Development of Floating Strip Micromegas Detectors

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Why Detector R&D for High Energy Physics?

- ATLAS muon spectrometer: New Small Wheel
- High-Lumi-LHC: high-rate background $\mathcal{O}(20 \text{ kHz/cm}^2)$
- large-area Micromegas detectors $\mathcal{O}(\text{m}^2)$
Why Detector R&D for Medical Physics?

• tumor irradiation with ions: accurate dose deposition
Why Detector R&D for Medical Physics?

- tumor irradiation with ions: accurate dose deposition
- ions with known initial energy, higher than in therapy
- residual energy measurement → energy loss → contrast
- Micromegas: track single particles with accuracy < 0.5 mm
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 mm$^2$ (Raether limit)
- conductive channel $\rightarrow$ potentials equalize
- non-destructive, but dead time $\rightarrow$ efficiency drop

Diagram showing cathode, mesh, copper anode strips, pillars, Ar:CO$_2$ gas, and voltage and time measurements.
Floating Strip Micromegas

-300V

Ar:CO₂

0.5kV/cm

6mm

128μm

+500V

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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

→ 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 $\sim 80$ ms
- intermediate: 1 MΩ
  20 V drop, dead time $\sim 10$ ms
- floating strip: 22 MΩ
  0.5 V drop $\rightarrow$ negligible
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

Expected correlation

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- 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

- muon tracking in high-rate background
- tracking of high-energy pions
- tracking of ions at highest rates
Cosmic Muon Tracking under High-Rate Background Irradiation

floating strip Micromegas
- active area: $6.4 \times 6.4 \, \text{cm}^2$
- 128 strips, 300 µm width, 500 µm pitch
- 10 mm drift gap

reference tracking system
- two non resistive Micromegas
- two resistive Micromegas
- $2 \times 3$ trigger scintillators

proton background irradiation
- 20 MeV protons, 550 kHz
- lateral beam spot: $6 \times 0.5 \, \text{cm}^2$
- traverse detector $\rightarrow$ signal on all strips

questions:
- muon identification @ 550 kHz background
- efficiency
- spatial resolution
- stability
Distinguishing Cosmic Muon and Proton Background Signals

Cosmic Muon + Proton Event

- proton produces coincident signals on many strips
- muon signal shape similar to proton
- use reference track for cluster selection

two event classes:
- only muon
- coincident muon and proton → direct influence on signal
Cosmic Muon Tracking in High-Rate Background

**residual distribution**

![Graph showing muon detection and proton contamination](image)

- muon detection in background possible
- occasionally background misinterpreted as muon

**spatial resolution**

![Graph showing spatial resolution](image)

- no indirect effects as e.g. space charge
- only deterioration if muon and proton are coincident

**efficiency**

- expectation for complete blinding: \( \frac{\varepsilon_{\text{irrad}}}{\varepsilon_{\text{no irrad}}} = 0.617 \)
- \( \frac{\varepsilon_{\text{irrad}}}{\varepsilon_{\text{no irrad}}} = 0.709 \)

**stability**

- discharge rate 0.17 Hz
- inefficiency: \( 4.1 \times 10^{-6} \)

→ minimum ionizing particle tracking in high-rate background possible
**50 \times 48 \text{ cm}^2 \text{ Micromegas in 120 GeV Pion Beam @ H6 SPS}**

**floating strip Micromegas**
- 1920 strips, 150 \mu \text{m} width, 250 \mu \text{m} pitch
- 8 mm drift gap
- x-y- and angular scans

**tracking system:**
- six non resistive Micromegas
- two resistive Micromegas
- $2 \times 3$ trigger scintillators

**questions:**
- efficiency
- spatial resolution
- homogeneity
- inclined track reconstruction

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50 × 48 cm² Micromegas in 120 GeV Pion Beam @ H6 SPS

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Pulse Height

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

- exponential rise as expected (Townsend theory)
- gas gain can be selected over wide range as needed
- $37.5 \text{kV/cm} \simeq 480 \text{ V}$

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

- $E_{\text{drift}} < 0.4 \text{kV/cm}$:
  - low charge separation
  - low drift velocity
- $E_{\text{drift}} > 1.0 \text{kV/cm}$:
  - low electron mesh transparency
Efficiency & Drift Field

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

inefficient spots ⇔ pillars

optimum value: $(95 \pm 2)\%$, limited by mesh supporting pillars
Determining the Spatial Resolution

\[ \hat{\text{resid}} = x_{\text{track}} - x_{\text{meas}} \]

- doing this for many tracks
- residual distribution

\[ \sigma_{\text{resid}} = \sqrt{\sigma_{\text{track}}^2 + \sigma_{\text{SR}}^2} \]
Spatial Resolution & Drift Field

- optimum value: $(49 \pm 2) \mu m$
- no strong dependence on absolute pulse height
- resolution $\leftrightarrow$ number of electrons, entering the amplification gap + low diffusion

$\rightarrow$ spatial resolution better $50 \mu m$
Track Inclination Reconstruction in a Single Detector Plane

- **Measurement:** 120 GeV Pion Tracking

- **Method:**
  - arrival time $\leftrightarrow$ 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

- **Systematics:**
  - capacitive coupling of signals onto neighboring strips
  - simulation with parameter-free LTSpice detector model
track inclination reconstruction possible for angles $20^\circ \leq \vartheta \leq 40^\circ$

with angular resolution $(+6^\circ, -4^\circ)$

- systematic effect understood $\rightarrow$ calibration possible

- combined position reco possible ($\mu$TPC + centroid)
Ion Tracking with Thin Micromegas at Highest Rates @ HIT

beams

- $^{12}\text{C}$ @ 88 MeV/u to 430 MeV/u
  2 MHz to 80 MHz
- $^{1}\text{p}$ @ 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

- $6.4 \times 6.4 \text{ cm}^2$ doublet
- low material budget
  ($\text{FR4 + Cu} \leq 200 \mu\text{m}$)

additional detectors

- $9 \times 9 \text{ cm}^2$ monitoring Micromegas with x-y-readout
- trigger on secondary charged particles
Beam Characterization

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

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

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

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

3 particles clearly distinguishable
\rightarrow single particle tracking possible

integration over \(\sim 800\) coincident particles
\rightarrow envelope of beam profile
Pulse Height & Spatial Resolution for 88 MeV/u Carbon Ions

- 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

\[ p, \ 221 \text{ MeV} \]

\[ \text{mean particle rate [Hz]} \]

\[ 0 \]

\[ 500 \]

\[ 1000 \]

\[ 1500 \]

\[ 2000 \]

\[ 6 \]

\[ 10 \]

\[ \times \]

\[ \text{efficiency} \]

\[ 0.7 \]

\[ 0.75 \]

\[ 0.8 \]

\[ 0.85 \]

\[ 0.9 \]

\[ 0.95 \]

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

reconstructed hits per multi-event

\[
\text{number of hits in detector} \times 10^6
\]

\[
\text{mean particle rate [Hz]}
\]

- 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 \( \iff \) line in Hough space

- line in position space \( \iff \) point in Hough space

- up to seven coincident tracks reconstructable
Summary

- floating strip Micromegas were optimized and work discharges:
  - behavior and topology understood
  - negligible influence on efficiency
- cosmic muon tracking in intense proton background possible (≈ 500 kHz/strip)
- high-energy pion tracking using a 48 × 50 cm$^2$ floating strip Micromegas:
  - efficiency > 0.95
  - spatial resolution < 50 µm
  - homogeneous pulse height
- medium-energy carbon ion and proton tracking at highest rates
  - separation of all particles at rates ≤ 10 MHz
  - only 20% pulse height reduction at 80 MHz
  - spatial resolution better 180 µm at all rates ≤ 80 MHz
- stable operation up to highest rates of 2 GHz

floating strip Micromegas:
versatile, discharge tolerant, high-rate capable
tracking detectors with good spatial resolution

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Dorothee Schaile
DFG
Raphaela Bortfeldt
Summary

- floating strip Micromegas were optimized and work
- discharges:
  - behavior and topology understood
  - negligible influence on efficiency
- cosmic muon tracking in intense proton background possible ($\approx 500$ kHz/strip)
- high-energy pion tracking using a $48 \times 50$ cm$^2$ floating strip Micromegas
  - efficiency $>0.95$
  - spatial resolution $<50$ $\mu$m
  - homogeneous pulse height, efficiency & position resolution
- medium-energy carbon ion and proton tracking at highest rates
  - separation of all particles at rates $\leq 10$ MHz
  - only 20% pulse height reduction at 80 MHz
  - spatial resolution better 180 $\mu$m at all rates $\leq 80$ MHz
  - stable operation up to highest rates of 2 GHz

floating strip Micromegas:
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floating strip Micromegas:
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Thank you!
backup – Discrete & Integrated Floating Strip Micromegas

- Discrete:
  - SMD capacitor 15pF
  - mesh
  - copper strips
  - SMD resistor 22MΩ
  - cathode -300V
  - +500V

- Integrated:
  - mesh
  - copper strips
  - resistor 10MΩ
  - cathode -HV

- Anode strips: connected to HV via printable paste resistors
- Readout strips: second layer of copper strips
- Capacitive coupling through the board, intrinsically HV sustaining

- 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
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

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