Characterization of Charge Spreading & Gain of Encapsulated Resistive Micromegas Detectors for the Upgrade of the T2K Near Detector Time Projection Chambers

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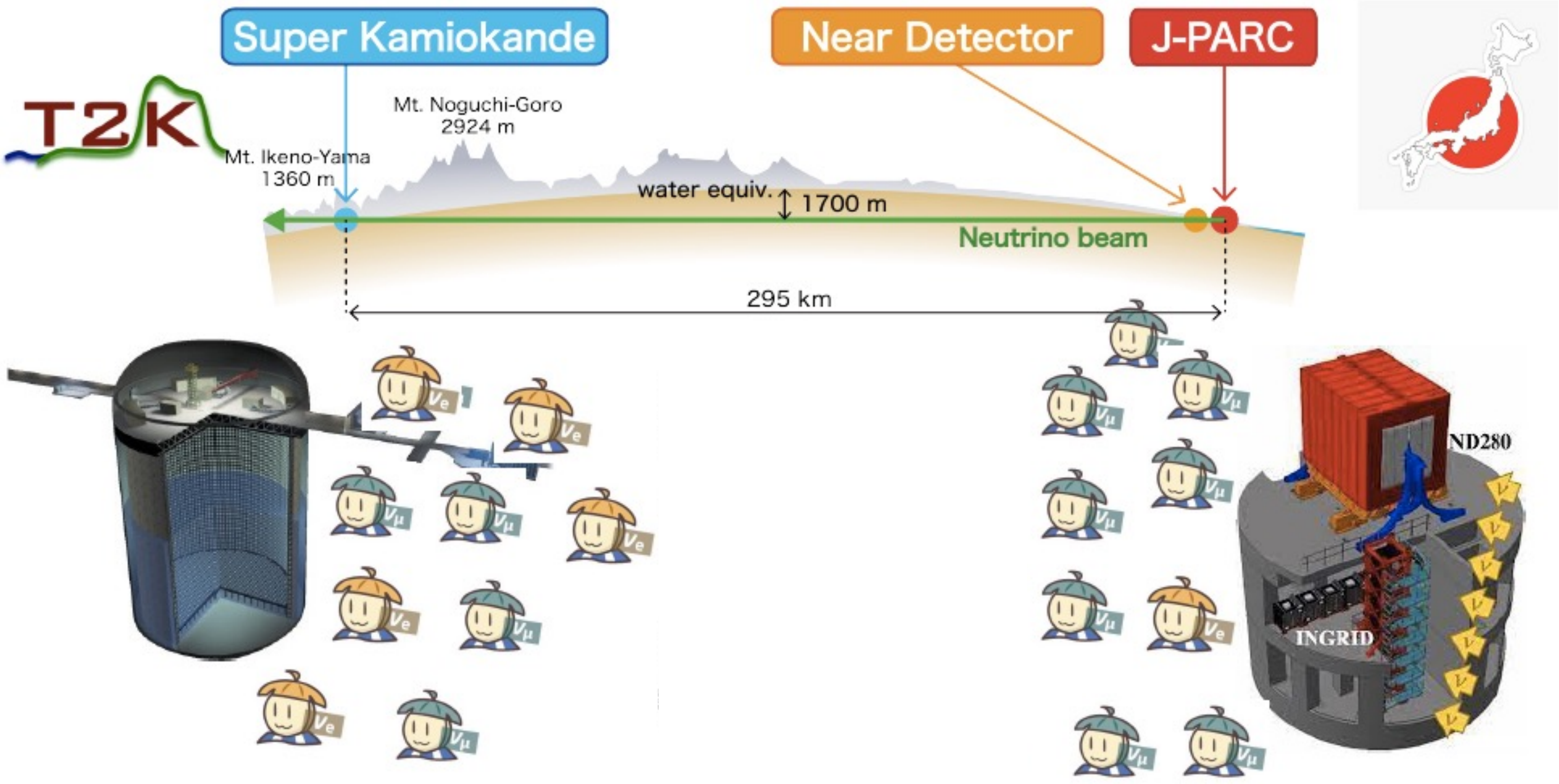
3rd P2IO BSM-ν Workshop (May 25th)

Outline

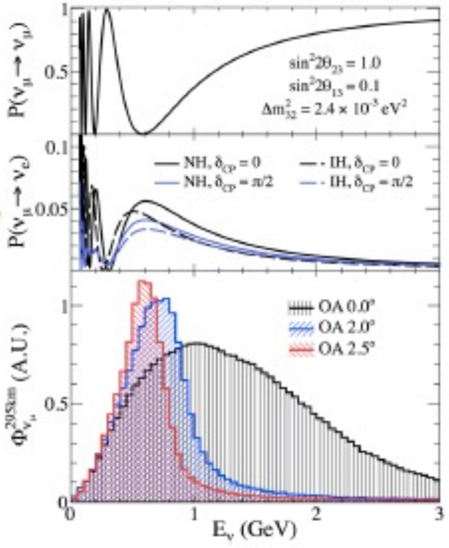
1. T2K near detector upgrade (ND280) using resistive Micromegas for HA-TPC
2. DLC resistivity measurements
3. Modelling of charge spreading with resistive Micromegas.
4. Resistive Micromegas performance using X-ray data.
5. Conclusion

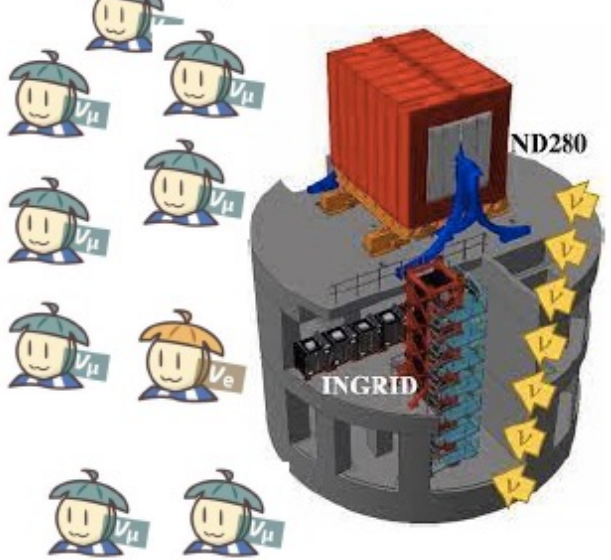
The T2K Experiment: Tokai to Kamioka



Neutrino cartoons by Yuki Akimoto

The T2K experiment: Tokai to Kamioka





Off-axis angle

Neutrino cartoons by Yuki Akimoto

The Precision Era of ν Oscillations

- Lastest results: Hints of CP violation !
- CP conservation excluded at ~2σ (Nature, 580 (2020) 339-344)
  → results limited by available statistics
- Neutrino interaction uncertainties must be reduced for DUNE / Hyper-K to succeed

The international journal of science / 16 April 2020

nature

THE MIRROR CRACK'D

An indication of matter–antimatter symmetry violation in neutrinos

Current systematic uncertainties

Source (T2K)	$N(\nu_e)$
Binding Energy	7.1%
Total Syst.	**8.8%**

Nature **580**, 339-344 / arXiv:2101.03779

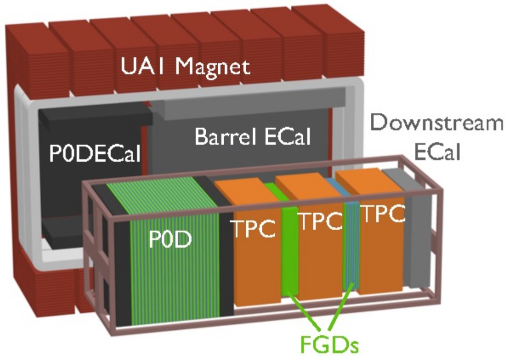
Source (NOvA)	$N(\nu_e)$
$\sigma_{\nu N}$ and FSI	7.7%
Total Syst.	**9.2%**

Phys. Rev. D **98**, 032012

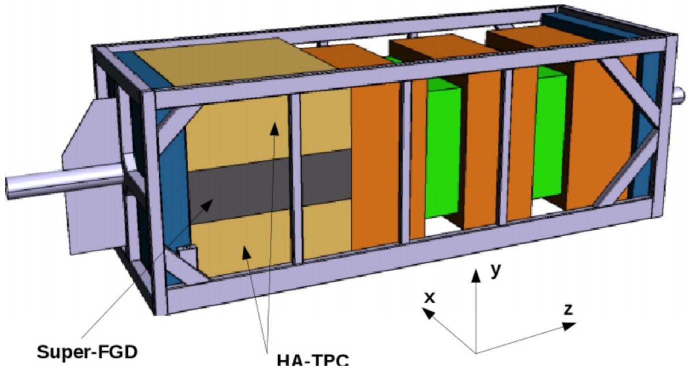
- Current results use ~100 $\nu_e + \bar{\nu}_e$, expect **1000-2000** for DUNE/HK
- ~2-3% stat. precision on CP asymmetry

ND280 Upgrade: General Idea

Now



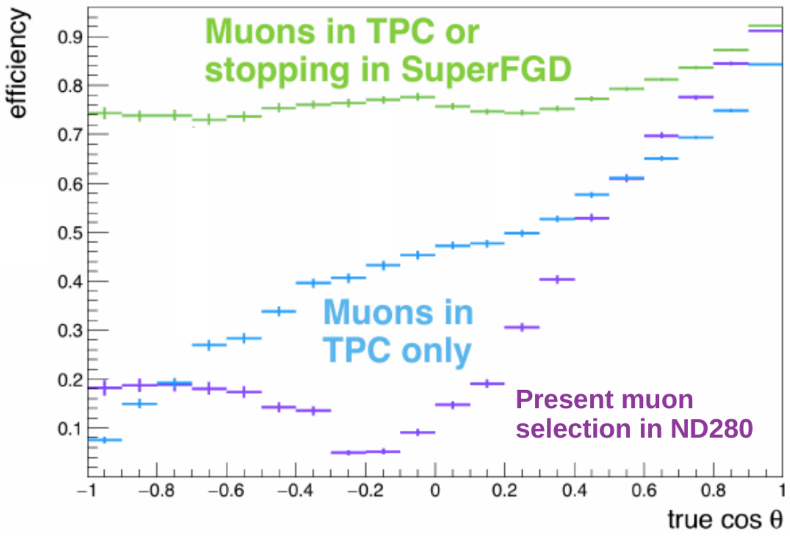
After Upgrade



ND280 measures beam spectrum and flavor composition before the oscillations

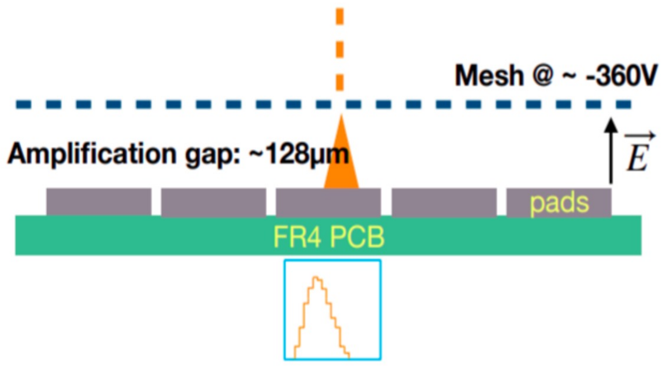
- **The HA-TPC should have at least the same performance of the 'old' vertical TPCs**
  - Average 700 μm space resolution (and possibly even better)
  - 7-8% energy loss resolution for MIP
  - Stability and longevity (>10 years)

- **New horizontal TPC**
  - Better angular acceptance
  - Similar spatial resolution with larger pad size
- **Super FGD**
  - Lower thresholds for particles stopping
  - Capability of measuring neutrons

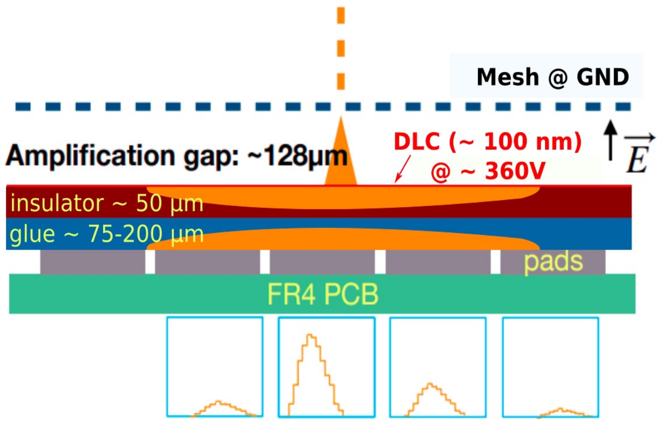


HA-TPC : Resistive Micromegas Detectors

bulk MicroMegas



resistive anode MicroMegas



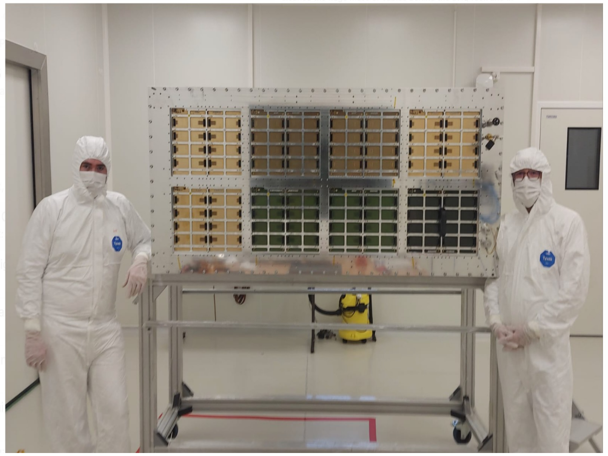
Resistive MicroMegas detectors achieved thanks to the addition of a resistive layer Diamond Like Carbon (DLC)

- Charge sharing between pads ⟶ More precise position reconstruction
- Better resolution with lower number of pads.
- Reduced risk of sparks ⟶ No need for protection circuit on readout electronics
- Allows to put mesh at ground for better E-field uniformity.
- Smaller RC ⟶ Larger charge spreading (better spatial resolution)

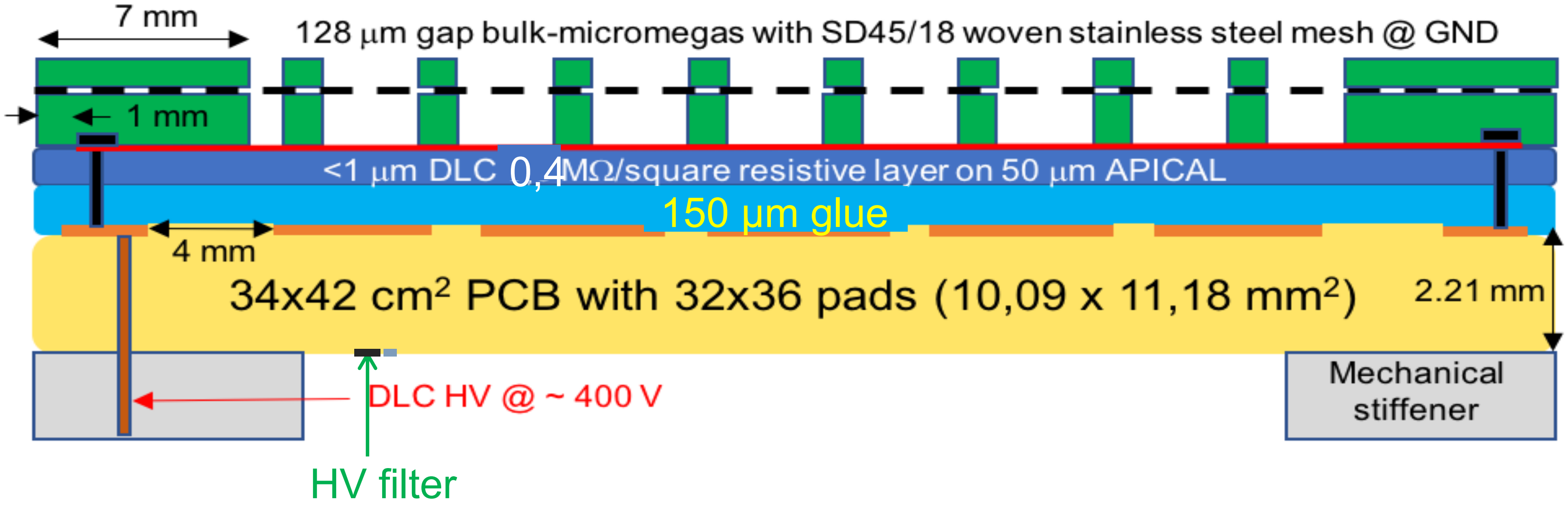
$$\rho(r,t) = \frac{RC}{4\pi t} e^{\frac{-r^2 RC}{4t}} \qquad \sigma_t = \sqrt{\frac{2t}{RC}}.$$

R = Surface resistivity
C = Capacitance / unit area

1. ERAM Detector



Encapsulated Resistive Anode Micromegas (ERAM) Characteristics



Production version of the ERAM (Encapsulated Resistive Anode Micromegas) detector

- Readout PCB: HA-TPC
- 36 × 32 pads
- 11,18 × 10,09 cm² pads
- ~400 kΩ/❑ (after annealing in air at 220°C, ~ 1MΩ/❑ before)
- 150 µm of glue
- HV filter directly on the PCB using a switchable common ground

Summary of ERAM Development

D. Attié et al. NIM A984, (2020), 163286.
doi:10.1016/j.nima.2019.163286

D. Attié et al. NIM A1025, (2022), 1661109.
doi:10.1016/j.nima.2019.166109

2018 | 2019 | 2020 | Nov. 12 PRR | Pre-series To series production | 2021

CERN/T9 test beam

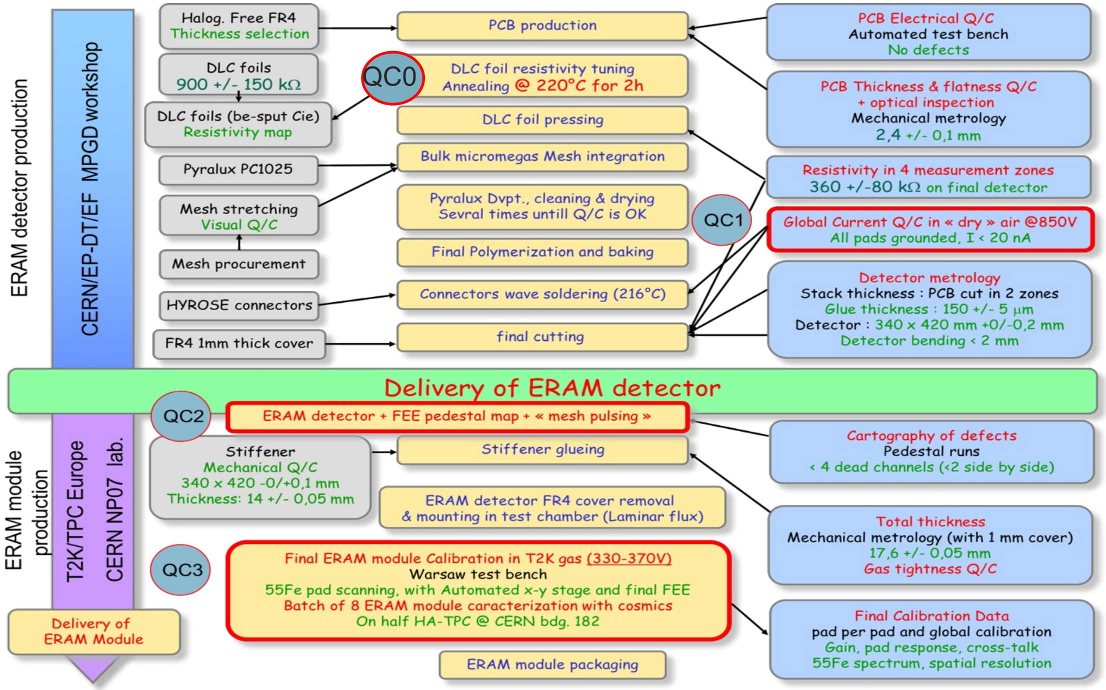
DESY test beam

ERAM-01 @ DESY 2021
½ TPC @ CERN/T10 sept. 2022

	2018 MM0-DLC#	2019 MM1-DLC1 & 2	2020 ERAM-P1 & P2	Production ERAM-xx (ERAM-01-28)
Readout PCB	Original T2K-TPC	HA-TPC V1 + ARC FEE	HA-TPC V2 + final FEE V1	HA-TPC V2 + final FEE V2
Size	34 × 36 cm²	34 × 42 cm²	34 × 42 cm²	34 × 42 cm²
Pads	48 × 36 cm²	32 × 36 cm²	32 × 36 cm²	32 × 36 cm²
Pad size	6,85 × 9,65 mm²	10,09 × 11,18 mm²	10,09 × 11,18 mm²	10,09 × 11,18 mm²
Number of pads	1728	1152	1152	1152
DLC resistivity (MΩ/sq.)	~2,5 (original foil) Not meas.on detector	0,32-0,44 (batch#P1 foils) 0,2-0,27 (meas. on detector)	0,28-0,40 (batch#P1 foils) 0,15-0,22 (meas. on detector)	**~1 (foils) / ~0.28-0,4 (det.)** Top TPC: 1-1.5 (foils) **After baking : ~0,4-0,55**
RC_{design} [ns/mm²] RC_{data} [ns/mm²]	~400	60<RC<80 X-ray scan to process	24<RC<35	**55<RC<78** **102<RC<145 (this talk)**
Insulation layer	200 μm glue + 50 μm APICAL	75 μm glue + 50 μm APICAL	200 μm glue + 50 μm APICAL	150 μm glue + 50 μm APICAL
σ (mm) For 200 ns peaking t For 412 ns peaking t	~1,6 ~2,3	~3,8 ~5,4	~5,8 ~8,3	~3,9 ~5,6
dE/dX (measured 1 det.) Extrapol. to 2 detectors	9 to 9.5% (e- & p) <7%	9 to 9.5 % (e-) with 0.2T <7%	Energy resolution @5.9 keV ~20% FWHM	8.5 to 10 % (e-) with 0.2T <7%
Spatial resolution (μm) Beam (Horizontal tracks) cosmics	300 (0T)	MM1-DLC1 200 (0 or 0.2T, 200/400 ns t_p) 700 (MM1-DLC2, @370V)	300-350 (ERAM-Px @370V)	@ DESY 07/ 21 200-800 μm (ERAM-01) / horizontal – 45° tracks (412ns)

Development validated by cosmics, X-rays data at IRFU and 5 test beam campaigns at DESY and CERN

ERAM Production QA &QC



ERAM detector production

CERN/EP-DT/EF MPGD workshop

Halog. Free FR4
Thickness selection

DLC foils
900 +/- 150 kΩ

DLC foils (be-sput Cie)
Resistivity map

Pyralux PC1025

Mesh stretching
Visual Q/C

Mesh procurement

HYROSE connectors

FR4 1mm thick cover

QC0

PCB production

DLC foil resistivity tuning
Annealing @ 220°C for 2h

DLC foil pressing

Bulk micromegas Mesh integration

Pyralux Dvpt., cleaning & drying
Sevral times untill Q/C is OK

Final Polymerization and baking

Connectors wave soldering (216°C)

final cutting

QC1

PCB Electrical Q/C
Automated test bench
No defects

PCB Thickness & flatness Q/C
+ optical inspection
Mechanical metrology
2,4 +/- 0,1 mm

Resistivity in 4 measurement zones
360 +/-80 kΩ on final detector

Global Current Q/C in « dry » air @850V
All pads grounded, I < 20 nA

Detector metrology
Stack thickness : PCB cut in 2 zones
Glue thickness : 150 +/- 5 µm
Detector : 340 x 420 mm +0/-0,2 mm
Detector bending < 2 mm

Delivery of ERAM detector

ERAM module production

T2K/TPC Europe CERN NP07 lab.

QC2

ERAM detector + FEE pedestal map + « mesh pulsing »

Stiffener
Mechanical Q/C
340 x 420 -0/+0,1 mm
Thickness: 14 +/- 0,05 mm

Stiffener glueing

ERAM detector FR4 cover removal
& mounting in test chamber (Laminar flux)

QC3

Final ERAM module Calibration in T2K gas (330-370V)
Warsaw test bench
55Fe pad scanning, with Automated x-y stage and final FEE
Batch of 8 ERAM module caracterization with cosmics
On half HA-TPC @ CERN bdg. 182

ERAM module packaging

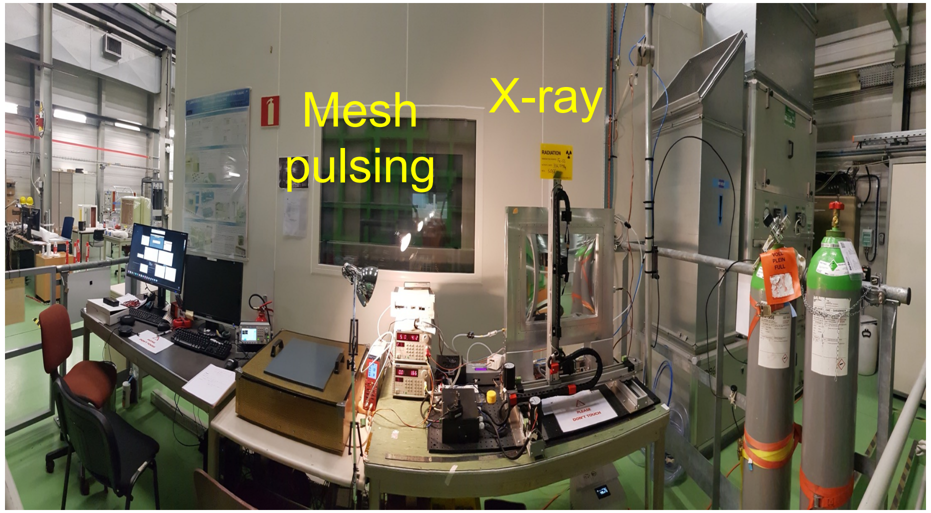
Delivery of
ERAM Module

Cartography of defects
Pedestal runs
< 4 dead channels (<2 side by side)

Total thickness
Mechanical metrology (with 1 mm cover)
17,6 +/- 0,05 mm
Gas tightness Q/C

Final Calibration Data
pad per pad and global calibration
Gain, pad response, cross-talk
55Fe spectrum, spatial resolution

NP07 working area at CERN bdg. 182

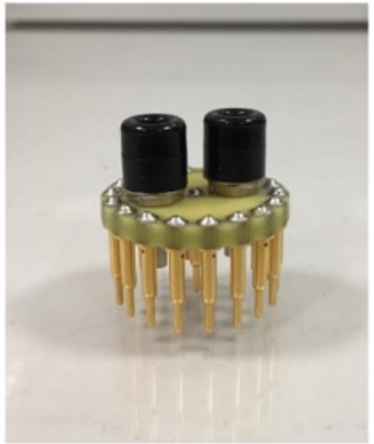


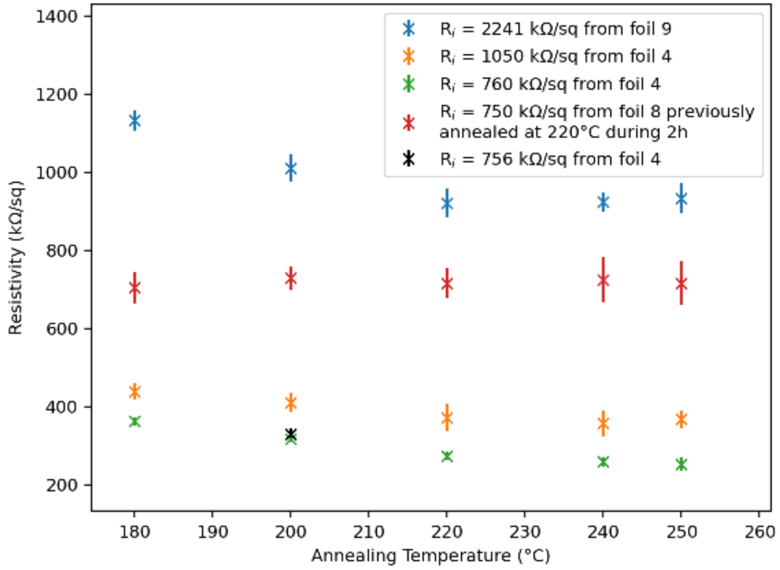
- **The manufacture of ERAM technology is a complex and delicate task, and is further complicated by the difficulty of DLC procurement.**
- However, the expertise and excellent partnership with the CERN/PCB workshop enabled a high yield (~80%) of high quality production of 23 ERAMs up to now.
- Two Quality Control tests are performed:
  - **Mesh pulsing**: spot low gain region before gluing stiffener on PCB
  - **X-ray test bench**: Complete characterization of ERAM response, individual pad response (gain, resolution) and gain scan as function of voltage.
- **Calibration of electronic cards** and association with a detector before X-ray scan

2. DLC Resistivity Measurements

DLC Resistivity Measurement

- DLC ensures charge spreading over several pads
- DLC production is insured by Be-Sputter Company in Japan
- There was no common way to measure resistivity: two probes designed “Ochi” & “CERN”
- Used “CERN” after tests insuring reproducible results





- DLC Identify evolution of resistivity during detector production
  - DLC resistivity evolves as function of temperature: @220 °C → /2.3
  - Decided to bake DLC before mounting to stabilize it
  - Works! No change of resistivity during process
- We order DLC to reach a final resistivity of 400 kΩ/☐ but received batches of ~200 kΩ/☐ & ~400 kΩ/☐
- R&D shows that charge spreading could be adapted with glue thickness
  - BUT higher risk of sparks! Reliability issues?

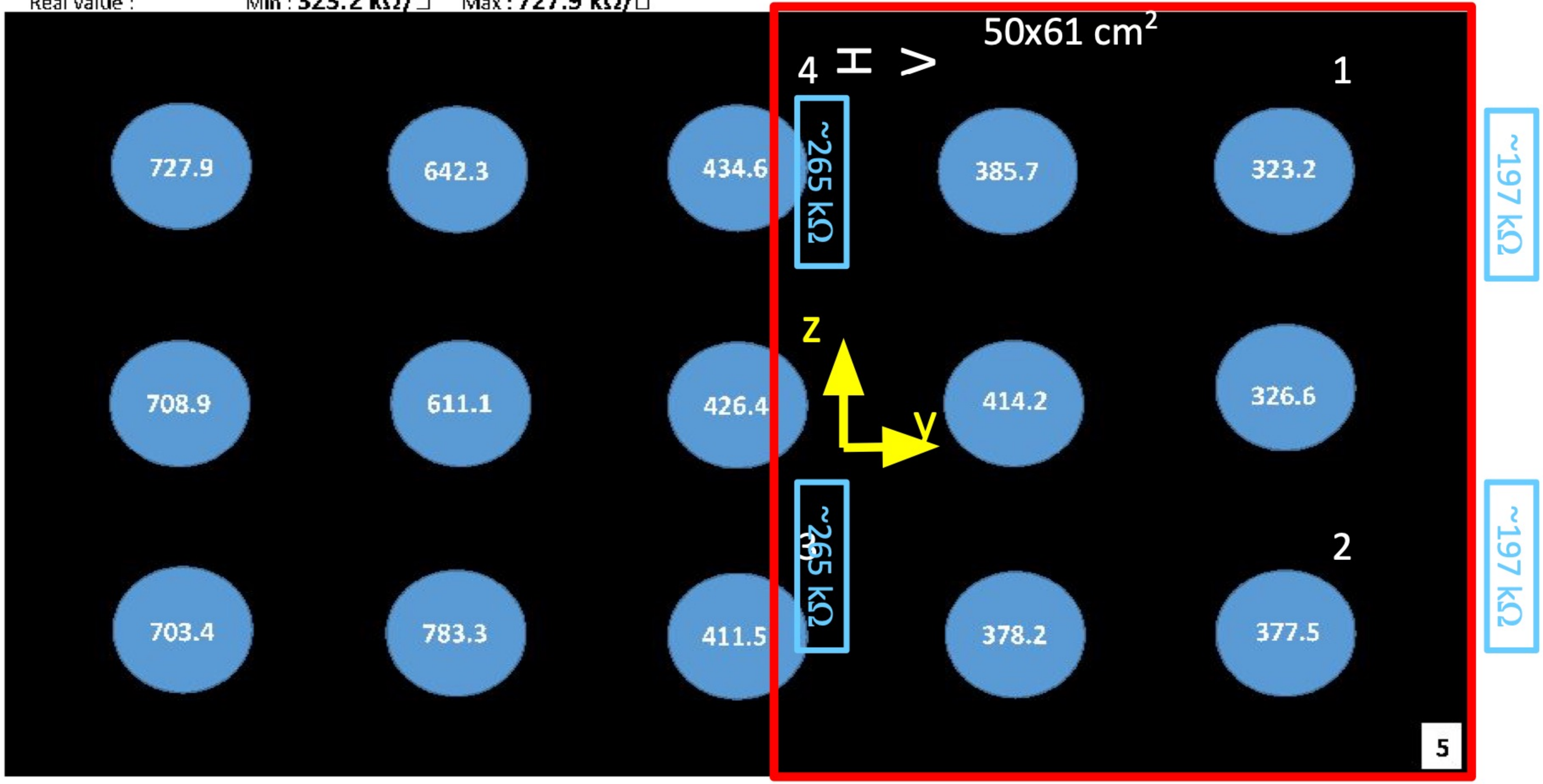
Example of DLC Resistivity Measurements

Theoretical value **500 kΩ/□**

Part of DLC foil #5 used for MM1-DLC2

Foil size : **100x61cm**

Real value : Min : **323.2 kΩ/□** Max : **727.9 kΩ/□**

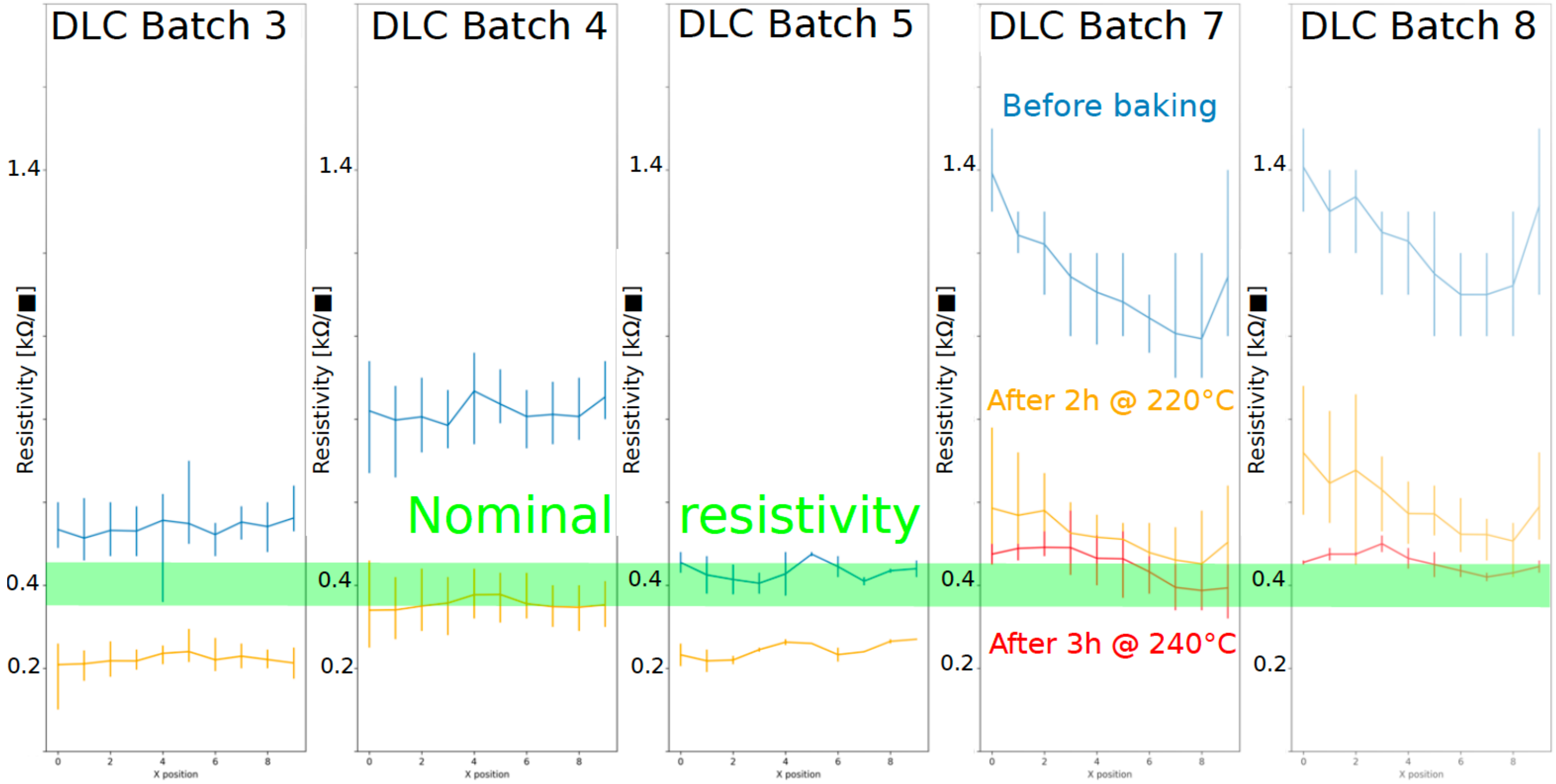


R=197 KΩ
RC = 49 ns/mm²

R=265 KΩ
RC = 67 ns/mm²

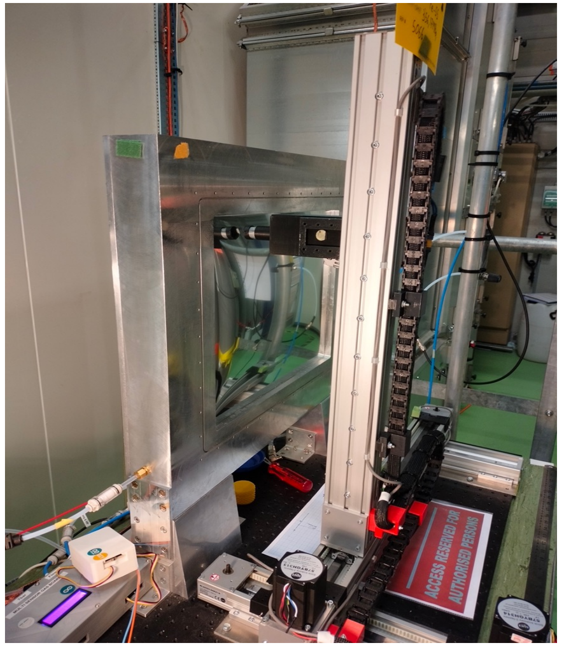
In blue : measured value outside detector area once detector is finished

DLC Foil Selection For ERAMs

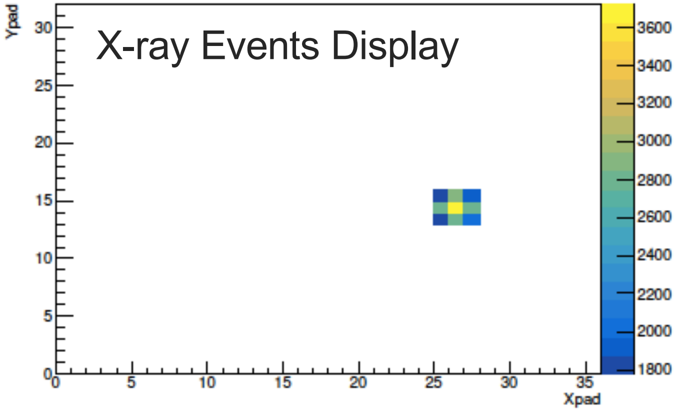


- A batch = 7 DLC foils (0,6x1,2 m^2)
- **Batch 4** with nominal resistivity ⇒ 9 final detectors
- **Batch 3 and 5** with half nominal resistivity ⇒ Prototypes
- **Bacthes 7 and 8** needed 2 bakings to provide nominal resistivity ⇒ ~ 8 final detectors
- 23/32 final detectors produced

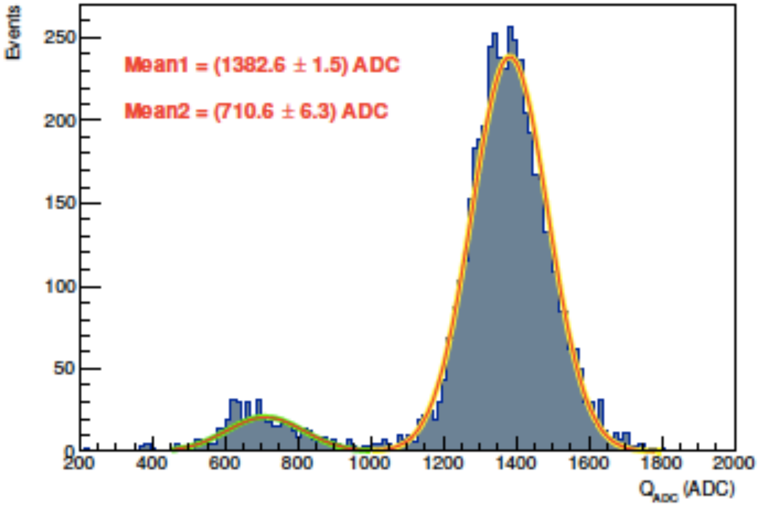
ERAM Tests with X-rays



- Each pad(1152) of an ERAM placed inside an X-ray chamber is scanned using a robot holding an ^{55}Fe X-ray source.
- Charge is deposited in targeted pad and its neighboring pads (due to charge spreading), from electron avalanche caused by an X-ray photon.
- ^{55}Fe spectrum can be reconstructed using all events in one pad → Summing all waveforms in each event and taking amplitude max of summed waveforms
- **Gain Method** : is obtained for a pad by fitting its ^{55}Fe spectrum. Resolution of 10% is obtained.



Example of a ^{55}Fe spectrum in 1 Pad



3. Modelling the Charge Dispersion Phenomena

Charge Dispersion Principle

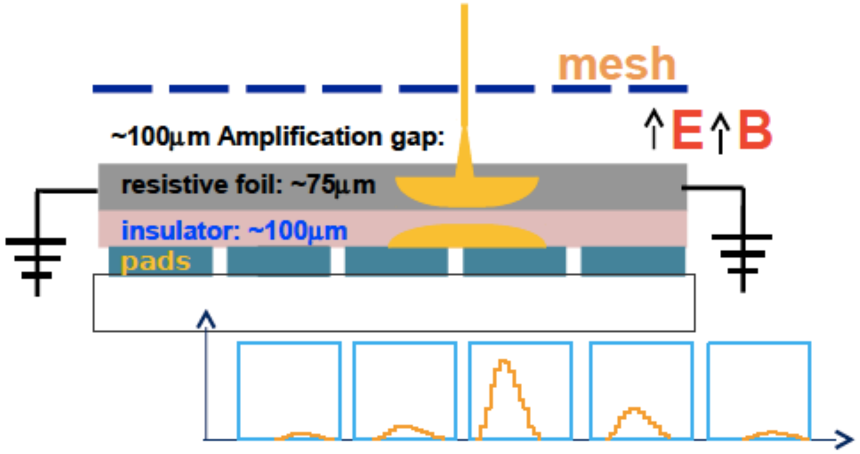
- Continuous RC network, defined by material properties and geometry, spreads evenly the charge among several pads.
- The spatial spread of the charge on the resistive layer is governed by the diffusion equation:

$$\boxed{\frac{\partial\rho(r,t)}{\partial t} = \frac{1}{RC}\Delta\rho(r,t)}$$

- The charge density as a function of radius r and time t is given by:

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

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



Pad size 1.1x1.0 cm^2

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

Signal Model

Transverse diffusion

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

Longitudinal diffusion

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

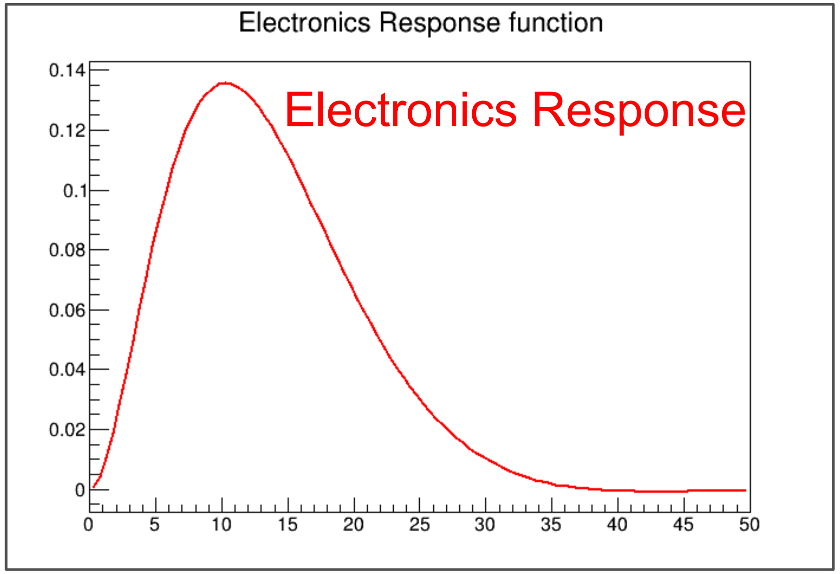
Electronics Response

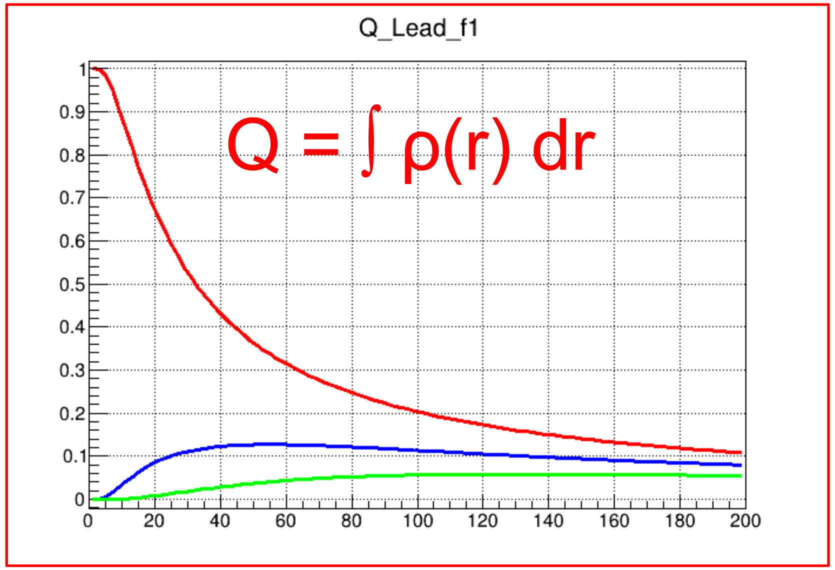
R(t)

Resistive foil + glue

$$\rho(r,t) = \frac{Q_e}{2\pi\sigma^2(t)} e^{-r^2/2\sigma^2(t)}$$

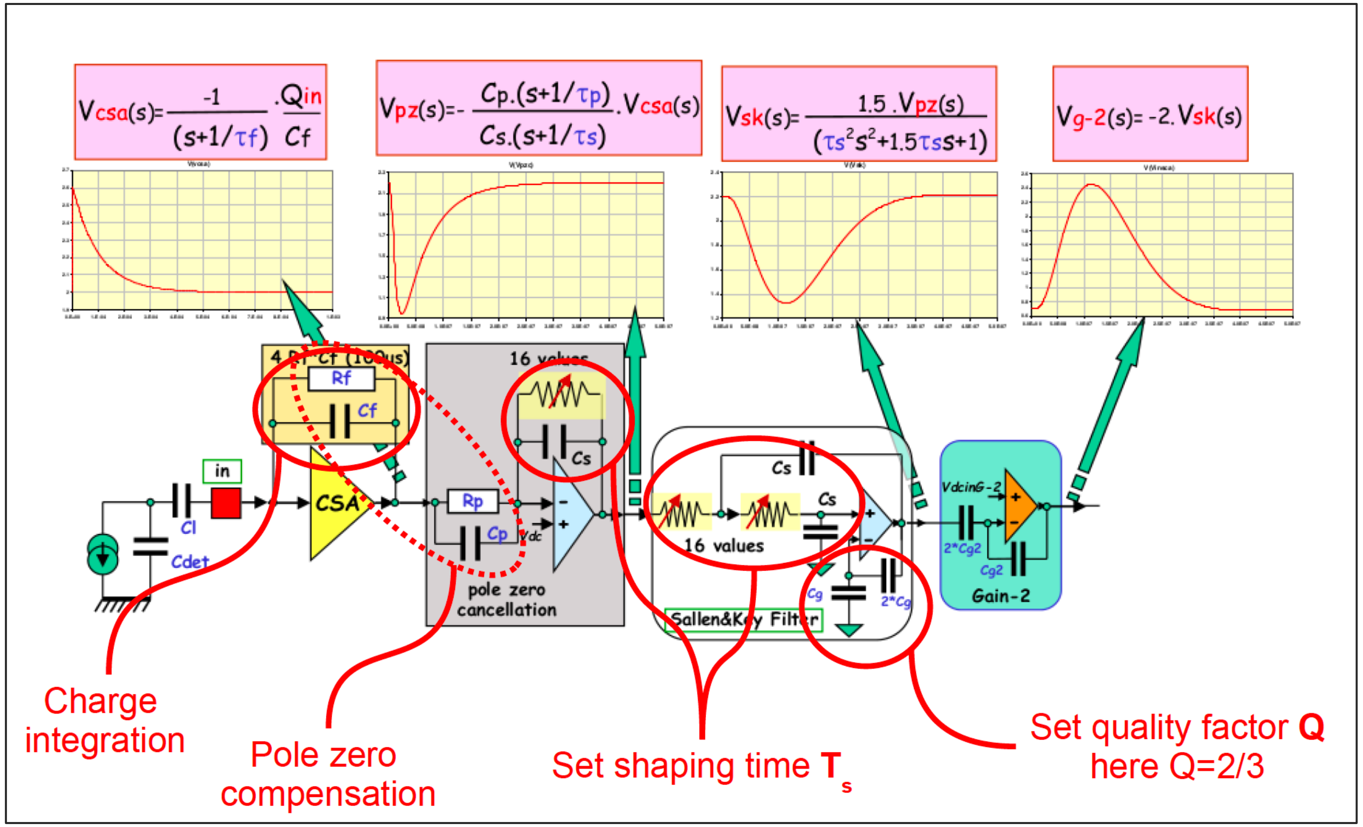
$$\sigma(t) = \sqrt{\frac{2t}{RC} + \omega^2}$$





Readout Electronics

After Chip



Charge integration

Pole zero compensation

Set shaping time T_s

Set quality factor **Q** here Q=2/3

Transfer function
$$\frac{V_0}{I_s} = \left[-\frac{1}{C_f}\frac{1}{w_f+s}\right]\left[-\frac{C_p}{C_s}\frac{w_p+s}{w_s+s}\right]\left[Q w_s^2 \frac{1}{s^2+\frac{1}{Q}w_s s+w_s^2}\right]$$

with $T_f = w_f^{-1} = R_f C_f$, $T_p = w_p^{-1} = R_p C_p$ and $T_s = w_s^{-1} = R_s C_s$

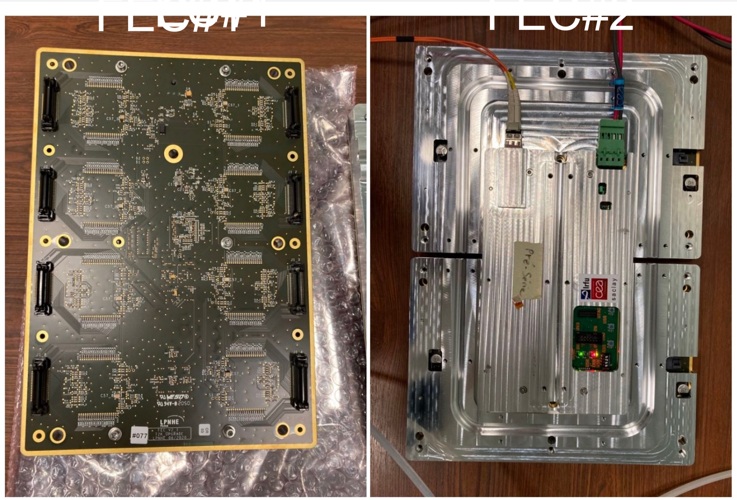
Response to a Dirac pulse
for perfect pole zero compensation

$$V_o(t) \propto e^{-w_s t} + e^{-\frac{w_s t}{2Q}}\left(\sqrt{\frac{2Q-1}{2Q+1}}\sin\left(\frac{w_s t}{2}\sqrt{4-\frac{1}{Q^2}}\right)-\cos\left(\frac{w_s t}{2}\sqrt{4-\frac{1}{Q^2}}\right)\right)$$

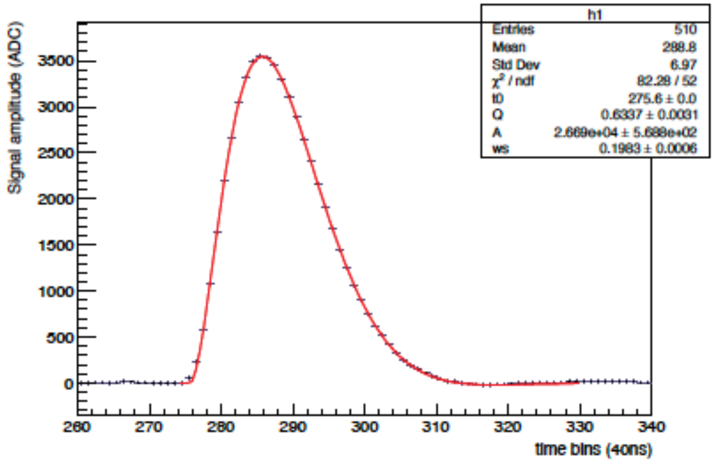
but a normalization factor depend on 2 parameters:
T_s and Q

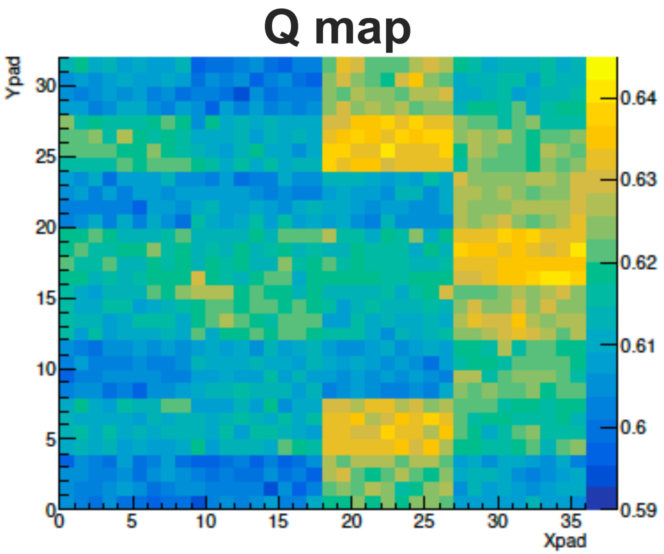
Validation of Electronic Model using Calibration data

- 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.**
- Parameterized by two 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.



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





Q = 0.6368
w_s = 0.1951

fixed (412ns peaking time)

Signal Model

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

$$S(t) = Q_{pad}(t) \circledast \frac{\mathrm{d}(ADC^{D}(t))}{\mathrm{d}t}$$

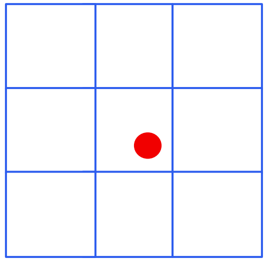
- **Integrating charge density function over area of one readout pad.**

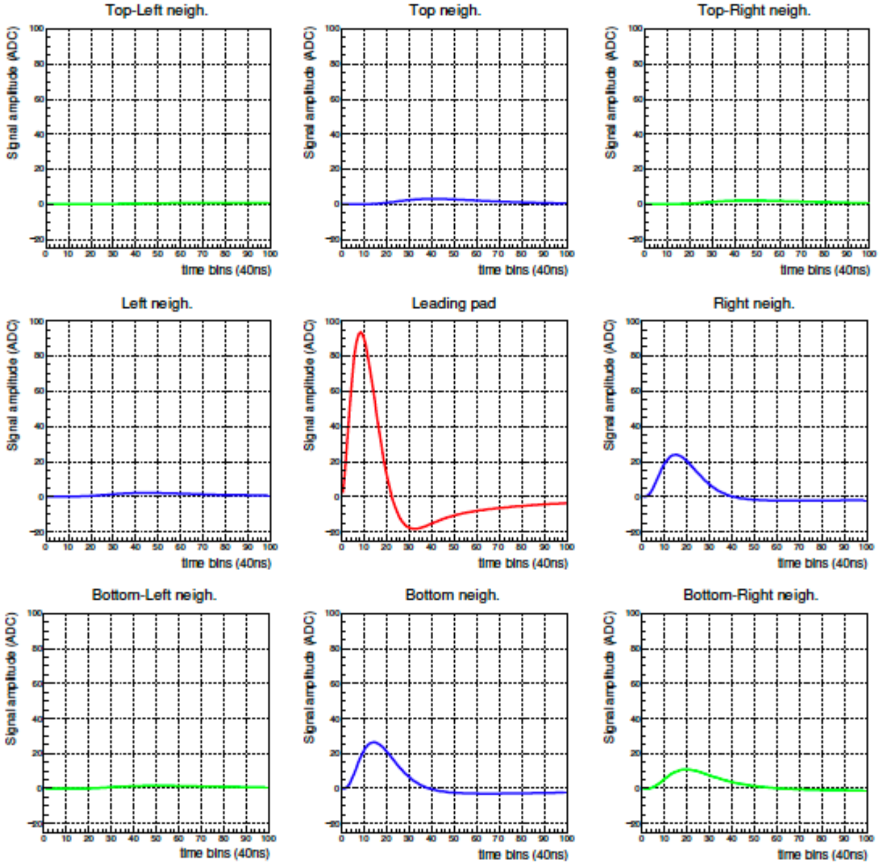
$$Q_{pad}(t) = \frac{Q_e}{4} \times \left[erf\left(\frac{x_{\mathrm{high}} - x_0}{\sqrt{2}\sigma(t)}\right) - erf\left(\frac{x_{\mathrm{low}} - x_0}{\sqrt{2}\sigma(t)}\right) \right] \times \left[erf\left(\frac{y_{\mathrm{high}} - y_0}{\sqrt{2}\sigma(t)}\right) - erf\left(\frac{y_{\mathrm{low}} - y_0}{\sqrt{2}\sigma(t)}\right)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

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

- **Parameterized by 5 variables:**
  - x_0
  - y_0

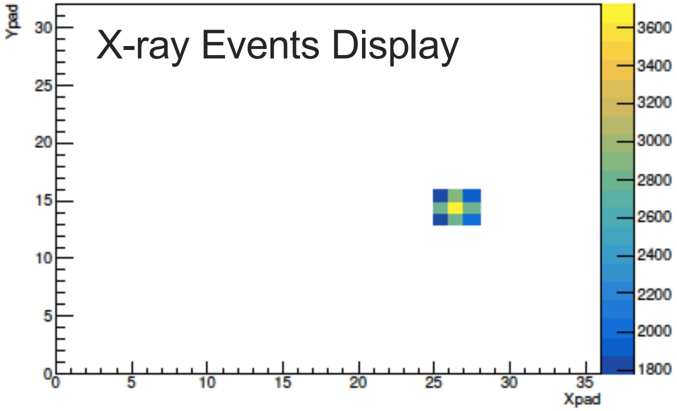
  Initial charge position
  - t_0 : Time of charge deposition in leading pad
  - RC : Describes charge spreading
  - Q_e : the initial charge after charge multiplication in the amplification region





4. RC Measurements using X-rays Data

Examples of Waveforms Fit



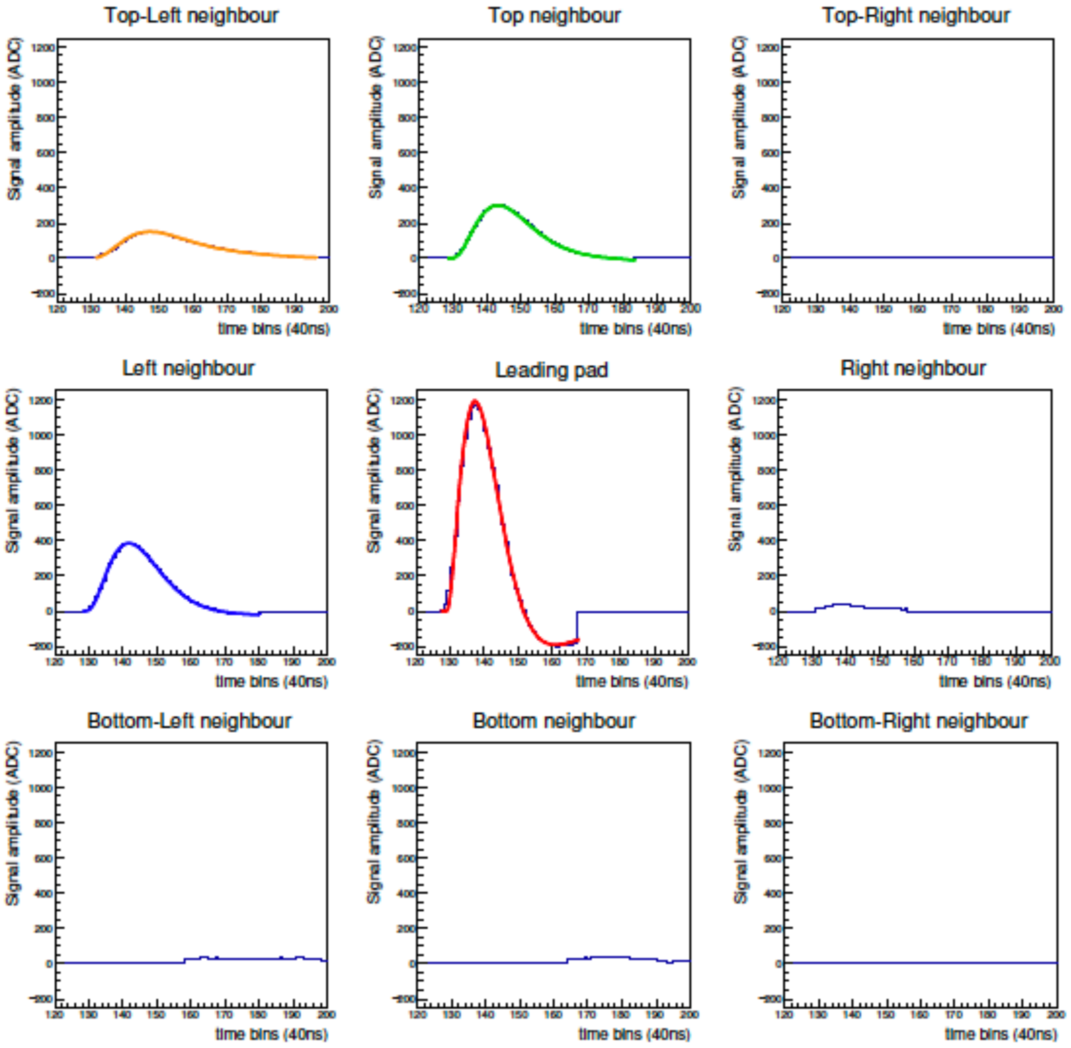
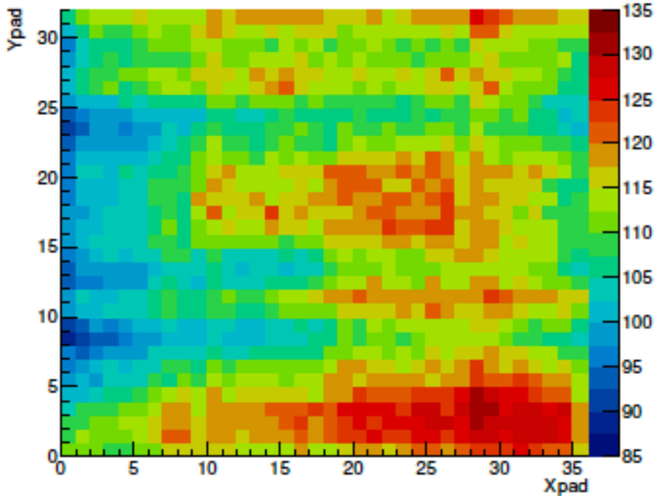


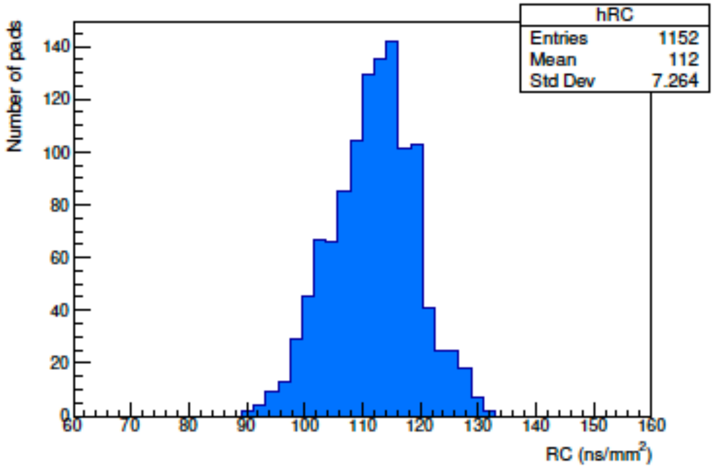
Figure 18: An example of a simultaneous fit of four waveforms of an X-ray generated event. Fit results: $RC = (146.6 \pm 1.6\ \mathrm{ns/mm}^2)$, $Q_e = (327.6 \pm 1.8) \times 10^3 e$, (x_0, y_0)= (-0.442 cm, 0.352 cm) (w.r.t center of leading pad) , $\chi^2/\mathrm{Ndf} = 1.08$.

RC Map from Fit of Waveforms using X-ray Data

RC map of ERAM30



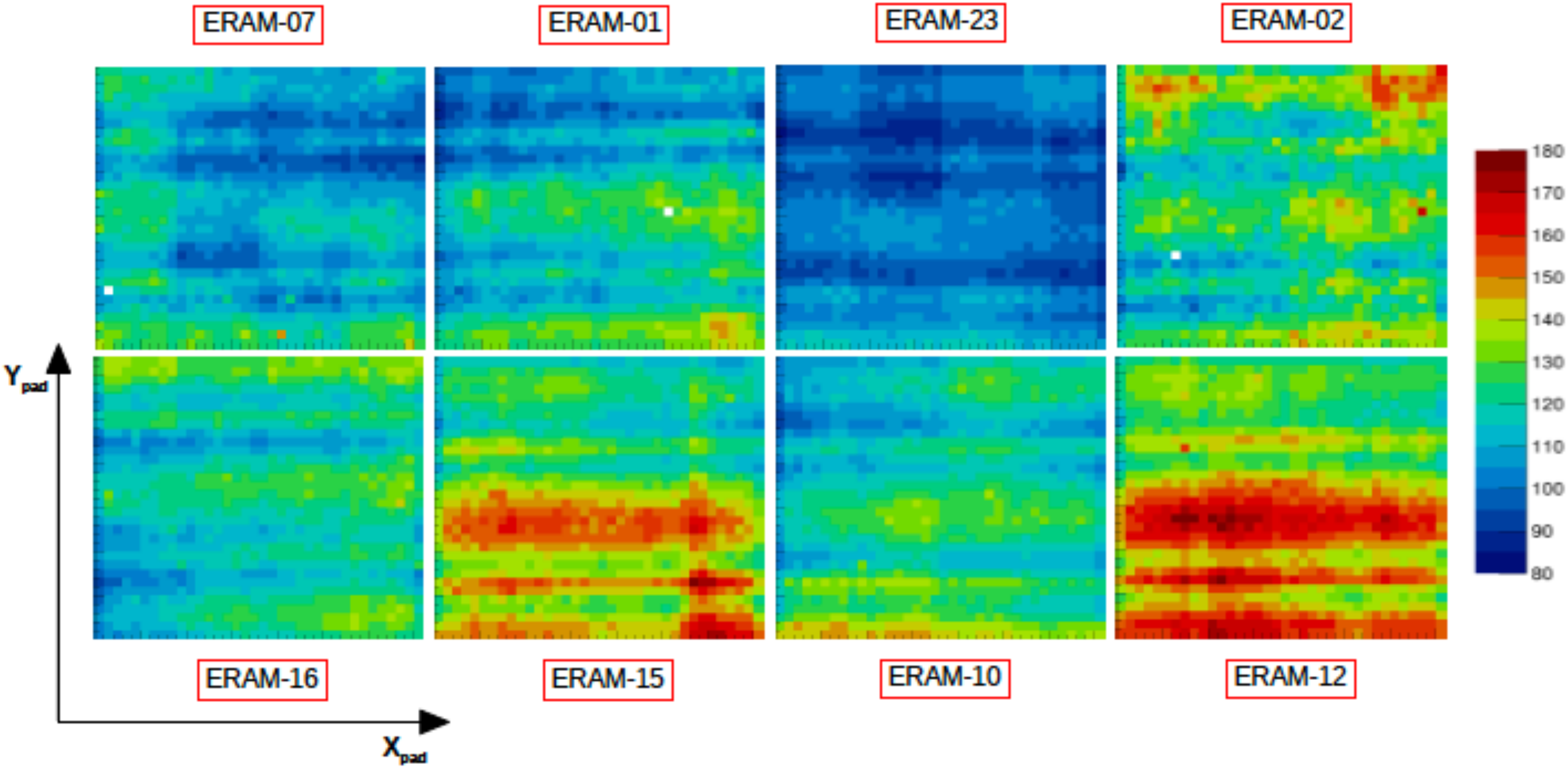
RC distribution of ERAM30



RC_{mean} = 112 ns/mm^2

- Results from simultaneous fit of events from all pads.
- RC non-uniformity is observed.

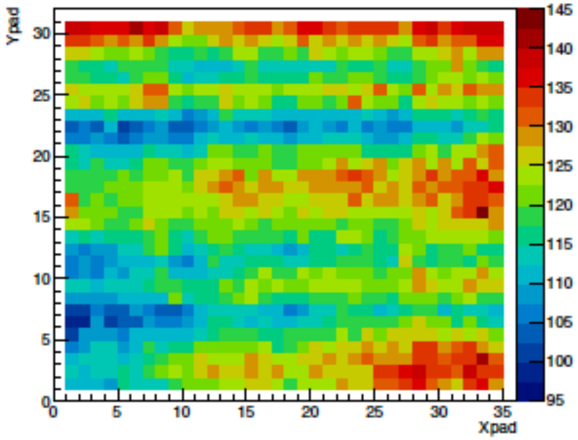
RC Map of other ERAMs



Do we understand RC Map Structure ?

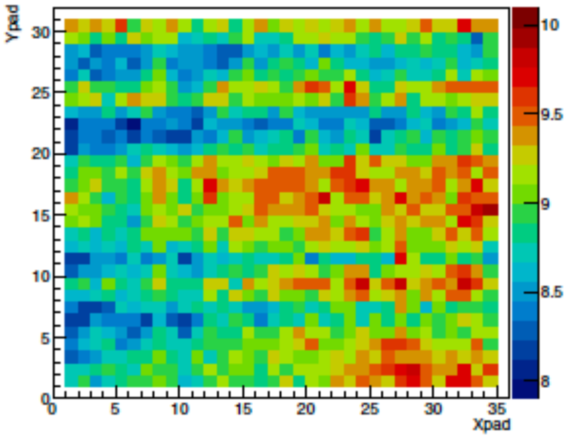
Reconstruction of basic level variables

RC map from fit



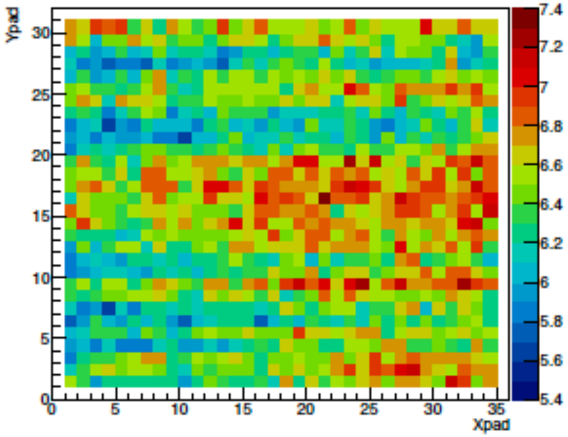
(a)

Basic level variable (var2) map

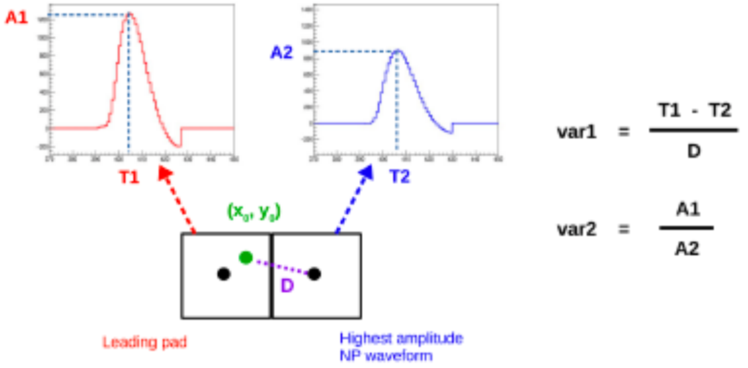


(b)

Amplitude Ratio (var1) map



(c)



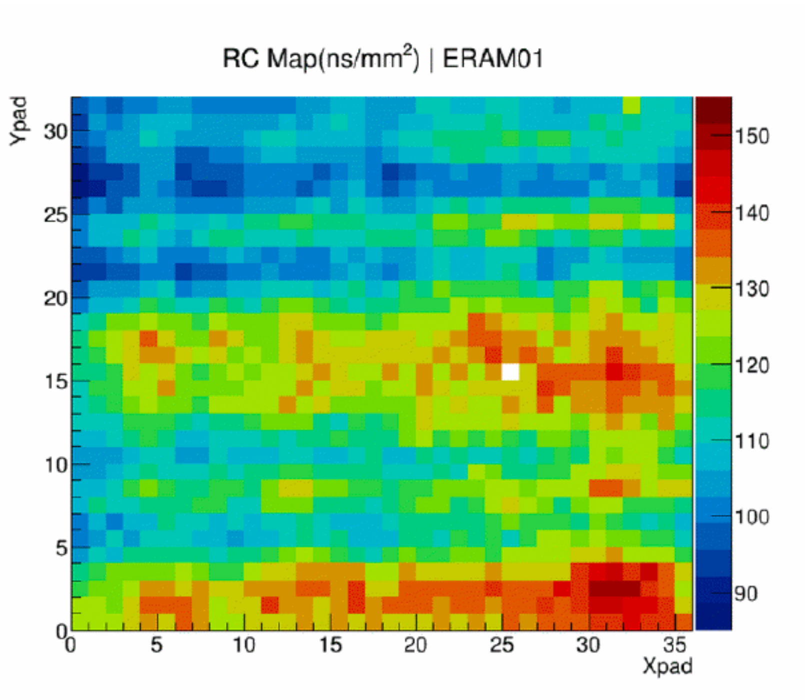
$$var1 = \frac{T1 - T2}{D}$$

$$var2 = \frac{A1}{A2}$$

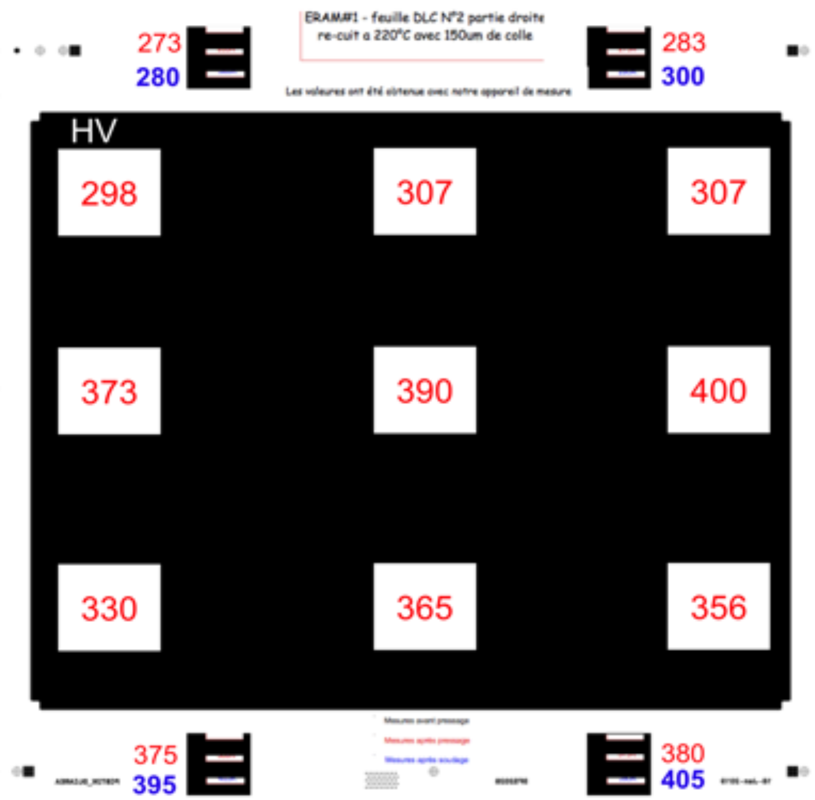
(d)

Do we understand RC Map Structure ?

ERAM-01: RC map from fit



ERAM-01: Resistivity Measurements



- RC map structure seems to be correlated to the resistivity (R) measurements.

Do we Understand RC Value?
RC Calculation from First Principle

Plane capacitance

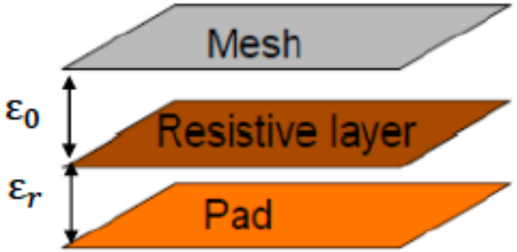
$$C = \frac{\varepsilon_0 \times \varepsilon_r \times S}{d}$$

$$R \times \left(\frac{C}{S}\right) = \frac{\varepsilon_0 \times \varepsilon_r}{d}$$

- Vaccum permitivity ε_0 = 8.854x10^{-12} Fm^{-1}
- Relative permitivity ε_r [APICAL]~3.3 and ε_r [glue] ~4.8
- d = 150 (glue) + 50 (Apical) = 200 μm
- R = 280-405 kΩ /☐

R = 280 kΩ/☐
RC = 75 ns/mm^2

R = 405kΩ/☐
RC = 108 ns/ mm^2



RC from fit is ~1.3 - 2 times higher than the RC from simple calculation ?!

- **Uncertainties on RC calculation:**
  - How well do we measure R?
  - Do we know precisely the distance d ?
  - Is ε_r value precise or approximate?

Do we Understand RC Value?
RC Calculation from First Principle

Plane capacitance

$$C = \frac{\varepsilon_0 \times \varepsilon_r \times S}{d}$$

$$R \times \left(\frac{C}{S}\right) = \frac{\varepsilon_0 \times \varepsilon_r}{d}$$

- Vaccum permitivity $\varepsilon_0 = 8.854\times10^{-12}$ Fm^{-1}
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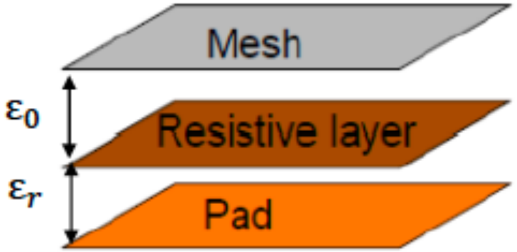
- d = 150 (glue) + 50 (Apical) = 200 μm
- R = 280-405 kΩ /□



R = 280 kΩ/□
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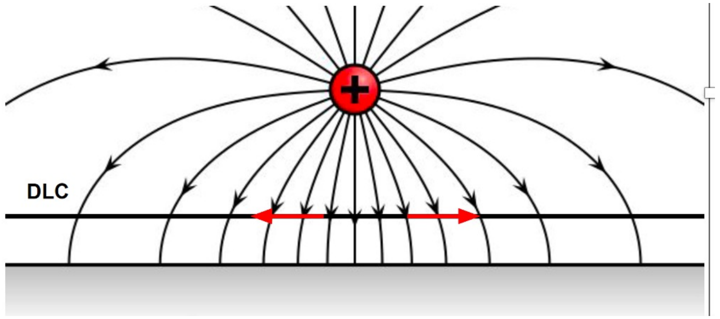
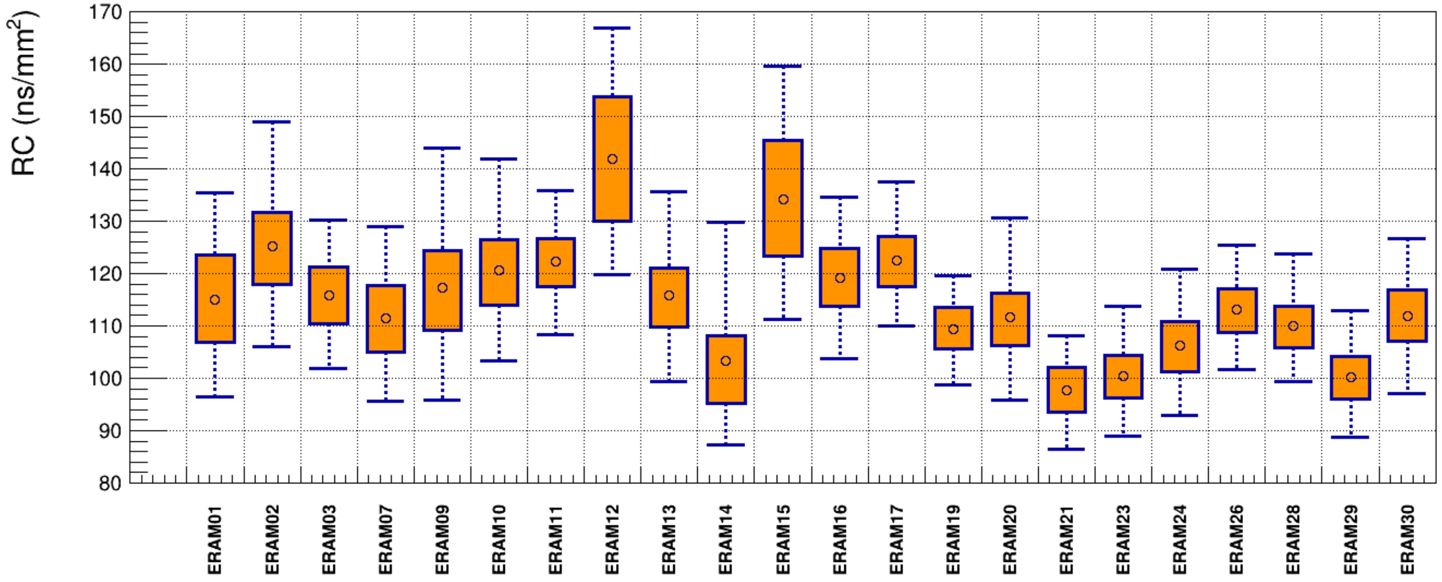
RC = 108 ns/ mm^2

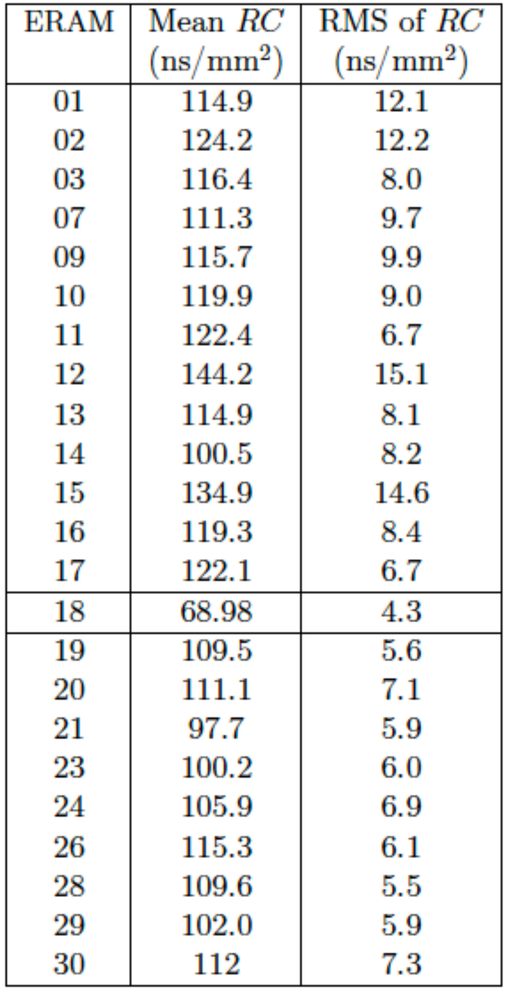
RC from fit is ~1.3 - 2 times higher than the RC from simple calculation ?!

- **Uncertainties on RC calculation:**
  - How well do we measure R?
  - Do we know precisely the distance d ?
  - Is ε_r value precise or approximate?
- **Ion field effect on DLC? SHEPHERD DOG EFFECT ?**



Mean RC values of 23 ERAMs





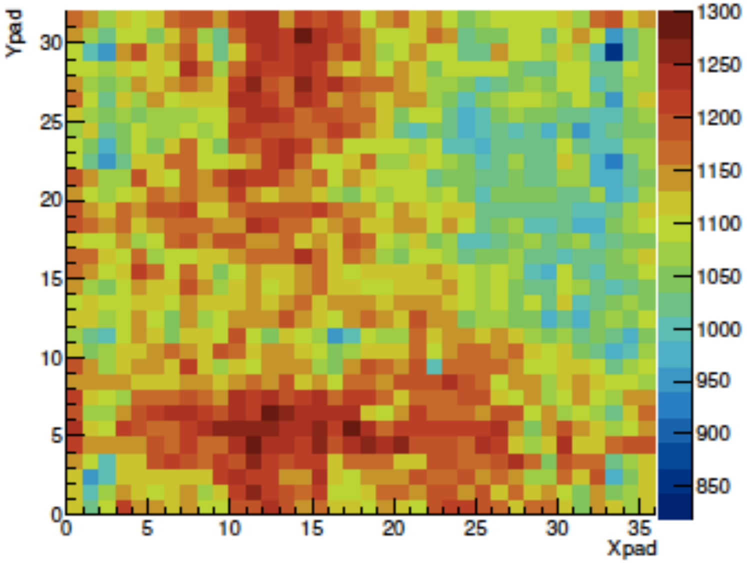
ERAM	Mean *RC* (ns/mm^2)	RMS of *RC* (ns/mm^2)
01	114.9	12.1
02	124.2	12.2
03	116.4	8.0
07	111.3	9.7
09	115.7	9.9
10	119.9	9.0
11	122.4	6.7
12	144.2	15.1
13	114.9	8.1
14	100.5	8.2
15	134.9	14.6
16	119.3	8.4
17	122.1	6.7
18	68.98	4.3
19	109.5	5.6
20	111.1	7.1
21	97.7	5.9
23	100.2	6.0
24	105.9	6.9
26	115.3	6.1
28	109.6	5.5
29	102.0	5.9
30	112	7.3

- Although a large variations in mean RC and mean gain are observed for the eight tested ERAMS, yet, comparable spatial resolutions for both particle types electron and muon are obtained in testbeam@CERN in 2022.

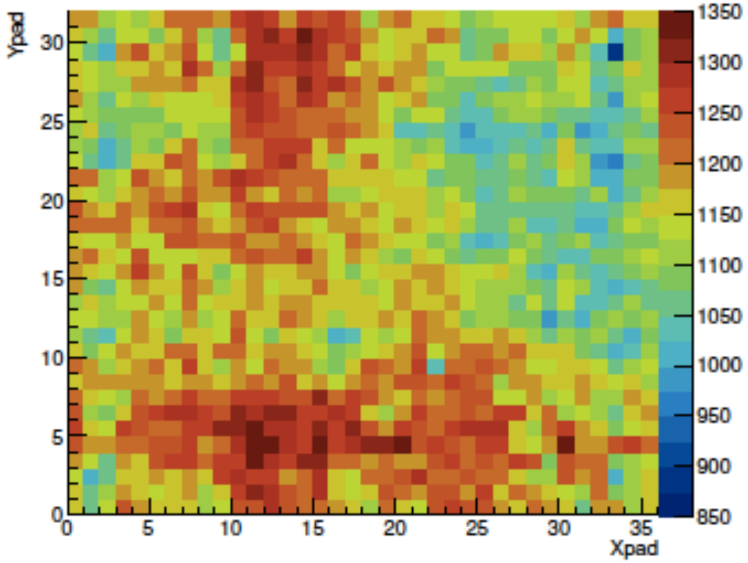
5. Gain Measurements using X-rays Data

Comparison of Gain from two methods

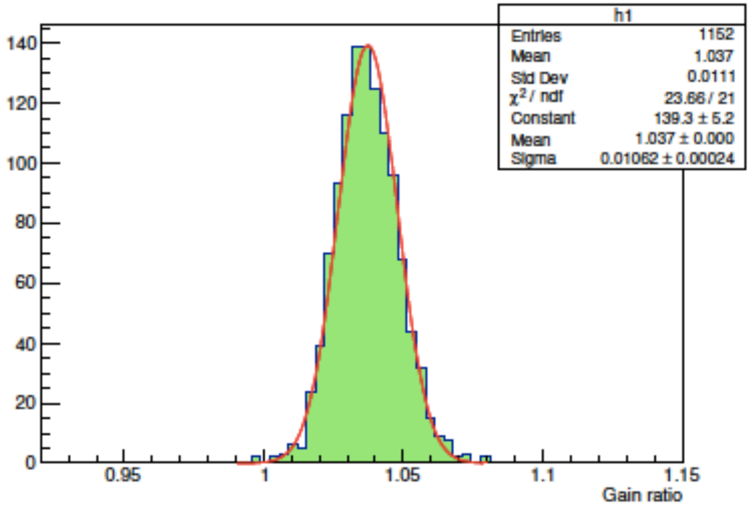
Gain map from waveform fit



Gain map from fit of ^{55}Fe spectrum



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

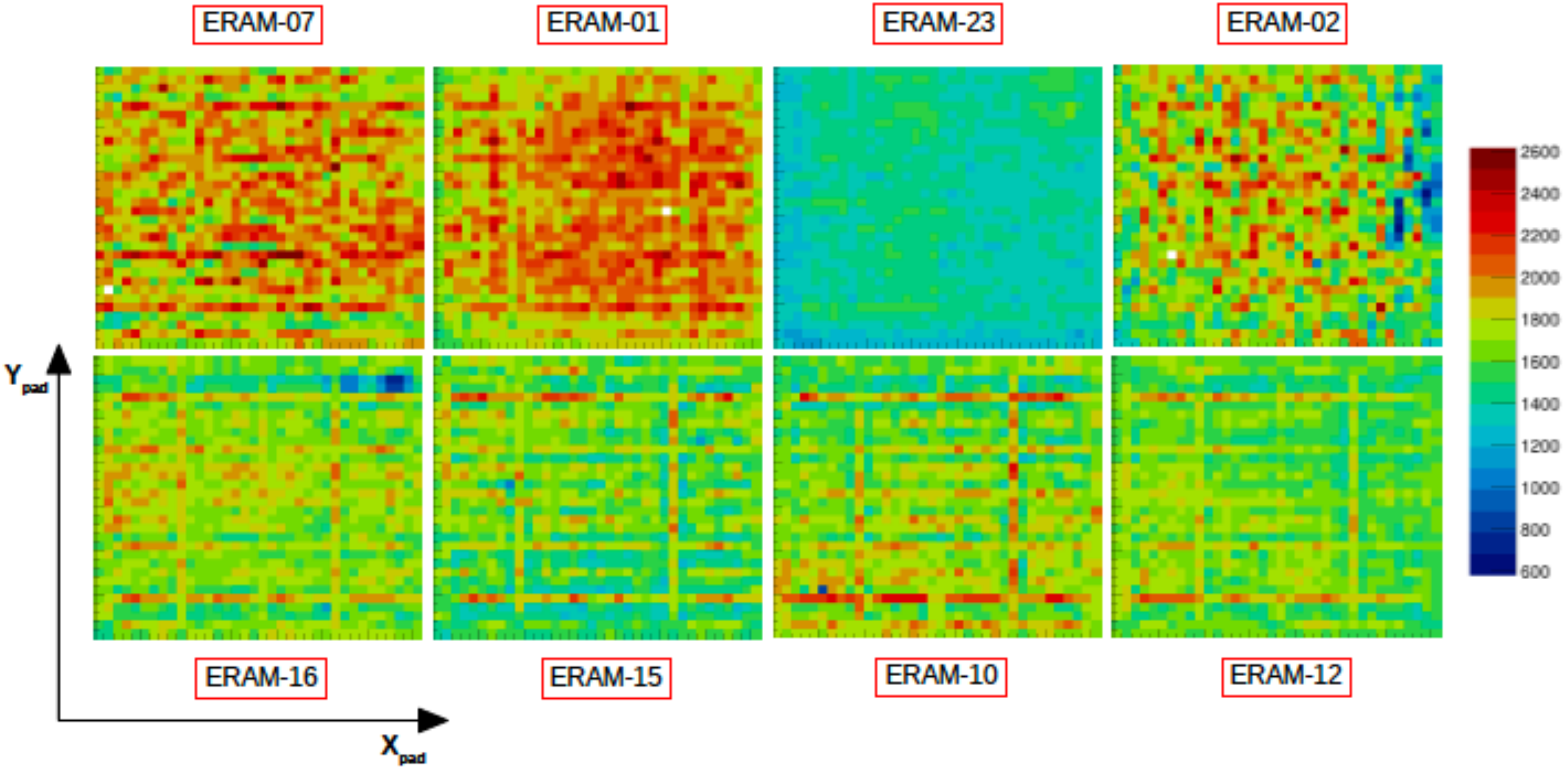


$\text{Ratio}_{\text{mean}} = 1.04$

- Very high similarity in gain maps obtained from two different methods.
  - **Method 1**: fit of the waveforms using the analytical model
  - **Method 2**: fit of ^{55}Fe spectrum obtained by summing all waveforms in each event and taking amplitude max of summed waveforms.

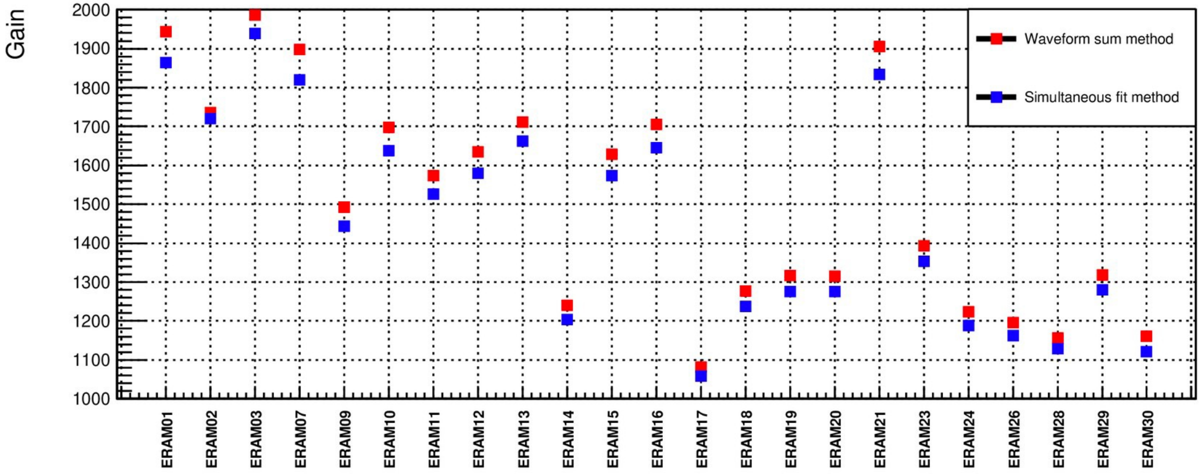
- Gain results serve as validation for Electronics Response function, and robustness of entire model.

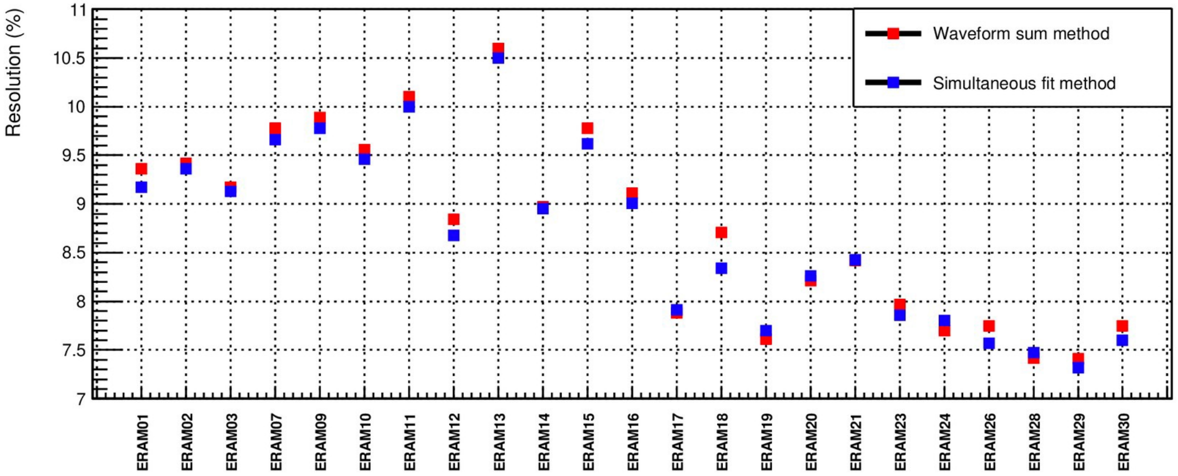
Gain Map of other ERAMs



- Various PCB designs visible due to mechanics ribs, not since ERAM-23→Problem solved

Mean Gain and Resolution of 23 ERAMs





- Absolute gain of ERAM detectors changes with design → Changes in the production process.
- The gain difference between the two methods for different ERAMs is less than 4%. This systematic difference is due to the electronics effect in the simultaneous fit.

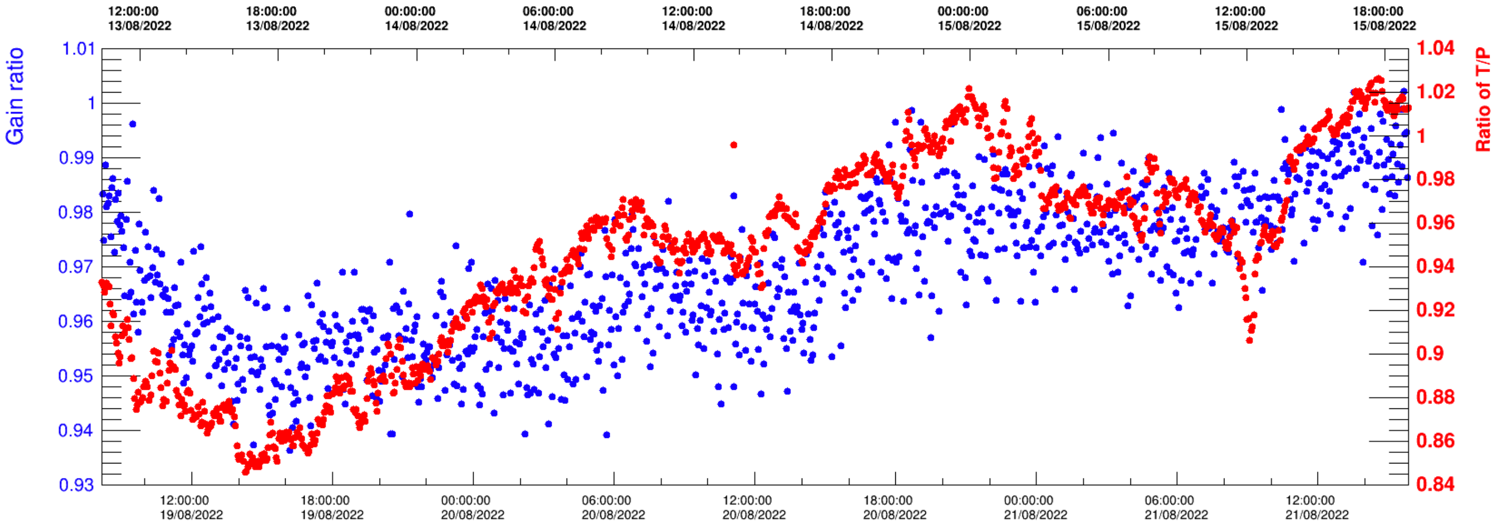
Effect of Environmental Conditions on Gain

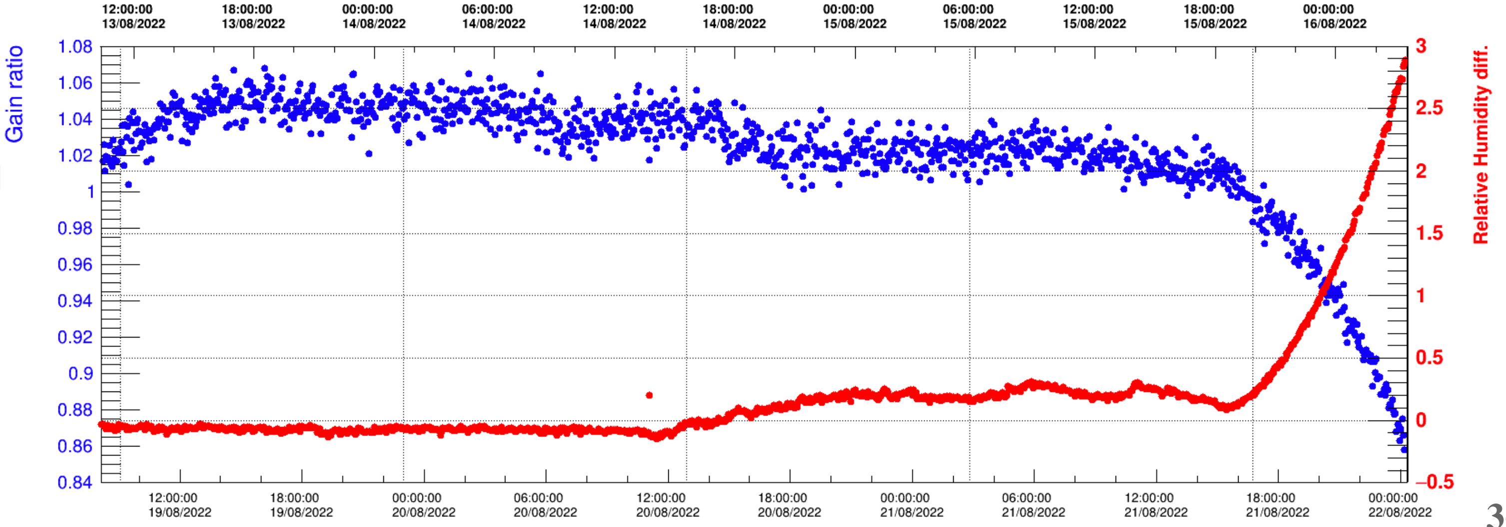
- The Effect of following environmental conditions, recorded during an X-ray test bench shift, on gain is studied:
  - Gas temperature
  - Chamber pressure
  - Relative gas humidity

- An ERAM was scanned twice at two different instances.

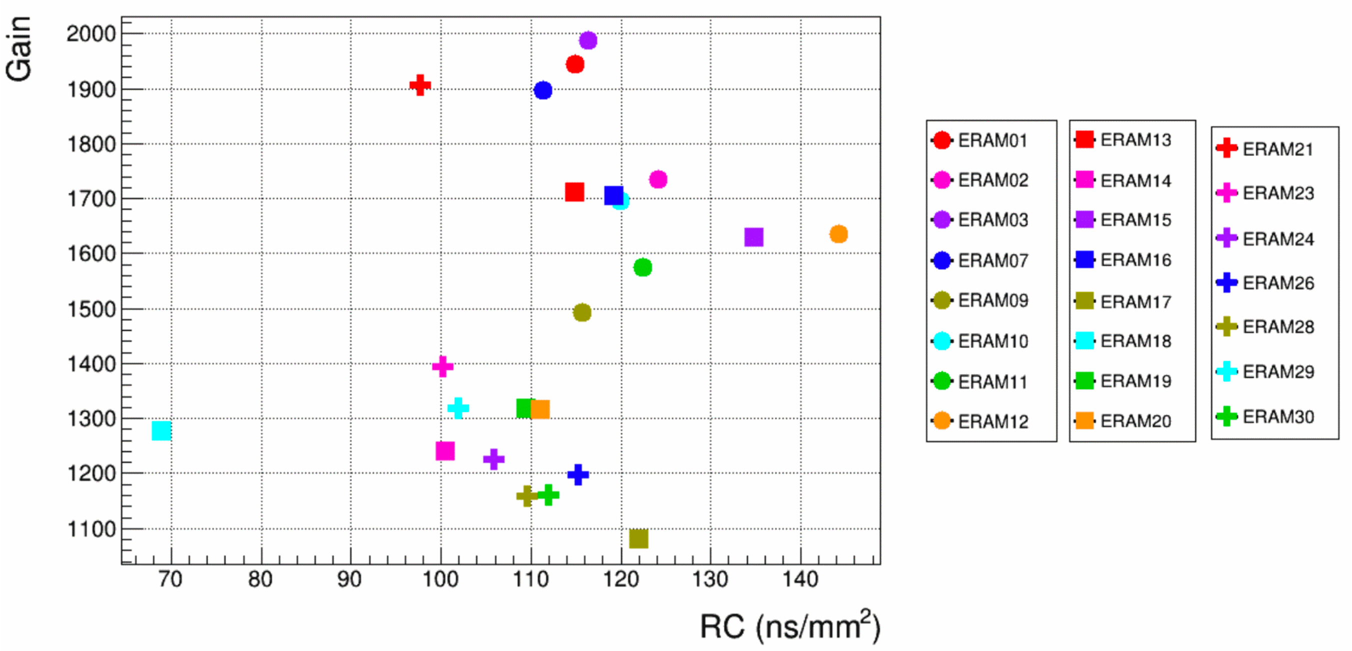
- Ratio of Gain of each pad from both the instances was compared with the ratio of environmental conditions recorded during those pad-scans.

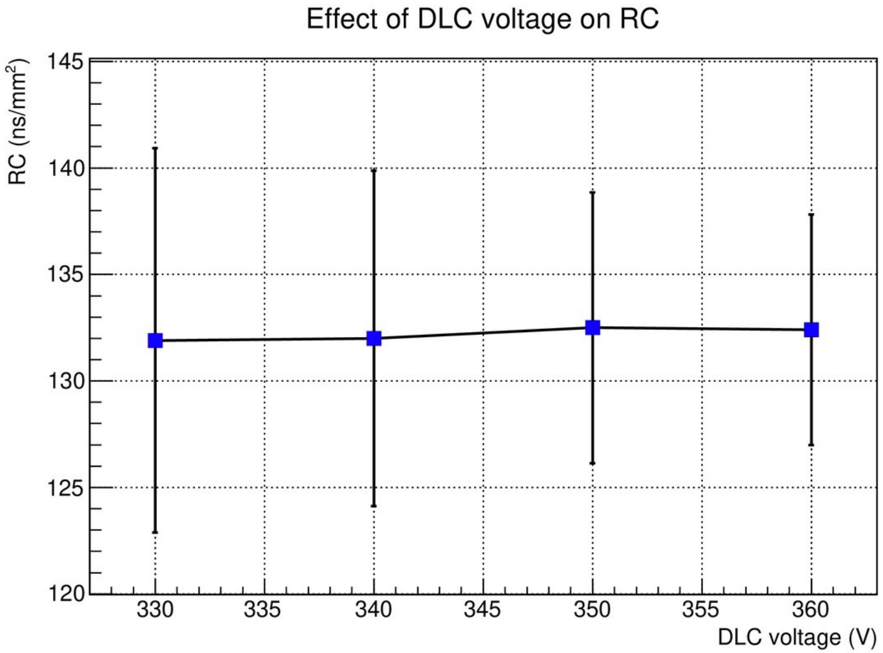
- Gain maps to be corrected in case of significant changes in environmental conditions.





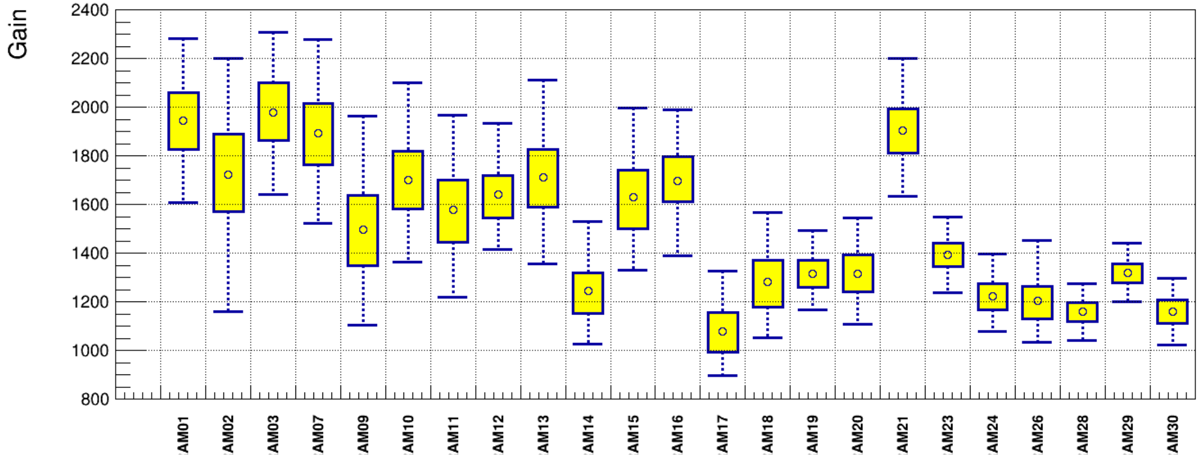
Correlation between RC and Gain Values

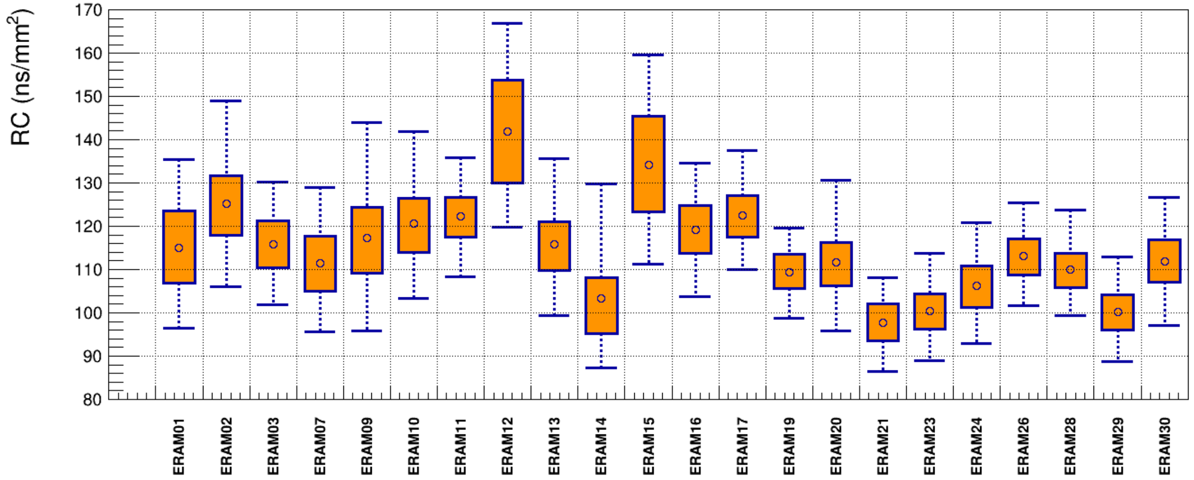


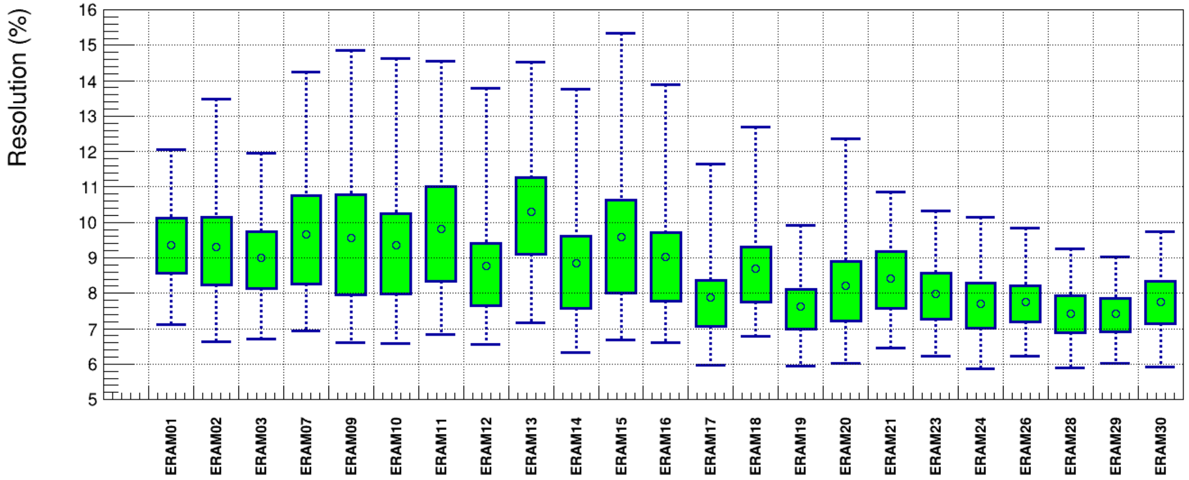


- There is no apparent correlation between mean RC and mean gain.
- This observation is confirmed by the fact that RC doesn’t change with DLC voltage.

Summary of Mean RC, Gain and Resolution of 23 ERAMs

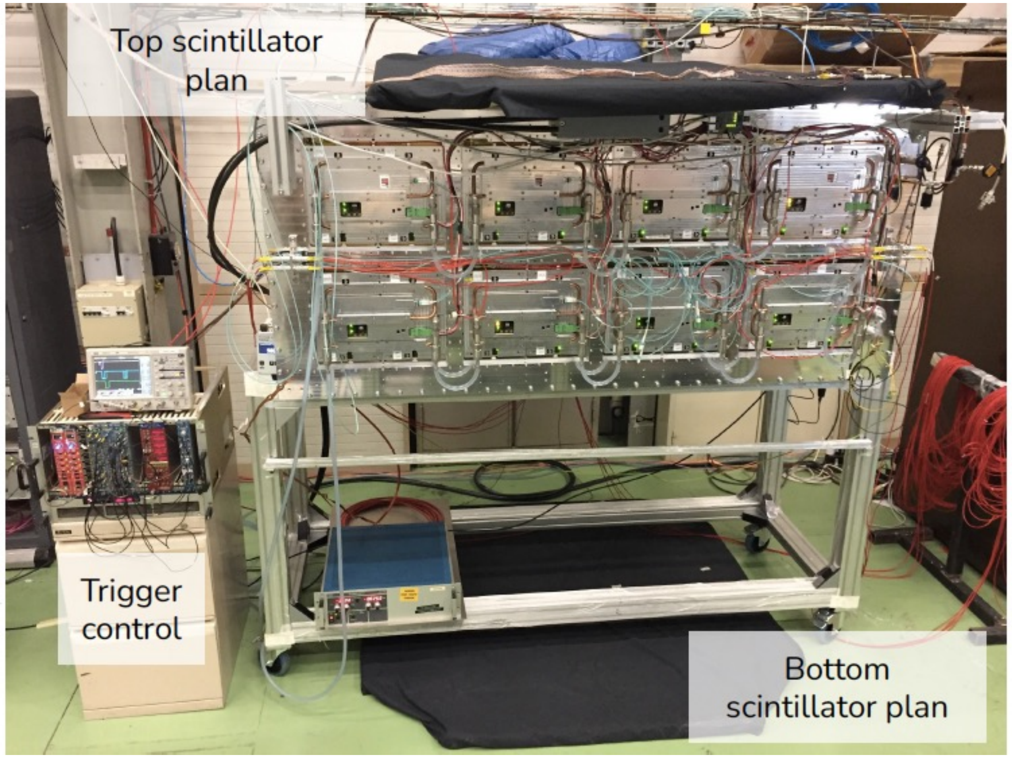




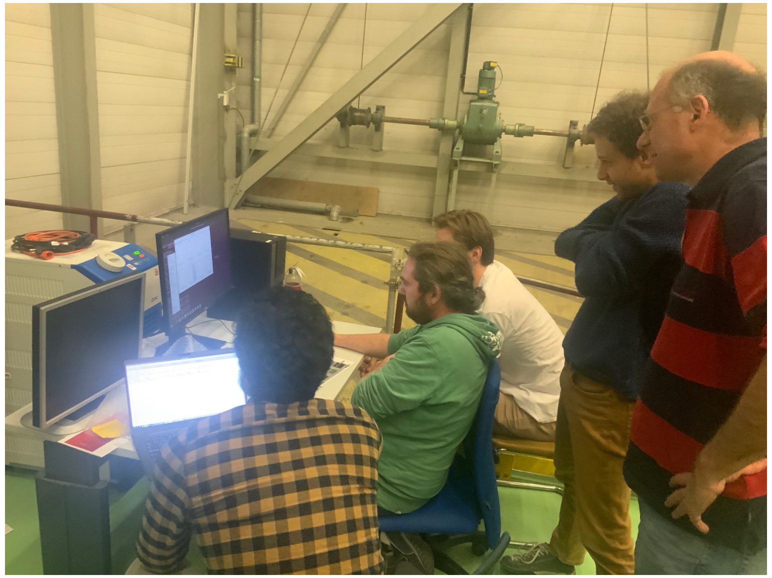


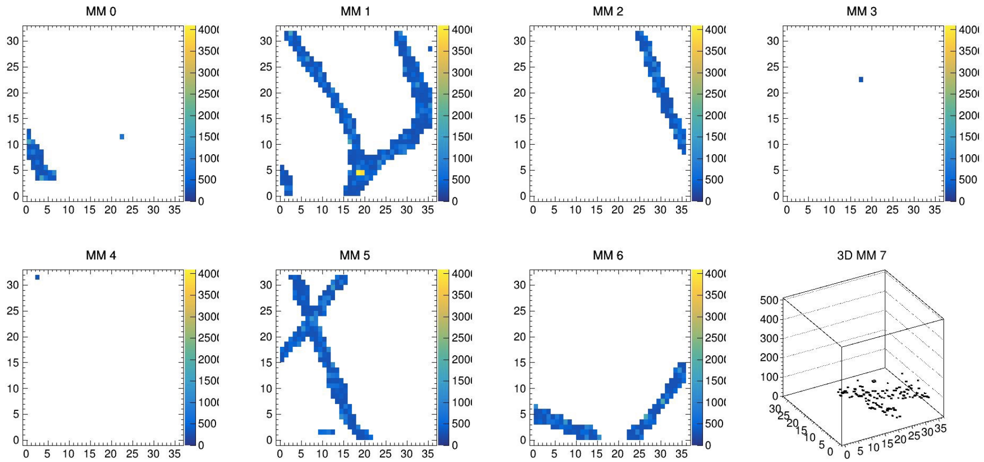
- These plots were used to choose the combination of eight ERAMs to equip the first field cage.

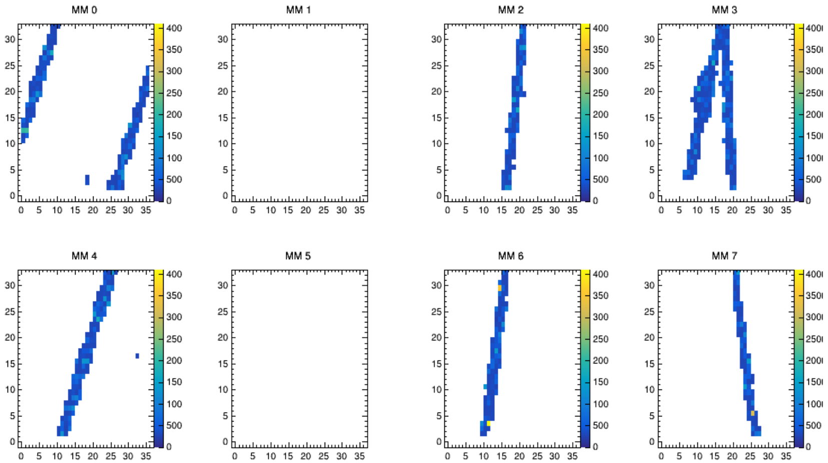
First Cosmic Rays Tracks seen in the First Half HATPC at CERN



The mechanical, electrical (VHV), and gas-related performance are all excellent.







Summary

- The production of encapsulated resistive anode bulk Micromegas modules is well underway.
  - **23/32 produced and fully validated.**

- The X-ray test bench is used to characterize the detectors by scanning each pad individually and precisely measure the uniformity of the gain and energy resolution over the pad plane.
  - **An energy resolution of about 10% was measured.**

- Charge spreading model is obtained from convolution of charge diffusion function and derivative electronics response function. The model is able to successfully fit waveforms from X-ray data.
  - **RC and Gain are simultaneously extracted from X-ray data.**
  - **The RC and gain maps uniformity are studied in detail.**
  - **Results submitted to NIMA (arXiv:2303.04481)**

- These performance were used to select the ERAMs to equip the first field cage.

- The measured RC and gain information will be used to feed the HA-TPC simulation and reconstruction

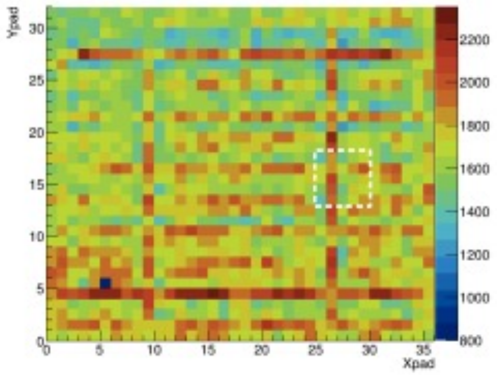
Merci

BACKUP

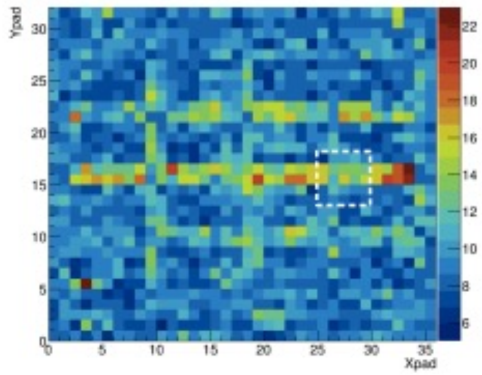
LARGER GAIN AND RESOLUTION ON SEVERAL DETECTORS

- For some modules, we have seen larger gain and energy resolution where the aluminum stiffener is glued (up to 20% corresponding to 1-2 µm of gap variation).
- This is due to local extra thickness of copper & soldermask on the backside of the PCB which affect the micromegas amplification gap after DLC foil & stiffener gluing under pressure
  →**solved with modified PCB**

Gain map



Resolution map



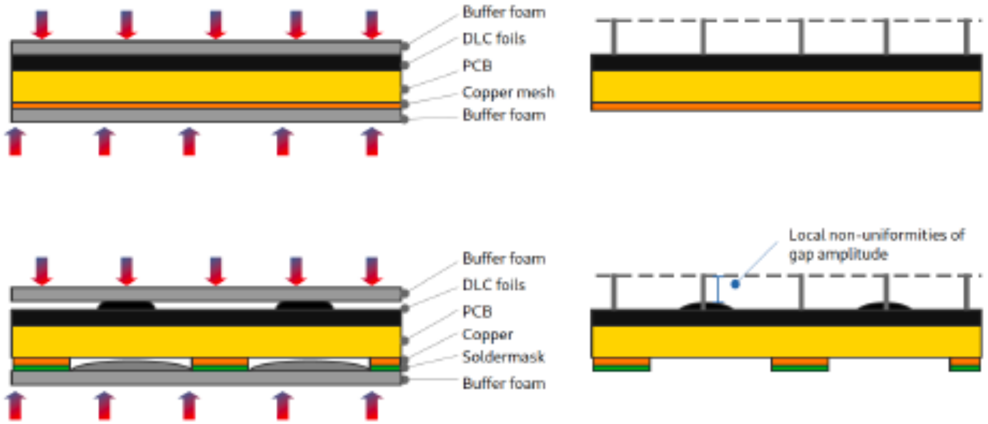


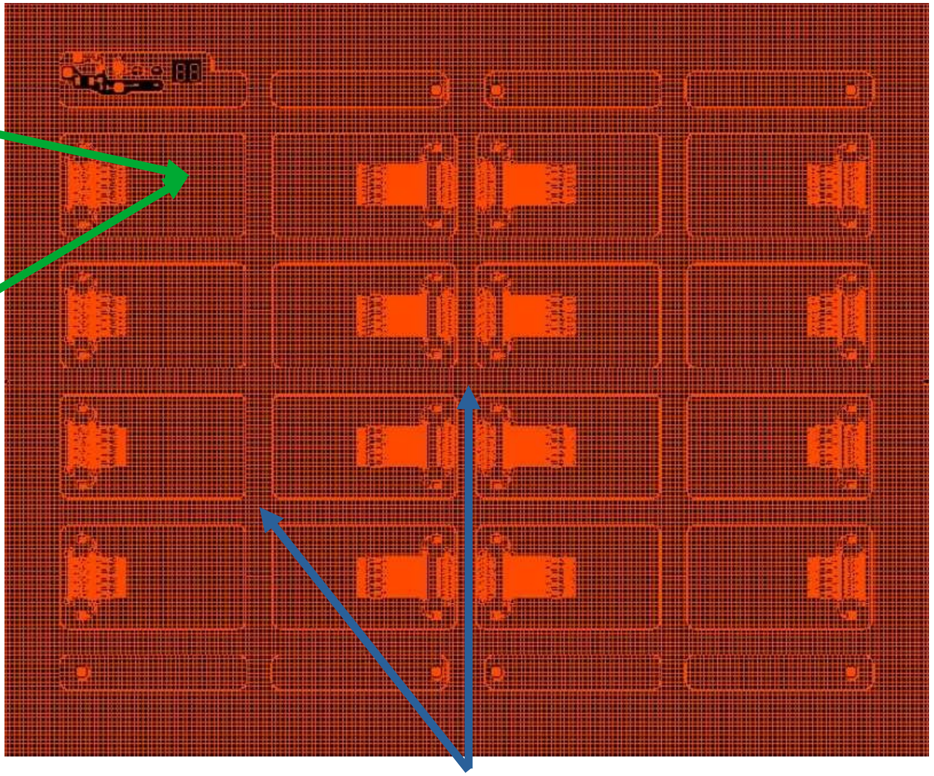
Figure 32: Schematic view of the DLC pressing on the PCB during detector assembly resulting in the non-uniformities observed on the 2D gain and energy resolution maps. The arrows represent the mechanical constraints applied which are evenly distributed when the soldermask is removed and replaced by the copper mesh.

ERAM PCB Modifications

- Stiffener gluing procedure was first suspect but no clear correlation found after several tests (change of gluing process)
- Assumption that non uniformity of PCB backside affects DLC side flatness and therefore amplification gap by a few microns after pressing DLC
- → **PCB modification!**

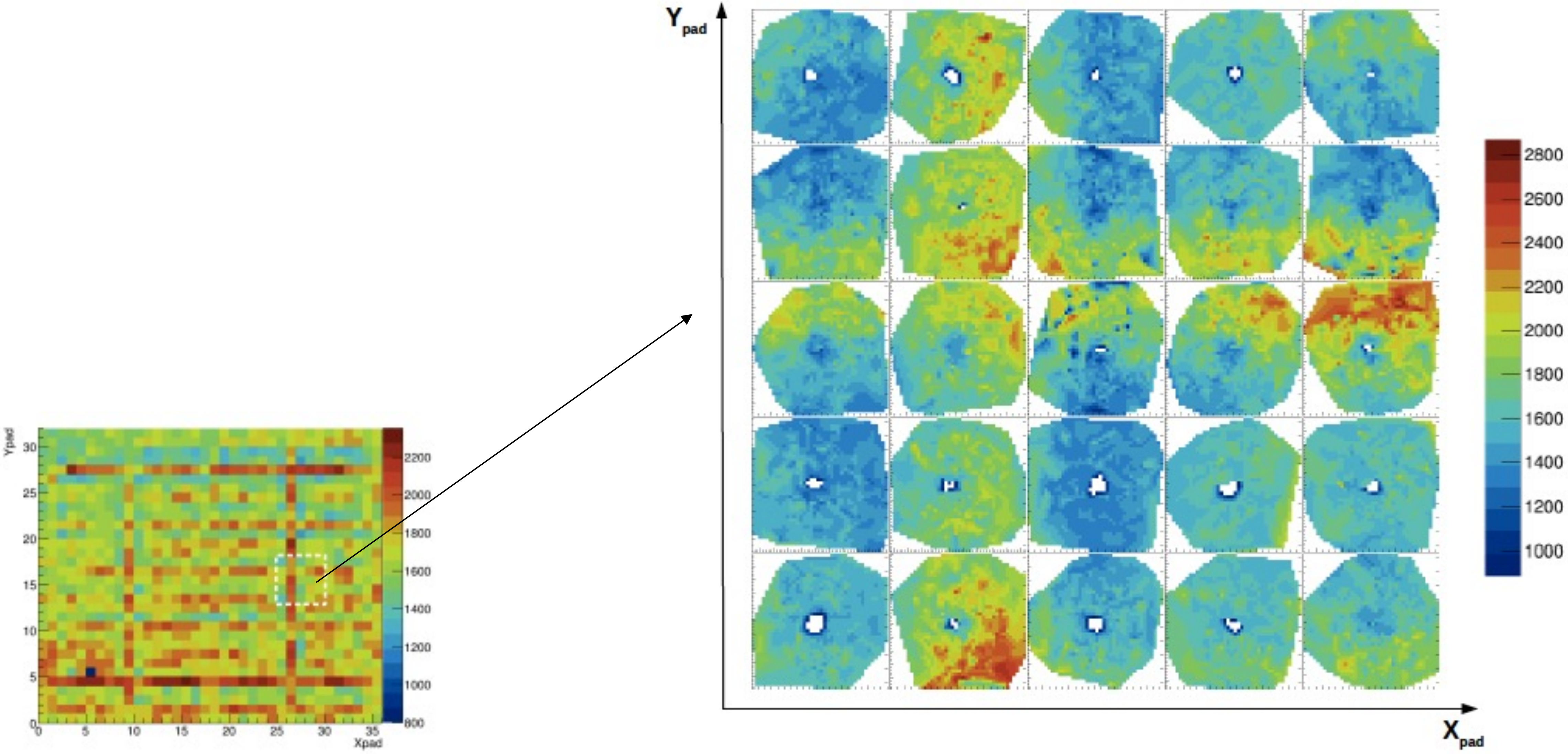
- ERAM up to 16
  - Those areas are also covered with green soldermask
- ERAM09-16
  - PCB produced by ELTOS Cie following industry IPC standard
  - Copper & soldermask is probably thicker than @ CERN
- ERAM17-24
  - Soldermask was removed
- ERAM23
  - Replaced copper pad by a copper mesh
  - **→More uniform PCB**
  - **→ More uniform Gain**

ERAM top layer up to ERAM-23



Stiffener is glued on the PCB TOP layer where copper mesh is

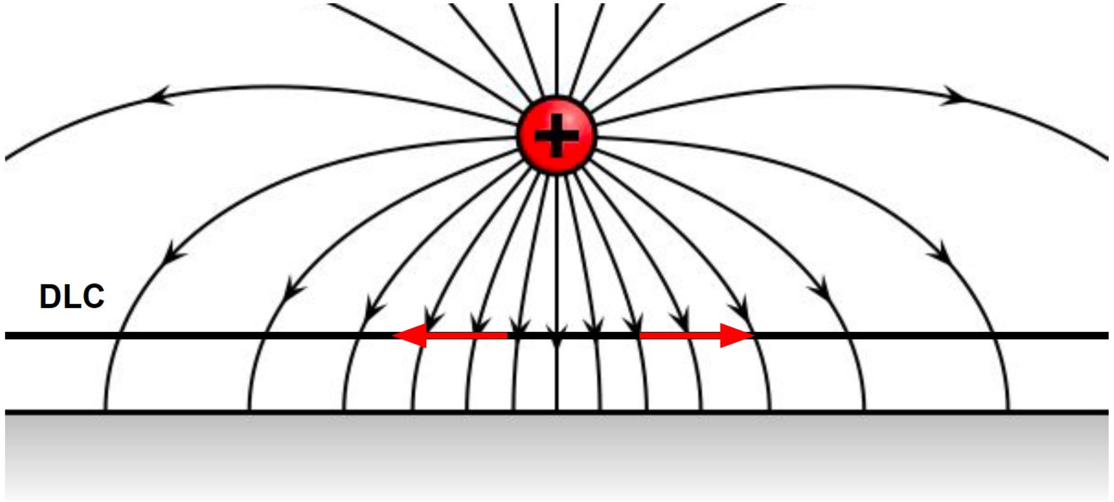
Gain Variation Within a Pad



WE UNDERSTAND RC VALUE?
SHEPHERD DOG EFFECT

Shepherd dog effect

Ion field on DLC greatly affects long distance charge spread



- **The ions limit the spread of the charge.**
- The RC value is a factor 2.7 greater than the one obtained without considering the ion contribution (from toy study).

Gain Map from Fit of Waveforms using X-ray data

The signal model is also used to extract the gain.

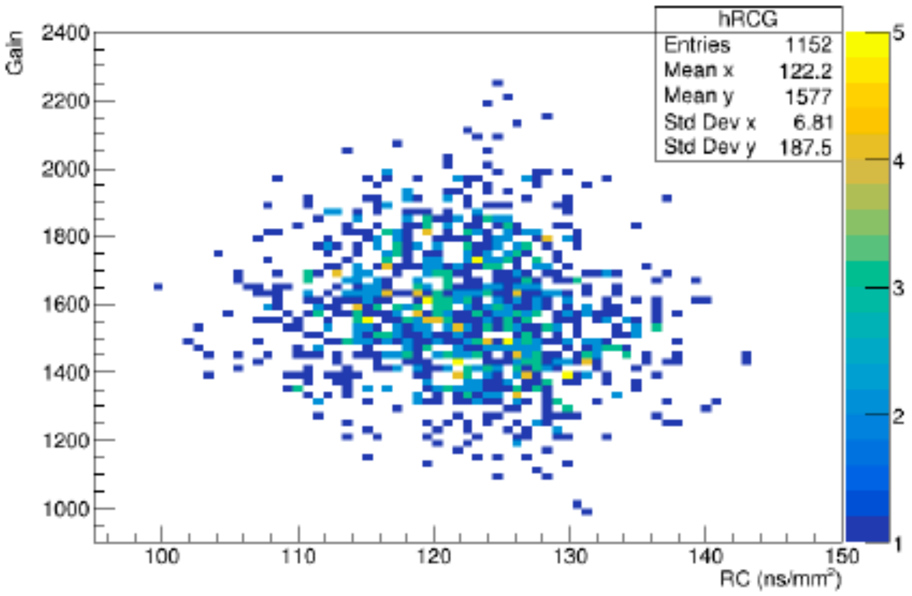
- **Charge density**: $$\rho_{0D}(r,t)=\frac{Q_{primary}G}{2\pi}\frac{1}{\sigma^2(t)}e^{-\frac{r^2}{2\sigma^2(t)}}$$
- **Charge on a pad**: $$Q_{pad}(t)=\boxed{\frac{Q_{primary}G}{4}}\left[\mathrm{erf}\left(\frac{x_H-X_0}{\sigma(t)\sqrt{2}}\right)-\mathrm{erf}\left(\frac{x_L-X_0}{\sigma(t)\sqrt{2}}\right)\right]\left[\mathrm{erf}\left(\frac{y_H-Y_0}{\sigma(t)\sqrt{2}}\right)-\mathrm{erf}\left(\frac{y_L-Y_0}{\sigma(t)\sqrt{2}}\right)\right]$$
- **Electronics response**: (up to ADC) Dirac impulse response:

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

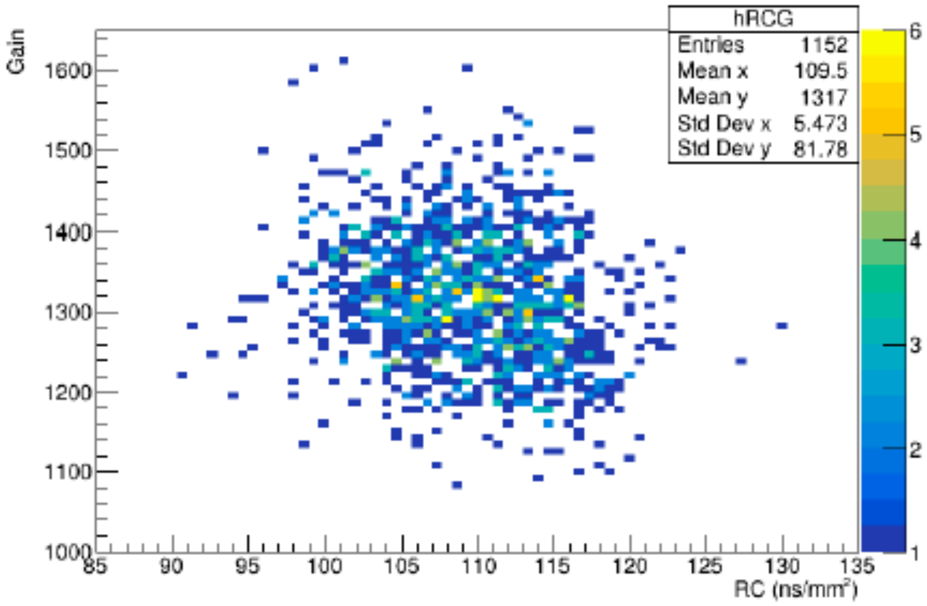
- Implementing the correspondence : 120 fC ↔ 4096 counts.
- Dirac current pulse carrying 120 fC → ADC(t) impulse response with a maximum amplitude of 4096 counts.

CORRELATION BETWEEN RC AND GAIN IN ONE ERAM

ERAM11

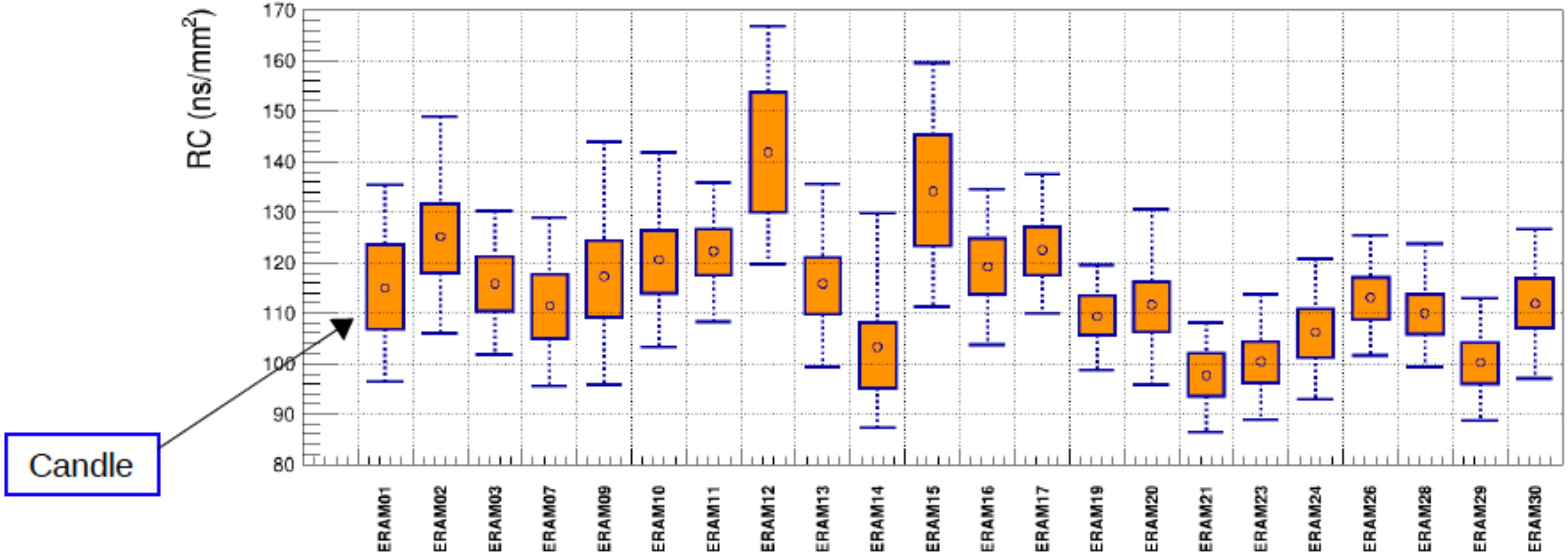


ERAM19



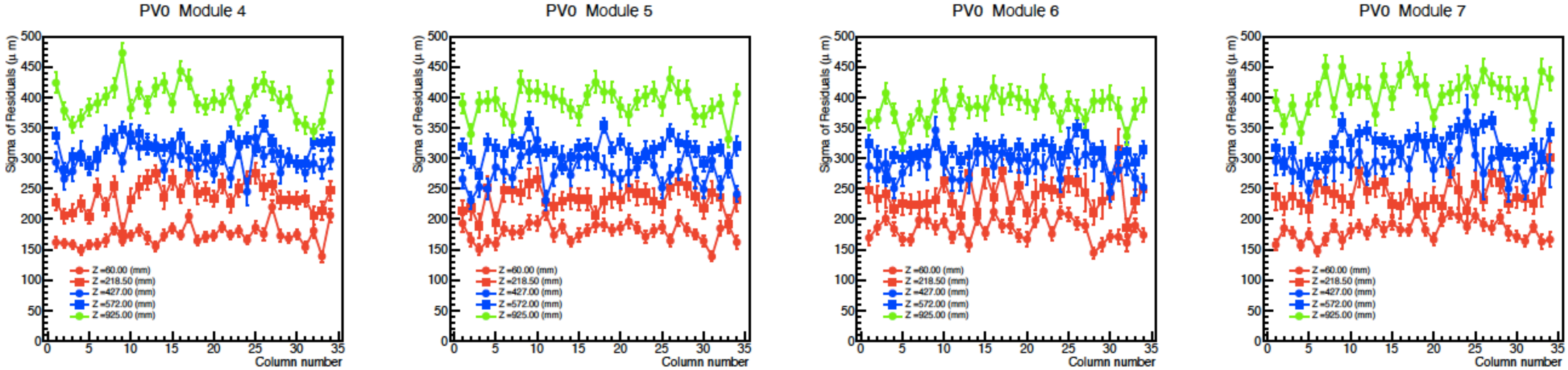
- No correlation seen between mean RC and mean Gain of each pad in 1 ERAM.

Mean RC Values

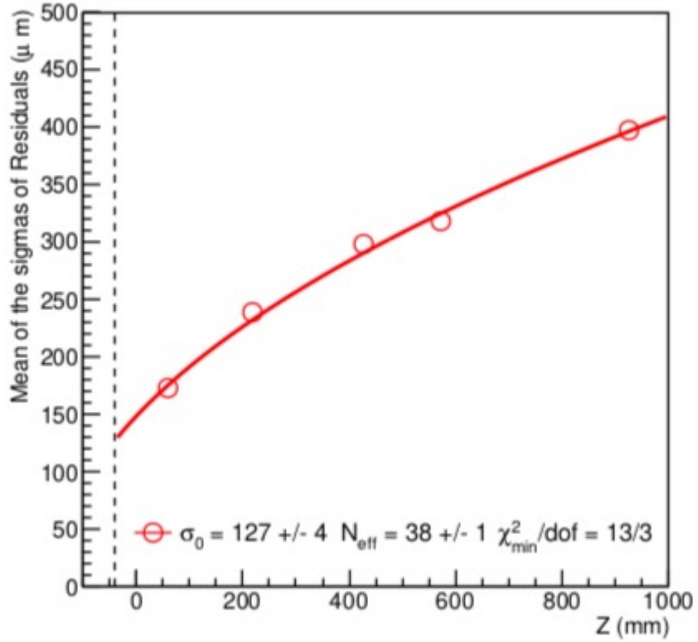


- Lower and upper bounds of box: [Mean – 25%, Mean + 25%] of distribution (50% of values within box).
- Lower and upper bounds of bars: [Mean – 48%, Mean + 48%] of distribution (96% of values within bars).
- 96% and not 100%, to avoid inclusion of values from some damaged pads.
- Width of box is not relevant.

Spatial Resolution VS Drift Distance

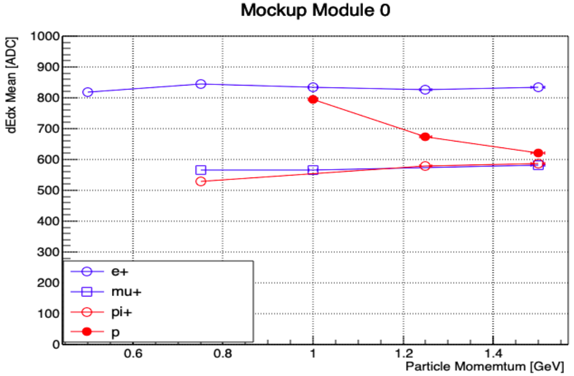


- The The spatial resolution as a standard deviation of the difference between the reconstructed position in a given cluster (obtained using Pad Response Function) and a global track fit
- Spatial resolution for horizontal tracks is within ND280 upgrade requirements

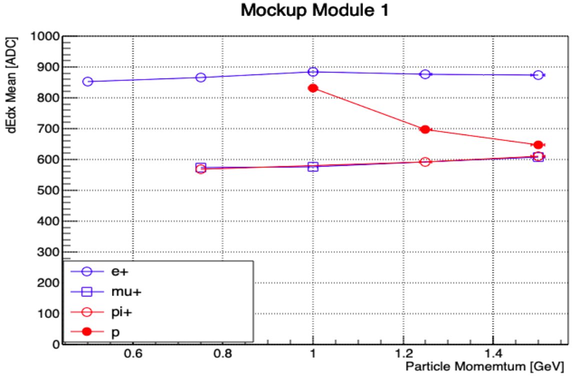


Enery Loss dEdx

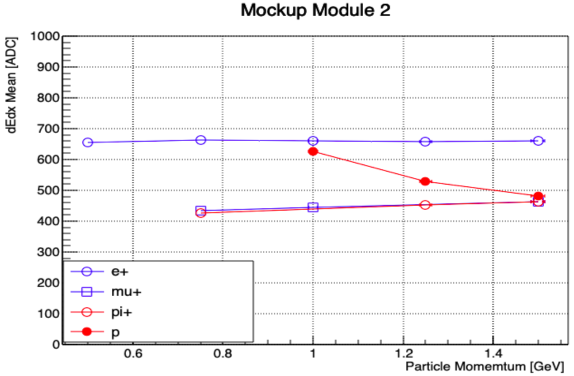
ERAM-07



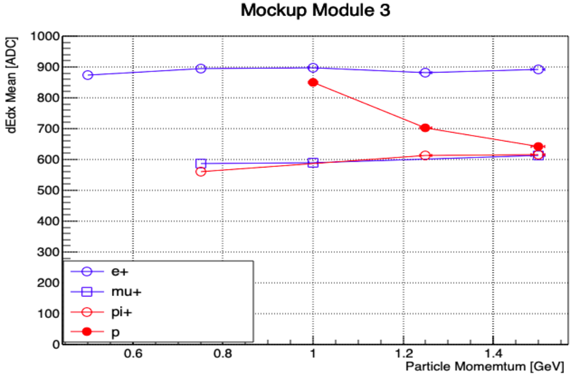
ERAM-01



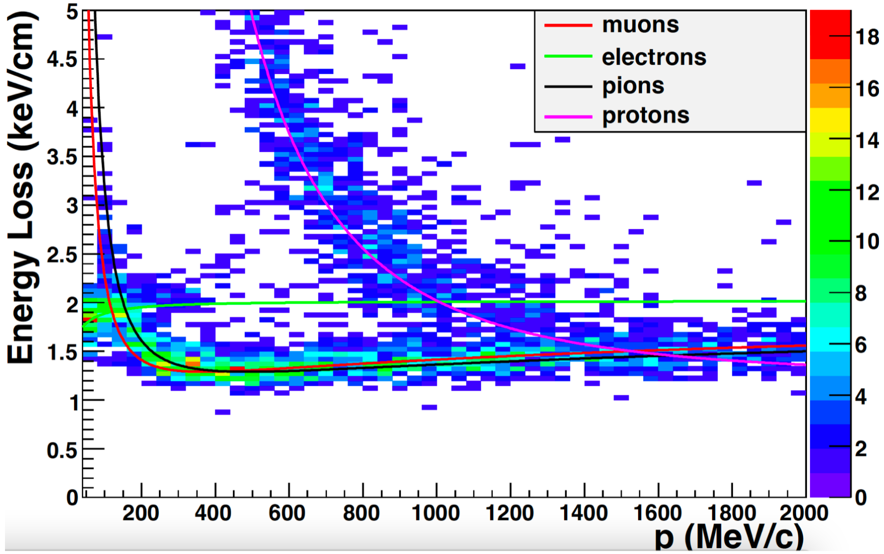
ERAM-23



ERAM-02

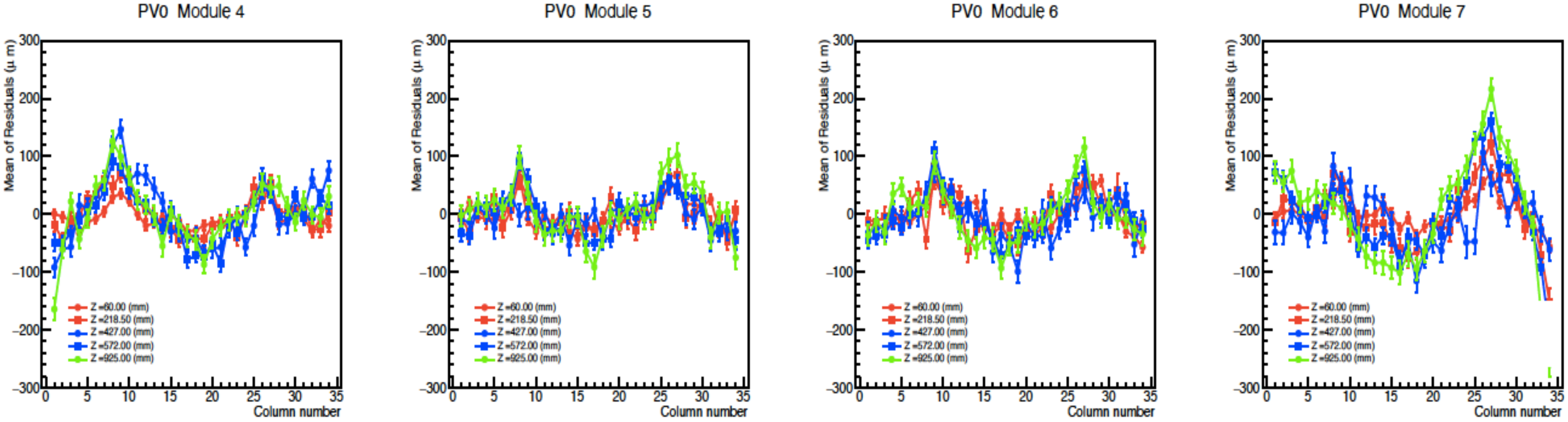


- The The mean dEdx for different ERAMs, particle and momentum are nicely following the simulation.
- ERAM-23 has small mean Eloss compared to the others →Should correct for the gain.
- dEdx resolution (10%) is within ND280 upgrade requirements



BIAS VS Z SCAN

Bias VS Column Number



- The bias is defined as the mean value of the residuals between the reconstructed position in a given cluster (obtained using Pad Response Function) and a global track fit.

- The bias are intrinsic to the device and not an artifact of the analysis method (we cross-checked the results with different methods)

- On going work to study the effect of non uniformity of pad responses, misalignment of the pads, RC non-uniformity,… using Monte Carlo