First radiation damage studies on the LHCb VELO Upgrade

On behalf of the LHCb VELO group.

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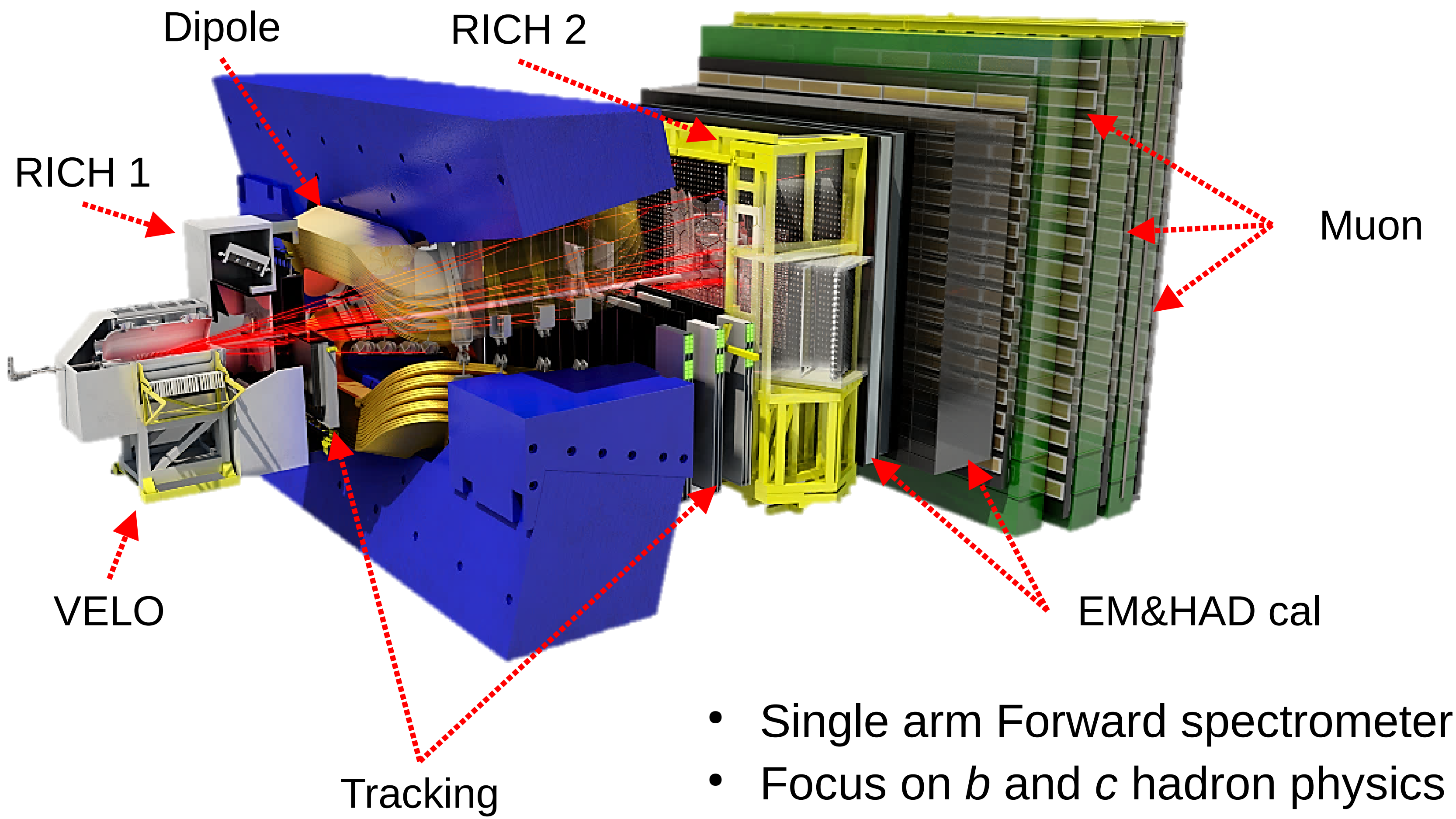
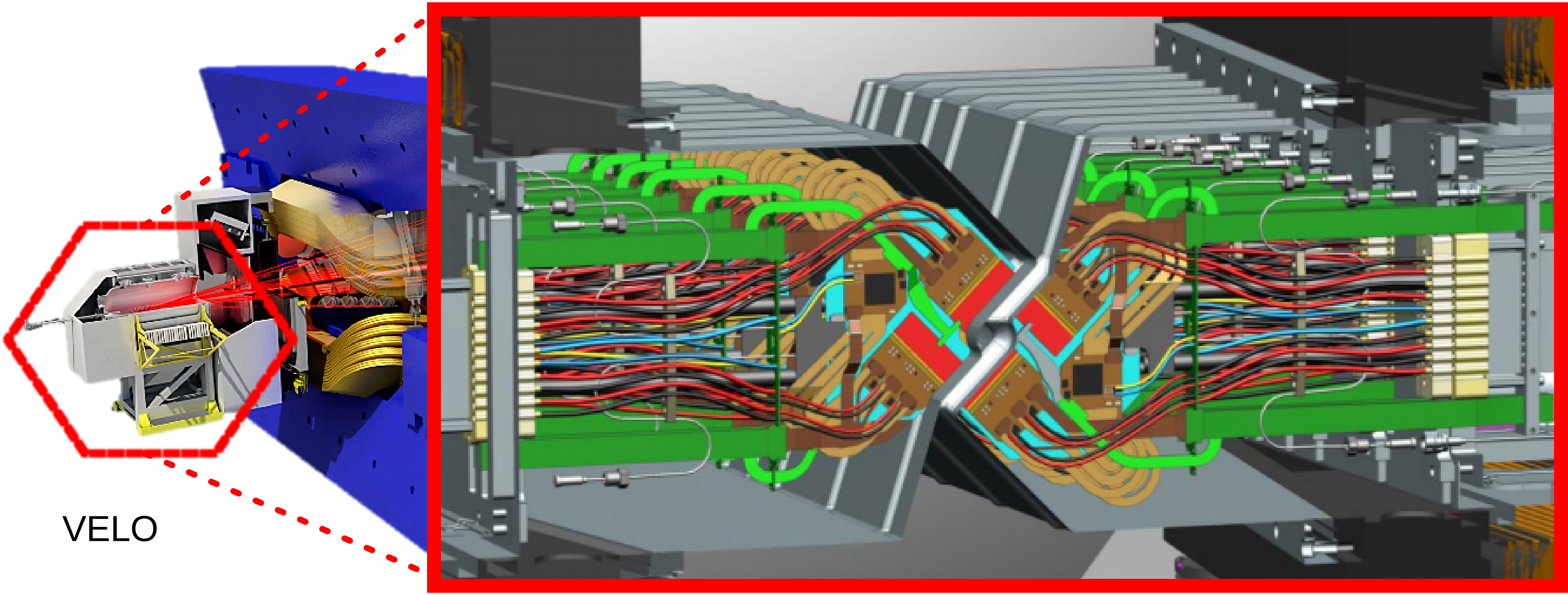
The LHCb Detector



- Single arm Forward spectrometer
- Focus on *b* and *c* hadron physics
- Studies rely on secondary vertices reconstruction
  - The Vertex Locator (VELO) plays a crucial role

The VErtexLOcator Upgrade

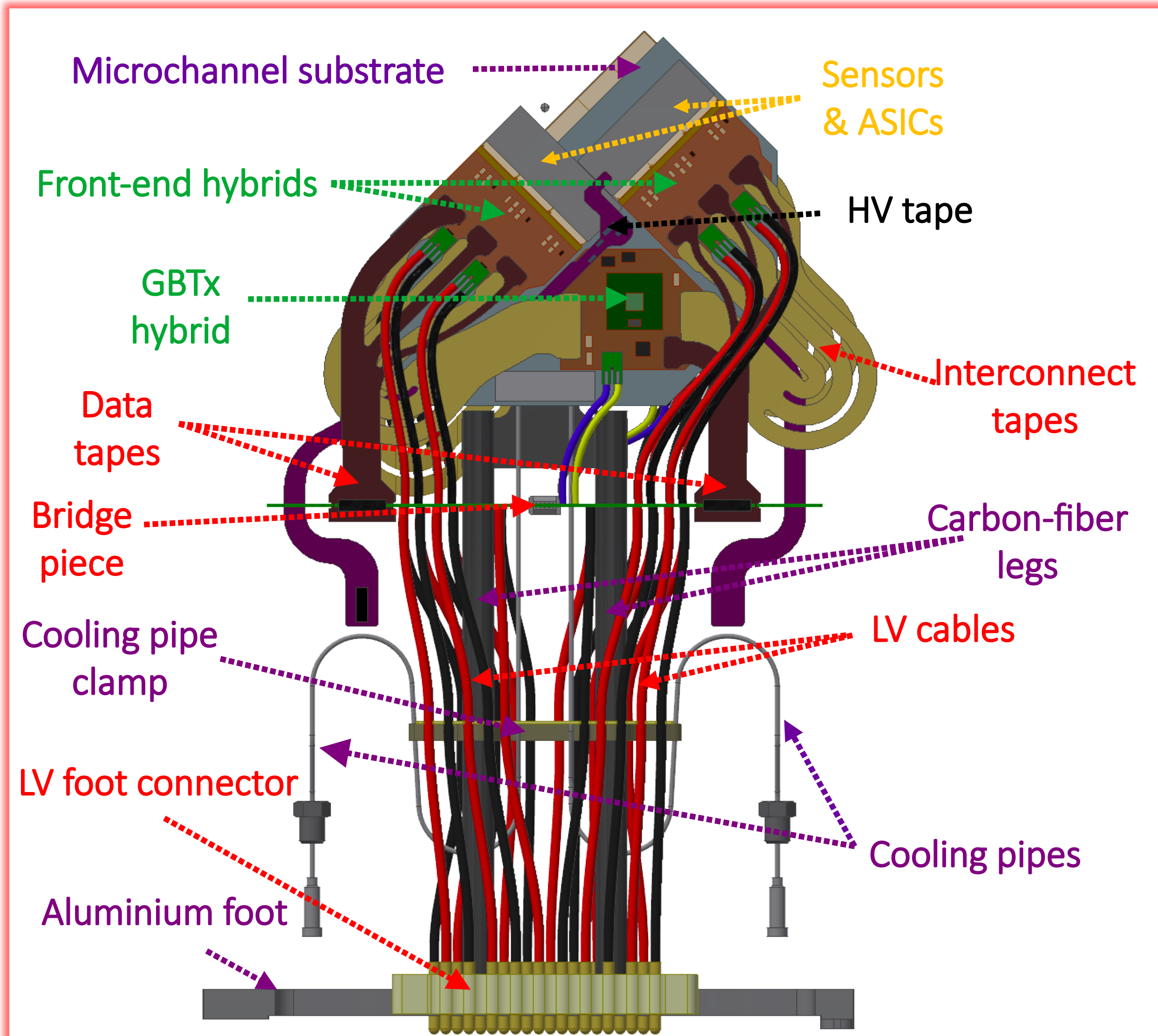


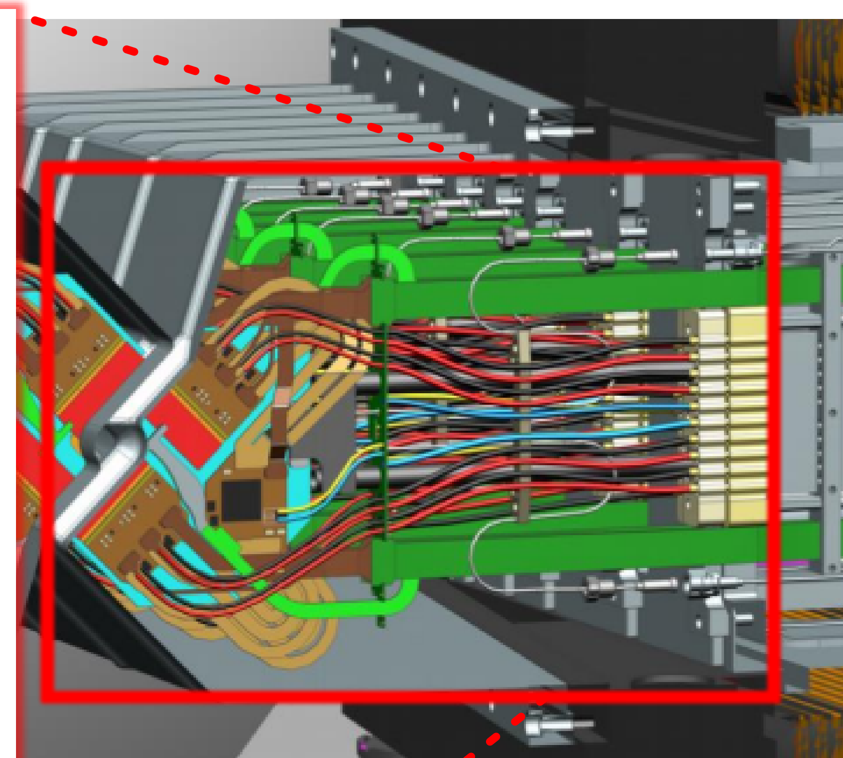
VErtex LOcator Upgrade:

- 52 modules divided in 2 retractable halves
- 5.1 mm close to the beam when closed
  - 5.2 mm in 2022 due to safety shims installed
- 4 Tiles (pixel sensor + ASIC) per module
  - 3 ASICs per Tile
  - 256x256 Pixel per ASIC, 55 × 55 μm^2 pixels

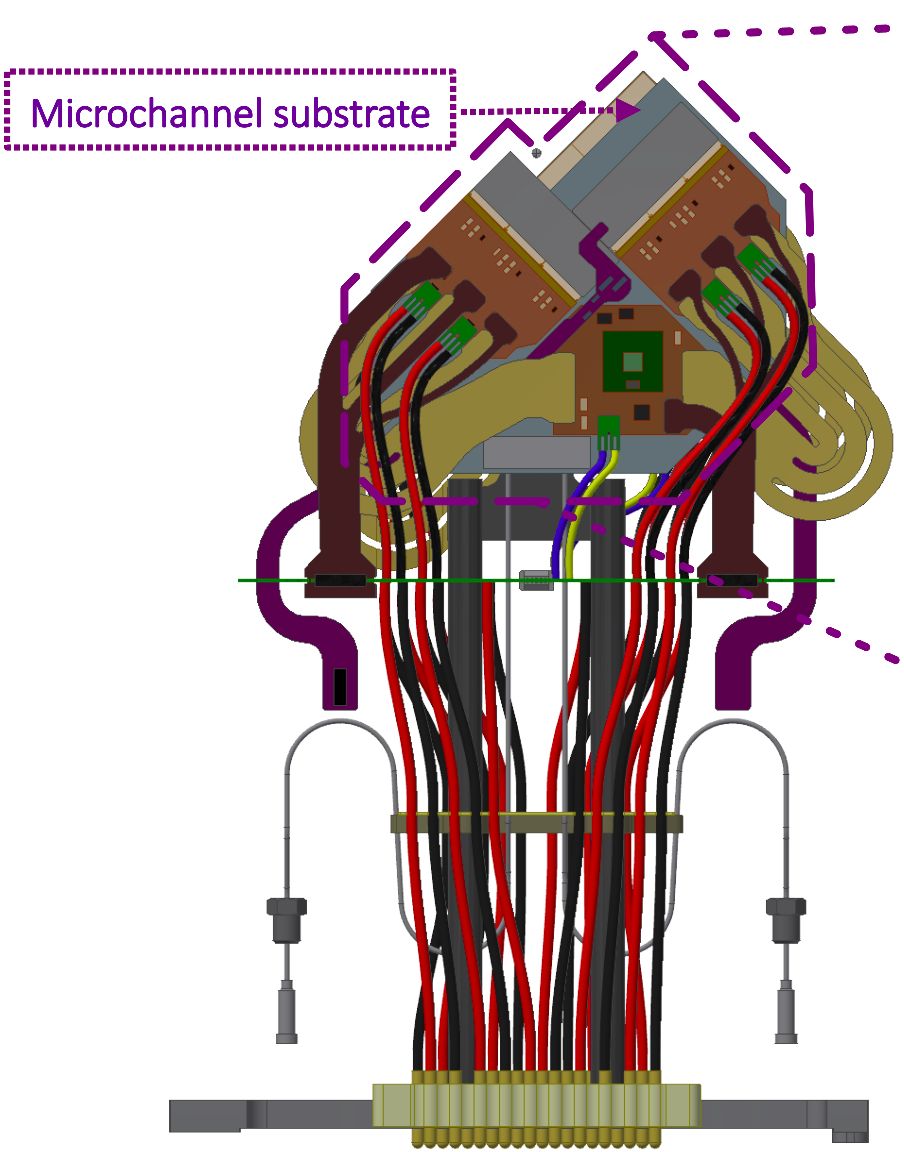
→ 41M pixels total

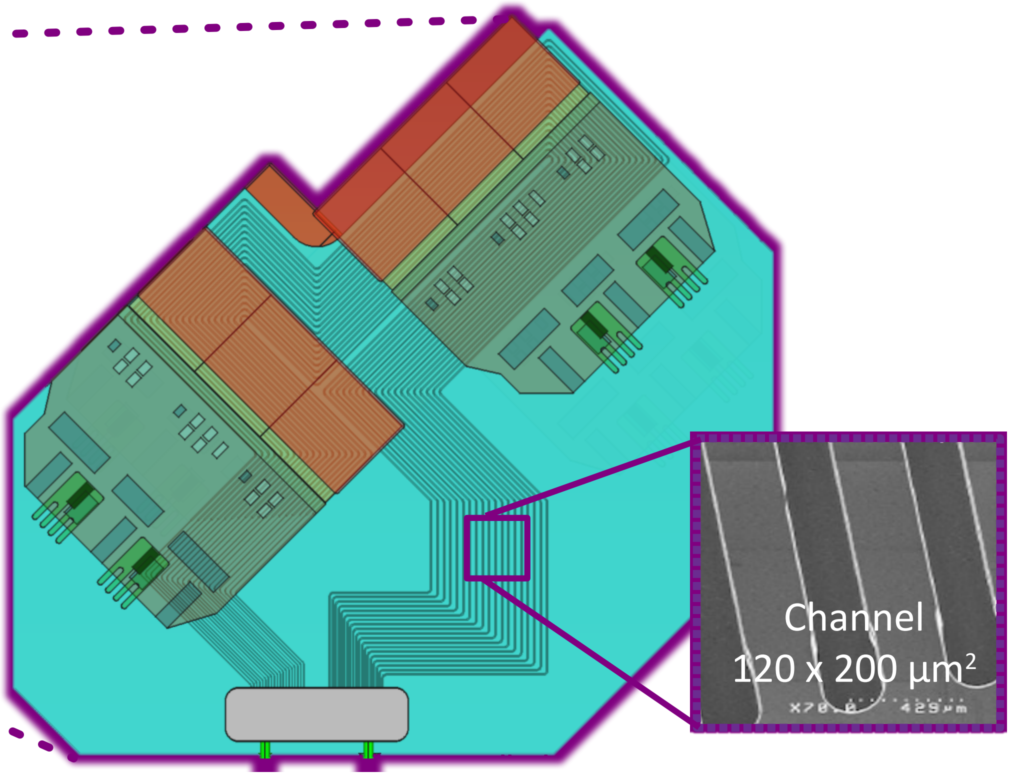
VELO Upgrade: overview





VELO Upgrade: Microchannel substrate

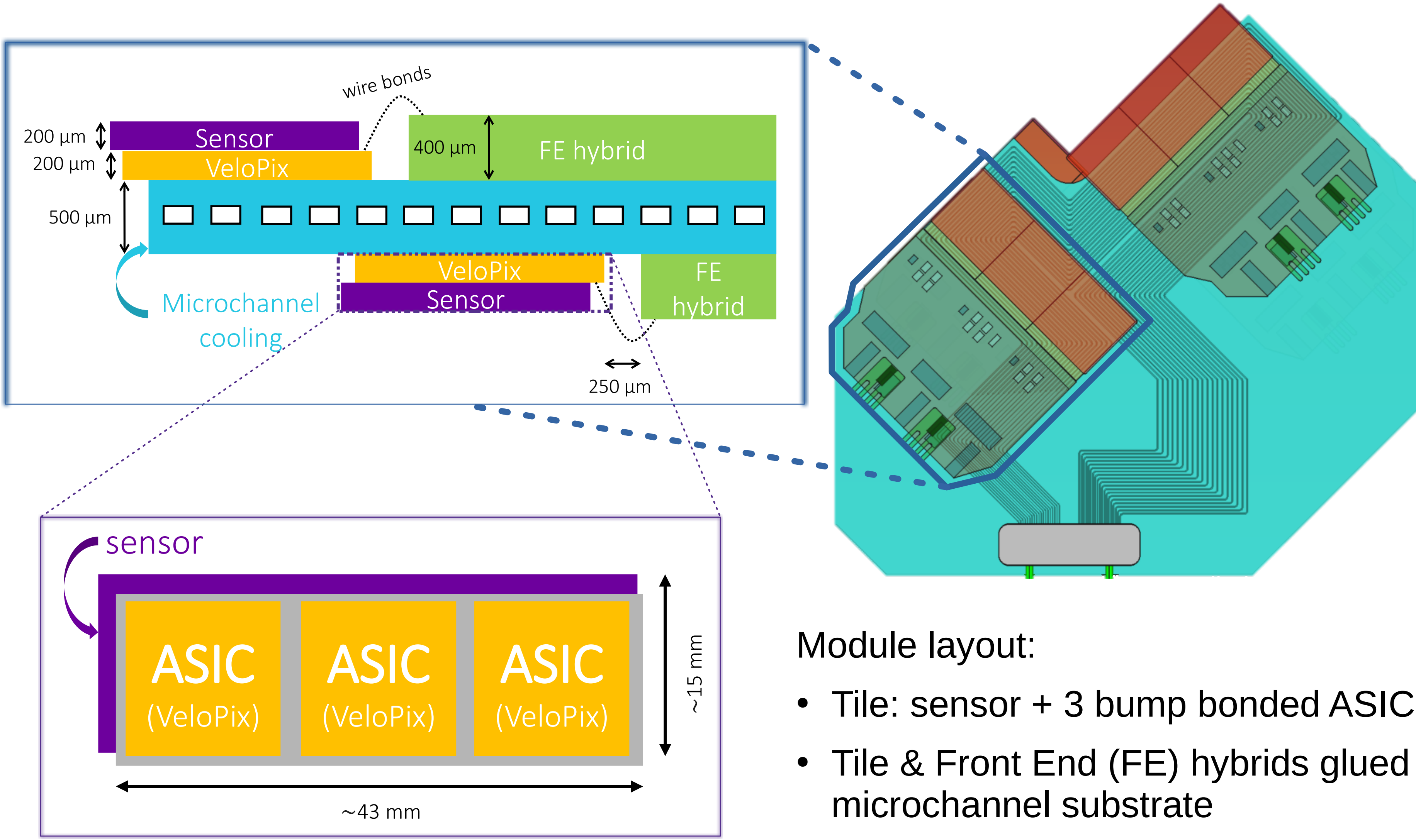




Microchannel silicon substrate:

- Provides structural support & cooling
  - 19 microchannels etched in the substrate
    - 140/240 μm from the chips
  - Uniform heat dissipation via evaporative CO_2
  - Dissipate up to 30W per module
  - Low budget material

VELO Upgrade: electronics layout



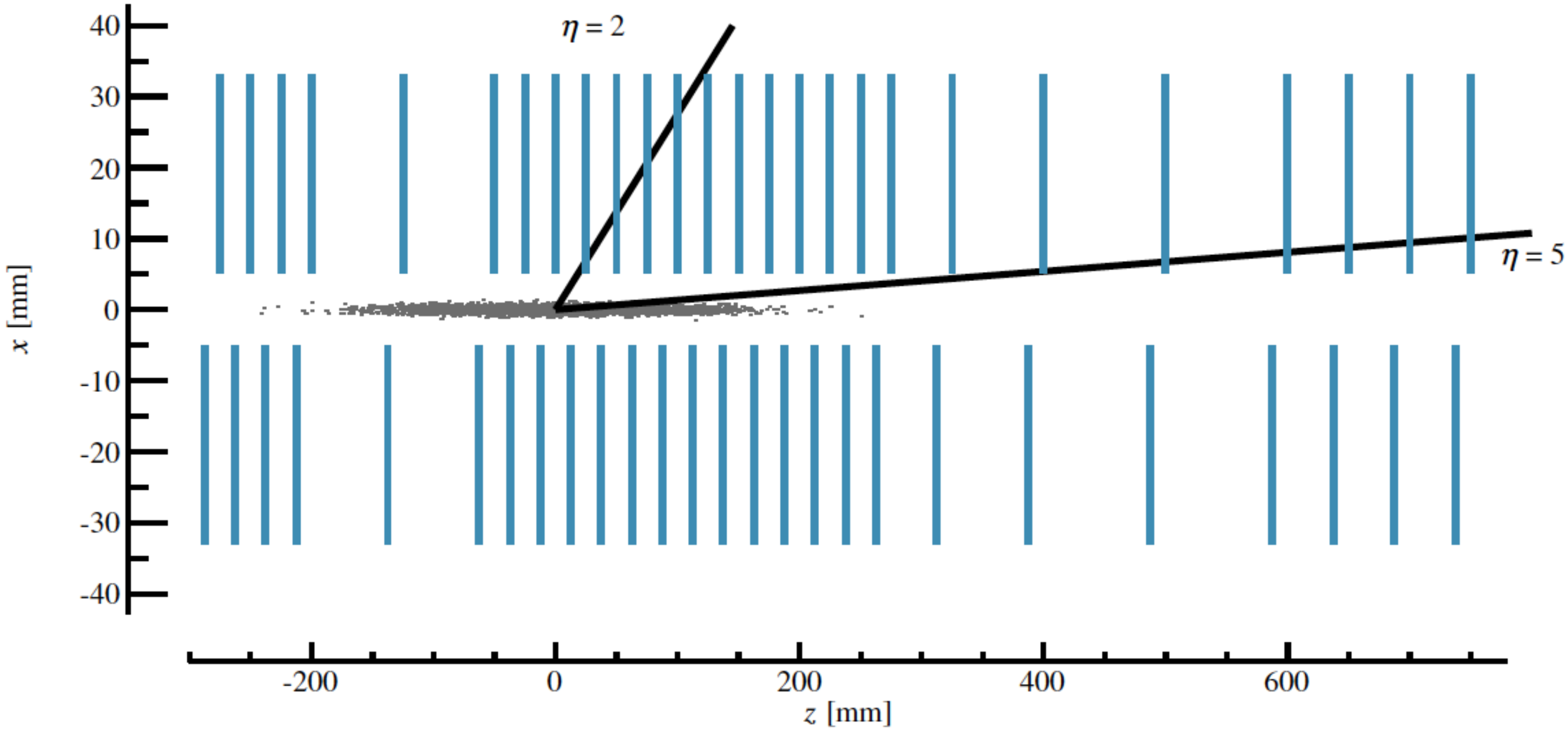
Module layout:

- Tile: sensor + 3 bump bonded ASICs
- Tile & Front End (FE) hybrids glued to microchannel substrate
- Microchannel path optimised to run beneath the tiles

VELO Upgrade: modules layout

Layout optimised to have tracks crossing at least 4 modules in detector acceptance:

- Modules distributed from Z ~ -300 to +800 mm
- Collisions around Z=0

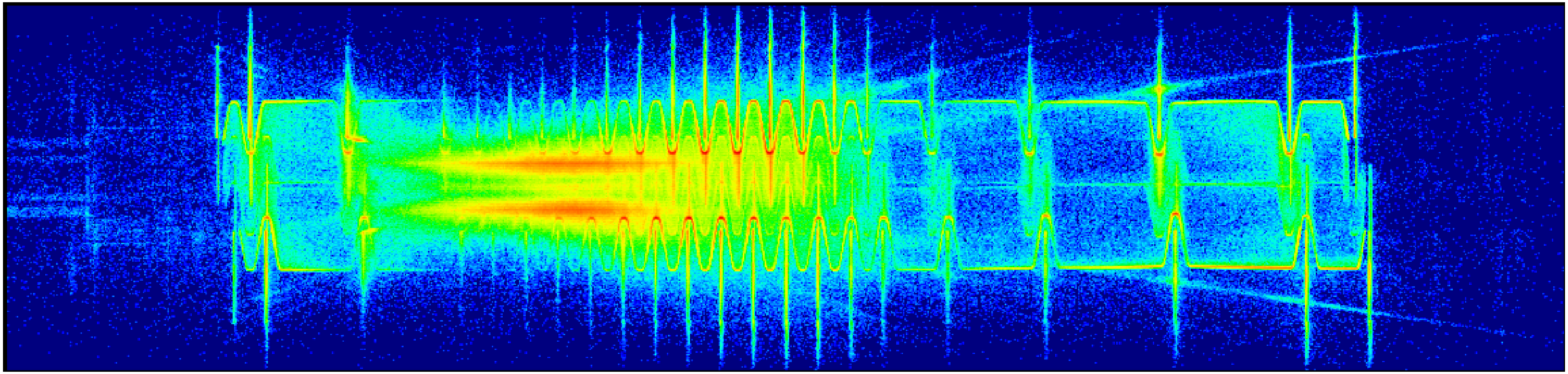


- Higher particle fluence expected to be higher near the interaction zone
  - Expect high radiation damage around Z~0 with lower impact on downstream modules

VELO Upgrade: Radiation Damage

Sensors expected to receive up to 8 x 10^{15} 1MeV n_{eq} /cm^2 during the detector lifetime:

- Max expected leakage current ~ 200 uA @ -20°C at 1000V at end of life
  - ~ 7nA for most irradiated pixel
- Irradiation profile strongly dependent on distance from interaction point
  - Expect a $\propto$ 1/R^2 curve

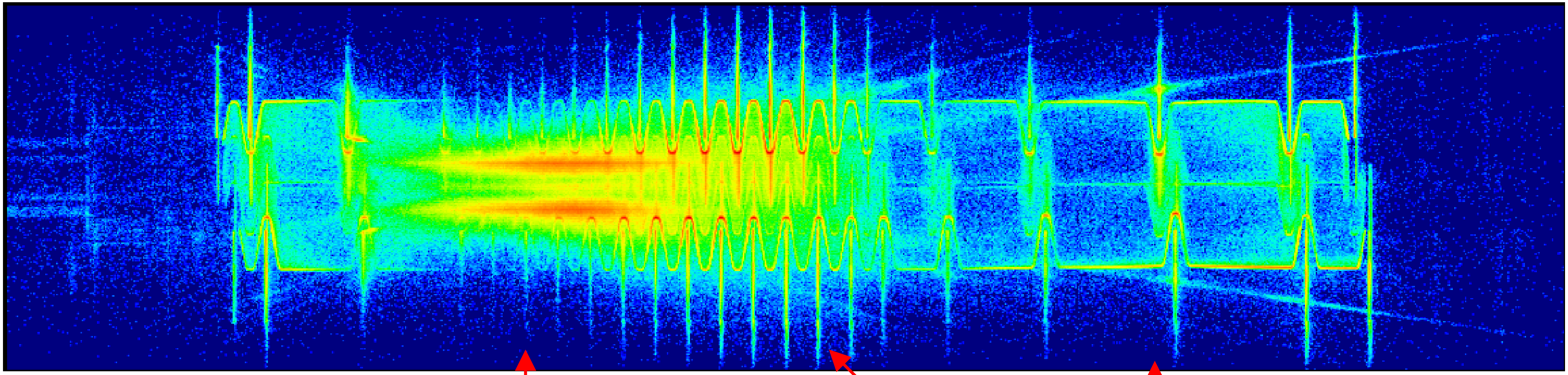


In this scenario Current vs Voltage (IV) scans of sensors offer a fundamental tool to monitor the evolution of radiation damage with fluence.

VELO Upgrade: Radiation Damage

Up to three IV scans taken for VELO modules at different delivered luminosities:

- 03 / 08 / 22 : 0.093 fb^{-1}, VELO Open
- 28 / 09 / 22 : 0.321 fb^{-1}, VELO Open
- 29 / 11 / 22 : 1.059 fb^{-1}, VELO both Open and Closed
  - 0.793 fb^{-1} VELO open
  - 0.264 fb^{-1} VELO closed

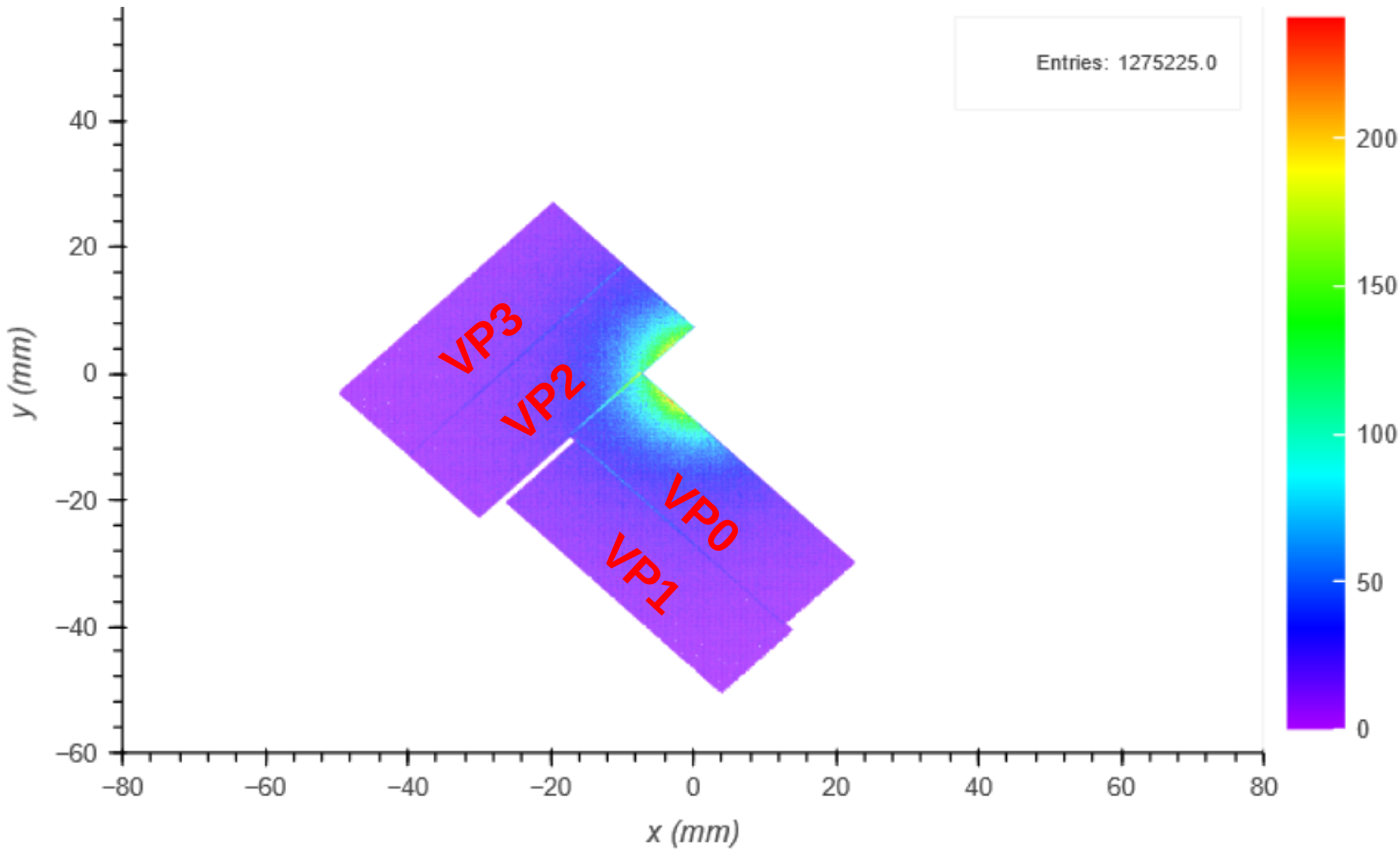


Will look at Module 15 (near interaction zone), 36 and 44 (downstream)

Tiles layout

Before looking at the IV scans: a quick reminder of the sensors layout:

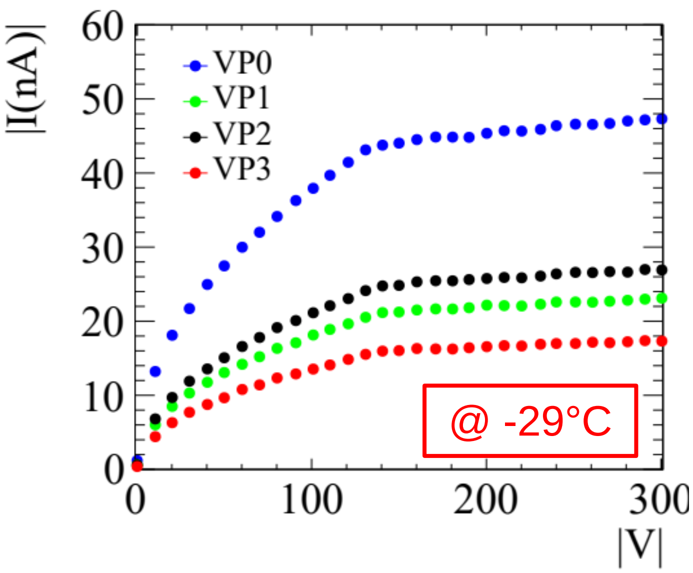
- VP0-2 closest tip at 5.2 mm from beam
- VP1-3 roughly at 22 mm



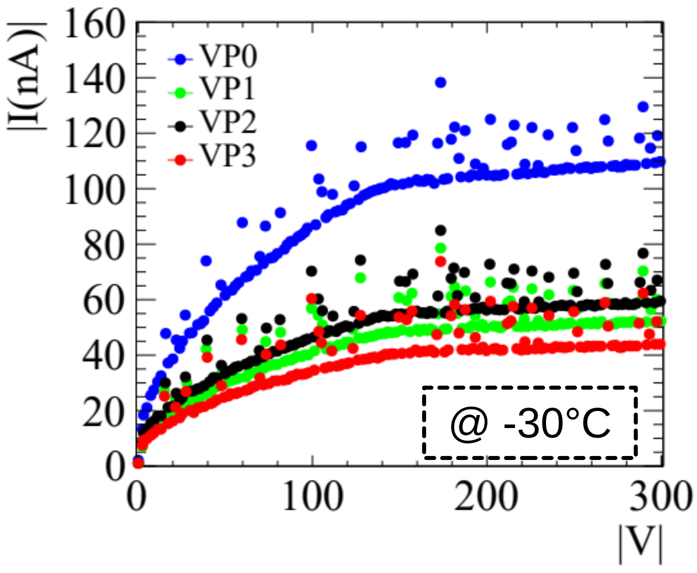
IV scans

IV scans for Module 44 (z=587.50)

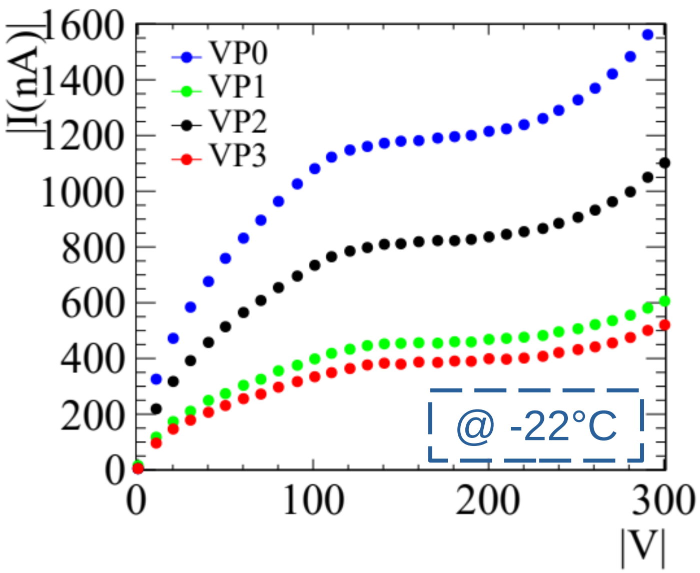
03 / 08 / 22 : 0.093 fb^{-1}



28 / 09 / 22 : 0.321 fb^{-1}



29 / 11 / 22 : 1.059 fb^{-1}



As scans have been taken at different temperatures, all data has been rescaled to -30°C using:

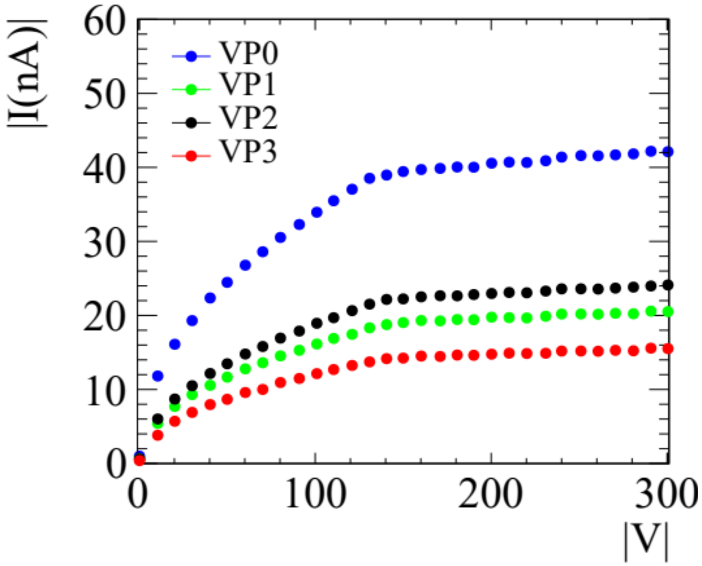
$$I(T)=I(T_{ref})\left(\frac{T}{T_{ref}}\right)^2 \exp\left(\frac{-E_g^{eff}}{2K_B}\left[\left(\frac{1}{T}\right)-\left(\frac{1}{T_{ref}}\right)\right]\right)$$

with E_g^{eff} = 1.21 eV and K_B = 8.617 10^{-5} eV / K

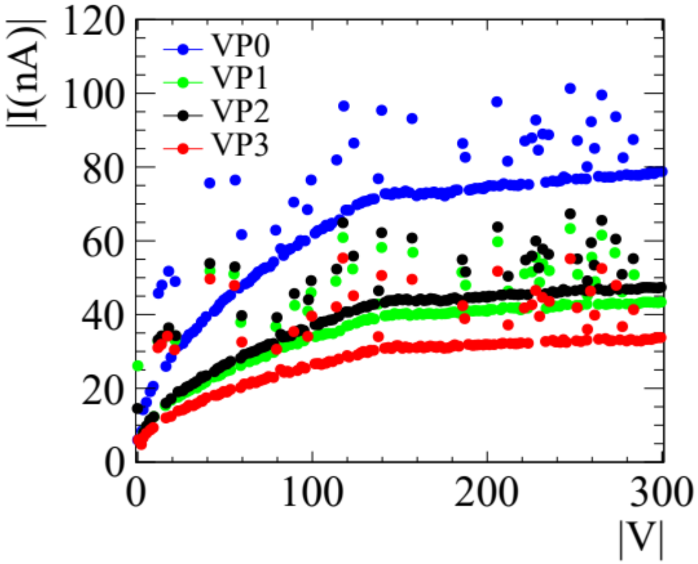
IV scans

IV scans for Module 44 (z=587.50)

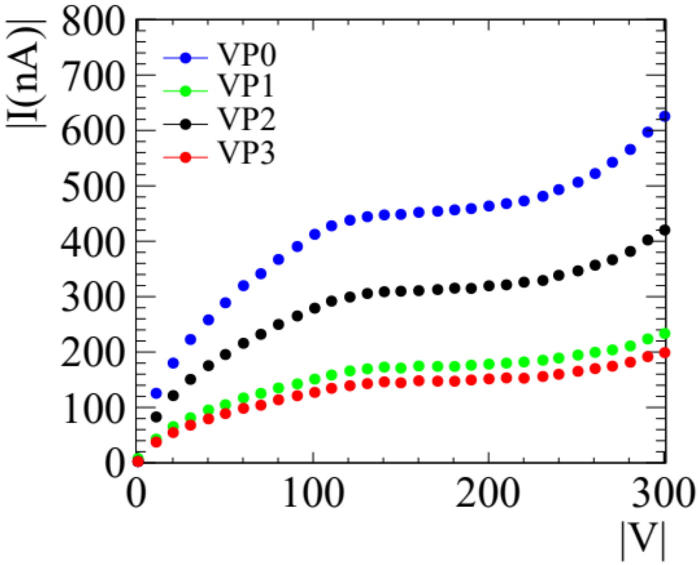
03 / 08 / 22 : 0.093 fb^{-1}



28 / 09 / 22 : 0.321 fb^{-1}



29 / 11 / 22 : 1.059 fb^{-1}



N.B.: all scans rescaled to -30°C

Some observations:

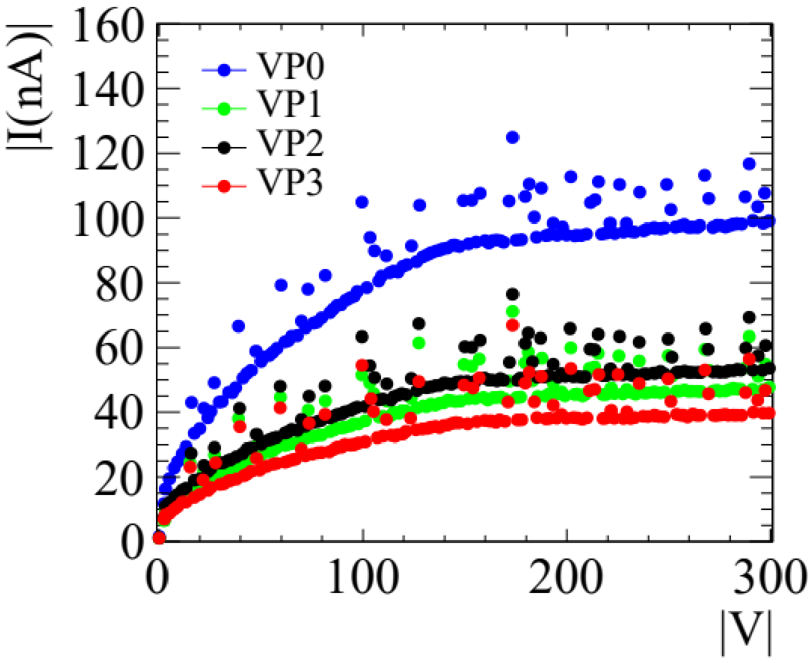
- Steep increase with luminosity when closed
- Sensors still fully depleted at 140V
- VP0 and VP2 (which are the closest to the beam) have higher current
- VP0 have higher current than VP2 (VP0 more overhanging)

IV scans

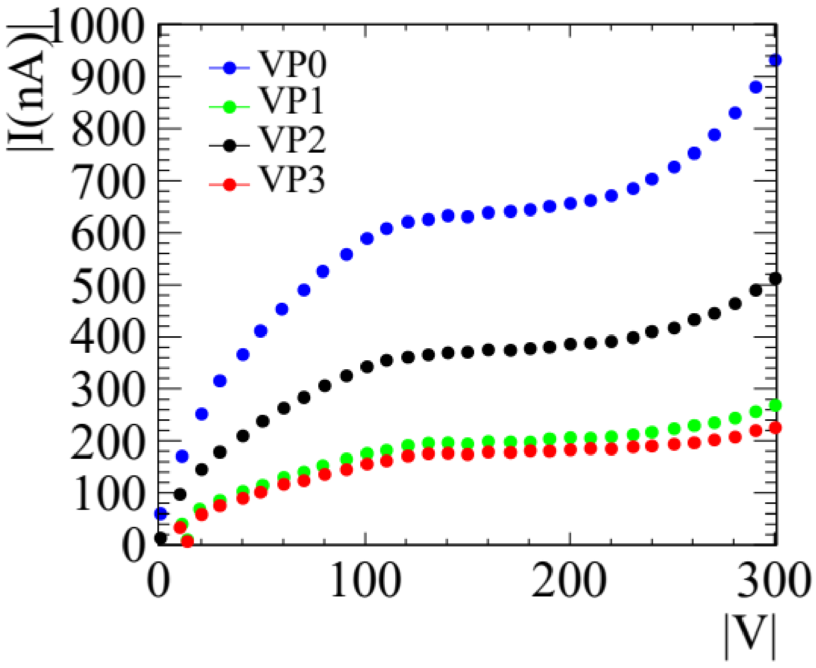
Scans for Module 36, closer to the interaction zone (z=262.50)

Only two points available this time

28 / 09 / 22 : 0.321 fb^{-1}



29 / 11 / 22 : 1.059 fb^{-1}



N.B.: all scans rescaled to -30°C

Some basic observations:

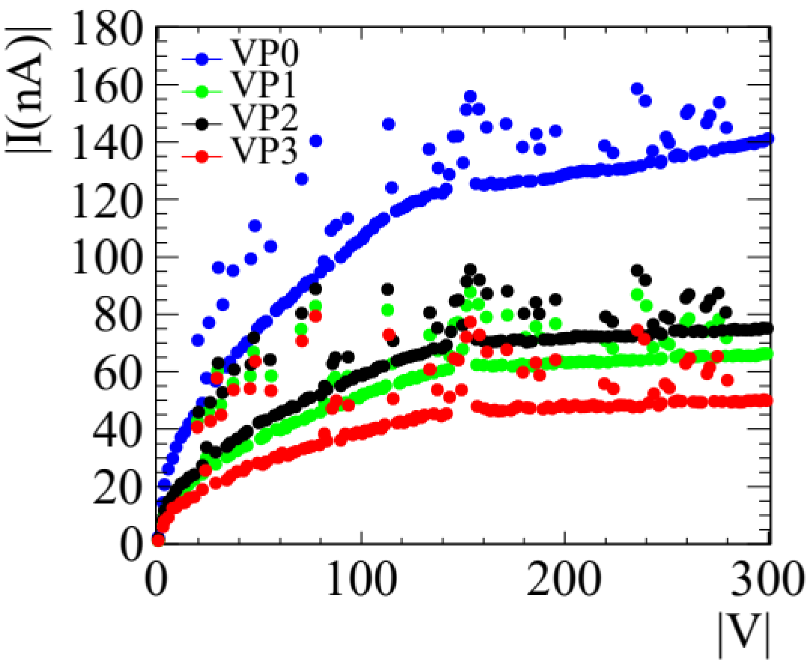
- Again 140V is full depletion
- VP0 and VP2 far higher current than VP1-3
- Again VP0 have higher current then VP2

IV scans

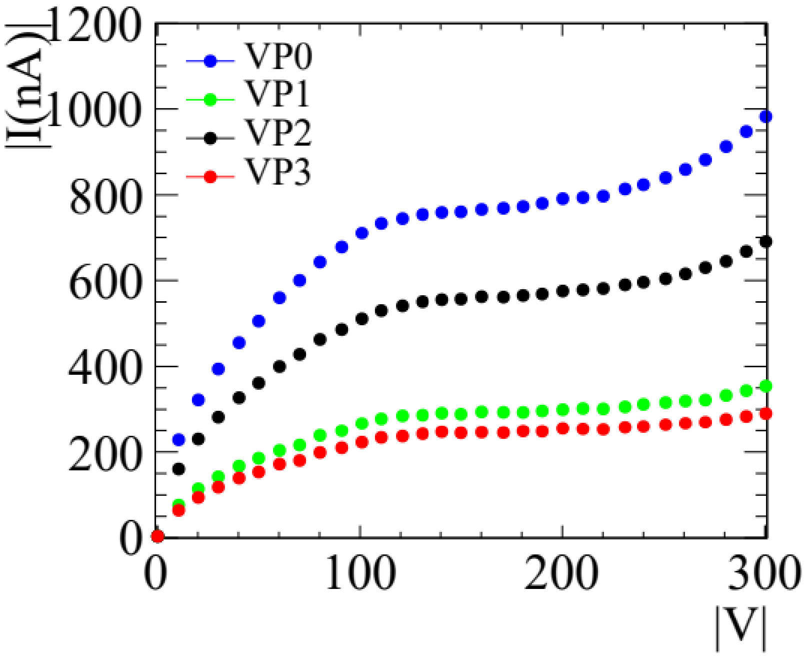
Let's look at an inner module: Module 15, near the interaction point (z=0)

Only two points available

28 / 09 / 22 : 0.321 fb^{-1}



29 / 11 / 22 : 1.059 fb^{-1}



N.B.: all scans rescaled to -30°C

Some basic observations:

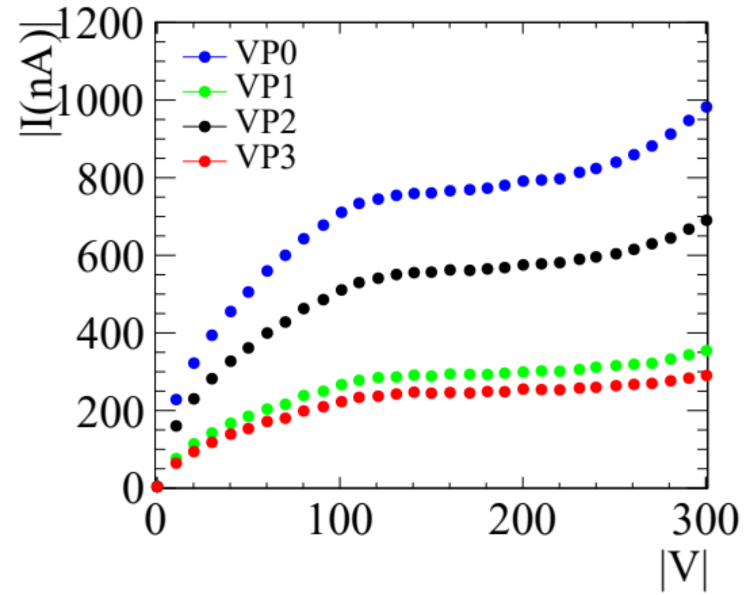
- Again 140V is full depletion
- VP0 and VP2 far higher current than VP1-3
- Again VP0 have higher current then VP2

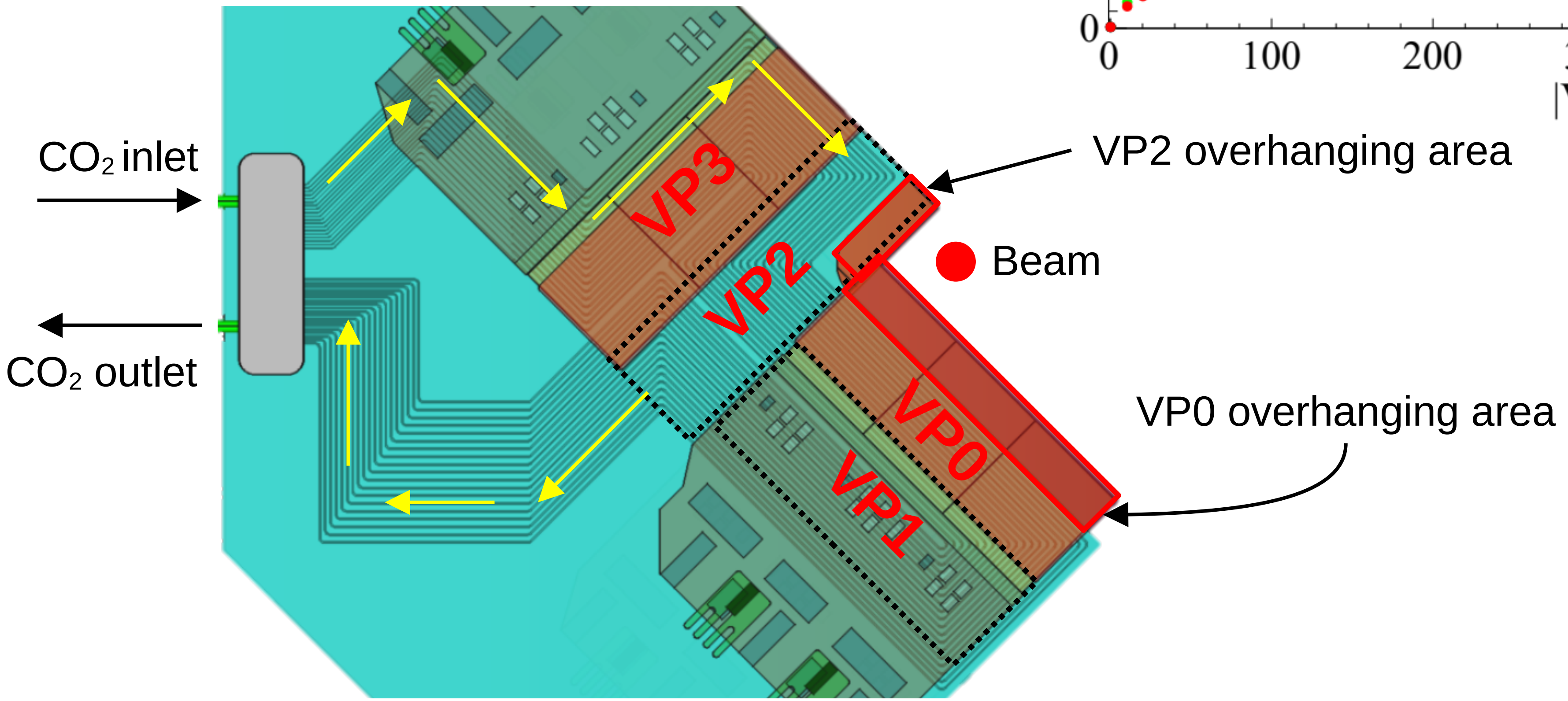
IV scans

$I_{VP0} > I_{VP2} > I_{VP1\text{-}3}$

Some considerations on the micro-channels path and tile positioning:

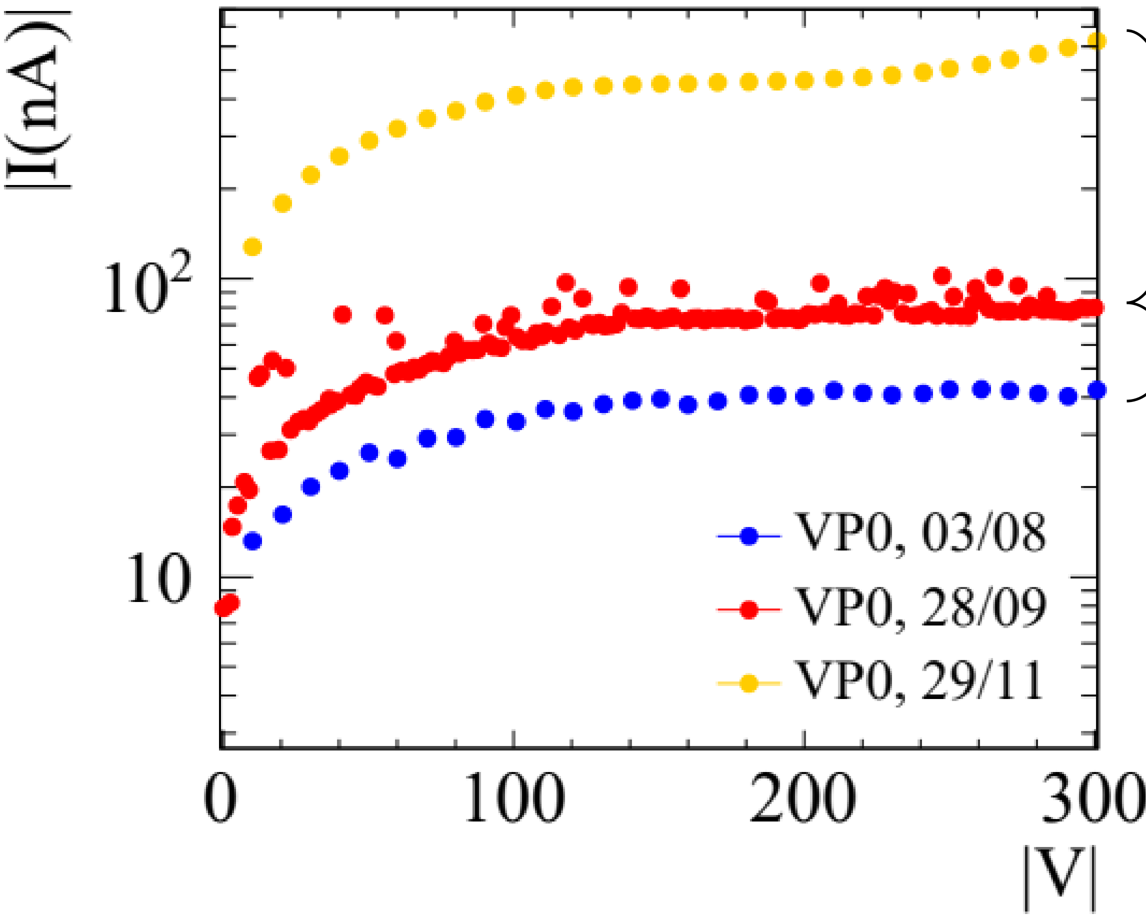
- VP0 and VP2 are the closest to the beam → higher irradiation
- VP0 more overhanging → overhanging area less efficiently cooled





IV scans

A closer look to Module 44 VP0 (tile closest to the beam)



Factor ~6 increase

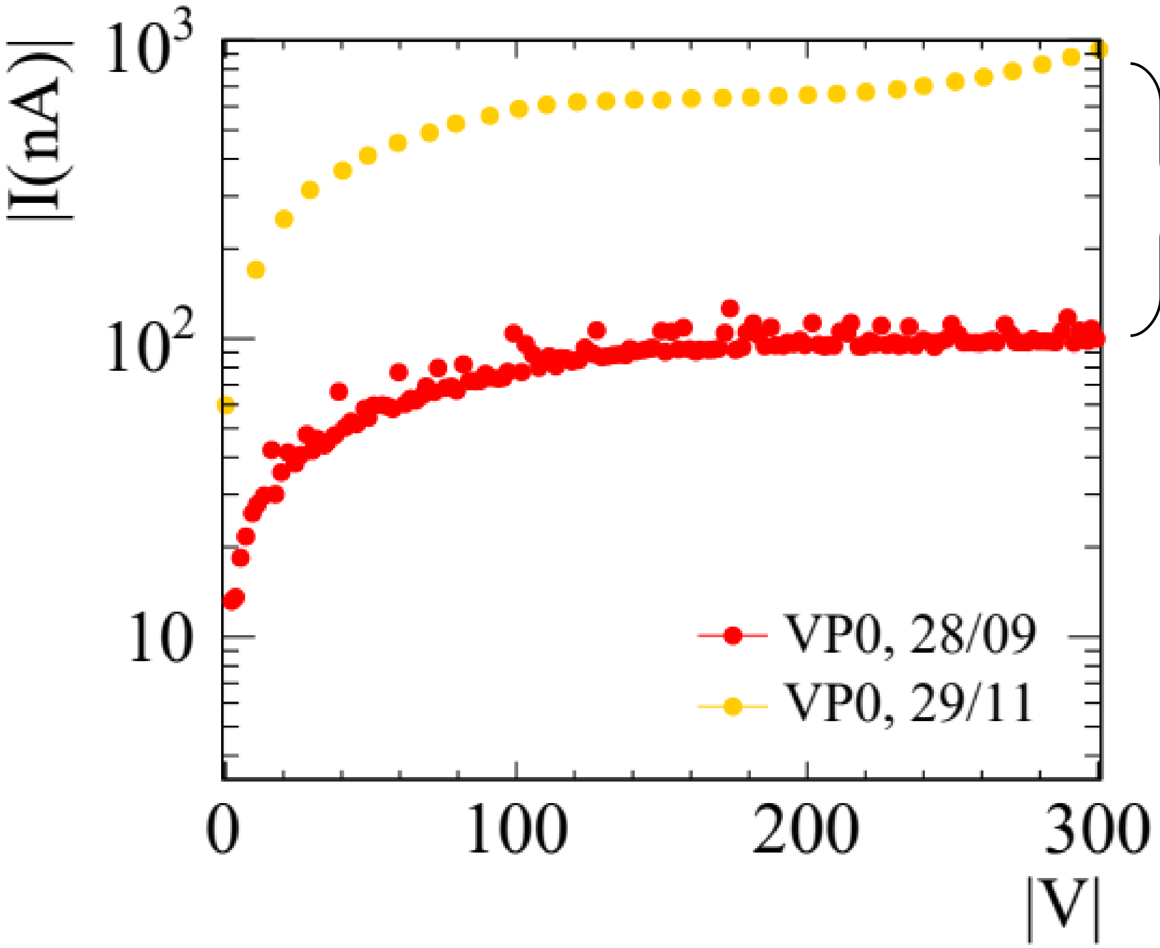
- ΔLumi ~ 0.7 fb^{-1}
- ~ 0.2 fb^{-1} of which with VELO closed

Factor ~2 increase

- ΔLumi ~ 0.2 fb^{-1}

IV scans

A closer look to Module 36 VP0

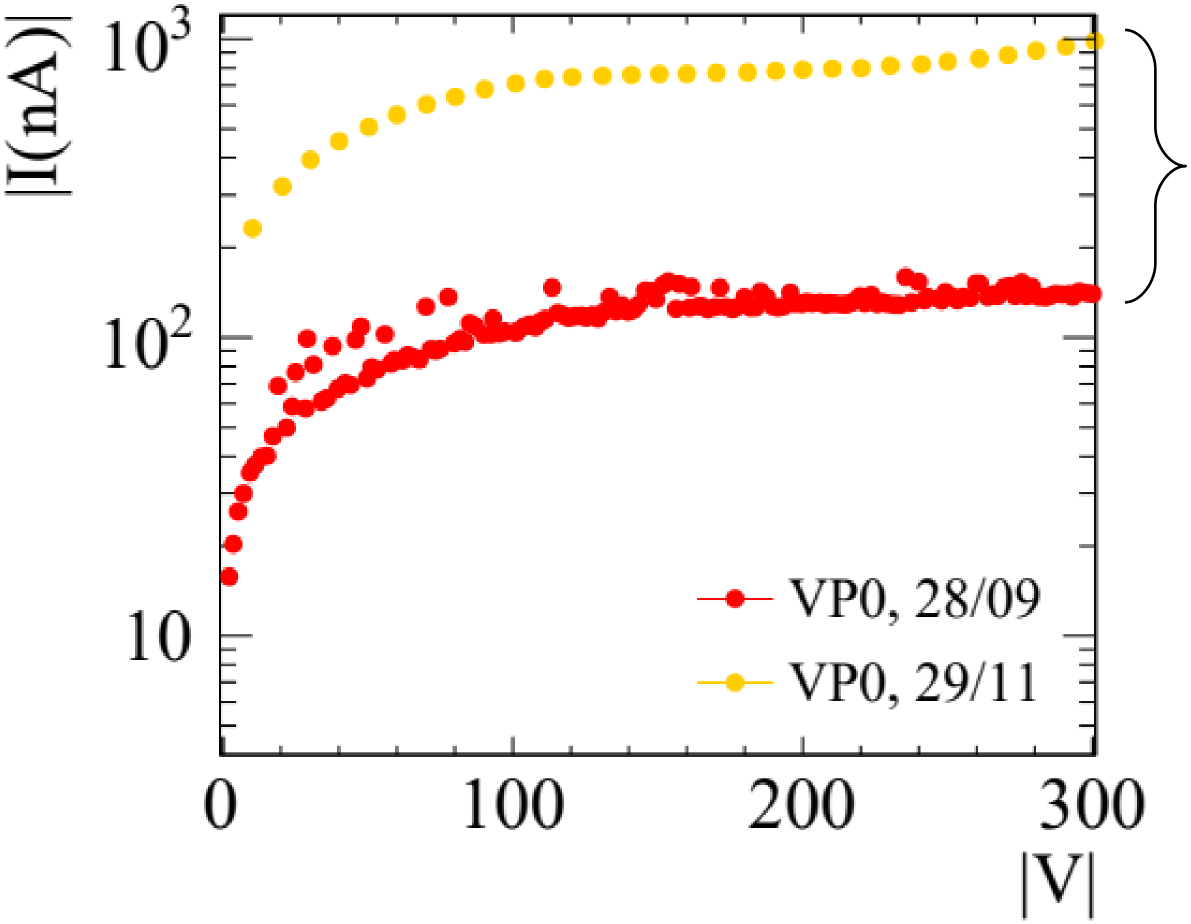


Factor ~6 increase

- ΔLumi ~ 0.7 fb^{-1}
- ~ 0.2 fb^{-1} of which with VELO closed

IV scans

A closer look to Module 15 VP0



Factor ~6 increase
- ΔLumi ~ 0.7 fb^{-1}
- ~ 0.2 fb^{-1} of which with VELO closed

Both the central and downstream Modules faced a 6-fold increase of leakage current. Is this expected?

Leakage current vs Fluence

Leakage current scales linearly with fluence:

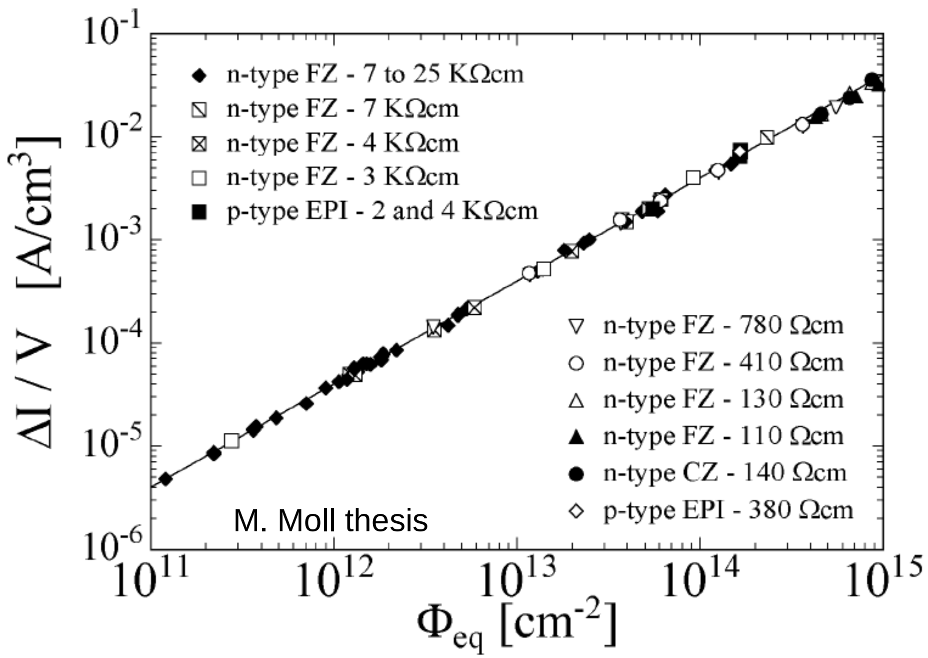
$$\Delta I/V = \alpha\,\phi$$

I = leakage current

Silicon volume

Proportionality factor

fluence

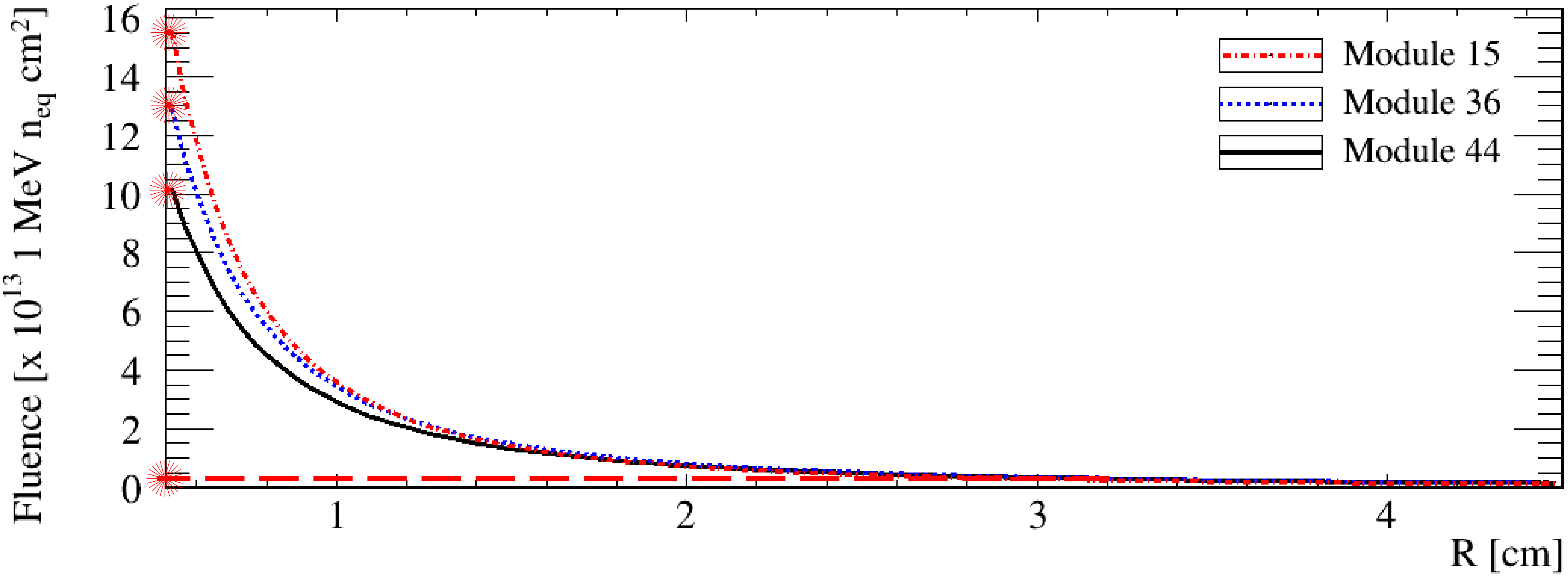


Fluence profiles

From TDR[1] reconstruct VP0 fluence curves for Module 44 (downstream), 36 and 15 (interaction zone).

Tile closest tip to the beam position (considering shims):

- VELO open: VP0 sits at 3.3 cm from the beam
- VELO closed: VP0 at 0.52 cm



For Module 44-36-15 one can estimate, per fb^{-1}:

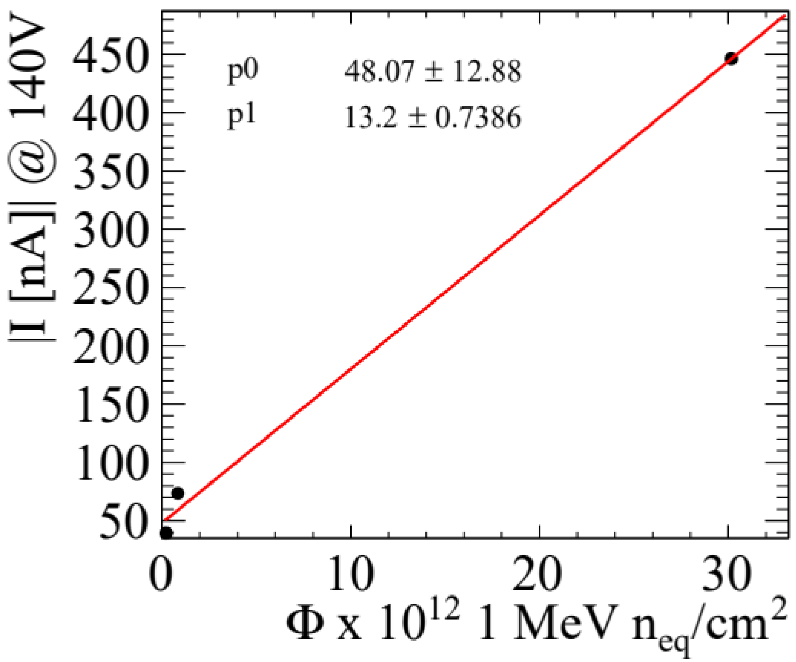
- Φ ~ 0.28 – 0.92 – 0.23 x 10^{13} n_{eq} / cm^2 when VELO open
- Φ ~ 10.6 – 37.8 – 16.2 x 10^{13} n_{eq} / cm^2 when VELO closed

Leakage current studies

Making the proportion between the estimated fluence per fb^{-1} and the delivered lumi we obtain, for Module 44 VP0:

- 03/08 -- > $\phi \sim 0.26 \times 10^{12}$ 1 MeV n_{eq}/cm^2
- 28/09 -- > $\phi \sim 0.89 \times 10^{12}$ 1 MeV n_{eq}/cm^2
- 29/11 -- > $\phi \sim 30.2 \times 10^{12}$ 1 MeV n_{eq}/cm^2 considering both open and close VELO

Take currents at 140V and check if the increase is linear



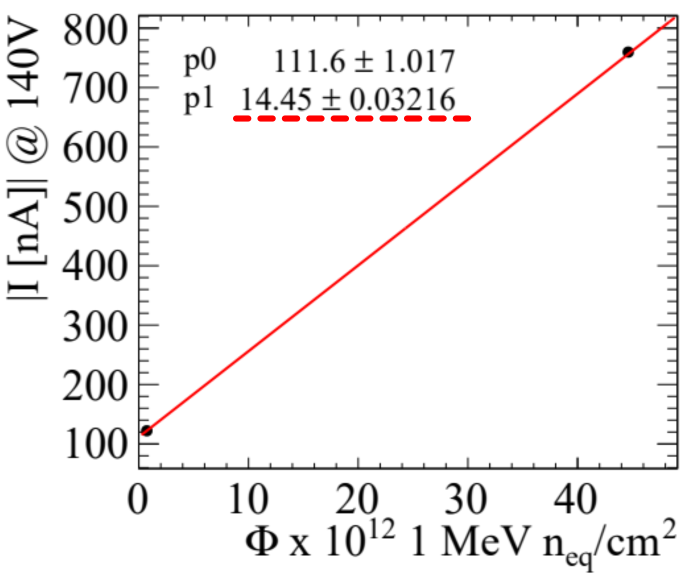
The fit shows that the increase is at first order linear, yet more points would be needed.

Leakage current studies

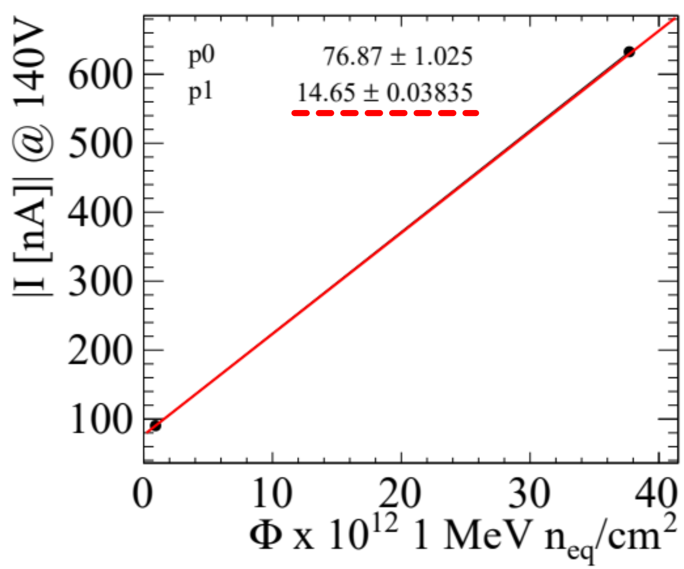
Repeat the process for Module 36 and 15 VP0:

- Plot currents at 140V vs ϕ, fit and compare slope (since only two points available)
- Compare slope with Module 44
- Check no anomalous current increase is occurring

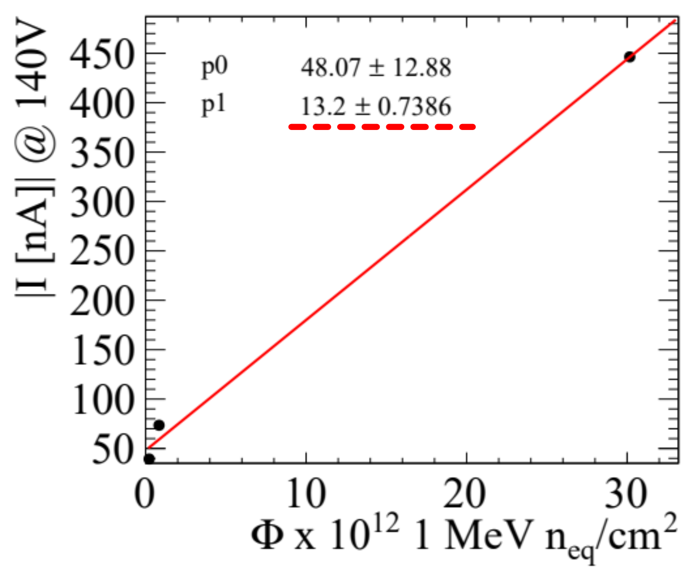
Module 15



Module 36



Module 44

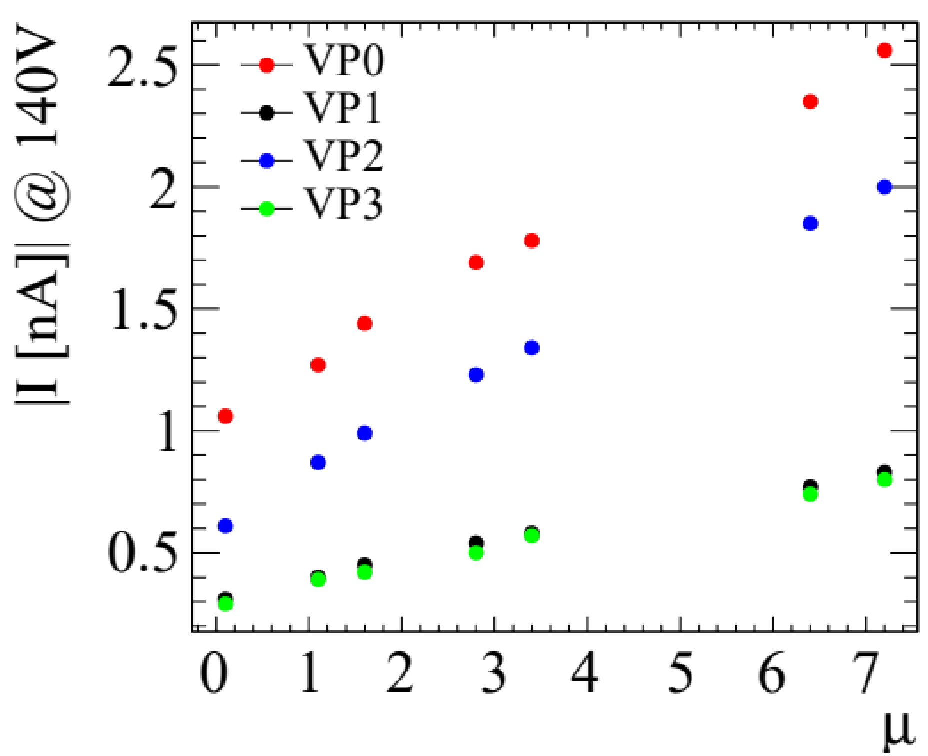


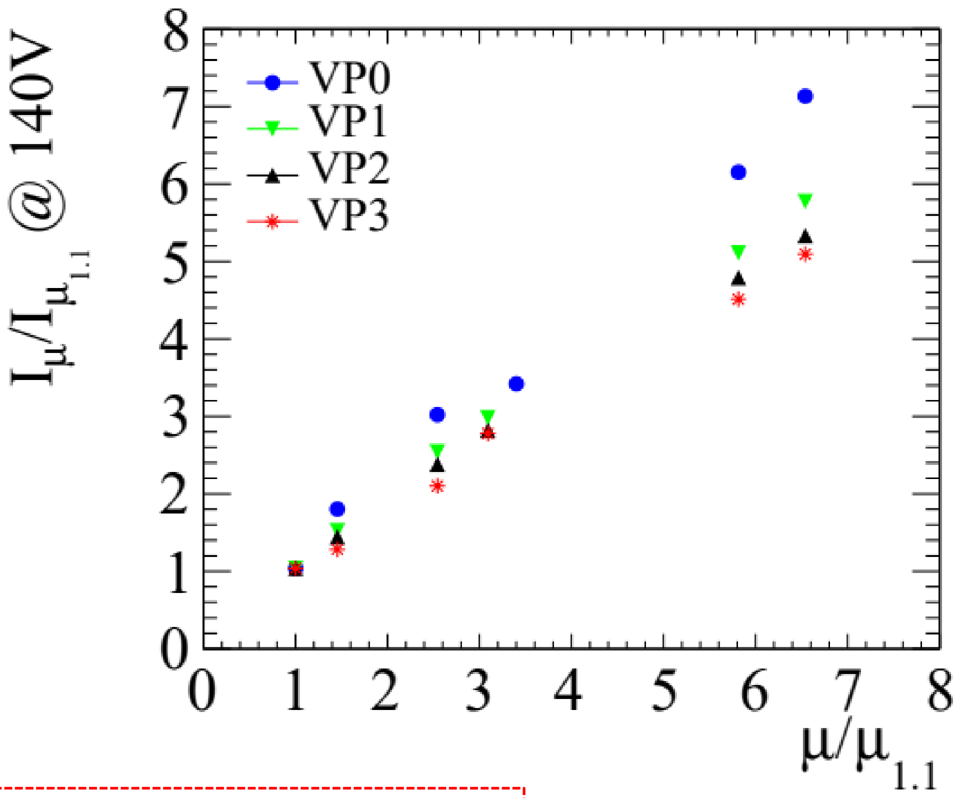
Radiation damage (slope) at first order is consistent across the whole detector.

Leakage current studies

Multiplicity (number of p-p interactions per bunch crossing) scan:

- Check that the current linearly increase with the multiplicity
- μ scan done on 25/11/22.
- Scanned μ target values: 0.1, 1.1, 1.6, 2.8, 3.4, 6.4, 7.2
- Used Module 18, z = 262.50





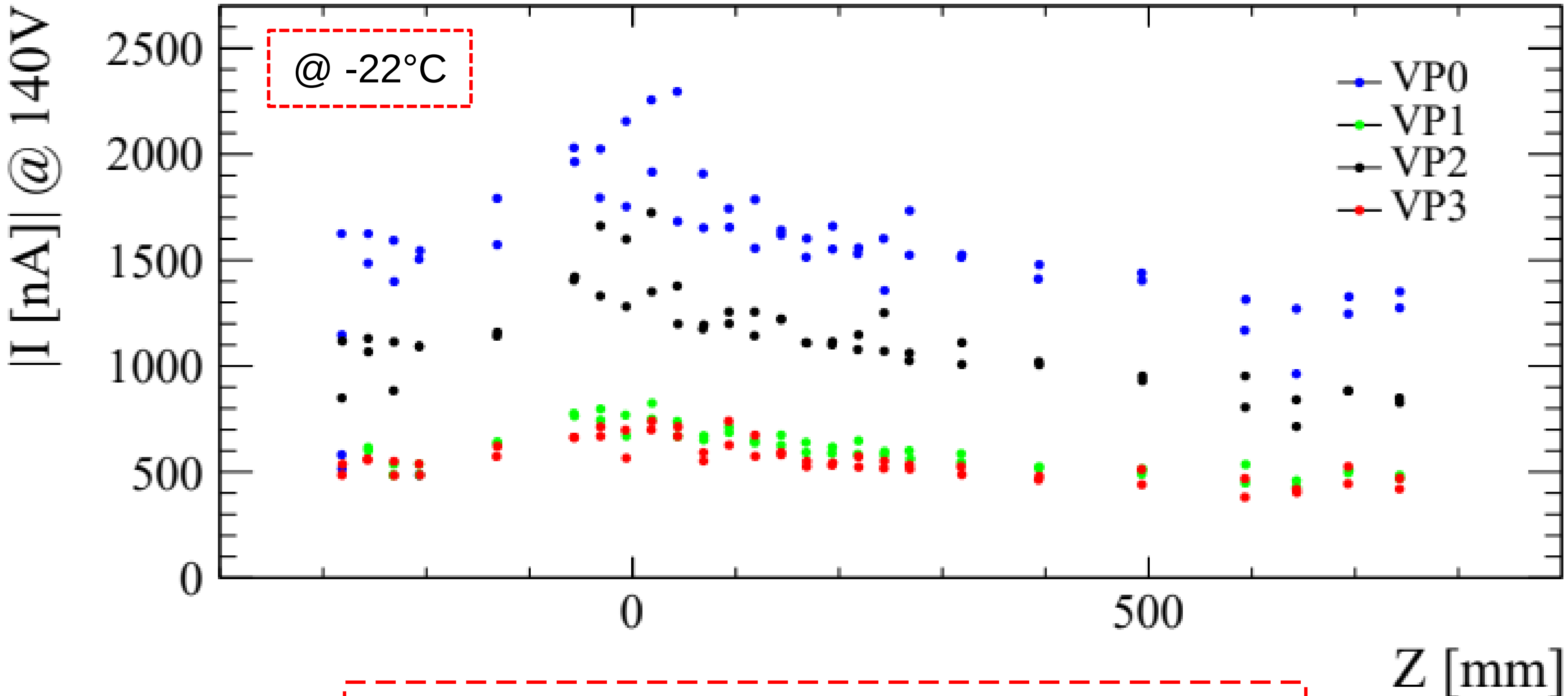
The increase is indeed linear.

Leakage current studies

Leakage current vs Z: a global view at end of 2022 data taking

Plot the I vs Z for each tile of each module @ 140 V:

- Check central modules have higher current
- Generally VP0 and VP2 expected to have more leakage current



- Central regions are “hotter” as expected
- VP0 and VP2 again show higher leakage current

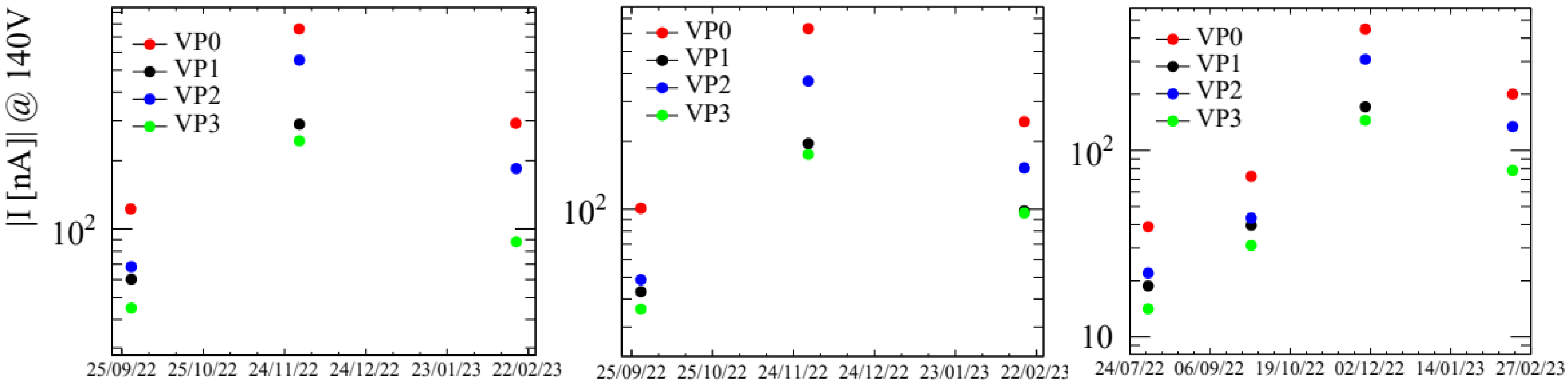
Annealing

VELO has gone through 35 days 23°C, which gives the chance to assess the impact of (any) beneficial annealing occurring:

- Beneficial annealing expected to remove part of radiation damage
  - Expect decrease in leakage current

Plot I @ 140V vs time to assess annealing impact on leakage currents

Module 15 Module 36 Module 44

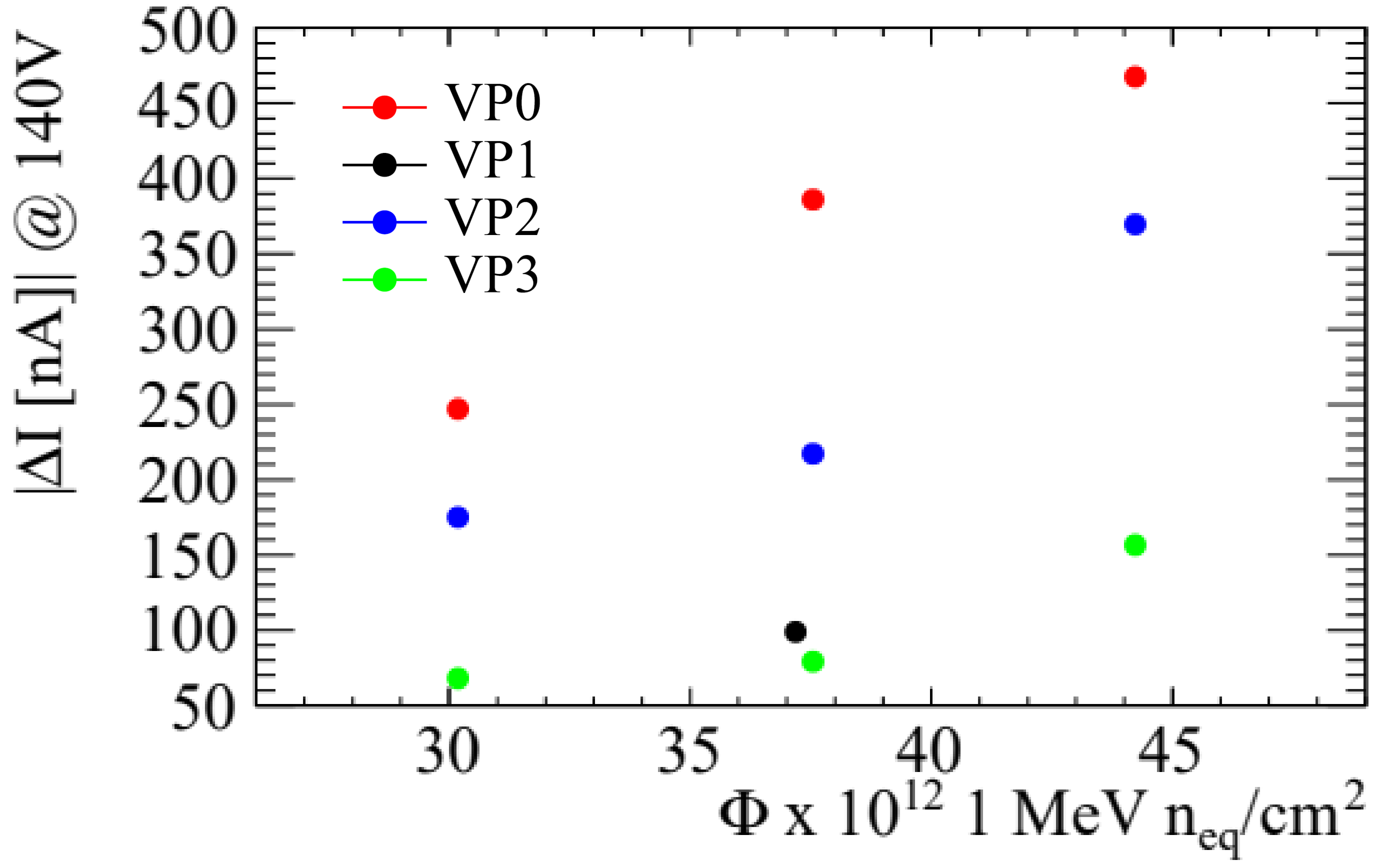


- Current reduction of ~ $O(10^2)$ nA for most irradiated tiles
  - Down to ~ $O(10)$ nA in less irradiated tiles
- Once again VP0 and VP2 show higher currents

Annealing

Visualise annealing impact plotting tiles $|\Delta I| = |I_{after} - I_{before}|$ annealing @ 140V vs ϕ

- Use Module 15, 36, 44 to assess trend across the detector

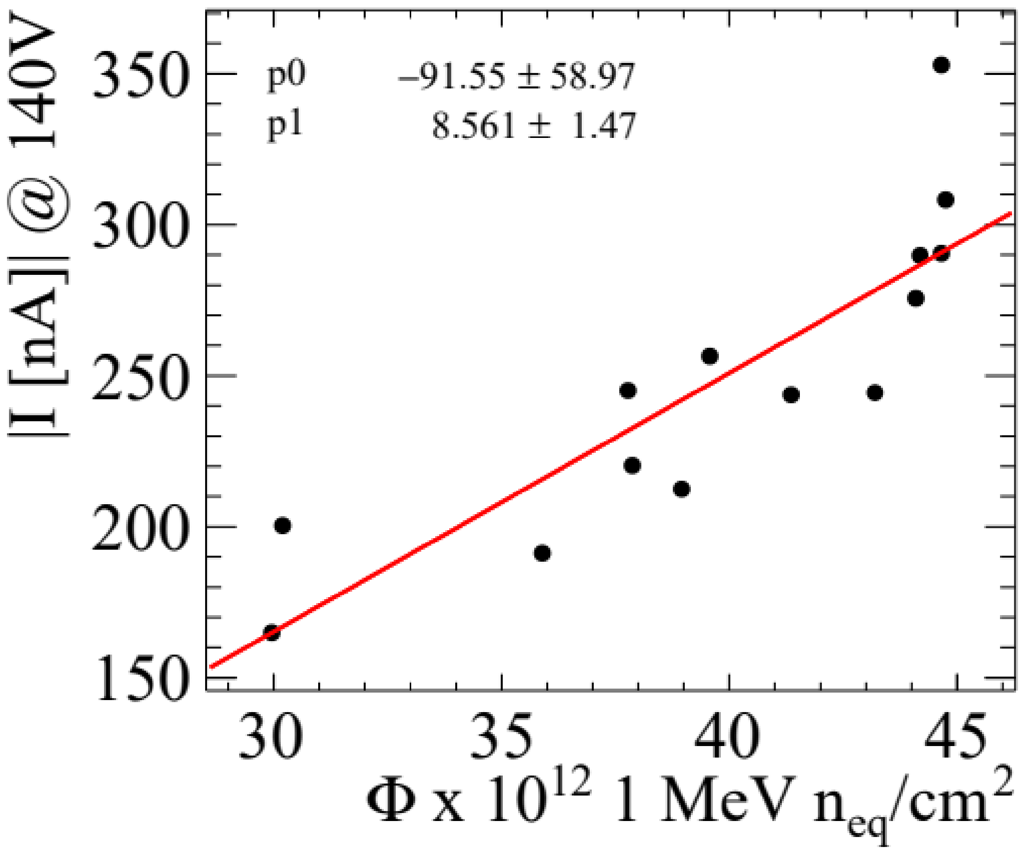


Beneficial annealing was most powerful in higher irradiation tiles

Annealing

Finally, check the increase in leakage current with fluence after annealing

- Use currents @140V from Module 0, 6, 10, 25, 16, 18, 22, 26, 30, 34, 38, 44, 50



Increase linear at first order as expected.
Data at higher fluences needed for more accurate assessment.

Conclusions

First assessment of radiation damage returns a coherent picture:

- Increase in current linear with increase in fluence
- Tile current scales with multiplicity
- Global I vs Z in line with expectations
- Effect of beneficial annealing resulted in sizeable decrease of leakage current
- I vs ϕ plot after annealing confirms radiation damage linearly increases with fluence

References

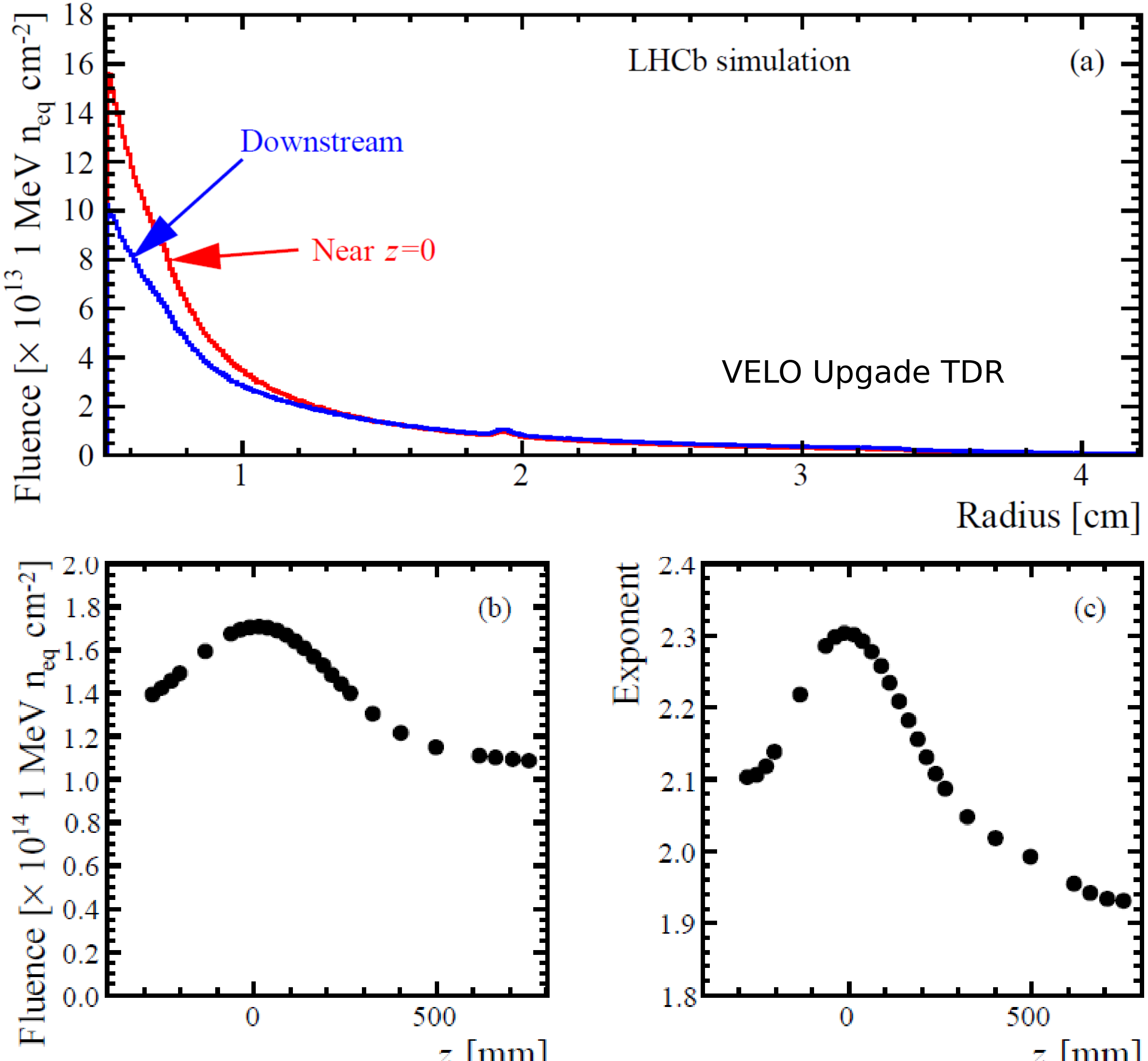
[1] LHCB-TDR-013

Backup

Fluence profiles

Estimation of fluence curves for fb^{-1} usind TDR simulations:

- For VP0 (tile closest to the beam) expect a $A\ R^{-k}$ shape



HV status

Annealing: we have the opportunity to observe the effect of beneficial annealing on the sensors after 35 days at 23°C

- VP0 and VP2 still with higher currents
- Current decrease Mod15
  - VP0 467 nA
  - VP1 no data
  - VP2 369 nA
  - VP3 156 nA

- VP0 and VP2 still with higher currents
- Current decrease Mod22
  - VP0 488 nA
  - VP1 194 nA
  - VP2 361 nA
  - VP3 163 nA

- VP0 and VP2 still with higher currents
- Current decrease Mod44
  - VP0 246 nA
  - VP1 no data
  - VP2 174 nA
  - VP3 67 nA

- VP0 and VP2 still with higher currents
- Current decrease Mod36
  - VP0 386 nA
  - VP1 98 data
  - VP2 174 nA
  - VP3 79 nA

To summarise, beneficial annealing was most powerful in higher irradiation tiles