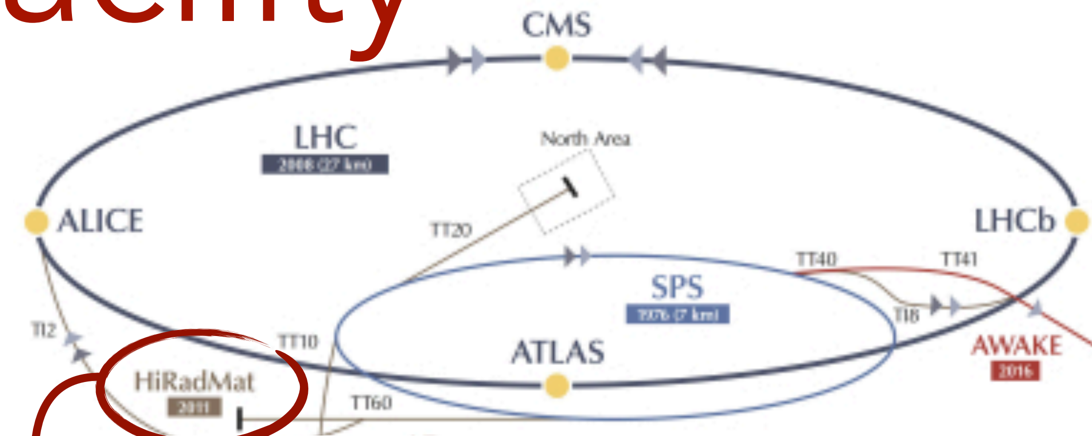
- The **new inner tracker (ITk) will be an all Si Tracker system** which will replace the current ID.

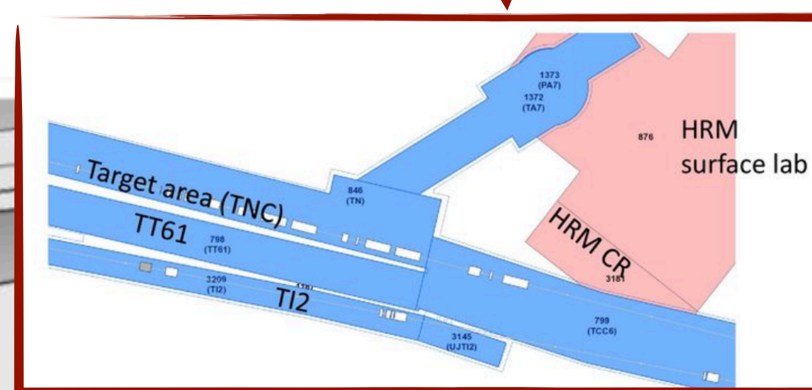
ITk Strip & Pixel TDRs



HiRadMat Facility

- Facility at CERN providing high-intensity pulsed beam.
- 440 GeV proton beam extracted from CERN SPS.
- Two separated tunnels: beam line and read-out system.

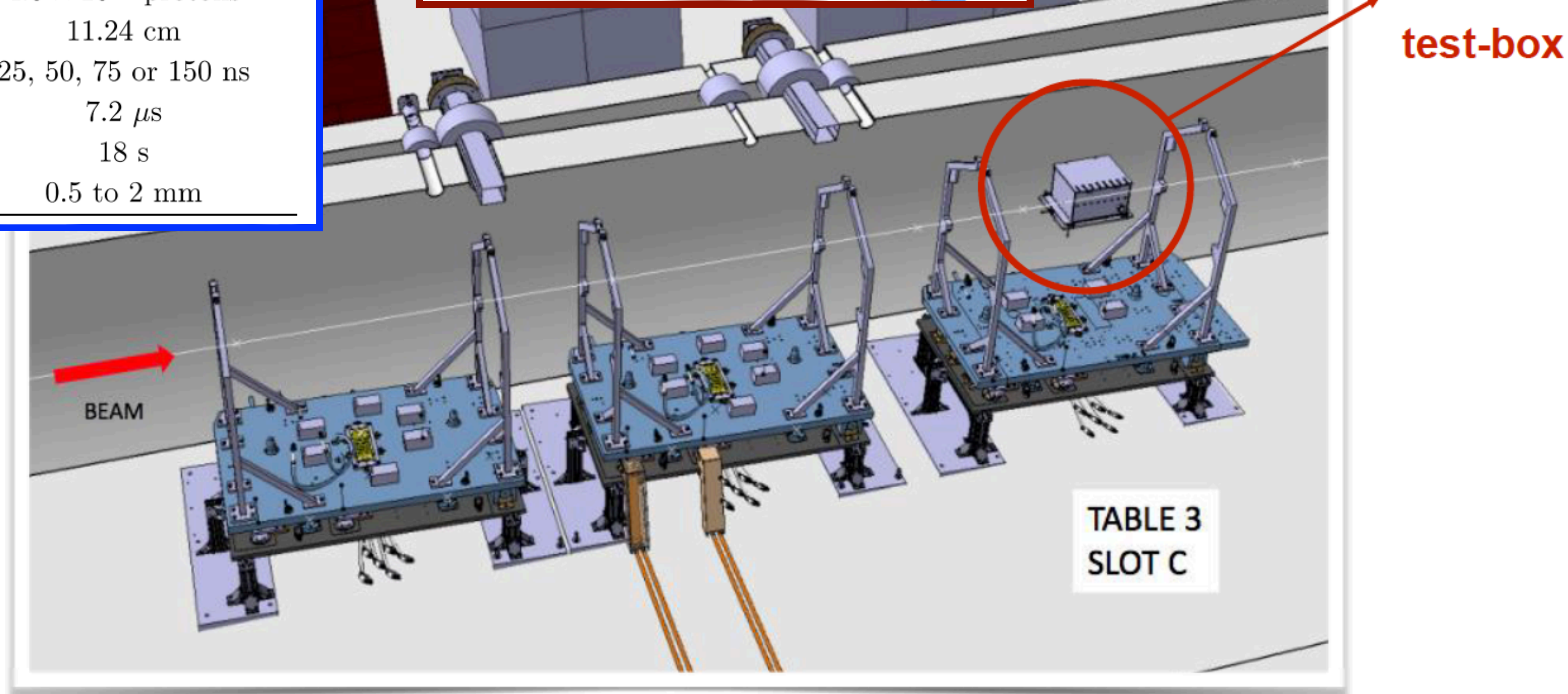




Proton Beam Parameters	Value
Beam Energy	440 GeV/c^2
Pulse Energy	up to 3.4 MJ
Bunch intensity	up to 1.2×10^{11} protons
Number of bunches	1 to 288
Maximum pulse intensity	4.0×10^{13} protons
Bunch length	11.24 cm
Bunch spacing	25, 50, 75 or 150 ns
Maximum pulse length	7.2 μs
Cycle length	18 s
Beam radius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

HiRadMat High-Radiation to Materials

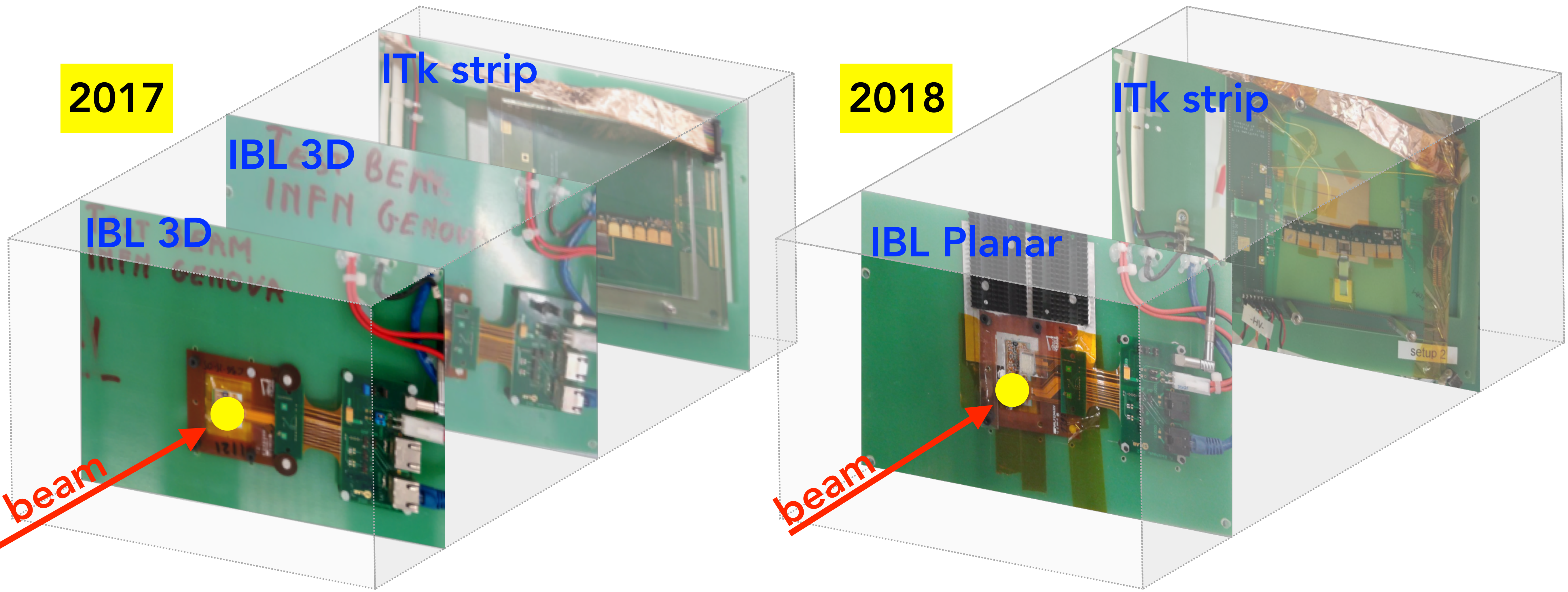
Fixed 90° impact



Experimental Setup

Design and construction of the test-box:

- Material: epoxy fiber glass, makrolon and aluminium.
- Designed to host a maximum of 8 detector modules.
- Cooling system: 4 fans (12x12 cm) with filters.
  - In 2017: important temperature variation affected modules performance
  - Aluminium plane and dissipator added in 2018.

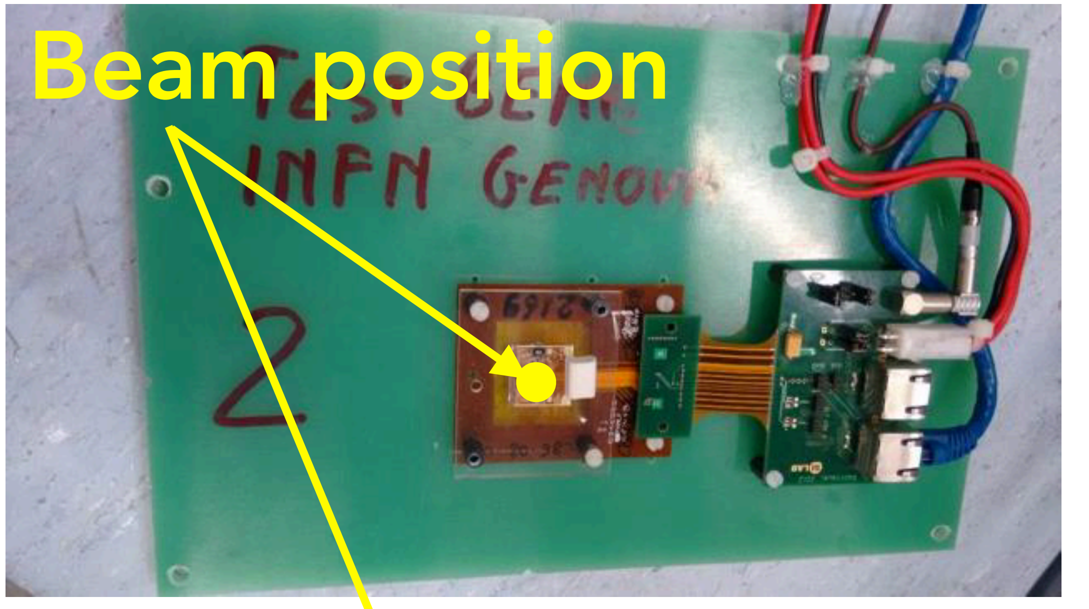


Beam-loss studies July 2017: Modules

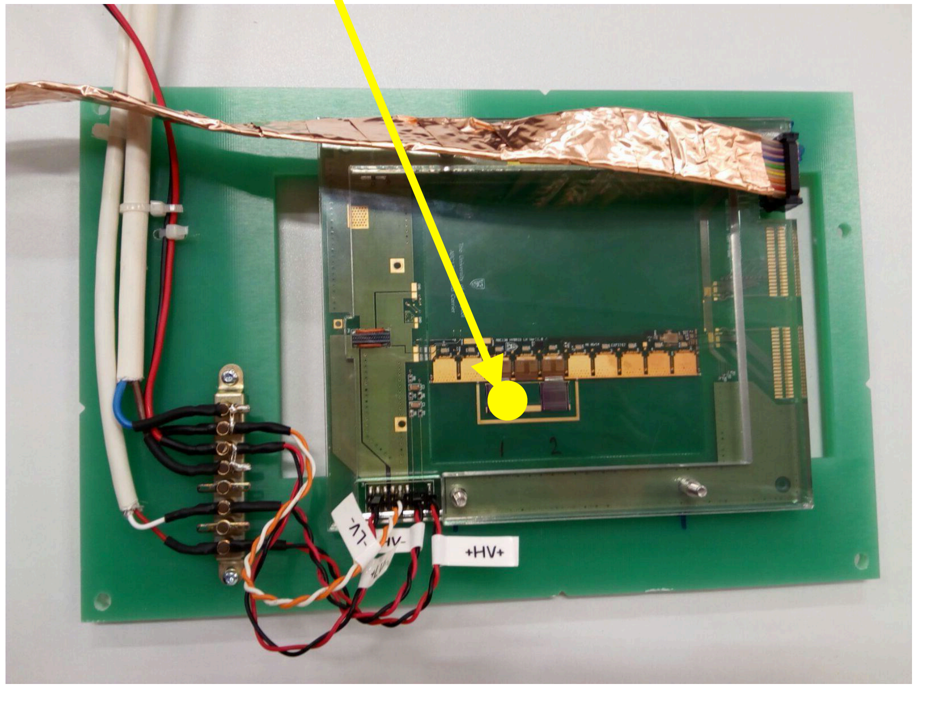
- ITk strip miniature sensor available for the beam test.
- ITk Pixel prototype with RD53A not available at that time, used most advance technology IBL .
  - Not proper cooling system, no constant temperature: **T~[30,60]°C**

Module	IBL	ITk
Type	n^{+}-in-p, 3D	n^{+}-in-p, ATLAS12
Chip	FE-I4	ABC130
Total Size	2x2 cm^2	1x1 cm^2
Thickness	230 μm	320 μm
Channel/ pitch	26680 (50x250 μm^2)	104 (74.5 μm)
Max. Dose	250 MRad	35 MRad

IBL 3D



ITk DAQLoad

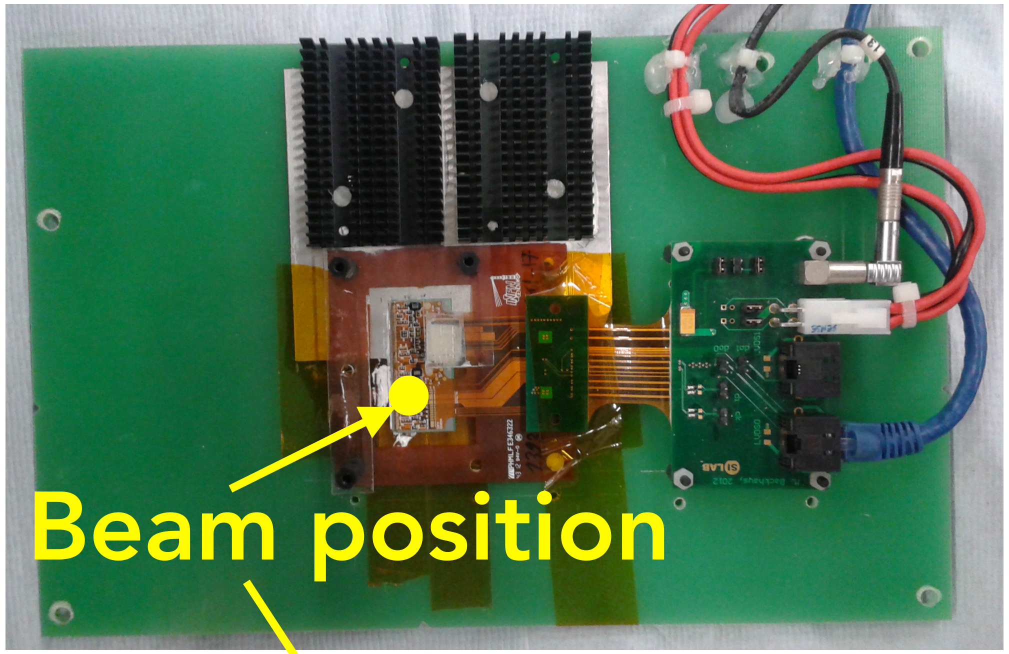


Beam-loss studies July 2018: Modules

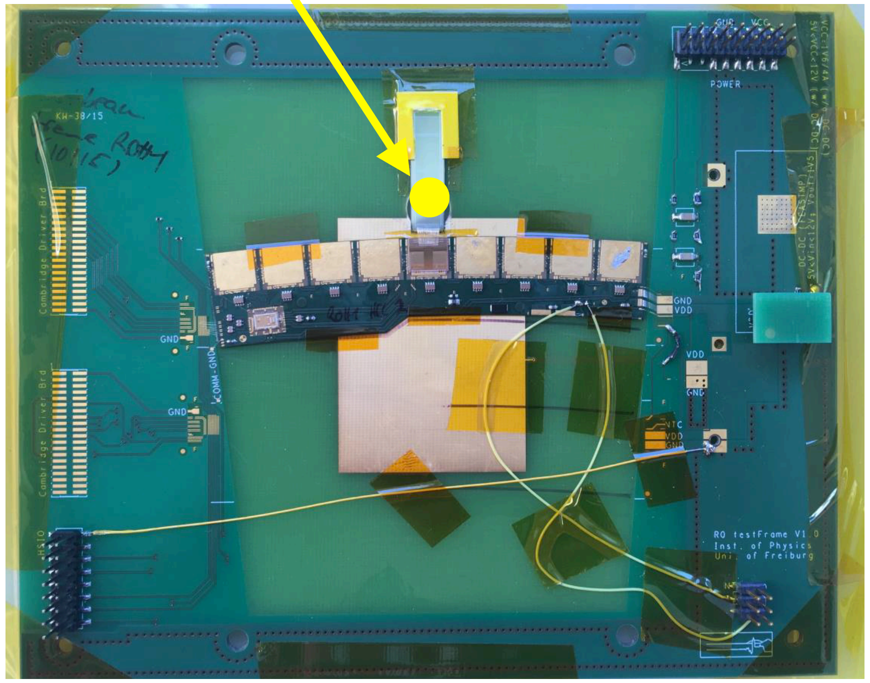
- ITk strip miniature sensor available for the beam test.
- ITk Pixel prototype with RD53A not available at that time, used most advance technology IBL
  - Improved cooling system via aluminium and dissipator: **T~36°C**

Module	IBL	ITk
Type	n+-in-n, Planar	n+-in-p, Low-R
Chip	FE-I4	ABC130
Total Size	2x4 cm^2	0.7x2.6 cm^2
Thickness	200 μm	310 μm
Channel/ pitch	2x26680 (50x250 μm^2)	64 (77 μm)
Max. Dose	250 MRad	35 MRad

IBL Planar



ITK DAQLoad

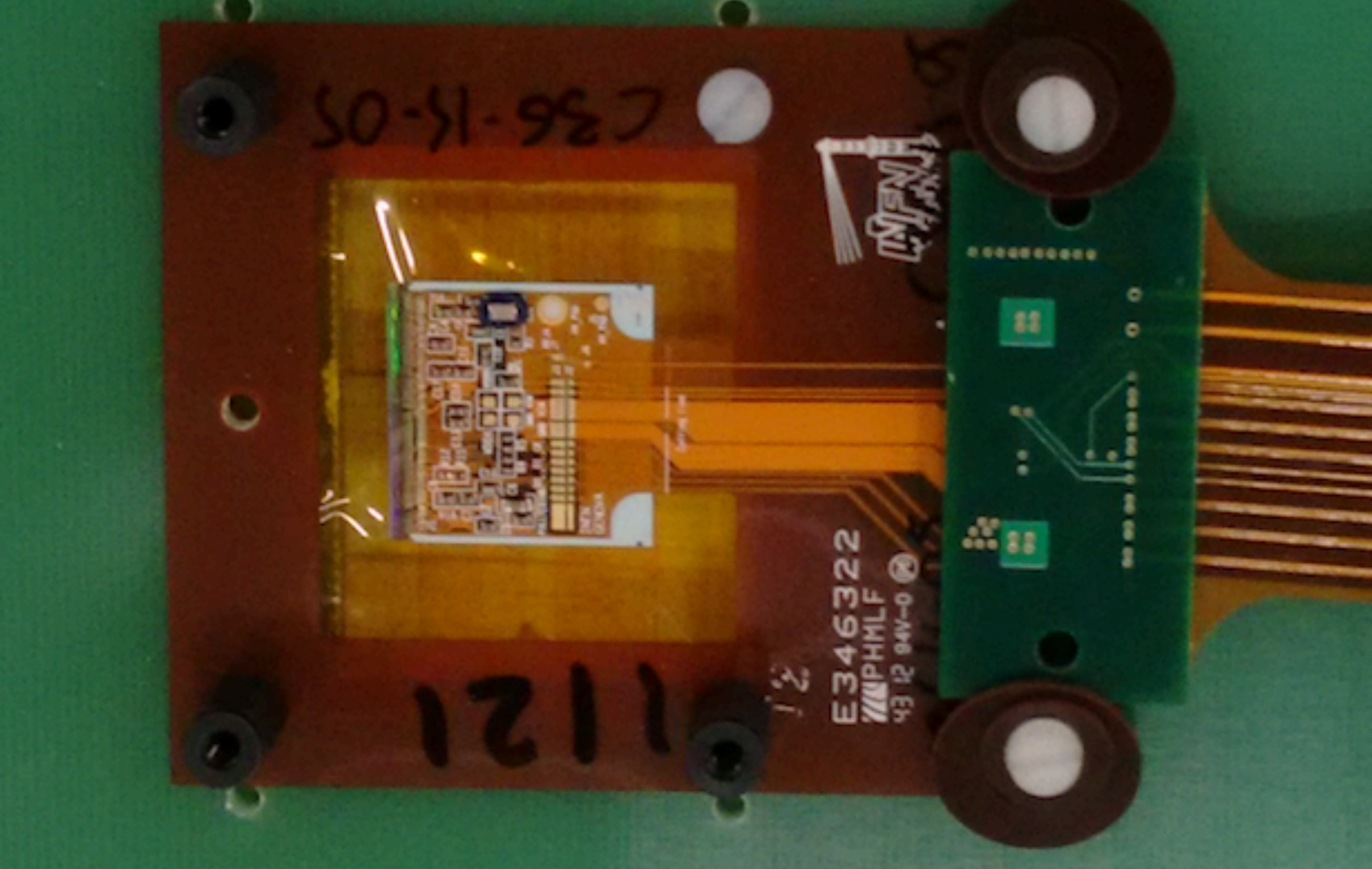


Beam pulse list

- 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}	$2.6 \cdot 10^{12}$

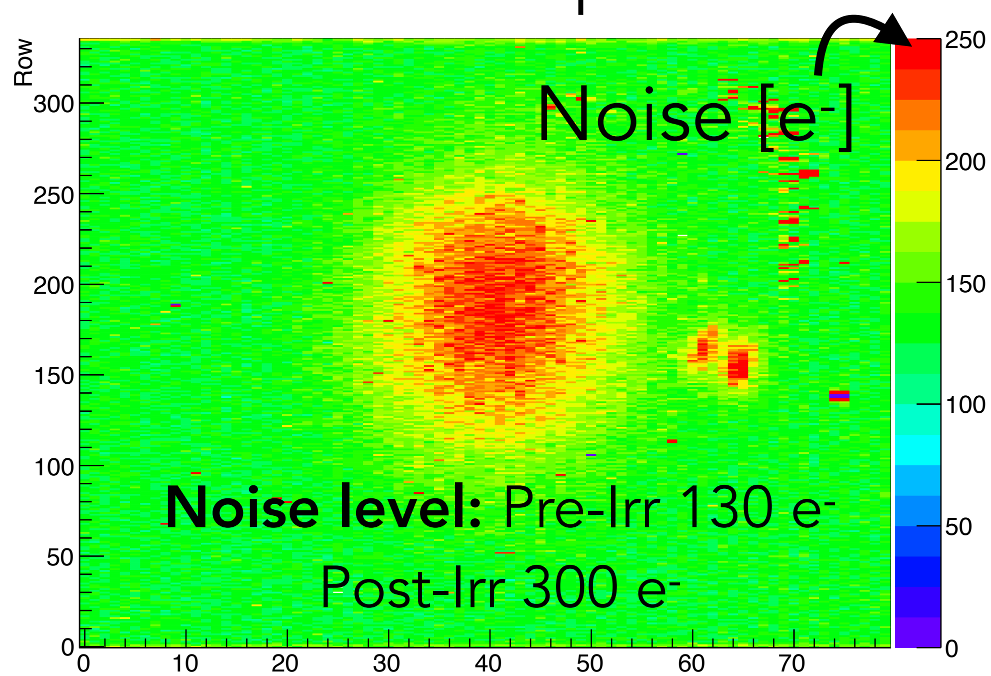
Pixel 2018/17



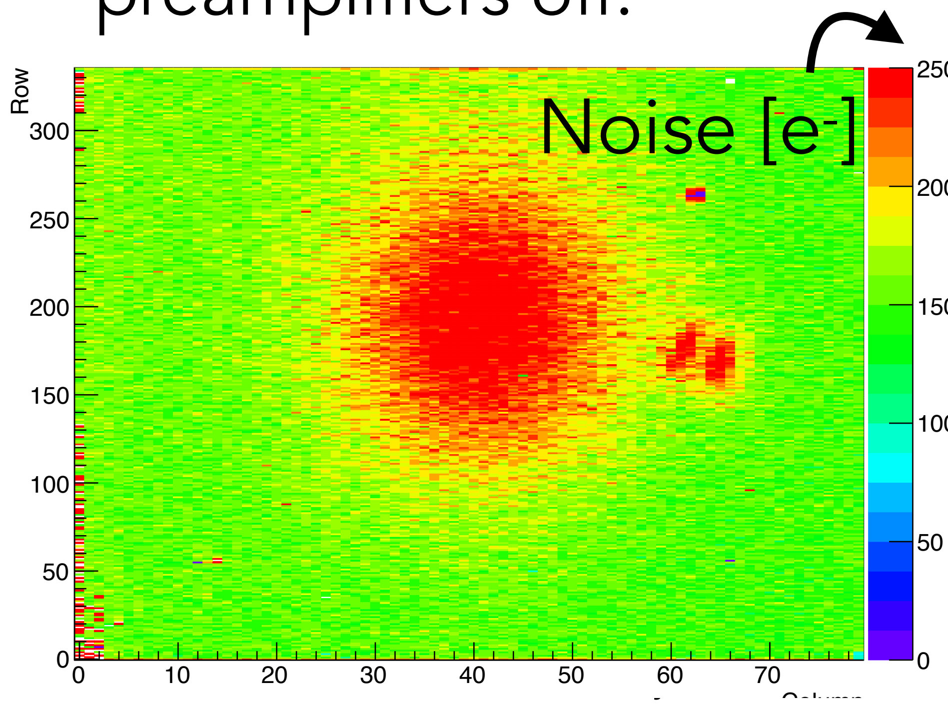
IBL 3D: Noise 2017

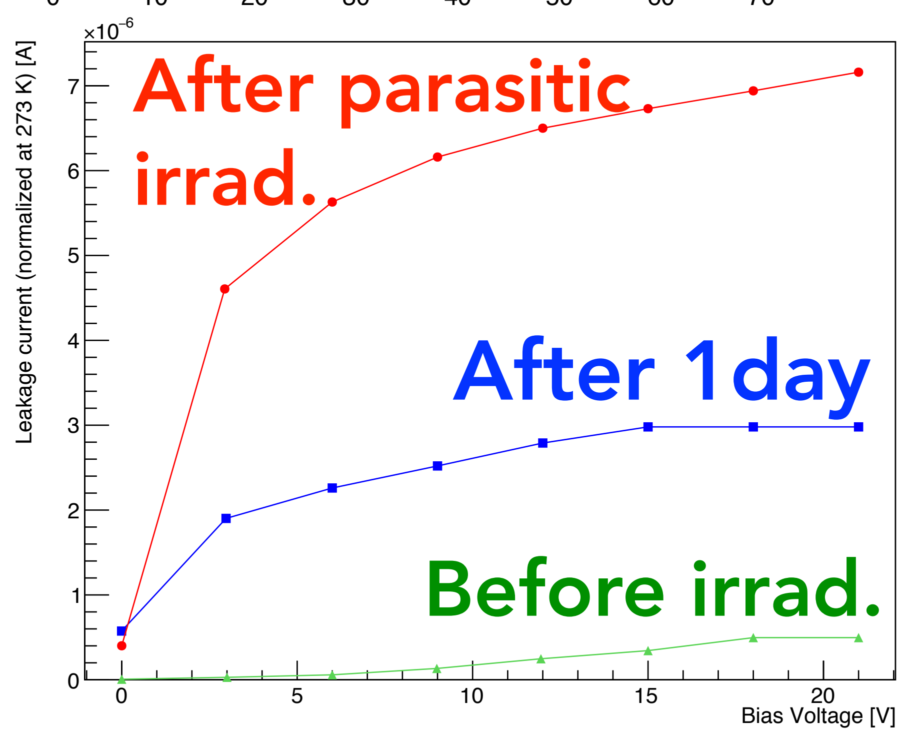
- Two IBL modules configurations used
  - Noise 2D map extracted from threshold scan (HV On: -20 V)
- **Leakage current of the sensor, normalised at 273 K**, for different days.
  - Temperature not under control: **T~[30,60]°C**

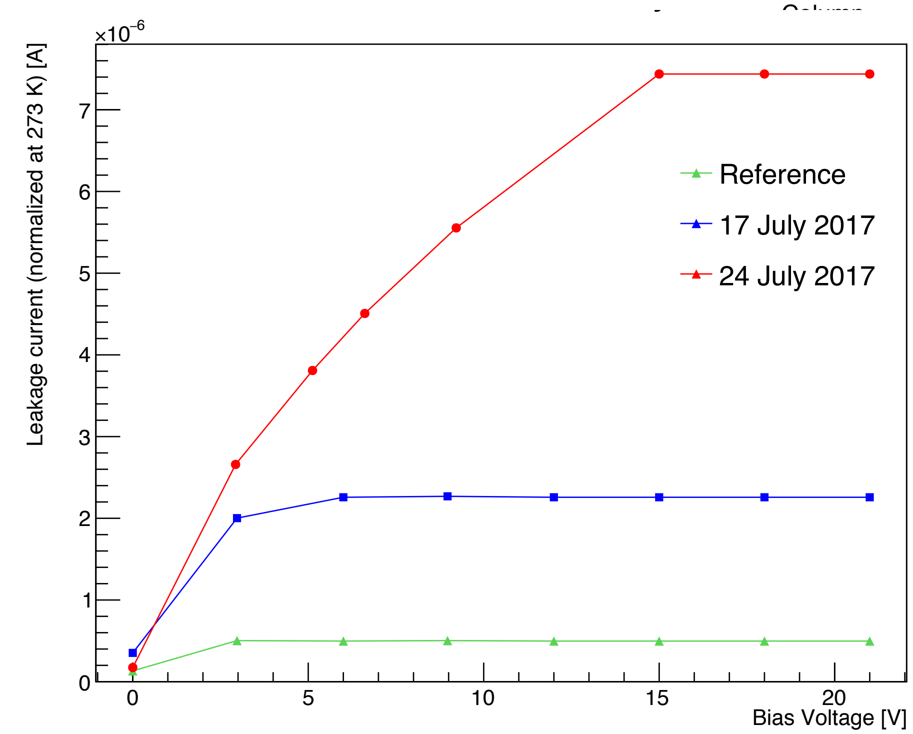
ATLAS in Stable beam operation: sensor bias on and FE amplifiers on.



ATLAS in Stand-by: sensor bias off and FE preamplifiers off.







NB: Results updated wrt Hiroshima2017

IBL 3D: Occupancy 2017

Global irradiation: 2 mm beam.

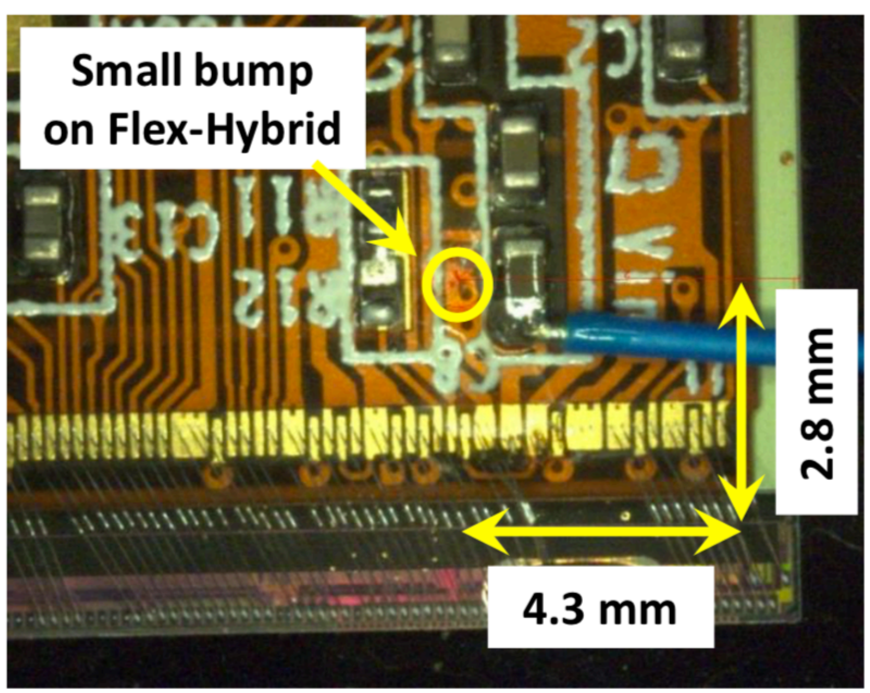
- Beam spot due to material activatio
- The intensity of the spot was increasing after each shot.

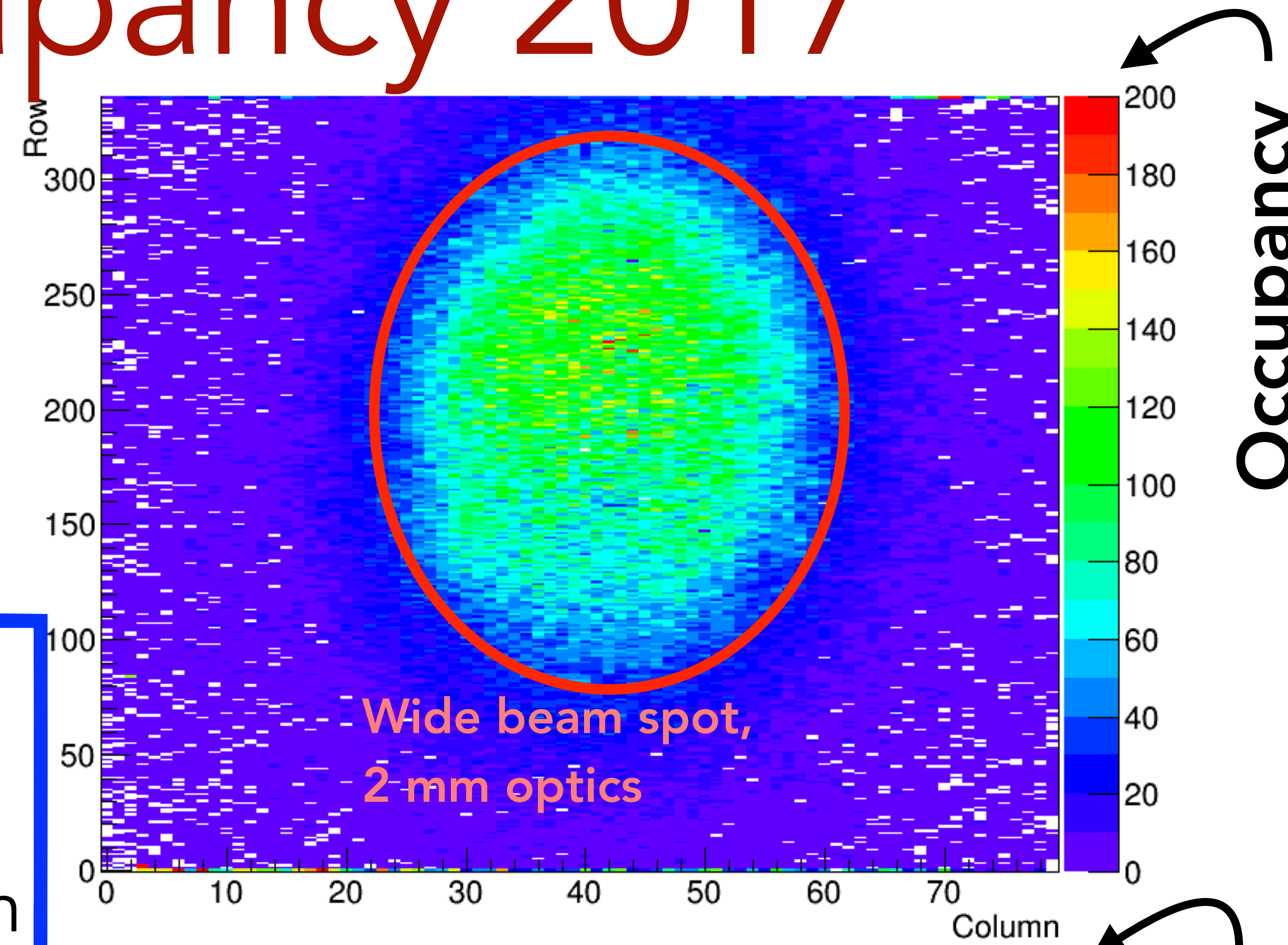
Limit on the damage threshold with large beam spot: $1 \cdot 10^{13}$ p/cm^2.

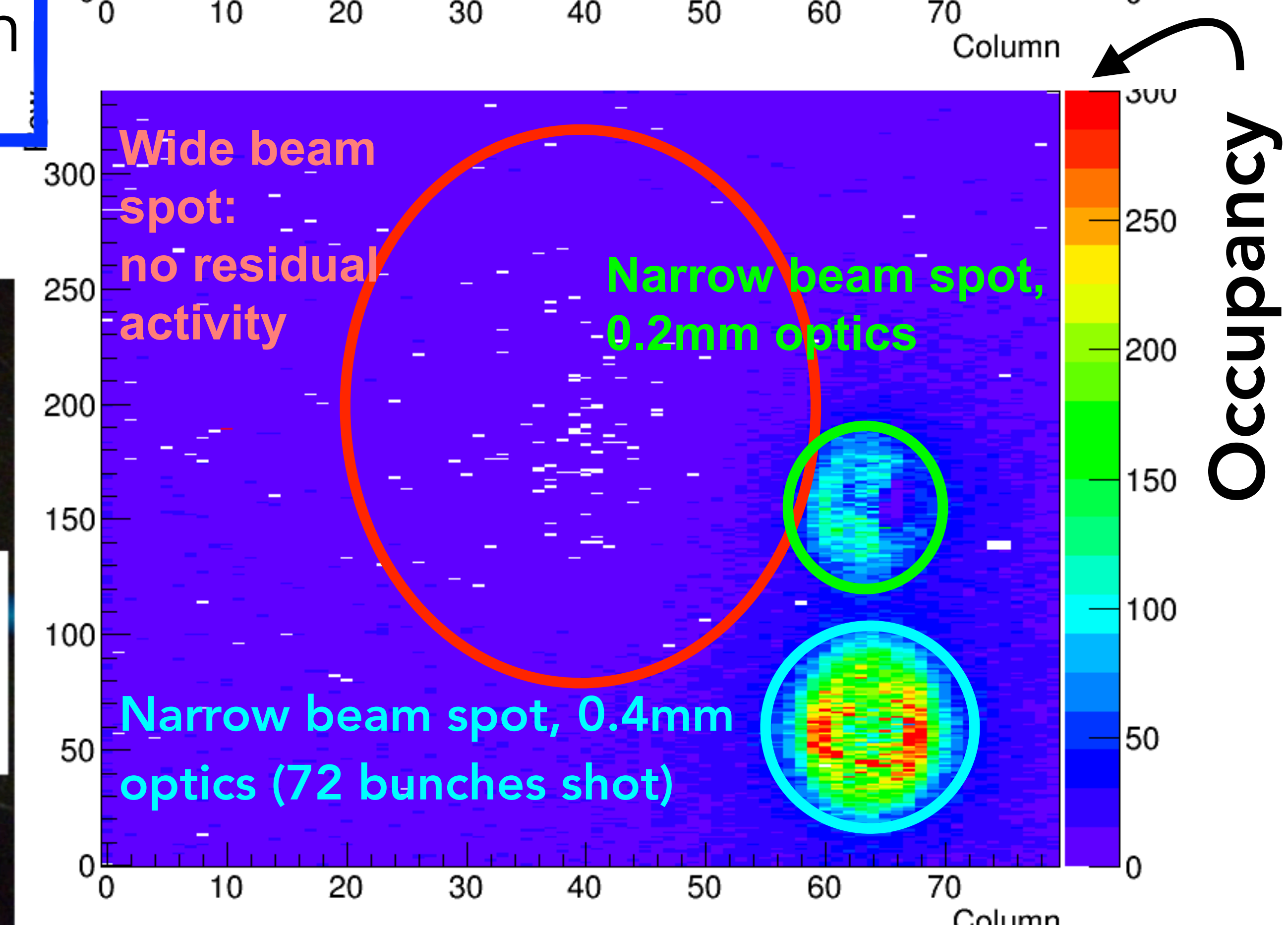
- ✤Radius of damage: 15 pixels ~0.38 cm

Local Irradiation: 0.4 mm beam.

- Detector dead after 288 bunches.
  - FE supply in short.

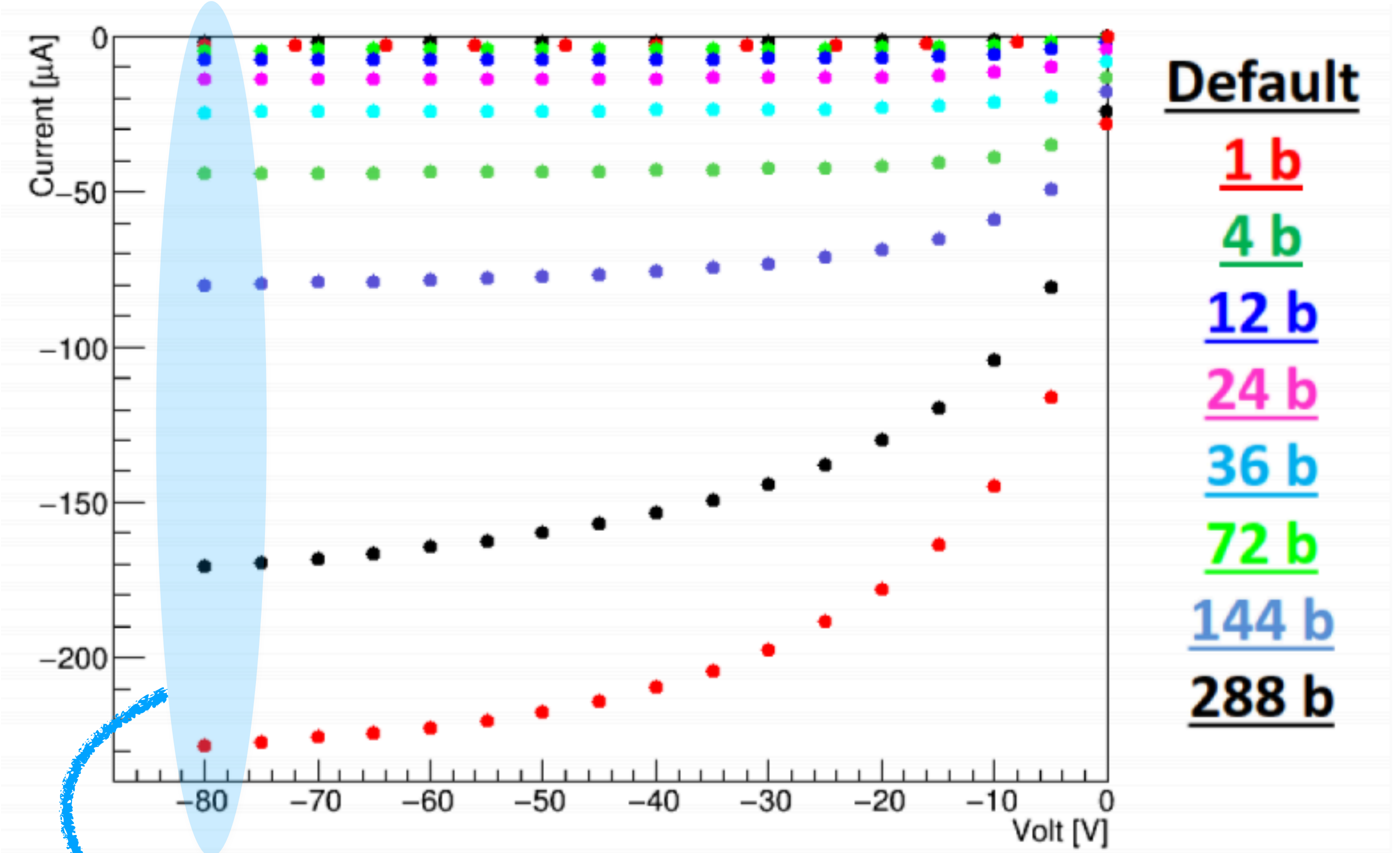






IBL Planar: IV scan 2018

- Stable beam configuration used.
- Bulk and surface damage post-irradiation, cause a **linear increase of the leakage current with the fluence.**
  - Increase to ~230 μA at 80 V.



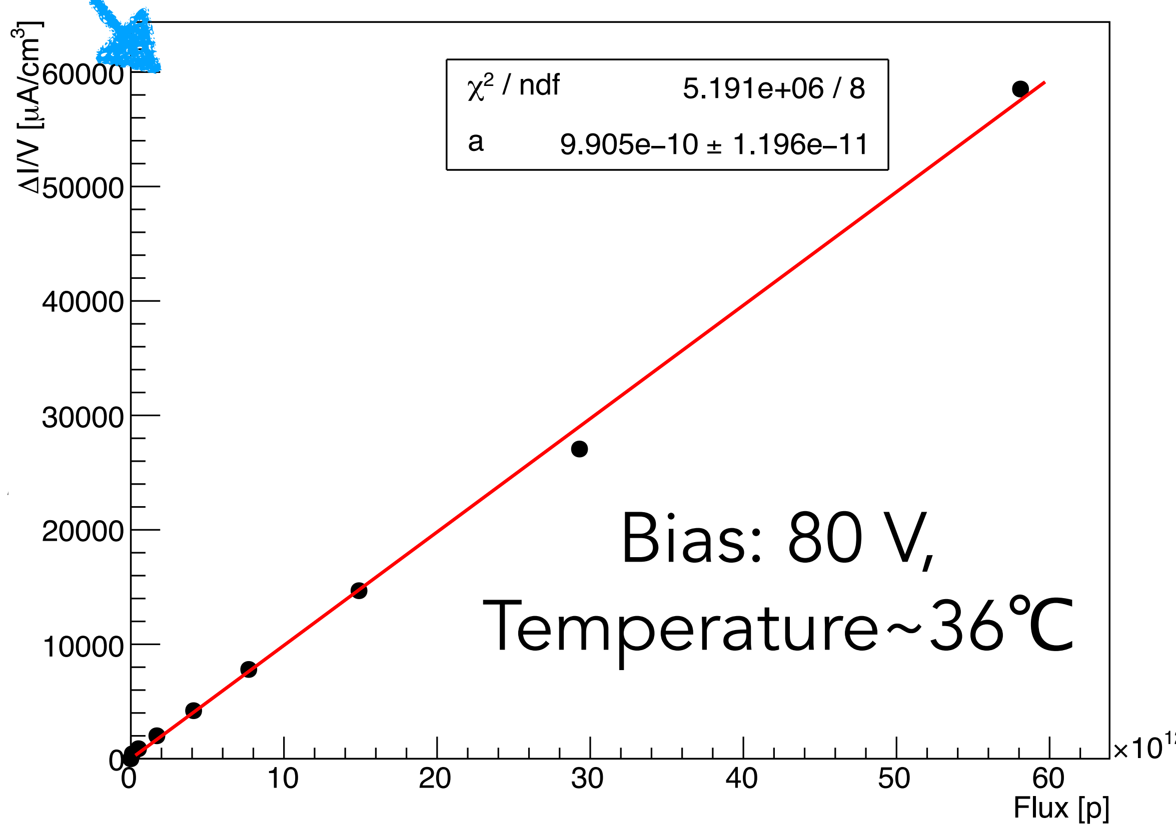
$$\Delta I \simeq \alpha \Phi V$$

ΔI: increase of leakage current before and after irradiation.

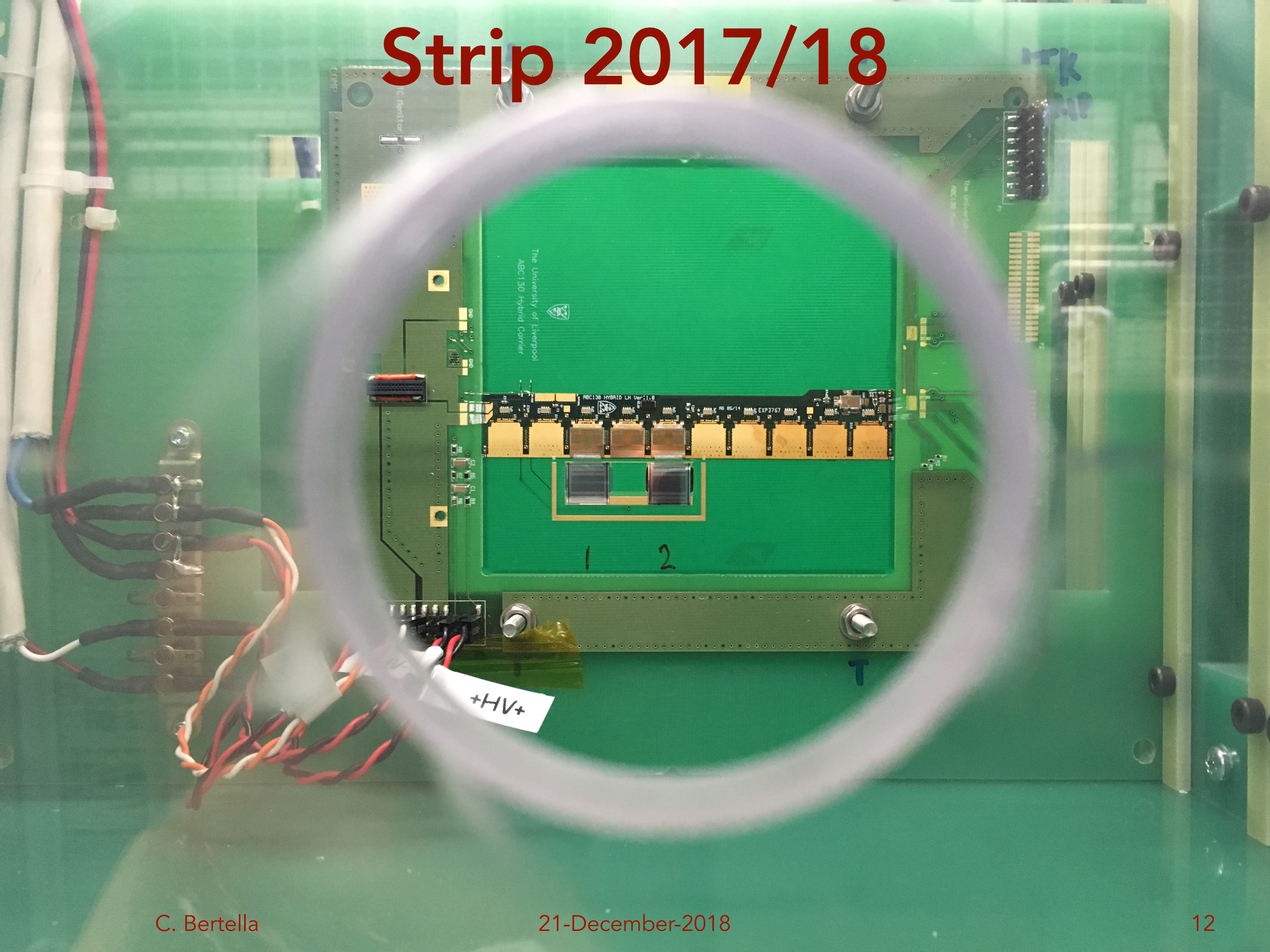
Φ: integrated proton flux (0-288·10^{11}).

V: Volume= Surface x thickness.

α: Current related damage rate.

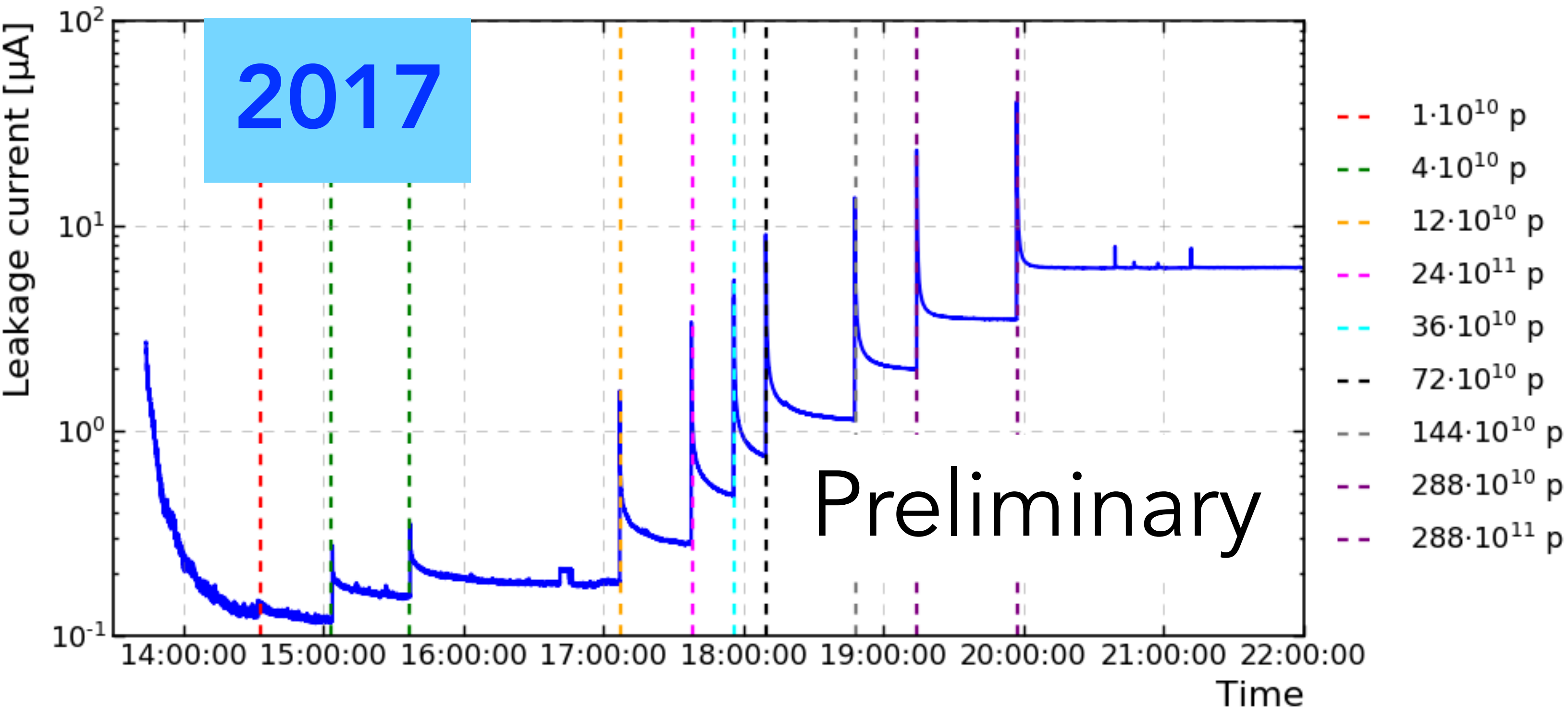


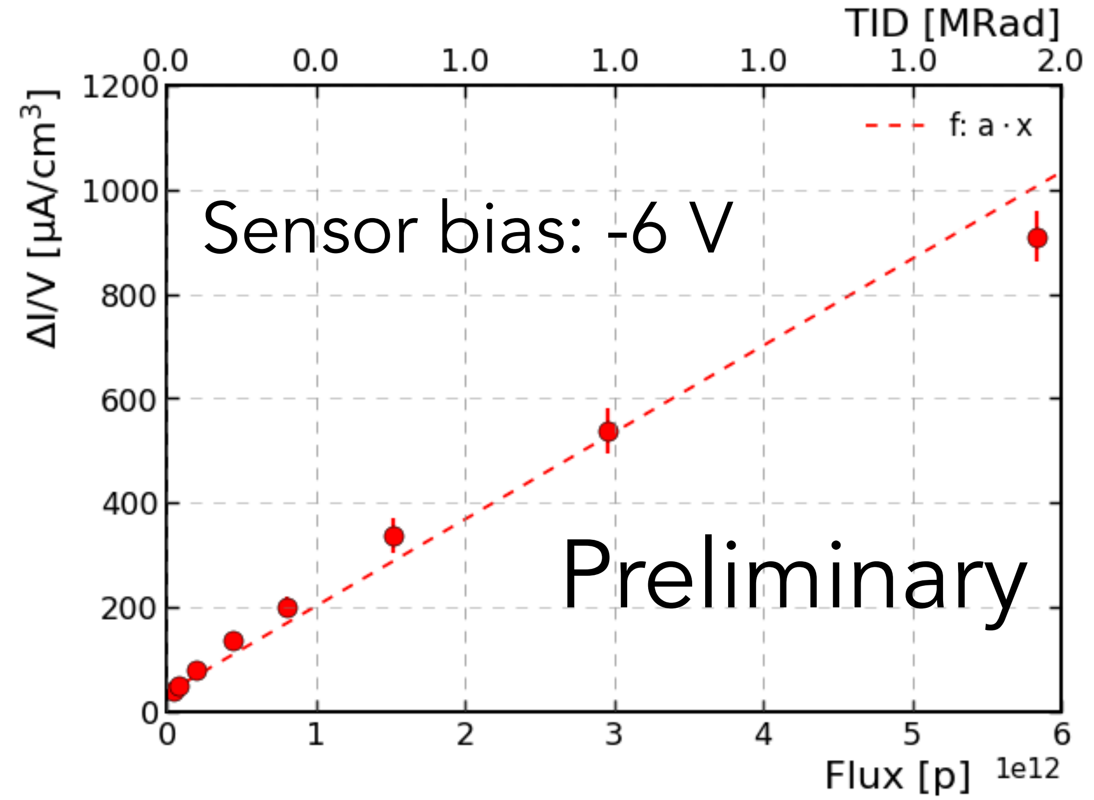
Strip 2017/18

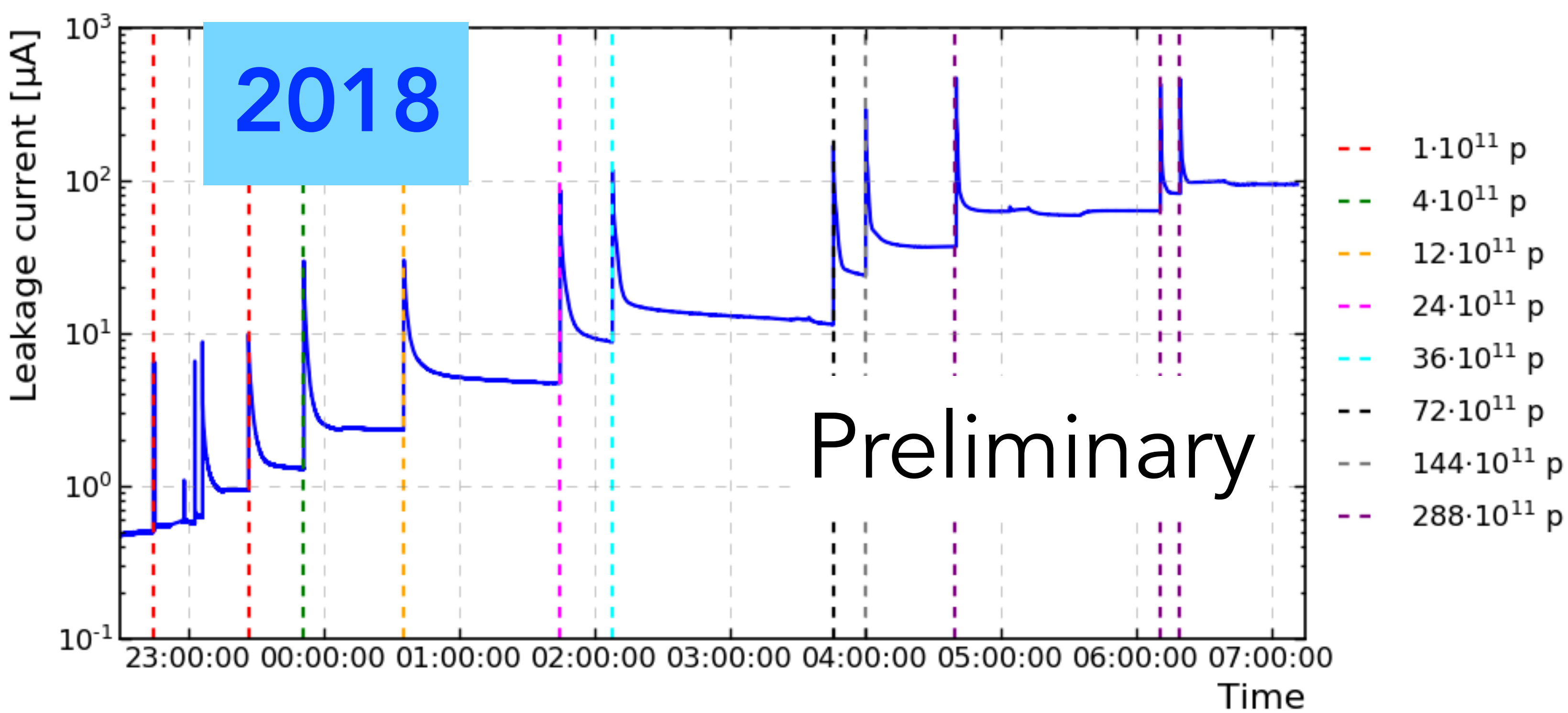


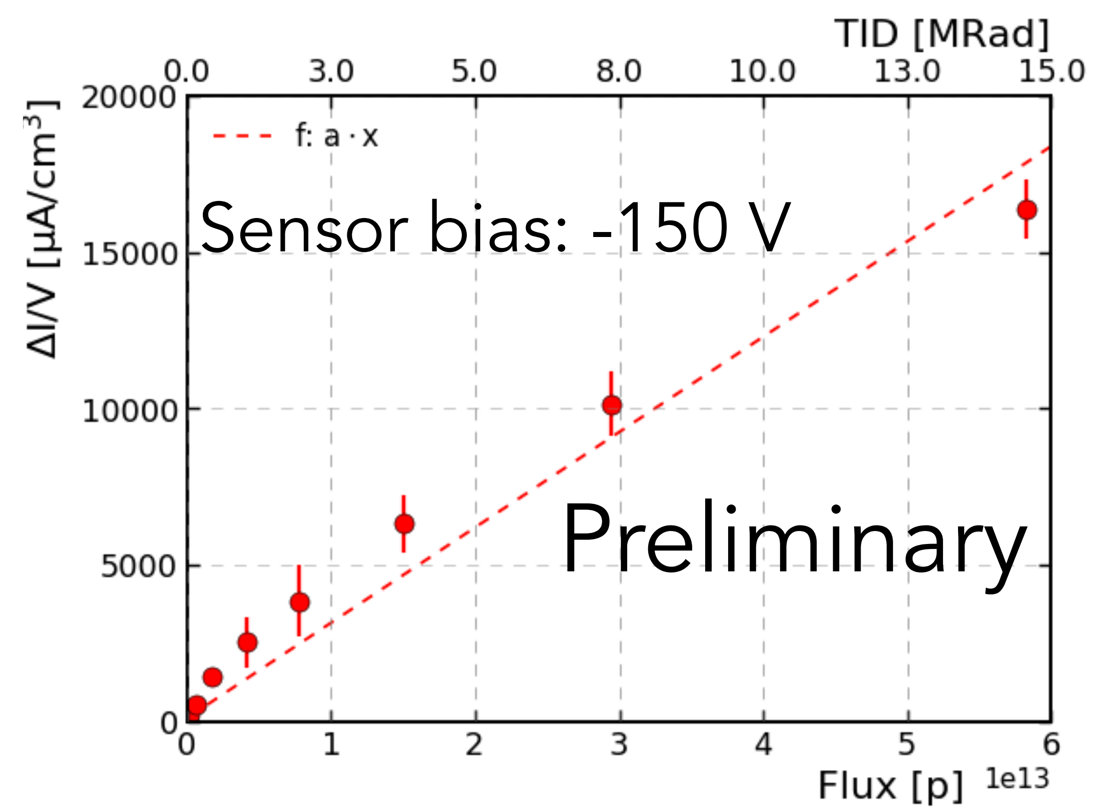
ITk strip: Leakage current evolution

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

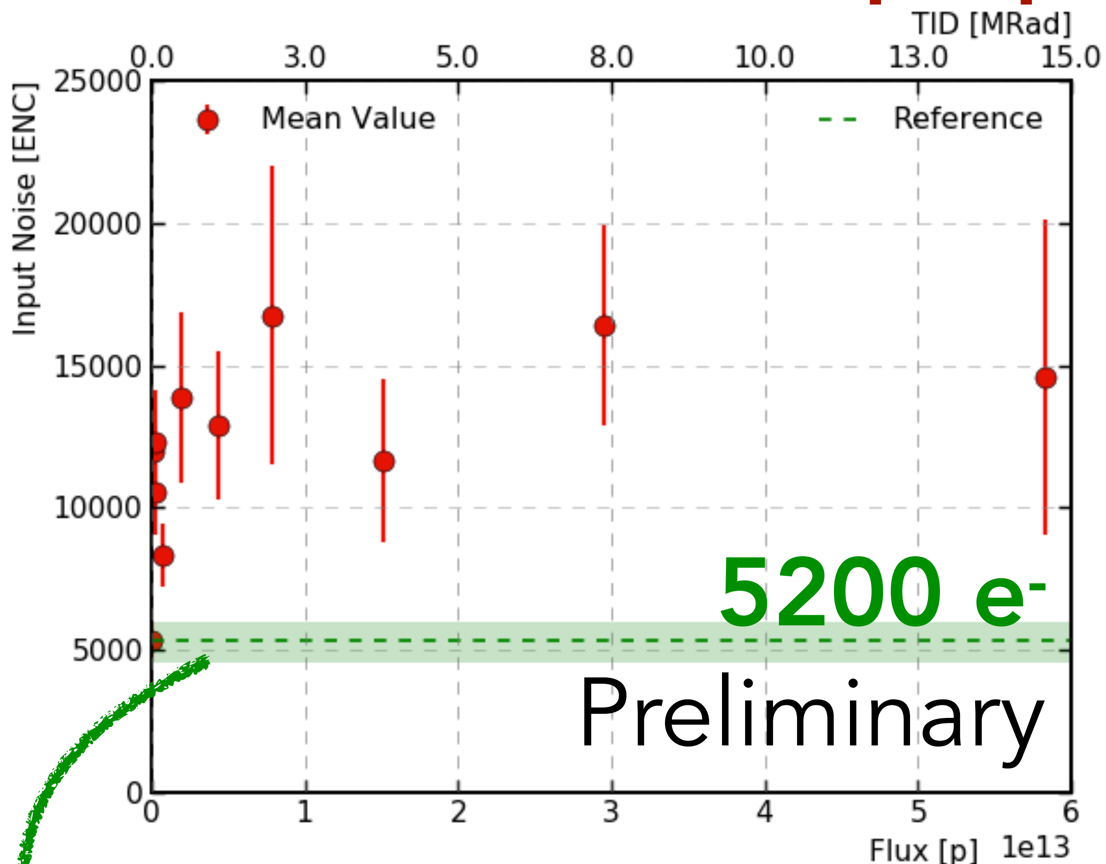


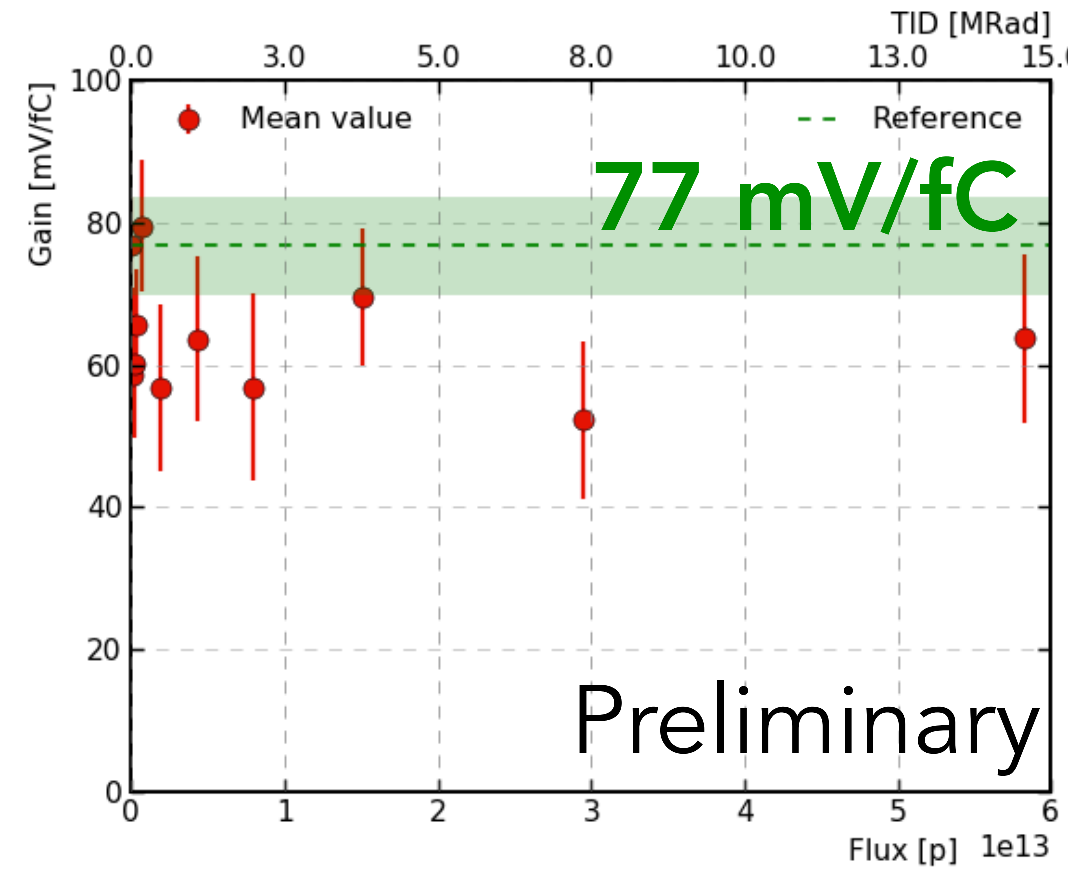




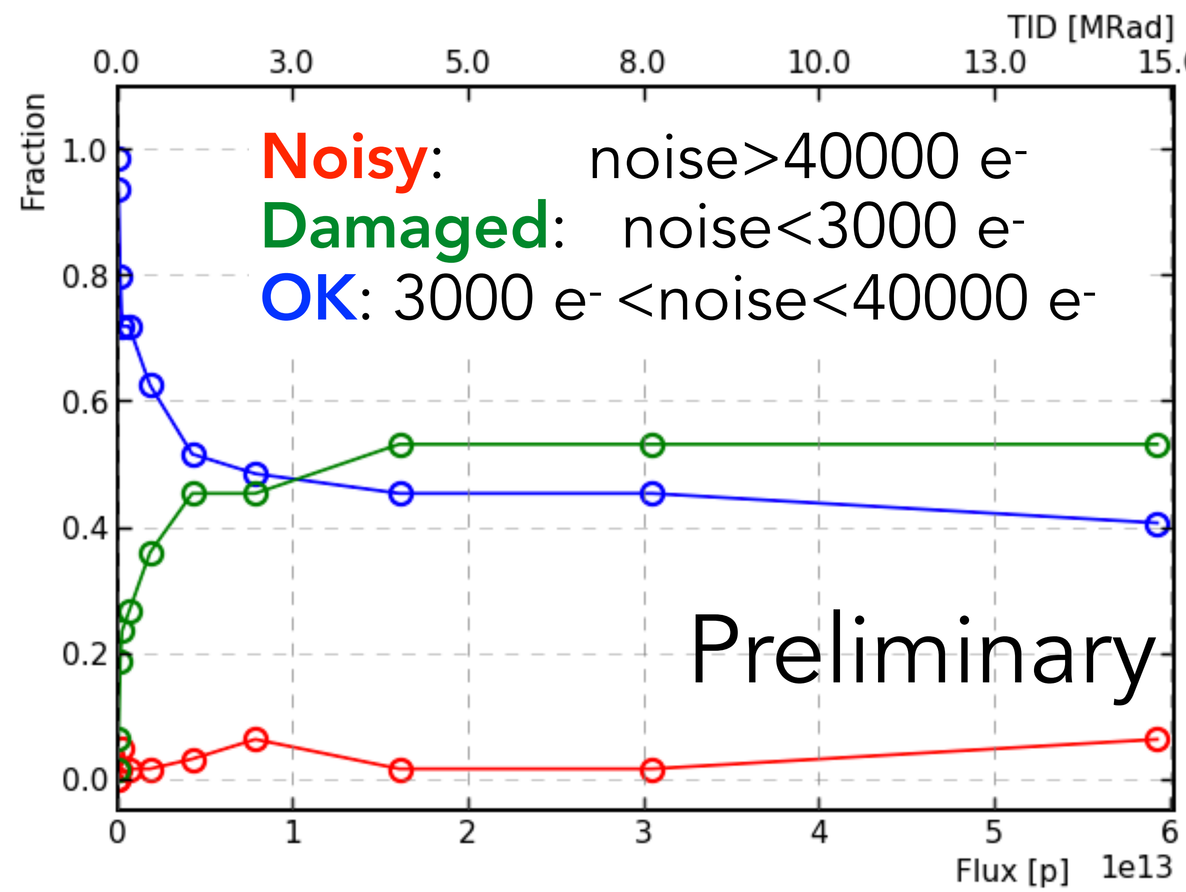


Strip performance





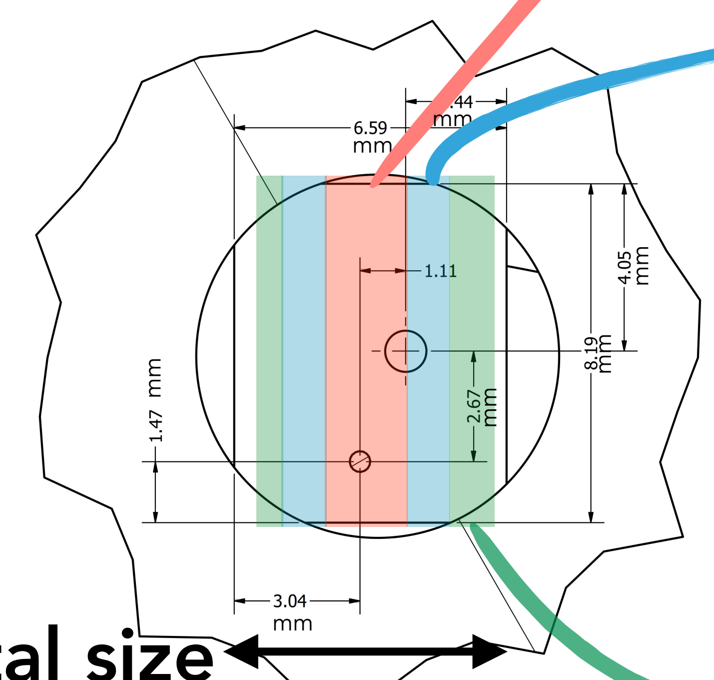
- High nominal noise associated to temperature and circuit.
- Level of **Noise** or **Gain** used to characterise the strip behaviour.
- **~40%** of the strip shows **good performance**.



Channel behaviour: around the beam

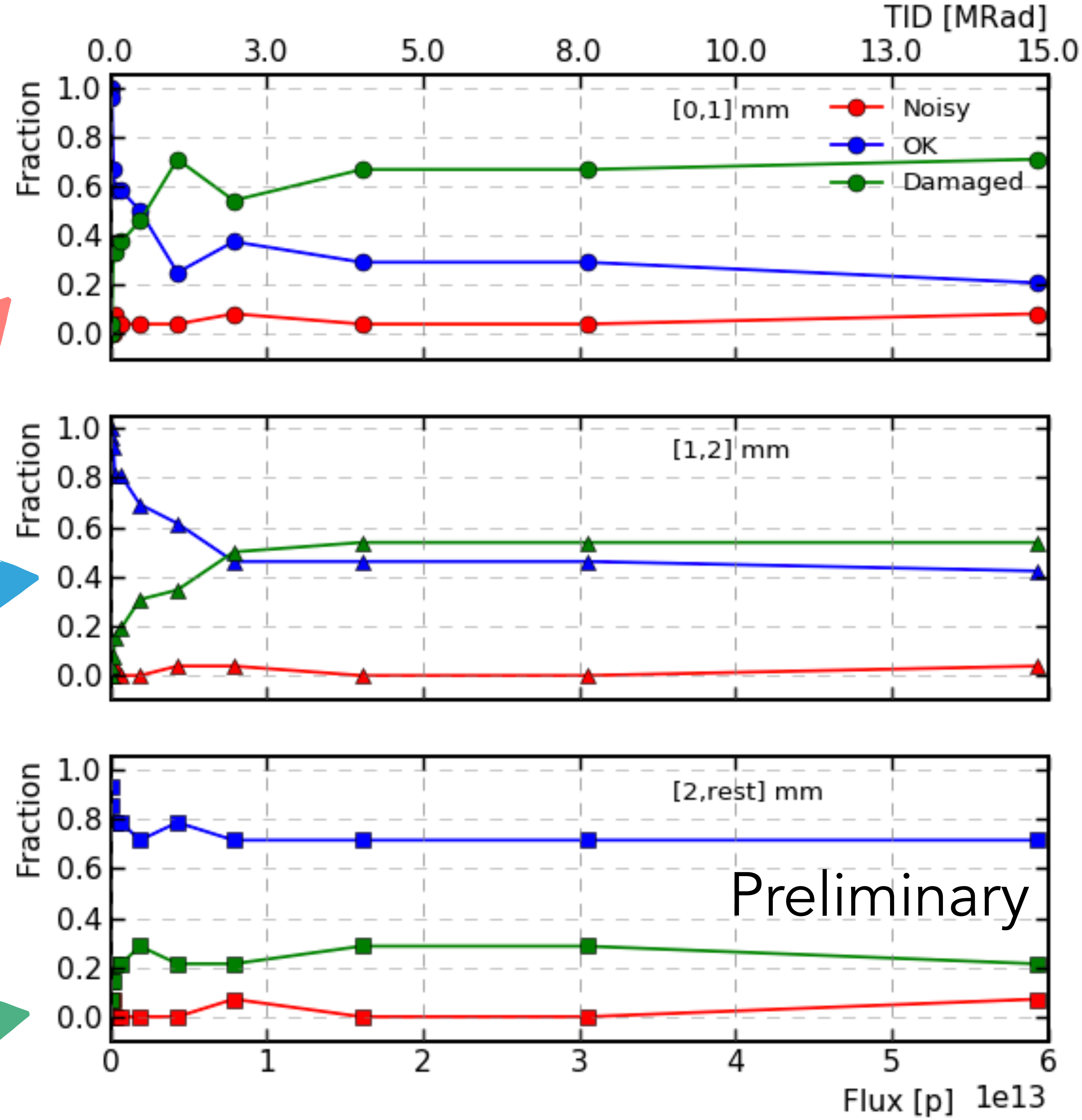
Sensor slices to study behaviour near/far away the beam centre.

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



Total size 6.59 mm

Active size 4.99 mm



Conclusion

Pixel

- Three IBL modules tested with two configurations @HiRadMat facility.
  - ATLAS stable beam and stand-by configurations used.
  - Two different IBL structure tested: 3D and Planar.
- Noise increases around the beam spot similarly for the three modules.

Limit on the damage threshold $1 \cdot 10^{13}$ p/cm^2 (2017/18)

Strip

- Increase in leakage current follows the increase of beam intensity.
- Fraction of fully working channels decrease at high dose.
  - 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)

Thanks for your attention!

[Hiroshima2017](), [Vertex2018](), [Pixel2018]()

Acknowledgments to

ATLAS ITk

HiRadMat team

ARIES*

CERN FLUKA team

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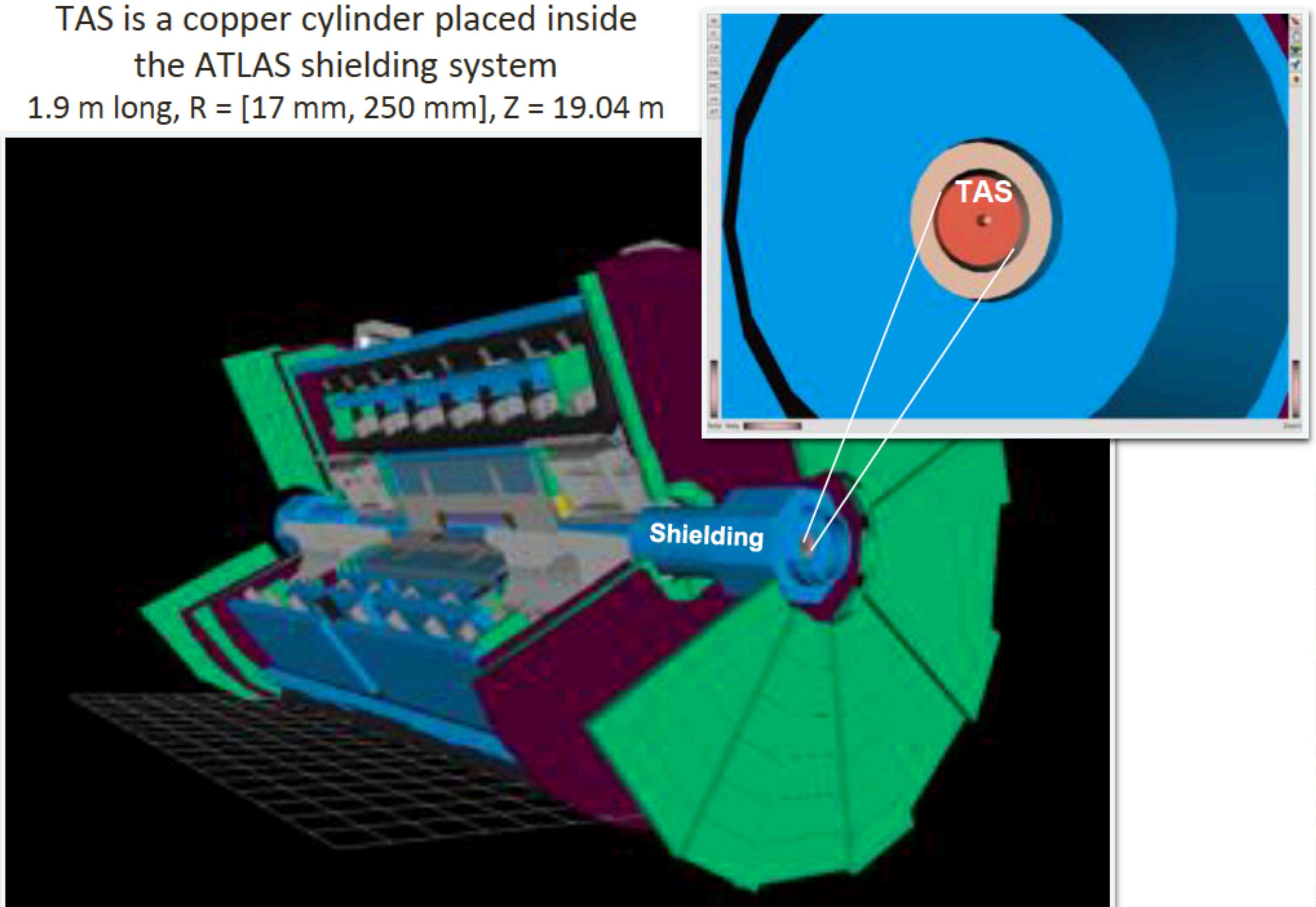
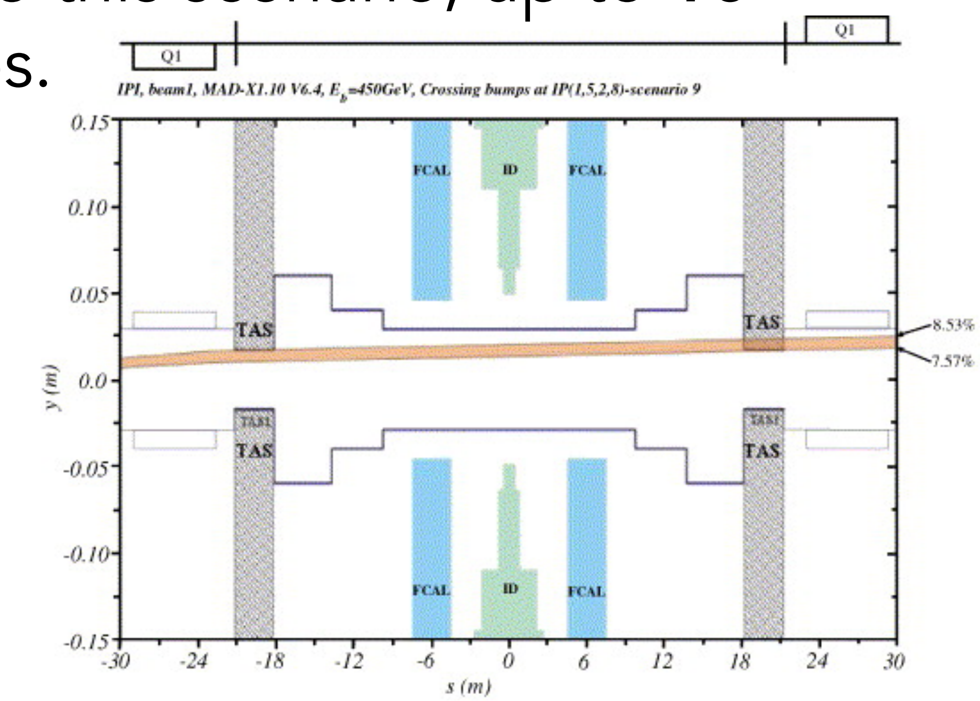
Studies done in 2006

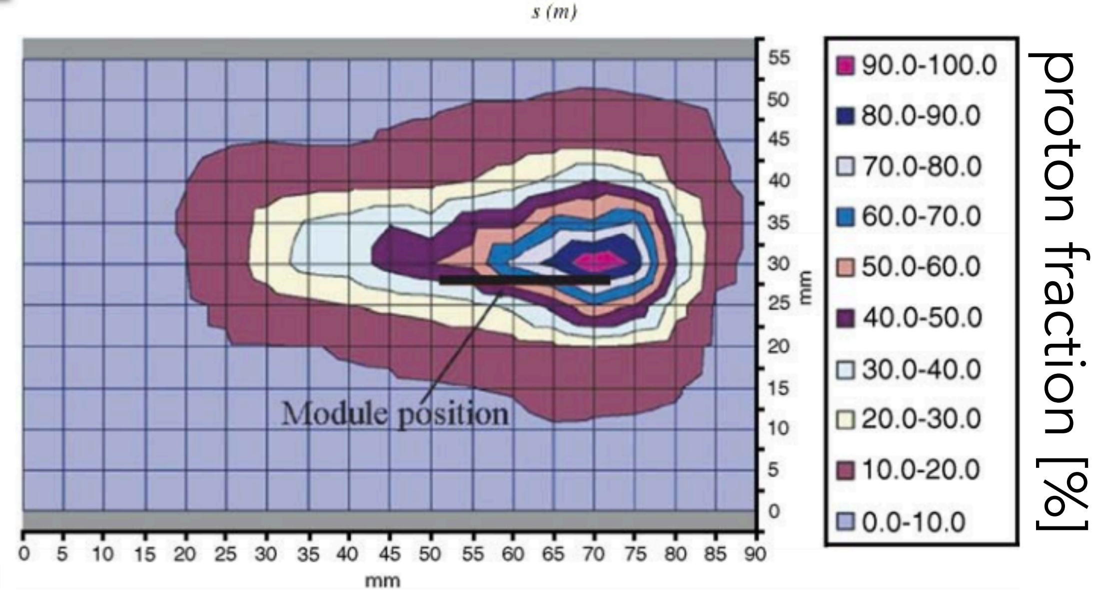
The effects of accidental beam losses were tested using a **24 GeV proton beam** at the CERN PS on, [NIM A565 (2006) 50-54]:

- ATLAS Pixel modules: radiation hardness up to **10^{15} 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

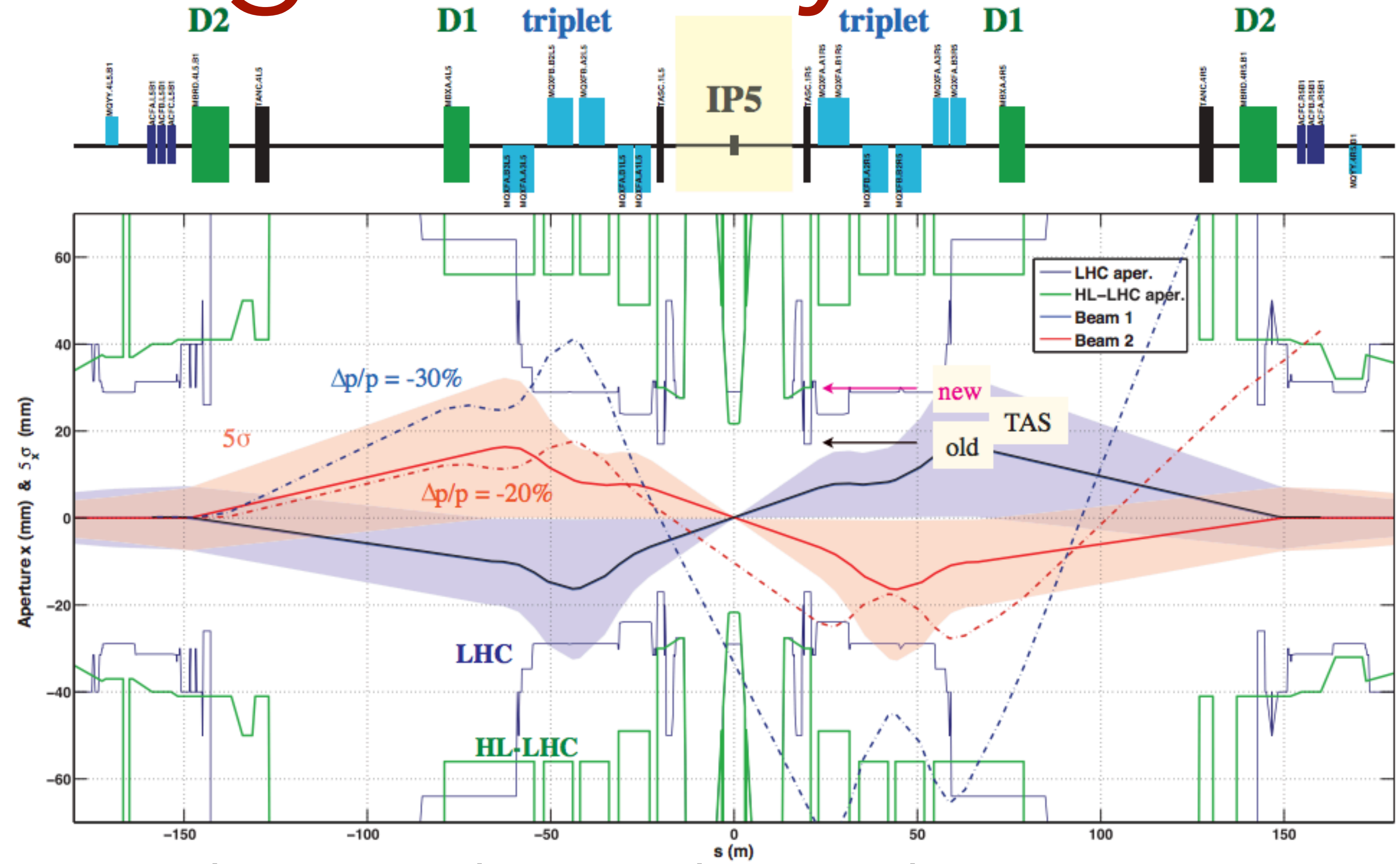


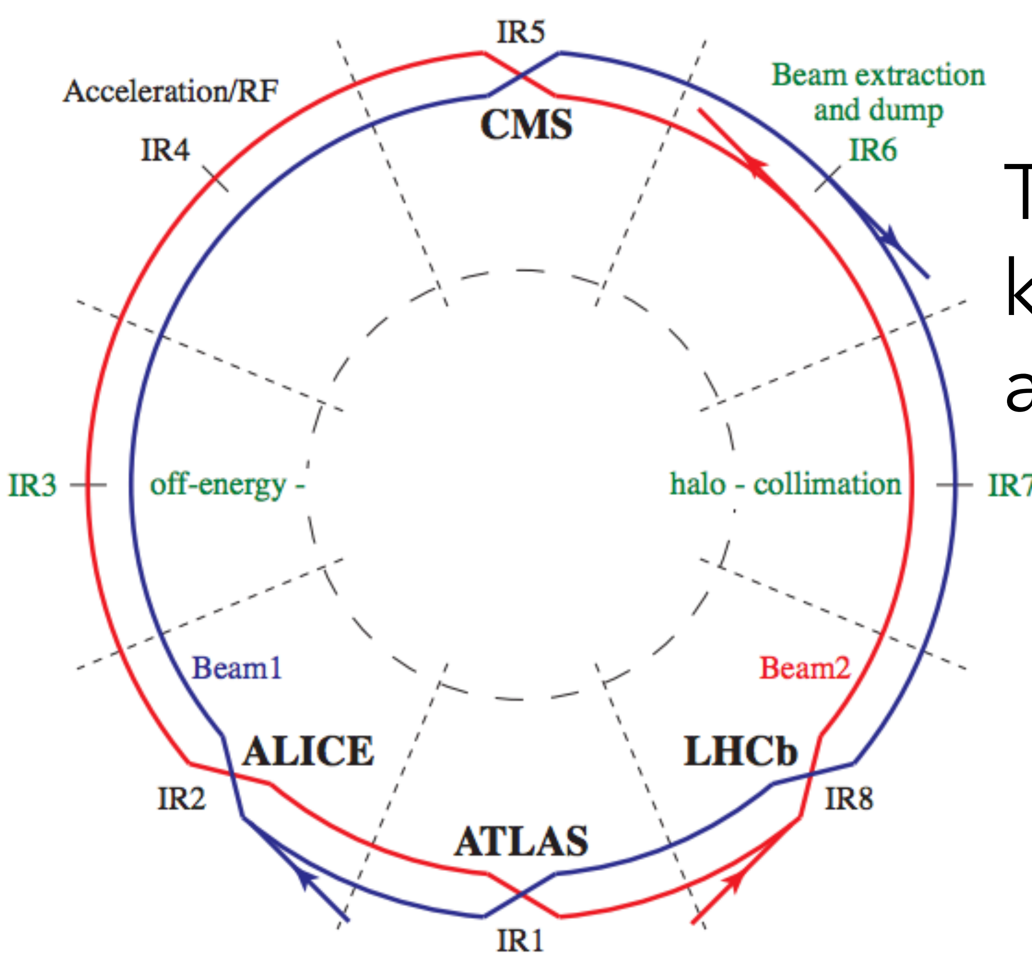




(HL-)LHC geometry [HL-LHC, IPAC'14]

- 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.



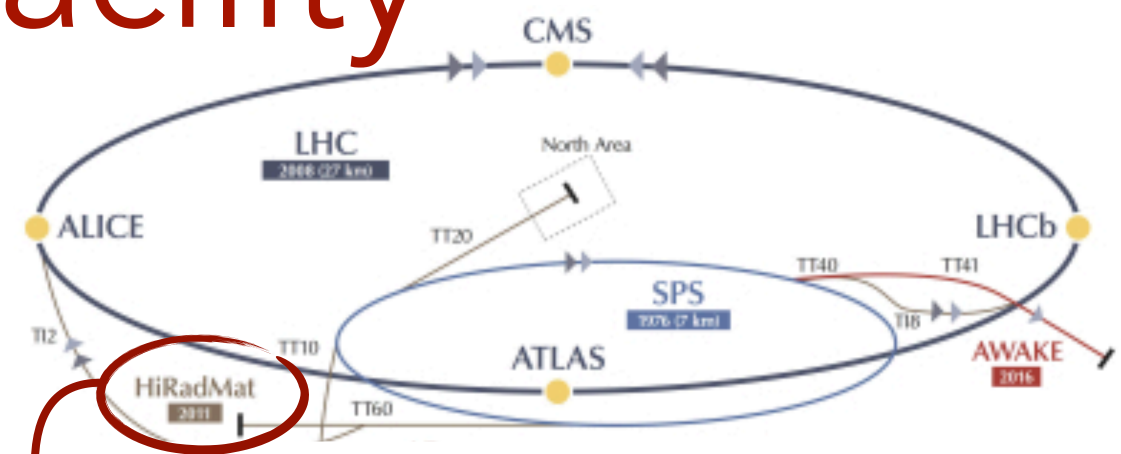


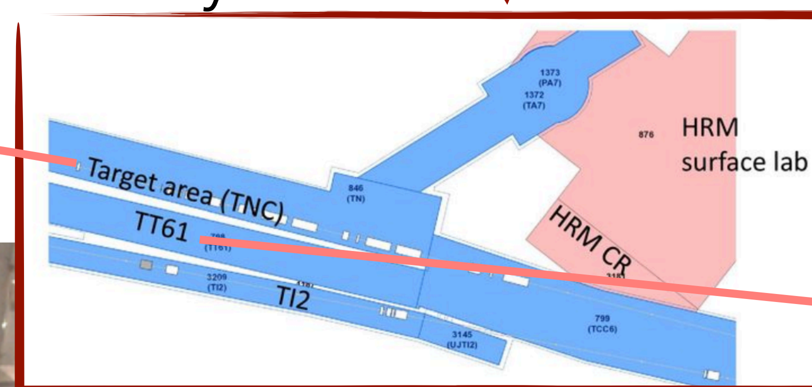
The asynchronous beam dump: the extraction kicker field switch-on is not synchronised with the abort gap [Animation].

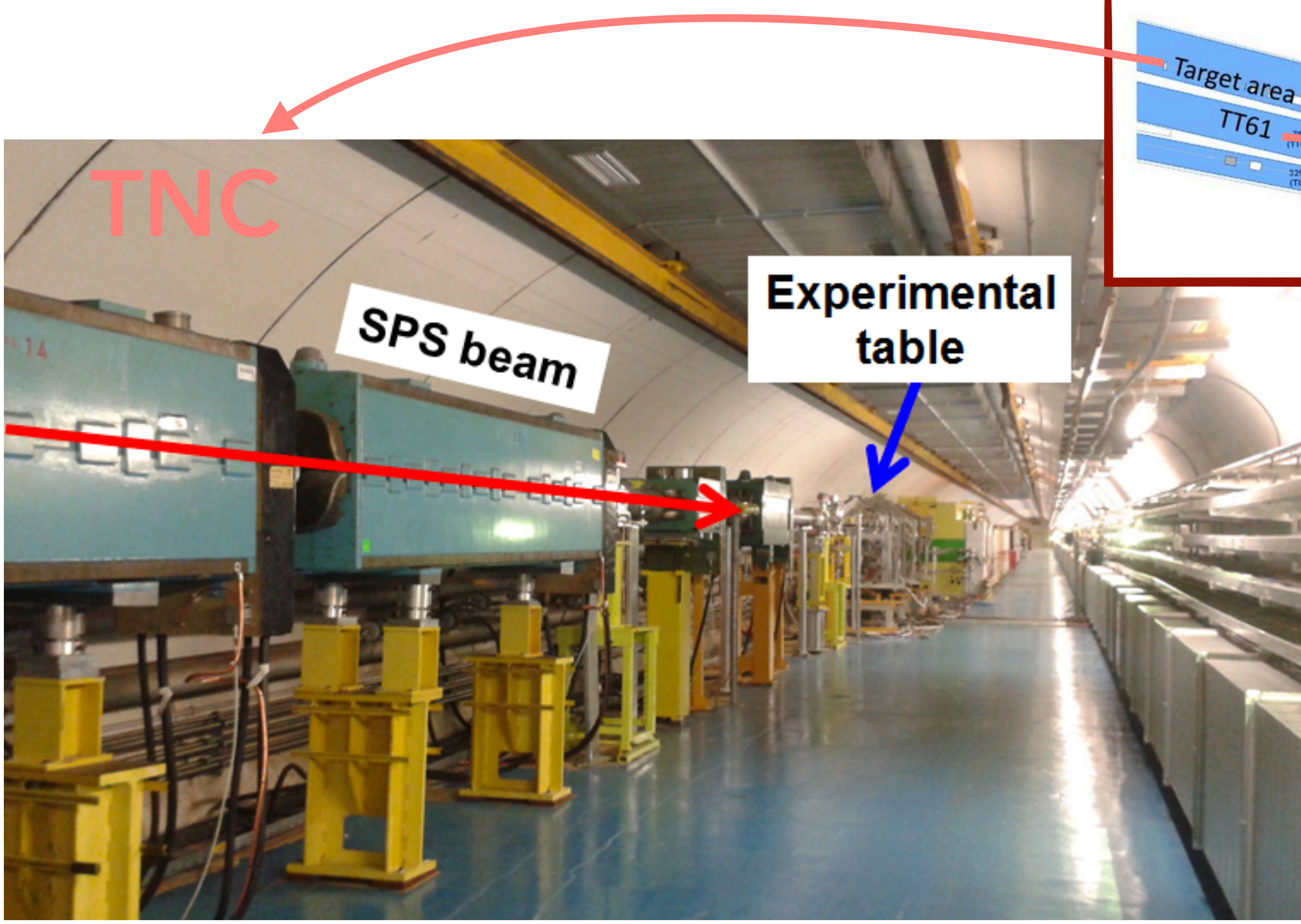
- Unlikely off-orbit protons hit directly the experiments.
- Possible scenario: protons hit the TCT4 collimators (120 m away from the IP) and shower into the experiments.

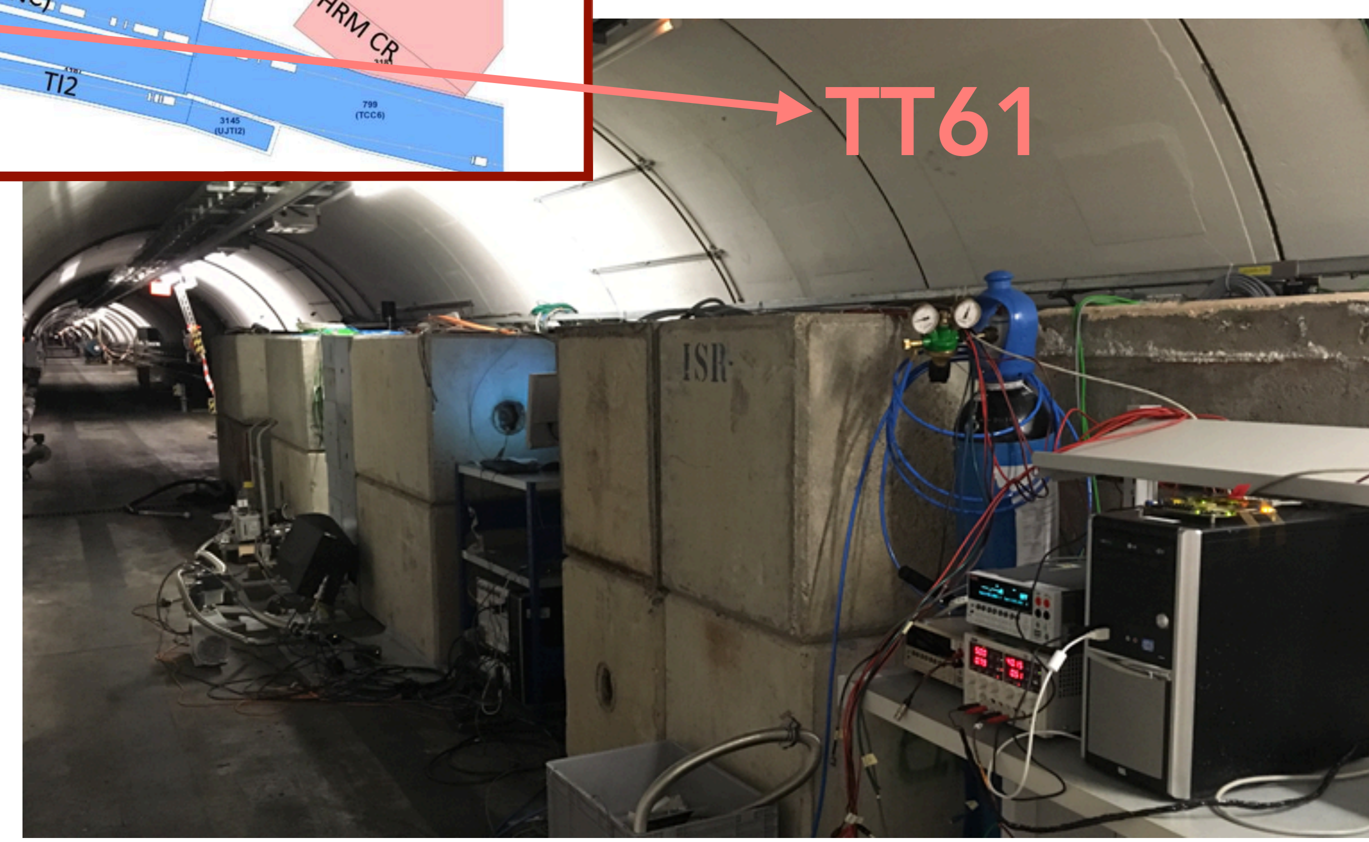
HiRadMat Facility

- 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.





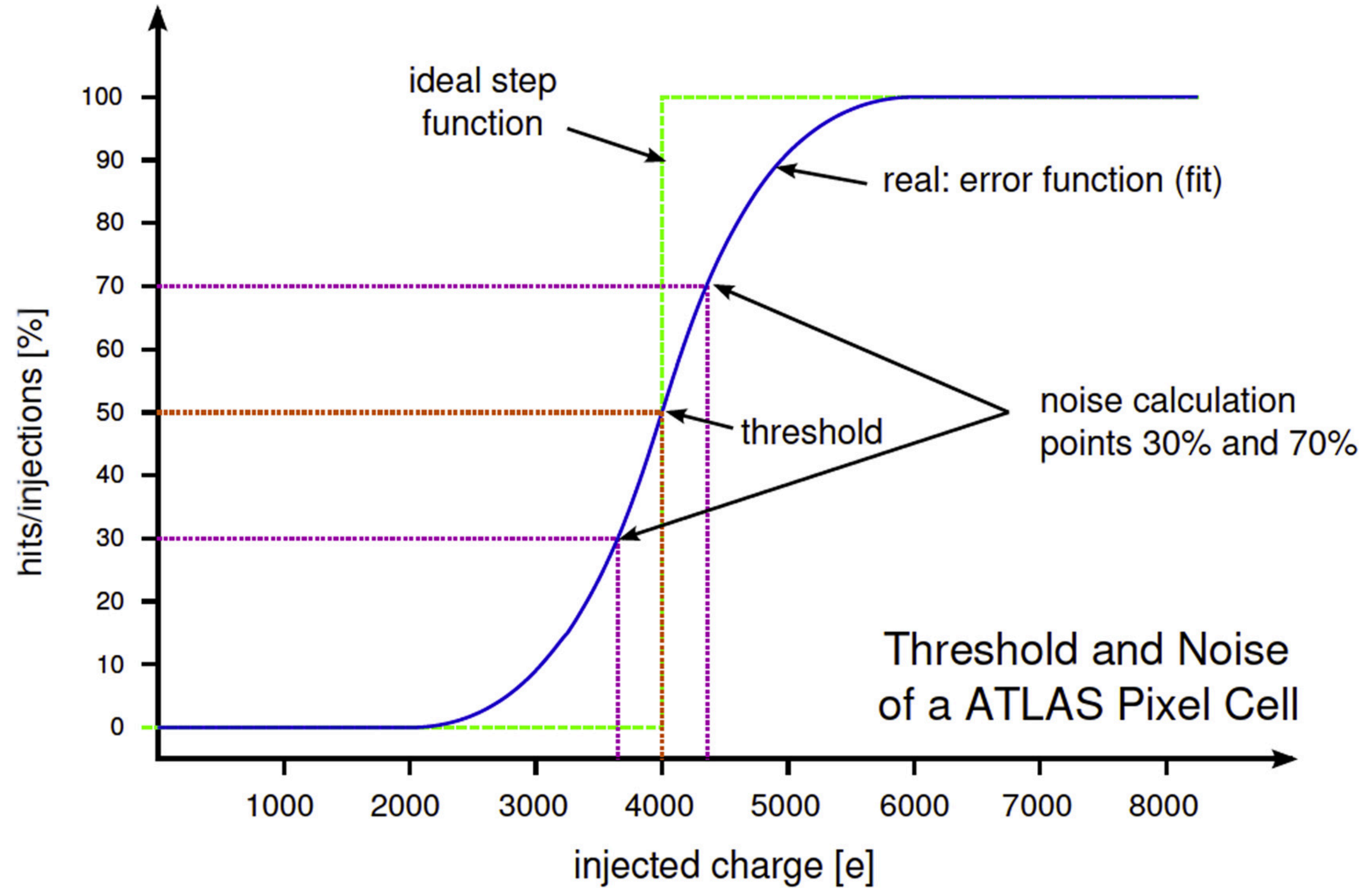




Hiroshima2017

IBL 3D: Noise

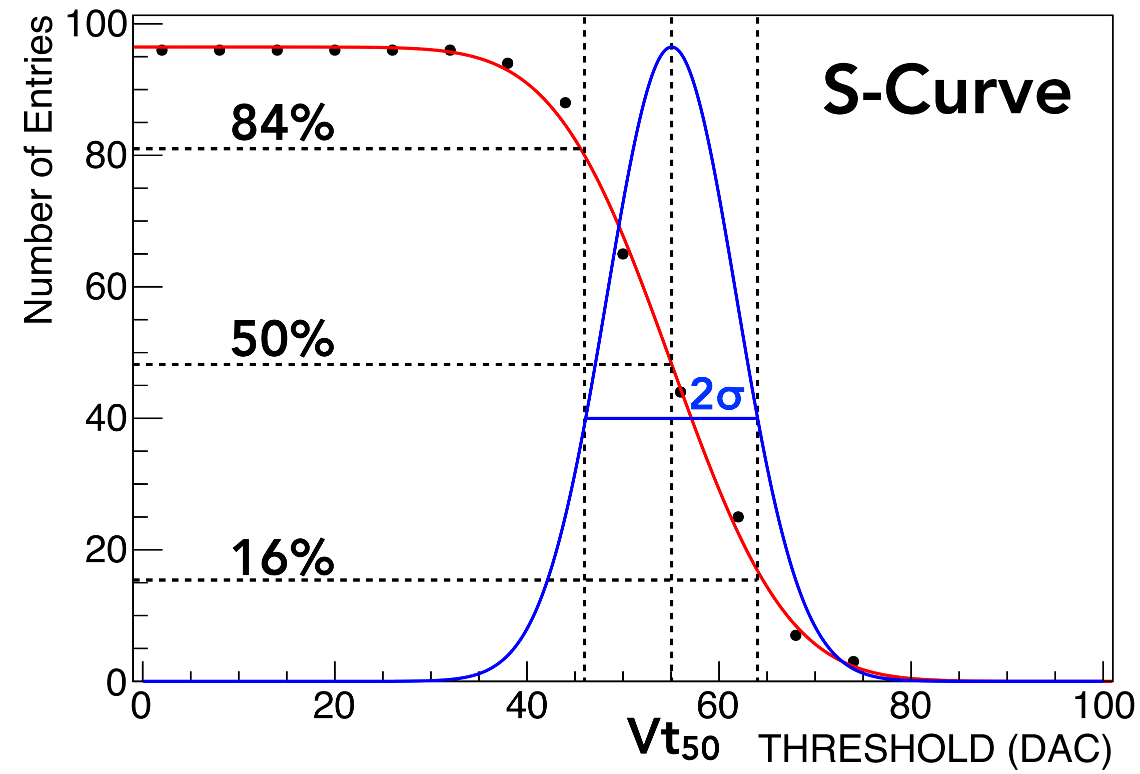
- Two IBL modules configurations were used in 2 different configurations.
  - **ATLAS in Standby**: sensor bias and FE preamplifiers off.
  - **ATLAS in Stable beam** operation: sensor bias and FE amplifiers on.
- In the inter-fill, tests **were performed with sensor bias on for both modules.**

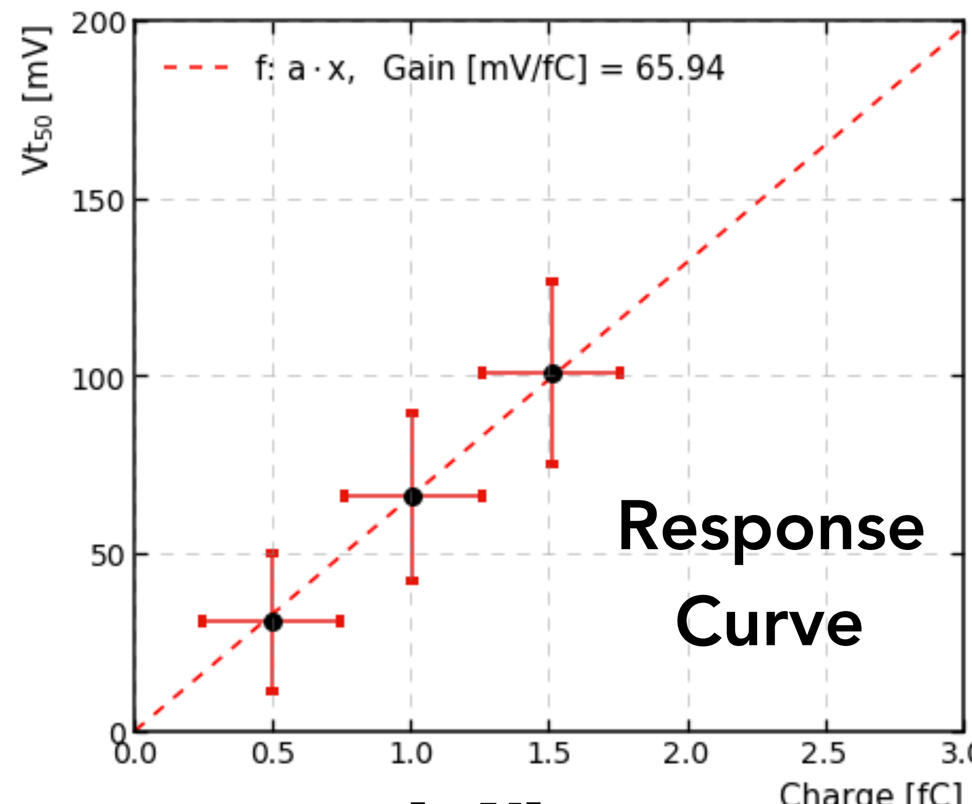


- Threshold scan measures the occupancy at different injected charges for a fixed threshold (2500 e^-).
- Response curve fitted with a sigmoid curve, where the **slope is a characteristic of the noise**.

ITk strip: Gain & Noise definition

- 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.



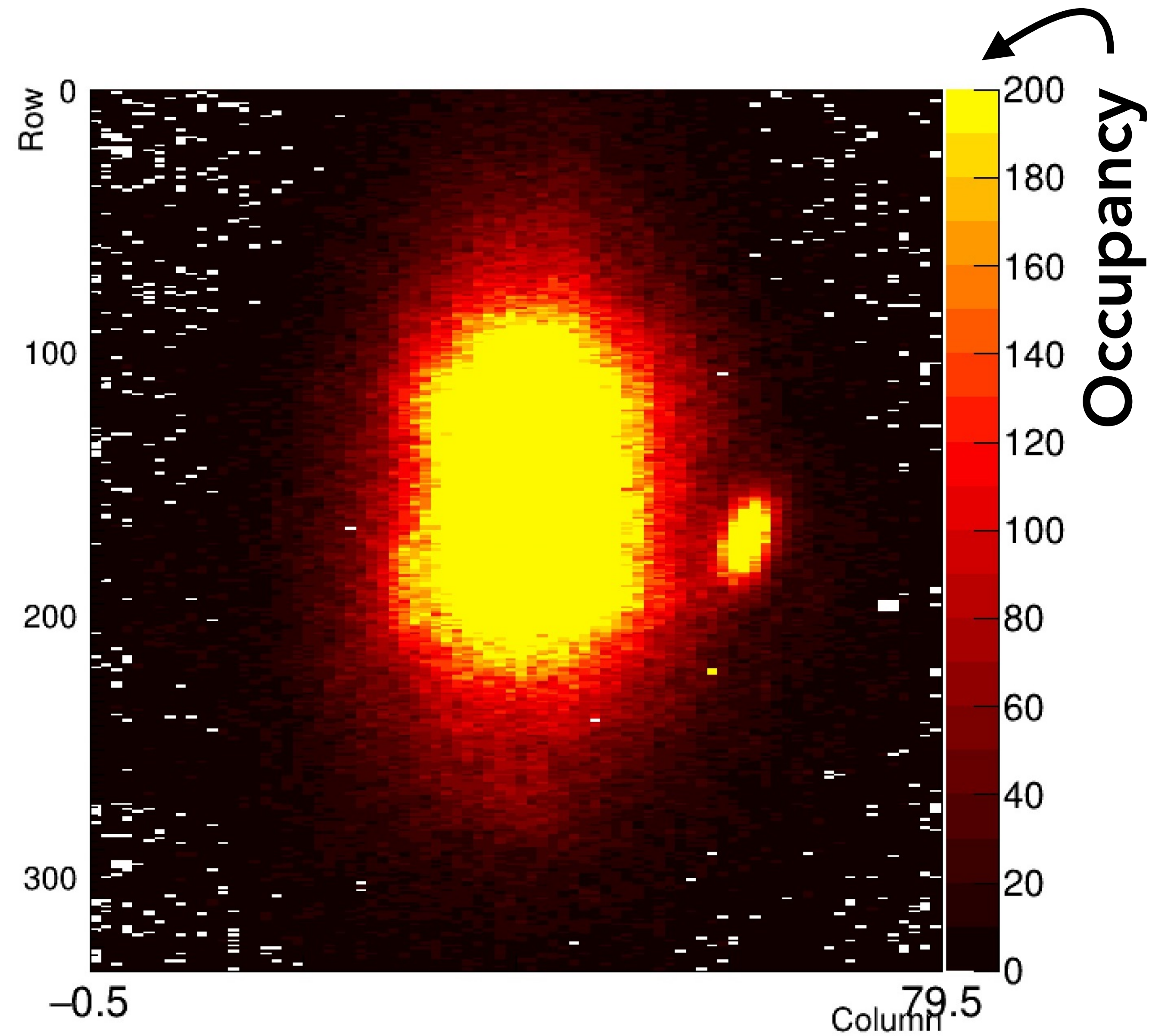


$$ENC = \frac{\sigma[mV]}{gain[mV/fC]},\ 1fC = 6241e^{-}$$

IBL 3D: Material Activation

[Hiroshima2017]

- **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.

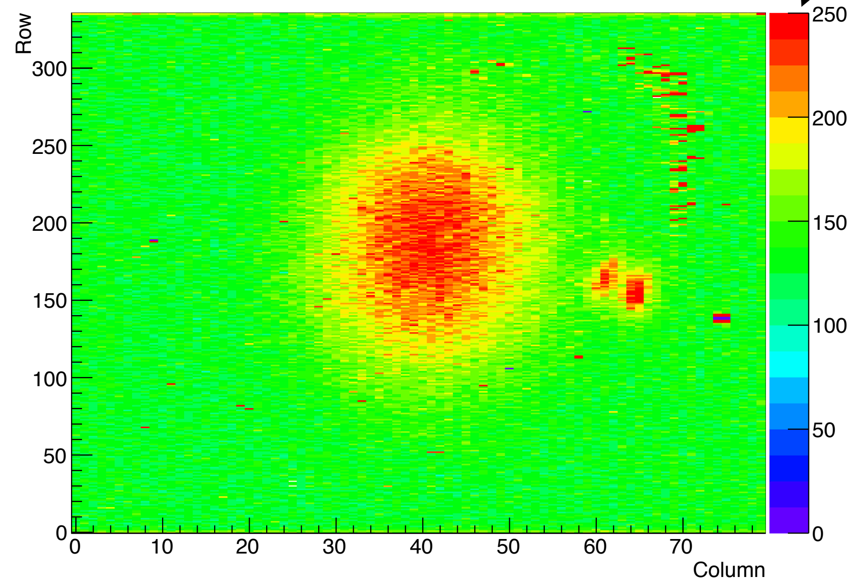


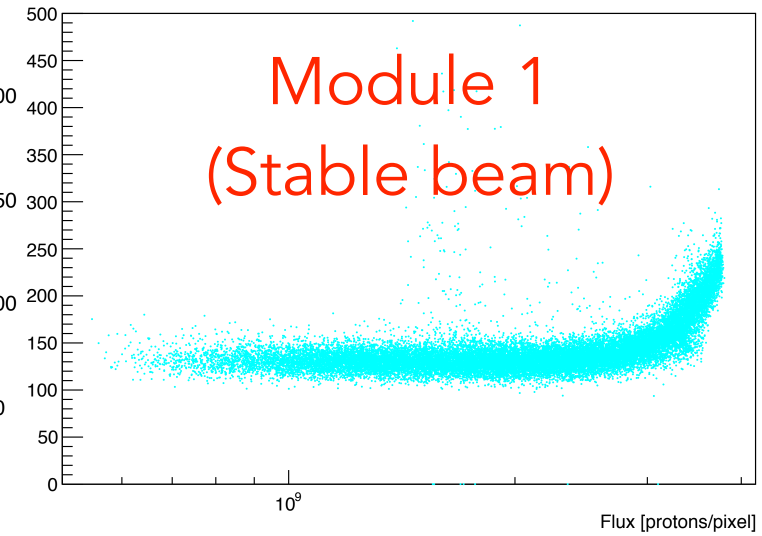
IBL 3D: Noise

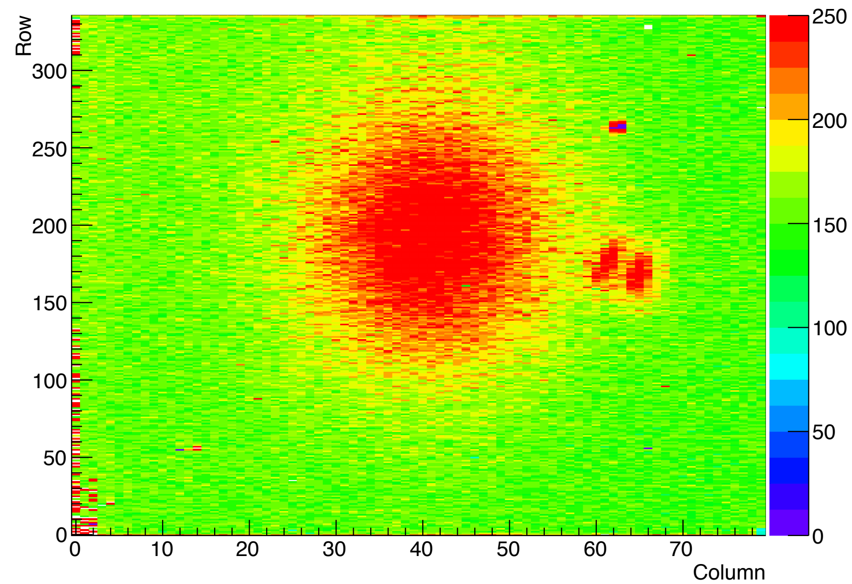
- Two IBL modules configurations were used in 2 different configurations:
  - **ATLAS in Stand-by**: sensor bias off and FE preamplifiers off.
  - **ATLAS in Stable beam** operation: sensor bias on and FE amplifiers on.
- **Correlation between performance degradation and proton fluence**
  - Noise increase per pixel used as figure of merit.
- Proton beam simulated to take into account beam position.

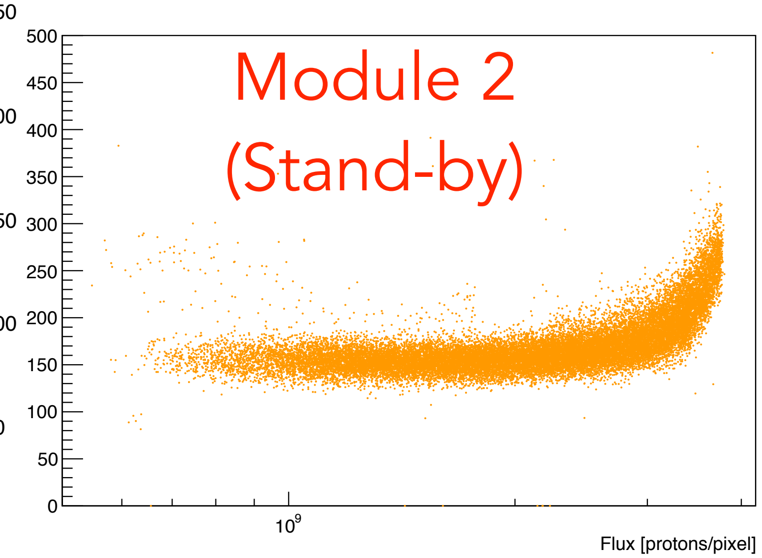
Noise level: Pre-Irr 130 e$^-$ —>Post-Irr 300 e$^-$

Noise [e$^-$]







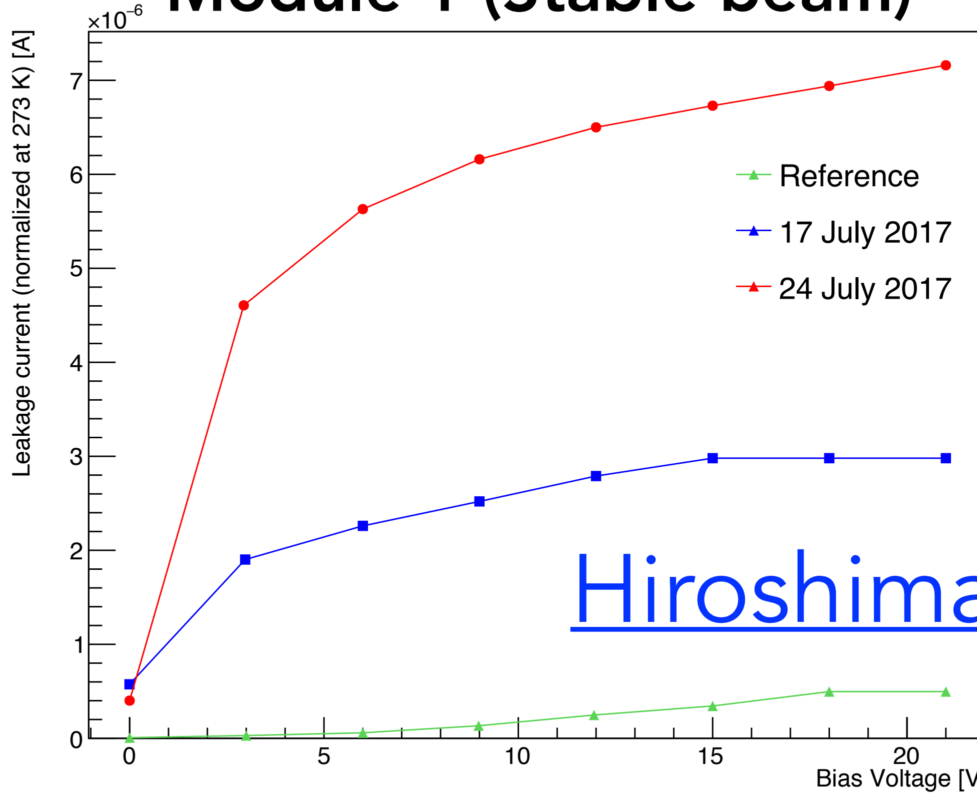


NB: Results updated wrt Hiroshima2017

IBL 3D: Leakage current

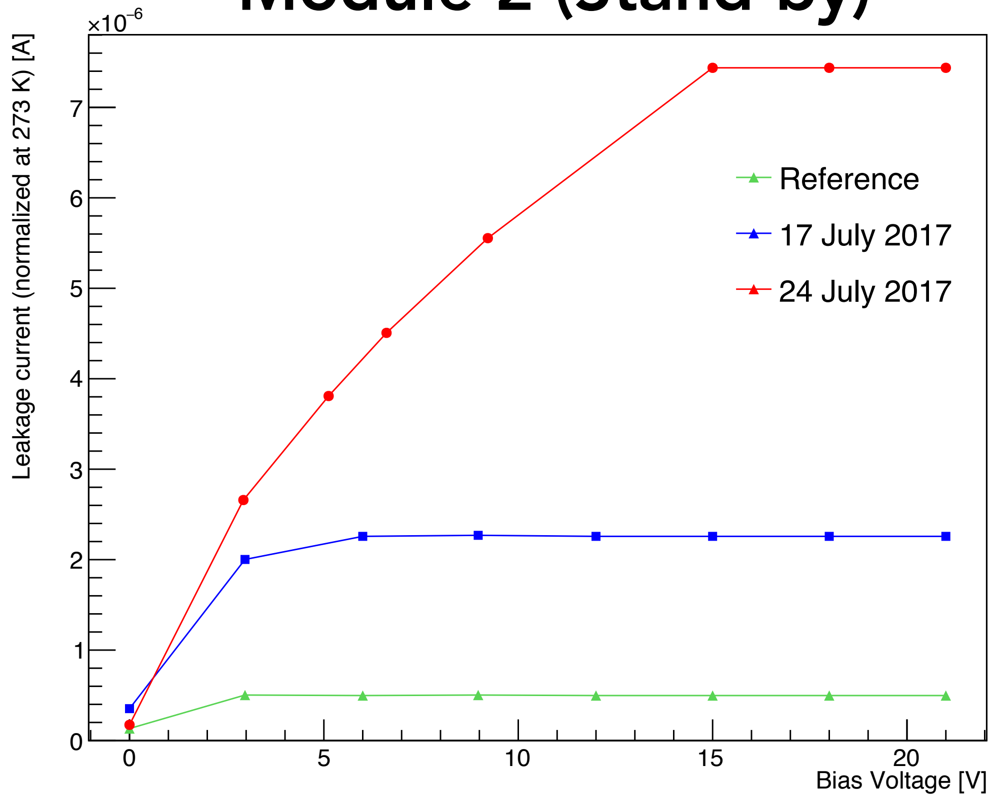
- **The variation of leakage current of the sensor, normalised at 273 K**, for different days.
  - Temperature not under control: **T~[30,60]°C**
  - Leakage current follows the beam intensity.
  - Noise of the first amplification stage of FE-I4 is strictly dependent from that.
- **Leakage current measured 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.

Module 1 (Stable beam)



Hiroshima2017

Module 2 (Stand-by)



IBL 3D: 2017 summary

Global irradiation: 2 mm beam.

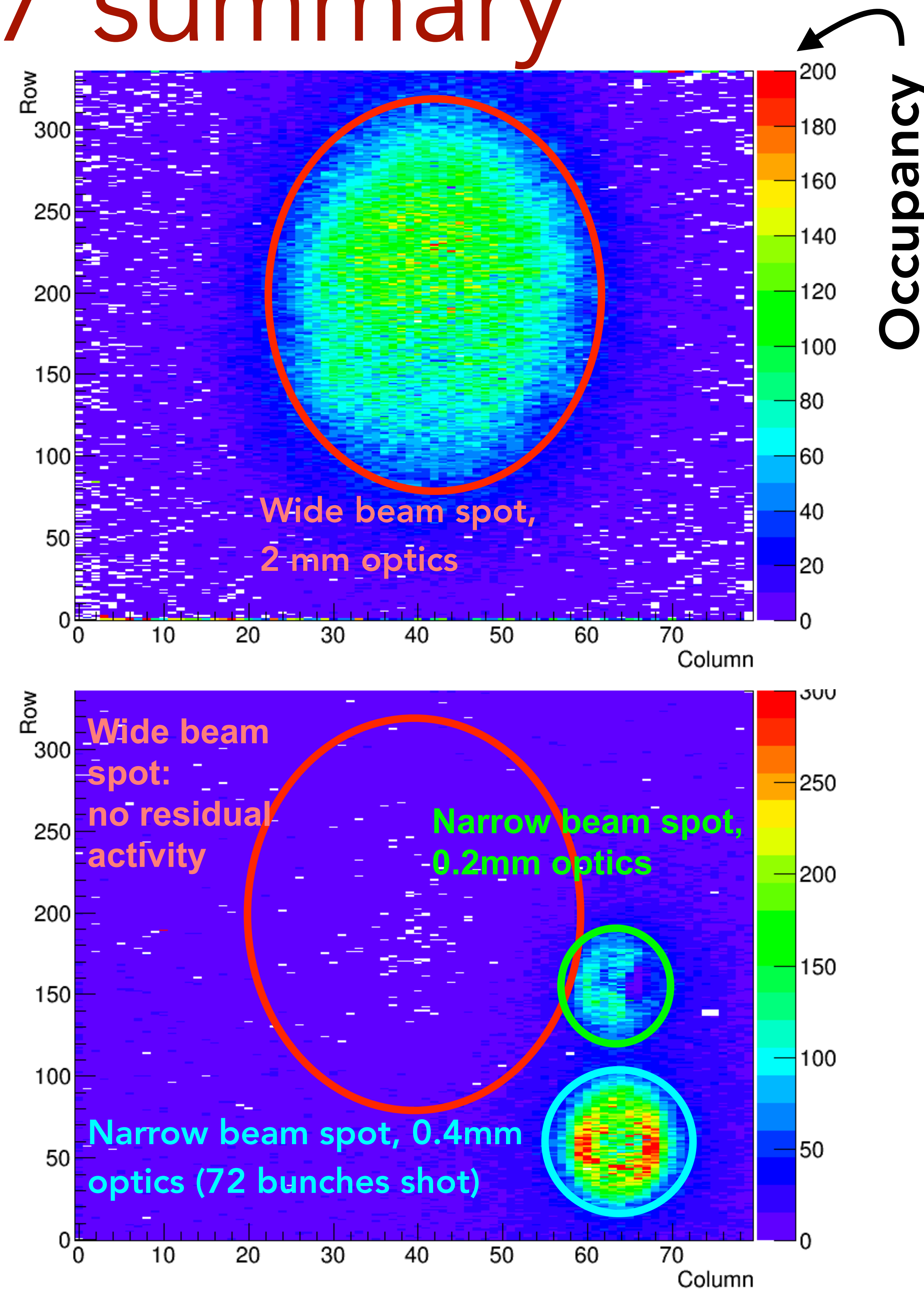
- Beam spot due to material activation (after glow).
- The intensity of the spot was increasing after each shot.
- The intensity of the spot was decreasing with time.

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

- Radius of damage: 15 pixels ~0.38 cm

Local Irradiation: 0.4 mm beam.

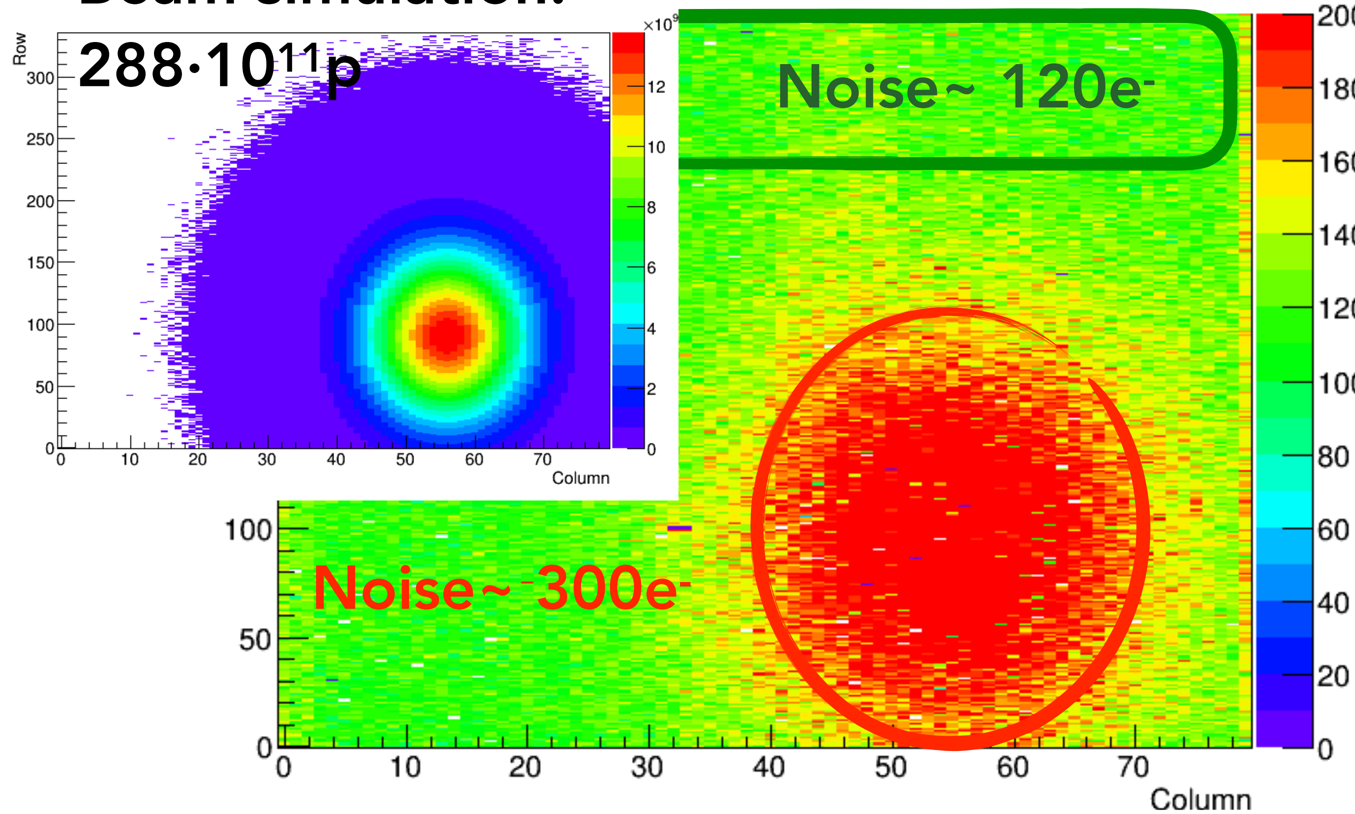
- Detector dead after 288 bunches.
  - FE supply in short.
- Small bump on the Flex-Hybrid visible under microscope, caused by a short between ground and analog voltage.



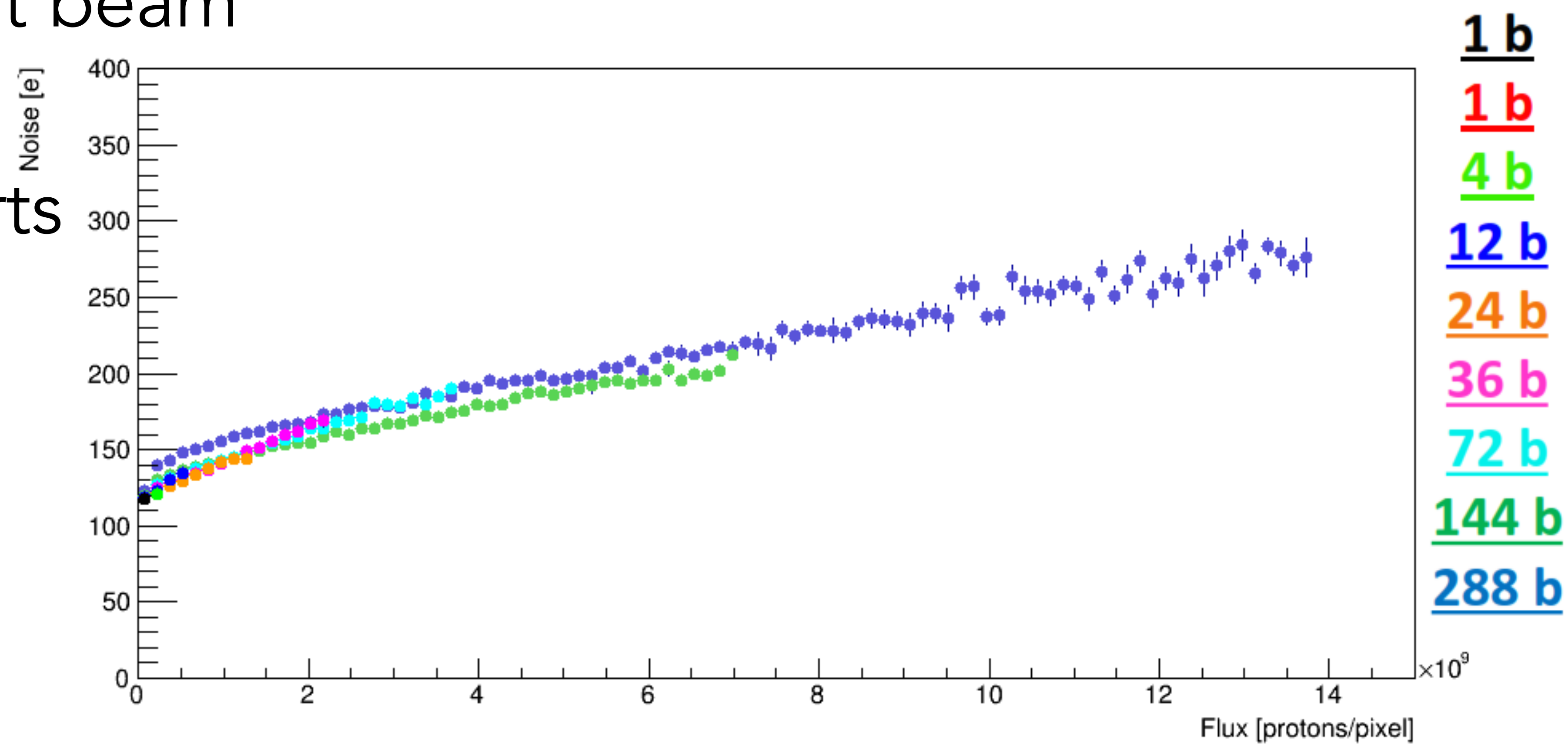
IBL Planar: Noise&Fluence

- **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

Beam simulation:



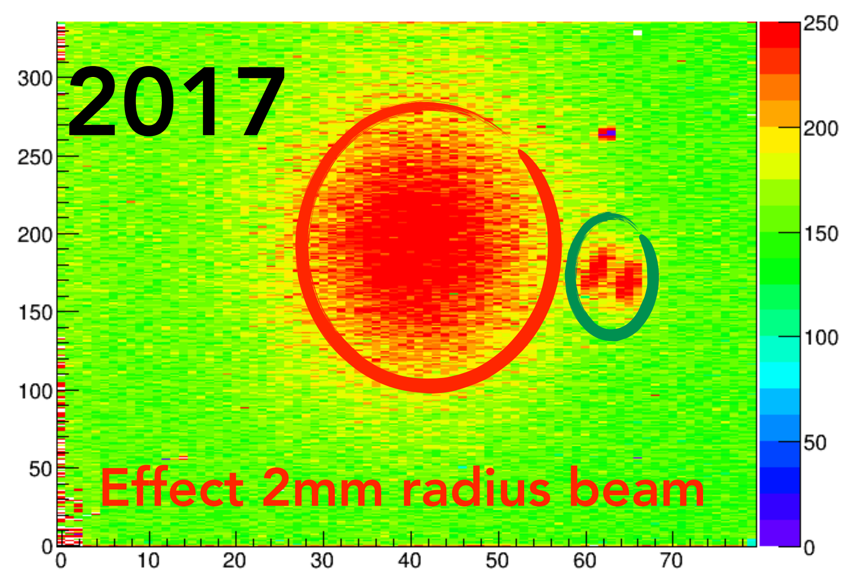
✤**Noise** increasing starts after 4 bunches, and **constantly increases after each pulse** following a specific trend



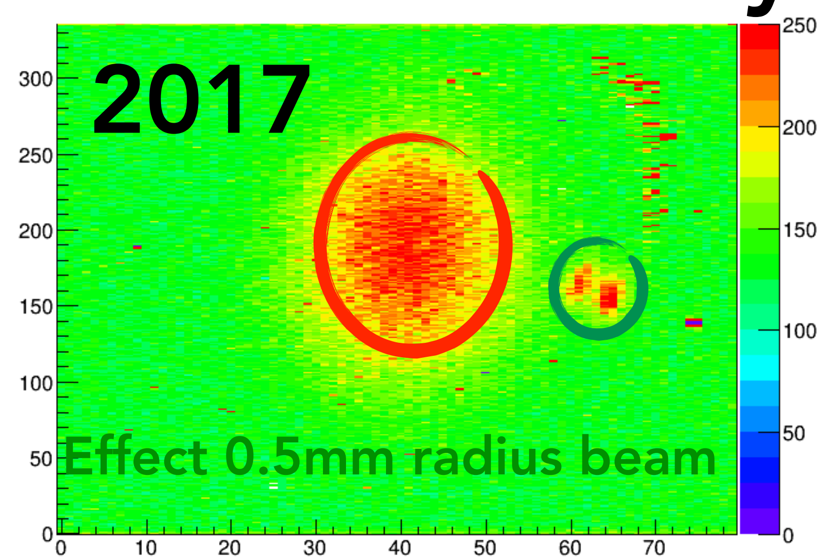
Conclusion: IBL

- 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.

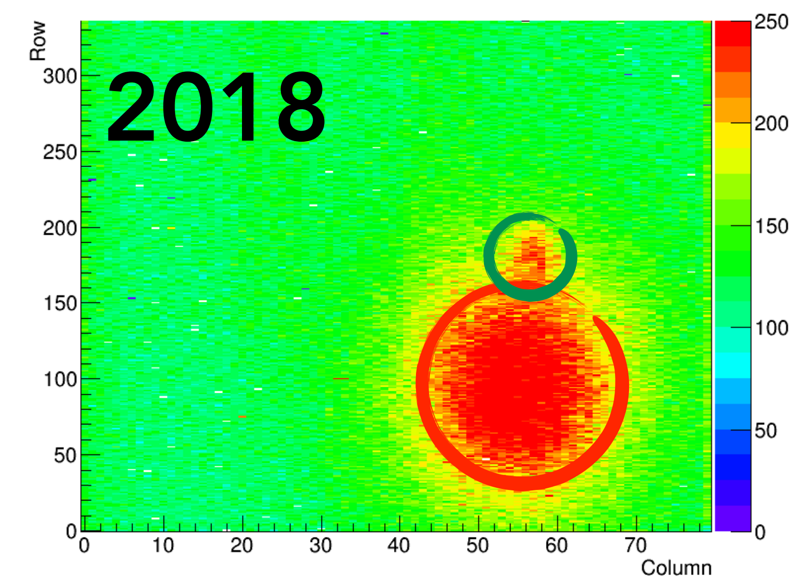
IBL 3D: stable-beam



IBL 3D: stand-by

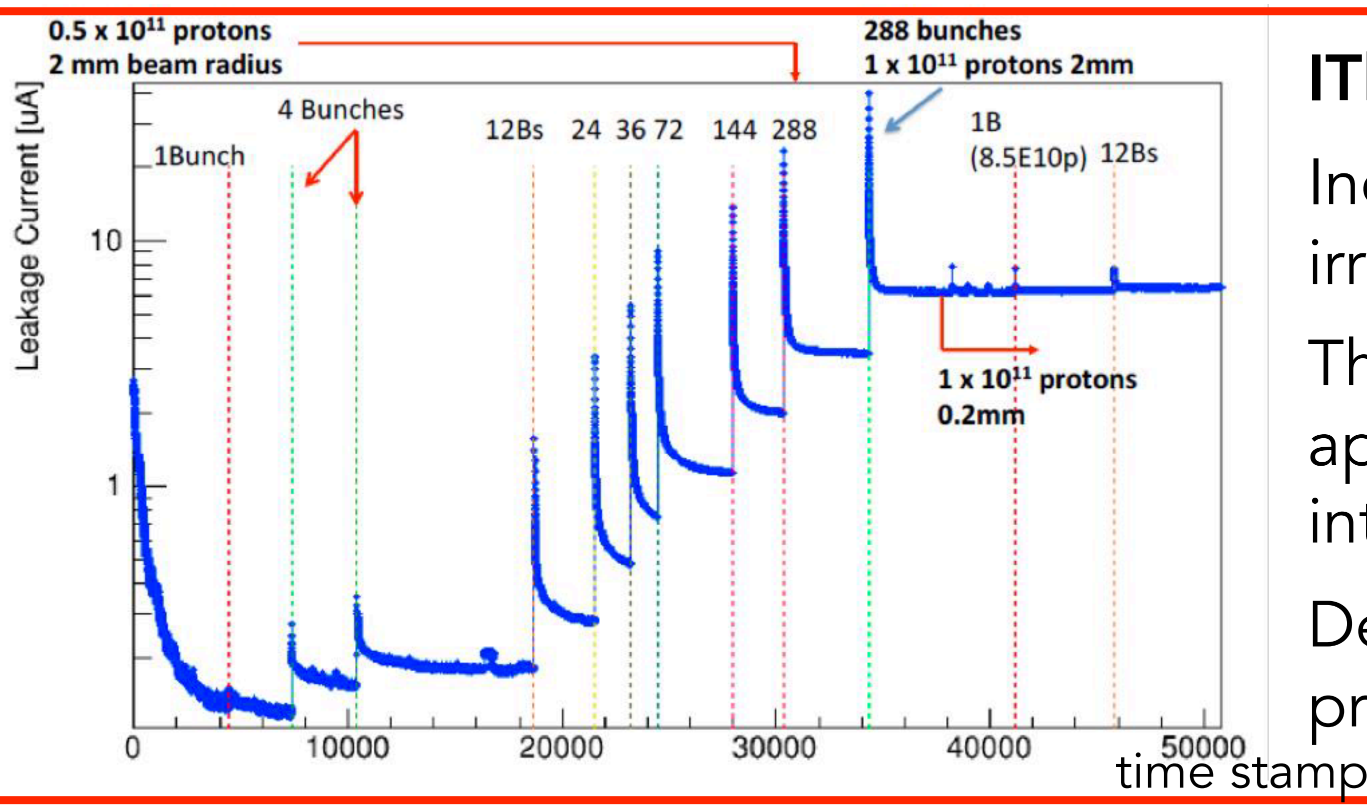


IBL Planar



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

ITk: Global and Local irradiation



ITk strip (Global irradiation)

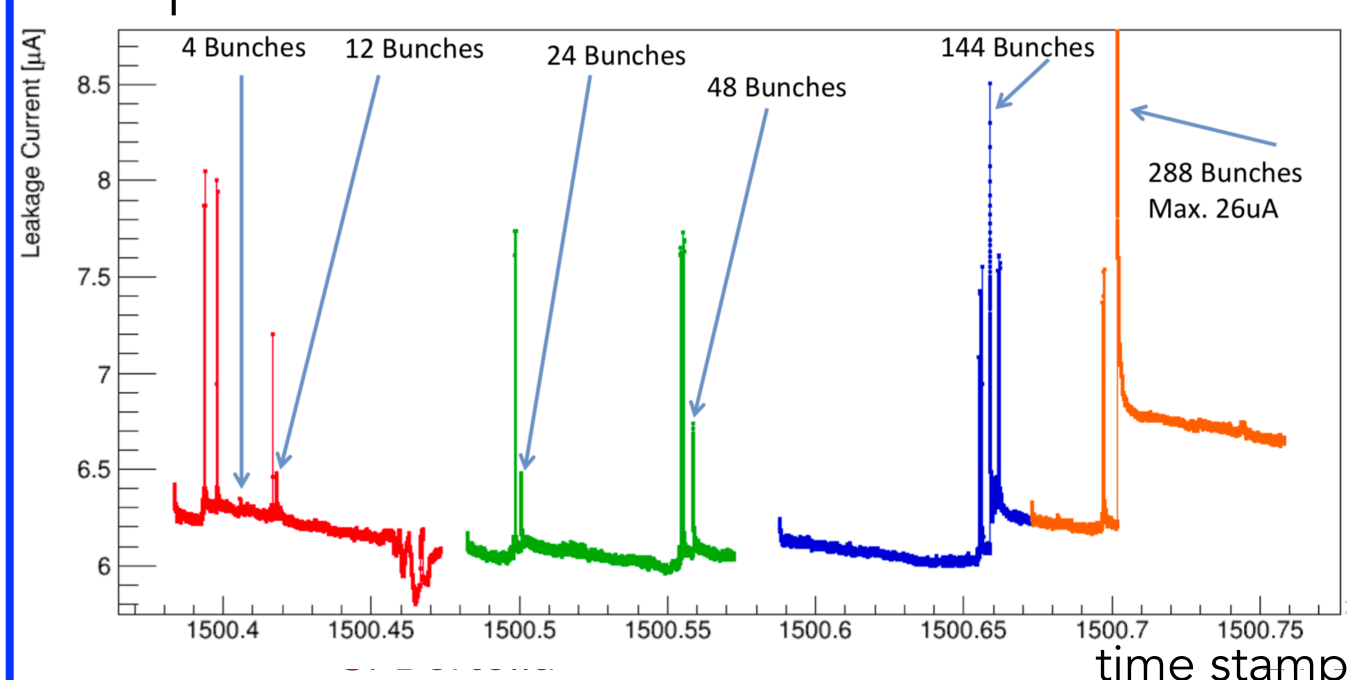
Increase of the leakage current with global irradiation (2 mm optics).

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

Detector still alive after 288 bunches (10^{11} protons). [Hiroshima2017]

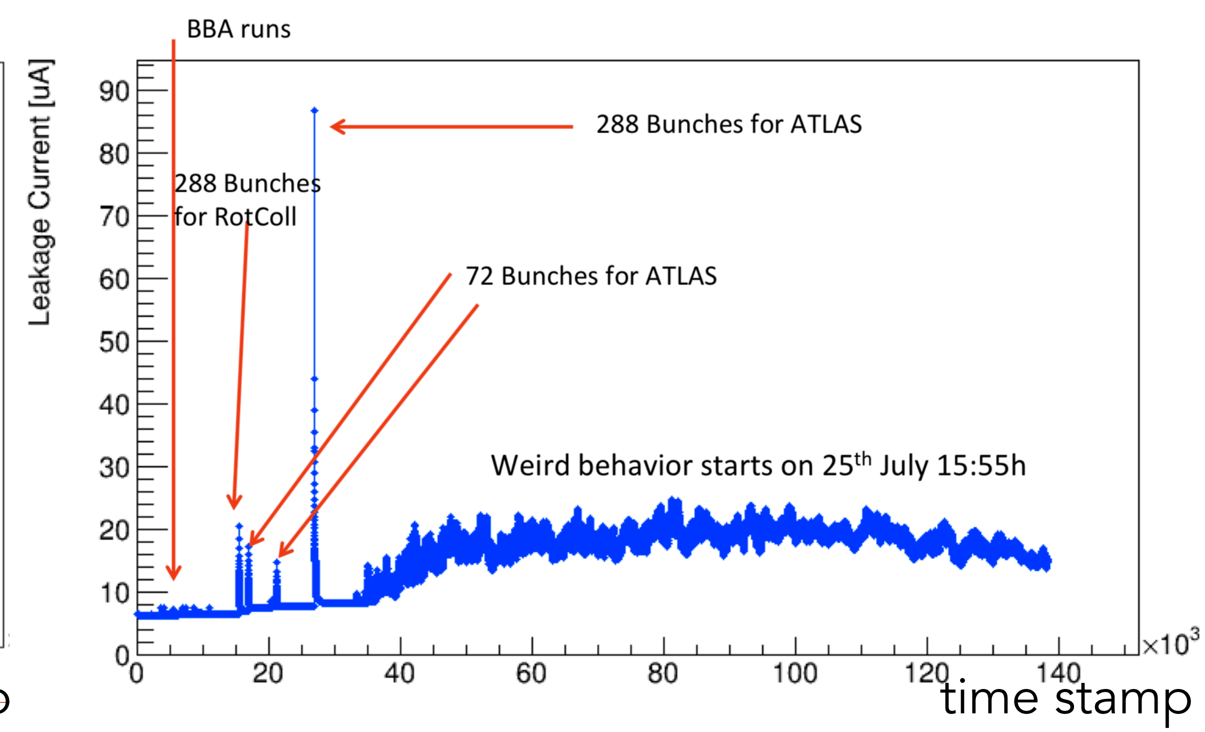
ITk strip (Local irradiation)

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



Shots of bunches with 1 x 10^{11} p/bunch and 0.4 mm beam

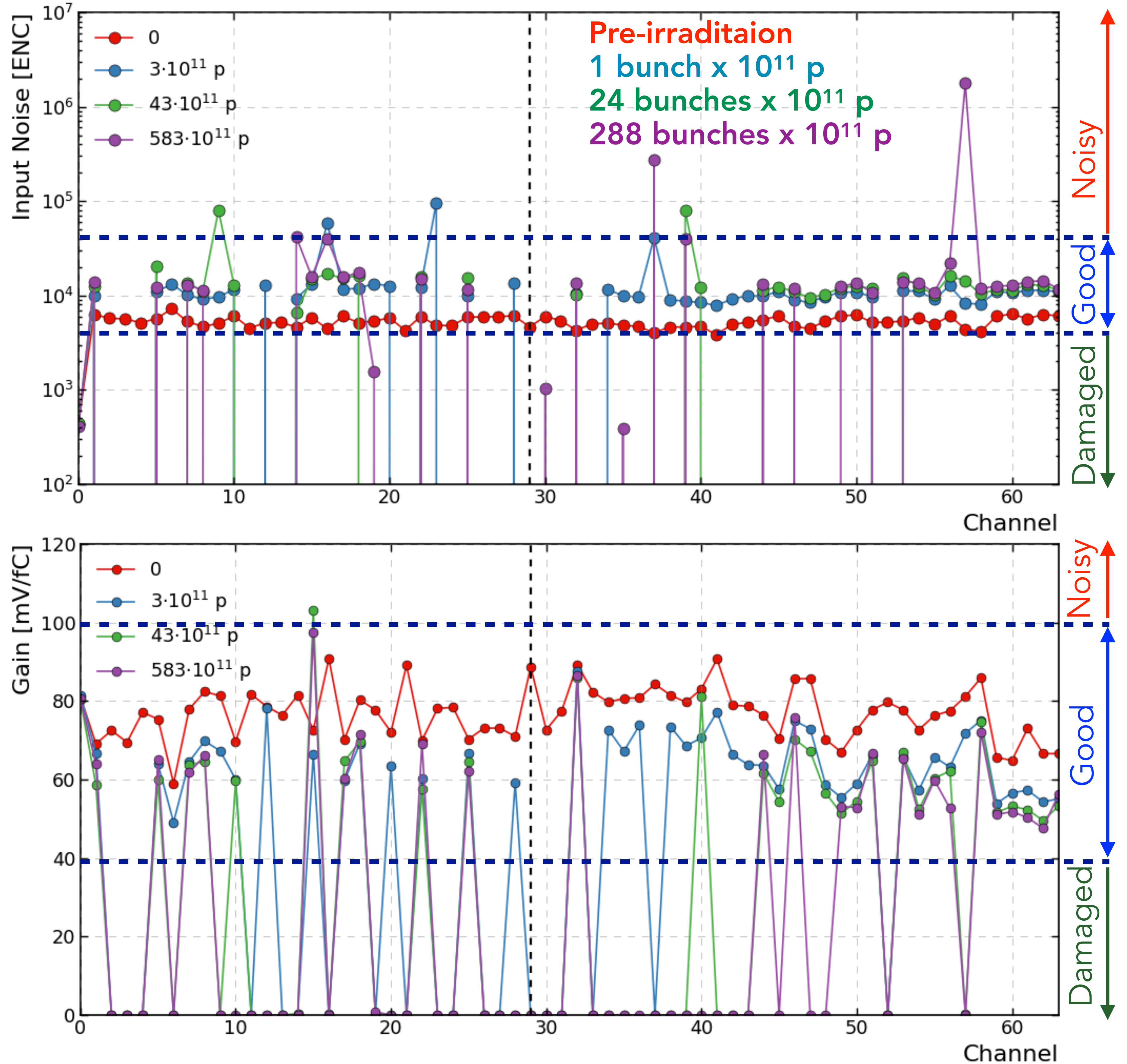
Probably detector died after 288 bunches



Channel behaviour

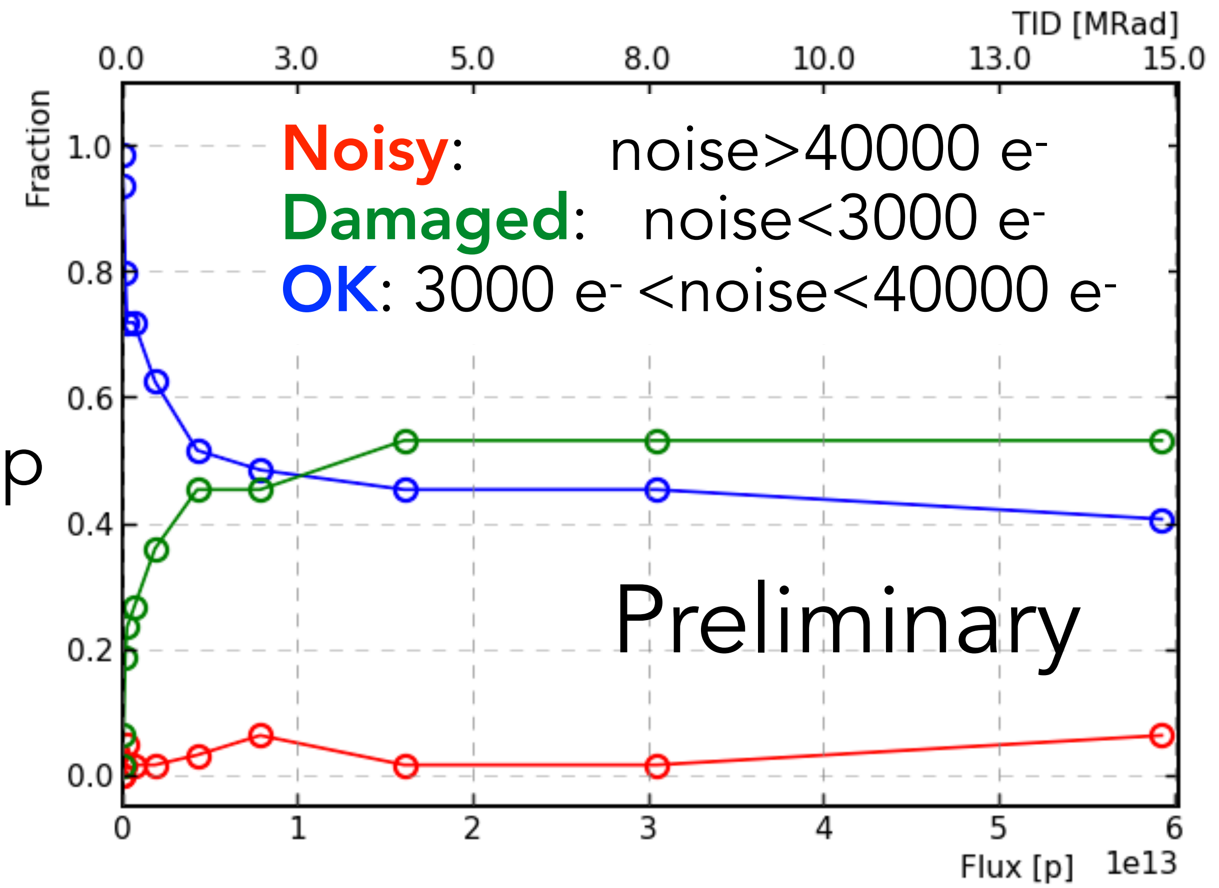
Preliminary

- Monitoring the 64 channels with each beam shot.
- Gain and Noise displayed for few beam shots.
- Used those variables to define the sensor performance.

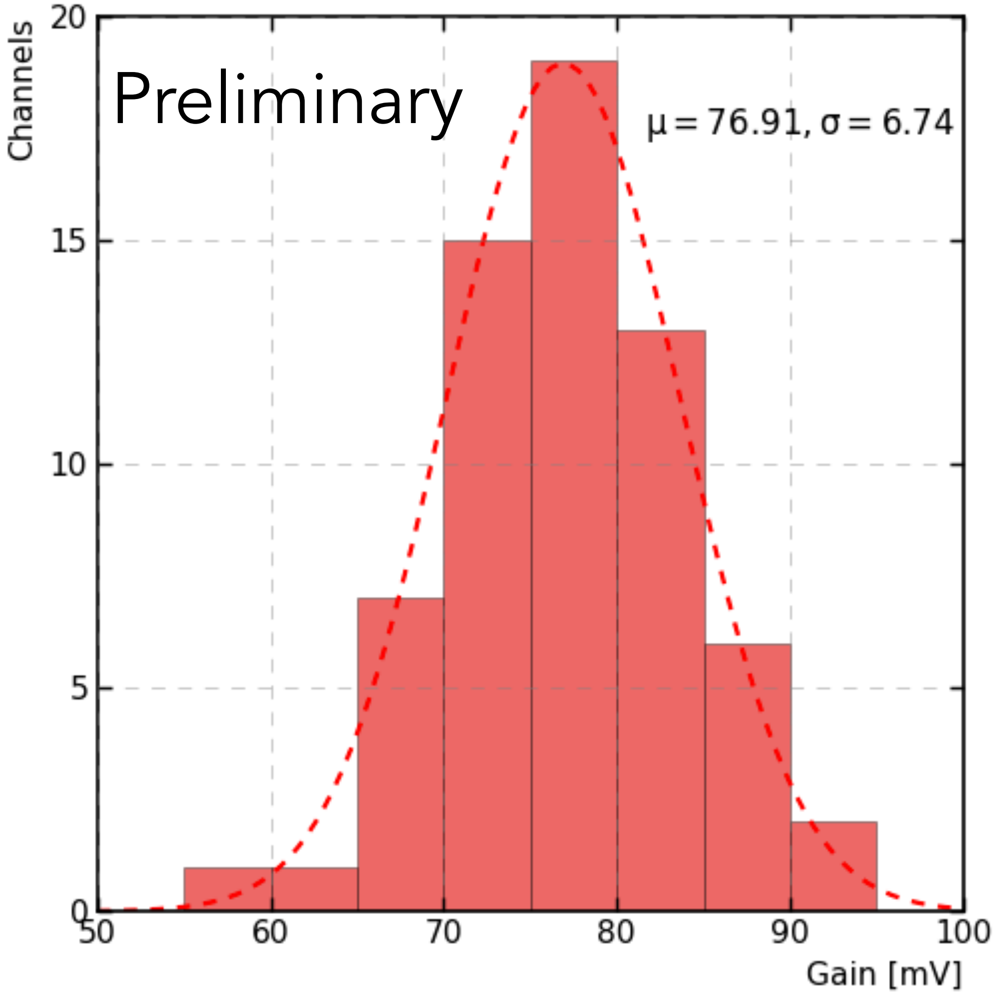


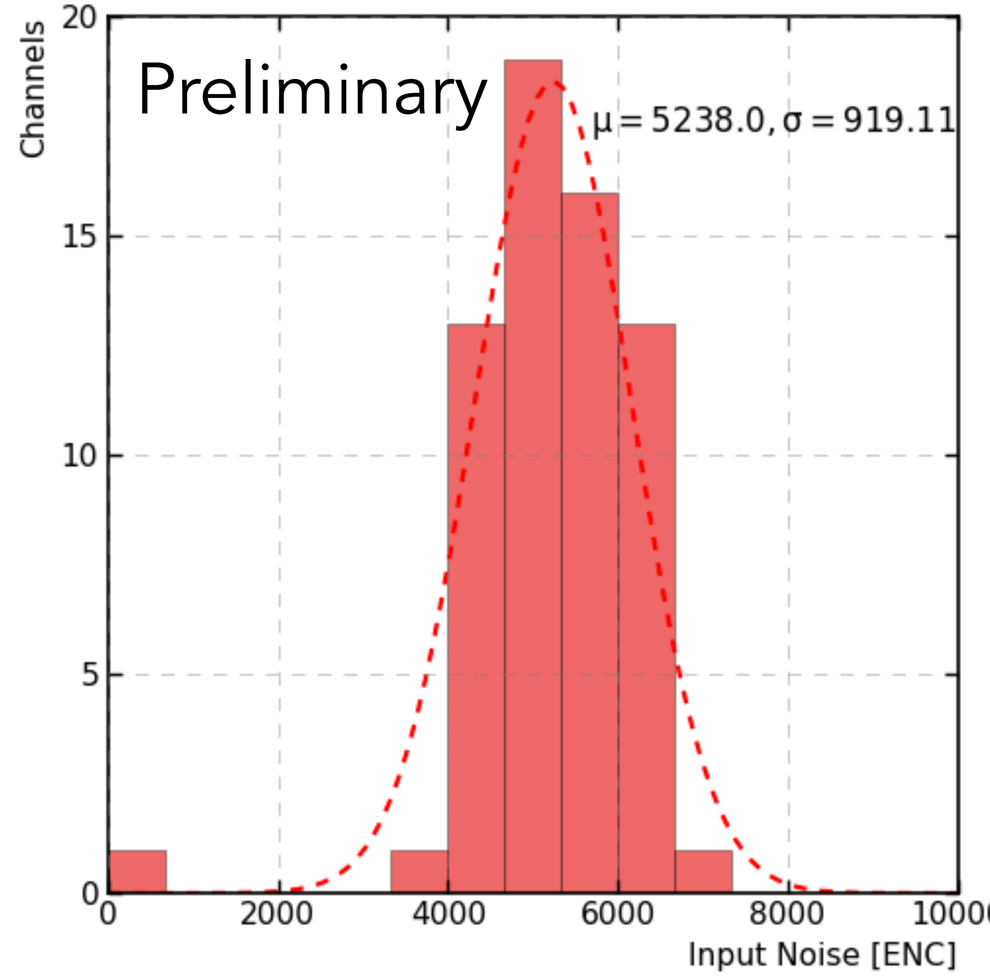
Conclusion: ITk

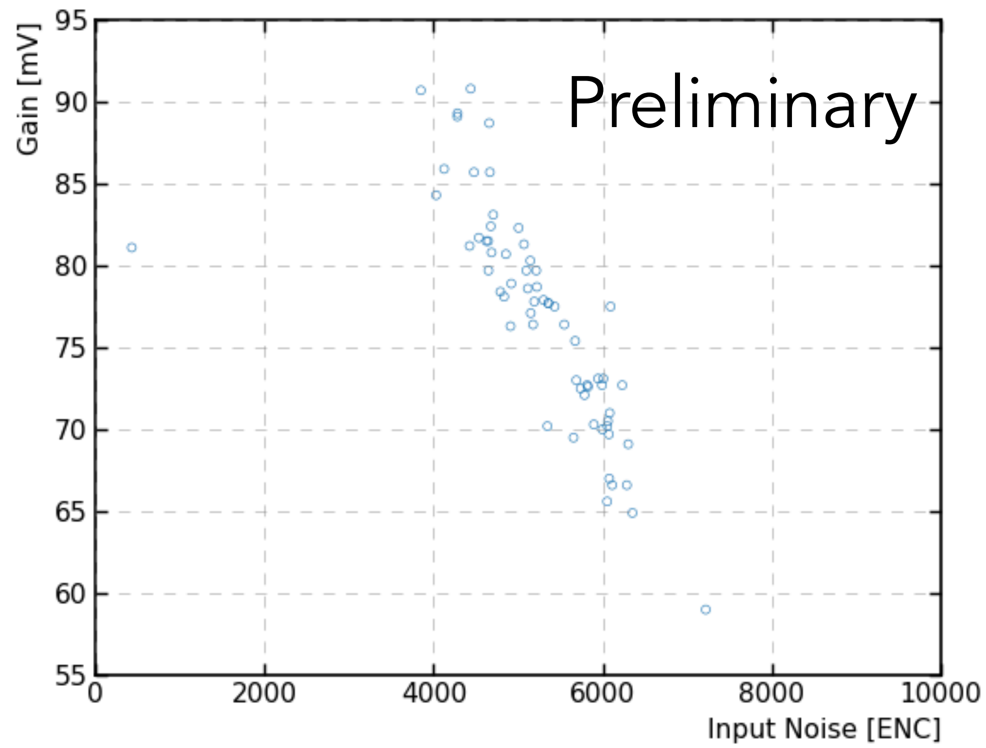
- Increase in leakage current follows the increase of beam intensity.
- Noise level increases as a function of the proton flux, while gain decreases.
- Fraction of fully working channels decrease with the increase of the dose received.
  - Large effect observed around the beam centre.
- Sensors presents 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.



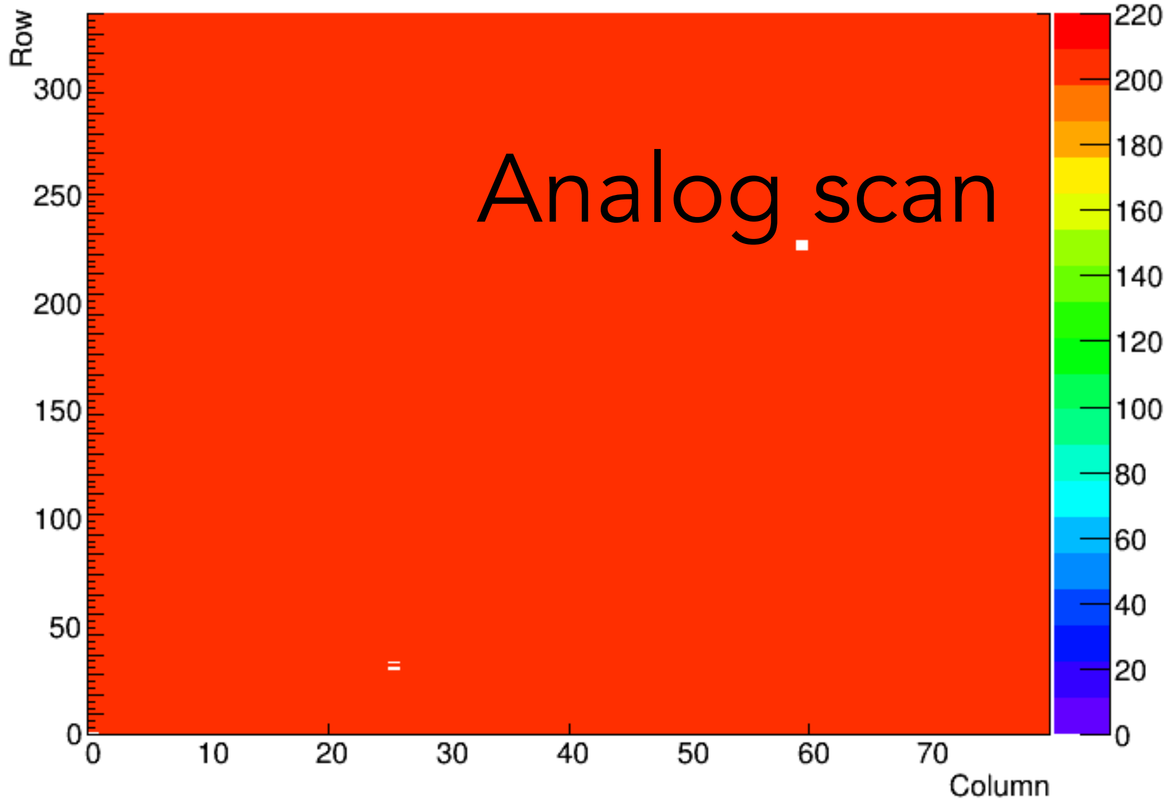
Initial condition: noise and gain

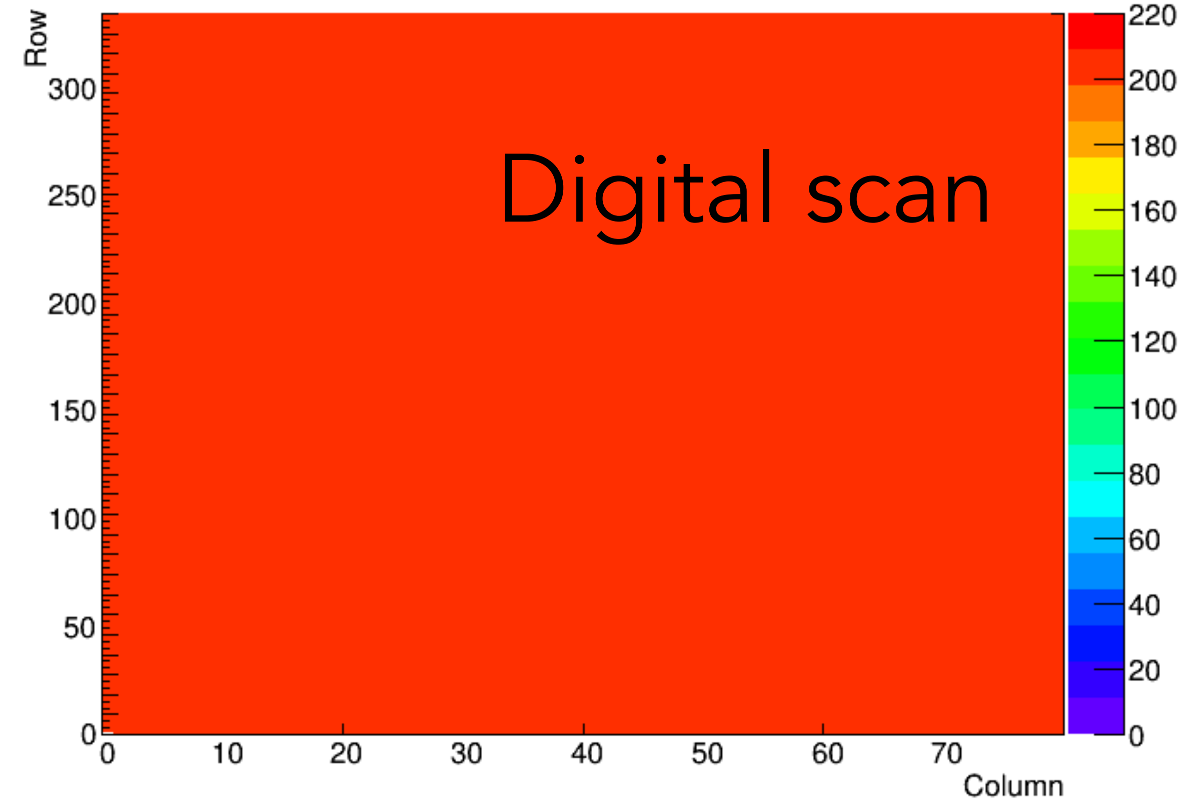






IBL Initial condition





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.

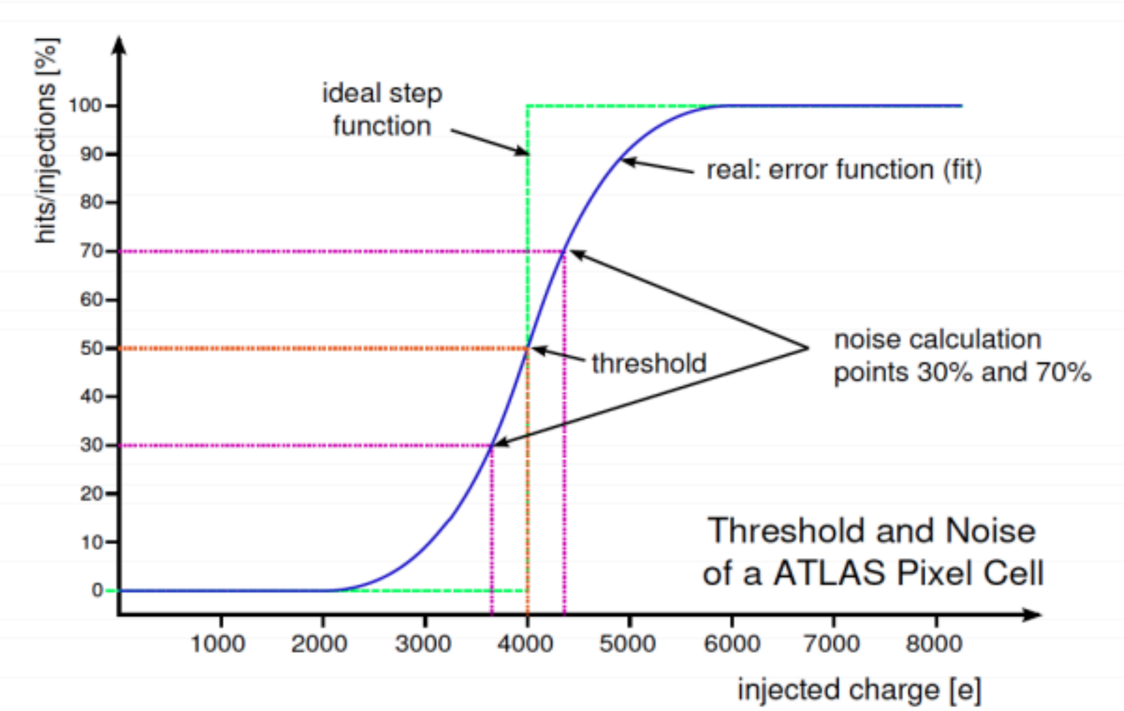
1. or each pixel, 200 pulses are fed at low frequency to the output of the discriminator, simulating the discriminator signal when a preamplifier pulse the discriminator. This part of the test checks the readout chain from the pixel cell down to the data LVDS transmitter of the chip.

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.

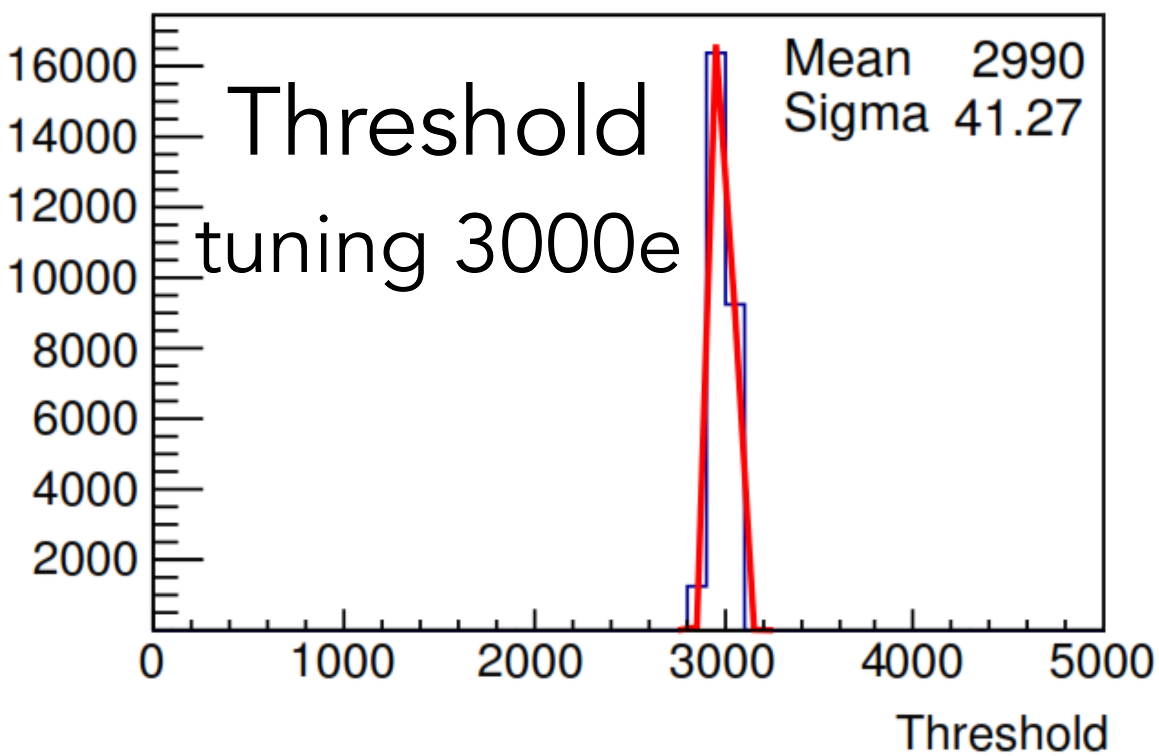
- A voltage pulse Vcal is injected on the calibration capacitance Cinj of each pixel.
- It generates a signal at the input of the preamplifier equivalent to the one generated by a charge Q=Vcal*Cinj.
- A set of 200 pulses is generated for different value of the injected charge (from 0 to ~10000: electrons, 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

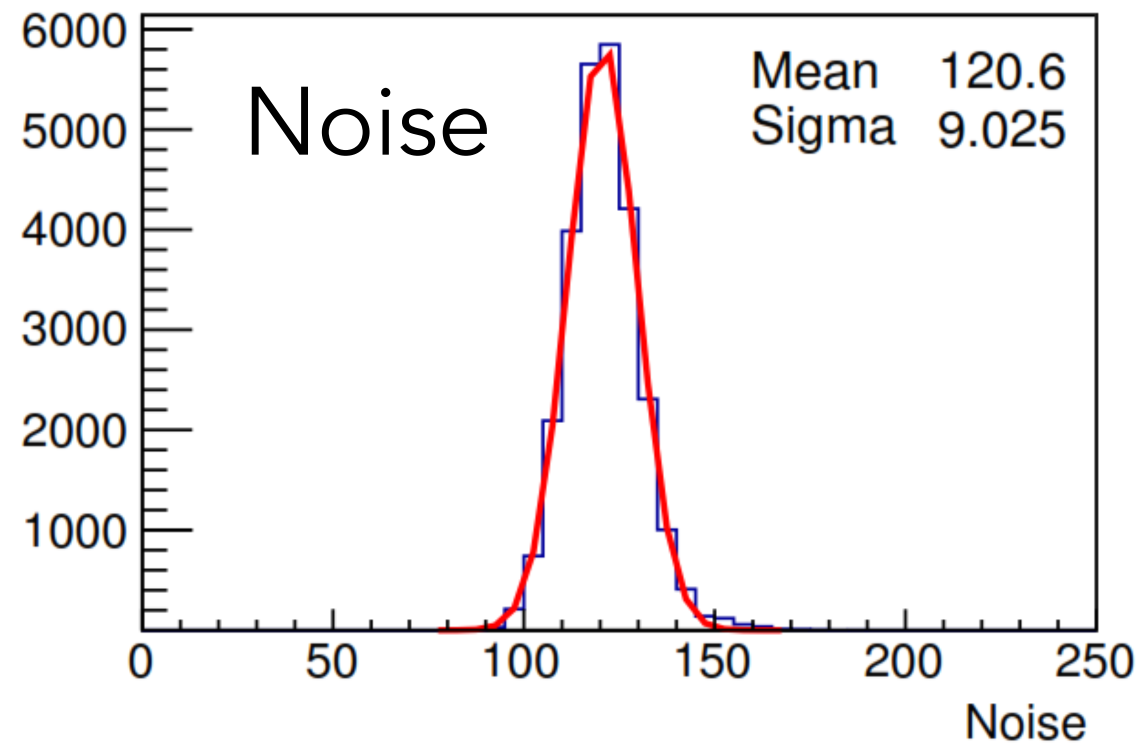


Source Scan identifies pixels that are not answering to ionisation because of either bumps defects (disconnected, merged) or read-out defects (badly tuned).

- 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.

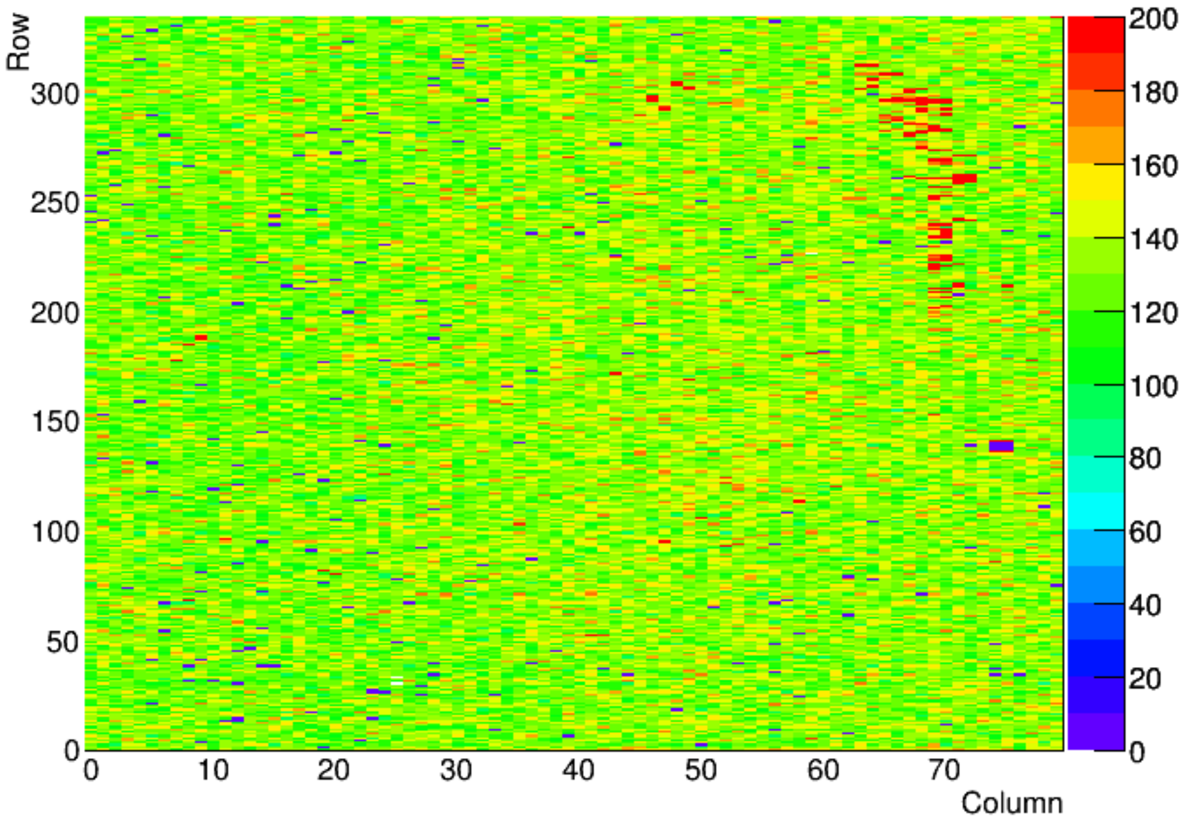
IBL Initial condition



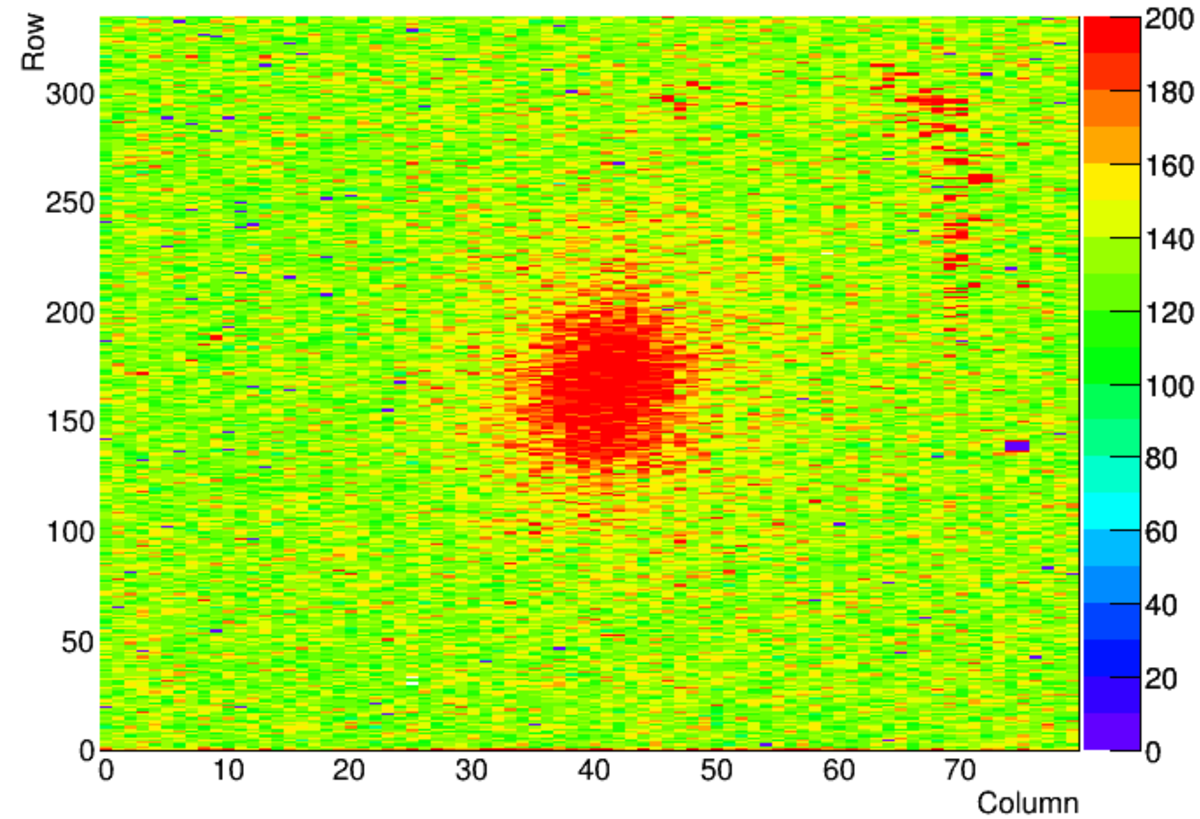


IBL Noise

Pre-Irradiation

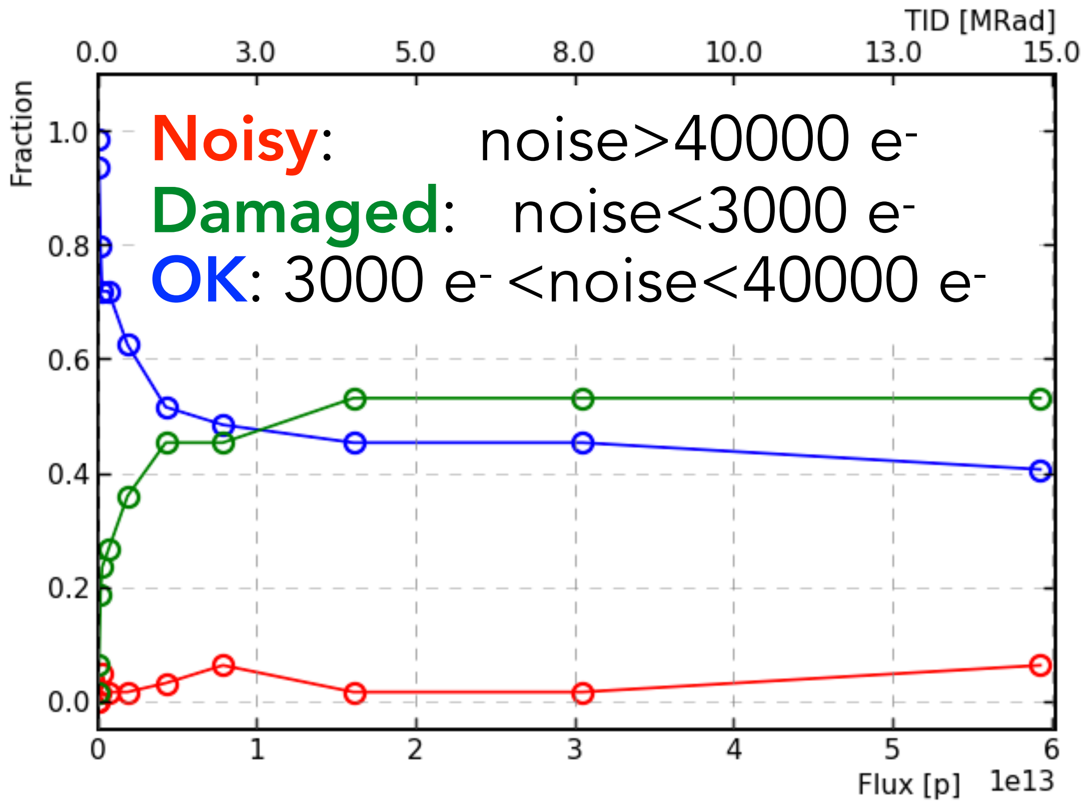


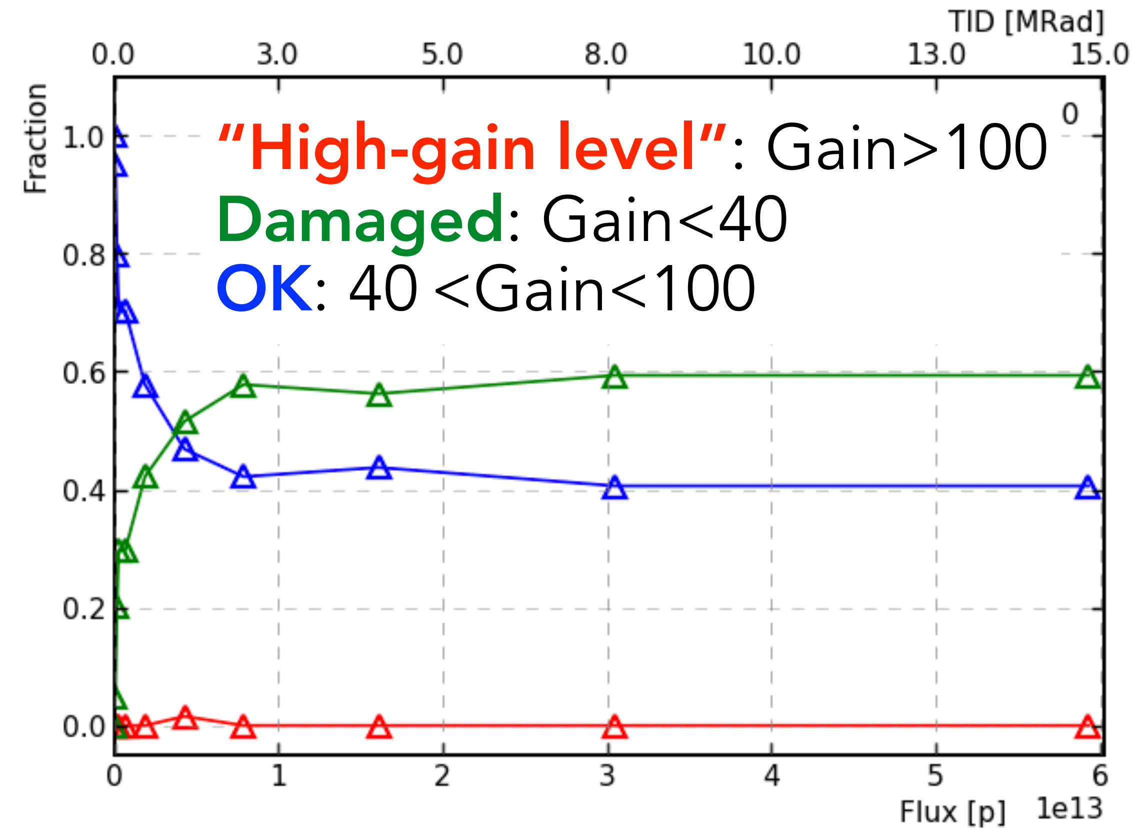
After-Irradiation



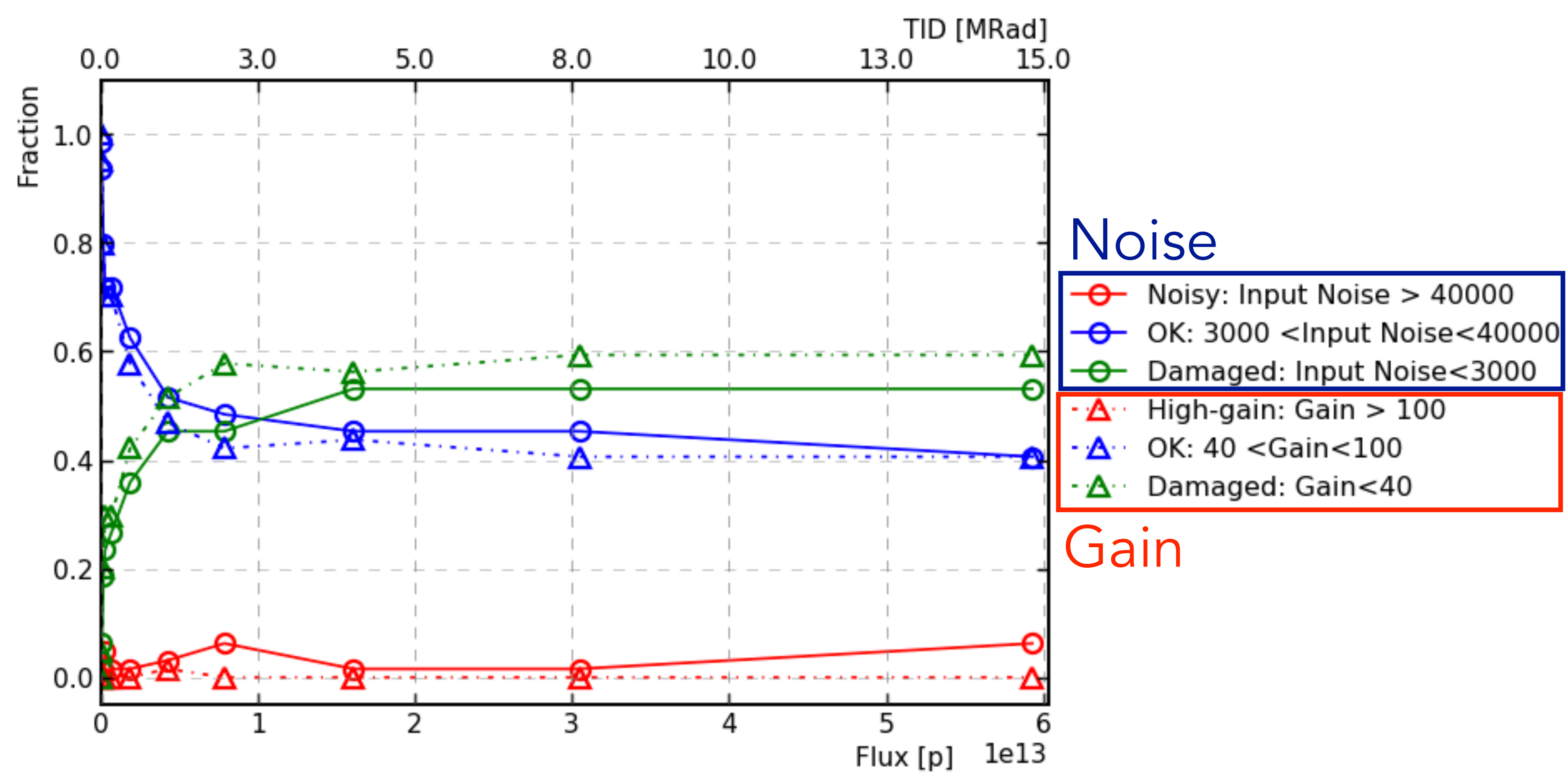
Noise increases in correspondence of irradiated region

Channel behaviour





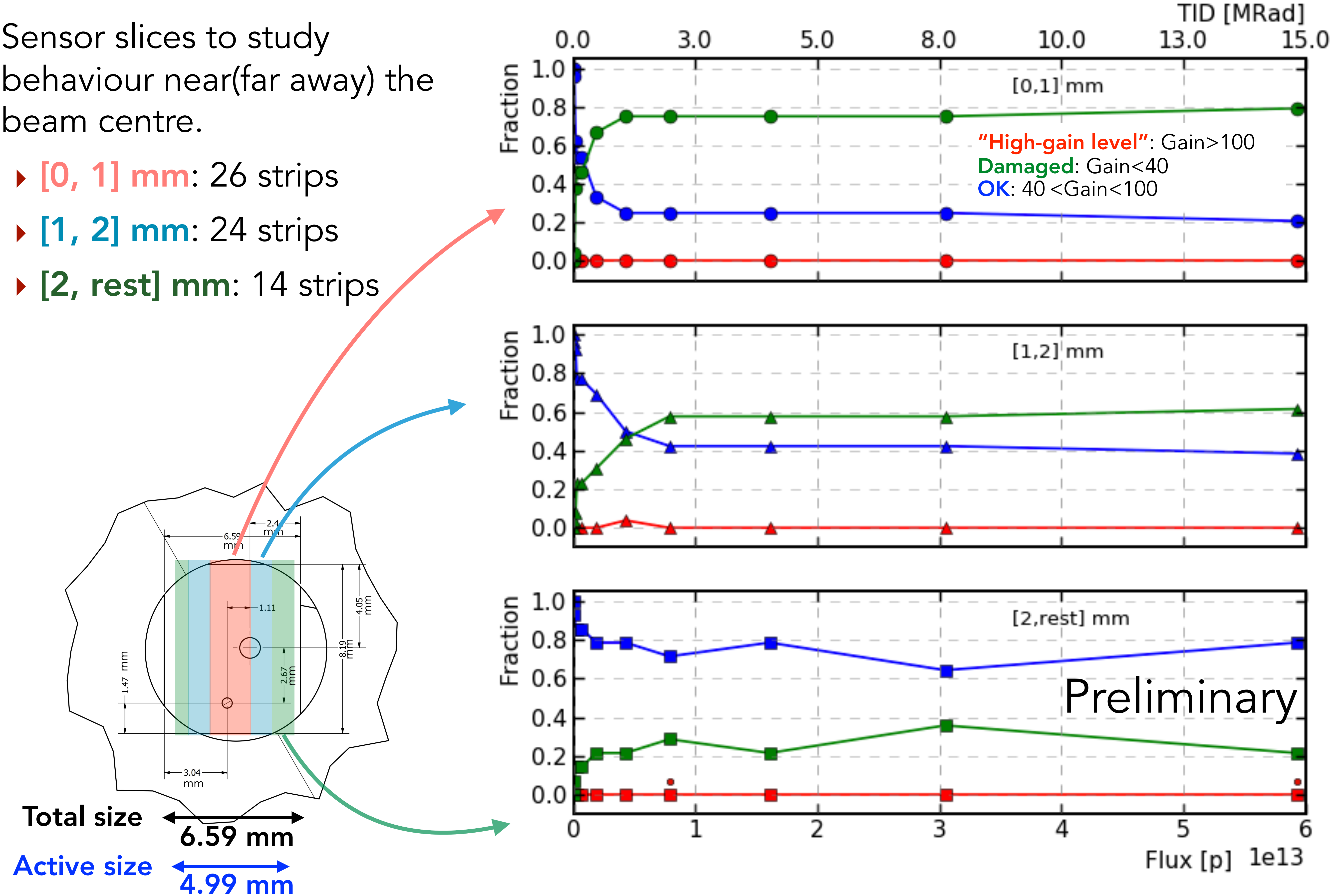
- Level of Noise or Gain used to characterise the strip behaviour.
- ~40% of the strip shows good performance.



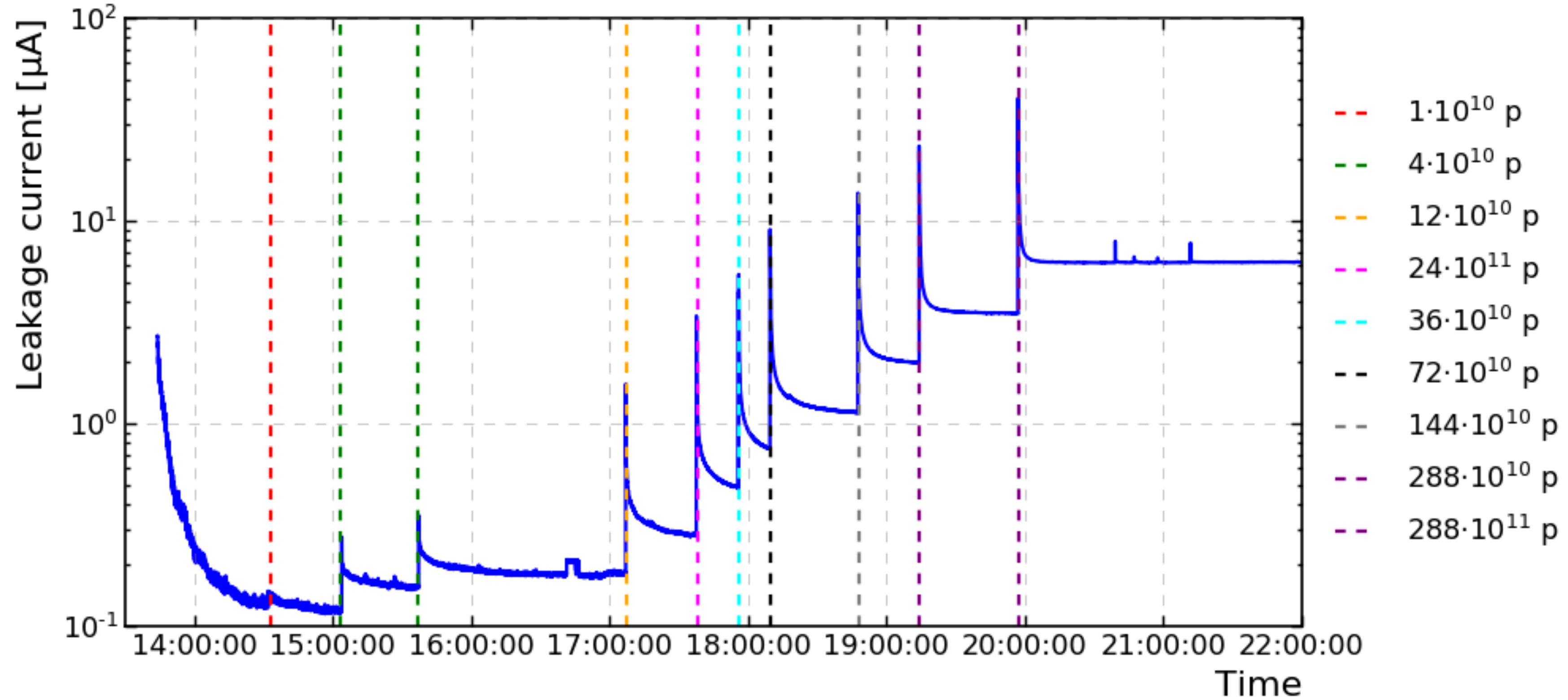
Channel behaviour: around the beam

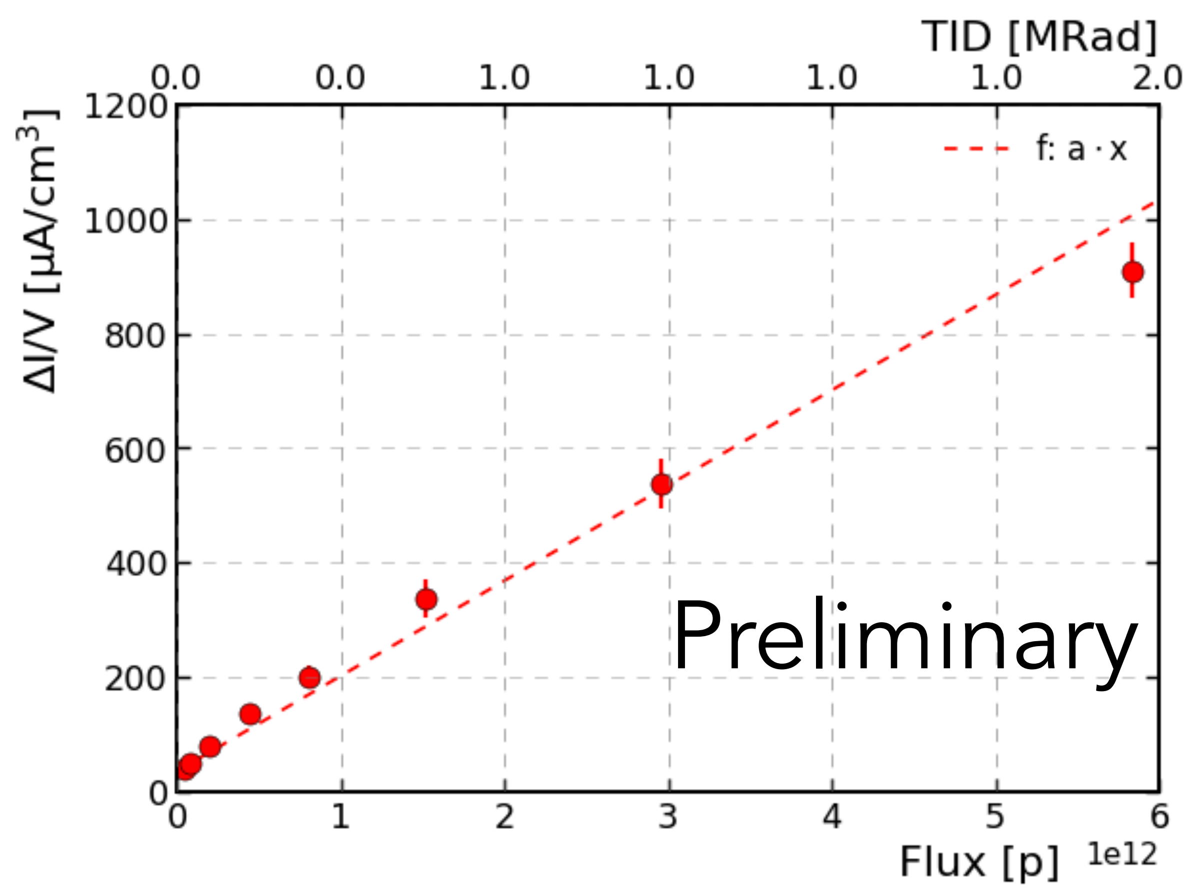
Sensor slices to study behaviour near(far away) the beam centre.

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



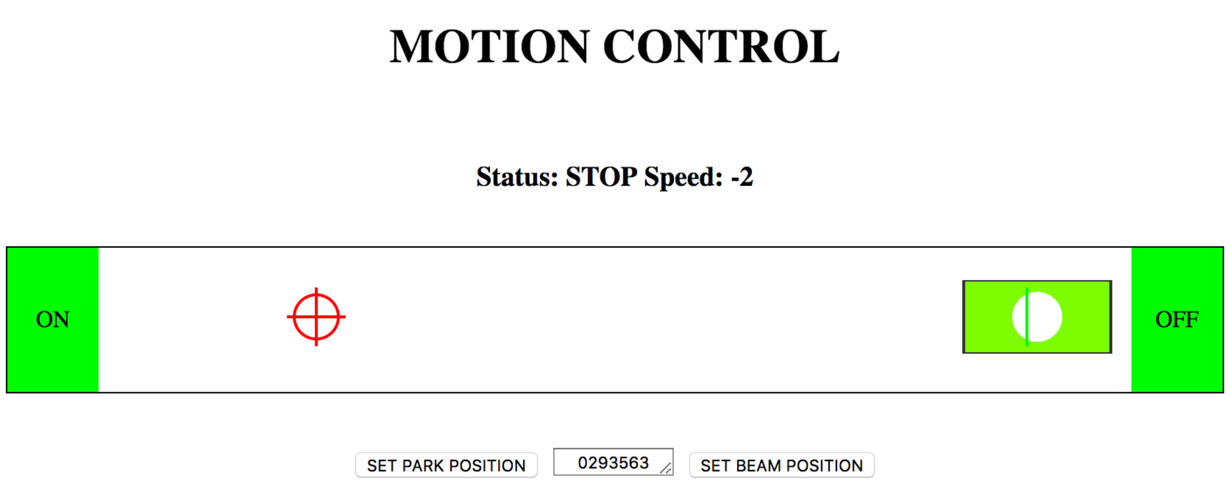
Leakage current 2017

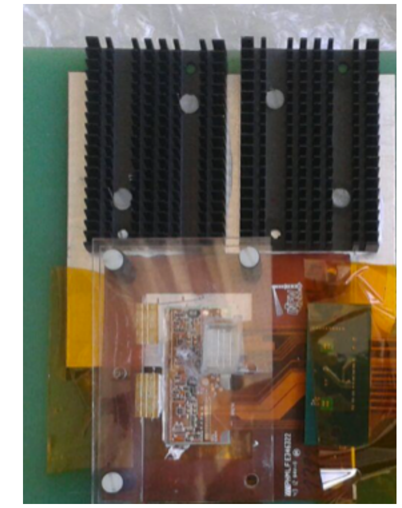




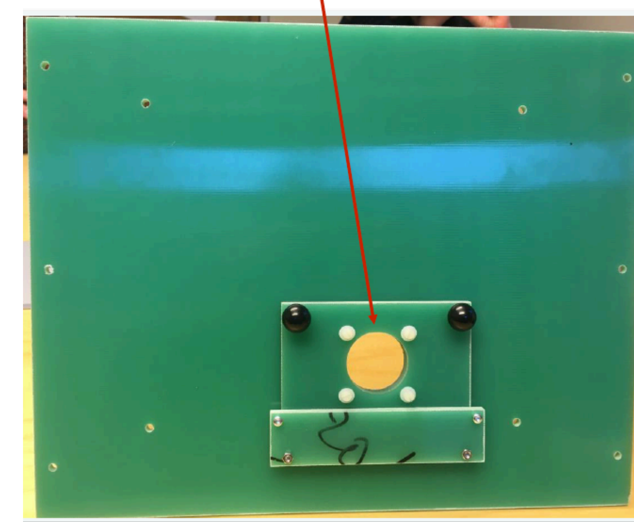
Beam-loss studies May 2018: Improvement

- 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.

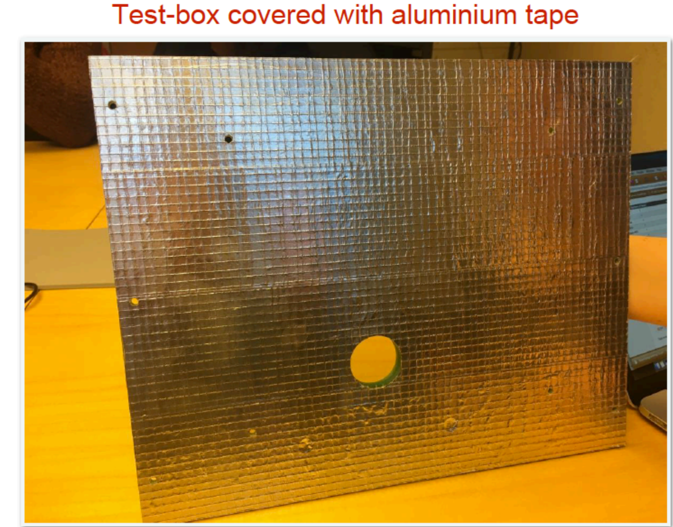




2x support for aluminium foils



Test-box covered with aluminium tape

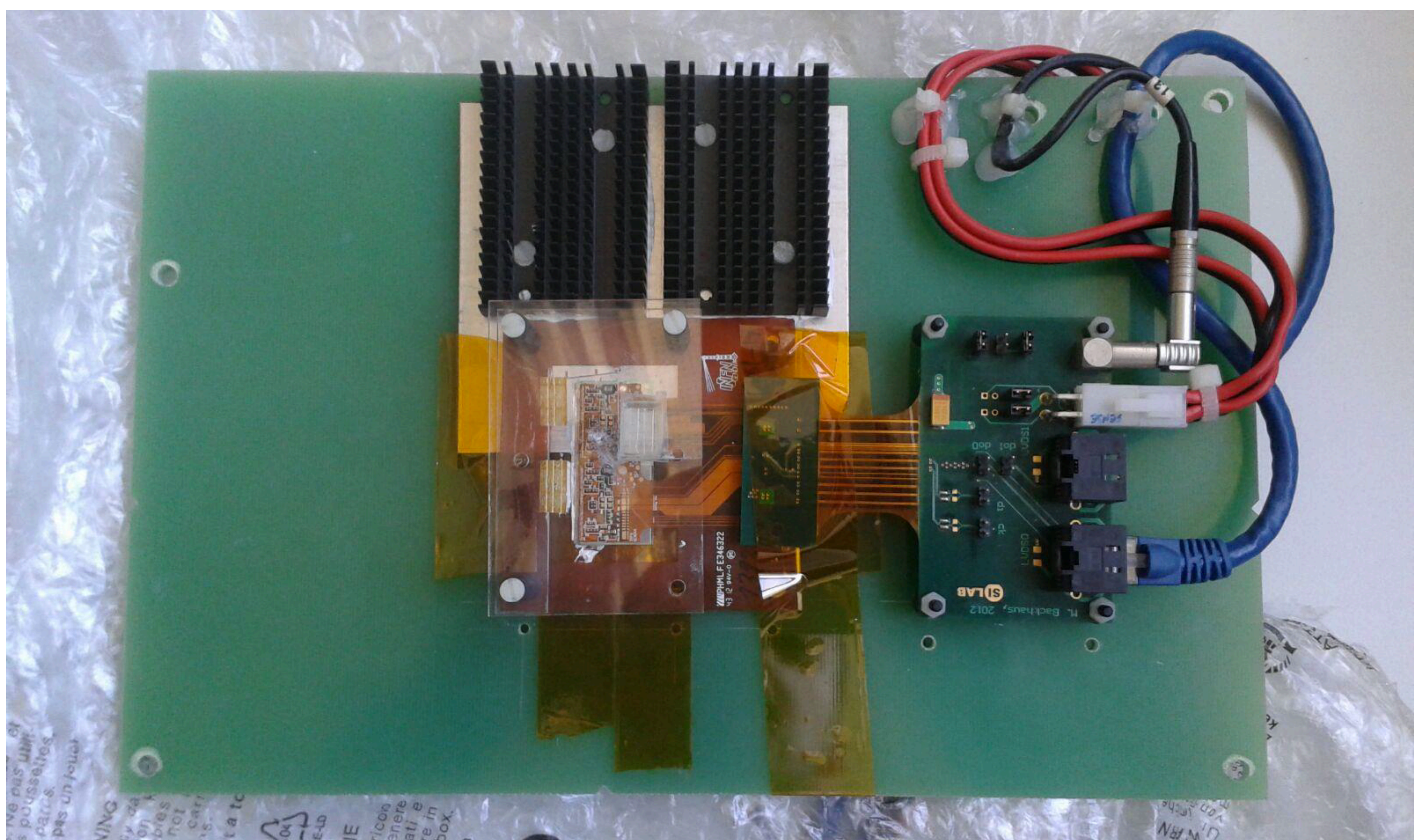


Beam-loss studies May 2018:Modules

Plans for IBL Pixel in May 2018

- 1xPixel 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

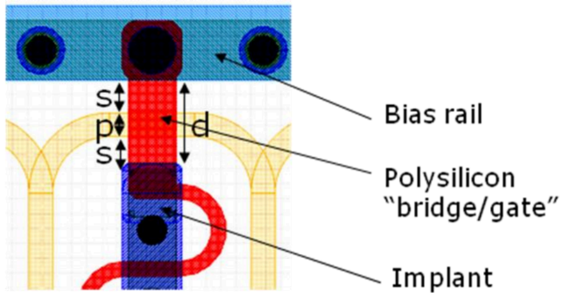
ITk DAQloads, CNM provided p-type sensors

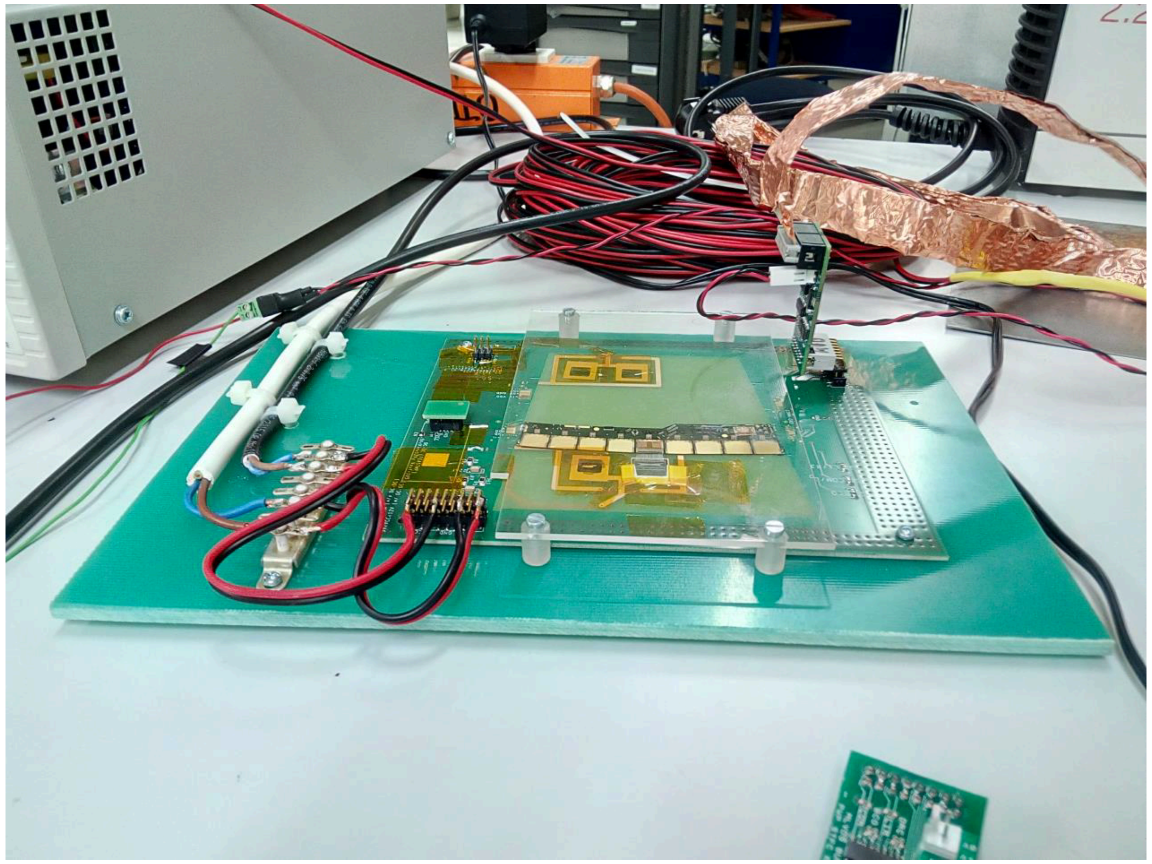
DAQload from Valencia

- 1x sensor without PTP
  - mini petalet: barrel
    - embedded: 6271_w06
  - 1x ABC130

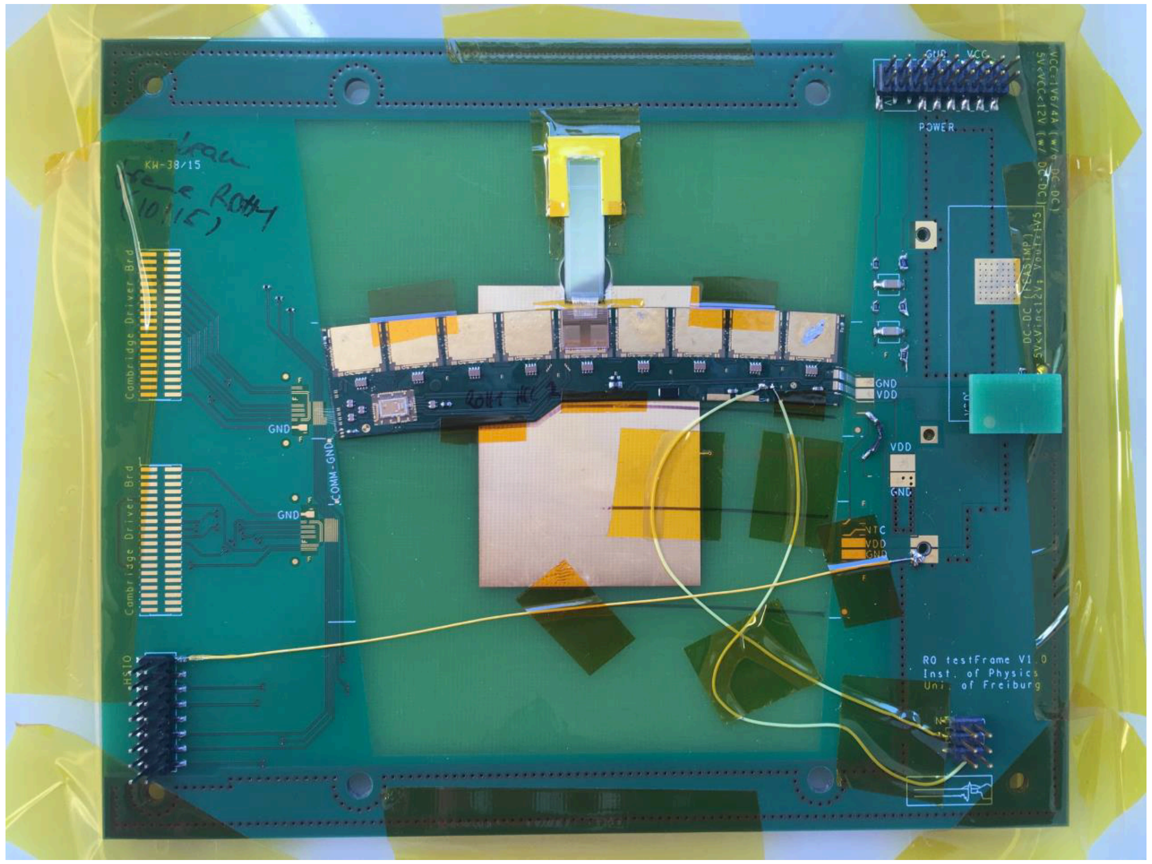
DAQload from Freiburg

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





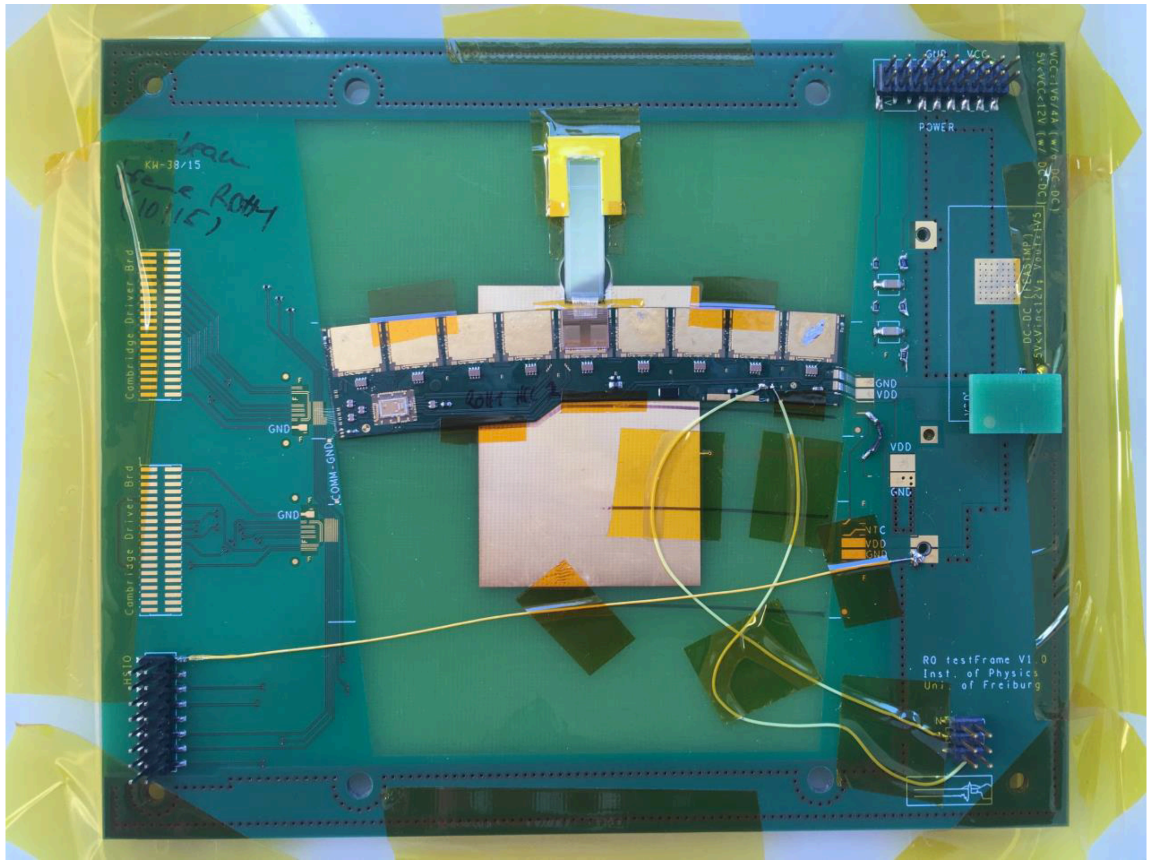
CNM sensor (6271_w06)



CNM sensor (6958_w08_s1c)

Beam-loss studies May 2018: Module

CNM provided p-type sensors

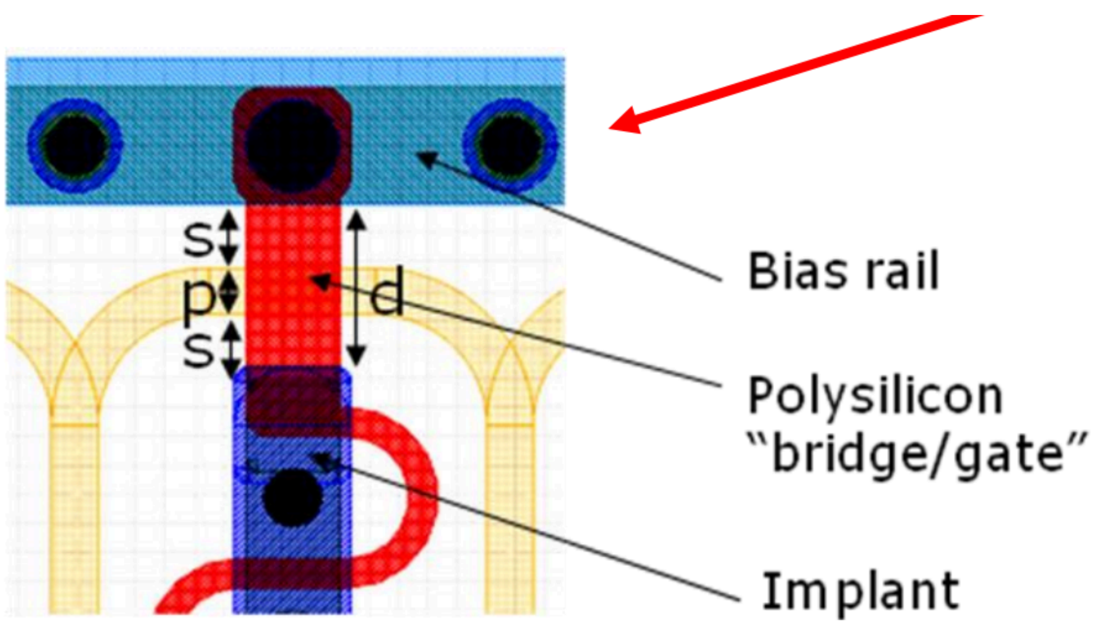


CNM sensor (6958_w08_s1c)

- **Size**:
  - Active part: **4.99** x 23.960 mm2
  - Full x-size: **6.59** mm
- Thickness: 310 µm
- Strip pitch: **~77 µm**
- Num strip: 64

DAQload from Freiburg

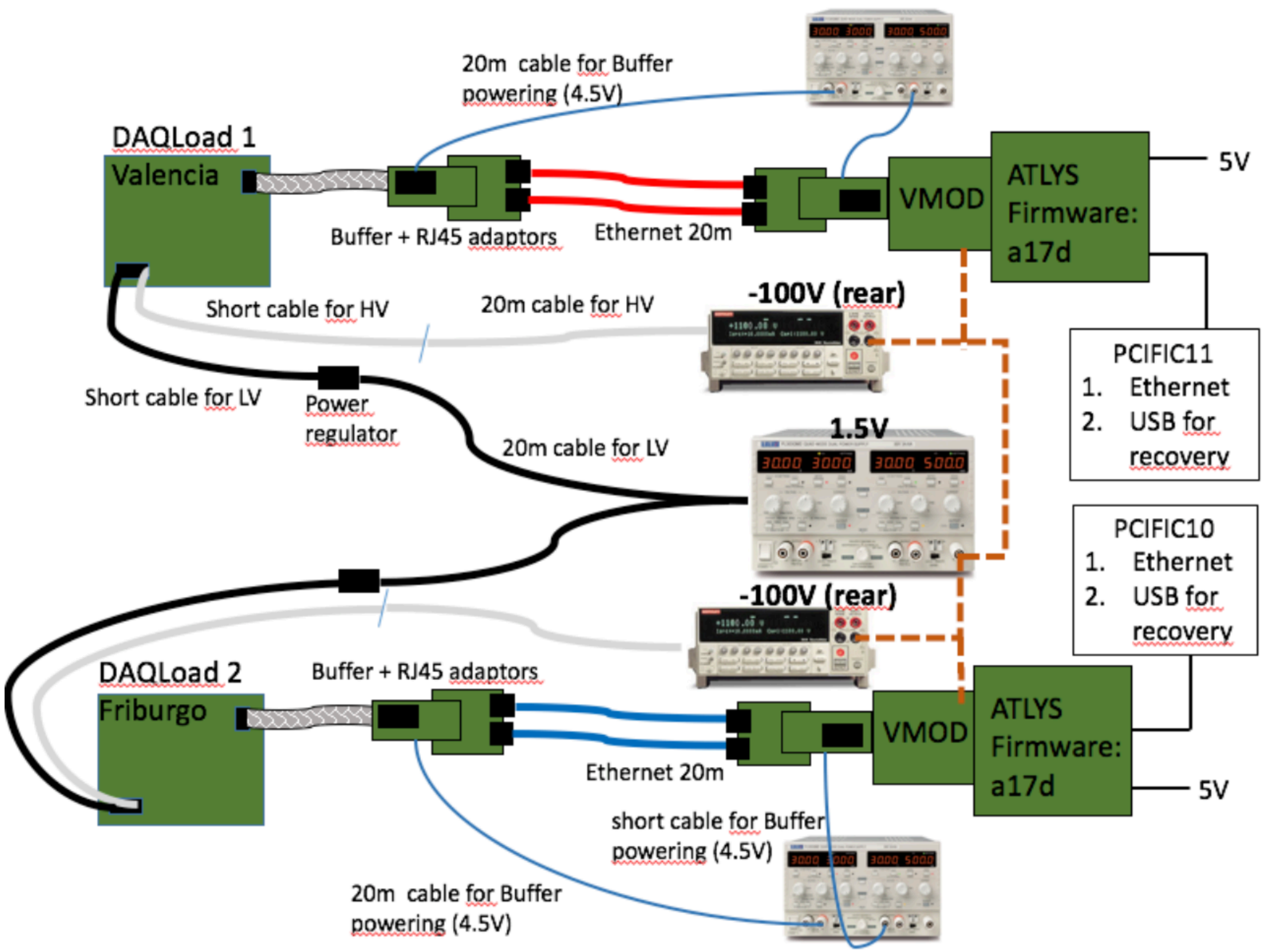
- 1x sensor with PTP
  - LowR: 6958_w08_s1c
  - gated PTP structure
    - d=20µm / p=4µm / s=8µm
  - p-stop width = 4 µm
- 1x ABC130

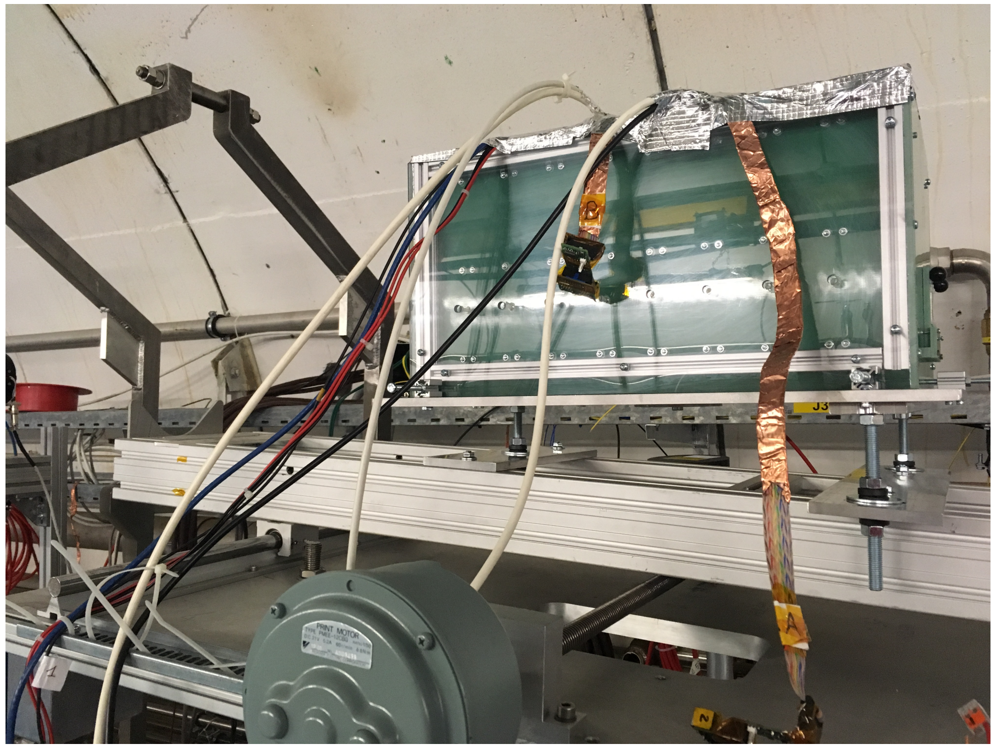


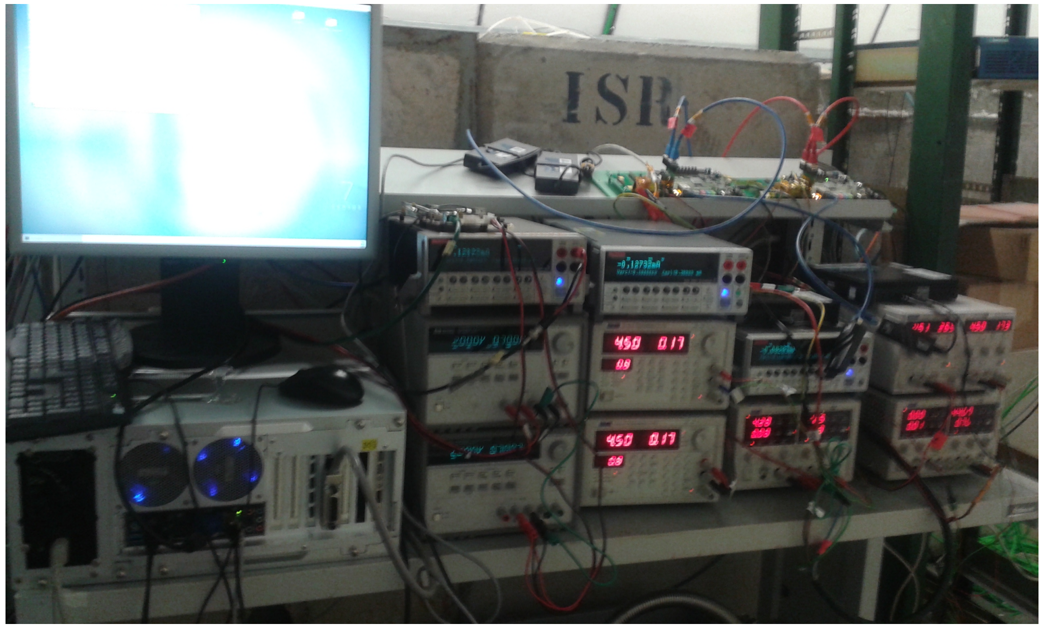
ITk Read-out: 2018

NB:

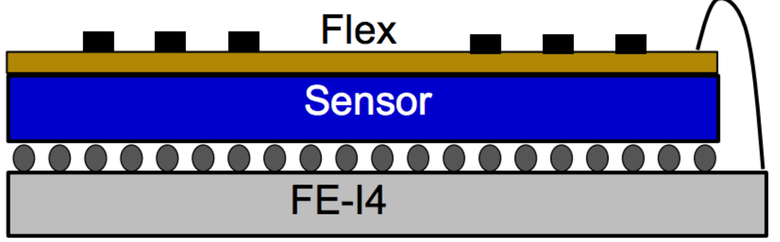
- Note 2 Modules installed
- Connection with Petalet module lost after installation in the tunnel







IBL modules



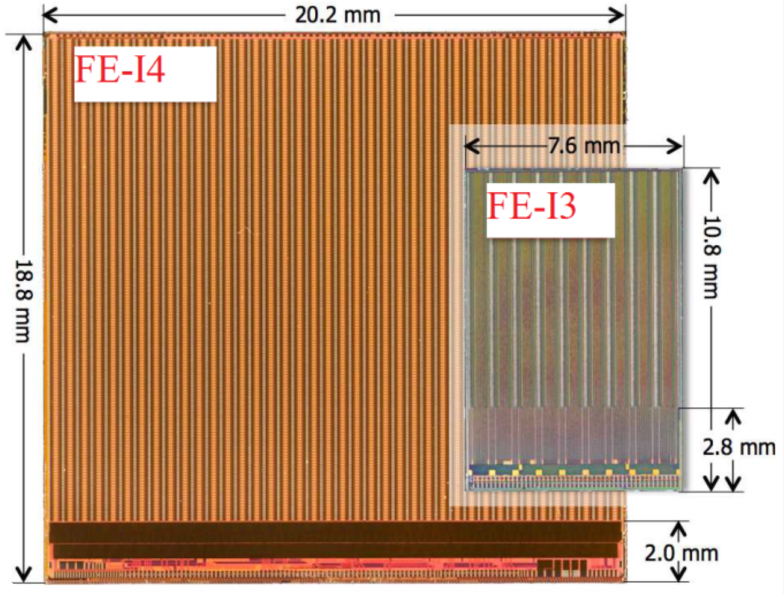
Single Chip (July 2017) vs Double Chip (May 2018)

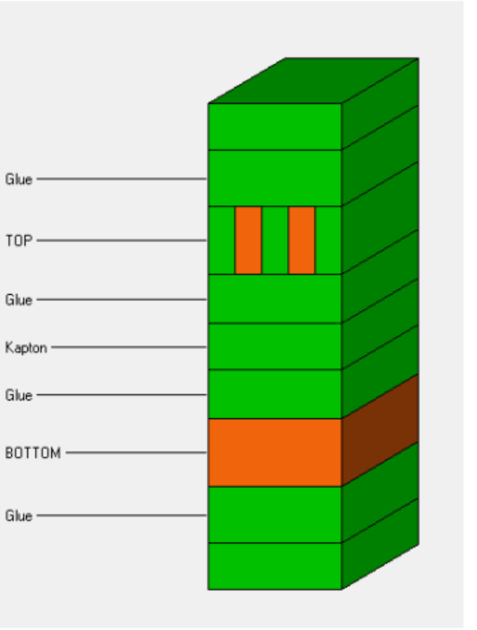
2017: 1x Pixel Single Chip (IBL 3D sensor + FE-IF chip)

- chip centered on beam axis

2018: 1x Pixel Double Chip (IBL Planar sensor + FE-I4 chip):

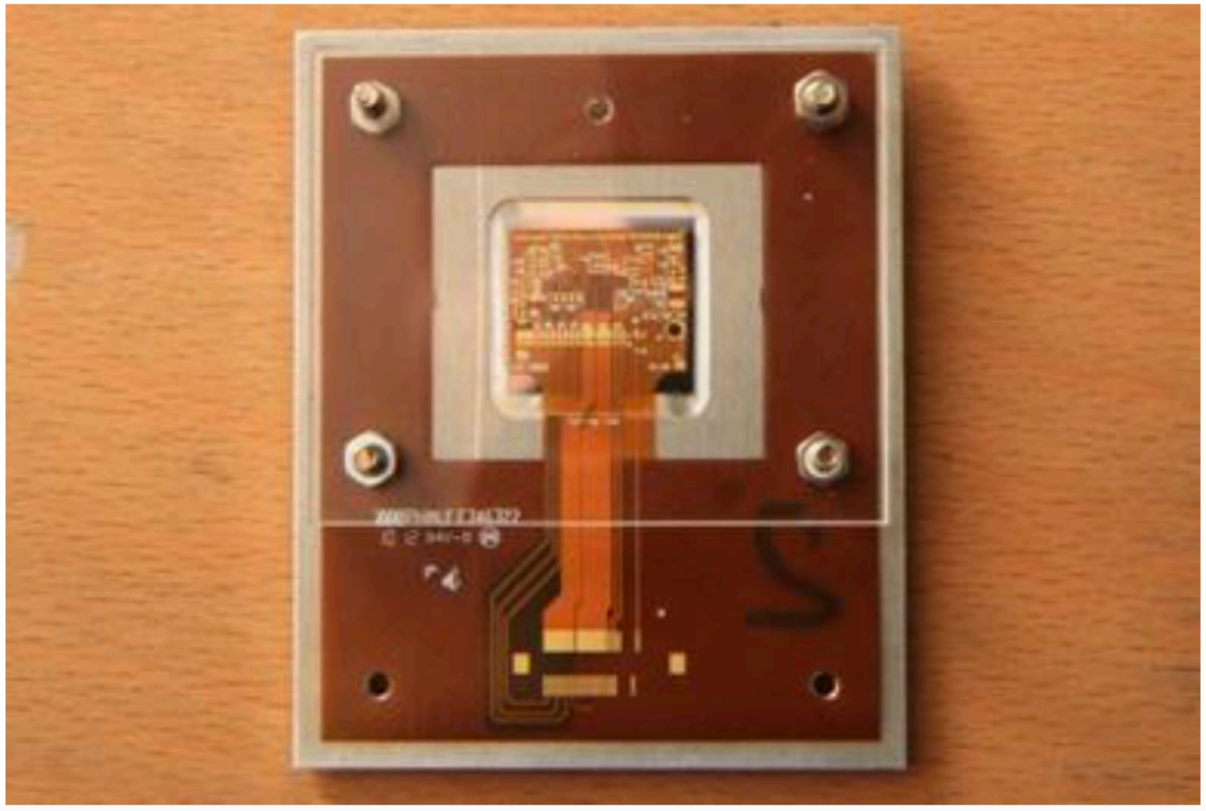
- 1x chip centered on beam axis
- 1x chip used as metallic contact to Al heat sinks



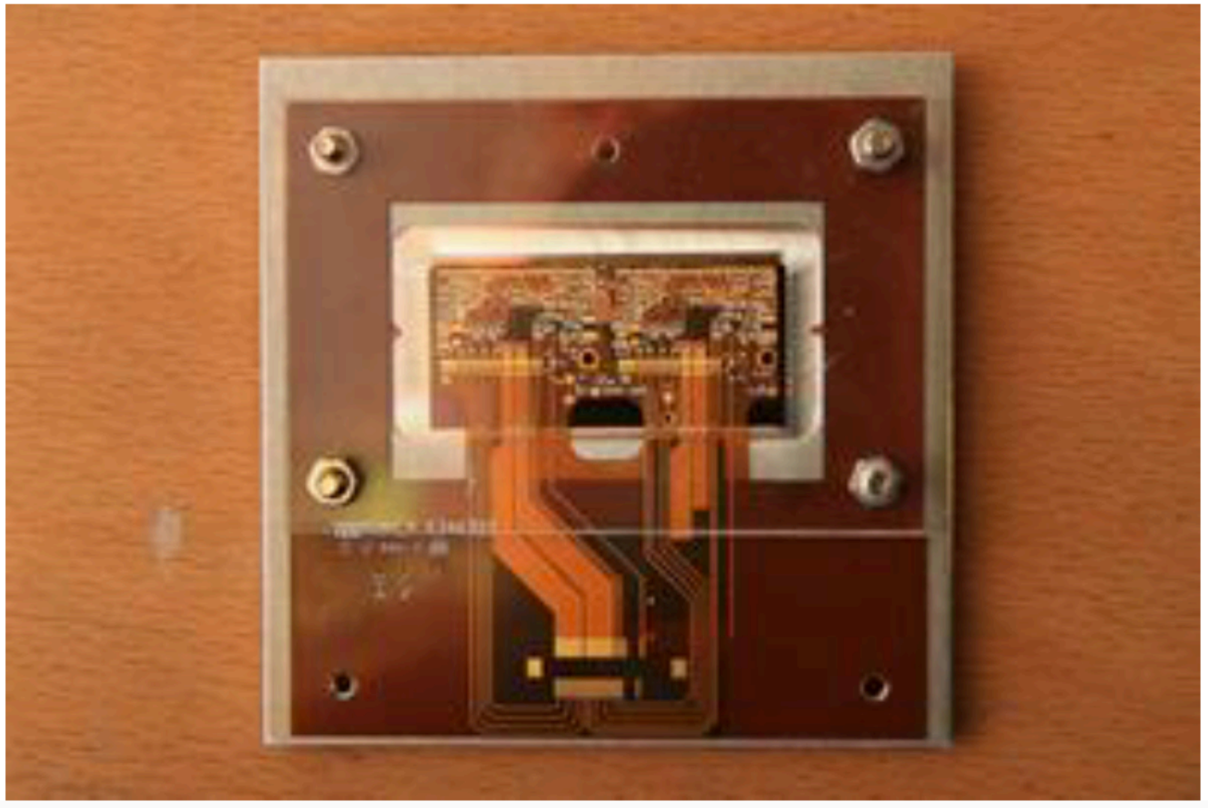


IBL TDR

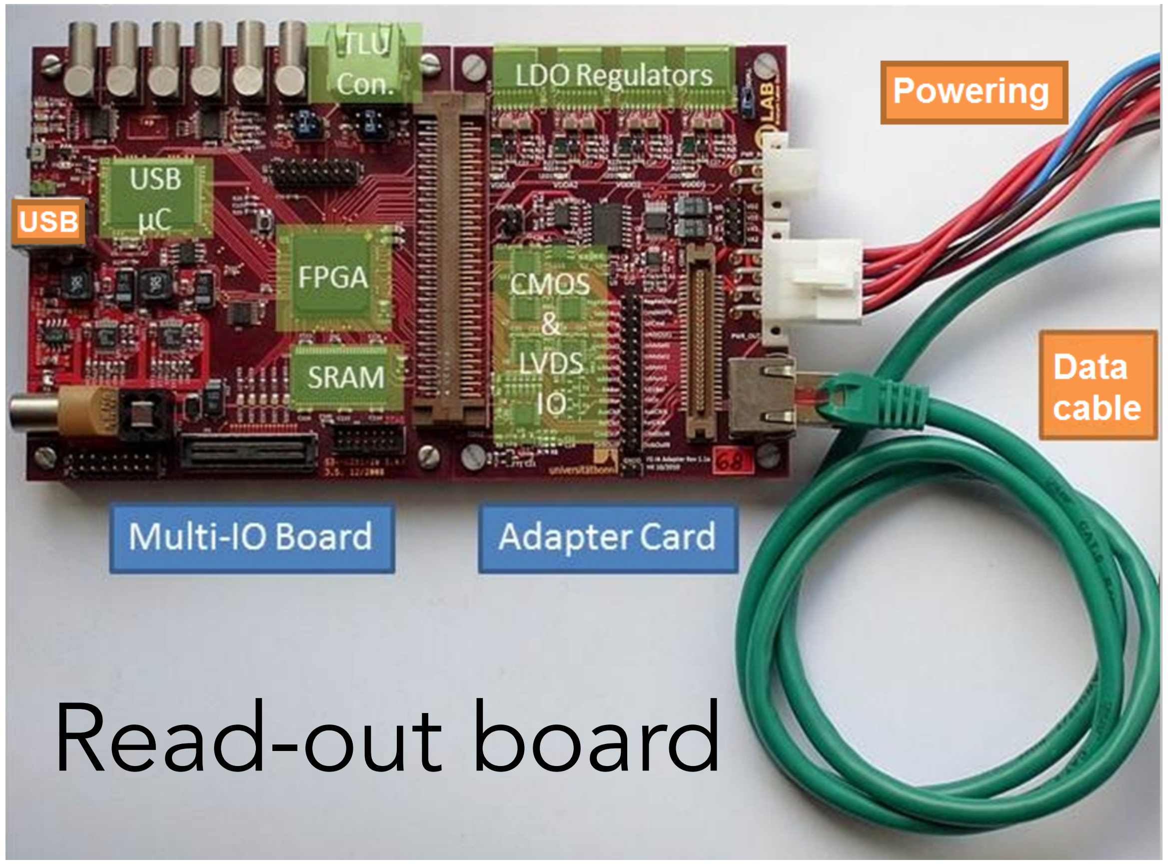
IBL SC module (3D)

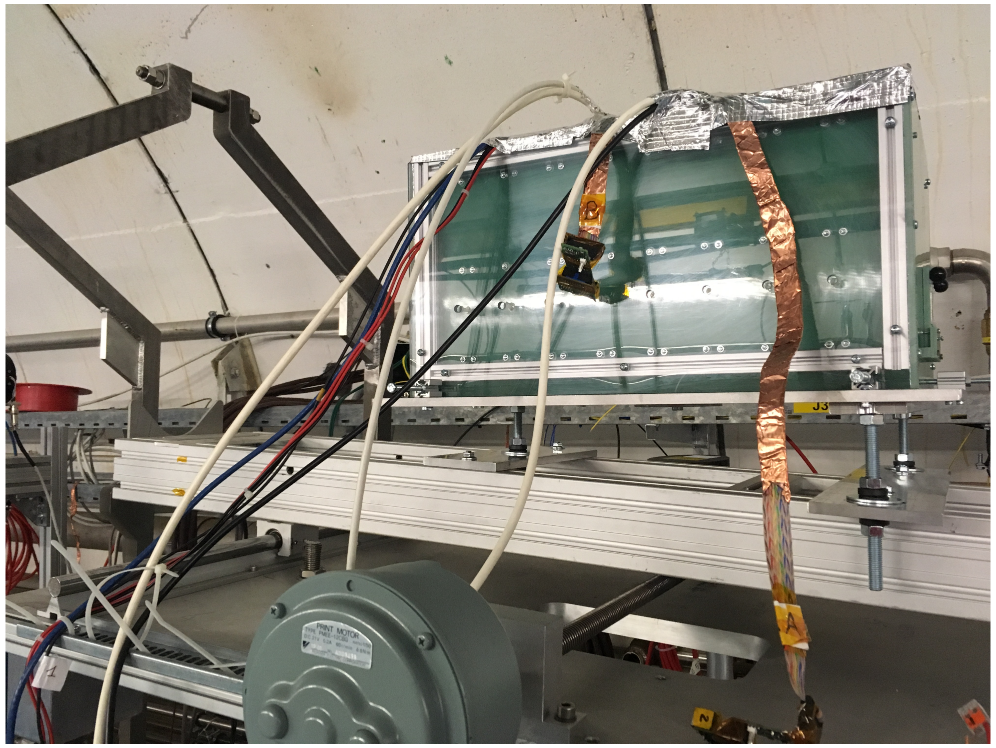


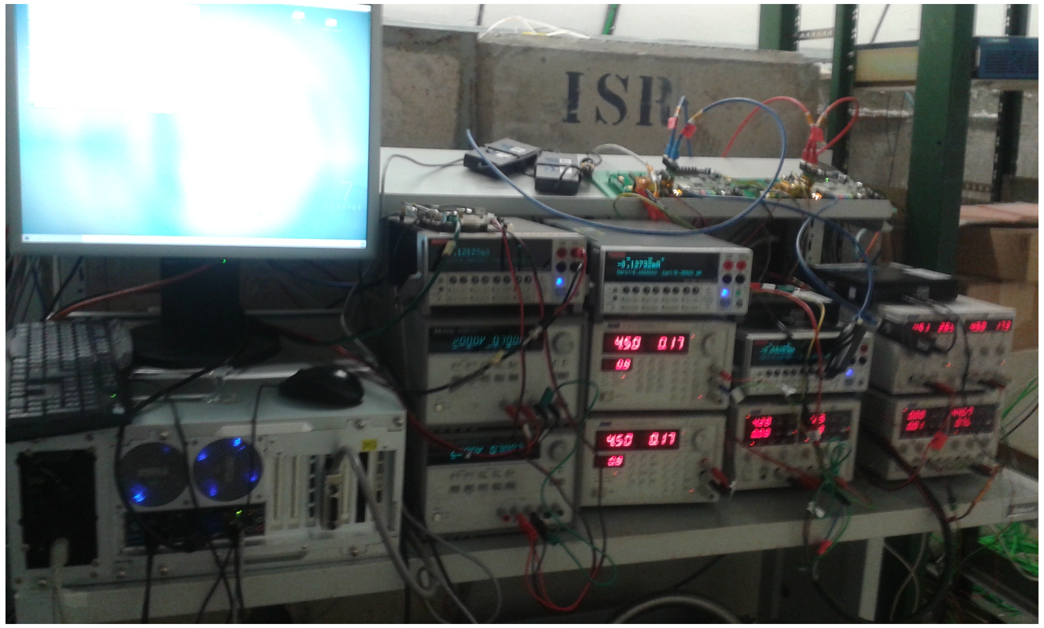
IBL DC module (Planar)



IBL Read-out


TLU
Con.
LDO Regulators
Powering
USB
USB
µC
FPGA
CMOS
&
LVDS
IO
SRAM
Data
cable
Multi-IO Board
Adapter Card
Read-out board




ISR

IBL damage

Damaged IBL Pixel in July 2017

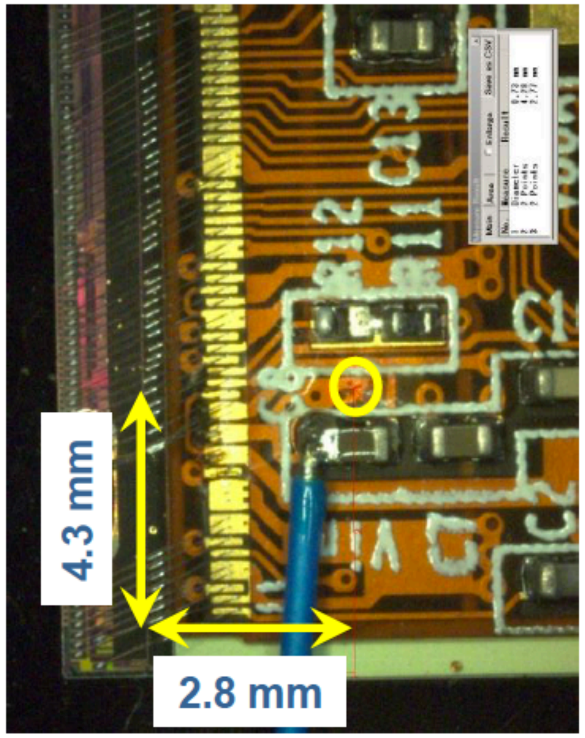
IBL module with 80x336 pixels (250x50 µm each)

		X	Y
72b damage position (Pixel)	:	63	280
288b beam position extrapolation	:	4.25 mm	2.8 mm
Visible damage position	:	4.28 mm	2.77 mm

<u>Overlapping of 288b expected beam position and visible damage position</u>

- Same damage visible both IBL pixel modules
- Flex contacts tested, working properly
- FE could be damaged instead

Both Pixel Modules damaged by 288 bunches (0.3 mm)



Axis definition

$$Flux[p] = \sum_{i \in [1,288]} n^i_{buch} \cdot n_p = \sum_{i \in [1,288]} n^i_{buch} \cdot 10^{11} p$$

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

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

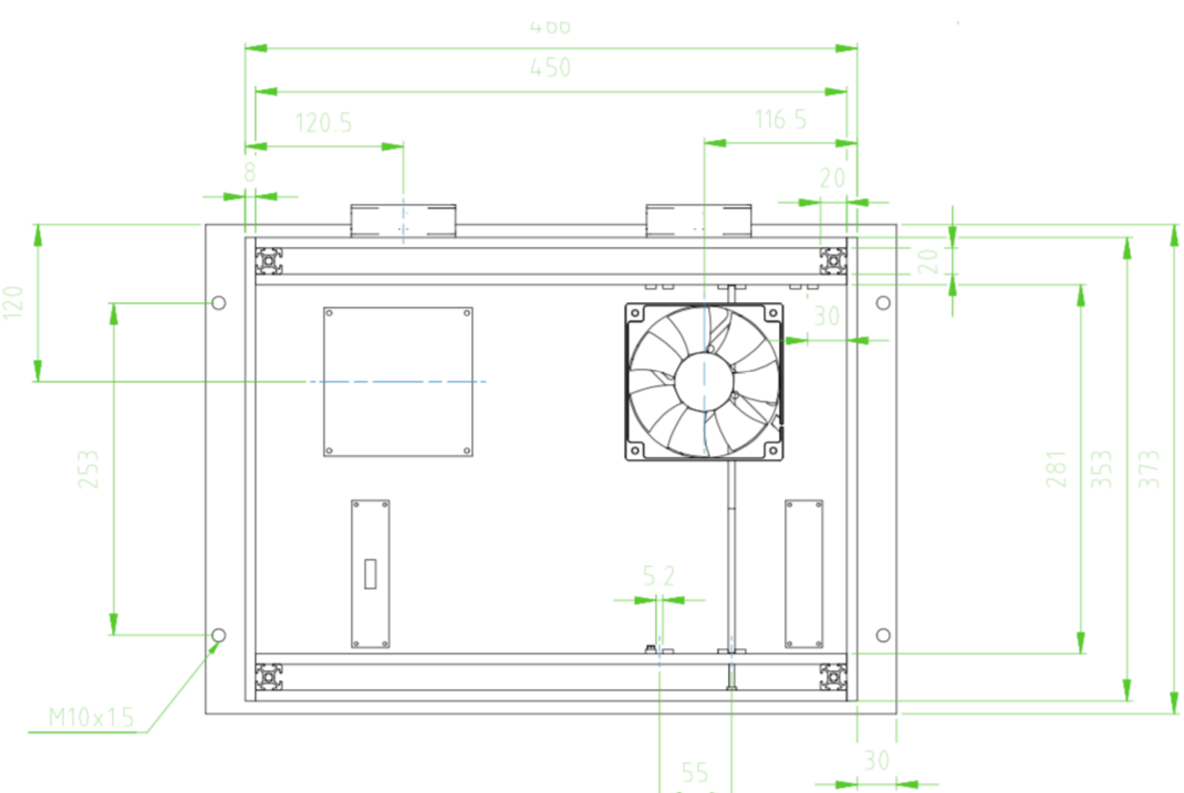
$$= 25.5 \cdot 10^{-10} Gy = 25.5 \cdot 10^{-8} Rad$$

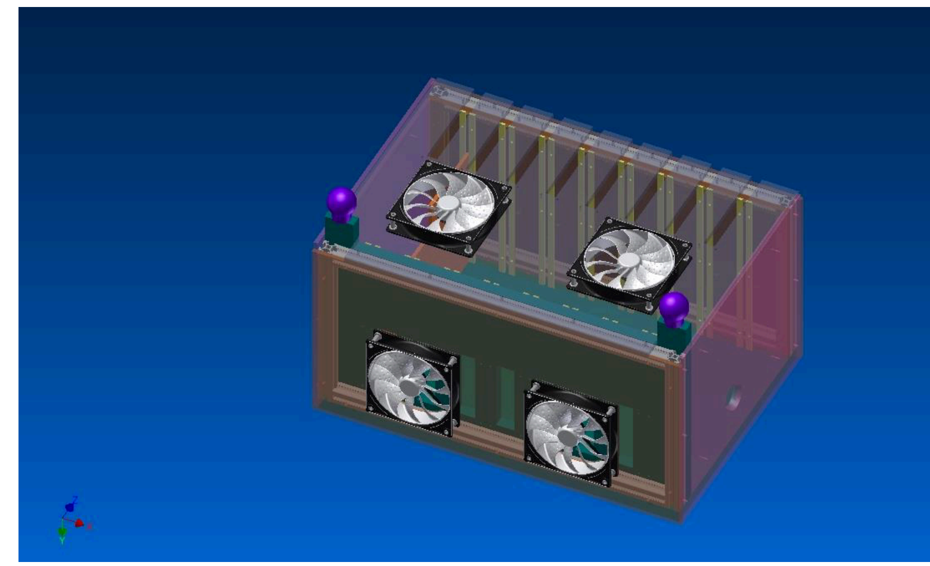
$$TID_{Total} = TID_{1p} \cdot Flux$$

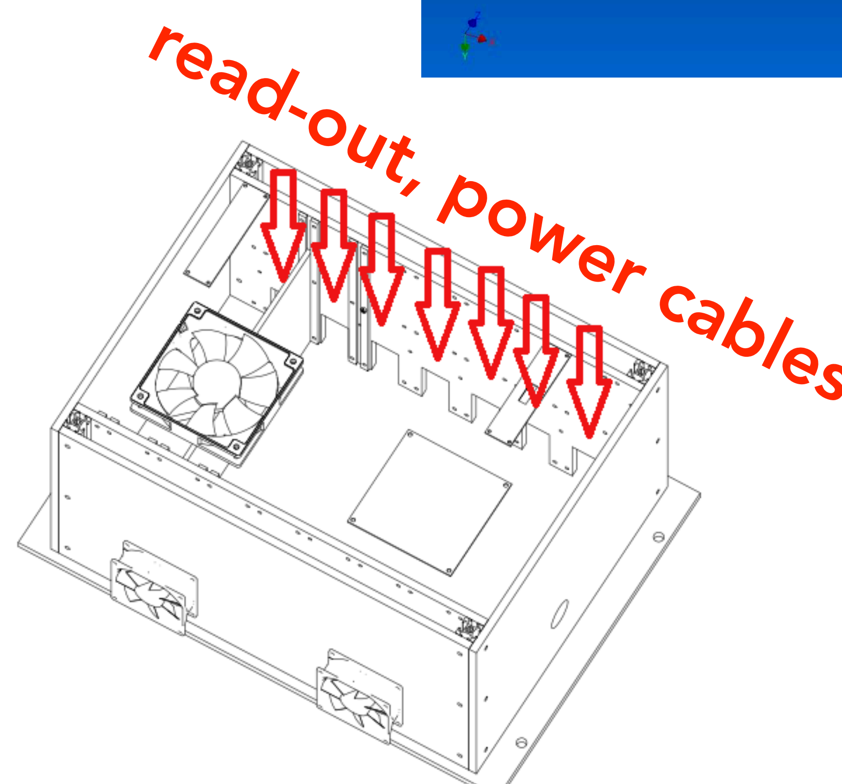
Beam-loss studies: Setup

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.

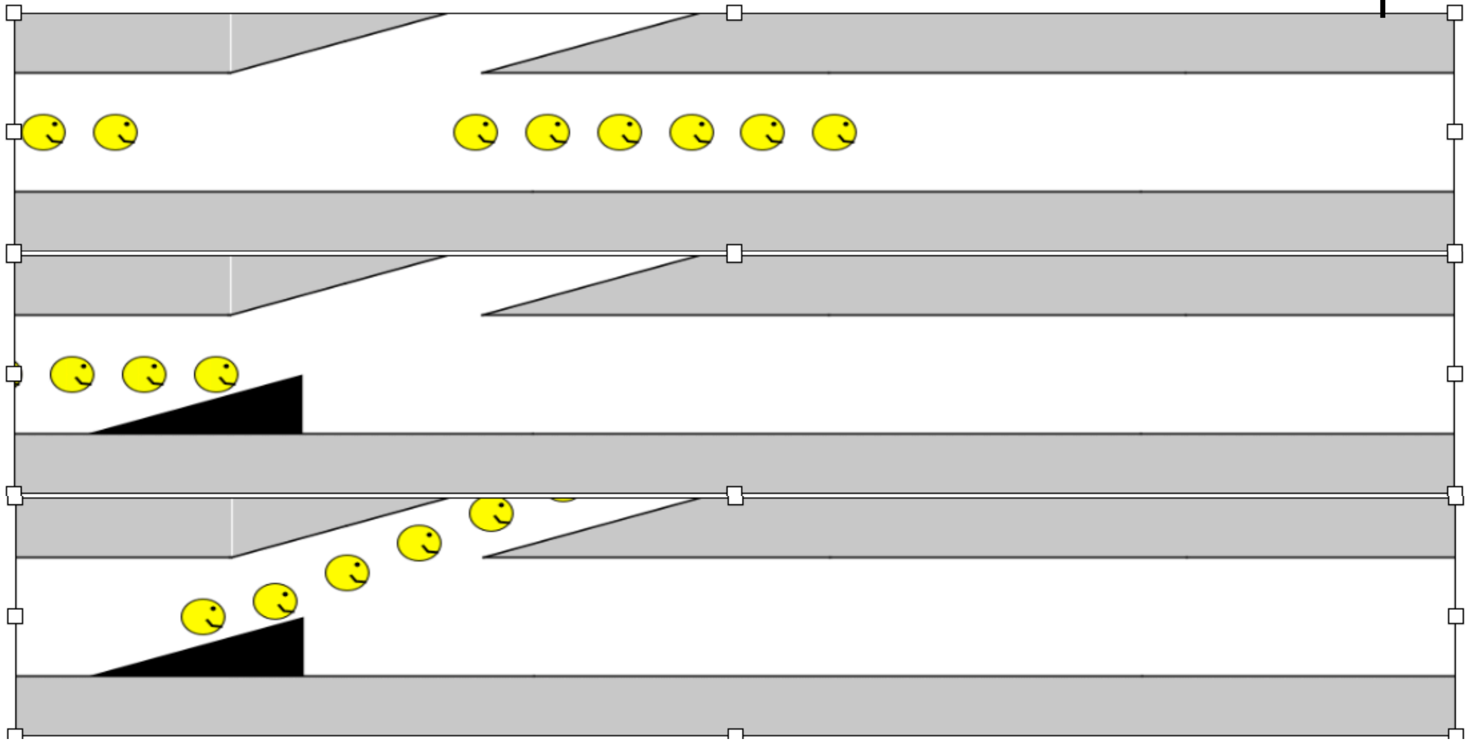






Asynchronous beam dump

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