2nd DRD1 collaboration meeting - WG1

Charge spreading in resistive Micromegas for the T2K/ND280 TPC

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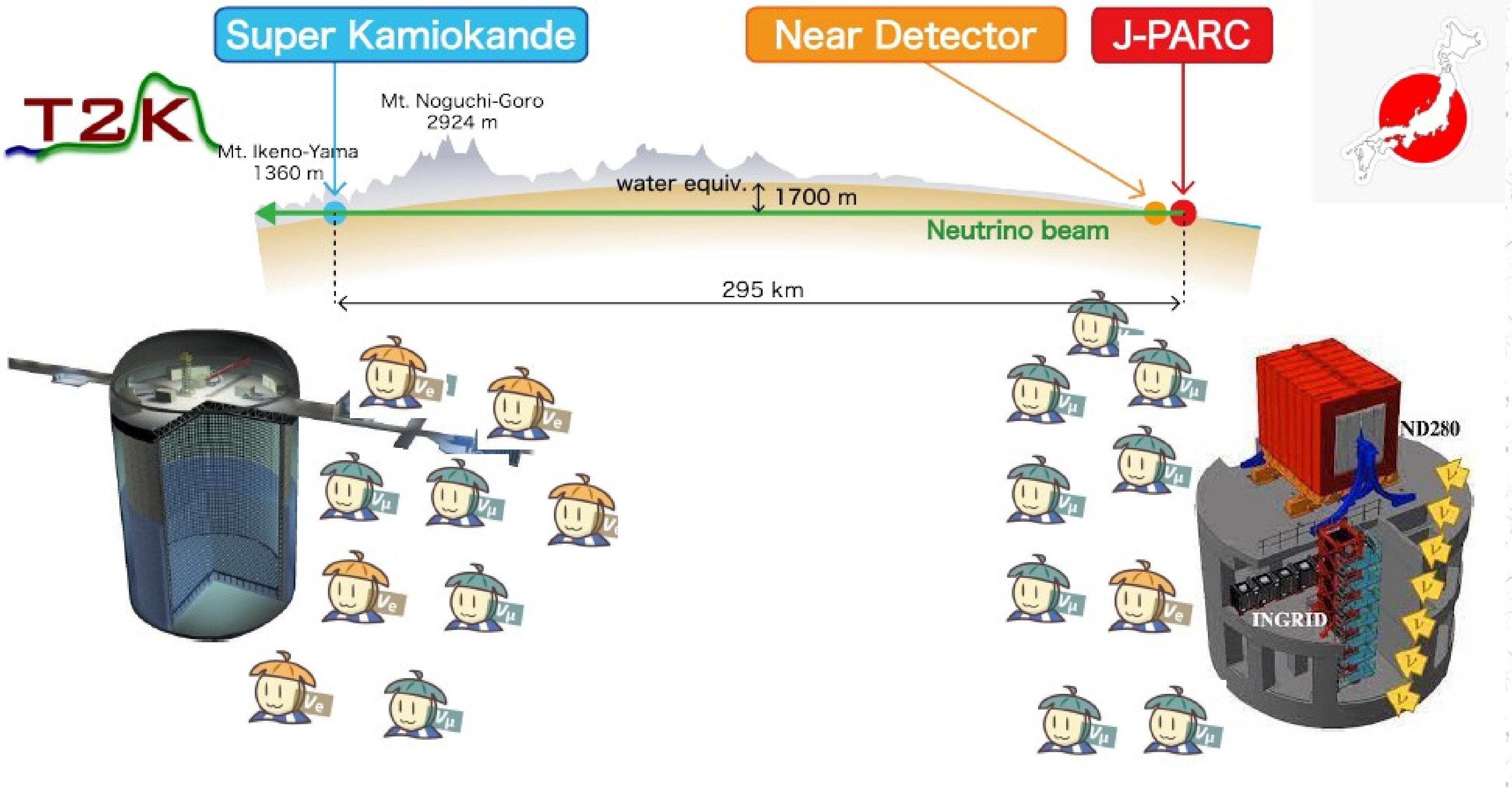
Contents

01

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

The T2K experiment: Tokai to Kamioka

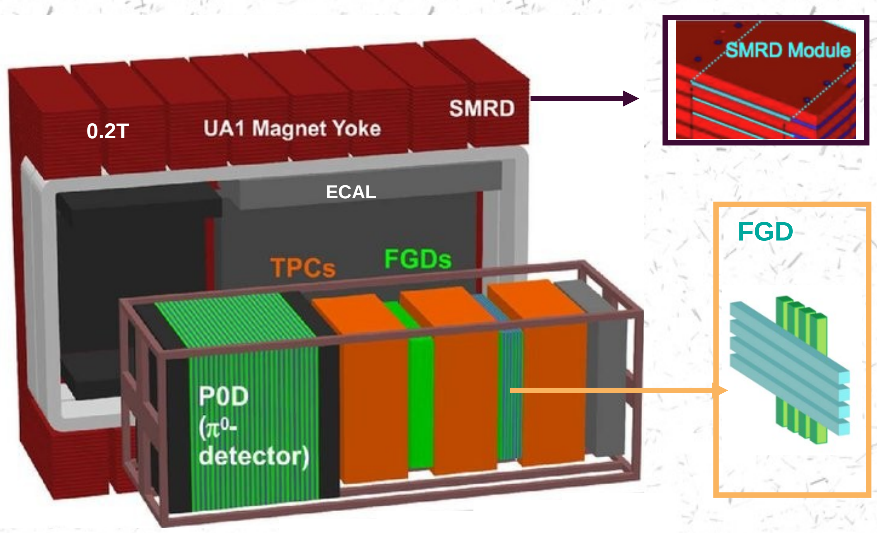


Off-axis angle

Neutrino cartoons by Yuki Akimoto

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.

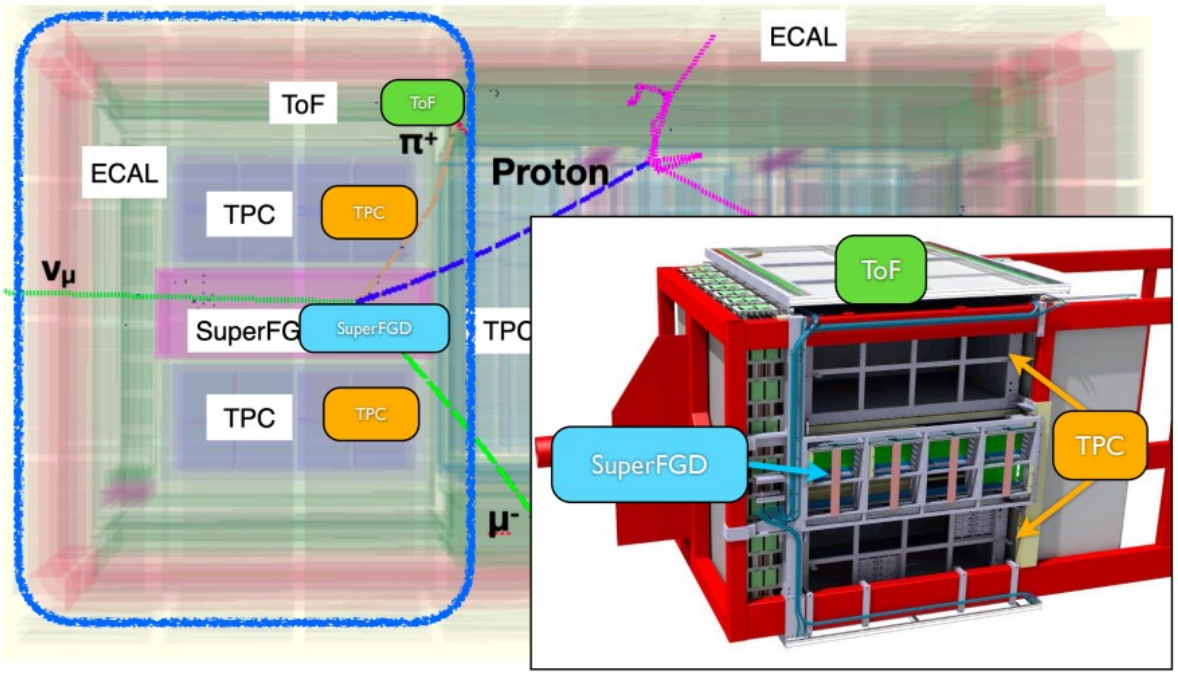
ND280 measures beam spectrum and flavor composition before the oscillations

- Detector installed inside the **UA1/NOMAD magnet (0.2 T)**
- **A detector optimized to measure π^0 (P0D)**
- **An electromagnetic calorimeter to distinguish tracks from 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



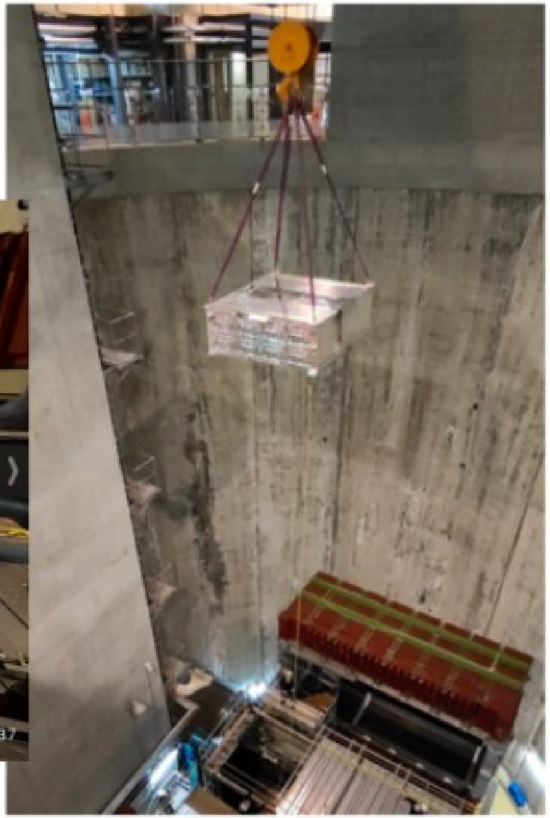
P0D replaced with a new scintillator target (Super-FGD), two High-Angle TPCs and six ToF planes.

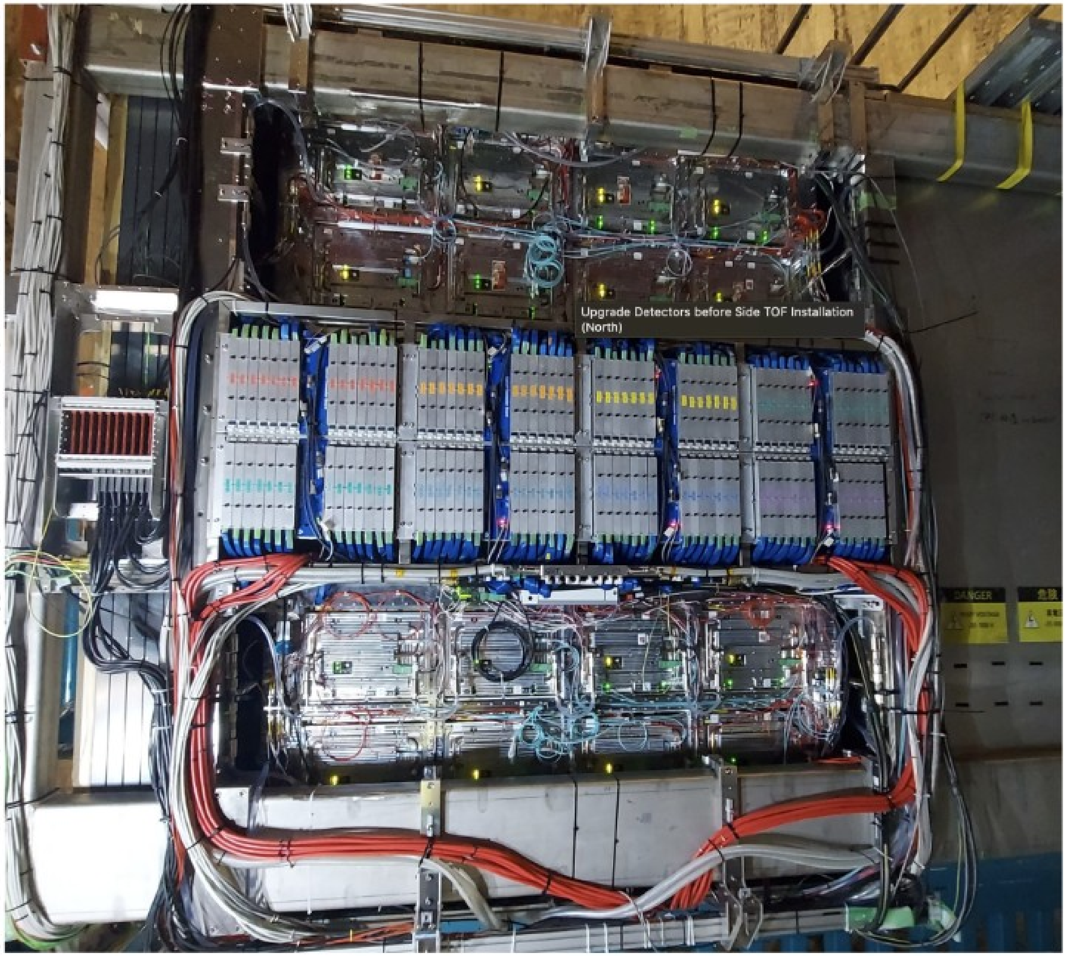
- High-Angle TPCs allow to reconstruct muons at any angle with respect to beam.
  - Readout using resistive Micromegas.
  - Spatial resolution better than 800 µm and dE/dx resolution better than 10% for all incident angles and drift distances.

- 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 by using time of flight between anti-ν interaction vertex and neutron re-interaction in the detector.

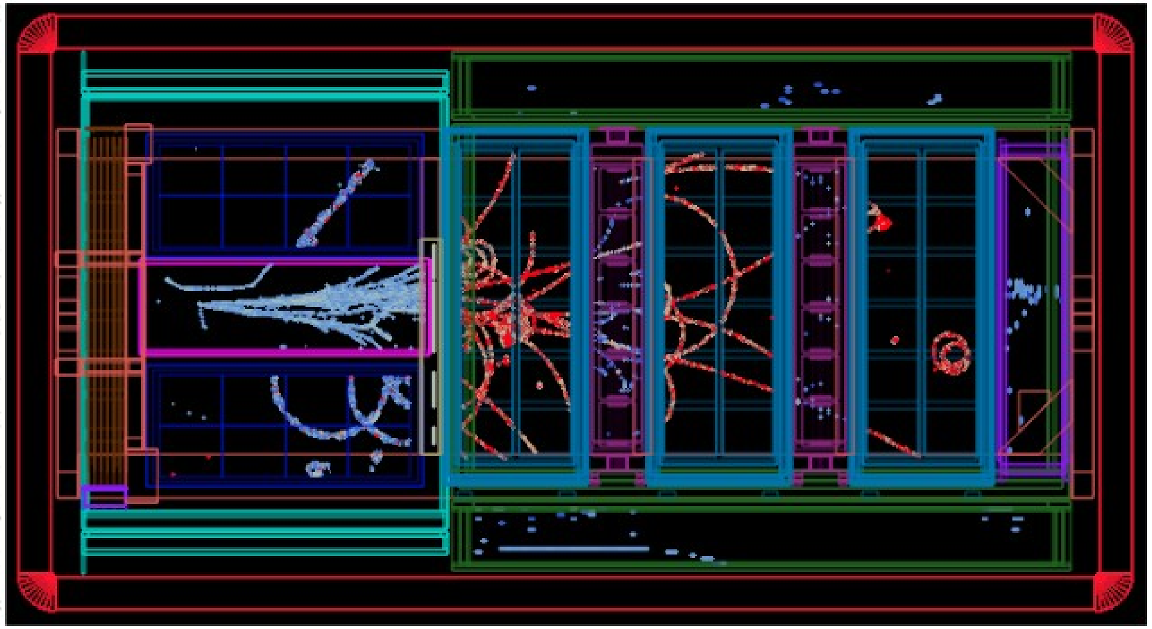
- ToF planes allow to veto particles originating from outside the ND280 fiducial volume.

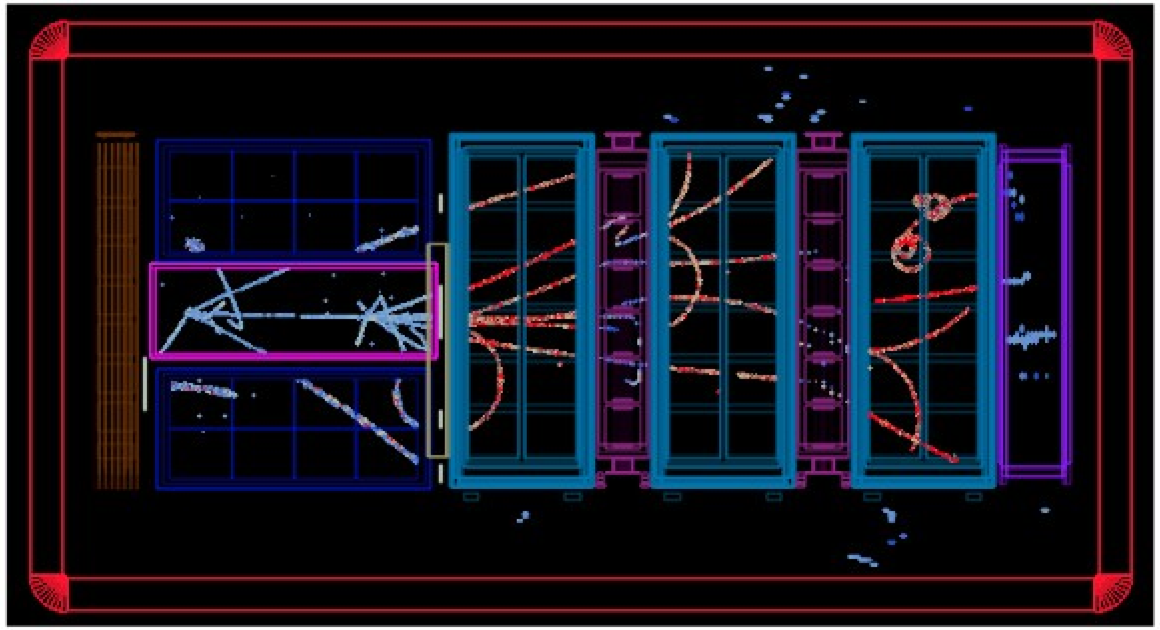
Detector installation in ND280 pit



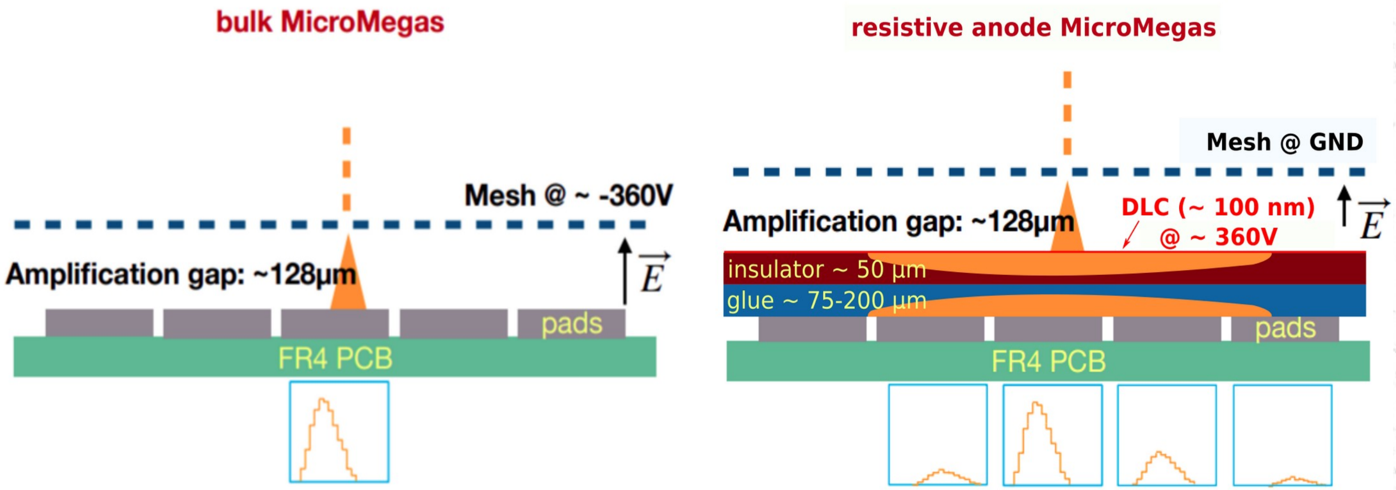


First neutrino interactions with full ND280 upgrade!





HA-TPC: Resistive Micromegas detectors



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

Pad size: 1.1 * 1 cm^2

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

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

- Charge sharing between pads ⟹ More precise position reconstruction
- Better resolution with lower 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.
- DLC allows smaller RC ⟹ Larger charge spreading (better spatial resolution)

R = Surface resistivity
C = Capacitance / unit area

➔ Telegrapher's equation:

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

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

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

02

Modeling of charge spreading with resistive Micromegas

Ingredients for charge spreading model

Transverse diffusion

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

RMS spread = 540 µm (accounted for)

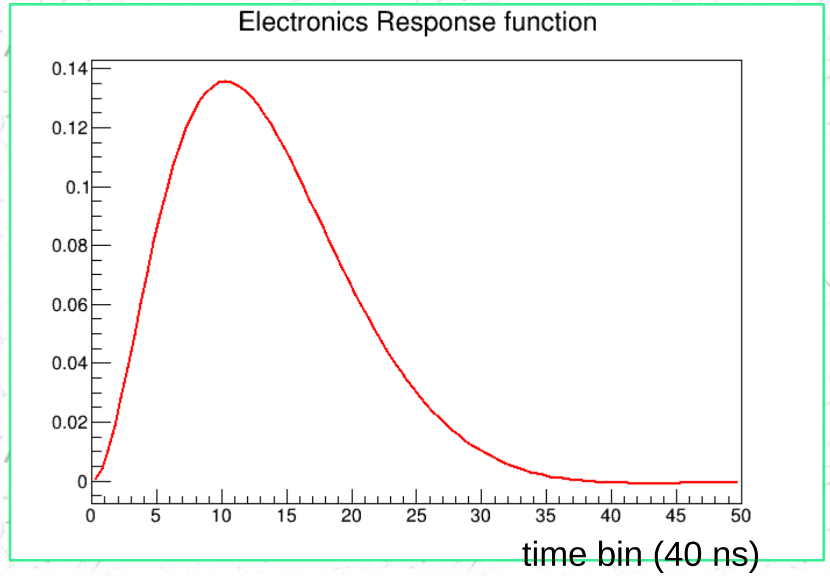
Longitudinal diffusion

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

RMS spread = 4.5 ns (neglected)

Electronics Response

R(t)



Resistive foil + glue

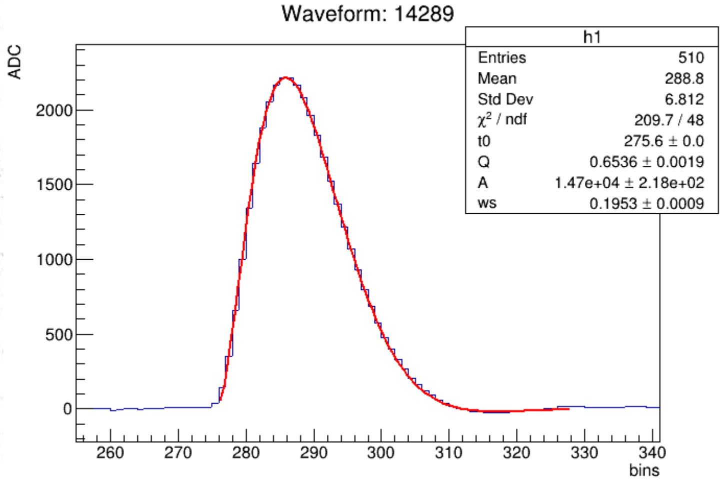
$$\rho(x,y,t) = \left(\frac{1}{\sigma_t \sqrt{\pi t h}}\right)^2 \exp\left(\frac{-(x^2+y^2)}{4th}\right)$$

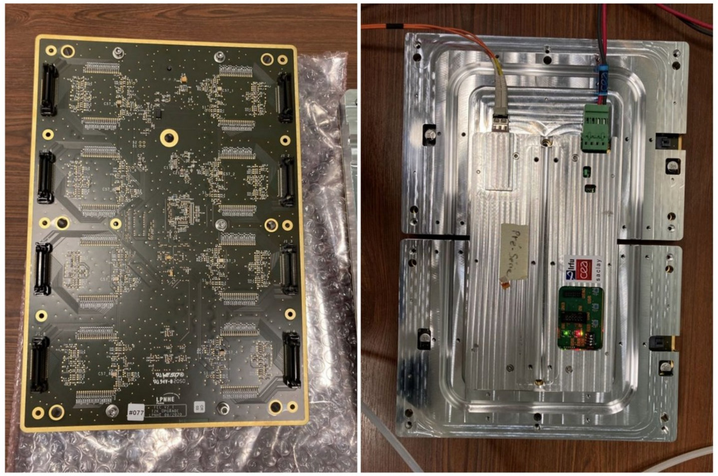
$$h = 1/RC$$

Electronics Response 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.

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

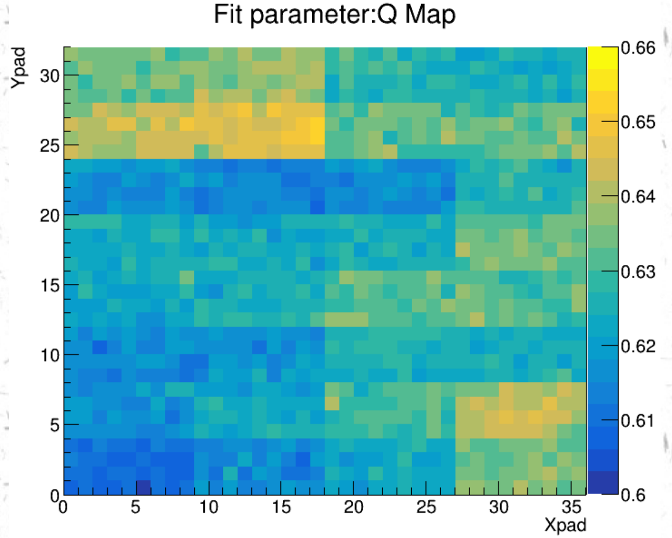




- Parameterized by 2 main variables related to shape of a signal waveform: **Q** and **w_s**.
- Variation in these fit parameters over all the pads was studied to determine if they can be set as constants.

- Q = 0.6368
- w_s = 0.1951

} **fixed (412ns peaking time)**



Ingredients for charge spreading model

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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)

Electronics Response

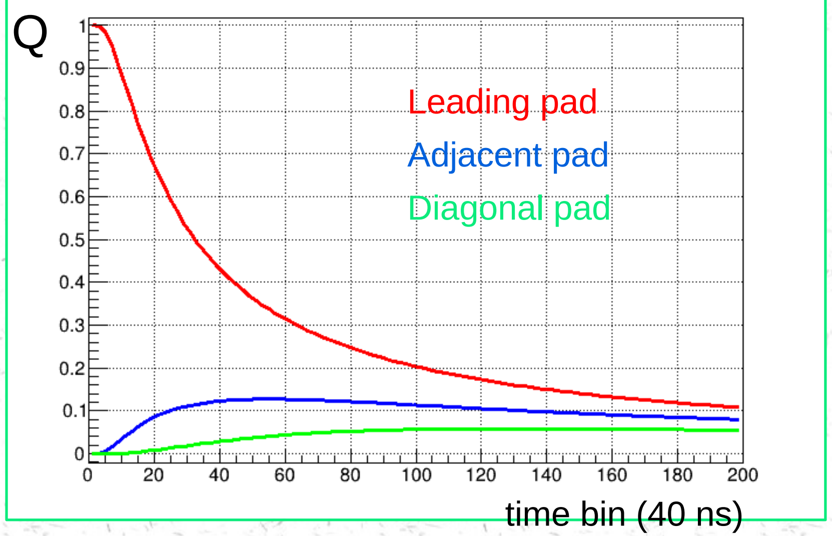
R(t)

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 spreading model

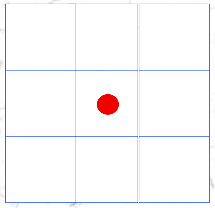
Charge diffusion function:

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

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

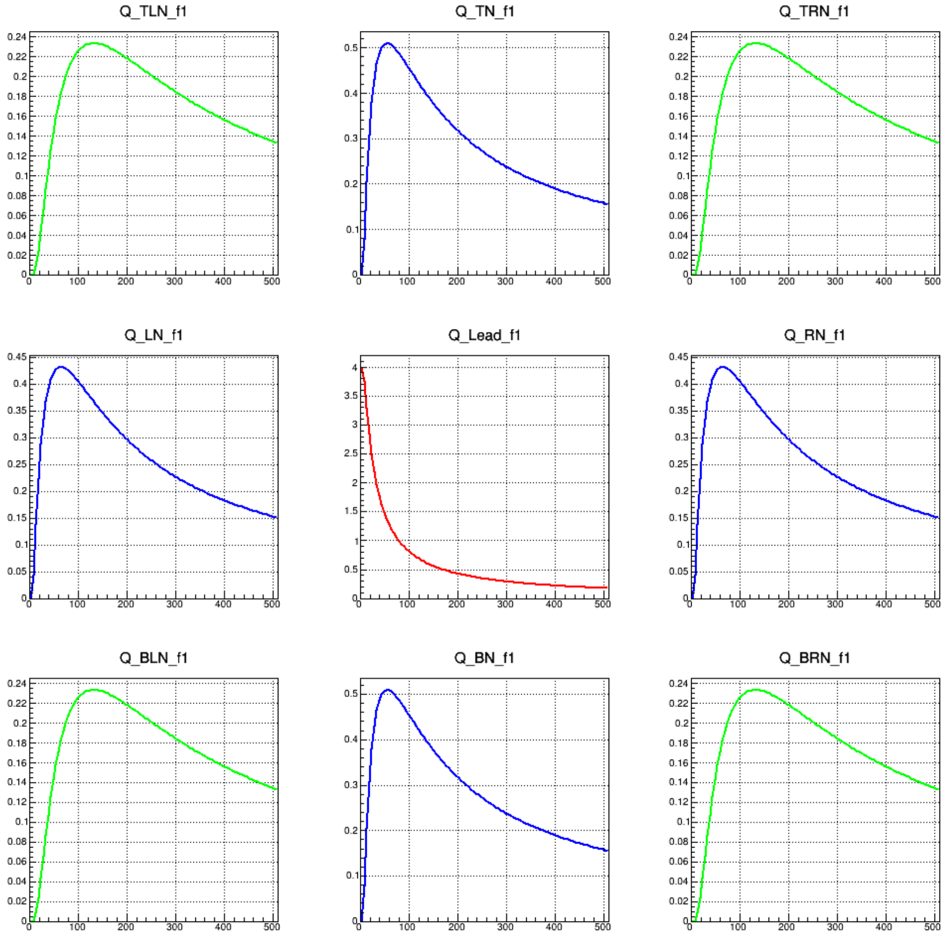
- Obtained from Telegrapher's equation for charge diffusion.
- Integrating charge density function over area of 1 readout pad.
- Parameterized by 5 variables:
  - x_0
  - y_0

    } Initial charge position
  - t_0: Time of charge deposition in leading pad
  - RC : Describes charge spreading
  - Q_e : Total charge deposited in an event



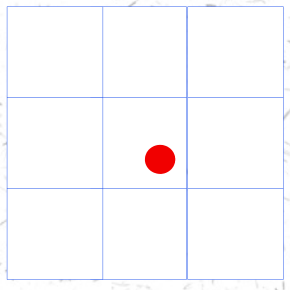
x_H, x_L: Upper and lower bound of a pad in x-direction
y_H, y_L: Upper and lower bound of a pad in y-direction

RC = 60 ns/mm^2
Q_e = 4 e^-



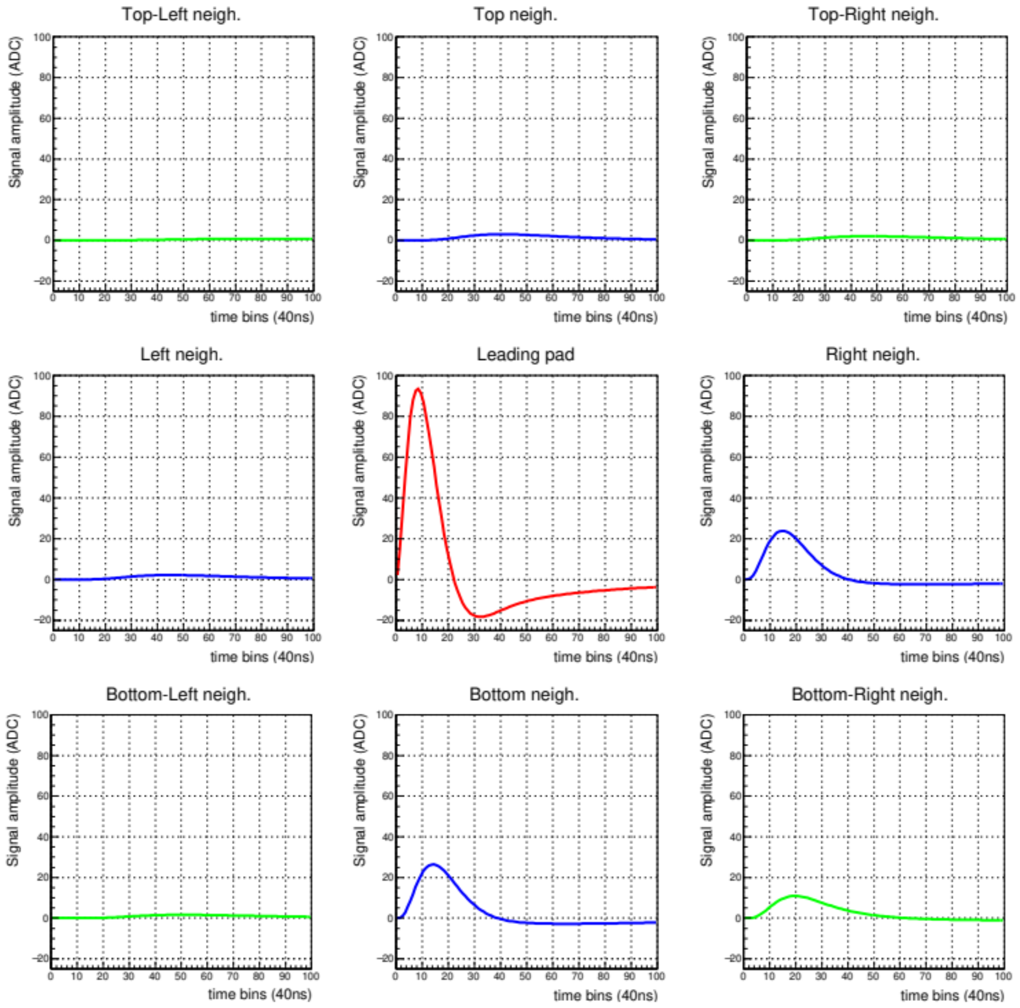
Signal model

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



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

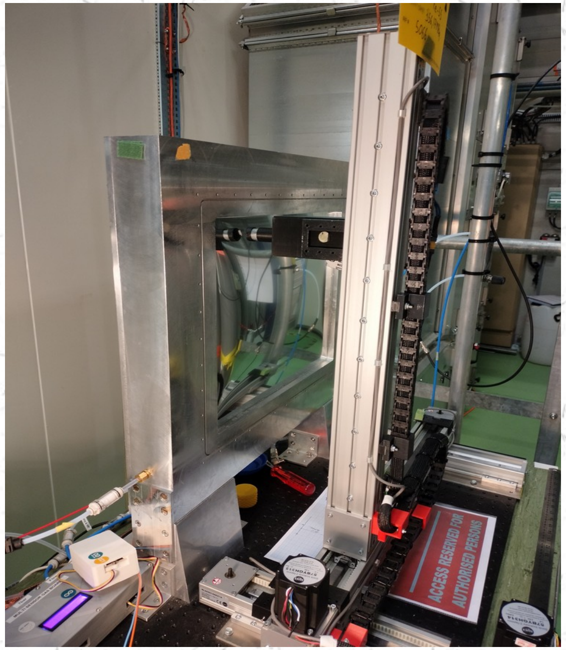
RC = 60 ns/mm^2
Q_e = 24845 e^-



03

Application of charge spreading model in X-ray data

X-ray test bench



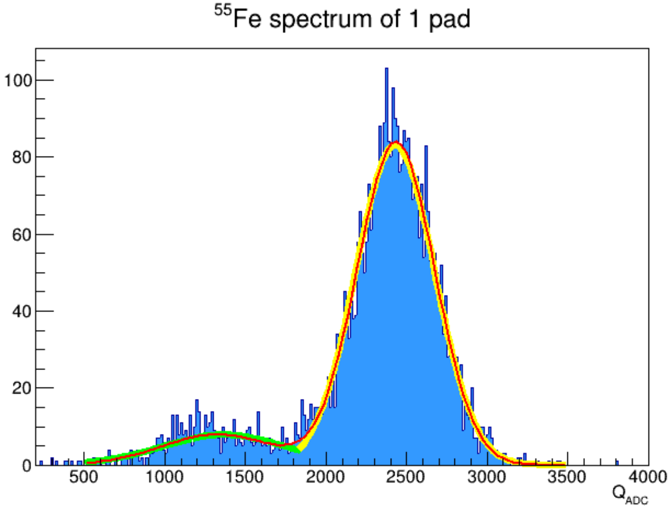
X-ray test bench @ CERN

Drift gap: 3 cm

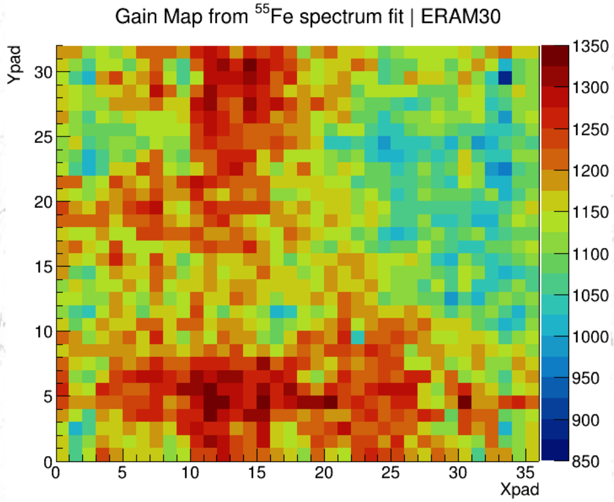
- Each pad(1152) of an ERAM placed inside an X-ray chamber is scanned using a robot holding an ^{55}Fe X-ray source.
- ^{55}Fe spectrum can be reconstructed using all events in one pad.

Summing all waveforms in each event and taking amplitude of summed waveform

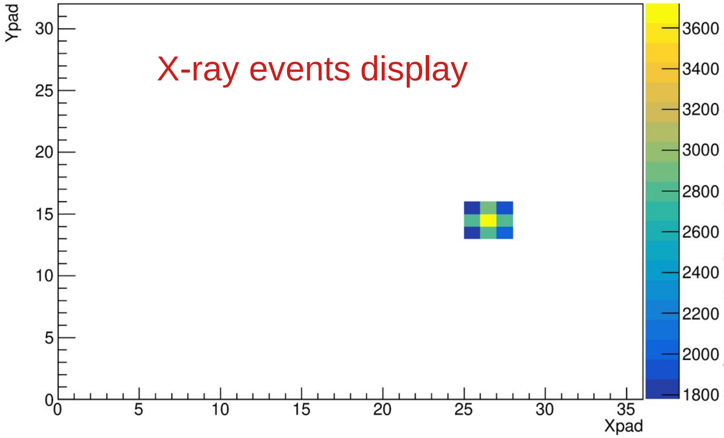
- Gain is obtained for a pad by fitting its ^{55}Fe spectrum. Resolution of < 10% is obtained.



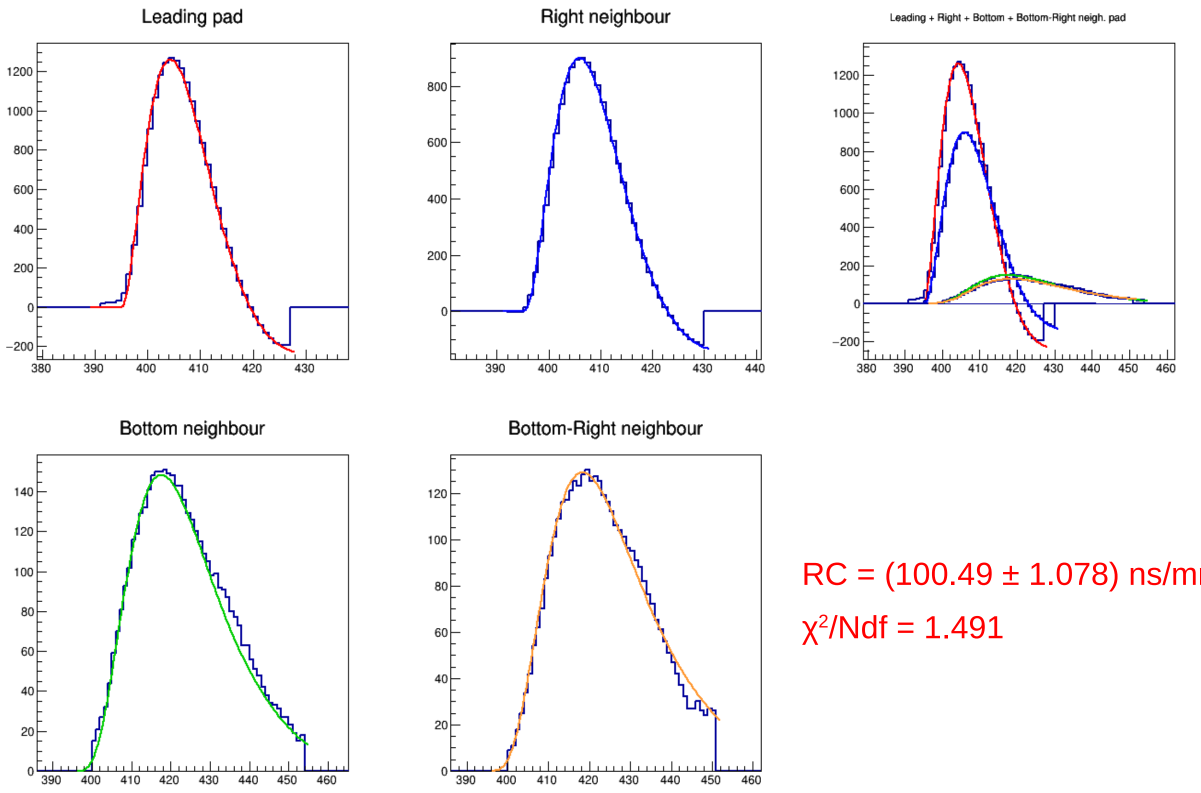
Example of an ^{55}Fe spectrum



Gain map of ERAM-30



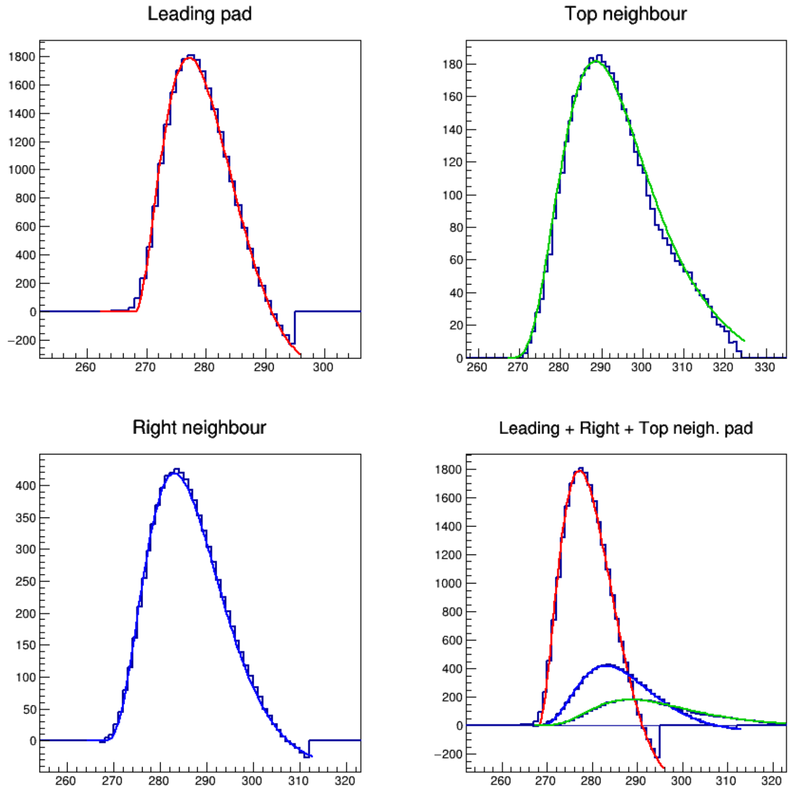
Application of Signal model on X-ray data



RC = (100.49 ± 1.078) ns/mm^2

χ^2/Ndf = 1.491

4-waveform simultaneous fit of an X-ray event



RC = (110.82 ± 1.363) ns/mm^2

χ^2/Ndf = 1.903

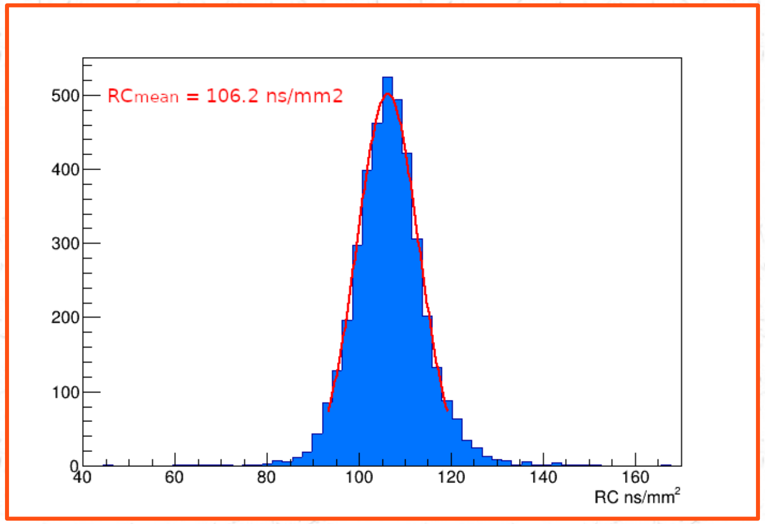
3-waveform simultaneous fit of an X-ray event

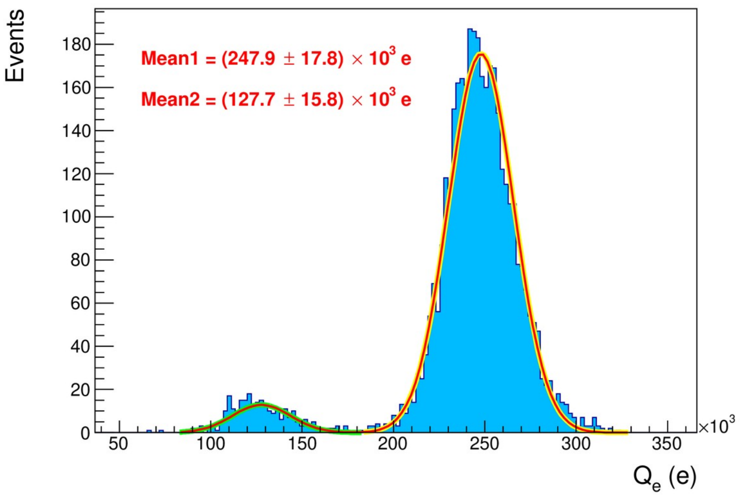
- RC is obtained for a pad by simultaneous fit of waveforms in each event.

Simultaneous fit: Leading pad + Neighbouring pads are fitted simultaneously

Results from fitting events in 1 pad

RC distribution

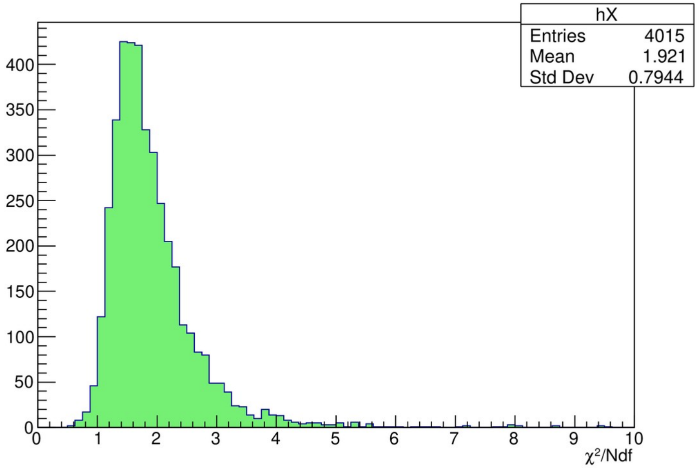


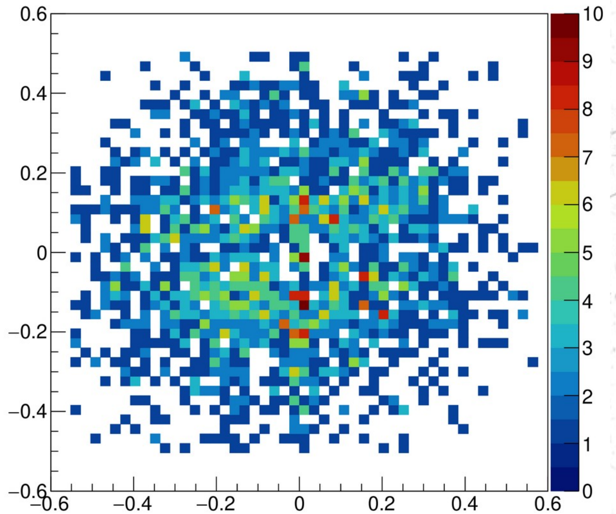


Q_e distribution

- Reconstruction of ^{55}Fe spectrum.

χ^2/Ndf distribution



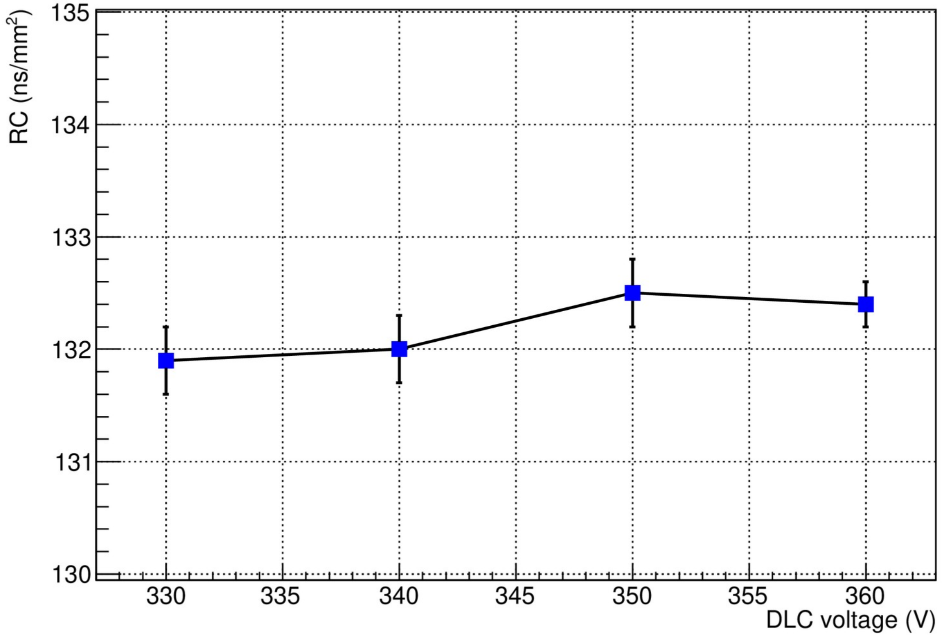


Distribution of charge deposition points (x_0, y_0)

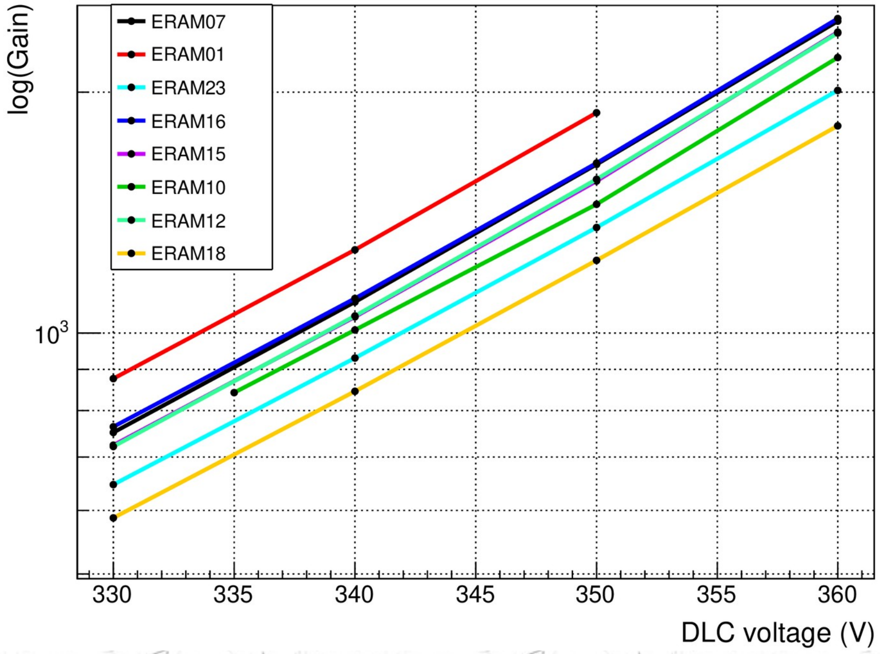
Dependence of RC and Gain on DLC voltage

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

RC v/s DLC voltage



Gain v/s DLC voltage

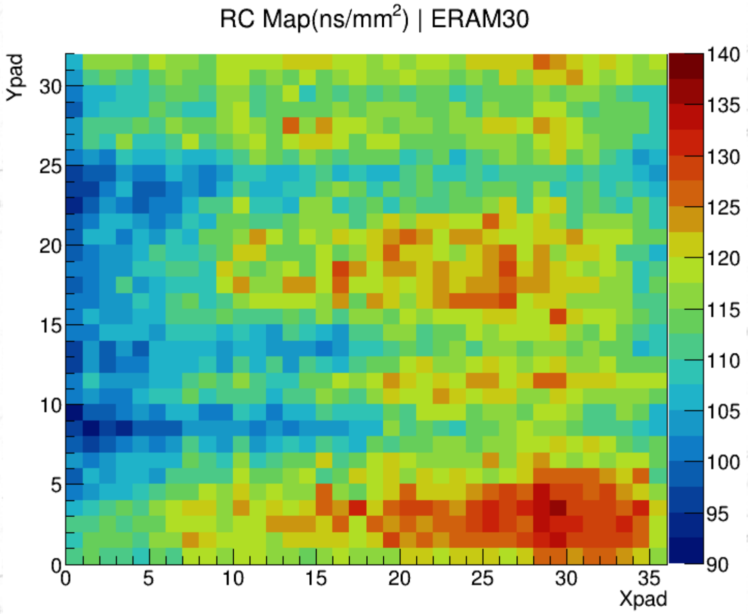


- RC is largely invariant w.r.t DLC voltage.
- Linear relation between Gain and DLC voltage in log scale.

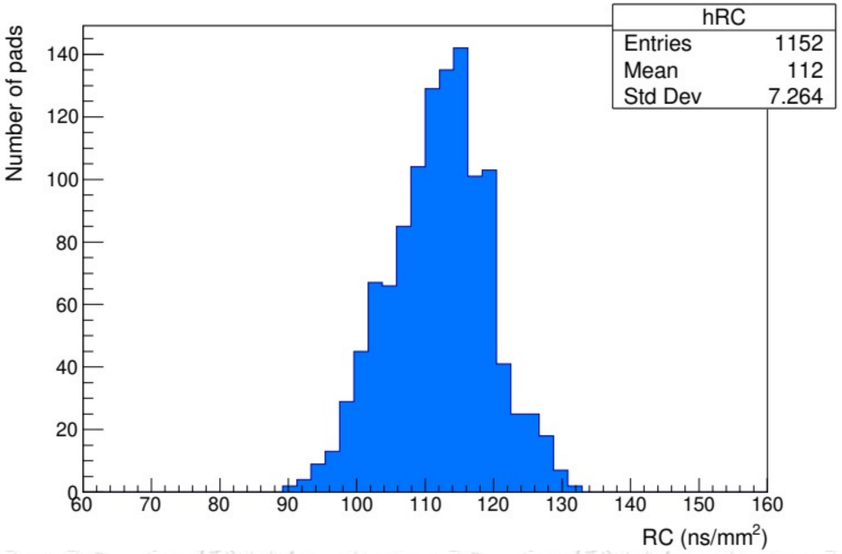
RC extraction from all ERAM pads

- 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.

RC_{mean} = 112 ns/mm^2

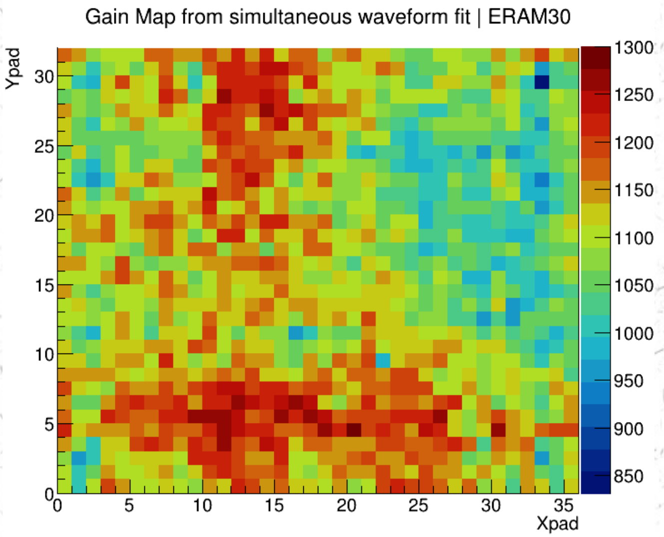


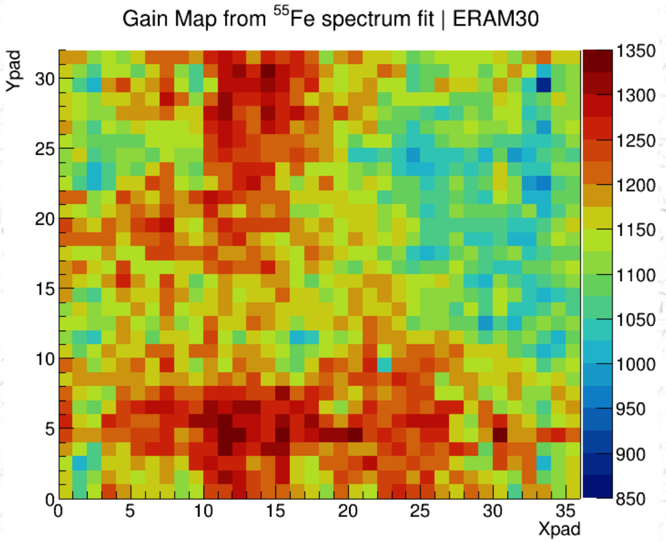
RC map of ERAM-30



RC distribution of ERAM-30

Validation of Signal model

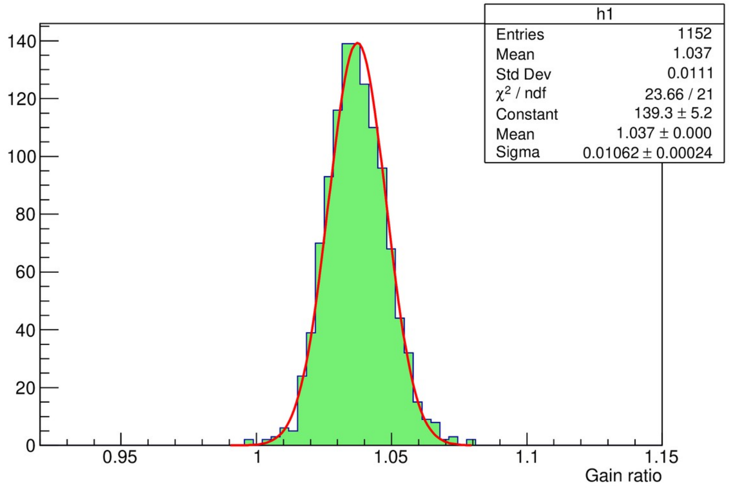




Gain map from simultaneous fit method

Gain map from waveform sum method

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



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

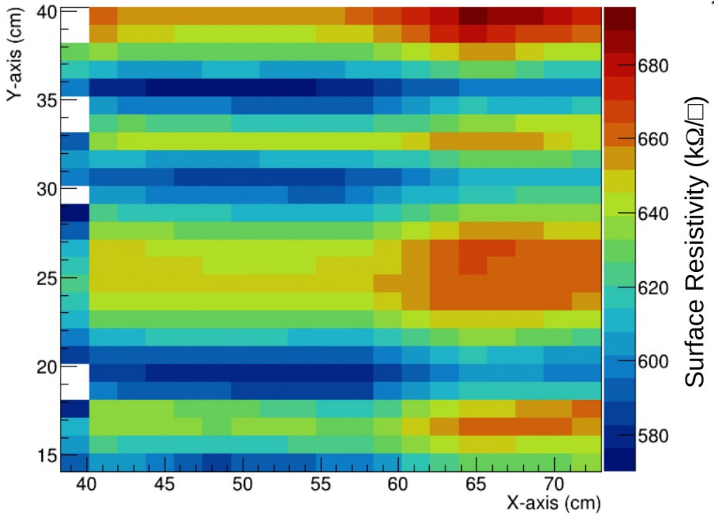
- Very high similarity in Gain maps obtained from 2 different methods.
- Gain results serve as validation for Electronics Response function, and robustness of entire model.

04

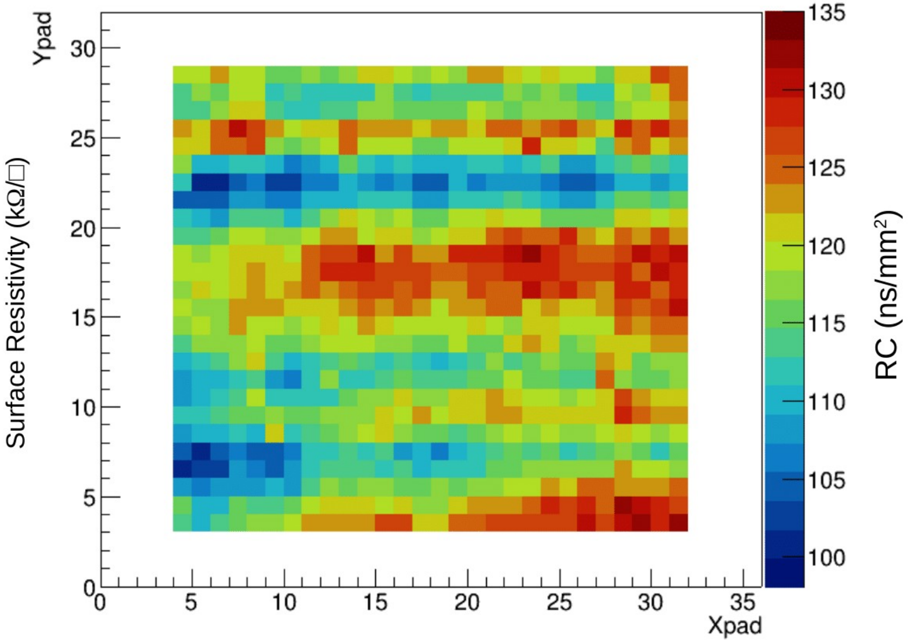
RC results from ERAM data analysis

Understanding RC map features: Compare with R values

ERAM-PCB: R measurements



ERAM-16: RC map from fit



- 90 R-measurements → 18 rows x 5 columns
- Upon applying probe correction factor, mean value of surface resistivity → 620 kΩ/□.
- Assuming plane capacitance, RC = 118 ns/mm^2.
- RC value in accordance with that of ERAMs produced with same DLC foil batch.
- Note: Variation in resistivity measurements is seen from probe to probe.

- Standard production values for majority of ERAMs -

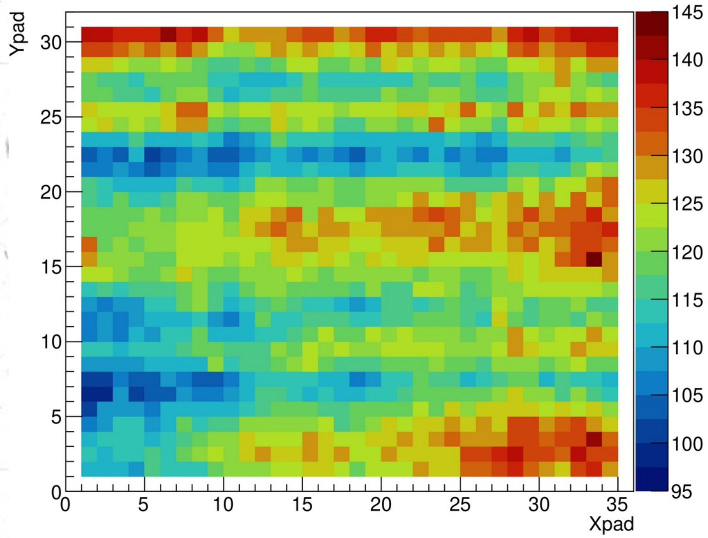
DLC resistivity: 400kΩ/□

Glue thickness: 150 μm

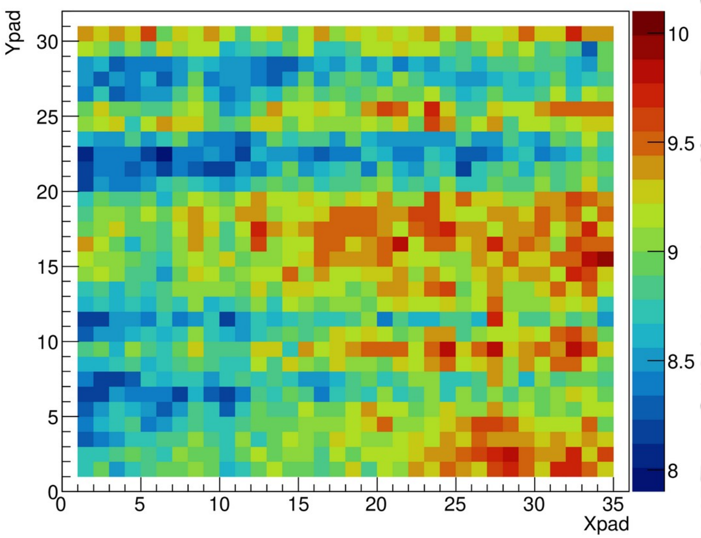
- RC map structures seem to be correlated with R measurements.

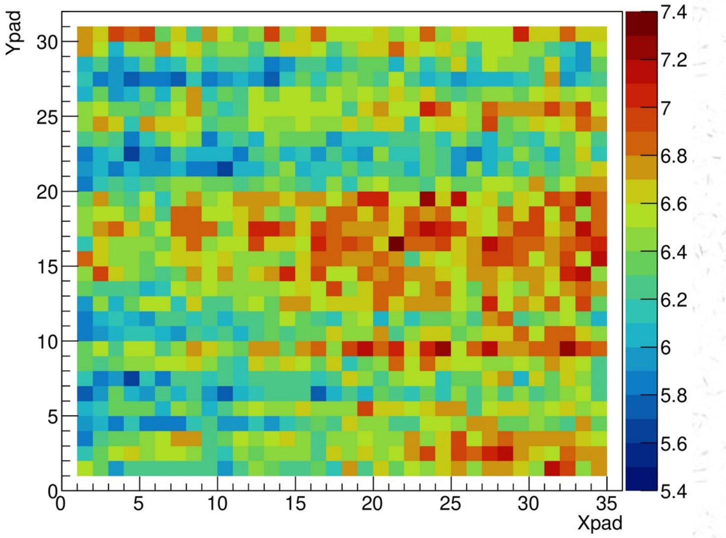
Understanding RC map features: Charge spreading using basic-level variables

RC map of ERAM-16

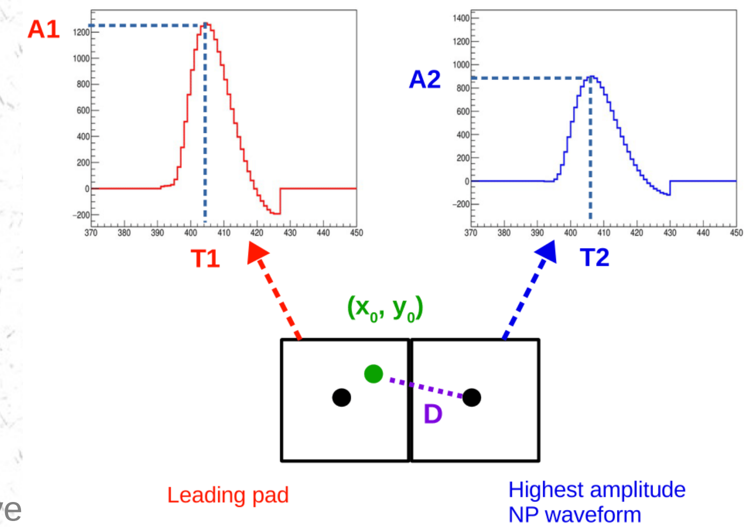


Basic-level variable maps





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



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

- ➢ Both non-transformed variable maps exhibit key features of RC map with varying degrees of precision.

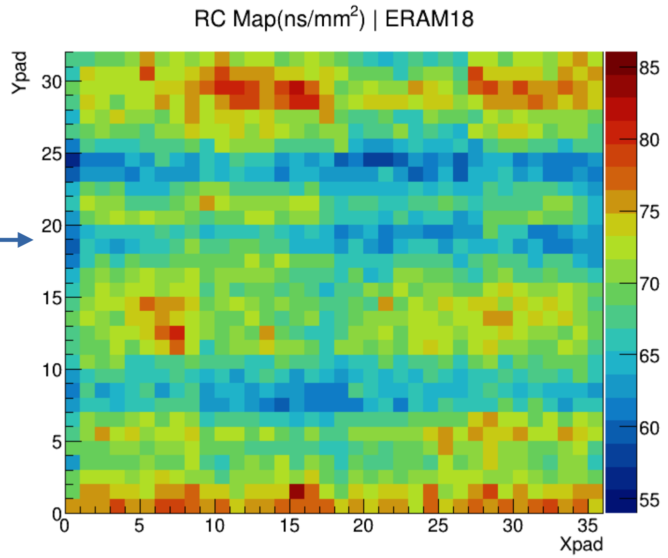
- Note: Charge deposition point is computed using center-of-charge method

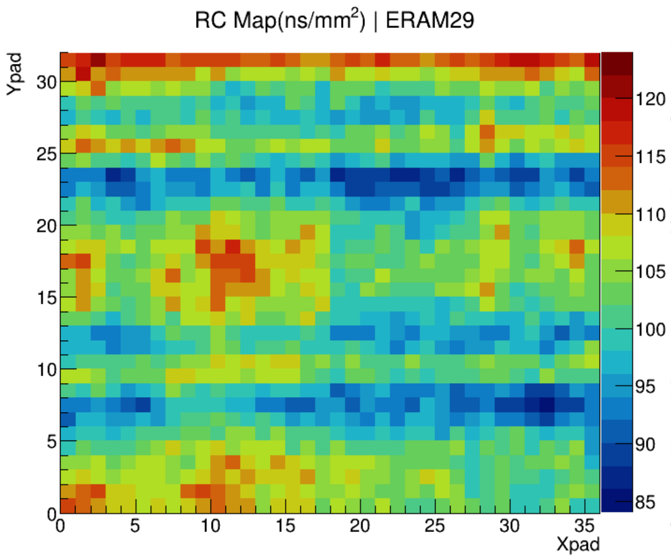
RC maps of two atypical ERAMs

ERAM-18

DLC resistivity: 200kΩ/□

Glue thickness: 150 µm



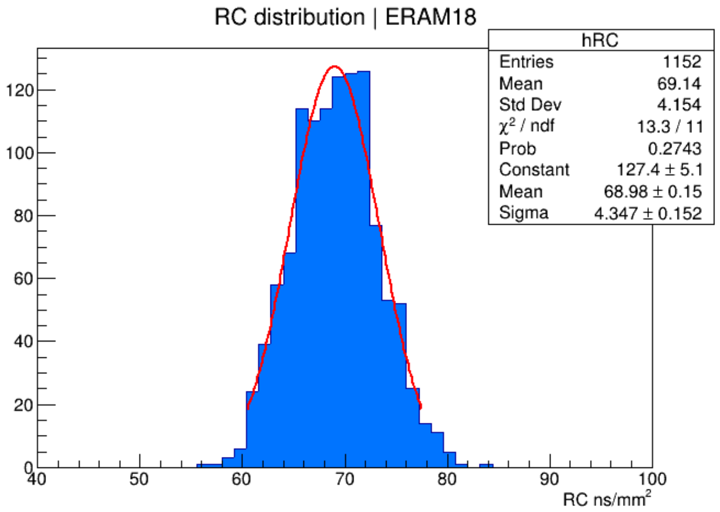


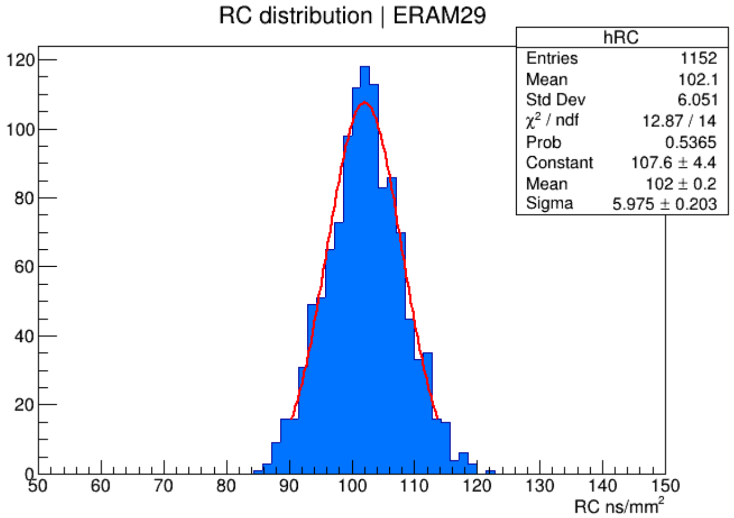
ERAM-29

DLC resistivity: 200kΩ/□

Glue thickness: 75 µm

- Half the typical resistivity used for other ERAMs.





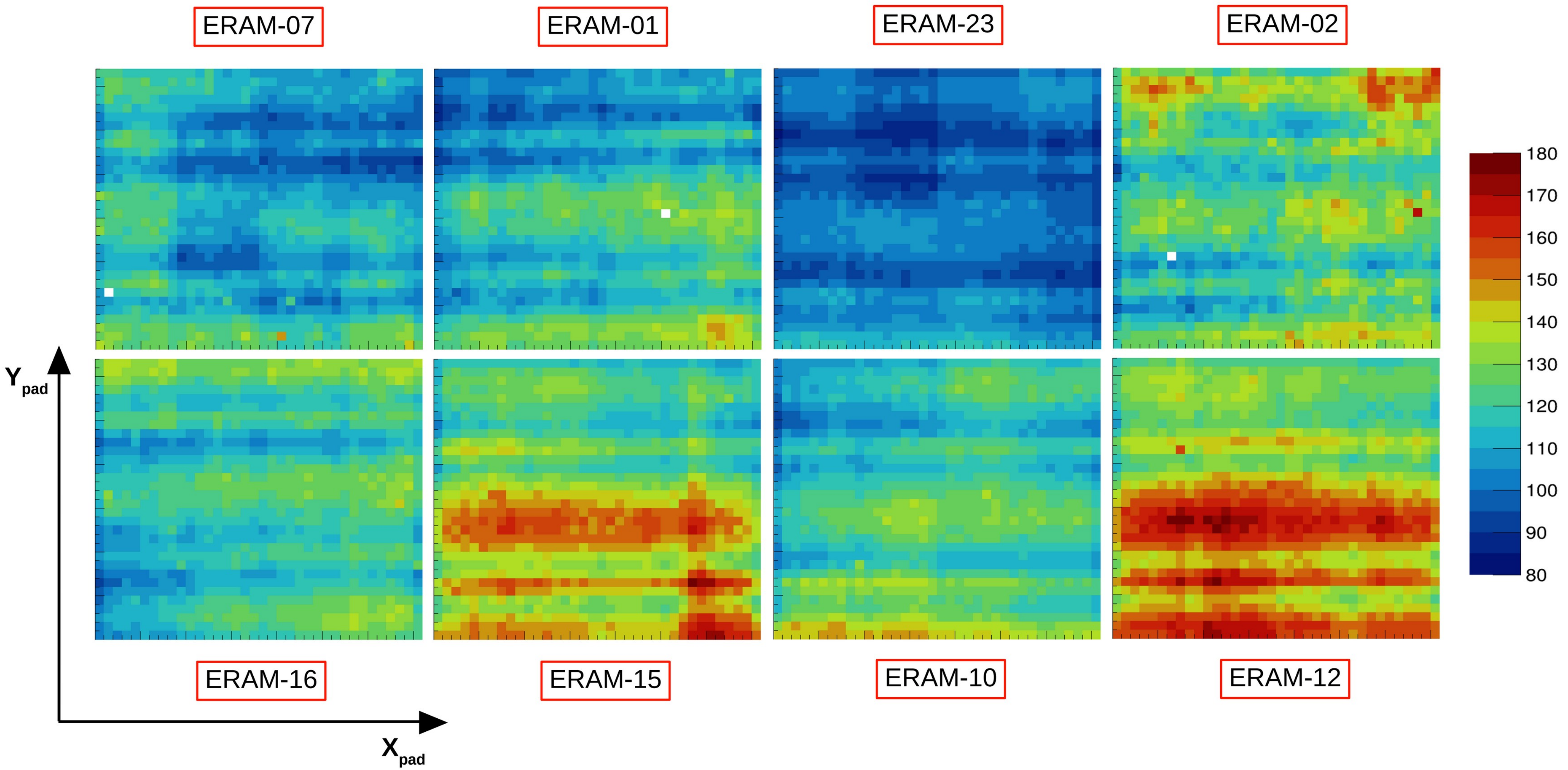
- Half the typical resistivity used for other ERAMs.
- Half the glue thickness used for other ERAMs.

RC_{mean} = 68.98 ns/mm²

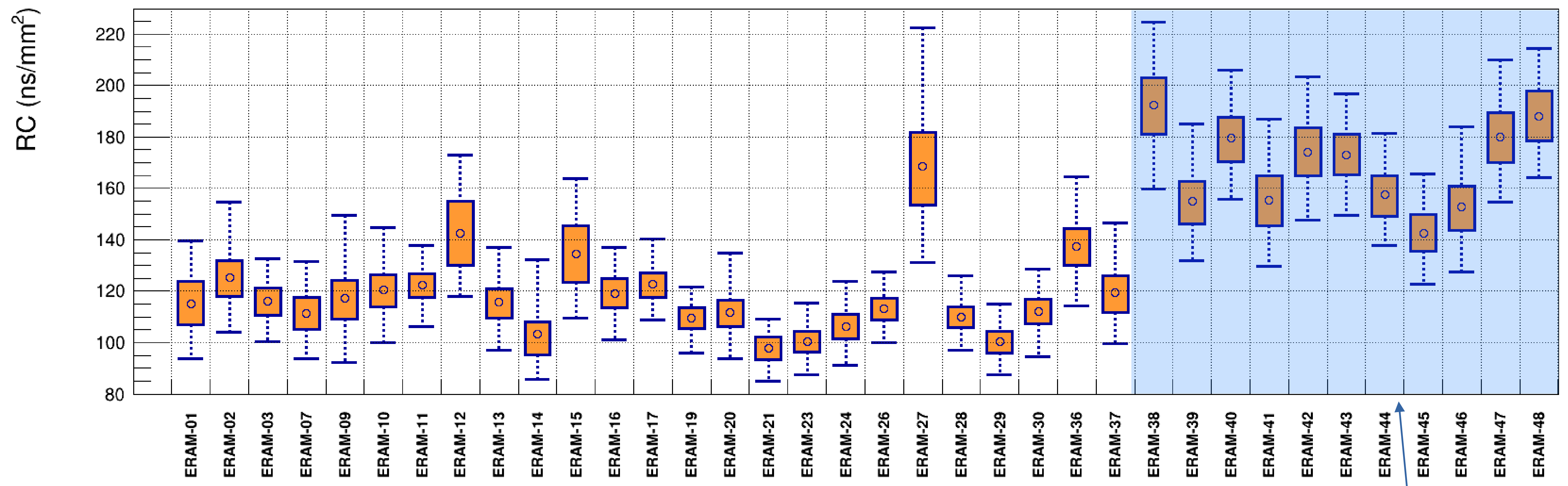
RC_{mean} = 102 ns/mm²

- 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



RC information of all analyzed ERAMs

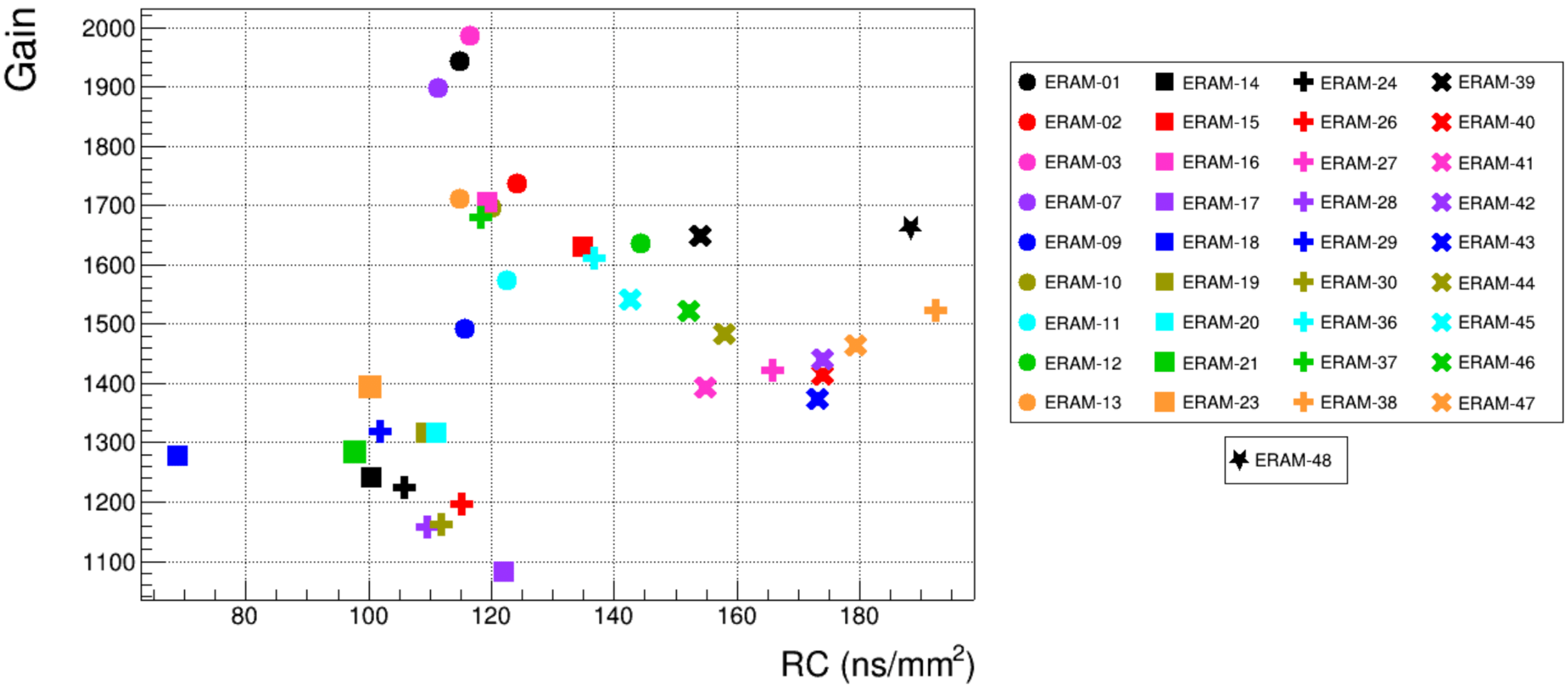


DLC resistivity ≈ 500kΩ/□

Glue thickness: 150 µm

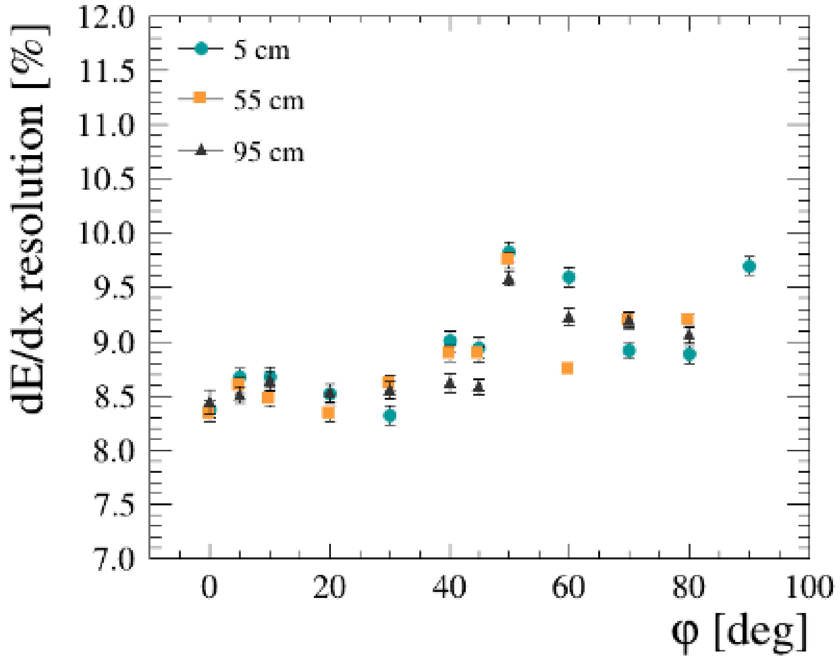
- Lower and upper bounds of box: [Mean – 25%, Mean + 25%] of distribution (50% of values within box).
- Lower and upper bounds of bars: [Mean – 49%, Mean + 49%] of distribution (98% of values within bars).

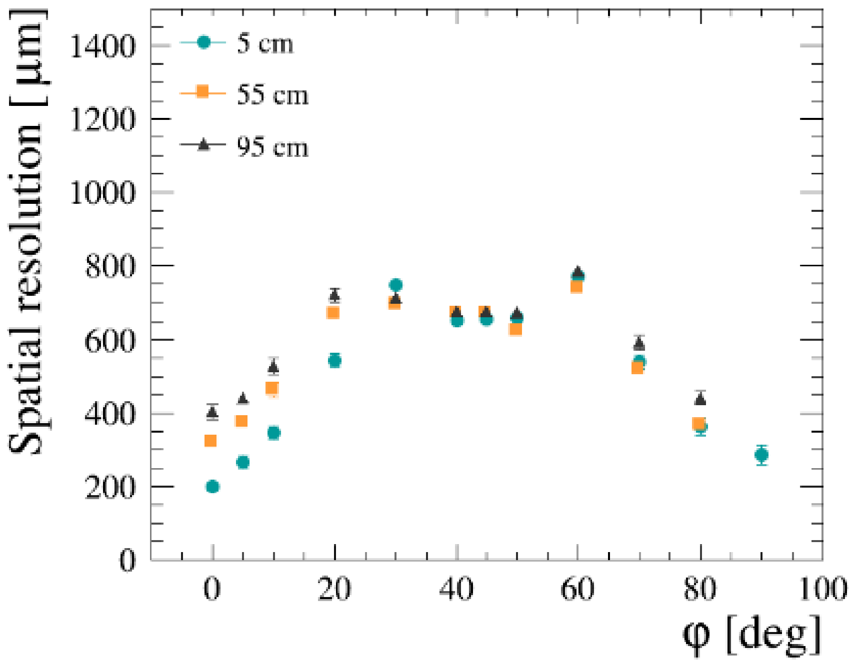
Mean RC and Gain of all analyzed ERAMs



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

Performance of resistive Micromegas





- 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.

Conclusion

- Upgrade of ND280 has been successfully completed!
- ND280 upgrade employs resistive Micromegas for the read-out of HA-TPC, which works on the principle of charge spreading.
  - **37 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.

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

THANK YOU!

Back-up

Gain extraction from simultaneous fit

- **Charge density:**

$$\rho_{0D}(r,t)=\frac{Q_{primary}G}{2\pi}\frac{1}{\sigma^2(t)}e^{-\frac{r^2}{2\sigma^2(t)}}$$

- **Charge on a pad:**

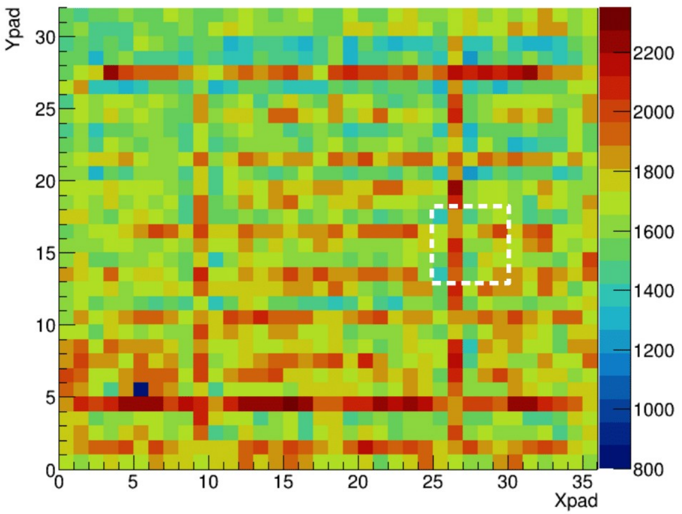
$$Q_{pad}(t)=\boxed{\frac{Q_{primary}G}{4}}\left[\mathrm{erf}\left(\frac{x_H-X_0}{\sigma(t)\sqrt{2}}\right)-\mathrm{erf}\left(\frac{x_L-X_0}{\sigma(t)\sqrt{2}}\right)\right]\left[\mathrm{erf}\left(\frac{y_H-Y_0}{\sigma(t)\sqrt{2}}\right)-\mathrm{erf}\left(\frac{y_L-Y_0}{\sigma(t)\sqrt{2}}\right)\right]$$

- **Electronics response:** (upto ADC) Dirac impulse response

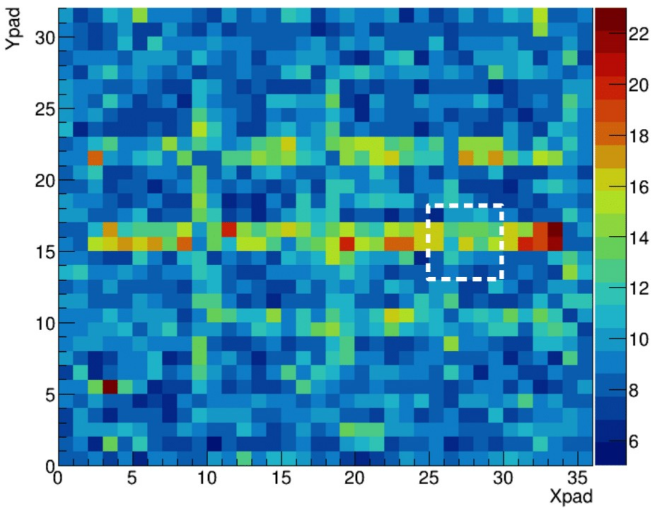
$$ADC_{Dirac}(t)=\boxed{\frac{4096}{120\,fC}\frac{F(t)}{F^{Max}}}\text{with } F(t)=e^{-w_s t}+e^{-\frac{w_s t}{2Q}}\left(\sqrt{\frac{2Q-1}{2Q+1}}\sin\left(\frac{w_s t}{2}\sqrt{4-\frac{1}{Q^2}}\right)-\cos\left(\frac{w_s t}{2}\sqrt{4-\frac{1}{Q^2}}\right)\right)$$

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

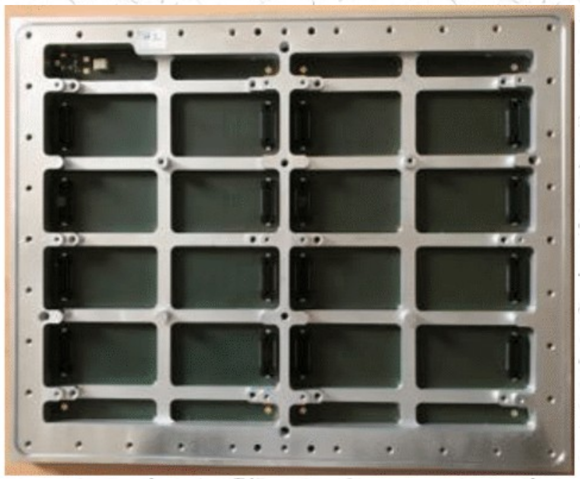
Effect of PCB design on Gain



Gain map of ERAM-10

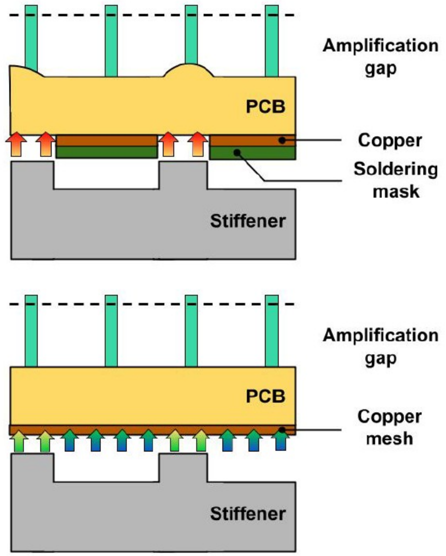


Resolution map of ERAM-10



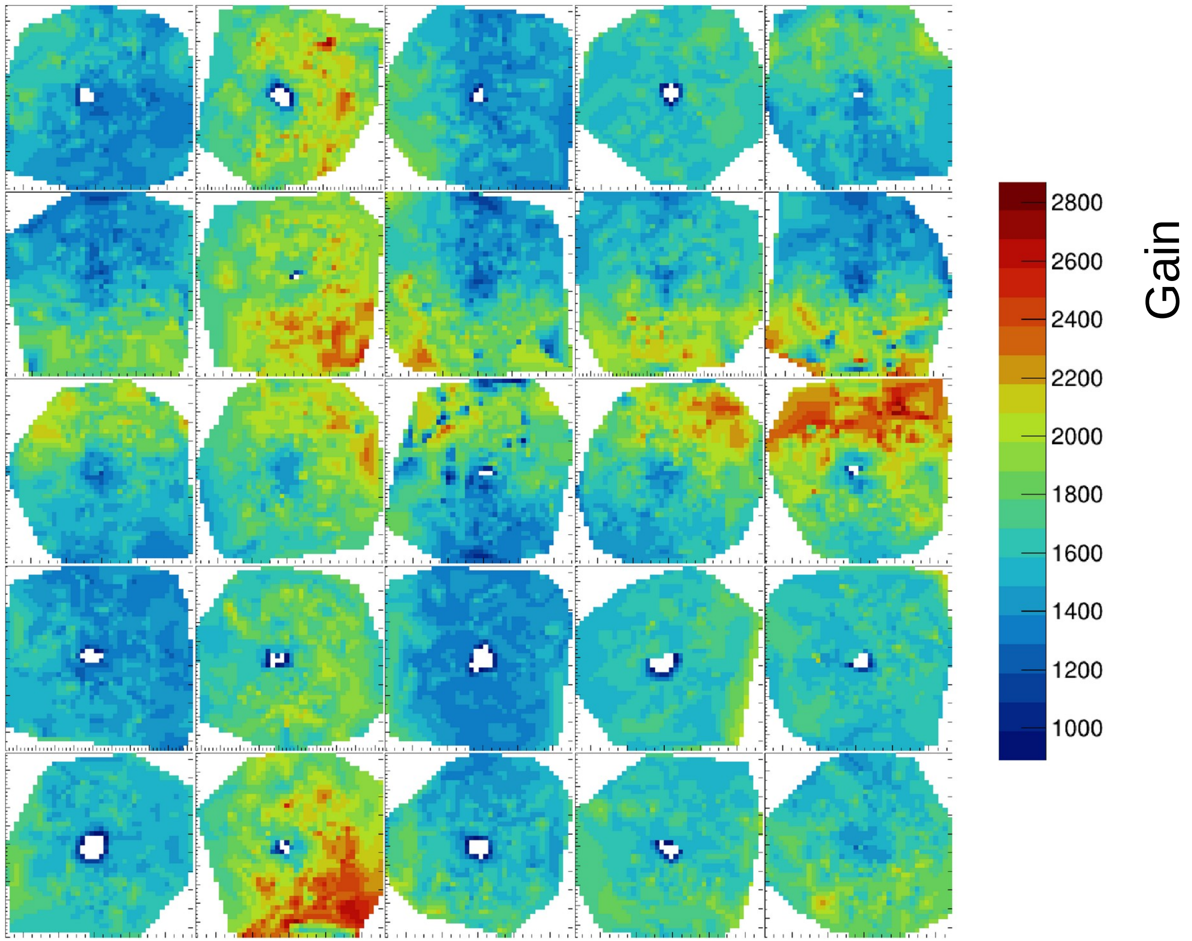
ERAM stiffener

- 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, 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.

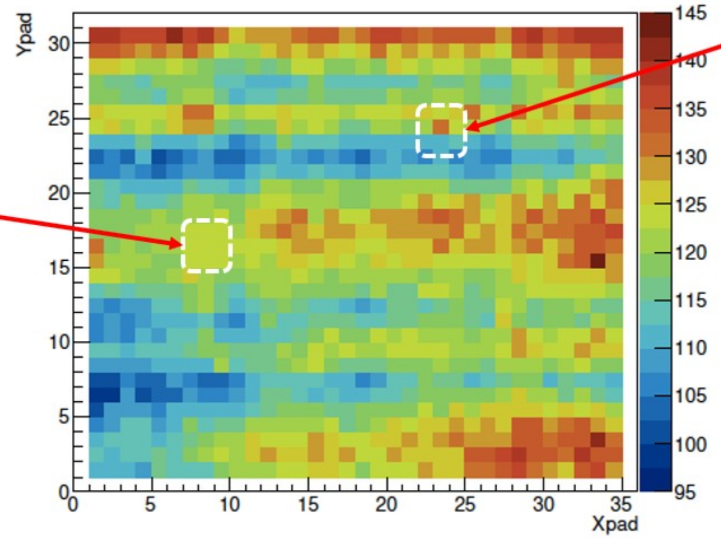


Discretization of RC

Zone 1

119.95	121.93	122.85
119.84	121.59	123.52
118.20	123.30	122.03

ERAM 16 RC map

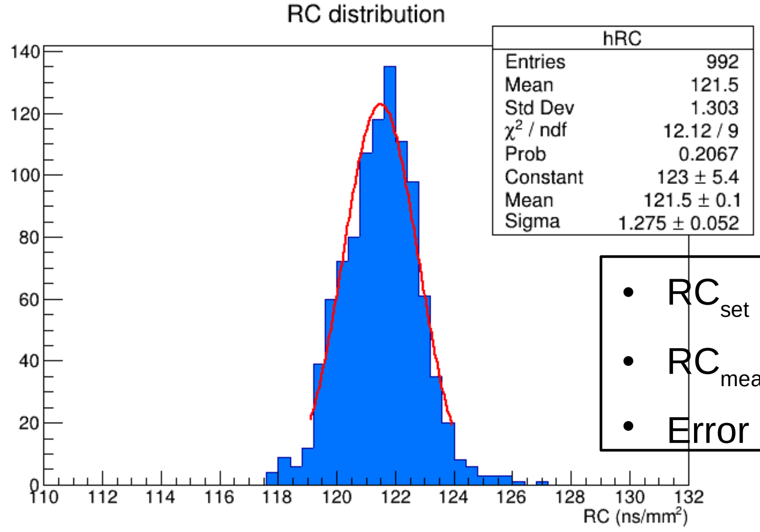


Case 1:
RC values to input
In the toys

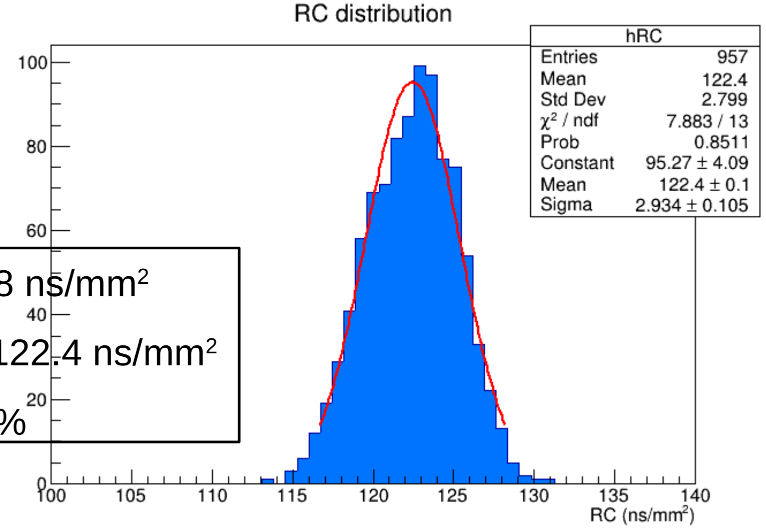
Case 2:
RC values to input
In the toys

Zone 2

124.62	122.66	125.21
120.82	128.8	121.43
110.31	112.5	113.47

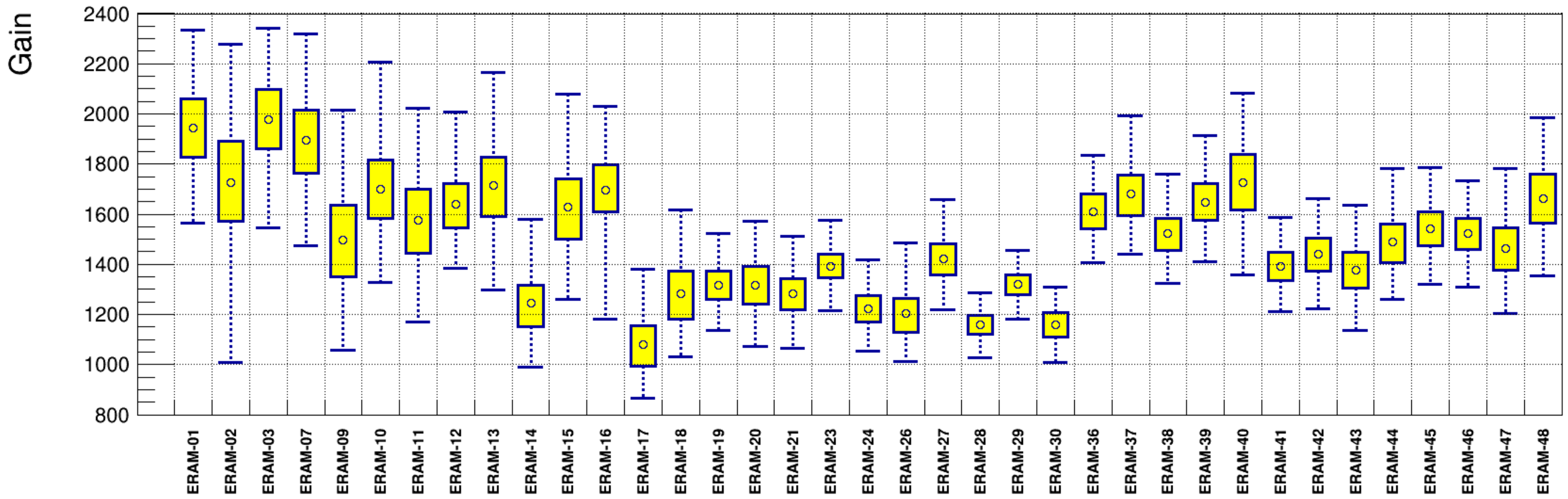


- RC_{set} = 121.59 ns/mm²
- $RC_{measured}$ = 121.5 ns/mm²
- Error = 0.07%



- RC_{set} = 128.8 ns/mm²
- $RC_{measured}$ = 122.4 ns/mm²
- Error = 4.97%

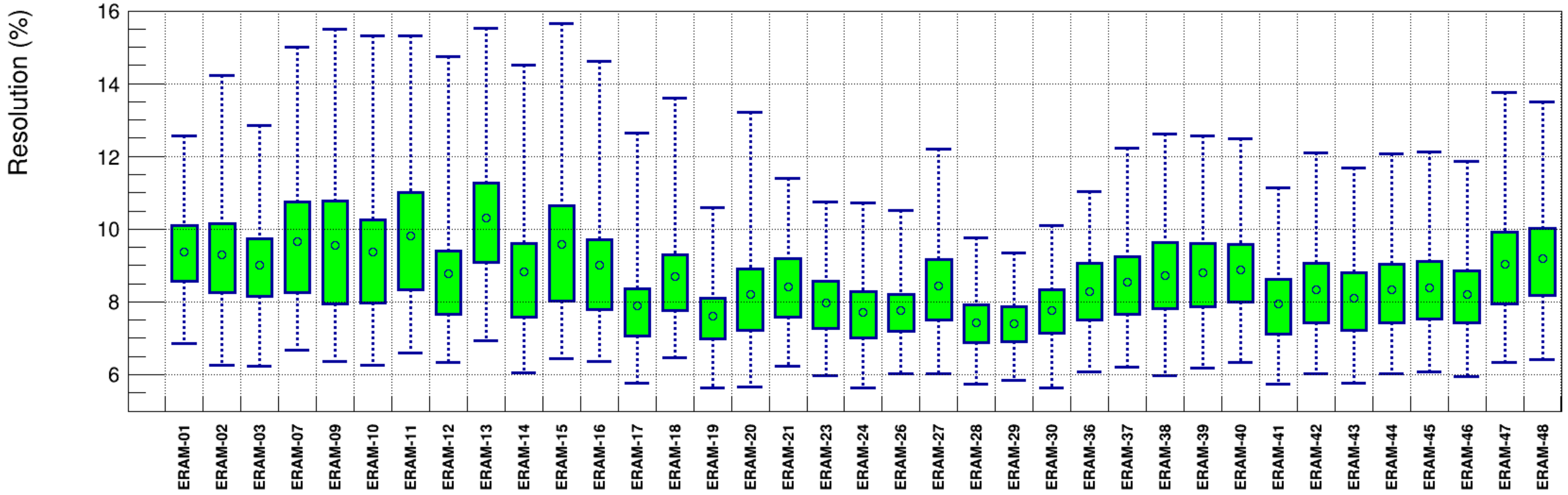
Gain and resolution of analyzed ERAMs



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)