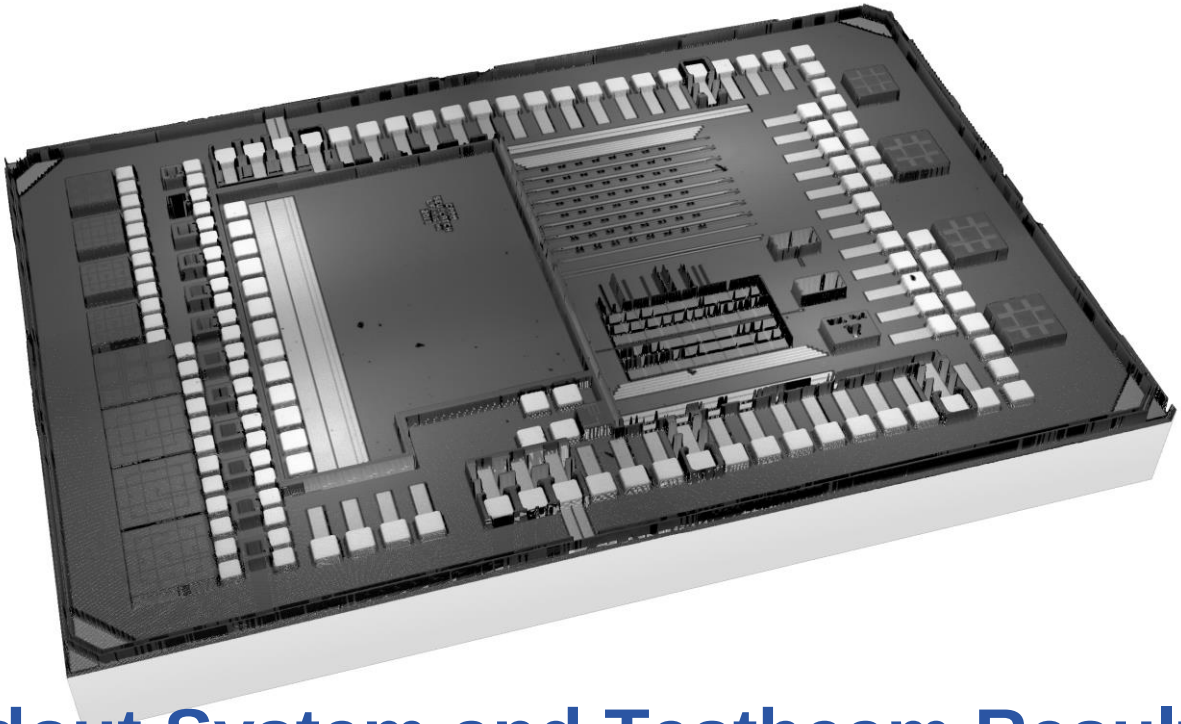
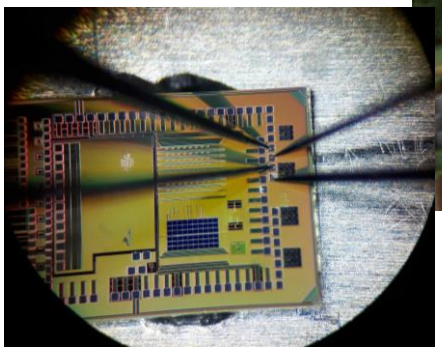
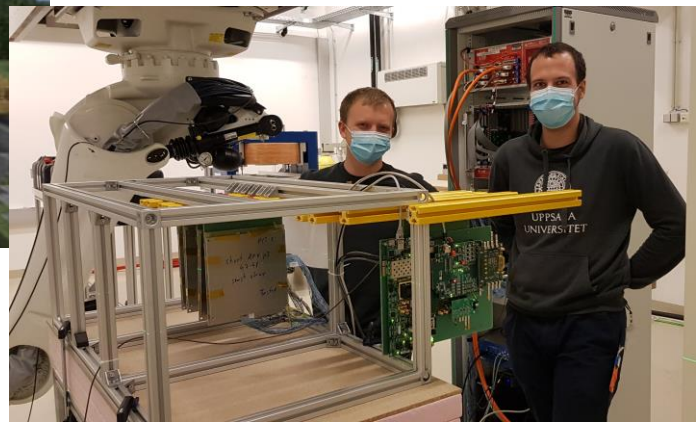


Readout System and Testbeam Results of the RD50 MPW2 HV-CMOS pixel chip

Patrick Sieberer

Work performed in the framework of RD50





Outline

Hardware, Firmware and Software to fill the gap between analogue sensor tests and digital readout in a telescope

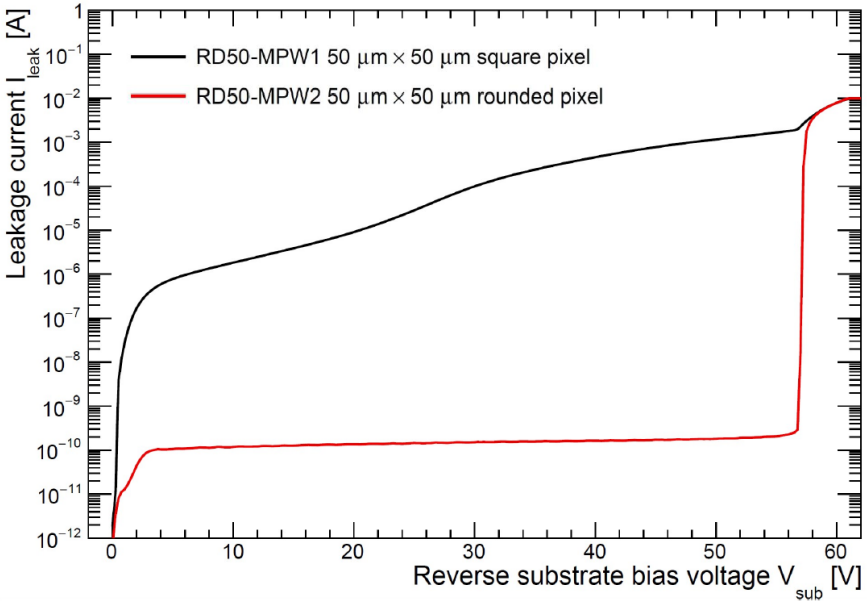
[1] https://www.planetminecraft.com/project/wooden-suspension-bridge/

Setting the stage…

INTRODUCTION

RD50 HVCMOS-Roadmap

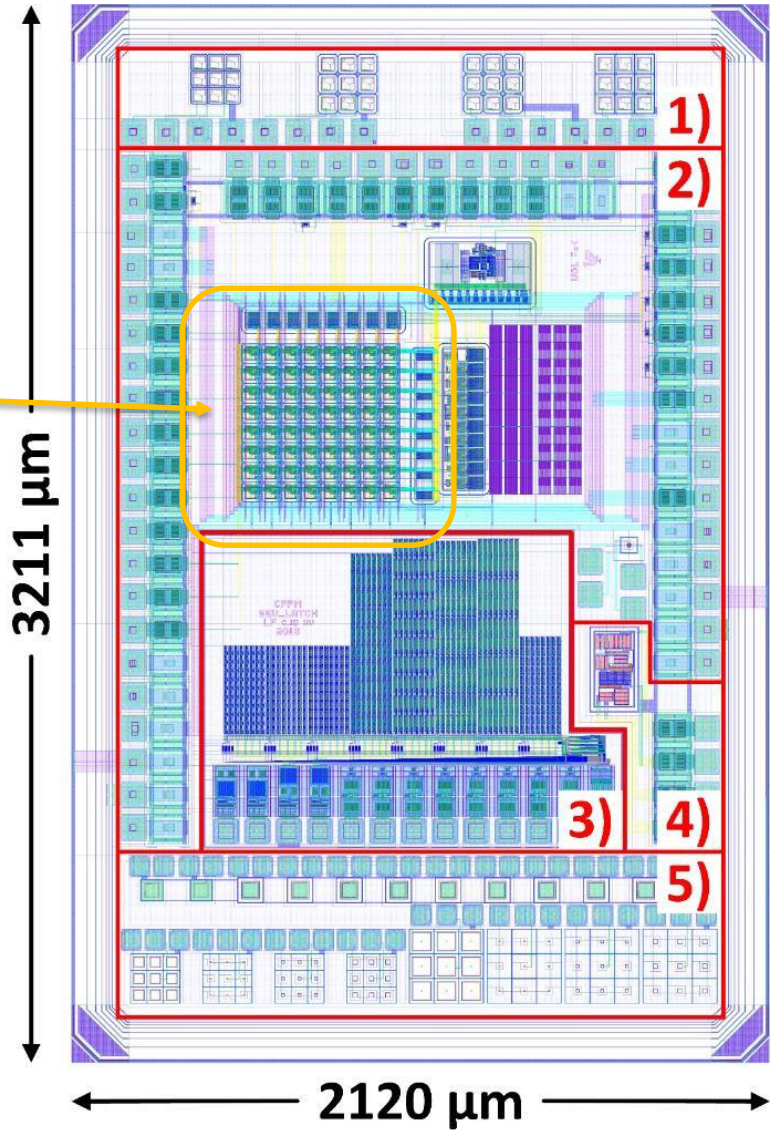
- RD50-MPW1 (2017)
  - High leakage current
  - Low breakdown voltage
  - Some issues: crosstalk, voltage drop, readout
- RD50-MPW2 (2019)
  - I_{leak} ↘ ✓
  - V_{bd} ↗ ✓
  - **Analog pixels only**
  - **Digital DAQ only in FPGA**



- More results:
  - Talk from S. Powell at 35th RD50 workshop
  - Talk from M. Franks at 36th RD50 workshop

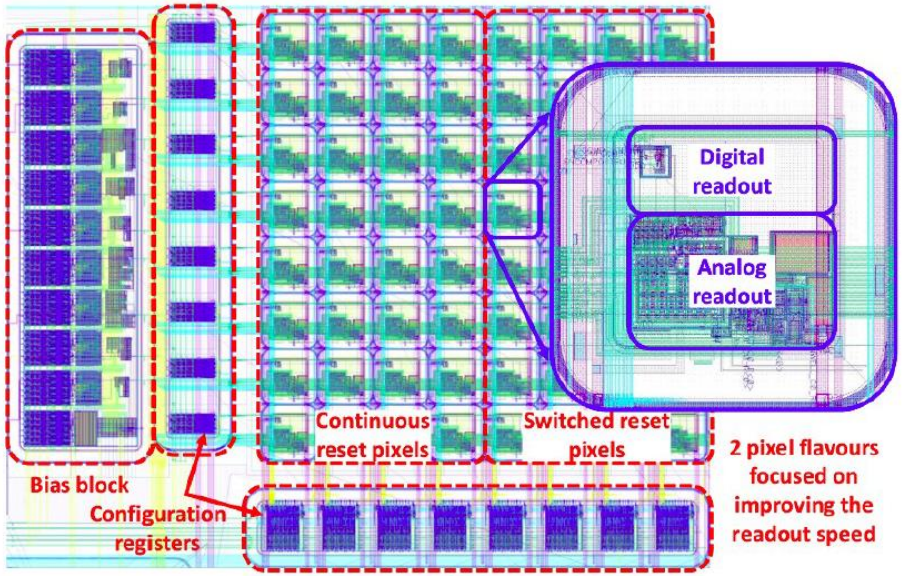
Introduction RD50-MPW2

- LFoundry 150nm process
- Different Wafer resistivities and fluences available
- Passive test-structures 1)
- **Active matrix of DMAPS pixel, including analogue readout 2)**
- SEU tolerant memory array 3)
- Bandgap reference voltage 4)
- Test structures with SPADs 5)
- Details on 3) and 4): See talk from R. Marco Hernandez at 36th RD50 workshop
- Details on 1): See talk from M. Franks at 36th RD50 workshop or from R. Marco Hernandez at VERTEX 2020

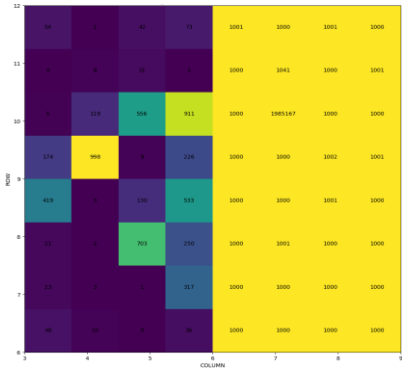


Active Pixel Matrix - Overview

- 64 pixels, 60µm x 60µm
- **Two flavors** of readout:
  - Continuous reset (Col 0-3)
  - Switched reset (Col 4-7)
- Bias-Block: Generates bias voltages to set the transistor operating points
- Configuration Registers: for Bias-Block and pixel TRIMDAC voltages
- Analogue buffer and multiplexer to monitor voltages and analogue pixel readout

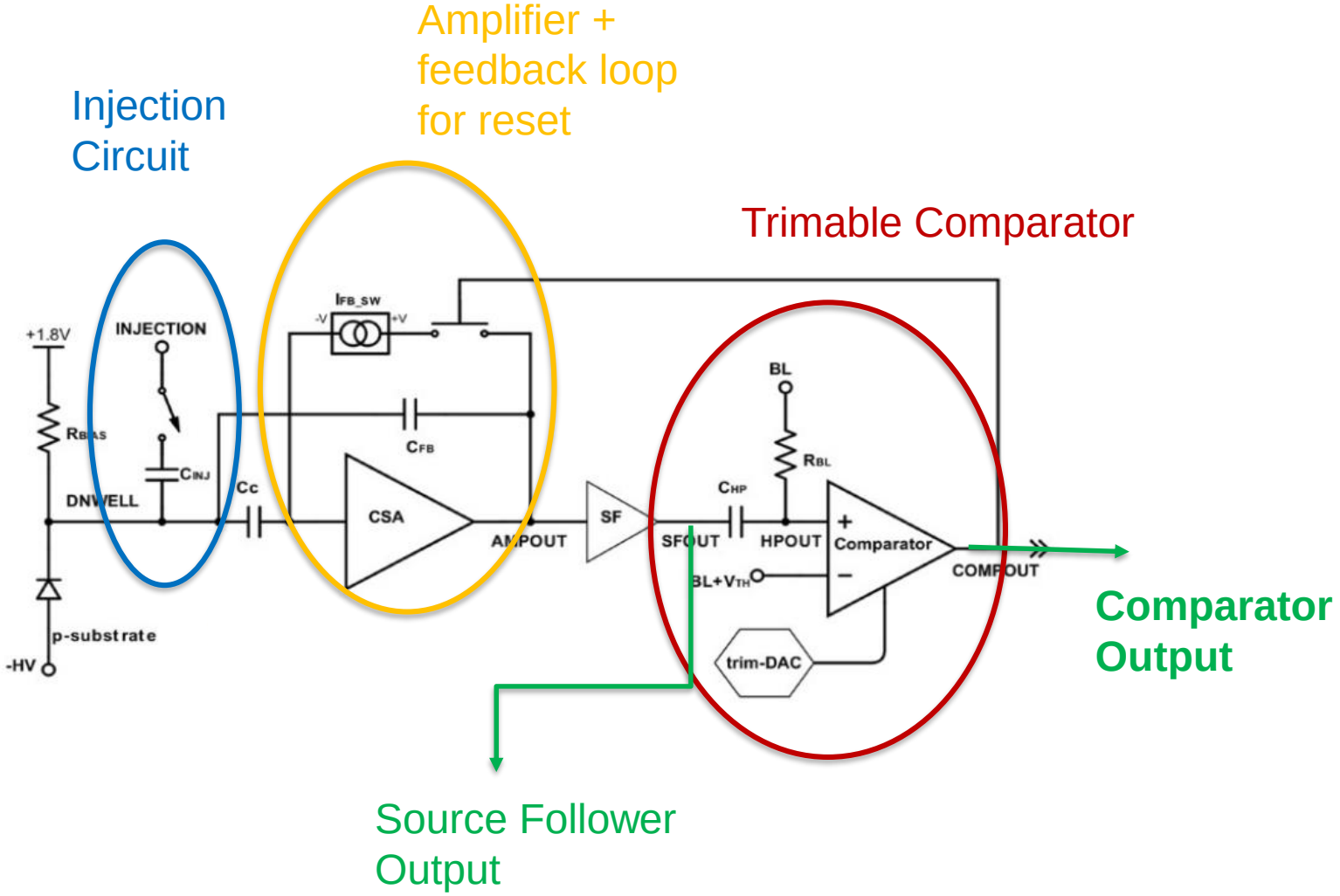


Active pixel matrix floorplan.



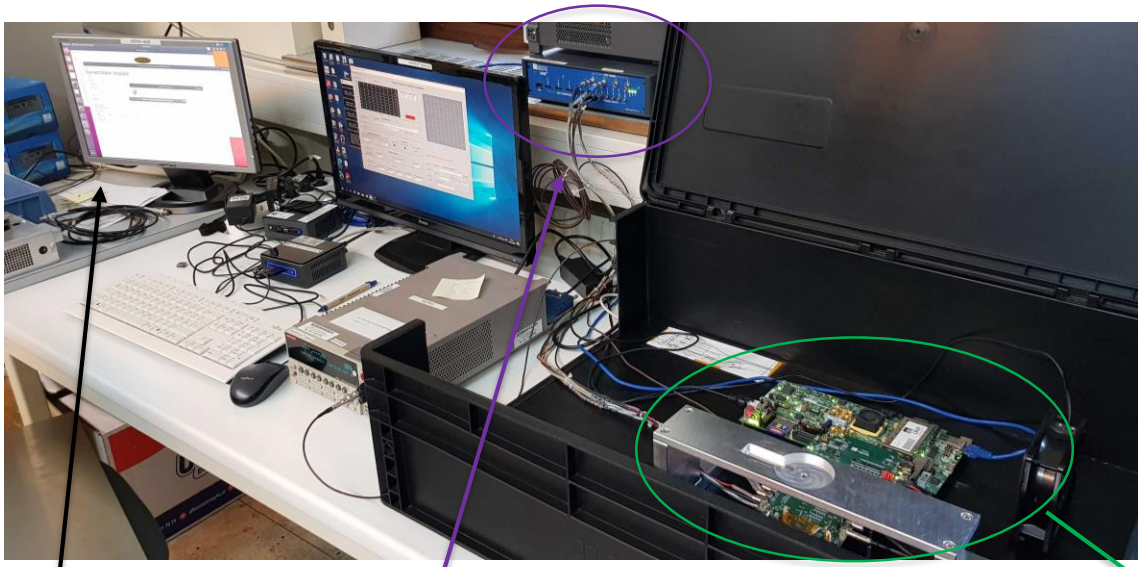
continuous switched

Example: Switched Reset Pixels



READOUT ELECTRONICS

Sr90 Source Test Setup



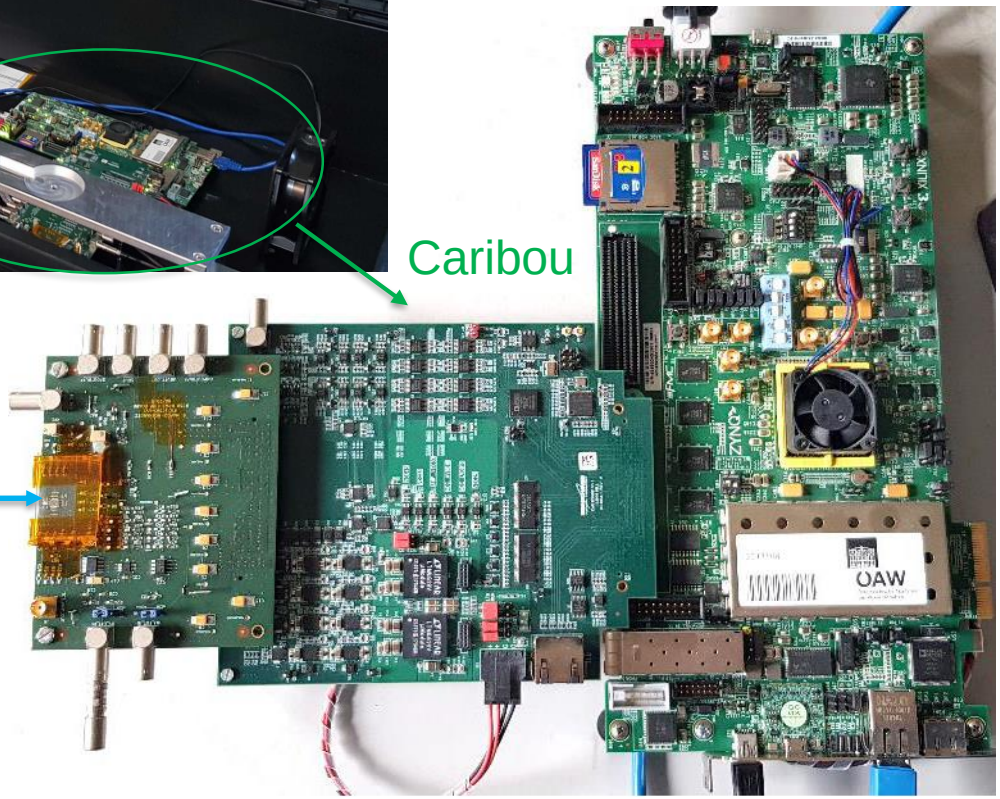
More details on Hardware
See C. Irmler's talk at 36th RD50 workshop
and Caribou:
Paper published at PoS (Tomas Vanat)

Run Control (EUDAQ)

AIDA TLU

Caribou

RD50 MPW2

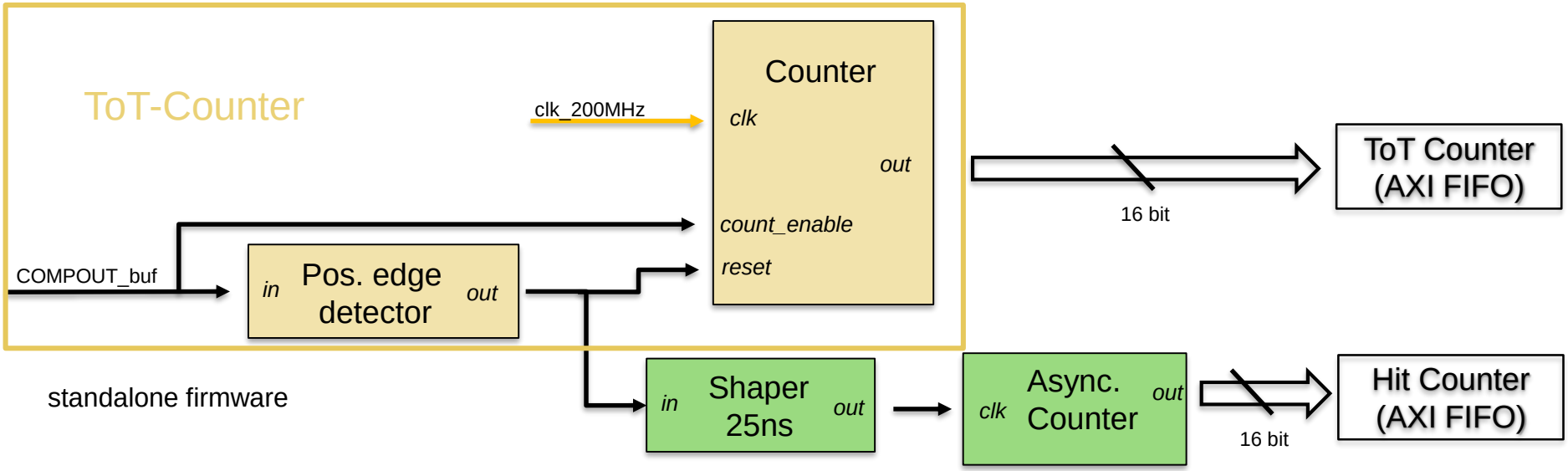


- HV supply
- Scintillators
- Sr90 source

MPW2-chip board CaRoard SoC (ZC706)

Simple Firmware + Software

- COMPOUT connected to FPGA
- Simple ToT measurement implemented in FPGA
- ToT and Hit Counter written to AXI FIFO of the Evaluation Board
- AXI FIFO readout by Caribou-Peary
  - Simple peary module written to store ToT and Hit Counter in a ASCII file

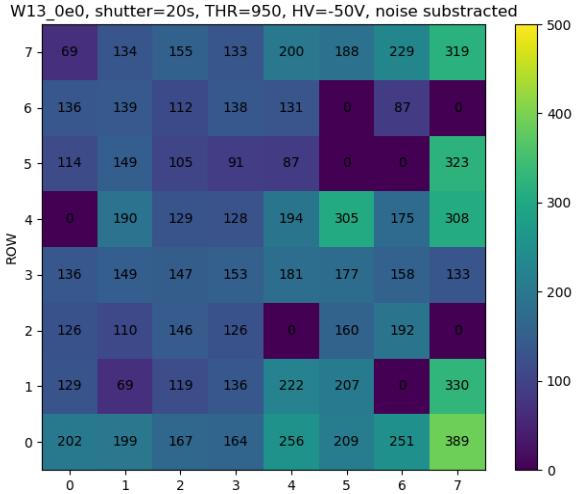


-> Simple Readout Chain, **using only the Caribou-Board** for Slow Control and Data Path
-> Can already be used for injection pulses and with a radioactive source

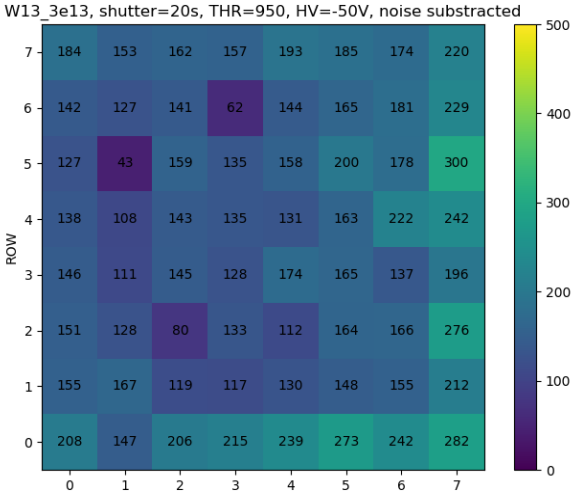
Sr90 source: Irradiated samples

- Hit-maps at -50V Bias
- 3 different fluences
- Sr90 source (10mCi)
- Noise subtracted

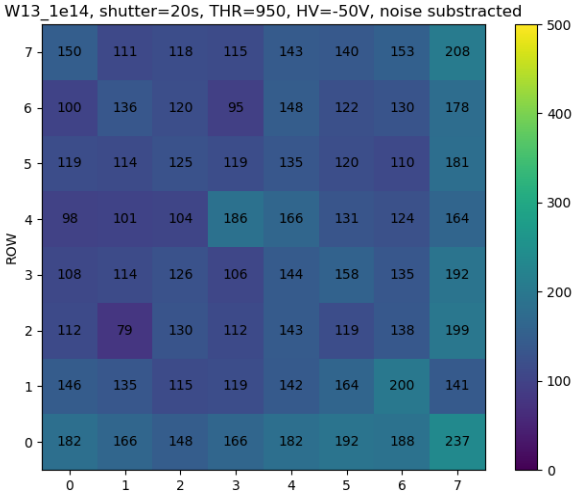
Number of hits decreasing for higher fluences



Wafer 13, unirradiated



Wafer 13, 3e13N_{eq}

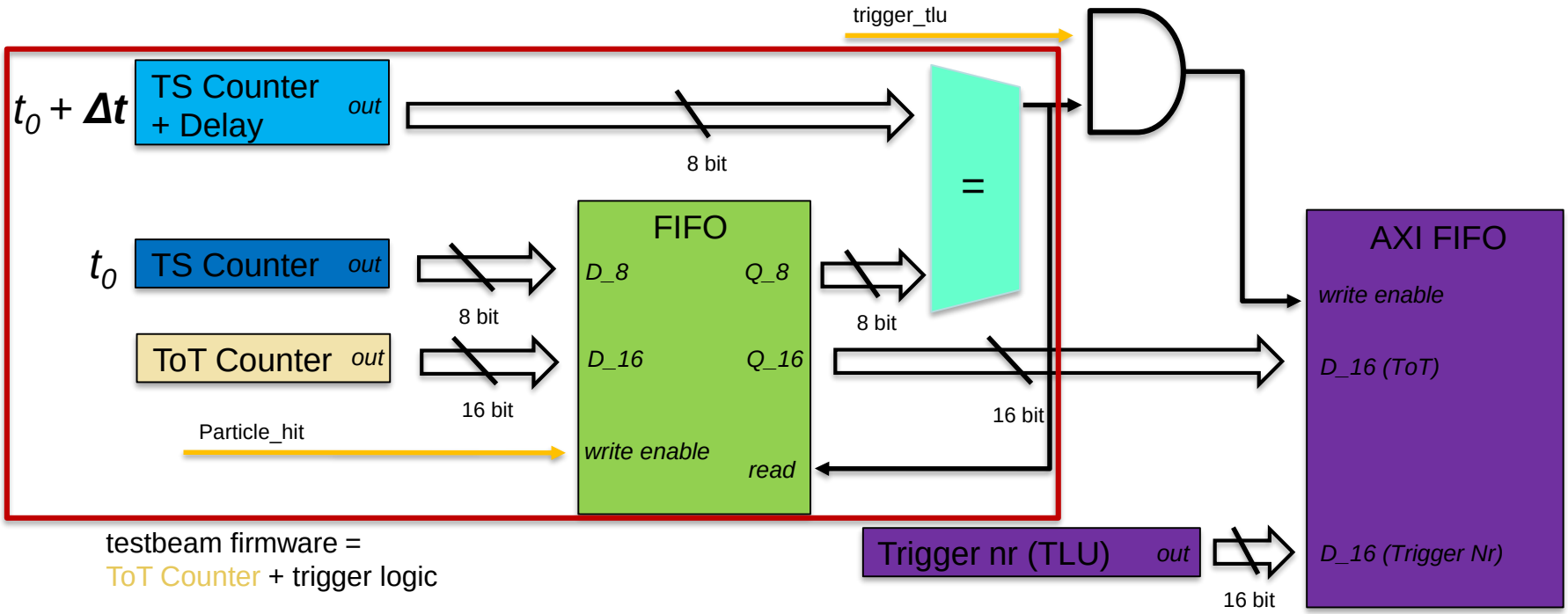


Wafer 13, 1e14N_{eq}

For more results, see this talk from P. Sieberer at 37th RD50 workshop

FIRMWARE

Firmware for testbeam



testbeam firmware =
ToT Counter + trigger logic

- Every hit stored in the FIFO (ToT + internal TS)
- Delayed TS is computed and compared with first TS
- Data (ToT value + Trigger Number from TLU) only to AXI FIFO, when there is a trigger issued

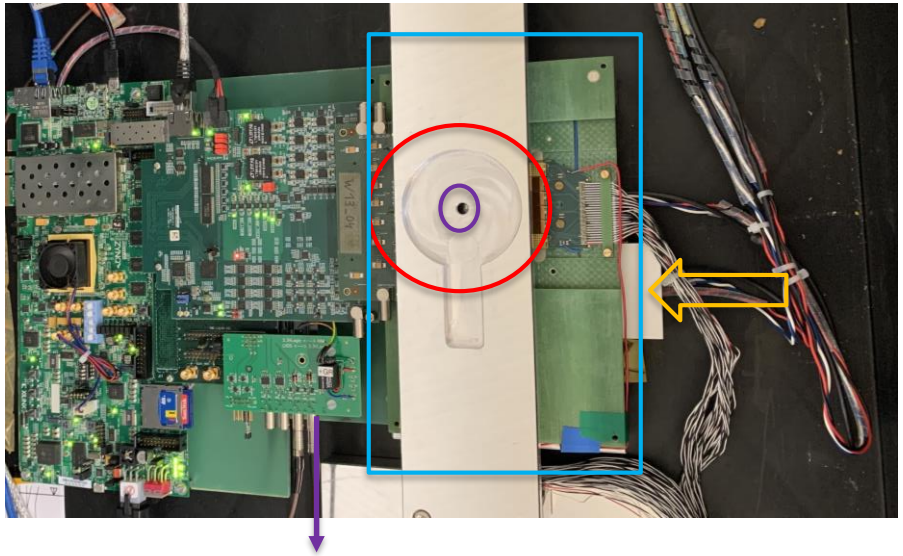
Synchronization effort:

⇒ **Delay of TS Counter needs to match the Trigger Delay**

⇒ Particles that hit pixel, without issuing a trigger are not stored. (Important for events that are not recorded by the (slower) telescope, or do not hit scintillators anymore due to too low energy, …)

Timing

- Trigger delay needs to be determined.



holder for Sr90 source

telescope plane

scintillator

RD50-MPW2

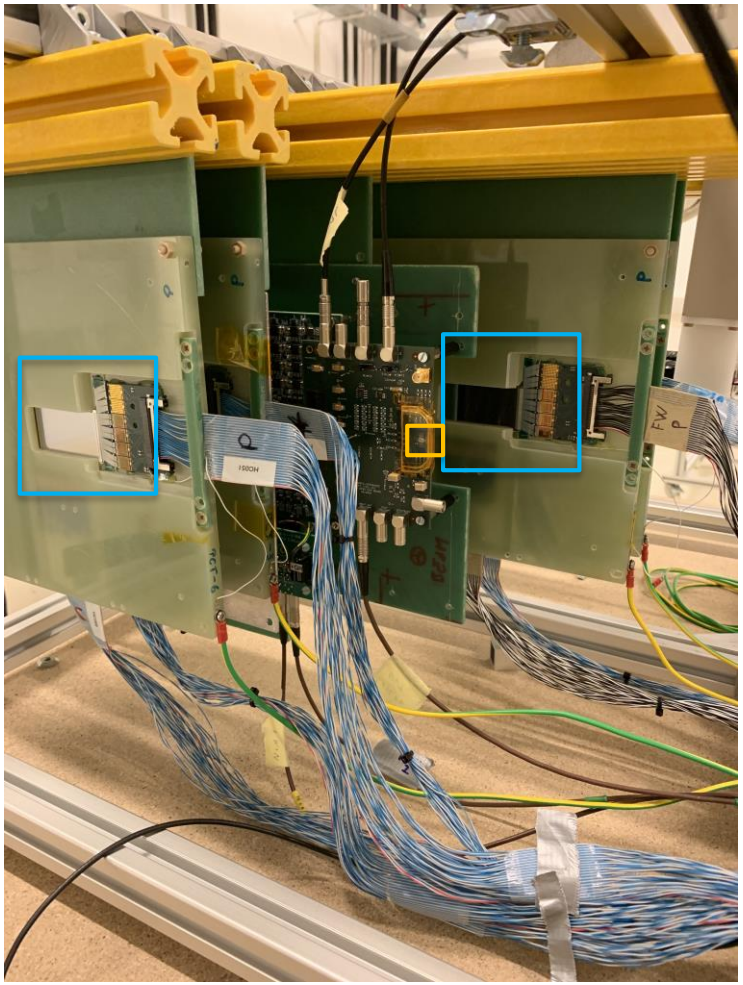
- Overall data rate: ~1 particle every minute
  - Geometric acceptance, rate reduction due to absorption
  - We can be sure that if we measure a particle on RD50-MPW2 + scintillator, the recorded data belongs to the same particle
  - No particle at all will be recorded, if delays don't match
- ***Δt* = Difference between mpw2_hit_out and trigger output of the TLU**

TESTBEAM AND ANALYSIS SOFTWARE

Testbeam setup

Testbeam done at MedAustron:

- 60-800MeV protons
- “Low Flux”, e.g. ~3.5 MHz particle rate
- 3cm spotsize
- Spill structure: 5s with 2.5s pause
- Paper submitted to NIM-A (F. Ulrich-Pur)



Detectors used:

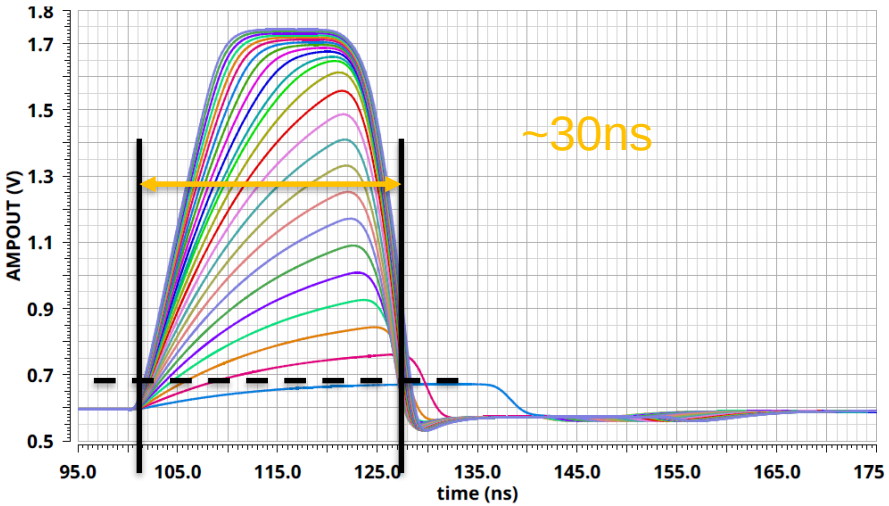
- 4 DSSDs as telescope
  - APV25 based readout
- RD50-MPW2 as DUT
- Scintillators in the back
- Triggered with AIDA-TLU

Energy Scan with ToT

Simulation Data

- Switched reset pixel -> ToT at ~30ns for all energies
- Threshold: 60mV above baseline

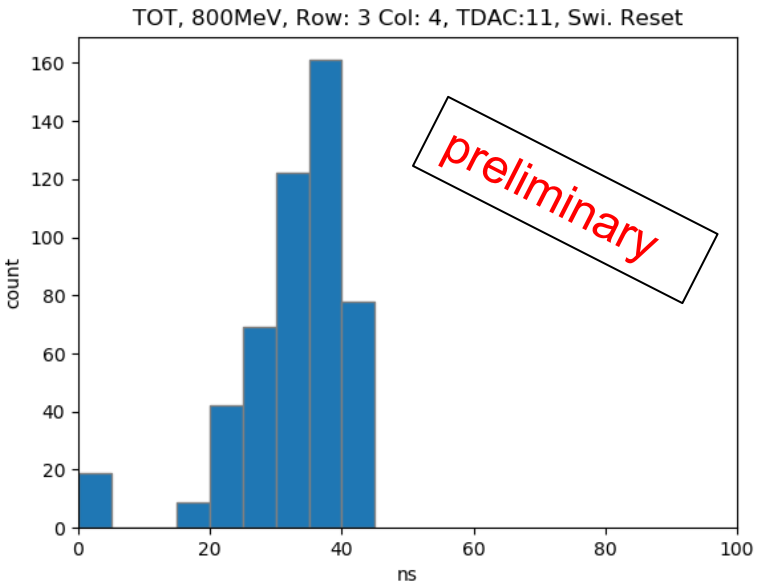
COMPOUT from 1-25ke$^-$



C. Zhang RD50-MPW2 Documentation

Testbeam results

- 800MeV protons
- Switched Reset Pixel

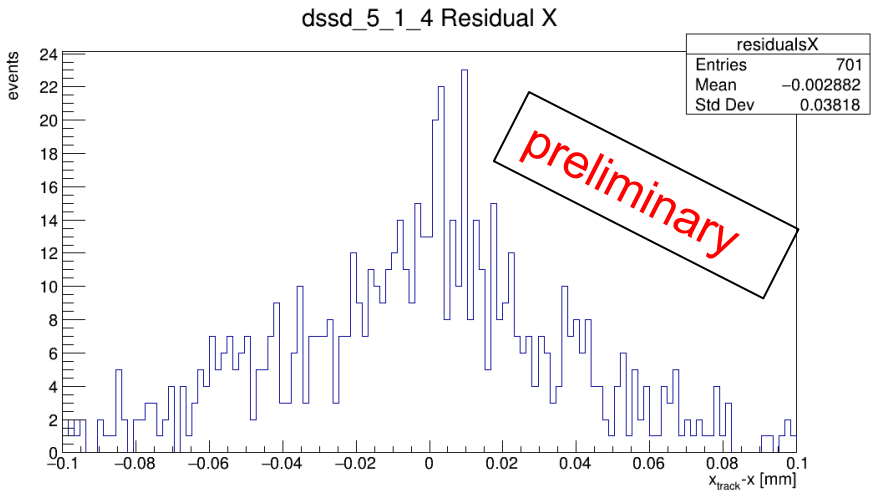


ToT time bins: 5ns

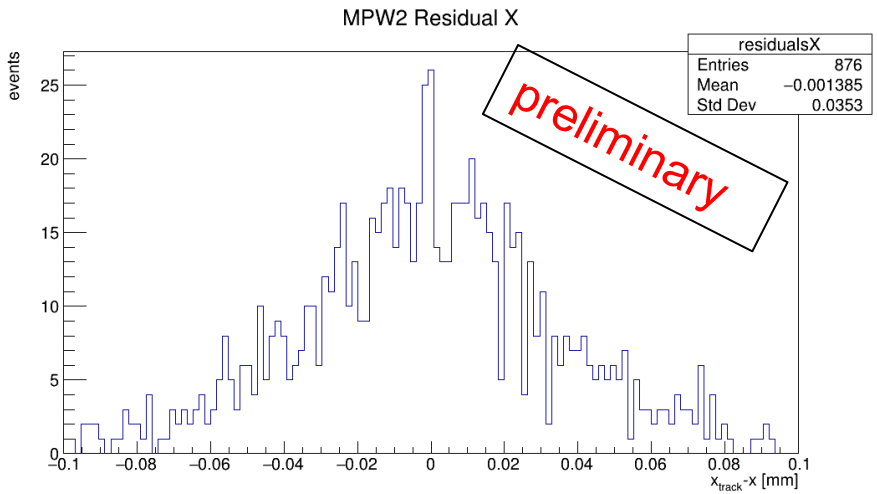
- *Standalone Firmware* can be used
- Testbeam results measured with ToT counter in FPGA in agreement with simulations
- More results soon

Tracking-Alignment

- Data recorded with Caribou-DAQ system and *testbeam firmware* can be loaded into a tracking framework (**Corryvreckan**)
- **Telescope and MPW2 data are consistent** (timing and triggering is working)
- More results will follow, analysis still ongoing



Residuals telescope plane 4



Residuals DUT

- Very preliminary results (analysis just started)
  - Alignment not yet perfect
  - Quite some issues with multiple-scattering in air
- Single pixel readout
  - Track selection by region-of-interest (ROI), see slide 37 in backup

CONCLUSION AND OUTLOOK

Conclusion and Outlook

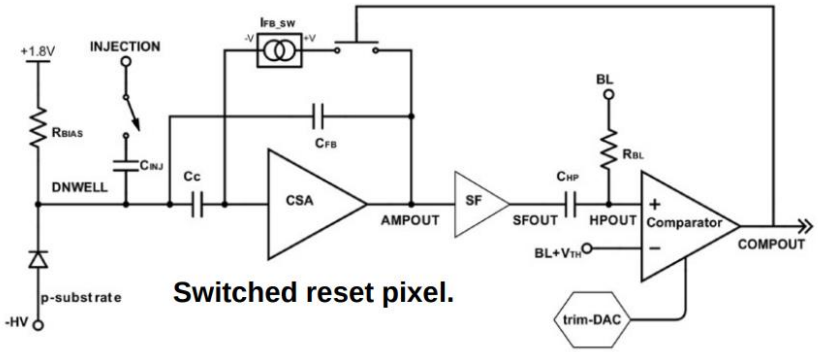
- RD50-MPW2 works as expected for all different signal sources (injection, radioactive source and protons)
  - Analog performance in agreement with simulation
  - Digital DAQ system gives consistent results
  - Integration to analysis software is working

- RD50-MPW3 currently designed
  - Improved analogue performance
  - Full (on-chip) digital periphery
    - Capability to read out full pixel matrix
  - Submission expected in October 2021

BACKUP

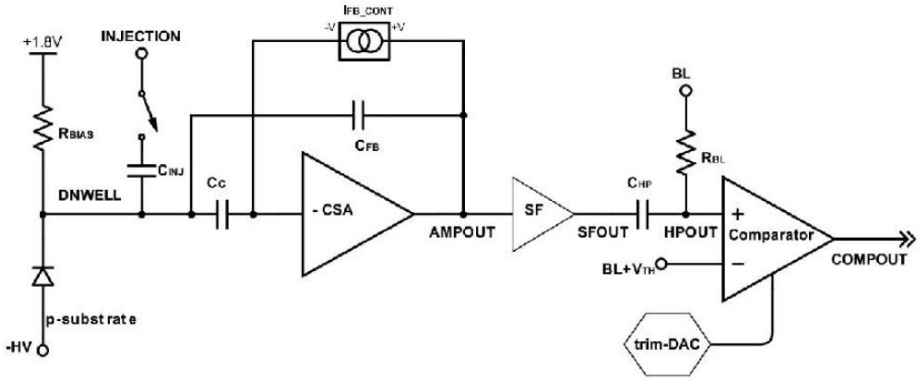
Pixel Flavors

Switched Reset Pixel



Switched reset pixel.

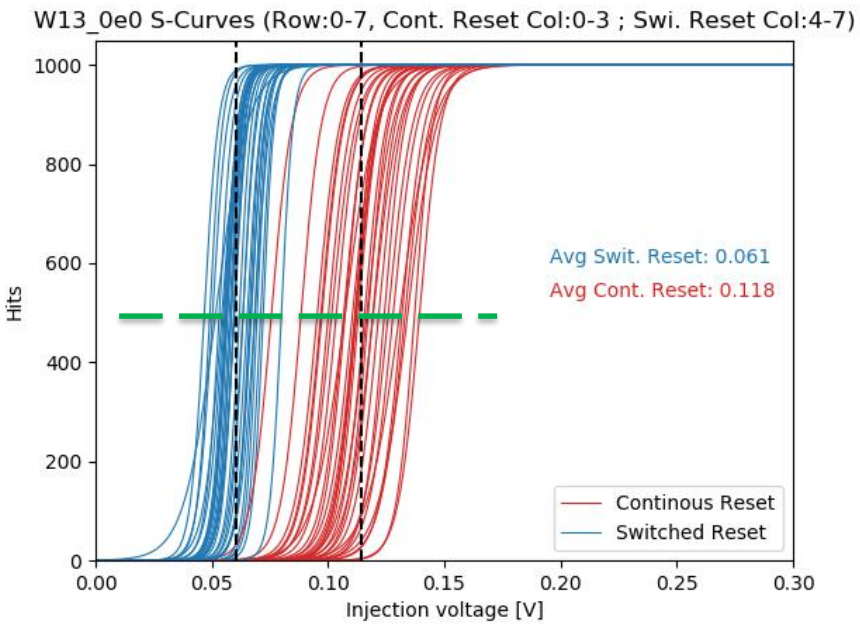
Continuous Reset Pixel



INJECTION PULSES

Injection: S-CURVES

- **Finding the comparator threshold**
- Comparator baseline (BL) at 900mV (subtracted in plot)
- Threshold at 950mV
- 1000 Pulses per voltage step (Step size 10mV)
  - Sigmoid function fitted
  - Counted after COMPOUT

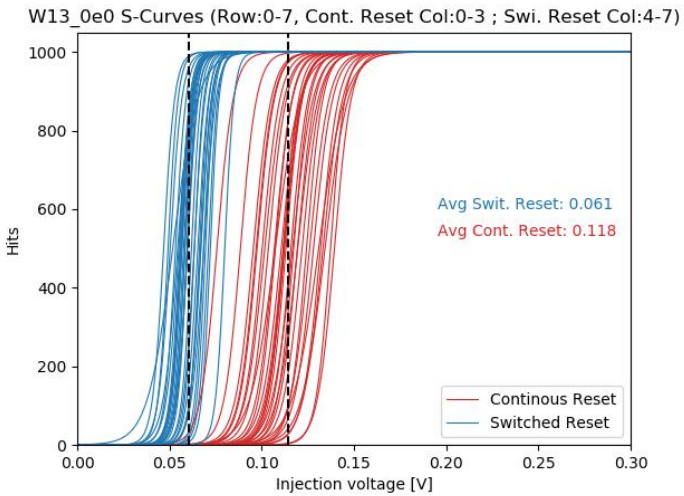


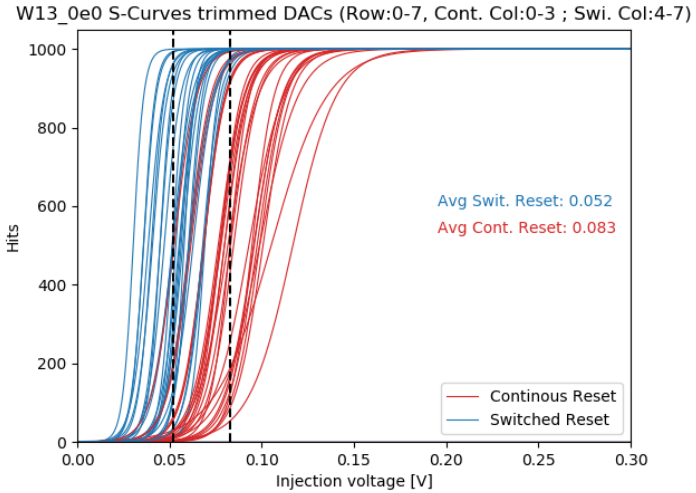
-> Threshold of Continuous Reset Pixels higher than for Switched Reset pixel

-> Quite some variation between pixels -> TRIMDACs implemented for compensation

TRIMDAC Adjust

- Highest possible pixel sensitivity if comparator **threshold** just **slightly above noise-level**
- Adjust TRIMDACs: Lowest possible value, where number of hits is below a certain threshold
  - Shutter 2s
  - Highest possible DAC with nr. of hits >0 (Better sensitivity than lowest TDAC with 0 hits)
- The goal is NOT to decrease the spread of the S-Curves

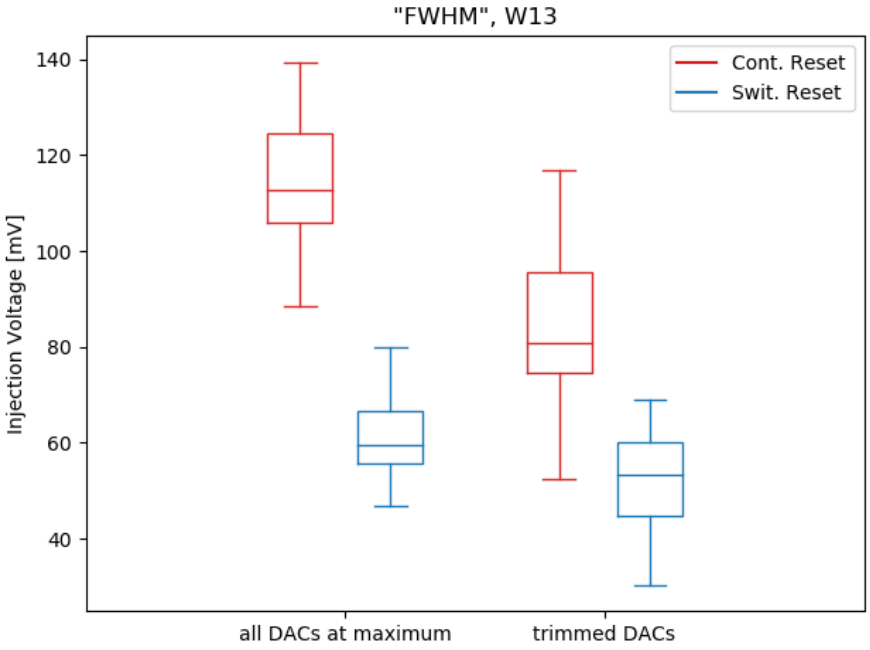




11 pixels masked (noisy)

Injection: TRIMDAC Adjust

- Highest possible pixel sensitivity if comparator **threshold** just **slightly above noise-level**
- Adjust TRIMDACs: Lowest possible value, where number of hits is below a certain threshold
  - Open a shutter for 2s, count (noise) hits
  - Highest possible DAC with nr. of hits >0 (Better sensitivity than lowest TDAC with 0 hits)
- The goal is NOT to decrease the spread of the S-Curves



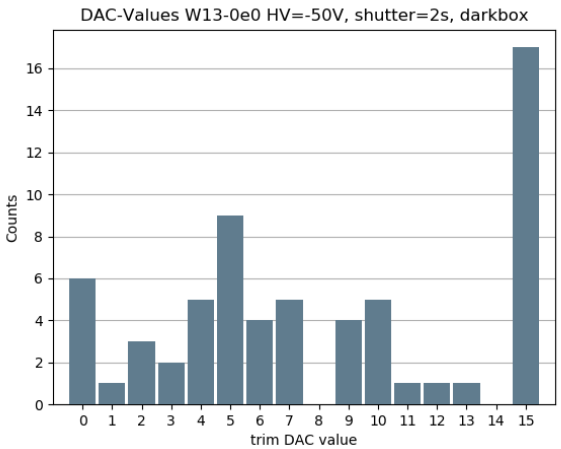
Irradiated samples

- Average number of hits per voltage plotted
  - No noise subtracted
    - Small effect (see backup)
    - Doubles measurement time

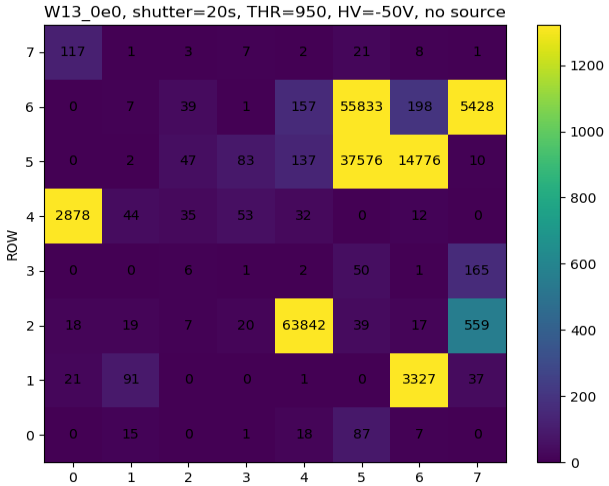
-> More hits for switched reset pixels (Lower threshold)
-> Less hits seen for higher fluences (both pixel flavors)
-> Continuous reset pixels less effected by fluence (to be confirmed)

Open Shutter - Darkcount

1. Set Bias Voltages
2. Adjust TRIMDACs per pixel as mentioned before
   - Needs to be re-done if environment changes (light, temperature, …)
3. Put radioactive source (Sr90, 10mCi / 370MBq) on top
4. Open a Shutter window (20s) for each pixel and count amount of hits



This peak includes noisy pixels



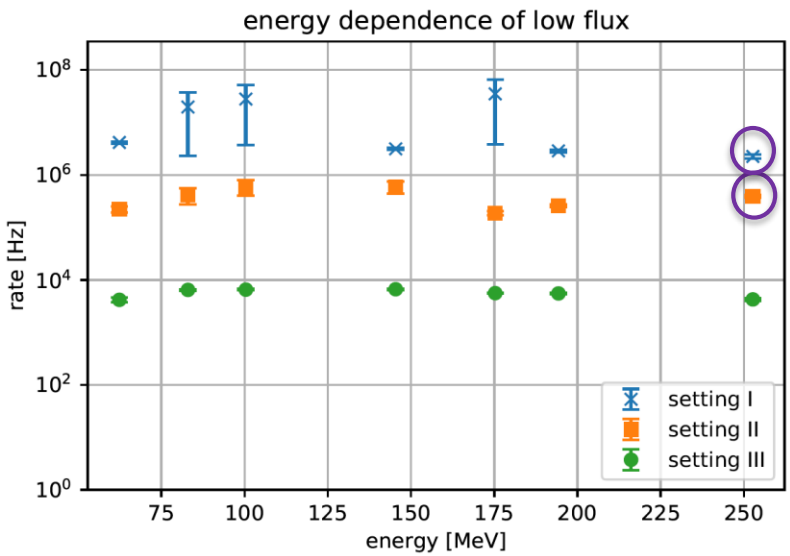
Top: Distribution of adjusted TRIMDAC values for pixels
Bottom: Example Hit-map without source

TESTBEAM

Beam Settings

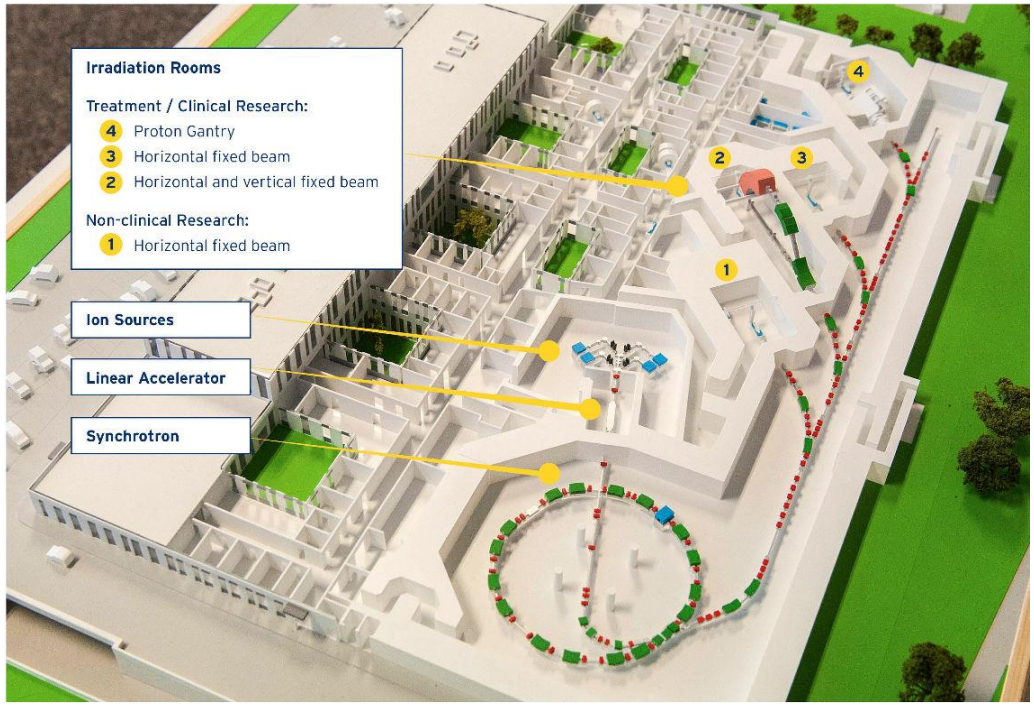
- Testbeam at MedAustron with protons
  - Ion cancer treatment (GHz rate)
- 2 different “Low Flux”- Settings used
  - Complete different beam settings, thus different rate
- Beam Energy: 252.7 MeV (both settings)
- Particle Rate: 2.2MHz and 400kHz
- Beam – Spotsize: ~7mm (both settings)
  - All particles hit scintillators
  - Very few particles hit a pixel (60um x 60um)

Setting	Mean Rate	StdDev Rate
I (at 252.7 MeV)	2.25e6	1.87e5
II (at 252,7 MeV)	3.92e5	1.86e4



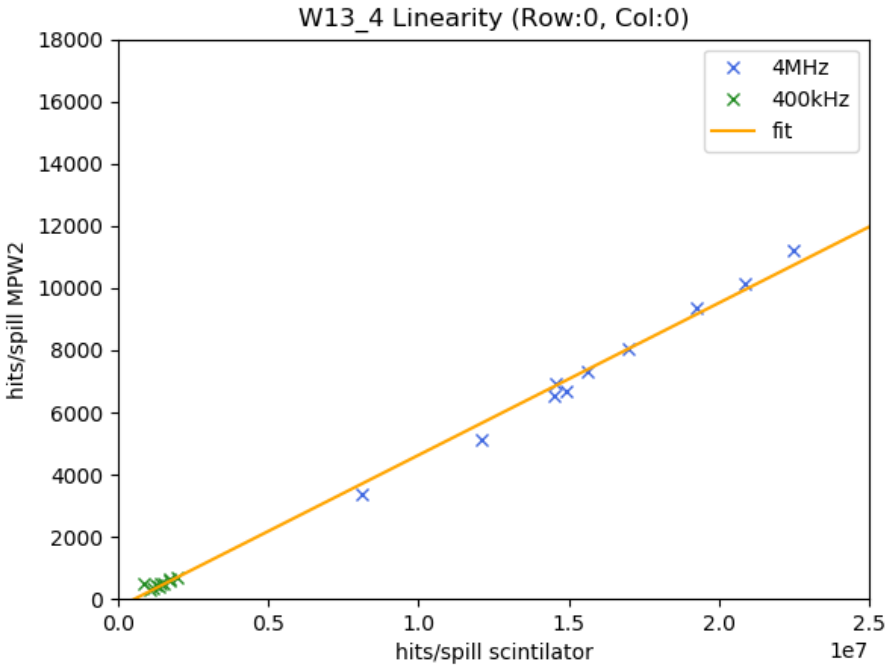
MedAustron – in a nutshell

- Medical Accelerator close to Vienna
- 3 clinical irradiation rooms + 1 additional room for research
- Particle rate: $\geq=10^{10}$ (protons), $\geq 10^{8}$ (carbon ions)
- Spill structure: 5s spill, 5s pause
- Beam energy: [60,800] MeV

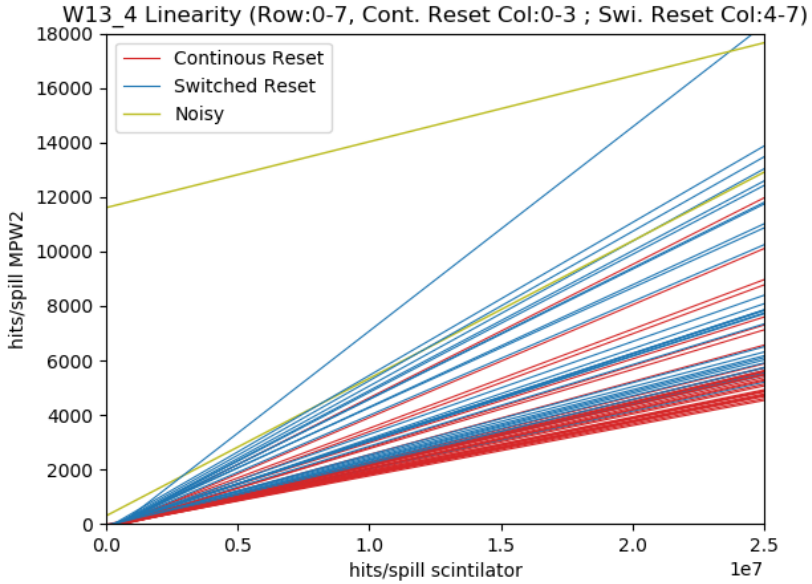


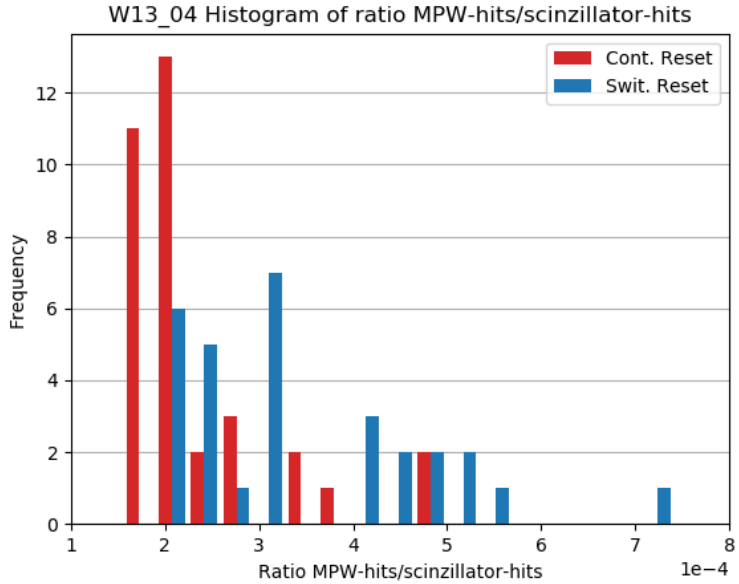
Simple counting

- 20 spills (5s) for each pixel measured
  - 10 spills per rate
  - Hits summed up over whole spill
- 400kHz Beam rather stable particle rate
- 2.2MHz Beam larger variation of particle rate per spill
  - as seen on previous slide
- Much higher rates (10^9) possible
  - Scintillators not fast enough for single particle counting



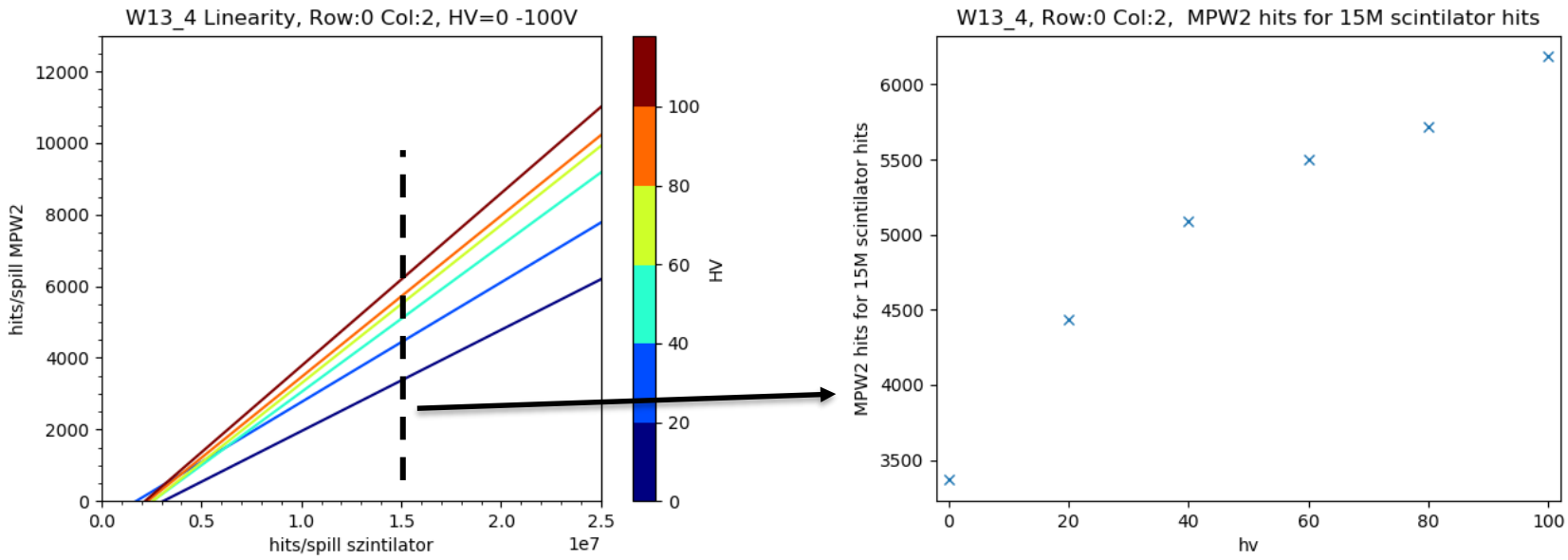
Linearity





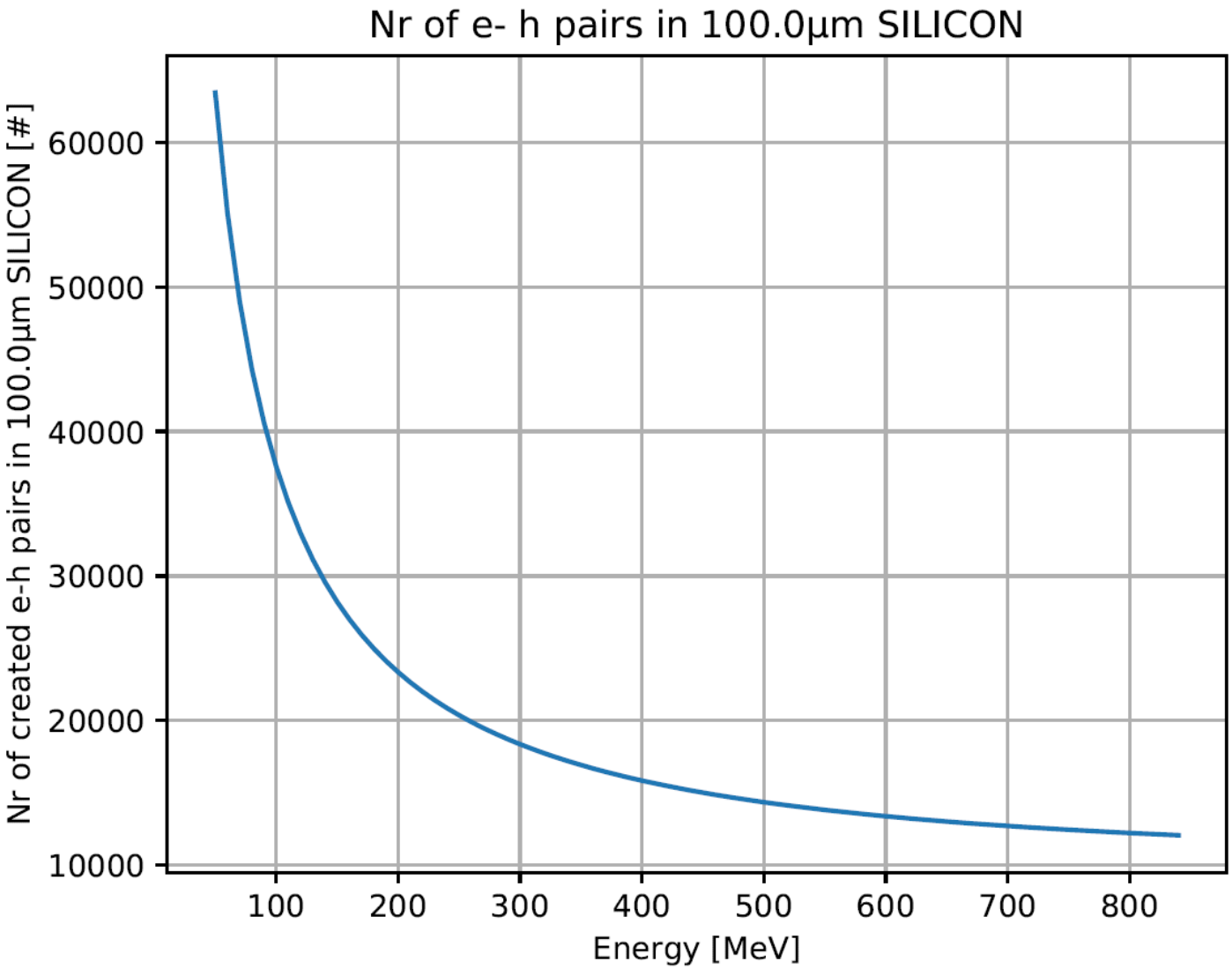
- Straight line fit plotted for all pixels
- Switched reset pixel see more hits (Thus better sensitivity)
  - Already known from source-measurements

HV Scan



- Just one Pixel for one rate ramped over HV (20V stepsize)
- Better performance for higher bias voltage (as expected)
- Follows expected sqrt(U) function, but low statistics

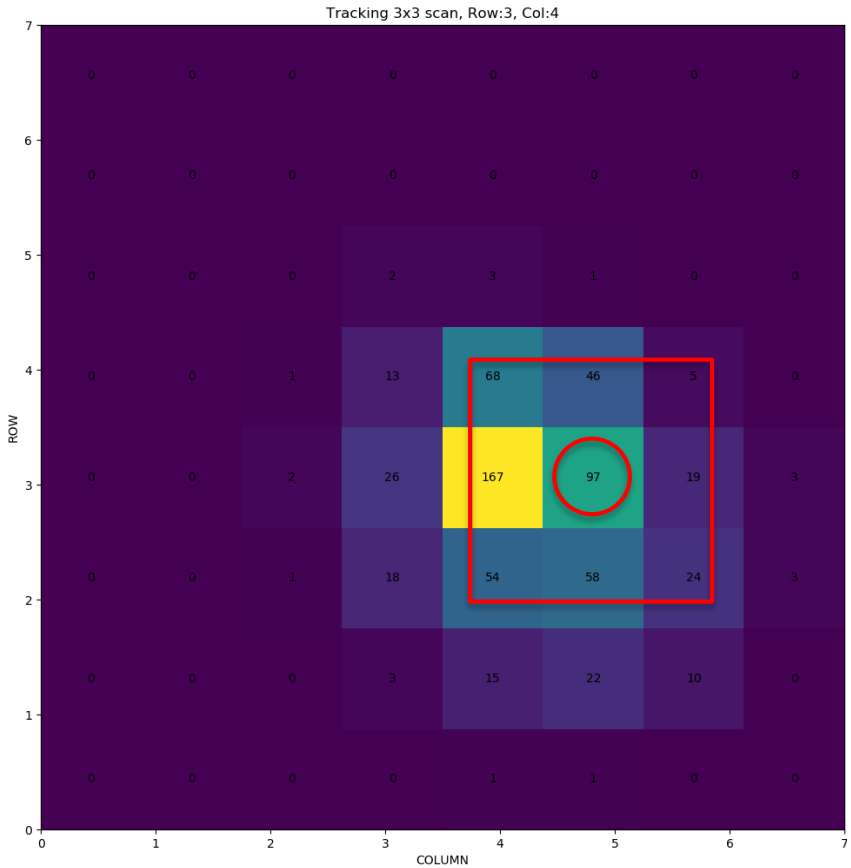
NIST pstar


Nr of e- h pairs in 100.0µm SILICON
Nr of created e-h pairs in 100.0µm SILICON [#]
60000
50000
40000
30000
20000
10000
100
200
300
400
500
600
700
800
Energy [MeV]

Tracking

- Synchronization not easy: **Both firmware versions implemented in parallel** in the FPGA
  - Problem: only 15bit for Trigger number, much higher data rate -> **overflow**!
  - Hit counter of firmware version 1 used to count trigger overflows
  - Trigger-number (of firmware version 2) corrected for overflows in readout software

ROI Scan



- ROI of 3x3 pixels
- Active Pixel is R3 C4 (switched reset)
- Middle pixel of ROI changed for each analysis.
- E.g. Measurement of Pix R3 C5:
  - all tracks in shown ROI accepted
  - Still Pix R3 C4 measured
  - Due to measured pixel still in ROI + charge sharing of tracks right from the pixel, we still see hits