Upgrade of Belle II Vertex Detector with CMOS Pixel Technology

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On Behalf of the Belle II VTX Upgrade Group

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GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

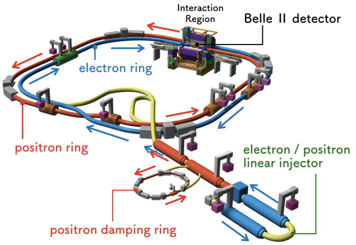
Bundesministerium für Bildung und Forschung

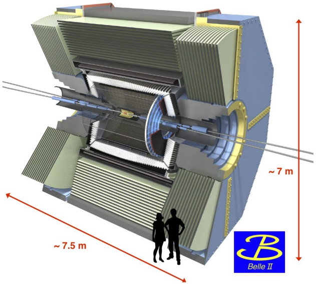
Belle II

Belle II and SuperKEKB

- Located at the SuperKEKB collider in Tsukuba/Japan
- Asymmetric e^+e^- collider at $\sqrt{s} = M_{\Upsilon(4S)} = 10.58$ GeV
- Luminosity frontier experiment
- Target $\mathcal{L}_{int} = 50\ \text{ab}^{-1}$
  - Current $\mathcal{L}_{int} = 428\ \text{fb}^{-1}$ since 2019
  - Long-shutdown since last June
  - Restart at beginning of 2024
- Record $\mathcal{L}_{max} = 0.47 \cdot 10^{35}\ \text{cm}^{-2}\ \text{s}^{-1}$ in June 2022
- Target peak $\mathcal{L} = 6 \cdot 10^{35}\ \text{cm}^{-2}\ \text{s}^{-1}$

  $\rightarrow$ Upgrade ~2027 foreseen
  - High currents & nano-beam scheme
  - Challenging background conditions





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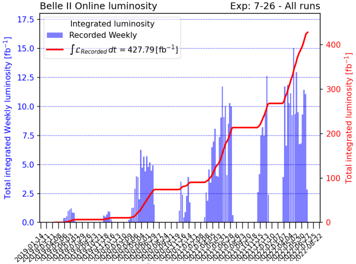
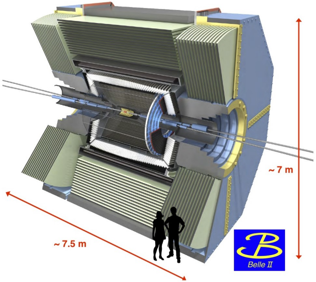
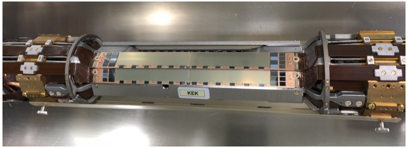
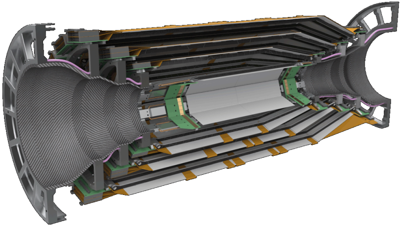




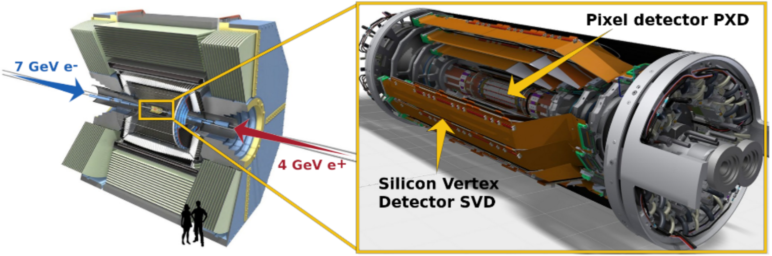
Belle II Vertex detector

- Current Vertex Detector (VXD):
  - 2 inner layers with DEPFET based pixel sensors
  - 4 layers double sided strip detector
- Low mass ladder design with total material budget of $3.8\% X_0$
- PXD:
  - Thin sensors (75µm) and small pixel pitch (50-75 µm)
  - Long integration time (20µs)
- SVD :
  - Very good cluster time resolution 3 ns , but long strips (6 cm)
  - Spatial resolution of 10 -25 µm





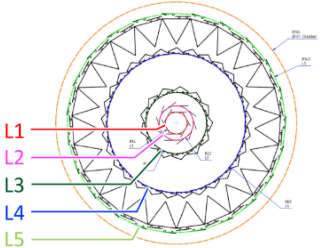
VXD in High Luminosity Environment

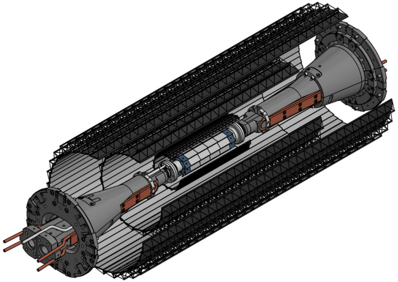


- Current occupancy $< 1\%$
- Background extrapolation uncertain $\rightarrow$ 3 scenarios
- Performance degradation possible for higher occupancy
- May reach limits of current detector for high lumi. environment occupancies $\gtrsim 3\%$

Vertex Detector Upgrade Proposal

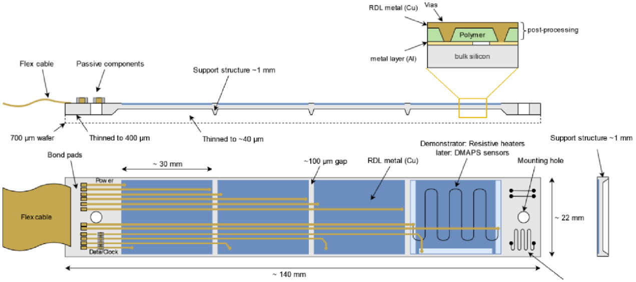
- SuperKEKB upgrade likely to change interaction region for high luminosity environment during LS2
- Opportunity to upgrade current vertex detector with 5 straight layers Depleted CMOS MAPS
- Reduced material budget $\sim 2.5\% X_0$
- Increase space-time granularity
- Requirements:
  - Robust against inner layer background
  - Hit-rate up to 120 MHz/cm^2
  - Resolution $<$15 µm
  - High efficiency
  - Ionizing dose $\sim$ 10 kGy/year
  - NIEL $5 \cdot 10^{13} n_{eq}/cm^2/year$

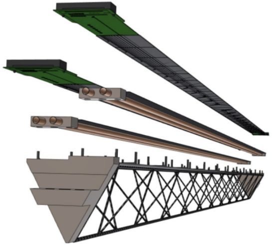




VTX detector mechanics

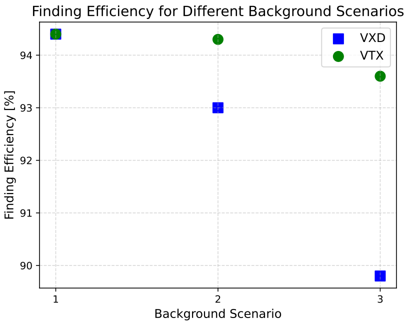
- 5 straight DMAPS layers
- Radii at 14, 22, 39, 90, 140 mm
- Ladder/stave design
- iVTX:
  - L1 & L2
  - All silicon ladders
  - Air cooling
  - $\sim 0.1\% X_0$
- oVTX:
  - L3 & L4 & L5
  - Carbon-fibre structure support frame
  - Cooling plate with water cooling
  - $\sim 0.3 - 0.5\% X_0$ L3 & L4
  - $\sim 0.8\% X_0$ L5

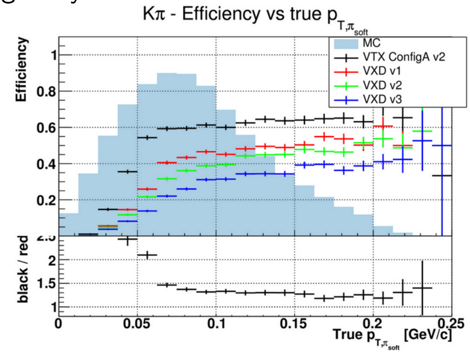




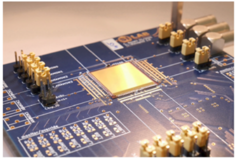
VTX Tracking Performance

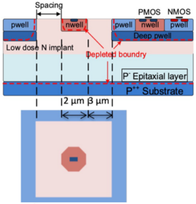
- Based on simulations of 1000 $B\bar{B}$ events and respective overlay background files
- Background overlays range from best case scenario (1) to worst case (3)
- VTX gives better tracking efficiency than VXD for Full Tracking (vertex tracking combined with CDC)
- In particular soft pion signal efficiency effected greatly

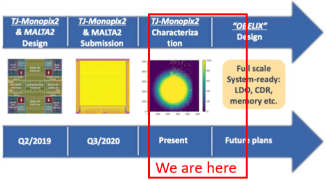




TJ-Monopix2







Nucl. Instrum. Methods Phys. Res. A, 978 (2020) 164460

- Developed for ATLAS
- DMAPS in TowerJazz (TJ) 180 nm process
- Proposed as starting point for OBELIX design

→ Copy of pixel matrix + trigger adaptation in periphery

- 2×2 cm^2 chip, 512×512 pixels
- Pixel pitch: 33.04×33.04 μm^2
- Expected from design:
  - $\sim 100\ e^-$ min. threshold
  - 5-10 e^- threshold dispersion (tuned)
  - >97% efficiency at $10^{15} n_{eq}/cm^2$
  - $\sim 5\ e^-$ noise
  - Fully efficient with hit rate 120 MHz/cm^2
  - MIP $\sim 2500 e^-$

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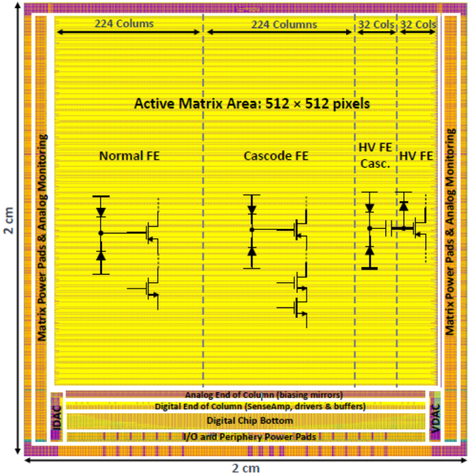
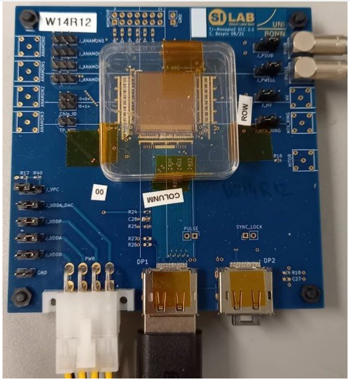


4 pixel Front-End (FE) flavours with differences in pre-amplifier, sensor coupling, biasing

- Normal and Cascode FE:
  - DC coupled to charge collection electrode
- HV and HV Cascode FE:
  - AC coupled to charge collection electrode
  - Allows higher bias voltages
- Cascode and Non-Cascode versions:
  - Differ only by one transistor → designed to increase gain

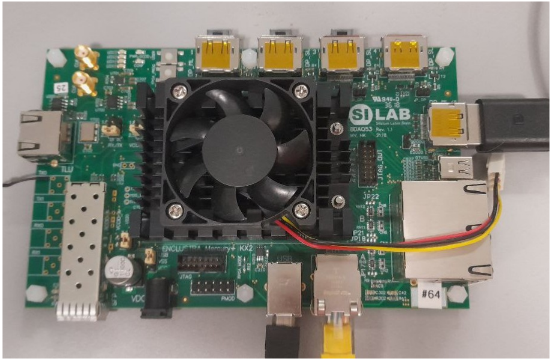
Lab Set-up



- Commercial 2 channel power supply
- 1.8 V supply voltage
- Up to 6/60 V bias voltage

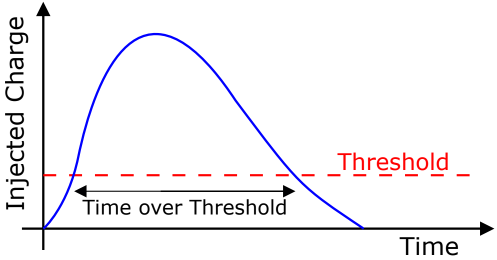
Simple and user-friendly set-up:

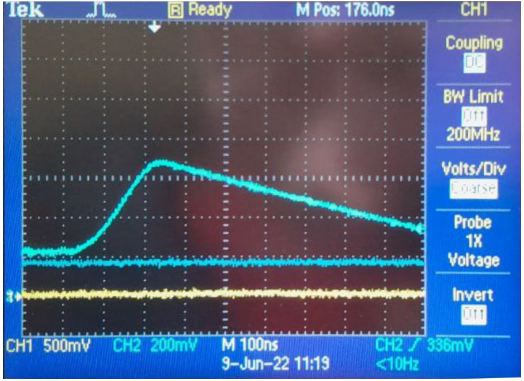
- Carrier PCB with FPGA readout
- Bdaq53 board with TJ-Monopix2 firmware based on Basil



TJ-Monopix2 lab testing

- Internal injection tests
  → inject known charge in pre-amplifier
- Output: ToT (Time over Threshold)
- ToT in units of 25 ns 7-bit encoded





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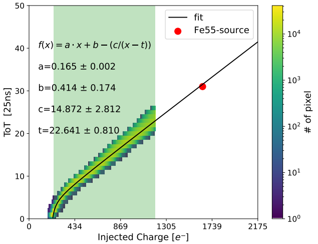
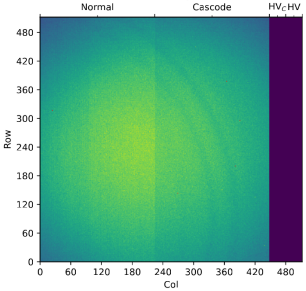
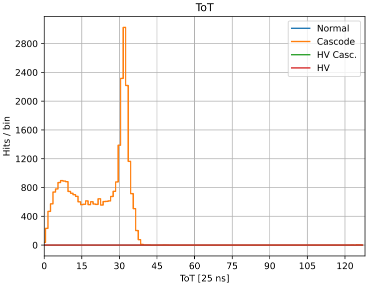


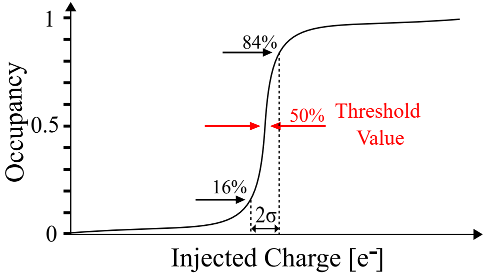


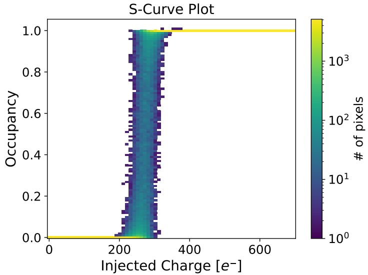
- Testing in Bonn, Pisa, HEPHY, CPPM, Göttingen
- Calibrate ToT responds with injection test
- Absolute calibration with Fe^{55} agrees with design
- Measurements ranging 8.5 - 10 e-/DAC

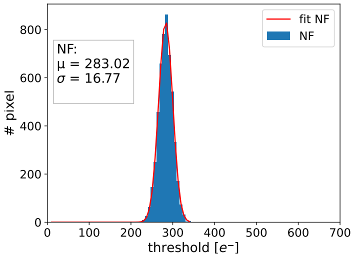


TJ-Monopix2 lab testing

- S-curve tests with internal injection
- Determine threshold
- Tune sensor for low threshold and low dispersion
- Threshold: $280e^{-} \pm 17e^{-}$
- Noise: $8e^{-}$







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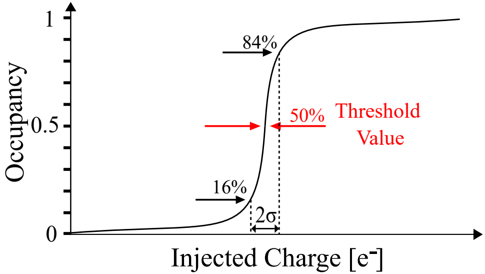
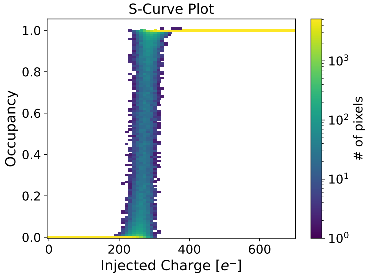
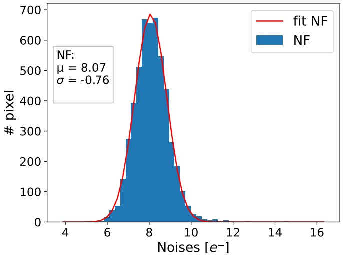
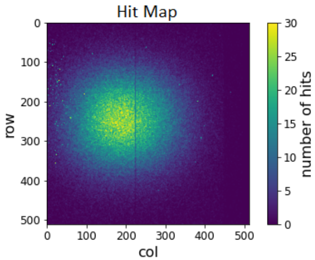
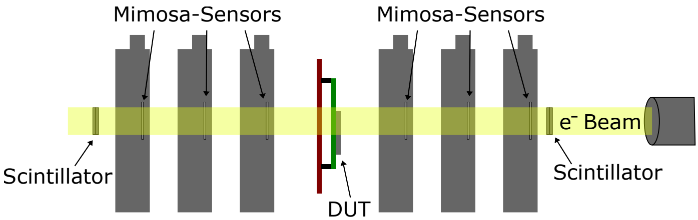


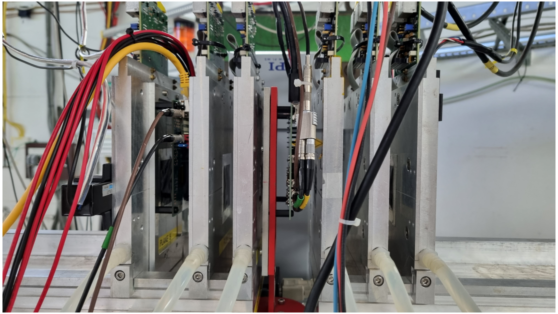




Beam Test Set-up



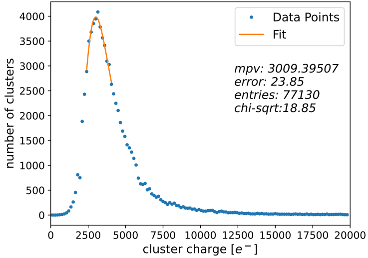


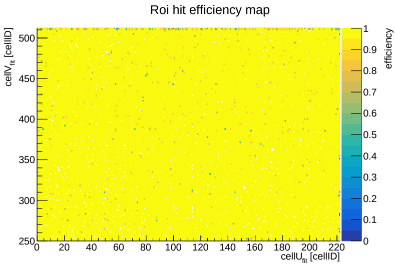


- 3-5 GeV e^- at DESY June 2022
- Mimosa EUDET-Telescope
- Unirradiated chips
- Preliminary settings used $\rightarrow$ Very high thresholds $\sim 500\ e^-$

Efficiency and Resolution

- 4 GeV, Perpendicular incidents
- Hit efficiency: $\epsilon = \frac{n_{matched}}{n_{tracks}}$
- ϵ at $\sim 500e^-$ threshold: 99.54 ± 0.04 %
- $\sim$9.15 µm cluster position resolution
  $\rightarrow$ Better than pitch$/\sqrt{12} \sim 9.5$ µm
- Next: Irradiation to $10^{14} - 10^{15}$ n_{eq}/cm^2
- Test beam in July 2023





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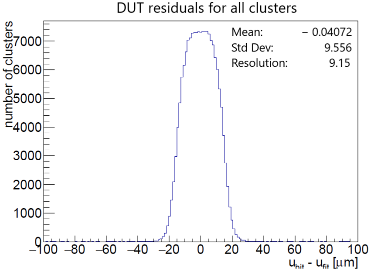
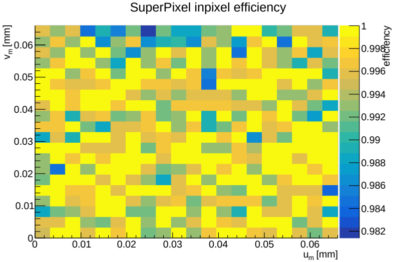




Conclusion and Outlook

Conclusion:

- Important to carefully characterise TJ-Monopix2, since sensor matrix design will be carried over to OBELIX
- Main performance figures of non-irradiated TJ-Monopix2 matching requirements
- Successful test beam with stable module operation over long times

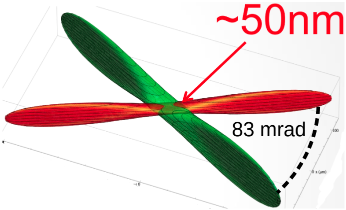
Outlook:

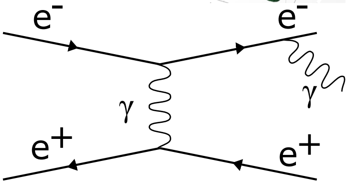
- Preparing measurements on irradiated sensors
- Additional test beam in July at DESY
- OBELIX design, targeting submission in autumn 2023

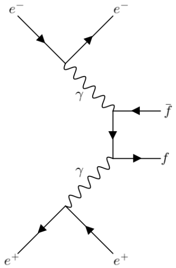
Back up

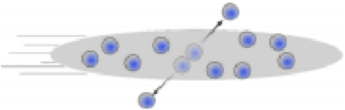
Nano-beam and beam background

- Squeeze beam for smaller cross-section
- High Luminosity backgrounds
  $\rightarrow$ scales with luminosity
  - 2γ
  - radiative bhabha-scattering
  - elastic scattering of $e^- e^+$
- Storage background
- Injection backgrounds



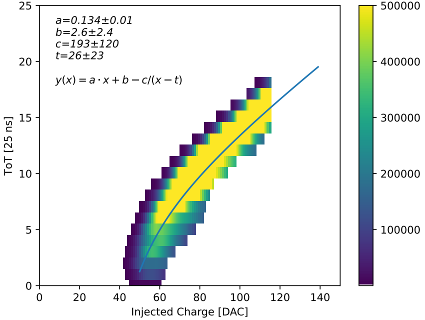


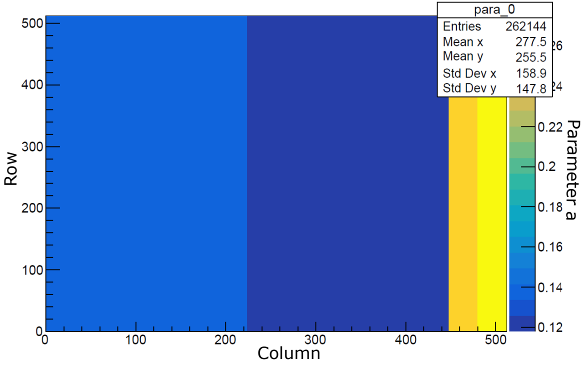




In-Pixel calibration

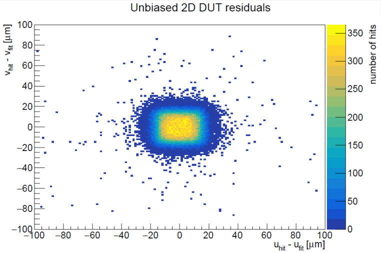
- Conversion of ToT to charge in electron, before clustering
- Inj. charge in DAC · 10.1= charge in e
- Calibration parameters from scans on the sensor
- F
  F

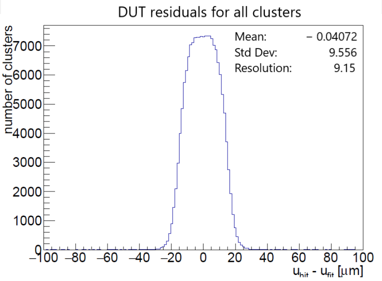


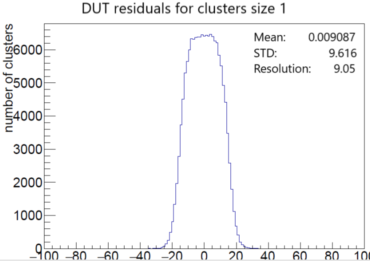


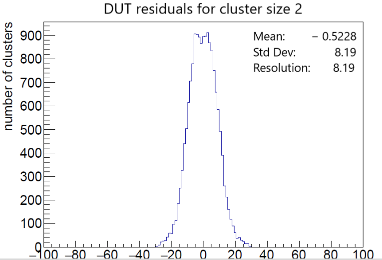
Residuals

- W5R9: epi module
- Residuals at 3V PSUB/PWELL
- Uncertainty of telescope intersection at DUT plane ∼3.5 µm
- Expected res. from pixel pitch: 9.54 µm
- **Resolution of 9.14 µm**

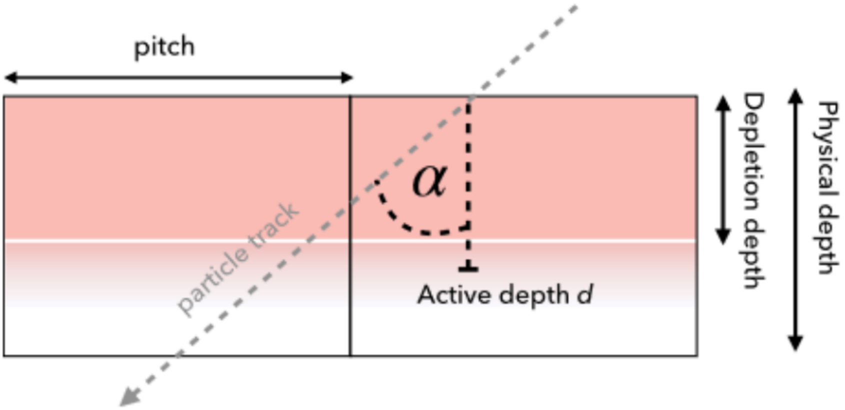








TJ-Monopix2


pitch
particle track
α
Active depth d
Depletion depth
Physical depth

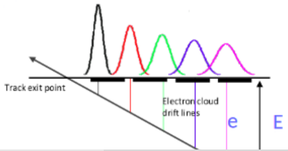
TJ-Monopix2

Register	Default Settings ("Göttingen ")	Improved Settings ("Patrick")	HV Settings	HV Settings W8R3 "HEPHY"
ITHR	64	**50**	**30**	**30**
IBIAS	**50**	100	**60**	**60**
VRESET	143	143	**100**	**95**
ICASN	0	0	**8**	**8**
VCASP	93	93	**40**	**40**

VTX Digitizer: from tracks to digits

Based on digitizer for PXD in the Belle II software. Rather simple and generic code.

- Start: List of Geant4 steps on sensitive (depleted) Si
- Check if the particle hit is inside the integration time window T_{int}
- Split the path of the particle in the VTX depleted Si into segments and drift the charges from the center of each segments.
  - The transverse diffusion (coefficient D) follows a Gaussian with a width defined as :
    sigmaDiffus = sqrt (D * e /2)
- Integrate smeared charge clouds per pixel area and add the noise to the charge
- Subtract hit threshold
  Charge -= chargeThreshold
- Check if Charge > 0
- Amplify and digitize charge
  ToT = F(Charge)



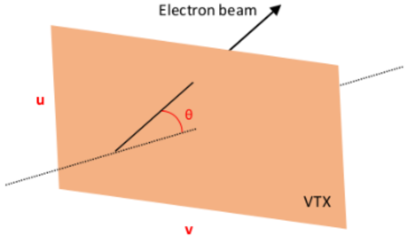
Digitizer

Test beam simulations

- Simplified simulation in basf2 software. No simulation of telescope and tracking is done, just using true hits instead.

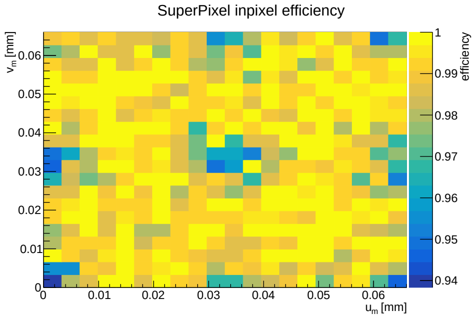
- ParticleGun shooting electrons at 4.0 GeV perpendicular to 1 VTX sensor in +X

uPitch:	0.003304 cm
vPitch :	0.003304 cm
Active Thickness:	0.0025 cm
Charge Threshold:	500 e^-
Electronic Noise:	20 e^-
Max ToT :	127 (7 bits)
D:	8.5e-05 cm

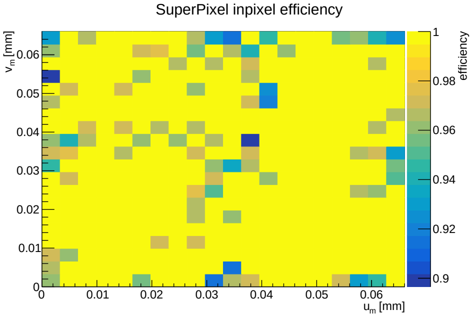


Efficiency

0°

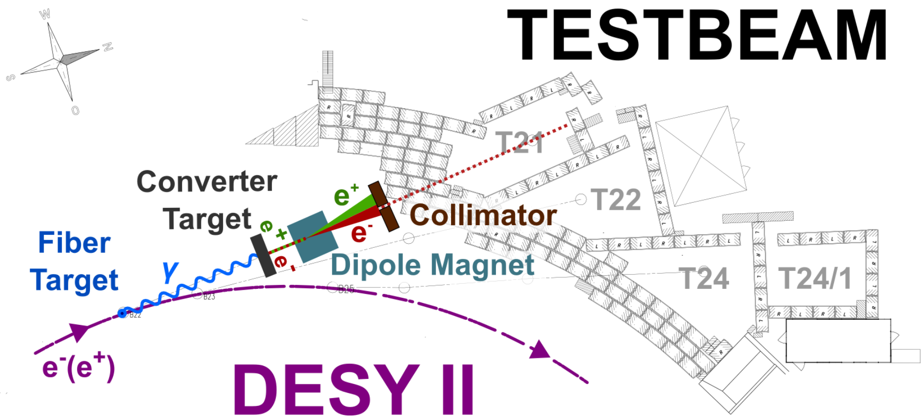


10°



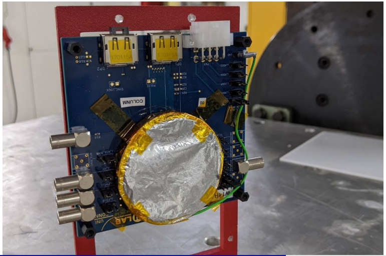
DESY Test Beam Facility

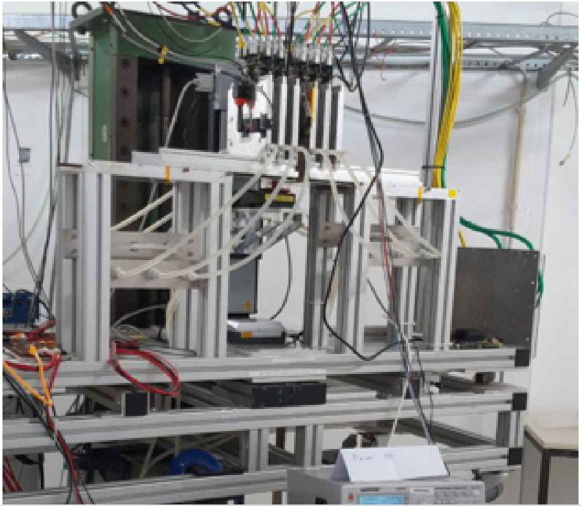
- Duration: 2022-06-27 to 2022-07-11
- Beam line: TB22
- 2-5 GeV electron beam



test beam Set-up

- DESY test beam facility
- AIDA TLU v2
- Mimosa26-based DURANTA Telescope
- Upstream scintillator





VTX Tracking Performance

Tracking Validation results

SVD/CDC only
Full tracking

Based on simulated sample of 1000 $B\bar{B}$ events + respective overlay background files

Slides by Jarek

Bkg type	Finding Efficiency [%]	Hit Efficiency [%]	Fake Rate [%]	Clone Rate [%]	SVD: SVD L3 occup. [%] ONline (u/v) OFFline (u/v)	CDC (bkg hits only): Hit Rate (R) [kHz/wire] (inner / outer)
v1	94.6 / 81.3 94.4	94.8 / 86.4 82.0	4.9 / 2.5 4.6	0.5 / 0.7 3.9	4.3 / 3.5 2.2 / 2.1	204.0 / 145.9 **Total: 148.9**
v2	92.9 / 78.2 93.0	93.6 / 83.8 79.5	8.1 / 2.9 6.7	2.7 / 0.7 4.2	7.2 / 5.5 4.2 / 3.9	308.7 / 203.8 **Total: 209.1**
v3	89.3 / 70.3 89.8	91.1 / 80.0 74.8	18.0 / 3.2 13.8	2.6 / 0.8 4.5	12.2 / 9.2 7.5 / 7.1	469.5 / 293.6 **Total: 302.4**

R_{av} = N / (408.7 ns * 1280 wires + 754.6 ns * 13056 wires)

N – total number of CDC hits (per event)

VTX only/CDC only
Full tracking

From Benjamin study

BG type	Finding efficiency	Hit efficiency	Fake rate	Clone rate	R_{av} kHz/wire	VTX L1 occupancy
v1	0.979/0.813 0.944	0.943/0.866 0.824	0.043/0.028 0.043	0.014/0.010 0.048	219	0.0016%
v2	0.974/0.781	0.943/0.841	0.063/0.031	0.014/0.008	276	0.0023%