Pixel Detector for LHCb VELO Upgrade

INFIERI 8th Workshop

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on behalf of LHCb VELO Upgrade Group

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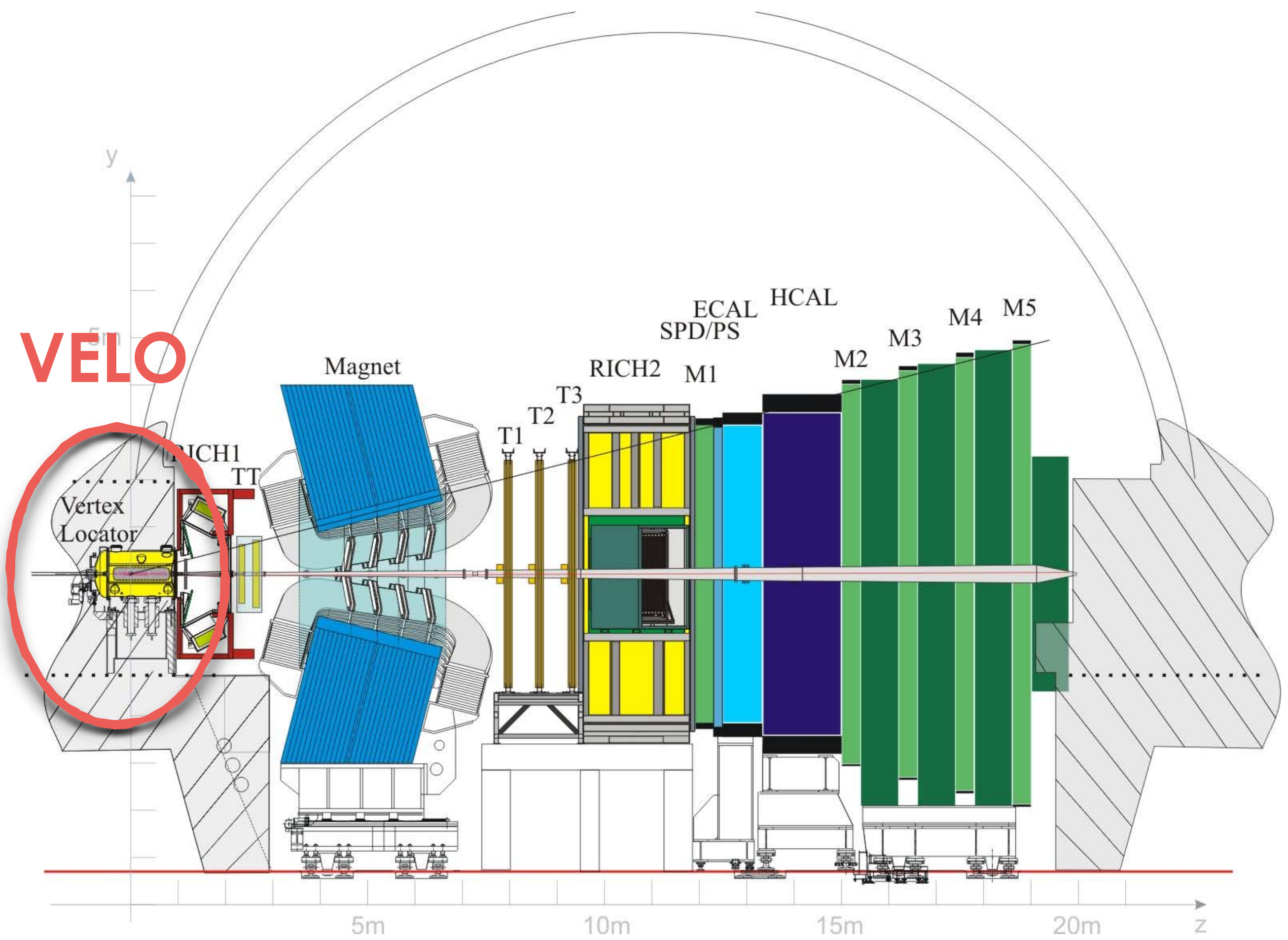
LHCb: Why Upgrade?



Dedicated to the search for New Physics studying beauty and charm mesons decays

- Luminosity of 4 x 10^{32} cm^{-2} s^{-1}
- Integrated luminosity expected to increase to 8 fb^{-1} at the end of Run II (2018)

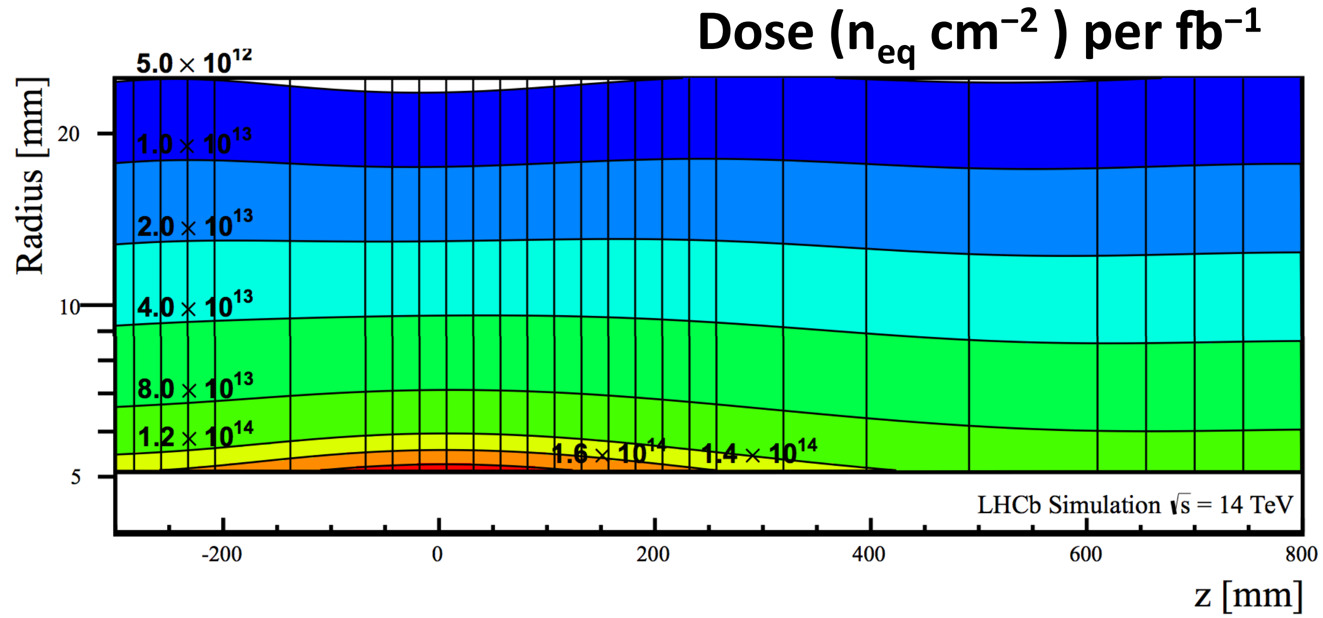
- Increase in precision on key parameters → more statistics needed
- Increase hadronic yield by factor ~10 → increase luminosity to 2 x 10^{33} cm^{-2} s^{-1}
- Limited to 1 MHz readout by hardware trigger → triggerless readout at 40 MHz

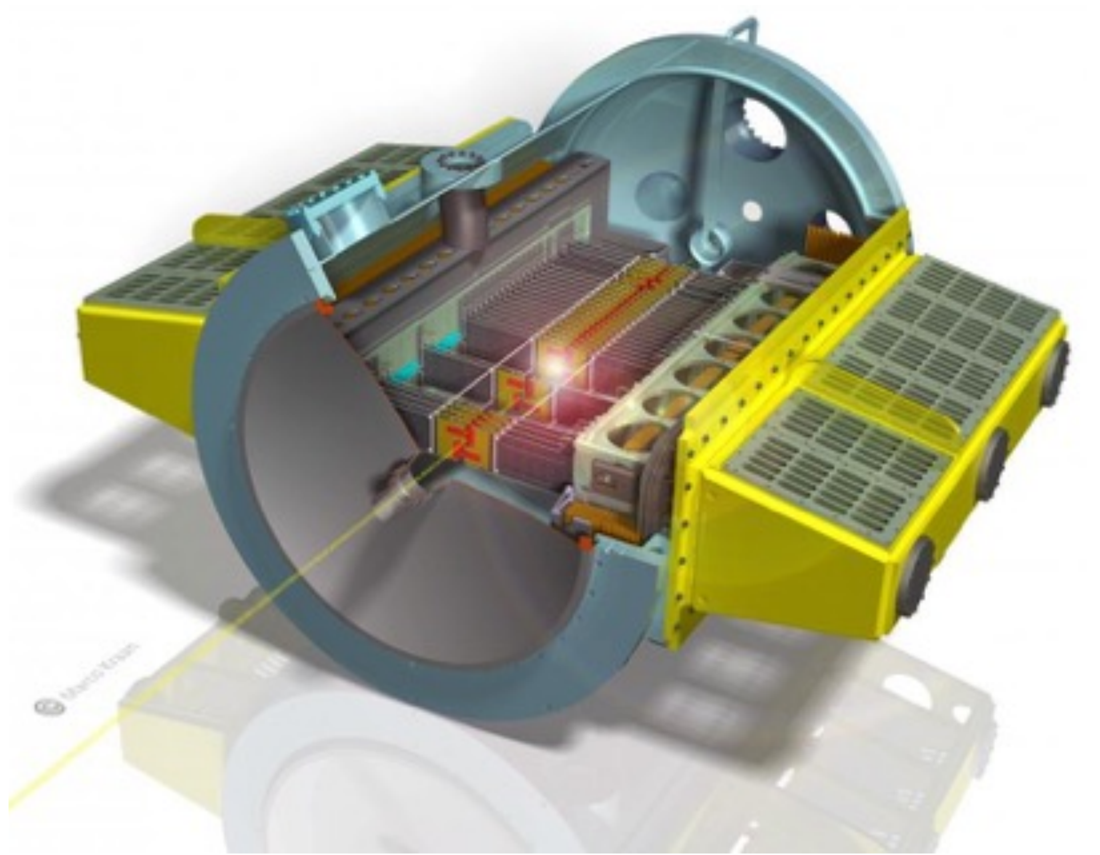
Upgrade of the whole detector planned during LS2 (2019/2020)

VELO Upgrade

Challenges

- Maintain or improve performance of current VELO
- Increased data rate and fluence
- Non uniform radiation exposure:
  - 8×10^{15} n_{eq}/cm^2 at the close edge
  - 0.2×10^{15} n_{eq}/cm^2 at the outer edge
- Minimise material in the acceptance



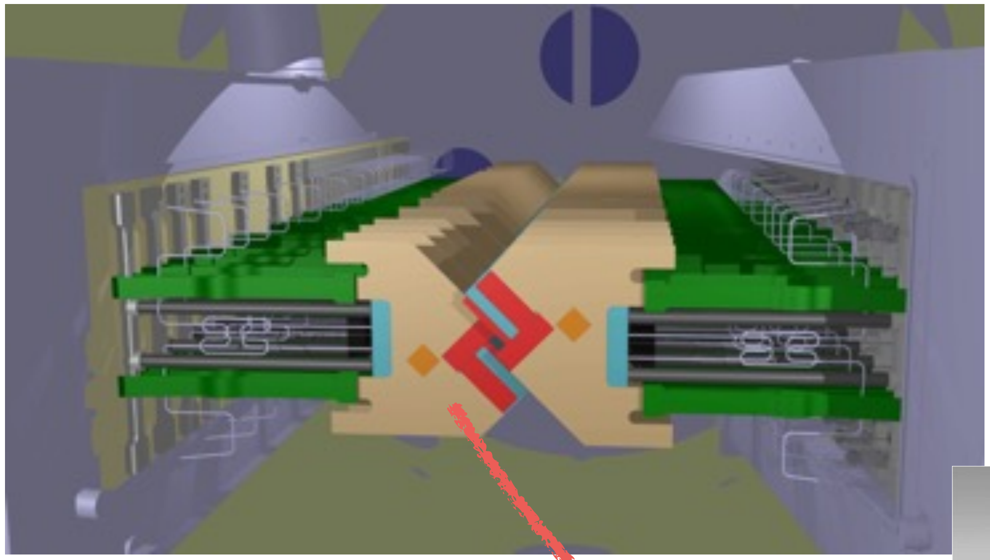


Changes

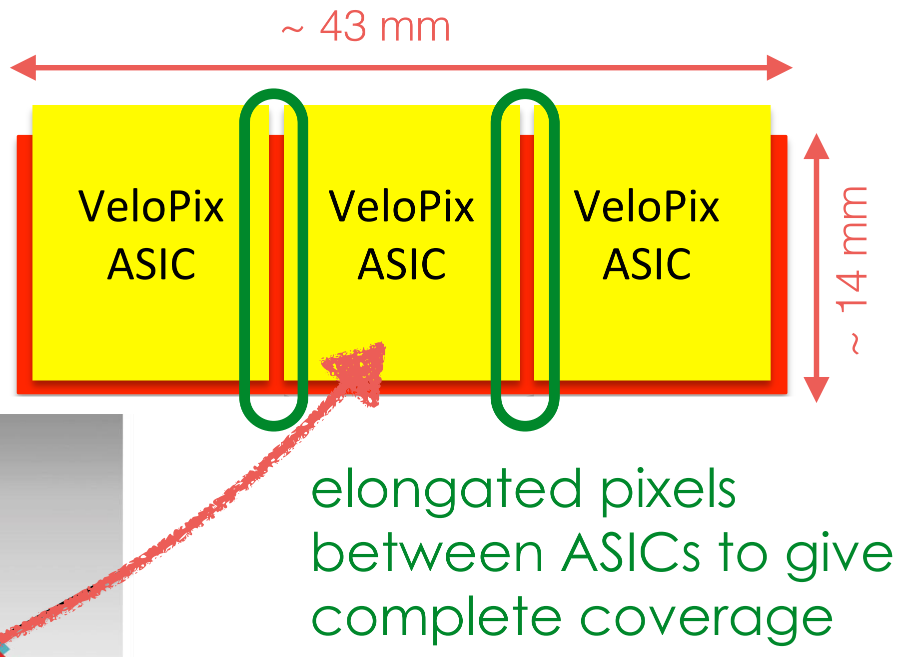
- From strip sensors to hybrid pixel detectors
- Closer to the beam (from 8.2 mm to 5.1 mm)
- CO_2 cooling in micro-channel substrate
- New RF box
- All data to CPU farm

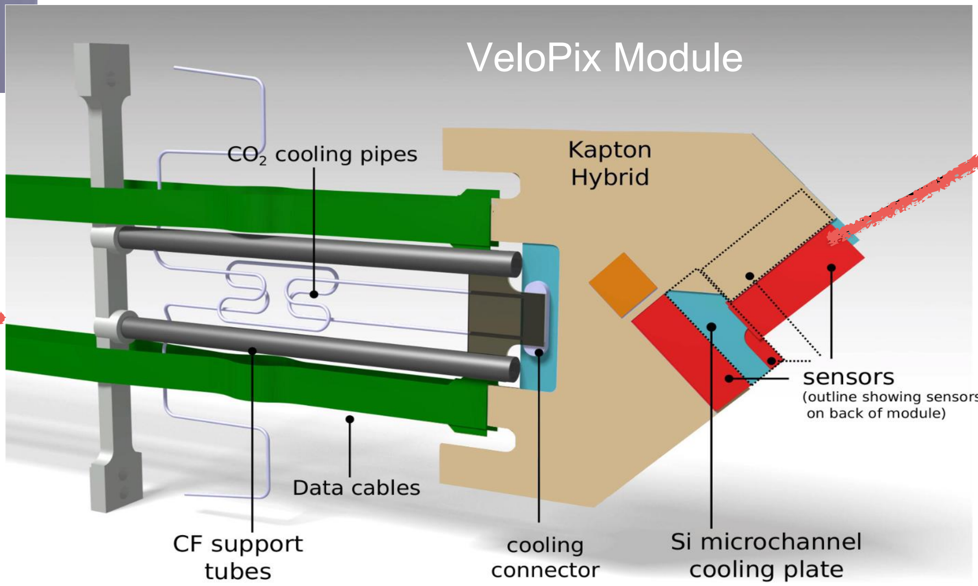
VELO Upgrade

- 52 modules in total (26 per half)



- each sensor bonded to 3 VeloPix ASICs
- 256 x 256 pixels per ASIC





- 2 sensor tiles on the front and 2 on the back
- mounted on silicon substrate etched with CO_2 cooling micro channels

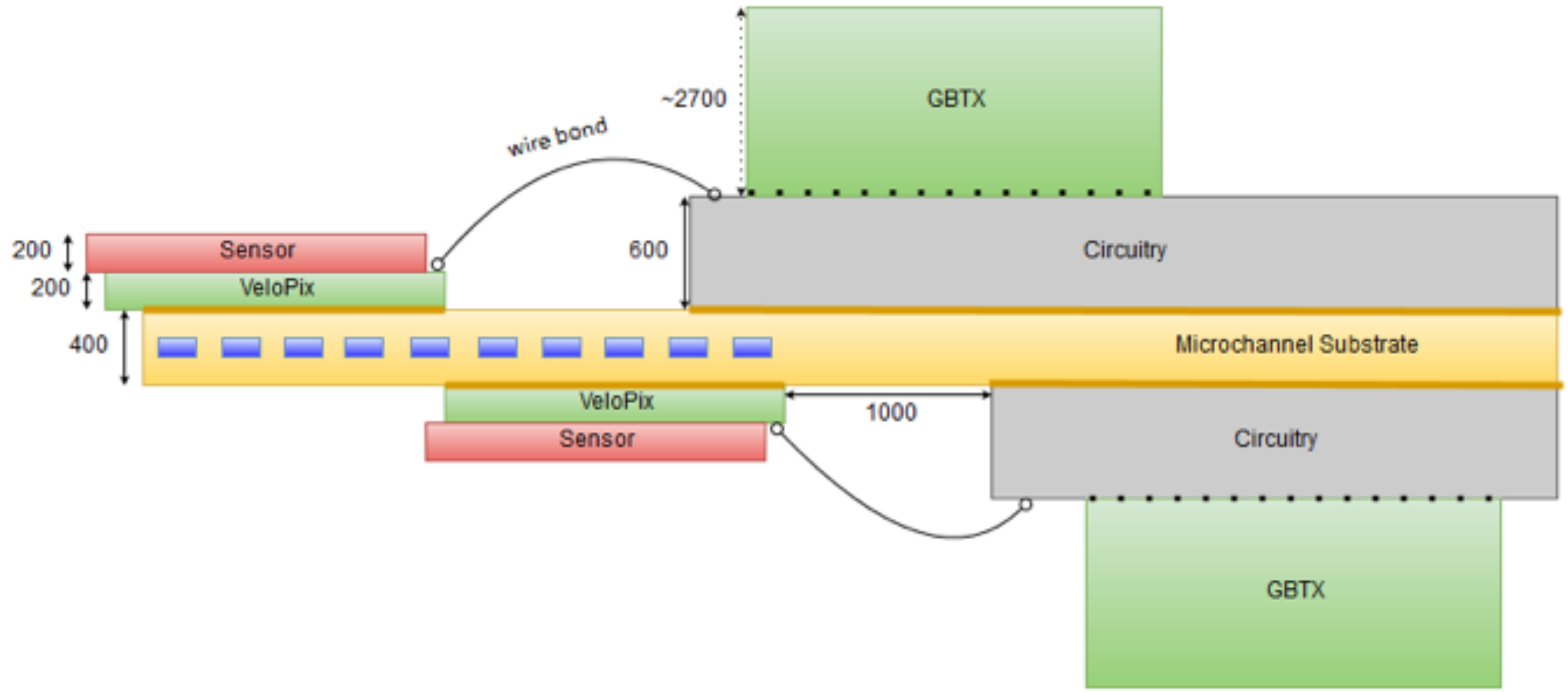
Hybrid Pixel Detector

Sensor

Test and characterisation of prototype sensors from 2 different manufacturers in combination with Timepix3 ASIC

VeloPix

Custom developed ASIC based on Timepix/Medipix family



Hybrid Pixel Detector

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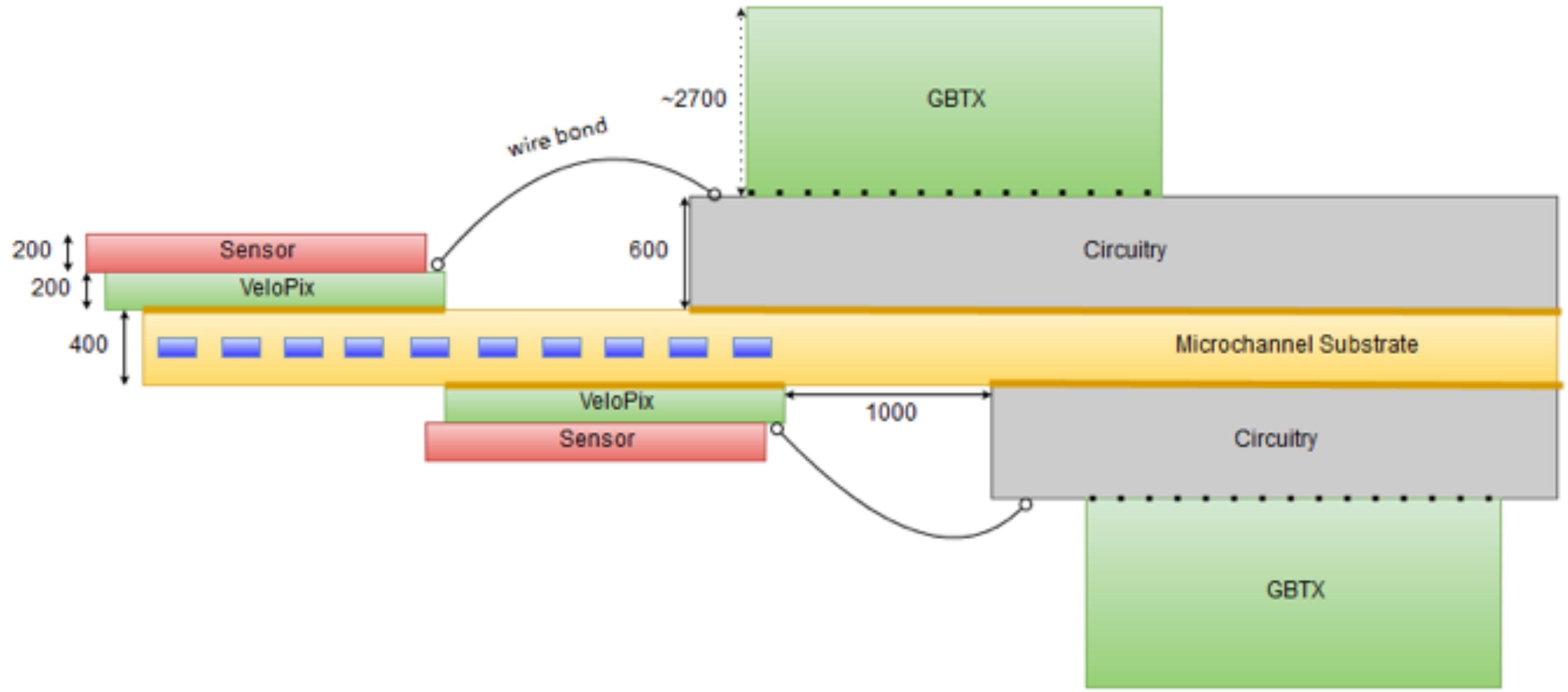
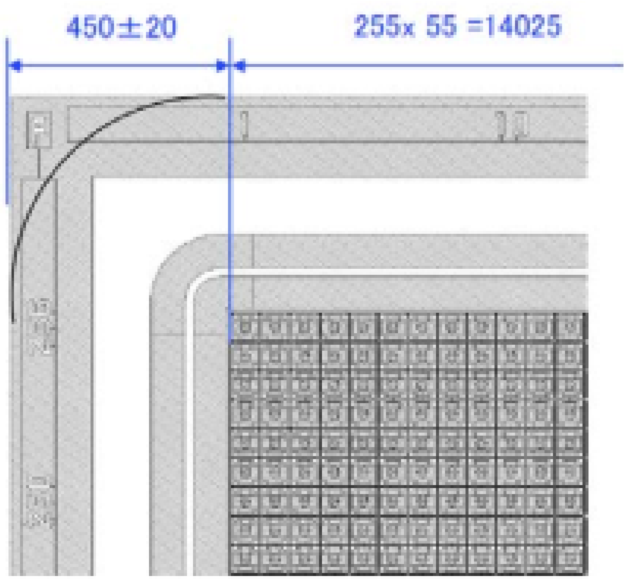


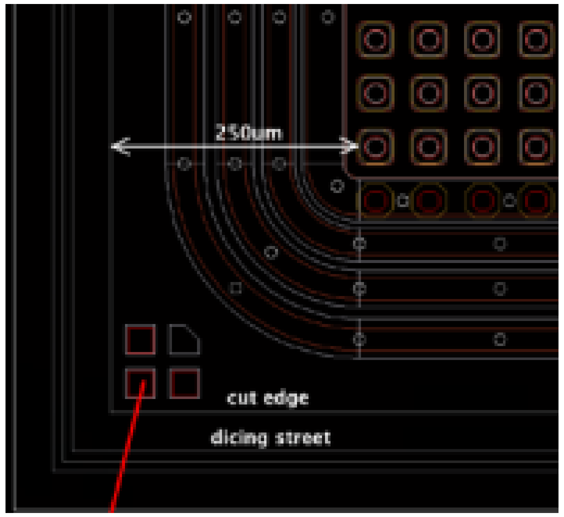
Sensors

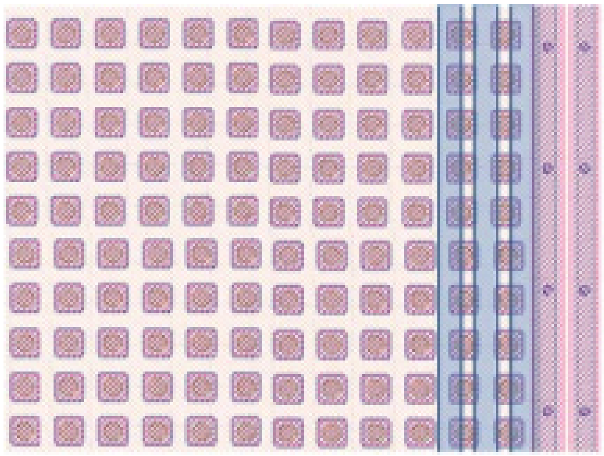
Baseline: n-on-p, 200 µm thick, 450 µm guard ring size

Hamamatsu
- n-on-p (200 µm thick)
- implant width: 35 µm, 39 µm
- guard ring size: 450 µm, 600 µm



Micron
- n-on-p (200 µm thick)
- n-on-n (150 µm thick)
- implant width: 36 µm
- guard ring size:
  450 µm, 250 µm, 150 µm



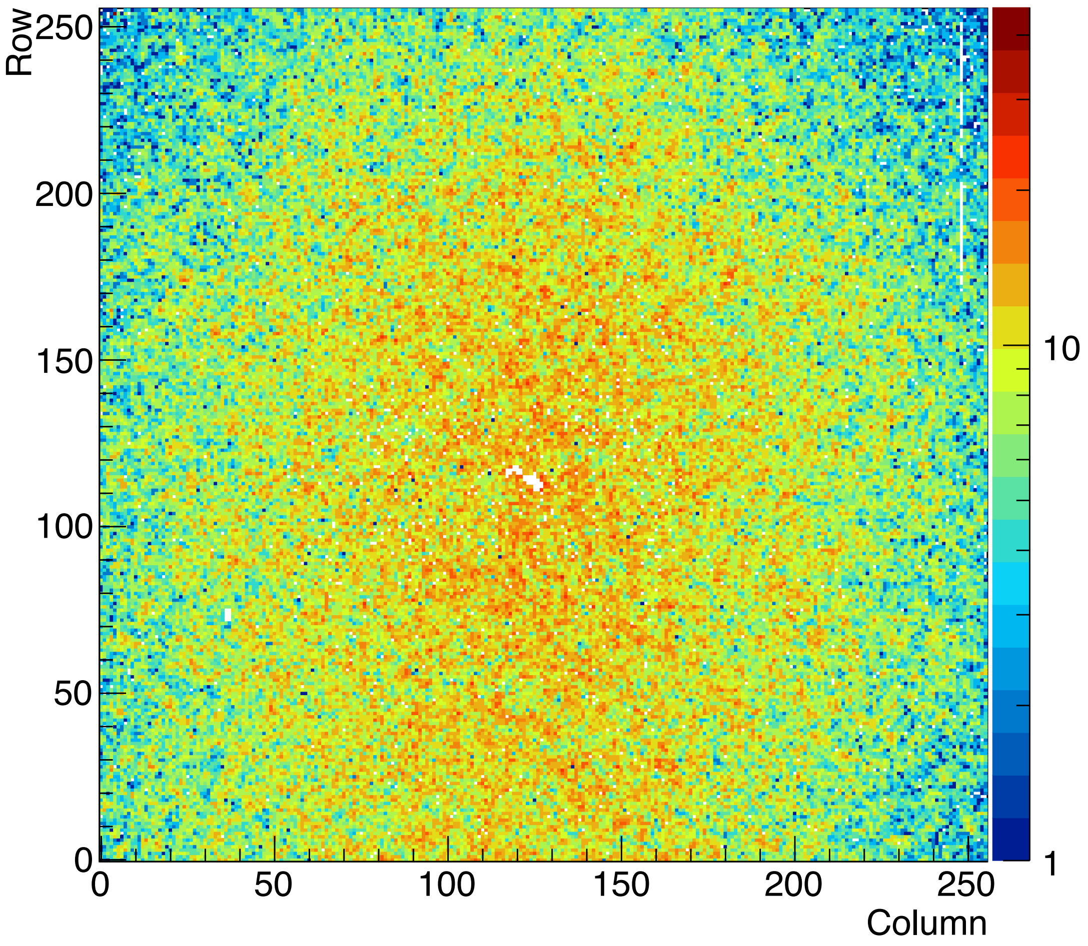


Radiation

The behaviour after irradiation is a key factor in our R&D:

- prototype sensors irradiated at full and half fluence
- uniformly and non-uniformly irradiated to better simulate conditions of the upgraded detector
- neutron and proton irradiated
- Facilities: KIT, IRRAD, JSI, Birmingham

IRRAD

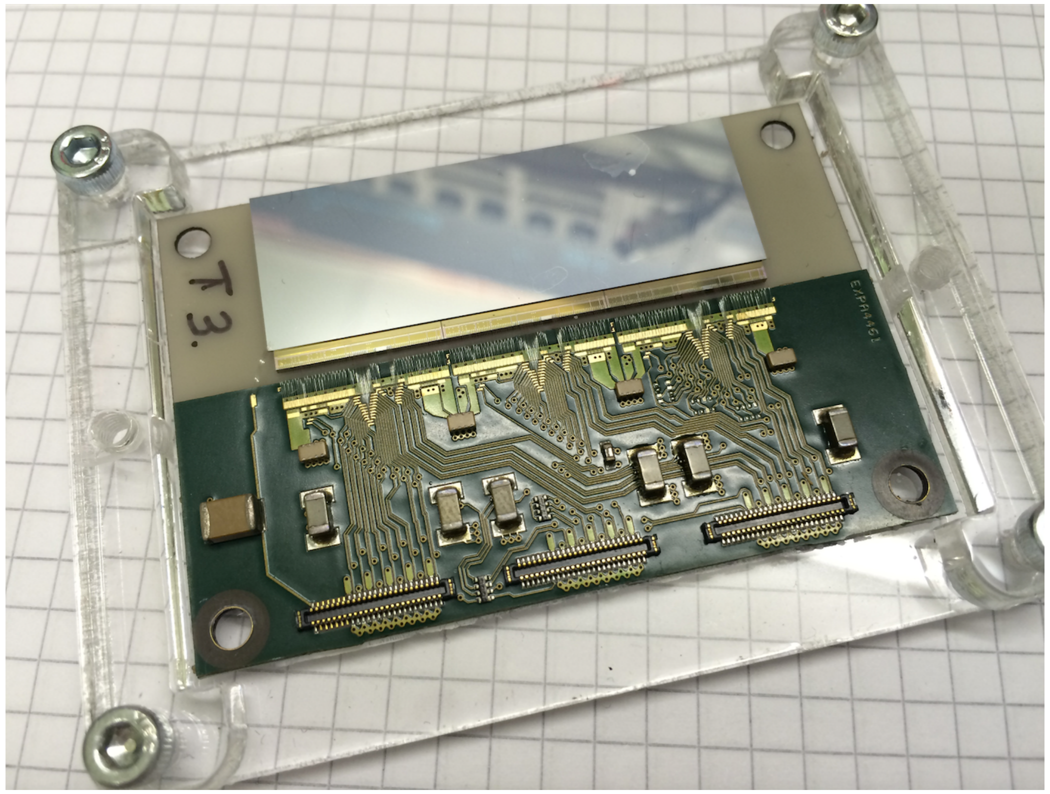


Sensor non-uniformly proton irradiated with the full dose of 8 x 10^{15} n_{eq}/cm^2

Irradiation profile obtained from activity of the assembly itself!

Timepix3

Sensors have been tested so far in combination with Timepix3 ASIC



Timepix3

- matrix 256x256 square pixels
- pixel size 55x55 μm^2
- can measure simultaneously ToA and ToT (can be converted to charge)
- gives a timestamp with 1.6 ns accuracy
- calibration with test pulse, crossed checked with radioactive sources

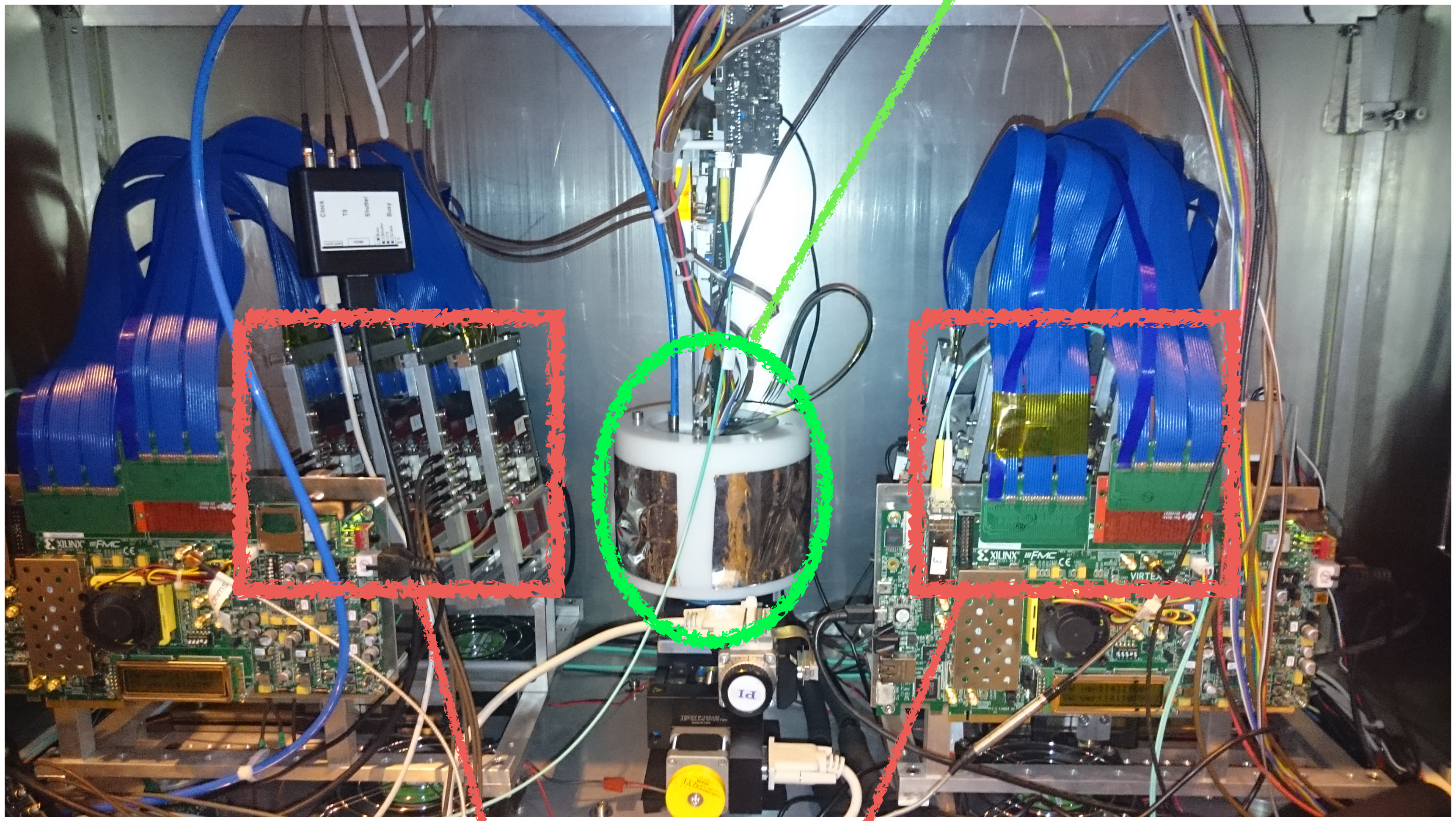
→ this makes Timepix3 ideal for sensor testing!

Timepix3 Telescope

dedicated telescope to provide particle tracking position and timestamp at high rate

- pointing resolution ~2 µm for a 180 GeV beam
- time resolution ~1 ns
- up to 5 million tracks/s reconstructed

Device Under Test



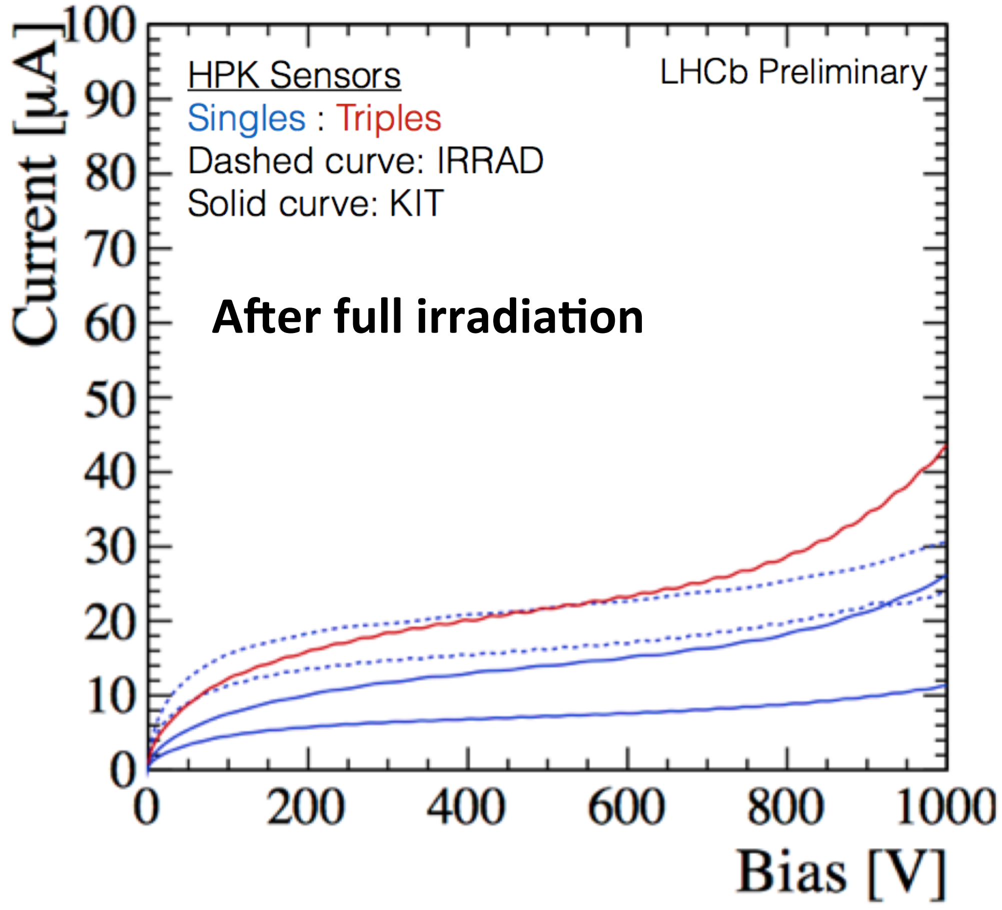
4 + 4 Timepix3 planes

Sensor Requirements

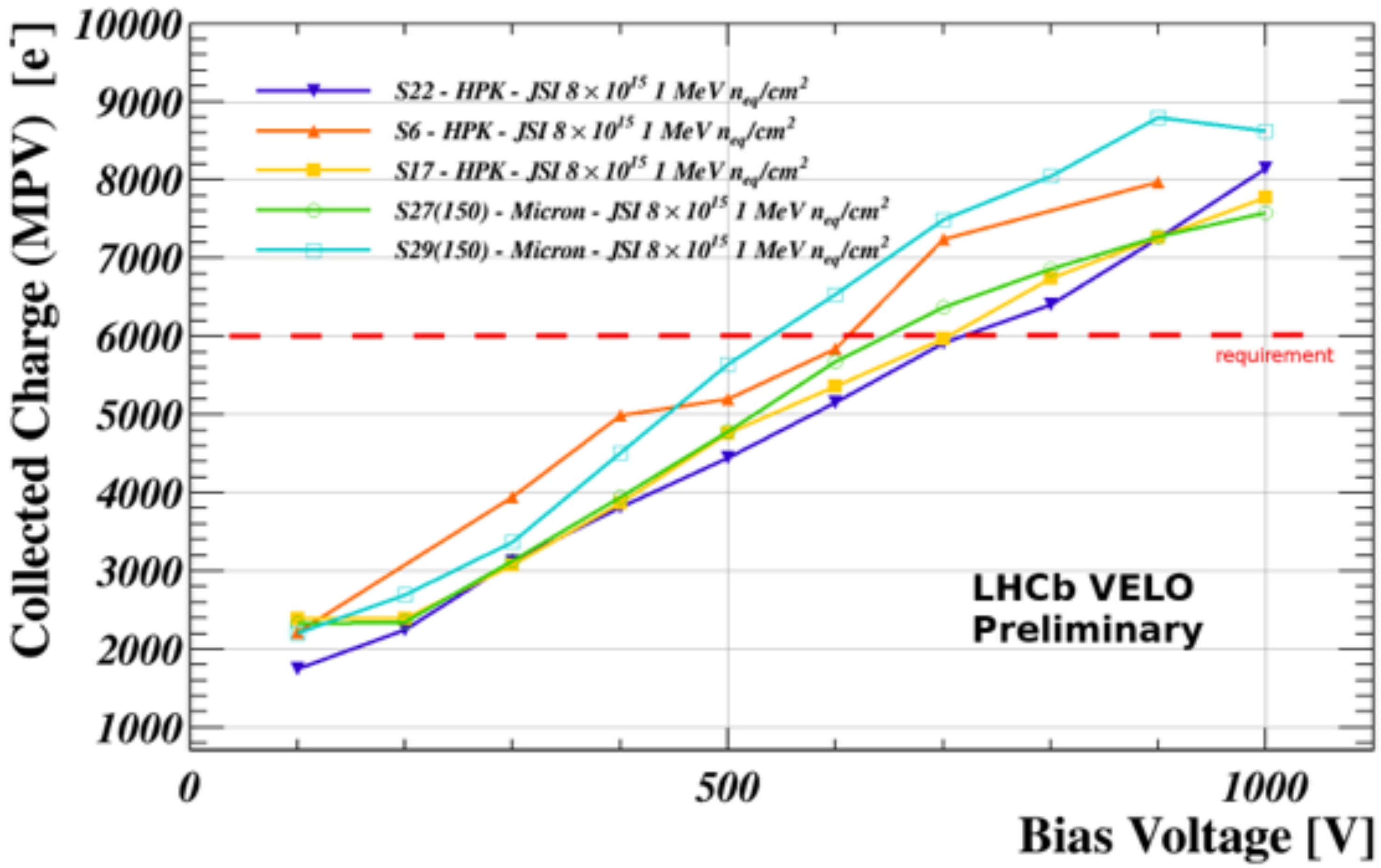
	Requirement	HPK	Micron n-on-p	Micron n-on-n
HV tolerance	>1000 V			
Charge Collection	> 6000 e-			
Efficiency	> 99% uniform			
Spatial Resolution	excellent			
Edge Effect	none			

HV Tolerance & Charge Collection

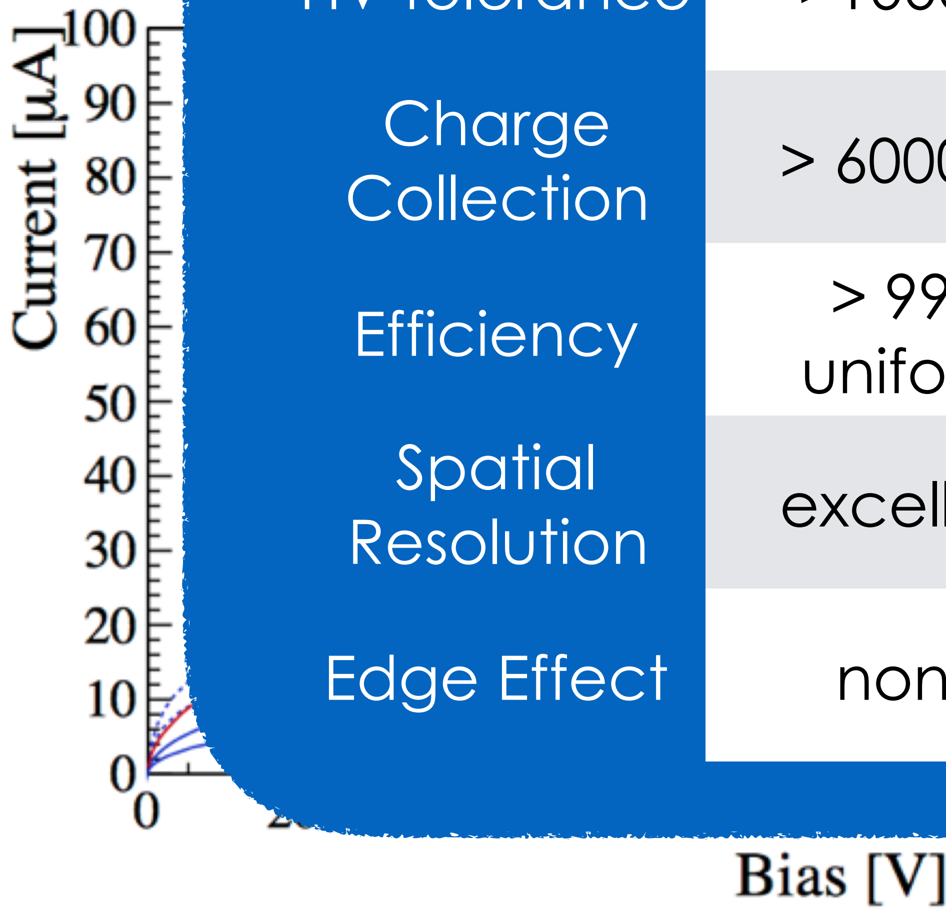
Sensors must withstand
-1000 V after full irradiation



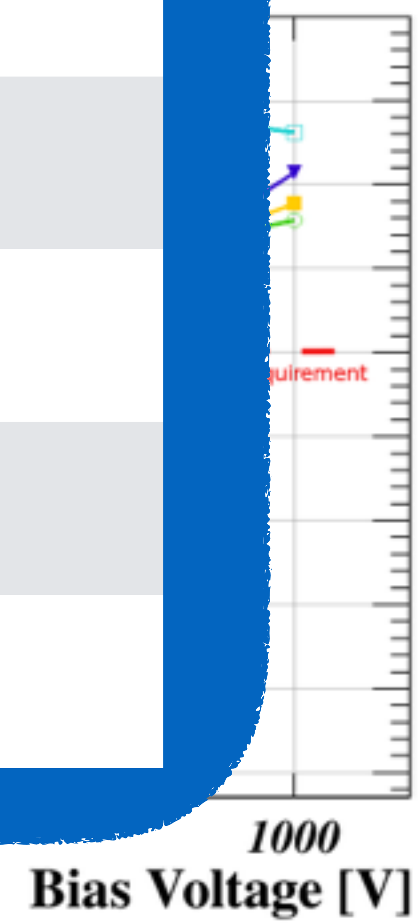
Sensors must collect >6000 e- at
-1000 V after full irradiation



HV Tolerance & Charge Collection



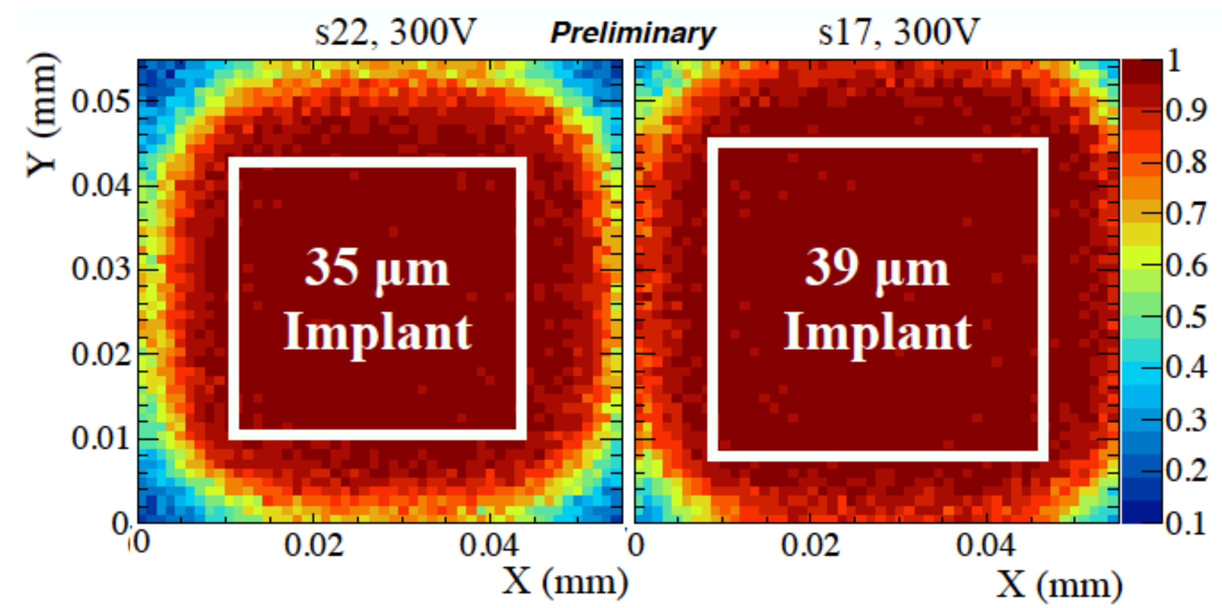
	Requirement	HPK	Micron n-on-p	Micron n-on-n
HV tolerance	>1000 V	✔	✔	✔
Charge Collection	> 6000 e-	✔	✔	✔
Efficiency	> 99% uniform			
Spatial Resolution	excellent			
Edge Effect	none			

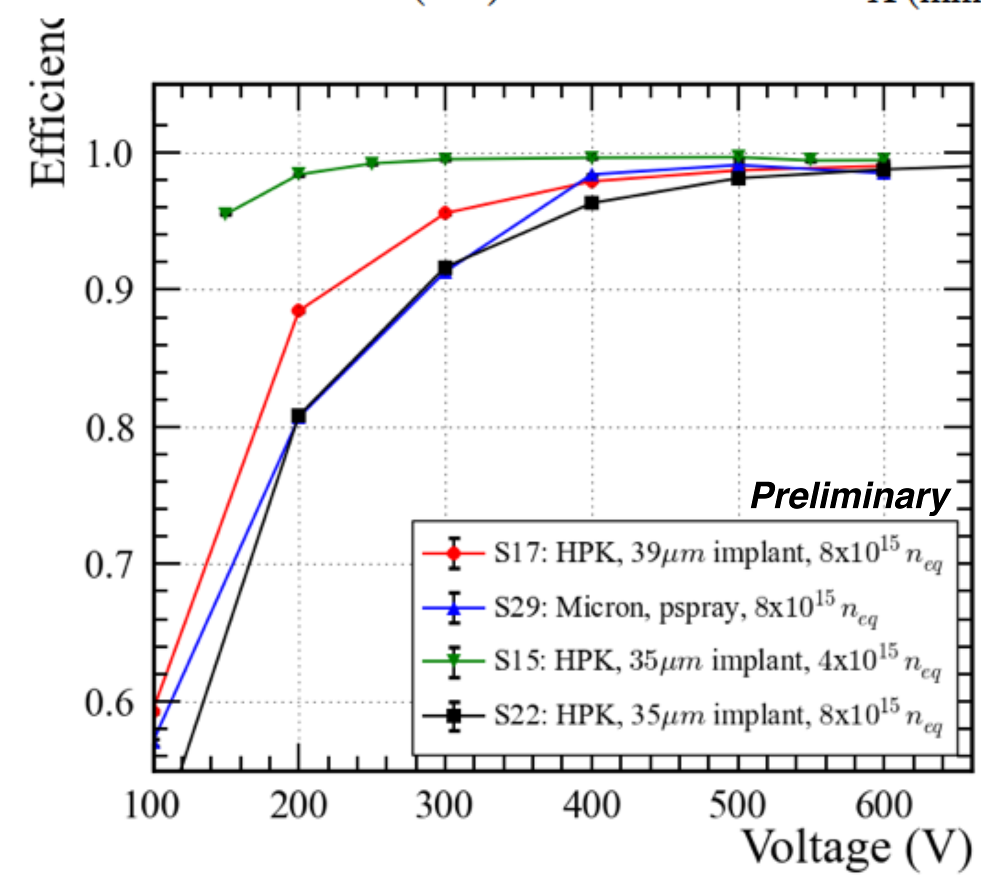


Efficiency

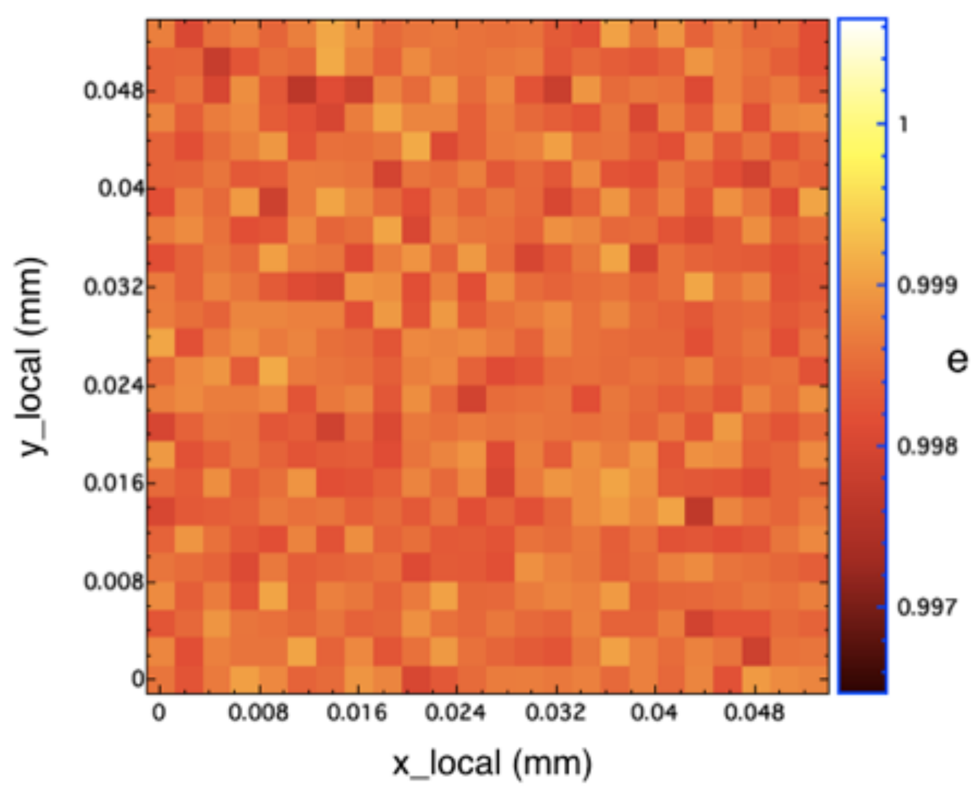
Cluster finding efficiency must be >99% and uniform among the sensor

Uniformly irradiated





Non irradiated at depletion V



Efficiency

Uniformly irradiated

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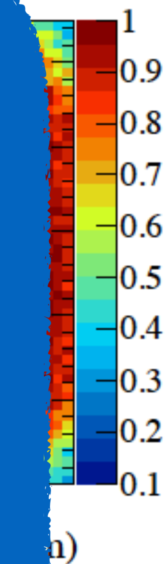
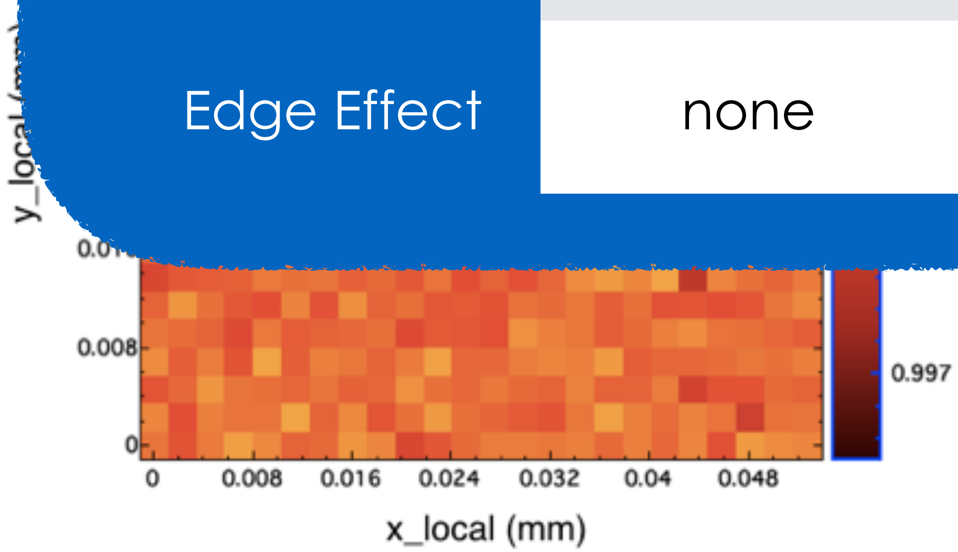
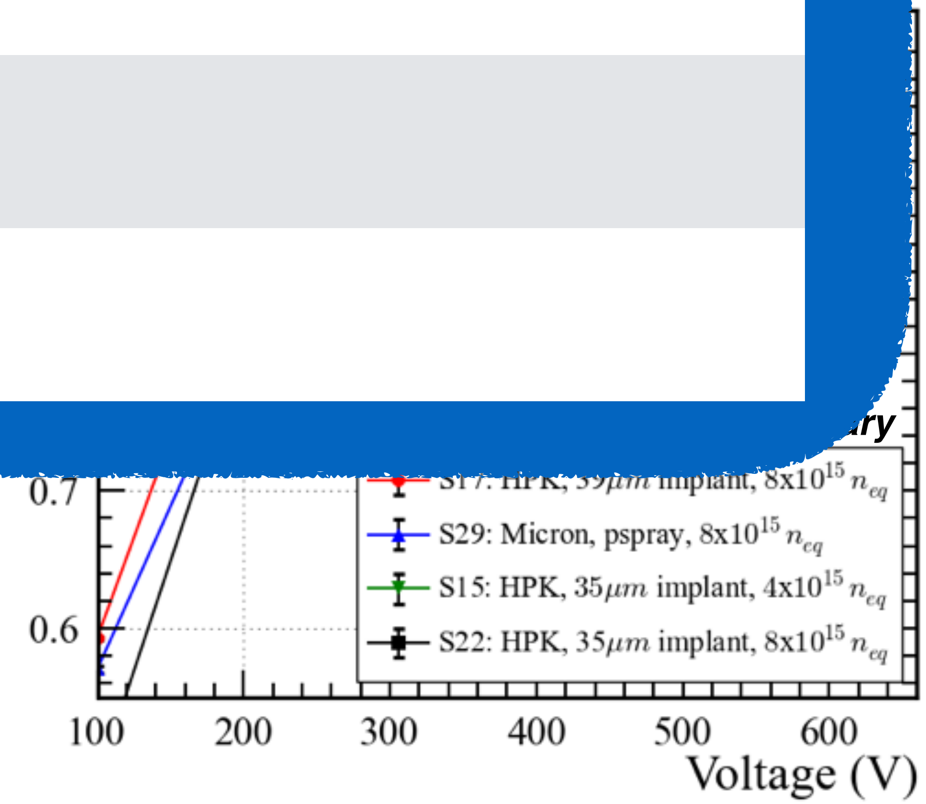
	Requirement	HPK	Micron n-on-p	Micron n-on-n
HV tolerance	>1000 V	✔	✔	✔
Charge Collection	> 6000 e-	✔	✔	✔
Efficiency	> 99% uniform	✔	✔	✔
Spatial Resolution	excellent			
Edge Effect	none			

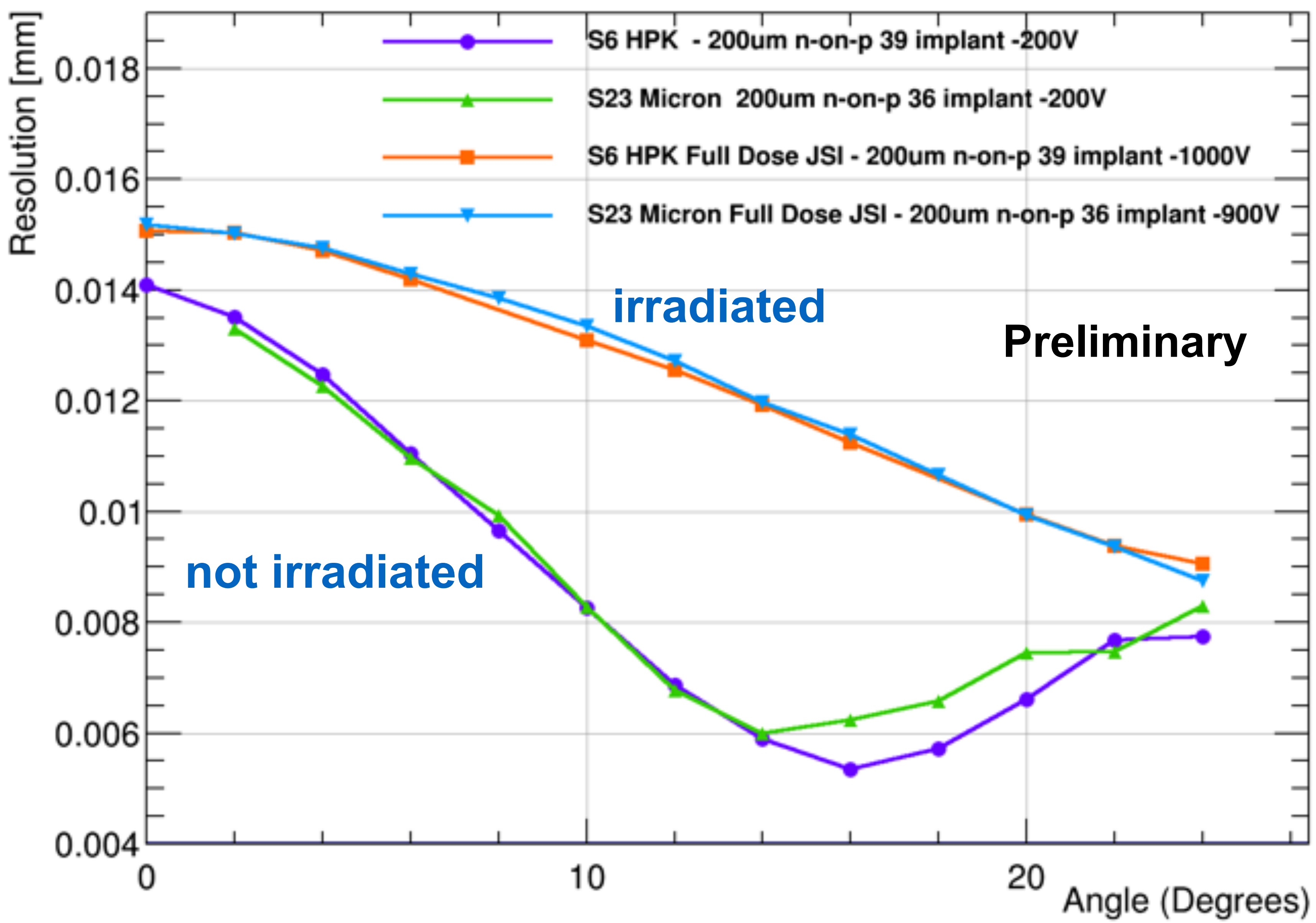






Resolution

The spatial resolution must be excellent even after full irradiation



Resolution

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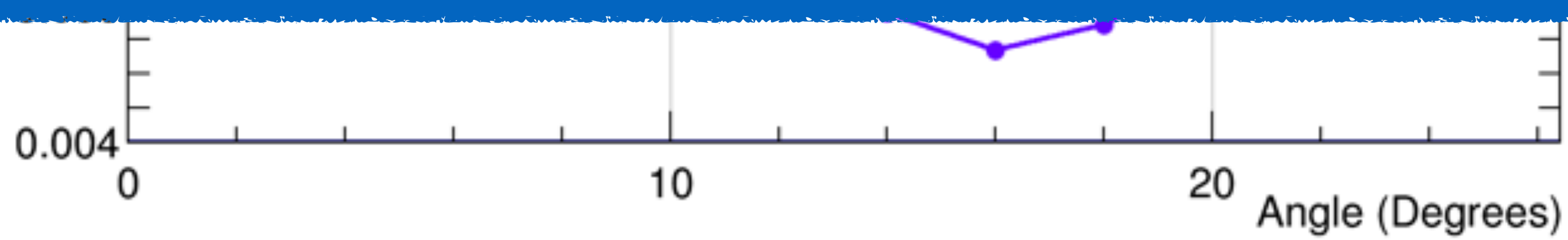
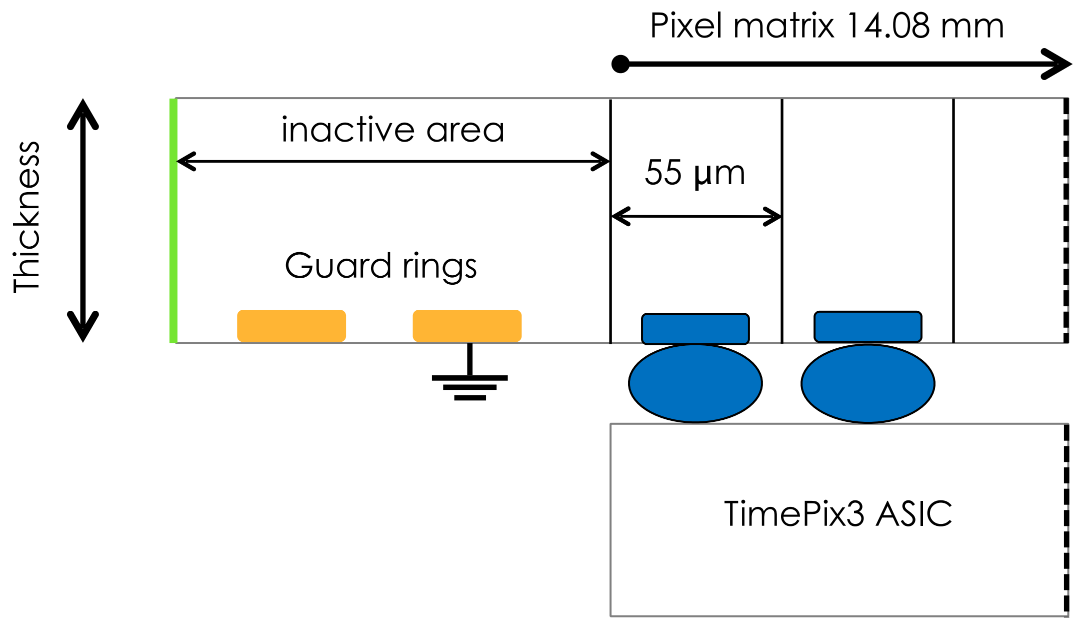
	Requirement	HPK	Micron n-on-p	Micron n-on-n
HV tolerance	>1000 V	✔	✔	✔
Charge Collection	> 6000 e-	✔	✔	✔
Efficiency	> 99% uniform	✔	✔	✔
Spatial Resolution	excellent	✔	✔	✔
Edge Effect	none			



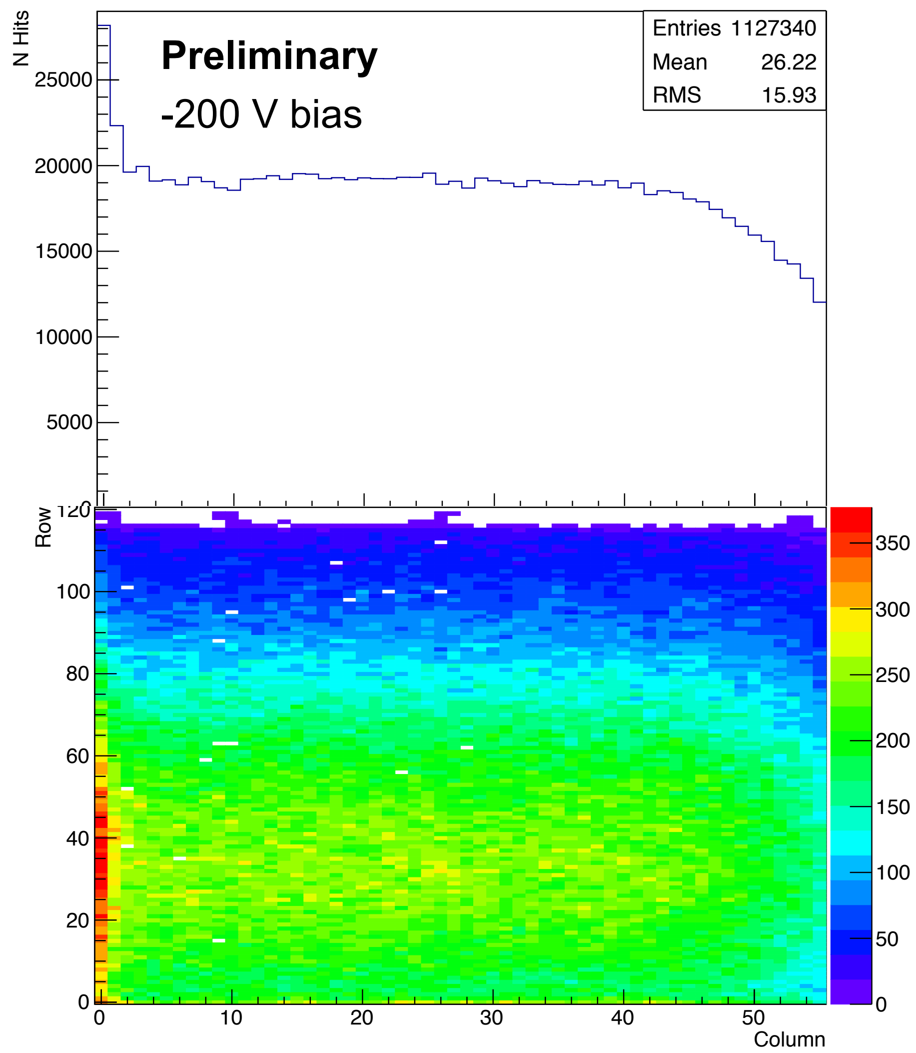
Edge Effect

The sensors must be fully efficient up to the edge

distortions of the electric field that would lead to a worse spatial resolution should be avoided



Micron n-on-p



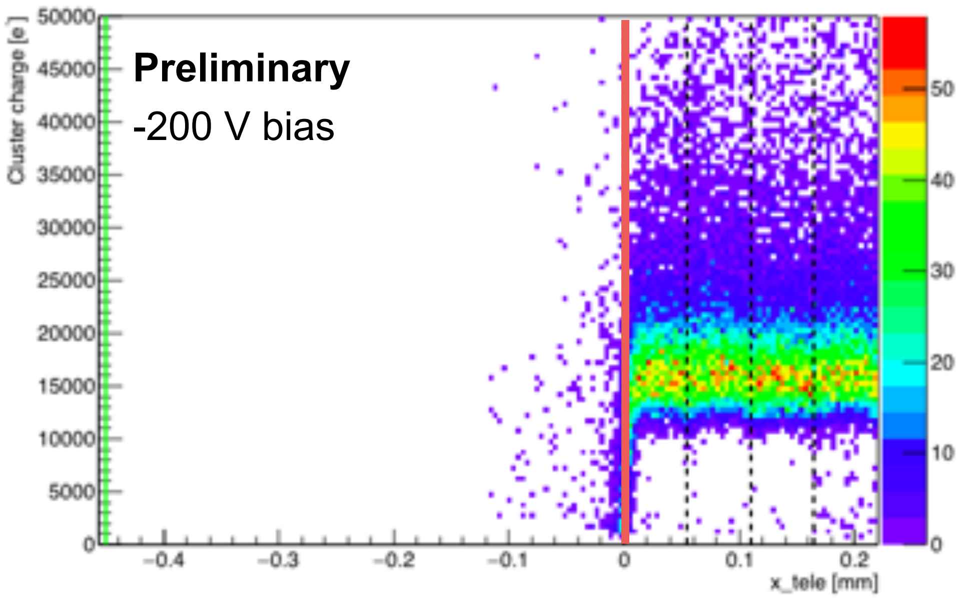
Excess of hits in the first column!

...leading to:

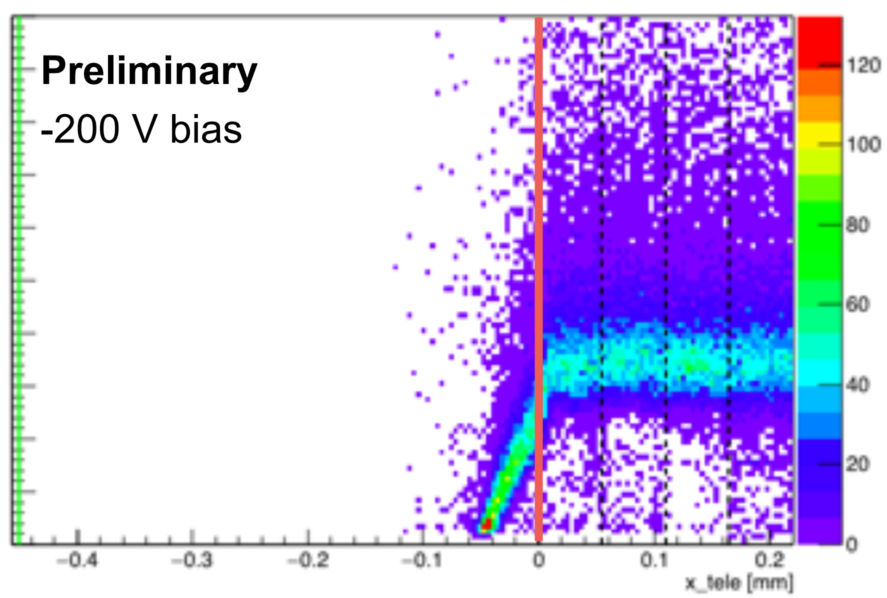
- higher occupancy and data rate issue
- worse resolution for the first measured point

Edge Effect

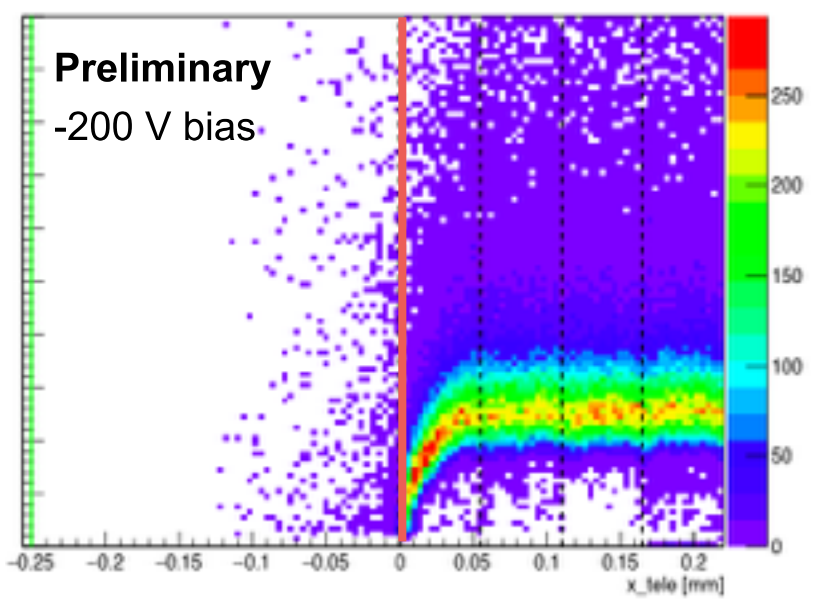
HPK



Micron n-on-p



Micron n-on-n



Expected behaviour

First column collects charge from tracks going through the guard ring area

Loss of efficiency in the first column: charge is drained by the guard rings

See poster for the detailed study!!

The angle runs allow to understand that the charge distribution is due to a tilted collection region

Edge Effect

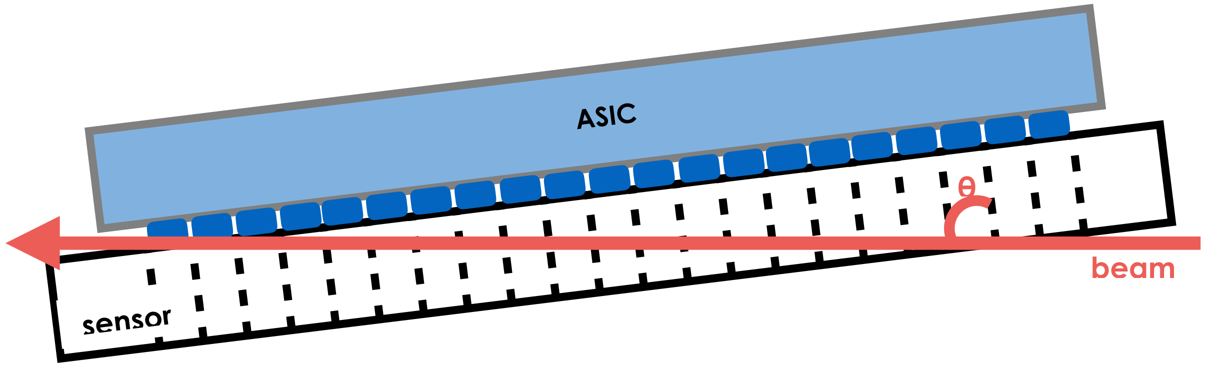
	Requirement	HPK	Micron n-on-p	Micron n-on-n
HV tolerance	>1000 V	✔	✔	✔
Charge Collection	> 6000 e-	✔	✔	✔
Efficiency	> 99% uniform	✔	✔	✔
Spatial Resolution	excellent	✔	✔	✔
Edge Effect	none	✔	X	X

For the next round of prototype testing Micron will provide a new design:
2 extra rows and columns of floating pixels to drain the charge

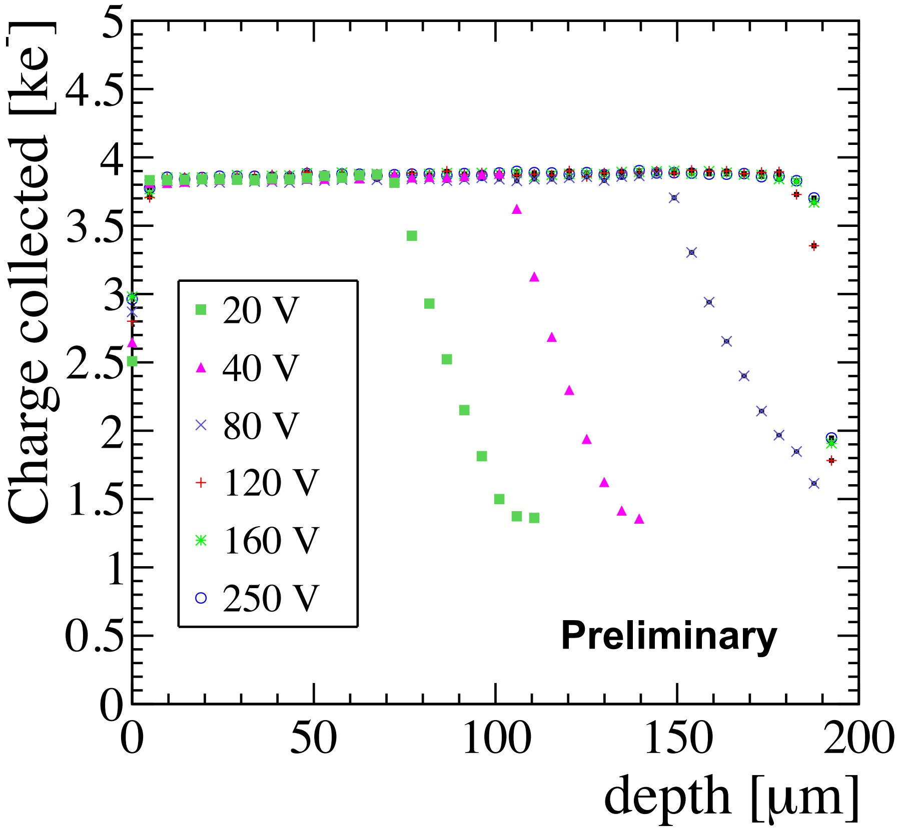
Grazing Angles

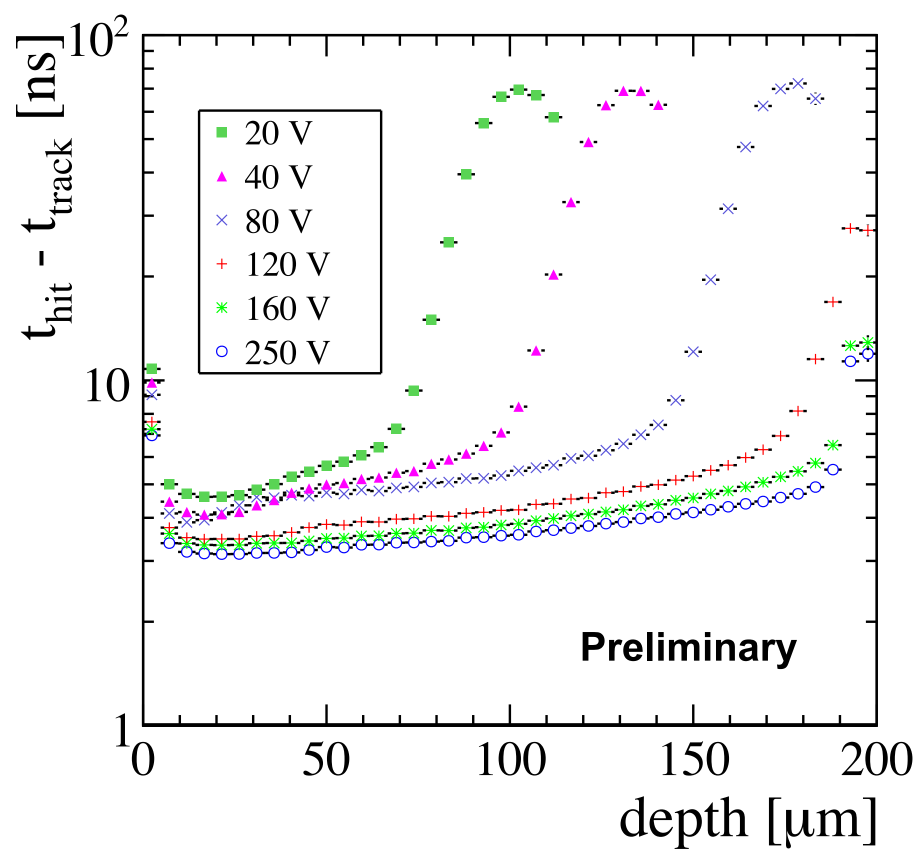
The grazing angle technique consists in rotating the sensor a very large angle with respect to the beam to study:

- Charge collection as a function of depth
- Time required to cross the threshold as a function of depth



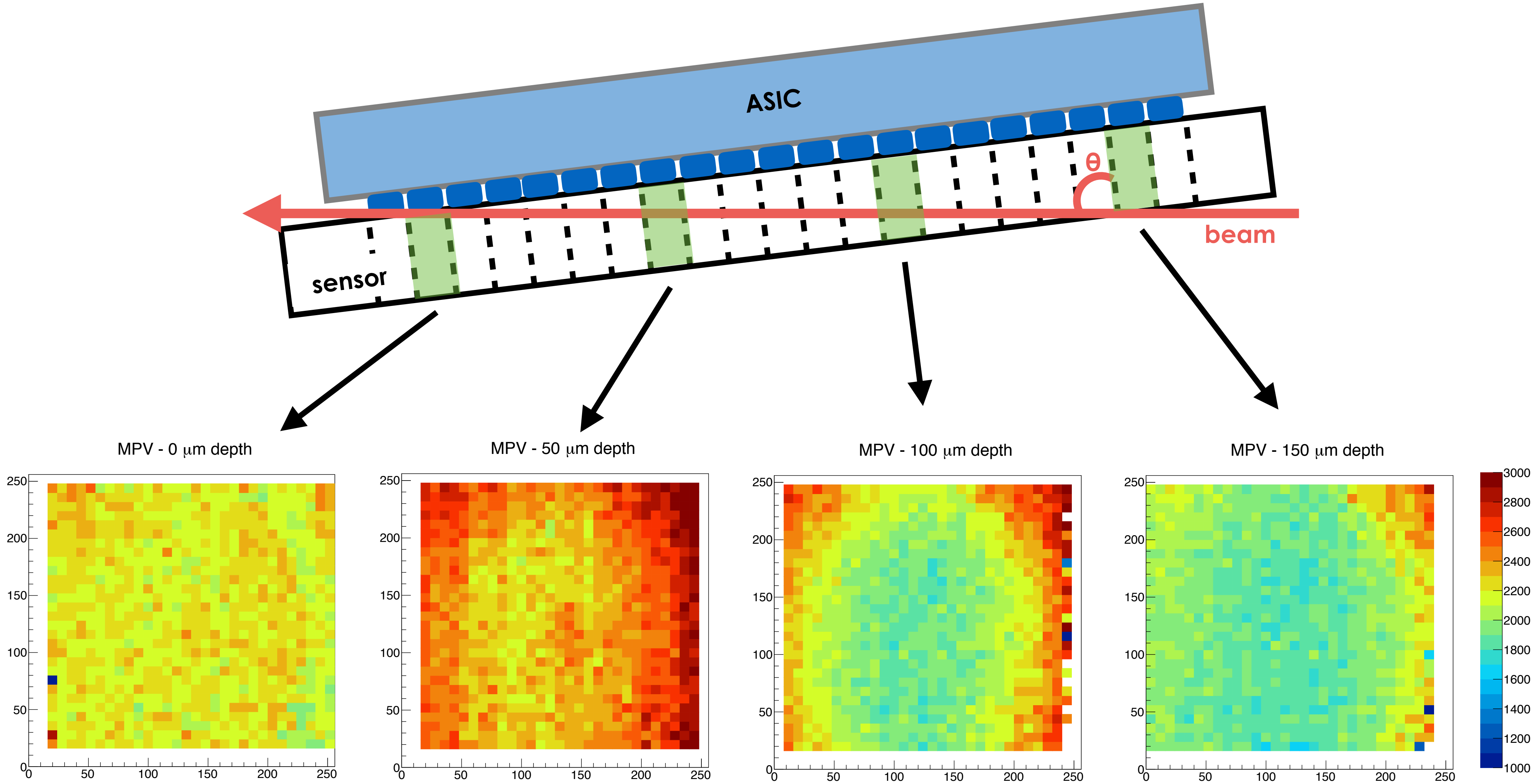
HPK non-irradiated HV -200V





Grazing Angles

We can also see the irradiation profile at different depths due to the effect of the effective depletion region!



Micron n-on-n IRRAD
HV -850V angle 83 deg

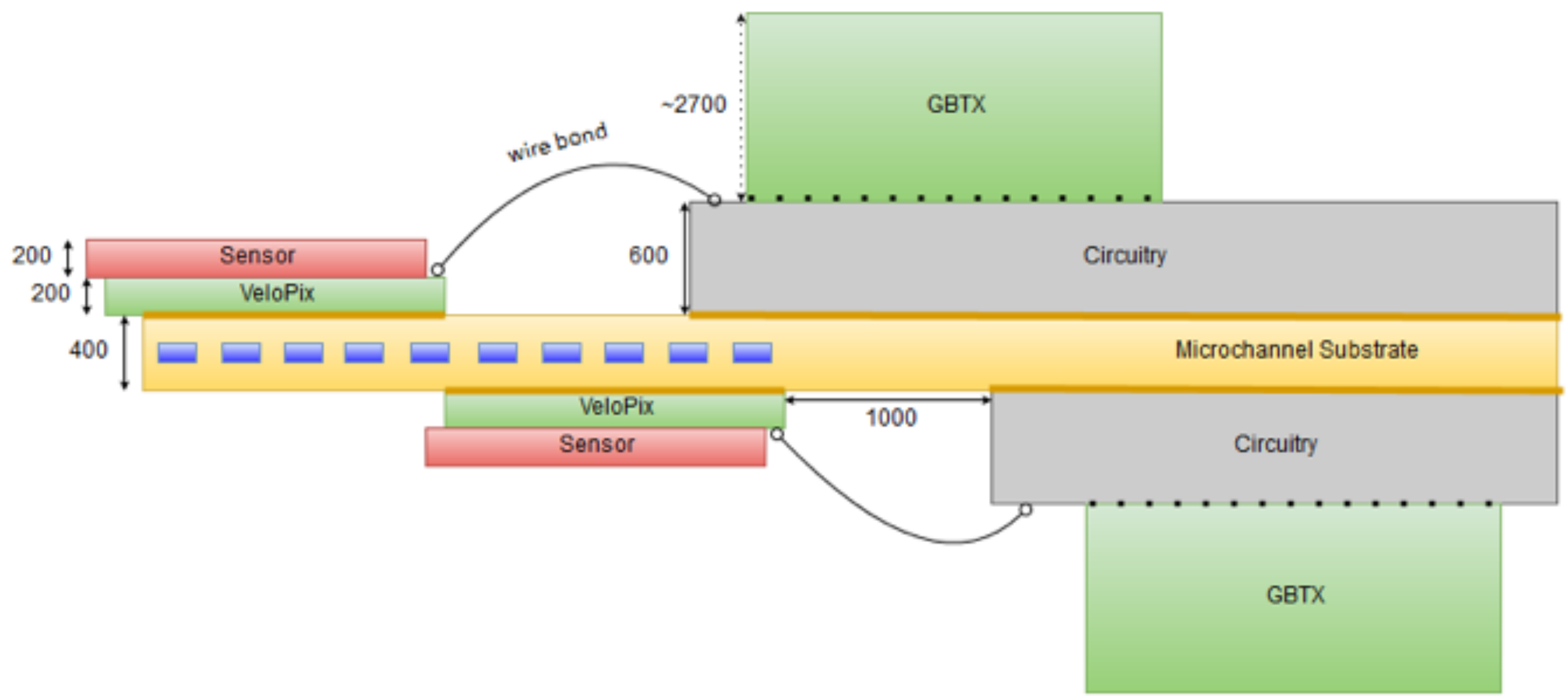
Hybrid Pixel Detector

Sensor

Test and characterisation of prototype sensors from 2 different manufacturers in combination with Timepix3 ASIC

VeloPix

Custom developed ASIC based on Timepix/Medipix family



VeloPix vs Timepix3

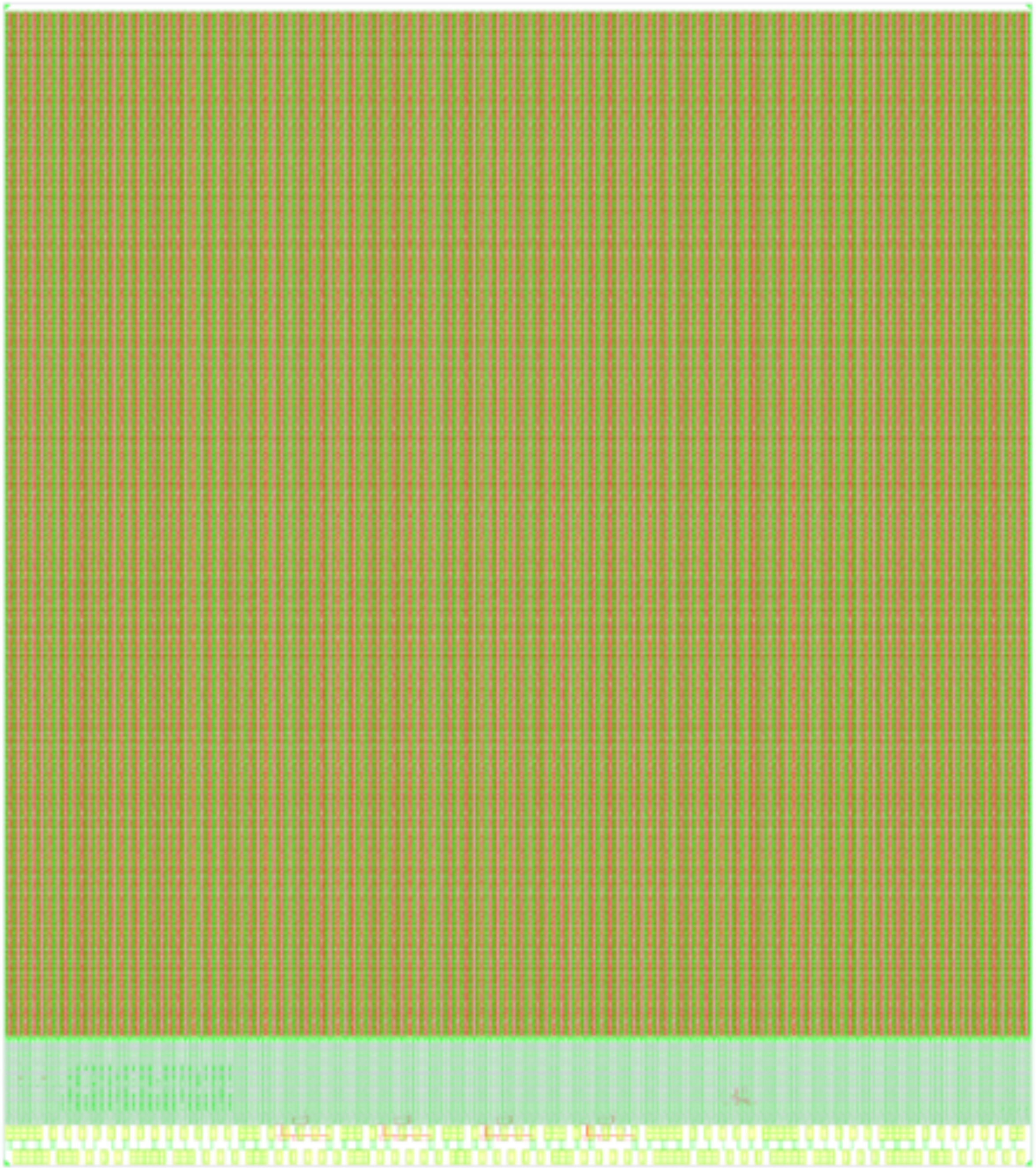
	Timepix3	VeloPix
Readout Type	continuous, triggerless, ToT	continuous, triggerless, binary
Timing Resolution	1.6 ns	25 ns
Power Consumption	< 1.0 W cm^{-2}	< 1.5 W cm^{-2}
Pixel Matrix, Pixel Size	256 x 256, 55 x 55 μm^2	256 x 256, 55 x 55 μm^2
Radiation Hardness	not specified	400 Mrad, SEU tolerant
Peak Hit Rate	80 Mhits/s/ASIC	900 Mhits/s/ASIC
Sensor Type	various, e- and h+ collection	planar silicon, e- collection
Max Data Rate	5.12 Gbps	20.48 Gbps
Technology	130 nm CMOS	130 nm CMOS

radiation hardness

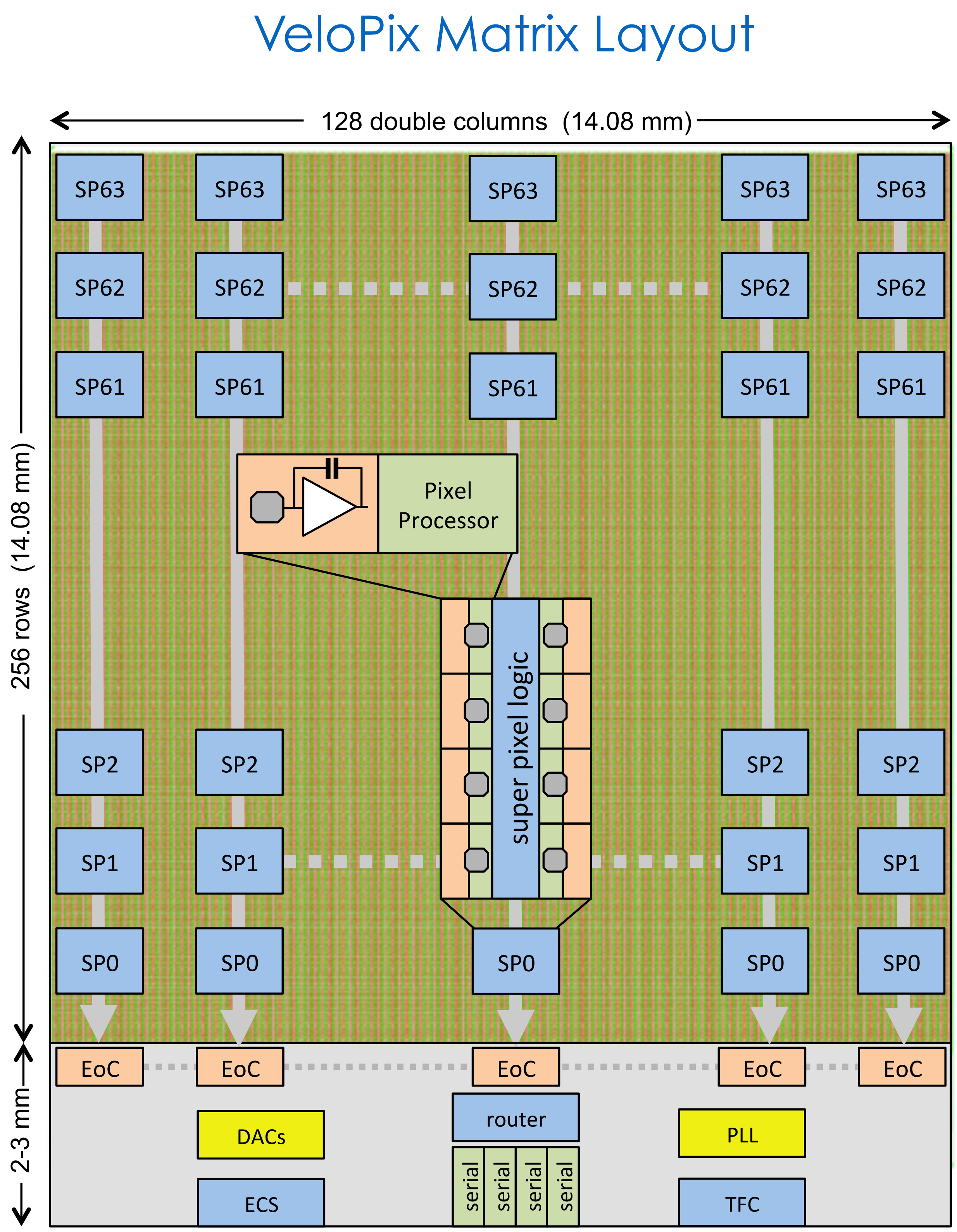
increased data rate!

VeloPix Architecture

VeloPix Matrix Layout



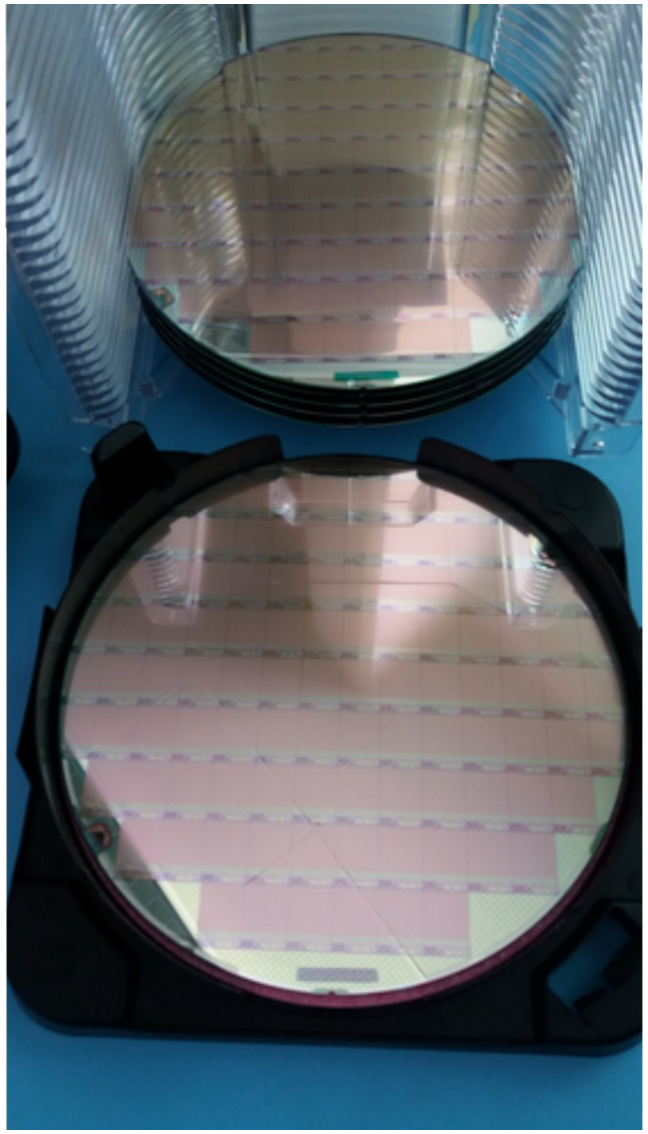
VeloPix Architecture



- Super-pixel packet (2x4 pixels): 30% reduction of the data rate vs single-pixel
- Analog front-end sets 2 thresholds (chip-wide and trim DAC) + digital threshold on hit charge
- Data gathered column wise in the EoC logic
- Data from EoC routed to 4 output serialisers

VeloPix Status

- Design started in June 2013
- VeloPix submitted on May 26th after 3 year design
- Wafers back August 31st
- Fabricated and diced chips back at CERN on September 7th
- Irradiation campaign in the future bump bonded to sensors

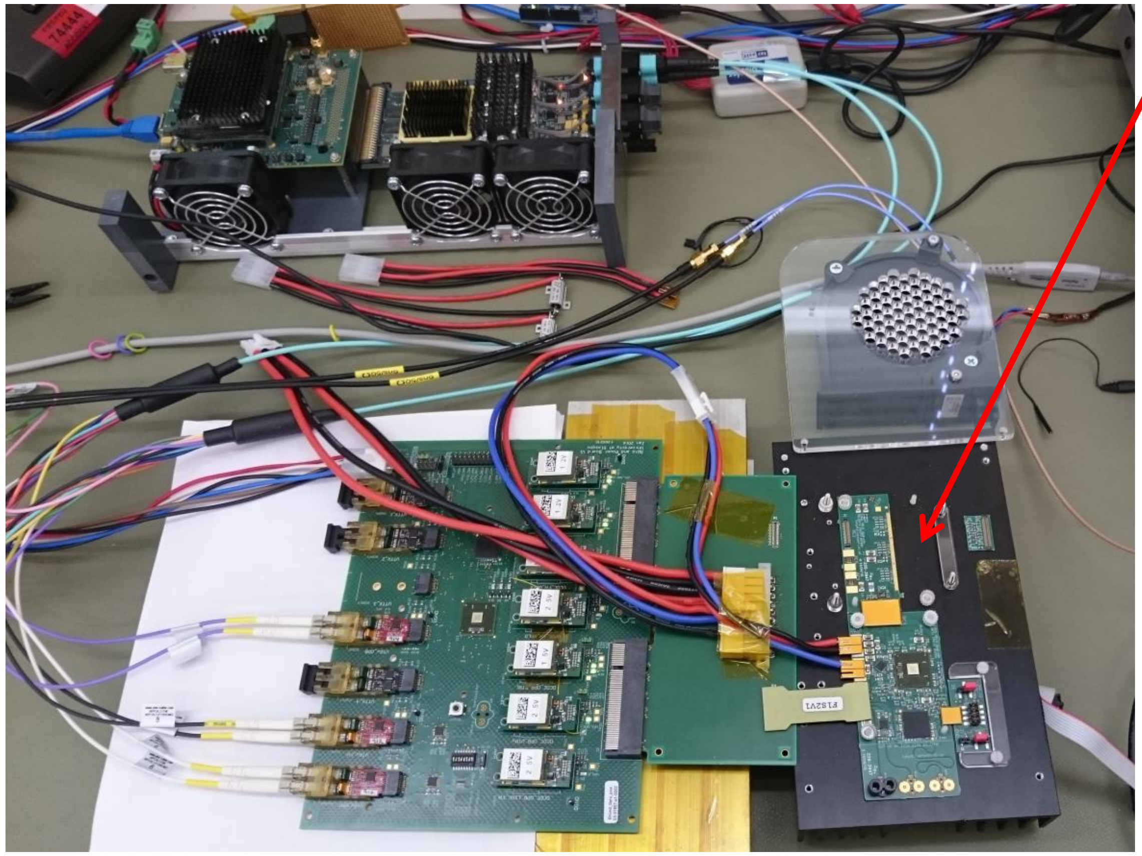


Large number of tests planned:

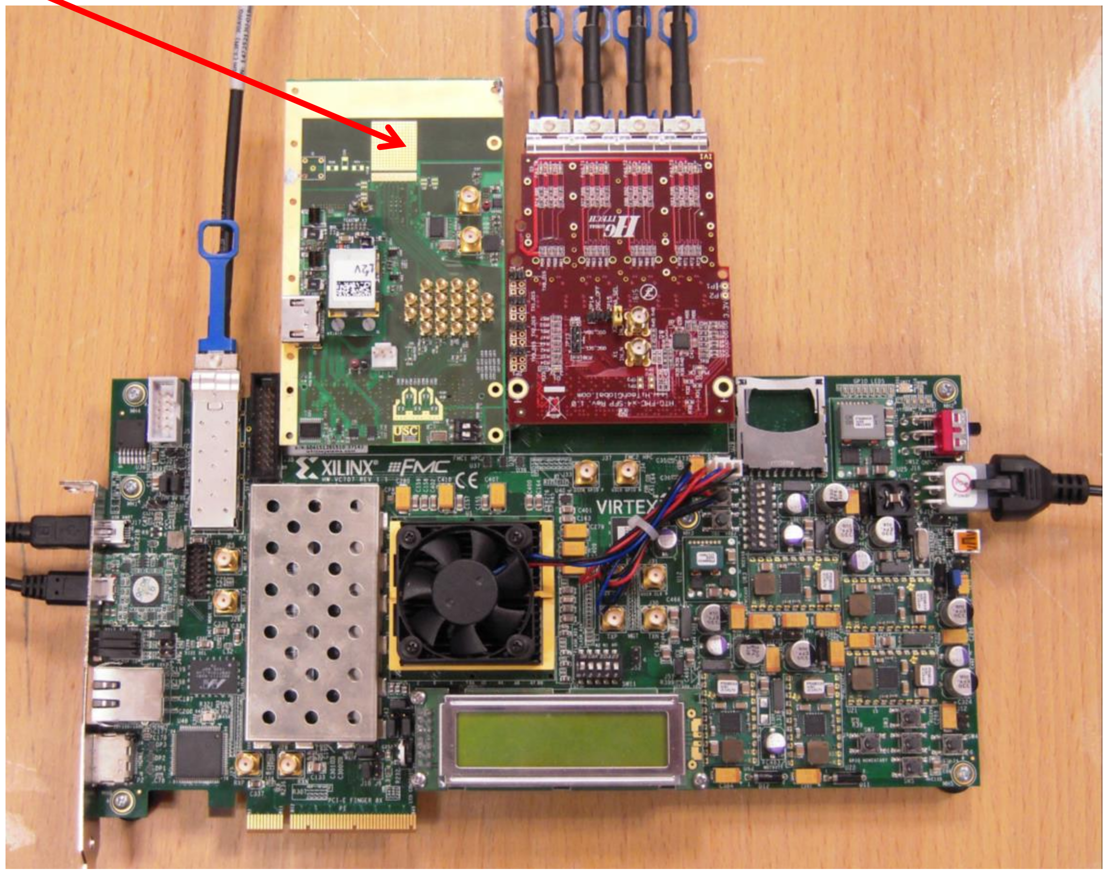
- bench test
- X-ray irradiation
- SEU qualification
- beamtest with sensor

VeloPix Test Setup

placement sites for VeloPix chip



prototype of the official readout chain

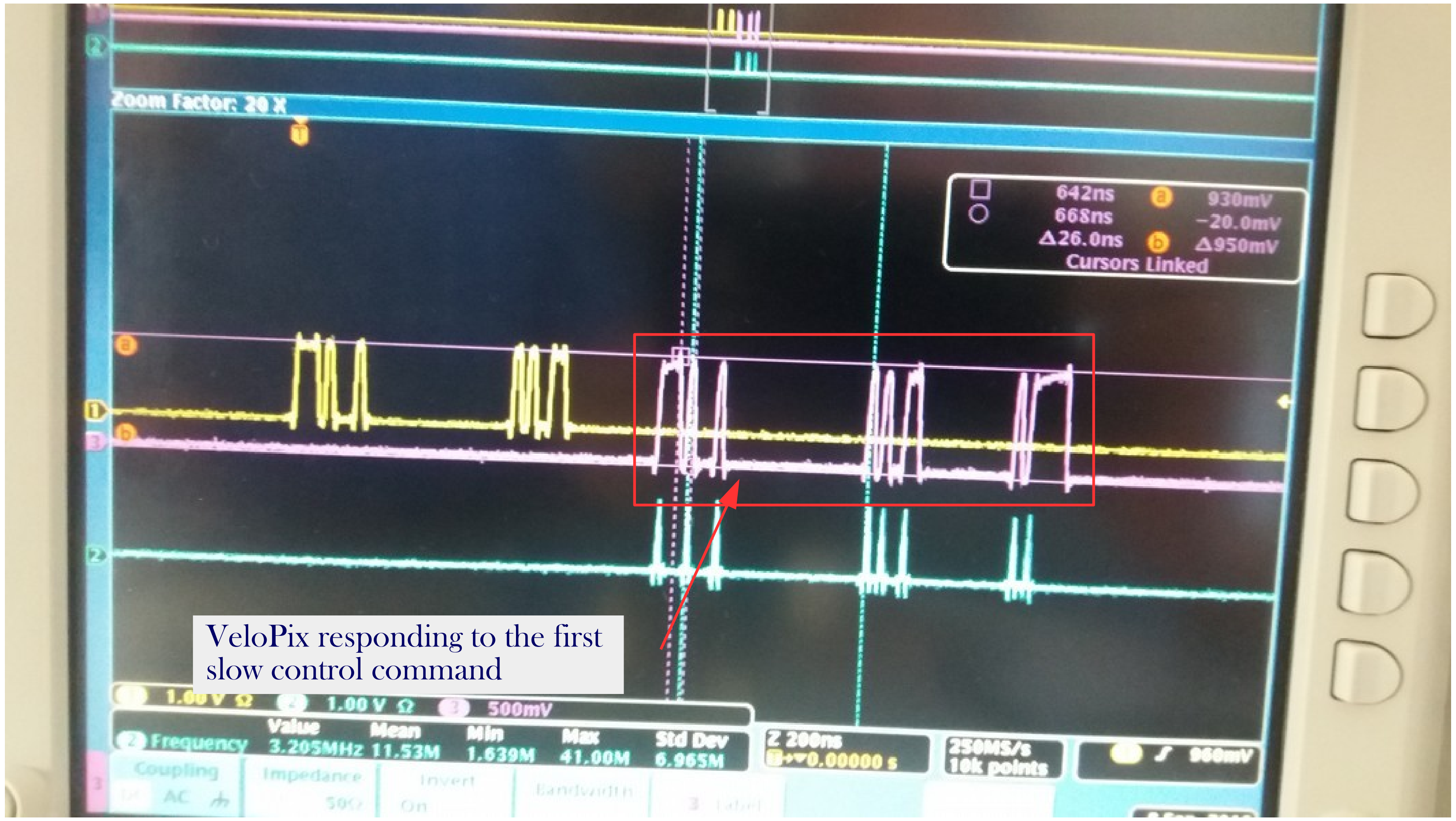


additional readout system (SPIDR)

VeloPix Testing: First Results!!

First tests:

- pixel matrix is resettable, readable and writable
- Analog and digital front ends respond to testpulses correctly
- Packet latency corresponds to expected
- Slow control responds
- Timing and fast control working



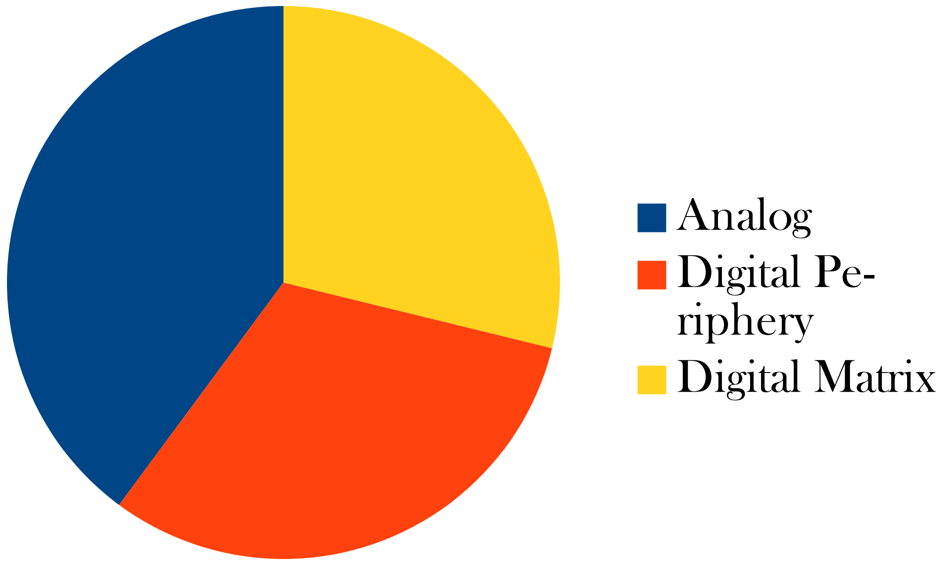
VeloPix Testing: First Results!!

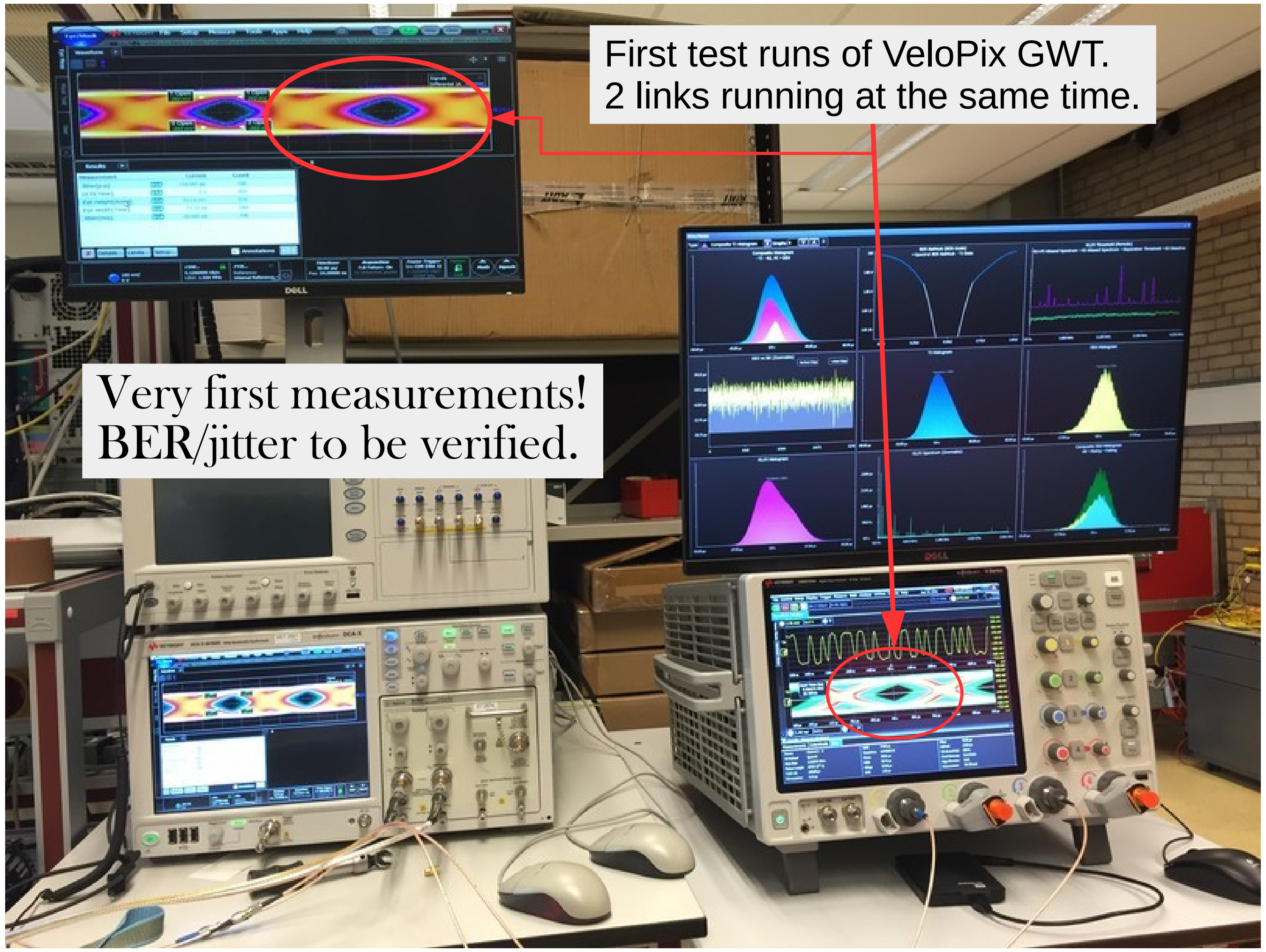
Power consumption

total: 1.2 W (0.52 W/cm^2)

(it might go up with activity in the chip)

within specifications (< 1.5 W/cm^2)



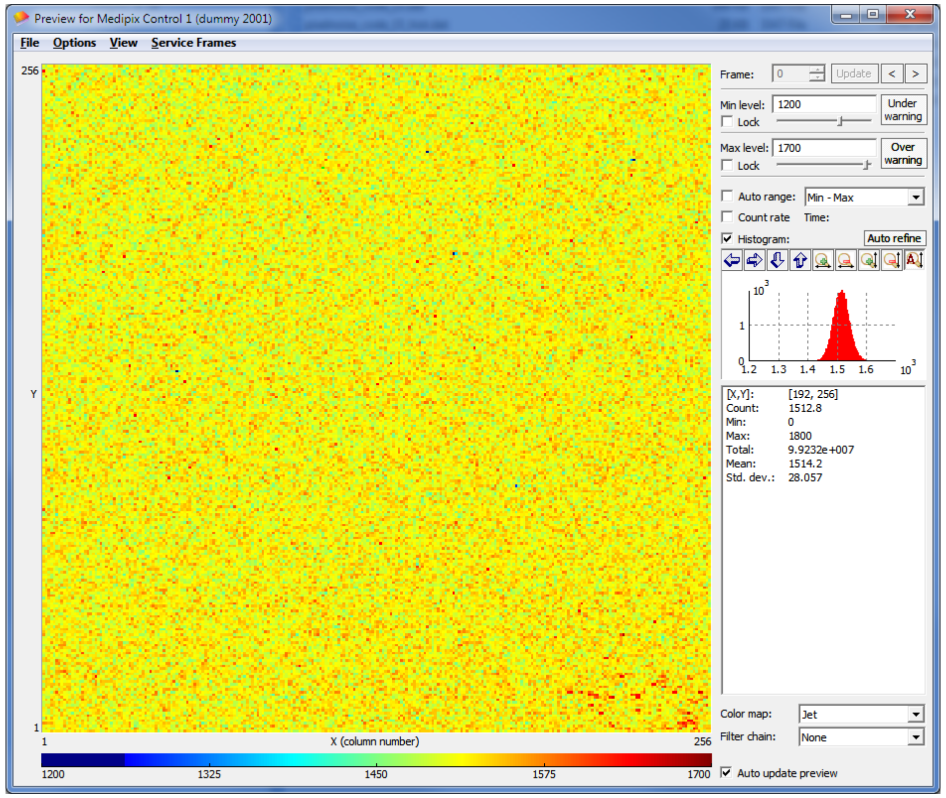


GWT eye diagram at 5.12 Gbps

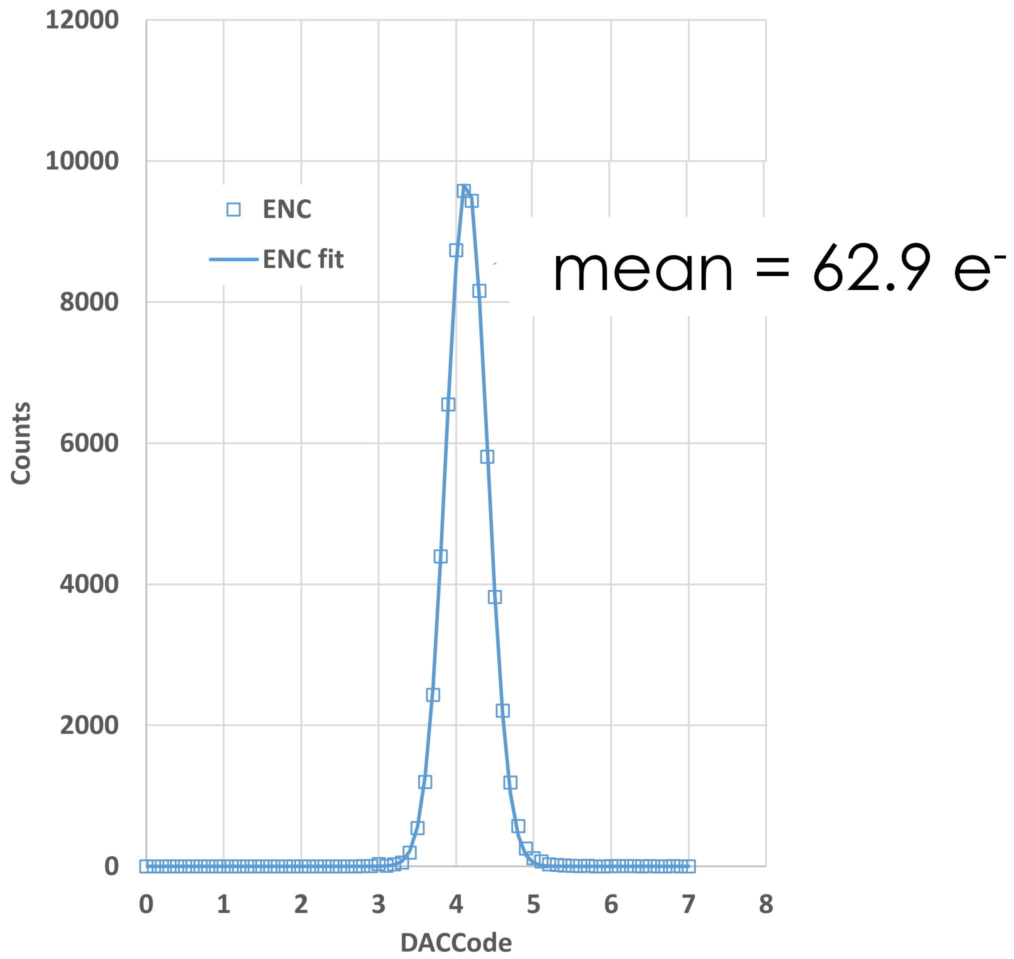
VeloPix Testing: First Results!!

- noise level ~60 e^-
- threshold stable over pixel matrix (variation ~40 e^-)
- no systematics observed

Unequalised threshold distribution

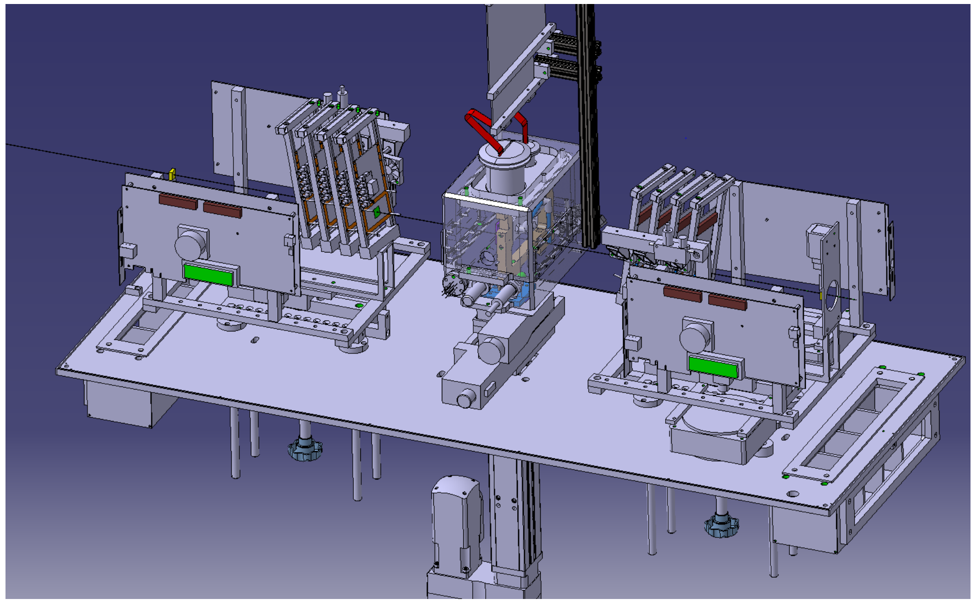


Electronic Noise



Summary

- Challenging requirements on both sensor and ASIC due to the high rate and high radiation environment of the upgraded detector
- The Timepix3 Telescope allowed to test beautifully all the sensor designs we have, before and after irradiation (of different type and dose)
- Sensor designs show already good results!
- First VeloPix chips have been tested: results correspond to expectations!



Testbeam in less than 2 weeks:

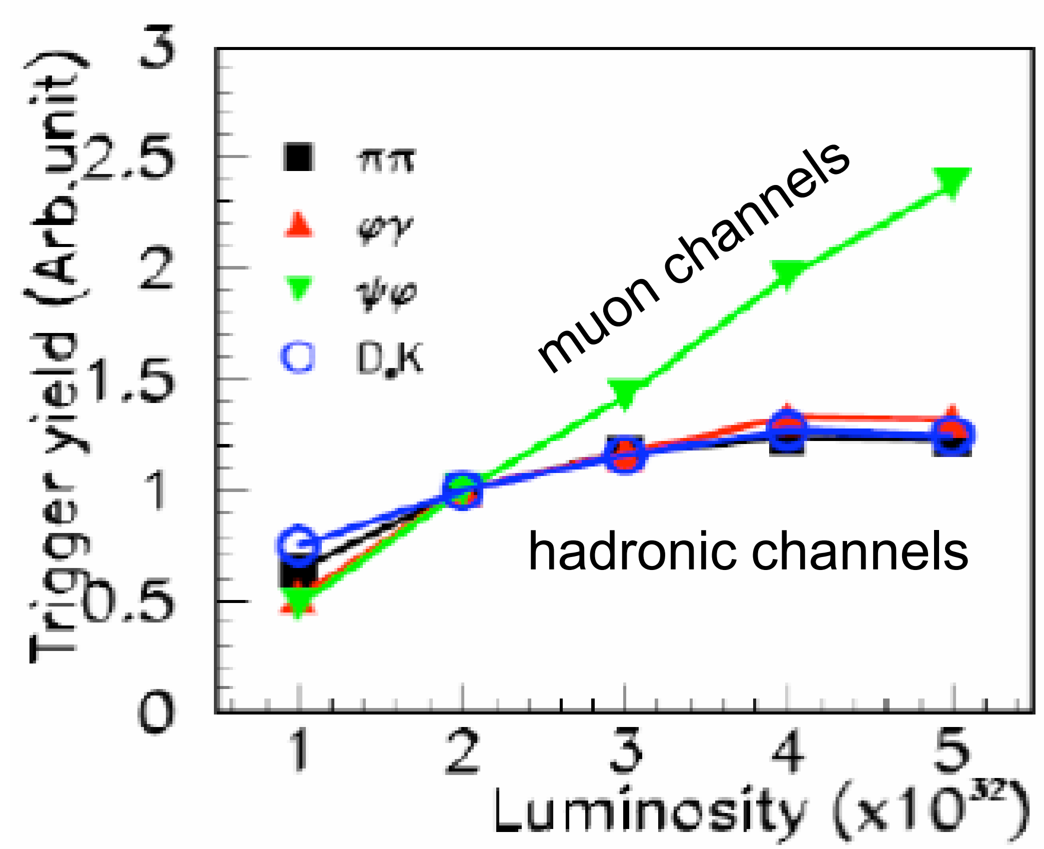
- Test of new sensors design, including the round edges HPK
- Test of the VeloPix bump bonded to the sensors
- The readout chain for the VeloPix is being debugged
- The telescope has been equipped with a vacuum box for the DUT

Back Up

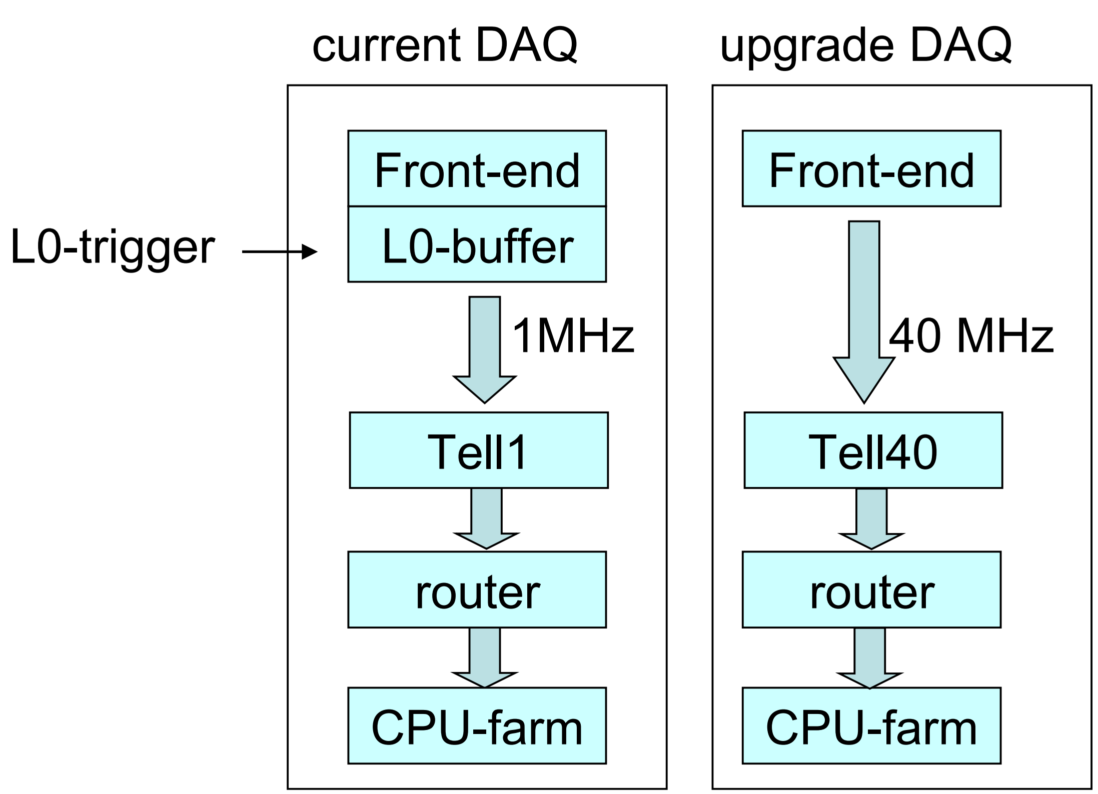
VELO Upgrade

many B event yields do not increase with luminosity

rather saturate!!!



Solution



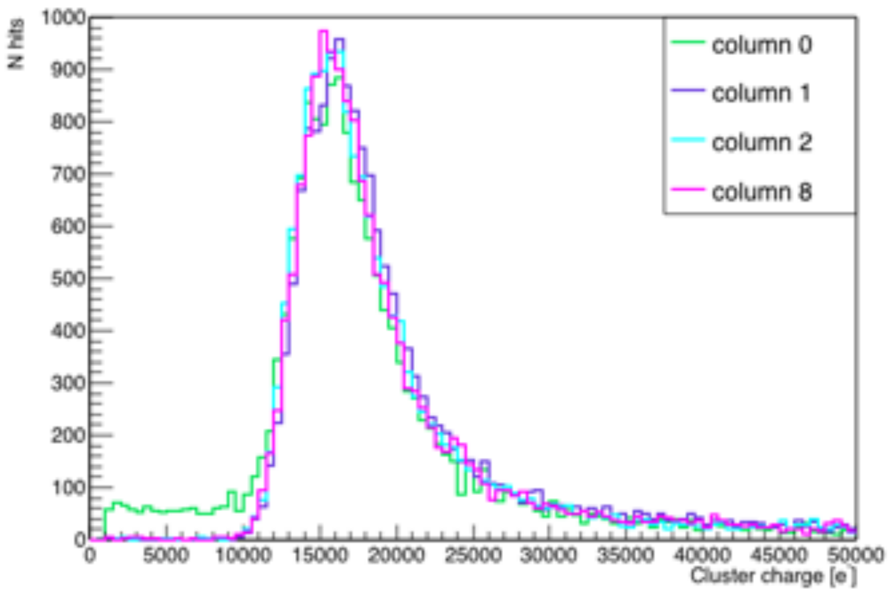
new DAQ system will transfer all, zero-suppressed front end data straight to the CPU farm through a huge optical network and router

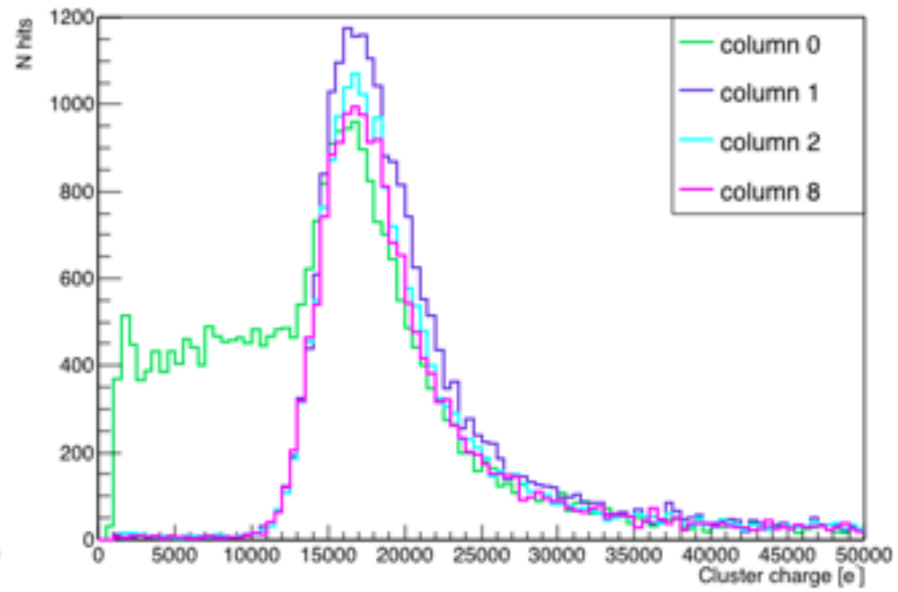
Edge Effect

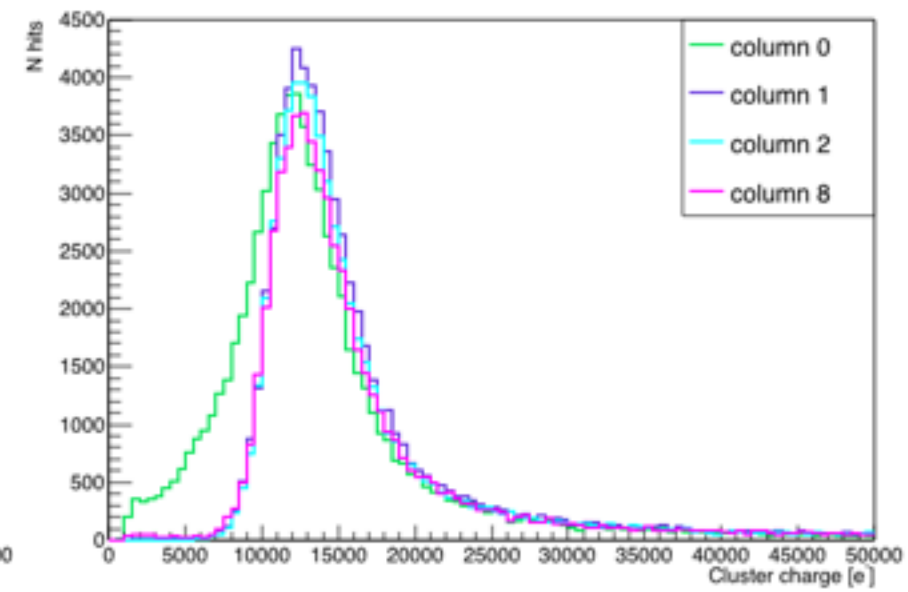
HPK

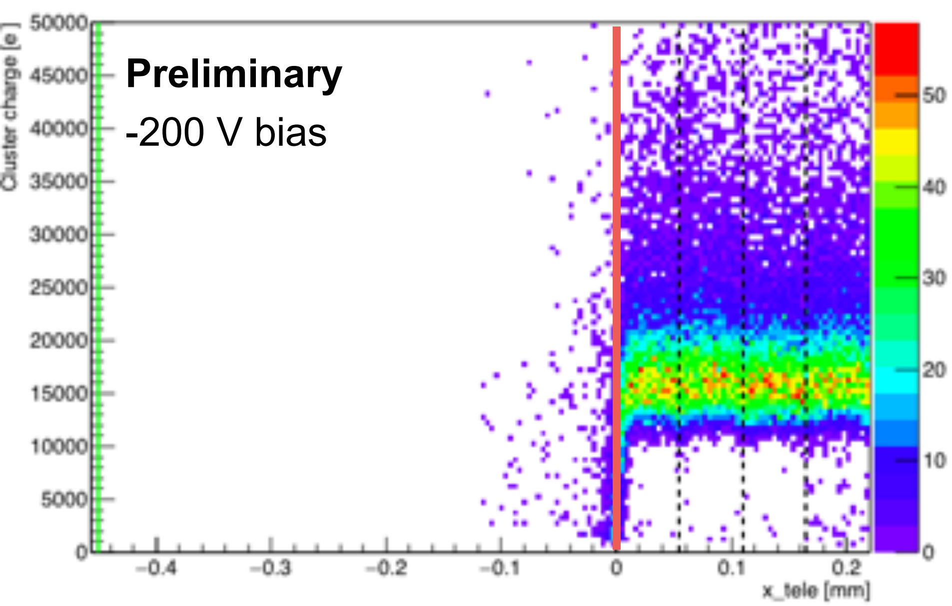
Micron n-on-p

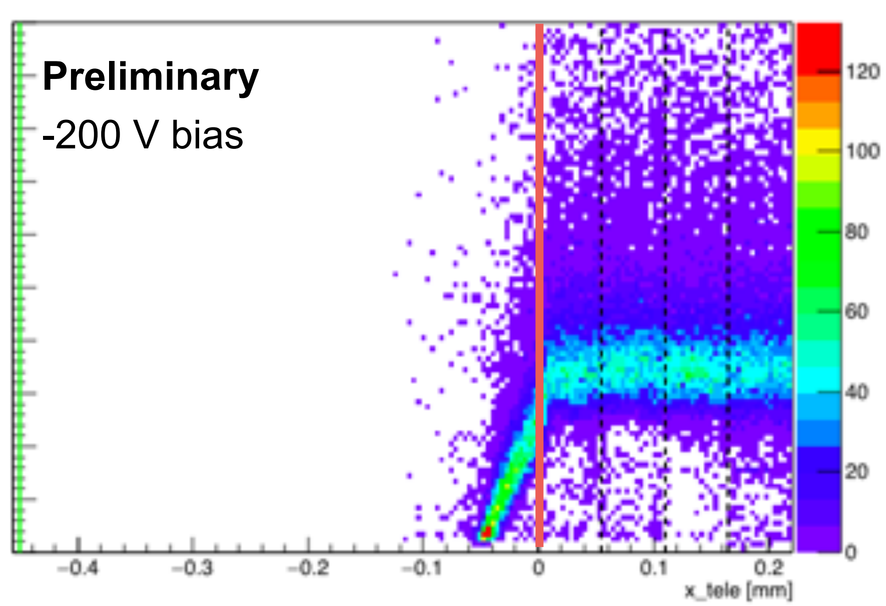
Micron n-on-n

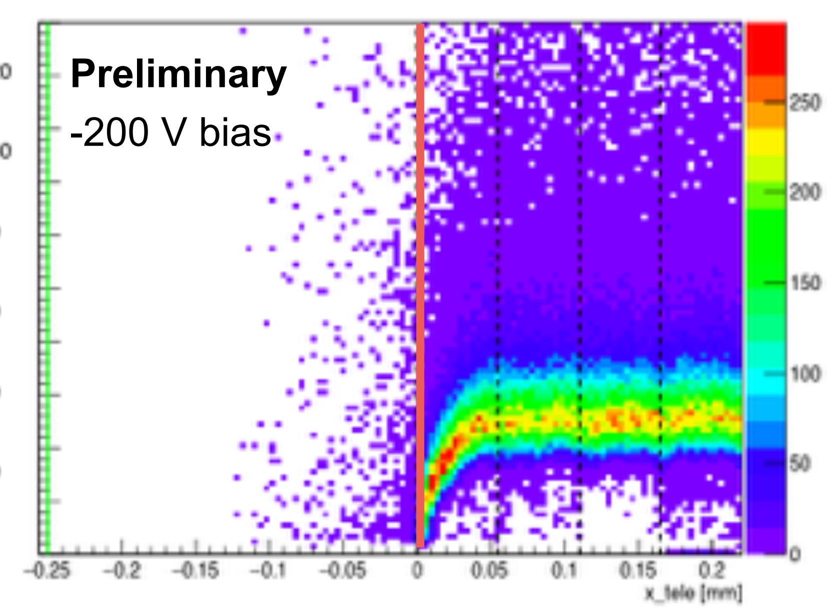




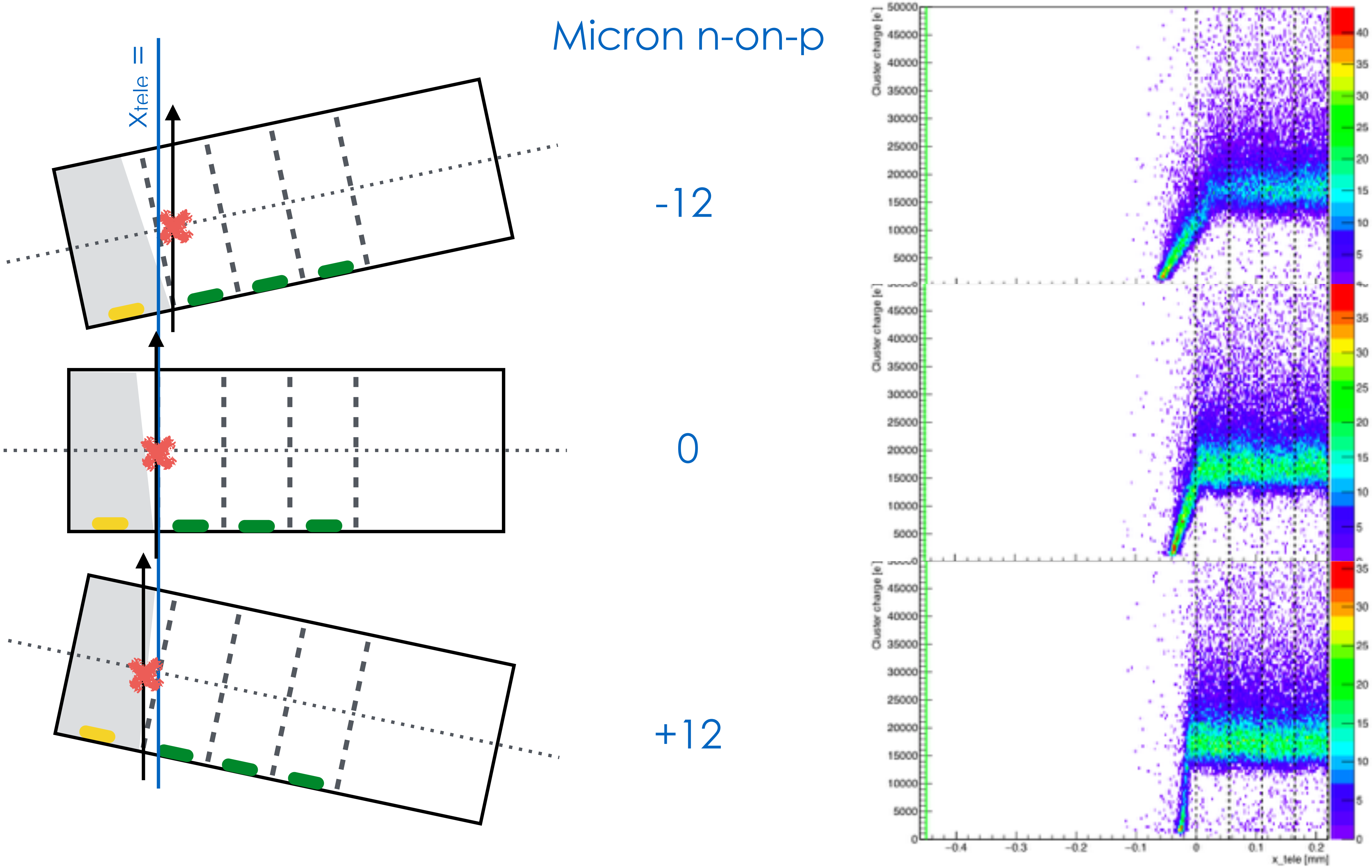






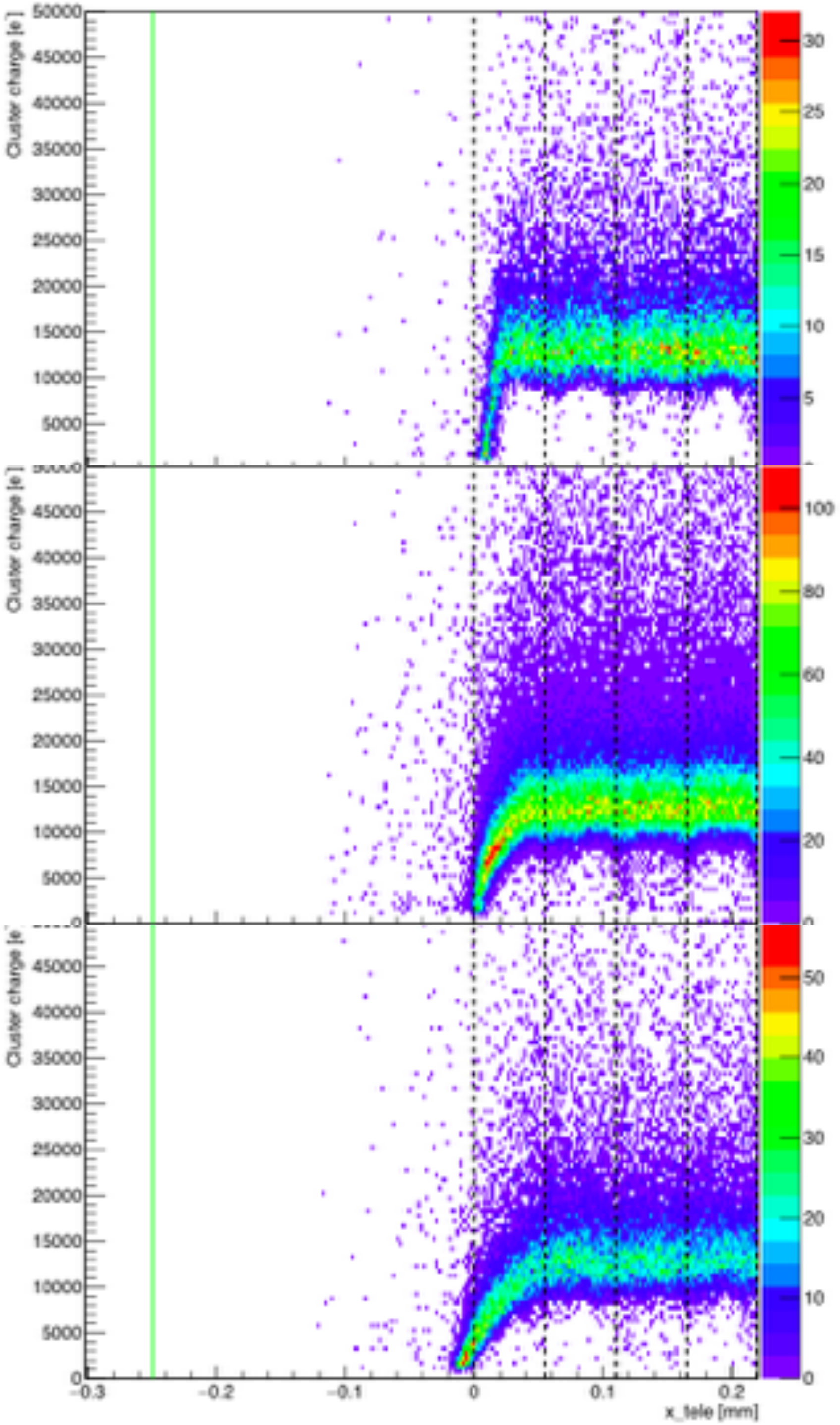


Edge Effect



The angle runs allow to understand that the charge distribution is due to a tilted collection region

Edge Effect

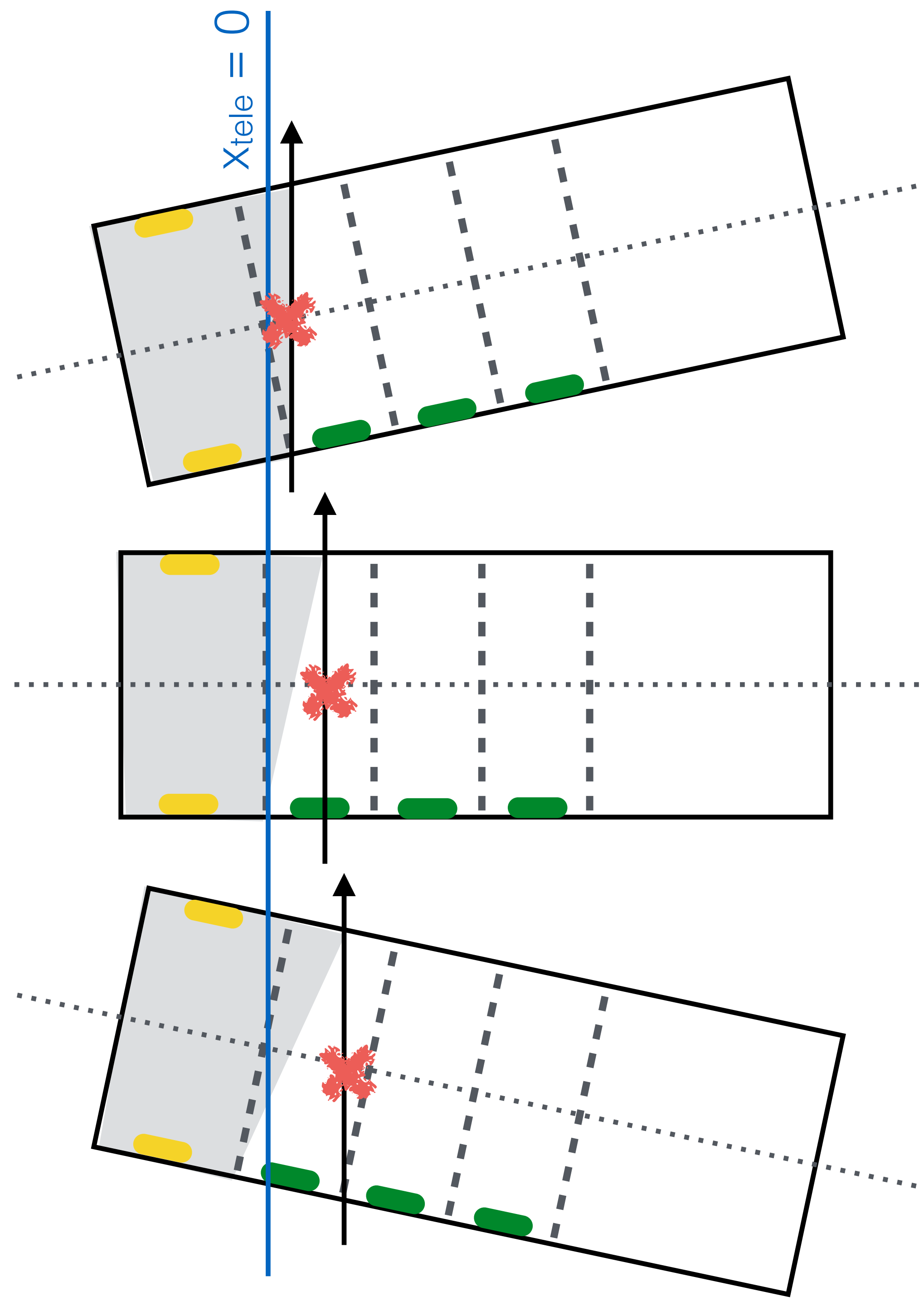


Micron n-on-p

-12

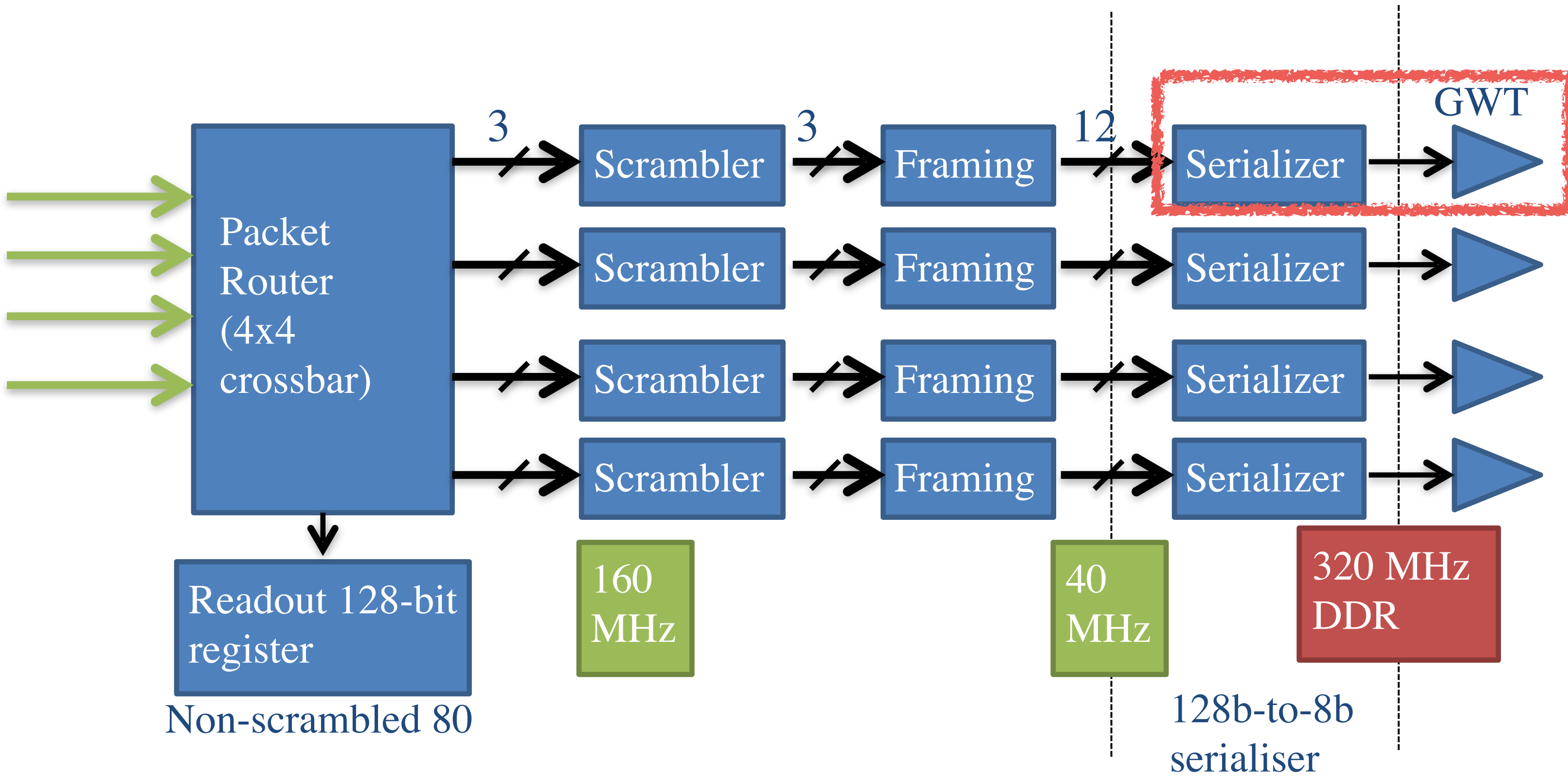
0

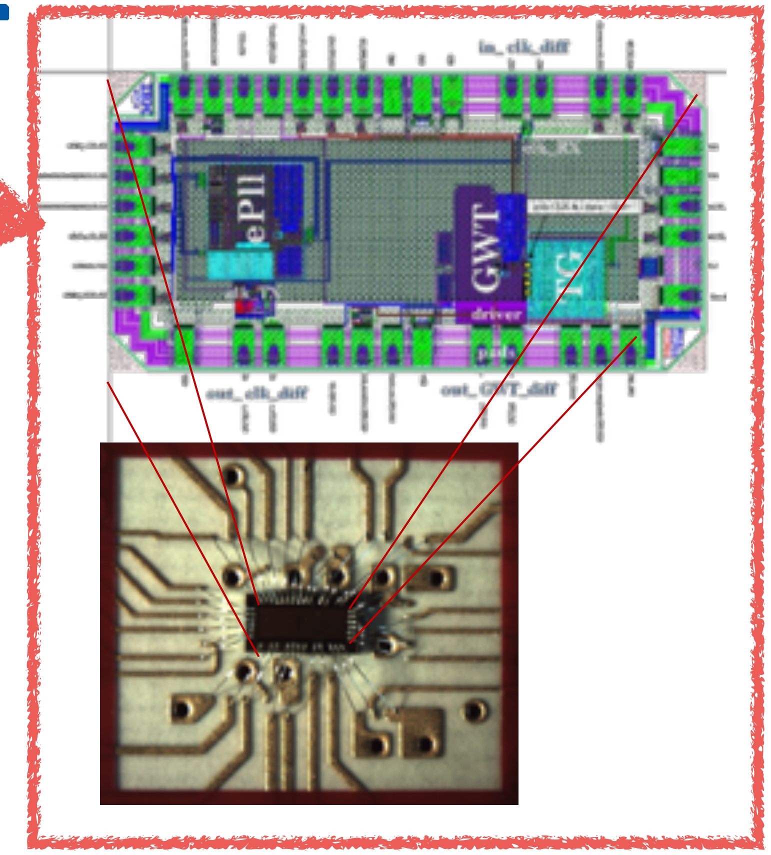
+12



The angle runs allow to understand that the charge distribution is due to a tilted collection region

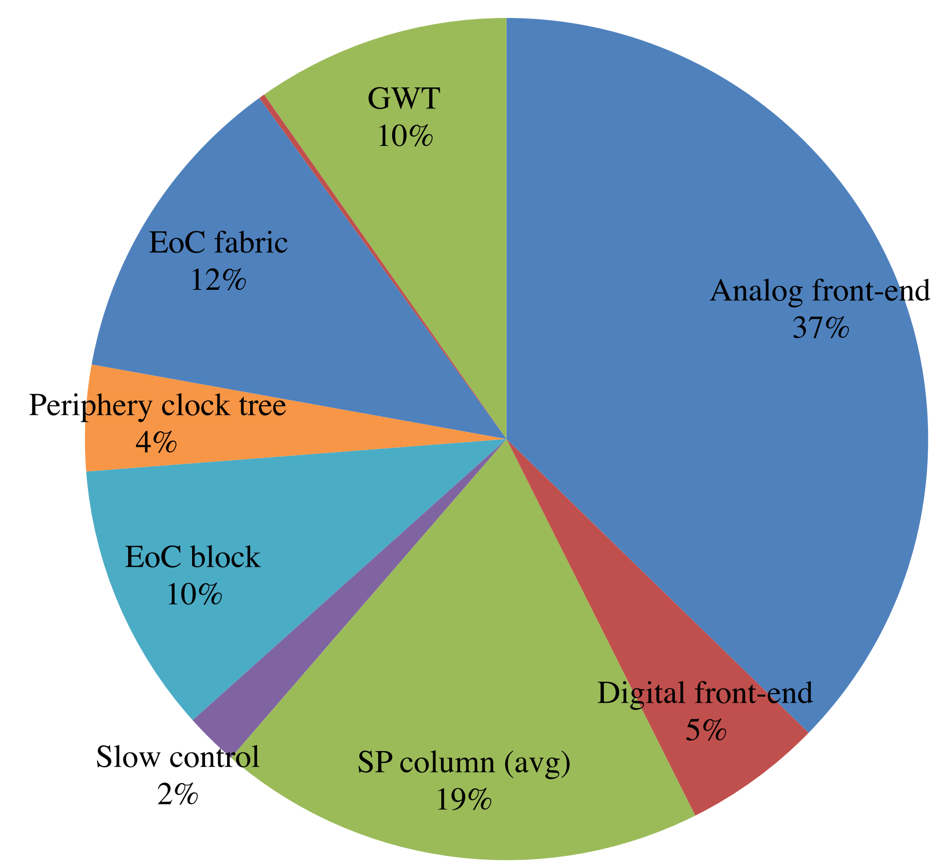
Output Logic





GWT: Gbps data serialiser and Wireline Transmitter

- 5.12 Gbps serialiser in 130 nm technology
- low power consumption: serialiser 15 mW, wireline driver 45 mW
- 4 GWT units on each VeloPix contributing only 10% to the chip power budget



Preliminary Results VeloPix

Pixel gain	~24.6 mV/Ke$^-$
Pixel to pixel gain variation	~3.3%
Pixel ENC	62.9 e$^-$
Pixel to pixel threshold mismatch	410 e$^-$rms
Pixel to pixel threshold mismatch calibrated (Threq)	40.3 e$^-$rms
Expected minimum threshold $= 6\sqrt{ENC^2 + Threq^2}$	> 450 e-

Threshold equalization only calculated not measured on chip
All measurements assuming Ctest=5fF

In the LHC Upgrade…

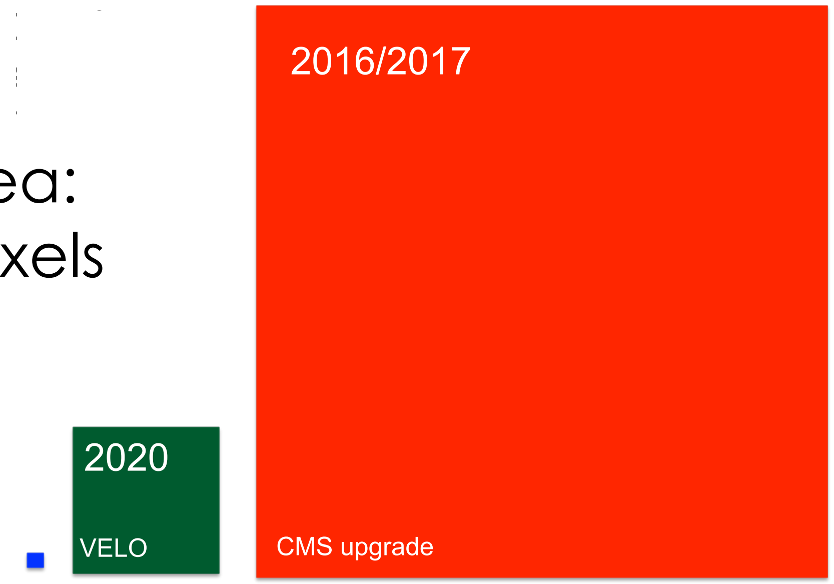
VELO

CMS phase I pixel upgrade

NA62 GTK

SIZE

VELO surface area:
1243 cm^2 , 41M pixels



COOLING

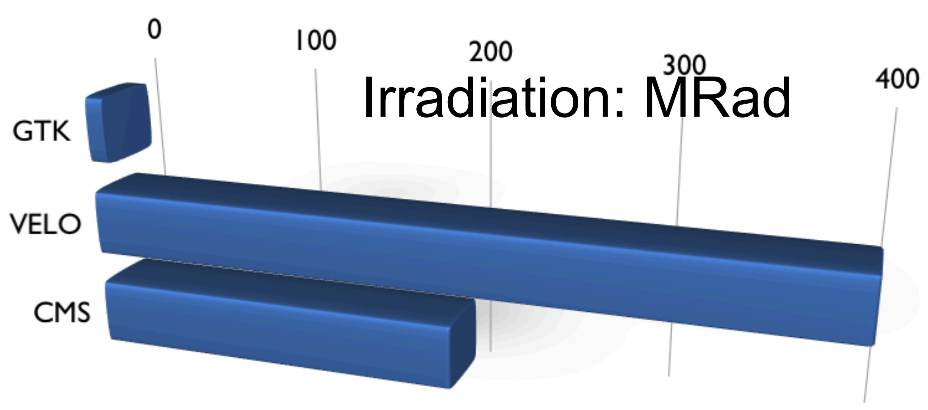
CO_2 for CMS

microchannels for NA62

both for LHCb

IRRADIATION

$8 \times 10^{15}\ n_{eq}\ cm^{-2}$ after 50 fb^{-1}



Current VELO

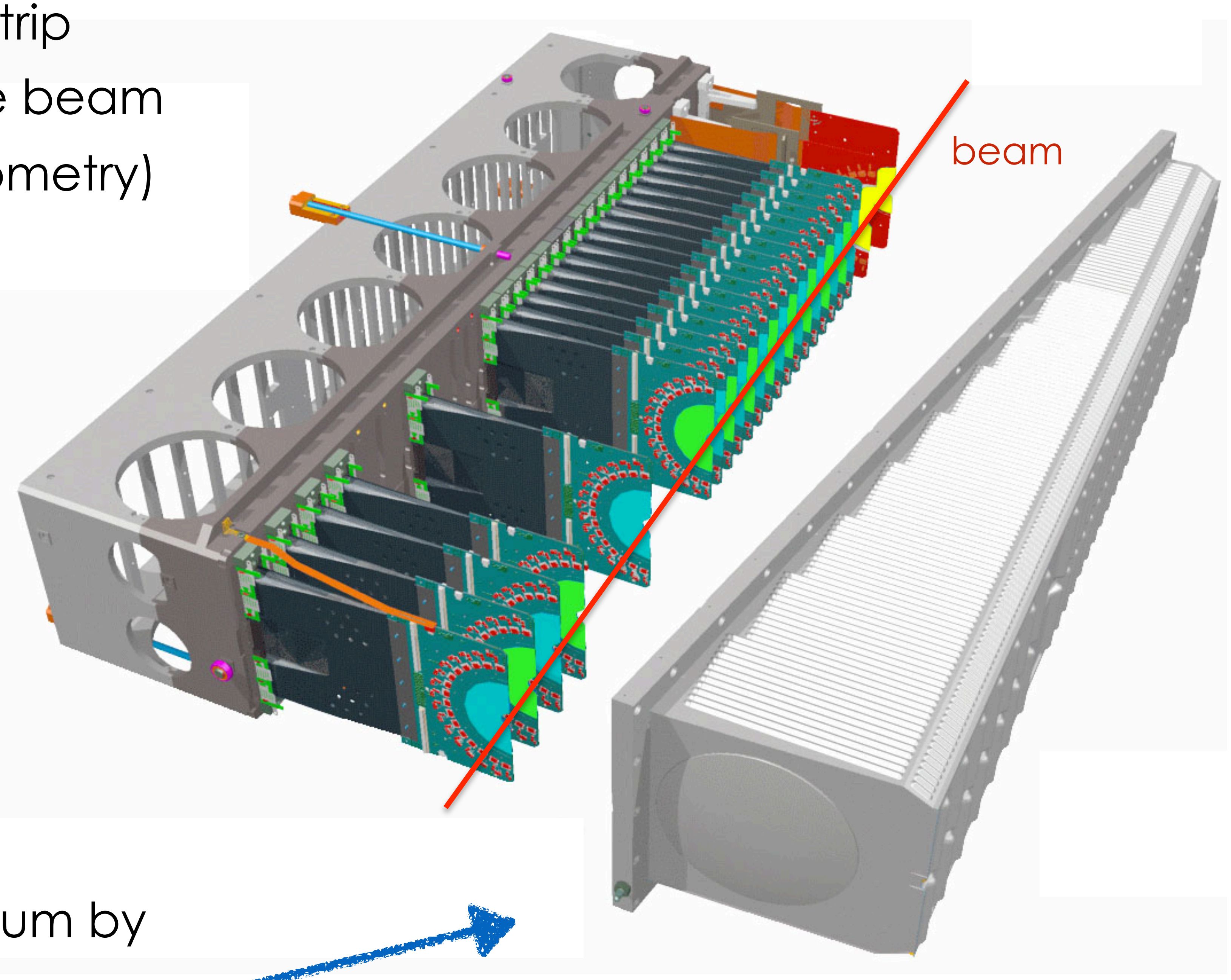
One half of the VELO

23 stations of n-on-n silicon strip sensors perpendicular to the beam (alternating radial/axial geometry)

Retractable for safe operations outside of stable beam conditions

Active area 8.2 mm from beam

Separated from beam vacuum by RF foil (aluminum)



"Performance of the LHCb Vertex Locator"
J. Instrum. 9 (2014) P09007, arXiv:1405.7808

Why closer to the beam?

Tracks originating from secondary vertices with large impact parameters are the principal signature of beauty and charm hadrons in LHCb

performance of the detector evaluated in terms of impact parameter resolution

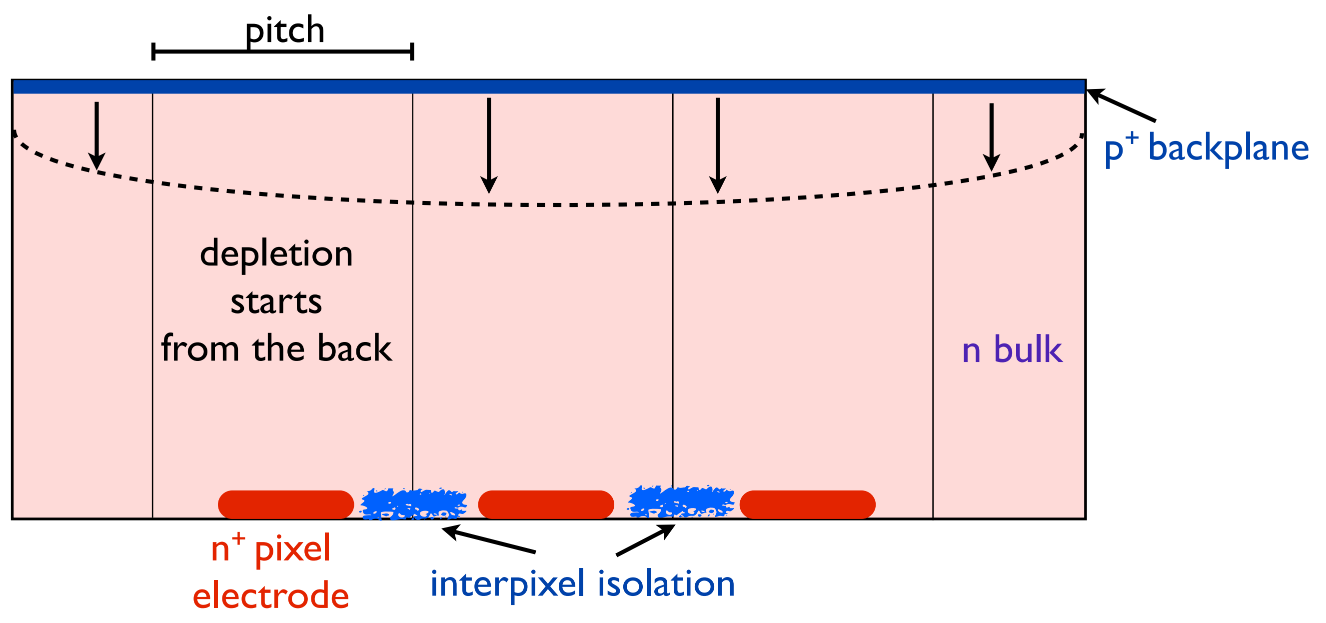
$$\sigma_{\mathrm{IP}}^2 = \frac{r_1^2}{{p_{\mathrm{T}}}^2}\left(0.0136\ \mathrm{GeV}/c\sqrt{\frac{x}{X_0}}\left(1+0.038\ln\left(\frac{x}{X_0}\right)\right)\right)^2 + \frac{\Delta_{02}^2\sigma_1^2+\Delta_{01}^2\sigma_2^2}{\Delta_{12}^2}$$

it scales with the radius r_1 of the first measured point on the track

Sensor Types

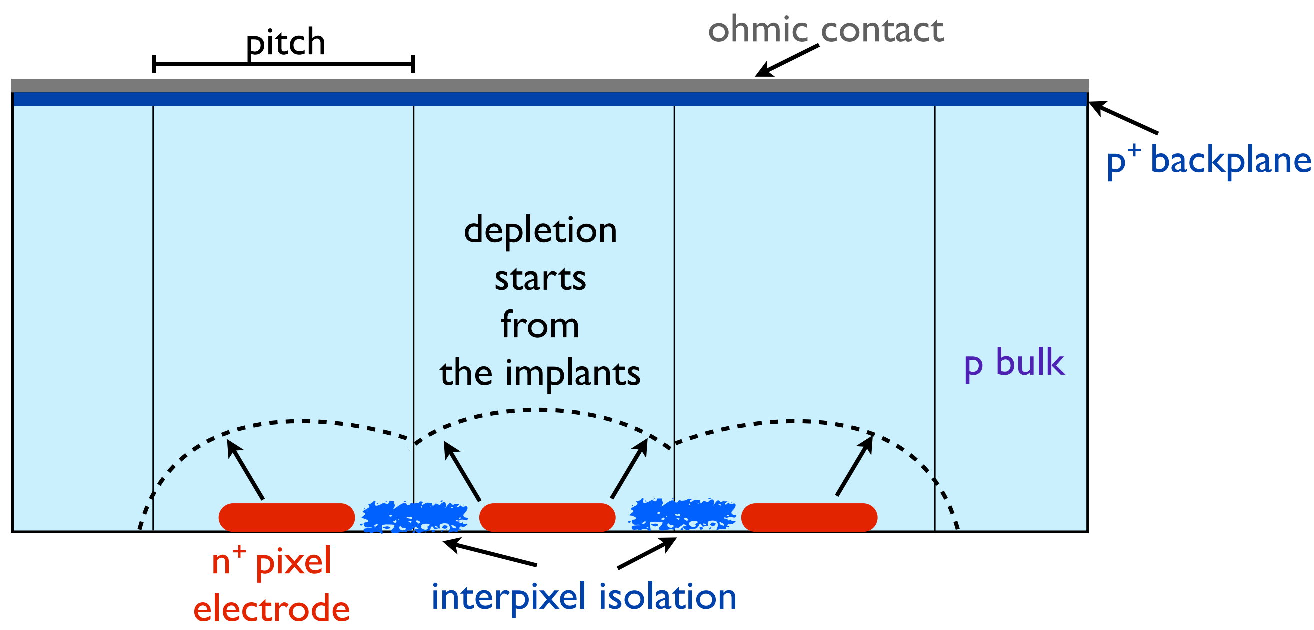
n-on-n

- n^+ pixel electrodes collect e^-
- depletion starts from backplane
- under irradiation: type inversion
  → the sensor turns to n-on-p
- double sided process, but preferred when high irradiation



n-on-p

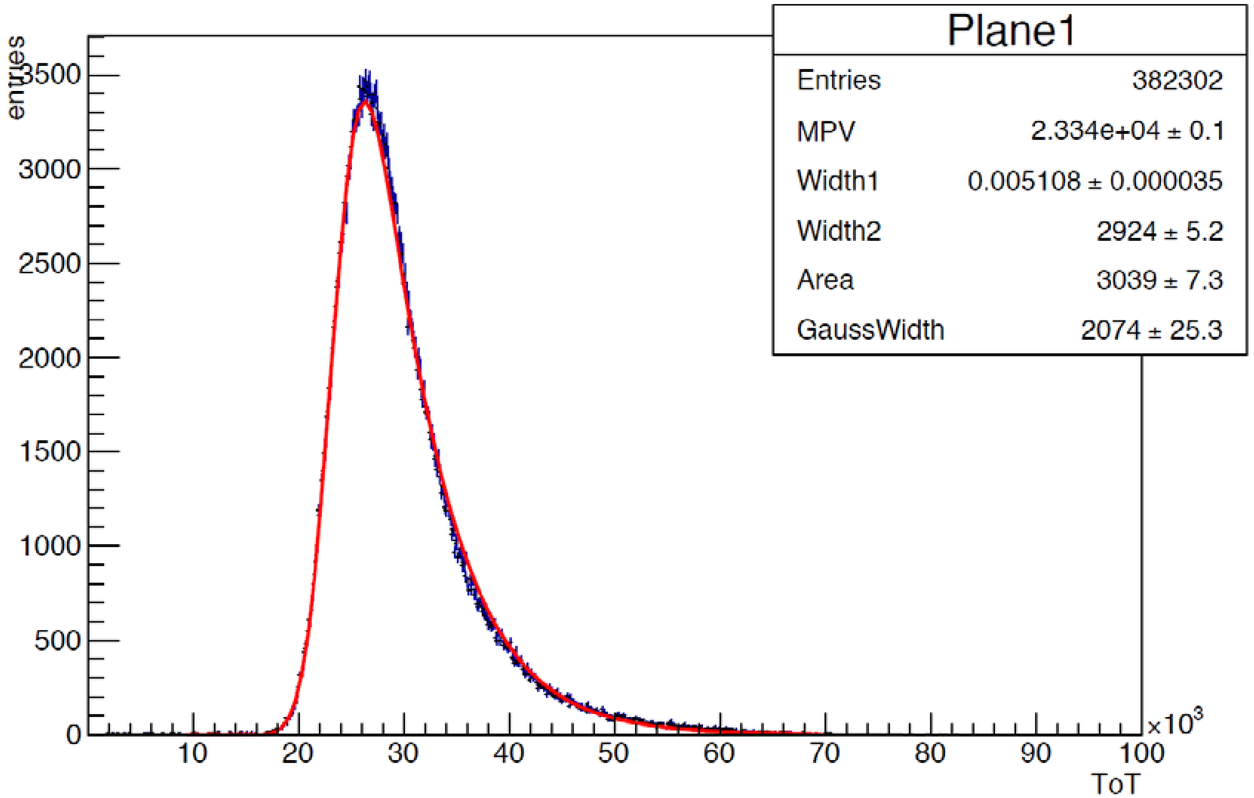
- n^+ pixel electrodes collect e^-
- depletion starts from pixel side
- under irradiation: increase of the p-type effective doping concentration
- single sided process, therefore easier to realise



Charge Collection

Timepix3 allows to measure the ToT → we can convert ToT counts in number of electrons via test pulses

Example of charge collected before calibration



Calibration curve for a single pixel