High-Rate Capable Micromegas Detectors for Ion Transmission Radiography Applications

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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 \(\sim 3.4\) mm FWHM)
- integrate over several \(10^2\) to \(10^4\) particles
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**Future**

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

→ improve spatial resolution, decrease dose
The Micromegas Detector

- gas amplification $10^3$ to $10^4$
- charge signal on strips
  - single strip readout
  - spatial resolution $\mathcal{O}(50\mu m)$
  - timing $\mathcal{O}(\text{ns})$
- 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 $\geq 2 \times 10^6$ e/0.01 mm² (Raether limit)
- conductive channel $\rightarrow$ potentials equalize
- non-destructive, but dead time $\rightarrow$ efficiency drop

![Diagram of Floating Strip Micromegas]

- cathode
- mesh
- pillars
- copper anode strips
- Ar:CO$_2$

- $-800$ V
- $0.5$ kV/cm
- $6$ mm
- $128$ μm
- $-500$ V
- $39$ kV/cm

![Graph of voltage vs. time]

- voltage [V]
- time [ms]

- standard Micromegas

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Floating Strip Micromegas Principles

**Challenge:** Discharges

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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

Diagram:
- Cathode
- Mesh
- Anode strips
- 22MΩ
- 10nF
- 15pF
- +HV

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Optimization of the Floating Strip Principle

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

measured average voltage pulse
Detailed Investigation of the Global Voltage Drop

- measure voltage drop of common HV potential
- discrete structure
  → probably corresponds to discharge of one, two or three strips
- how can we show this?
  → investigate discharge topology
  → develop simulation
  → 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
• 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
- $^{12}\text{C} \atop @\ 88\text{ MeV/u}$ to $430\text{ MeV/u}$
  - $2\text{ MHz}$ to $80\text{ MHz}$
- $p \atop @\ 48\text{ MeV}$ to $221\text{ MeV}$
  - $80\text{ MHz}$ to $2\text{ GHz}$
- thanks to S. Brons and the HIT accelerator team for the support

floating strip Micromegas
- $6.4\times6.4\text{ cm}^2$ doublet
- low material budget
  - (FR4 + Cu $\leq 200\ \mu\text{m}$)
- Ar:CO$_2$ 93:7 gas mixture

additional detectors
- $9\times9\text{ cm}^2$ monitoring Micromegass with x-y-readout
- trigger on secondary charged particles
Pulse Height for 88 MeV/u $^{12}$C

**pulse height vs $E_{\text{amp}}$**

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

**pulse height vs $E_{\text{drift}}$**

- $E_{\text{drift}} < 0.15 \text{kV/cm}$:
  - low charge separation
  - low drift velocity
- large $E_{\text{drift}} > 0.5 \text{kV/cm}$:
  - low electron mesh transparency
Efficiency for 88 MeV/u $^{12}$C

**efficiency vs $E_{\text{amp}}$**

**efficiency vs $E_{\text{drift}}$**

optimum value:

> 99% in micom0

> 94% in micom 1 due to production fault
Beam Characterization

signal timing $^{12}\text{C}$, $5 \times 10^6$ Hz

- good multihit resolution
- bunch spacing measurable
- bunch filling measurable
Signals at Lowest and Highest Rate

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

$p, \ E = 221 \text{ MeV}, \ 2 \text{ GHz}$

3 particles clearly distinguishable → single particle tracking possible

integration over $\sim 800$ 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

$p$, 221 MeV

→ no efficiency & up-time reduction in floating strip Micromegas
Rate Capability & Multi-hit Resolution

- reconstruction of all particles up to 10 MHz = 7 MHz/cm²

- Hough transform: \( d = x \cdot \cos(\alpha) + z \cdot \sin(\alpha) \)
  - point in position space \( \Leftrightarrow \) line in Hough space
  - line in position space \( \Leftrightarrow \) point in Hough space

- up to seven coincident tracks reconstructable
23 MeV Proton Tracking at the Tandem/Garching

floating strip Micromegas
- two $6.4 \times 6.4 \text{ cm}^2$ doublets, 128 strips
- low material budget (FR4 + Cu $\leq 200 \mu \text{m}$)
- 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
  $\leftrightarrow$ decrease signal duration
  $\rightarrow$ 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

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

→ excellent performance with new mixture

- above 96% for all drift fields
Track Inclination Reconstruction in a Single Detector Plane

**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

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

![Diagram showing cathode, mesh, and cluster with equations: $z_{\text{cluster}} = t v_{\text{drift}}$, $x_{\text{cluster}}$, and graphs for linear fit to data points, rise time fit, simulated signals, charge vs. time, and rise time for strips 5 to 11.](image)
Track Inclination Measurement in a Single Detector Plane with Ar:CO₂ 93:7

- Track inclination reconstruction possible for angles $20^\circ \leq \vartheta \leq 40^\circ$ with angular resolution $(^{+6}_{-4})^\circ$
- Systematic effect understood $\rightarrow$ calibration possible
- Combined position reco possible ($\mu$TPC + centroid)
Track Inclination Measurement with the New Gas Ne:CF$_4$

- track inclination reconstruction possible with fast Ne:CF$_4$ gas mixture
- angular resolution ($^{+5}_{-4} \degree$) for $E_{\text{drift}} < 0.6$ kV/cm
Improvement of High-Rate Capability with Ne:CF$_4$

- signal duration = electron drift time $+$ ion drift time
- electron drift time: 150 ns $\rightarrow$ 60 ns
- ion drift time: 260 ns $\rightarrow$ 85 ns
$\rightarrow$ 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
→ \( \Delta E_{\text{FWHM}} / E \sim 1 \)

- 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 $\sim 0.8$ mm due to multiple scattering

<table>
<thead>
<tr>
<th>hit position x [mm]</th>
<th>mean particle range [mm]</th>
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<tbody>
<tr>
<td>18</td>
<td>0</td>
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<tr>
<td>20</td>
<td>0.5</td>
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<tr>
<td>22</td>
<td>1</td>
</tr>
<tr>
<td>24</td>
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<td>26</td>
<td>2</td>
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<td>2.5</td>
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<td>3</td>
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<td>32</td>
<td>3.5</td>
</tr>
<tr>
<td>34</td>
<td>-1</td>
</tr>
</tbody>
</table>

- mean particle range $[mm]$

- no absorber
- 1mm absorber
- difference

<table>
<thead>
<tr>
<th>hit position x [mm]</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
<th>Integral</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>6020</td>
<td>48.05</td>
<td>5.647</td>
<td>280.7</td>
</tr>
</tbody>
</table>

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First Two-Dimensional Ion Radiography

- PLA step phantom visible

- Ball point pen visible

- Spatial resolution limited by multiple scattering

- Resolution improvable by additional MM layers
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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 $\leq 10 \text{ MHz}$
  • spatial resolution better 180 $\mu\text{m}$ at all rates $\leq 80 \text{ MHz}$
  • 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

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backup – Hough Transform Based Track Building

track with slope \(-b_1\) & intersect \(a_1\)

point in position space \((z_i, x_i)\)  
line in position space \(x = -b_j z + a_j\)  

line in Hough space \(a = z_i b + x_i\)  
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