A CMOS pixels upgrade for the Belle II Vertex Detector

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on behalf of the Belle II VTX collaboration

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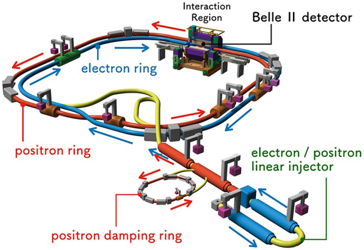
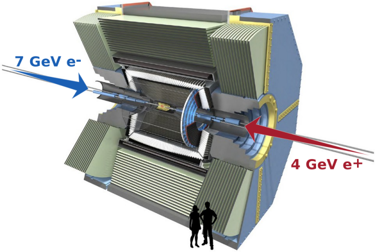
The Belle II experiment at the SuperKEKB collider

- Asymmetric e^+e^- collider
  - $\sqrt{s} = M_{\Upsilon(4S)} = 10.58\,\text{GeV}$
- Luminosity frontier experiment
  - Flavor physics $(b, c, \tau, \dots)$
  - Dark matter searches
  - ...
- Target $\int \mathcal{L} = 50\,\text{ab}^{-1}$
  - Data taking started in 2019
  - Current $\int \mathcal{L} = 0.428\,\text{ab}^{-1}$
  - In long-shutdown since last June
  - Restart at beginning of 2024
- Target peak $\mathcal{L} = 6 \times 10^{35}\,\text{cm}^{-2}\,\text{s}^{-1}$
  - High currents & nano-beam scheme
- Record $\mathcal{L}_{\text{max}} = 0.47 \times 10^{35}\,\text{cm}^{-2}\,\text{s}^{-1}$
  - Keep increasing in the future
  - Challenging background conditions





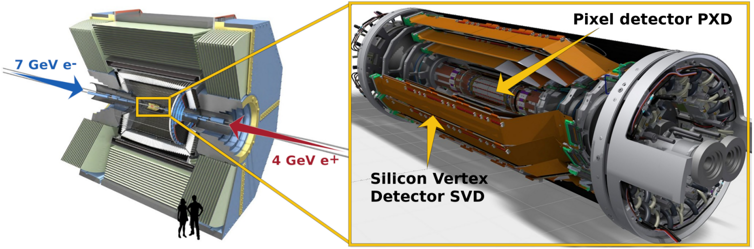
The Belle II VerteX Detector (VXD)

2 inner layers
PiXel Detector (PXD)

- DEPFET sensors
- 14–22 mm radii
- 50×55–$85\,\mu m^2$ pitches
- 20 μs integration time

4 outer layers
Silicon Vertex Detector (SVD)

- Double-sided silicon strips
- 39–135 mm radii
- 50–75×160–$240\,\mu m^2$ pitches
- 3 ns cluster time resolution



Motivation for a VXD upgrade

- SuperKEKB upgrade planned in ~ 2027 (Long Shutdown 2)
  - Necessary to reach luminosity target
  - Redesign of the interaction region being considered
  - Opportunity to install new vertex detector
- Higher luminosity $\Rightarrow$ higher backgrounds $\Rightarrow$ higher occupancy
  - Extrapolations show we may reach the current detector's limits
  - This limits the machine's freedom in pursuing higher luminosity
  - Larger safety factors would help
  - Current occupancy is $\mathcal{O}(1\%)$, upgrade target is $\leq \mathcal{O}(0.1\%)$
- Physics performance improvement possible
  - Material budget reduction
  - Space resolution improvement
  - Usage of all layers in track finding / pattern recognition
    - PXD (2 innermost layers) has long integration time
    - Only used for track extrapolation to interaction point for vertex resolution
    - No pattern recognition $\Rightarrow$ lower efficiency at very low p_T

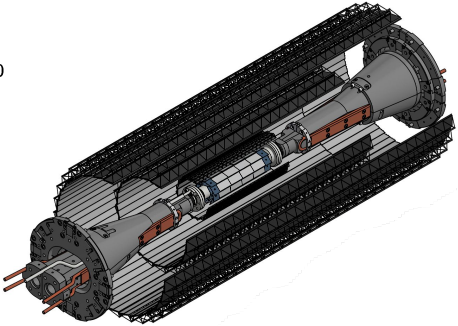
The VTX detector concept

Replace VXD with 5 layers of pixels

- Depleted CMOS MAPS
  - Same chip for all layers
- 14–135 mm radii (like VXD)
- 30–40 µm pitch
- 25–100 ns timestamp resolution
- Reduced material budget
  - $\sim 2.5\% X_0$ instead of $3.8\% X_0$
  - Improves tracking resolution
- Fast sparsified readout
  - In-pixel discrimination
  - Track finding with all layers

Robust against inner layer background

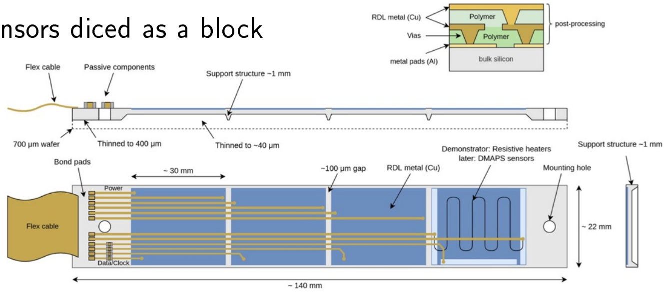
- Hit rate up to $120\,\mathrm{MHz\,cm^{-2}}$
- Ionizing dose $\sim 100\,\mathrm{kGy/year}$
- NIEL $\sim 5 \times 10^{13}\, n_{\mathrm{eq}}/\mathrm{cm}^2/\mathrm{year}$



The VTX detector mechanics

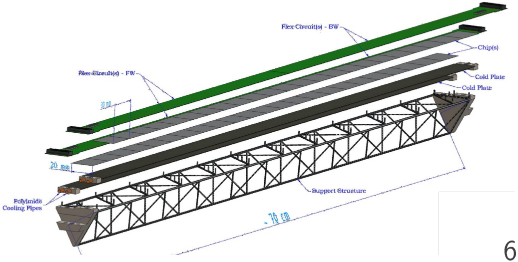
2 inner layers: all-Si modules

- 4 contiguous sensors diced as a block
- Self-supporting
- Air-cooled
- $200\,\mathrm{mW/cm^2}$
- $\sim 0.1\% X_0$



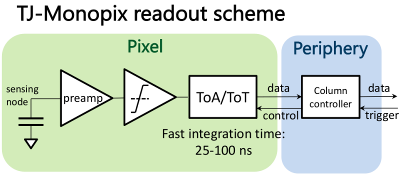
3 outer layers: long ladders

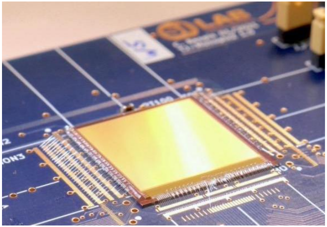
- Carbon-fiber structure
- Water-cooled with cold plate
- ~ 0.3–$0.5\% X_0$ layers 3–4
- $\sim 0.8\% X_0$ layer 5



The TJ-Monopix2 prototype

- Developed for ATLAS
  - FE derived from ALPIDE
  - Column-drain R/O architecture
- $\geq 25\,\mu\text{m}$ depletion thickness
  - CMOS process modification
  - Required for radiation hardness
  - $\sim 2000\,e^-$ MPV for a MIP
- $2 \times 2\,\text{cm}^2$ chip, 512×512 pixels
- $33\,\mu\text{m}$ pitch, $25\,\text{ns}$ timestamping
- 7-bit charge info (time over threshold)
- 3-bit per-pixel threshold tuning
- Expected (from design/simulation)
  - $\sim 100\,e^-$ minimum threshold
  - 5–10 e^- dispersion (w/tuning)
  - $\sim 5\,e^-$ noise
  - $> 97\%$ efficiency at $10^{15}\,n_{\text{eq}}/\text{cm}^2$





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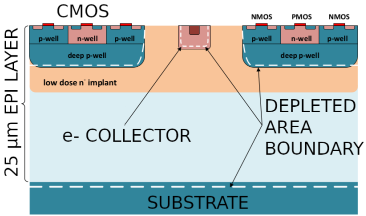
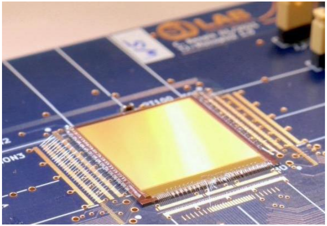
- Developed for ATLAS
  - FE derived from ALPIDE
  - Column-drain R/O architecture
- $\geq 25\,\mu m$ depletion thickness
  - CMOS process modification
  - Required for radiation hardness
  - $\sim 2000\, e^-$ MPV for a MIP
- $2 \times 2\, cm^2$ chip, 512×512 pixels
- $33\,\mu m$ pitch, 25 ns timestamping
- 7-bit charge info (time over threshold)
- 3-bit per-pixel threshold tuning
- Expected (from design/simulation)
  - $\sim 100\, e^-$ minimum threshold
  - 5–10 e^- dispersion (w/tuning)
  - $\sim 5\, e^-$ noise
  - $> 97\%$ efficiency at $10^{15}\, n_{eq}/cm^2$





Drawings: CERN-THESIS-2021-146
Process modification: J NIMA 2017 07 046

The TJ-Monopix2 prototype

- Developed for ATLAS
  - FE derived from ALPIDE
  - Column-drain R/O architecture
- $\geq 25\,\mu\text{m}$ depletion thickness
  - CMOS process modification
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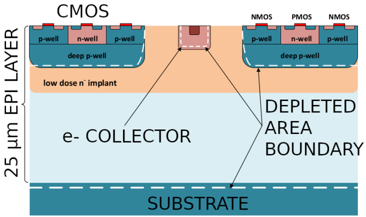
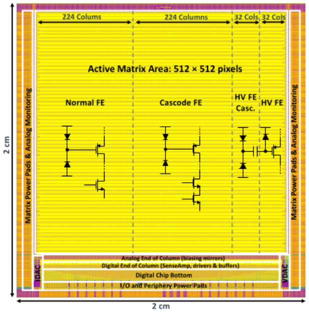
  - $\sim 2000\,e^-$ MPV for a MIP
- Expected (from design/simulation)
  - $\sim 100\,e^-$ minimum threshold
  - 5–10 e^- dispersion (w/tuning)
  - $\sim 5\,e^-$ noise
  - $> 97\%$ efficiency at $10^{15}\,n_{\text{eq}}/\text{cm}^2$
- 4 pixel front-end flavors
  - Differences in preamplifier, sensor coupling, and biasing





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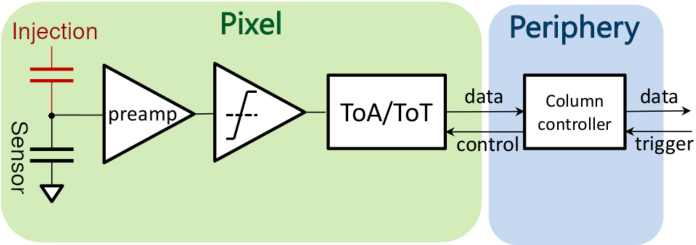
TJ-Monopix2 laboratory testing

Ongoing testing in Pisa, HEPHY, Bonn, Göttingen, CPPM, ...

- Internal injection tests



Voltage step applied through injection capacitor
⇒ known charge on preamp input

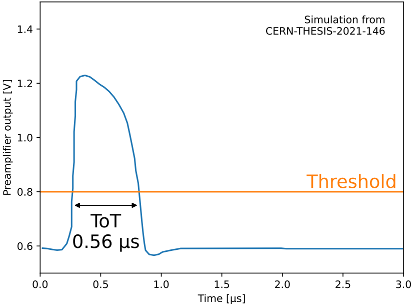
TJ-Monopix2 laboratory testing

Ongoing testing in Pisa, HEPHY, Bonn, Göttingen, CPPM, ...

- Internal injection tests
  - Time-over-threshold vs charge

ToT increases with charge

$Q = 300\,e^-$



TJ-Monopix2 laboratory testing

Ongoing testing in Pisa, HEPHY, Bonn, Göttingen, CPPM, . . .

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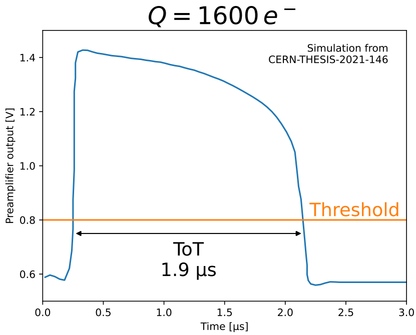
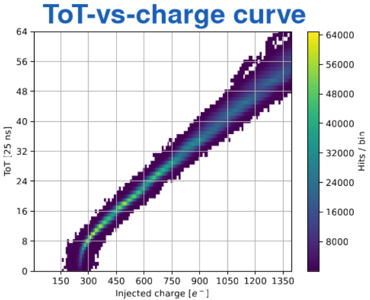


TJ-Monopix2 laboratory testing

Ongoing testing in Pisa, HEPHY, Bonn, Göttingen, CPPM, ...

- Internal injection tests
  - Time-over-threshold vs charge

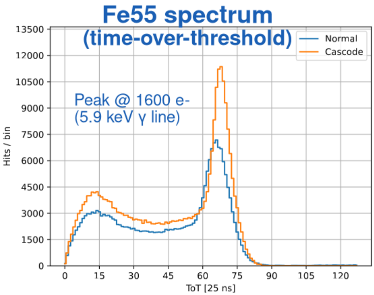
Plot for 1k pixels (cascode FE)

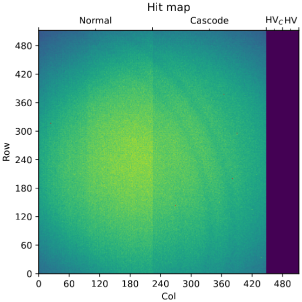


TJ-Monopix2 laboratory testing

- Internal injection tests
  - Time-over-threshold vs charge
- Radioactive source measurements
  - Absolute ToT calibration: compare Fe55 peak with its expected pos. from prev. plot

Plots from whole matrix

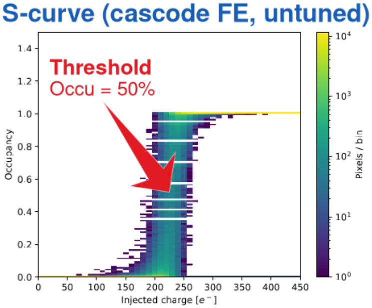




TJ-Monopix2 laboratory testing

- Internal injection tests
  - Time-over-threshold vs charge
- Radioactive source measurements
  - Absolute ToT calibration: compare Fe55 peak with its expected pos. from prev. plot
- S-curve tests w internal injection
  - Threshold (s-curves)

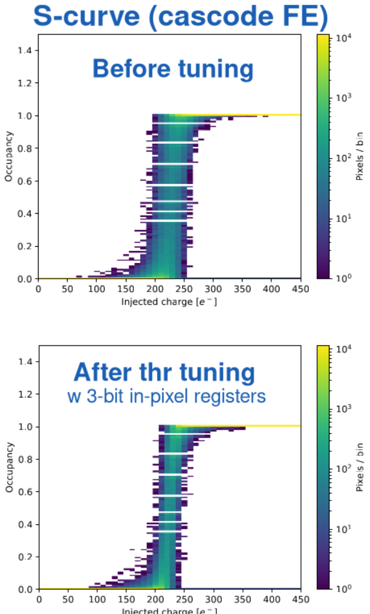
Plot for 12k pixels



TJ-Monopix2 laboratory testing

- Internal injection tests
  - Time-over-threshold vs charge
- Radioactive source measurements
  - Absolute ToT calibration: compare Fe55 peak with its expected pos. from prev. plot
- S-curve tests w internal injection
  - Threshold (s-curves)
  - Threshold dispersion & tuning

Plots for 12k pixels



TJ-Monopix2 laboratory testing

- Internal injection tests
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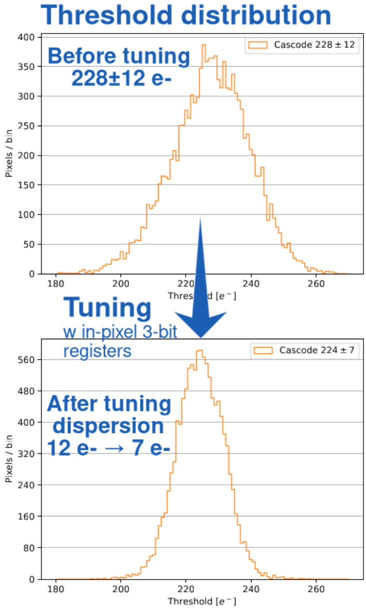
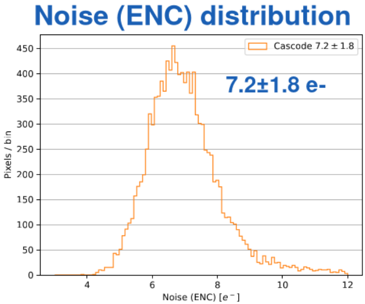
Plots for 12k pixels



TJ-Monopix2 laboratory testing

- Internal injection tests
  - Time-over-threshold vs charge
- Radioactive source measurements
  - Absolute ToT calibration: compare Fe55 peak with its expected pos. from prev. plot
- S-curve tests w internal injection
  - Threshold (s-curves)
  - Threshold dispersion & tuning
  - Noise

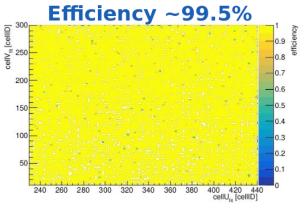
Plot for 12k pixels



TJ-Monopix2 beam testing

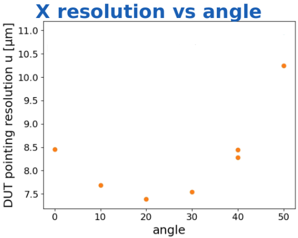
Beam test performed at DESY in Jun 2022

- Unirradiated chips
- Preliminary settings used
  - Very high thresholds $\sim 550\, e^{-}$
- TB22, DURANTA telescope



Results

- $> 99\%$ efficiency
- $\sim 8.5\,\mu\text{m}$ cluster position resolution
  - Better than pitch$/\sqrt{12} \sim 9.5\,\mu\text{m}$

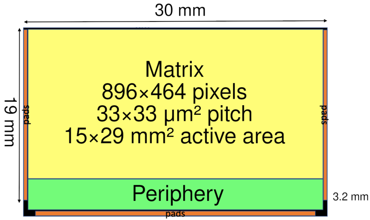


Next steps

- Irradiation to 10^{14}–$10^{15}\, n_{\text{eq}}/\text{cm}^2$
- Test beam in first half of 2023

OBELIX (Optimized BELle II pIXel sensor)

Design ongoing, targeting submission in autumn 2023



Pixel matrix

- Same pixel cell as TJ-Monopix2
- Same R/O scheme as TJ-Monopix2
  - Can handle up to 600 MHz/cm^2
- Timestamp $\sim$ 30–100 ns

Periphery

- Trigger memory and logic adapted to Belle II
  - Can handle up to $\mathcal{O}$(100 MHz/cm^2)
- Single serial output at 320 MHz

Power pads

- Power regulators included to simplify integration

Power dissipation

- Expected 160–220 mW/cm^2 at max hit rate (preliminary)

Summary

- Belle II is considering a vertex detector upgrade in $\sim$ 2027
- VTX: all-layer depleted monolithic pixel detector
  - Improved performance
  - Increased machine background tolerance
- R&D activities ongoing
  - TJ-Monopix2 lab and beam testing for finalizing OBELIX design choices
  - OBELIX design, targeting submission in autumn 2023
  - Thermomechanical and electrical design and mockup testing
  - Performance studies on simulations

Thanks for your attention

The Belle II VTX collaboration

O. Alonso[1], F. Arteche[2], D. Auguste[3], M. Babeluk[4], M. Barbero[5], P. Barrillon[5], G. Batignani[6,7], J. Baudot[8], C. Beigbeder[3], T. Bergauer[4], F. U. Bernlochner[9], C. Bespin[9], S. Bettarini[6,7], J. Bonis[3], F. Bosi[6], R. Bouroumiya[10], P. Breugnon[5], Y. Buch[11], I. Caicedo[9], G. Casarosa[6,7], D. Charlet[3], C. Colledani[8], A. Dieguez[1], J. Dingfelder[9], A. Dorhokov[8], J. Duarte[12], T. Fillinger[8], C. Fink[8], F. Forti[6,7], A. Frey[11], T. Hemperek[9], S. Hidalgo[13], C. Hu[8], C. Irmler[4], M. Karagounis[10], E. Kou[3], H. Krueger[9], J. L. Soler-Fernandez[1], F. Le Diberder[3], C. Marinas[14], M. Massa[6,7], L. Massaccesi[6,7], J. Mazorra[14], M. Minuti[6,7], N. Moffat[13], S. Mondal[6,7], D. Moya[12], P. Pangaud[5], E. Paoloni[6,7], G. Pellegrini[13], H. Pham[8], G. Rizzo[6,7], P. Robbe[3], L. Schall[9], C. Schwanda[4], B. Schwenker[11], M. Schwickardi[11], J. Serrano[5], P. Sieberer[4], K. Trabelsi[3], I. Valin[8], I. Vila[12], M. Vogt[9], N. Wermes[9], C. Wessel[9], M. Winter[3]

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[13] Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona, Spain

[14] IFIC - Instituto de Física Corpuscular (CSIC/University of Valencia), Valencia, Spain

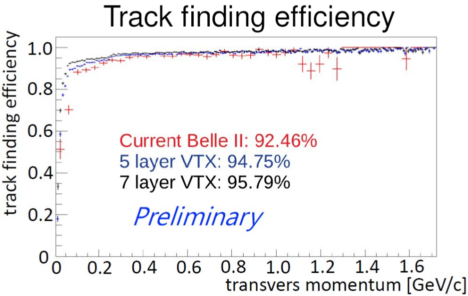
Backup: VTX physics performance

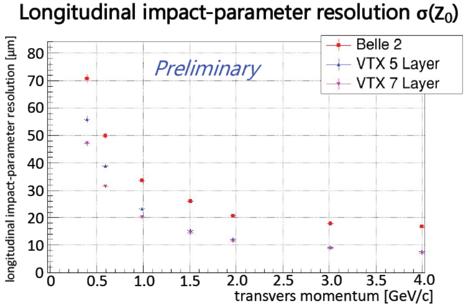
Realistic simulation using Belle II software framework

- Realistic pixel sensor model tuned on TJ-Monopix1 data
- Full Belle II geometry with upgraded vertex detector
- Full Belle II tracking chain including drift chamber

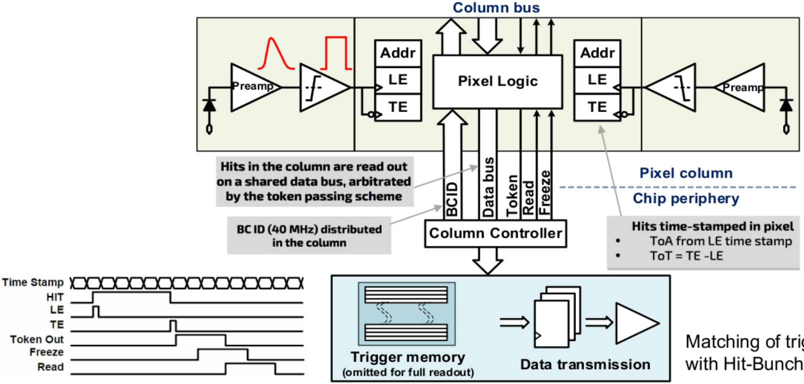
Results (wrt current Belle II)

- Higher efficiency
  - Especially at low p_T
- Improved impact parameters resolution





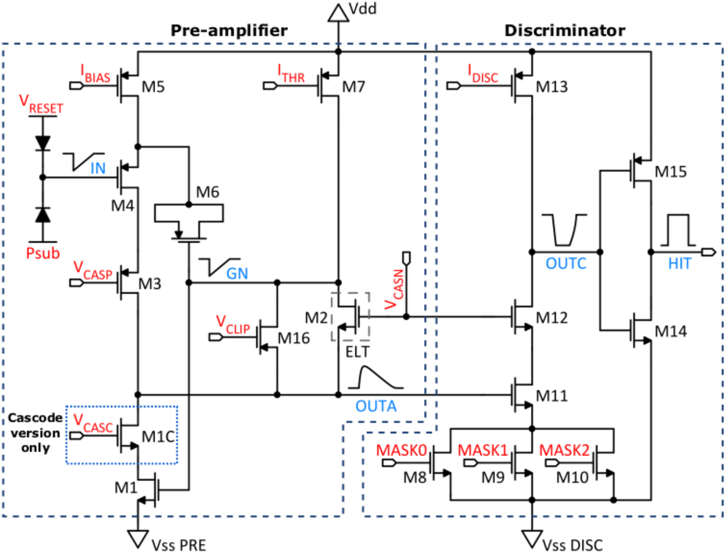
Backup: TJ-Monopix2 readout



Matching of trigger-ID with Hit-BunchCrossingID

[CERN-THESIS-2021-146]

Backup: TJ-Monopix2 cell schematic



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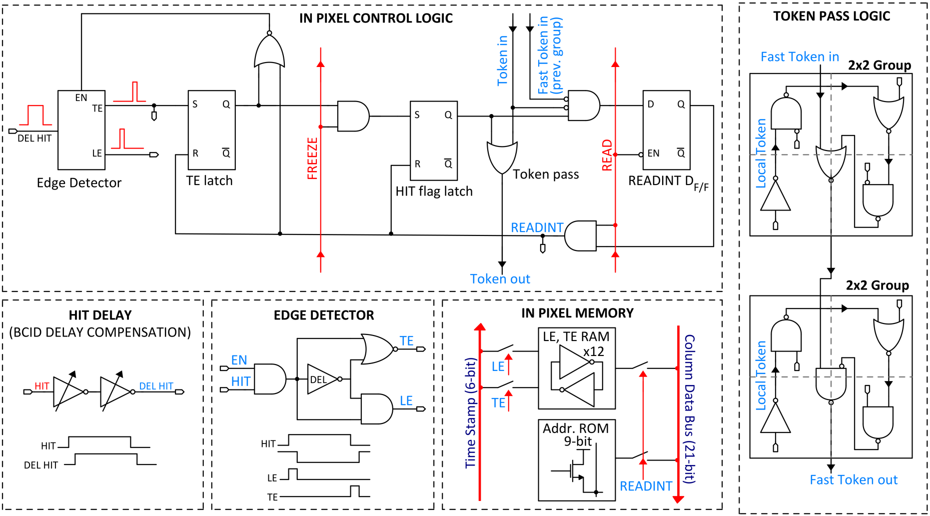
Backup: TJ-Monopix2 in-pixel logic



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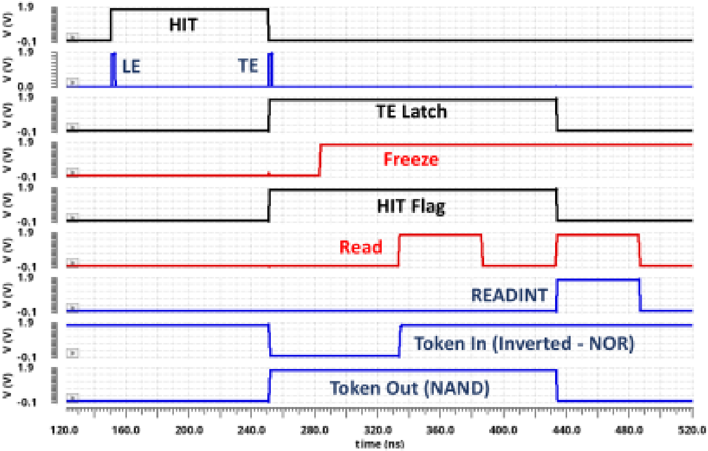
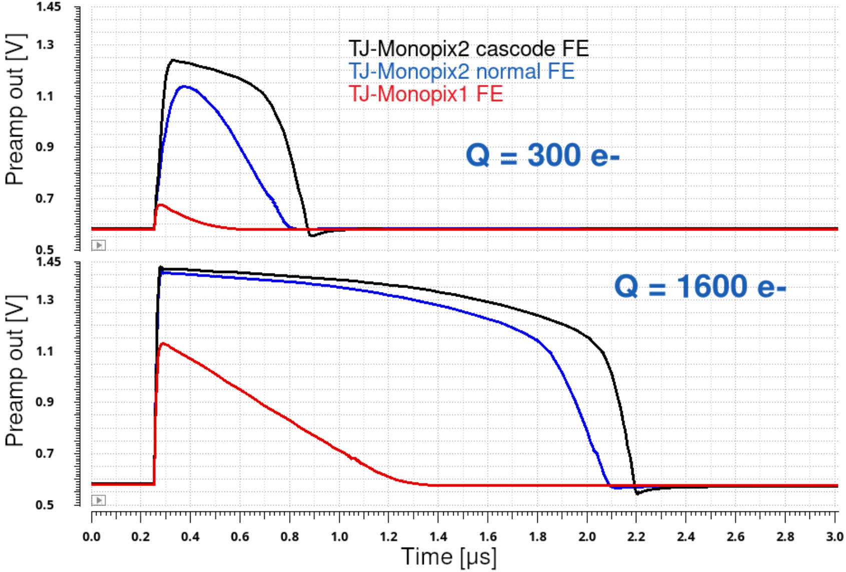
Backup: TJ-Monopix2 readout sequence and signals



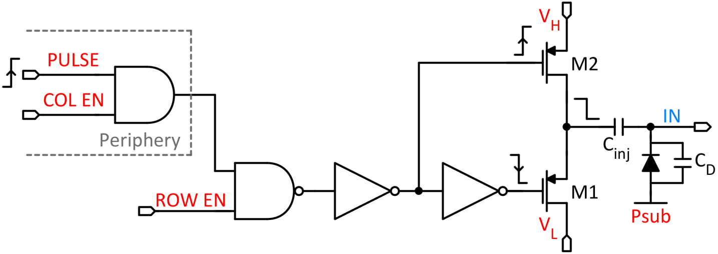
CERN-THESIS-2021-146

Backup: TJ-Monopix2 preamplifier output



CERN-THESIS-2021-146

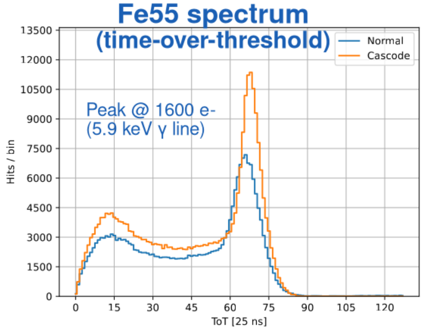
Backup: TJ-Monopix2 injection circuit



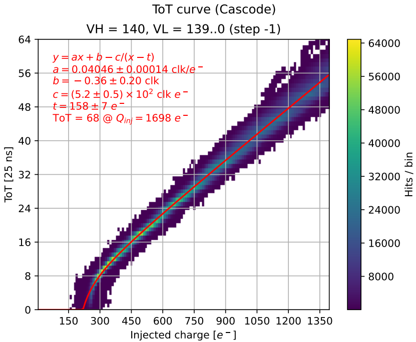
CERN-THESIS-2021-146

Backup: TJ-Monopix2 absolute calibration

Fe55 peak at ToT $= 68 \times 25\,\text{ns}$ (cascode FE)



Fit to ToT-vs-Q_{inj} curve (1k pixels in plot)



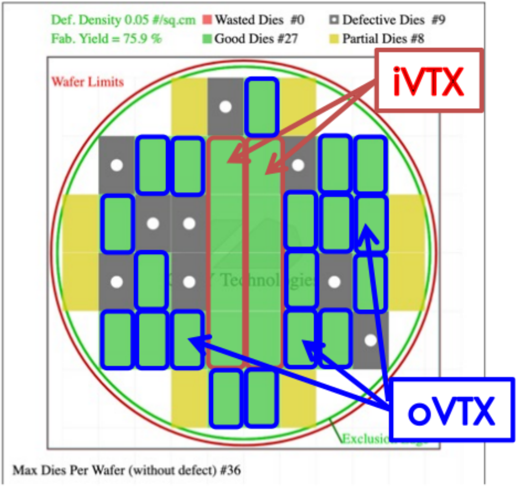
Extrapolate ToT-vs-Q_{inj} fit to Fe55 peak's ToT $\Rightarrow$ corresp. Q_{inj} is $1698\,e^{-}$

Calibration is off by $\sim 5\%$, which is within uncertainties

Backup: OBELIX all-silicon ladders

2 inner layers (iVTX)

- 4 contiguous sensors diced as a block
- Self-supporting
- Air-cooled
- 200 mW/cm^2
- $\sim 0.1\% X_0$



3 outer layers (oVTX)

- Carbon-fiber structure
- Water-cooled with cold plate
- $\sim 0.3\% X_0$ layers 3–4
- $\sim 0.8\% X_0$ layer 5

Backup: requirements for OBELIX

- Spatial resolution $< 10\,\mu m \Rightarrow$ pitch $< 40\,\mu m$
- Hit time-of-arrival resolution $\lesssim 100\,ns$
- Power dissipation $< 200\,mW/cm^2$
- Ionizing radiation TID 100 kGy/year
- NIEL fluence $5 \times 10^{13}\,n_{eq}/cm^2/year$