Performances of a resistive MicroMegas module for the Time Projection Chambers of the T2K Near Detector upgrade

César JESÚS-VALLS  cjesus@ifae.es
on behalf of the ND280/HA-TPC collaboration
The T2K experiment
The ND280 Near Detector

- **T2K**: Long baseline neutrino experiment from Tokai to Kamioka.
- **Goals of ND280**:  
  - Measure flux & spectrum of neutrinos before oscillation.
  - Measure $\nu$-nucleus cross-sections.
  - Measure $\nu_e$ contamination.

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K. Abe et al., NIMA 659 (2011), p.106
The ND280 upgrade
Motivations

- Current ND280
  Good acceptance only for forward tracks

- Proposed ND280 upgrade
  2 High-Angle TPCs
  + a new highly granular scintillator detector (Super-FGD)
  + 6 TOF planes surrounding the new tracker

- T2K-II phase:
  - Installation begins in 2021
  - Beam power upgrade (~two-fold)
  - Goal: measure $\delta_{CP}$ at $3\sigma$
    by decreasing of systematic errors in ND280 from 6% to 4%

ND280 upgrade TDR: arXiv:1901.03750v1
The ND280 upgrade
The new HA-TPCs overview

- New HA-TPCs:
  - New field cage. Thin composite material.
  - New readout system. Based on Resistive MicroMegas

- Goal of the TPCs:
  - Particle identification using:
    - ionization (dE/dx)
    - Momentum via curvature (spatial resolution)
The new HA-TPCs readout
The resistive MicroMegas concept

Standard Bulk-MM

Mesh @ ∼ -400V
Amplification gap: ∼128μm
E

FR4 PCB

If a single pad is fired, then resolution:

\[ \sim \text{pad}_{size} \sqrt{12} \]

Resistive Bulk-MM

Mesh @ GND

~128μm
E
DLC@ ∼ +400V
d

Insulator: ∼50μm
Glue: ∼75μm
Pads
FR4 PCB

• Charge dispersion in 2-D RC network
• Gaussian spreading as a function of time

\[
\rho(r, t) = \frac{RC}{2t} e^{-\frac{r^2RC}{4t}} \quad \sigma_r = \sqrt{\frac{2t}{RC}}
\]

R: surface resistivity
C: capacitance/unit area

M. S. Dixit et al., NIMA 518 (2004), p.721
ILC-TPC R&D: P. Colas et al.
Resistive MicroMegas specifications  
For ND280 new HA-TPCs

Two beam tests used 2 different resistive MM modules.

| Name         | CERN TESTS                                      | DESY TESTS                                      |
|--------------|-----------------------------------------------|-----------------------------------------------|
| MM0-DLC#     | MM0 is same layout as current ND280 v-TPCs MicroMegas but with resistive foil. | MM1-DLC#                                       |
| Readout PCB  | Original T2K-TPC                              | HA-TPC                                         |
| Size         | 34 × 36 cm²                                   | 34 × 42 cm²                                   |
| Pads         | 48 × 36 cm²                                   | 32 × 36 cm²                                   |
| Pad size     | 6,85 × 9,65 mm²                               | 10,09 × 11,18 mm²                             |
| Pad number   | 1728                                          | 1152                                          |
| Isolation layers | 75-200 µm glue + 50 µm APICAL                  | 75 m glue + 50 µm APICAL                       |

In total 33% channels reduction!
CERN T9 BEAM TEST
Overview

• Remarks:
  • Without Magnetic Field
  • Not final Field Cage
  • Looking only to beam straight tracks

• Beam Test Goal:
  • Prove of concept
Multi-Particle beam was used
- 0.5-1GeV data
- Gain scan with MM 330-380V
- Different drift distances 10,30,80cm
- Cosmic data for gas monitoring
- $^{55}$Fe source placed at the cathode.

$\pi, e, p$ trigger

Original Event

Selected track
CERN T9 BEAM TEST
Gas quality

- Drift velocity time evolution
- Gain time evolution
- Attenuation length time evolution

- Computed using cosmics crossing anode & cathode
- Computed using the $^{55}$Fe source in the cathode
- Computed using cosmic charge collected vs distance

- No monitoring chambers
- Reduction on gas flow + humidity in HARP TPC decreased gas quality over time.
- Correction factors were computed
CERN T9 BEAM TEST
Gain studies

**55Fe X-ray source spectrum**
- 5.9 keV
- 2.9 keV

**Energy resolution VS DLC voltage**
- best gas quality
- -340V
- 5.9 keV energy
- 8.9% energy resolution ($\sigma/\mu$)

**Gain VS DLC voltage**
- best gas quality (green)
- Gain(V) ~ exp(V)

**Gain Map Uniformity**
- $104 \geq Q_{pad\ ave} \geq 88$ [ADC]
- Border pads

**Gain Uniformity Histogram**
- uniformity 3% ($\sigma/\mu$)
- Border pads

**PLOT For current v-TPCs**

Abgrall et al., NIMA 674 (2011) p.25-46
CERN T9 BEAM TEST
dE/dx measurements

**dE/dx for different triggers at 0.8GeV/c**

**dE/dx for pion trigger vs distance after attenuation corrections**

**dE/dx resolution vs number of clusters**

Extrapolation for 2 MM (68 pads) is ~7%

**dE/dx vs Distance**

- Proton
- Electron
- Pion

9-11% energy resolution ($\sigma/\mu$)

**PLOT For current v-TPCs**

- $\chi^2$/ndf: 63.88 / 26
- Prob: 4.944e-05
- Constant: 191.9 ± 6.9
- Mean: 1.333 ± 0.003
- Sigma: 0.1041 ± 0.0023

MIPS dE/dx resolution is 7.8%

Abgrall et al., NIMA 674 (2011) p.25-46
CERN T9 BEAM TEST
Charge spreading analysis

Charge spread example

When the track crosses main pad center:
- $q_{\text{max}}/q_{\text{cluster}} \rightarrow 1$
- $\delta t$: $\delta t_1 \approx \delta t_2$
- $v_s \approx \text{pad size}/\delta t$

Clusters
- Beam: All pads with same column.
- Cosmic: All pads with same row.

Definitions
- $q_{\text{pad}}$: pad waveform’s maximum.
- $t_{\text{max}}$: time for $q_{\text{max}}$
- $q_{\text{max}}$: max $q_{\text{pad}}$ in the cluster
- $q_{\text{cluster}}$: $\sum q_{\text{pad}}$ for all pads in cluster.
- multiplicity: number of $q_{\text{pad}} > 0$ in the cluster
CERN T9 BEAM TEST
The Pad Response Function (PRF)

Simplest way to estimate the track position in the cluster ($x_{\text{reco}}$): $x_{\text{reco}} = \text{Center of Charge (CoC)}$, i.e weighted mean of the position of the fired pads center.

However, there is a systematic bias in the true track position over the pad given that the pad size is finite.

- If we study this effect by quantifying $x_{\text{true}} - x_{\text{reco}}$ we can build a pad response function, such that we can correct it.
- In previous slide we have seen $q_{\text{pad}}/q_{\text{cluster}}$ is an estimator of the distance to true track position. Therefore, we can build a PRF such as:

$$\text{PRF}(x_{\text{track}} - x_{\text{pad}}) = q_{\text{pad}}/q_{\text{cluster}}$$
CERN T9 BEAM TEST
Spatial resolution and PRF

PRF Map

\[ PRF(x, \Gamma, \Delta, a, b) = \frac{1 + a_2 x^2 + a_4 x^4}{1 + b_2 x^2 + b_4 x^4} \]

\[ \chi^2 = \sum_{pads} \frac{Q_{pad}/Q_{cluster} - PRF(x_{track} - x_{pad})}{\sqrt{Q_{pad}/Q_{cluster}}} \]

Residuals \( \mu \)

Residuals dispersion \( \sigma \)

\( x_{track} \) computed from fit to track in 2D plane
\( \) we estimate \( x_{pad} \) using \( Q_{pad}/Q_{cluster} \)

For each column we can compute:
- \( \mu = x_{track} - x_{pad} \) mean
- \( \sigma = x_{track} - x_{pad} \) dispersion
The larger the voltage difference, the largest the multiplicity and therefore better the spatial resolution.

- Much better resolution thanks to charge spreading.
- Specially better for tracks close to the anode.
High energy electron beam was used
- 1-5 GeV, most of the data with 4 GeV
- Gain scan with MM voltages 330 - 400 V
- \( Y \) and \( Z \) position scan (in the detector plane and along drift distance)
- 0, 20, 30, 45, 60, 80 degree MM rotation

- Remarks:
  - Magnetic Field
  - Not final Field Cage
  - Final MicroMegas layout (Resistivity could change).

- Beam Test Goals:
  - Check performance in larger pads.
  - Scan over parameters.
  - Characterize the charge spreading.
Increasing MM voltage also increases # of saturated pads. Best compromise could be around 360V.

Below 10% for all momentums with single MM -> ~7% with 2 modules

Resolution < 200µm with 33% less # pads
PRELIMINARY RESULTS

DESY BEAM TEST
Parameters scan

Collected Charge

x axis: Drift distance

Charge [c.u.]

- 200 ns 0.2 T
- 200 ns 0. T
- 412 ns 0.2 T
- 412 ns 0. T.

Z position [mm]

dEdx resolution

x axis: Peaking Time

Resolution [%]

- 200 ns 0.2 T
- 200 ns 0. T
- 412 ns 0.2 T
- 412 ns 0. T.

Z position [mm]

Spatial resolution

x axis: Peaking Time

Resolution [µm]

- 430 mm
- 530 mm

Peaking time [ns]

Improves with B field

- stable with peaking time

shows B field robustness

- stable with peaking time
CERN Field Cage Prototype with MM1

Tests ongoing

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  - Scan over parameters.
  - Characterize the charge spreading.
Conclusions

The resistive MicroMegas concept was successfully evaluated using CERN beam test data using current v-TPCs MM + resistive foil, providing figures of merit satisfying ND280 upgrade HA-TPCs requirements. [C.Jesús-Valls, S.Suvorov et al., NIMA 957 (2020): 163286](https://www.sciencedirect.com/science/article/pii/S0168900219315426)

The new layout with ~30% less pads and increased resistivity was tested last fall at DESY. Preliminary results show very good performance.

- There are studies ongoing analyzing:
  - Foil Resistivity.
  - 2D PRF method
  - Development of simulations based on data.

  Remarkably, preliminary results show that this new technology improves the resolution for straight tracks ~x3, while reducing ~30% of pads.

The first field cage prototype is being tested at CERN using cosmic tracks and there is an ongoing analysis to measured E field distortions.

There are plans to take new data in DESY this autumn using both a field cage prototype and the final resistive MicroMegas.

Installation is scheduled for fall 2021.
Back Up
Back Up
Extra upgrade motivations

µ selected at ND280
e⁻ selected at SK

\(\theta_\mu \text{ [°]}
\)
\(P_\mu \text{ [MeV/c]}
\)

\(\theta_\mu \text{ [°]}
\)
\(p_\mu \text{ (MeV)}
\)

\(\text{true \cos } \theta
\)
\(\text{efficiency}
\)
To keep $\frac{\Delta E_{\perp}}{E_{\parallel}} \leq 10^{-4}$ confined at $<1.5$ cm from FC walls, the TPC cage requirements are:

- Field Cage walls flatness better than 0.3 mm,
- Voltage divider resistors matched within rms $\sim 0.1\%$

### Table

| Parameter                          | HA-TPC          | v-TPC        |
|------------------------------------|-----------------|--------------|
| Overall $x \times y \times z$ (m)  | $2.0 \times 0.8 \times 1.8$ | $0.85 \times 2.2 \times 1.8$ |
| Drift distance (cm)                | 90              |              |
| Magnetic Field (T)                 | 0.2             |              |
| Electric field (V/cm)              | 275             |              |
| Gas Ar:CF$_4$:iC$_4$H$_{10}$ (%)   | 95 - 3 - 2      |              |
| Drift Velocity $cm/\mu s$          | 7.8             |              |
| Transverse diffusion ($\mu m/\sqrt{cm}$) | 265             |              |
| Micromegas gain                    | 1000            |              |
| Micromegas dim. $z \times y$ (mm)  | 340x420         | 340x360      |
| Pad $z \times y$ (mm)              | 10 x 11         | 7x10         |
| N pads                             | 36864           | 124272       |
| el. noise (ENC)                    | 800             |              |
| S/N                                | 100             |              |
| Sampling frequency (MHz)           | 25              |              |
| N time samples                     | 511             |              |

### Table

| Material                          | thickness $d$ (mm) | $X_0$ (mm) | $d/X_0$ (%) |
|-----------------------------------|--------------------|------------|-------------|
| Double layer strip foil (+glue)   | 0.05               | 14.3 (Cu)  | $\sim 0.07$ |
| Copper strips                     | $\sim 0.005$      | 14.3 (Cu)  | $\sim 0.07$ |
| Aramid Fiber Fabric (Twaron)      | 2.0                | $\sim 240$ | 0.70        |
| Aramid honeycomb panel (Nomex)    | 25                 | 14300      | 0.17        |
| Aramid Fiber Fabric (Twaron)      | 2.0                | $\sim 240$ | 0.70        |
| Kapton tape (+glue)               | 0.125              | 285        | 0.04        |
| Aluminized Mylar (+glue)          | 0.05               | 89 (Al)    | $\sim 0.02$ |
| Aluminum layer                    | 0.01               | 89 (Al)    | $\sim 0.02$ |
| Total                             | $\sim 30$         | $\sim 1.6$ |             |
Back Up
The new HA-TPCs electronics

MM-DLC PCB
Irfu / Cern

- 36 x 32 = 1152 pads
- 2 x 576 channel FEC
- 8 vertical FX23 Hirose floating connectors

16xAFTER
Irfu

MM Stiffener
IFJ PAN

2x FEC-II cards with cooling plates LPNHE

1x PDC card
Irfu

1x FEM-II + backend TDCM
Irfu

DAQ software
IFAE

Test benches
Warsaw univ.

M. Riallot (CEA/Irfu)

FEM-II cooling plate
Irfu

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32
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Back Up
Details on CERN BeamTest gas quality

**Experimental conditions:**

- HARP TPC stored in air for more than 10 years.
- No FC drying before operation.
- Gas gas reduced from 60L/h to 25L/h to save gas.
- There were no gas monitoring chambers.

**Simulations:**

- Drift velocity was at most 5.5cm/µs, should have been 6.8cm/µs.
- Small attenuation and large reduction in drift velocity points out to humidity.

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Drift velocity MAGBOLTZ simulation for T2K gas + contaminants
Performances of a resistive MicroMegas module for the Time Projection Chambers of T2K ND280 Upgrade

Truncated mean method

Optimum truncation keeping 21 clusters (out of 34)
Performances of a resistive MicroMegas module for the Time Projection Chambers of T2K ND280 Upgrade

Back Up
Charge Spread MM0 (CERN TESTS)

Cluster multiplicity

Events

Cluster multiplicity

Events

2Pad Clusters

3Pad Clusters

3Pad Clusters

δ(t_{max} - t_{secondmax}) [ns]

δ(t_{max} - t_{secondmax}) [ns]

δ(t_{max} - t_{thirdmax}) [ns]