ANP-Seminar

Developing high resolution Time Projection Chambers

–

a GEM and TimePix approach

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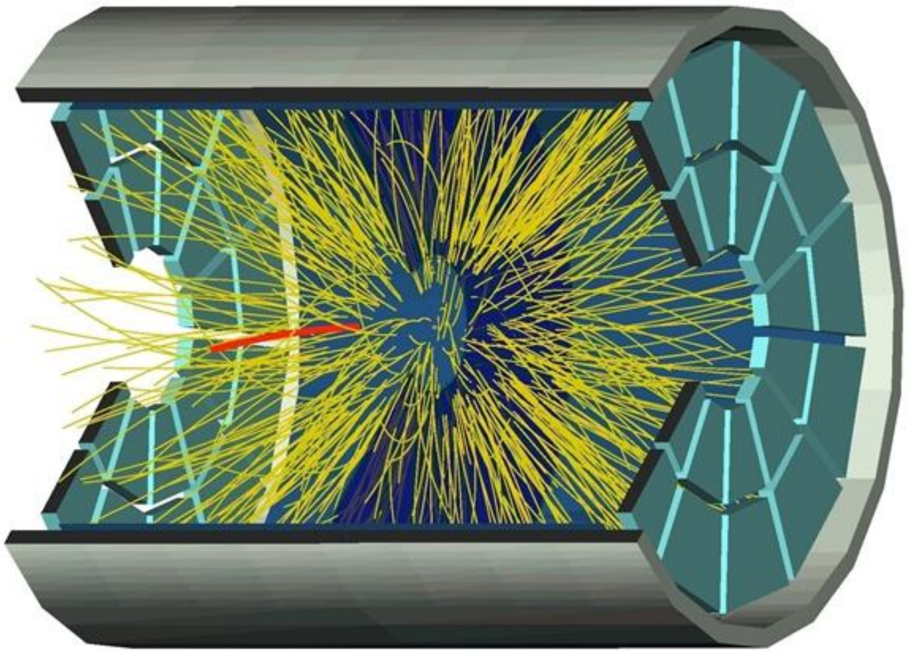
Albert-Ludwigs-Universität
Freiburg i. Br.

Supported by

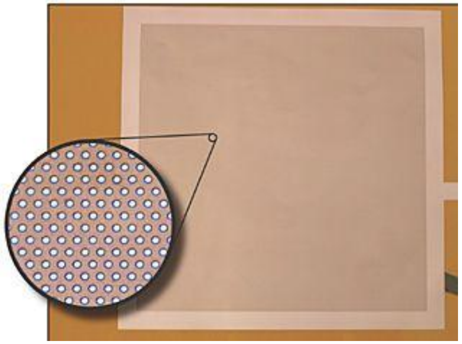
Outlook

Time Projection Chamber



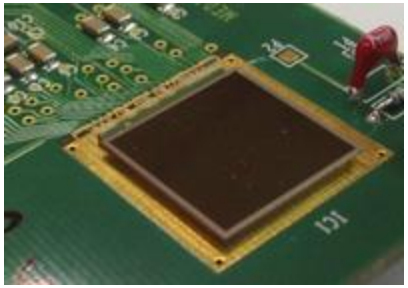
[1]

Gas Electron Multiplier



[2]

TimePix



[3]

Primary Ionization ⟶ **Charge Multiplication** ⟶ **Readout**

[1] STAR TPC http://www.star.bnl.gov/public/tpc/tpc.html
[2] Tech-Etch: http://www.tech-etch.com/flex/images/Gem-Foil.jpg
[3] IEAF: http://aladdin.utef.cvut.cz/ofat/others/Timepix

Contents

Concepts

- TPC
- GEM
- TimePix

Part I

Diploma thesis

- Construction of the test chamber

Part II

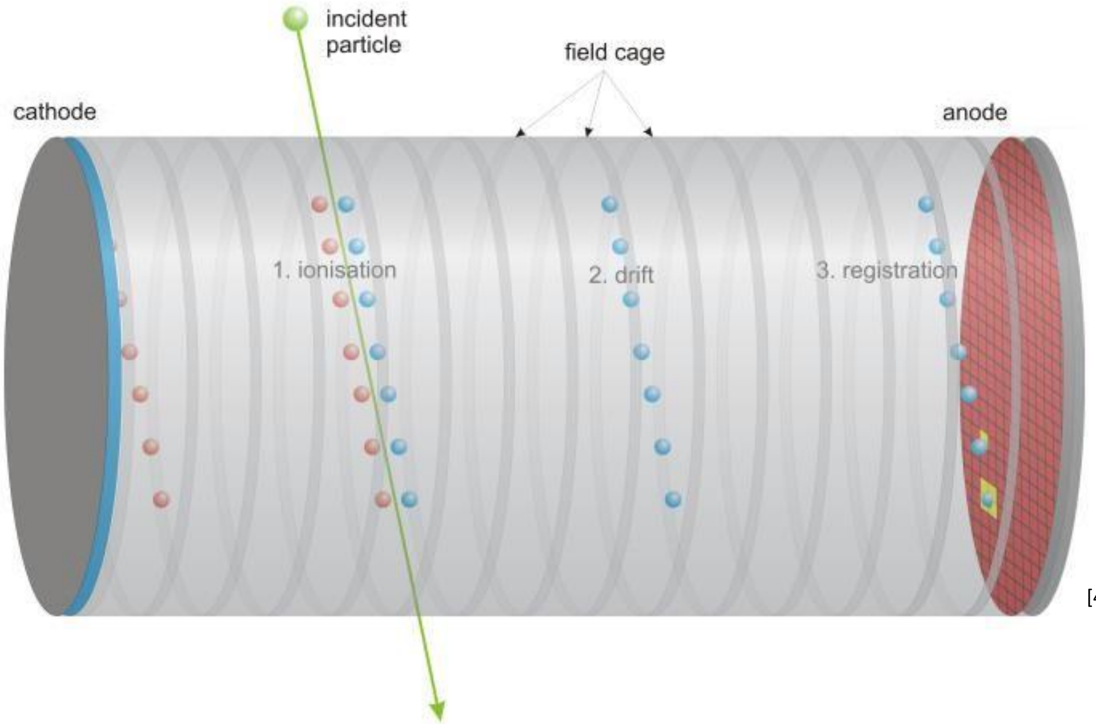
- Calibration of TimePix chips
- Studies on pixel enlargement

Part III

Part I

Technologies
&
concepts

Time Projection Chambers



[4]

1. **Charged particles ionize gas**
2. **Primary charge drifts along the electric field E towards the end plates**

   Magnetic field parallel to E reduces transverse diffusion and allows measurement of the particle momentum

   Positive Ions distort drift field

3. **At the end plate the primary electrons are multiplied**

Readout of the signal

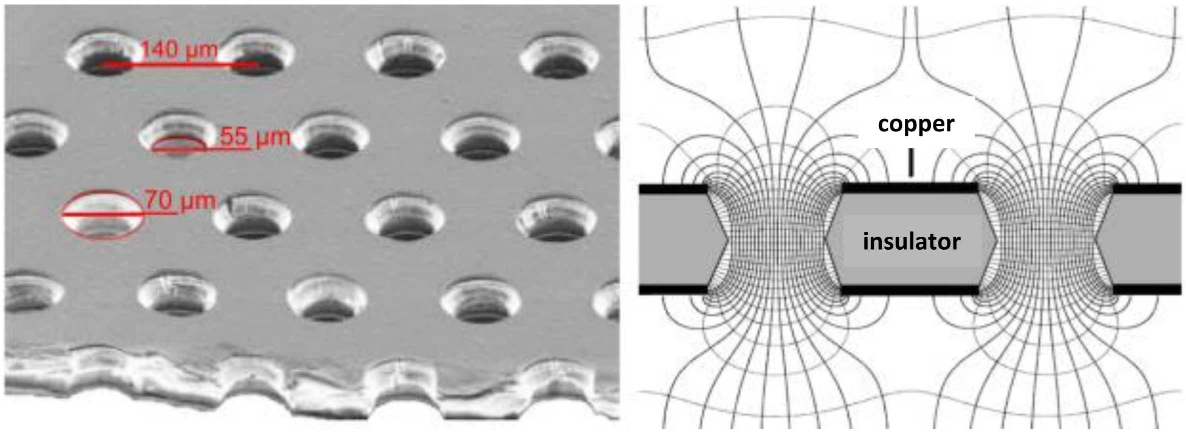
- **Projected track (2D plane)**
- **Time (spacial depth)**

[4] LCTPC group: http://www.lctpc.org/e8/e57671/

Gas Electron Multipliers

Principle

charge multiplication in strong electric fields within holes



[5]

Geometry

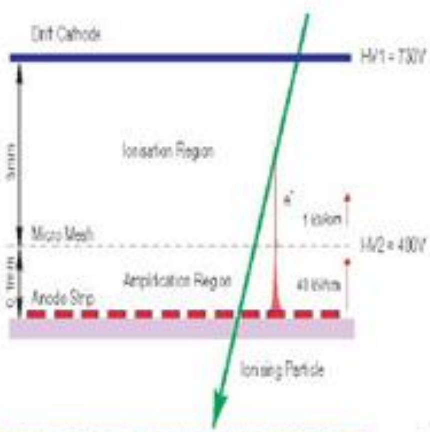
- **50 µm thick foil made of Kapton (insulator) coated with copper**
- **conical etched holes with 55 µm diameter**

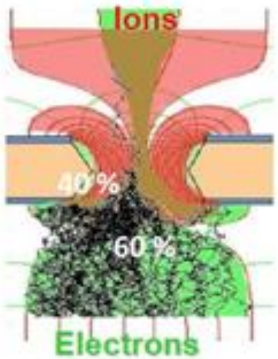
Features

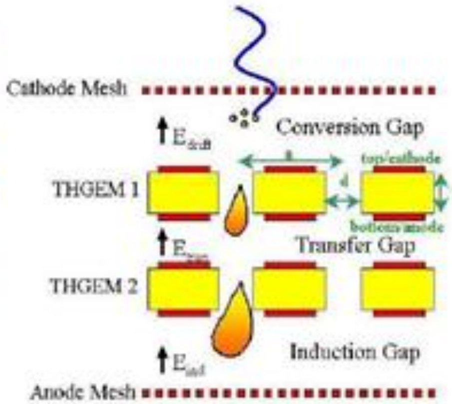
- **fields in holes (60-80) kV/cm**
- **effective gas gain O(100)**
- **multiple GEM layers necessary for high gain**
- **positive ion backdrift to drift volume minimal**

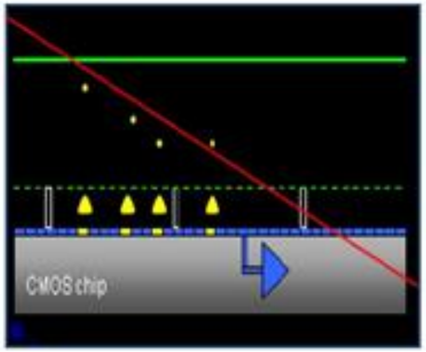
[5] Sauli, F. ; Sharma, A.: *Micropattern Gaseous Detectors*. In: Annual Review of Nuclear and Particle Science 49 (1999)

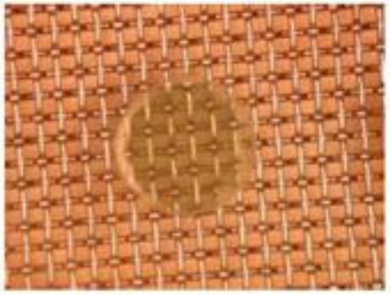
Alternative technologies:



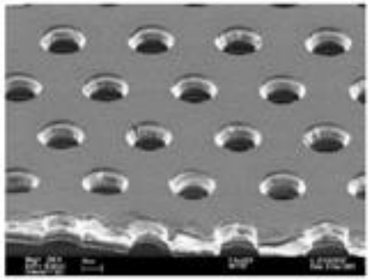




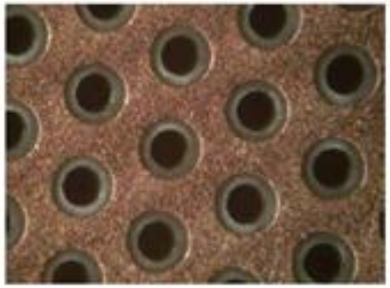




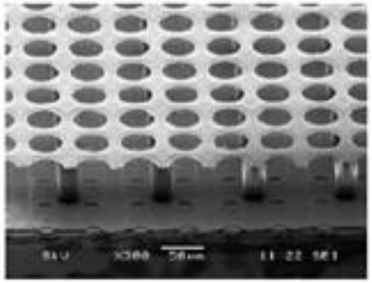
Micromegas



GEM



THGEM



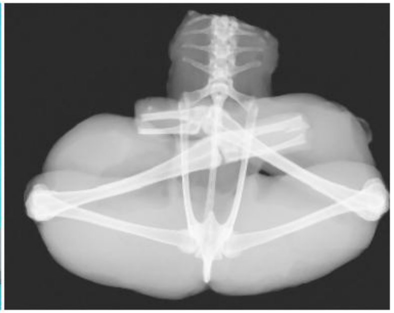
[6]

Ingrid

[6] Ropelewski, L.: RD51 2009 meeting summary

MediPix Applications

X-Ray imaging



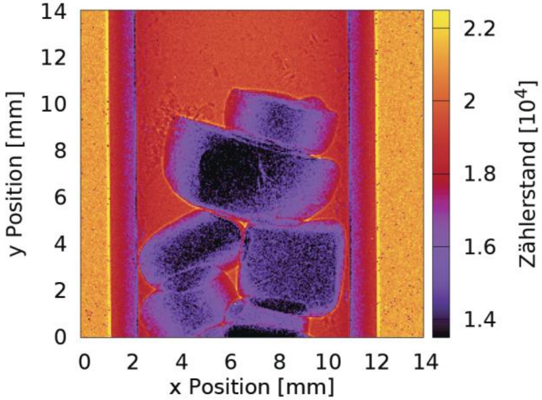
[3]

(photography)

X-Ray 25 kV, 300 µm Si sensor

Picture: frog legs

phase contrast imaging

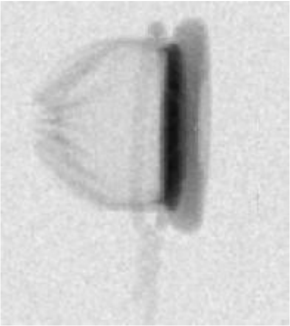


[8]

X-Ray 60 kV, 300 µm Si sensor

Picture: NaCl crystal in glas tube

Neutron tomography



[9]

(photography)

Picture: cartridge

‚standard' X-Ray

cold neutron beam,
300 µm Si + ≈80 µm LiF sensor

[8] Bartl, P.; *Phasenkontrast-Bildgebung mit photonenzählenden Detektoren*, University of Erlangen-Nürnberg, 2010
[9] Jakubek, J. et al.; *High Resolution Neutron Tomography with MEDIPIX-2*, Czech Technical University, Prague, 2004

MediPix family

Concept:

Hybrid-Detector – readout electronics and sensor are separated

MediPix 1

[10]

1997

- active area 1,2 cm²
- matrix of **64 x 64 pixels**
- 1,6 M transistors/chip
- **170 x 170 µm² per pixel**

- 1 discriminator per pixel
- 15-bit counter
- threshold (whole chip): ≈ 1500 e⁻

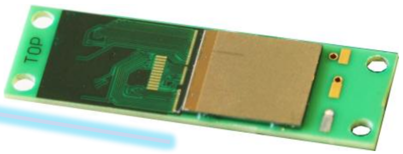
MediPix 2

2001

- 1,4 x 1,4 cm²
- matrix of **256 x 256 pixels**
- 0.25 µm CMOS technology (33M transistors/chip)
- **55 x 55 µm² per pixel**

- serial or parallel I/O (min. readout time of full matrix 266 µs)
- preamplifier/shaper (t_{rise} ≈ 150 ns)
- 2 discriminators (lower and upper threshold)
- 14-bit counter
- threshold (whole chip): ≈ 1000 e⁻

TimePix



2006

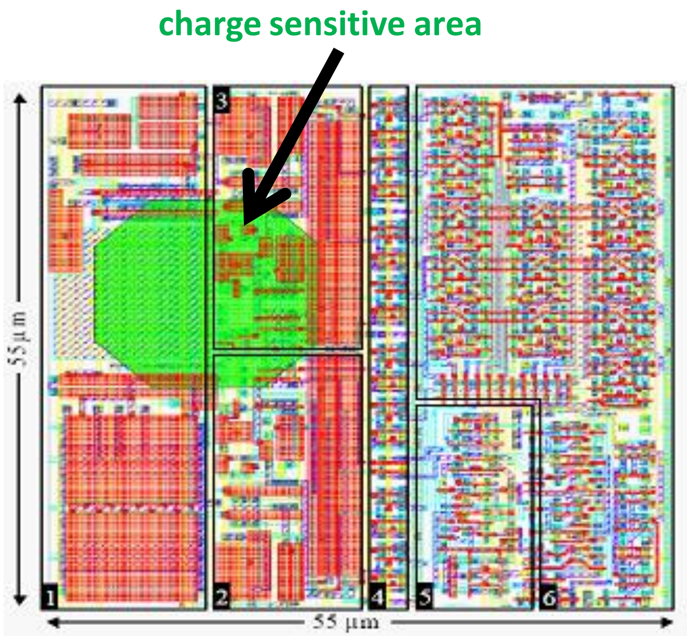
[10] http://medipix.web.cern.ch/medipix/pages/images.php

The TimePix chip

Motivation: **A modified MediPix 2 chip for TPC applications**

knowing the time of arrival of avalanches at pixels

→ **use 14bit counter not for counting the #hits, but for counting clock cycles**



[11]

TimePix single pixel with active area (green)

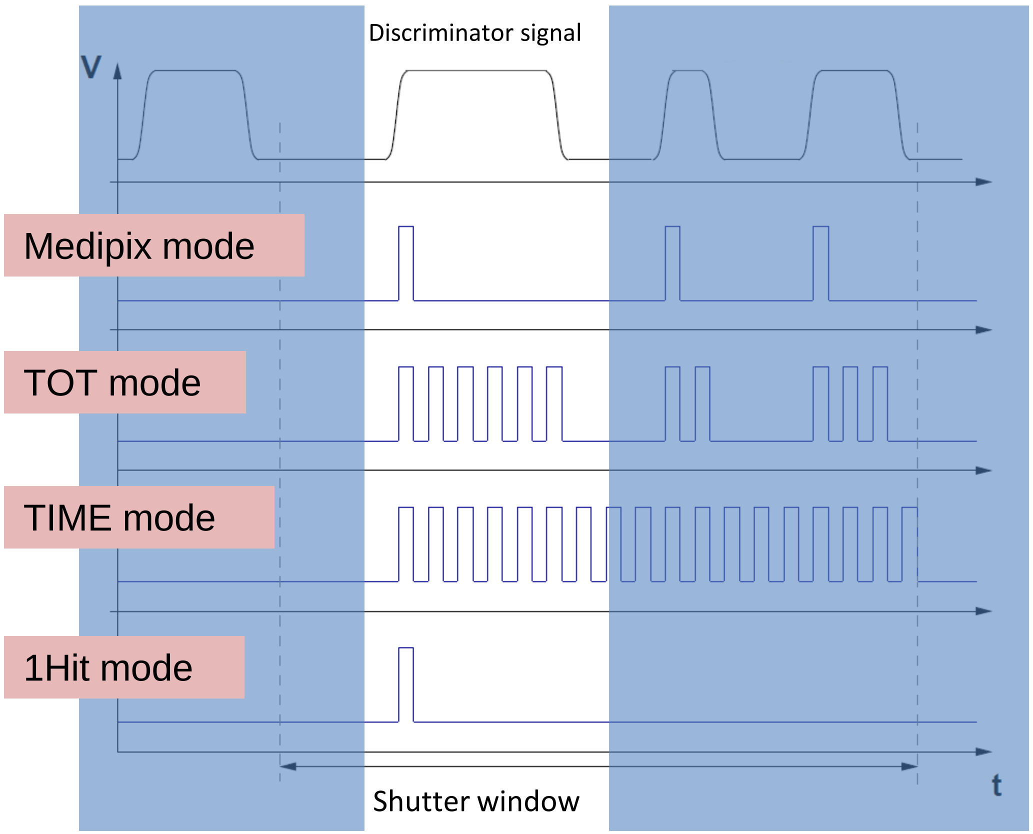
- (only lower threshold)
- clock up to 100 MHz in each pixel
- threshold (whole chip): ≈ 700 e^-
- 4 different modes possible

modes definable for every pixel using a "*map*"

[11] Llopart, X.: *TimePix Manual v1.0,* CERN: MediPix2 Collaboration, August 2006

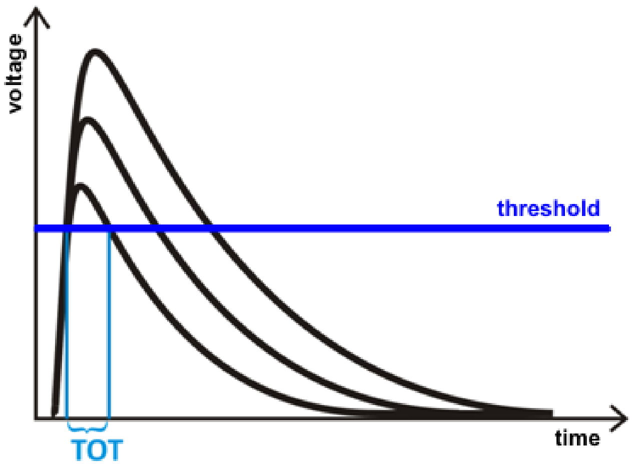
The TimePix modes

Pixel operating modes



[12]

TPC-Setup:
- use Time-arrival mode
- use TOT for calculating charge

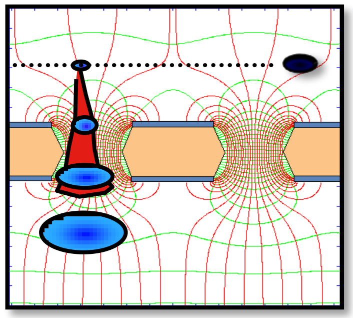


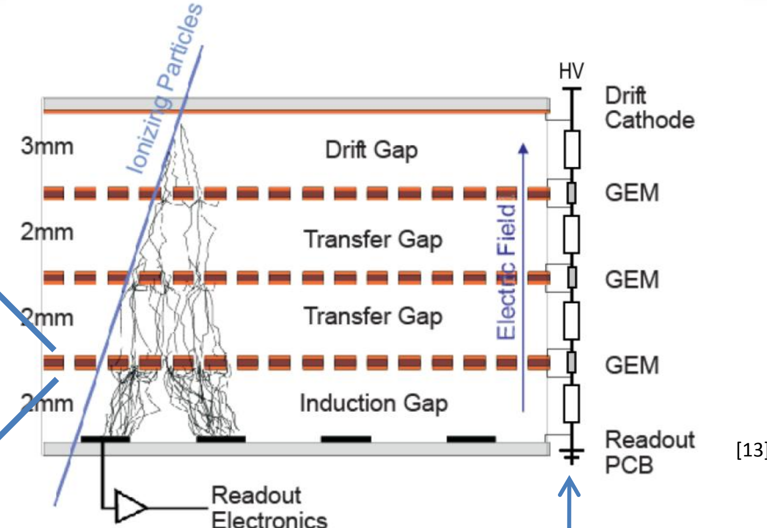
signal shape of charge deposition of a pixel

[12] Ummenhofer, M.: *Inbetriebnahme einer Zeitprojektionskammer mit Pixel-Auslese,* University of Bonn, Diploma thesis, 2008

GEM + TimePix

3-GEM setup





resistive voltage devider:
same potential difference (**ΔV_{GEM}**) per GEM

- **Triple-GEM-Setup: Gas gain up to 10^5 in $ArCO_2$**
  - Necessary as **charge is spread over *several pixels***
  - **few e^- per channel (strong diffusion effects within the GEM-stack)**

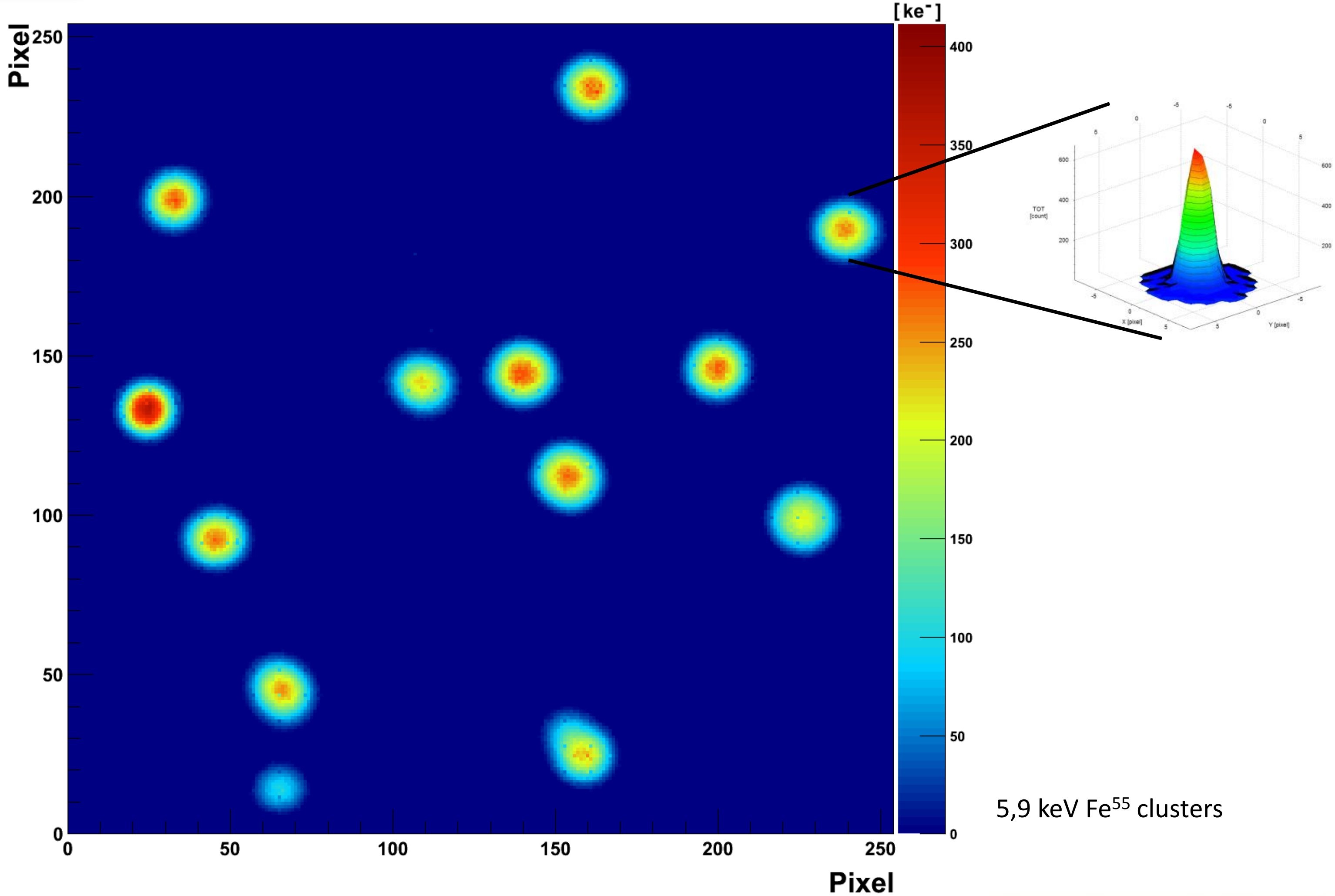
Consequences → **high gas gain necessary for detection of *minimal ionizing particles***

→ **large number of positive ions created**

[13] Modified from http://gdd.web.cern.ch/GDD/compass.html

Illustrating clusters

Event display

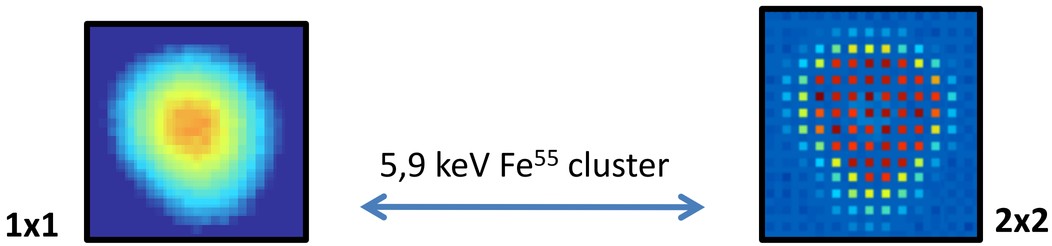


5,9 keV Fe^{55} clusters

Pixel geometries

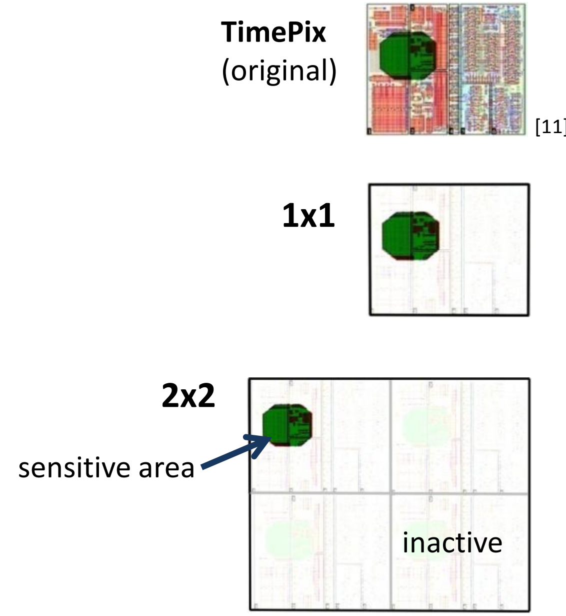
Motivation: enlarged pixels

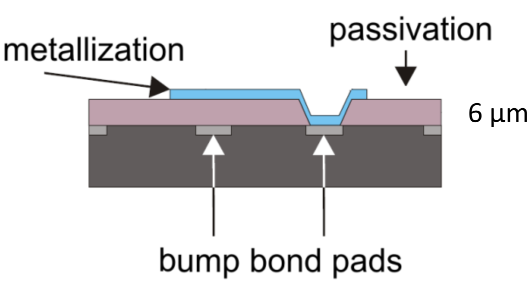
- **more charge per pixel**
  ⟶ higher probability of detection
- **less gas amplification needed ⟶ fewer positive Ions**
- **optimization of spatial resolution vs. pixel size**



Postprocessed chips (Bonn, IZM)

- **1x1:** metalliziation extended from
  ≈20x20 μm² to ≈50x50 μm²
- **2x2:** 3 of 4 pixels passivated, then metallized
  pixel size 105x105 μm²
- **$\overline{\text{2x2}}$:** according to 2x2, *no pixel connected*
- **3x3**: according to 2x2





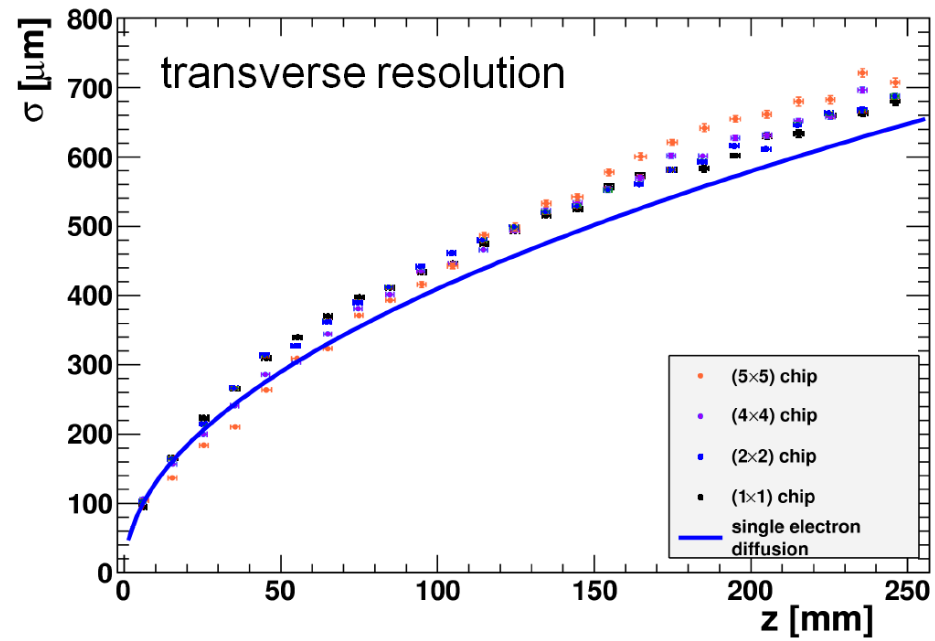
profile - postprocessed pixel

Tracks in small TPC prototype

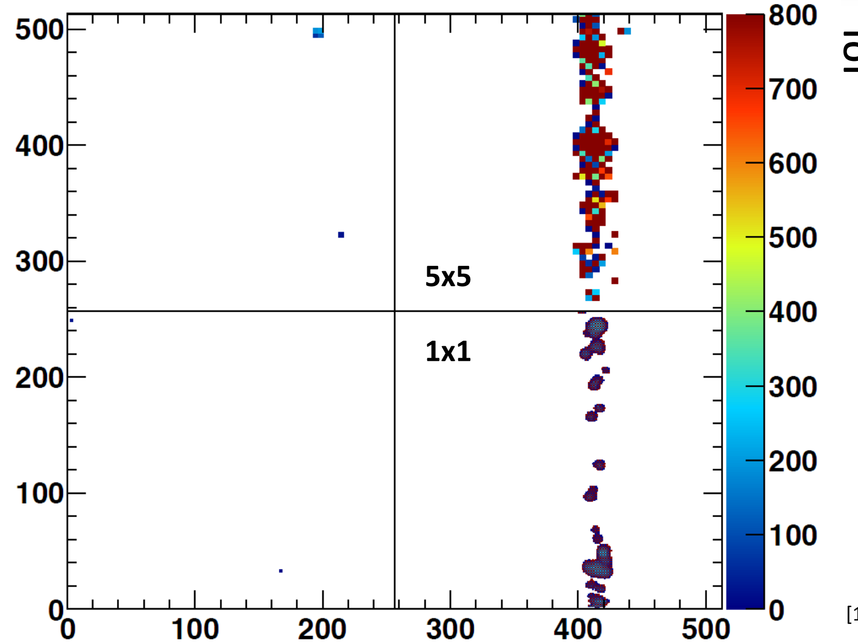
tracks recorded on Quad-chip board

universitätbonn

Charge spreading (Myons 150 GeV)



[14]



[14]

Chip	σ_0 [μm]	D_t [μm/√cm]
(1x1)	(56.4 ± 0.1)	(138.264 ± 0.005)
(2x2)	(55 ± 1)	(139.0 ± 2)
(4x4)	(68 ± 13)	(140.0 ± 0.5)
(5x5)	(75 ± 9)	(146.4 ± 0.6)

only statistical errors

[14] Schultens, M.; *Teststrahlmessungen mit hochgranularer Auslese einer Zeitprojektionskammer bei verschiedenen Pixelgrößen*, Diploma thesis, University of Bonn, 2010

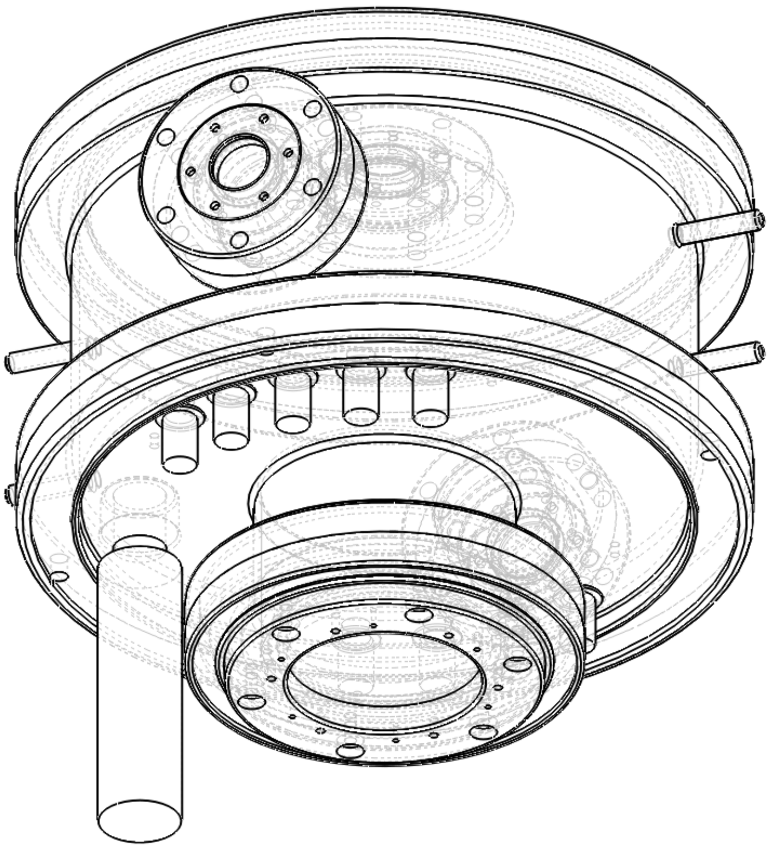
Part II

Construction of the test chamber

System requirements

Goals

- modular construction
- non magnetic materials
- gas-tight (several gases)
- DAQ for
  temperature and pressure



Devices:

- GEM (12x12 cm^2) incl.
  - high voltage, 8 potentials
  - variable position (height)
- TimePix
  - simple exchange of chips

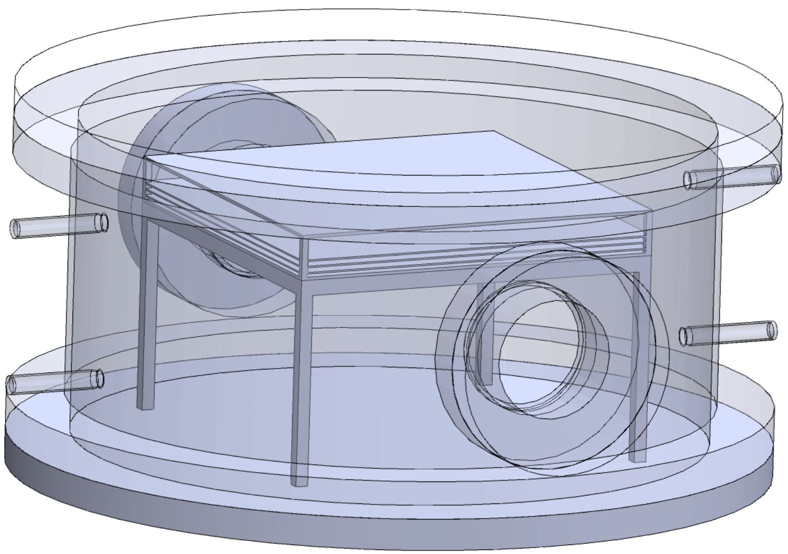
Experiments with:

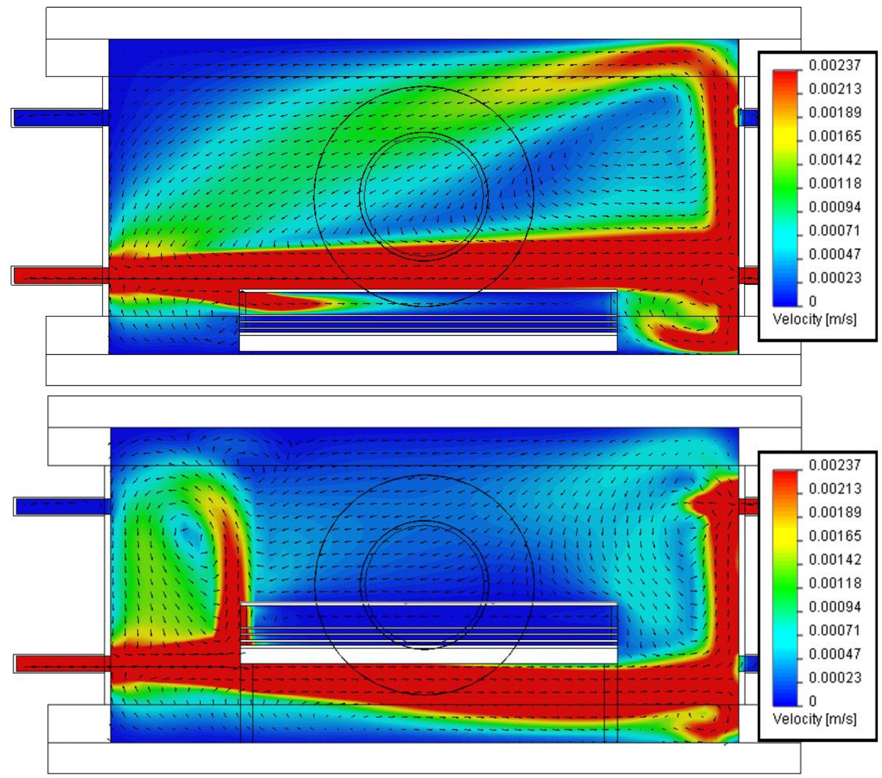
- N_2-laser (UV)
- testbeam
- radioactive source

Simulation of the gas flow

Determine
- placement of gas in- & outlets
- quality of gas flow
- pressure variations

Procedure
- use reduced model geometry
- start with detailed computational mesh
  (high computing time)
- reduce number of mesh points
  as long as results not differ





Of materials and sensors

Materials

Structure
all non magnetic, non corrosive

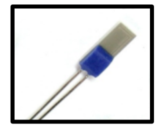
Stainless steel
- **316L** (weldable)
- **304L** (cheaper)

Aluminim- & brass-alloys (lath work)

Seals
EPDM & FKM (not outgassing and inert)

Windows
Plexiglas (top cover)
Fused Silica (UV Laser)

Sensors



Temperature
PT1000 resistors, class Y, 4-wire measurement
(Prec. 0,1K + 0,0017 · ΔT)

Pressure
piezoresistive thinfilm strain gauge sensor + transducer
(Prec. 0,18% in 0…1,6 Bar)

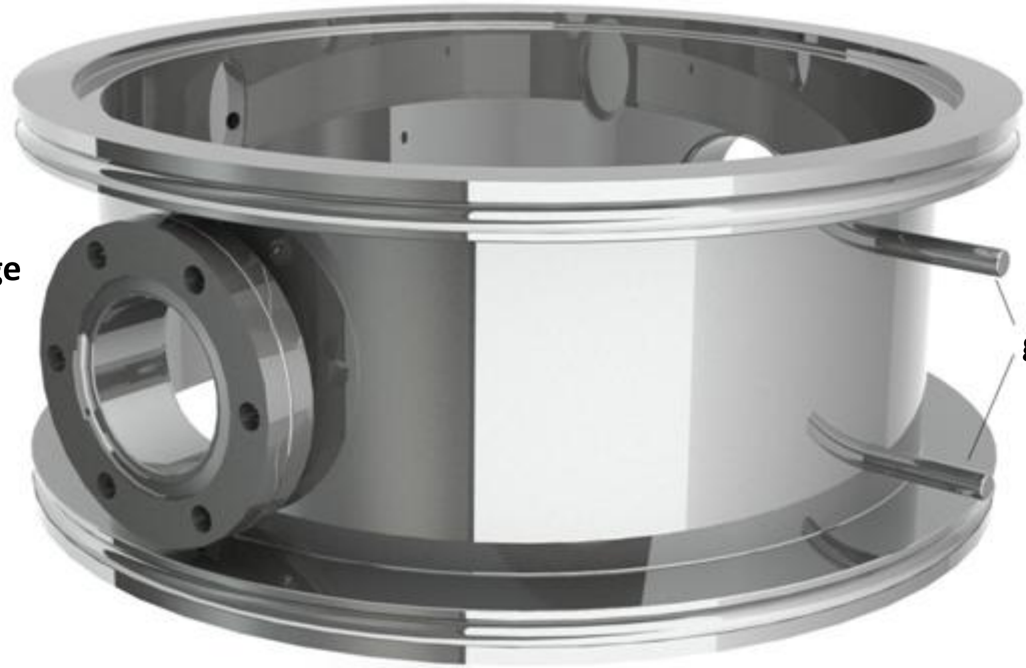
Charge
pA charge amplifiers
(2,5-5,5 V/pC)

Data Acquisition
Agilent 20 channel multiplexer
(34970A with 34901A)

Body and windows

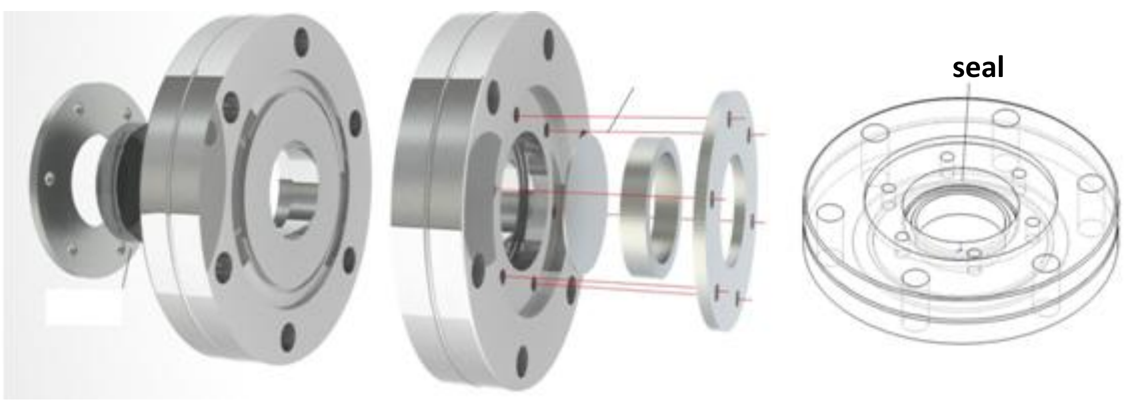
ISO-K flange

CF flange



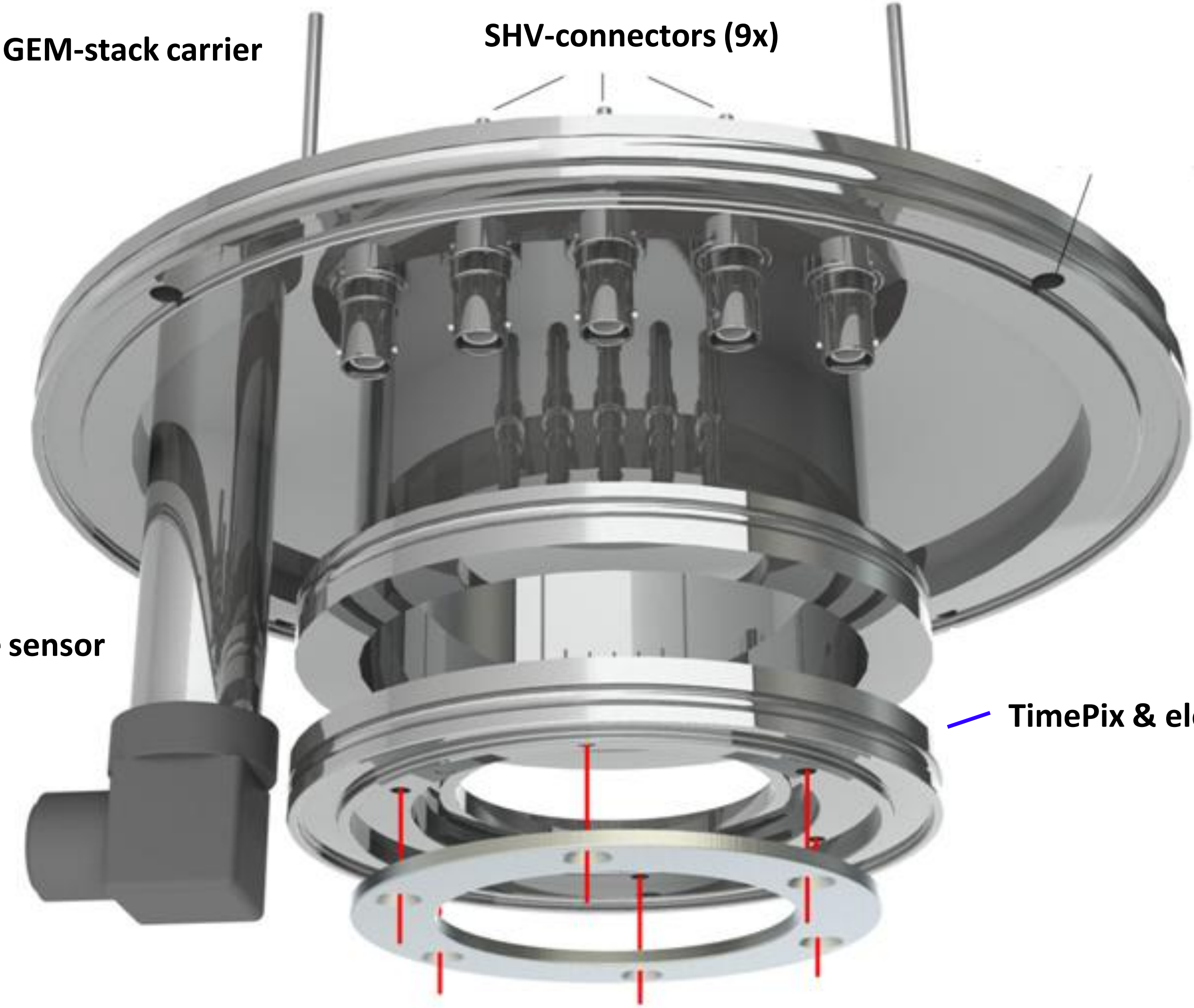
gas inlets

seal

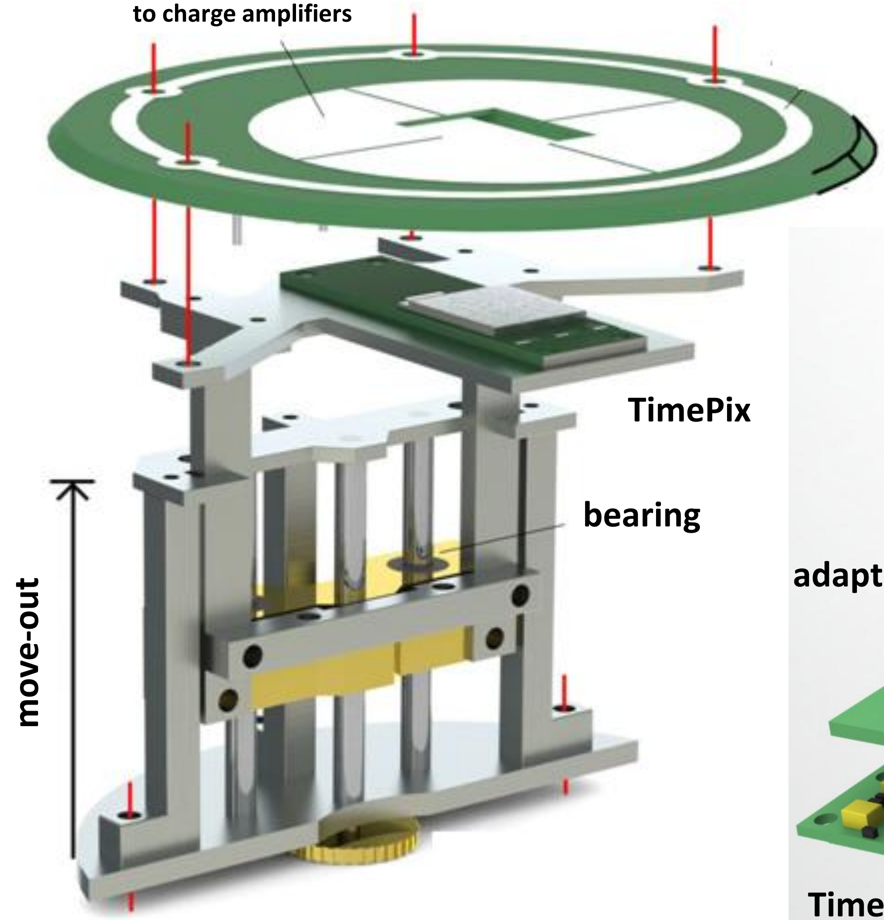


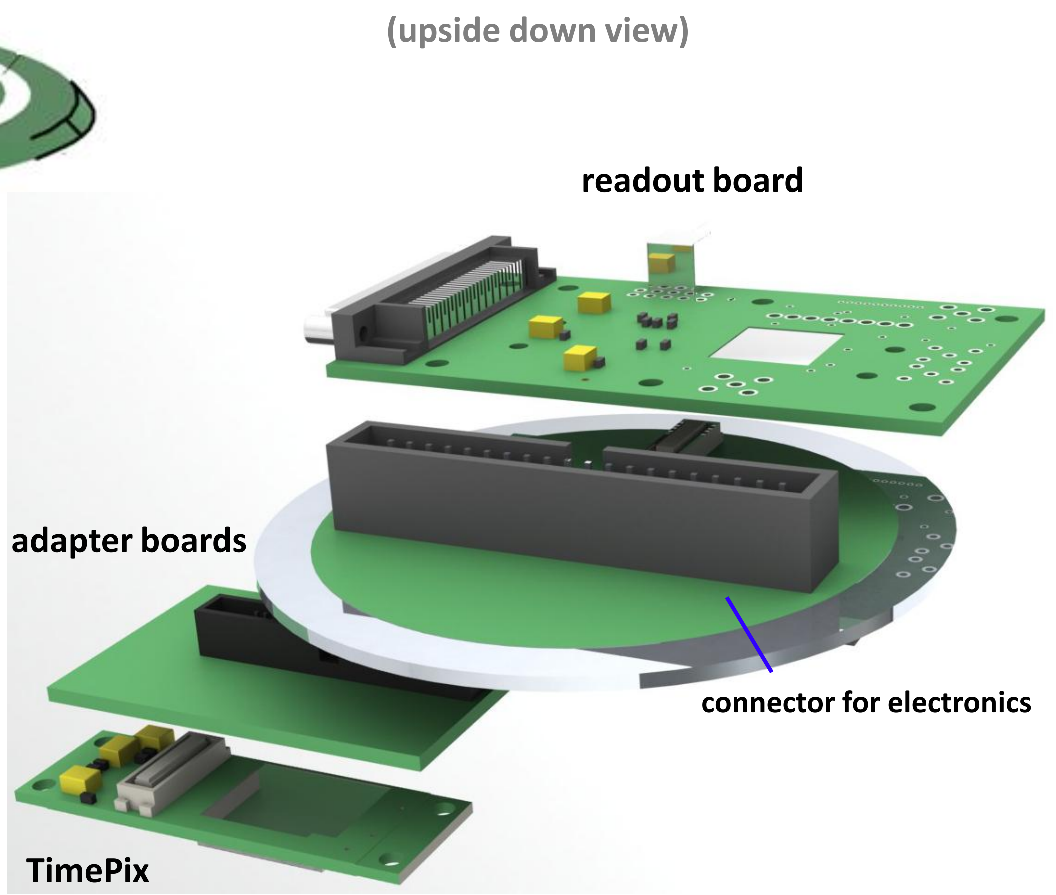
Laser / e⁻-beam window

Bottom view

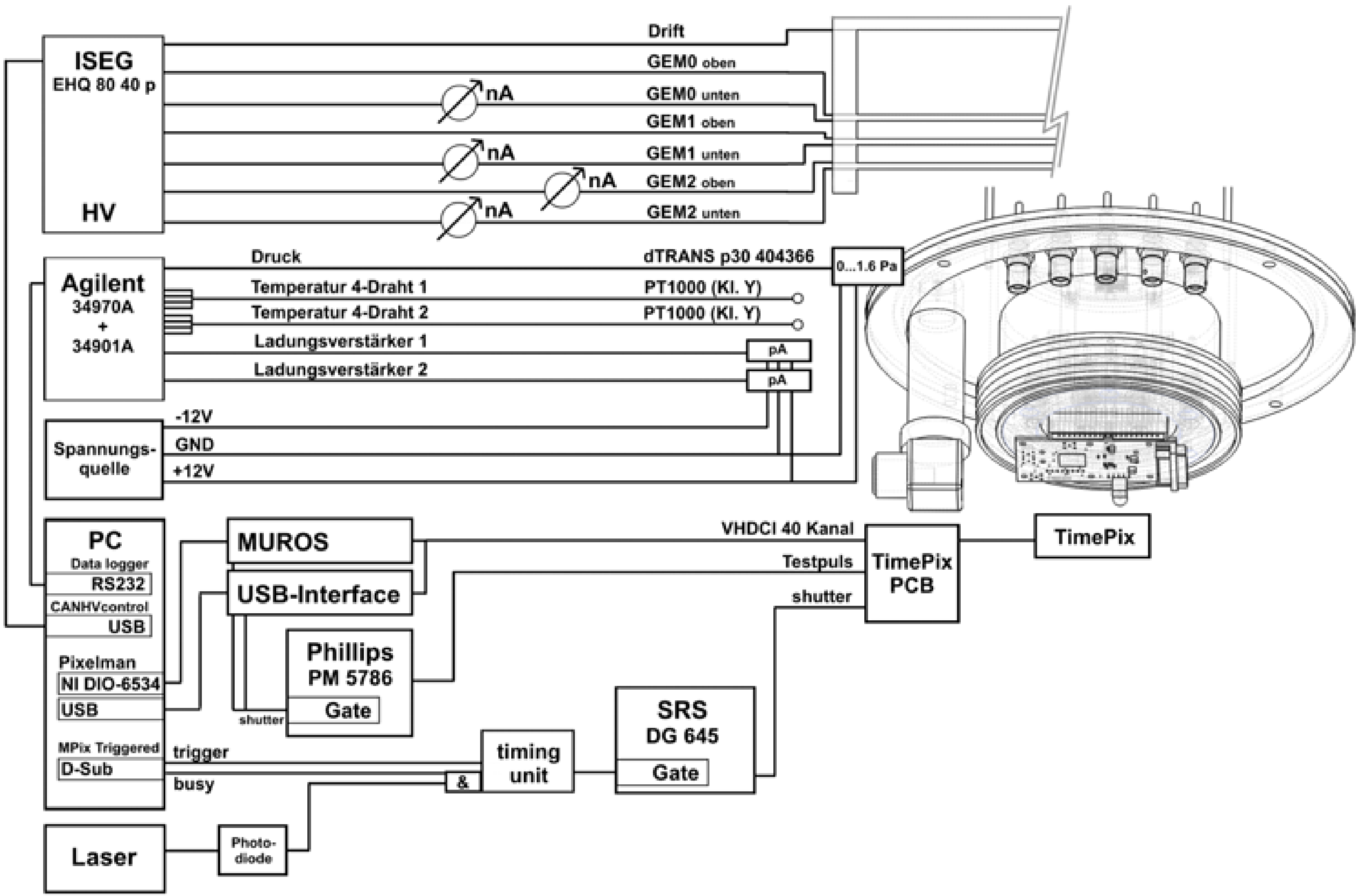

GEM-stack carrier
SHV-connectors (9x)
pressure sensor
TimePix & electronics duct

Lifting table & el. connections

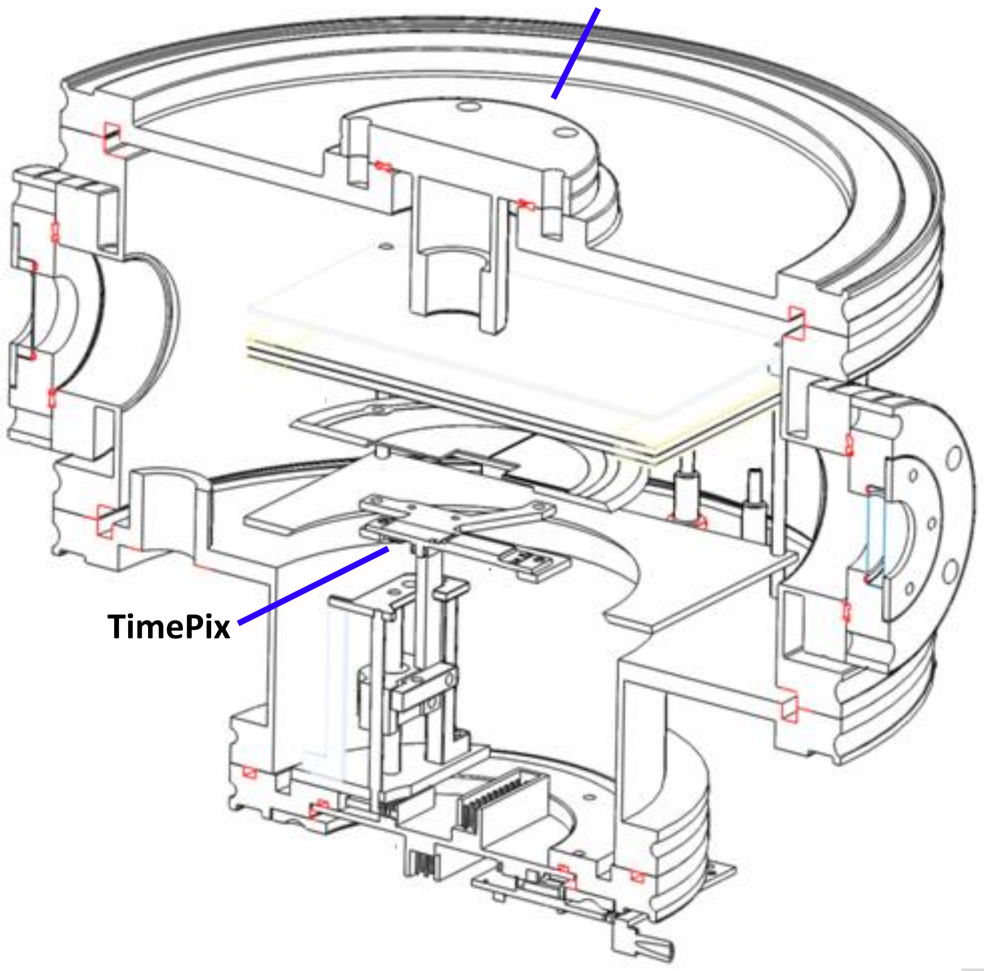


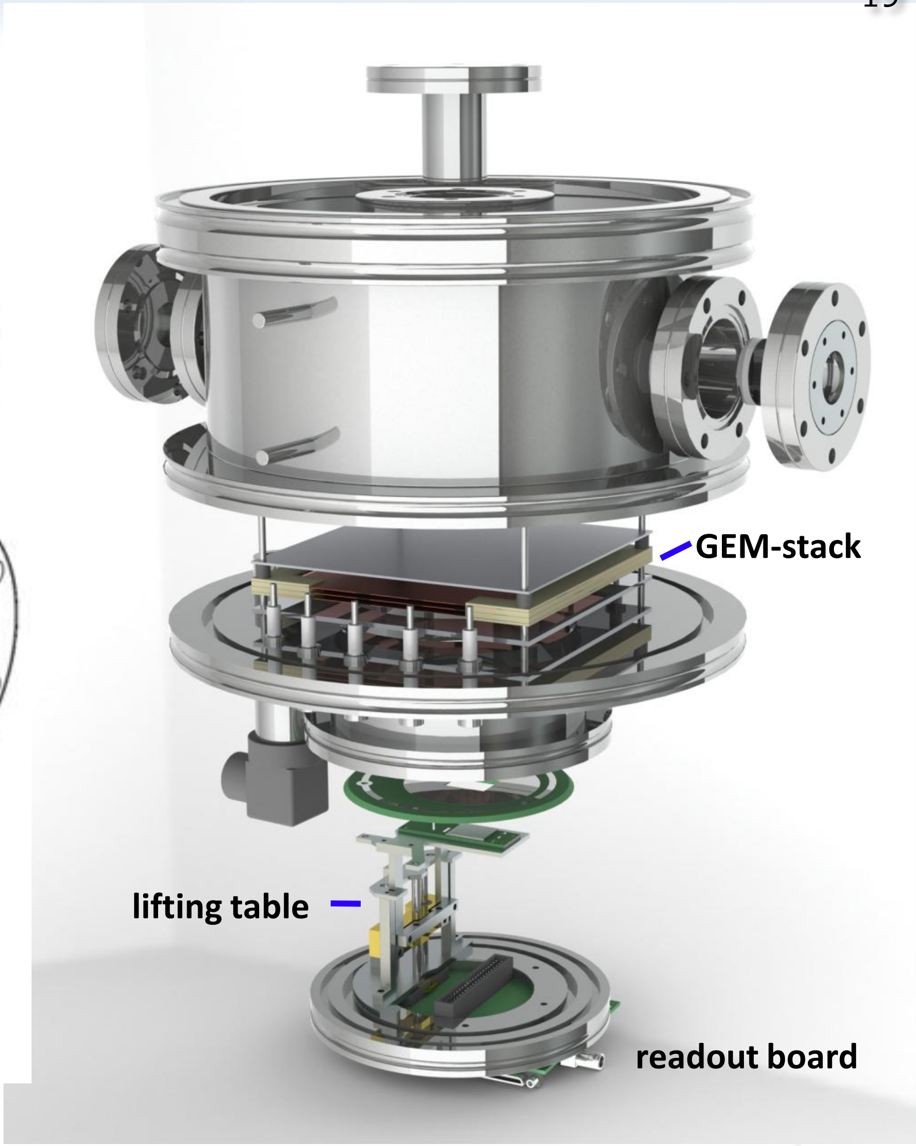


Electrical connections



General view and cut view





red = seals

Part III

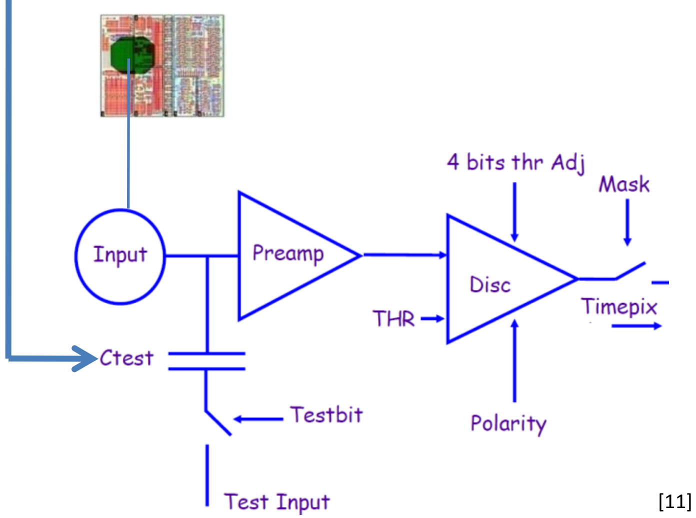
Studies on the performance of enlarged pixels

1 charge calibration

Pixel calibration

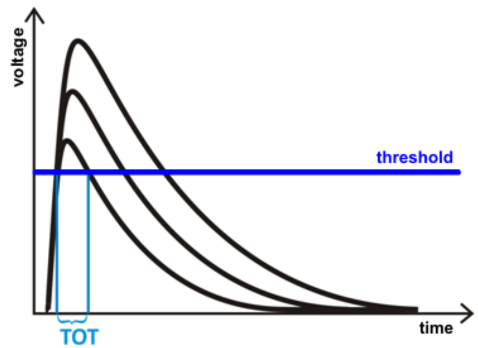
Procedure:

- **test pulse at test capacity Ctest (ca. 8 fF) injected charge on pixel**



TOT counts depend linearly on the deposited charge

TOT = b · Q + a



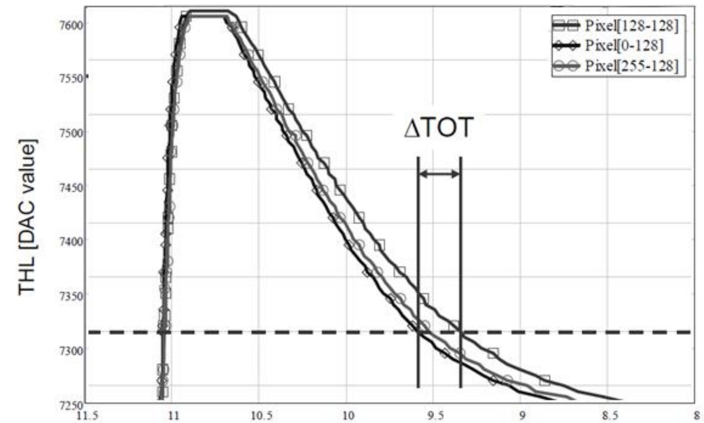
Until now: calibration *chipwise* (mean over all pixel)

but...

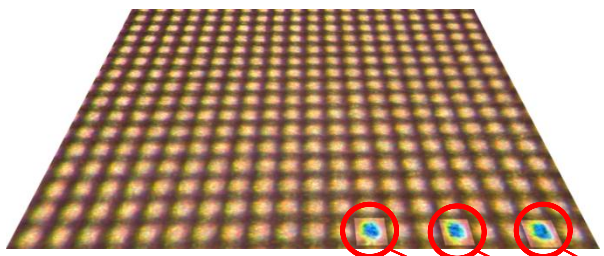
Pixel calibration

Problem:

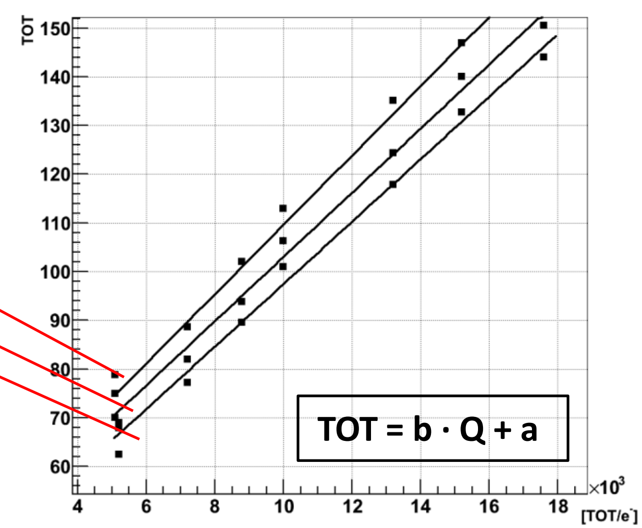
…Every pixel has its own response function:



current in discharging flank varies from pixel to pixel



(Detail TimePix)



→ **Would a pixelwise calibration improve the charge calibration?**

Llopart , X.; *Design and characterization of 64K pixels chips working in single photon processing mode*, 2007

TimePix – slope distribution

Precision of the fit parameters for slopes

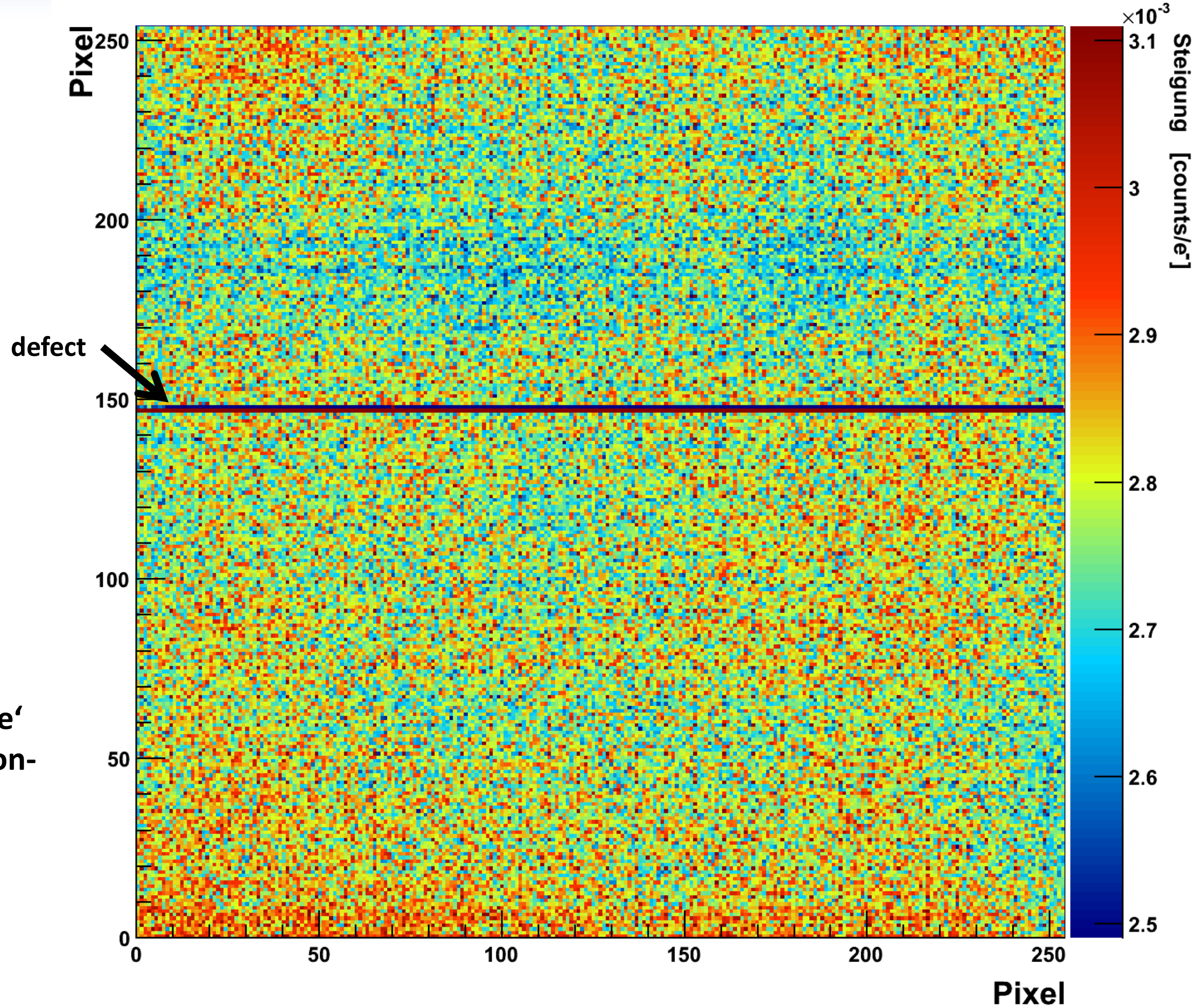
$$\frac{\sigma_{\overline{p_1}}}{\overline{p_1}} = (2{,}13 \pm 0{,}12)\,\%$$

Width of overall chip slope distribution

$$\frac{\Gamma_{\overline{S}}}{\overline{S}} = (3{,}244 \pm 0{,}007)\,\%$$

Assuming this chip distribution results from a convolution of ‚true' distribution and slope error, the on-chip variation is

$$(2{,}45 \pm 0{,}10)\,\%$$

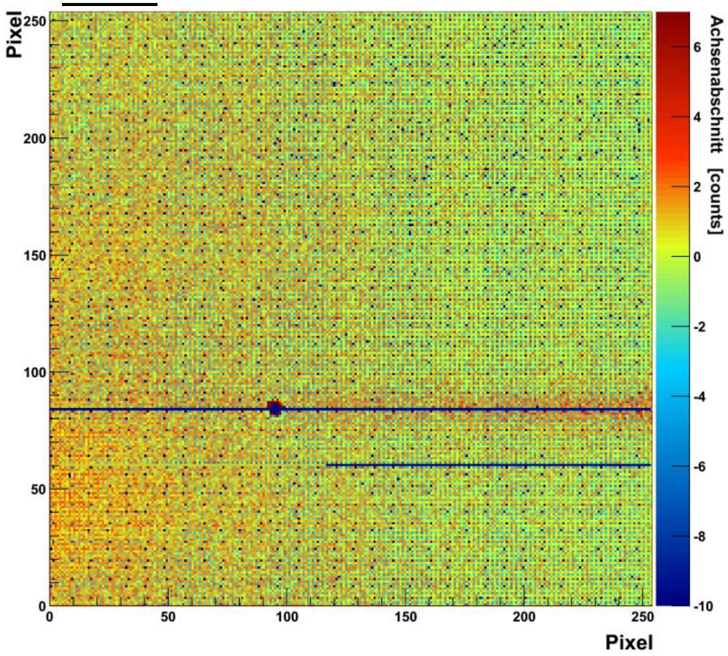


2x2 - slope & offset distribution

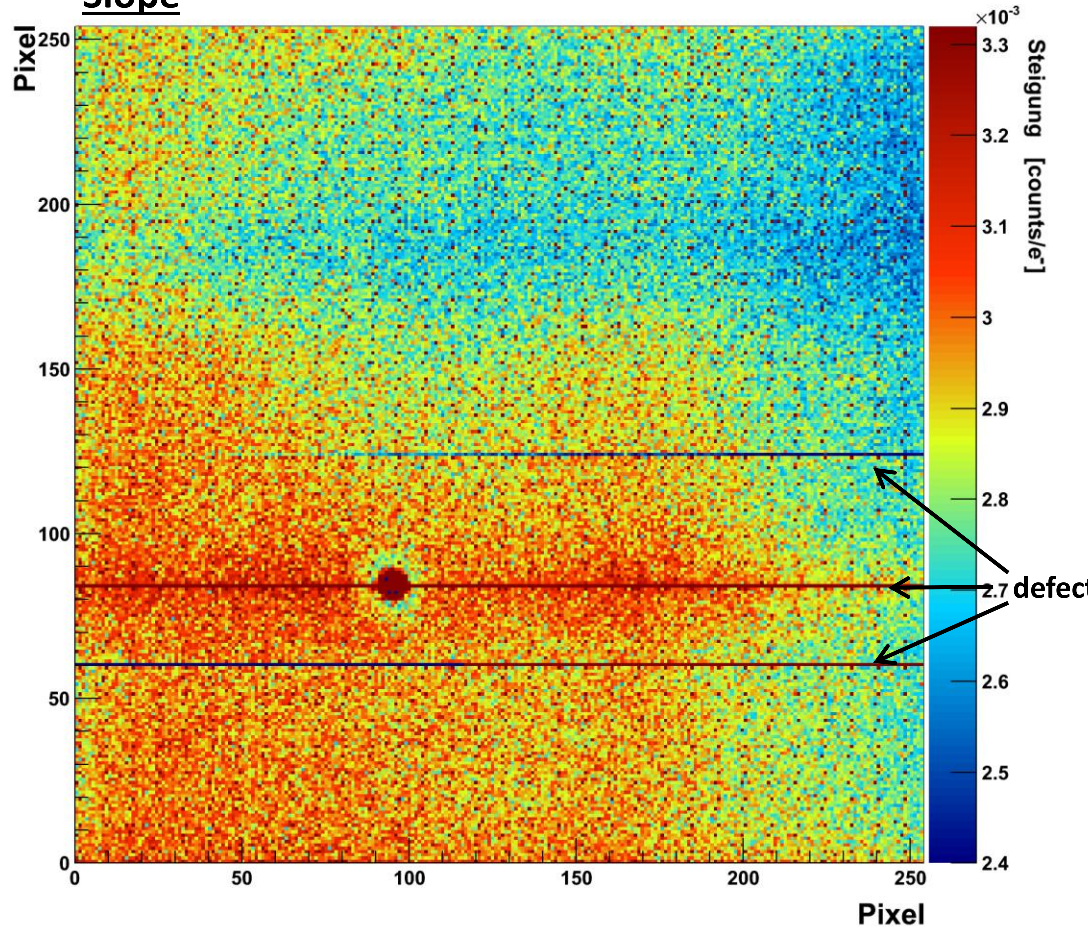
Remarks:

- local variation in slope
- slope not anticorrelated to offset

Offset

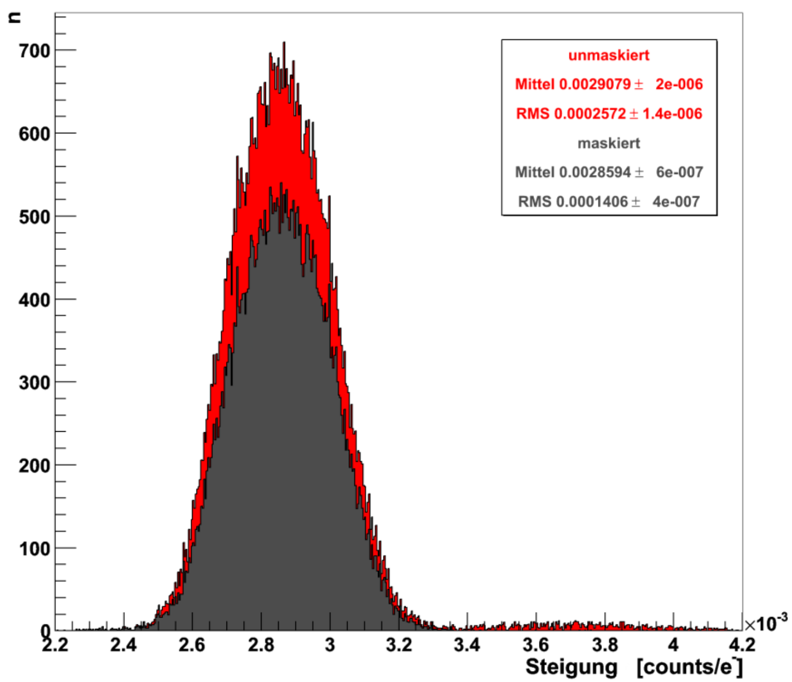


Slope

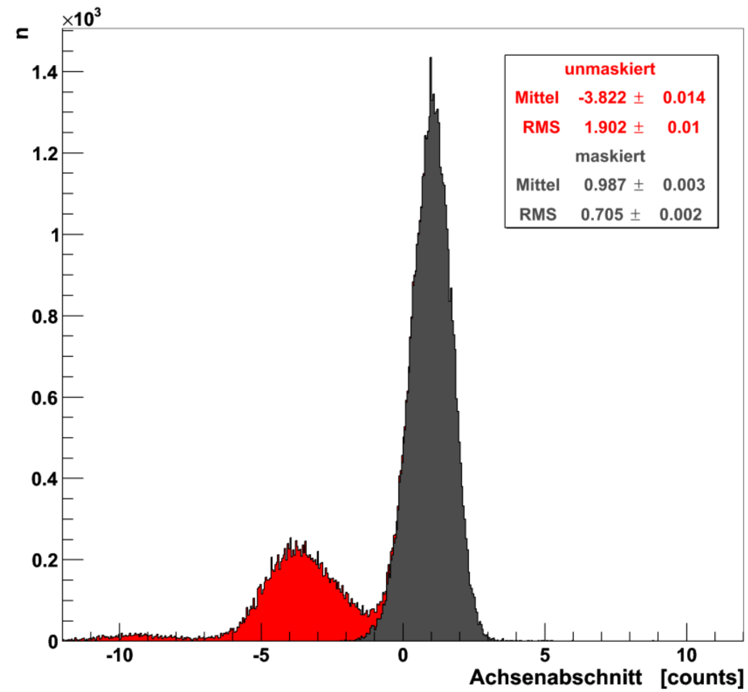


2x2 – slope distribution

slope



offset



connected pixels
unconnected pixels

Conclusions:

- counting e^- (slope) not affected
- virtual threshold (offset) of connected pixels higher

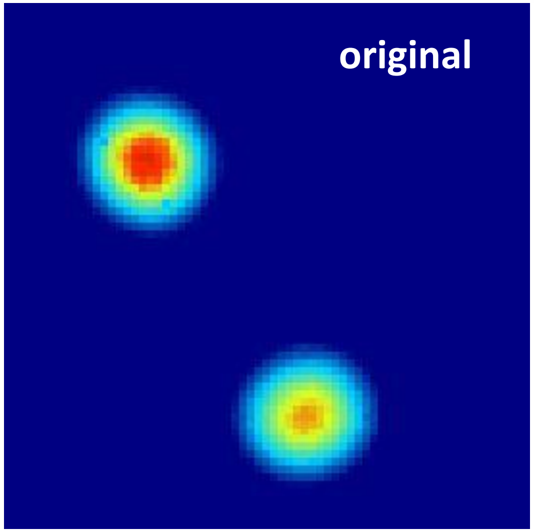
→ **Passivation affects physical behavior of pixels**

Part III

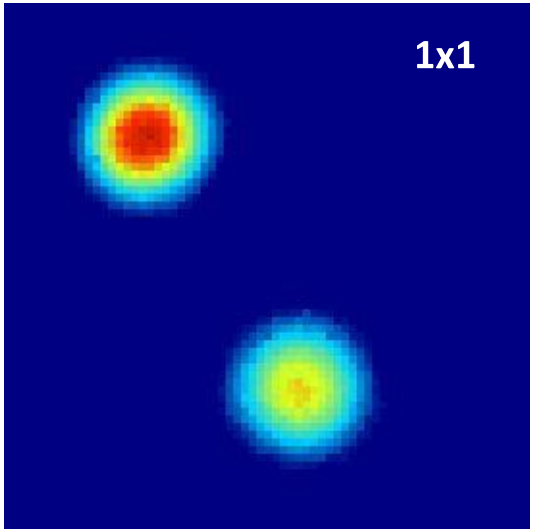
Studies on the performance of enlarged pixels

2 preparing data

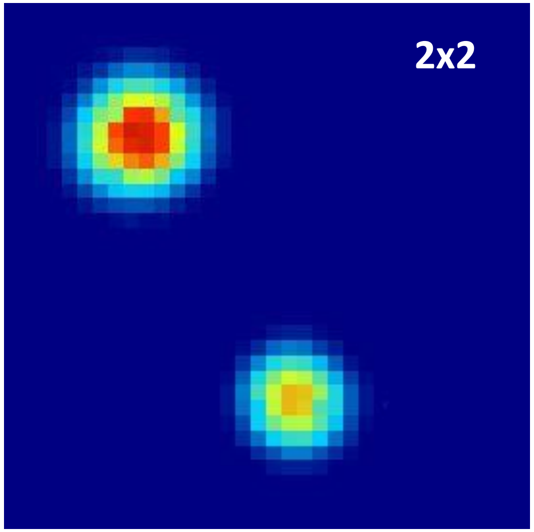
Examples of some records



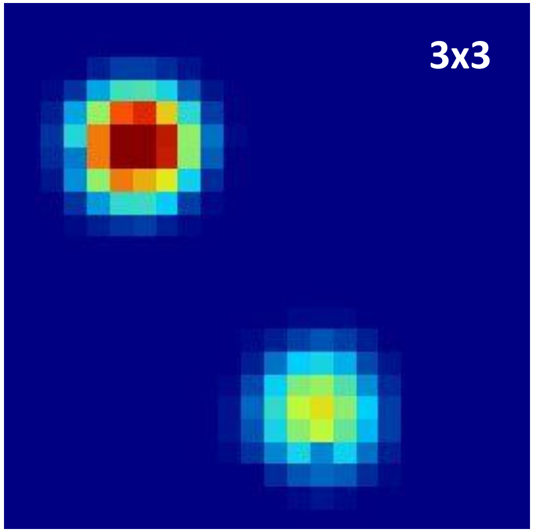
max: 200 ke$^-$



max: 250 ke$^-$



max: 1100 ke$^-$



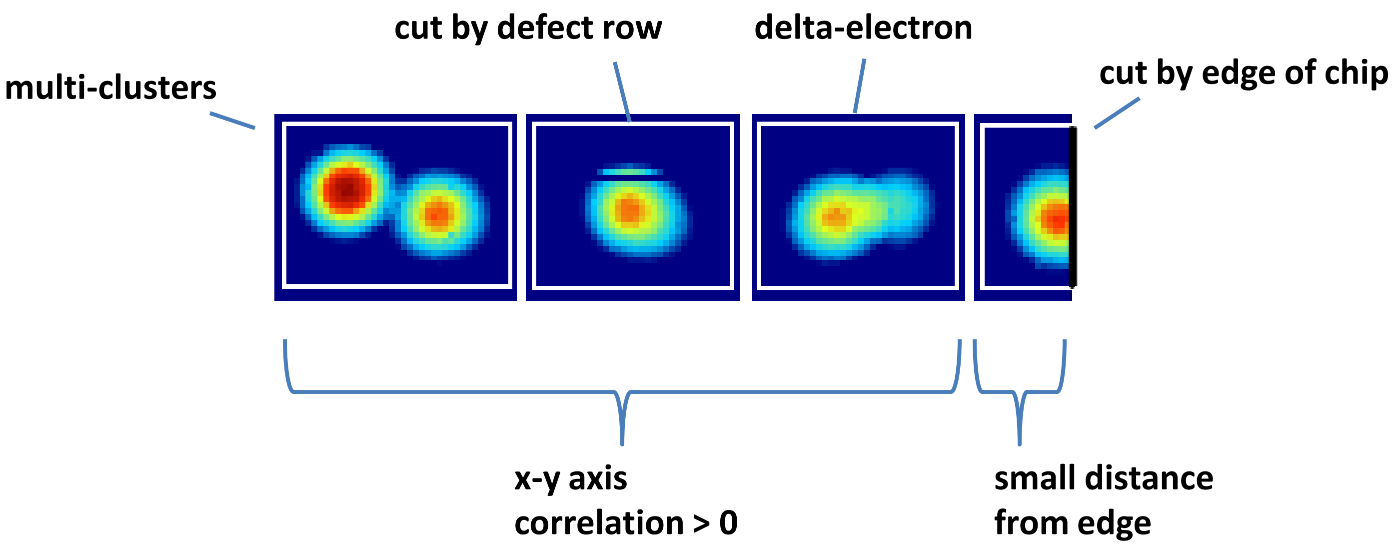
max: 1700 ke$^-$

<u>All examples:</u>
clusters of 5,9 keV
^{55}Fe decay at
ΔV_{GEM} = 385 V

Cleaning the data

Problem: there are clusters with wrong information for
- charge or
- area

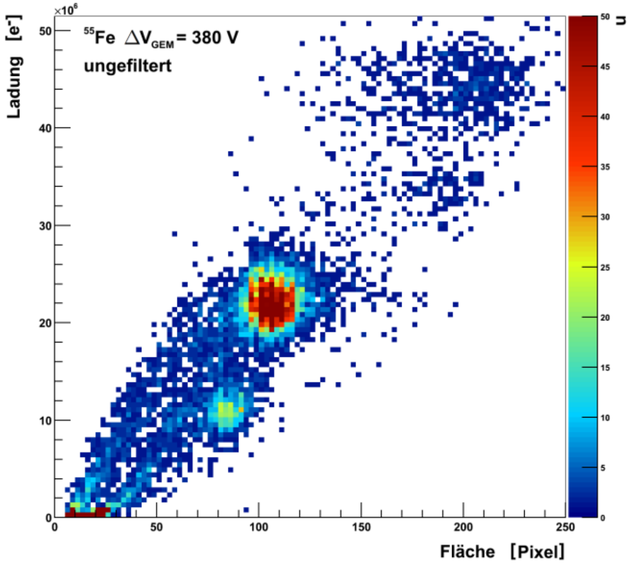
Types of ‚undesired' clusters:



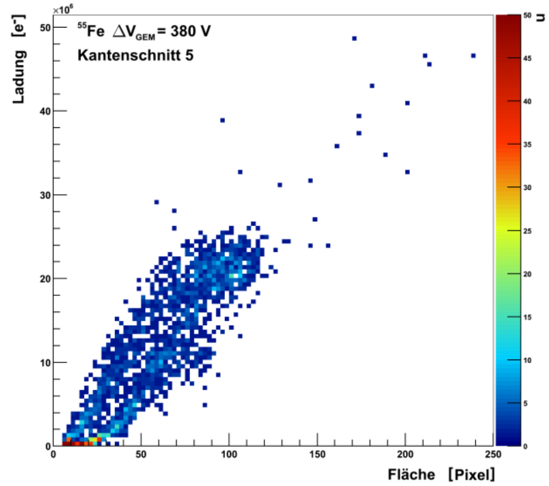
→ cut on these parameters

Qualitative illustration

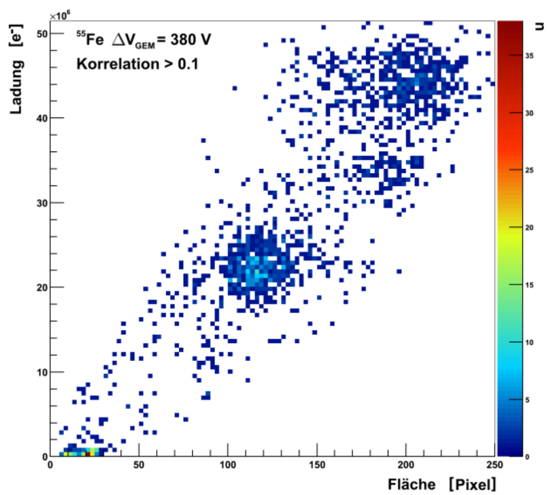
before cuts



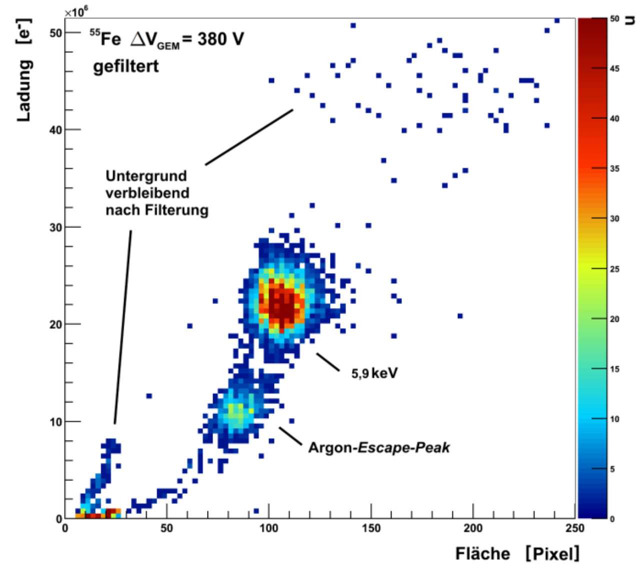
edge cut



x-y correlation cut

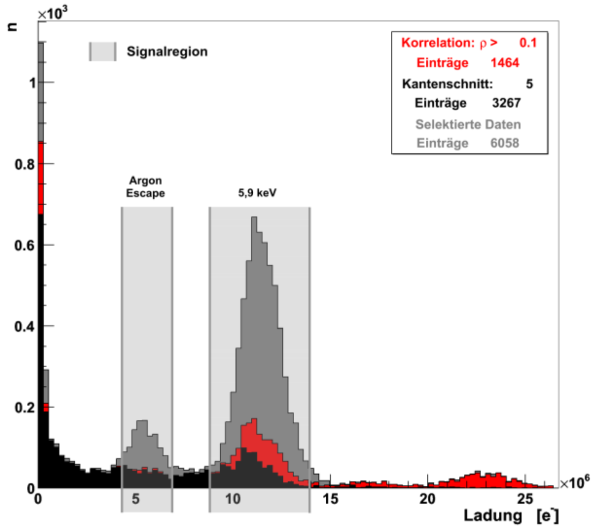


after cuts

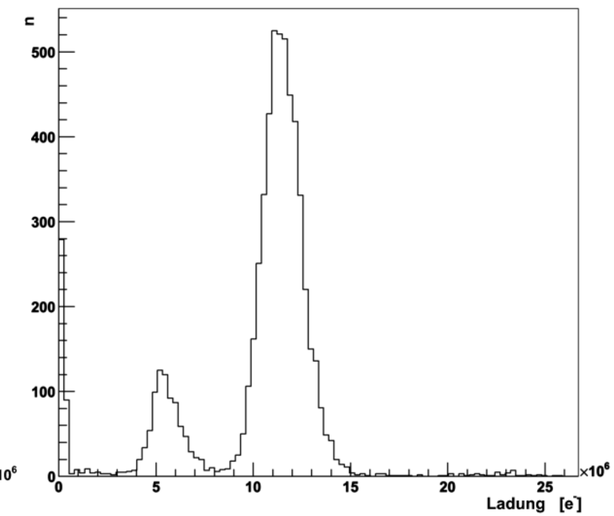


Cuts

before cuts



after cuts



x-y correlation cut

edge cut

remaining entries

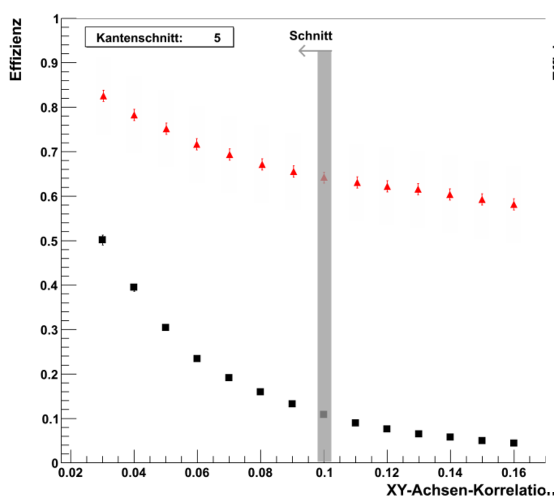
Procedure

- define ‚signal region'
- optimize cuts on

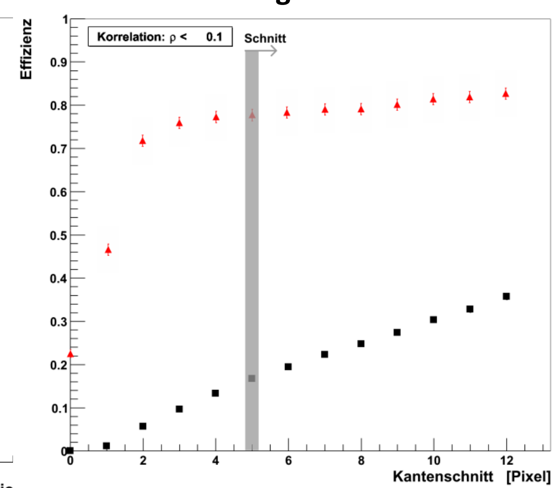
  minimal signal rejection

  maximum background rejection

x-y correlation cut



edge cut



signal rejection

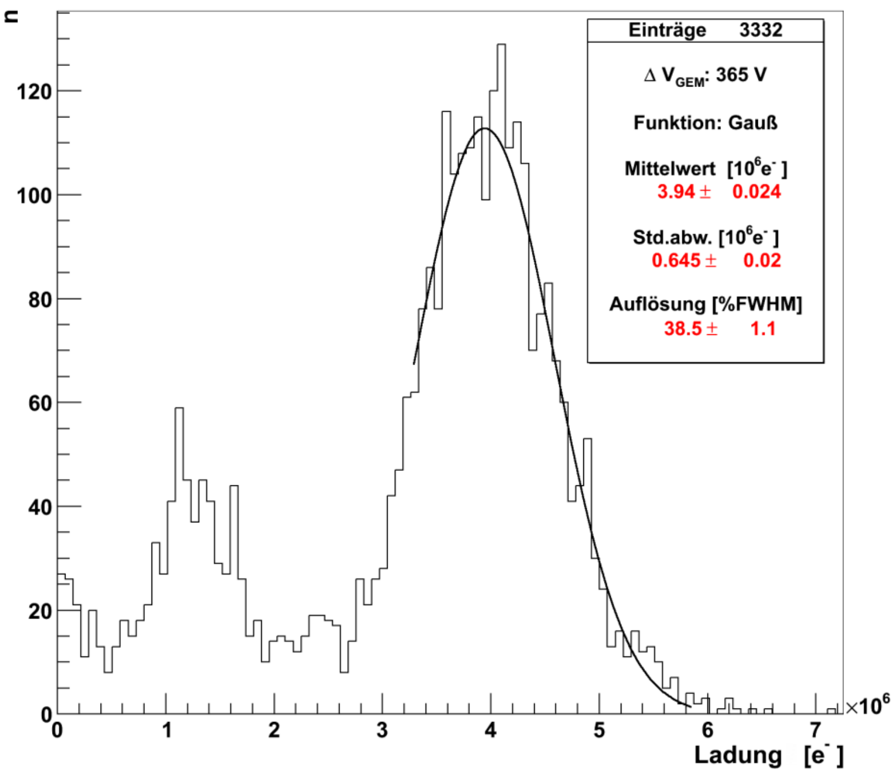
background rejection

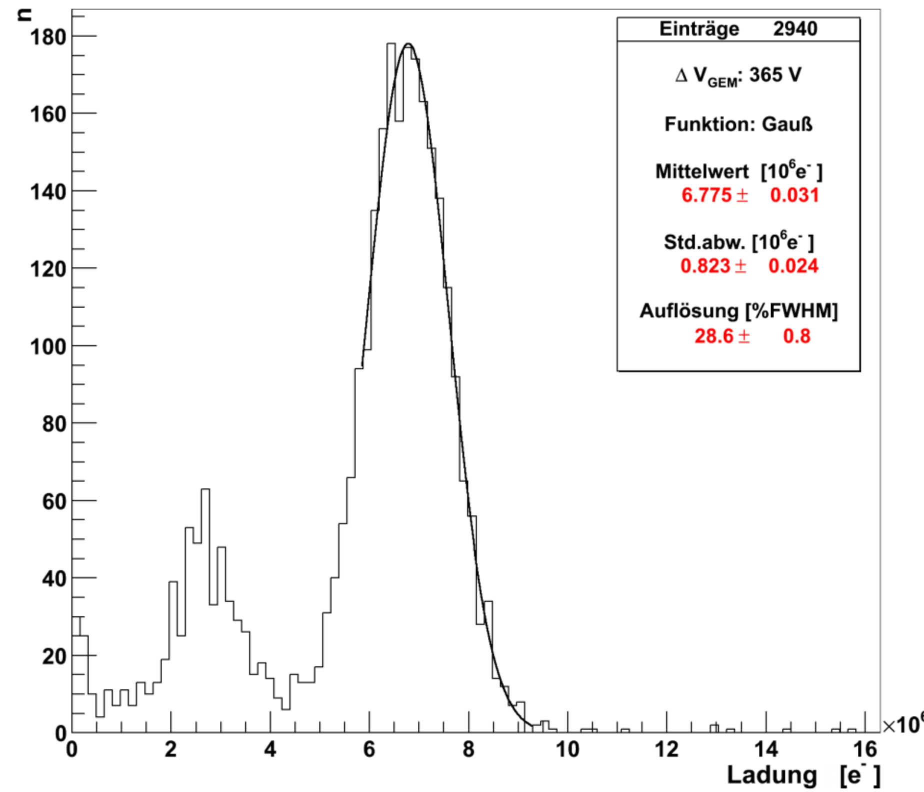
Spectra of TimePix and 1x1

Compare spectra

(same amplification)

TimePix ⟷ **1x1 postprocessed**





1x1:
- collects more charge
- leads to better separation of energy
  better resolution

Part III

Studies on the performance of enlarged pixels

3 discussing clusters

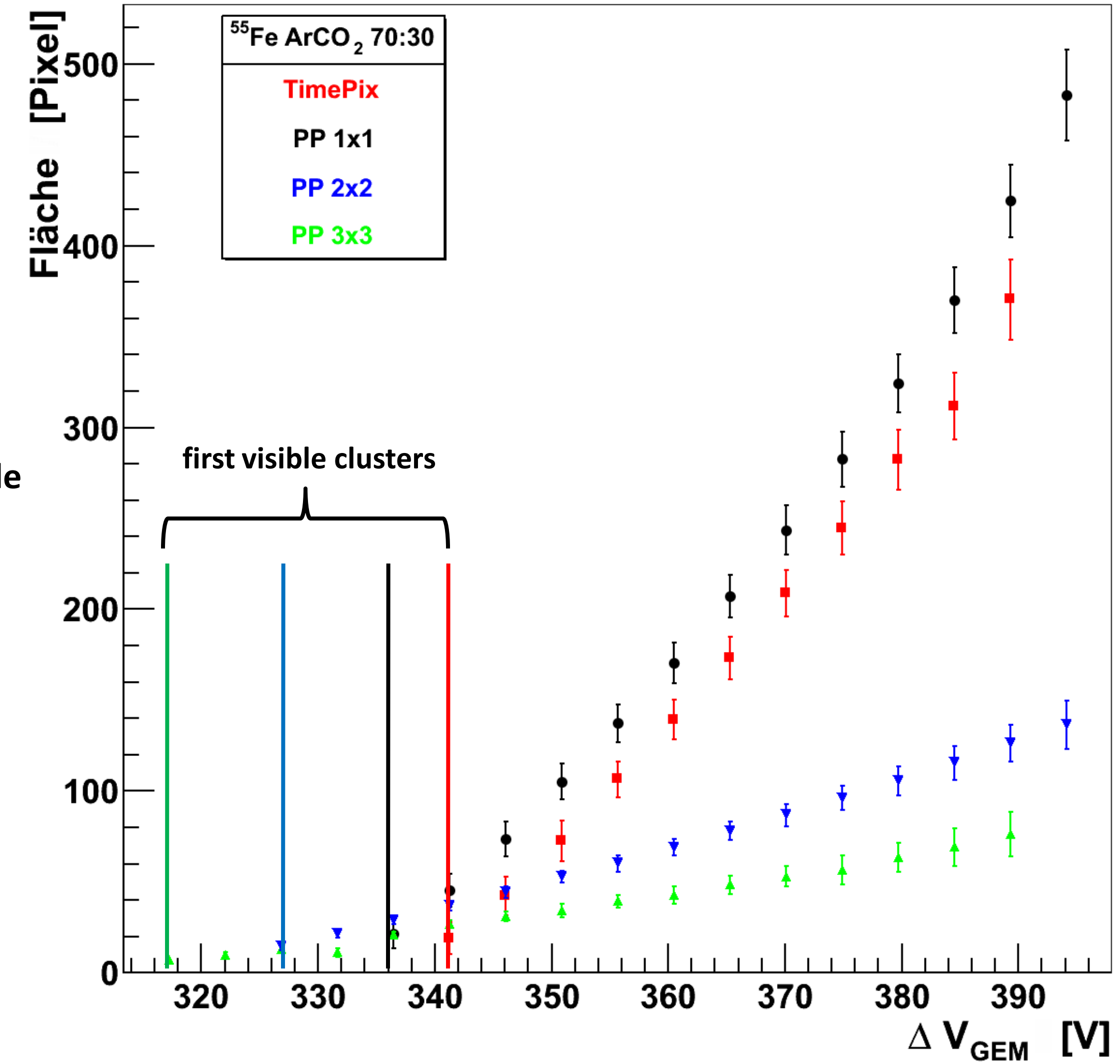
Comparison of cluster sizes

About cluster sizes

- Postprocessed 1x1 :
  clusters are larger than original TimePix

- For enlarged pixels
  → more charge per pixel
  → clusters with less gas gain detectable

…but why is cluster size constantly increasing?



A look at kurtosis

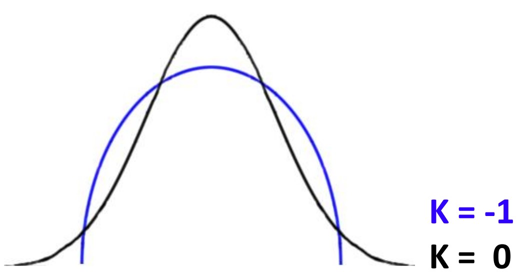
Cluster shape

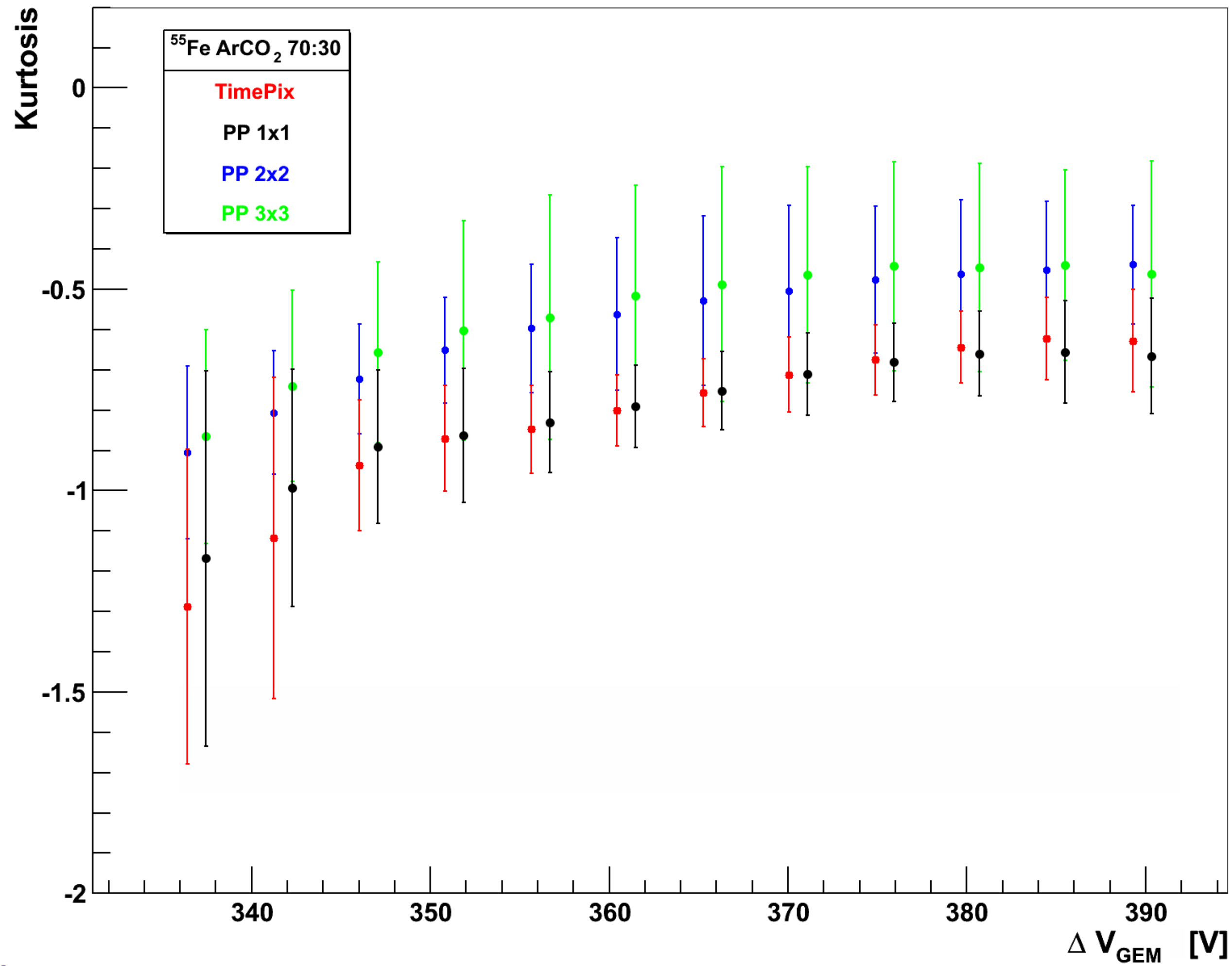
Model for electron diffusion predicts gaussian shape of charge cloud
⟶ Kurtosis K = 0

Result:

Kurtosis approaches a K < 0 for
- larger gas gain
- larger pixel size

⟶ clusters are more ‚centered'





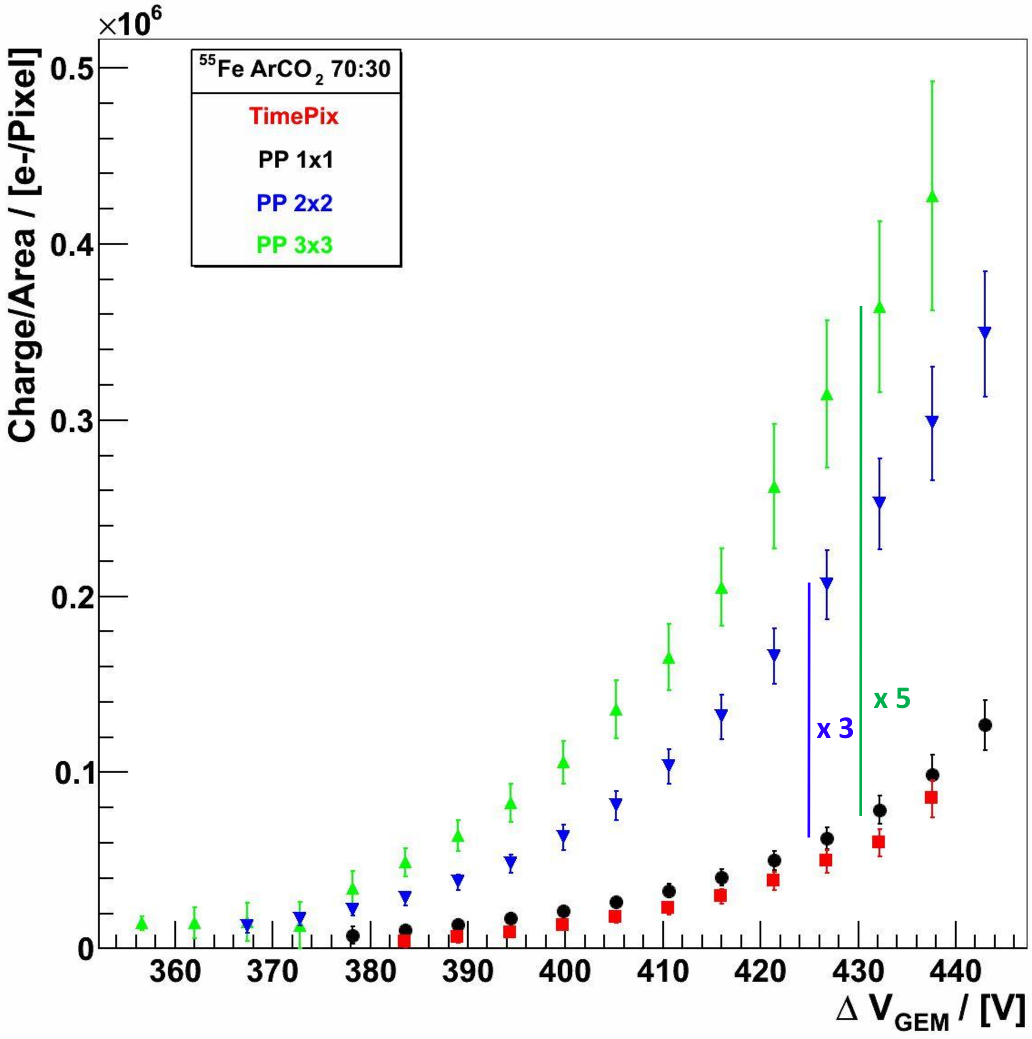
A look at charge per area

Bn

Cluster charge

- Postprocessed 1x1 : clusters contain more charge than original TimePix

- Not only area, but also charge / area increases



Conclusion:

Cluster shape is influenced by GEM amplification process itself

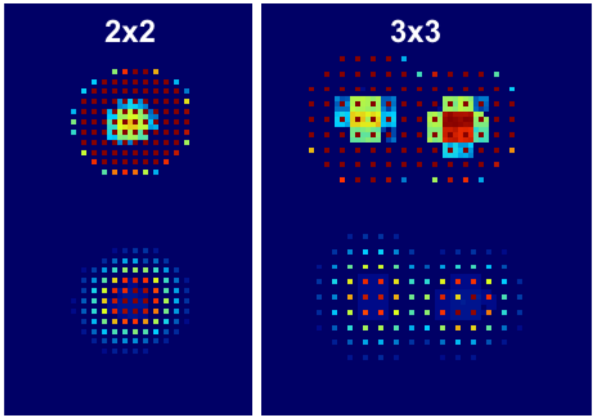
Passivated pixel cross-talk

Problem of ‚cross-talk‘:

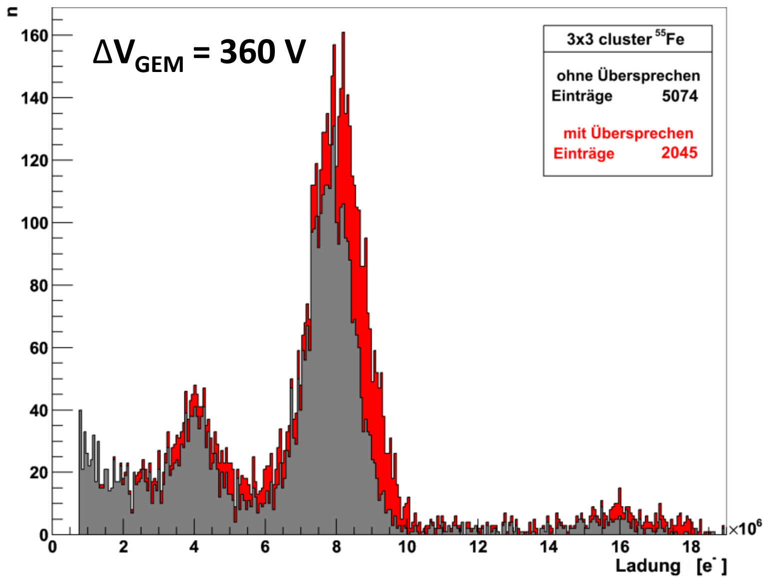
At high amplifications passivated pixels show signals

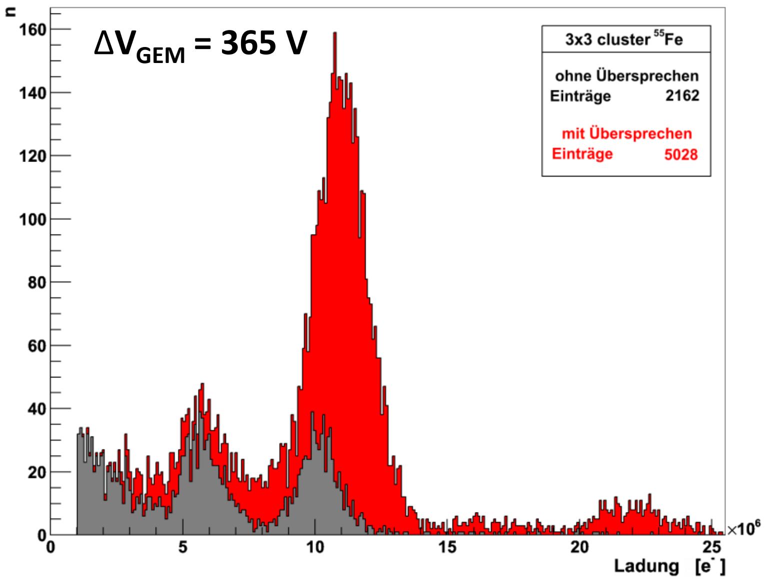
⟶ charge on connected pixels is reduced

⟶ avoid high amplifications



clusters of 5,9 keV ^{55}Fe decay at ΔV_{GEM} = 380 V





Clusters:
without crosstalk
with crosstalk

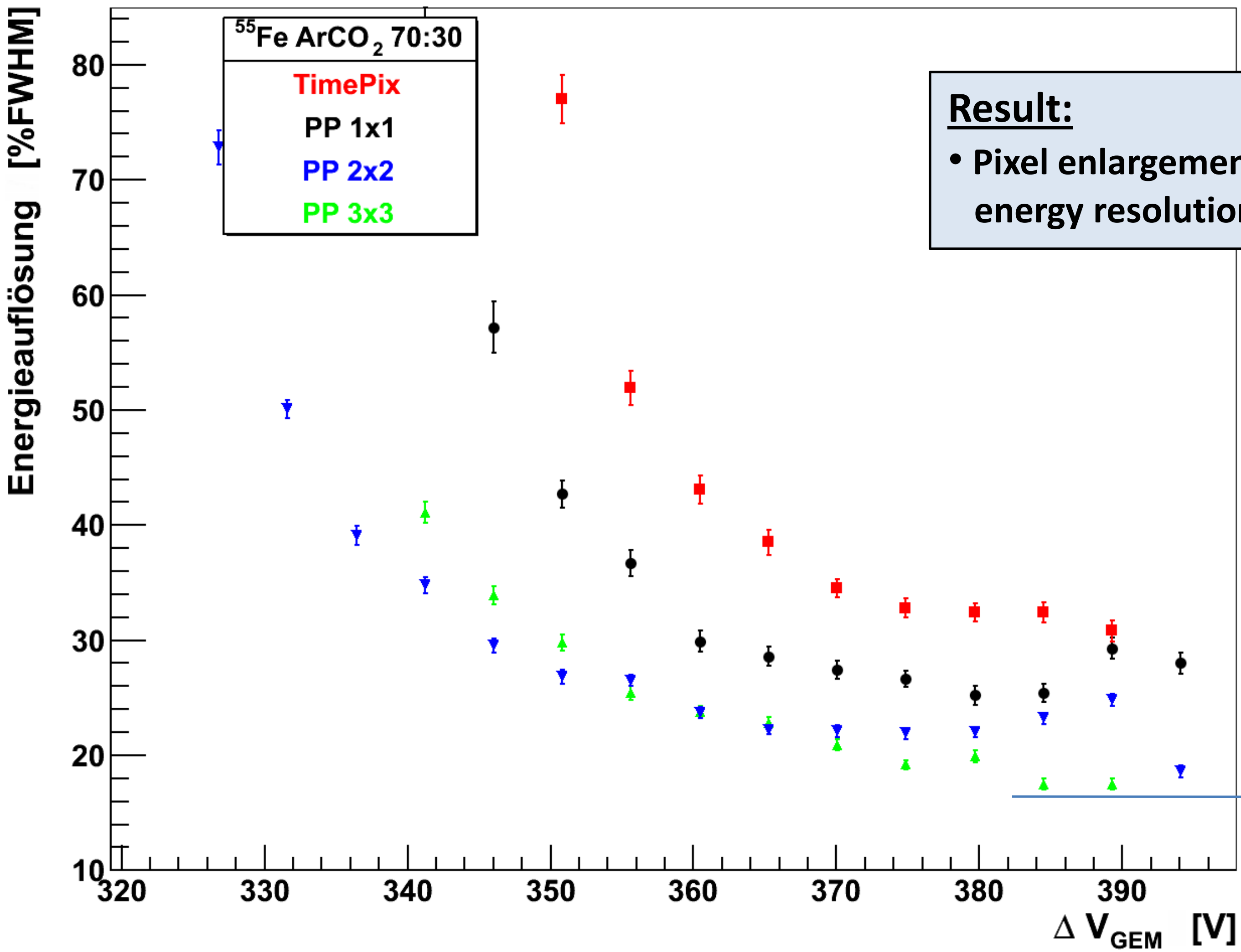
‚cross-talking‘ is a function field strenght as well as of deposited charge

Part III

Studies on the performance of enlarged pixels

4 general features

Energy resolution



Result:

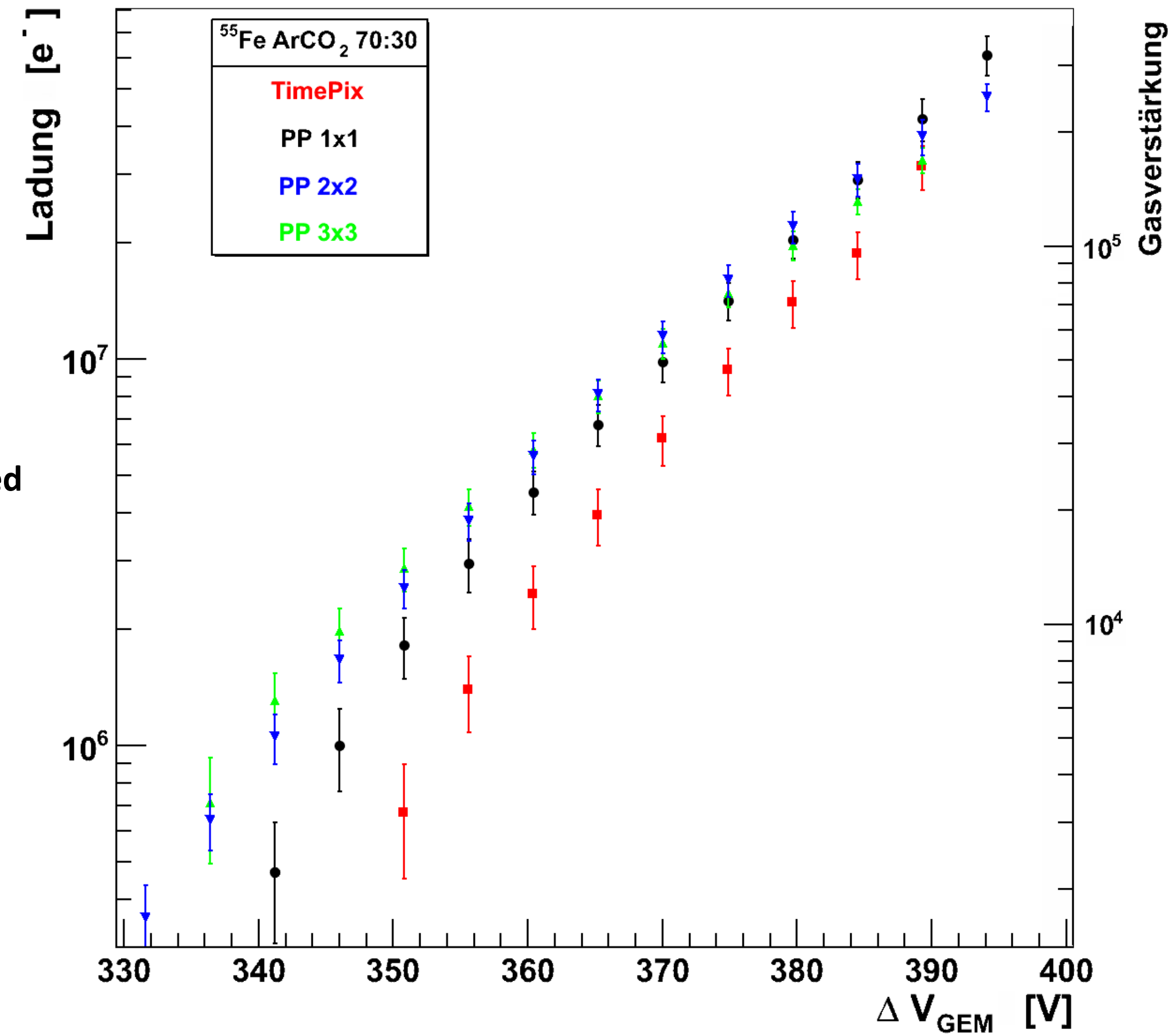
- Pixel enlargement improves energy resolution

Best (3x3): $(17{,}5 \pm 0{,}5)$ %FWHM

Gas gain in $ArCO_2$

Studies on gas gain

Expected number of primary electrons from 5,9 keV in $ArCO_2$(70:30): 212



Results:

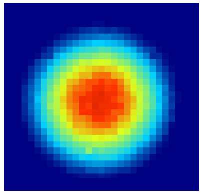
- gas gains up to $3 \cdot 10^5$ could be achieved
- with pixel enlargement less potential difference / gas gain needed for same charge per pixel

Summary

∑

- **Construction of a test chamber:**
  - A modular chamber has been developed
  - It features
    - a quick and easy exchange of TimePix chips
    - single potential definition for GEM-layers
    - monitoring of pressure and temperature
    - possibilities for Laser and testbeam measurements, as well as characterization with radioactive sources

- **Successful operation of postprocessed chips:**
  - 1x1 pixels collect more charge than TimePix original
  - For high amplifications: passivated pixel cross-talk

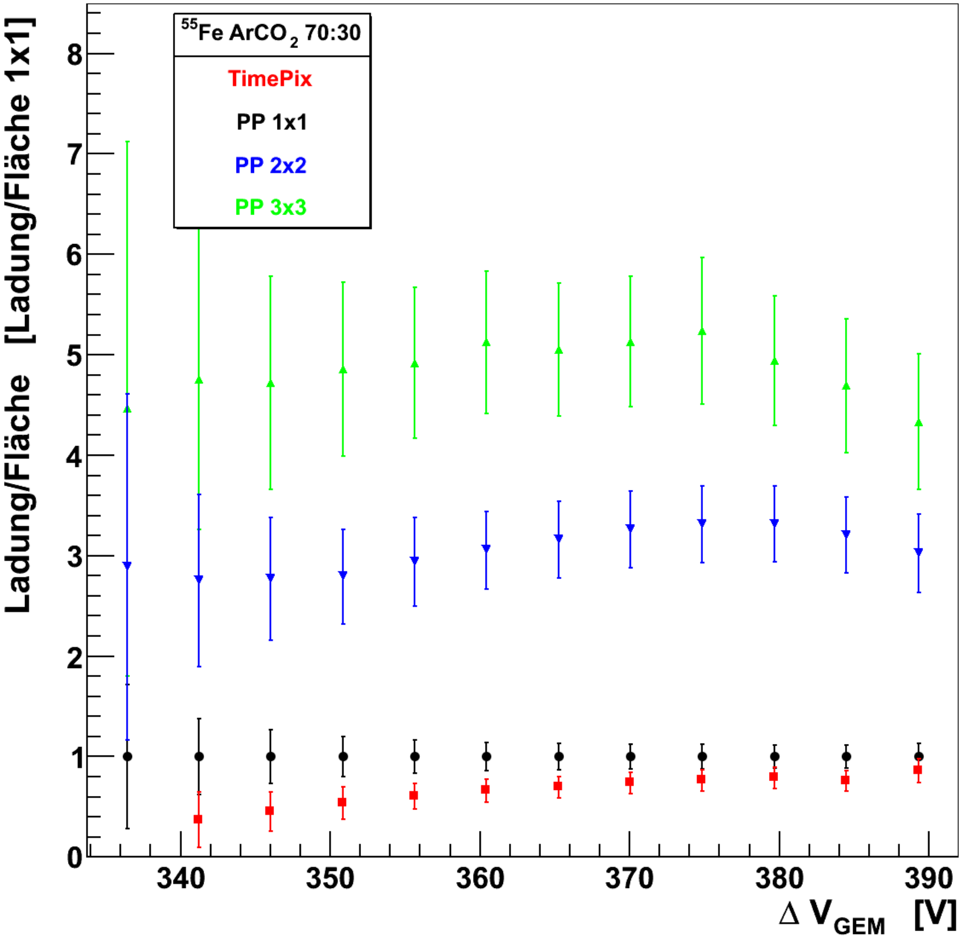


- **GEMs benefit from large pixels:**
  - Less gas gain needed
  - Energy resolution improved
  - Spatial resolution only slightly deteriorated

Backup

Charge per area

Charge per area normalized to TimePix 1x1



Single electron detection

Question:

Is it possible to detect single electrons?

Experiment:

A pulsed laser with low intensity generates photoelectrons at the cathode

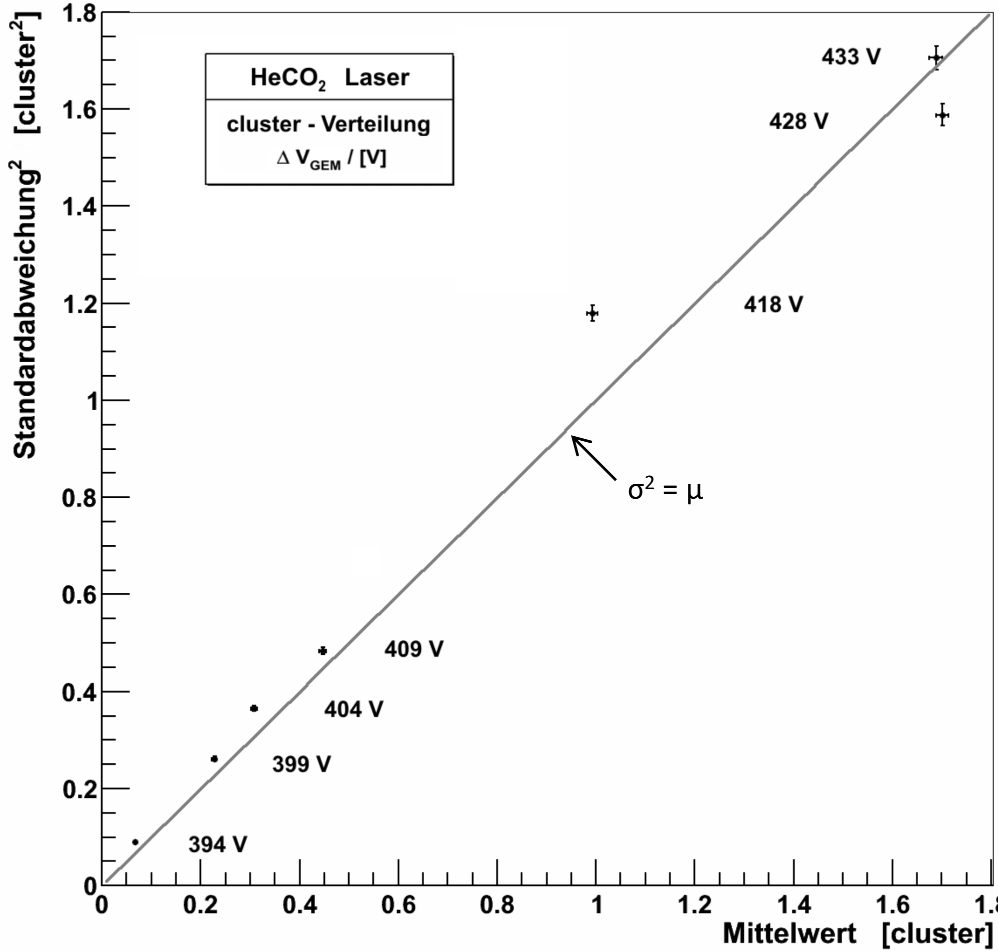
Expectation:

Number of electrons/shot is Poisson distributed

$\longrightarrow \sigma^2 = \mu$

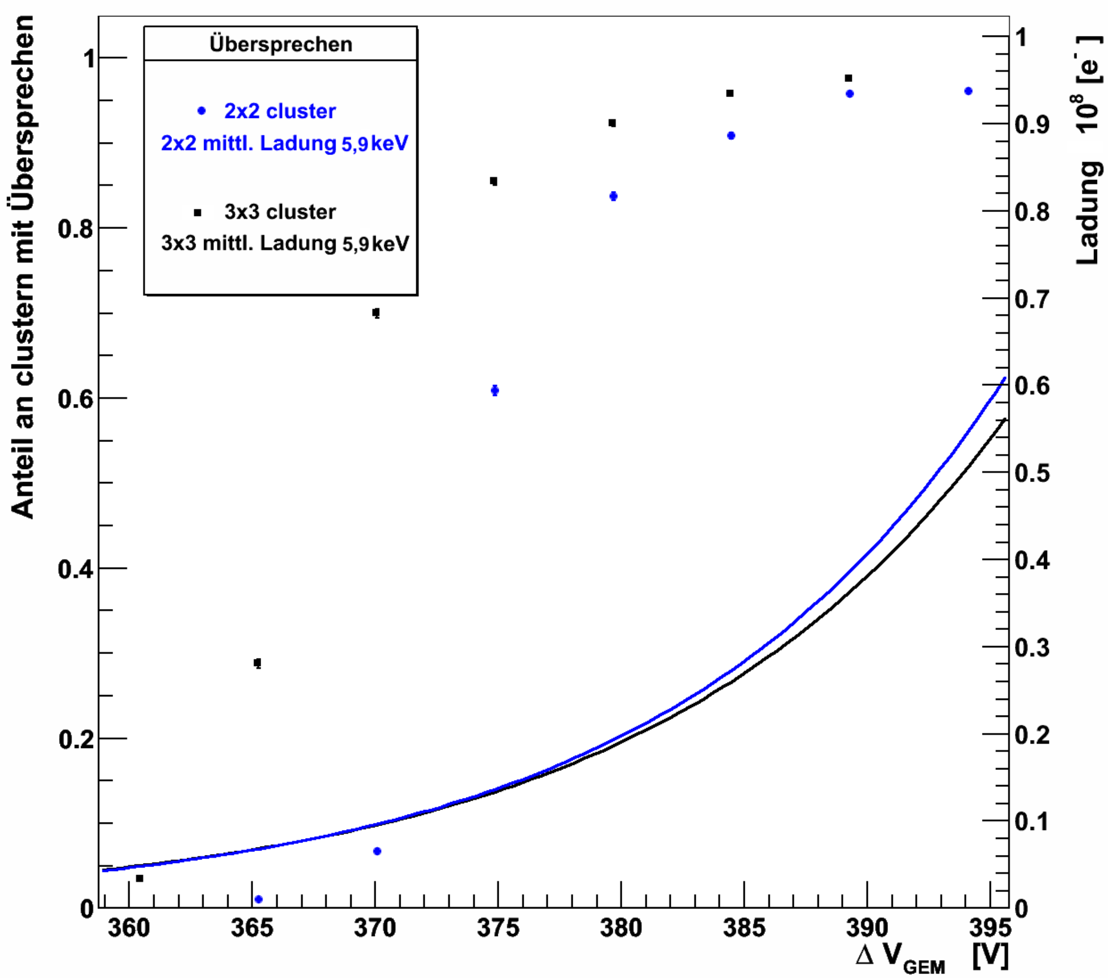
Result:

For high gas gains a single electron detection could be possible

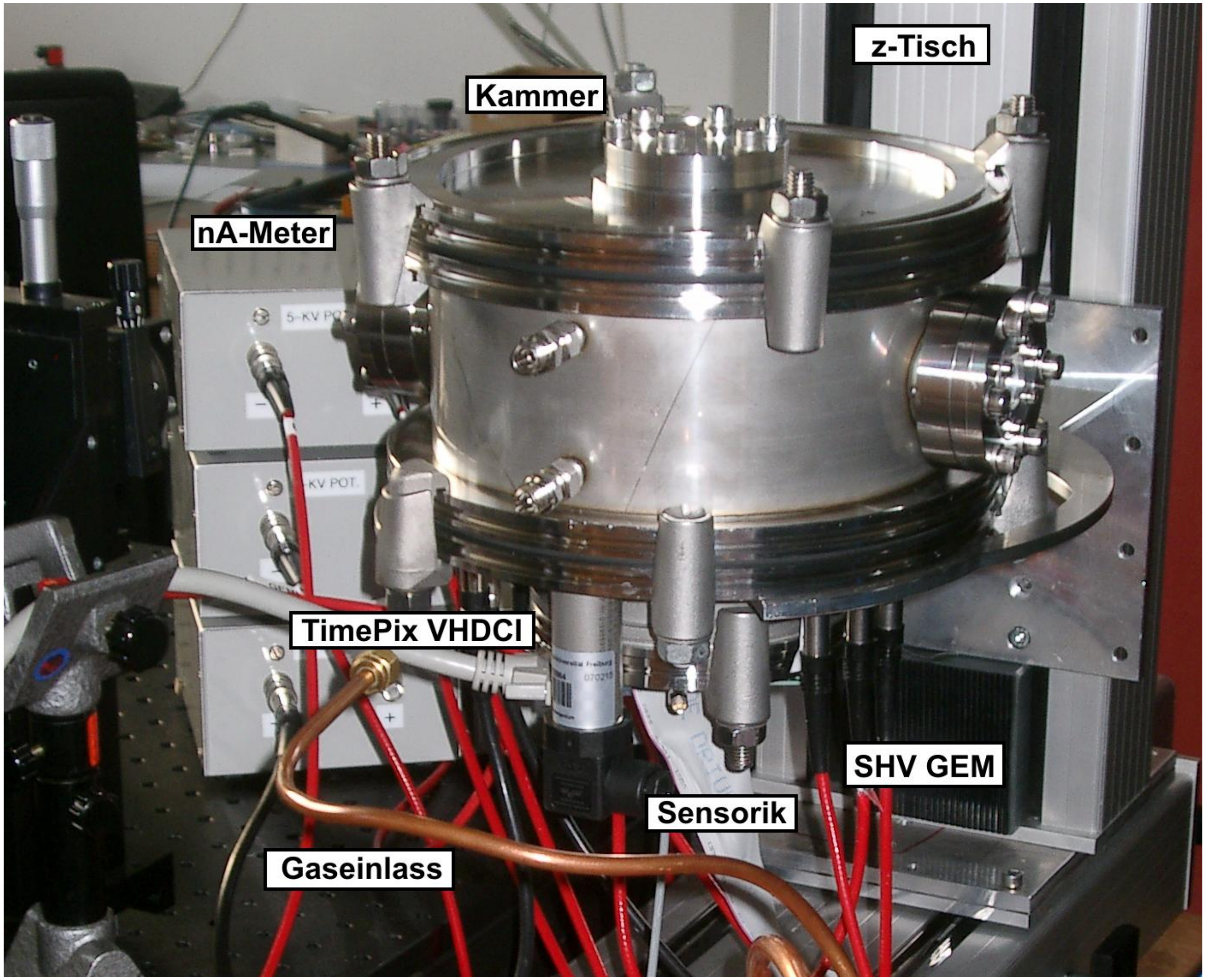


Passivated pixel cross-talk

Ratio of clusters with cross-talk vs. average deposited charge

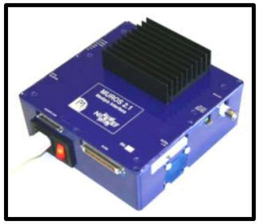


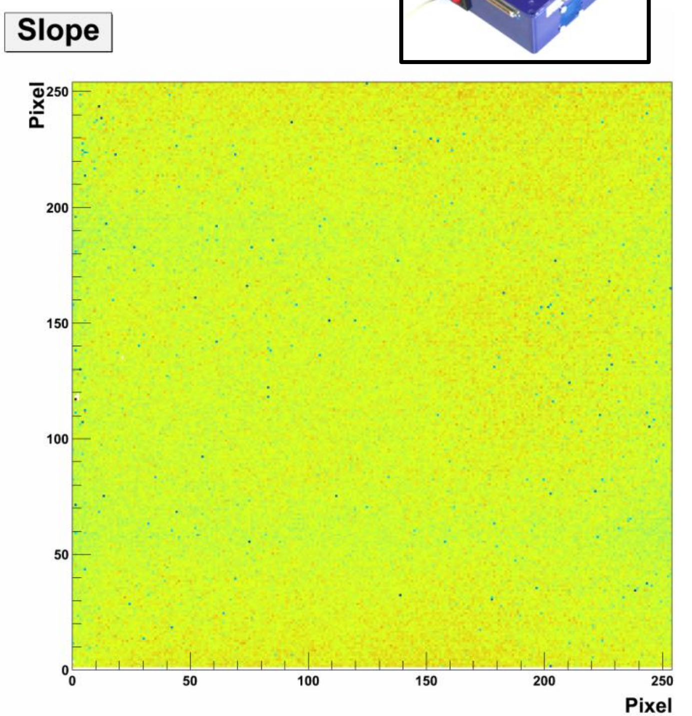
In laboratory



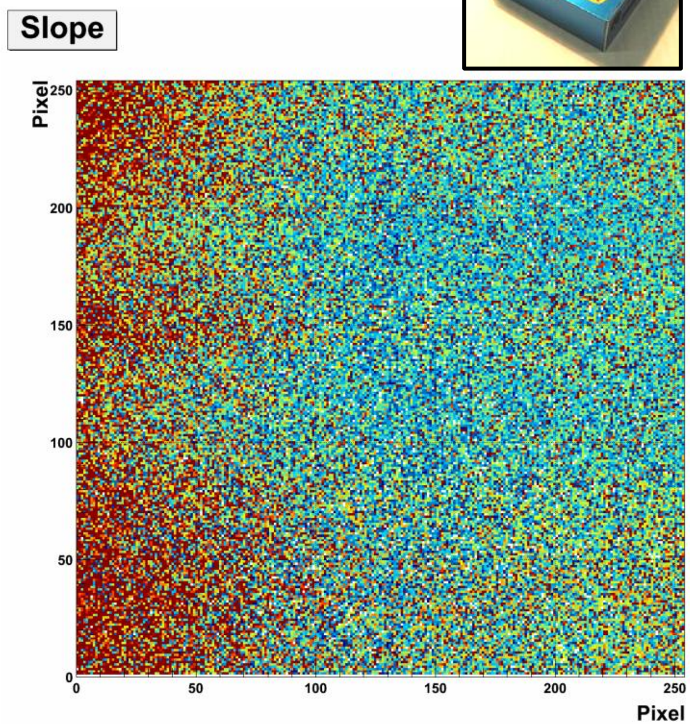
Muros and USB interface

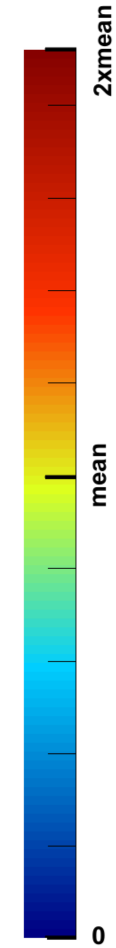
MUROS





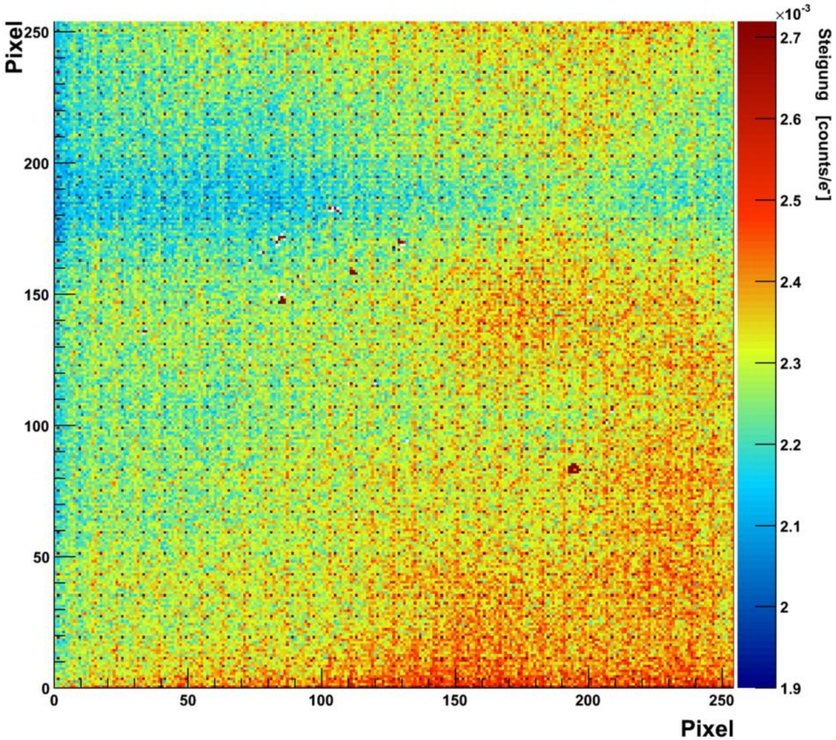
USB



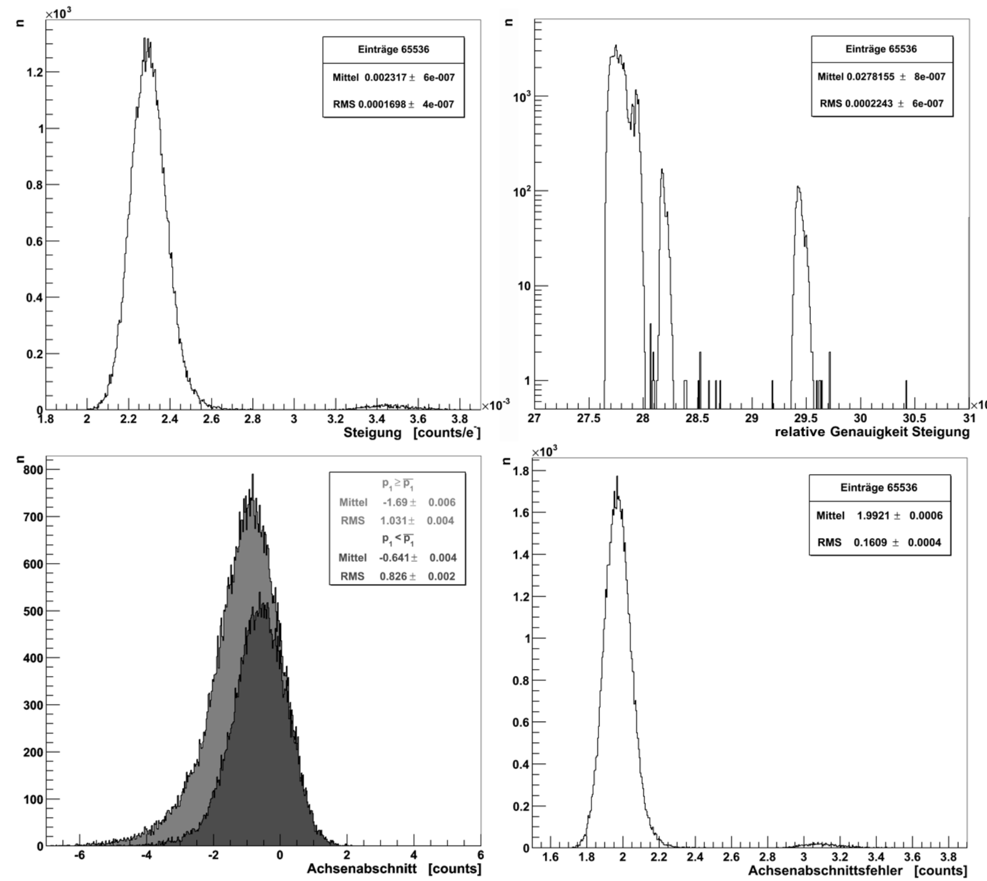


USB Interface(1.2.2): calibration with test pulses not possible

1x1 – slope distibution

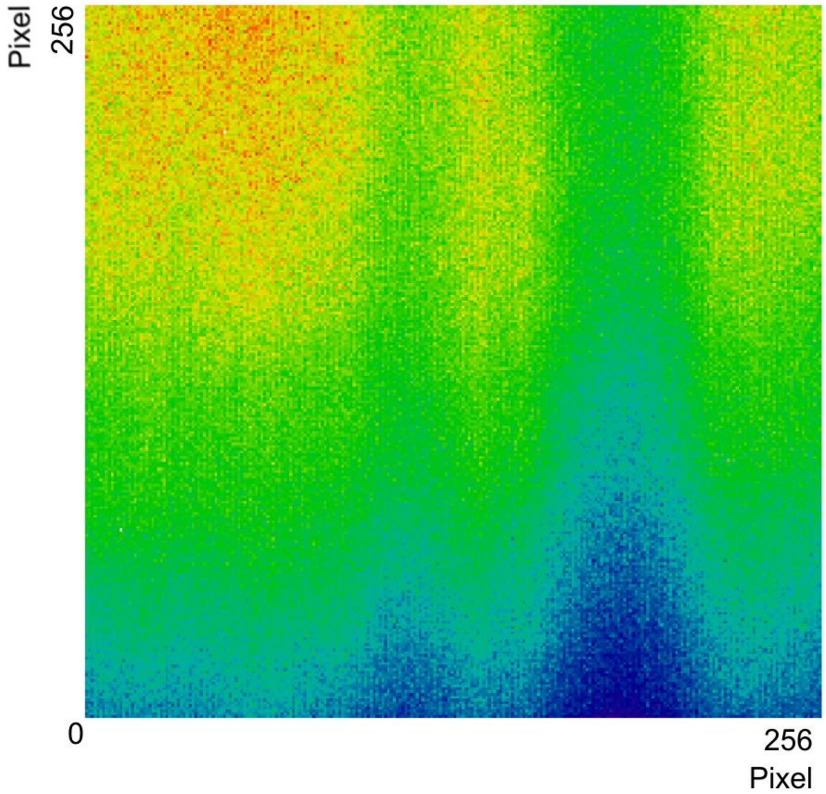


slope | slope error



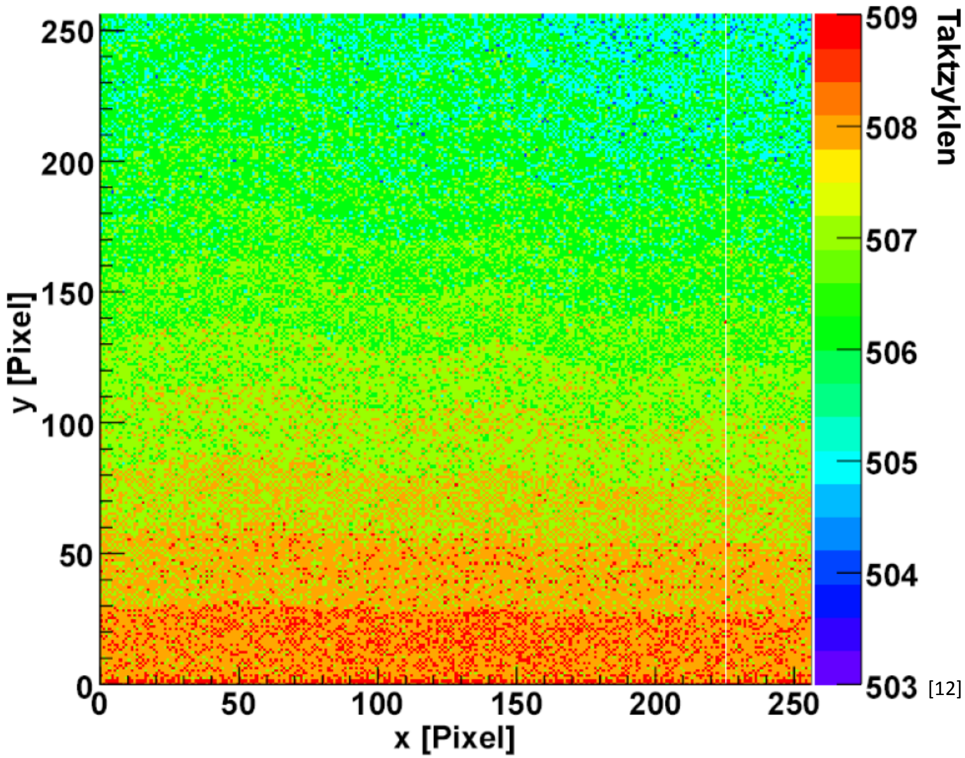
offset | offset error

Oberserved pixel variations



[11]

Spacial distribution of selectable threshold ranges for each pixel (blue = small, red = large)



[12]

Spacial distribution of signal time delays for each pixel (blue = small, red = large)