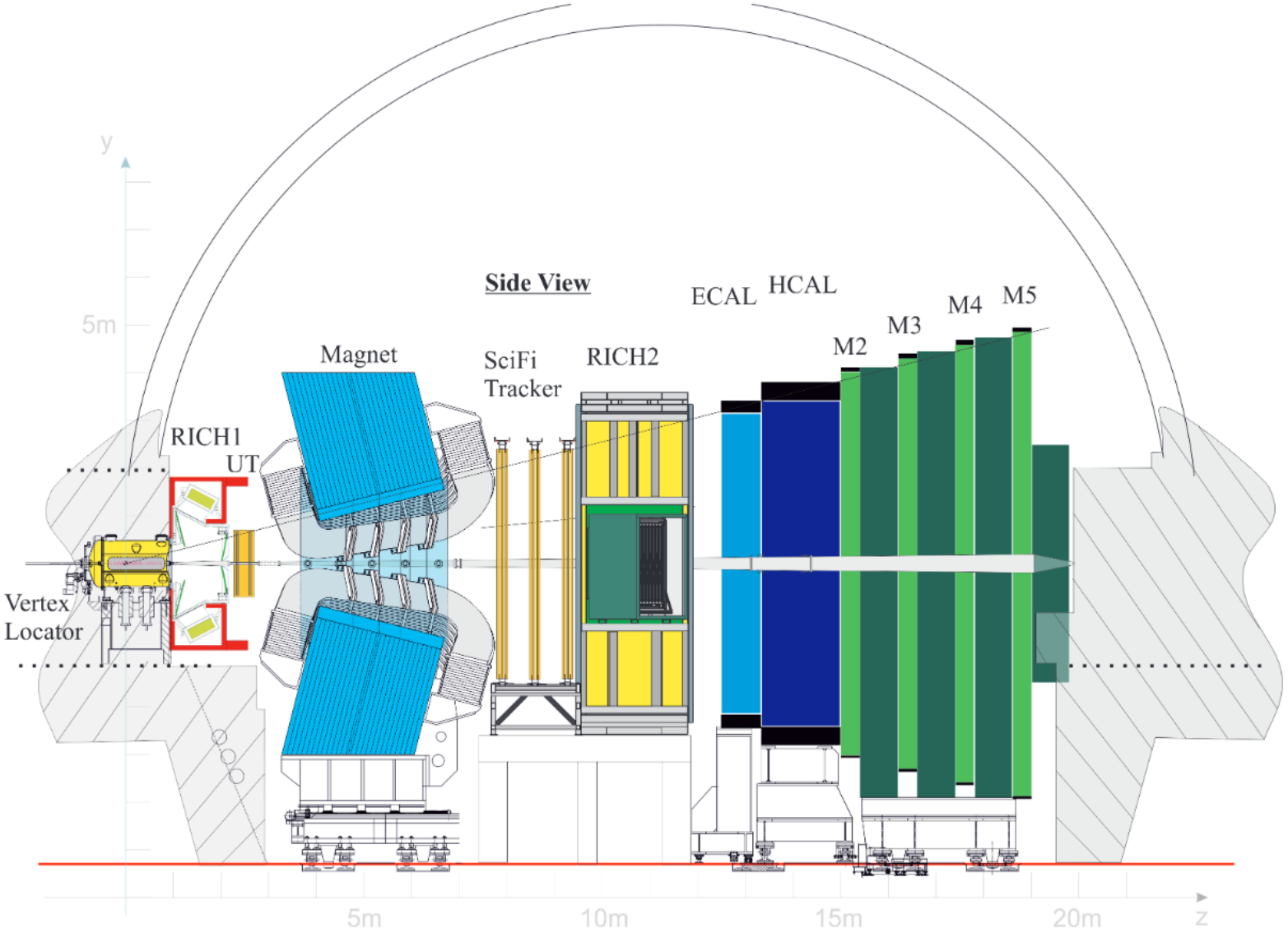
Sensor development and characterisation for Velo Upgrade

Robbert Geertsema on behalf of the LHCb Velo group

15th Trento Workshop – Vienna 2020

LHCb


Side View
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5m
Magnet
SciFi
Tracker
RICH2
ECAL
HCAL
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Vertex
Locator
5m
10m
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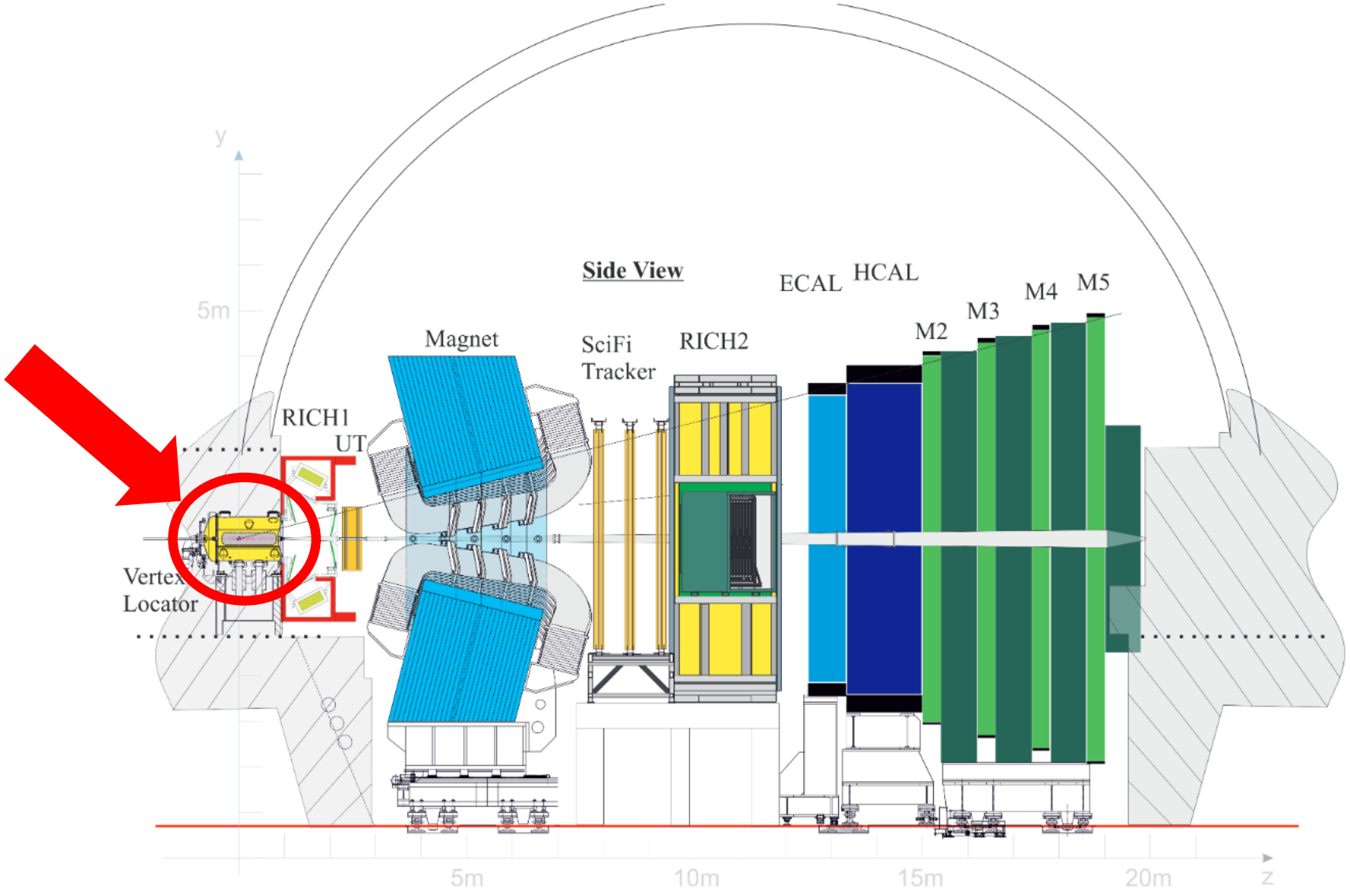
LHCb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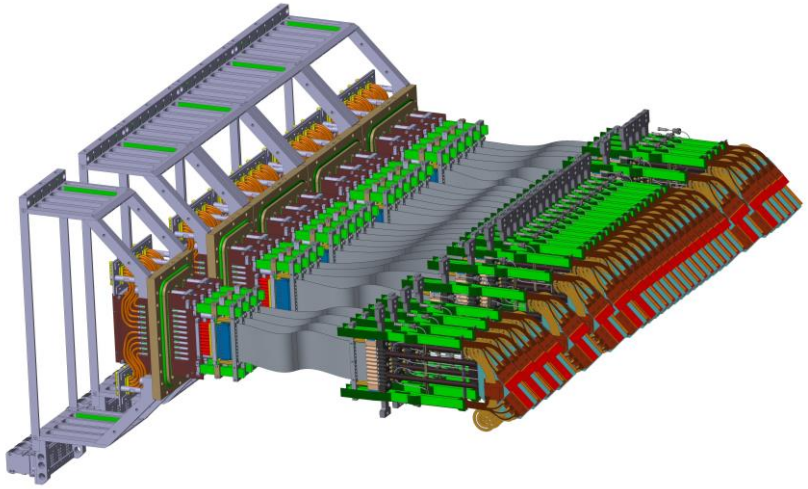
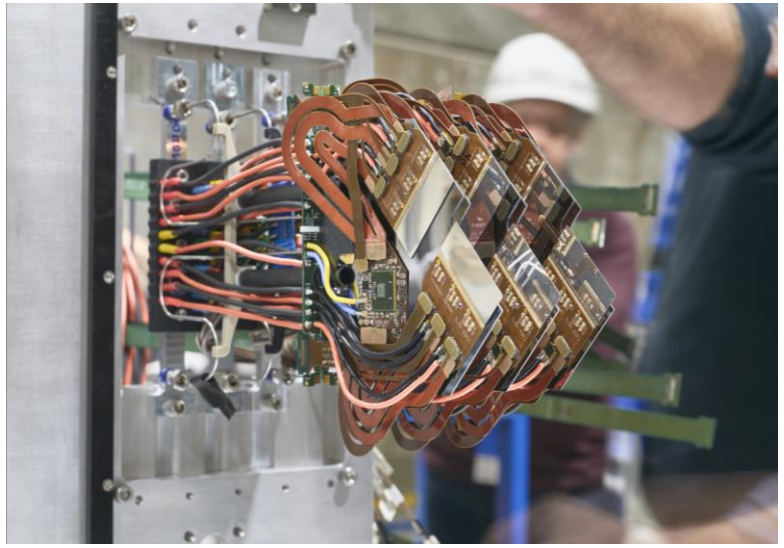
z

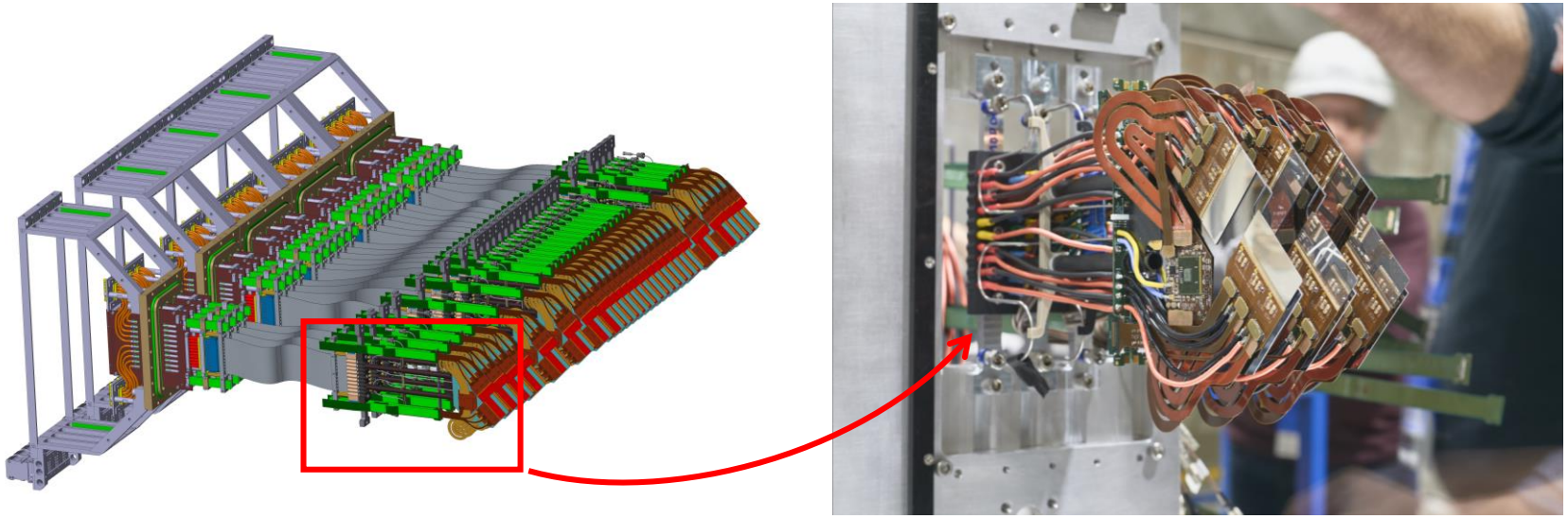
Vertex Locator (Velo) upgrade





52 modules make up the Velo
All separately connected to the outside

Vertex Locator (Velo) upgrade



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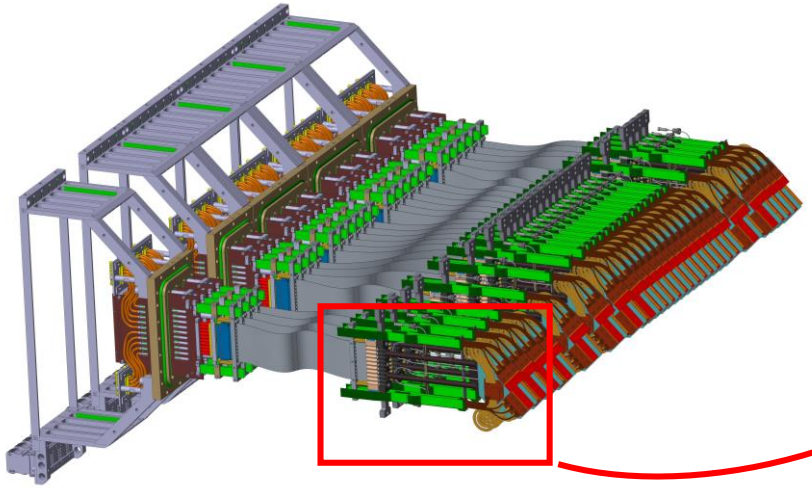
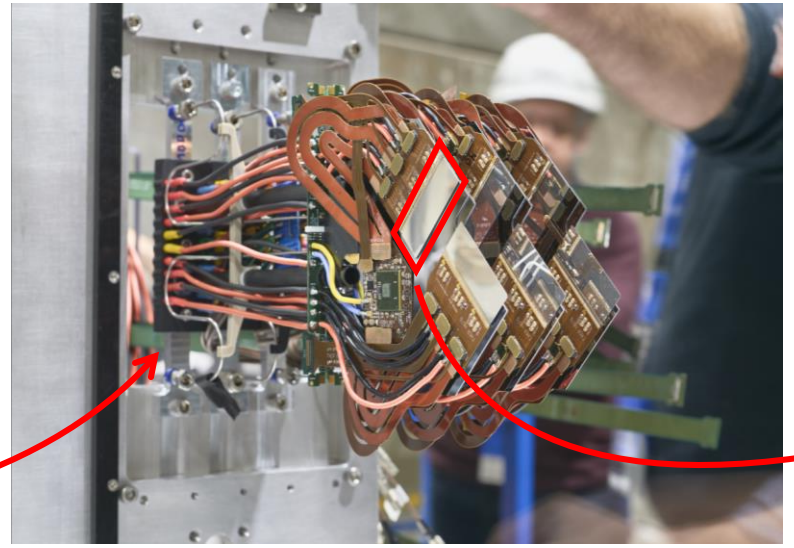
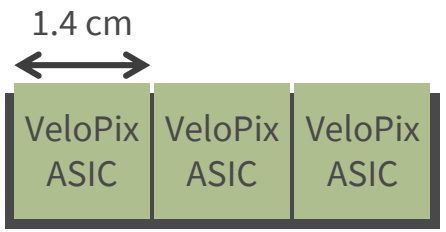
Vertex Locator (Velo) upgrade







52 modules make up the Velo
All separately connected to the outside

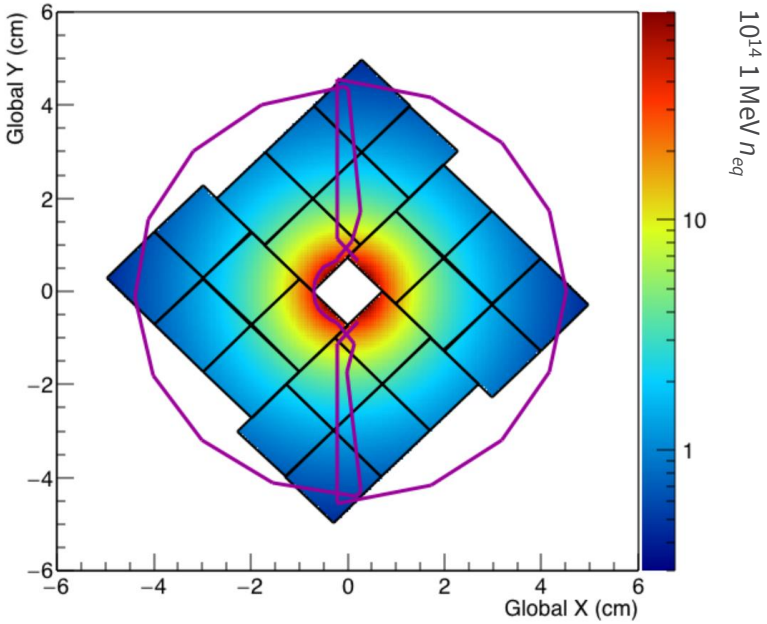
Each module consists of 12 ASICs, each with 65k pixels

This talk will mostly be focused on the sensors of the Velo
Currently modules are being produced, with the goal of mounting the Velo Upgrade before the start of first beam

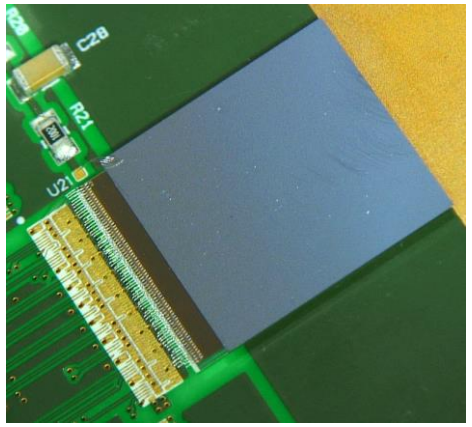
Challenge for Velo

- 5.1 mm sensitive distance to beam
  - Up to $\underline{8 \times 10^{15}}$ 1 MeV n_{eq} cm^{-2} (50 fb^{-1})
  - Non-uniform irradiation (factor 50 difference over a single module)
- Operate in vacuum
- Extremely high data rate, up to 15.1 Gbit/s for hottest module

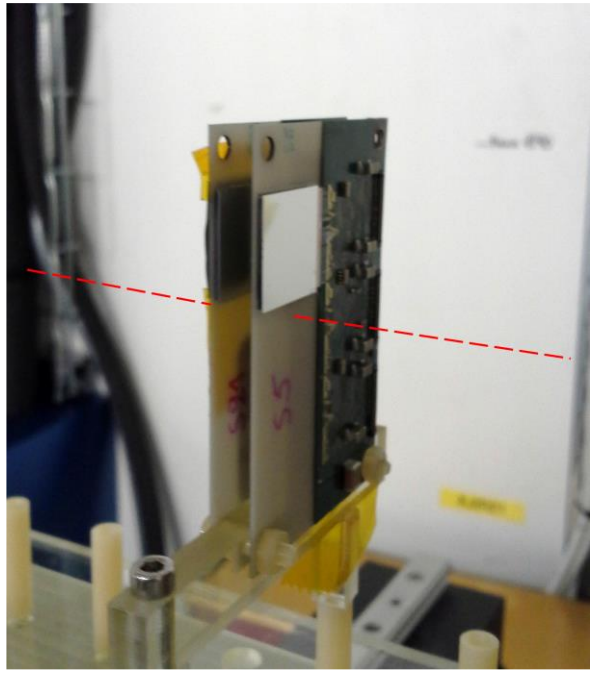
- Efficiency at least 99%
- Charge collection for MIP > 6000 e^- after 50 fb^{-1}
- Timewalk < 25 ns



Testing program

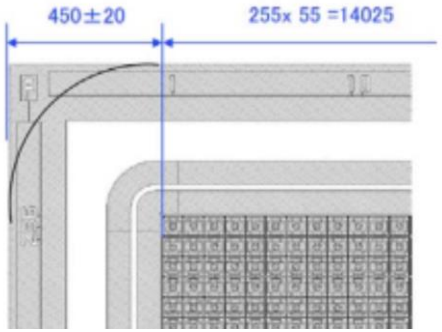


- Prototypes used Timepix3 (pitch of 55 µm) – Time-over-Threshold allows charge measurements, and Time-of-Arrival allows time measurement (1.56 ns)
- The Velo sensors must withstand 370 Mrad ~ 8 x 10^{15} 1 MeV $n_{eq}cm^{-2}$
  - The ATLAS IBL – at 550 fb^{-1} – expects 3.3 x 10^{15} 1 MeV $n_{eq}cm^{-2}$ or 160 MRad

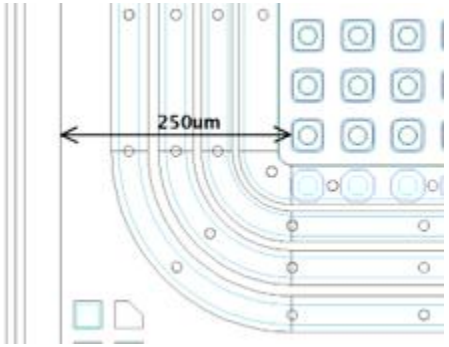


- Resolution, efficiency, charge collection:
  - Measurements at the SPS using the Timepix3 telescope
- Calibrations performed in the lab (not discussed in this talk) :
  - Test pulses
  - Radioactive sources
  - Synchrotron x-rays

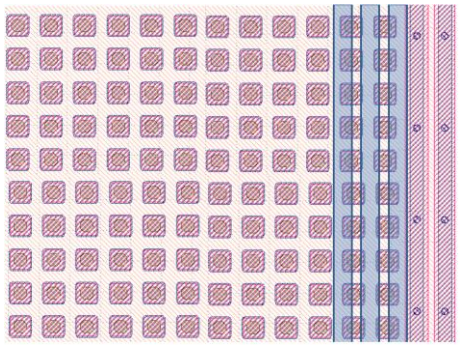
Sensor prototypes



Hamamatsu (HPK):
n-on-p, 200 µm thick, 450(600) µm pixel-to-edge,
35 (39) µm implant size



Micron:
n-on-p, 200 µm thick, 450(250) µm pixel-to-edge,
36 µm implant size



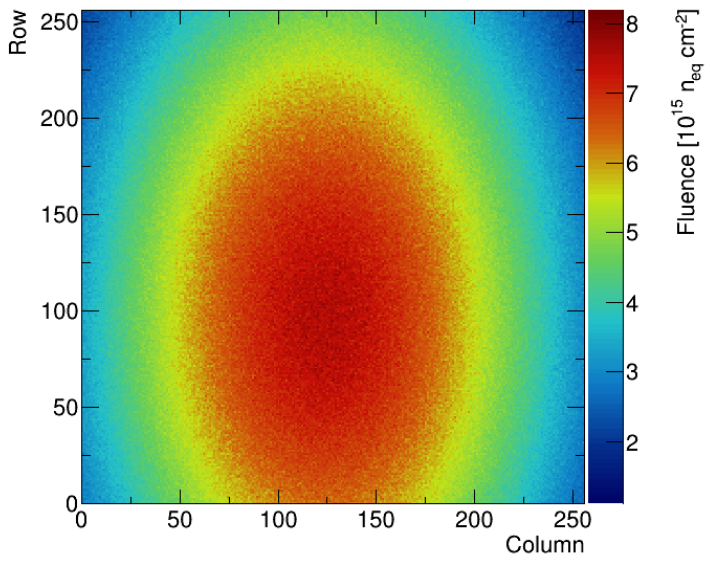
Micron:
n-on-n, 150 µm thick, 450(250, 150) µm pixel-to-edge,
36 µm implant size

Irradiation campaign

IRRAD

Protons, 24 GeV

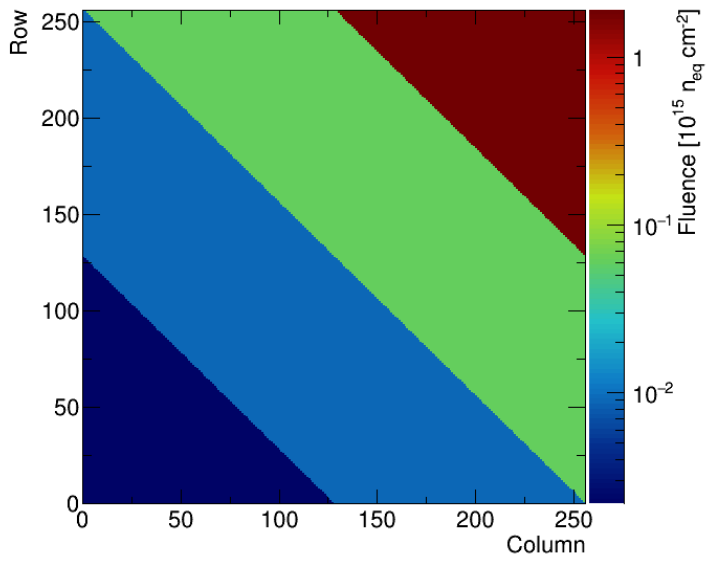
Non-uniform:
Up to 8×10^{15} 1 MeV n_{eq} cm^{-2}



KIT

Protons, 24 MeV

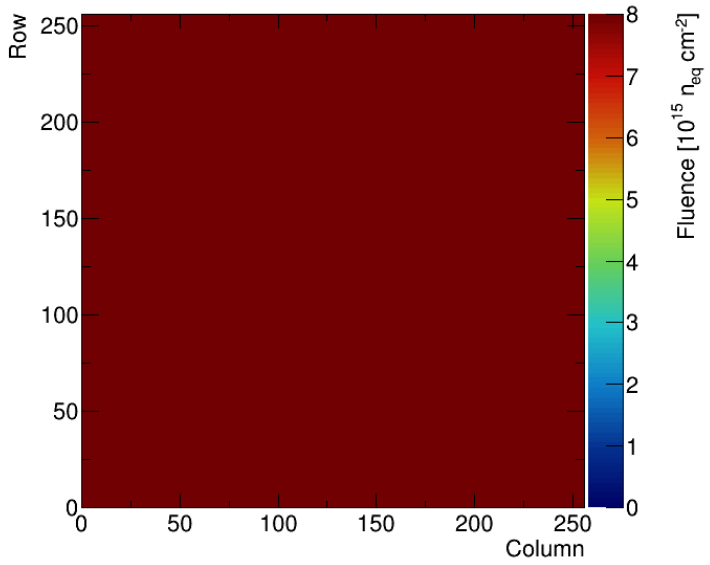
Non-uniform:
Up to 8×10^{15} 1 MeV n_{eq} cm^{-2}



JSI

Neutrons

Uniform:
4×10^{15} <u>or</u> 8×10^{15} 1 MeV n_{eq} cm^{-2}

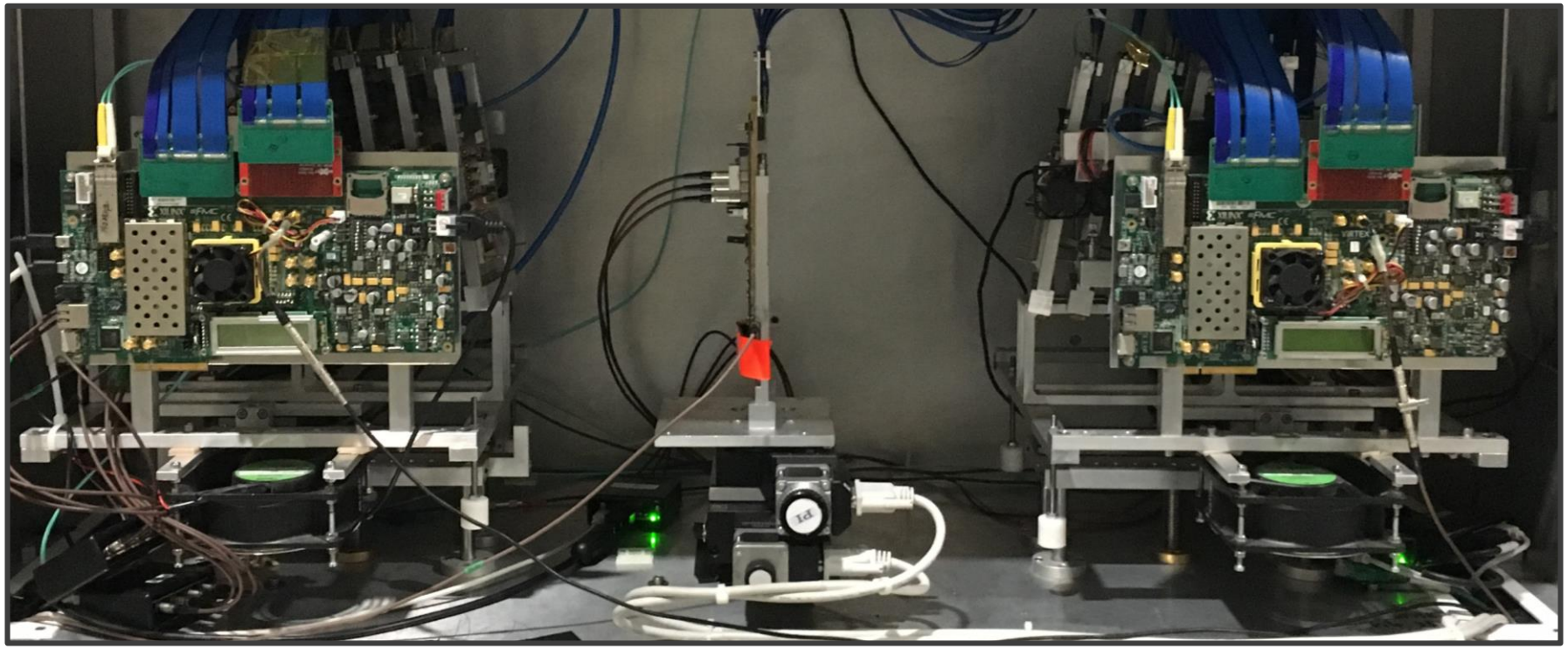


Timepix3 Telescope

- 8 Timepix3 planes
  - Particle track can be reconstructed through all 8 planes

- Pointing resolution:
  $\sigma_x = 1.69 \pm 0.16\ \mu m$
  $\sigma_y = 1.55 \pm 0.16\ \mu m$

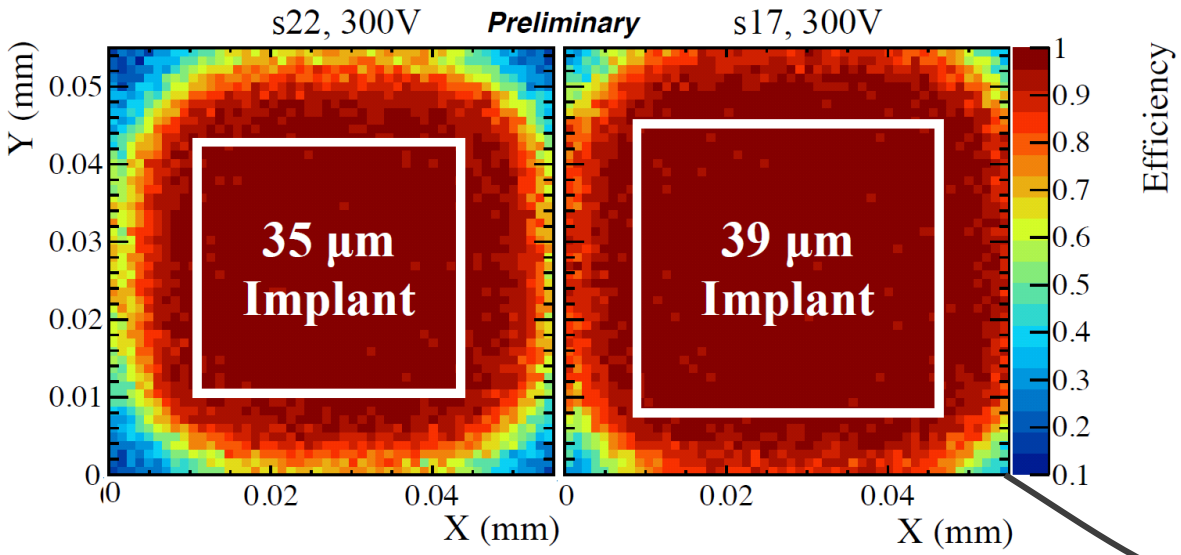
- Time resolution:
  Either using two scintillators (σ_t=390 ps, σ_t=190 ps)
  Or using the time of Timepix3 hits ($\sigma_t = 350\ ps$ or $\sigma_t = 271\ ps$, soon to be submitted)



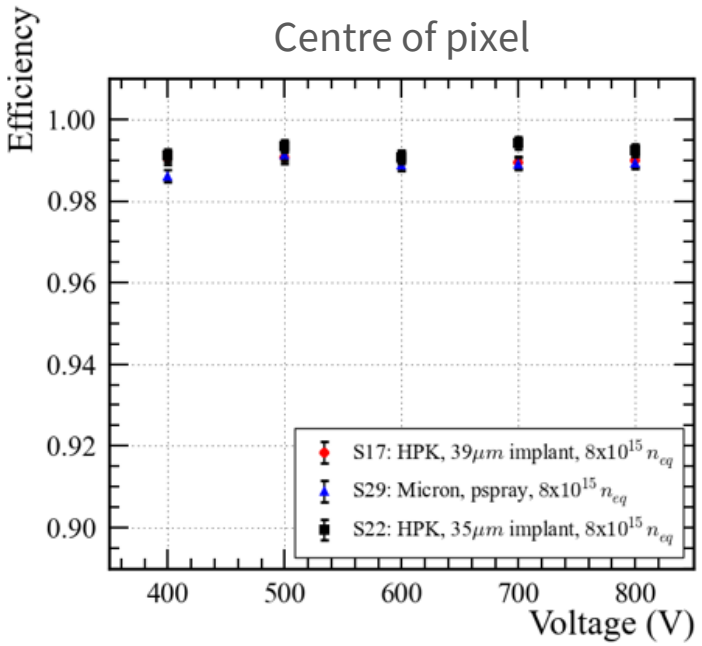
Akiba, Kazu, et al. LHCb VELO Timepix3 telescope. *Journal of Instrumentation*, 2019, 14.05: P05026.

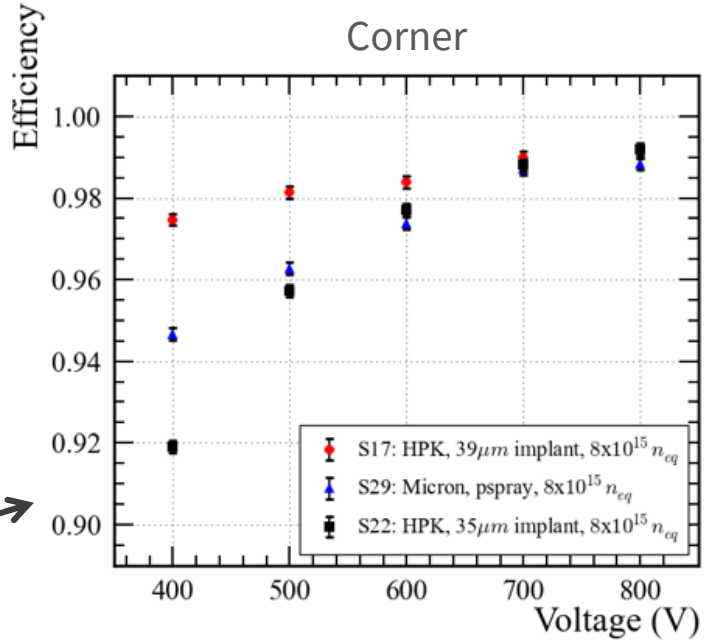
Efficiencies

- First requirement: efficiency > 99%
- Achieved for > 800 V
- Observed: larger implant increases efficiency



JSI, 8 × 10^{15} 1 MeV n_{eq} cm^{-2}



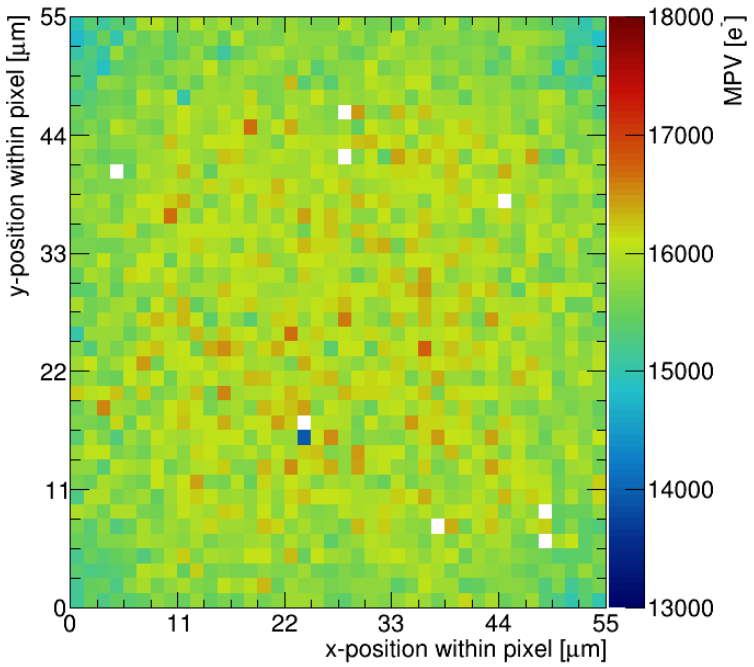


Corners recover at 800 V

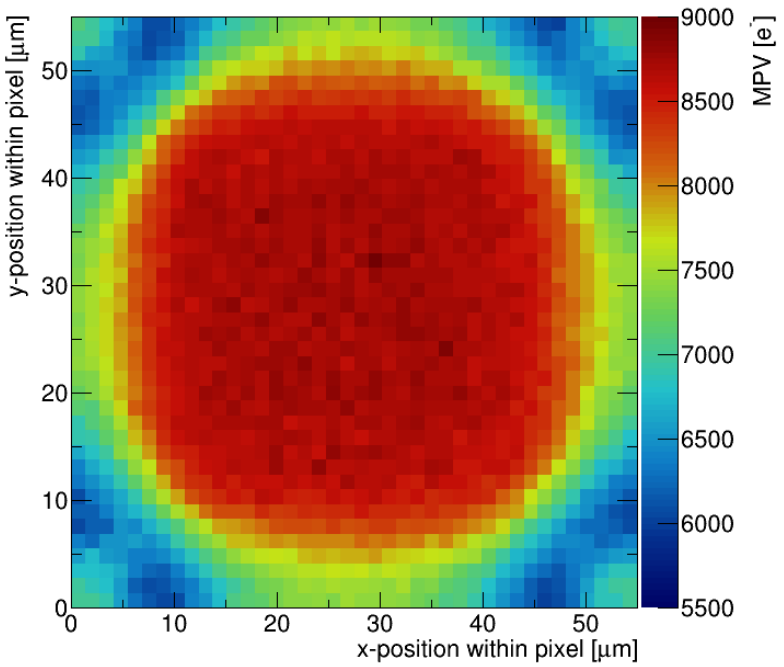
Intra-pixel collected charge

- Using tracking of telescope, the measured charge within the pixel can be determined

HPK n-on-p (35 µm) – 800 V



24 GeV proton irradiation



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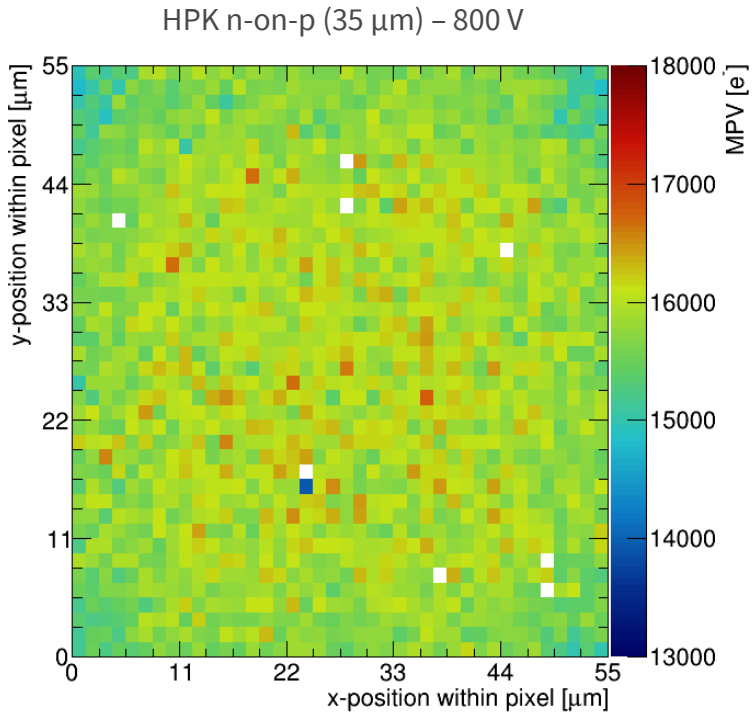

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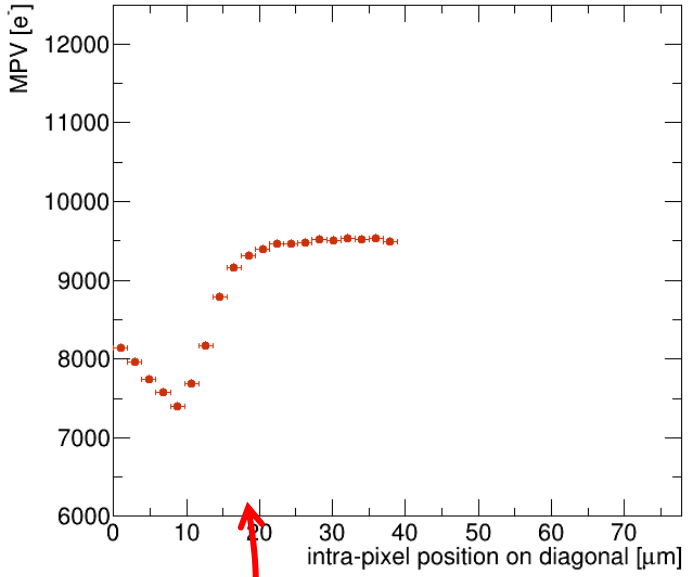

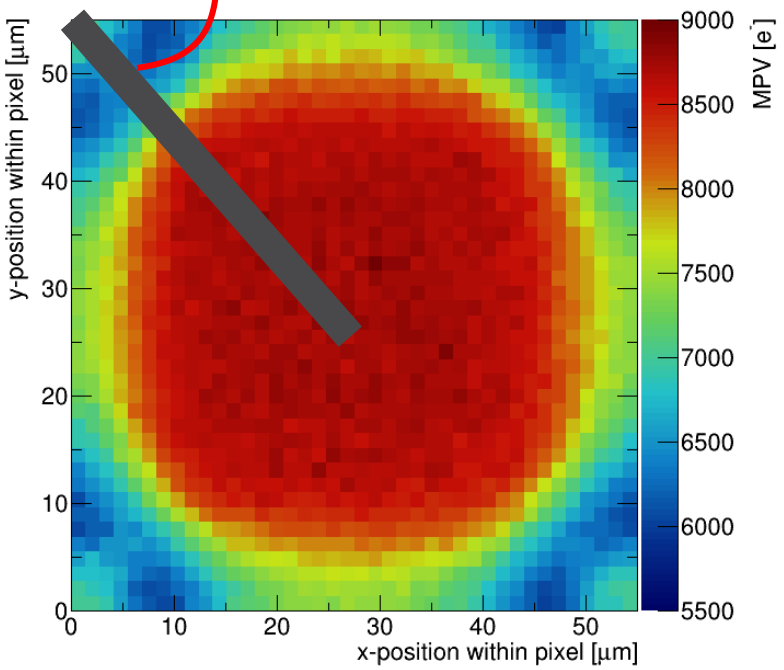

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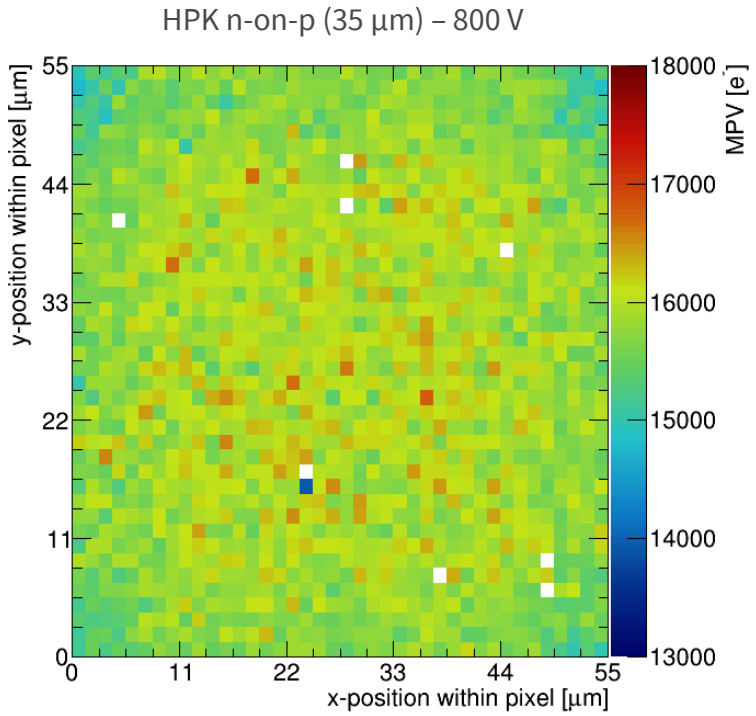

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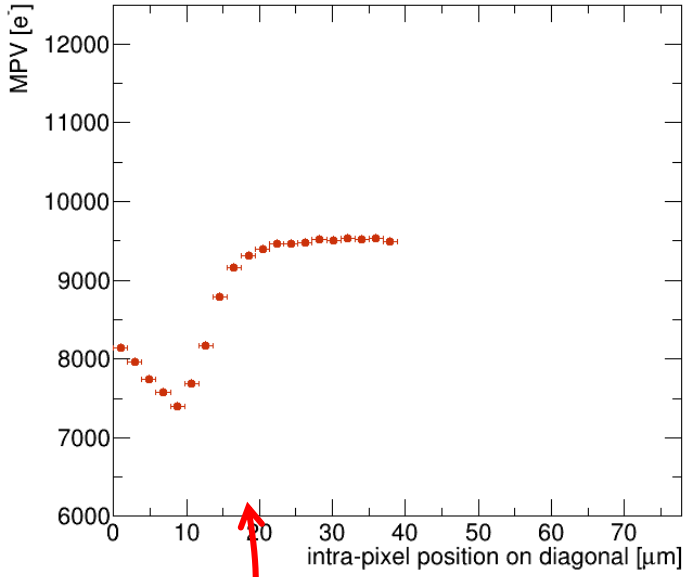

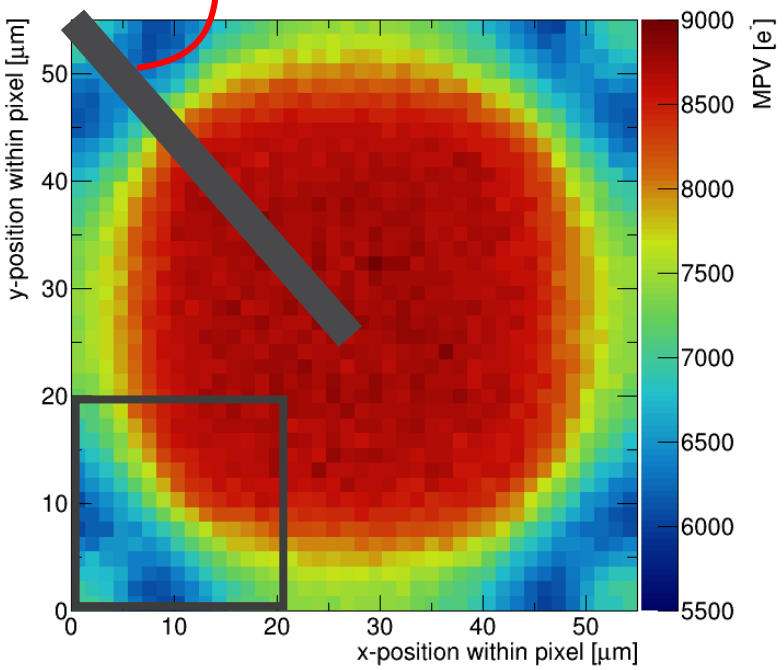

Intra-pixel collected charge

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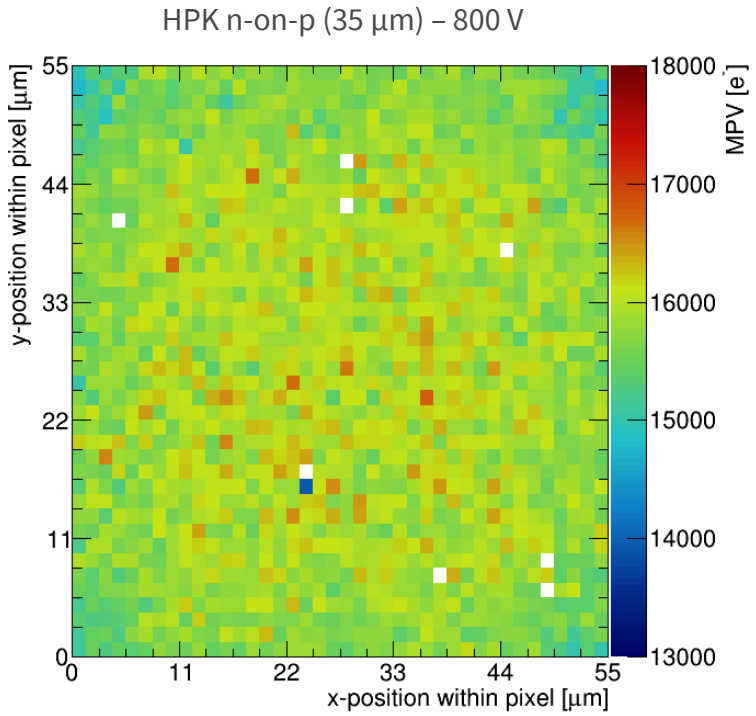
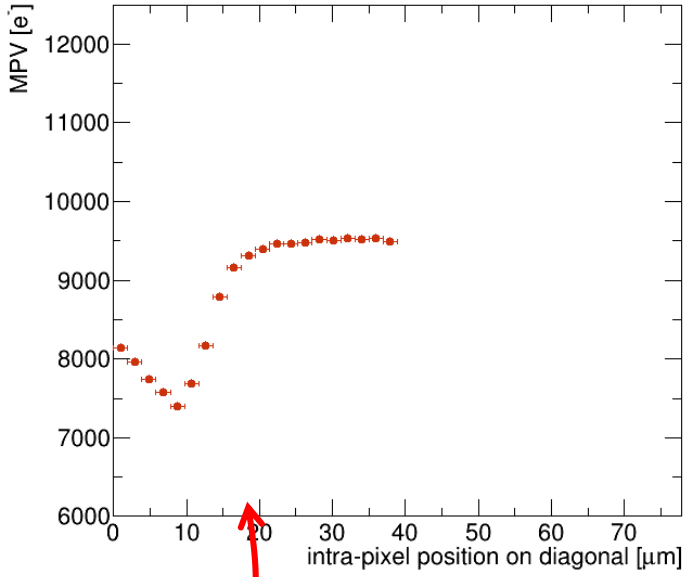
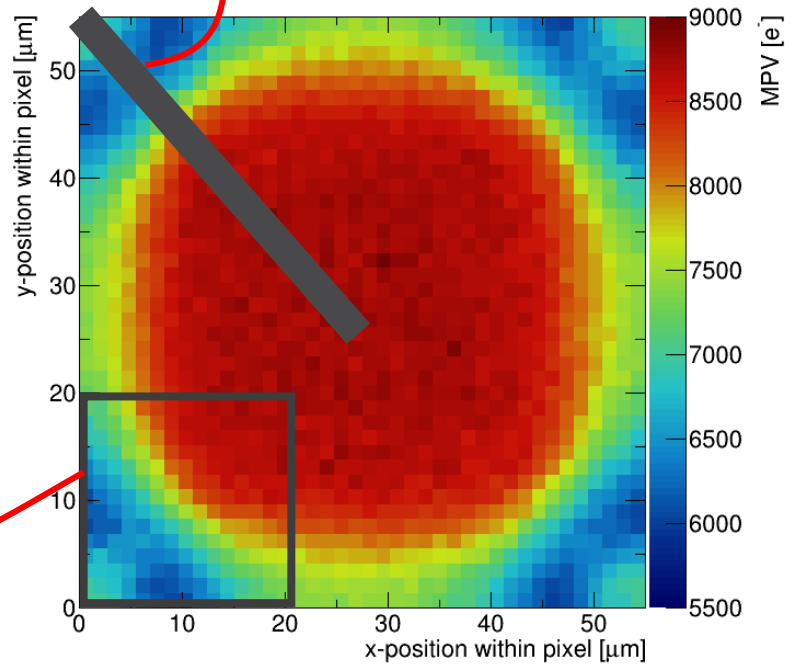


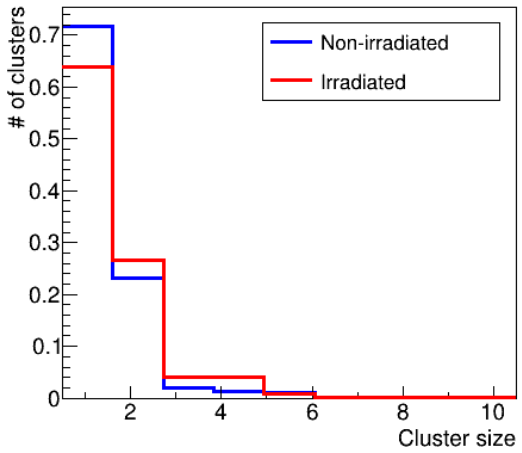
24 GeV proton irradiation



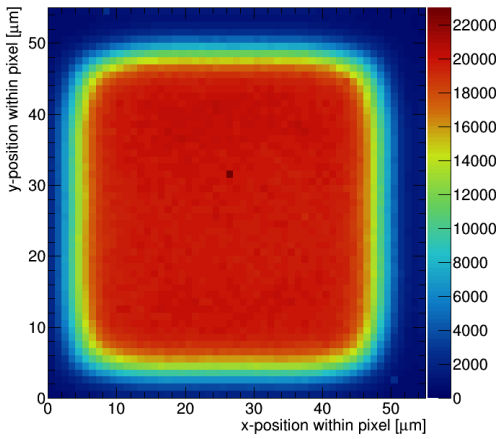


Cluster size

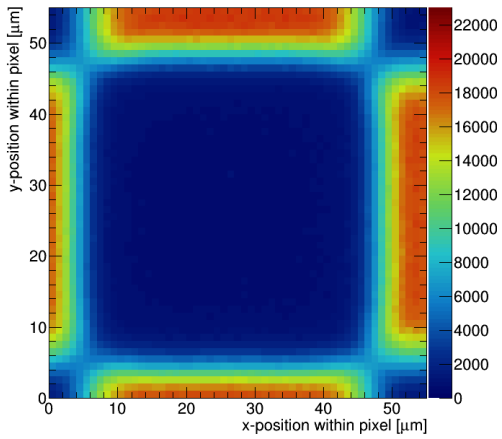
- Mainly cluster size 2 & 3 around the corner
- The dip seems to be due to a threshold effect



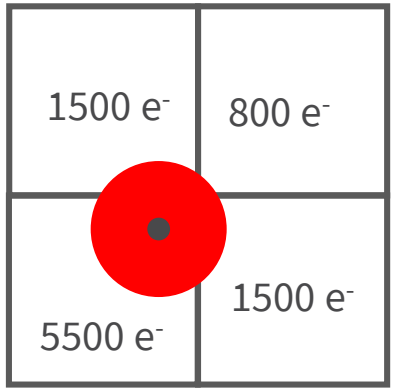
Cluster size 1



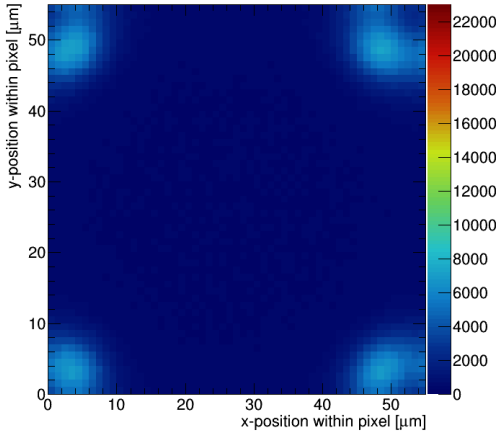
Cluster size 2



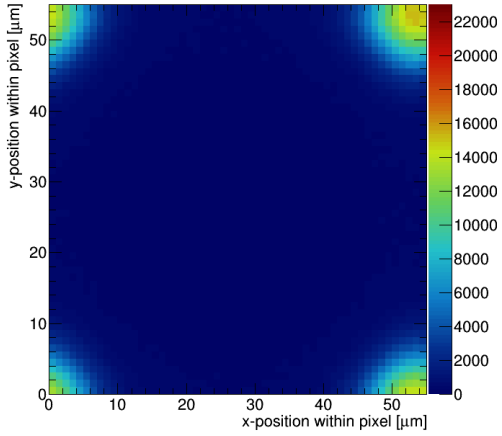
Threshold @ 1000 e⁻

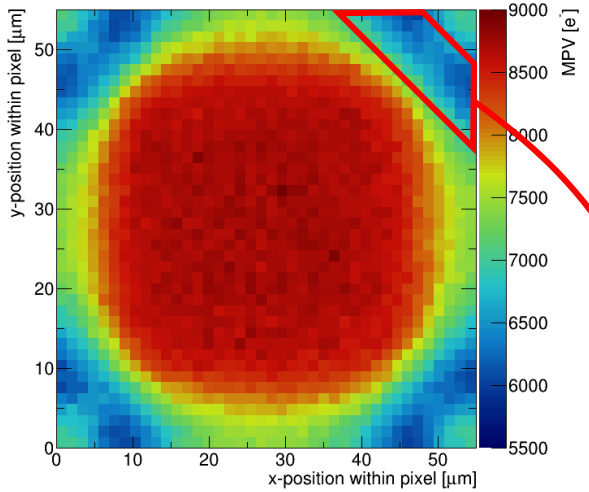


Cluster size 3



Cluster size 4



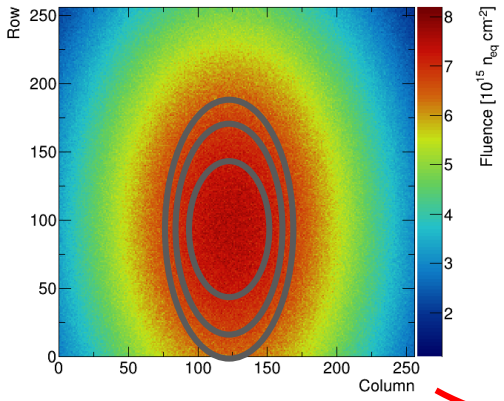


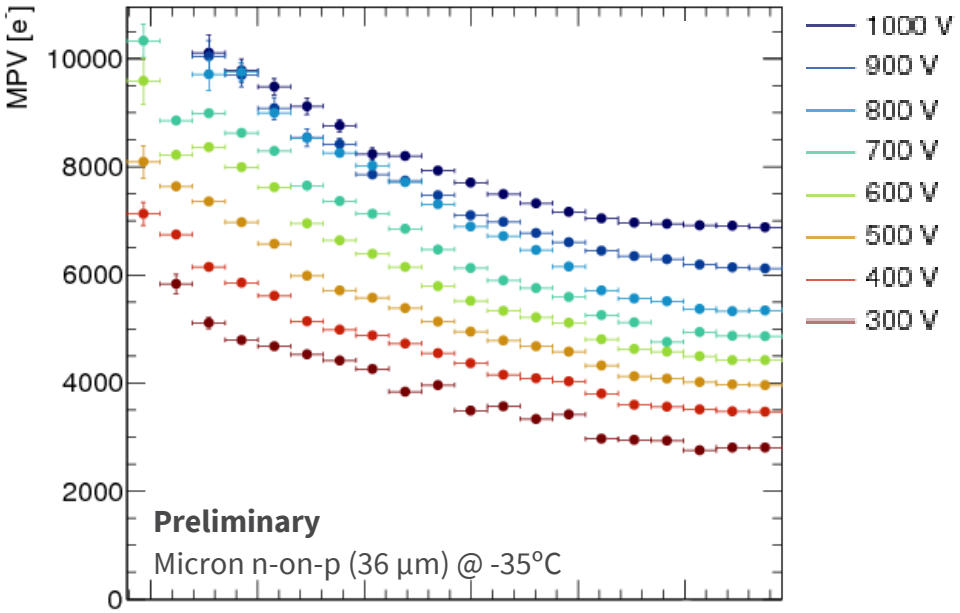
Due to cluster size 2 & 3

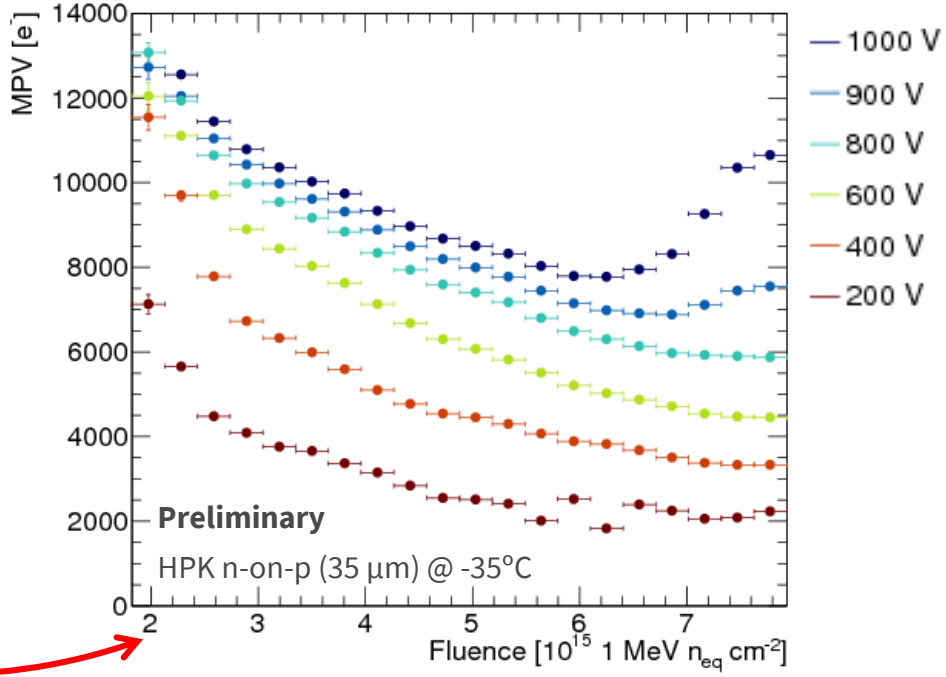
Collected charge

- Collected as function of voltage and fluence
- Overall: less charge for higher fluence
- Charge multiplication observed for 2 sensor
  - Other sensors could not reach 1000 V or started to become too noisy

- Goal achieved of MIP > 6000 e^- for > 900 V at full fluence



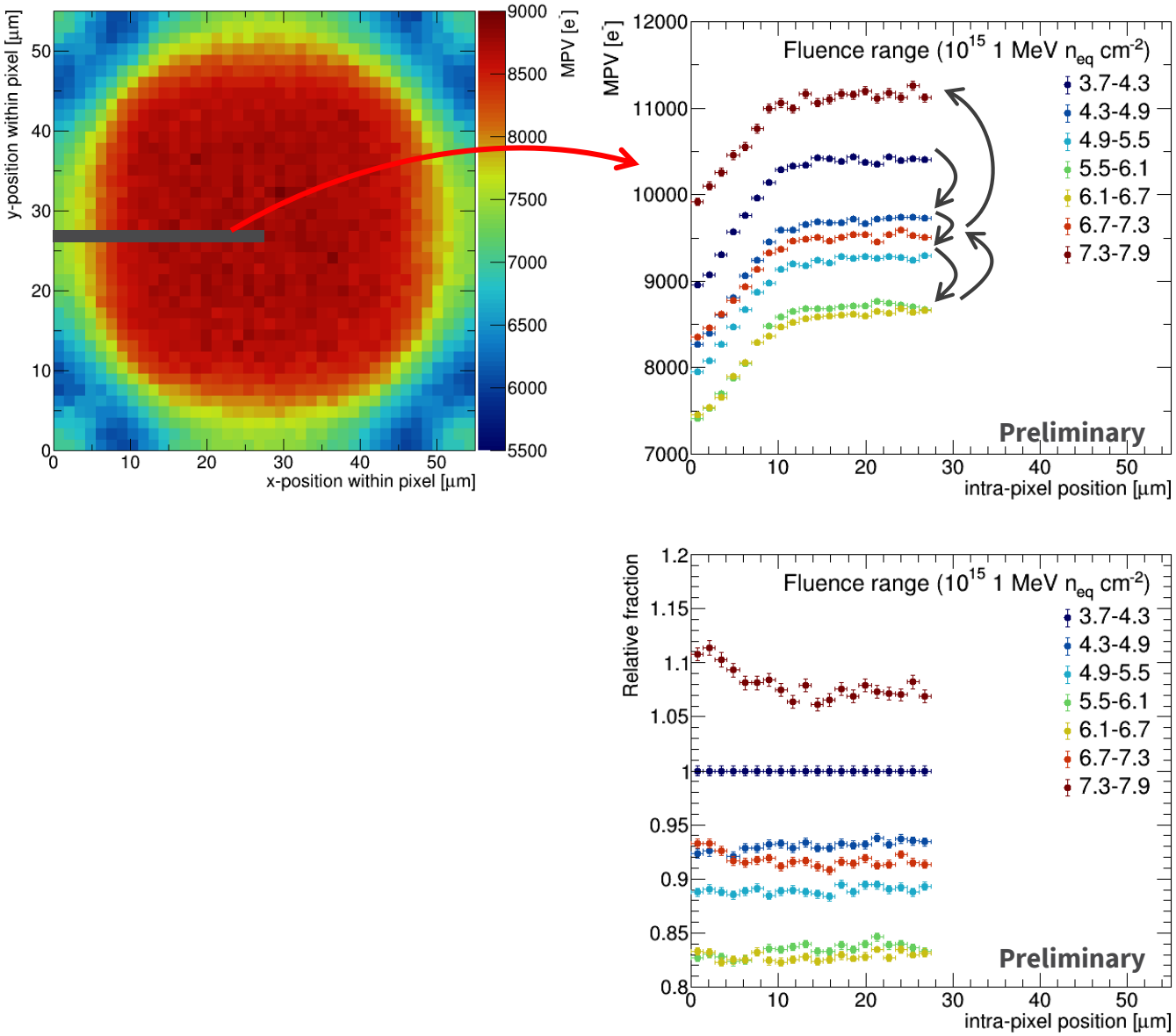




Collected charge

- Investigation of intra-pixel behavior for charge multiplication
- Multiplication onset at 6.1×10^{15} 1 MeV n_{eq} cm^{-2} at 1000 V
- Only observed in proton irradiated sensors
- Observed in only 2 out of 4 (IRRAD) sensors
  - Other sensors could not reach 1000 V

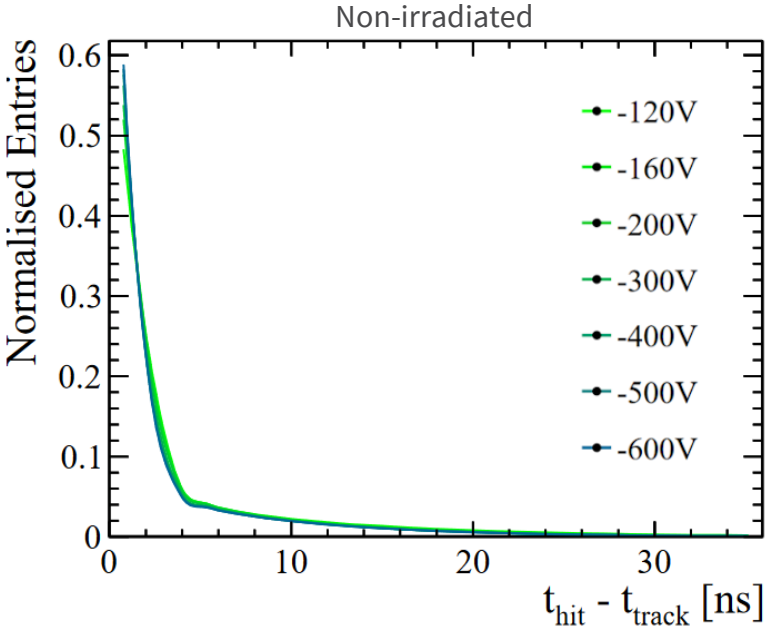
HPK n-on-p (35 µm) – 1000 V

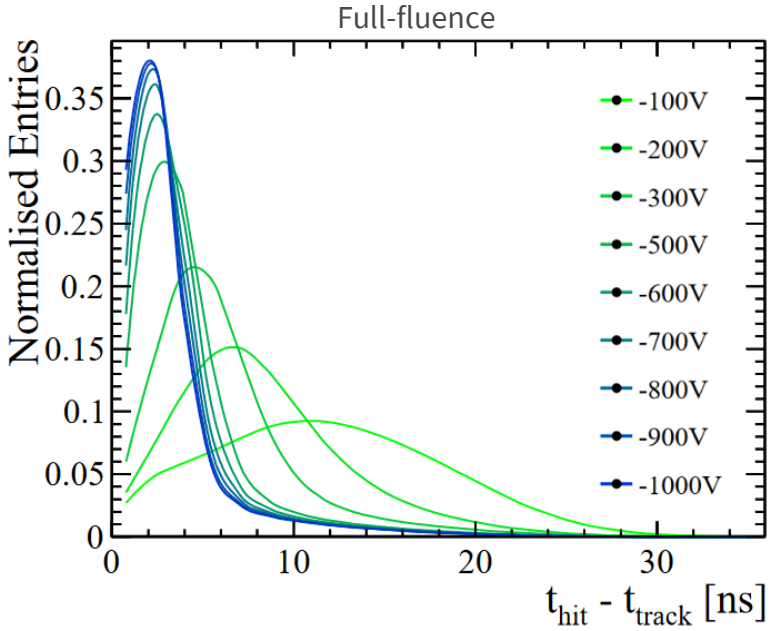


Timing studies

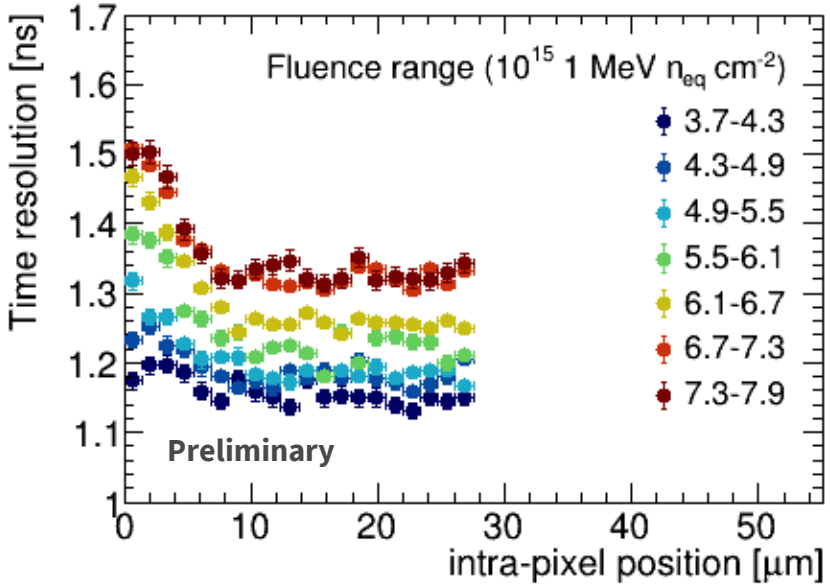
- Required to be less than bunch crossing rate (25 ns)
- For > 600 V, timewalk is small enough
- Time resolution decreases with higher fluence

HPK n-on-p (35 µm)





HPK n-on-p (35 µm) – 1000 V

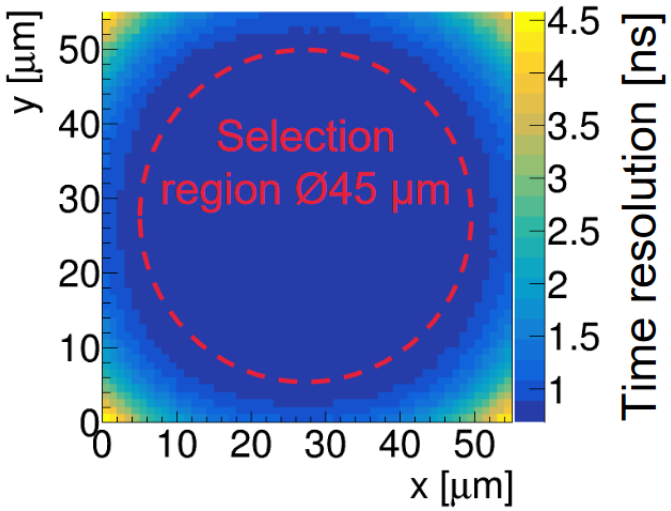


Dall' Occo, E. (2016). *Sensor Developments for the LHCb VELO Upgrade*. 4th BTTB Workshop

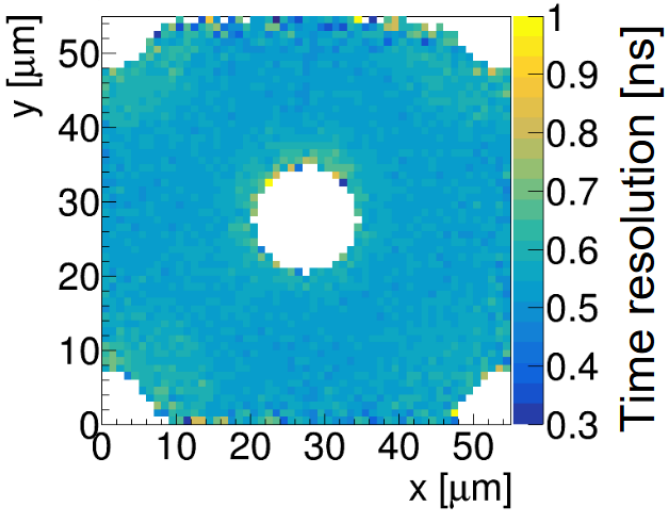
New Velo, new sensors (R&D work at Nikhef)

Upgrade 2 for Velo is scheduled for 2031, will require new sensors
Separate R&D work ongoing at Nikhef (not specifically for LHCb)

- Thin planar 50 µm (with thanks to CLIC)
  - p-on-n, Advacam
  - Depletion voltage 15-20 V
  - Bias 90 V
  - $\sigma_t = 588\ ps$ (best hits, with ASIC contribution)



- 3D 285 µm (with thanks to R. Bates)
  - n-type bulk, CNM-IBM
  - Depletion voltage 20 V
  - Bias 60 V
  - $\sigma_t = 590\ ps$ (best hits, with ASIC contribution)



K. Heijhoff (2019). *Timepix3 Telescope Temporal Resolution Studies*. IEEE NSS MIC

Summary & Outlook

- Sensors from HPK and Micron have been tested with non-uniform irradiation
- Sensors have been found to withstand the radiation up to 8×10^{15} 1 MeV n_{eq} cm^{-2} while achieving the minimum requirements set
- Main findings:
  - Large implants for better efficiency
  - High voltage required to large enough signals (mitigate timewalk)

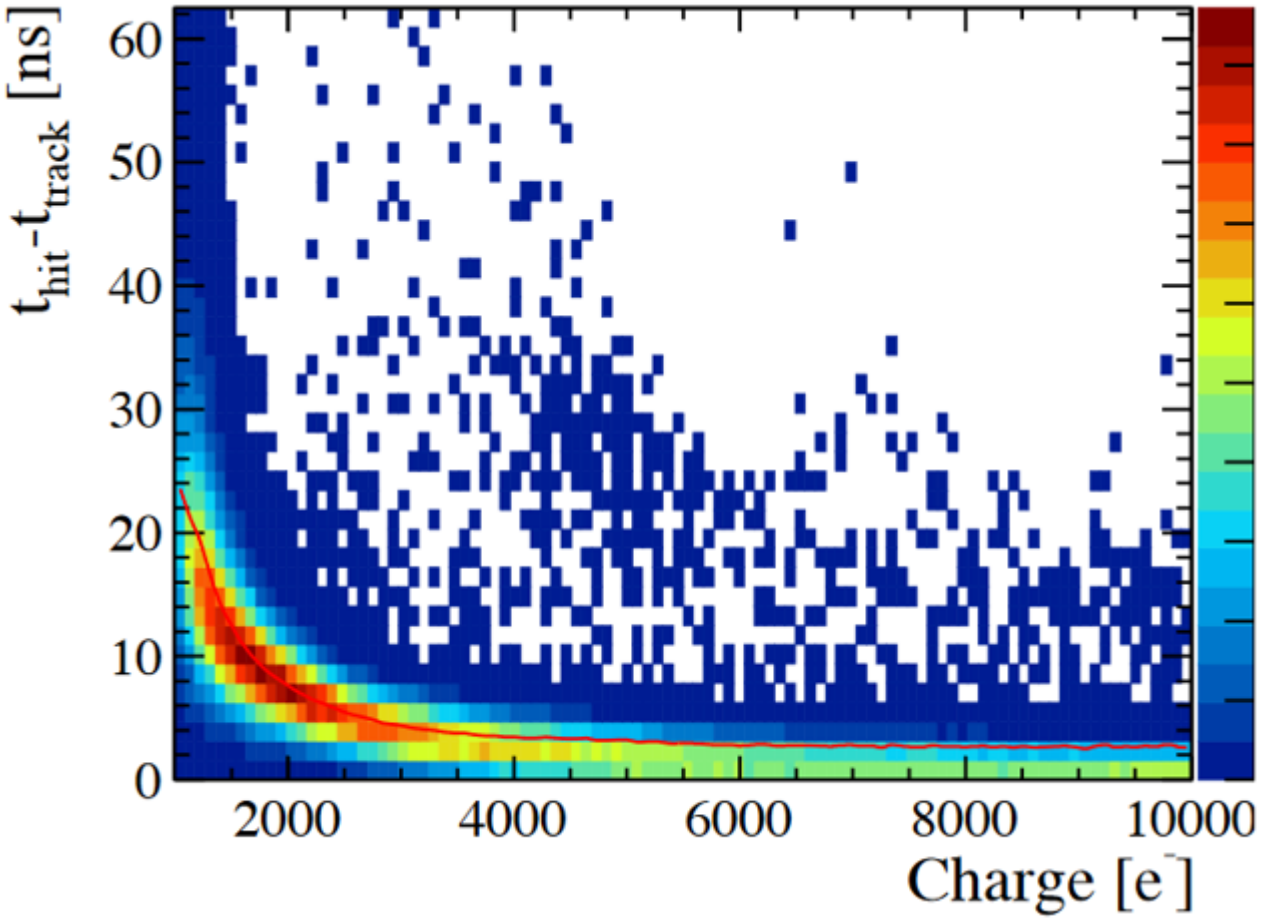
- Working on Upgrade 2 (2031)
  - New sensor designs/types?
  - 3D, LGAD, AC-LGAD?

Thank you for the attention!

r.geertsema@nikhef.nl

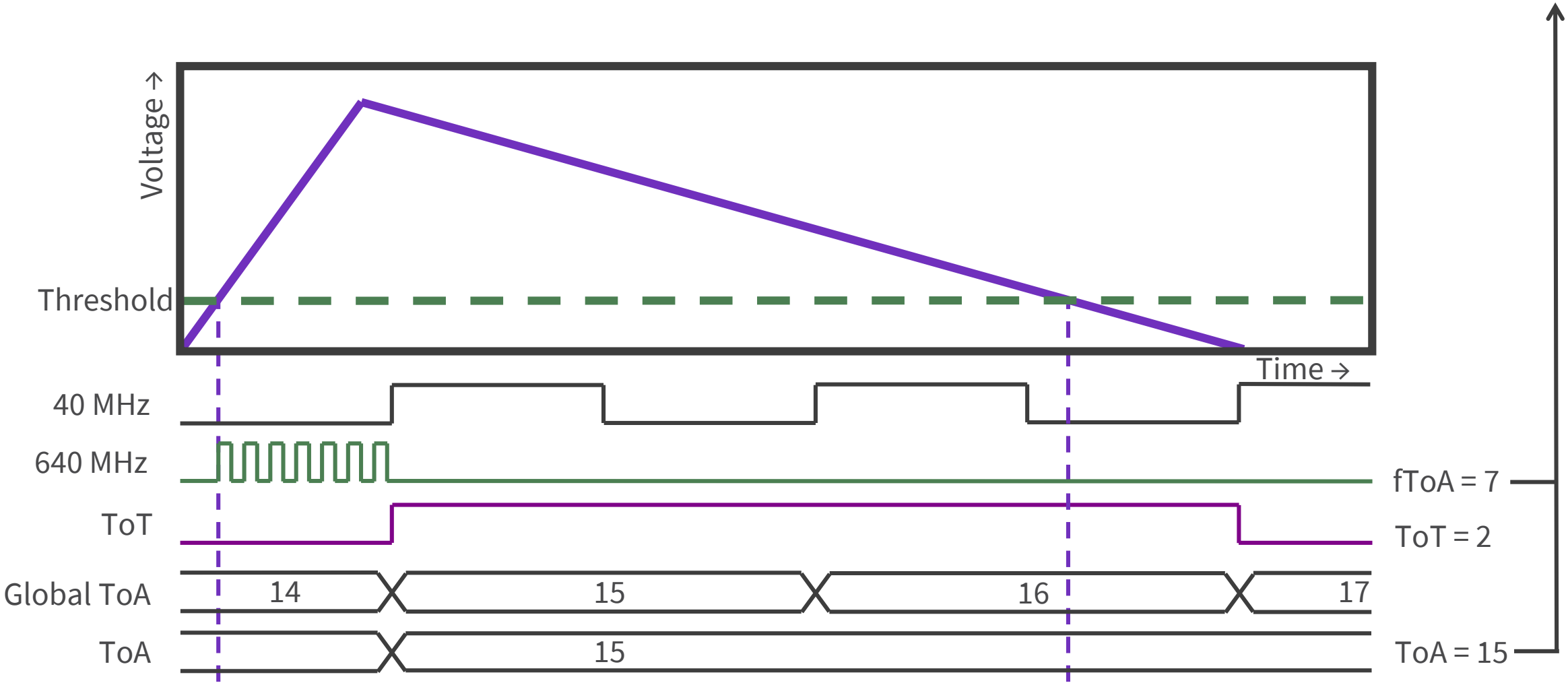
Backup: Timewalk

- Due to a lower charges taking longer to reach threshold

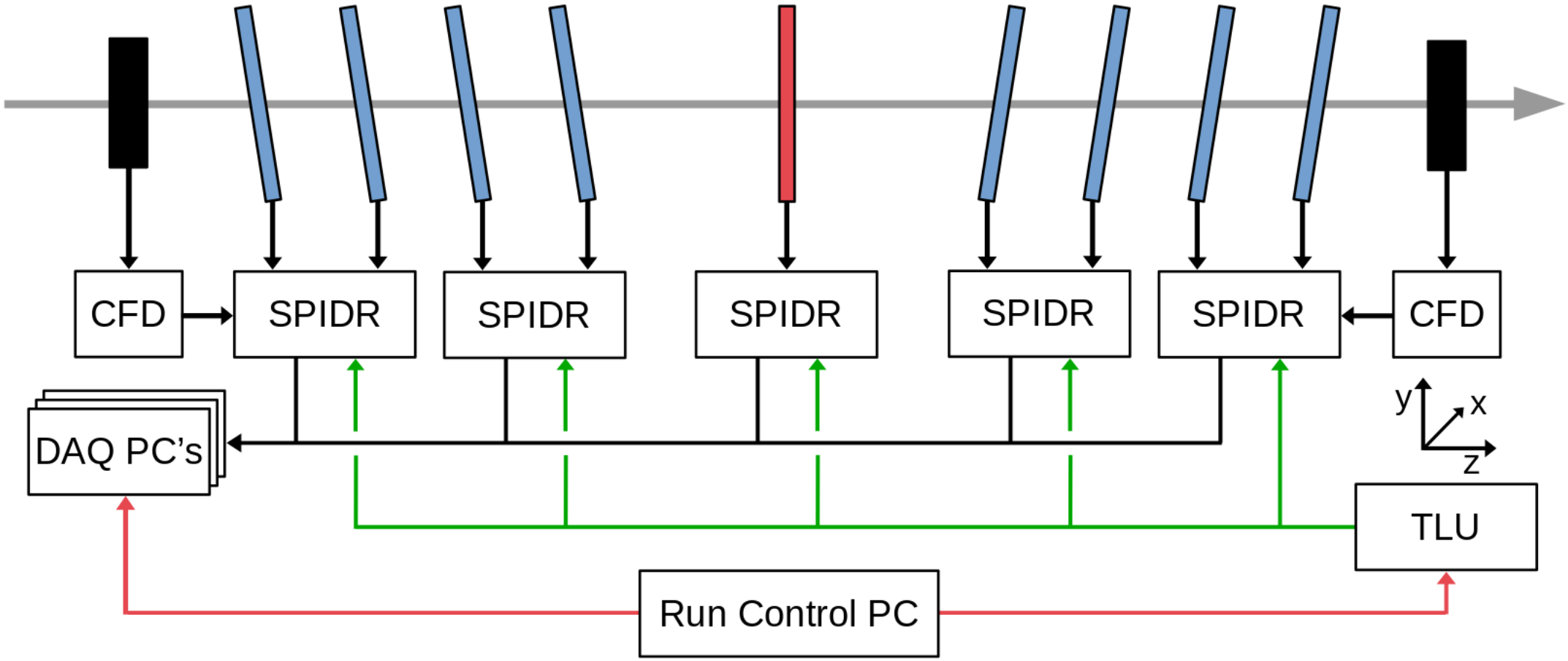


Backup: Timepix3

Time [ns] = 25 * ToA – 1.56 * fToA = 364.1 ns

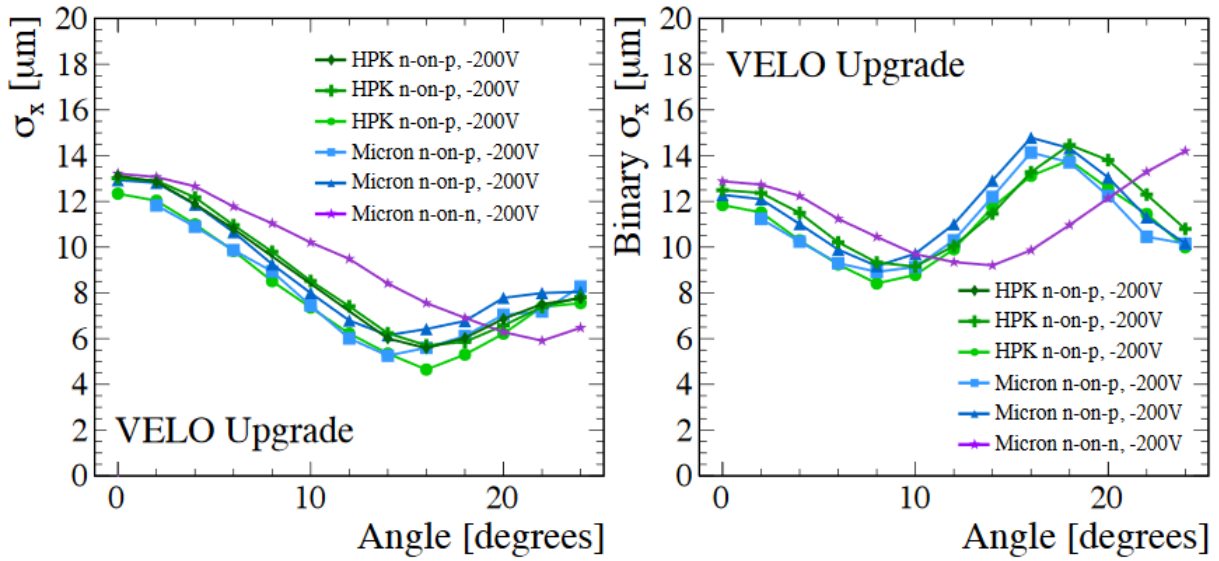


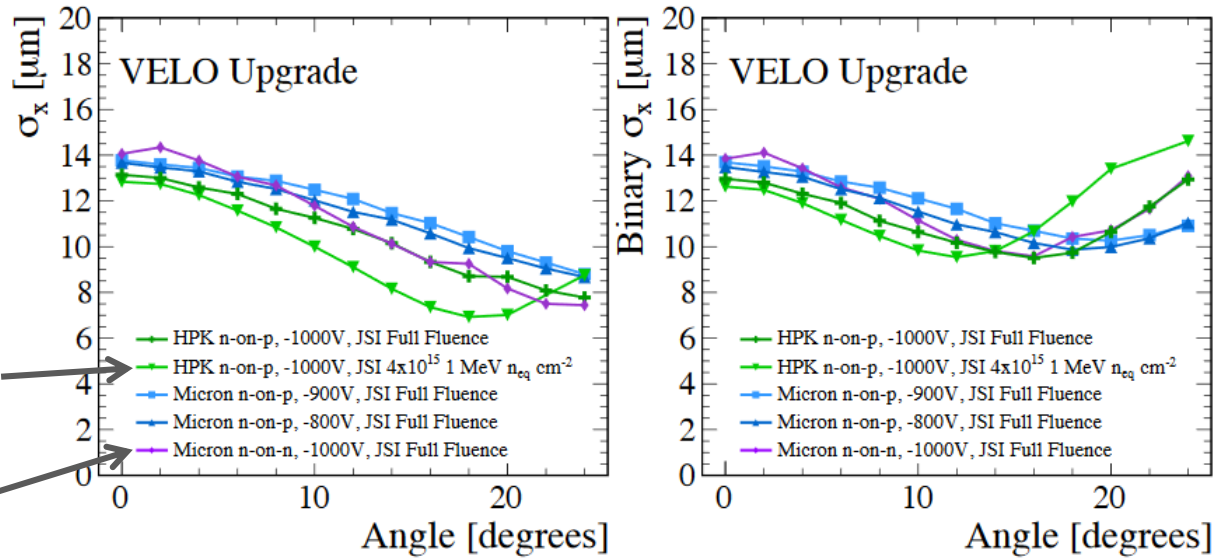
Backup: Timepix3 telescope



Hit resolution

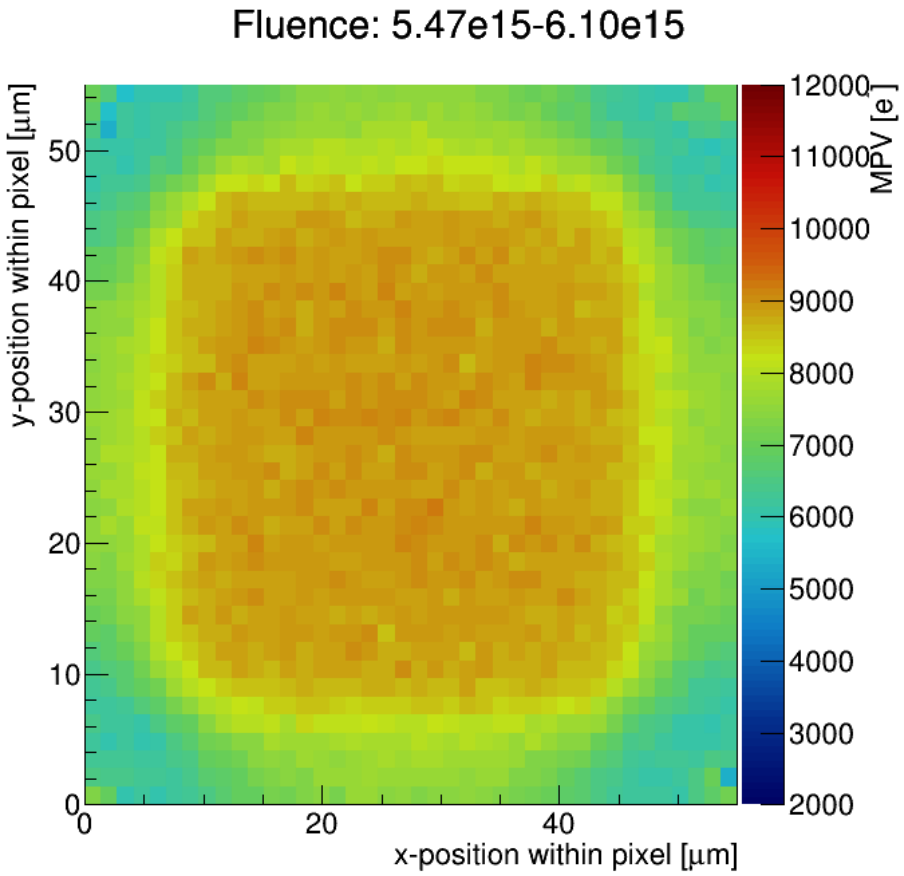
- Important to achieve small error on IP
- Hit resolution determined before (top) and after (bottom) irradiation
- Systematically worse after irradiation

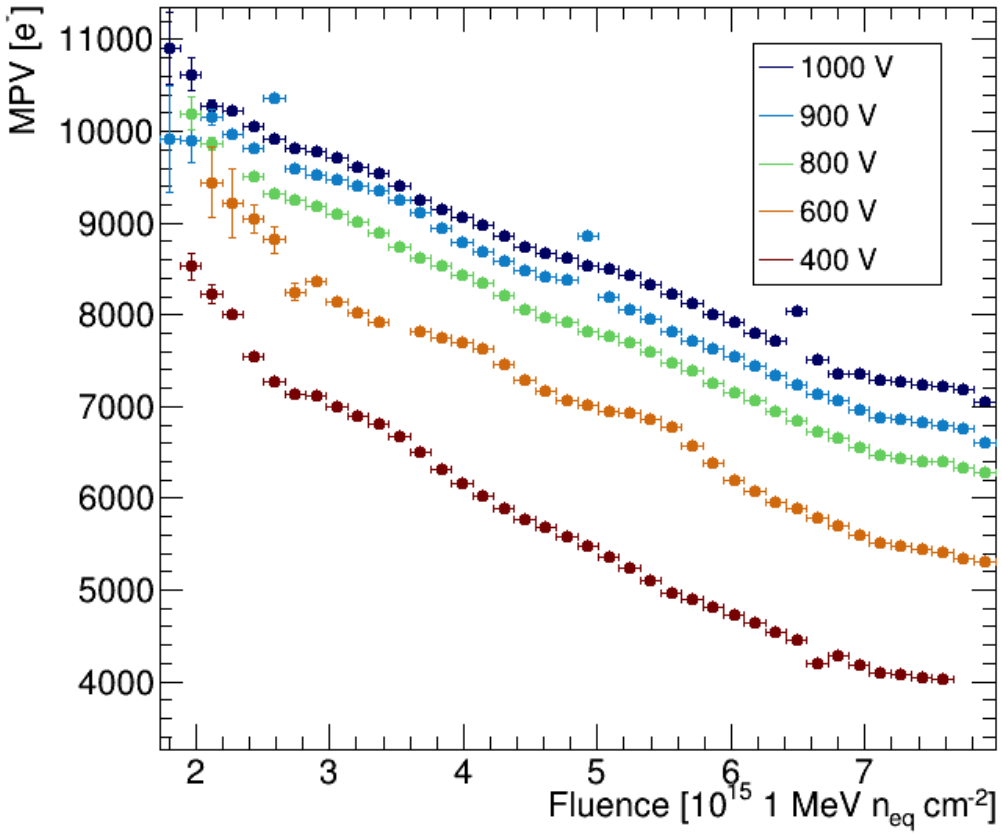




E. Dall'Occo, "The Timepix3 Telescope and Sensor R&D for the LHCb VELO Upgrade," *2018 IEEE Nuclear Science Symposium and Medical Imaging Conference Proceedings (NSS/MIC)*, Sydney, Australia, 2018, pp. 1-8.

Backup: Additional sensors – Micron n-on-n





Backup: Additional sensors – Micron n-on-p