High-Rate Capable Micromegas Detectors for Ion Transmission Radiography Applications

Jona Bortfeldt et al.

LS Schaile
Ludwig-Maximilians-Universität München

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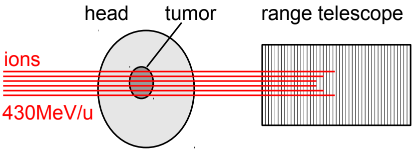
Katia Parodi: Motivation and Requirements

Ion Transmission Radiography

- ions with known initial energy, higher than in therapy
- residual energy measurement
  → energy loss
  → contrast



Present Setup at HIT

- mean particle position from steering magnets (carbon beam ∼3.4 mm FWHM)
- integrate over several 10^2 to 10^4 particles

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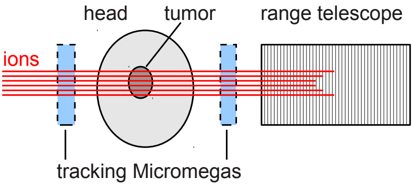

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- mean particle position from steering magnets (carbon beam ∼3.4 mm FWHM)
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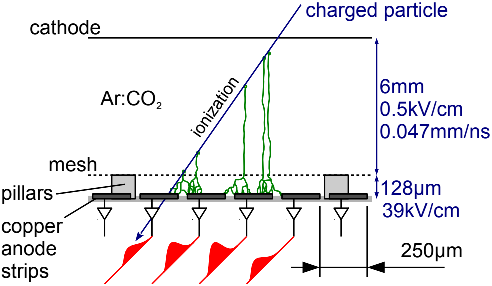
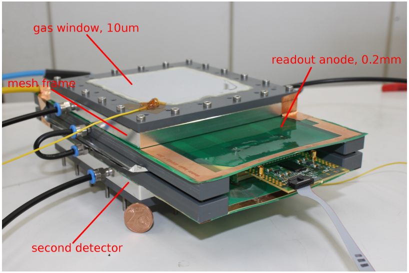
Future

- single particle tracks from Micromegas
  - spatial resolution ∼0.1 mm
  - MHz/cm^2 particle rate (multi-hit separation, signal duration)
  - low material budget
- single particle range/energy from suitable telescope
  - scintillator based
  - maximum rate $\mathcal{O}$(MHz)

→ improve spatial resolution, decrease dose

The Micromegas Detector

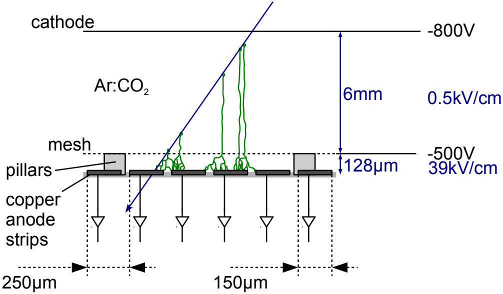




- gas amplification 10^3 to 10^4
- charge signal on strips
  single strip readout
  → spatial resolution $\mathcal{O}$(50µm)
  → timing $\mathcal{O}$(ns)
- thin amplification gap & fine segmentation
  → fast drain of positive ions
  → high-rate capable

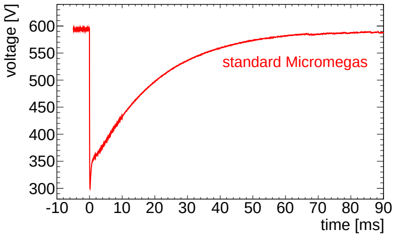
- COMPASS: precision tracker, high flux
- CAST: photon detector, good energy resolution, low background
- T2K: TPC readout, large area

Floating Strip Micromegas

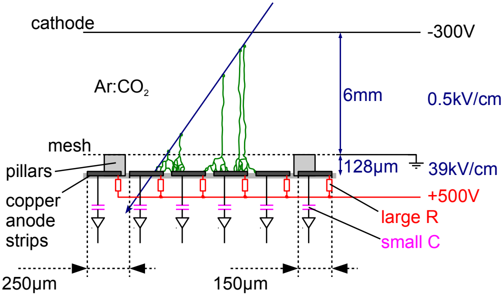


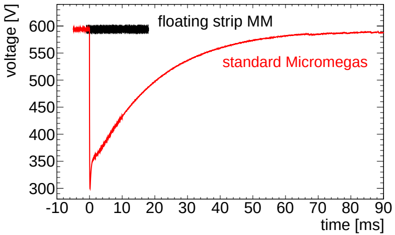
challenge: discharges

- charge density $\geq 2 \times 10^6\,\mathrm{e}/0.01\,\mathrm{mm}^2$ (Raether limit)
- conductive channel
  $\rightarrow$ potentials equalize
- non-destructive,
  but dead time
  $\rightarrow$ efficiency drop



Floating Strip Micromegas





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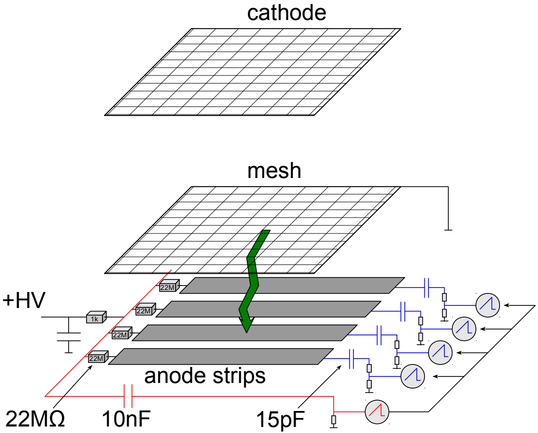
idea: minimize the affected region

- "floating" copper strips:
  - strip can "float" in a discharge
  - individually connected to HV via 22MΩ
  - capacitively coupled to readout electronics via pF HV capacitor
  - only two or three strips need to be recharged

$\rightarrow$ optimization in dedicated measurements & detailed simulation

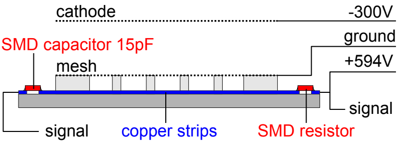
Discharge Study with Floating Strip Micromegas



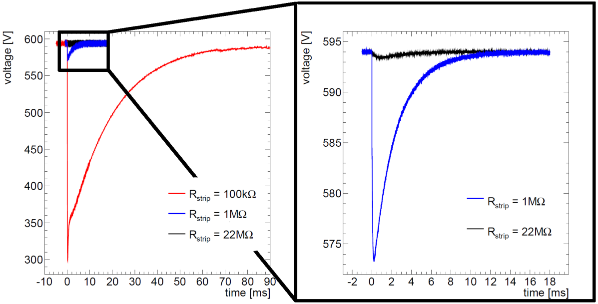
- alpha source
  → induces discharges
- voltage drop on one to three strips
  → recharge current
- global high voltage drop
  → affects all strips
- voltage signal on seven neighboring strips
  → discharge topology

Optimization of the Floating Strip Principle

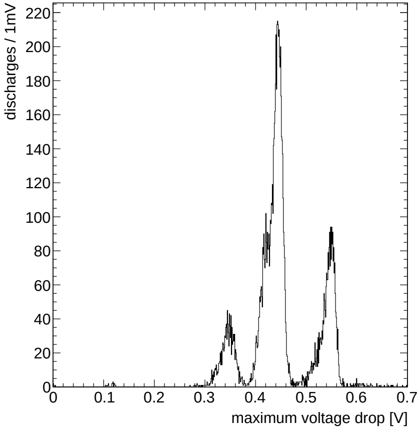
- standard Micromegas (approximate): 100 kΩ
  300 V drop, dead time ∼80 ms
- intermediate: 1 MΩ
  20 V drop, dead time ∼10 ms
- floating strip: 22 MΩ
  0.5 V drop → negligible



measured average voltage pulse

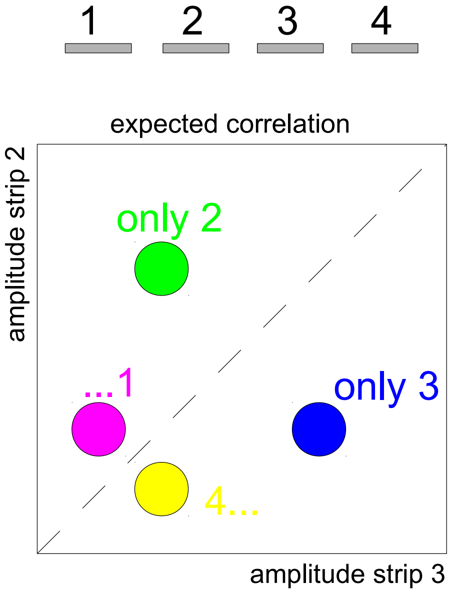


Detailed Investigation of the Global Voltage Drop



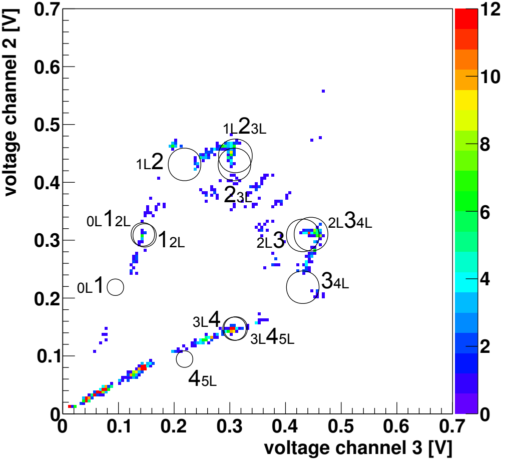
- measure voltage drop of common HV potential
- discrete structure
  $\rightarrow$ probably corresponds to discharge of one, two or three strips
- how can we show this?
  $\rightarrow$ investigate discharge topology
  $\rightarrow$ develop simulation
  $\rightarrow$ compare predicted with measured voltage drop

Discharge Topology - Expected Amplitude Correlation

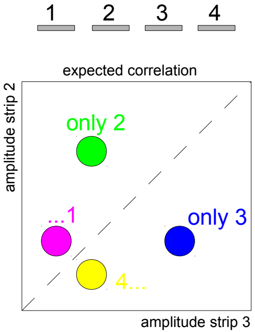


- measure voltage signal on neighboring strips
- two reasons for signals on strips:
  - discharge onto strip
  - capacitive coupling from neighboring strips

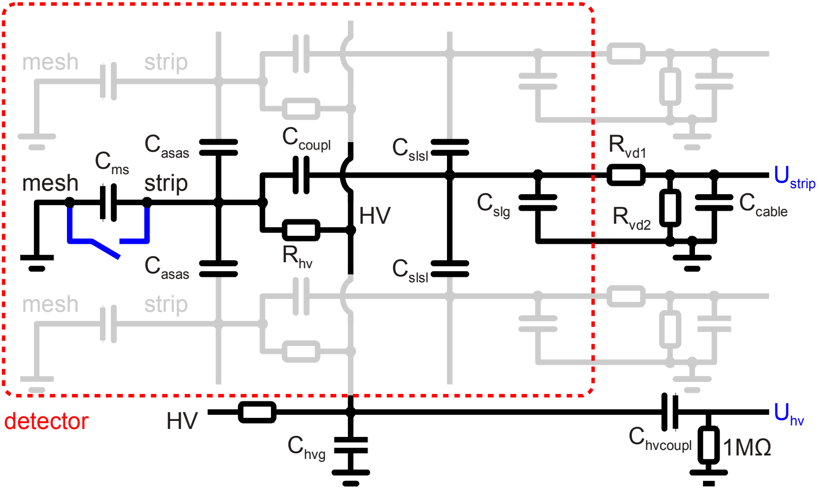
Discharge Topology - One Strip



- discharges on separate strips distinguishable
- substructure quantitatively described by simulation

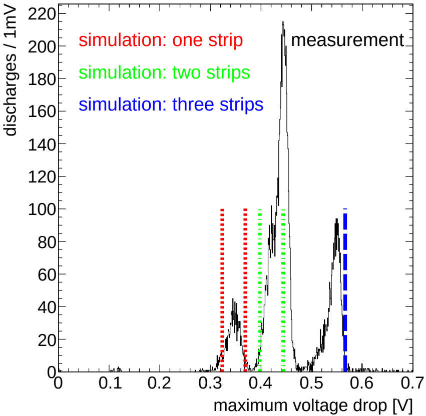


LTSpice Detector Simulation



- consider the involved capacitances e.g. between neighboring strips, coupling capacitors, cable capacitance ...
- simulate discharges (blue switch)

Optimum Configuration: Global Voltage Drop



- good agreement between simulation and measurement
- only two free parameters
  - response time of HV supply: 500 ms
  - voltage difference between strips at which leakage stops: 220 V
- peaks correspond indeed to discharge of one, two or three strip

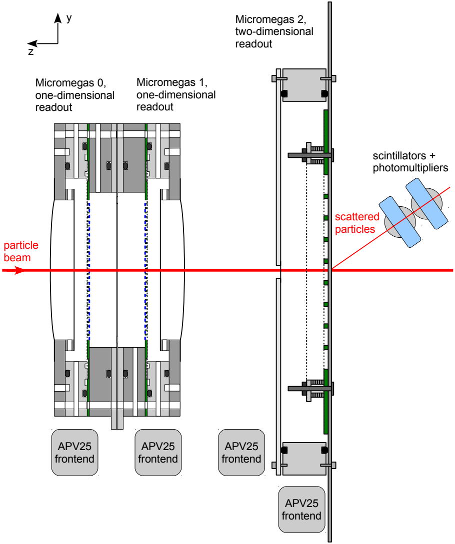
floating strip principle works

- discharges: negligible effect on common high-voltage
- discharges are localized

measurements

- ion tracking at highest rates at HIT – Micromegas tests
- gas studies and µTPC reconstruction at Tandem/Garching
- first test of a 2d ion radiography system at Tandem/Garching

Ion Tracking with Thin Micromegas at Highest Rates @ HIT



beams

- ^{12}C @ 88 MeV/u to 430 MeV/u
  2 MHz to 80 MHz
- p @ 48 MeV to 221 MeV
  80 MHz to 2 GHz
- thanks to S. Brons and the HIT accelerator team for the support

floating strip Micromegas

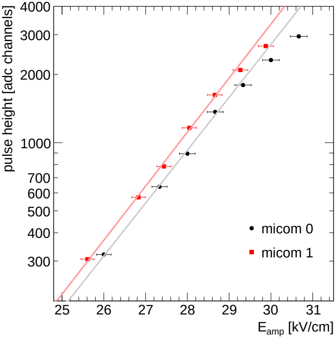
- $6.4\times6.4\,\mathrm{cm}^2$ doublet
- low material budget
  (FR4 + Cu $\leq$ 200 µm)
- Ar:CO_2 93:7 gas mixture

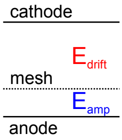
additional detectors

- $9\times9\,\mathrm{cm}^2$ monitoring Micromegas with x-y-readout
- trigger on secondary charged particles

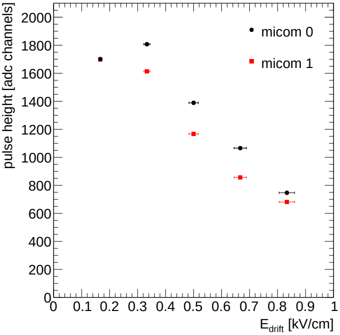
Pulse Height for 88 MeV/u ^{12}C

pulse height vs E_{amp}





pulse height vs E_{drift}



- exponential rise as expected (Townsend theory)
- gas gain can be selected over wide range as needed
- $30\,\mathrm{kV/cm} \mathrel{\hat{=}} 450\,\mathrm{V}$

$E_{\mathrm{drift}} < 0.15\,\mathrm{kV/cm}$:

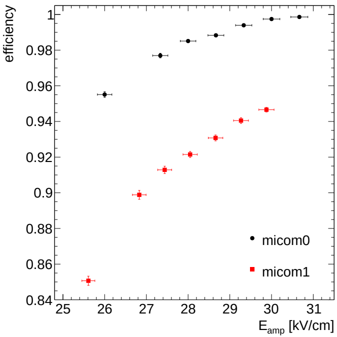
- low charge separation
- low drift velocity

large $E_{\mathrm{drift}} > 0.5\,\mathrm{kV/cm}$:

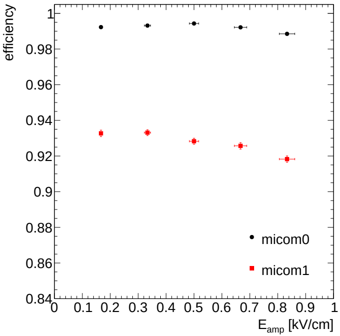
- low electron mesh transparency

Efficiency for 88 MeV/u ^{12}C

efficiency vs E_{amp}



efficiency vs E_{drift}



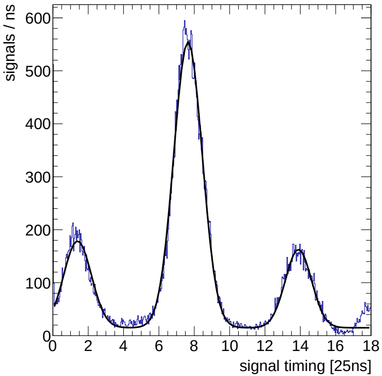
optimum value:

$>$ 99% in micom0

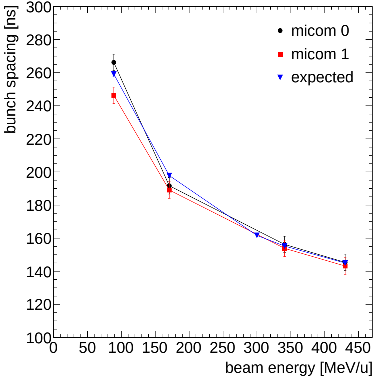
$>$ 94% in micom 1 due to production fault

Beam Characterization

signal timing ^{12}C, 5×10^6 Hz



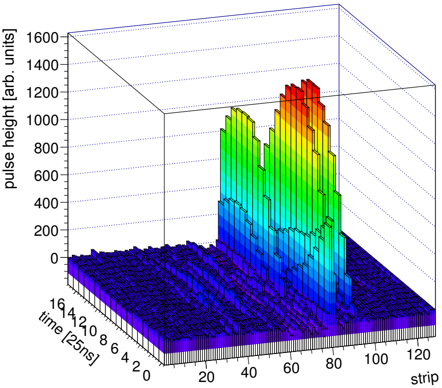
bunch spacing



- good multihit resolution
- bunch spacing measureable
- bunch filling measureable

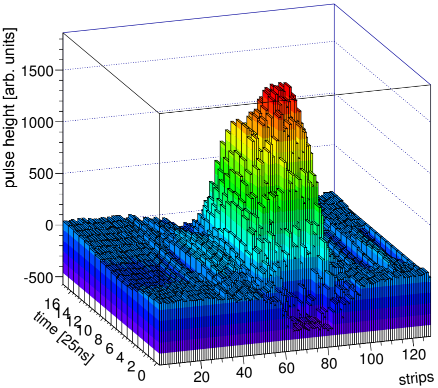
Signals at Lowest and Highest Rate

^{12}C, E = 430 MeV/u, 5 MHz



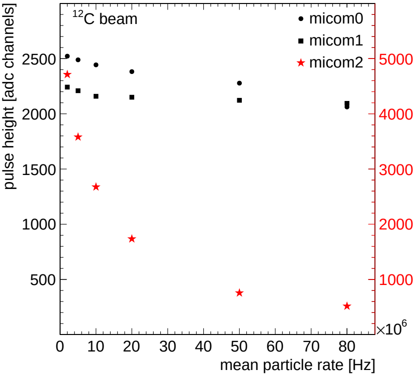
3 particles clearly distinguishable
→ single particle tracking possible

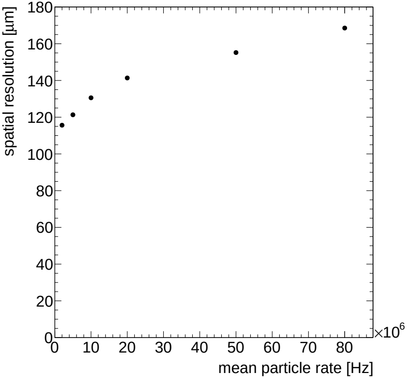
p, E = 221 MeV, 2 GHz



integration over ∼ 800 coincident particles
→ envelope of beam profile

Pulse Height & Spatial Resolution vs Rate for 88 MeV/u ^{12}C



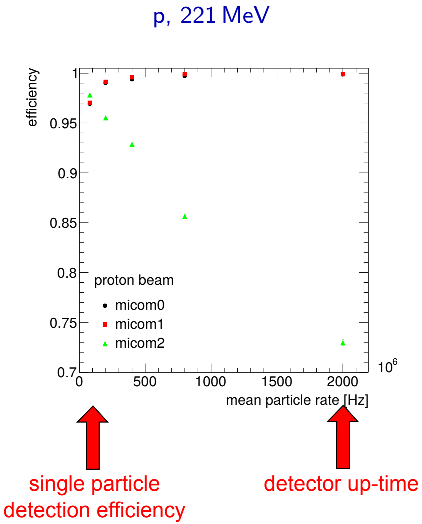


- up to 80 MHz single particle tracks visible but not all of them separable
- only 20% pulse height reduction @ 80 MHz

- highest rates: slight distortion of hit position by hits on adjacent strips
- limited by multiple scattering
- sufficient for medical application

→ tracking of carbon ions at highest rates possible

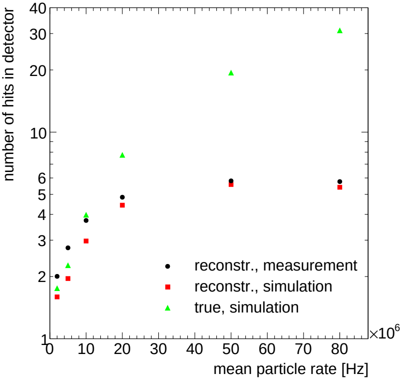
Detection Efficiency and Up-Time



→ no efficiency & up-time reduction in floating strip Micromegas

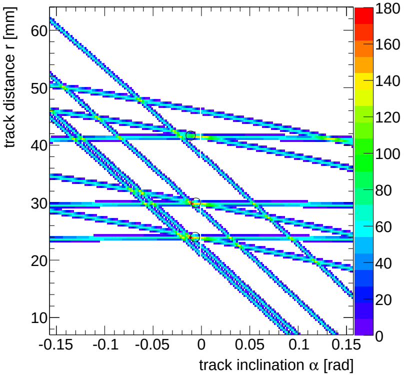
Rate Capability & Multi-hit Resolution

reconstructed hits per multi-event



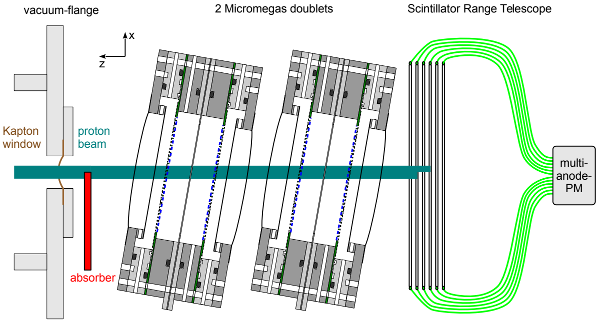
- reconstruction of all particles up to $10\,\mathrm{MHz} = 7\,\mathrm{MHz/cm^2}$

track finding algorithm



- Hough transform: $d = x \cdot \cos(\alpha) + z \cdot \sin(\alpha)$
  point in position space ⇔ line in Hough space
  line in position space ⇔ point in Hough space
- up to seven coincident tracks reconstructable

23 MeV Proton Tracking at the Tandem/Garching



floating strip Micromegas

- two 6.4×6.4 cm^2 doublets, 128 strips
- low material budget (FR4 + Cu ≤ 200 μm)
- APV25 based readout

range telescope

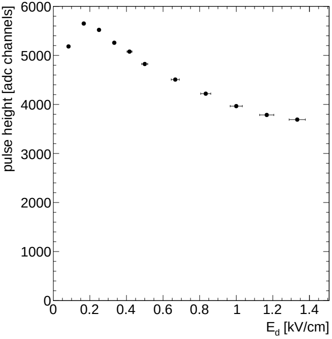
- 13 layers 1 mm scintillator
- two wavelength-shifting fibers per layer
- read out with 64 pixel multi-anode photomultiplier
- discrete voltage & spectroscopy amplifiers
- VME based QDC & TDC readout system

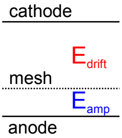
goal

- further improve Micromegas high-rate capability
  ↔ decrease signal duration
  → fast Ne:CF_4 gas mixtures
- investigate single plane track inclination reconstruction
- commission range telescope
- test custom amplifier electronics

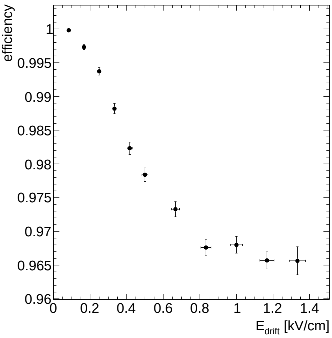
Pulse Height and Efficiency for Ne:CF_4 80:20

pulse height vs E_{drift}





efficiency vs E_{drift}

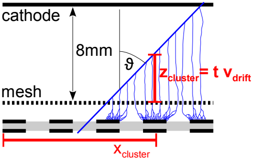


- high gas gain
- low diffusion
  → moderate decrease with increasing drift field

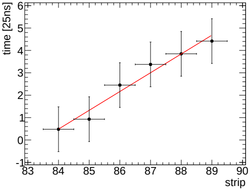
- above 96% for all drift fields

→ excellent performance with new mixture

Track Inclination Reconstruction in a Single Detector Plane



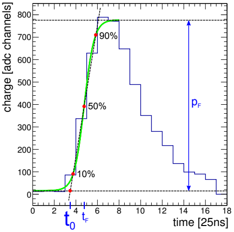
linear fit to data points



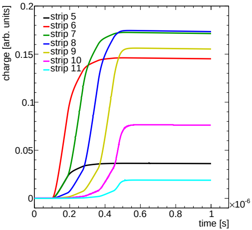
method:

- arrival time ↔ drift distance
- measure arrival time of charge cluster on strip
  → signal timing t_0
- linear fit to time-strip data points
  → track inclination
  → alternative hit position
  → drift velocity

rise time fit



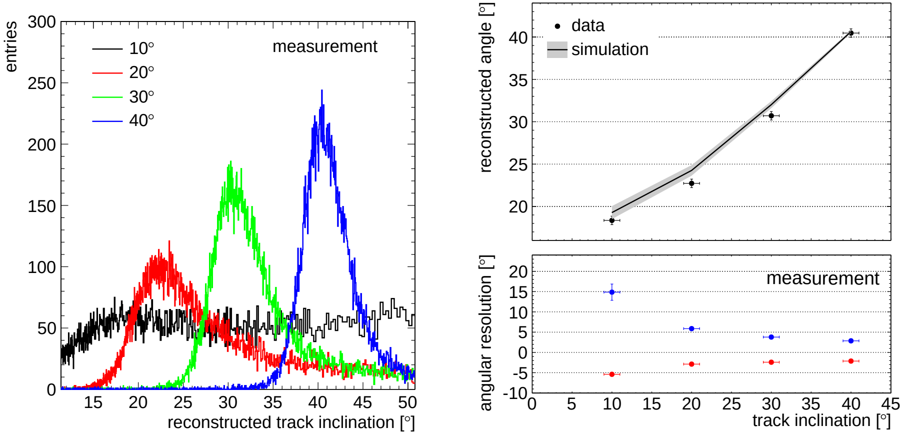
simulated signals



systematics:

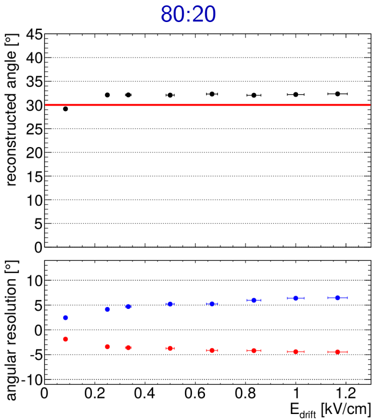
- capacitive coupling of signals onto neighboring strips
- simulation with parameter-free LTSpice detector model

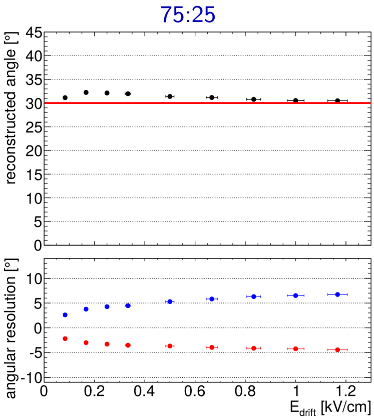
Track Inclination Measurement in a Single Detector Plane with Ar:CO_2 93:7



- track inclination reconstruction possible for angles $20^\circ \leq \vartheta \leq 40^\circ$ with angular resolution $\left(^{+6}_{-4}\right)^\circ$
- systematic effect understood → calibration possible
- combined position reco possible (µTPC + centroid)

Track Inclination Measurement with the New Gas Ne:CF_4

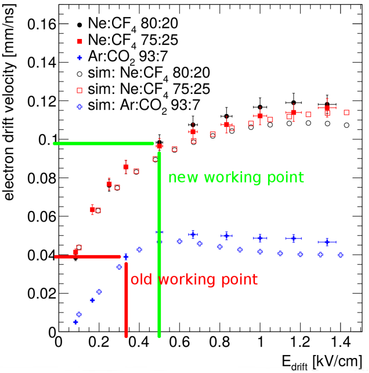




- track inclination reconstruction possible with fast Ne:CF_4 gas mixture
- angular resolution $\left(^{+5}_{-4}\right)^\circ$ for $E_\text{drift} < 0.6\,\text{kV/cm}$

Improvement of High-Rate Capability with Ne:CF_4

measured electron drift velocity

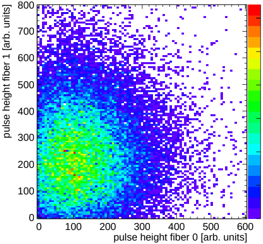


- signal duration = electron drift time + ion drift time
- electron drift time: 150 ns → 60 ns
- ion drift time: 260 ns → 85 ns

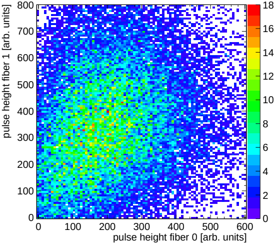
→ factor 3 improvement

Range Telescope Commissioning – Pulse Height Behavior

proton traverses layer
→ constant energy loss

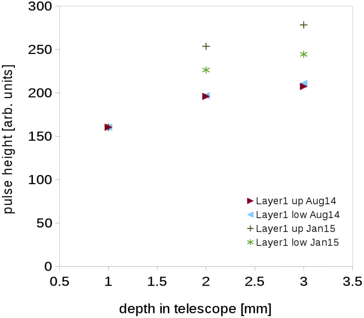


proton stops in layer
→ variable energy loss



only 0.1% of the photons detectable
→ $\sim 30 \pm 10$ photons
→ $\Delta E_{\mathrm{FWHM}}/E \sim 1$

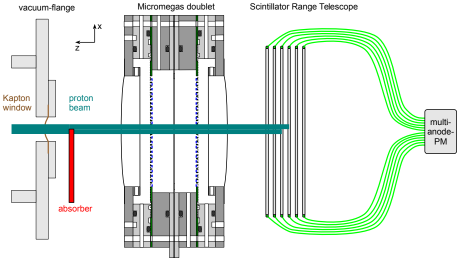
mean pulse height vs depth



- pulse height increases less than expected
- probably considerable quenching

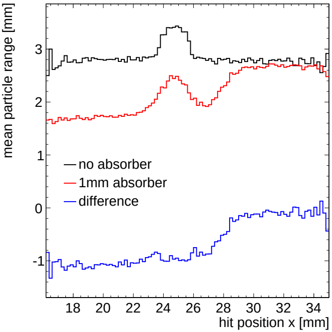
→ difficult to use pulse height information
→ rather use hit/miss info

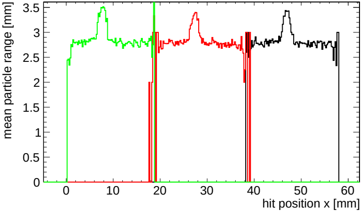
Range Telescope Commissioning – One-Dimensional Position Resolution



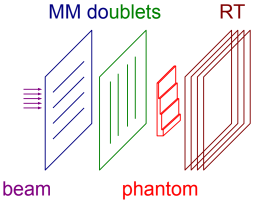
- Tandem beam not mono-energetic
  → use additional collimators behind bending dipole
- mean range homogeneous over detector
- absorber edge visible
  track resolution ∼ 0.8 mm due to multiple scattering

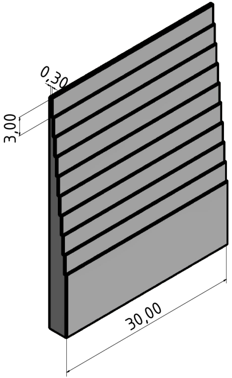
mean range vs position

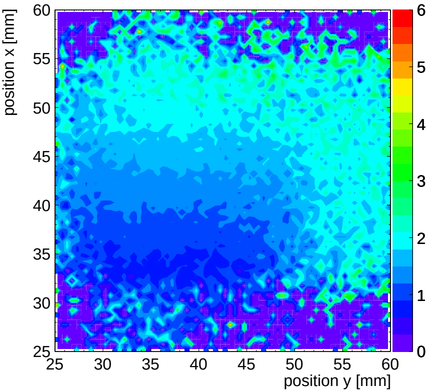




First Two-Dimensional Ion Radiography







- PLA step phantom visible

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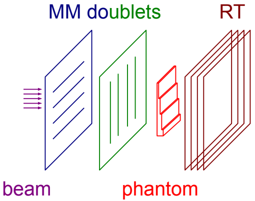

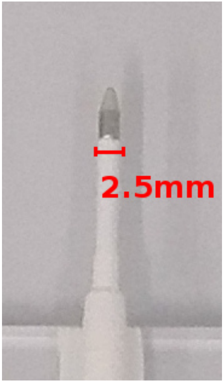

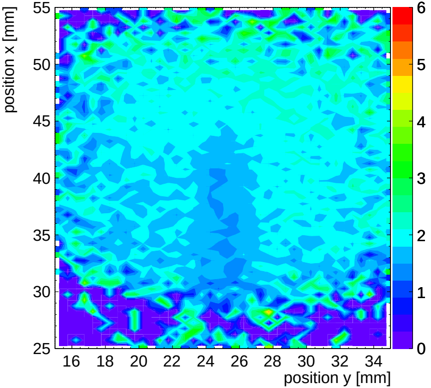

- PLA step phantom visible
- ball point pen visible
- spatial resolution limited by multiple scattering
- resolution improvable by additional MM layers

Summary

- floating strip Micromegas were optimized and work
- discharges:
  - behavior and topology understood
  - negligible influence on efficiency
- carbon ion and proton tracking at highest rates at HIT
  - separation of all particles at rates $\leq$10 MHz
  - spatial resolution better 180 µm at all rates $\leq$80 MHz
  - stable operation up to highest rates of 2 GHz
- 23 MeV proton tracking at Tandem/Garching
  - successful: fast Ne:CF_4 gas mixture
    $\rightarrow$ decrease signal duration by factor 3
  - single plane track inclination reconstruction possible
- Micromegas + scintillator range telescope in 23 MeV proton beams
  - single particle range determination using hit/miss information
  - first 2d ion radiography successful
  - spatial resolution limited by multiple scattering

floating strip Micromegas:
discharge tolerant, high-rate capable tracking detectors with good spatial resolution
$\rightarrow$ suitable for medical applications

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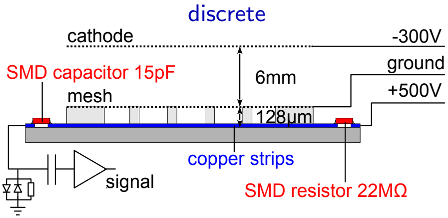
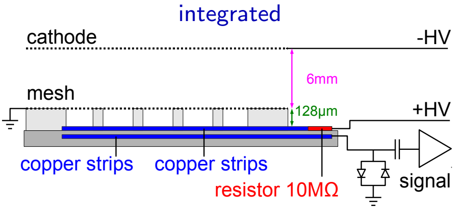
Thank you!

backup – Discrete & Integrated Floating Strip Micromegas

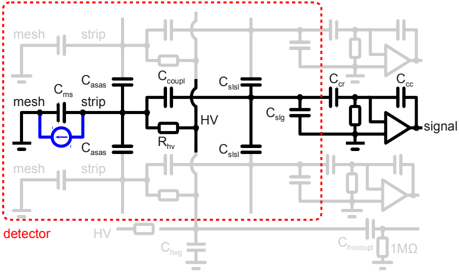




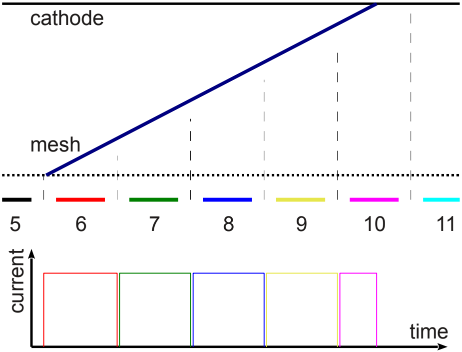
- exchangable Rs and Cs
  → optimization possible
- more complicated assembly
  → soldering ×2 for each strip
- space requirements due to HV sustaining components
  → strip pitch limited to 0.5 mm

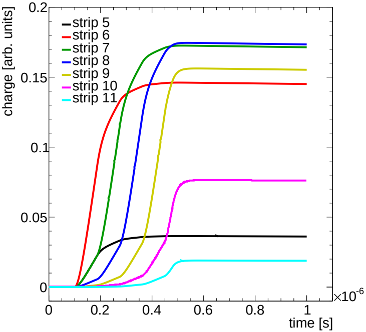
- anode strips: connected to HV via printable paste resistors
- readout strips: second layer of copper strips
  capacitive coupling through the board, intrinsically HV sustaining

backup – Track Inclination Reconstruction Systematics: LTSpice-Simulation

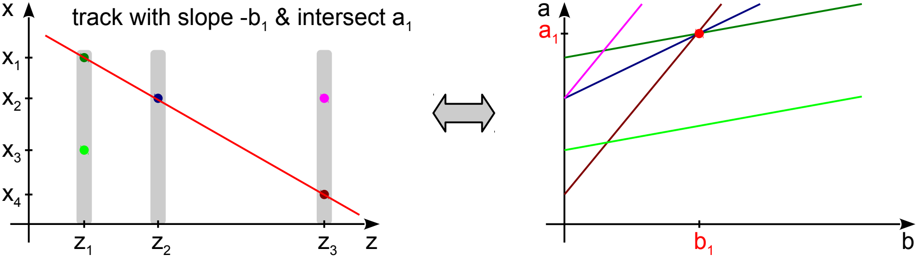


- use LTSpice to simulate 16 neighboring strips, read out via charge-sens.-preamps
- consider mesh-anode strip, anode strip-ground, anode strip-anode strip, coupling, stripline-stripline and stripline-ground capacitance, no free parameter
- inject time dependent current on anode strips → study signals on all other strips





backup – Hough Transform Based Track Building



point in position space (z_i,x_i) ⟺ line in Hough space $a = z_i b + x_i$

line in position space $x = -b_j z + a_j$ ⟺ point in Hough space (b_j,a_j)

- for improved stability: use Hesse normal form as transform function
- up to seven valid tracks reconstructed per event