14th Joint workshop of FKPPN and TYL/FJPPN
14-16 May 2025, University of Nantes

FJPPN NU-10 project

Characterization of resistive Micromegas for High Angle-TPC readout for the T2K Near Detector upgrade

Shivam Joshi

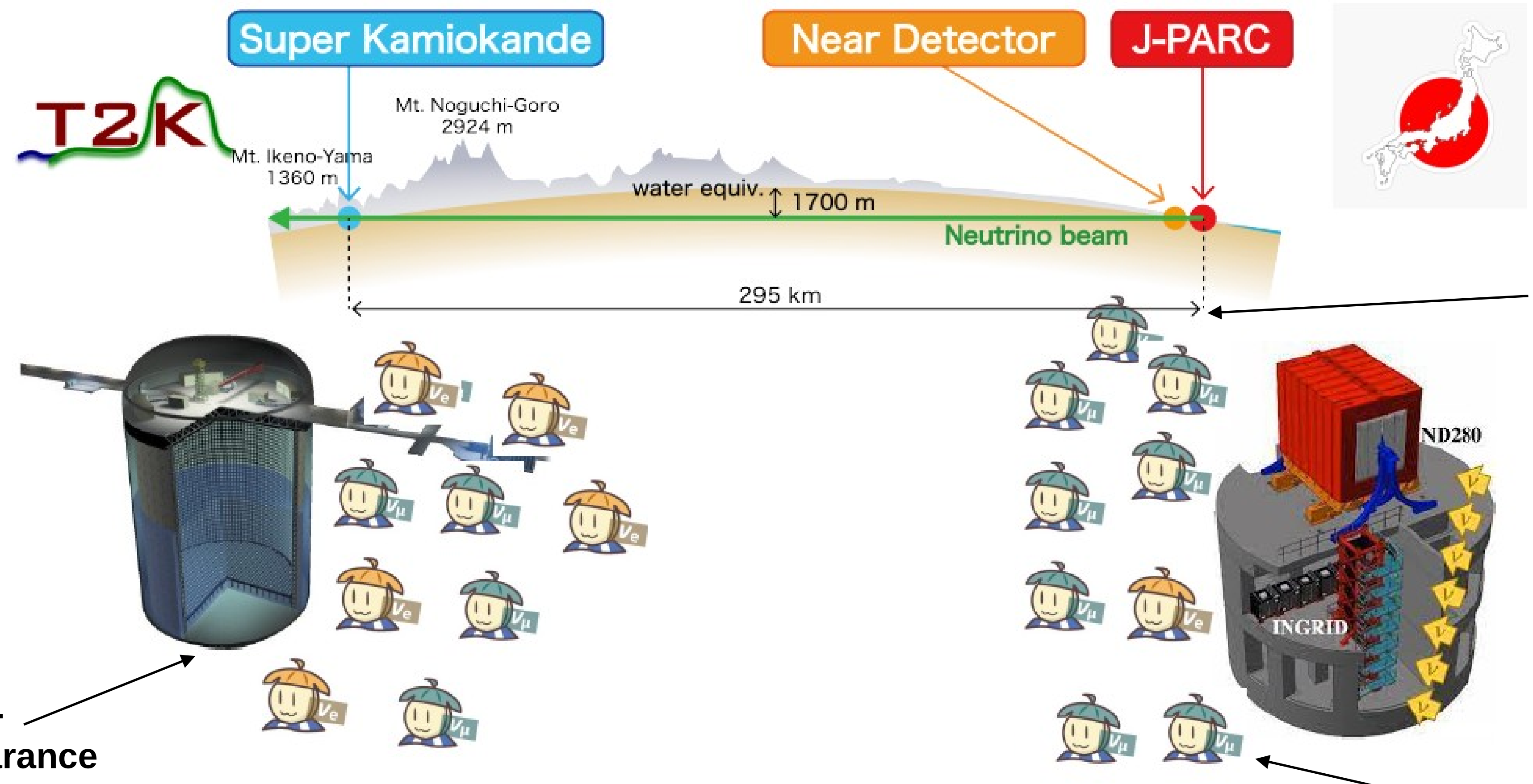
14th May 2025

Contents

01

The T2K experiment and near detector (ND280) upgrade

The T2K experiment: Tokai to Kamioka



Long baseline neutrino oscillation experiment

Measurement of -

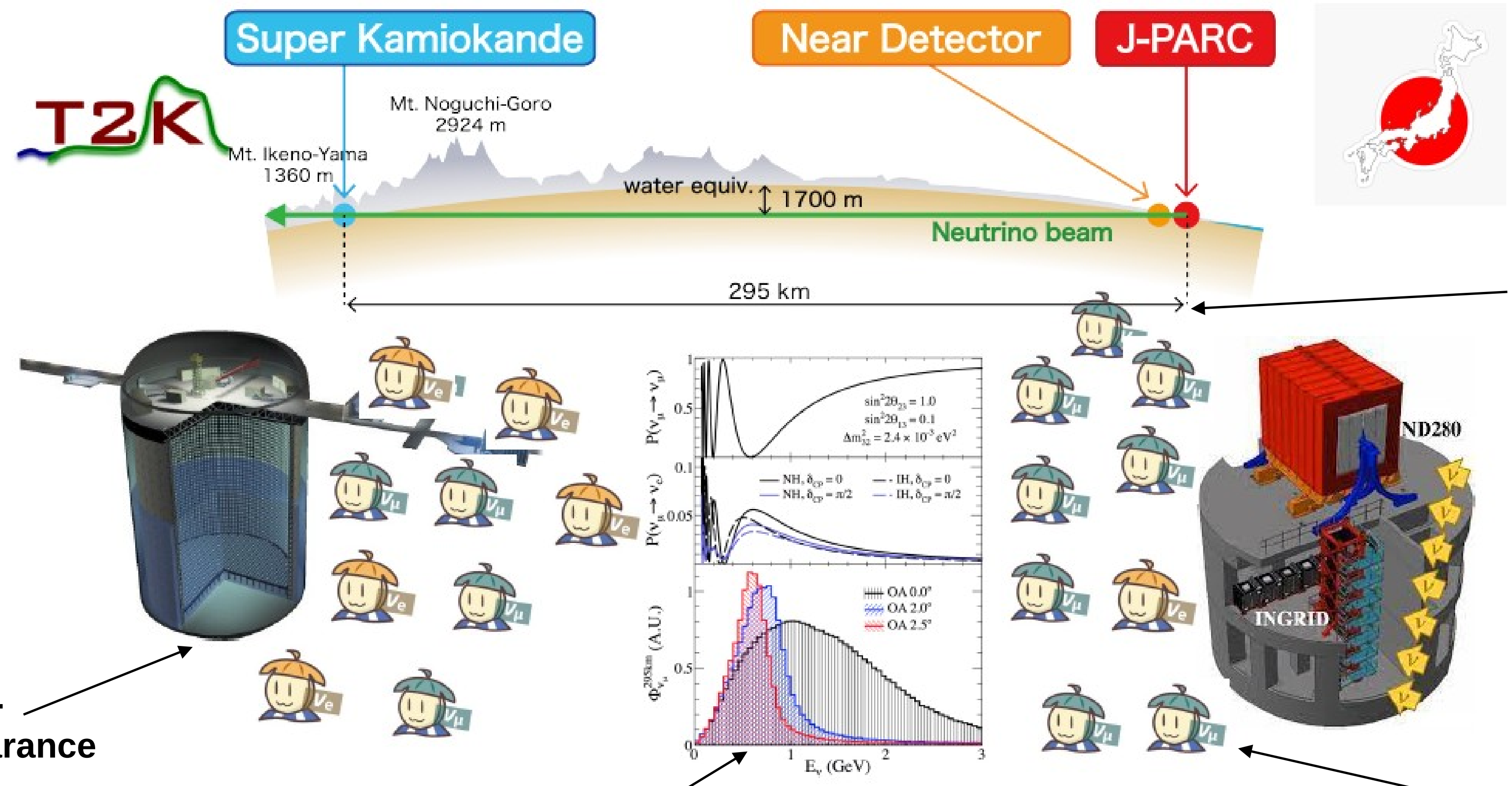
- **ν_μ ($\bar{\nu}_\mu$) disappearance**
- **ν_e ($\bar{\nu}_e$) appearance**

ν_μ ($\bar{\nu}_\mu$) beam

(p (30 GeV) + graphite $\longrightarrow$ π $\longrightarrow$ μ + ν_μ)

Neutrino cartoons by Yuki Akimoto

The T2K experiment: Tokai to Kamioka



Long baseline neutrino oscillation experiment

Measurement of -
- **ν_μ ($\bar{\nu}_\mu$) disappearance**
- **ν_e ($\bar{\nu}_e$) appearance**

Off-axis angle

Peak of ν_μ ($\bar{\nu}_\mu$) energy spectrum at 600 MeV

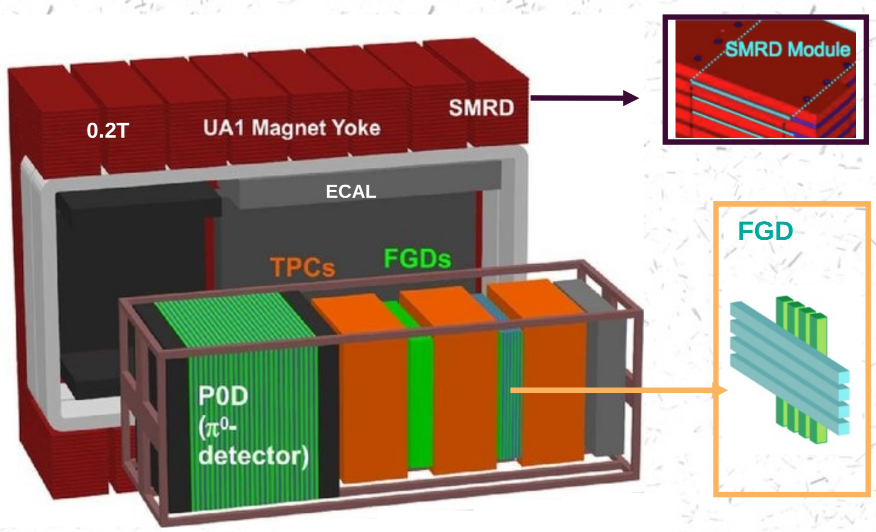
ν_μ ($\bar{\nu}_\mu$) beam

(p (30 GeV) + graphite $\longrightarrow \pi \longrightarrow \mu + \nu_\mu$)

Neutrino cartoons by Yuki Akimoto

T2K near detector: ND280

ND280 (before upgrade)



Limitations

- Low angular acceptance → mostly reconstruct forward going tracks entering the TPCs.
- Low efficiency to track low momentum protons → Have to use lepton kinematics only for E_ν reconstruction.

ND280 measures beam spectrum and flavor composition before the oscillations

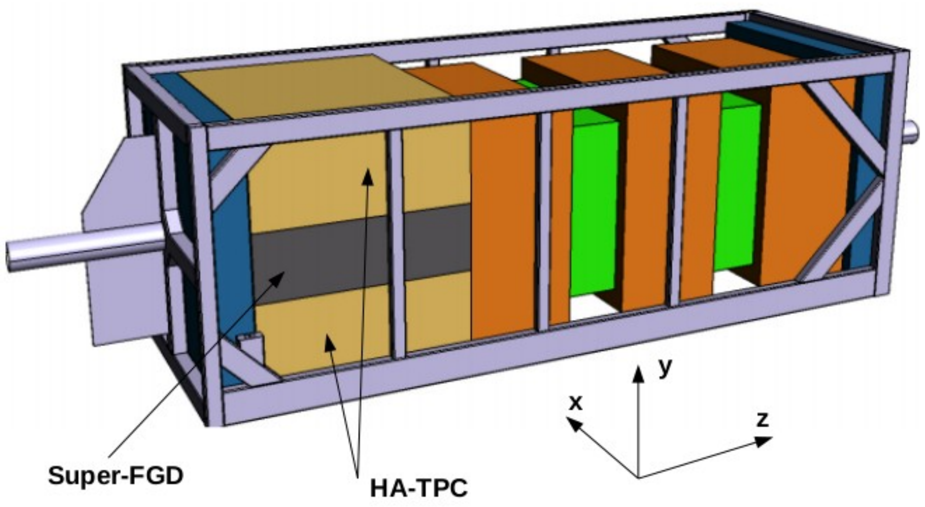
- Detector installed inside the **UA1/NOMAD magnet (0.2 T)**
- **A detector optimized to measure π^0 (P0D)**
- **An electromagnetic calorimeter for μ/e separation and energy measurement of EM showers.**

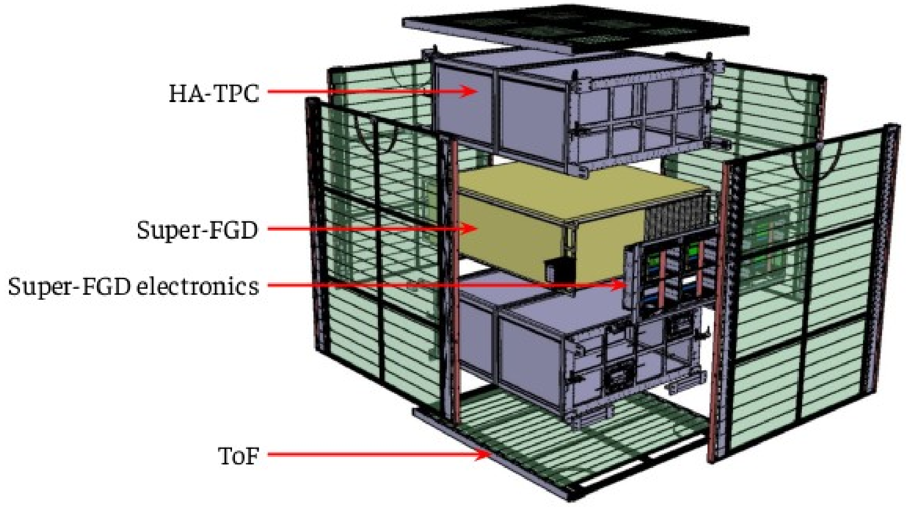
A target-tracker system composed of:

- **2 Fine Grained Detectors (target for ν 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**

ND280 upgrade design

P0D replaced with a new scintillator target (Super-FGD), two High-Angle TPCs and six Time-of-Flight planes.



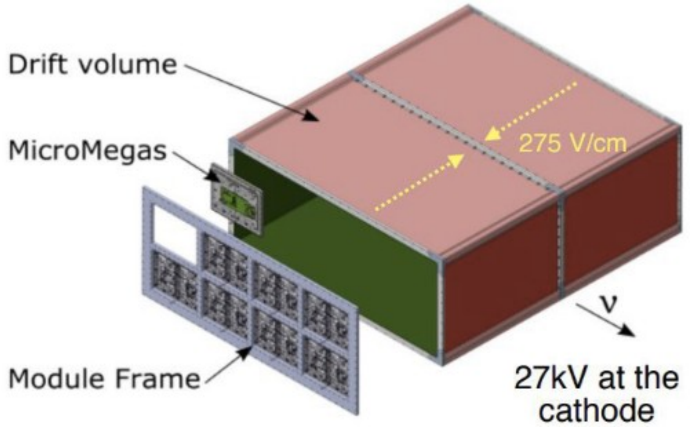


- Super-FGD allow to fully reconstruct tracks in 3D → lower threshold and excellent resolution to reconstruct protons at any angle.
  - Neutrons will also be reconstructed via proton recoil.
- High-Angle TPCs (x 2) provide additional high angle coverage for particle reconstruction.
  - Readout using resistive Micromegas.

Requirements:
- Momentum resolution <= 10%
- dE/dx resolution <= 10%

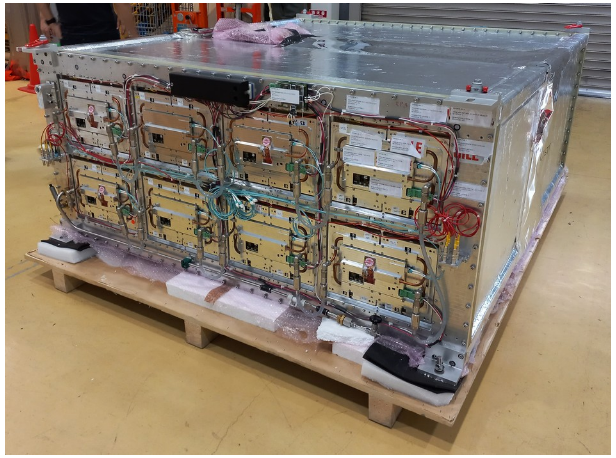
- ToF planes (x 6) allow to veto particles originating from outside the ND280 fiducial volume.

High Angle TPC (HA-TPC)

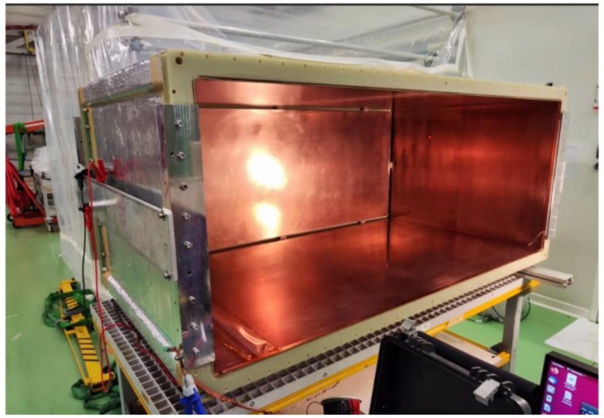


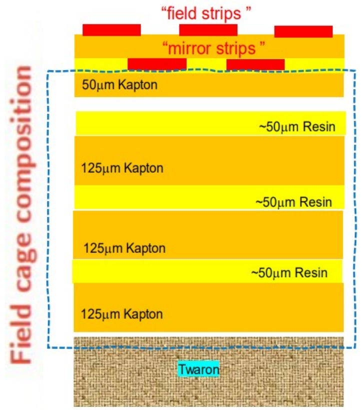
- Two field cages joined at the central cathode plane.
- Each anode plane instrumented with 8 Encapsulated Resistive Anode Micromegas (ERAM). [32 ERAMs in total]
- Purpose- 3D track reconstruction, PID, tracking high angle and backward-going particles.

HA-TPC instrumented with 16 ERAMs



→ New field cage design with thin walls to minimize dead material and maximize tracking volume. (Total width ≈ 4 cm / 2% X_0)

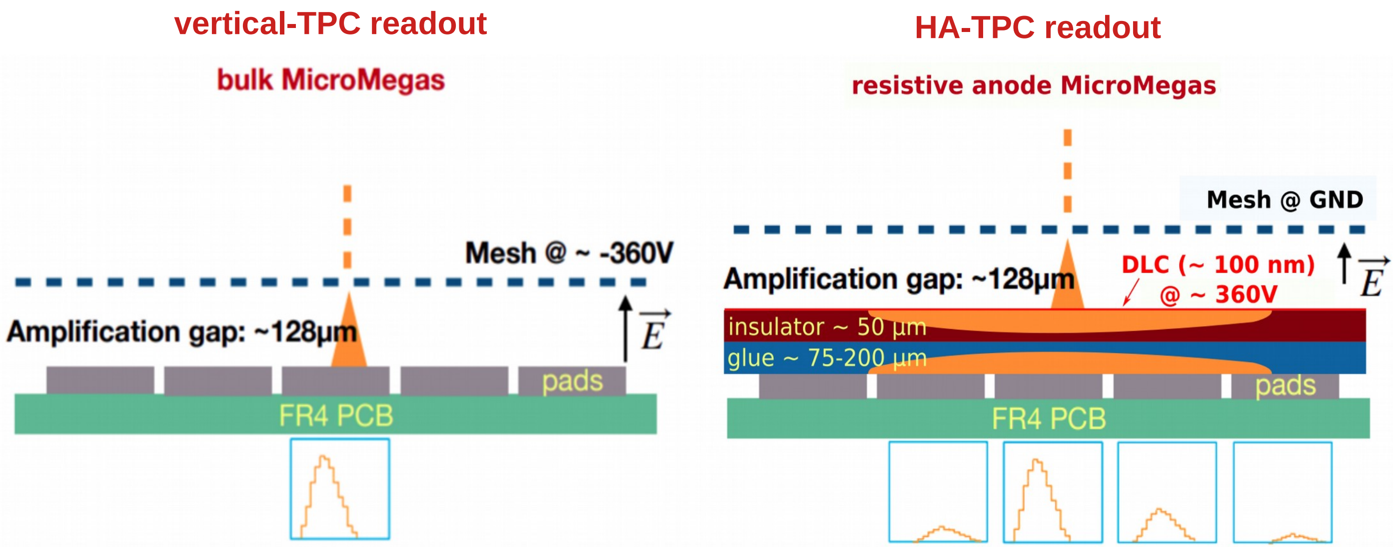




→ Readout using ERAM instead of standard bulk Micromegas.

HA-TPC readout: Micromegas detector

Pad size: 9.8 * 7 mm^2



Developed for ILC-TPC with pad size- 7 * 2 mm^2

Pad size: 11 * 10 mm^2

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

- Charge sharing between pads ⟹ More precise position reconstruction
- Better resolution with reduced number of pads ⟹ Cost-effective and compact technology
- Reduced risk of sparks ⟹ No need for protection circuit on readout electronics
- Allows to put mesh at ground for better E-field uniformity.
- More flexible design ⟹ Increase charge spreading to improve spatial resolution.

DLC foil

R = Surface resistivity
C = Capacitance / unit area

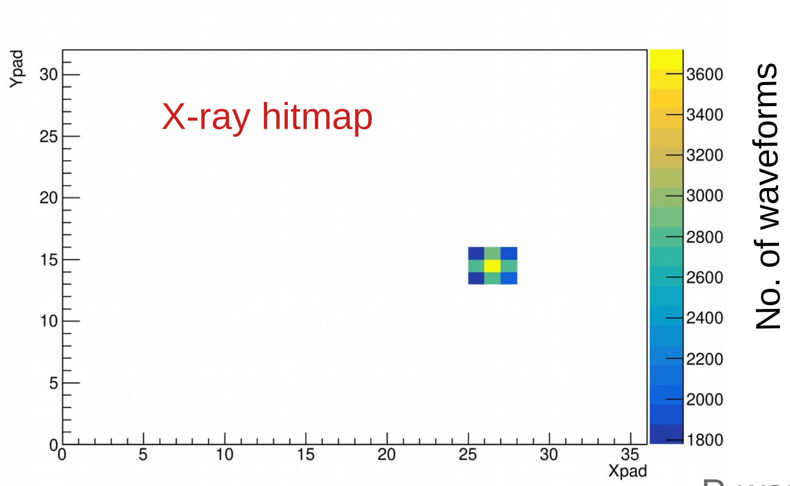
Glue thickness and permittivity

02

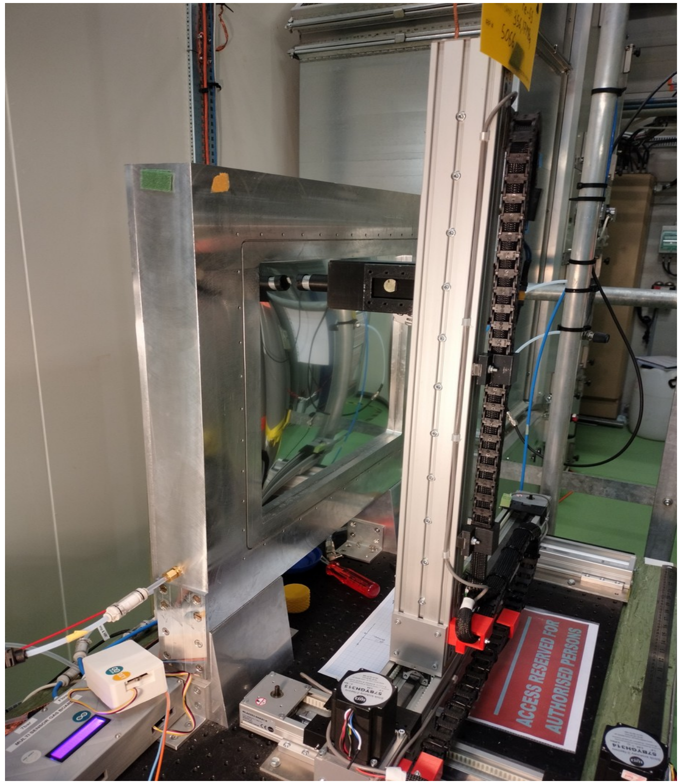
X-ray characterization of resistive Micromegas

X-ray test bench

- Chamber with aluminized mylar on one side to allow X-rays to pass.
- 3 cm drift distance.
- Robotic x-y-z arm system holding an ^{55}Fe X-ray source capable of precise movement.
- Each ERAM pad is exposed by the X-ray source for a duration of 3 minutes.
- Each event is a result of punctual charge deposit in leading pad.
- Environmental conditions such as pressure, temperature, humidity and gas purity are closely monitored.



X-ray test bench @CERN



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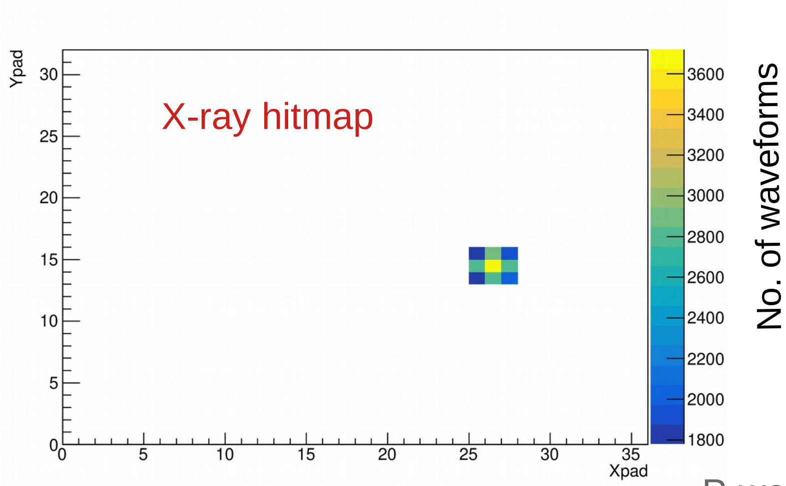

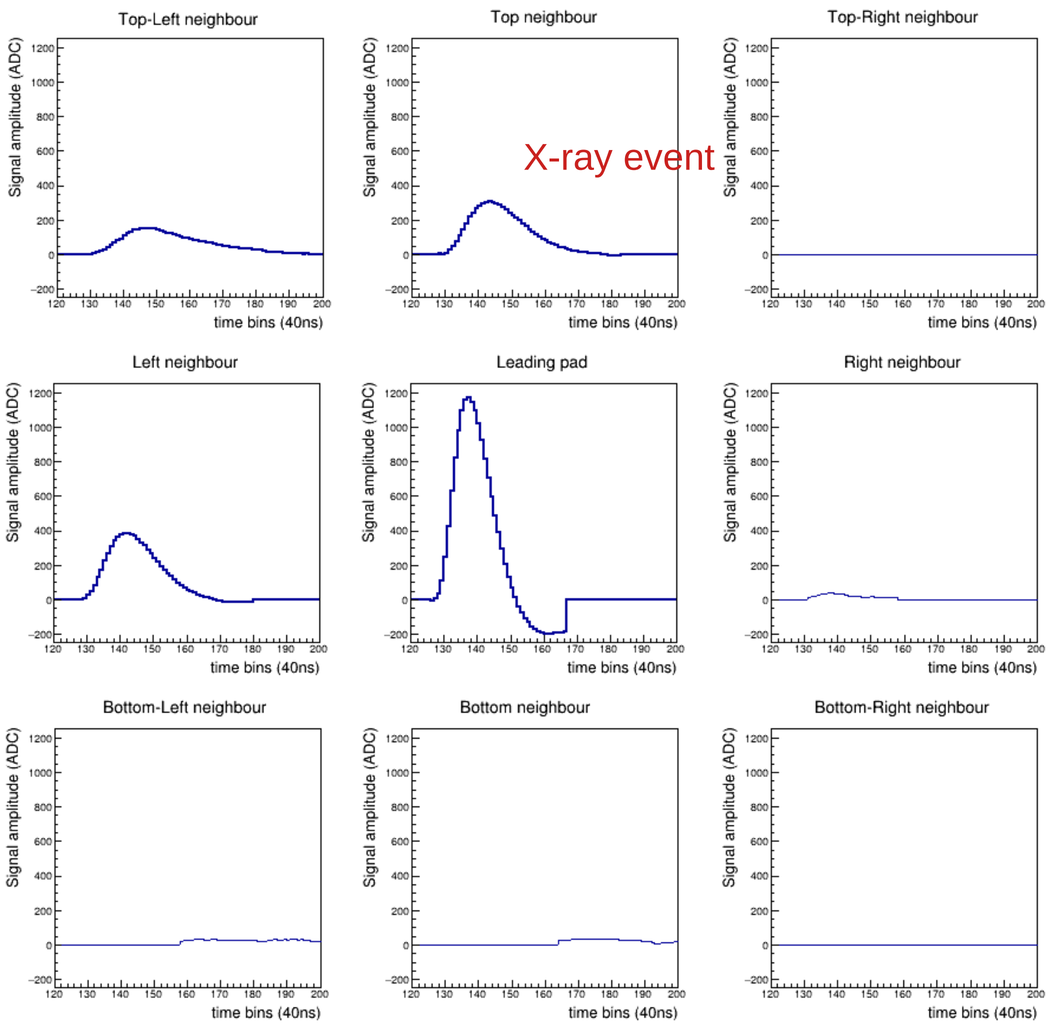

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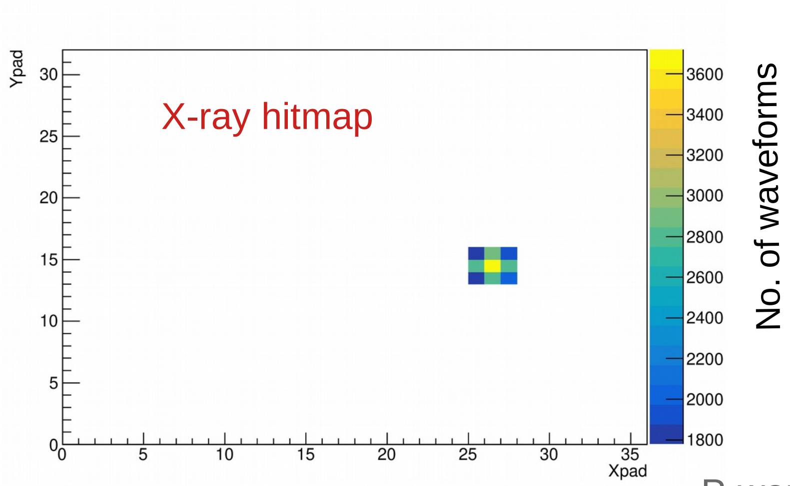
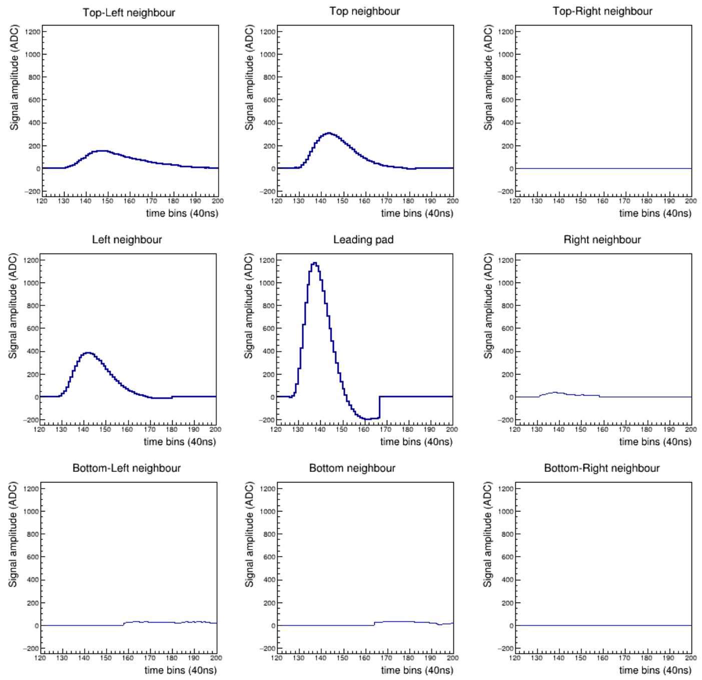
- Environmental conditions such as pressure, temperature and humidity are closely monitored.

<u>Objective</u>:

To characterize the gain and charge spreading of all operational ERAMs.

- Important ingredients for simulation and reconstruction algorithms.

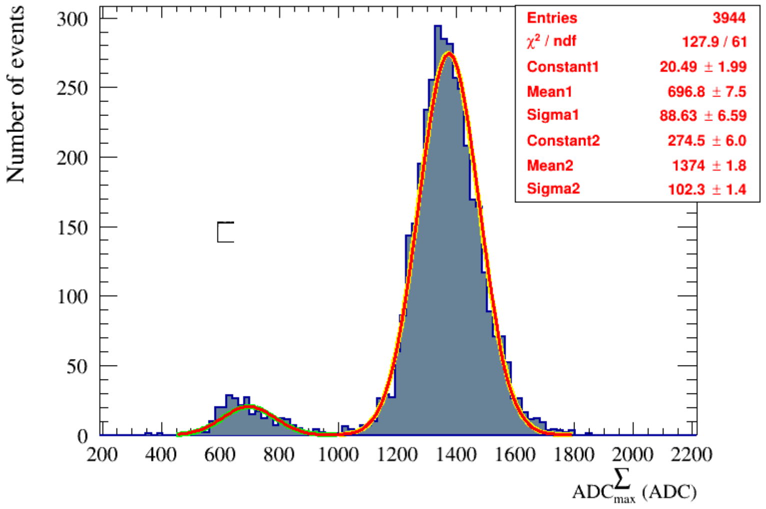




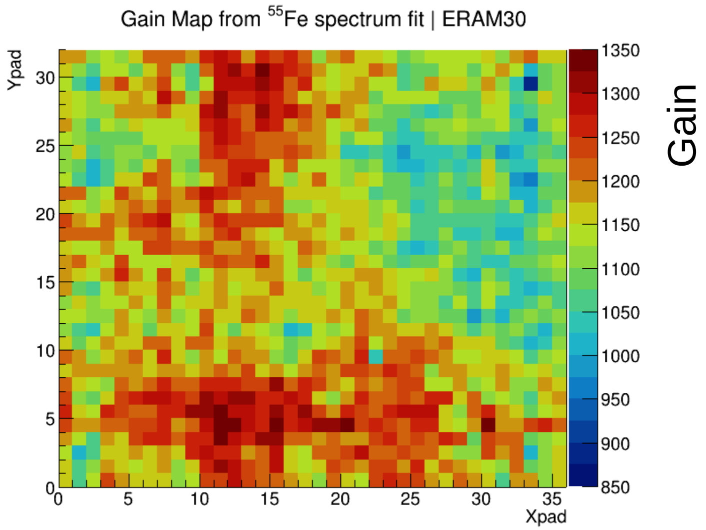
Gain calculation

- ^{55}Fe spectrum can be reconstructed using all events in one pad.
    - ➔ Summing all waveforms in each event and taking amplitude of summed waveform.
- Gain is obtained for a pad by fitting its ^{55}Fe spectrum and obtaining the amplitude of K_α-peak.
- Energy resolution of < 10% is obtained.

$$\text{Energy resolution (\%)} = \frac{\sigma}{\mu} * 100$$



Example of an ^{55}Fe spectrum



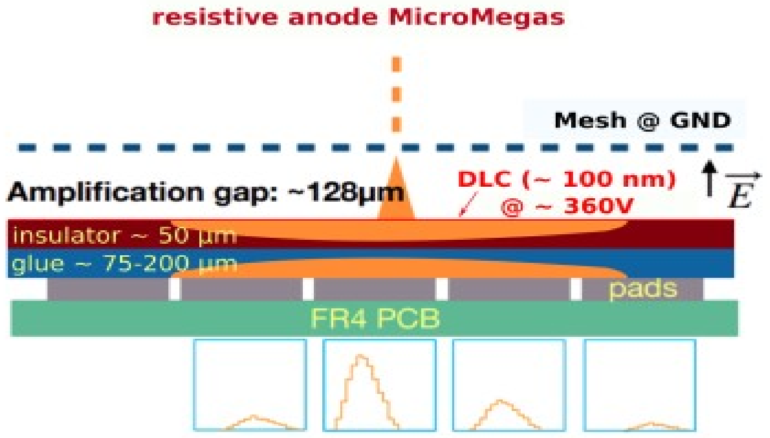
Gain map of ERAM-30

Charge dispersion principle

- Charge dispersion on anode achieved with a resistive foil glued on PCB.
- Continuous RC network, defined by material properties and geometry, shares evenly the charge among several pads.
- Obeys Telegraph equation:

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

$$\Rightarrow \quad \rho(r,t) = \frac{1}{4\pi(t/RC)} e^{-r^2/4(t/RC)}$$



- The anode charge density is time dependent and sampled by readout pads.

DLC resistivity: 400kΩ/□

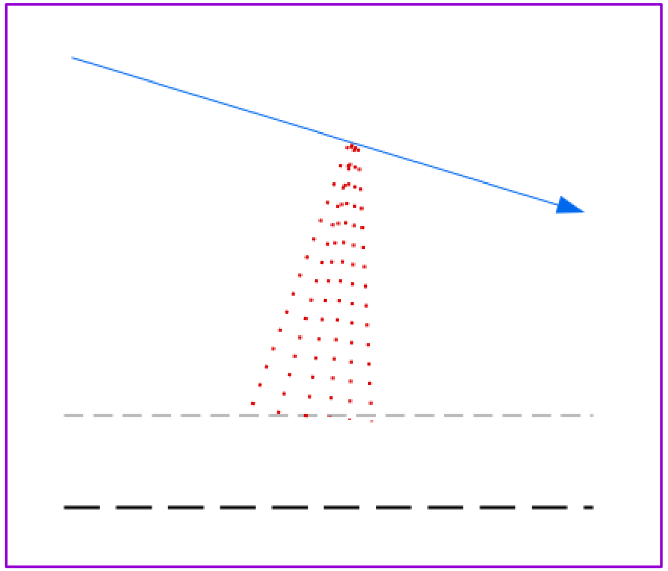
Glue thickness: 150 µm

References : M.S. Dixit et.al., NIM A518, 721 (2004) , M.S. Dixit & A. Rankin, NIM A566, 281 (2006)

Ingredients for charge spreading model (using test bench setup)

- Transverse diffusion

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



RMS spread = 540 µm (accounted for)

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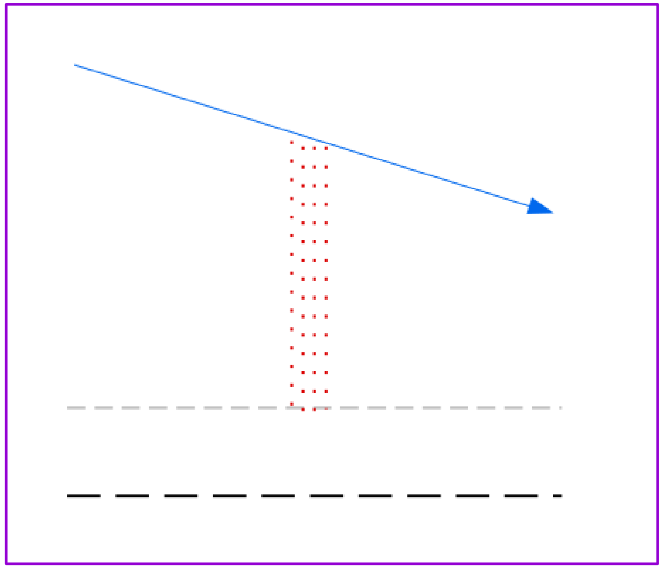
- Longitudinal diffusion

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



RMS spread = 4.5 ns (neglected)

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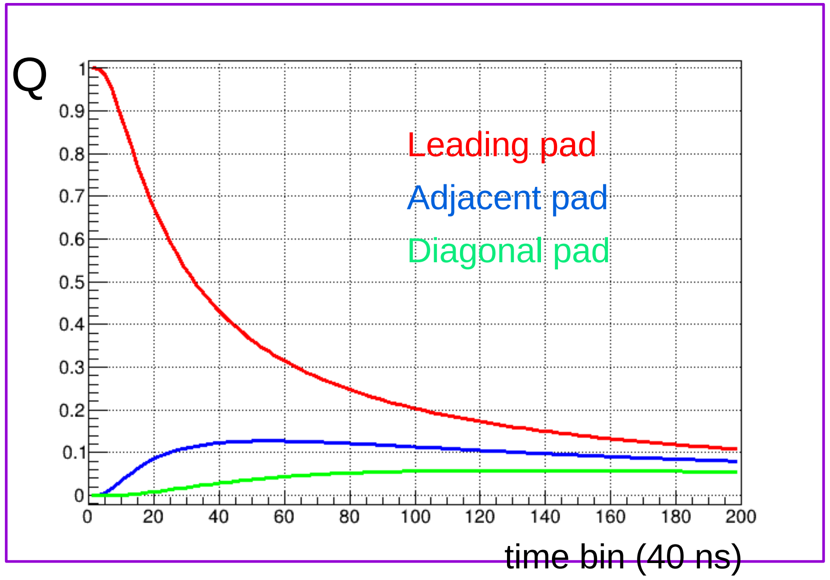
RMS spread = 4.5 ns (neglected)

- Resistive foil + glue

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

$$h = 1/RC$$



Q = ∫ ρ(r) dr

Charge diffusion function:

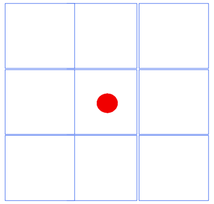
$$Q_{pad}(t) = \frac{Q_e}{4} \times \left[erf\left(\frac{x_{\text{high}} - x_0}{\sqrt{2}\sigma(t)}\right) - erf\left(\frac{x_{\text{low}} - x_0}{\sqrt{2}\sigma(t)}\right) \right] \times \left[erf\left(\frac{y_{\text{high}} - y_0}{\sqrt{2}\sigma(t)}\right) - erf\left(\frac{y_{\text{low}} - y_0}{\sqrt{2}\sigma(t)}\right)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

$Q_e = Q_{Primary} * G$

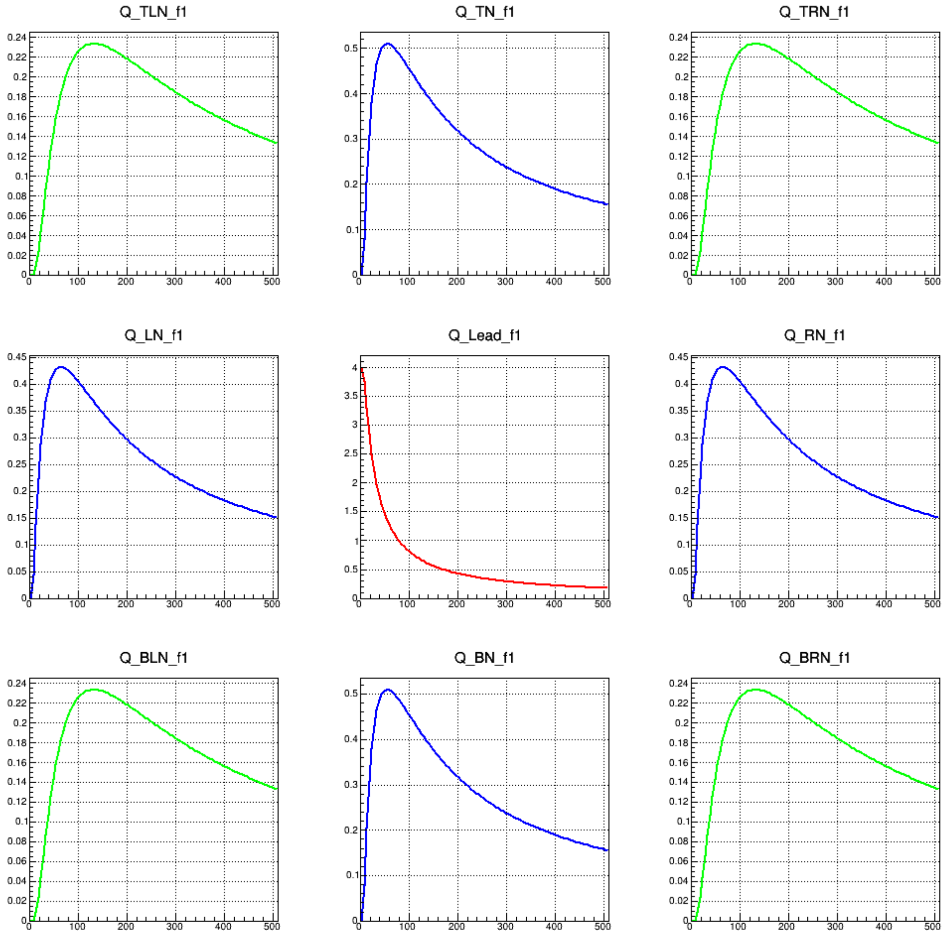
$$\sigma(t) = \sqrt{\frac{2t}{RC}}$$

- 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



RC = 60 ns/mm²



x_H, x_L: Upper and lower bound of a pad in x-direction
y_H, y_L: Upper and lower bound of a pad in y-direction

Ingredients for charge spreading model (using test bench setup)

- Transverse diffusion

$$T(x) = \frac{1}{\sigma_x\sqrt{2\pi}}\exp(\frac{-x^2}{2\sigma_x^2})$$

RMS spread = 540 μm (accounted for)

- Longitudinal diffusion

$$L(t) = \frac{1}{\sigma_t\sqrt{2\pi}}\exp(\frac{-t^2}{2\sigma_t^2})$$

RMS spread = 4.5 ns (neglected)

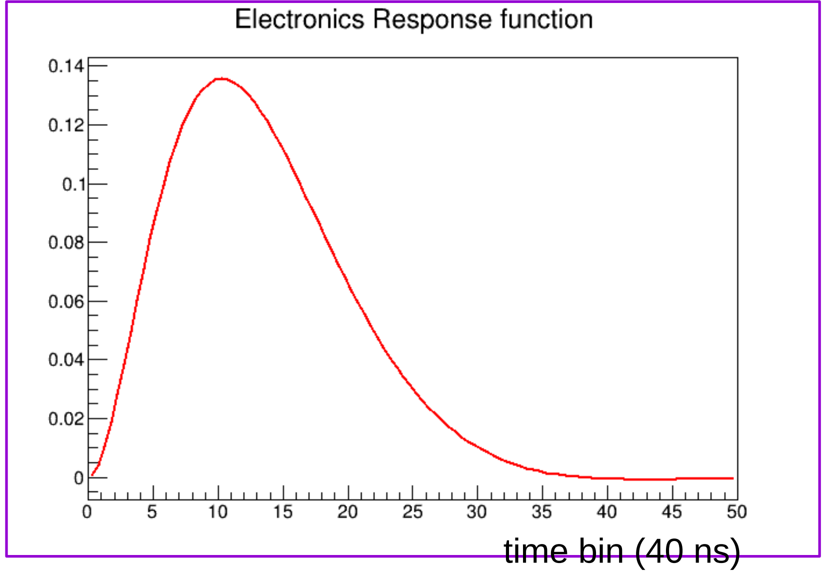
- Resistive foil + glue

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

$$h = 1/RC$$

- Electronics Response

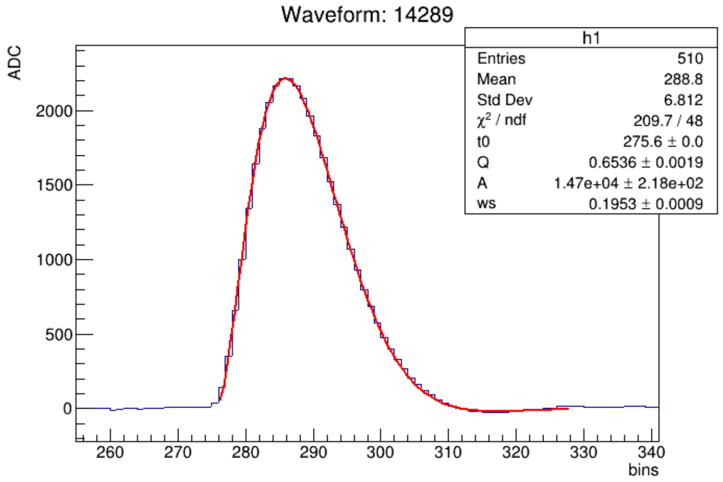
R(t)



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.

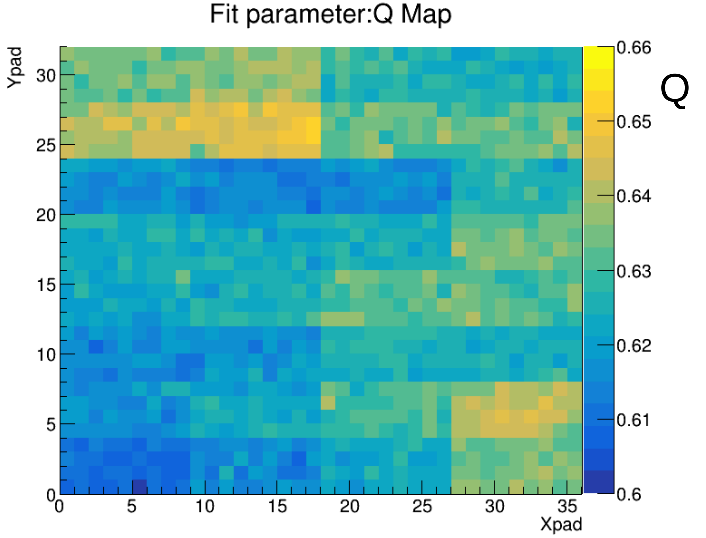
$$ADC^D(t; w_s, Q) = \frac{Q_{anode} \times ADC_0}{Q_0 \times f_{max}(w_s, Q)}\left[e^{-w_s t} + e^{-\frac{w_s t}{2Q}}\left[\sqrt{\frac{2Q-1}{2Q+1}}\sin\left(\frac{w_s t}{2}\sqrt{4-\frac{1}{Q^2}}\right) - \cos\left(\frac{w_s t}{2}\sqrt{4-\frac{1}{Q^2}}\right)\right]\right]$$



- 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.

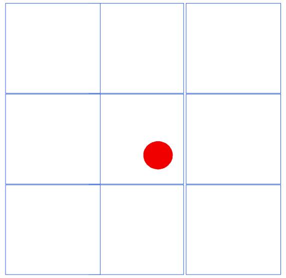
- Q = 0.6368
- w_s = 0.1951

fixed (412ns peaking time)



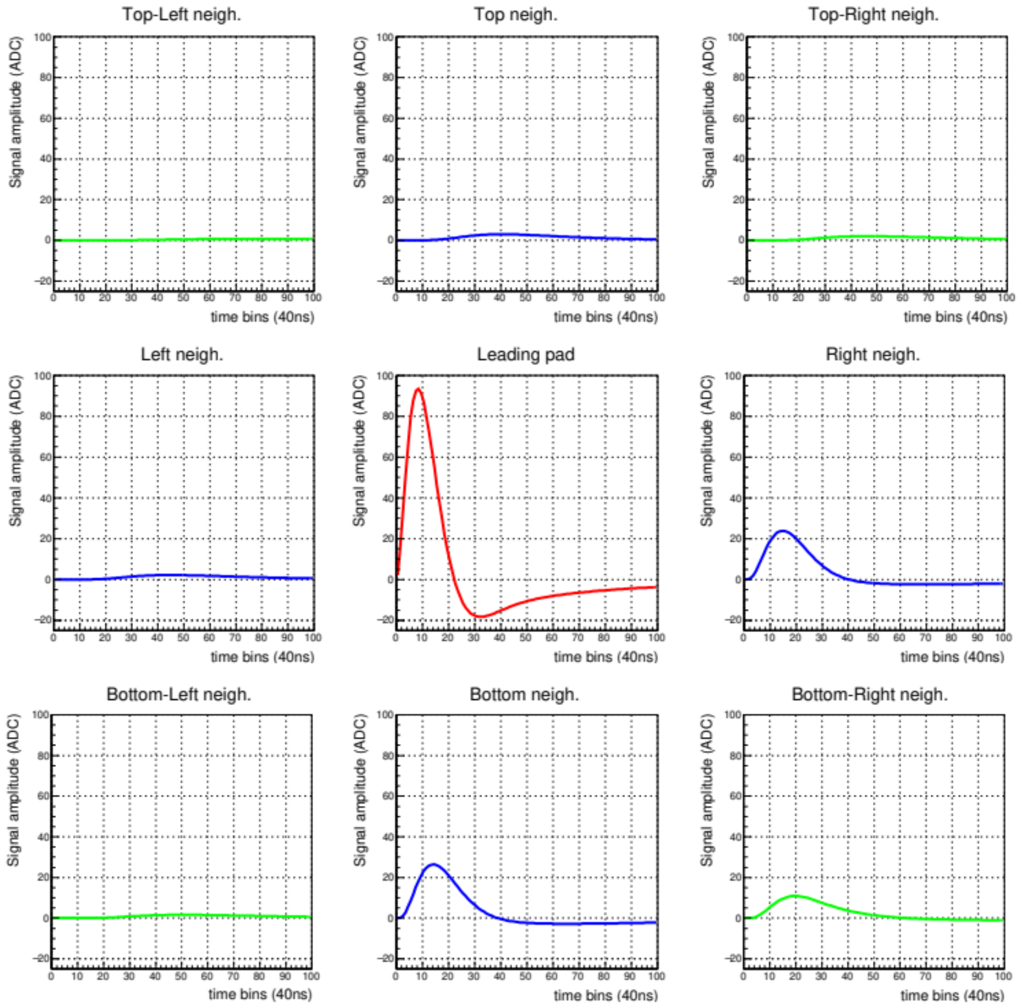
Signal model

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



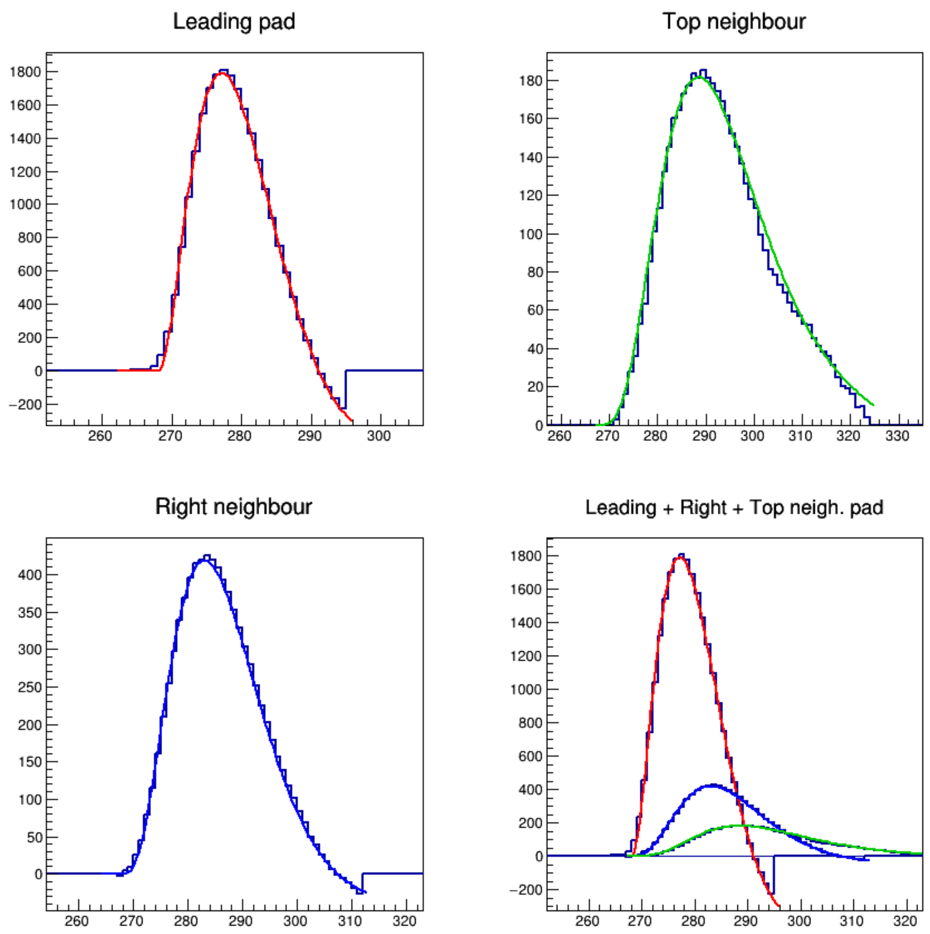
$$S(t) = Q(t) * \frac{dR}{dt}$$

RC = 60 ns/mm^2



Application of Signal model on X-ray data

Example 1:



3-waveform simultaneous fit of an X-ray event

RC = (110.82 ± 1.363) ns/mm^2

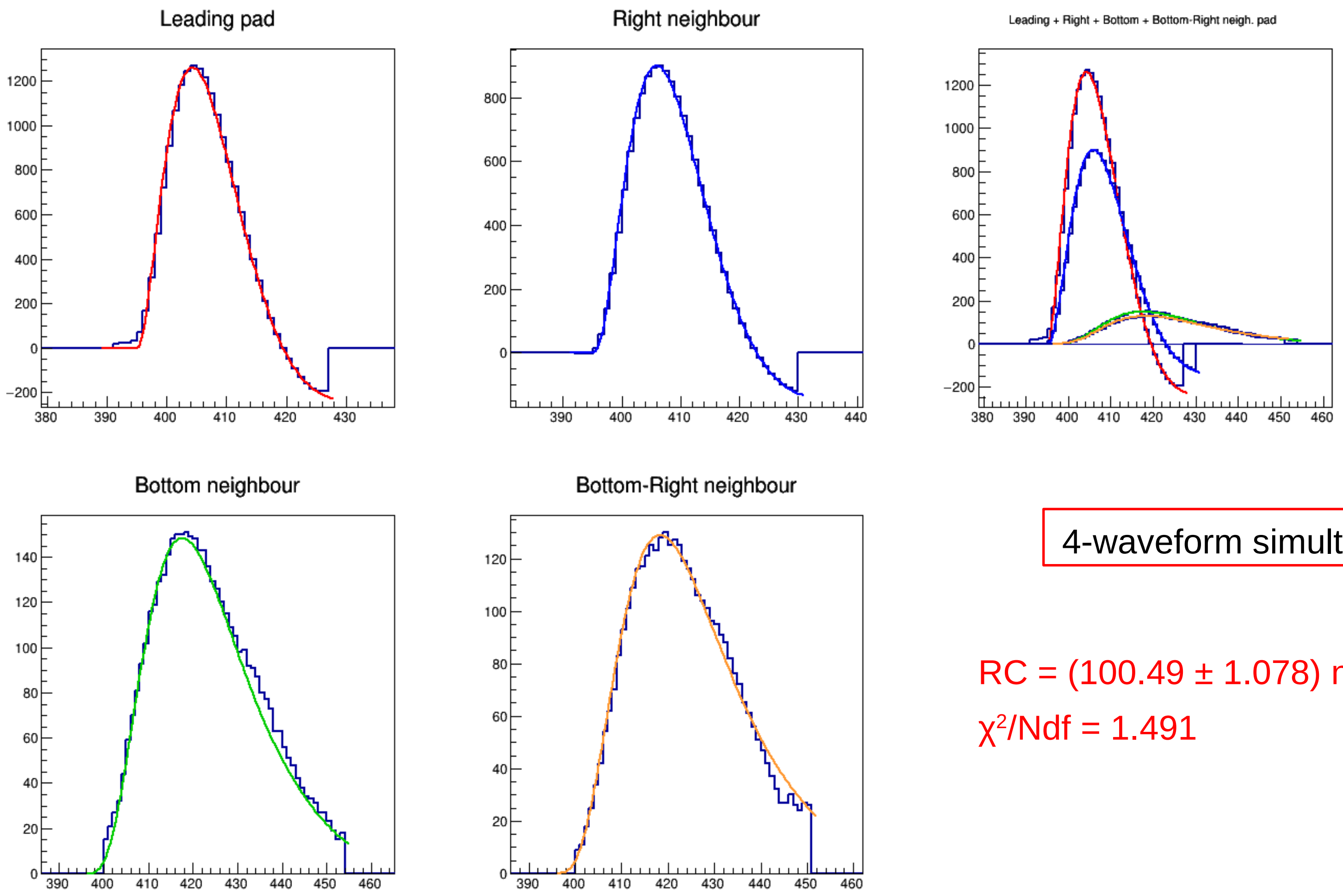
χ^2/Ndf = 1.903

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

Simultaneous fit: Leading pad + Neighbouring pads are fitted simultaneously

Application of Signal model on X-ray data

Example 2:



4-waveform simultaneous fit of an X-ray event

RC = (100.49 ± 1.078) ns/mm^2

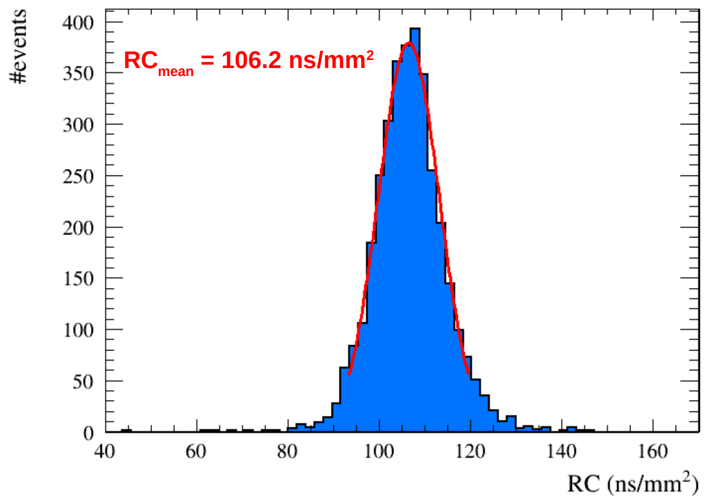
χ^2/Ndf = 1.491

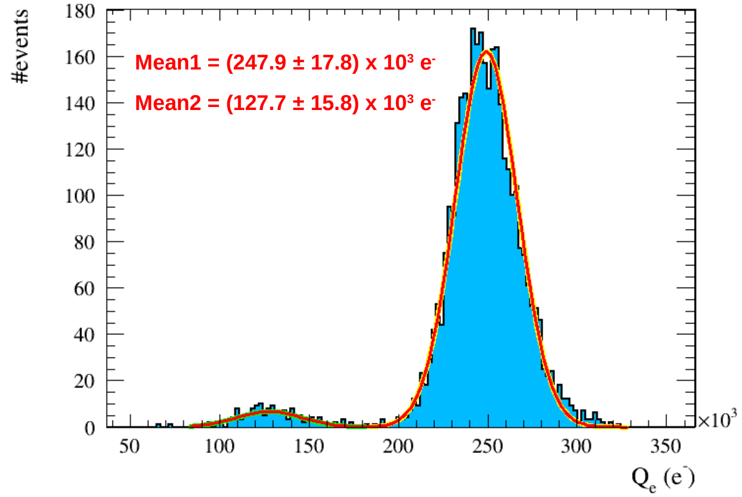
- RC is obtained for a pad by simultaneous fit of waveforms in each event.

Simultaneous fit: Leading pad + Neighbouring pads are fitted simultaneously

Results from fitting events in 1 pad

RC distribution

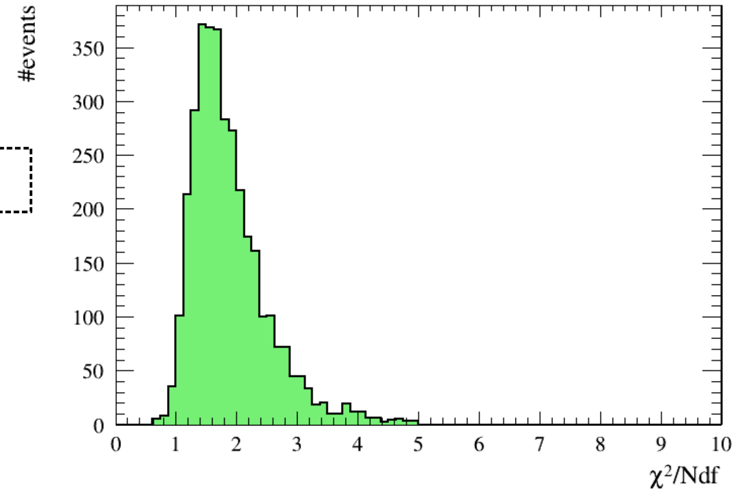


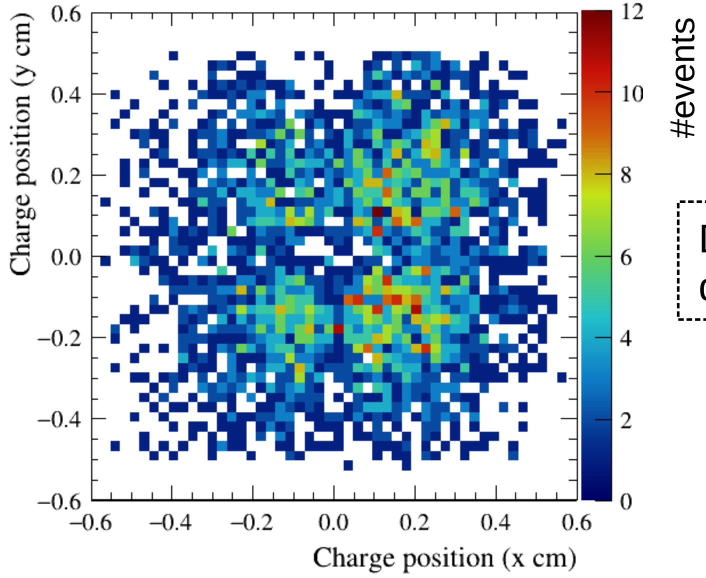


Q_e distribution

- Reconstruction of ^{55}Fe spectrum with correct peak positions.

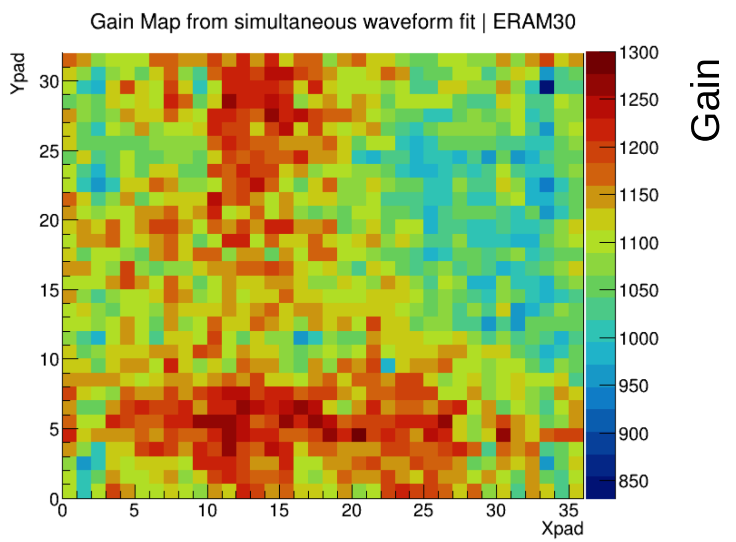
χ^2/Ndf distribution



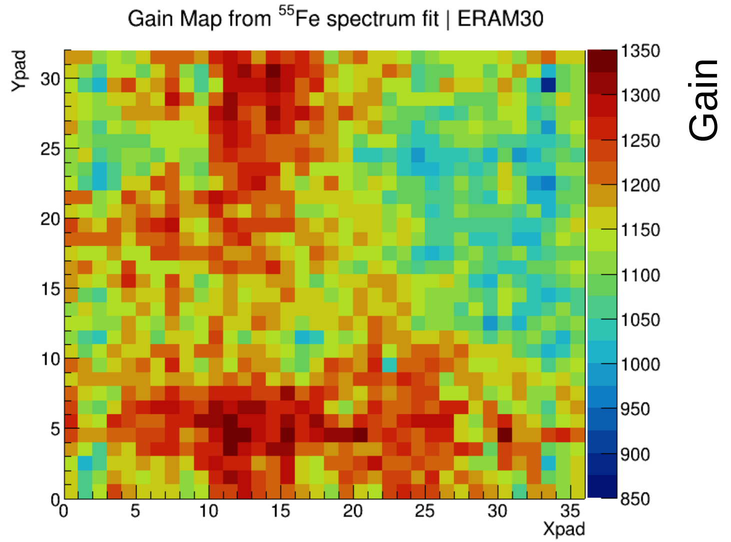


Distribution of charge deposition points (x_0, y_0)

Gain from simultaneous fit: Validation of Signal model

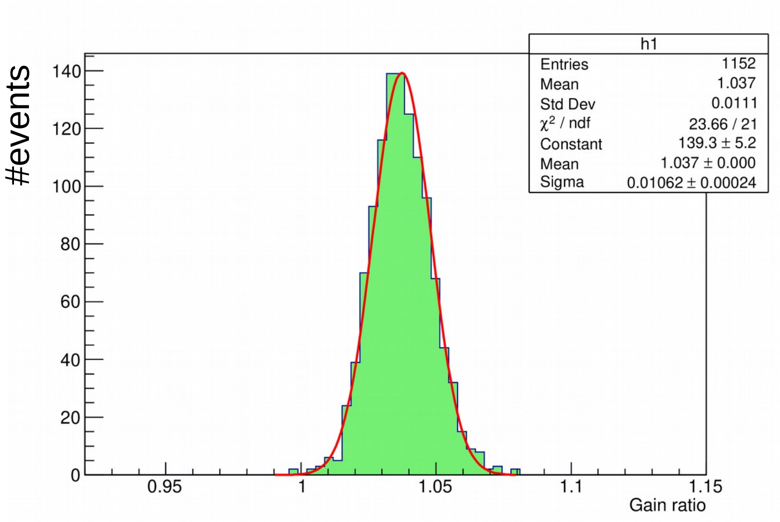


Gain map from simultaneous fit method



Gain map from waveform sum method

<u>Ratio of gain(of each pad) obtained from 2 different methods</u>

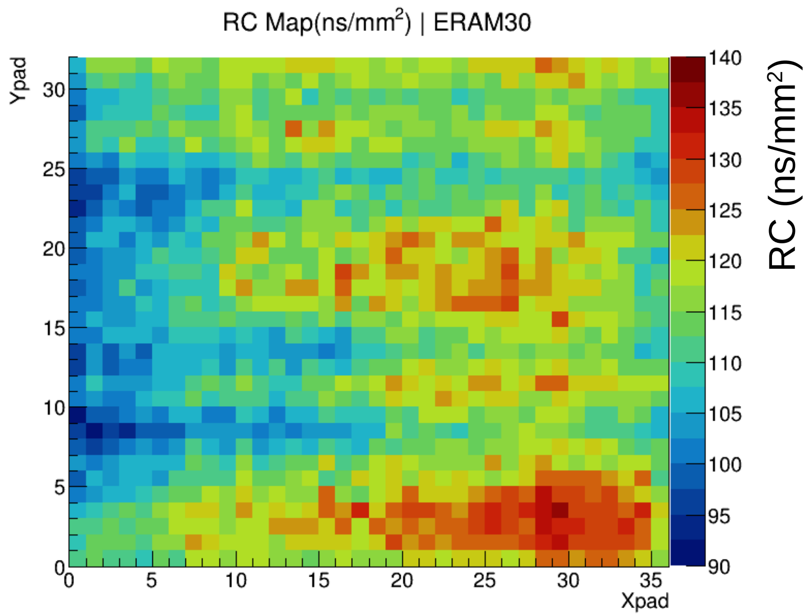


$\text{Ratio}_{mean} = 1.037$

- Very high similarity in gain maps obtained from two different methods.
- Gain results serve as validation for Electronics Response function, and robustness of entire model.

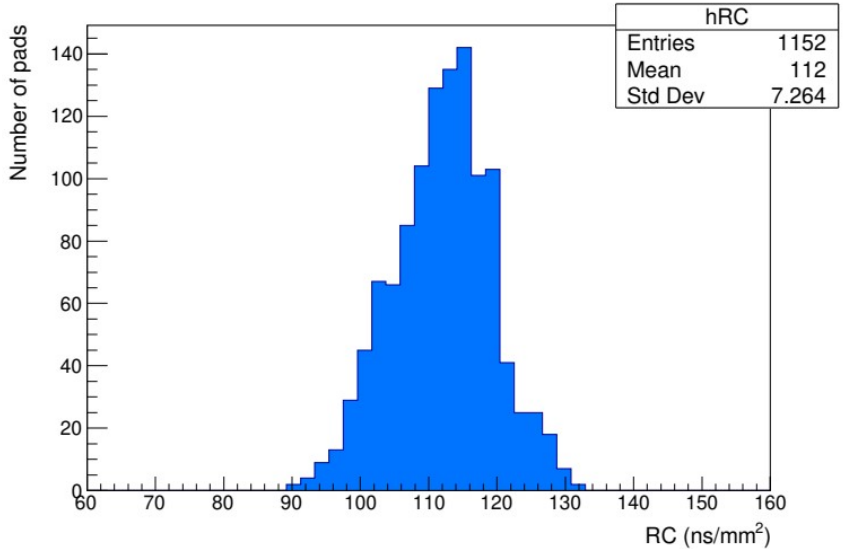
RC extraction from all ERAM pads

- Fitting process is carried out for all pads to obtain RC map.
- RC is more homogeneous in horizontal direction than in vertical direction.



RC map of ERAM-30

RC_{mean} = 112 ns/mm^2



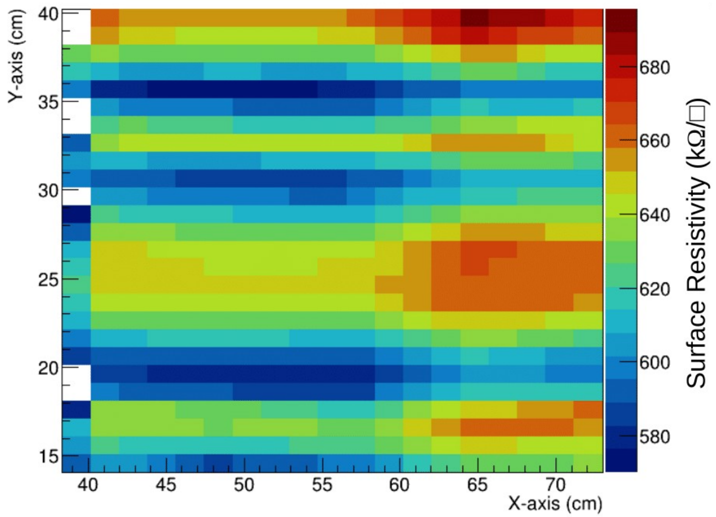
RC distribution of ERAM-30

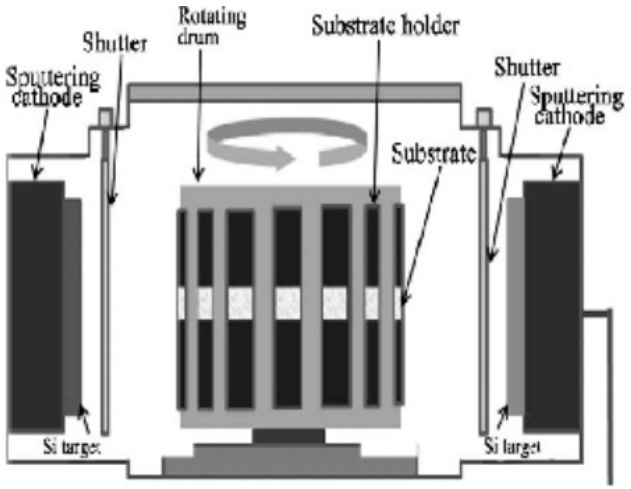
03

Understanding features in ERAM characteristics

Understanding RC map features:
Compare with resistivity values

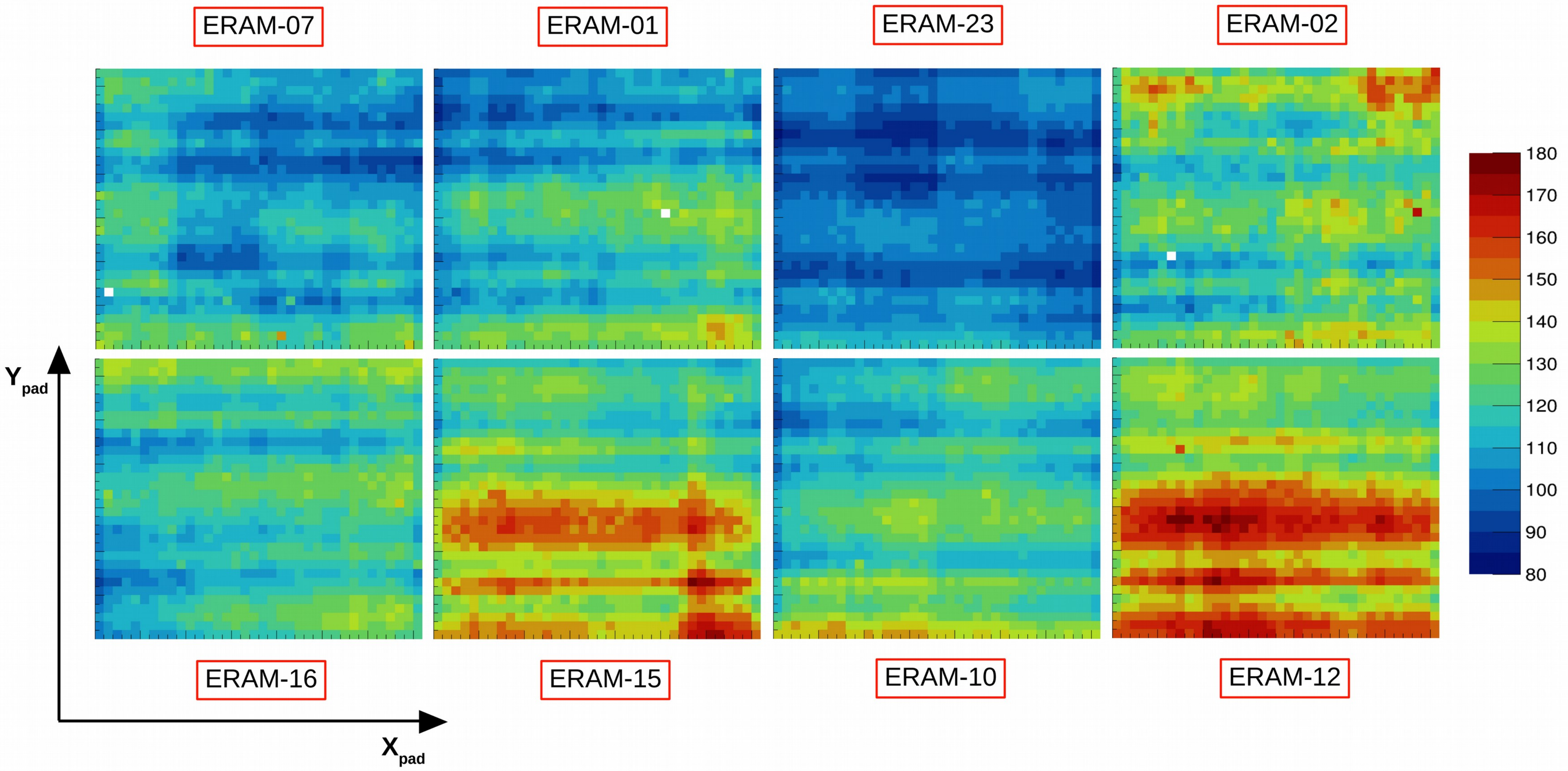
2D map of R measurements



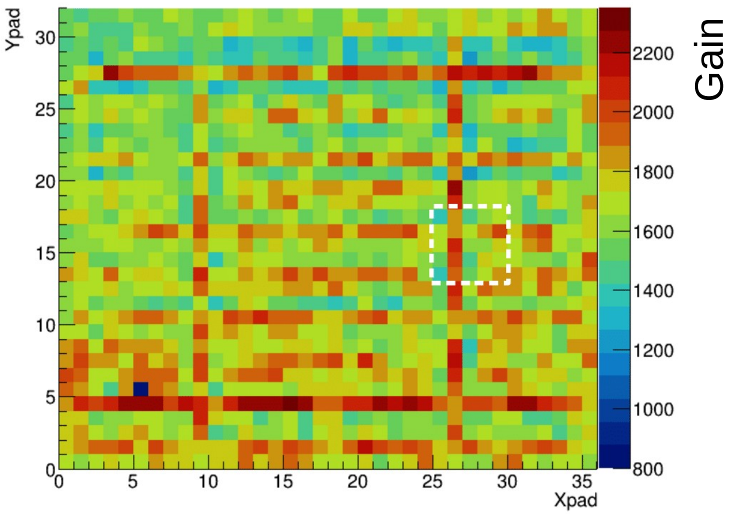


- ➔ 90 R-measurements → 18 rows x 5 columns
- ➔ Horizontally uniform features due to sputtering mechanism.
- ➢ RC map structures seem to be correlated with R measurements.

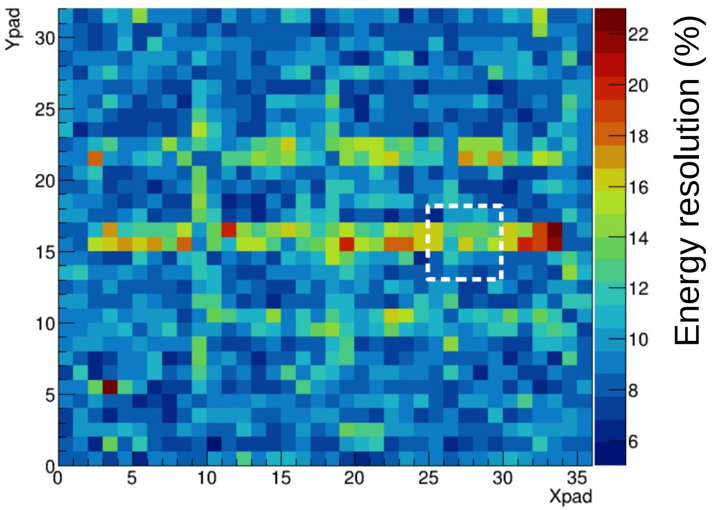
RC maps of ERAMs used in CERN 2022 test beam



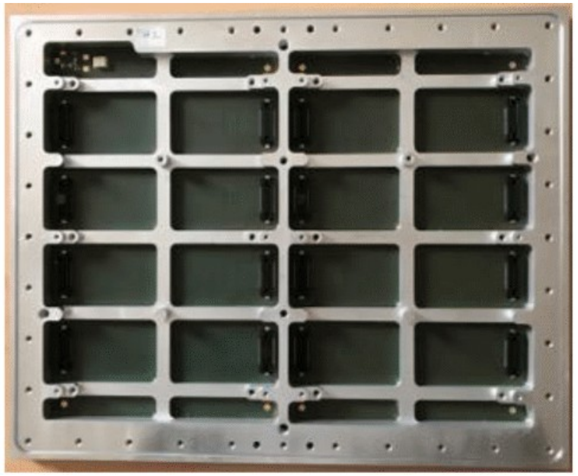
Mechanical impact on gain



Gain map of ERAM-10

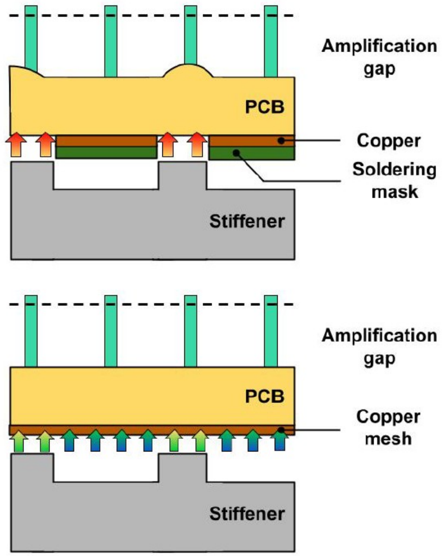


Resolution map of ERAM-10

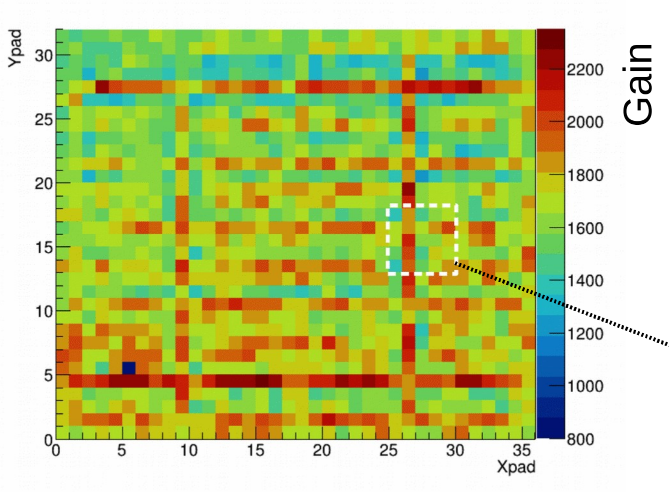


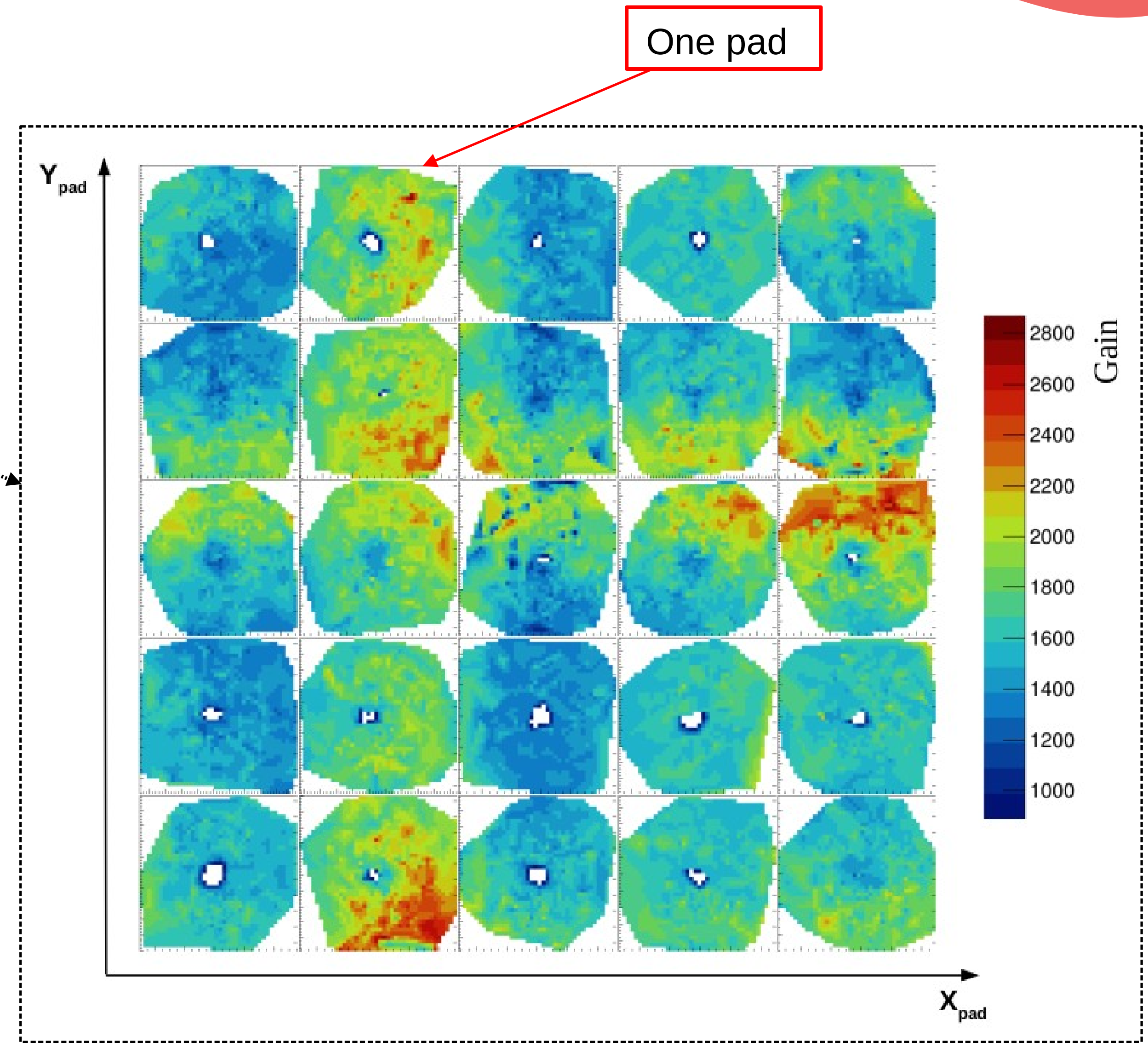
ERAM stiffener

- Copper + solder mask layer causes an unequal distribution of pressure from stiffener onto the PCB.
- Unequal pressure causes variations in amplification gap → gain increases, resolution worsens in pads on top of the PCB stiffener.
- Replacing copper + solder mask with a copper mesh fixed this issue.



Gain non-uniformity within a pad



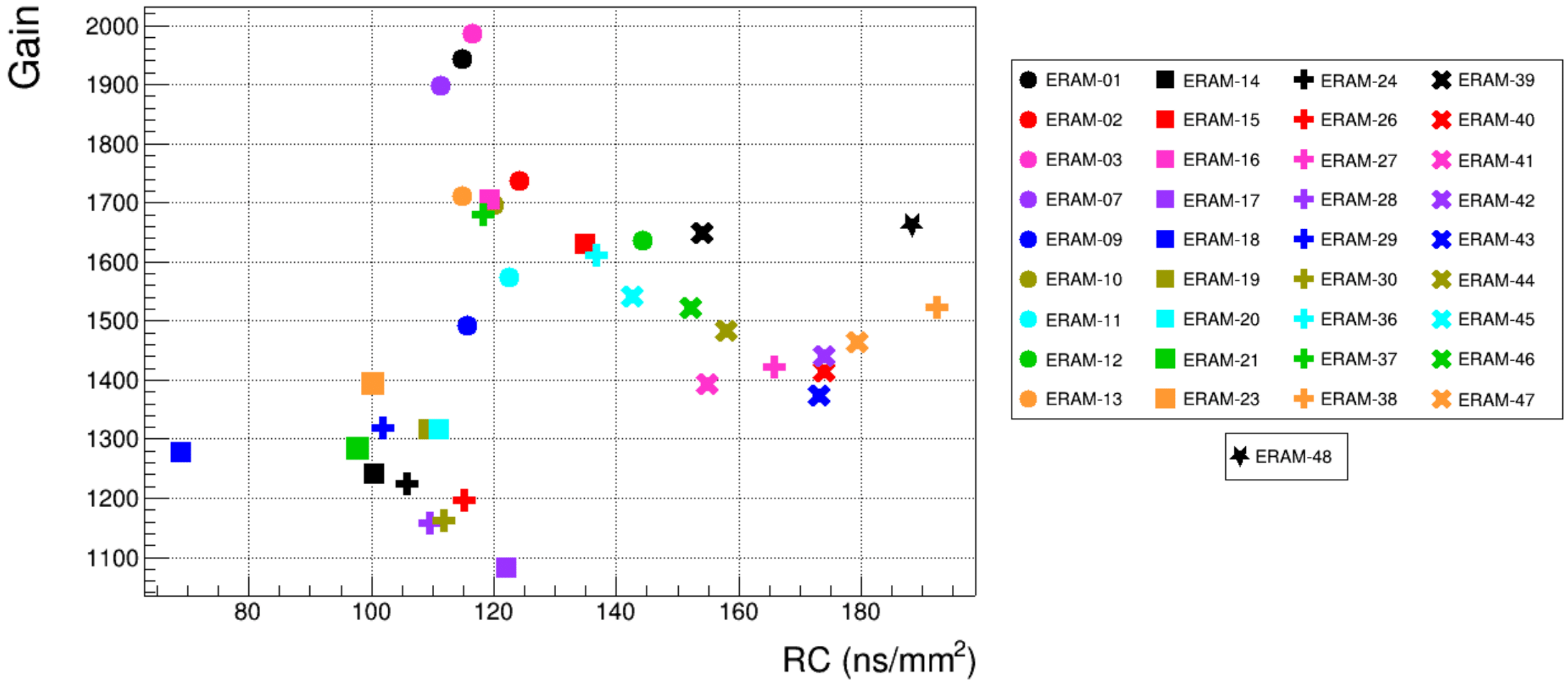


- High-granularity Gain map obtained using simultaneous fit.
- Gain variations seen within pads partly on top of PCB (soldermask + copper) overlay.
- Horizontal stiffener layer causes different gain in upper and lower halves of affected pads.

04

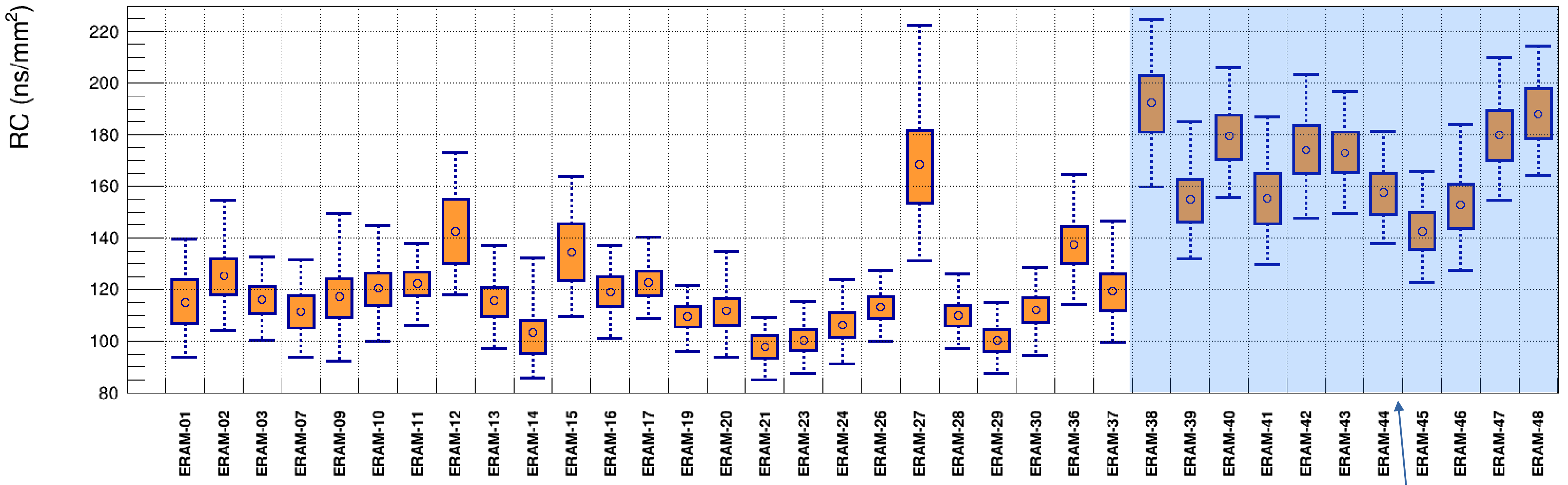
Results from ERAM data analysis

Mean RC and Gain of all operational ERAMs



- Mean RC value driven by DLC foil batch and mean gain value driven by lamination process used in a batch of produced ERAMs.

RC information of all operational ERAMs

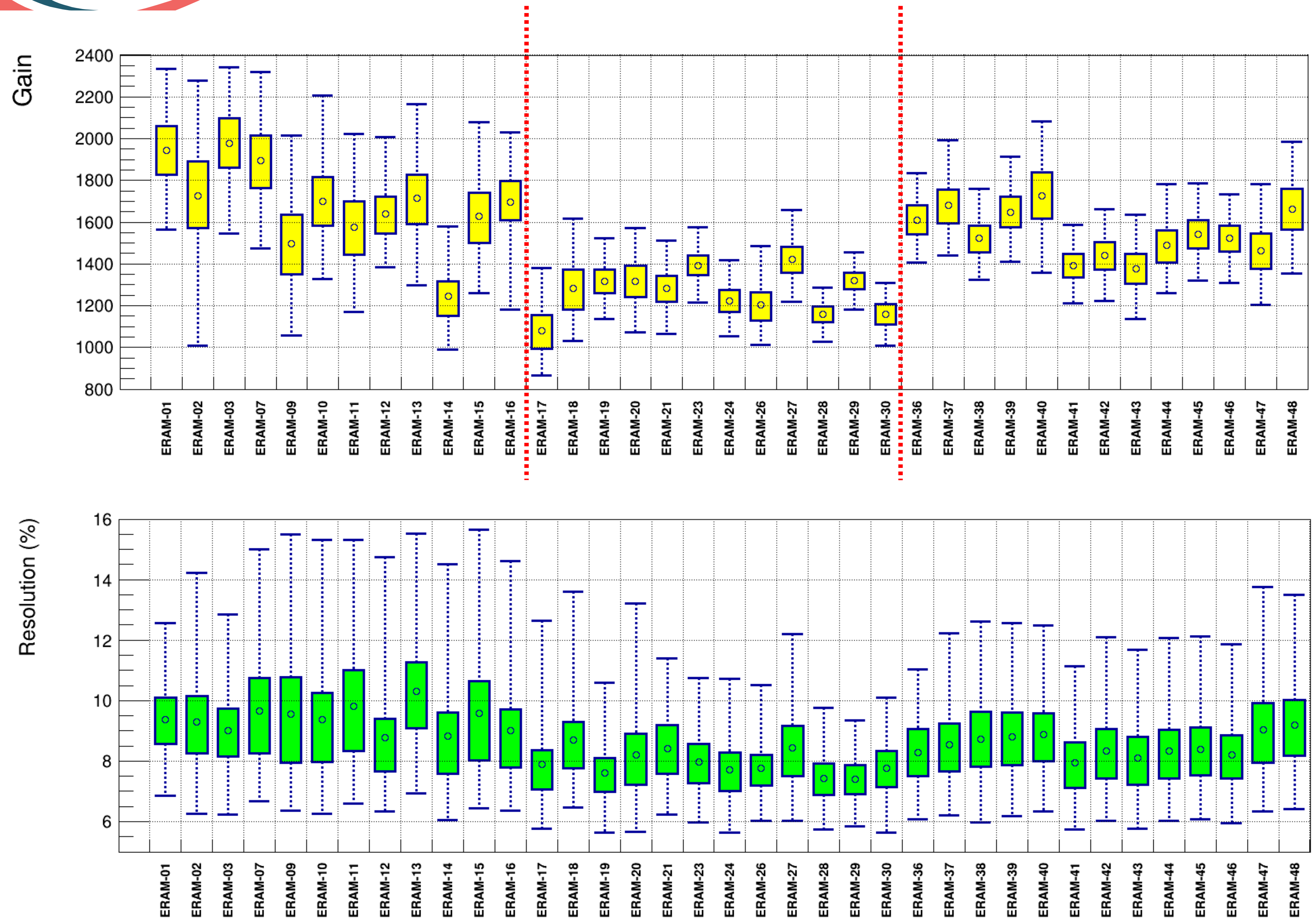


DLC resistivity ≈ 500kΩ/□

Glue thickness: 150 µm

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

Gain and resolution of operational ERAMs



Gain distribution

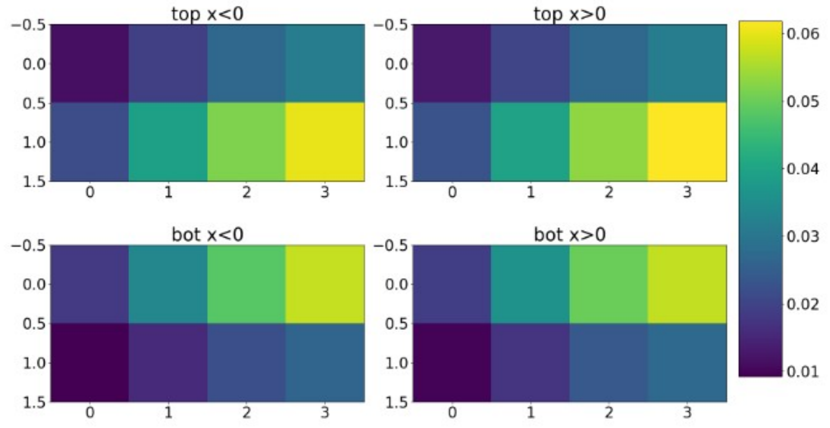
Candle with one bar noticeably longer than the other → ERAM with a problematic region of abnormal Gain (e.g. ERAM-02)

Resolution distribution

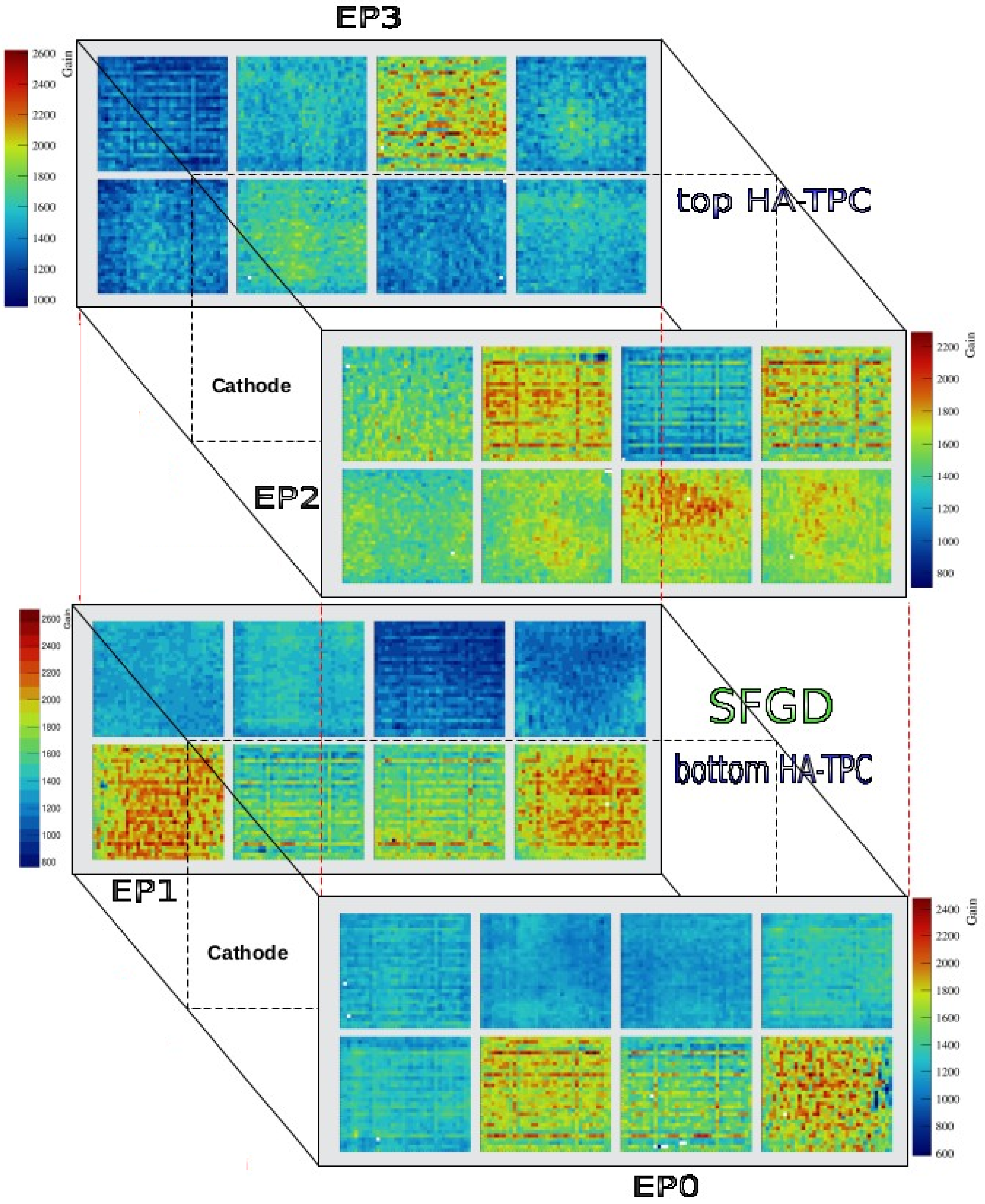
Candle with one bar longer than the other → ERAM with a stiffener structure (e.g. ERAM-09 to ERAM-18)

ERAM selection for HA-TPC installation

Occupancy of ERAM positions in HA-TPC endplates



- ERAM positions closest to SFGD should be installed with best functioning ERAMs.
- Criteria for best functioning ERAMs:
  - Similar mean gain values.
  - Good energy resolution profile.
  - RC should not be very high.



Conclusion

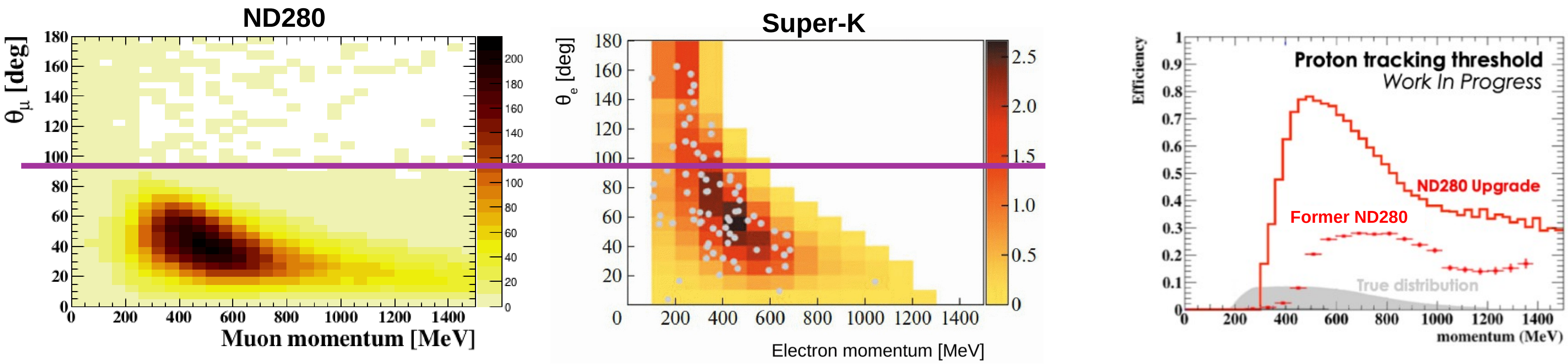
- ND280 upgrade employs resistive Micromegas for the read-out of HA-TPC, which works on the principle of charge spreading.
- ERAM signal model is obtained from convolution of charge diffusion function and derivative of electronics response function.
- The model is able to successfully fit waveforms from X-ray data.
  - Used to characterize all the operational ERAMs (**37**), obtaining their RC, gain and energy resolution information.
  - Energy resolution < 10% obtained for all ERAMs.
- Detailed understanding of features observed in RC and gain maps was acquired.
- ERAM characterization results directly led to the selection of particular ERAMs to be installed at particular positions in the two HA-TPCs.
- RC and gain results are very important inputs to HA-TPC simulation and reconstruction algorithms.

Link to paper: https://doi.org/10.1016/j.nima.2023.168534 OR https://arxiv.org/abs/2303.04481

THANK YOU!

Back-up

Motivations for ND280 upgrade

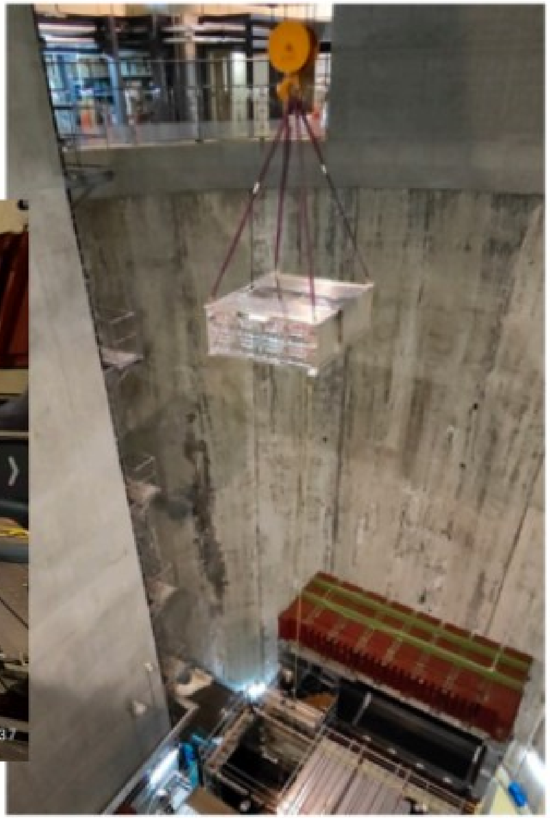


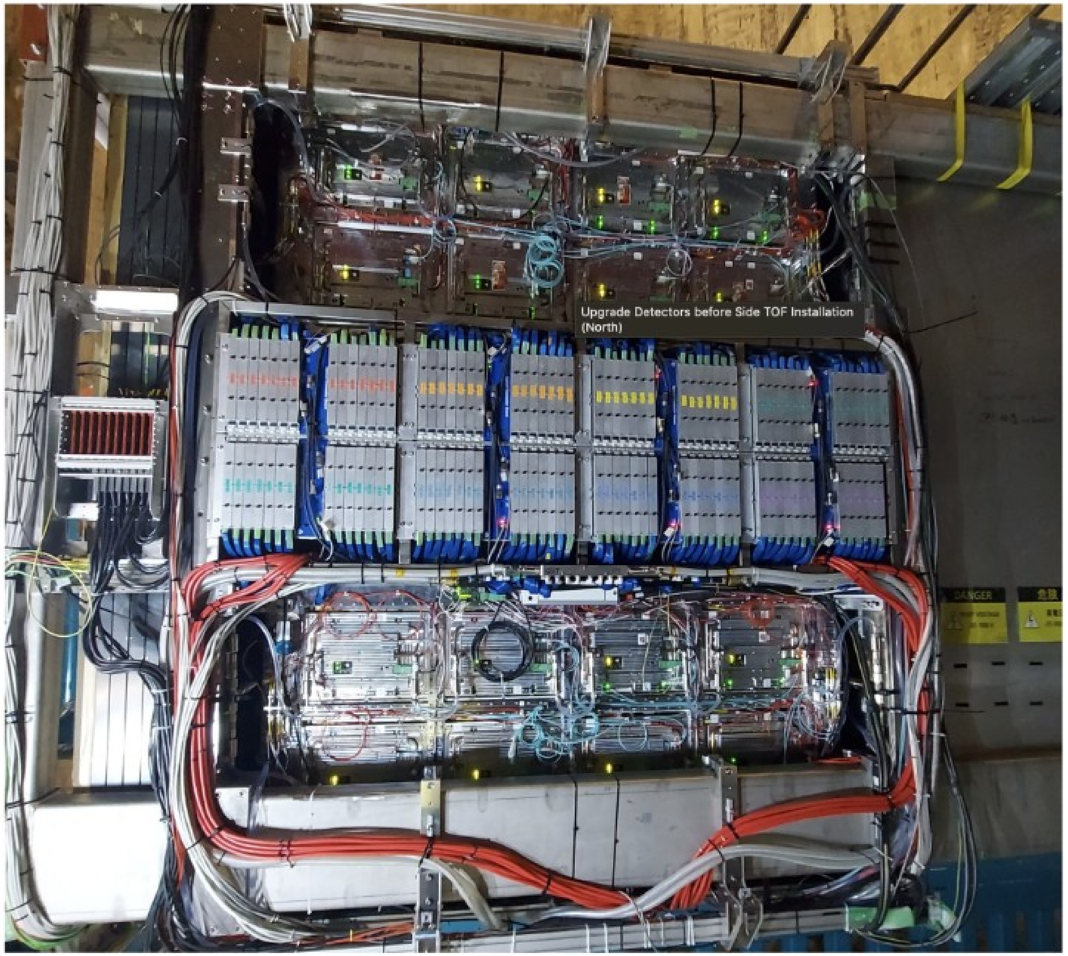
- Low angular acceptance (as opposed to 4π coverage at Super-K) ⟶ Mostly reconstruct forward going tracks entering the TPCs.
- Low efficiency to track low momentum protons ⟶ Have to use lepton kinematics only for E_ν reconstruction.
- No capability to detect/reconstruct neutrons.

$$E_{\text{rec}} = \frac{m_p^2 - (m_n - E_b)^2 + m_l + 2\,(m_n - E_b)\,E_l}{2\,(m_n - E_b - E_l + p_l \cos\theta_l)}$$

- Limited ToF information resulting in out-of-fiducial-volume (OOFV) background.
- Limited precision for ν_e cross-section measurements.

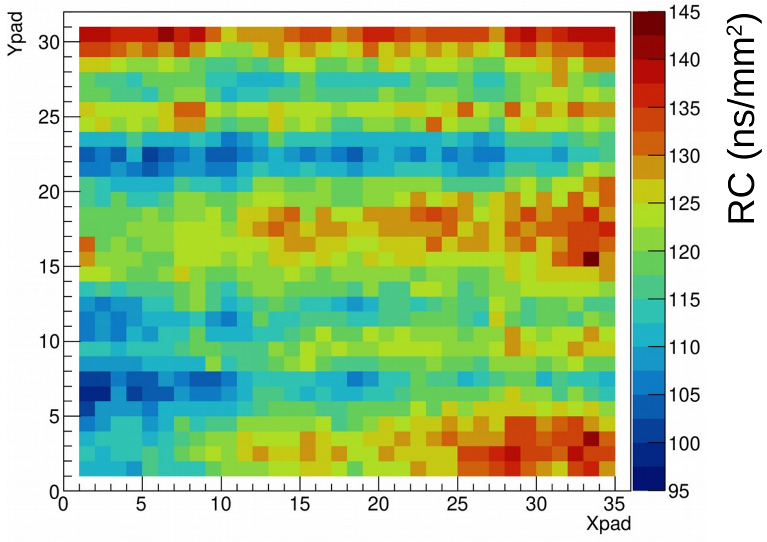
Detector installation in ND280 pit



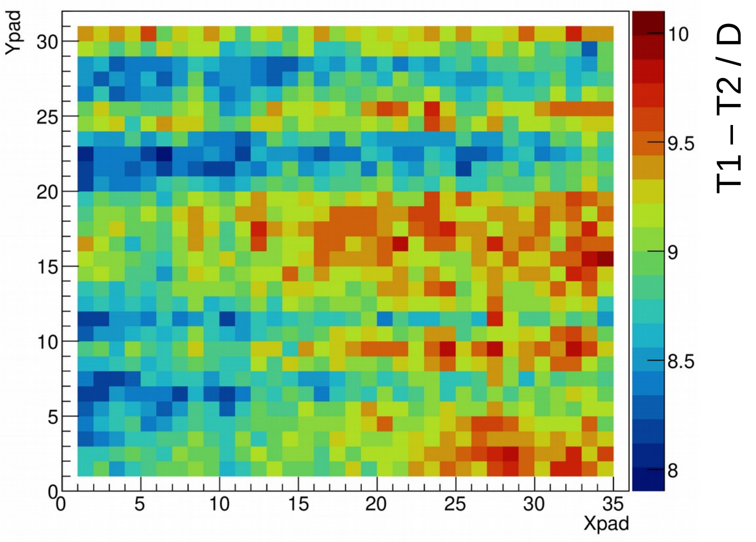


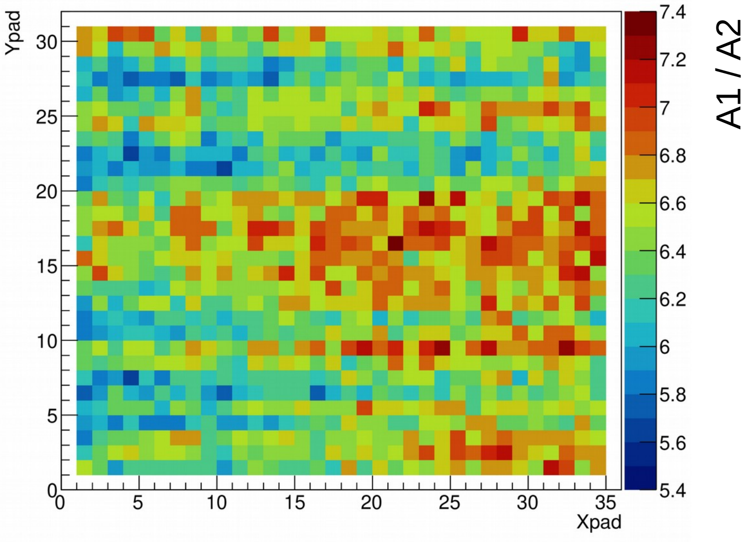
Understanding RC map features: Charge spreading using basic-level variables

RC map of ERAM-16



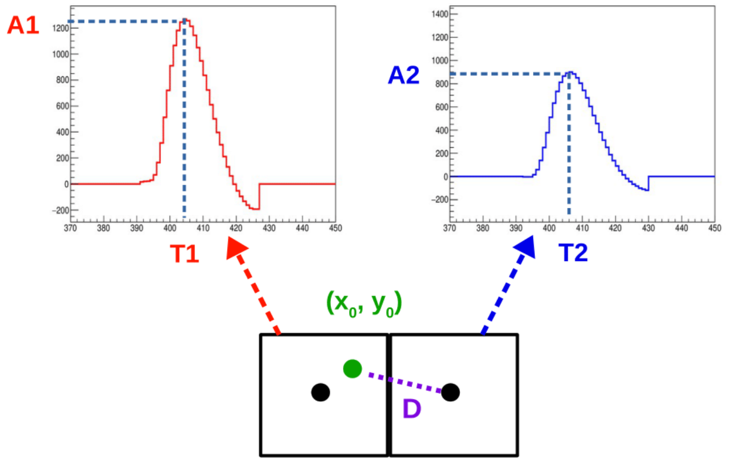
Basic-level variable maps





$$\frac{T1 - T2}{D}$$

$$\frac{A1}{A2}$$ Ratio of amplitudes



- ➢ 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

Effect of RC and gain on HA-TPC performance

[Performance plots from HA-TPC group]

- HA-TPC installed with higher-gain ERAMs have higher mean dE/dx.
- Spatial resolution is observed to be directly correlated to mean RC value of an ERAM.
- Applying RC tuning to ERAMs with large RC values greatly improves the spatial resolution.