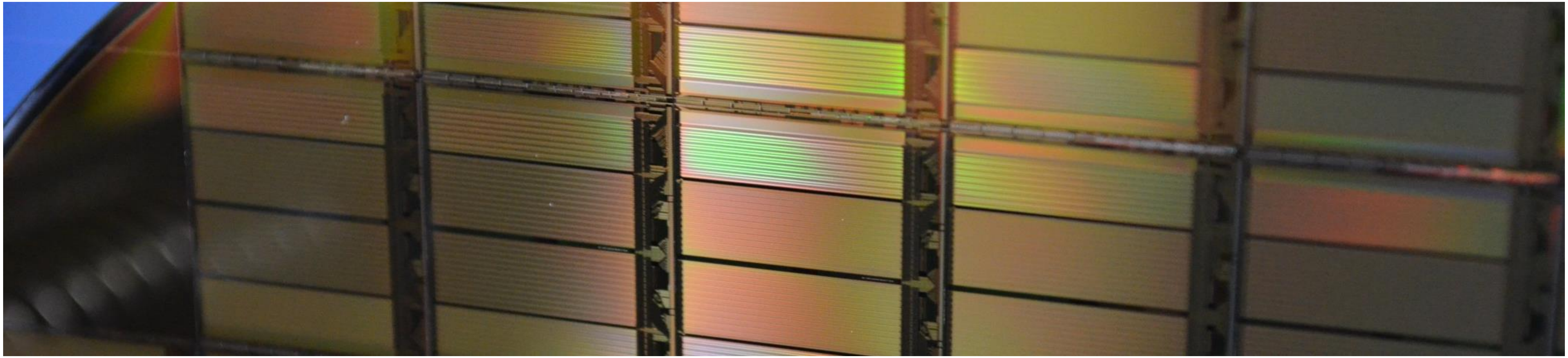
Development of a High-rate HV-CMOS Sensor for Real-time Monitoring of a Medical Ion-beam

F. Ehrler, M. Balzer, A. Dierlamm, R. Koppenhöfer, R. Lahmann, S. Maier, H. Mateos, M. Pittermann, I. Perić, R. Schimassek, B. Topko, E. Trifonova, A. Weber

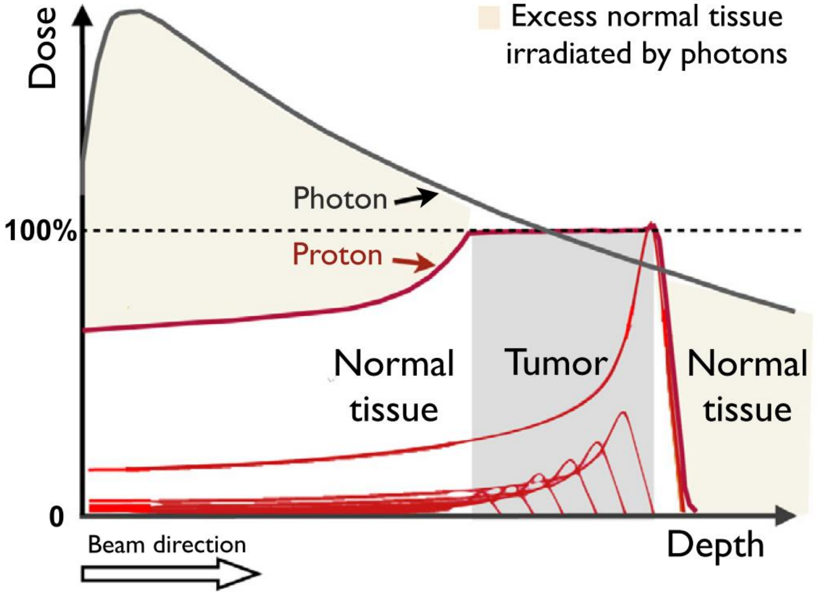


Motivation: Tumor Treatment

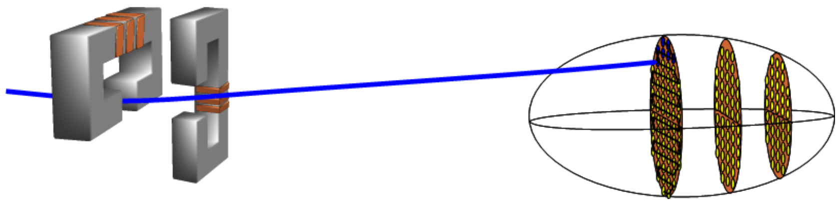
- In Germany, approximately 500 000 people are diagnosed with tumor or cancer every year
- Many diagnoses are not a death sentence anymore
- Some still are
- Treatment combines usually three approaches:
  - Resection
  - Chemotherapy
  - Radiotherapy
- A good prognosis depends primarily on an early diagnosis (do your medical checkups!). But also on the continuous optimization of the treatment.

Radiotherapy – External Beam Irradiation

- Destruction of tumor cells by ionizing radiation
- Healthy tissue should be spared
- Most common is photon irradiation
- Irradiation using heavy, ionized particles is different:
  - Bragg peak: irradiation in front of sensitive tissue
  - Lower dose to healthy tissue
  - Tumors are irradiated by scanning voxels: x, y, energy.



Source: Royce et al. „Proton Therapy for Prostate Cancer: A Review of the Rationale, Evidence and Current State.“ Urologic Oncology: Seminars and Original Investigations, 2019

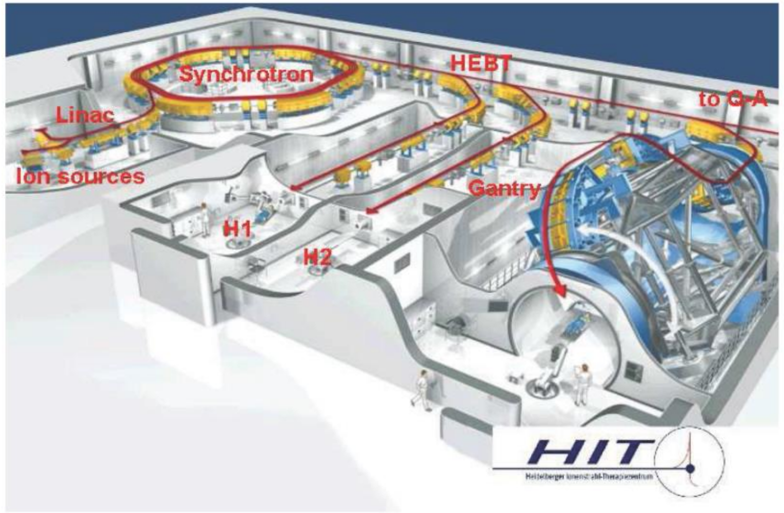


Challenges of Ion Irradiation

- Large accelerator needed
- Spatial aiming
  - Depth (via energy) is defined by the accelerator and filters
  - Position is defined by deflection and focusing magnets and has to be closely monitored
- Dose monitoring by ionization chambers
- Fast feedback and interrupt if
  - maximum dose is reached or
  - malfunction is detected
- Magnetic Resonance Imaging (MRI) during irradiation is not yet possible

Heidelberg Ion beam Therapy center (HIT)

- Started 2009
- Linac and synchrotron
- Energy range 7 – 430 MeV/u in 255 steps
- Protons and Carbon ions
- Intensity up to 2 x 10^9 per second
- 2 horizontal treatment rooms
- 1 Gantry treatment room
- 1 additional beam room for quality assurance and experiments



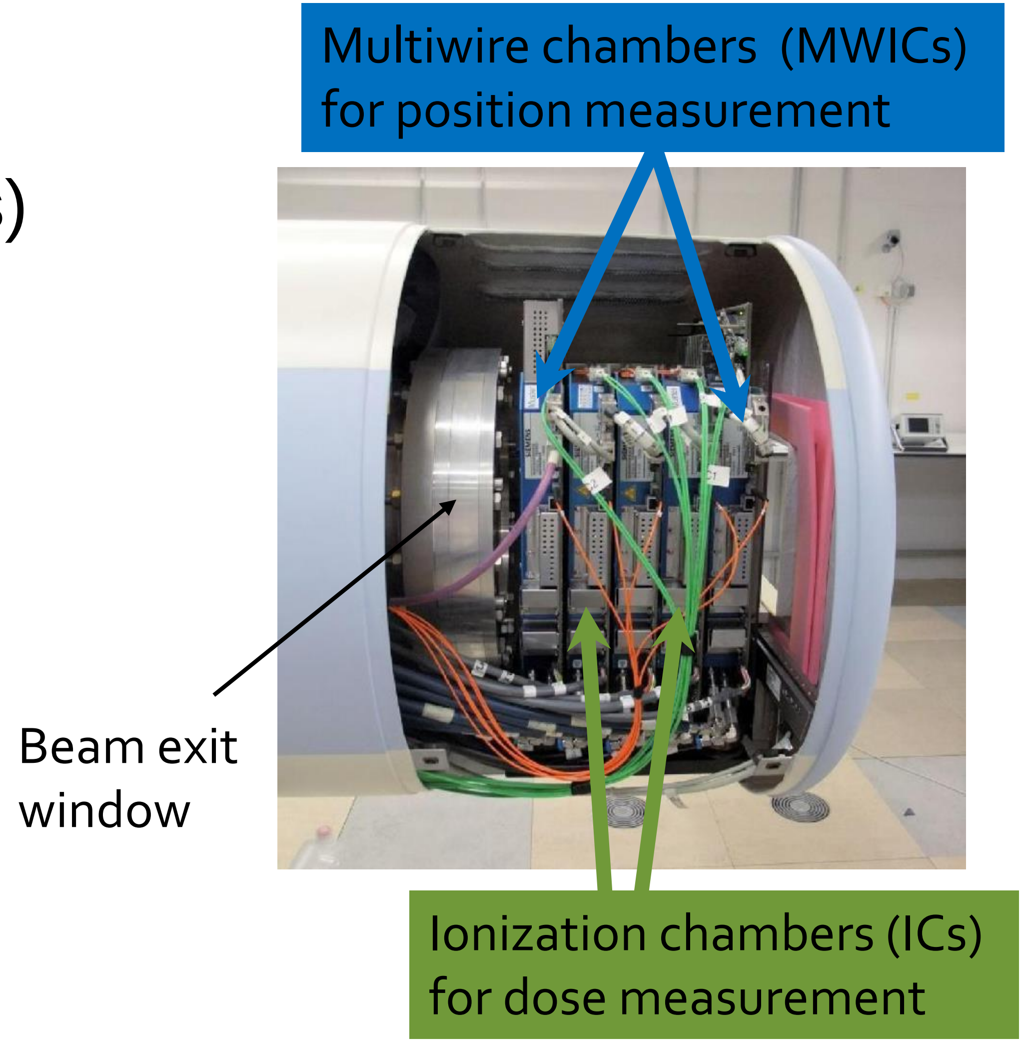
Source: HIT Betriebs GmbH

State of the Art: Multi-wire Chambers

- Low material (Gas filled chambers)
- Fast (dose 2 µs, position 125-500 µs)
- Proven technology: reliable

- Sensitive to magnetic field
- Only projection, no beam shape
- Not suitable for low signal per area

- Our goal is to offer a superior alternative



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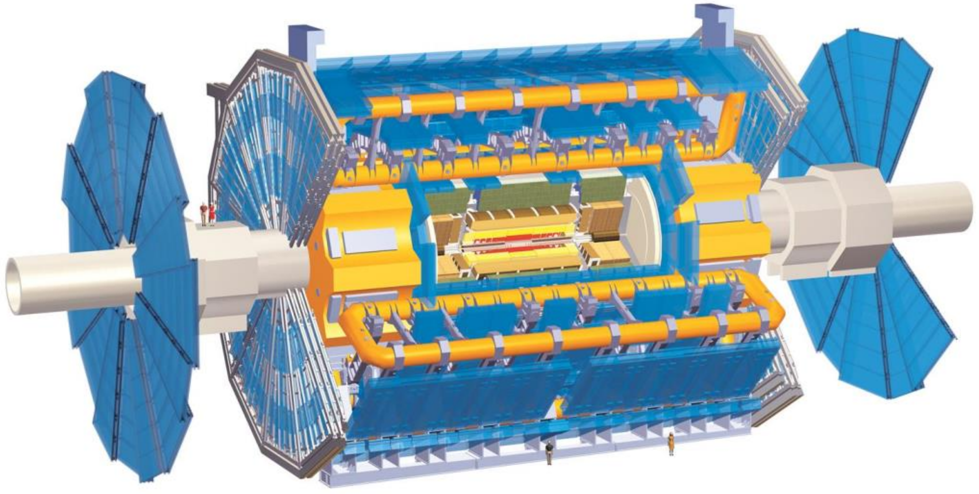
Differences to Pixel Detectors in High Energy Physics

- Not an experiment: A failure can not be fixed by repetition
- Higher particle rate (> 60 MHz/cm²)
- Smaller latency (100 µs)
- Homogeneity is important



- No tracking of individual particles
- Relaxed time resolution (µs, not ns)
- Relaxed spatial resolution (100 µm, not <1 µm)

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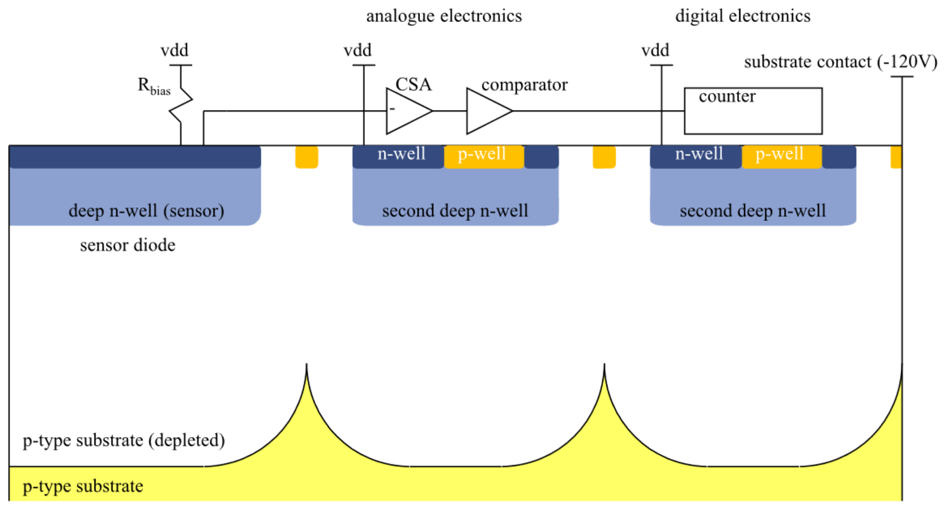
Benefits of an HV-CMOS Beam Monitor

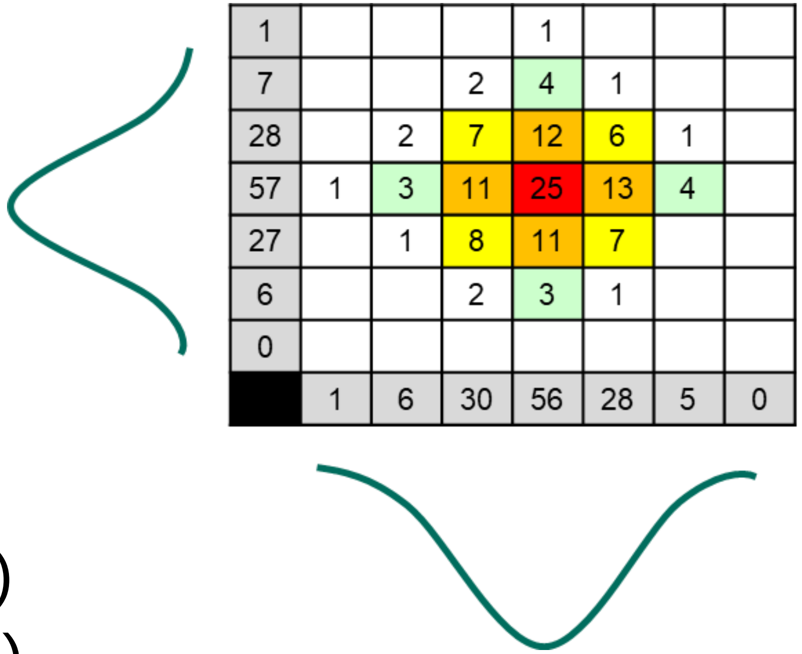
- Magnetic field tolerant
- Radiation tolerant
- Fast

- Low material budget (multiple-scattering)
- Homogeneous (cf. bump bonds, wires): no change of beam shape
- Comparably cheap



Sensor Design

- Monolithic HV-CMOS sensor
  - Sensor and electronics on same die
- Reticle size (2 x 2 cm²)
- Thin (~150 µm)
- Hit counting electronics in each pixel
- Frame readout (~10 µs)
- Two modes:
  - Readout of counter states (beam diagnostic)
  - On-chip calculation of projections (quasi live)
- Dose determination by total particle count



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28		2	7	12	6	1	
57	1	3	11	25	13	4	
27		1	8	11	7		
6			2	3	1		
0							
	1	6	30	56	28	5	0

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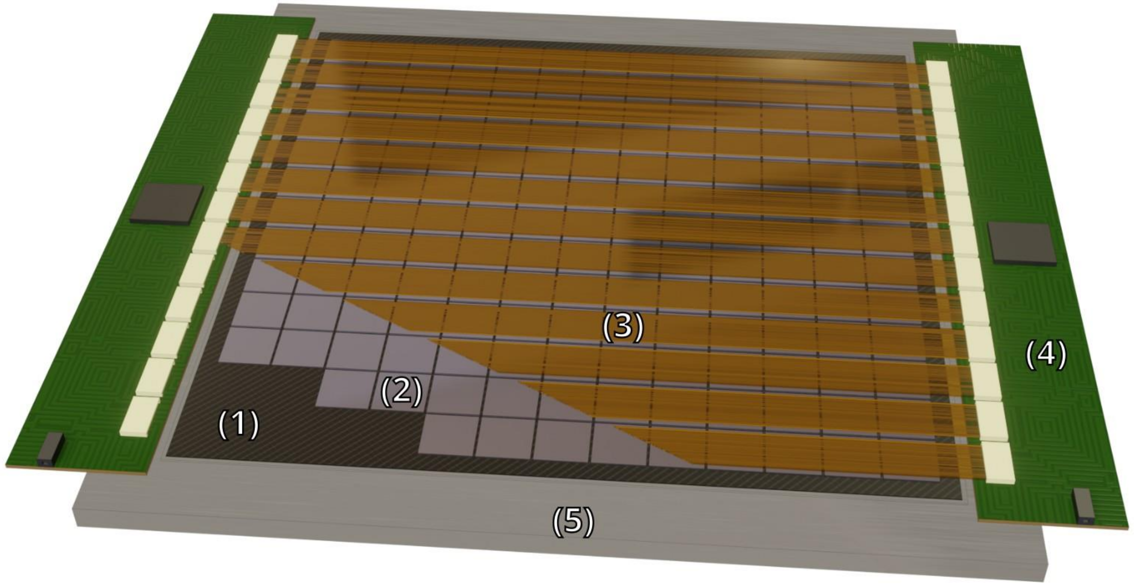
Proposed Detector Design

1) Carbon fiber plate
2) 13 x 13 sensors (2 x 2 cm^2 each)
3) Flex cables with aluminum traces
4) Electronics boards with FPGA for data processing
5) Stabilizing frame



Current Status

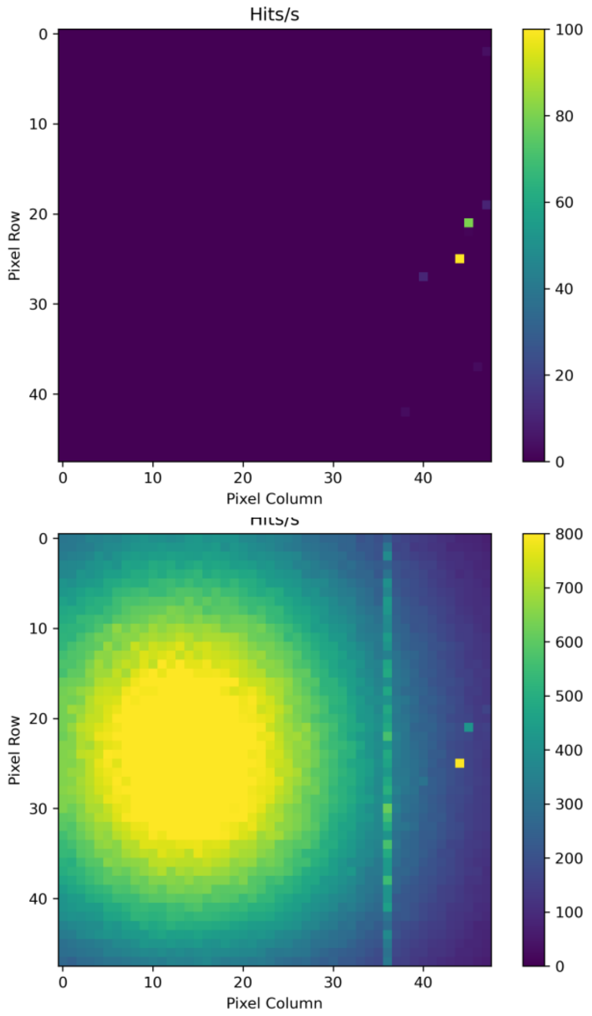
- 3 different chips
  - HitPix1, HitPixINT, HitPix2
- HitPix2, 1x1cm², (200µm)² pixels, works well in ion beam
- Radiation tolerant $>10^{15} n_{eq}/cm^2$ (>1y)
- Successfully tested in magnetic field
- Reconstruction algorithms for FPGA evaluated
- First demonstrator matrix assembled

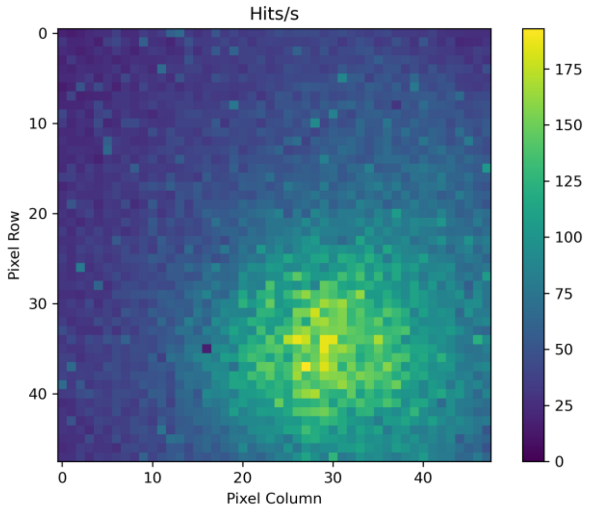
- Many test in lab, in beam, in magnetic field and micro ion beam

HIT Beam Area

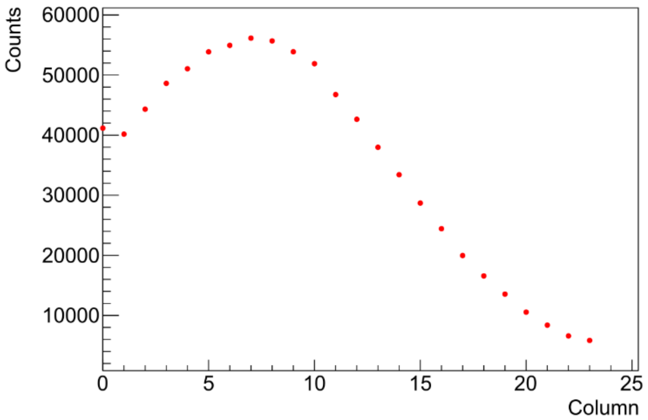
Single Chip Measurement

Irrad. chip ($5x10^{14}$ p_{23MeV}/cm^2)
w/o and with C12 beam





HitPix2 C12 beam spot



HitPix1 C12 beam projection

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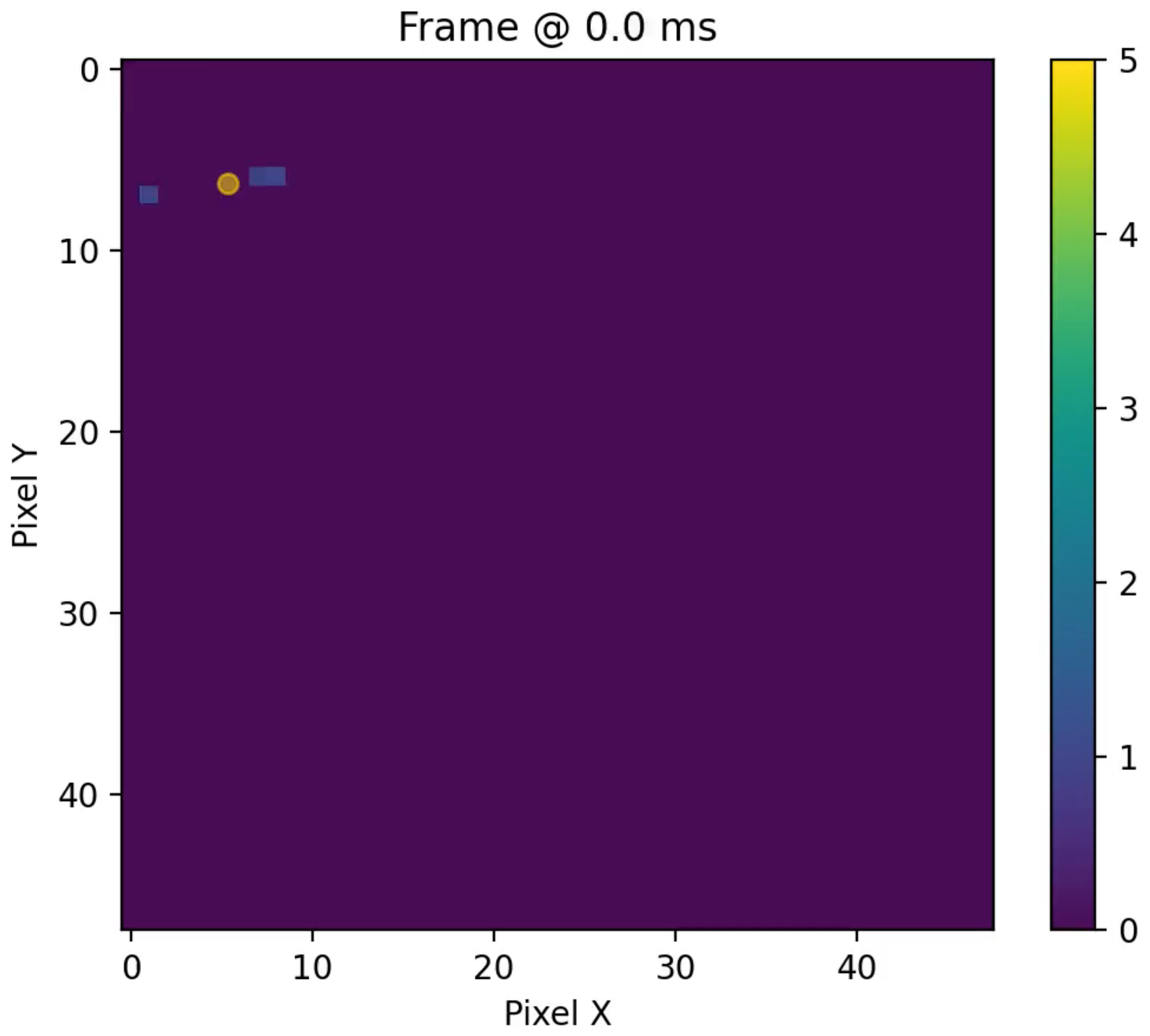
- Blue: pixel counts (number of particles passing a pixel / frame)
- Yellow: calculated mean position of the beam in a frame
- 1 frame = 50 µs
- 1 pixel = 200 µm
- 2D-mode: Duty cycle is 1/20
- Beam settings: C, E255, I3, F1

- Note: Beam outside sensor has the calculated mean position still on the sensor



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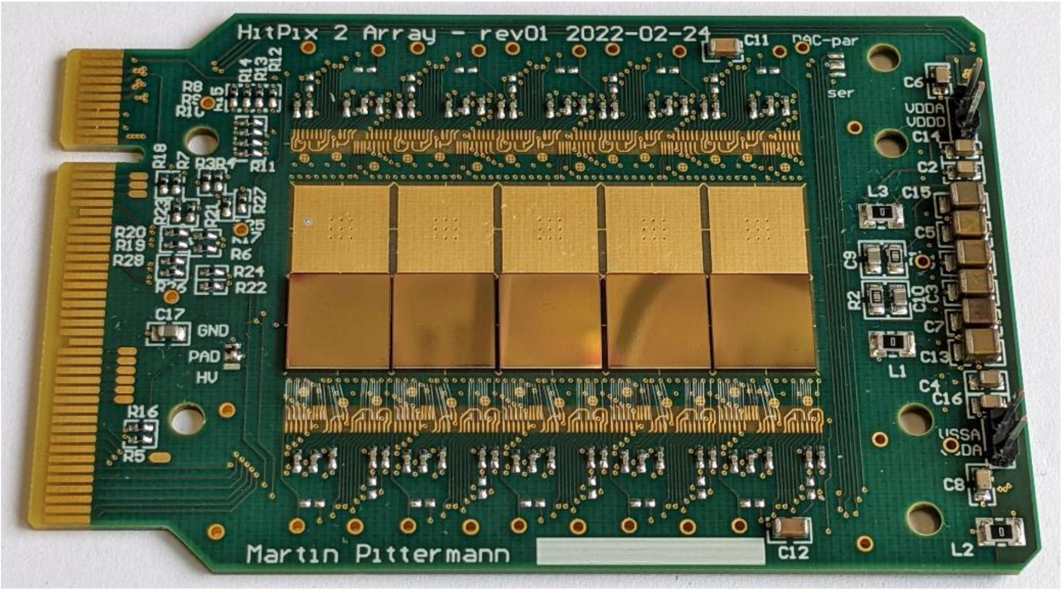
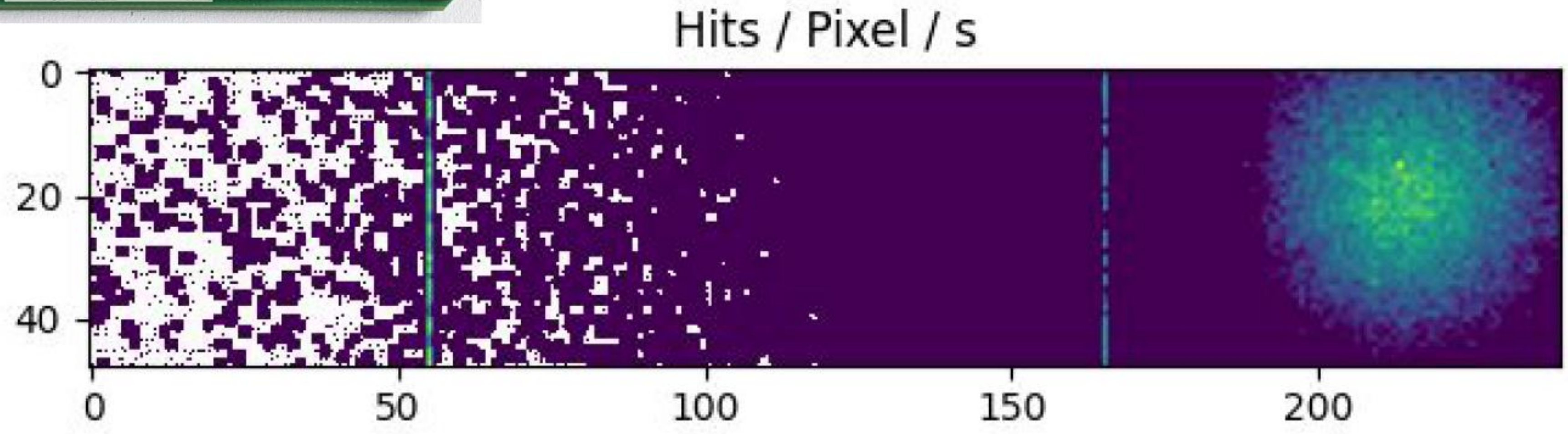
First Multi-Sensor Module



First multi-chip module, equipped with 5 sensors

Sr-90 hitmap recorded by module



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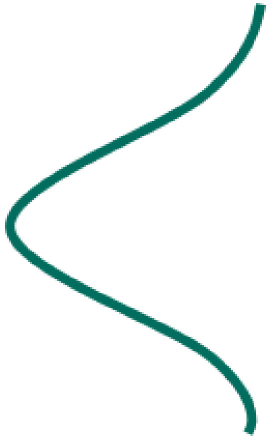
Open tasks and issues

- 2nd projection axis



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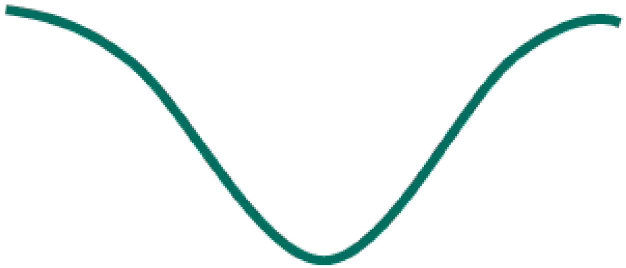

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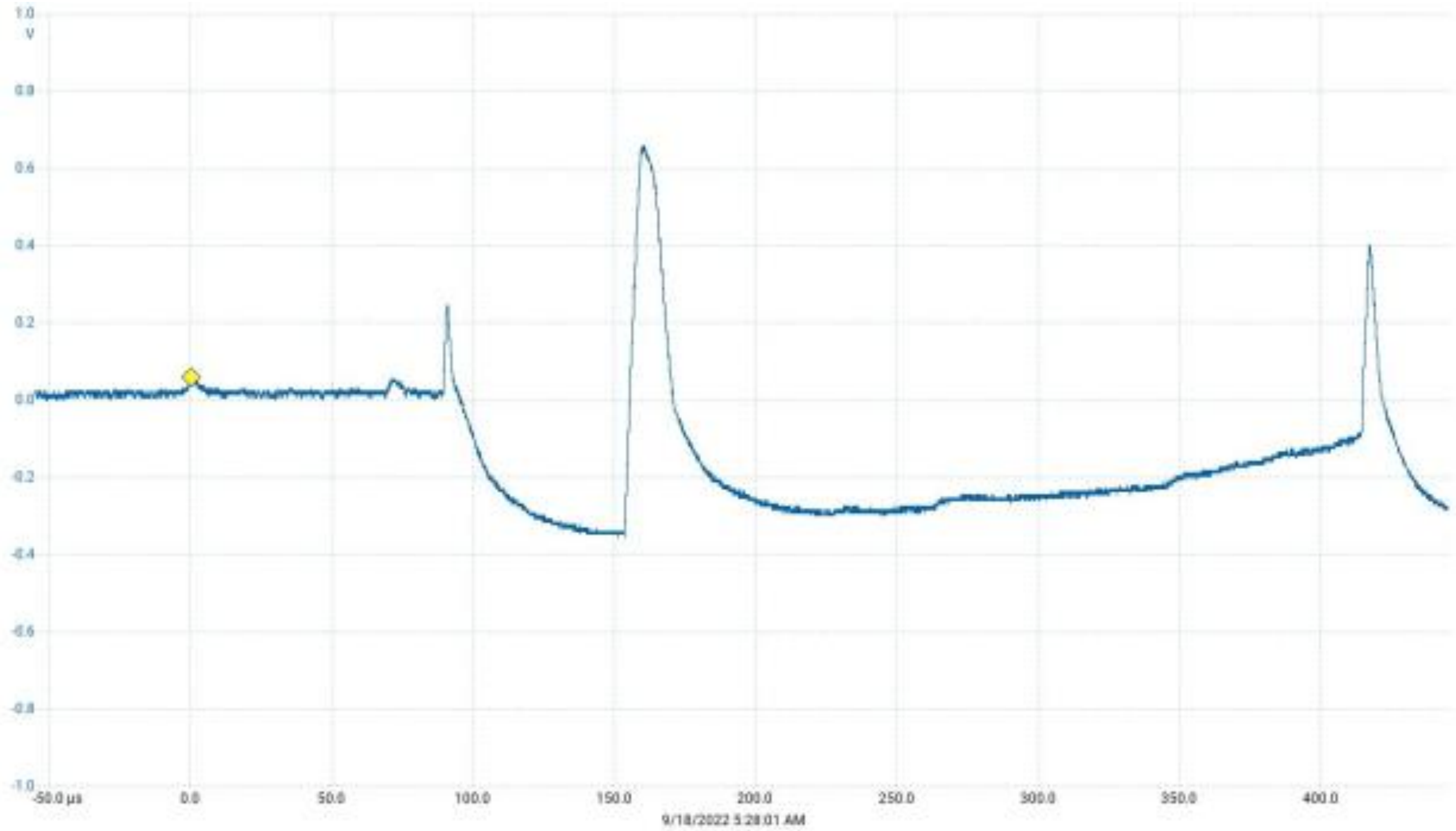
Open tasks and issues

- Hit detection efficiency loss due to amplifier baseline drop



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Open tasks and issues

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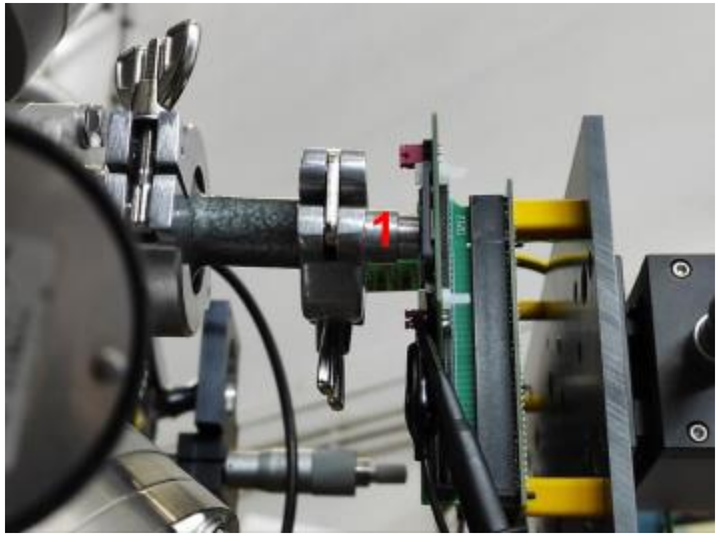

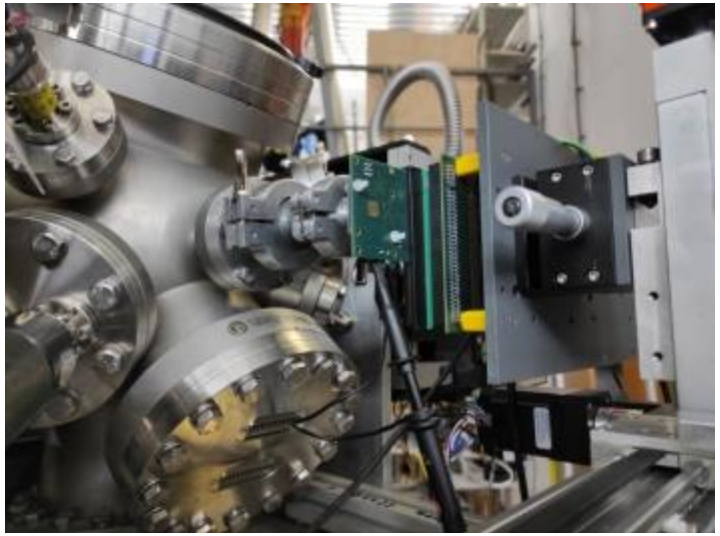

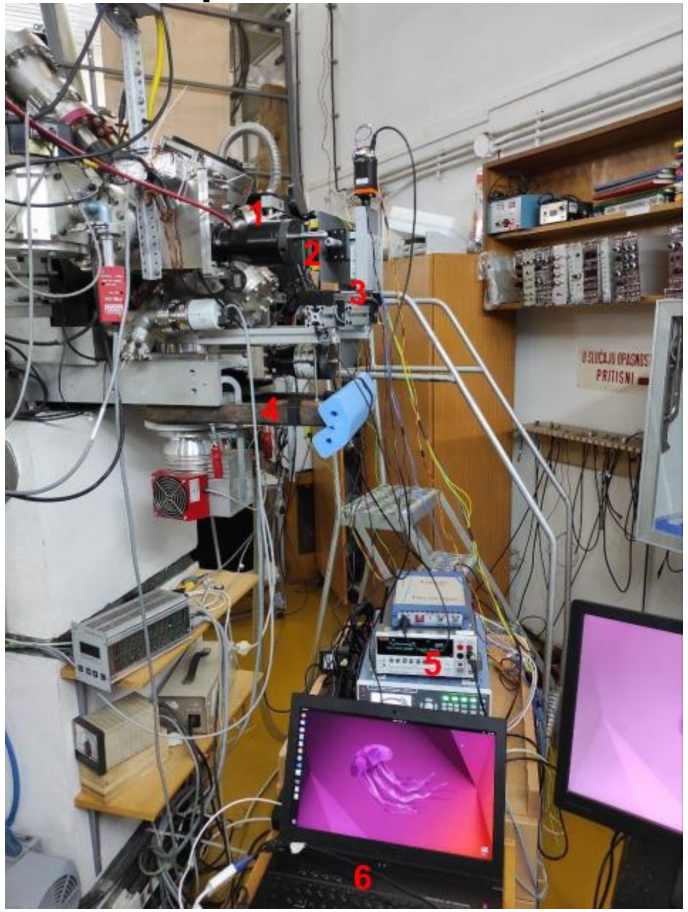

1 Beam nozzle
2 HitPix sensor
3 x-y-stage

4 Mechanical support
5 Power supply
6 Computer

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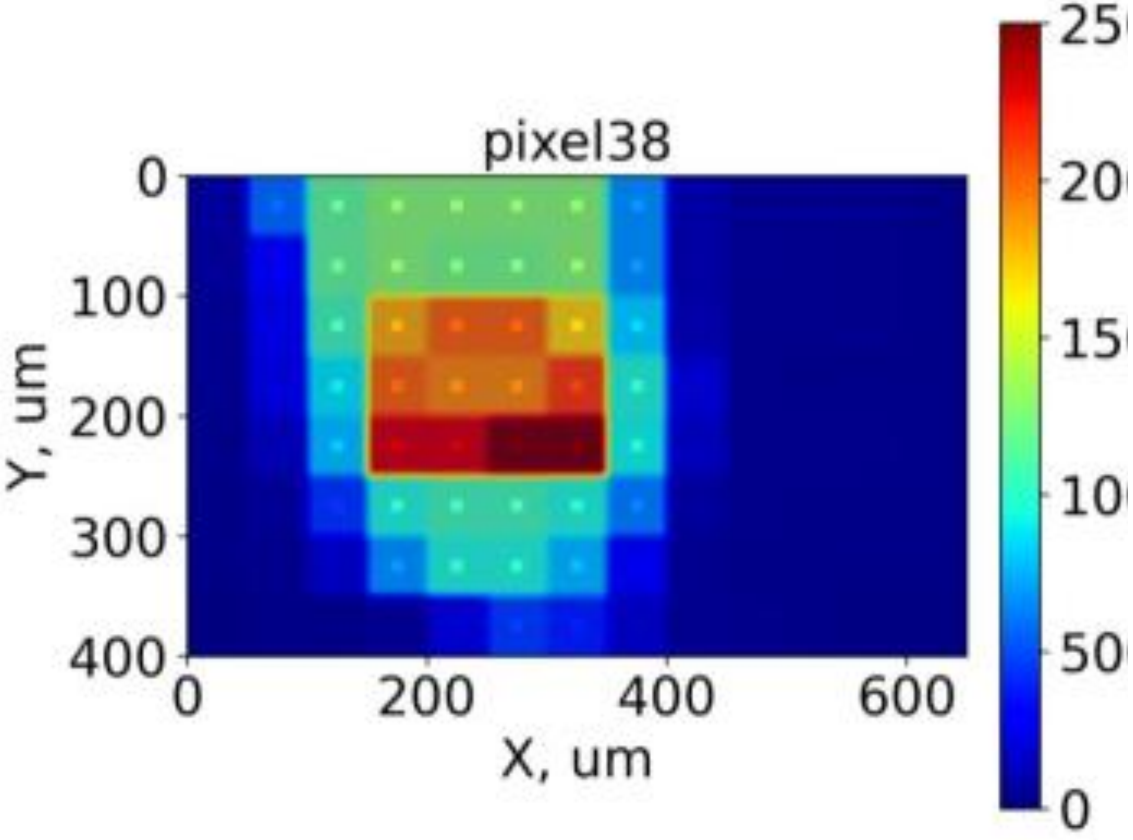
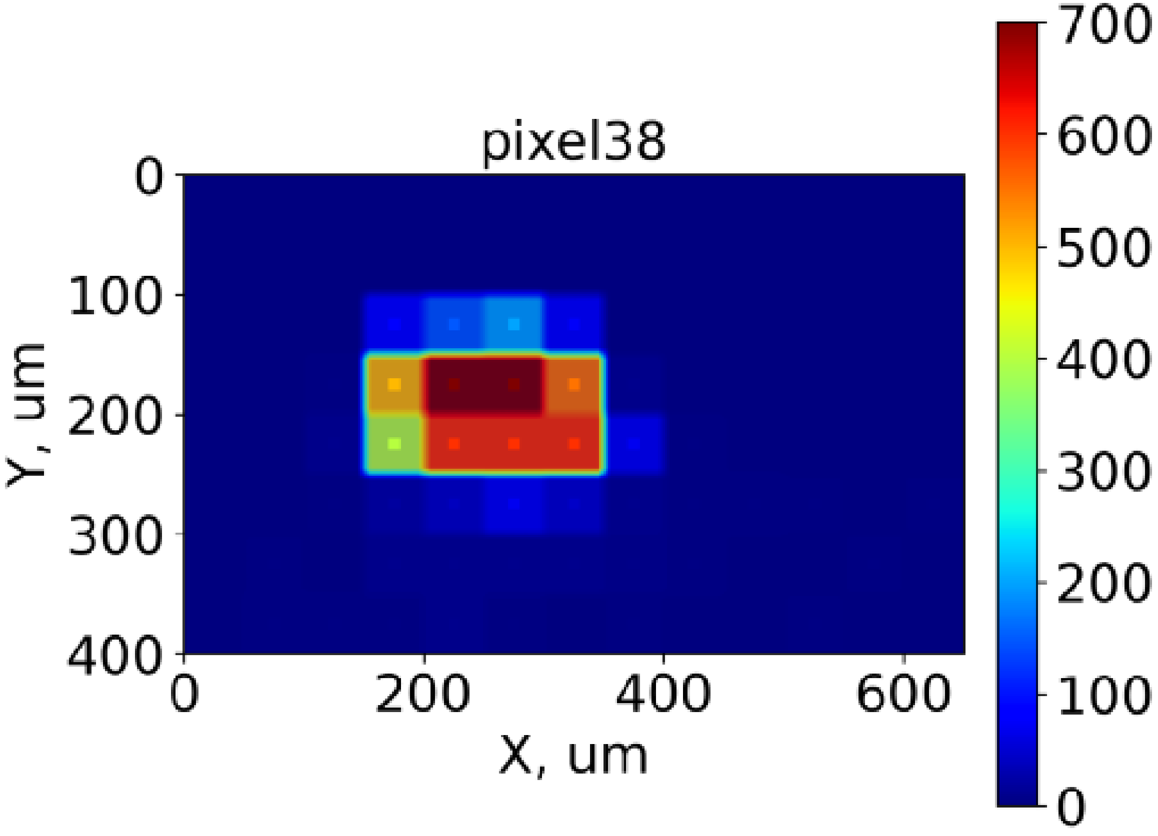
Open tasks and issues

- Hit detection efficiency loss due to amplifier baseline drop





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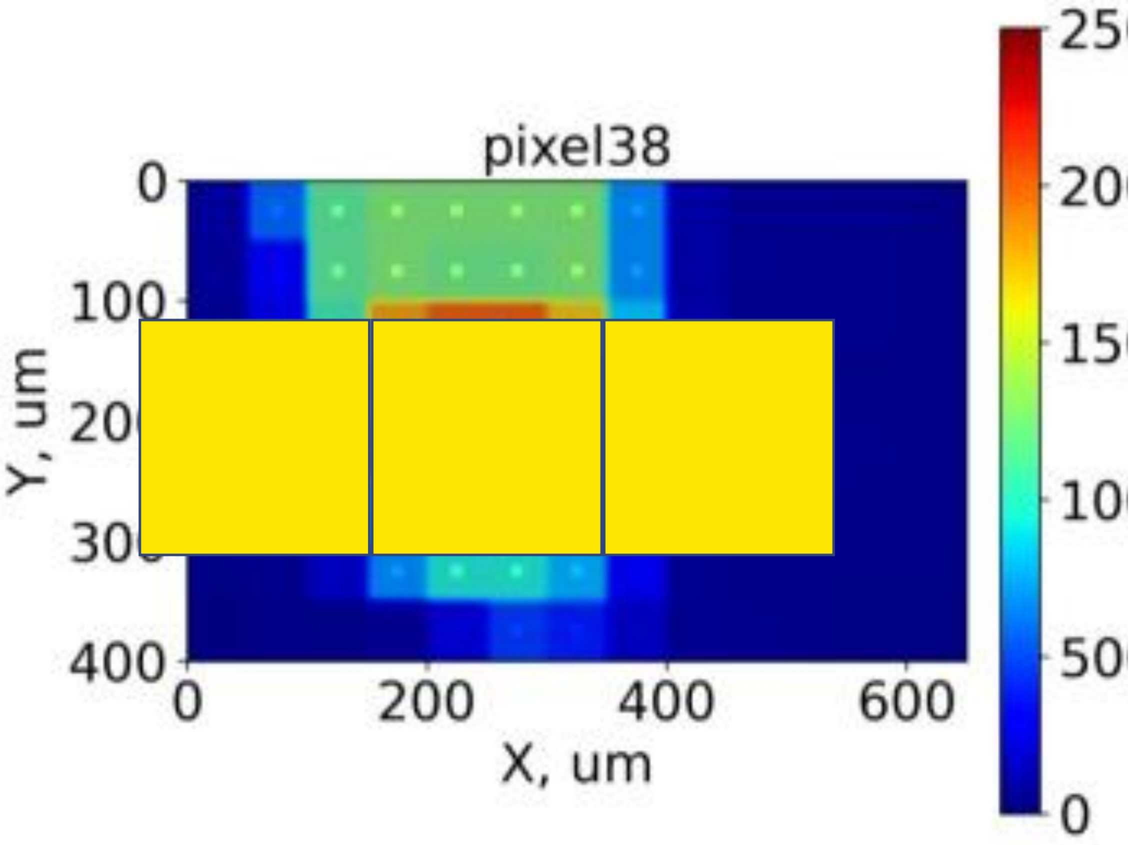

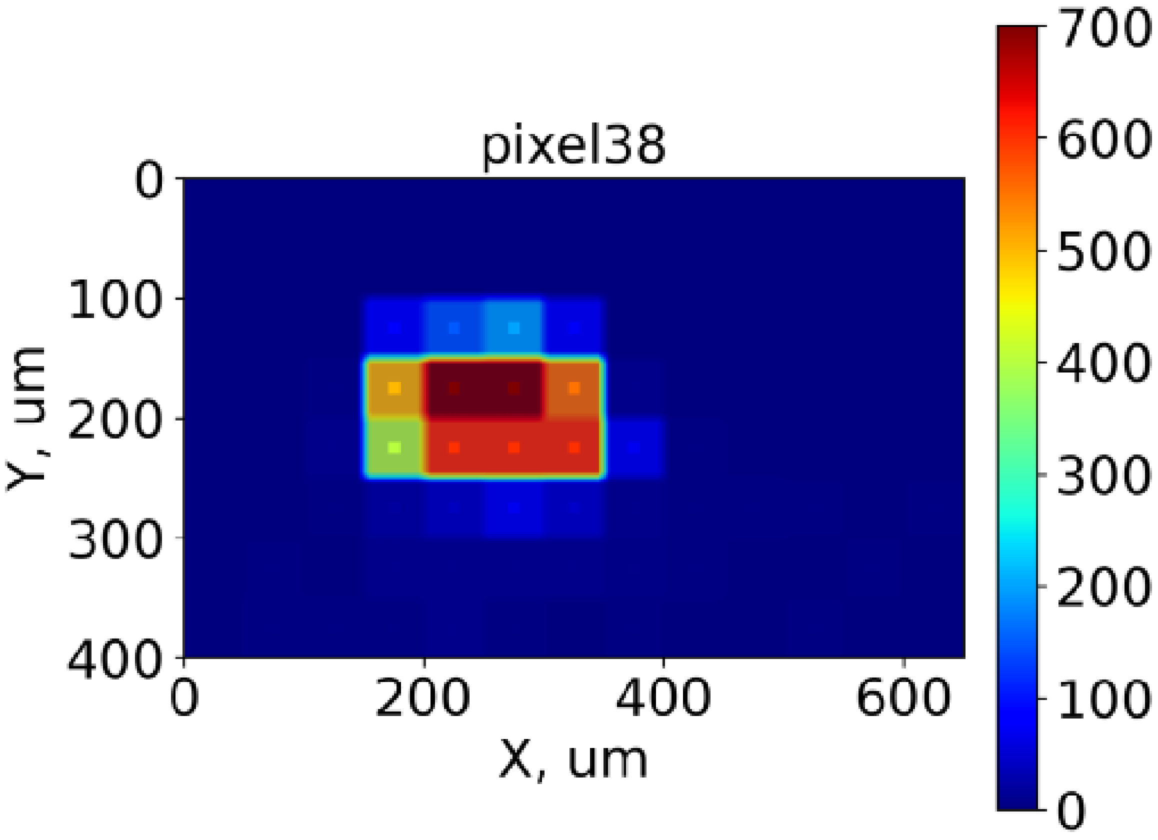

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Open tasks and issues

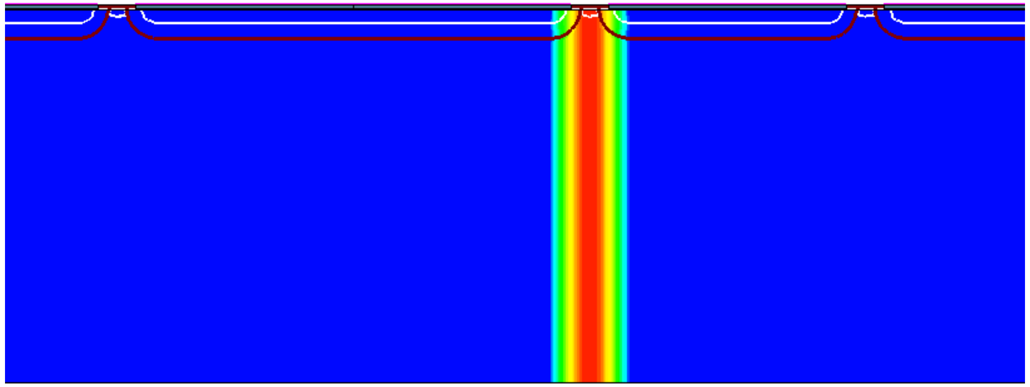
- Efficiency drop after irradiation due to inhomogeneous radiation damage
  - Noise in some pixels

    → Higher threshold needed
  - Lower amplification and less charge collection in some pixels

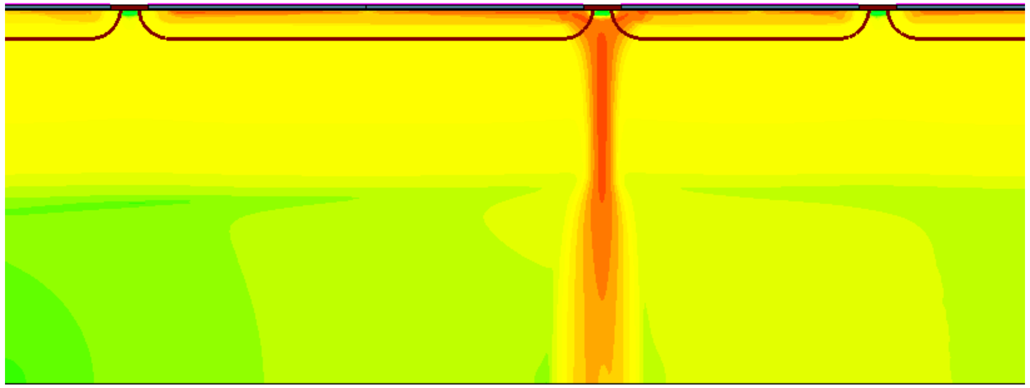
    → Lower threshold needed

Open tasks and issues

- Unclear charge collection
  - Charge collected in sensor n-well and electronics n-well



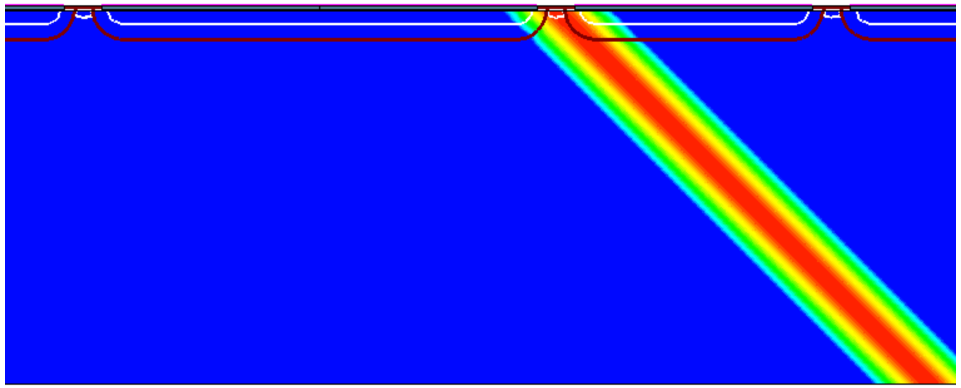
beam

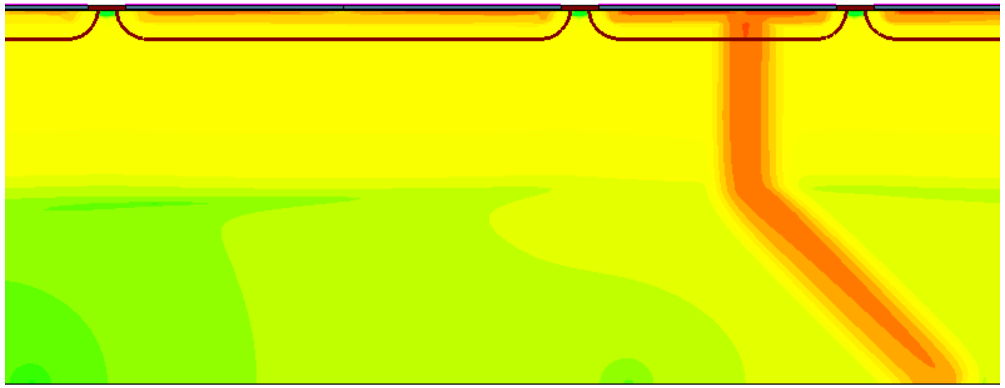


charge collection

Open tasks and issues

- Unclear charge collection
  - Charge collected in sensor n-well and electronics n-well





HitPix2b

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- 2^{nd} projection axis
→ Implemented in HitPix2b

- Hit detection efficiency loss due to amplifier baseline drop. Issue identified by micro ion beam
→ Isolation of n-wells by deep p-wells
→ Faster feedback for higher rate capability

- Efficiency drop after irradiation due to inhomogeneous irradiation damage
→ Implementation of threshold tuning

- Unclear charge collection
→ 100% fill-factor by isolation of n-wells by deep p-wells

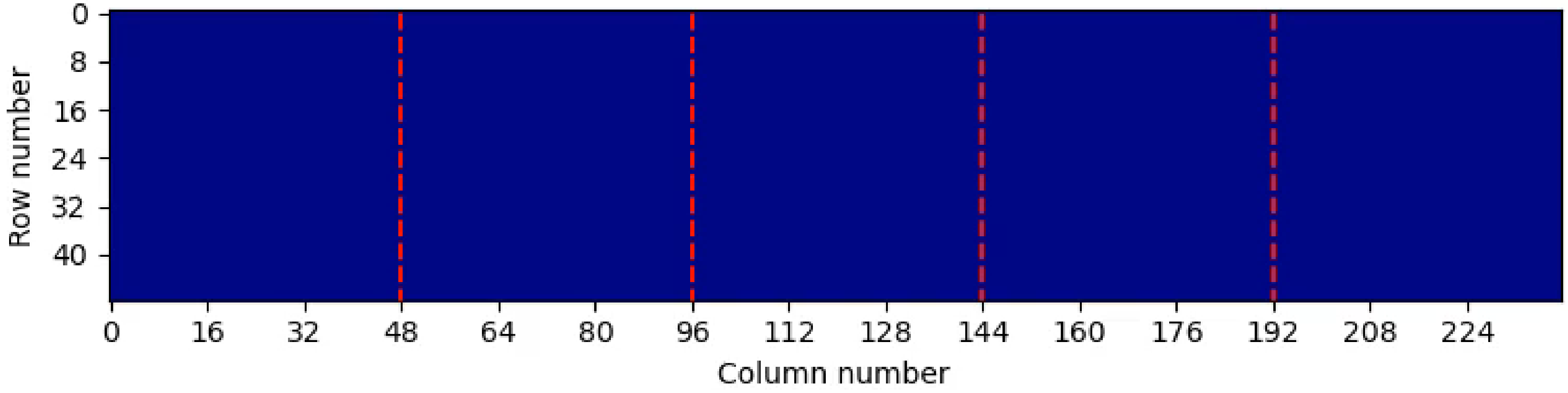
Conclusion and Outlook

- We have demonstrated the feasibility of HV-CMOS sensors as candidate for a beam monitoring system.
- Design of optimized successor HitPix2b is almost done, submission is this month.
- We have established a very good cooperation with the HIT team to develop tailored medical applications. A contract has been closed to assemble a matrix with 5 x 5 HitPix2b chips and system integration
- Publications
  - “A Beam Monitor for Ion Beam Therapy based on HV-CMOS Pixel Sensors”, in “Medical Applications of Particle Physics”, 2023
  - “Development and Characterization of High Voltage CMOS Particle Pixel Sensor with Integrating Electronics“, in NIM-A, 2022
  - „High Voltage CMOS active pixel sensor chip with counting electronics for beam monitoring”, IEEE TNS, 2022
  - A. Weber, „Development of Integrated Circuits and Smart Sensors for Particle Detection in Physics Experiments and Particle Therapy”, PhD thesis, 2021
  - F. Ehrler, “Characterization of monolithic HV-CMOS pixel sensors for particle physics experiments, PhD thesis, 2021”

Backup

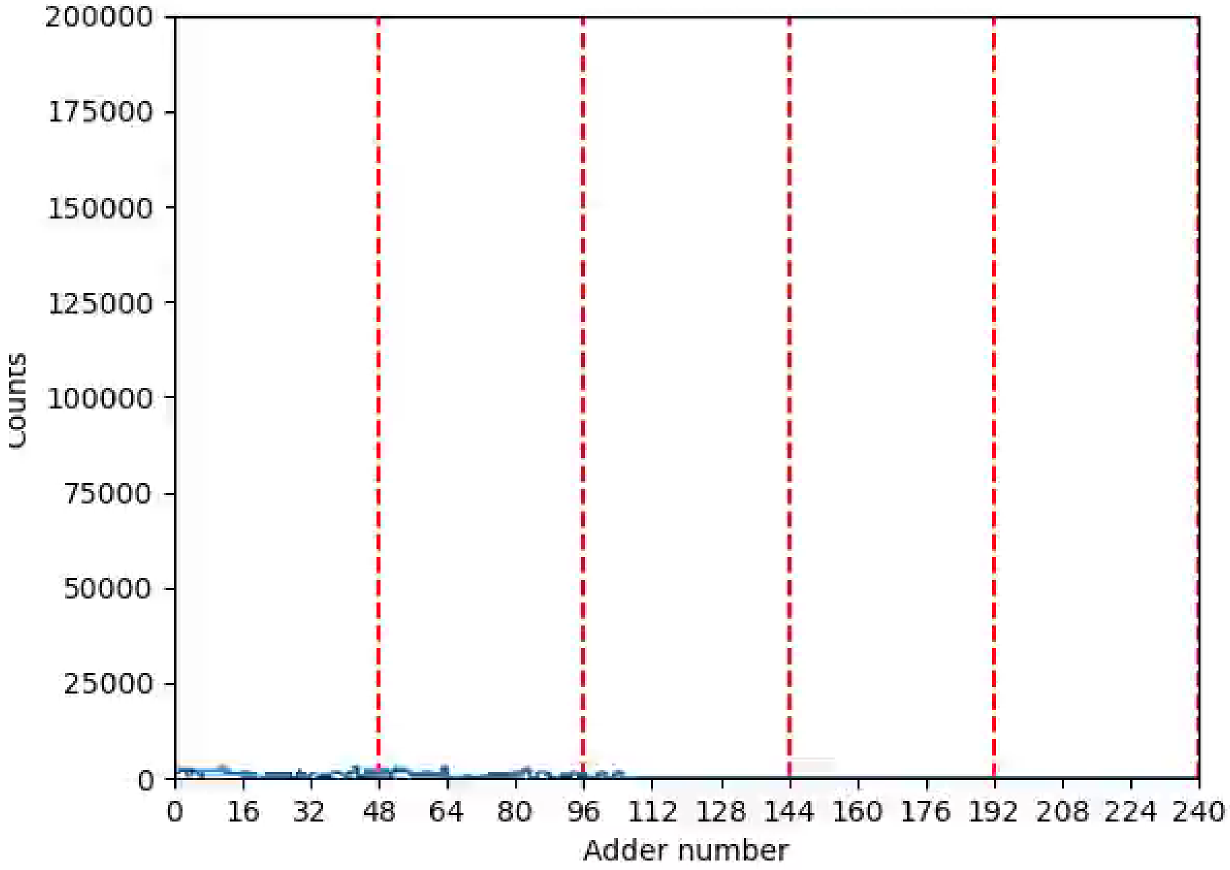
Compact MRI for field tests

Scanning the Matrix: 2D Mode



Beam settings: C, E255, I3, F1
Daisy chain readout

Scanning the Matrix: Projection Mode



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Requirements for Beam Monitor

- Light ions (proton - oxygen)
- For all beam parameters
- Beam position measurement better 200 µm
- Spot size measurement better 400 µm
- Dose measurement deviation better 0.5%
- Integration time less than 100 µs
- Additional latency less than 100 µs
- Value update every 1-2 µs
- Interlock generation in real time
- Radiation tolerant, detector in operation for 5 years (fluence: 3.5×10^{14} C/cm² and 6.5×10^{15} p/cm²)
- Size 25 x 25 cm²
- Material budget: 2 mm water equivalent for detector stack
- Detector has to tolerate light, acoustic noise and magnetic field

Sensor Design

Requirement	Design decision
Spatial/spot size resolution	200 x 200 µm² pixels
High-rate capability	In-pixel counting
Low latency	Column adder: Projection readout mode
2D beamshape	Frame readout mode
Material budget	Thinned sensors

- HitPix1 (5 x 5 mm²)
  - Hit counting electronics, 2D mode, projection mode
- HitPix2 (1 x 1 cm²)
  - Improved front-end
- HitPix_Integrating (5 x 5 mm²)
  - Charge integrating

HV-CMOS

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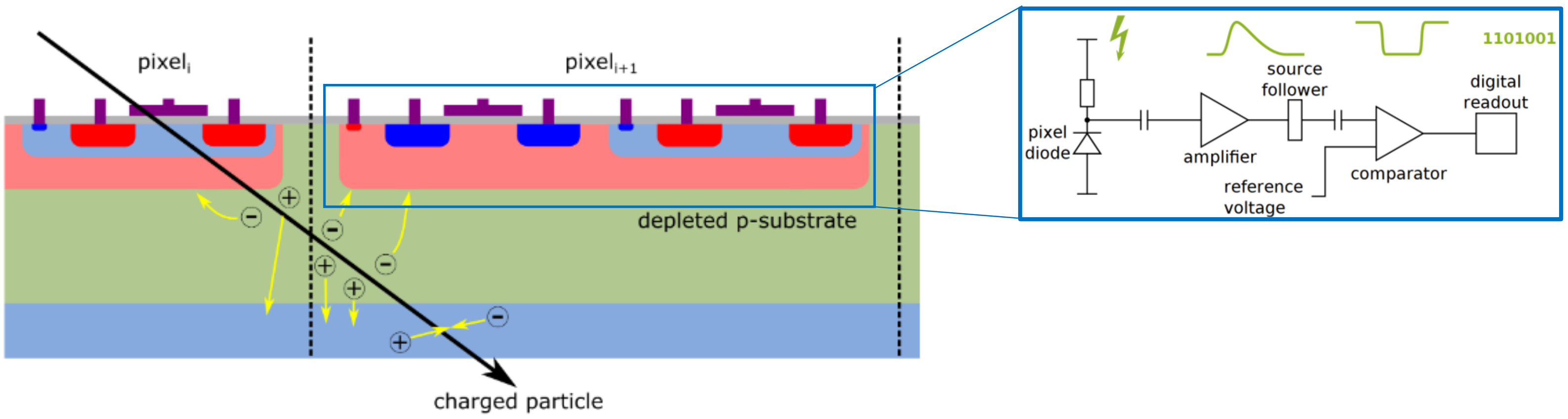
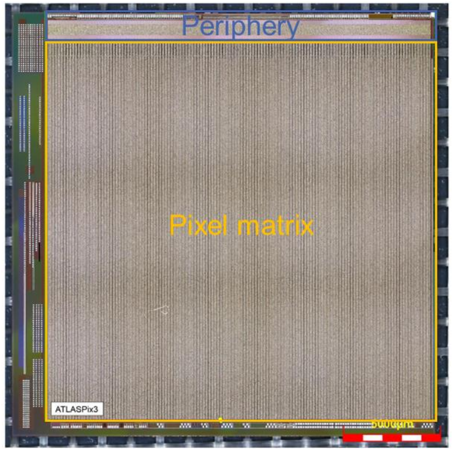
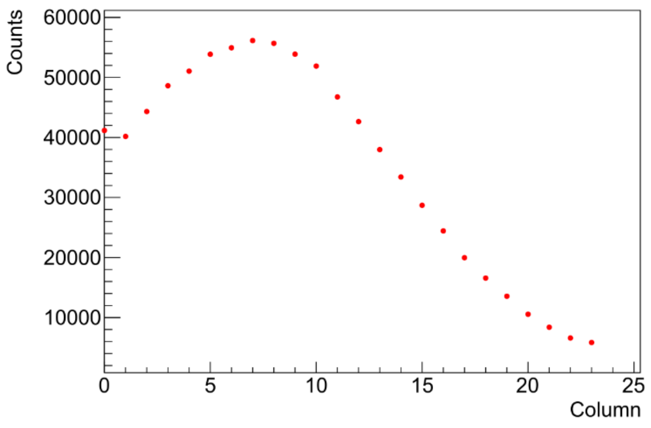
- Sensitive **sensor** and readout **electronics** in **one silicon piece**
  - basic electronics embedded in deep n-well (amplifier, shaper, comparator, counter, adder, masking,…)
- Produced in standard technology of **industrial chip producers**
  - 180nm HV-CMOS: developed for automotive industry
  - small pixel sizes: <50x50µm² possible (we will envisage 200x200µm²)
  - thin substrates: down to ~50µm possible (~150µm mechanically reasonable (~300µm water equivalent))
- Signals generated in depletion region below electronics island
  - additional applied high voltage (HV <100V) accelerates charge collection by drift → radiation harder and faster
- Existing chips have been tested in the particle beams at HIT to examine signal size and radiation hardness

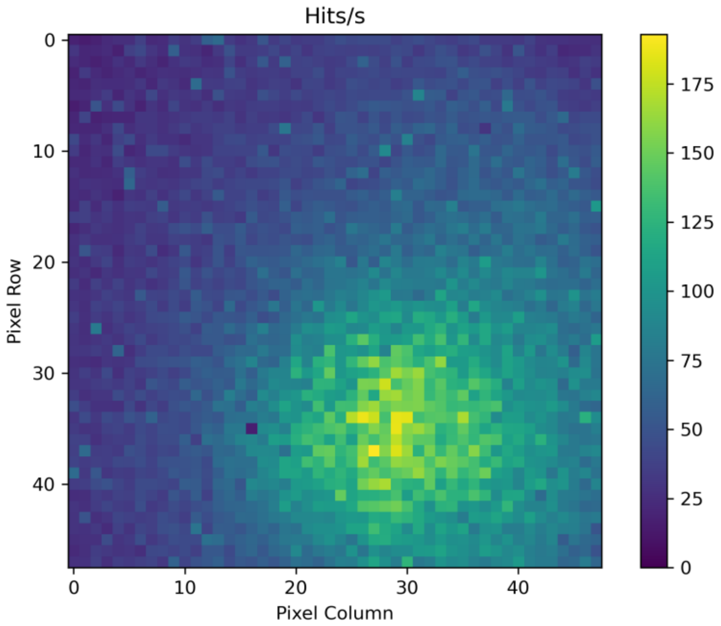




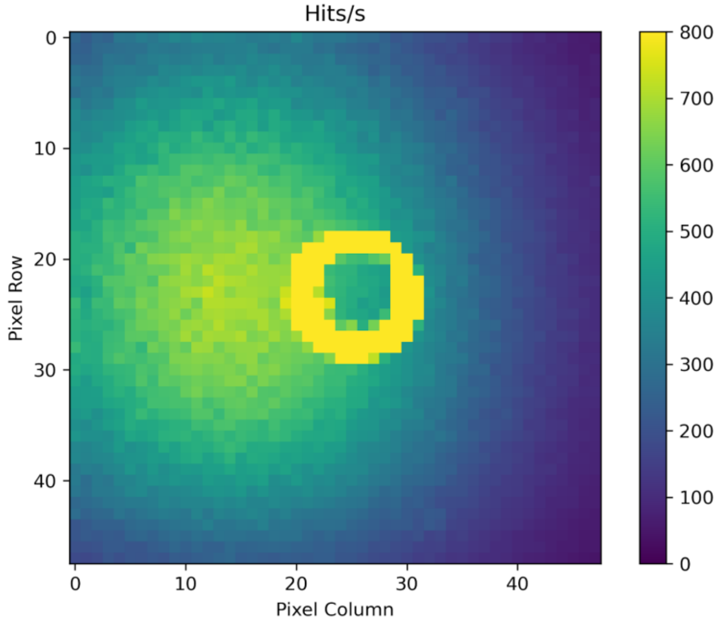
Some results



HitPix1 C12 beam projection



HitPix2 C12 beam spot



HitPix2 irradiation study:
- area inside ring is irradiated (1/2 annual dose)
- area outside ring is not irradiated

Fast and easy algorithm for FPGA implementation

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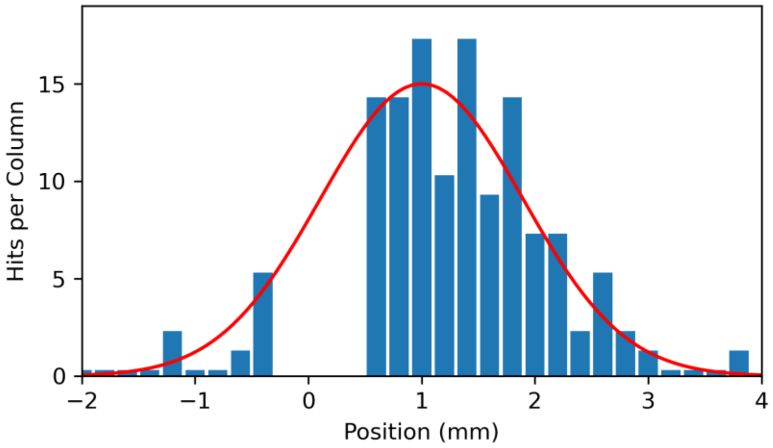
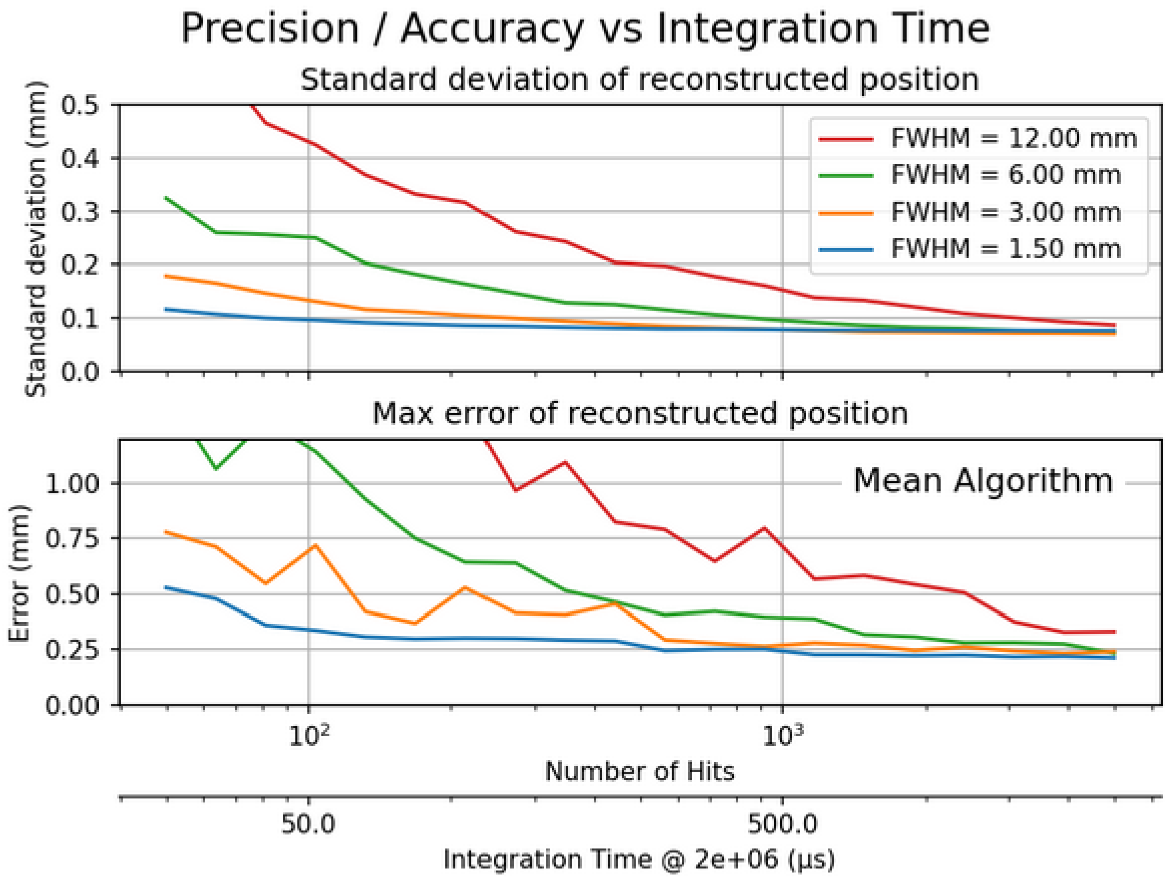
- Weighted mean
  - robust and precise
- Can be calculated while data is read out
  - very fast, minor delay





GEANT Simulation: material impact

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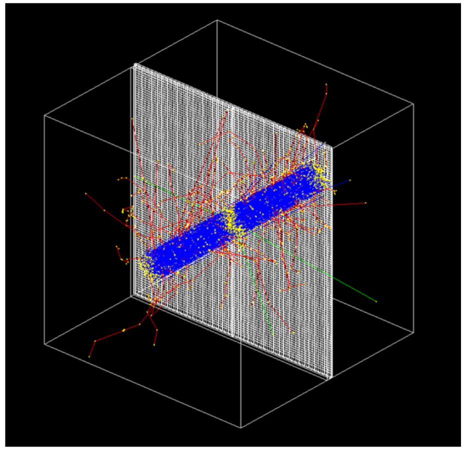
Simulated Geometry

simulate effect of detector stackup on beam deflection and energy degradation

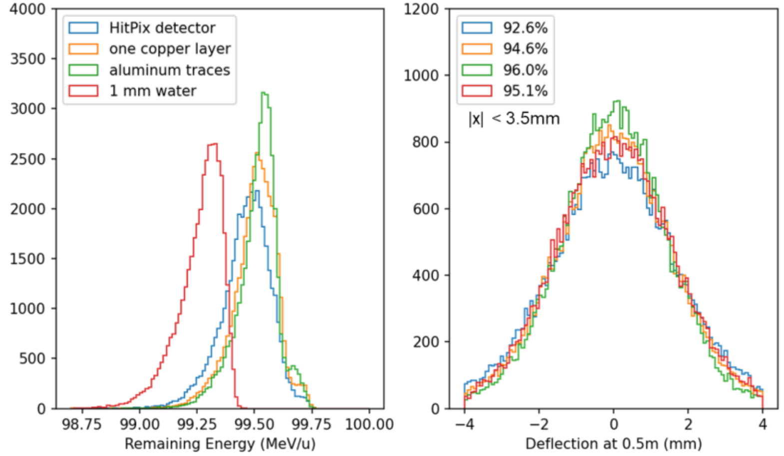
Stackup:

- backplate (200µm CFRP)
- sensor (100µm Si, with 100µm gap)
- PCB traces (18µm Cu, 50% fill)
- PCB substrate (91µm Kapton)
- PCB traces (18µm Cu, 50% fill)



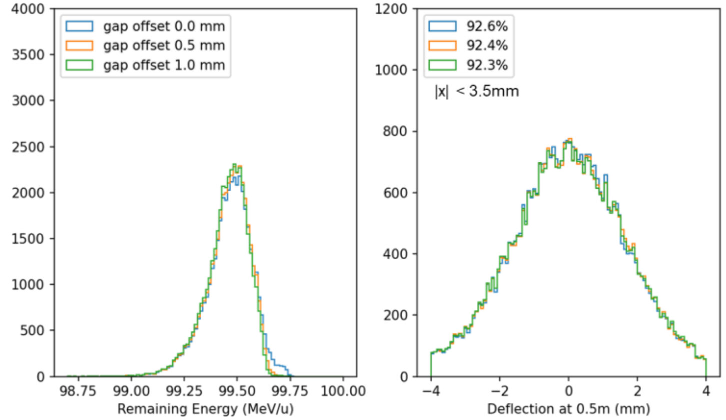
Beam: 1mm FWHM, 100MeV protons

GEANT4 Simulations - Different Stackups



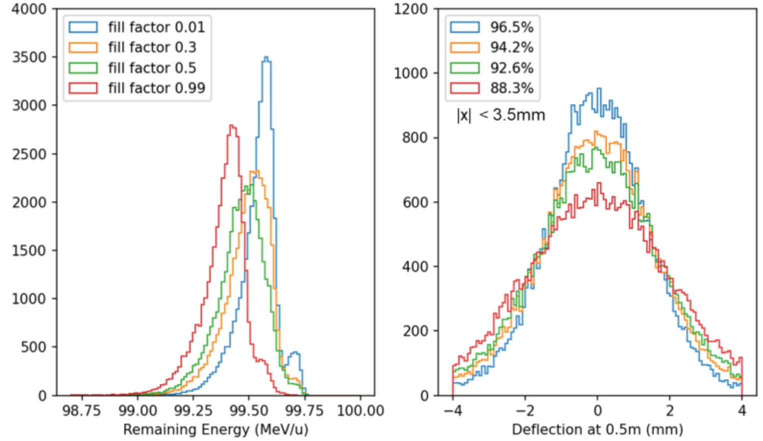
→ copper in PCB traces introduces a lot of deflection

GEANT4 Simulations - Gaps



→ small gaps between chips have little effect

GEANT4 Simulations - PCB fill factor



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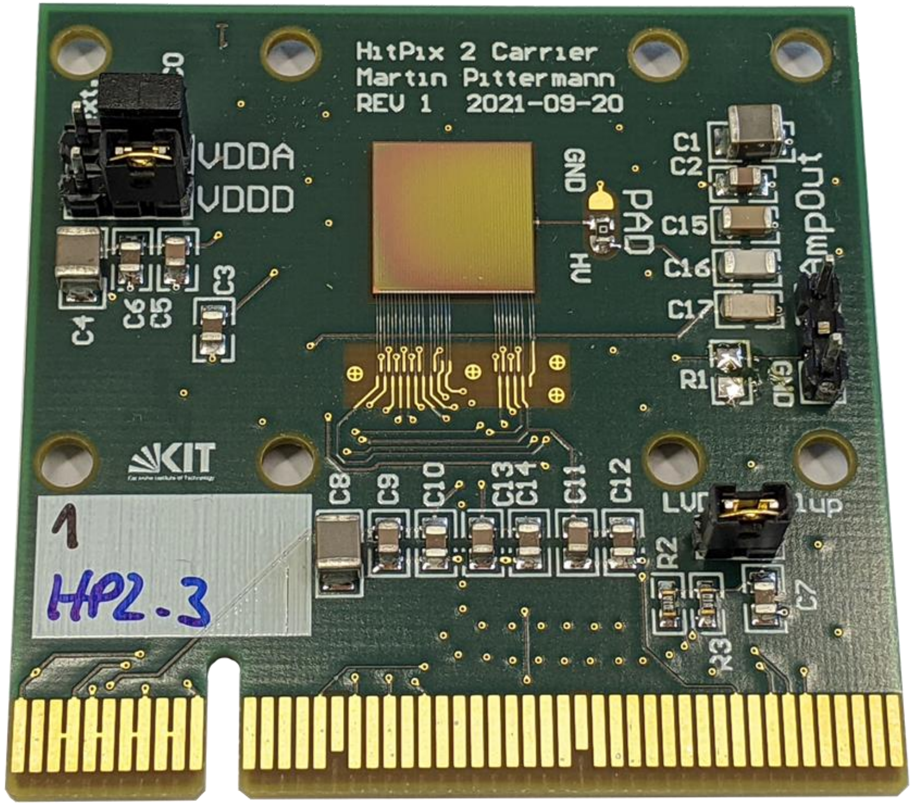
Single HitPix2 Carrier



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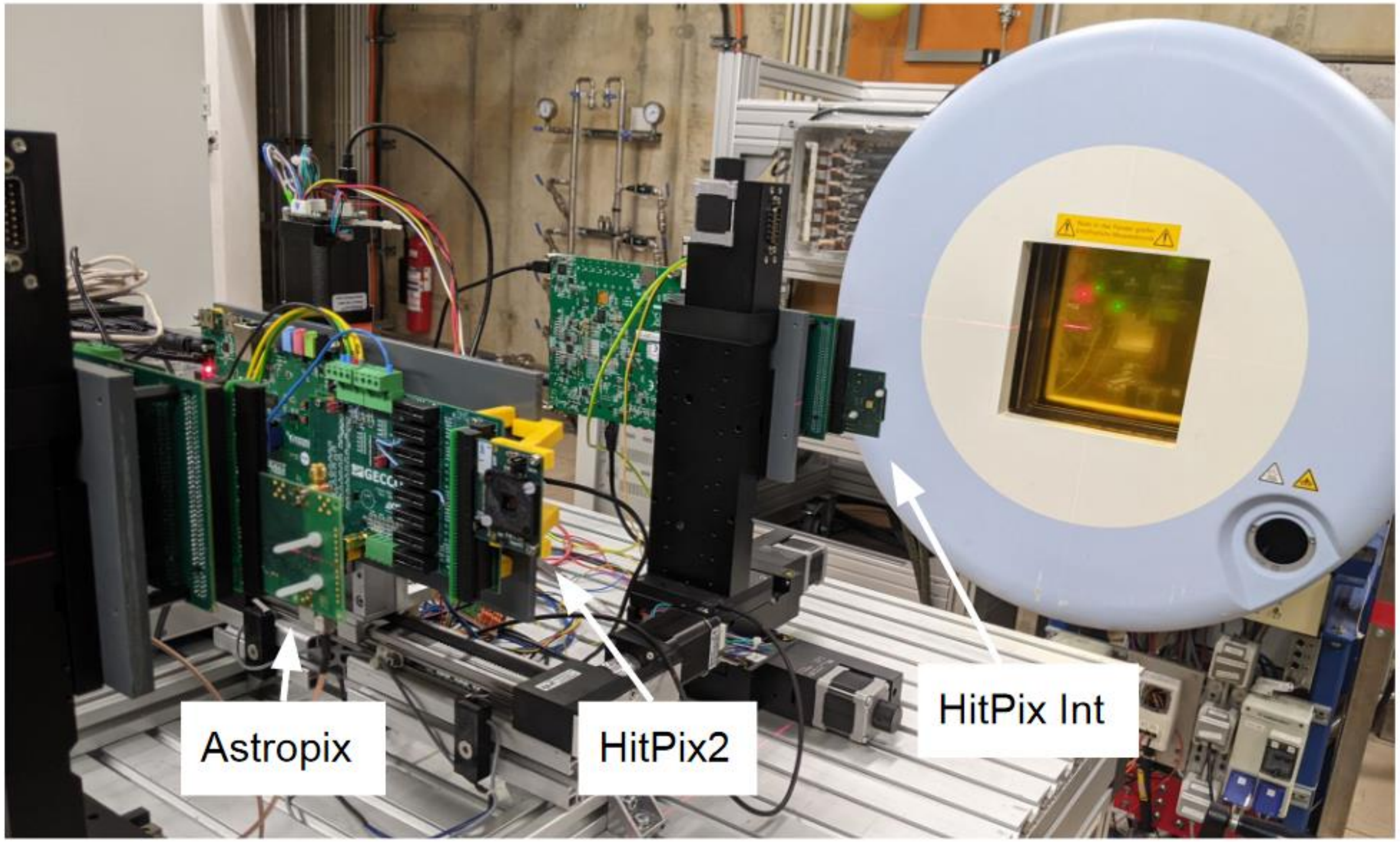
Test system

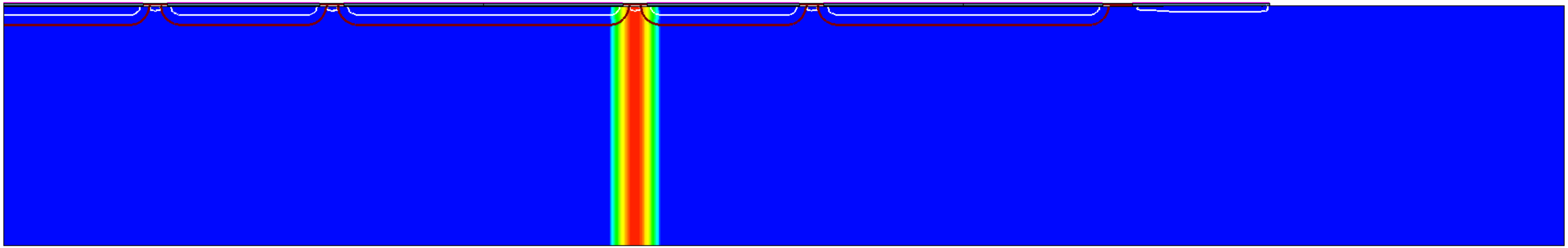
Artix-7 FPGA
(custom firmware)

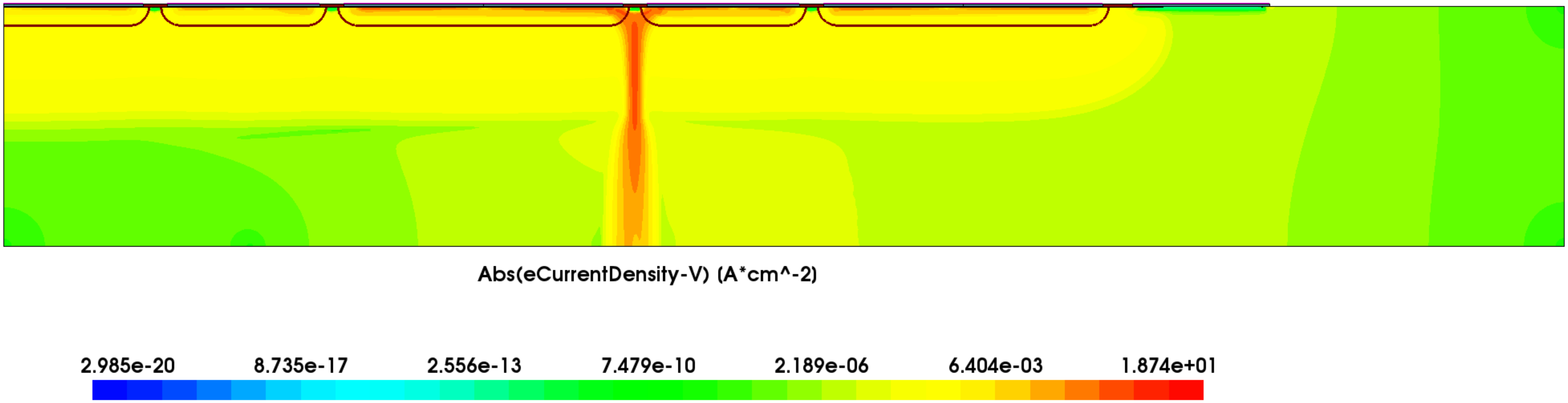
GECCO adapter board
(developed at IPE)

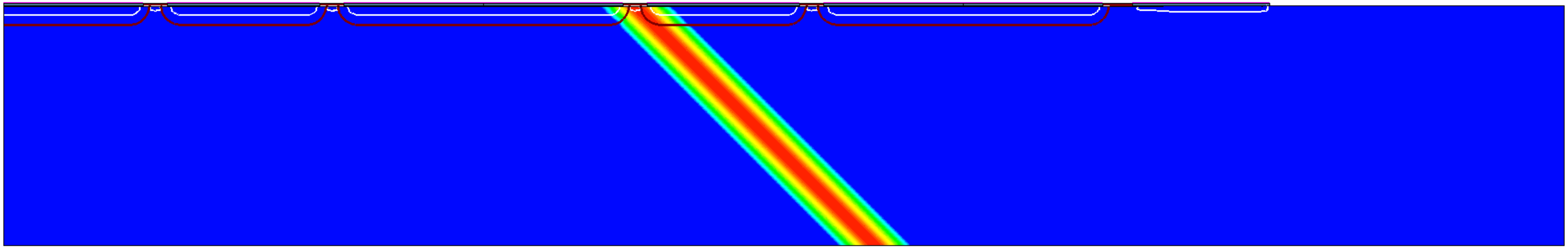
HitPix 2
Carrier PCB

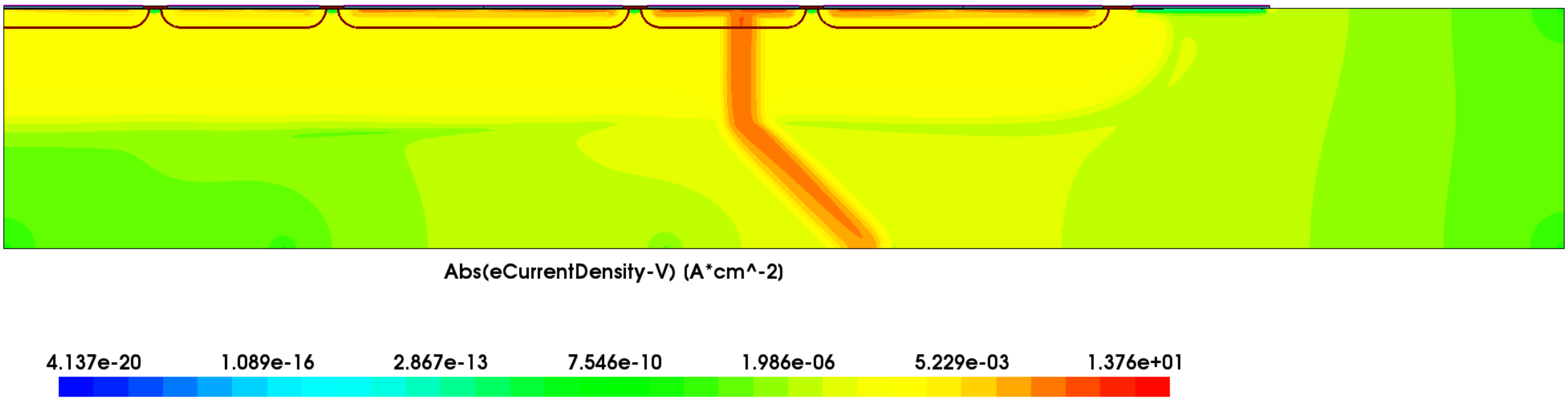
Beam Test Setup






Abs(eCurrentDensity-V) (A*cm^-2)
2.985e-20
8.735e-17
2.556e-13
7.479e-10
2.189e-06
6.404e-03
1.874e+01




Abs(eCurrentDensity-V) (A*cm^-2)
4.137e-20
1.089e-16
2.867e-13
7.546e-10
1.986e-06
5.229e-03
1.376e+01