Charge spreading and RC measurement in T2K Resistive Anode Micromegas

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1. T2K near detector (ND280) upgrade using resistive Micromegas for HA-TPC.

2. Modeling of charge spreading with resistive Micromegas

3. Application of charge spreading model on X-ray data

4. RC results from ERAM data analysis

5. Conclusion
T2K near detector (ND280) upgrade using resistive Micromegas for HA-TPC
The T2K experiment: Tokai to Kamioka

Off-axis angle

Neutrino cartoons by Yuki Akimoto
ND280 measures beam spectrum and flavor composition before the oscillations

- Detector installed inside the UA1/NOMAD magnet (0.2 T)
- A detector optimized to measure $\pi^0$ (P0D)
- An electromagnetic calorimeter to distinguish tracks from showers
- A tracker system composed of:
  
  - 2 Fine Grained Detectors (target for $\nu$ interactions).
    - FGD1 is pure scintillator,
    - FGD2 has water layers interleaved with scintillators
  - 3 vertical Time Projection Chambers: reconstruct momentum and charge of particles, PID based on measurement of ionization

Event display of neutrino interaction in ND280
ND280 upgrade: General Idea

The HA-TPC should at least have the same performance as the current vertical TPCs-

- Average 700µm space resolution (and possibly even better)
- 7-8% energy loss resolution for MIP
- Stability and longevity (>10 years)
HA-TPC: Resistive Micromegas detectors

Resistive MicroMegas detectors achieved thanks to the addition of a resistive layer (DLC)

- Charge sharing between pads $\rightarrow$ More precise position reconstruction
- Better resolution with lower number of pads $\rightarrow$ Cost-effective and compact technology
- Reduced risk of sparks $\rightarrow$ No need for protection circuit on readout electronics
- Allows to put mesh at ground for better E-field uniformity.
- DLC allows smaller RC $\rightarrow$ Larger charge spreading (better spatial resolution)

$R = \text{Surface resistivity}$
$C = \text{Capacitance / unit area}$


Continuous RC network, defined by material properties and geometry, shares evenly the charge among several pads.

Telegrapher's equation:

$$\frac{\partial \rho}{\partial t} = \frac{1}{RC} \left[ \frac{\partial^2 \rho}{\partial r^2} + \frac{1}{r} \frac{\partial \rho}{\partial r} \right]$$

$$\Rightarrow \rho(r,t) = \frac{RC}{2t} e^{-\frac{r^2}{4t}}$$

Developed for ILC-TPC with pad size - 7 * 2 cm$^2$
Modeling of charge spreading with resistive Micromegas
Ingredients for charge spreading model

Transverse diffusion

\[ T(x) = \frac{1}{\sigma_x \sqrt{2\pi}} \exp\left(-\frac{x^2}{2\sigma_x^2}\right) \]

Longitudinal diffusion

\[ L(t) = \frac{1}{\sigma_t \sqrt{2\pi}} \exp\left(-\frac{t^2}{2\sigma_t^2}\right) \]

Electronics Response

\[ R(t) \]

Resistive foil + glue

\[ \rho(x, y, t) = \left(\frac{1}{\sigma \sqrt{\pi h}}\right)^2 \exp\left(-\frac{(x^2 + y^2)}{4th}\right) \]

\[ h = \frac{1}{RC} \]
Electronics Response function

- Each channel of an Electronics card is injected with multiple pulses of different amplitudes.
- Resulting output signals (response of Electronic cards) are fitted with the Electronics response function.

\[ R(t) = A \left[ e^{-w_s t} + e^{-w_s t} \left( \frac{2Q - 1}{2Q + 1} \sin \left( \frac{w_s t}{2} \sqrt{4 - \frac{1}{Q^2}} \right) - \cos \left( \frac{w_s t}{2} \sqrt{4 - \frac{1}{Q^2}} \right) \right) \right] \]

- Parameterized by 2 main variables related to shape of a signal waveform: \( Q \) and \( w_s \).
- Variation in these fit parameters over all the pads was studied to determine if they can be set as constants.

- \( Q = 0.6368 \) fixed (412ns peaking time)
- \( w_s = 0.1951 \)
Ingredients for charge spreading model

Transverse diffusion

\[ T(x) = \frac{1}{\sigma_x \sqrt{2\pi}} \exp\left(-\frac{x^2}{2\sigma_x^2}\right) \]

Longitudinal diffusion

\[ L(t) = \frac{1}{\sigma_t \sqrt{2\pi}} \exp\left(-\frac{t^2}{2\sigma_t^2}\right) \]

Electronics Response

\[ q = \int \rho(t) \, dt \]

Resistive foil + glue

\[ \rho(x, y, t) = \left( \frac{1}{\sigma_t \sqrt{\pi h}} \right)^2 \exp\left(-\frac{(x^2 + y^2)}{4th}\right) \]

\[ h = 1 / RC \]
Charge spreading model

Charge diffusion function:

\[ Q_{pad}(t) = \frac{Q_e}{4} \times \left[ \text{erf}\left(\frac{x_{\text{high}} - x_0}{\sqrt{2} \sigma(t)}\right) - \text{erf}\left(\frac{x_{\text{low}} - x_0}{\sqrt{2} \sigma(t)}\right) \right] \times \left[ \text{erf}\left(\frac{y_{\text{high}} - y_0}{\sqrt{2} \sigma(t)}\right) - \text{erf}\left(\frac{y_{\text{low}} - y_0}{\sqrt{2} \sigma(t)}\right) \right] \]

\[ \sigma(t) = \sqrt{\frac{2t}{RC}} \]

- Obtained from Telegrapher’s equation for charge diffusion.
- Integrating charge density function over area of 1 readout pad.
- Parameterized by 5 variables:
  - \( x_0 \), \( y_0 \): Initial charge position
  - \( t_0 \): Time of charge deposition in leading pad
  - \( RC \): Describes charge spreading
  - \( Q_e \): Total charge deposited in an event

\( x_{\text{H}}, x_{\text{L}} \): Upper and lower bound of a pad in x-direction

\( y_{\text{H}}, y_{\text{L}} \): Upper and lower bound of a pad in y-direction

RC = 60 ns/mm²

\[ Q_e = 4 \ e^– \]
Signal model

- Convolution of charge diffusion function with derivative of electronics response function.

\[ S(t) = q(t) \ast \frac{dR}{dt} \]

RC = 60 ns/mm²
\( Q_e = 24845 e^- \)
Application of charge spreading model in X-ray data
Each pad (1152) of an ERAM placed inside an X-ray chamber is scanned using a robot holding an $^{55}$Fe X-ray source.

- $^{55}$Fe spectrum can be reconstructed using all events in one pad.
- Gain is obtained for a pad by fitting its $^{55}$Fe spectrum. Resolution of $<10\%$ is obtained.

Summing all waveforms in each event and taking amplitude of summed waveform.
Application of Signal model on X-ray data

RC is obtained for a pad by simultaneous fit of waveforms in each event.

Simultaneous fit: Leading pad + Neighbouring pads are fitted simultaneously.

RC = (100.49 ± 1.078) ns/mm²
χ²/Ndf = 1.491

RC = (110.82 ± 1.363) ns/mm²
χ²/Ndf = 1.903

4-waveform simultaneous fit of an X-ray event

3-waveform simultaneous fit of an X-ray event
Results from fitting events in 1 pad

- RC distribution

\[ \chi^2/Ndf \text{ distribution} \]

\[ Q_e \text{ distribution} \]

- Reconstruction of $^{55}$Fe spectrum.

Distribution of charge deposition points ($x_0$, $y_0$)
Dependence of RC and Gain on DLC voltage

- Same pad of an ERAM is scanned at 4 different DLC voltages.

RC v/s DLC voltage

- RC is largely invariant w.r.t DLC voltage.

Gain v/s DLC voltage

- Linear relation between Gain and DLC voltage in log scale.
RC extraction from all ERAM pads

- Fitting process is carried out for all pads to obtain RC map.
- RC is more homogeneous in horizontal direction than in vertical direction.
- RC maps and Gain maps will be used in global event reconstruction algorithm.

$\text{RC}_{\text{mean}} = 112 \text{ ns/mm}^2$

**RC map of ERAM-30**

**RC distribution of ERAM-30**
Validation of Signal model

Very high similarity in Gain maps obtained from 2 different methods.

Gain results serve as validation for Electronics Response function, and robustness of entire model.

Ratio of Gain (of each pad) obtained from 2 different methods

\( \text{Ratio}_{\text{mean}} = 1.037 \)
RC results from ERAM data analysis
Understanding RC map features: Compare with R values

ERAM-01: RC map from fit

ERAM-01: R measurements

- Standard values for majority of ERAMs -
  - DLC resistivity: 400kΩ/□
  - Glue thickness: 150 μm

RC map structures seem to be correlated with R measurements.

DLC resistivity: 400kΩ/□
Glue thickness: 150 μm
Both non-transformed variable maps exhibit key features of RC map with varying degrees of precision.

- Note: Charge deposition point is computed using center-of-charge method
RC maps of two atypical ERAMs

ERAM-18
- DLC resistivity: $200k\Omega/\square$
- Glue thickness: $150 \mu m$

RC mean = 68.98 ns/mm$^2$

ERAM-29
- DLC resistivity: $200k\Omega/\square$
- Glue thickness: 75 $\mu m$

RC mean = 102 ns/mm$^2$

- Half the typical resistivity used for other ERAMs.
- Half the glue thickness used for other ERAMs.

RC results of ERAMs with different DLC resistivity and glue thickness than usual, is coherent with theory.
RC maps of ERAMs used in CERN 2022 test beam

ERAM-07
ERAM-01
ERAM-23
ERAM-02
ERAM-16
ERAM-15
ERAM-10
ERAM-12
RC information of all analyzed ERAMs

- Lower and upper bounds of box: \([\text{Mean} - 25\%, \text{Mean} + 25\%]\) of distribution (50% of values within box).
- Lower and upper bounds of bars: \([\text{Mean} - 49\%, \text{Mean} + 49\%]\) of distribution (98% of values within bars).

DLC resistivity \(\approx 500\, \text{k}\Omega/\square\)

Glue thickness: 150 μm
Mean RC and Gain of all analyzed ERAMs

- No correlation between mean RC and Gain of analyzed ERAMs.
Conclusion

- ND280 upgrade will employ resistive Micromegas for the read-out of HA-TPC, which works on the principle of charge spreading.
  - **28/32 have been fully validated.**
- Charge spreading model is obtained from convolution of charge diffusion function and derivative of electronics response function.
- The model is able to successfully fit waveforms from X-ray data.
  - RC and Gain can be simultaneously extracted from X-ray data.
  - RC and Gain information will be a useful ingredient in the HA-TPC simulation and reconstruction.
  - No correlation seen between mean RC and Gain of all analyzed ERAMs.
- Features visible in RC maps are validated by R measurements of DLC foil and basic-level variables.
- RC results of ERAMs with different DLC resistivity and glue thickness is coherent with theory.

THANK YOU!
Gain extraction from simultaneous fit

- **Charge density:**
  \[
  \rho_D(r,t) = \frac{Q_{\text{primary}} G}{2\pi} \frac{1}{\sigma^2(t)} e^{-\frac{r^2}{2\sigma^2(t)}}
  \]

- **Charge on a pad:**
  \[
  Q_{\text{pad}}(t) = \frac{Q_{\text{primary}} G}{4} \left[ \text{erf} \left( \frac{x_H-X_0}{\sigma(t)\sqrt{2}} \right) - \text{erf} \left( \frac{x_L-X_0}{\sigma(t)\sqrt{2}} \right) \right] \left[ \text{erf} \left( \frac{y_H-Y_0}{\sigma(t)\sqrt{2}} \right) - \text{erf} \left( \frac{y_L-Y_0}{\sigma(t)\sqrt{2}} \right) \right]
  \]

- **Electronics response:** (upto ADC) Dirac impulse response
  \[
  \text{ADC}_{\text{Dirac}}(t) = \frac{4096}{120 \text{ fC}} \frac{F(t)}{F_{\text{Max}}} \quad \text{with} \quad F(t) = e^{-\frac{w_t^2}{2}} + e^{-\frac{w_t^2}{2Q+1}} \left[ \frac{2Q-1}{2Q+1} \sin \left( \frac{w_t t}{2} - \frac{1}{Q} \right) \cos \left( \frac{w_t t}{2} - \frac{1}{Q} \right) \right]
  \]

- Implementing the correspondence- 120 fC ↔ 4096 counts.
- Dirac current pulse carrying 120 fC → ADC(t) impulse response with a maximum amplitude of 4096 counts.
Environmental effects on Gain

- Effect of following environmental conditions, recorded during an X-ray test bench shift, on Gain is studied:

  - An ERAM was scanned twice at two different instances.
    - Gas temperature
    - Chamber pressure
    - Relative gas humidity

  - Gain maps to be corrected in case of significant changes in environmental conditions.

Gain of \(i^{th}\) pad [scan1] vs Condition during \(i^{th}\) pad scan [1]
Gain of \(i^{th}\) pad [scan2] vs Condition during \(i^{th}\) pad scan [2]
Gain and resolution of analyzed ERAMs

Gain distribution
Candle with one bar noticeably longer than the other
ERAM with a problematic region of abnormal Gain (e.g. ERAM-02, ERAM-26)

Resolution distribution
Candle with one bar longer than the other
ERAM with a stiffener structure (e.g. ERAM-09 to ERAM-18)

Gain distribution
Candle with one bar noticeably longer than the other
ERAM with a problematic region of abnormal Gain (e.g. ERAM-02, ERAM-26)

Resolution distribution
Candle with one bar longer than the other
ERAM with a stiffener structure (e.g. ERAM-09 to ERAM-18)
Due to the copper + soldering mask layer, there is an unequal distribution of pressure from stiffener onto the PCB.

This phenomenon causes variations in amplification gap, which in turn alters the gain and worsens the resolution in pads on top of the PCB stiffener.

Replacing copper + soldering mask with a copper mesh fixed this issue.
Gain non-uniformity within a pad

- High-granularity Gain map obtained using simultaneous fit by plotting $(x_0, y_0, \text{Gain})$ for each charge deposition.

- Gain variations seen within pads partly on top of PCB (soldermask + copper) overlay.

- Horizontal stiffener layer causes different gain in upper and lower halves of affected pads.
Discretization of RC

**Zone 1**

- $RC_{set} = 121.59$ ns/mm²
- $RC_{measured} = 121.5$ ns/mm²
- Error = 0.07%

**Zone 2**

- $RC_{set} = 128.8$ ns/mm²
- $RC_{measured} = 122.4$ ns/mm²
- Error = 4.97%
Spatial resolution better than 800 μm and dE/dx resolution better than 10% are observed for all the incident angles and for all the drift distances of interest.