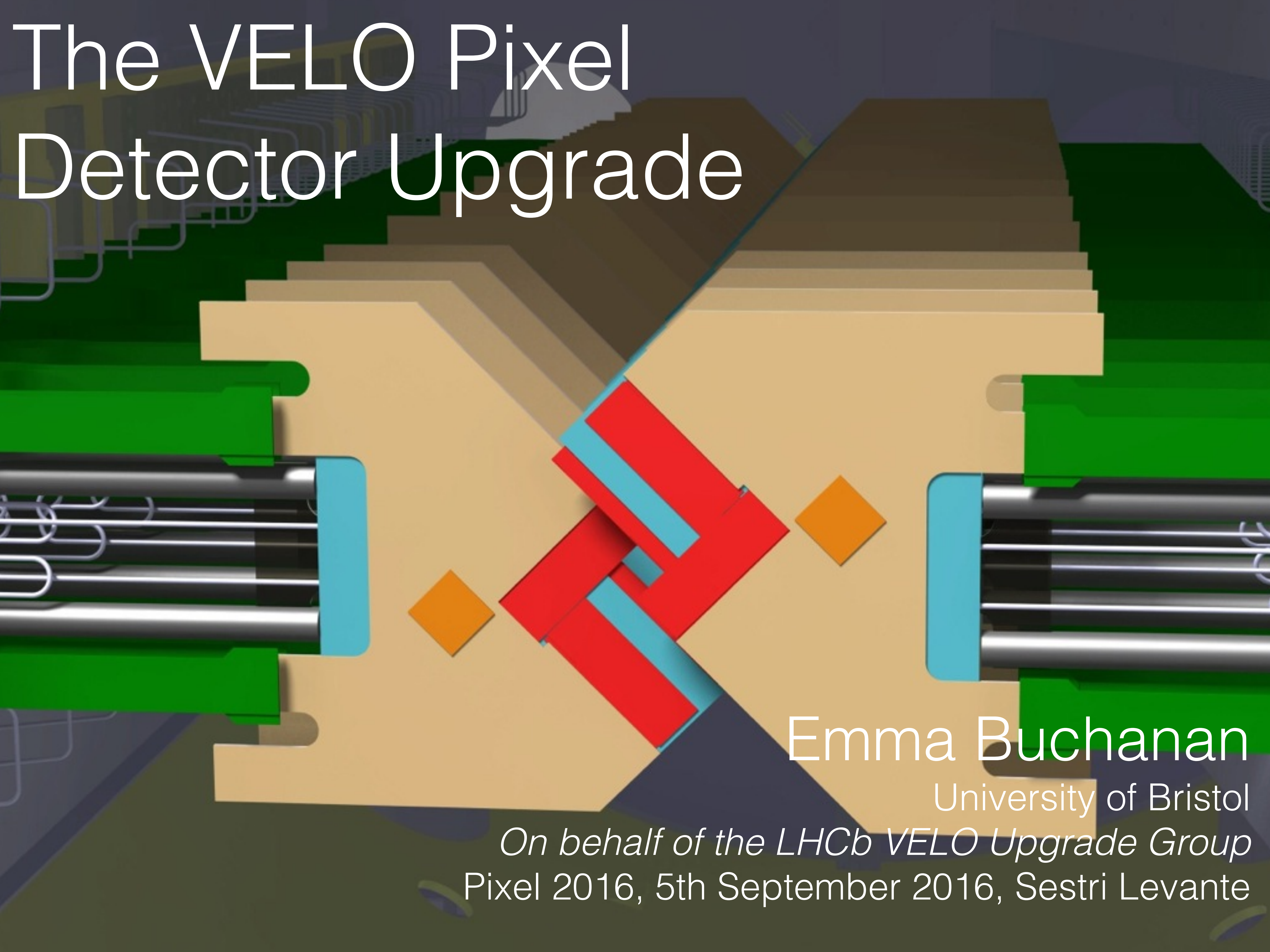

The VELO Pixel Detector Upgrade

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University of Bristol

On behalf of the LHCb VELO Upgrade Group

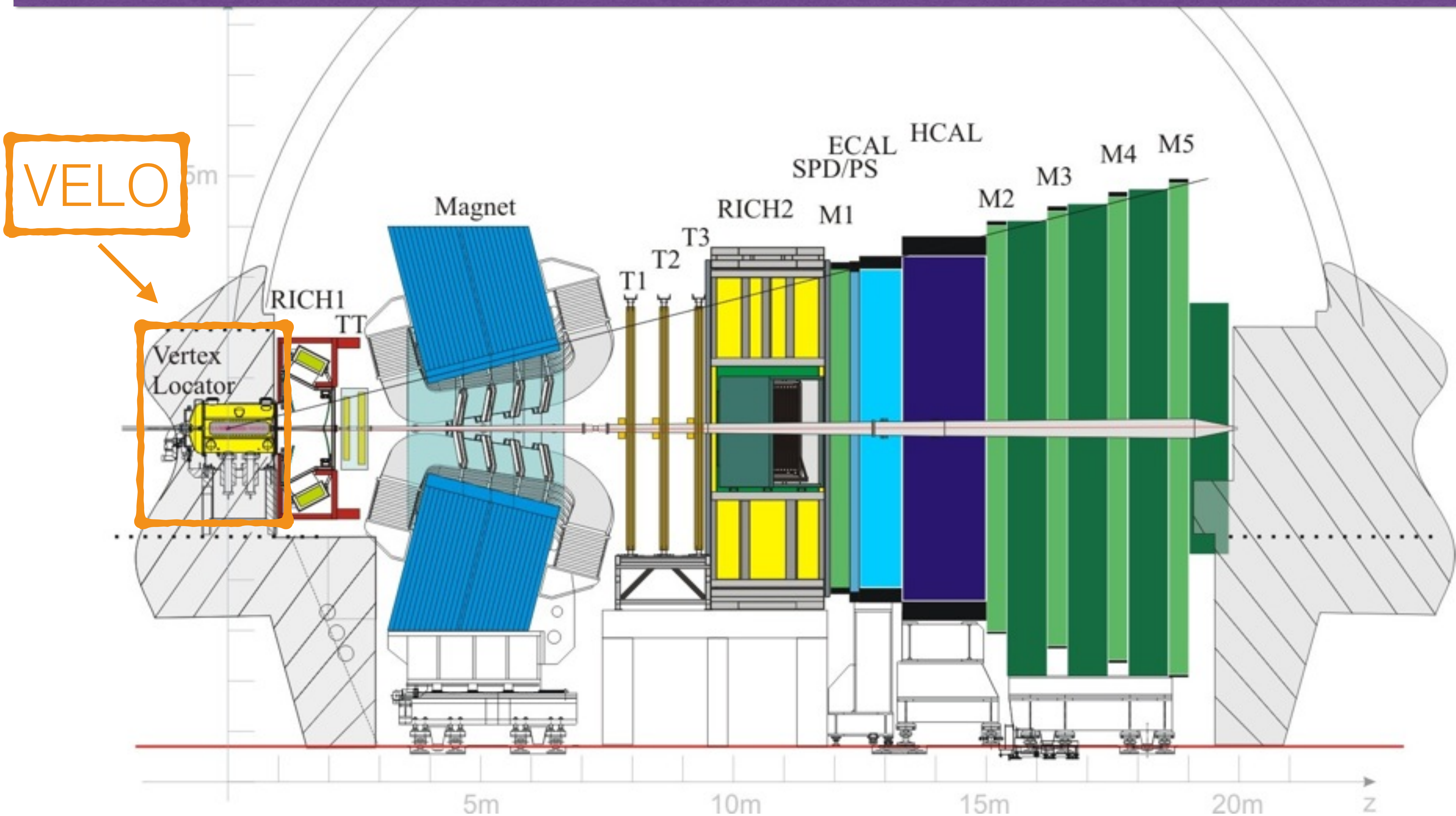
Pixel 2016, 5th September 2016, Sestri Levante

Overview

- LHCb Experiment and Upgrade Motivations
- Current VELO vs Upgraded VELO
- VELO Challenges and Upgrade Specifics
- Timeline of the Upgrade Campaign
- Sensor prototype testing
- Conclusions

The Large Hadron Collider Beauty Experiment (LHCb)

Searching for New Physics through measuring CP violation and rare decays of heavy flavour mesons



LHCb experiment: Utilising a tracking system, 2 RICH detectors for PID, Electromagnetic and Hadronic Calorimeters and a muon system.

Single arm spectrometer optimised to study particles containing b and c quarks

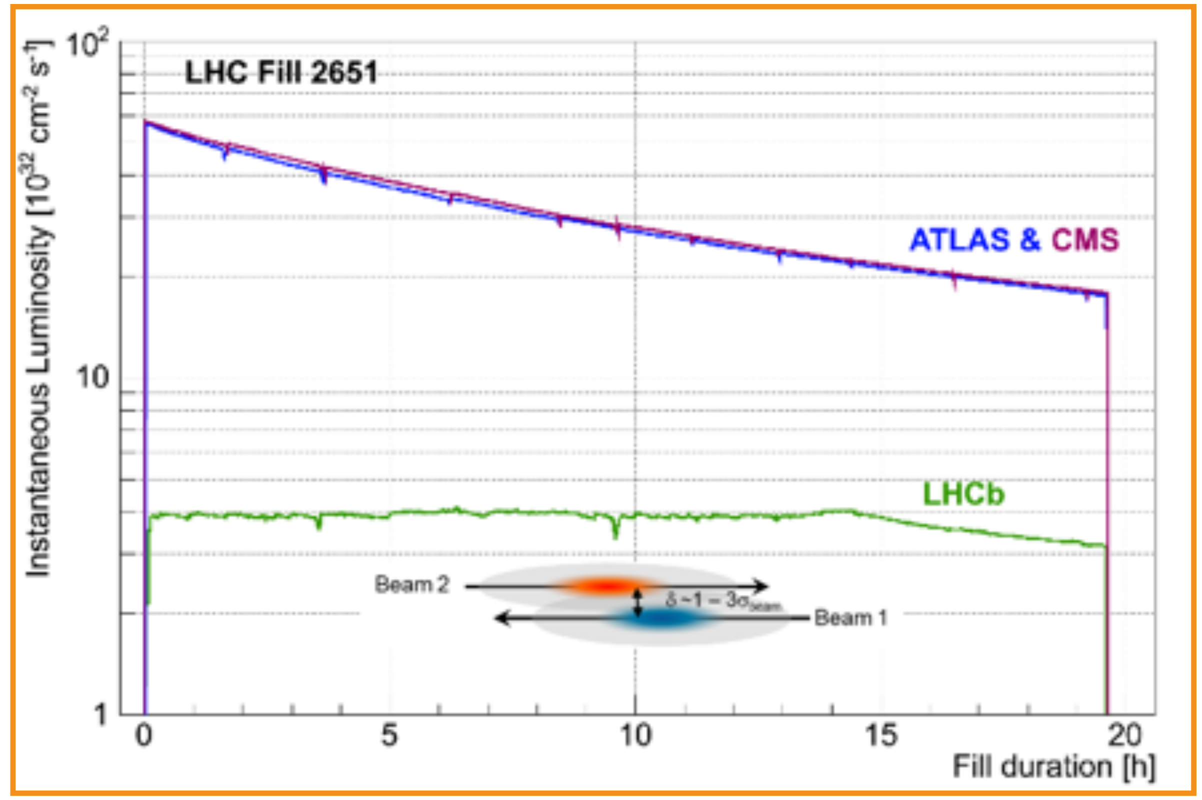
Why do we need to upgrade?

To Improve the physics performance!

Increased statistics

⟶ improved sensitivities to very rare decays

To achieve this we need to increase the luminosity



Instantaneous Luminosity: LHCb runs at ~20% of ATLAS and CMS Luminosity. Achieved using offset beams, moving closer during the fill

$$4 \times 10^{32} cm^{-2} s^{-1*} \longrightarrow 2 \times 10^{33} cm^{-2} s^{-1}$$

Limited by the trigger and the radiation damage

** Design luminosity of LHCb is* $2 \times 10^{32} cm^{-2} s^{-1}$

Challenges faced with increased luminosity

Current readout and trigger limits the amount of data that can be recorded

- 1.5 interactions per bunch crossing
- Hardware trigger limited to a 1MHz readout

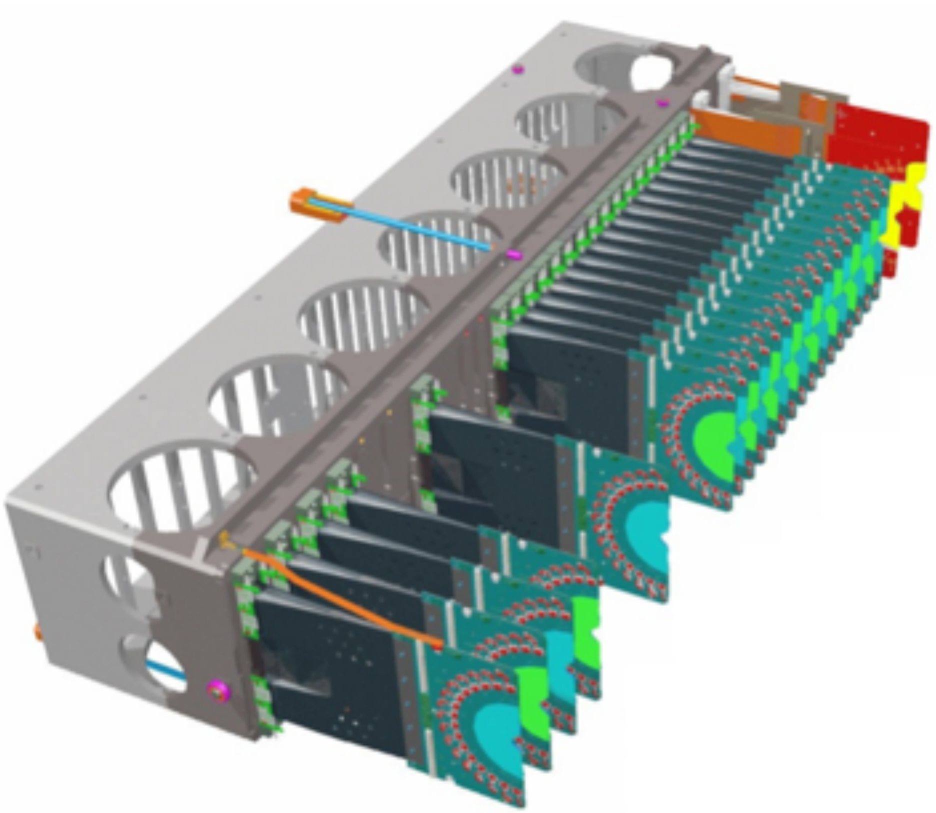
Will remove hardware trigger and replace with a flexible software trigger

- Readout at 40MHz
- 3.6 - 7.2 interactions per bunch crossing

To achieve this we must

- Upgrade all front end readout electronics
- Upgrade certain sub detectors to improve tracking and withstand the increased luminosity

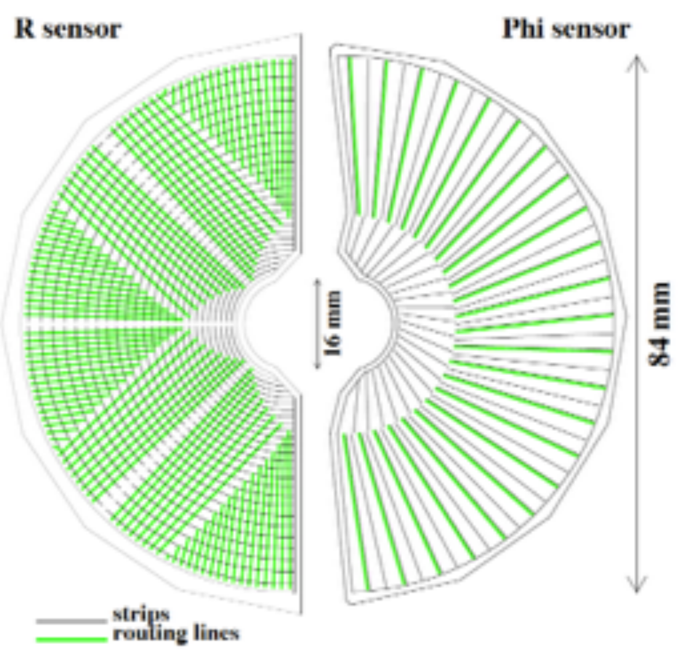
The Current VErtex LOcator (VELO)



One half of the VELO detector

Silicon strip detector surrounding the interaction region

- Reconstructs primary and secondary vertices
- 88 semi circular silicon sensors
  - 300μm
  - n-on-n strips
  - R-ϕ geometry
- ~8mm from the beam
  - Retractable during unstable beams
- Separated from LHC vacuum by RF Foils
- Cooling provided by evaporative CO_2



R-ϕ geometry

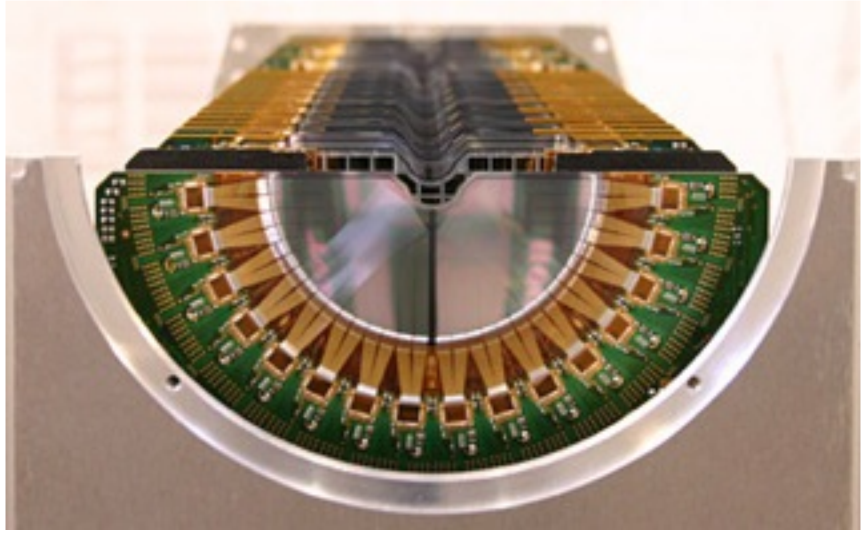
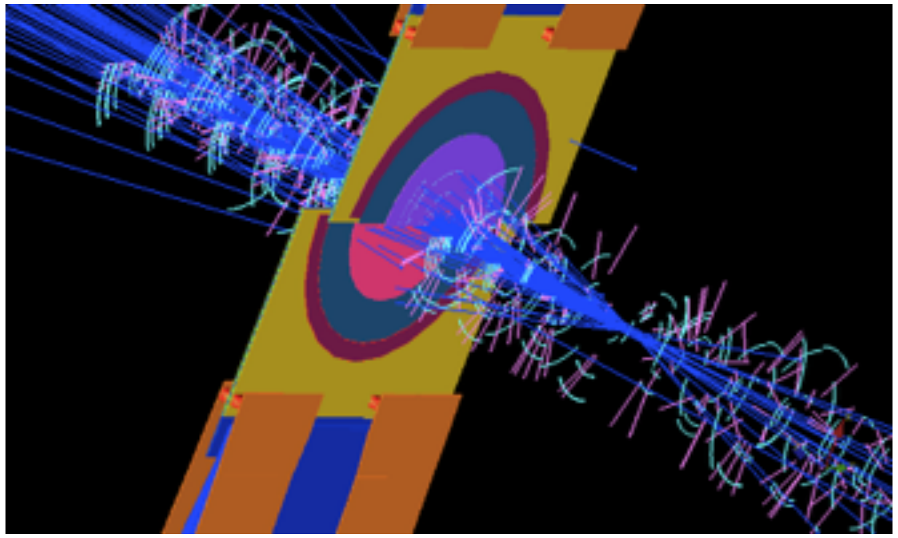


Photo of VELO strip sensors during assembly



Offline event display

The Upgraded VErtex LOcator (VELO)

New Hybrid Pixel Sensors with custom made VeloPix ASIC

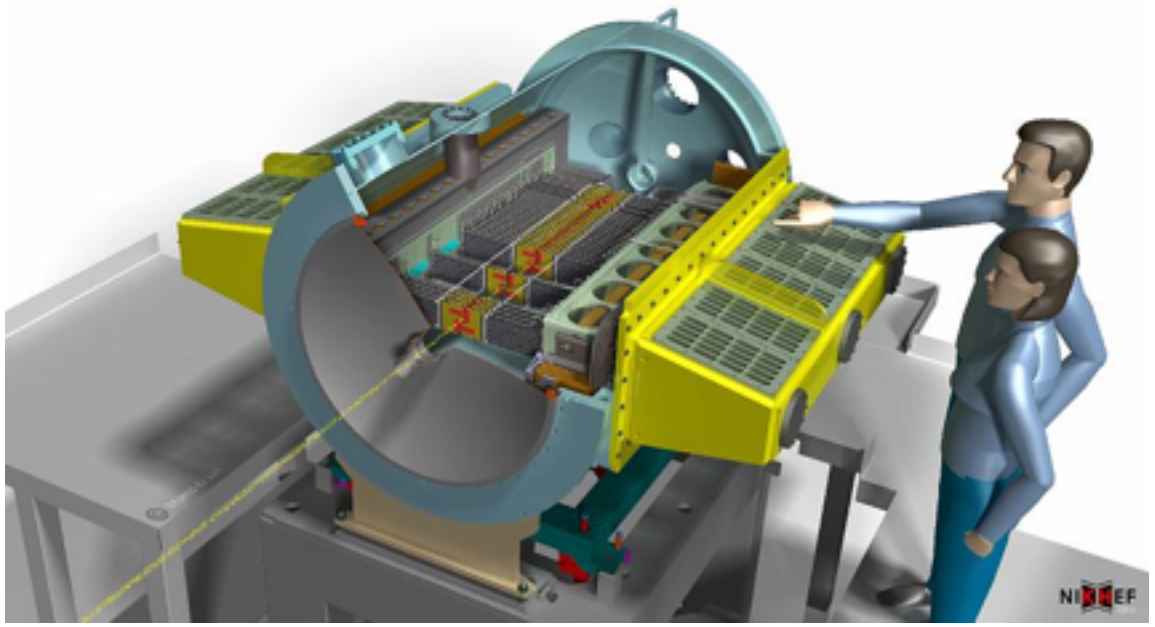
- New L shaped geometry
- Thinner Sensors

  300μm ⟶ 200μm

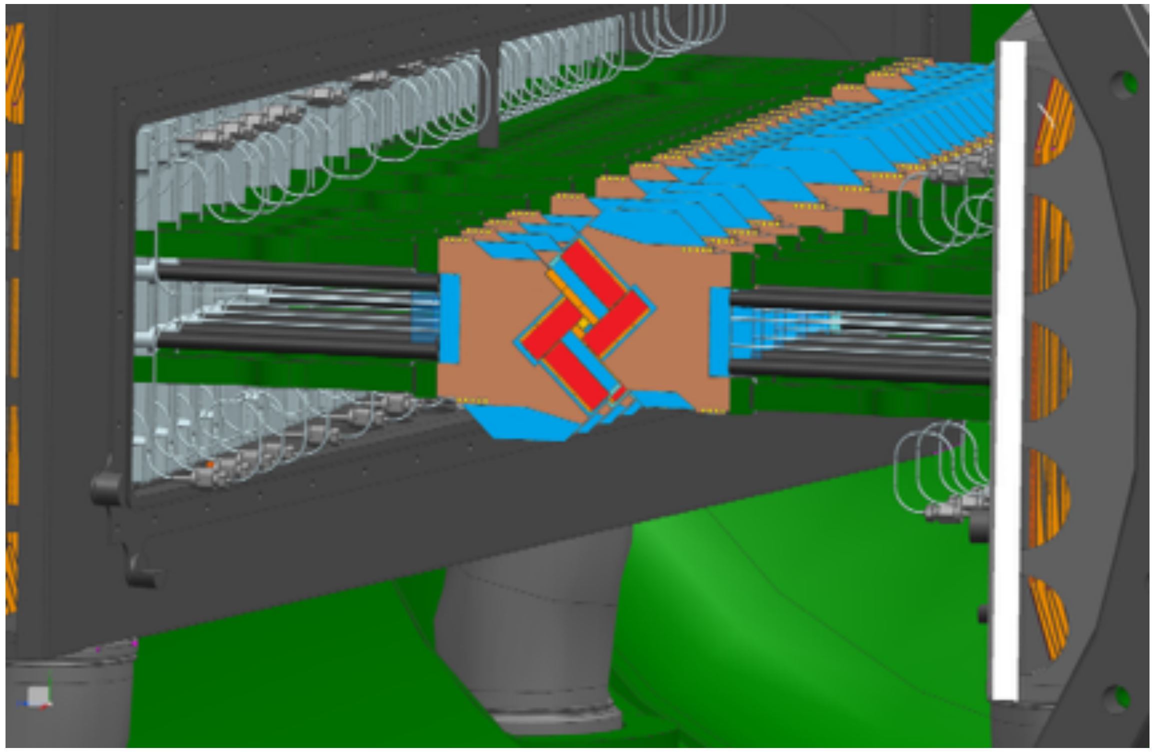
- Closer to the beam

  8 mm ⟶ 5.1mm from first active pixel

- Micro channel cooling
- Thinner RF foil
- Read out rate of 40MHz
- Main mechanical infrastructure will remain



Artists impression of installed upgraded VELO



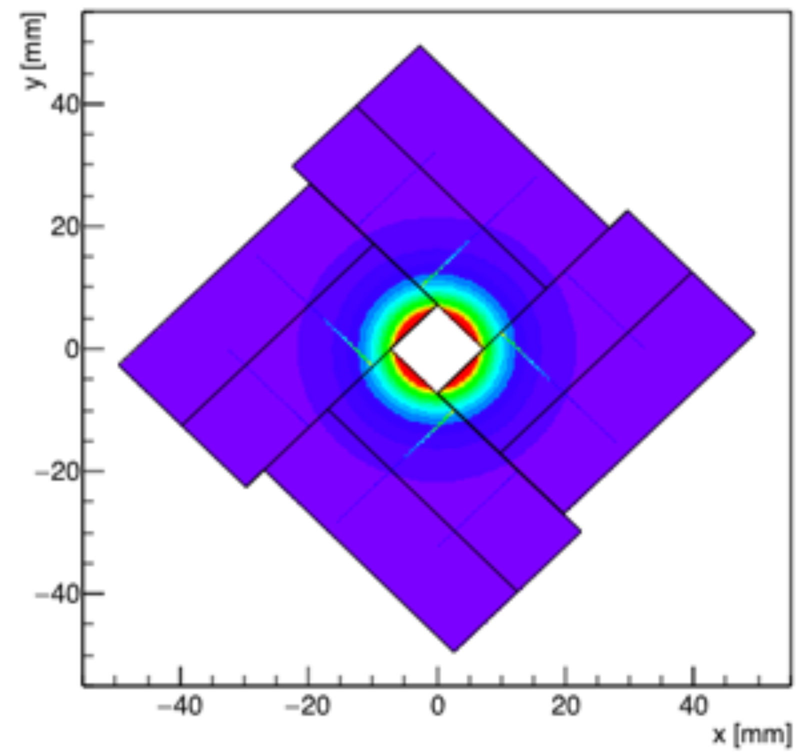
Closer look at the new VELO modules with changed geometry

Challenges for the VELO

Highly inhomogeneous irradiation damage

Max hadron fluence, $8 \times 10^{15} 1MeV n_{eq}/cm^2$ at innermost tip

- Factor 40 lower expected on opposite side
- Due to irradiation effects sensors needs to withstand greater HV



Expected Particle density, more irradiation expected at the inner most tip of the modules

Cooling system

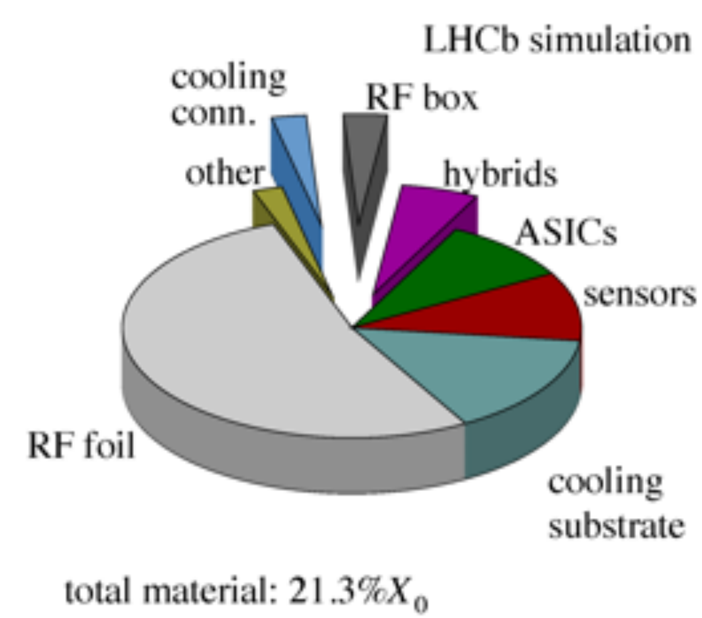
Greater power dissipation

- Cooling to avoid thermal runaway
- Power consumption ~1.5W per cm^2

Closer to the beam

Lower Material budget

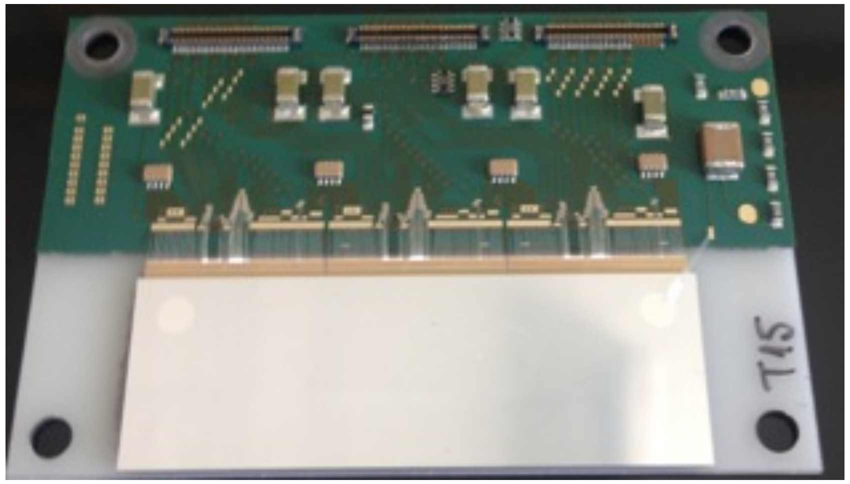
- Keep module design as thin as possible
- Closer and thinner RF foil



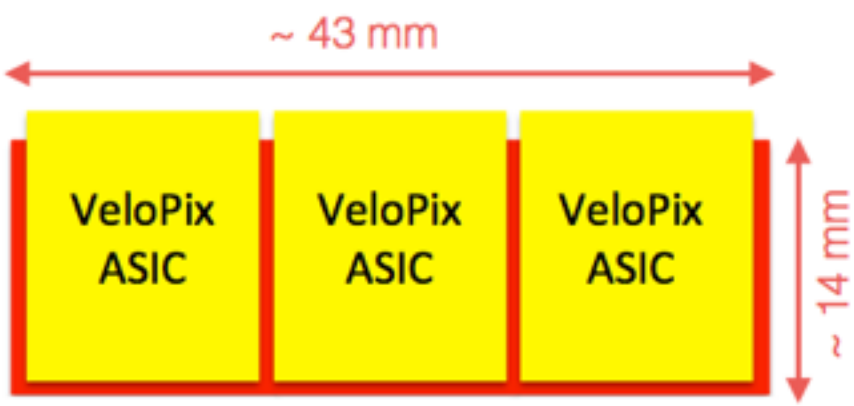
The different contributions to the total material budget of the upgraded VELO

The Sensors and ASIC

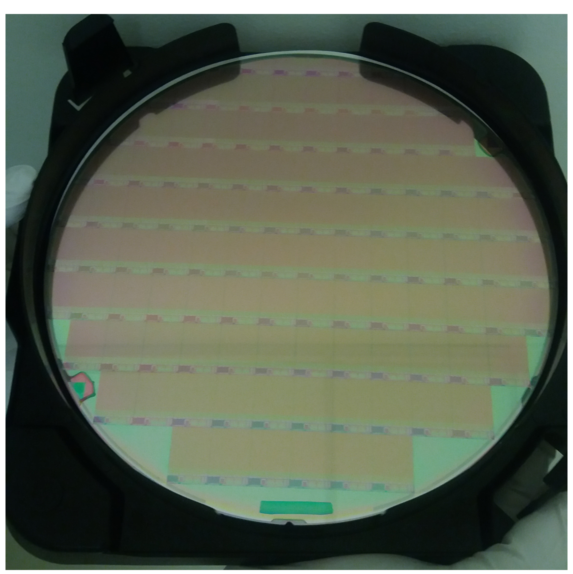
VeloPix Poster for more ASIC info



Prototype triple sensor bump bonded to a TimePix3 ASIC (predecessor of VeloPix)



One tile, is 3 ASICs (also known as a triple)



Newly arrived VeloPix wafer

Hybrid Pixel Detectors

Sensors

- n-on-p
- 200μm thick silicon
- Bump bonded to VeloPix ASIC
  - based on TimePix/MediPix family

VeloPix

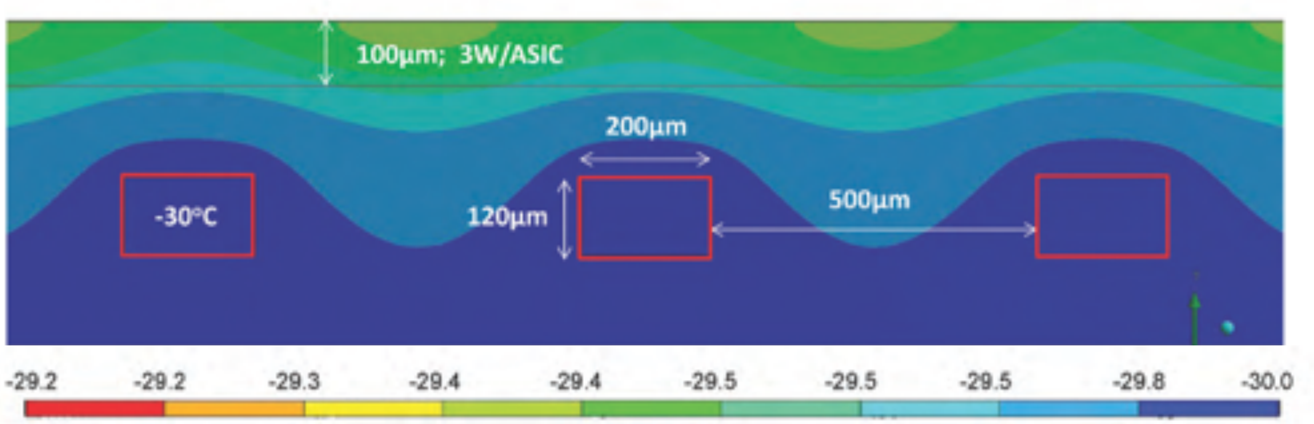
- 256x256 pixels/ASIC, 55x55μm^2 pixels
- Binary readout
- Thinned to 200μm
- Zero suppressed, data driven readout
  - every hit is time stamped and immediately sent of the chip
- Fast - Time walk ~25ns

Cooling

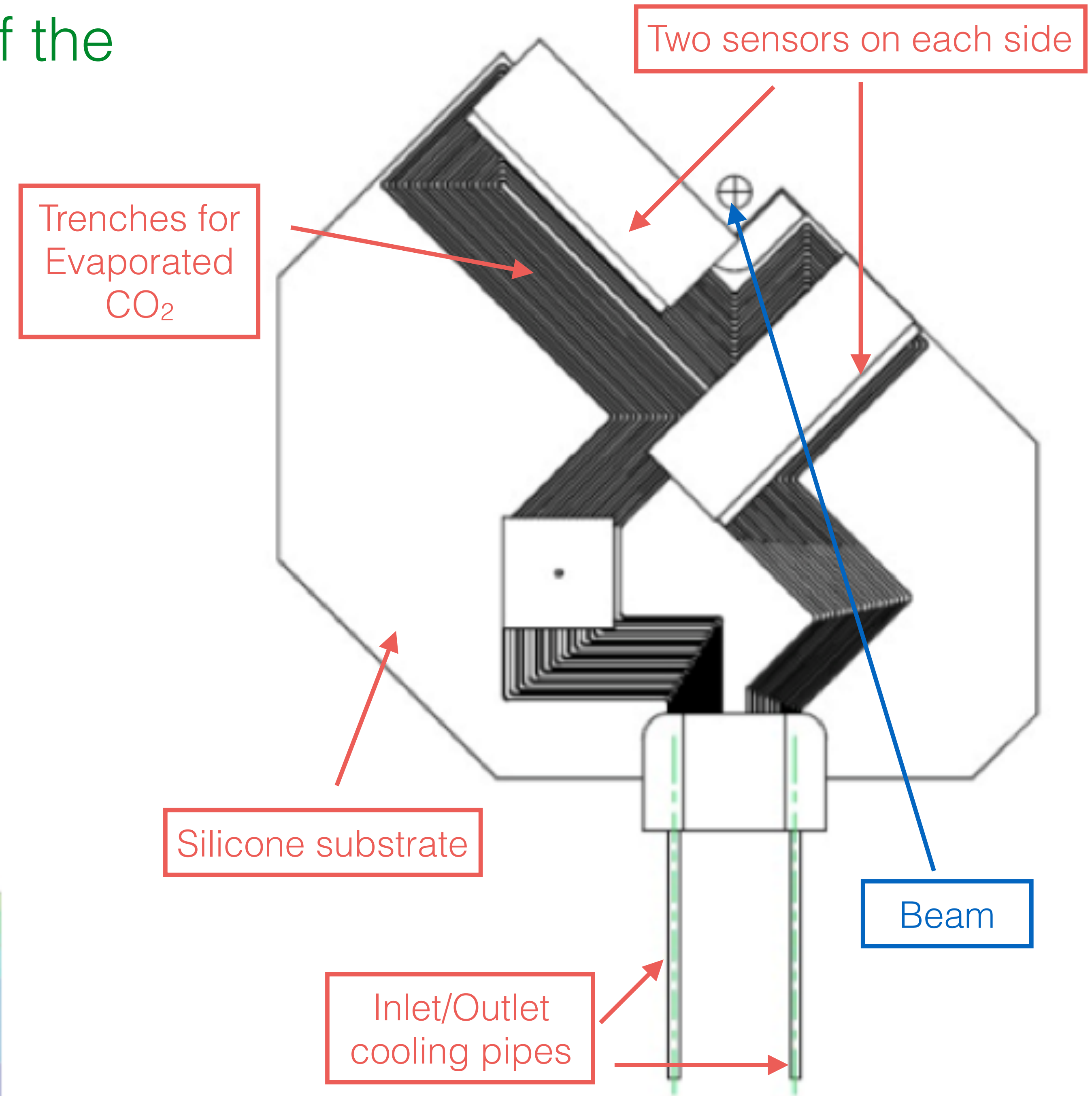
Evaporated CO2 flows via micro channel etched in the silicon substrate

Will act as the mechanical backbone of the module

- 2 sensors mounted on either side
- High thermal efficiency
  - Direct contact with ASIC surface
  - 19 channels under each ASIC
- Lower material budget
  - Combined thickness of 400μm
  - Trenches are 120μm deep
- Full sensor maintained at -30°C
- Radiation hard

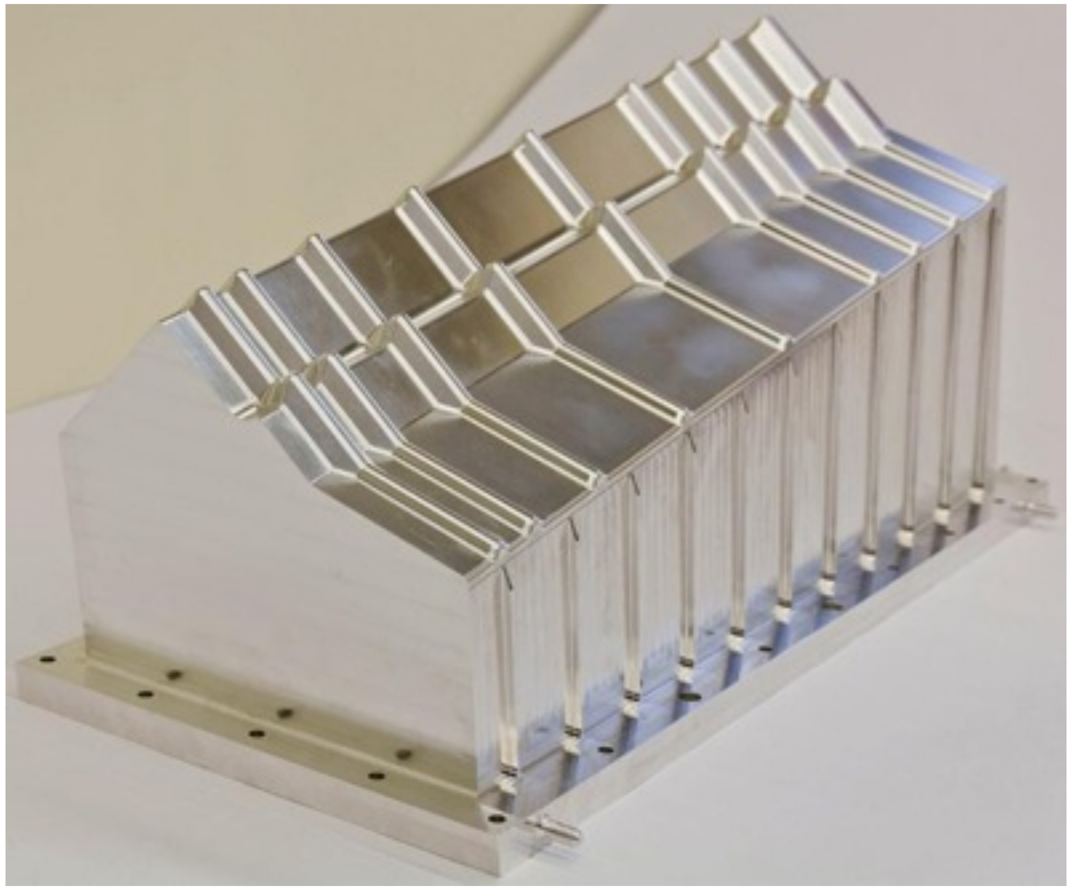


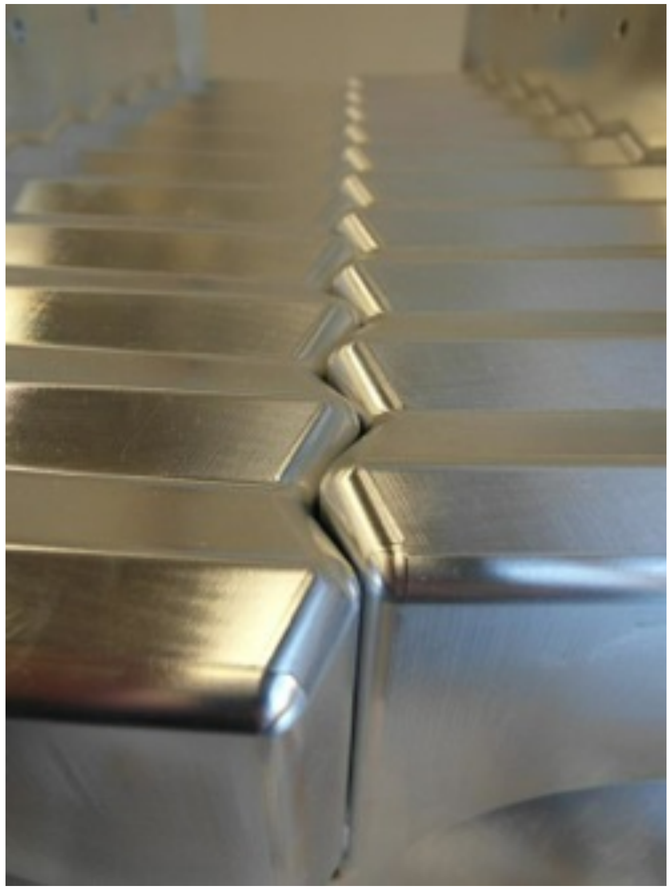
Thermal map from simulation (°C), variation of less than 1°C



Sketch of the micro-channel substrate

RF Foil





Photographs of the most recent RF foil prototypes

Two thin RF foils, leak tight barrier between LHC and VELO Vacuums

- Accommodate the modules
- 250μm thick Aluminium
  - Close to the beam (~3.5mm)
  - Allowing modules to close around interaction region
- Radiation Hard
- Thermal stability

Where are we?

Start up	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022+
Beam Crossing	50 ns			-		25 ns			-		25 ns		
TeV	0.9-7		8	LS 1		13-14			LS 2 LHCb Upgrade				
Instant Luminosity	10^{32}		$3-4 \times 10^{32}$			4×10^{32}					$10 - 20 \times 10^{32}$		
Integrated Luminosity	$3\ fb^{-1}$					$5-7\ fb^{-1}$					$> 50\ fb^{-1}$		

Start of LS2 upgrade delayed until 2019

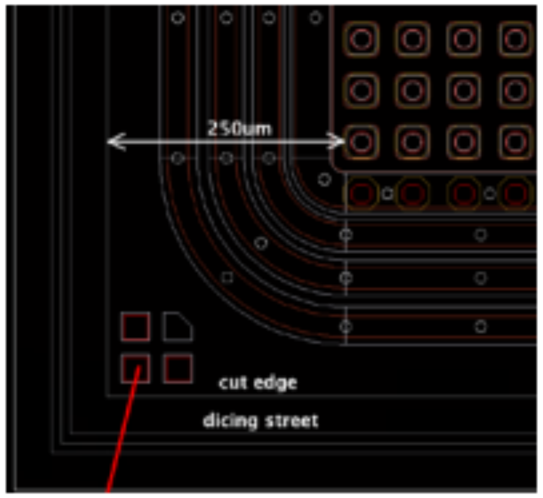
Upgrade will be during Long Shutdown 2!

Making good progress

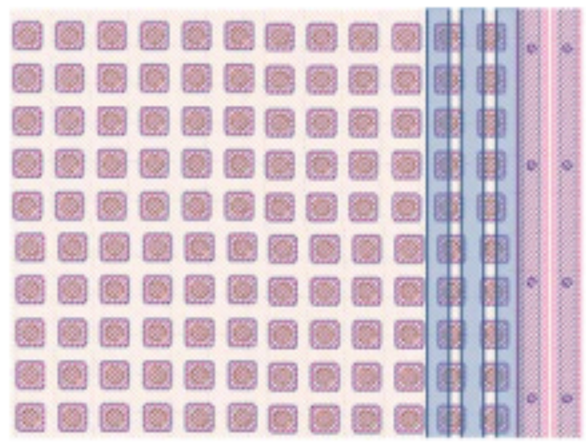
- Prototypes of both the RF foil and cooling substrates
- VeloPix has been submitted
  - Wafers on their way to CERN now for testing
- Sensor prototype testing has been ongoing since July 2014

Sensor Prototypes

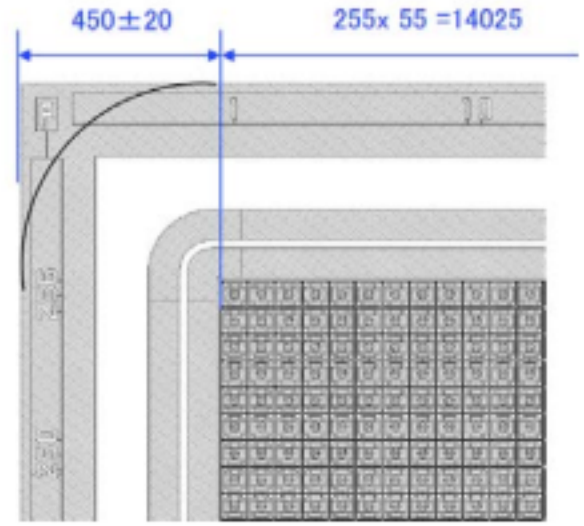
Testing sensors from both Hamamatsu and Micron



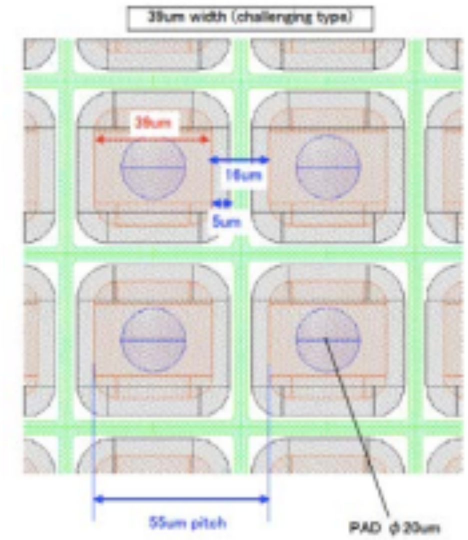
Micron n-on-p
- 250 µm GR
- 36 µm implant
- 150 µm thick



Micron n-on-n
- GR on back
- 150 µm thick



HPK n-on-p
- 450 µm GR
- 200µm thick



HPK n-on-p
- 200 µm thick
- 39 µm implant

- n-on-n and n-on-p
- 150 - 200µm thickness
- 250, 450, 500µm inactive edge
- 35 & 39µm implant width
- 256x256 pixels/ASIC, 55x55µm^2 pixels
- Bump bonded to TimePix3

Uniform and non-uniformly irradiated at KIT, IRRAD, JSI at fluences

$$4 \ \& \ 8x10^{15} 1MeVn_{eq}/cm^2$$

Sensor Requirements

As previously discussed the VELO is exposed to highly inhomogeneous irradiation damage

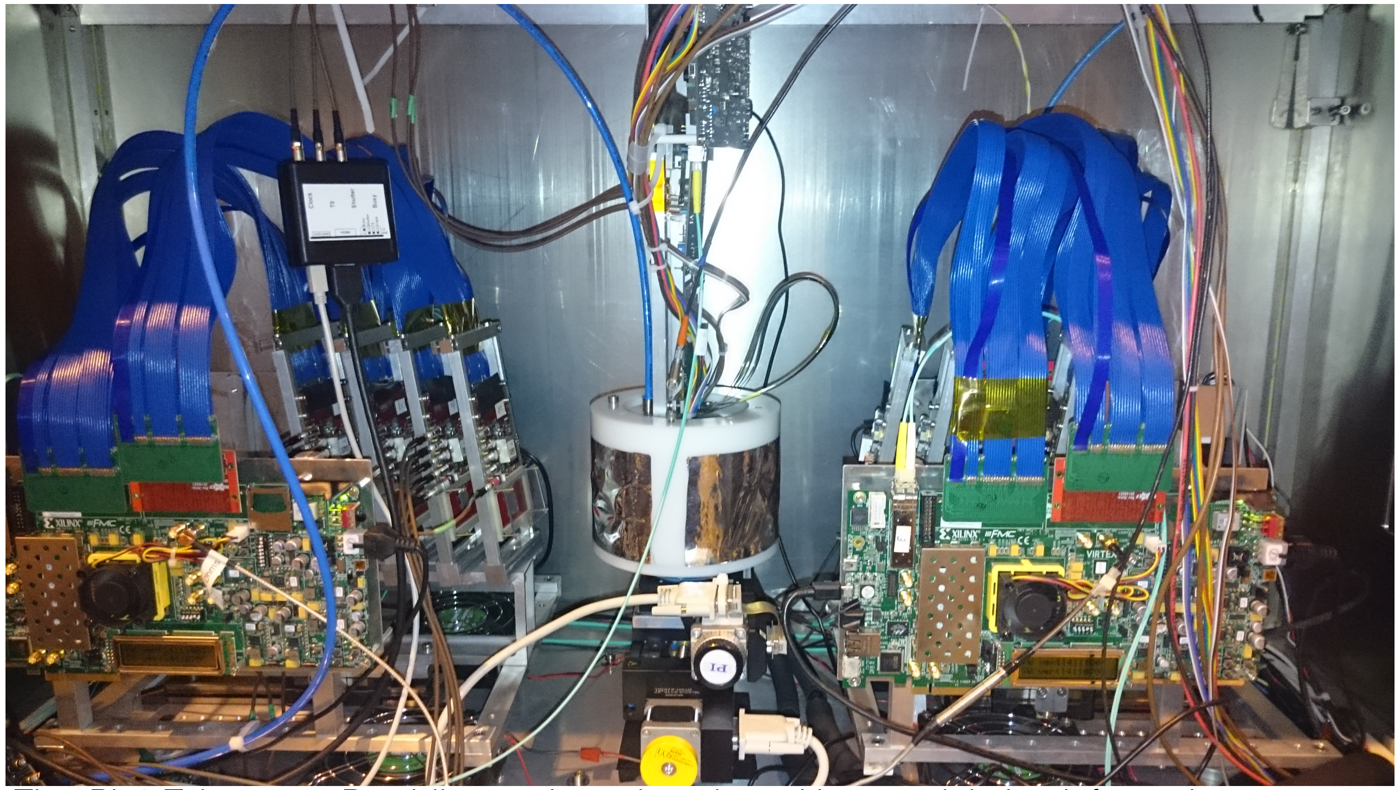
Require that sensors perform well both before and after irradiation

Benchmarks for detector performance are:

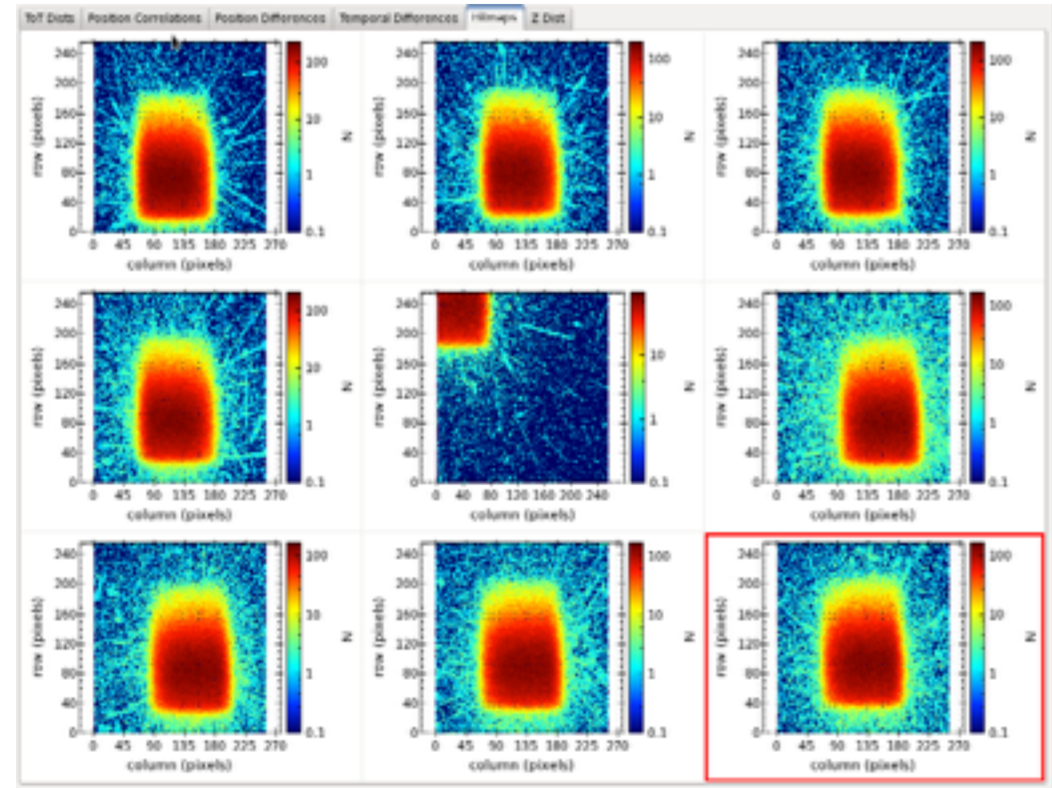
- Operate at high bias voltage
  - No breakdown before 1000V for irradiated sensors
- Uniform efficiency >99%
- Charge collection >6000e at the end of lifetime
- Excellent spatial resolution

Prototype sensors are tested in both the lab and testbeam environments

TimePix3 Telescope and SPS Testbeams



TimePix3 Telescope: Providing projected track positions and timing information



Data Quality Monitor of the telescope, while testing the corner of a DUT

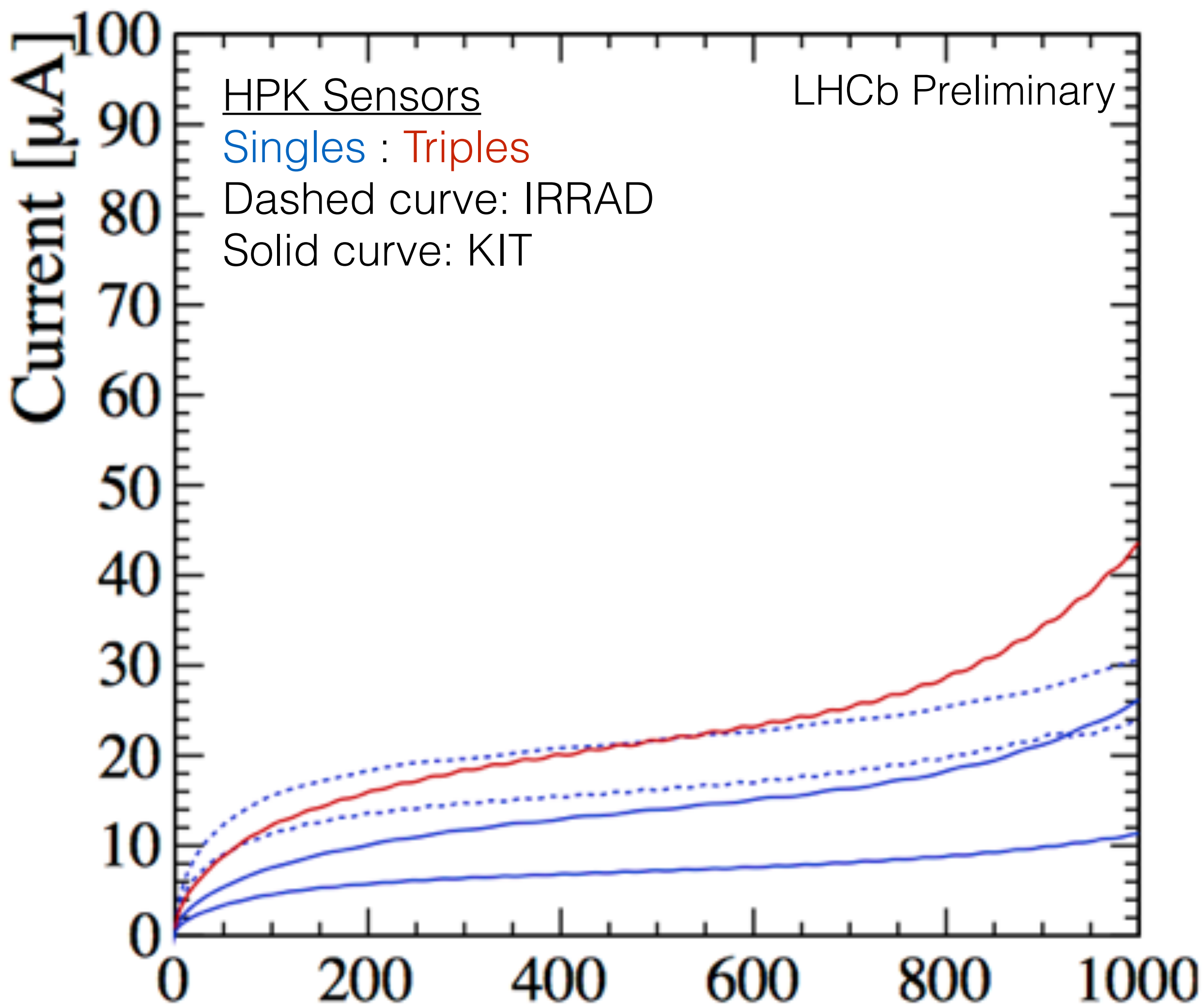
Constructed specifically for LHCb Upgrade studies

- Two arms with 4 TimePix3 devices each (bonded to 300μm silicon)
- Device Under Test (DUT) installed in the centre
  - Temperature controlled dry air cover
  - x, y and θ motion controls
  - HV controls
- Pointing resolution ~ 2μm for 180 GeV beam
- Timing resolution ~1ns

Testbeam Results - Bias Voltage

Irradiated sensors must reach 1000V without breakdown

- Radiation induced trapping centres degrade the signal
- Signal can be recovered by applying high bias voltages



Plot of the IV curves for irradiated Hamamatsu sensors

Non-Uniform irradiation profile across sensor

- Innermost region will require a high bias
- Outer region needs to sustain this voltage without breakdown

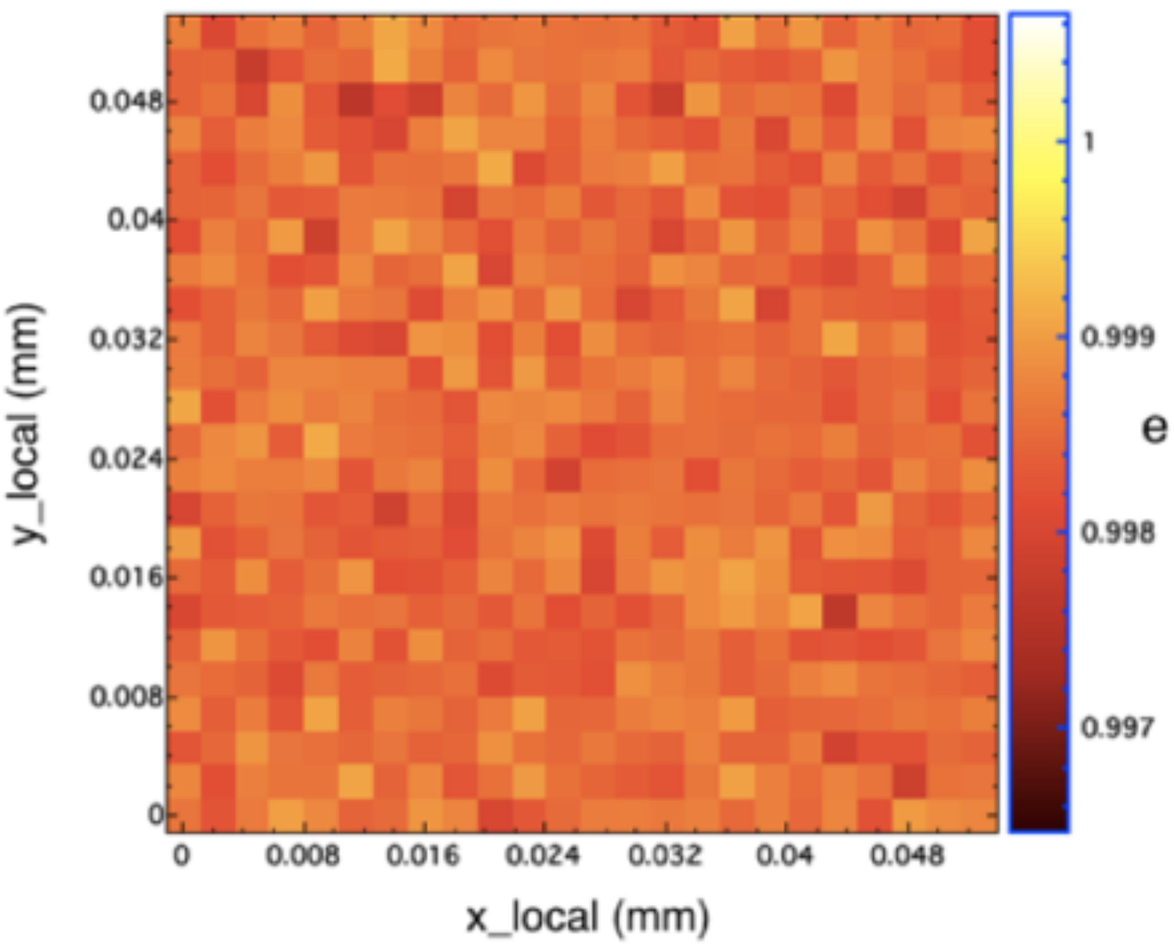
Majority of prototypes reach this requirement

Testbeam Results - Efficiency

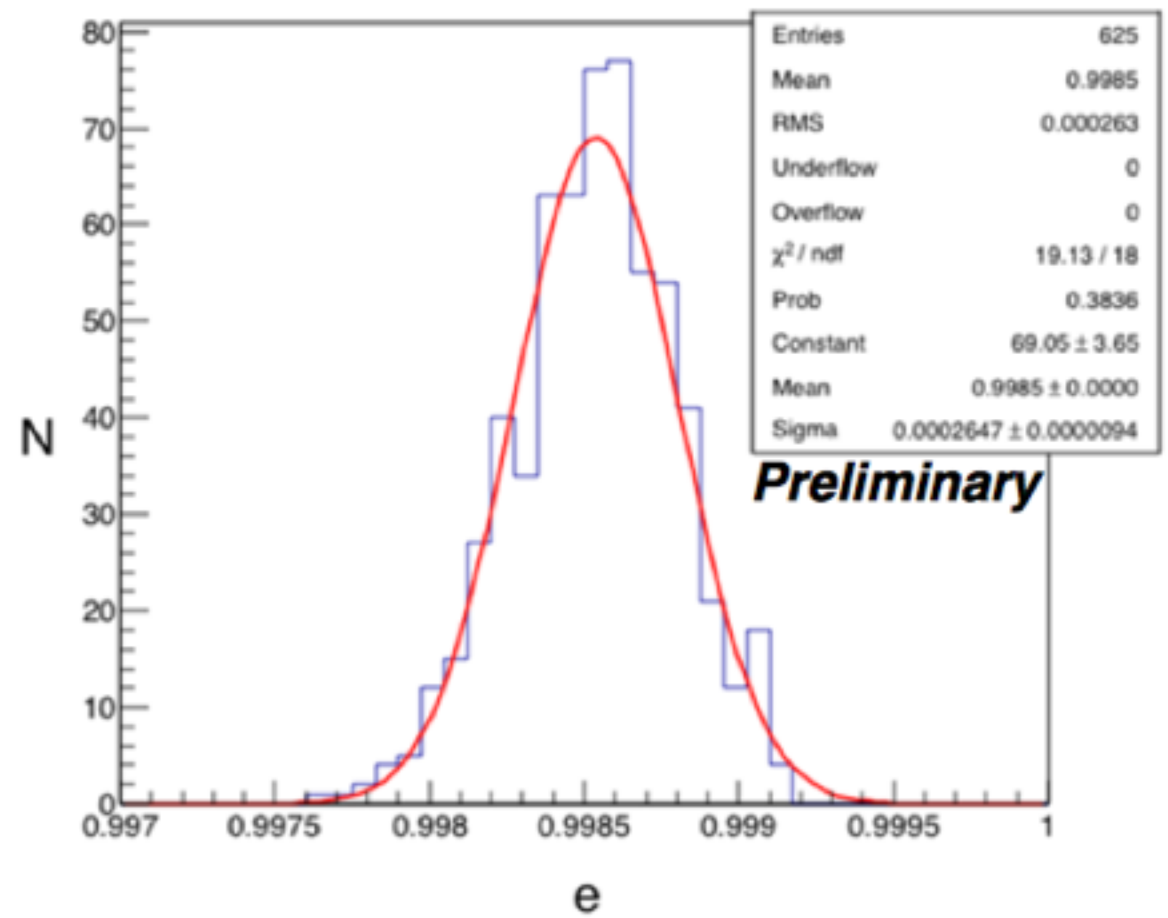
Require a uniform efficiency > 99% pre and post irradiation

$e = n_{\text{DUT\_Associated\_Clusters}} / \text{nTracks}$

Efficiency as a function of in-pixel position for **non-irradiated** sensor



In-pixel efficiency for non irradiated sensor



Distribution of In-pixel efficiencies to determine average

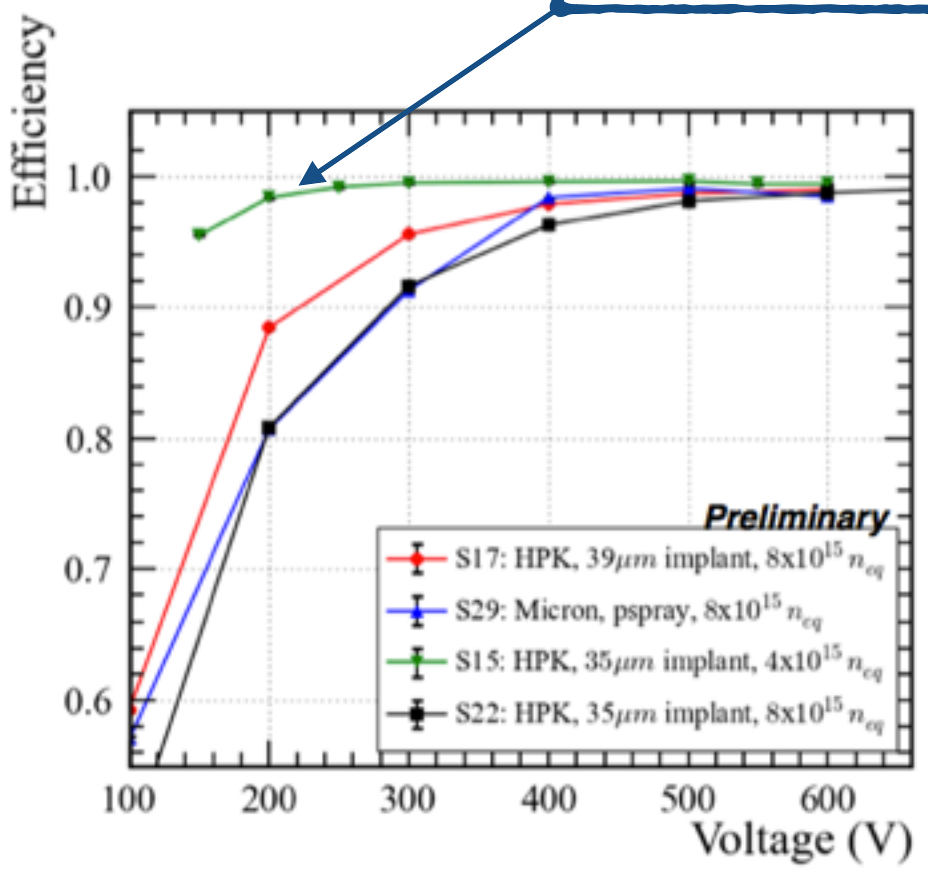
Sensor: 200 μm n-on-p sensor from Hamamatsu, 450 μm inactive edge, 39 μm implant width.

Average efficiency is (99.857 ± 0.003)% over full sensor

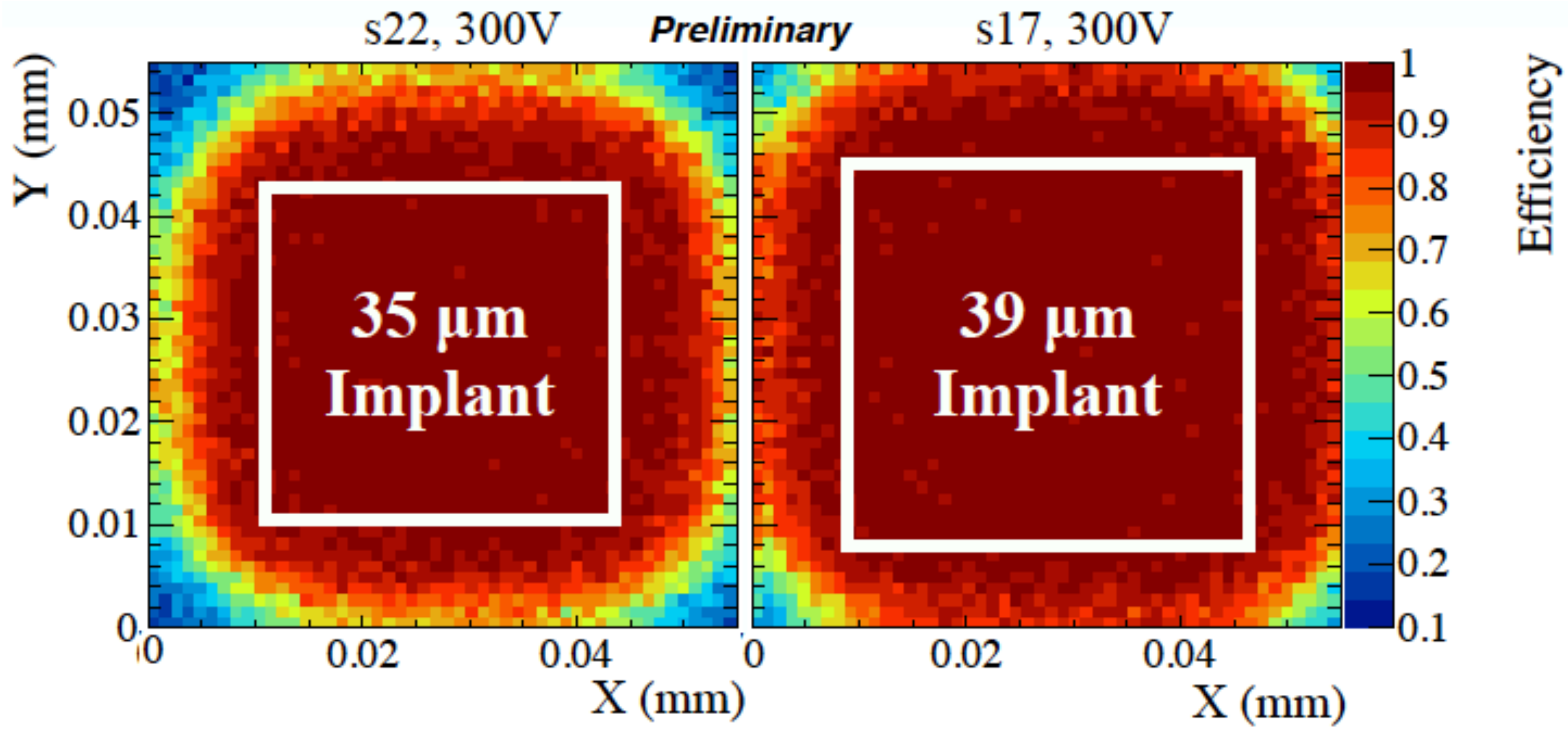
Testbeam Results - Efficiency

Efficiency as a function of in-pixel position for **irradiated** sensors
Inefficiencies are caused by decreased charge collection at the corners.

Notice half fluence



Efficiency as a function of voltage for a range of sensors



In-pixel efficiency for irradiated sensor for two different implant widths, uniform efficiency is seen in the corners when voltage is increased

Efficiency improves with bias voltage

Larger implant improves efficiency in corners

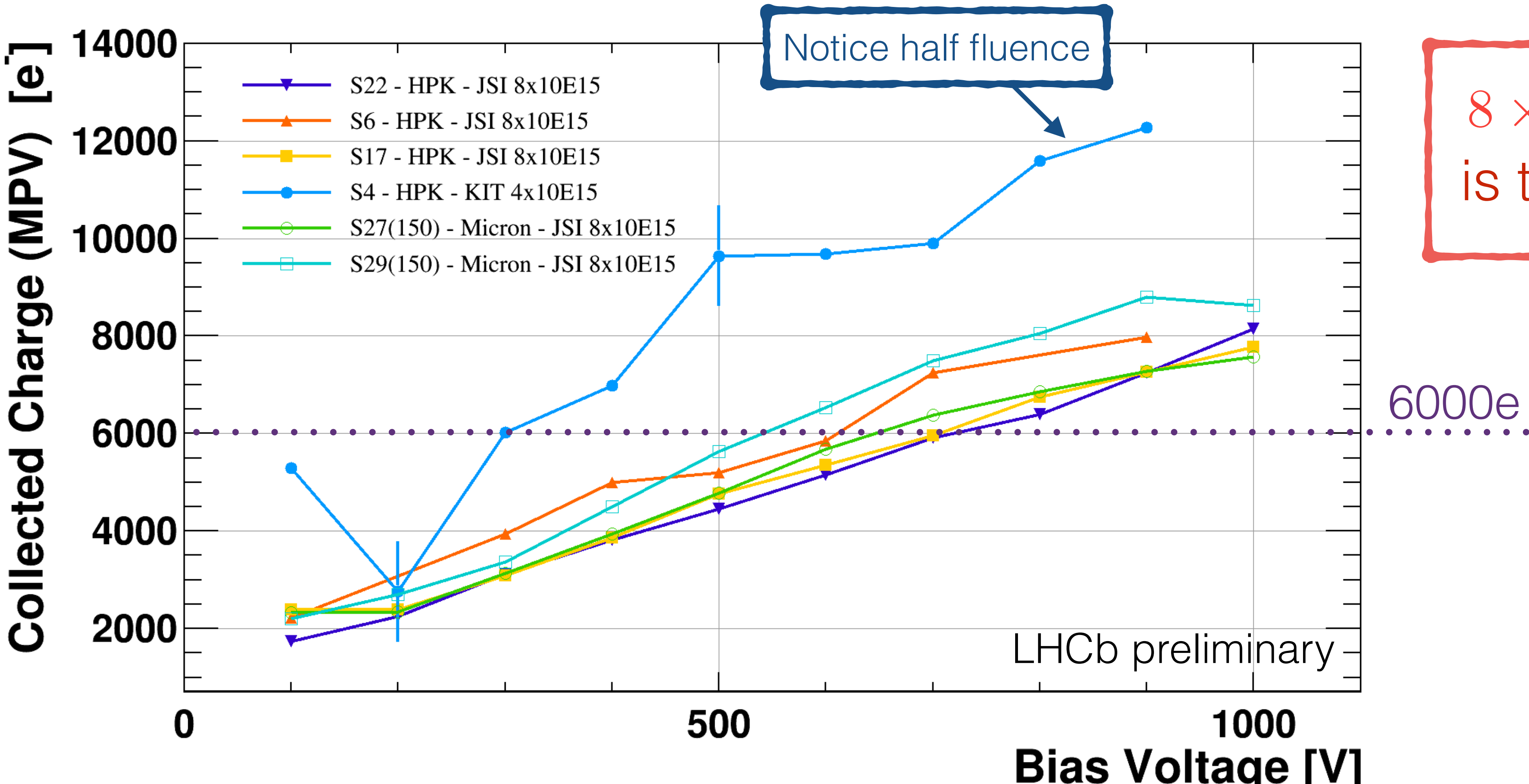
Average efficiency is reduced but still close to 99% at high bias voltage

S17, S15 & S22: 200µm HPK, n-on-p, 450 µm inactive edge
S29: 150µm Micron, n-on-n, 450 µm inactive edge

Testbeam Results - Charge Collection

Investigate the required bias voltage to recover lost charge at different operation times

- Radiation induced trapping centres degrade the signal -> reduced S/N
- Signal can improved by applying high bias voltages



Collected charge for a range of irradiated sensors, as a function of the bias voltage

$8 \times 10^{15} 1MeV n_{eq}/cm^2$
is the full lifetime dose

S6, S17 & S22: 200μm HPK, n-on-p, 450 μm inactive edge
S27 & S29: 150μm Micron, n-on-n, 450 μm inactive edge

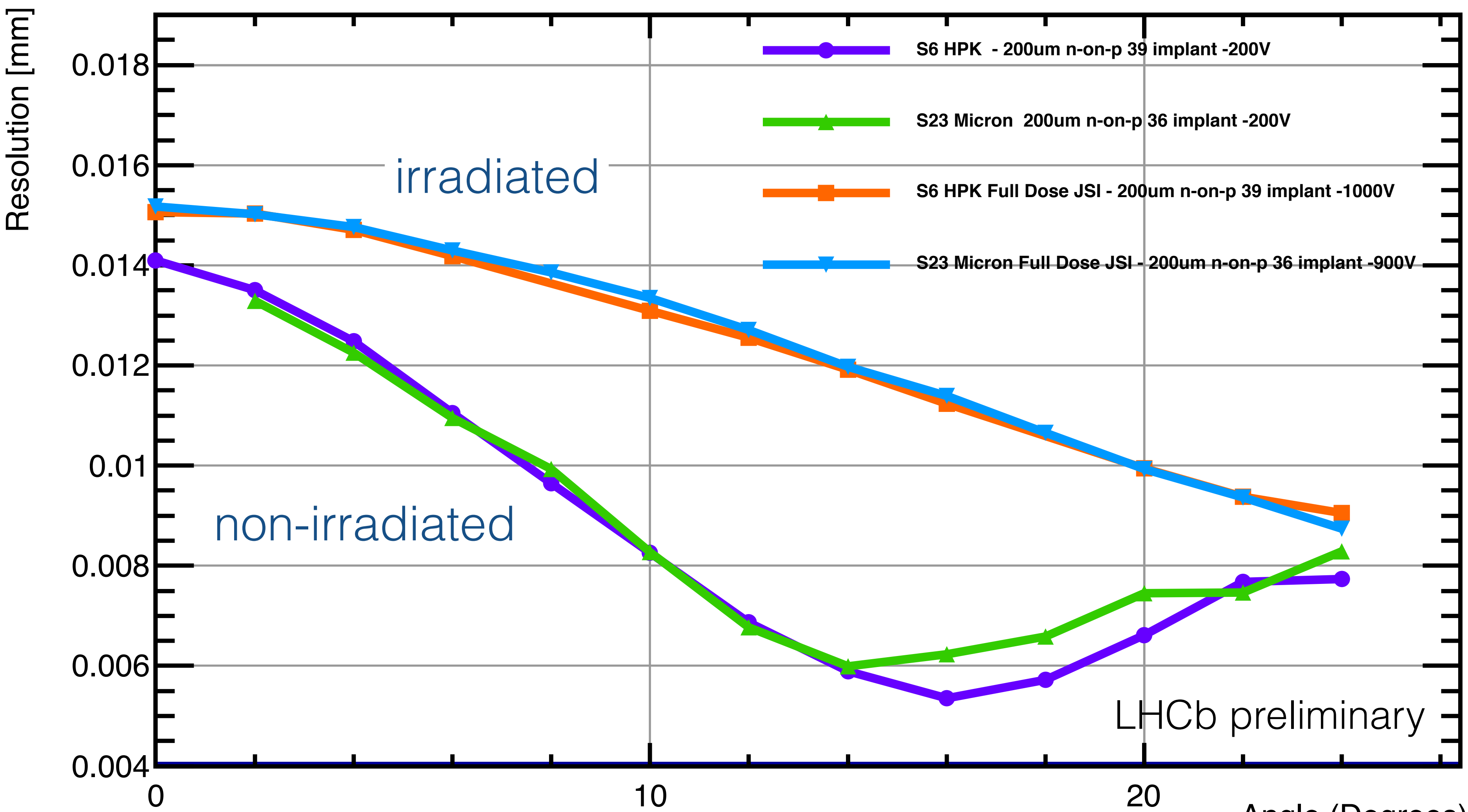
Collected charge improves with bias to sufficient level

Testbeam Results - Spatial Resolution

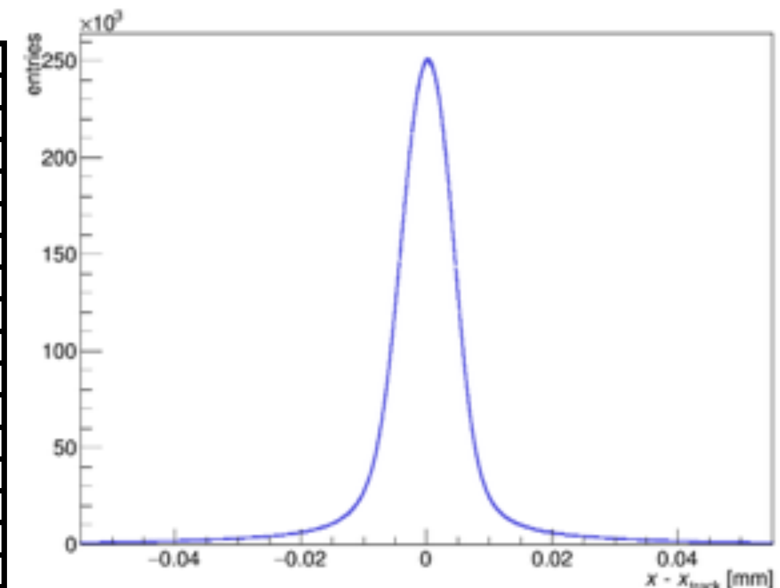
Need excellent spatial resolution

Resolution degrades due to charge trapping

σ = Cluster position - Predicted track position



Resolution as a function of angle, for two sensors pre and post irradiation



Example unbiased residual plot. The σ of a Gaussian fit to this distribution is one point in the neighbouring plot

Angle dependance on resolution due to increased charge sharing

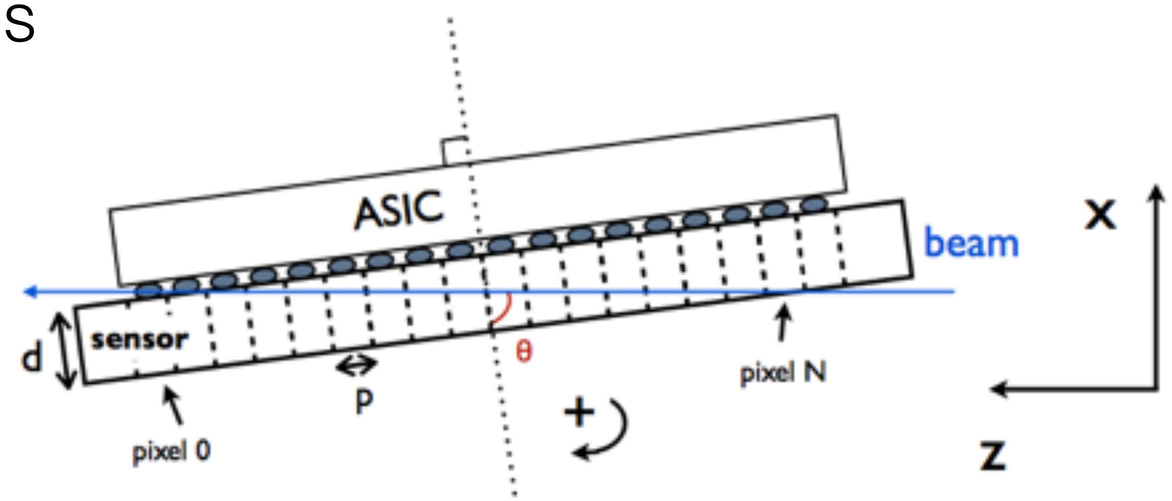
Resolution is ~5 μm pre irradiation and better than ~9 μm at optimal angle

Testbeam Results - Sensor Depth Properties

Can test timing and charge collection as a function of depth

- DUT placed 85 degrees w.r.t the beam
- Incoming particle travels through many pixels
- Long clusters ~42 pixels
- Each pixel is assigned a depth

Can calculate depth: $d(i) = \dfrac{P \times N(i)}{tan(\theta)}$



Sketch representing a grazing angle scan, where the DUT is at a 85 degree angle w.r.t the beam

For charge collection

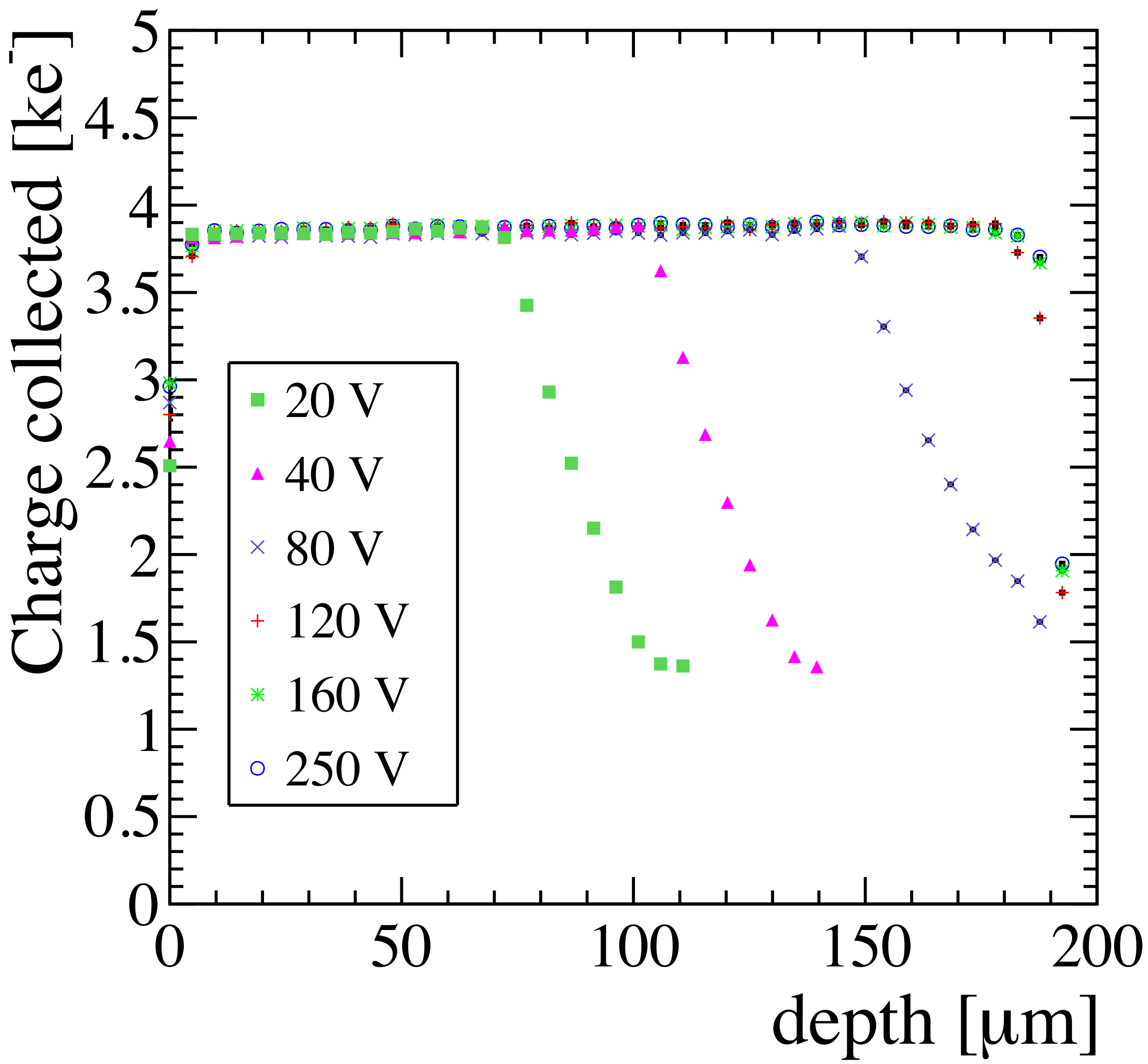
Charge distribution collected for each depth is fitted with a landau

For time walk

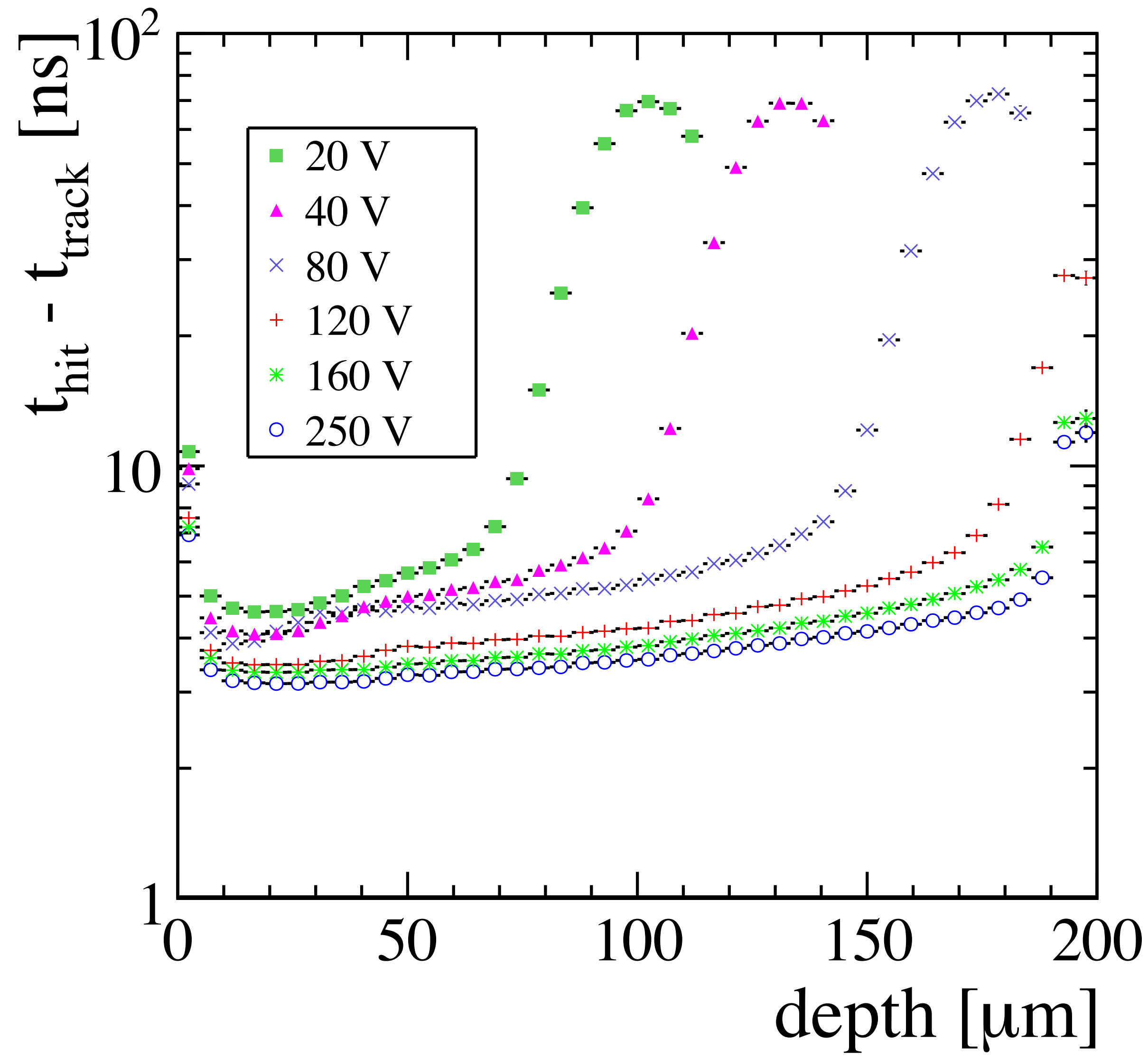
The time charge takes to cross threshold is compared to the time predicted by the tracking information

Testbeam Results - Sensor Depth Properties

S6: 200μm HPK, n-on-p, 450 μm inactive edge, non irradiated



Collected charge profilr as a function of depth



Time to threshold as function of depth

At depletion all charge is collected

- Below depletion the charge diffuses between the depletion edge and sensor backplane

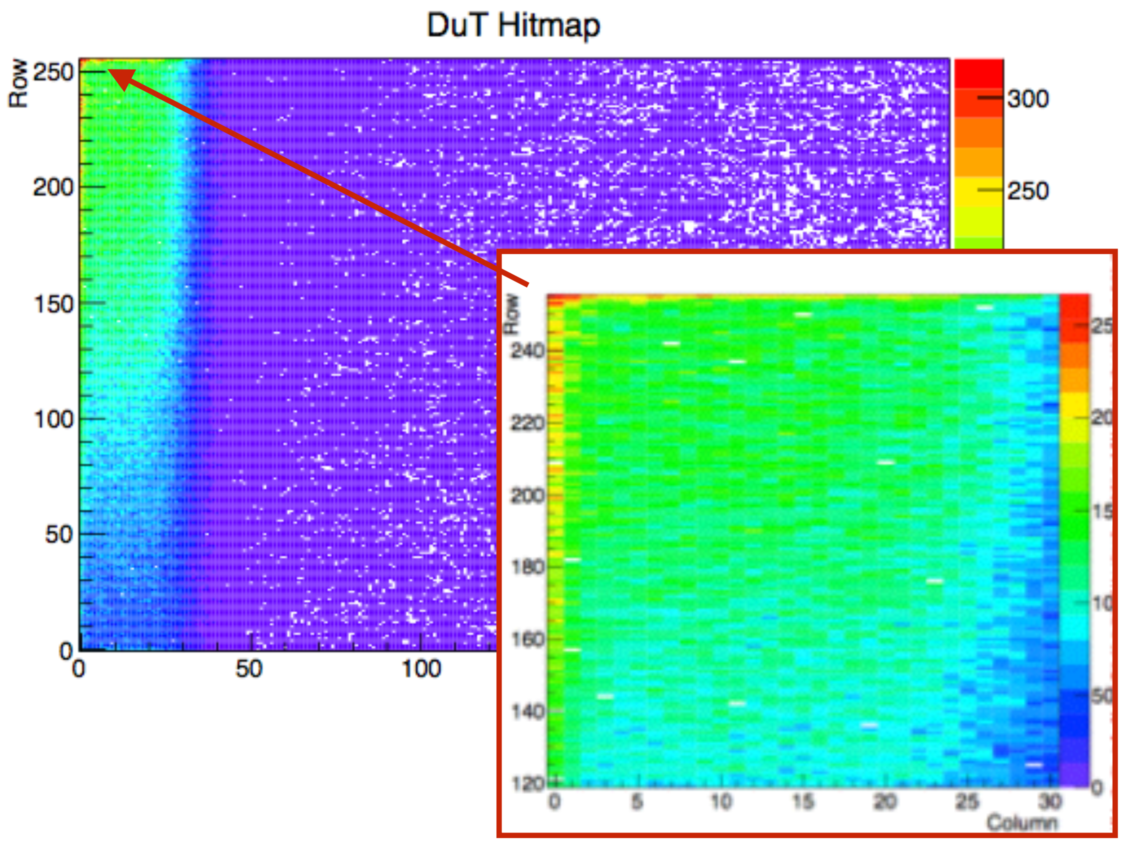
At depletion the time walk is < 4ns

- Below depletion charge needs more time
- > 10ns
- Again due to diffusion

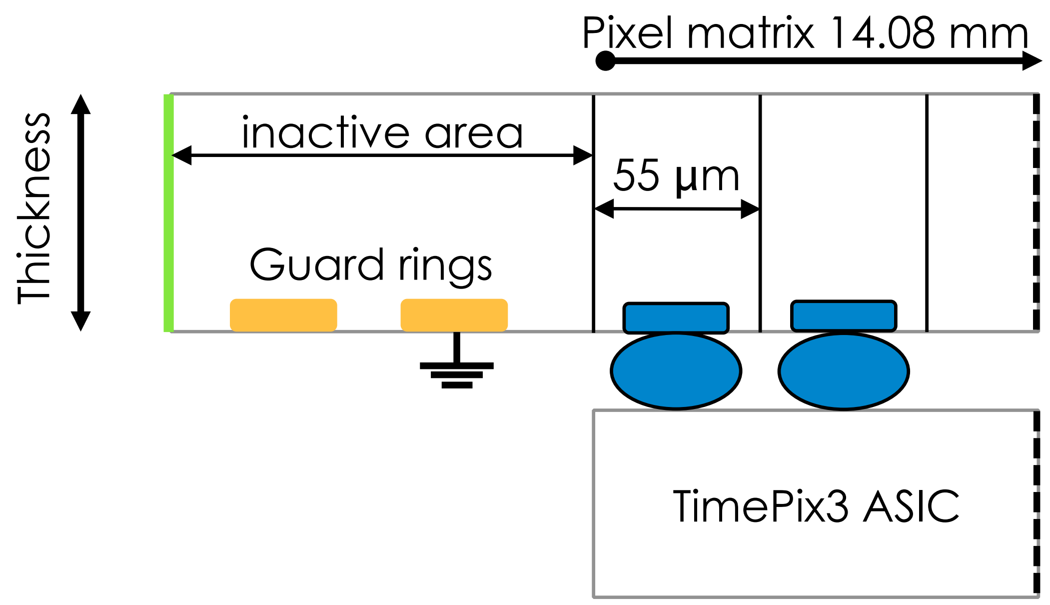
Testbeam Results - Edge Effects

Excess charge was found during a corner scan of a Micron n-on-p DUT

- Only seen in the first row and column next to the edge
- Suggests that the guard ring is not correctly draining the charge from tracks travelling through the inactive area



Hit map from testbeam, with zoom of one corner where excess charge in seen in the 1st row and column



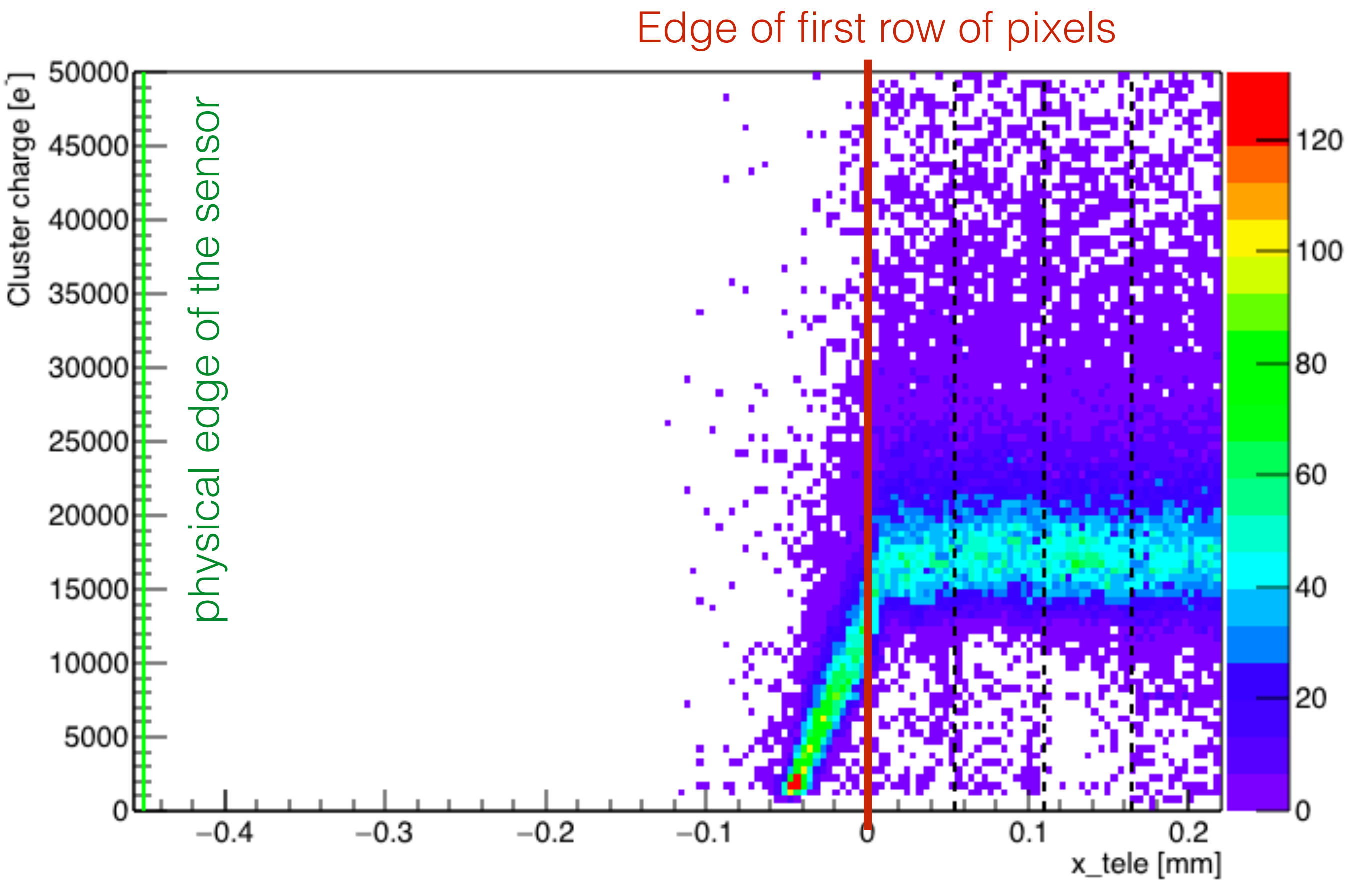
Between the physical end of the sensor and the first column and trow pixels there is an inactive area that contains the guard rings

To test this theory, need to investigate the deposited charge as a function of the predicted hit position from tracking

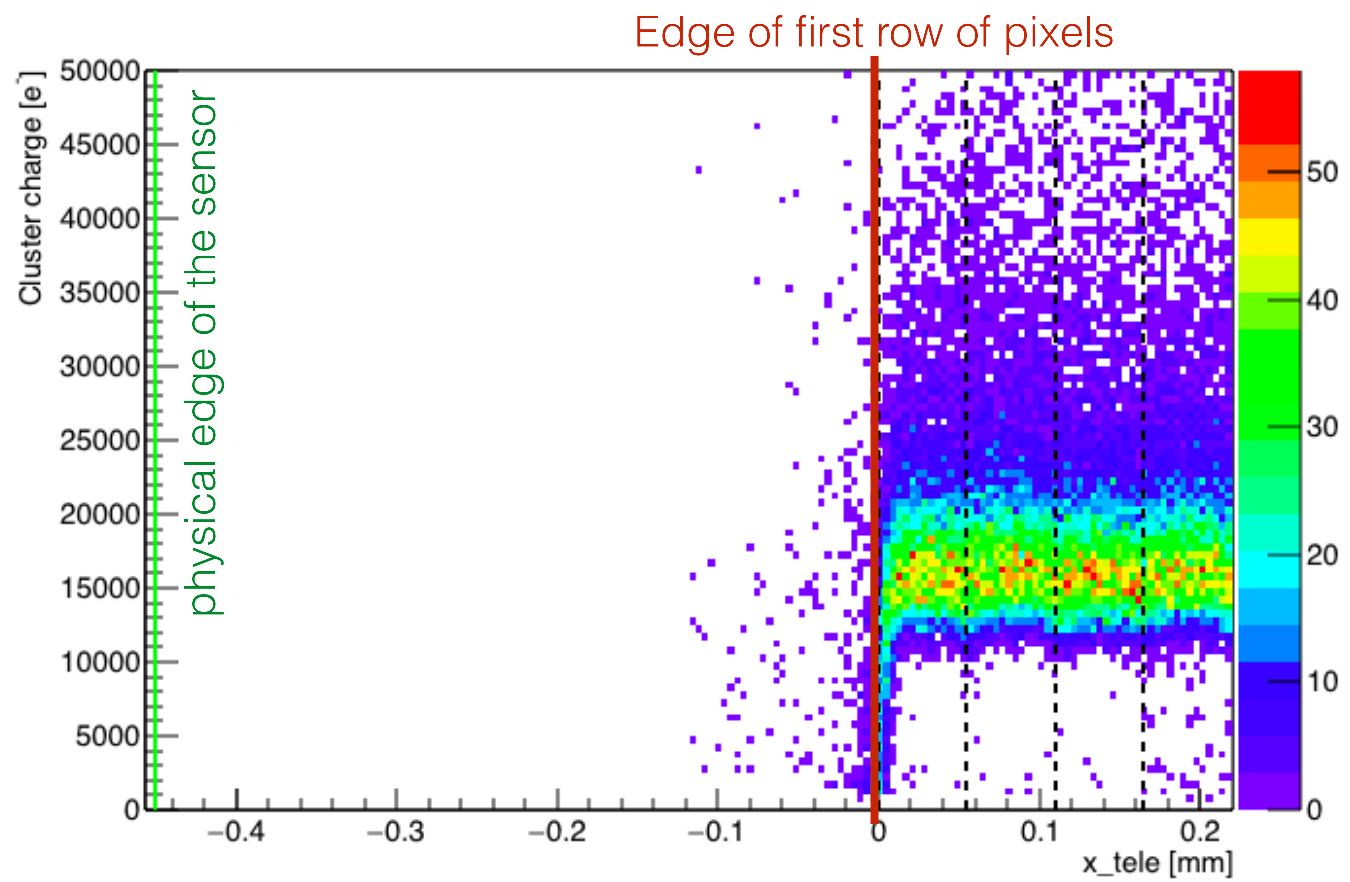
Testbeam Results - Edge Effects

The tracking does not use DUT cluster information

- Can extrapolate where the track passed through the sensor or guard ring



Deposited charge as a function of the predicted track position for Micron n-on-p



Deposited charge as a function of the predicted track position for Hamamatsu n-on-p

Can clearly see charge deposited past the edge of the 1st row of pixels

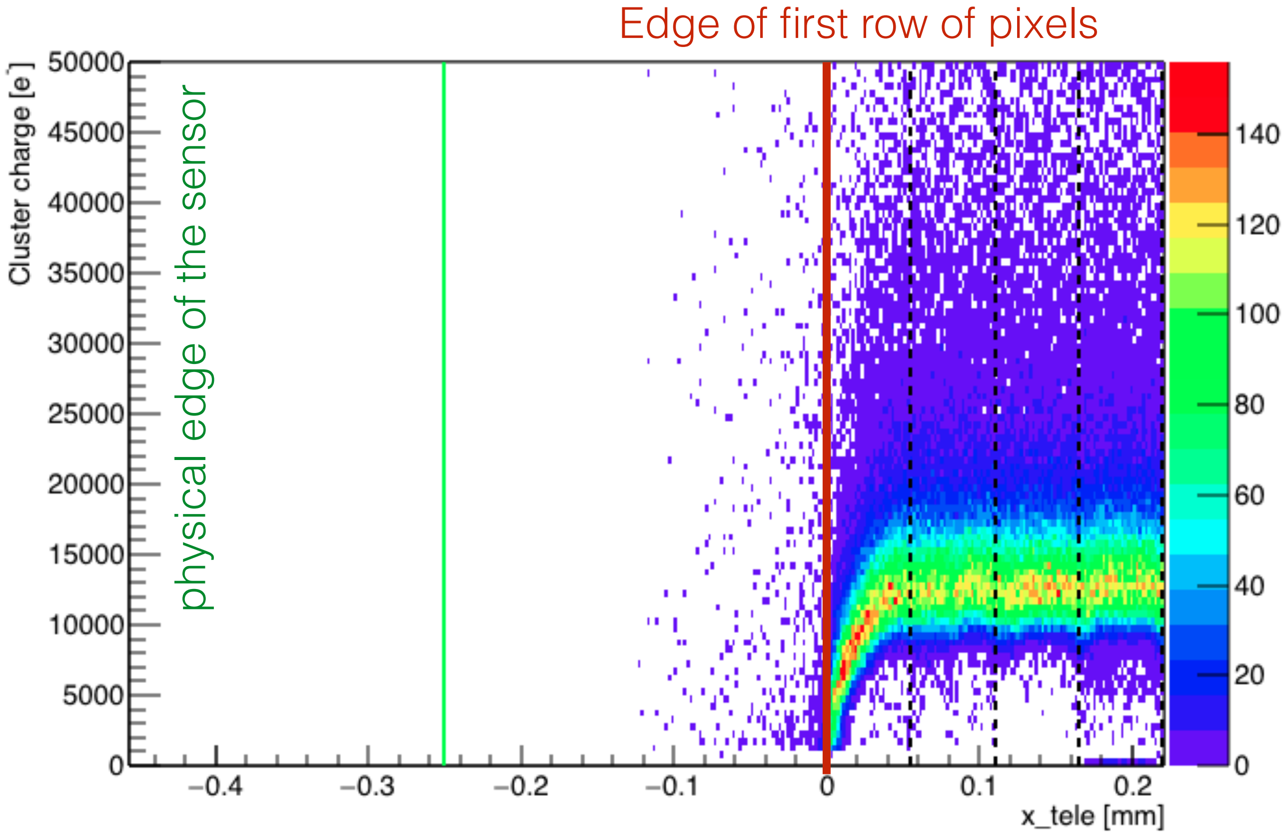
This effect is not observed in Hamamatsu n-on-p

→ Guard ring is not draining the charge correctly

Testbeam Results - Edge Effects

The opposite is seen for Micron n-on-n

The guard ring is draining the charge from the neighbouring pixels



Deposited charge as a function of the predicted track position for Micron n-on-n

Results for angle analysis found…

- Tilted border between collection region of guard ring and pixel matrix
- Field shape of the guard ring is such that it collects charge from tracks travelling through the first row/column

Effects are seen in the Micron n-on-n 250μm and n-on-p 250μm & 450μm guard ring designs

→ Potential to add 2 extra rows and columns of floating pixels to the edges to drain the charge

Conclusions

Redesign of the VELO to allow for increased data rate

Silicon strips $\longrightarrow$ Hybrid pixel detector

Cooling system and RF foil prototypes progressing well

Successful testbeam campaigns to test sensor performance

- ✓ Able to sustain high bias voltages
- ✓ Efficiencies ~99%
- ✓ charge collection >6000e
- ✓ Excellent spatial resolution

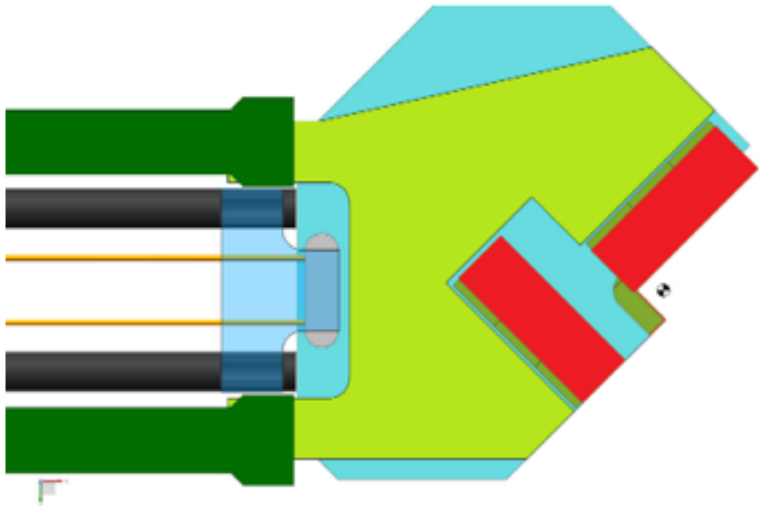
VeloPix was submitted in May and has arrived

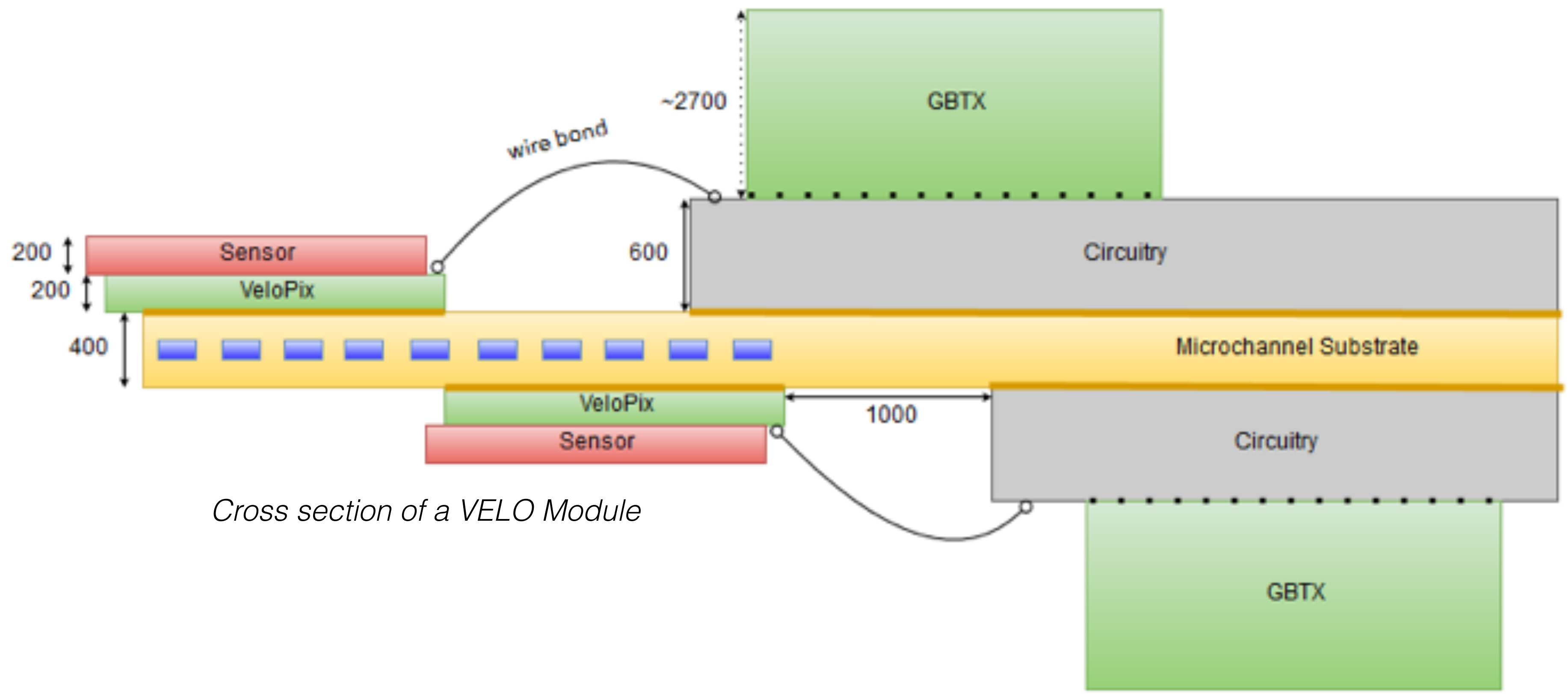
Presentation on physics benchmarks for the upgraded VELO will be presented tomorrow

On course to install during long shutdown 2!

Backup

Modules





Cross section of a VELO Module

One module consists of 4 sensors in a L shape geometry

- Two on each side
- Glued onto the micro channel silicon substrate
- Wire bonded to two hybrids
  - Providing the power, HV & chip control etc.

Testbeam Results - Timing

Collect maximum number of hits within a bunch crossing - 25ns

Hits with low charge will suffer time walk

→ Assigned to wrong bunch → ghost hits

$t_{hit} - t_{track}$ Is the difference between hit and track timestamps

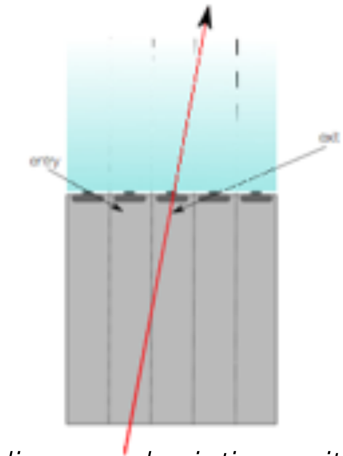
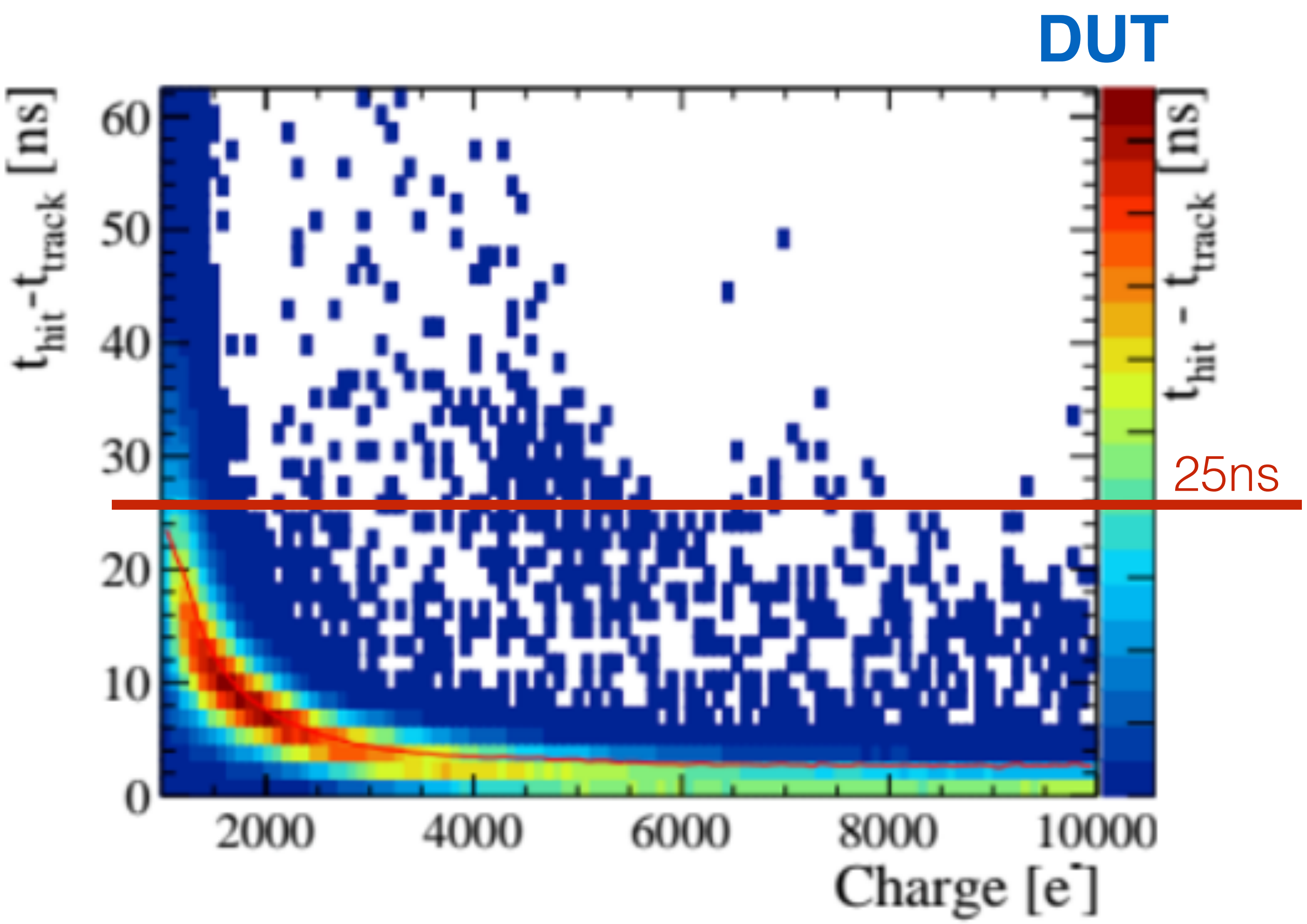
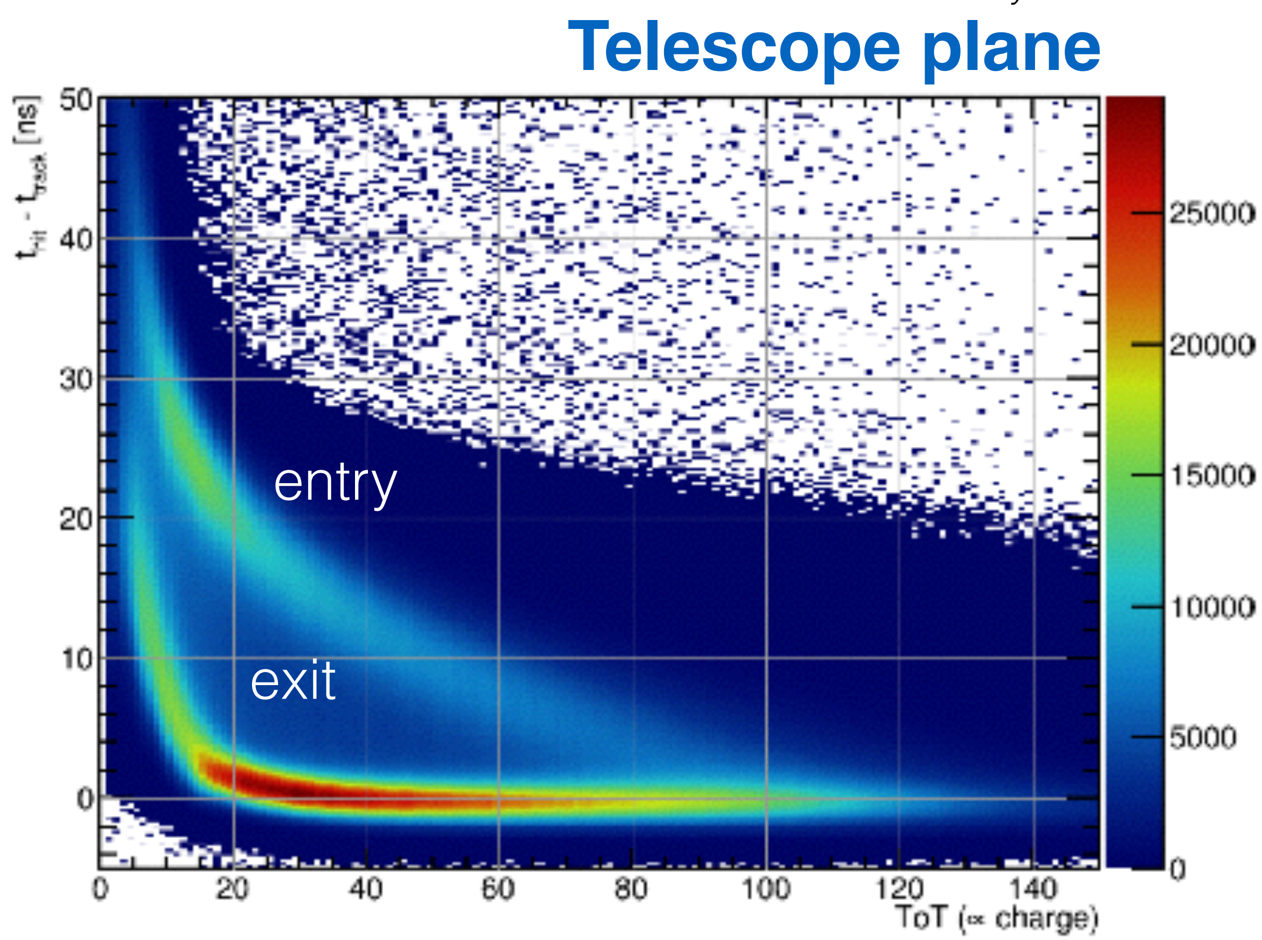


diagram depicting exit and entry of a track



Example time walk plot for a sensor tested using Timepix3



Timewalk for a telescope plane, the using Timepix3 but bonded to 300μm p-on-n silicon sensor

The TimePix3 has shown adequate timing, can expect similar performance in VeloPix