IRN Neutrino 2022

DE LA RECHERCHE À L'INDUSTRIE

Characterization of charge spreading in resistive Micromegas

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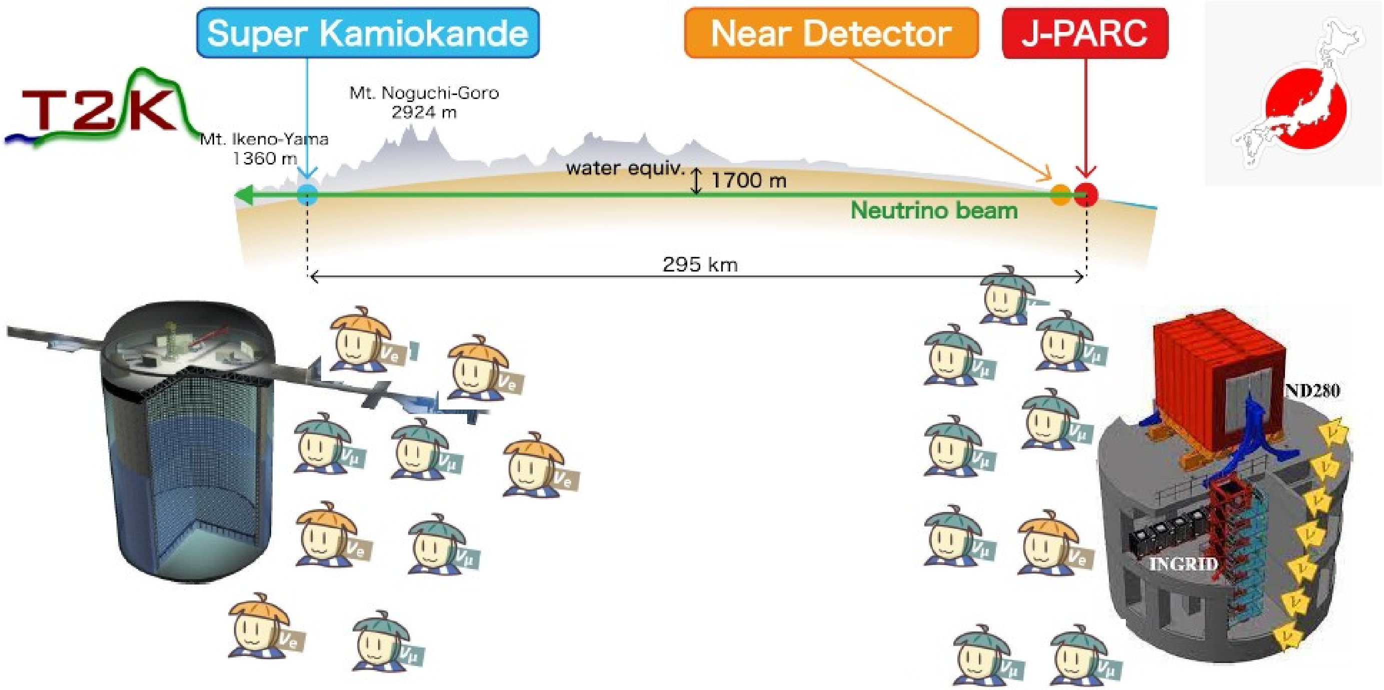
On behalf of ND280 Upgrade Group

www.cea.fr

OUTLINE

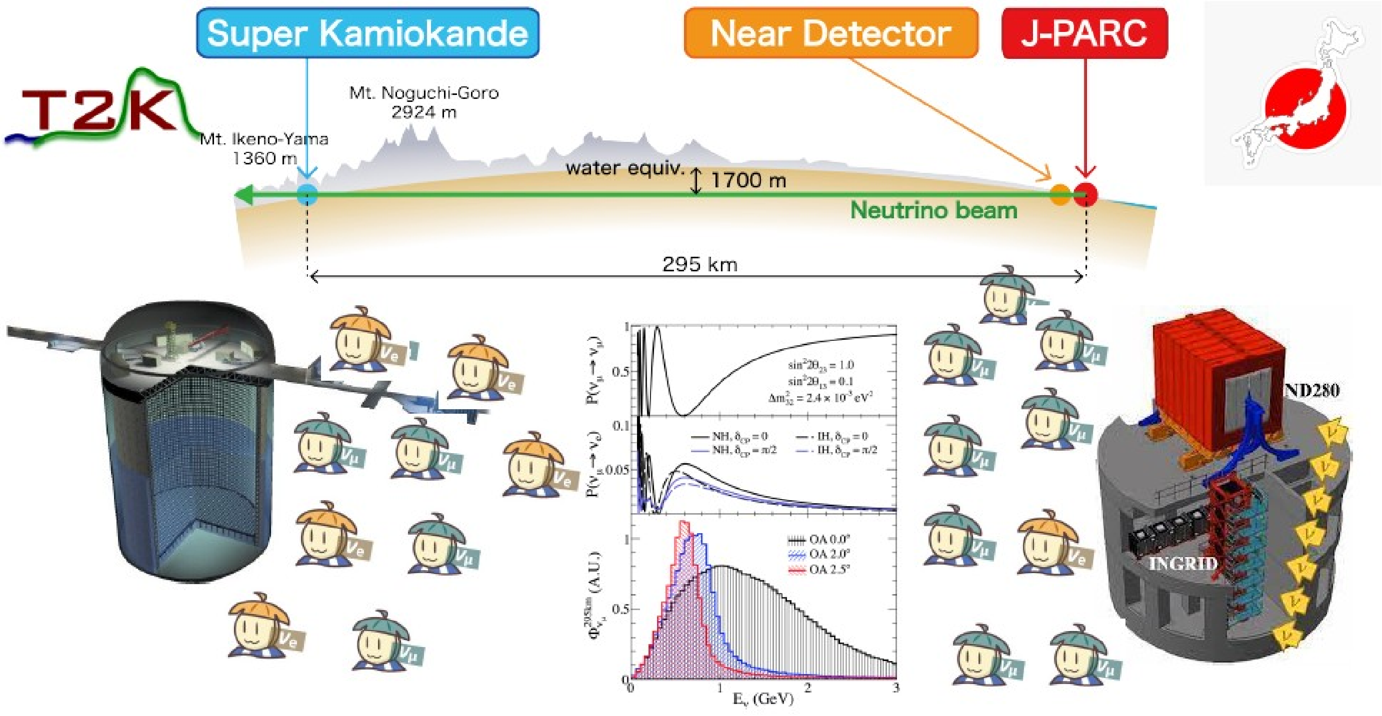
1. T2K near detector upgrade (ND280) using resistive Micromegas for HA-TPC.
2. Modelling of charge spreading with resistive Micromegas.
3. Model validation using both toy Monte Carlo and X-ray data.
4. Resistive Micromegas performance using testbeam data.
5. Conclusion

THE T2K EXPERIMENT: TOKAI TO KAMIOKA



Neutrino cartoons by Yuki Akimoto

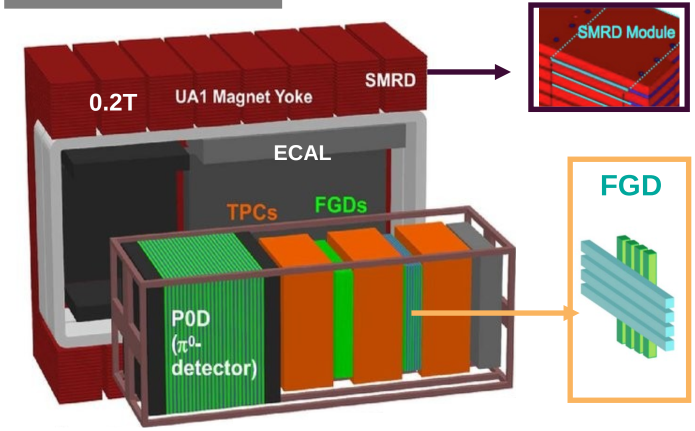
THE T2K EXPERIMENT: TOKAI TO KAMIOKA



Off-axis angle

Neutrino cartoons by Yuki Akimoto

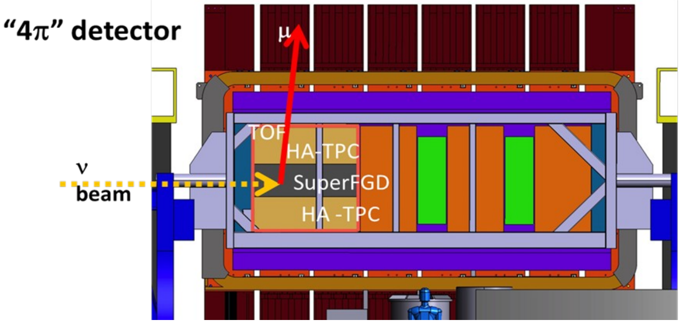
Current ND280



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 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

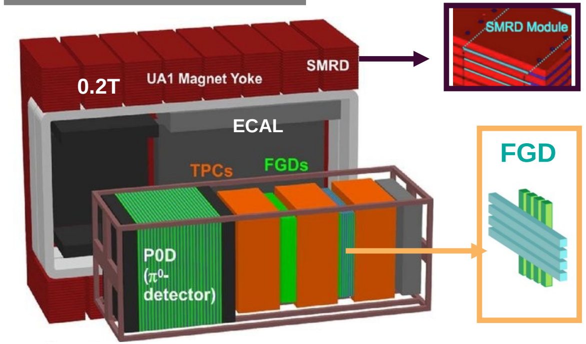


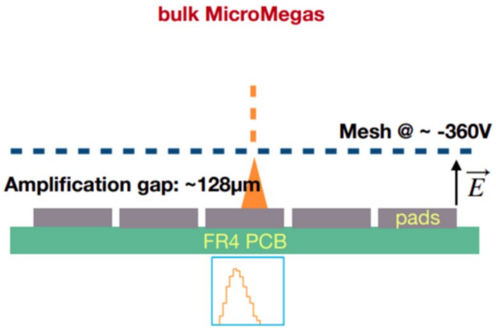
CERN-SPSC-P357

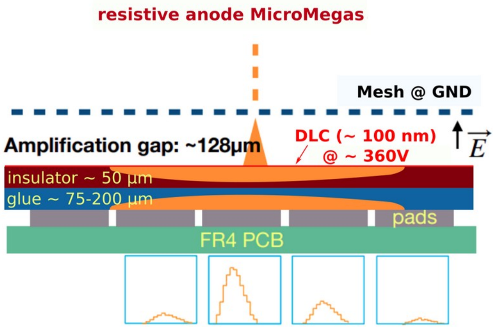
The HA-TPC should at least have the same performance as the current vertical TPCs

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

Current ND280







Pad size: 1.1 * 1 cm^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 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)

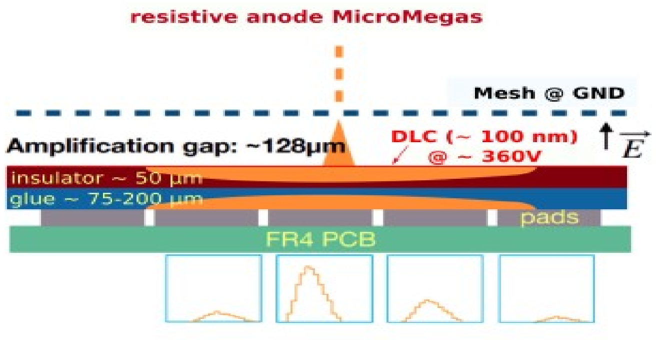
$$\rho(r,t) = \frac{RC}{4\pi t} e^{\frac{-r^2 RC}{4t}}$$

R = Surface resistivity
C = Capacitance / unit area

- 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:

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

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



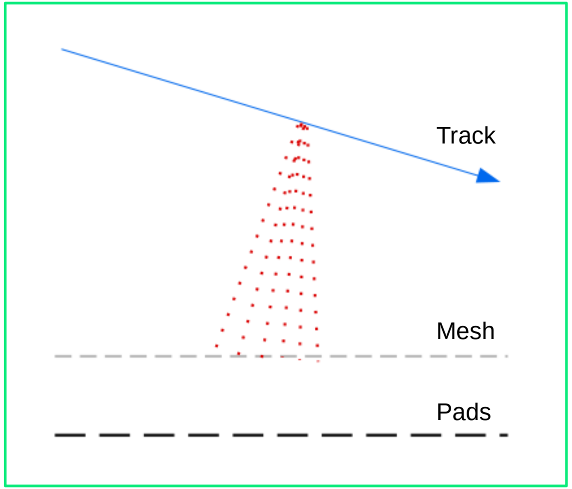
- The anode charge density is time dependent and sampled by readout pads.

Pad size: 1.1 * 1 cm^2

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

Transverse diffusion

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

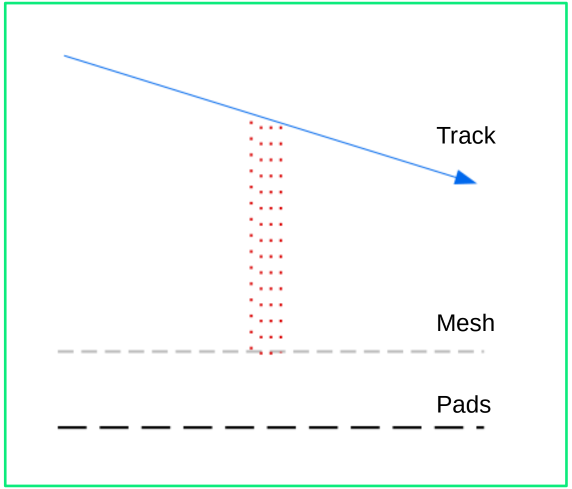


Transverse diffusion

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

Longitudinal diffusion

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



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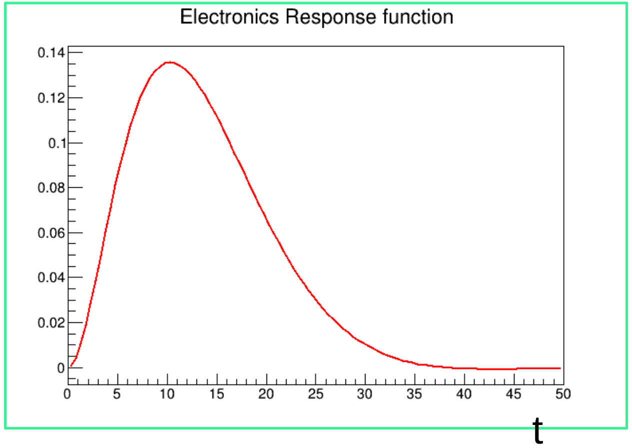
Electronics Response

R(t)



Transverse diffusion

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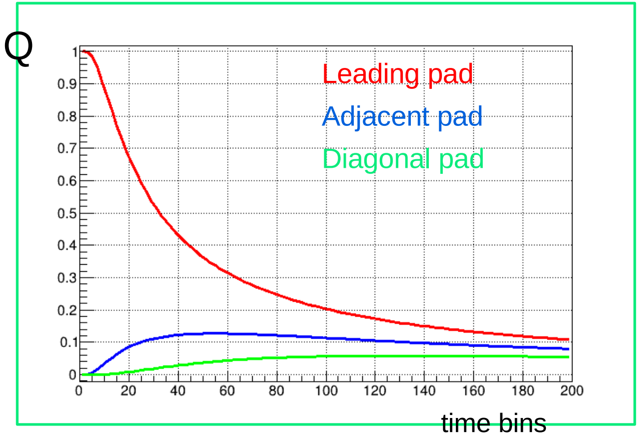
Longitudinal diffusion

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

Q = ∫ ρ(r) dr

Electronics Response

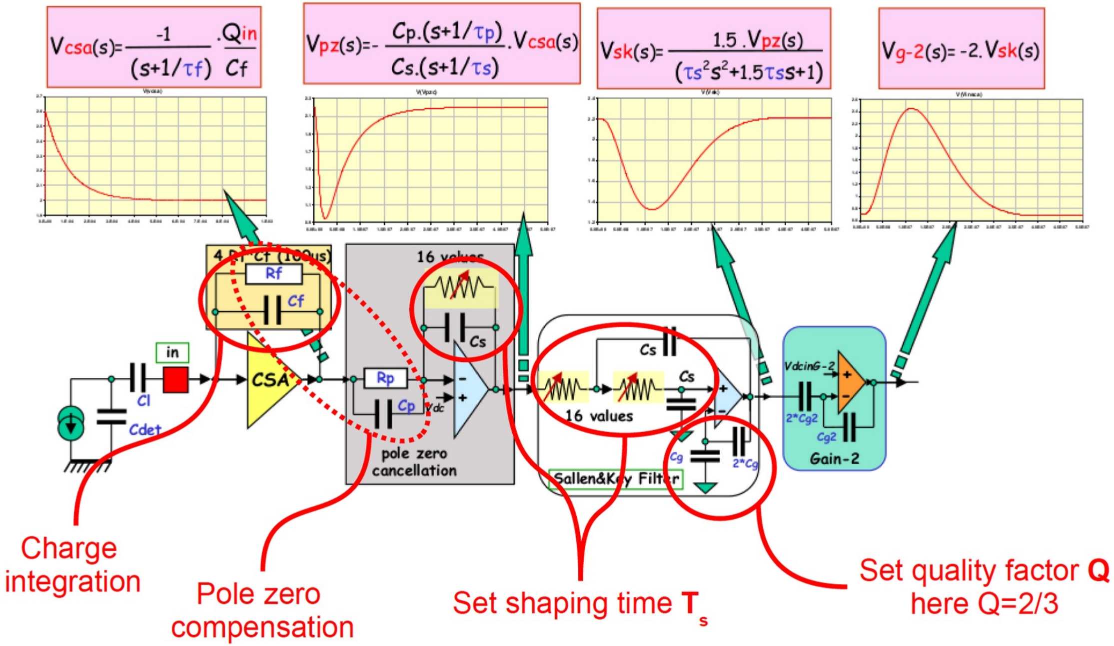
R(t)



Resistive foil + glue

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

$$h = 1/RC$$


Vcsa(s)= -1 / (s+1/τf) . Qin / Cf
Vpz(s)=- Cp.(s+1/τp) / Cs.(s+1/τs) .Vcsa(s)
Vsk(s)= 1.5 .Vpz(s) / (τs²s²+1.5τss+1)
Vg-2(s)= -2.Vsk(s)
Rf
Cf
in
Cl
Cdet
CSA
16 values
Cs
Rp
Cp
pole zero cancellation
Sallen&Key Filter
Cg
2*Cg
Gain-2
Cg2
2*Cg2
Charge integration
Pole zero compensation
Set shaping time Ts
Set quality factor Q here Q=2/3

AFTER CHIP IMPULSE RESPONSE

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 $T_s = w_s^{-1} = R_s C_s$

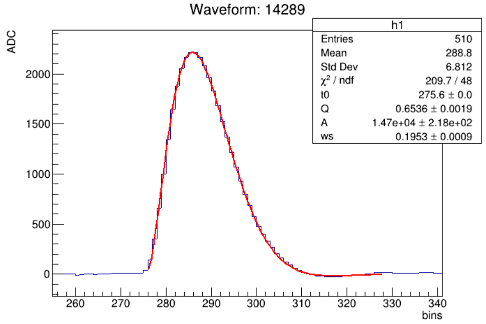
Response to a Dirac pulse
for perfect pole zero compensation

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

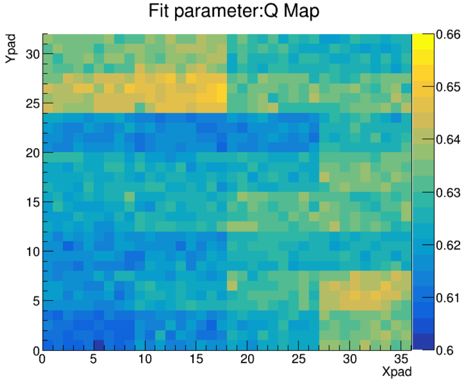
ELECTRONICS RESPONSE FUNCTION

- 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

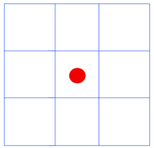
} **fixed (400ns peaking time)**

Charge diffusion function:

$$Q_{pad}(t) = \frac{Q_{norm}}{4}\left[erf\left(\frac{x_H - x_0}{\sigma(t)\sqrt{2}}\right) - erf\left(\frac{x_L - x_0}{\sigma(t)\sqrt{2}}\right)\right]\left[erf\left(\frac{y_H - y_0}{\sigma(t)\sqrt{2}}\right) - erf\left(\frac{y_L - y_0}{\sigma(t)\sqrt{2}}\right)\right]$$

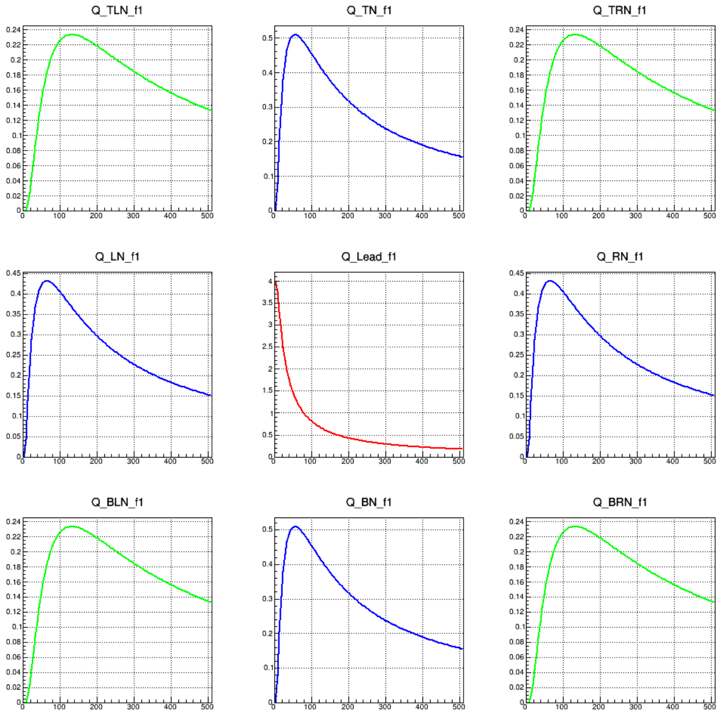
$$\sigma(t) = \sqrt{\frac{2t}{RC}}$$

- Obtained from Telegraph equation for charge diffusion.
- Integrating charge density function over area of 1 readout pad.
- Parameterized by 5 variables:
  - x_0 } Initial charge position
  - y_0
  - t_0: Time of charge deposition in leading pad
  - RC : Describes charge spreading
  - Q_{norm} : Total charge deposited in an event

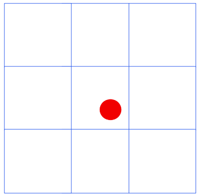


x_H, x_L: Upper and lower bound of a pad in x-direction
y_H, y_L: Upper and lower bound of a pad in y-direction

RC = 60 ns/mm^2
Q_{norm} = 4 units

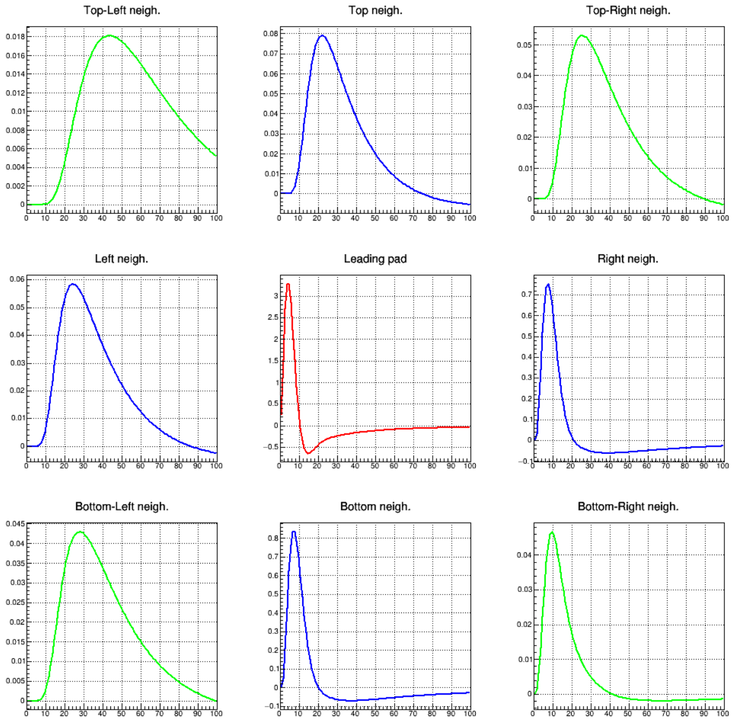


➢ Convolution of charge diffusion function with derivative of electronics response function.



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

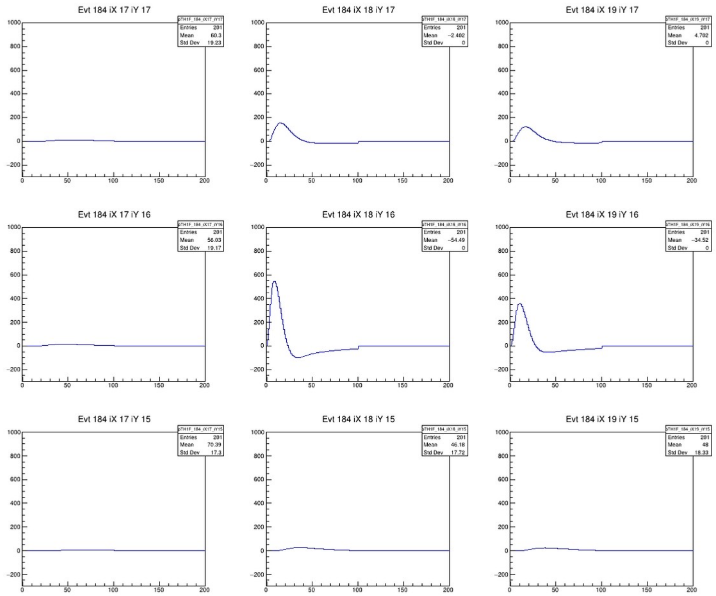
RC = 60 ns/mm^2
Q_{norm} = 4 units

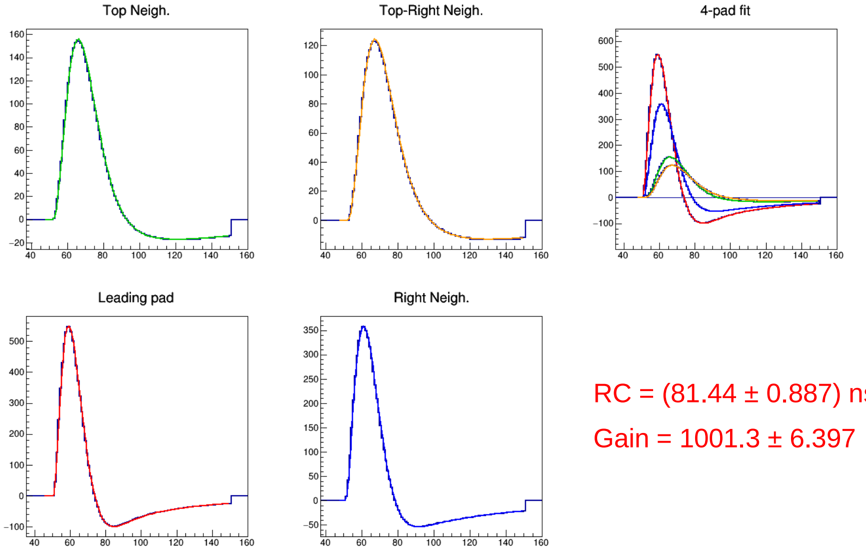


VALIDATION OF MODEL USING TOY MC

- 1000 events generated using toy MC with random charge deposition points(x_0, y_0), RC = 83 ns/mm^2 and Gain = 1000.
- All the waveforms(ADC > 70) in an event, fitted simultaneously with signal function.
- 5 fit parameters- t_0, x_0, y_0, RC and Q_{norm} are extracted from each fit.

Example of a generated event



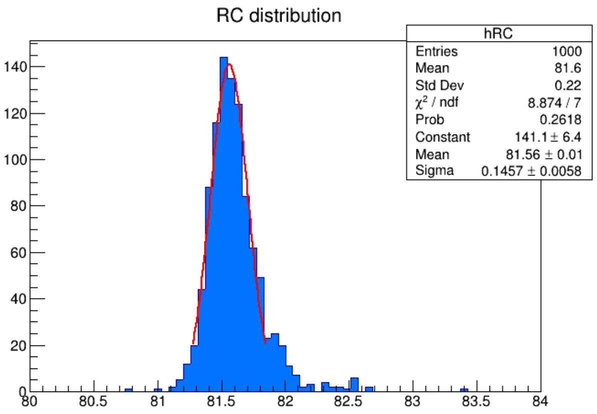


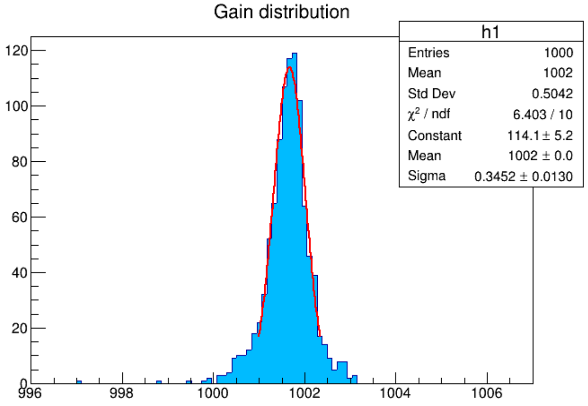
RC = (81.44 ± 0.887) ns/mm^2

Gain = 1001.3 ± 6.397

Simultaneous fit of that event

- Results from fitting all events-

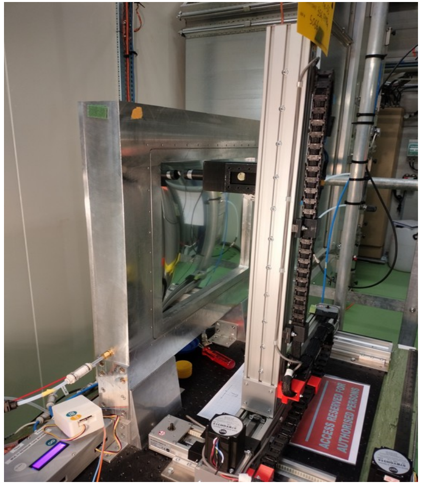




RC_{mean} = 81.56 ns/mm^2
σ = 0.15 ns/mm^2

$Gain_{mean}$ = 1002
σ = 0.34

- Toy MC with RC = 83 ns/mm^2 and Gain = 1000.
- Toy and fit are using independent codes.

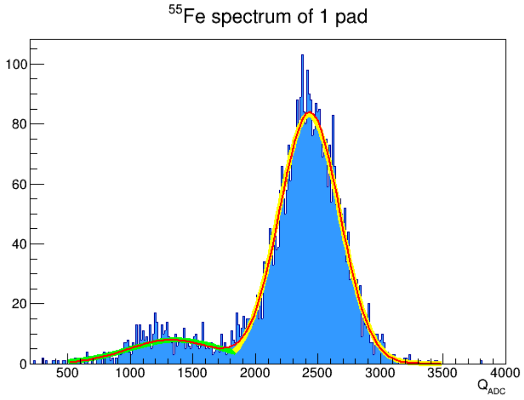


X-ray test bench at CERN

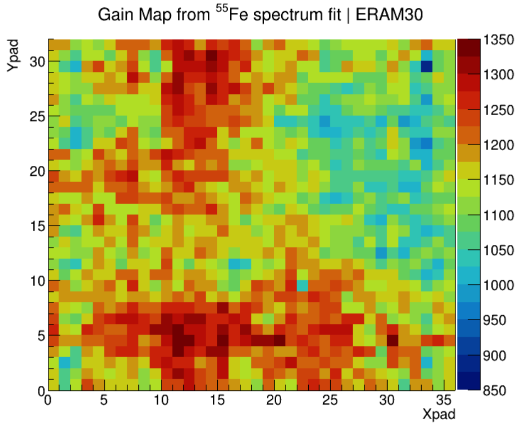
- Each pad(1152) of an ERAM placed inside an X-ray chamber is scanned using a robot holding an ^{55}Fe X-ray source.
- Source is collimated to ensure charge deposition in targeted pad and its neighbouring pads(due to charge spreading), from electron avalanche caused by an X-ray photon.
- ^{55}Fe spectrum can be reconstructed using all events in one pad.

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

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

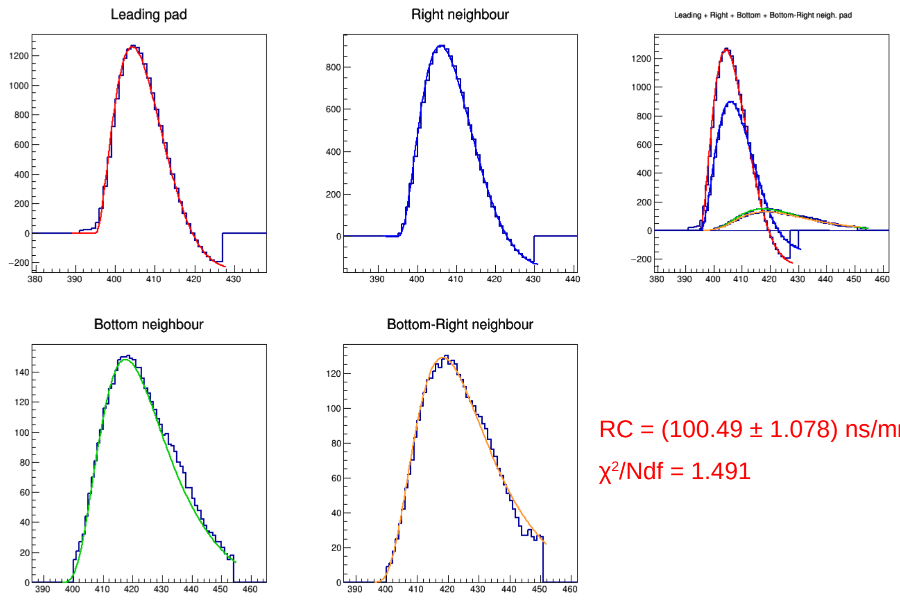


Example of an ^{55}Fe spectrum



Gain map of ERAM30

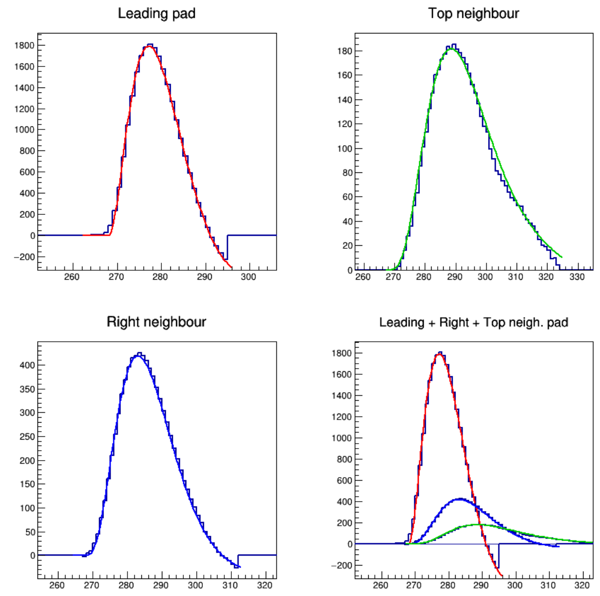
RC EXTRACTION FROM SIMULTANEOUS FIT



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

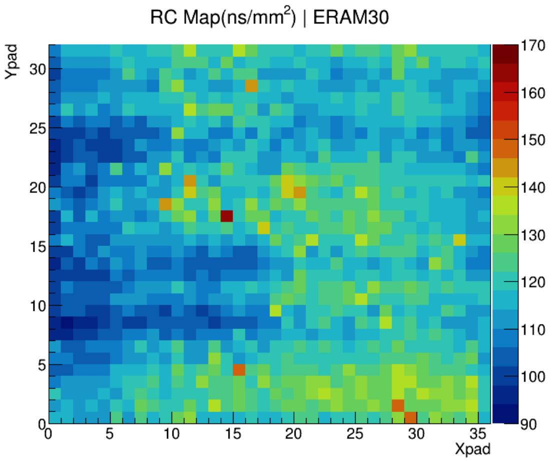
χ^2/Ndf = 1.903

3-waveform simultaneous fit of an X-ray event

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

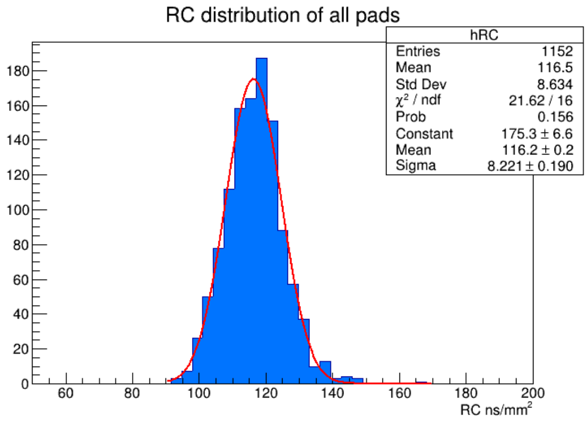
Simultaneous fit: Leading pad + Neighbouring pads are fitted simultaneously

- 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 map of ERAM30

RC_{mean} = 116.2 ns/mm^2



RC distribution of ERAM30

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:

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

Electronics response: (upto ADC) Dirac impulse response

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

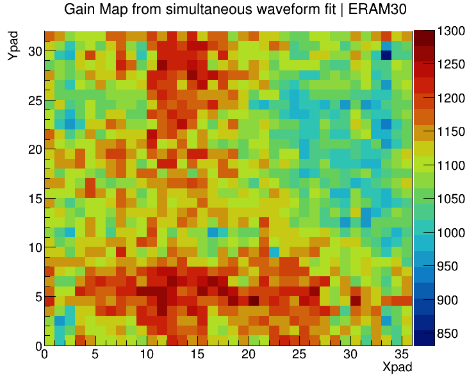
- Implementing the correspondence- 120 fC ↔ 4096 counts.
- Dirac current pulse carrying 120 fC ⟶ ADC(t) impulse response with a maximum amplitude of 4096 counts.

ADC counts:

$$ADC(t)=\frac{dQ}{dt}\otimes ADC_{Dirac}$$

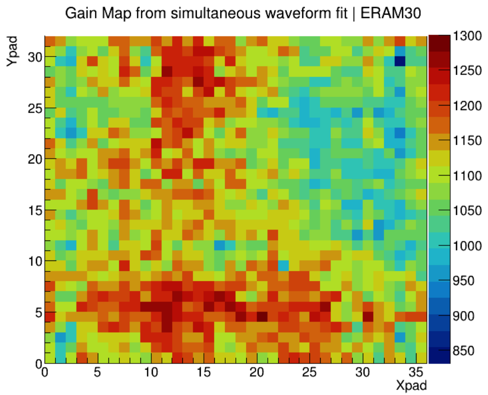
Gain

$$\boxed{\frac{Q_{norm}}{4}}=\frac{Q_{prim}\times \boxed{G}}{4}*\frac{4096}{120\,fC\times f_{max}}$$

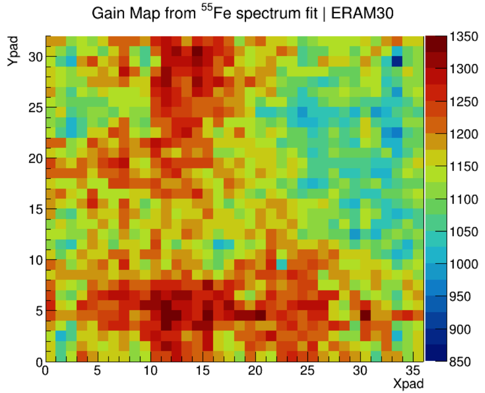


Gain map of ERAM30 from simultaneous fit

COMPARISON OF GAIN FROM TWO METHODS

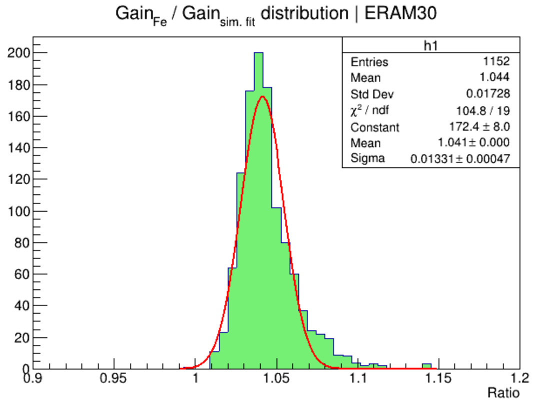


Gain map from simultaneous fit method



Gain map from waveform sum method

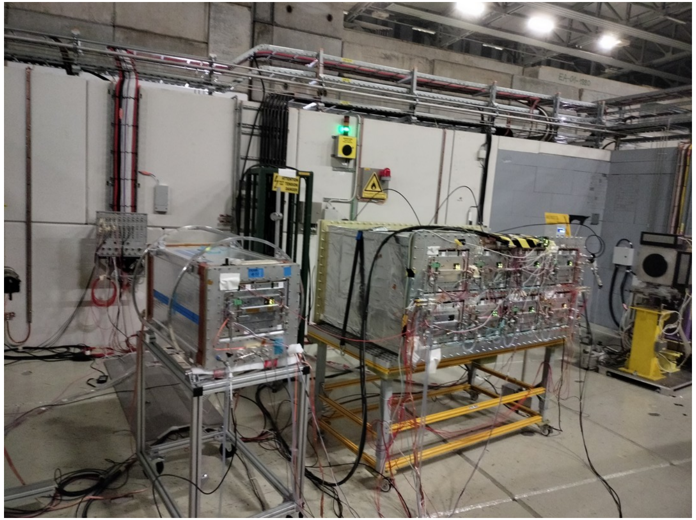
Ratio of Gain(of each pad) obtained from 2 different methods



$Ratio_{mean}$ = 1.041

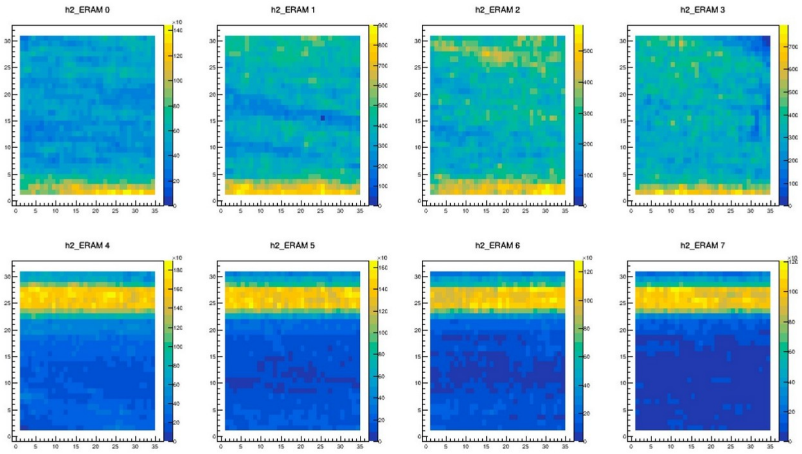
- Very high similarity in Gain maps obtained from 2 different methods ⇒ ^{55}Fe spectrum can be re-constructed from simultaneous fit(using Q_{norm}) too.
- Gain results serve as validation for Electronics Response function, and robustness of entire model.

- Commissioning with beam and characterization of final 8 ERAM detectors and electronics using Field Cage mockup.

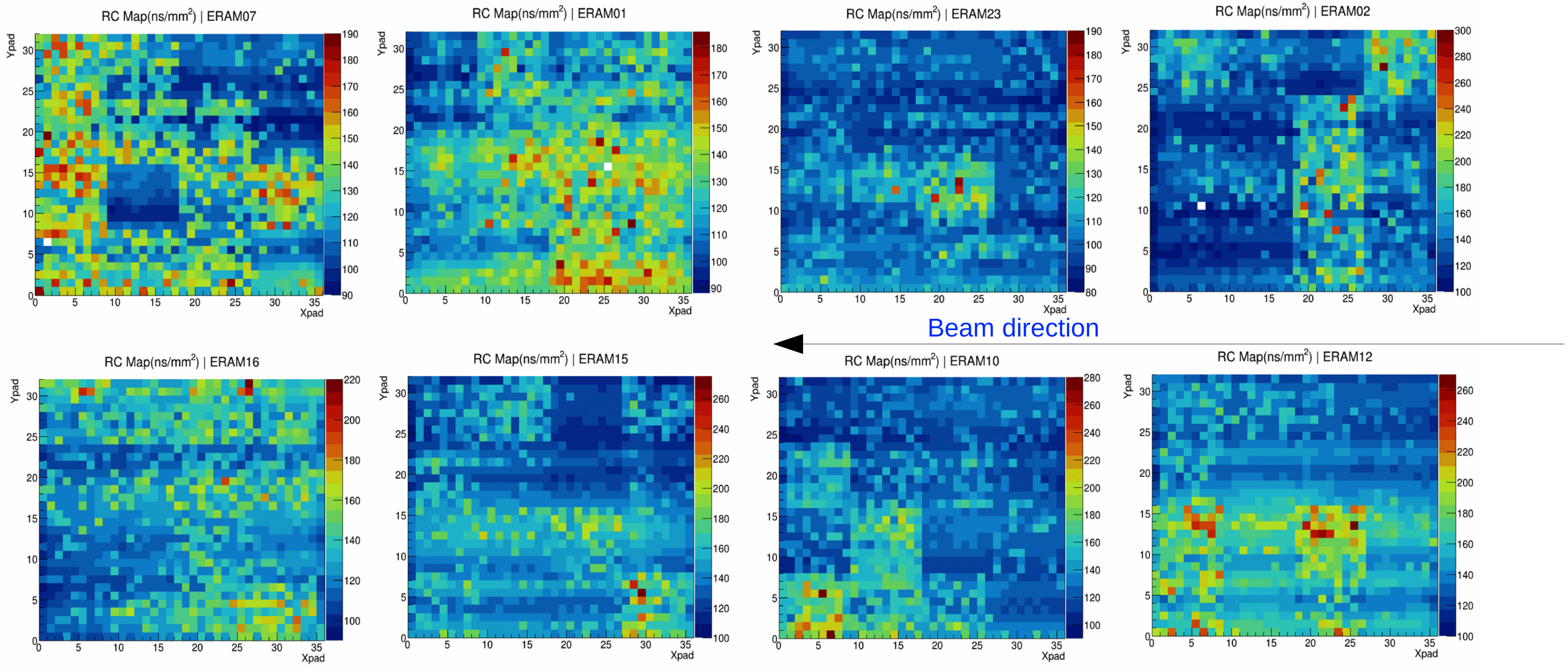


<u>Mockup Data analysis</u>:

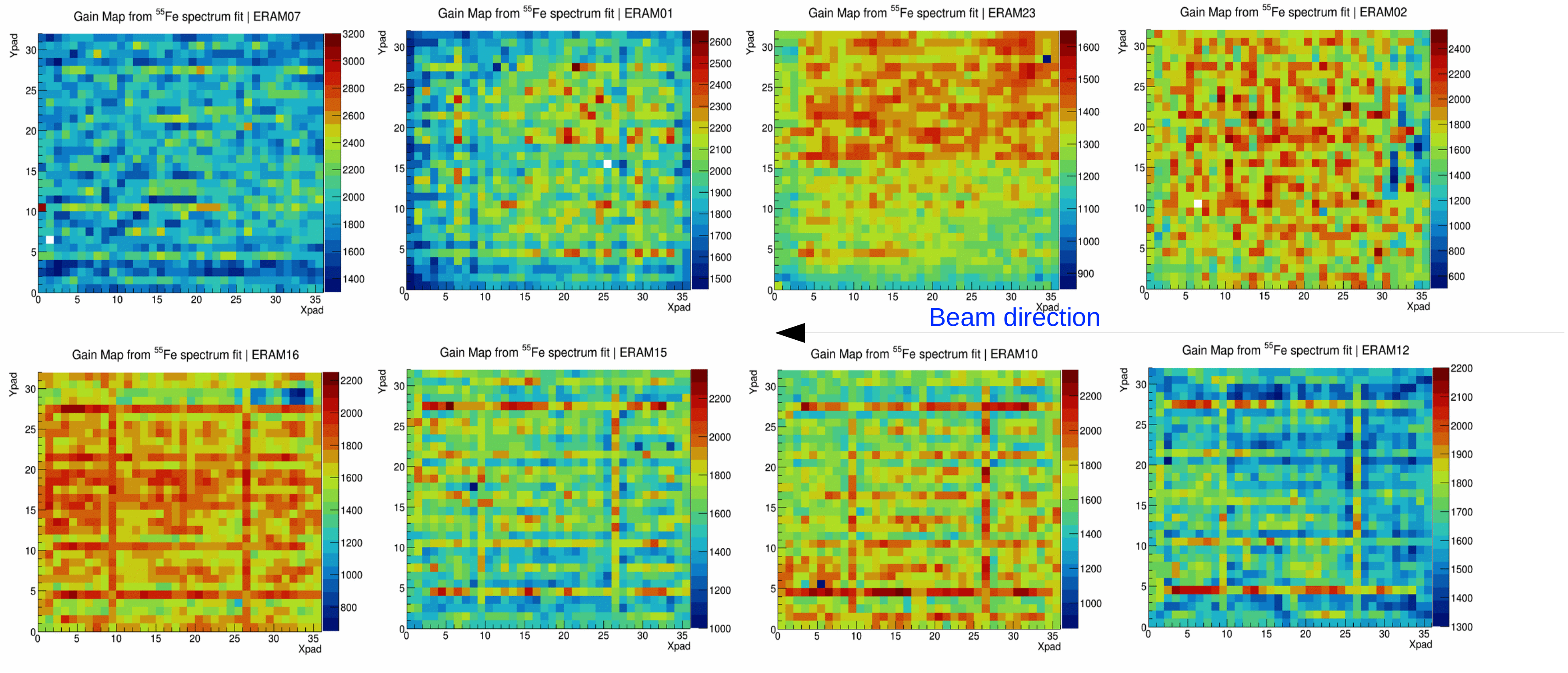
- Track dE/dx resolution & PID study:
  e^-, proton, muon, pion (momentum range 0.5 –1.5GeV).
- Track spatial resolution (No B field):
  scan along 5 drift distances and 3 Y-positions.



RC MAPS OF ERAMS USED IN TEST BEAM

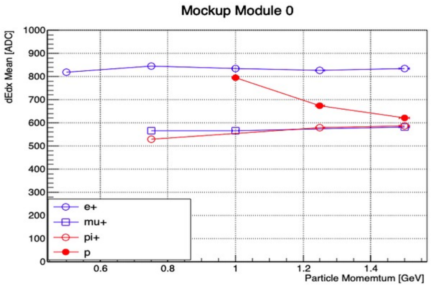


GAIN MAPS OF ERAMS USED IN TEST BEAM

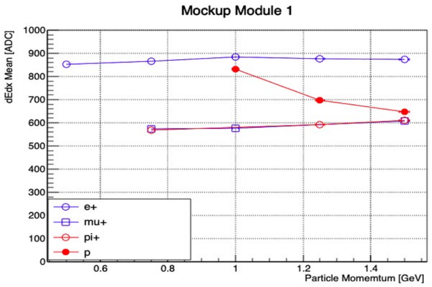


MOCKUP : DEDX MEAN

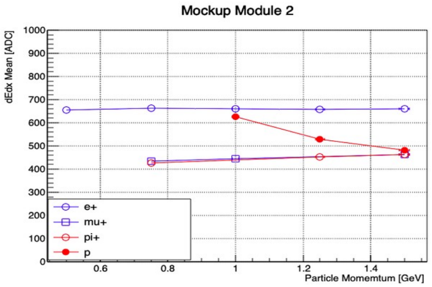
ERAM-07



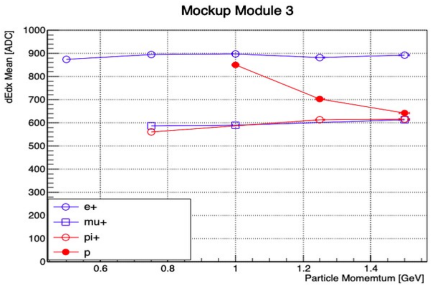
ERAM-01



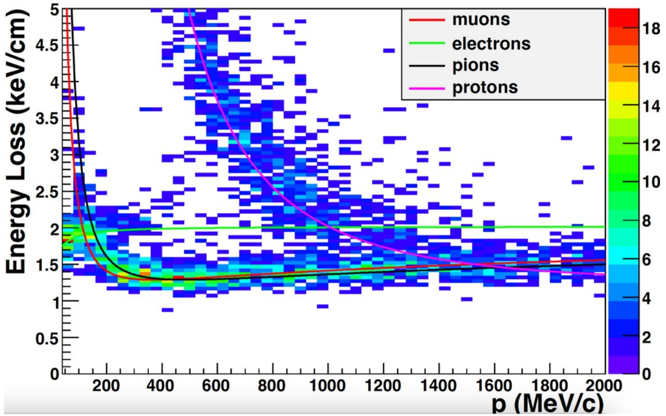
ERAM-23



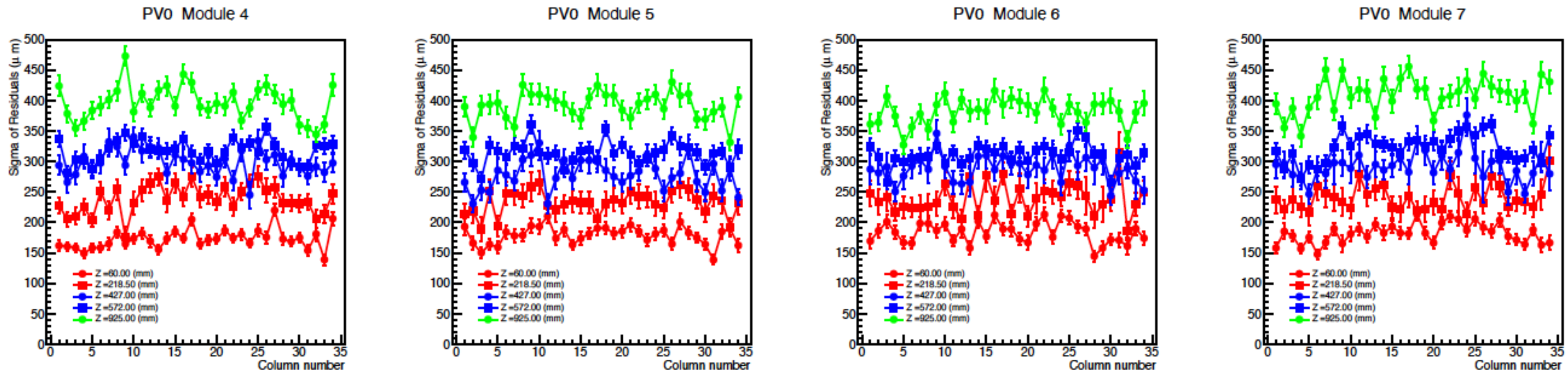
ERAM-02



- The mean dEdx for different ERAMs, particle and momentum are nicely following the simulation.
- ERAM-23 has small mean E_{loss} compared to the others.
- ERAM detectors show different Gains, correction necessary.
- dEdx resolution (10%) is within ND280 upgrade requirements.



Resolution VS Column number

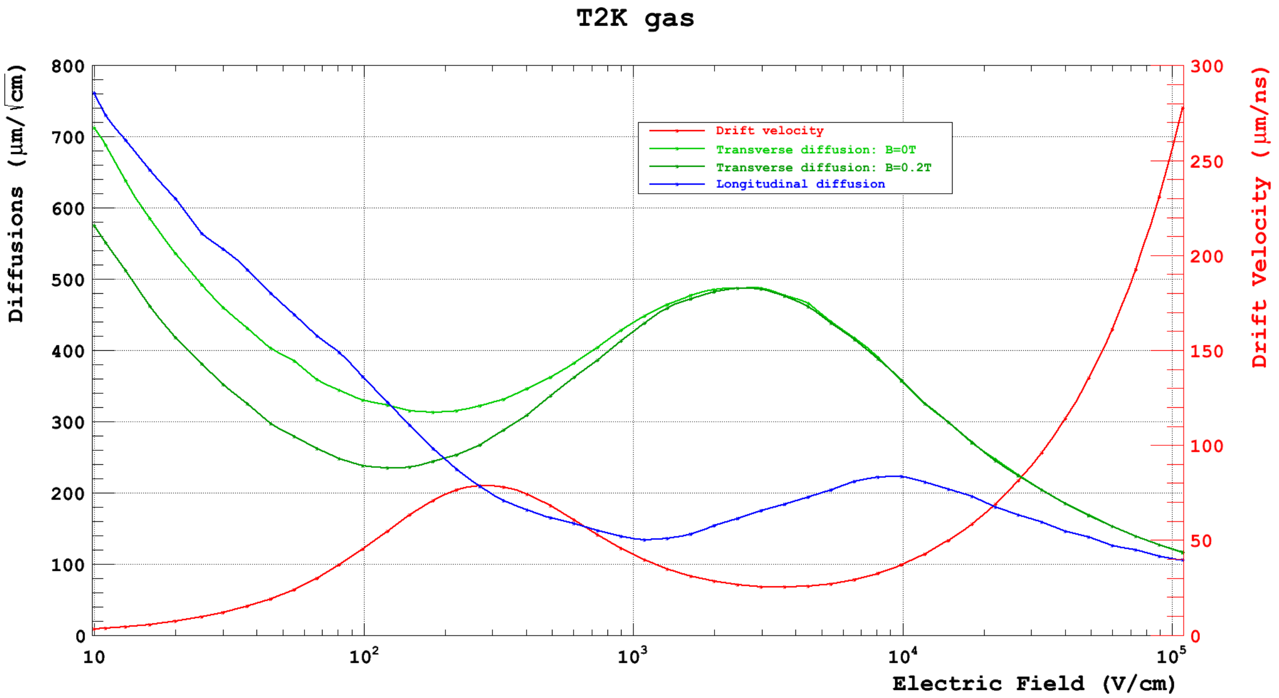


- Similar spatial resolution in 4 ERAM modules.
- Spatial resolution for horizontal tracks is within ND280 upgrade requirements

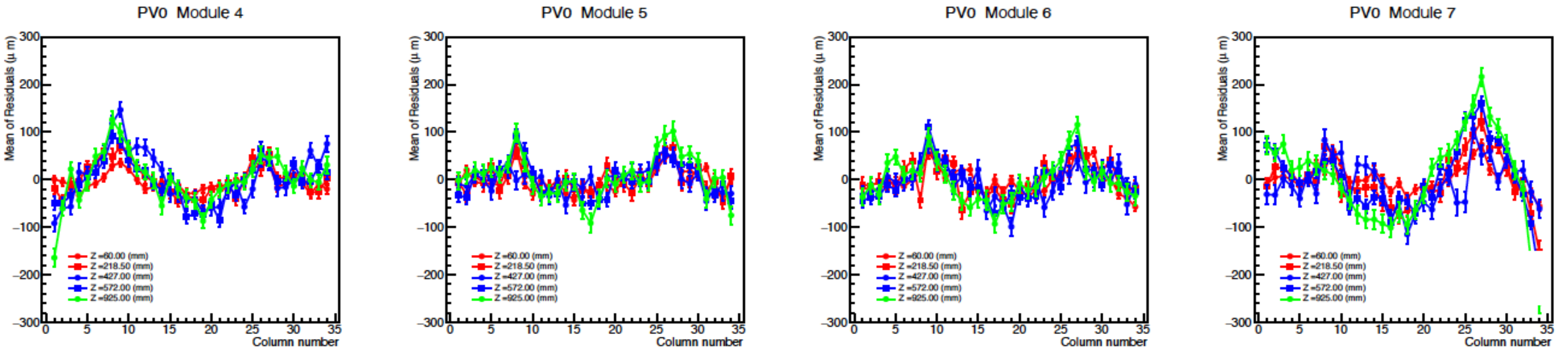
CONCLUSION

- ND280 upgrade will employ resistive Micromegas for the read-out of HA-TPC, which works on the principle of charge spreading.
- Resistive Micromegas will enable- better position reconstruction, reduction in sparks rate and improvement in E-field homogeneity.
- 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 both- toy MC and X-ray data.
  - RC and Gain can be simultaneously extracted from X-ray data.
  - RC maps and Gain maps will be useful in Global event reconstruction algorithm.
  - Gain obtained from simultaneous fit is in accordance with Gain obtained from waveform sum method.
- A test beam was conducted at CERN to characterize 8 ERAM modules inside a field cage mockup.
  - Mean dEdX of various ERAMs is in agreement with simulations, and within ND280 upgrade requirements.
  - Spatial resolution for horizontal tracks is also within ND280 upgrade requirements.
- Many Thanks to Samira Hassani and Jean-François Laporte for providing material for this talk.

BACKUP


T2K gas
Diffusions (μm/√cm)
Drift Velocity (μm/ns)
Electric Field (V/cm)
Drift velocity
Transverse diffusion: B=0T
Transverse diffusion: B=0.2T
Longitudinal diffusion
800
700
600
500
400
300
200
100
0
300
250
200
150
100
50
0
10
10^2
10^3
10^4
10^5

Bias VS Col. Nber



- Much more shaky than for ERAM 18
- Would this improve with Gain non-uniformity corrected for?
- Do we see Electric field non-uniformity on the mockup borders?
- Do we see the trace (L/R) of 2 electronics cards?

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