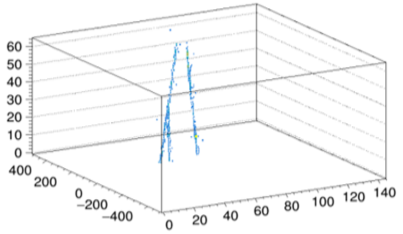
G.Collazuol on behalf of the ND280 Upgrade collaboration
Department of Physics and Astronomy
University of Padova and INFN

16th Pisa Meeting on Advanced Detectors
La Biodola, isola d'Elba
27/5 – 1/6 2024

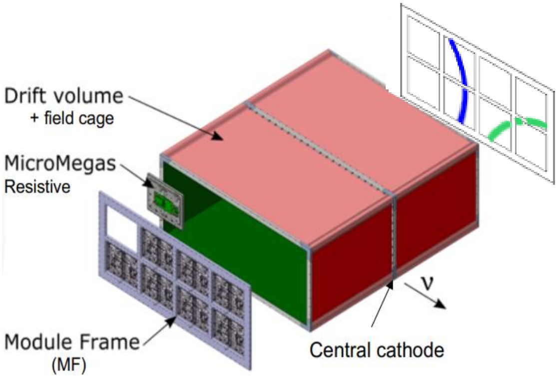
The new TPCs for the Upgraded Near Detector of T2K

Overview

- Introduction
- Highlights TPC Field Cages
- Highlights TPC ERAMs
- TPC performaces



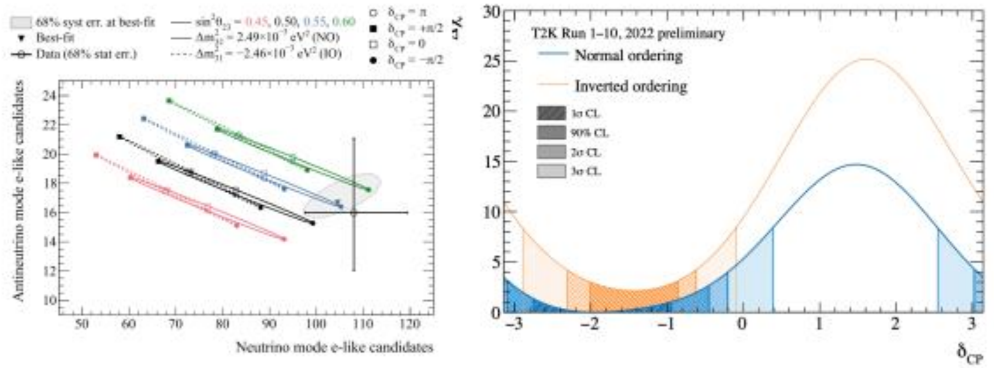
Cosmic tracks interaction evwnt

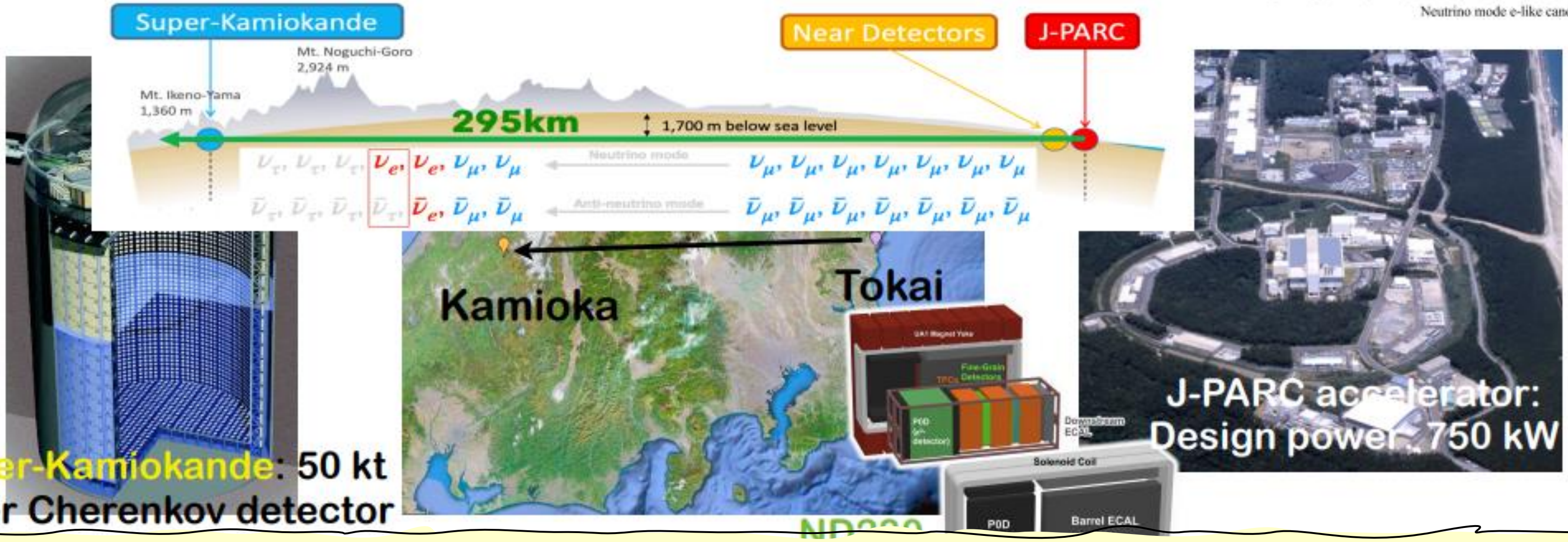


The T2K experiment

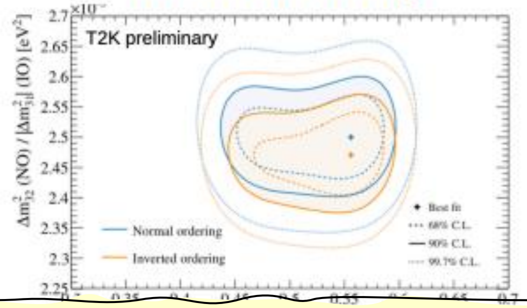
- High intensity ~600 MeV ν_μ beam at J-PARC (Tokai) → ν or $\bar{\nu}$ mode by changing the horn polarity
- Neutrinos detected at the Near Detector (ND280) and at the Far Detector (Super-Kamiokande)
  - ν_e and $\bar{\nu}_e$ appearance → determine θ_{13} and δ_{CP}
  - Precise measurement of ν_μ disappearance → θ_{23} and $|\Delta m^2_{32}|$

δ_{CP} ~ $-\pi/2$ → Several values of δ_{CP} excluded at more than 3σ





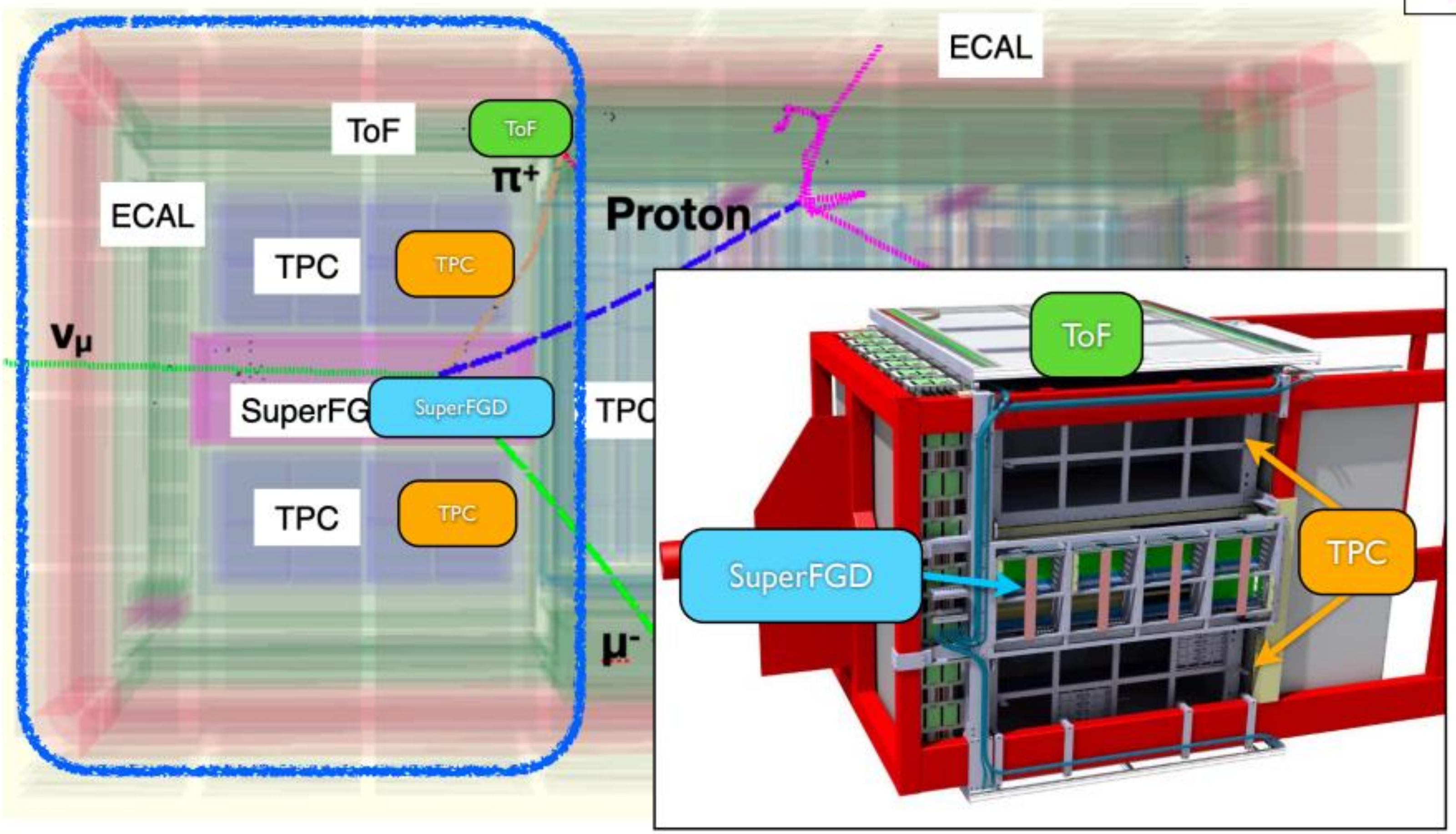
Precise measurement of Δm^2 (~2% uncertainty)
$\sin^2(\theta_{23})$ compatible with maximal mixing



ND to measure un-oscillated beam flux and ν cross sections

The ND280 Upgrade

arXiv:1901.03750



France (CEA Saclay, LLR, LPNHE), Germany (RWTH), Italy (INFN Sezioni di Bari, Napoli, Legnaro, Padova, Roma 1), Poland (IFJ Pan, NCBJ, WUT), Russia (INR and Dubna), Spain (IFAE), Switzerland (University of Geneva, ETHZ) + CERN

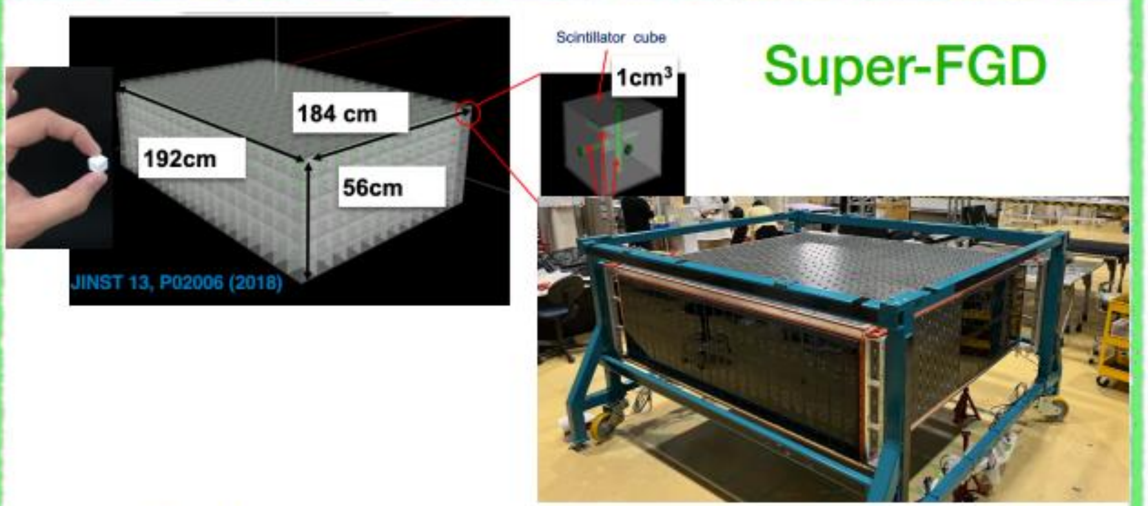
Japan: University of Tokyo, KEK, Kyoto University, Tokyo Metropolitan University

USA: Louisiana State University, University of Colorado, University of Pennsylvania, University of Pittsburgh, Stony Brook University, University of Rochester

MoU signed in 2020 → NP-07

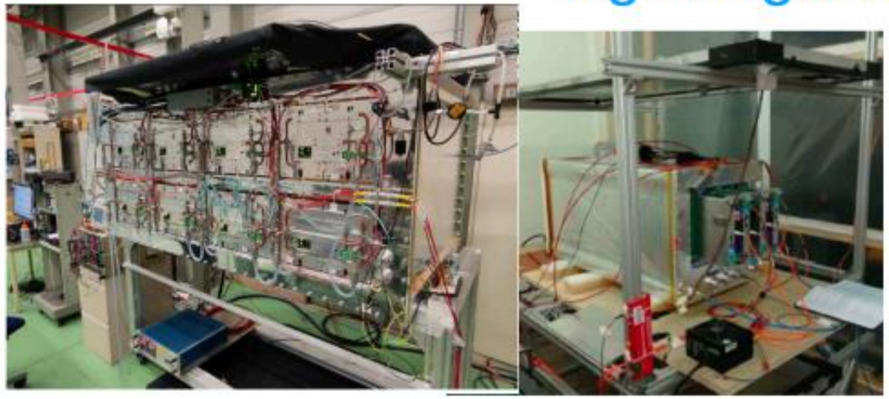
New detectors to extend acceptance for tracks at high angles

ND280 Upgrade new detectors



Super-FGD

- New concept of detectors, 2x10^6 1cm^3 cubes
- Each cube is read by 3 WLS → 3D view



High-Angle TPCs

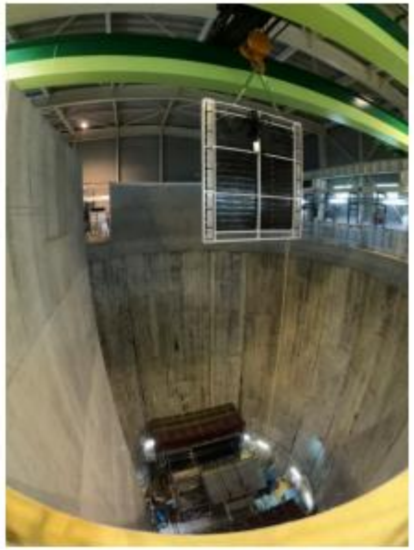
- New TPCs instrumented with Encapsulated Resistive Anode MicroMegas (ERAM)

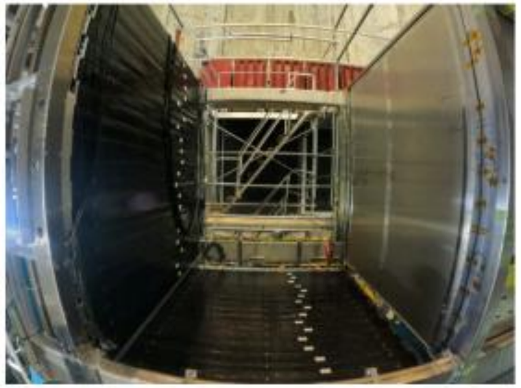
TOF

6 TOF planes to reconstruct track direction
Time resolution ~150 ps

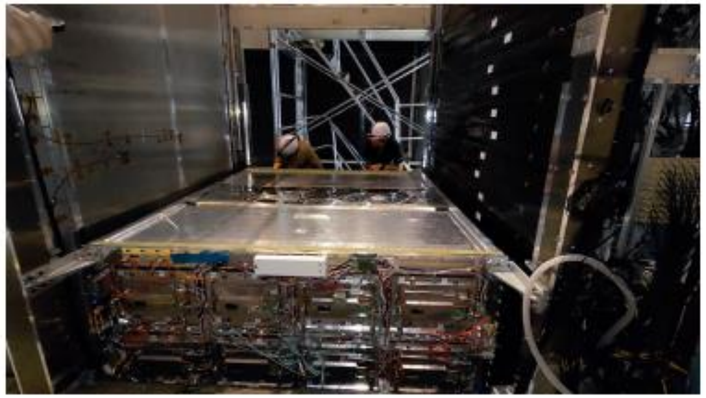
New detectors installation at JPARC

TOF installation (July 2023)



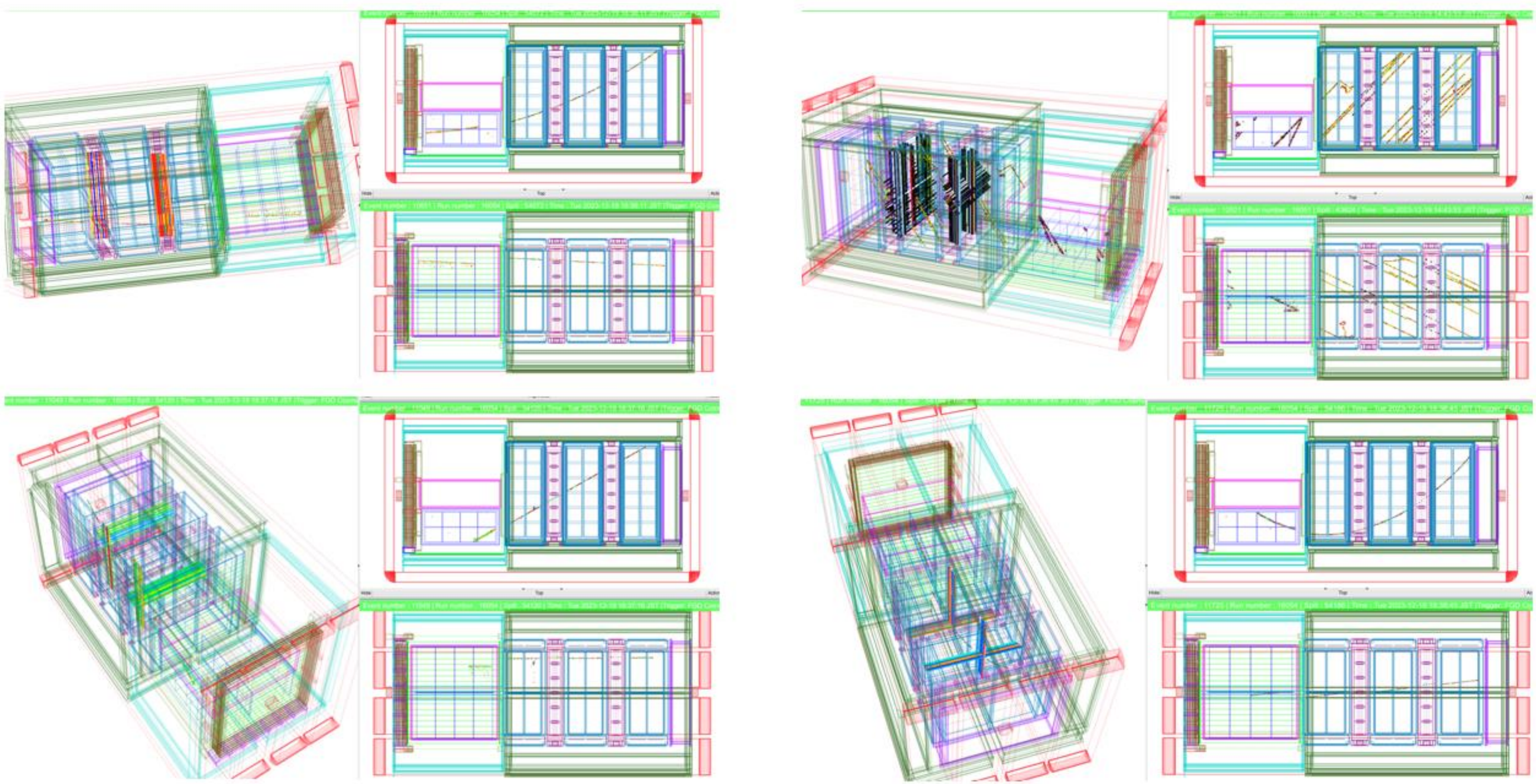


Bottom TPC installation (September 2023)



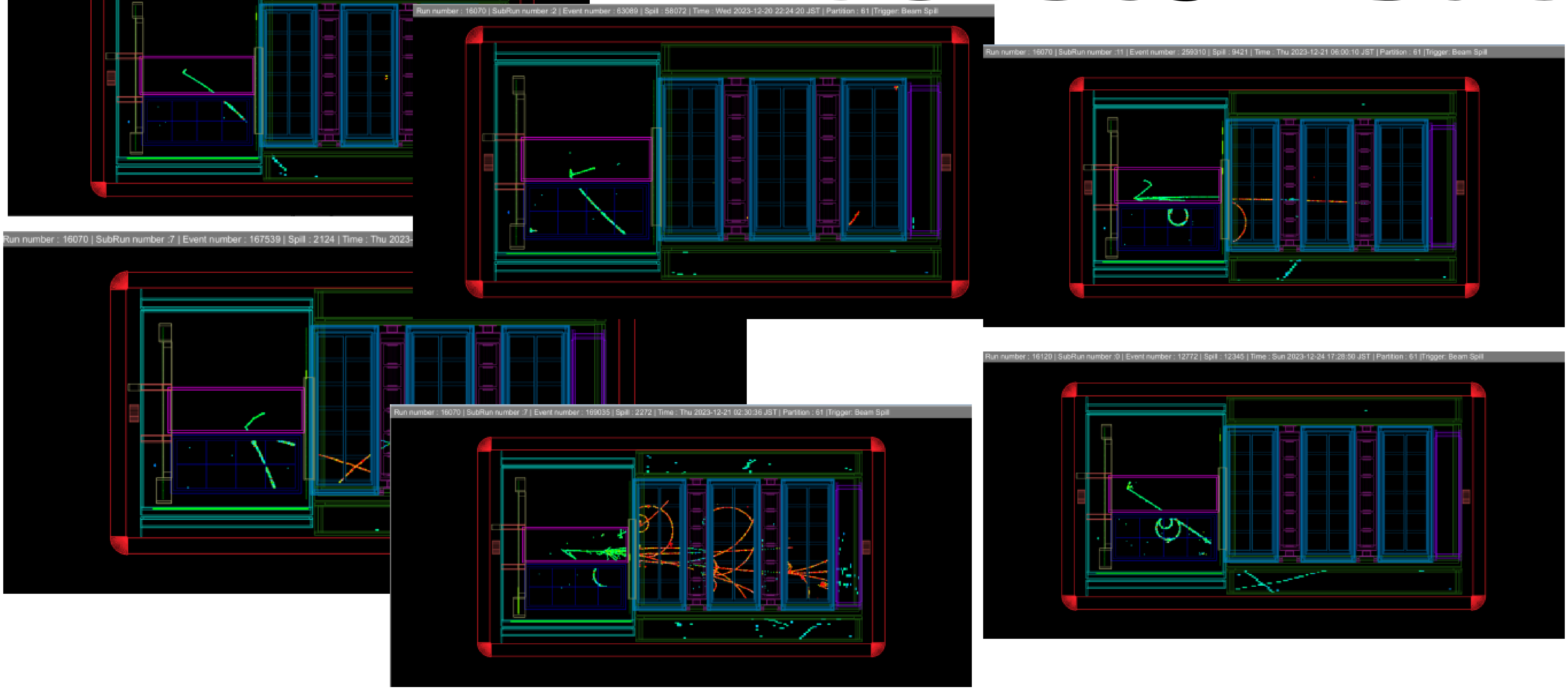
Super-FGD installation (October 2023)

Commissioning with Cosmics in Nov ‘23



Neutrino Beam Runs

Technical Runs in Dec‘23 and in Feb‘24

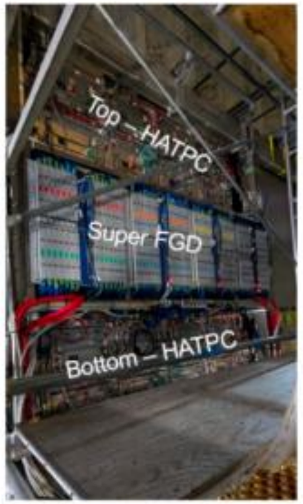


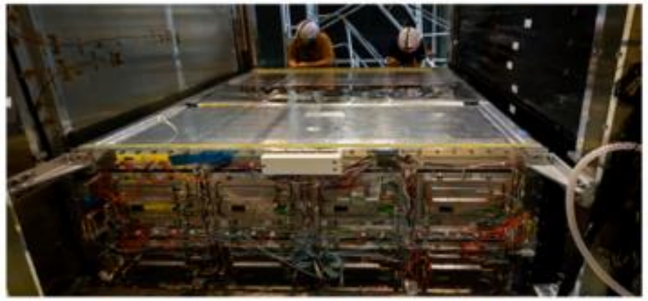
Top-HATPC installed end April 2024

Lowering bottom HATPC
2023.9.8

Top – HATPC in ND280

Bottom – HATPC in ND280





ND280 after lowering of top HATPC
2024.4.25

ND280 fully upgraded detector ready for next

→ Neutrino Beam Run … starting today

Overview

Highlights Field Cages

Mechanical - Building, assembly and characterization

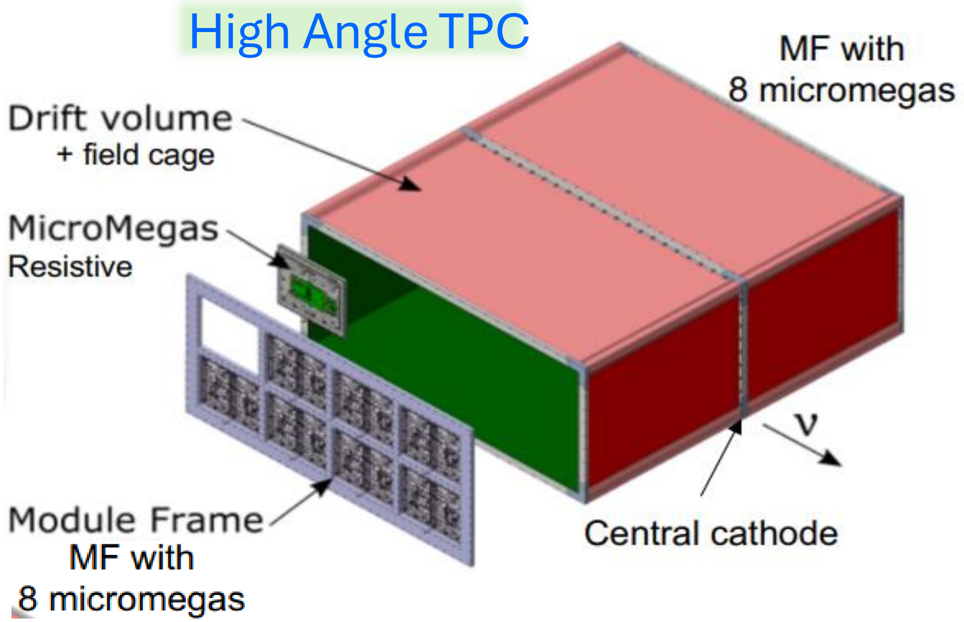
Electrical - High Voltage Insulation and Electric Field

Highlights ERAM sensors

Production of 50 sensros and Operations experiences

Detector response, signal and impact on reconstruction → TPC performances

HATPC specifications



Momentum resolution $\sigma_p/p < 9\%$ at 1GeV/c
(neutrino energy)

Energy resolution $\sigma_{dE/dx} < 10\%$
(PID muons and electrons)

Space resolution O(500 μm)
(3D tracking & pattern recognition)

Low material budget walls ~ 3% X_0
(matching tracks from neutrino active target)

Atmospheric pressure TPC

- Gas: T2K mixture (Ar-CF4-isoC4H10 = 95-3-2)
- Gas contaminants better than O(10 ppm) level
- Drift length 1m
- Central Cathode @ -27kV
- E field unif. < 10^{-3} @1cm from walls
- Low material budget, thin walls
- Active volume ~ O($3m^3$)

Resistive MicroMegas sensors (ERAMs)

- Overall anode active surface ~ O($3m^2$)
- Sampling length ~ 80-160 cm
- pads ~ $1x1cm^2$
- 10k+10k channels / TPC @ End Plates (Anodes)

Some HATPC features

Field Cages → thin walls, lightweight, robust & compact
→ Thin walls, low Z, solid dielectric composite materials
→ Rectangular shape to minimize dead space & maximize tracking volume
→ Electric field uniformity better than 10^{-3} @1cm from walls by

MicroMegas detectors
→ Encapsulated Resistive Anode MM (ERAM)
→ Charge spread: high spatial resolution with large pads
→ Intrinsic protection against sparks: simplified & very compact FE electronics

Field Cages – constraints & solutions

- Min dead space & max active vol in dipole magnet
  → Rectangular shape & thinnest walls & field shaping electrodes incorporated into wall
- Electric field uniformity better than 10^{-3} @1cm from walls
  → Mechanical accuracy = inner surfaces planarity & parallelism ~ O(0.2mm/m)
  → Electrode design = Field and Mirror copper strip layers on two sides of a Kapton foil
- Low material budget walls
  → lightweight & lowest Z & robust (self supporting)

Mechanical and Electric field constraints

→ **Building process** = hand lay-up of composite materials on a mould & polymerization in autoclave at high P

- autoclave dimensions → Field Cage comprising two halves (symm flanges at central cathode position)
- hand layup & large dimensions → several hours per process step → very long pot life epoxy resin
- mechanical accuracy of geometry → resin curing at low T < O(40ºC)

- HV insulation mantle R > 1TOhm and … no HV discharges
  → geometry = several cm paths for charge from -HV strips to GND shielding (cathode flanges)
  → insulating materials = very high resistivity & dielectric strength & lowest Z

Insulation constraints

→ **Materials of choice**

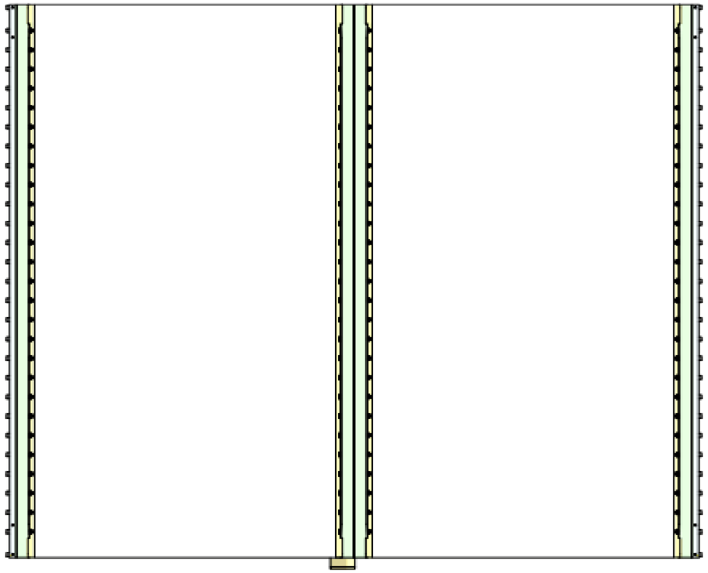
- lamination materials = Aramid polymers for peels (Twaron) and for honeycomb (Nomex paper)
- epoxy resin = very limited choice of epoxy & very important quality control against contaminants (water, …)
- high insulation layers = Kapton and lamination at low T < 40ºC (no Mylar)
- box skeleton material = high quality laminated G10

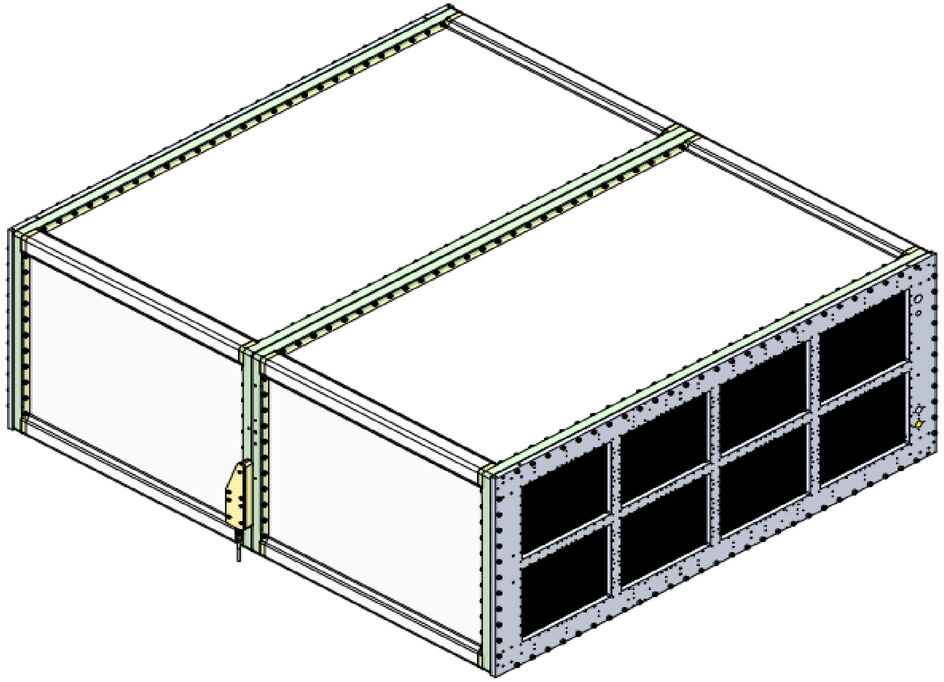
Highlights Field Cages

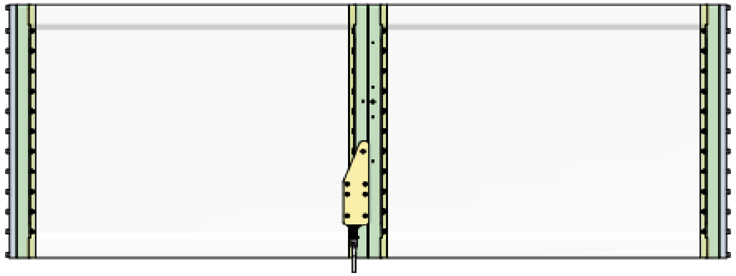
→ Mechanical - Building, assembly and characterization

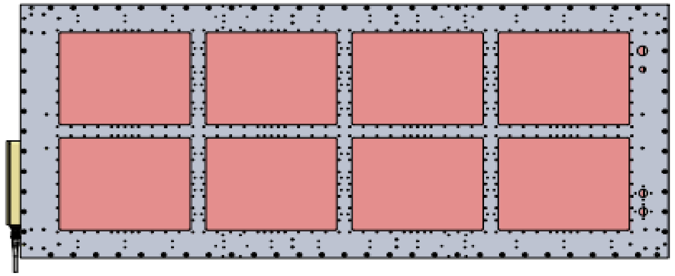
Electrical - High Voltage Insulation and Electric Field

Mechanical Field Cage assembly



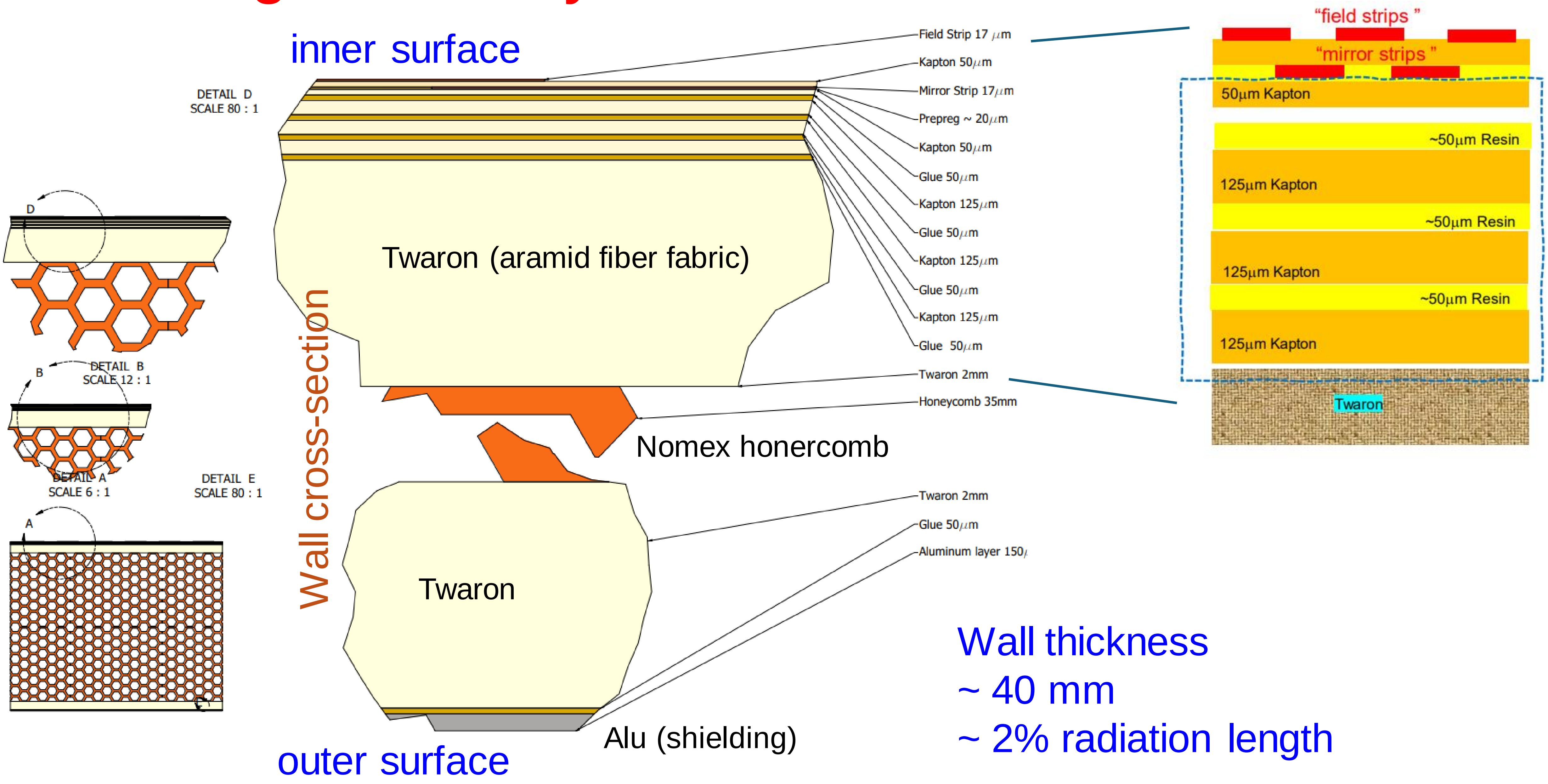






- HATPC in two half FCs
- Central cathode
- Special cathode flanges w/ HV ft
- Two End Plates (Al) supporting 8 Readout Modules each

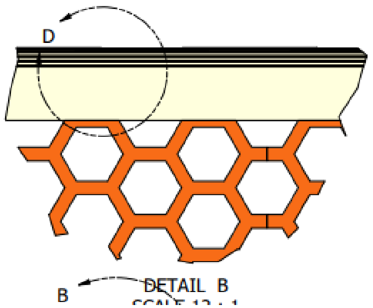
Field Cage walls layout

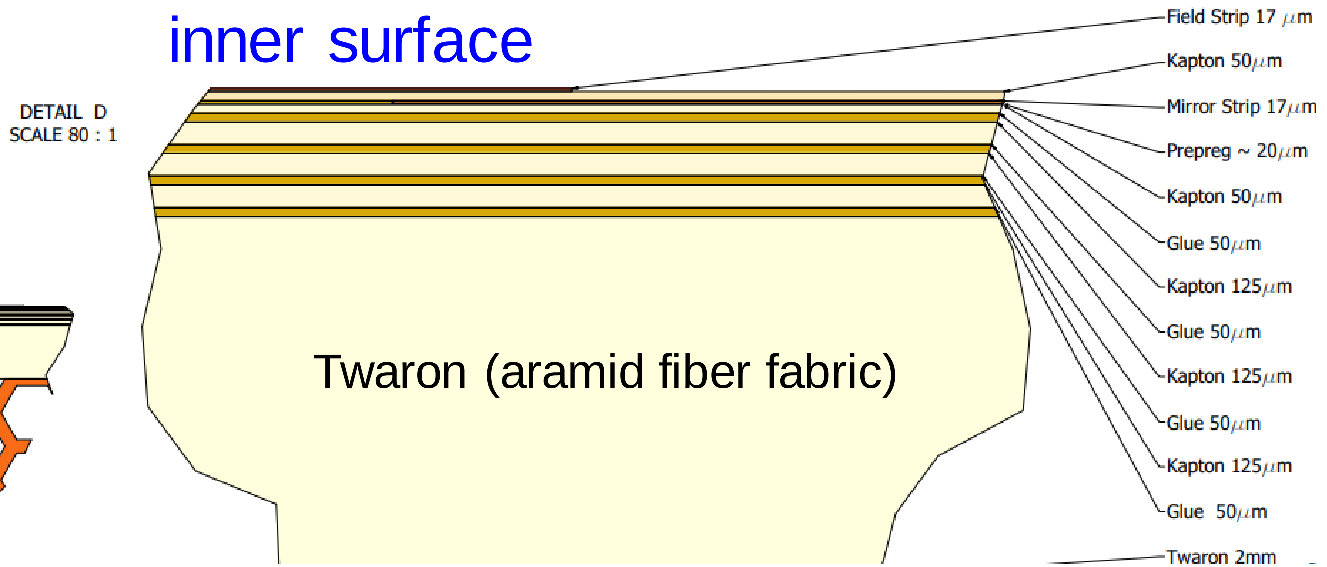


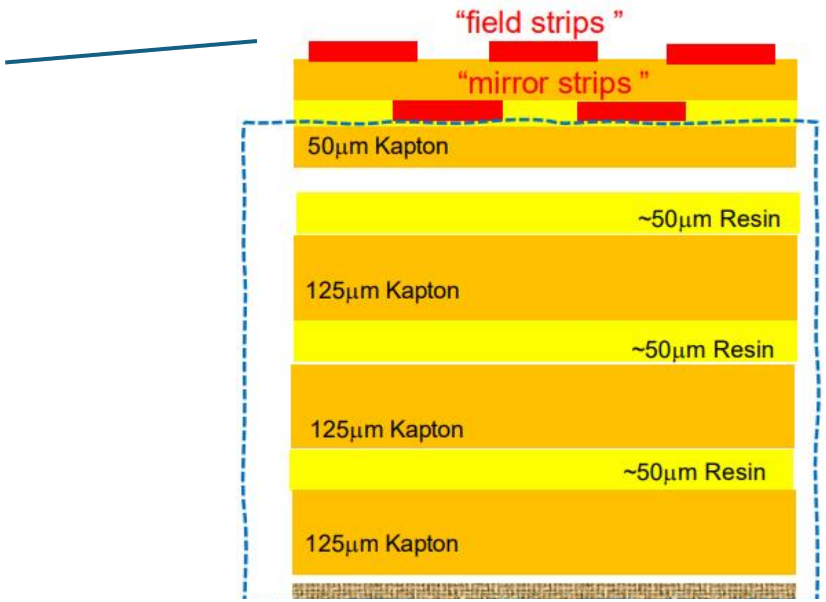
Wall thickness
~ 40 mm
~ 2% radiation length

Field Cage walls layout

inner surface

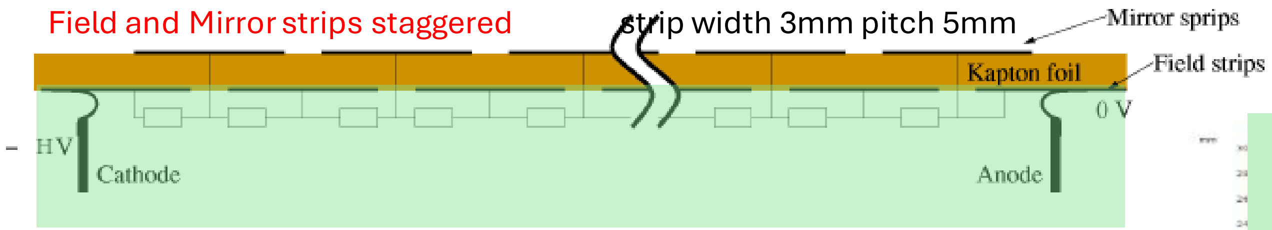




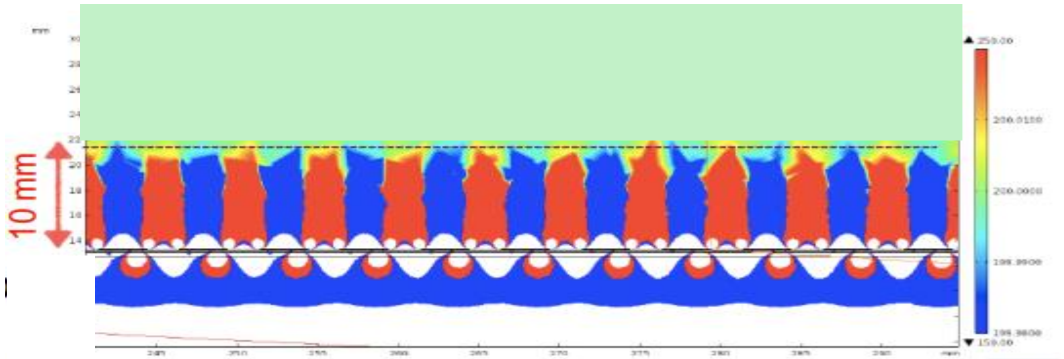


Electric field shaping by two Cu strips layers ('Field' and 'Mirror' strips)

Field and Mirror strips staggered



First ERAM pad @ 15mm from the wall
where electric field uniformity better than 10^{-3}



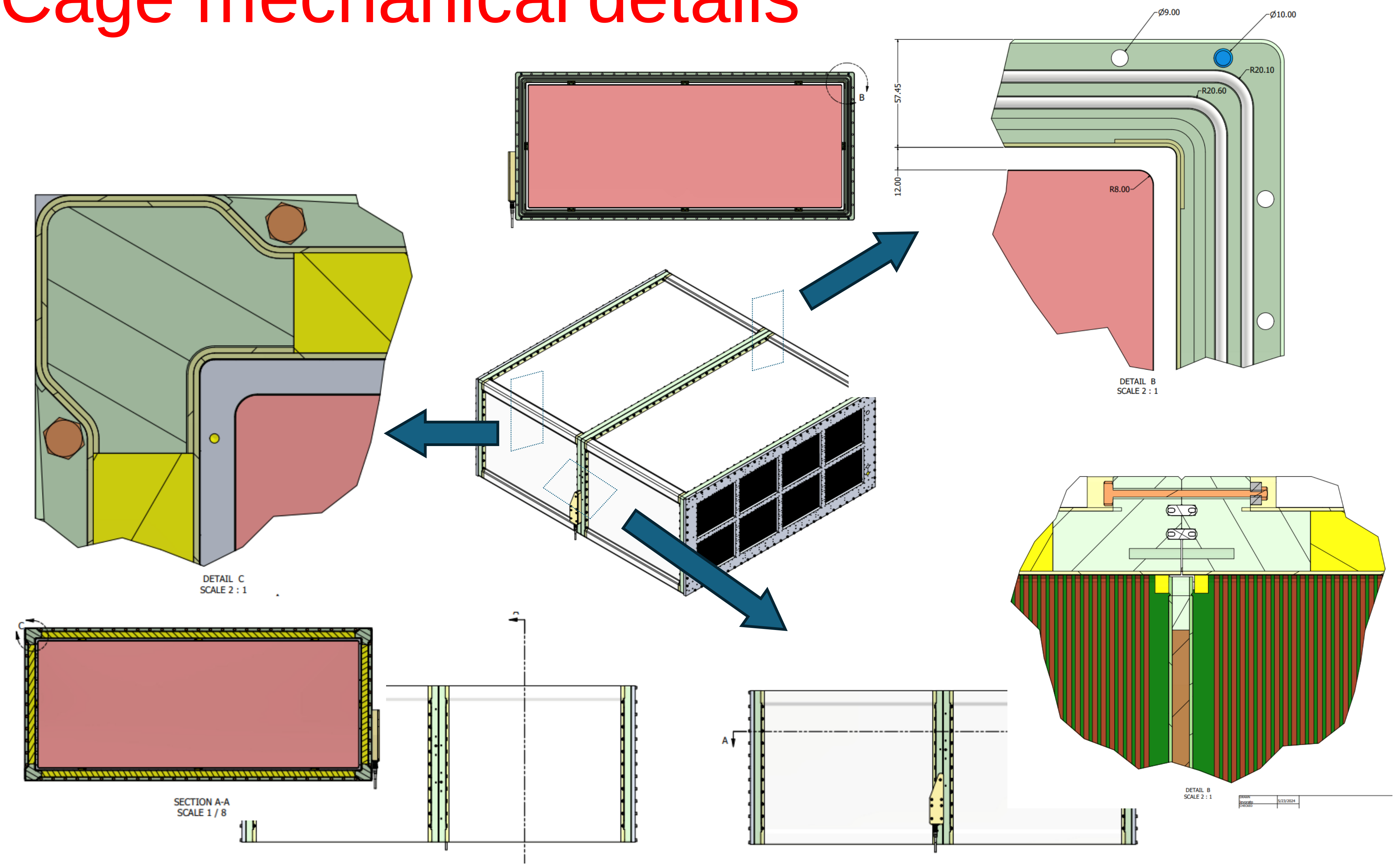
Simulation Electric Field near walls

Double layer of strips on Kapton foil

Dimensions = 5m (inner surface cage perimeter) x 1m (drift distance)

Resistors soldered on the inners surface (contact Mirror strips by vias)

Field Cage mechanical details

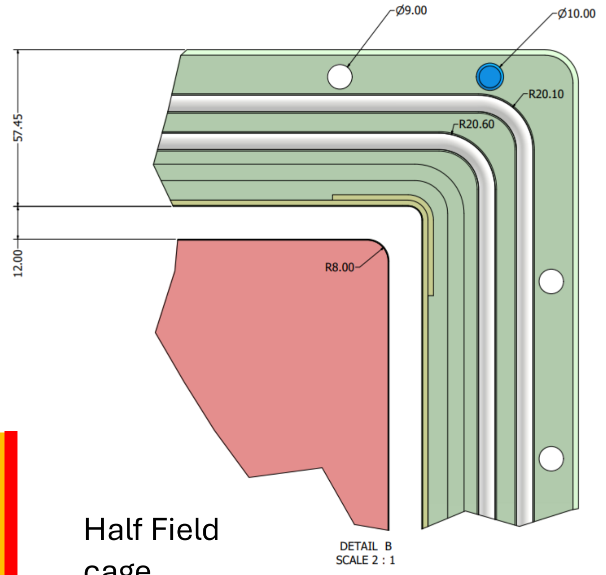


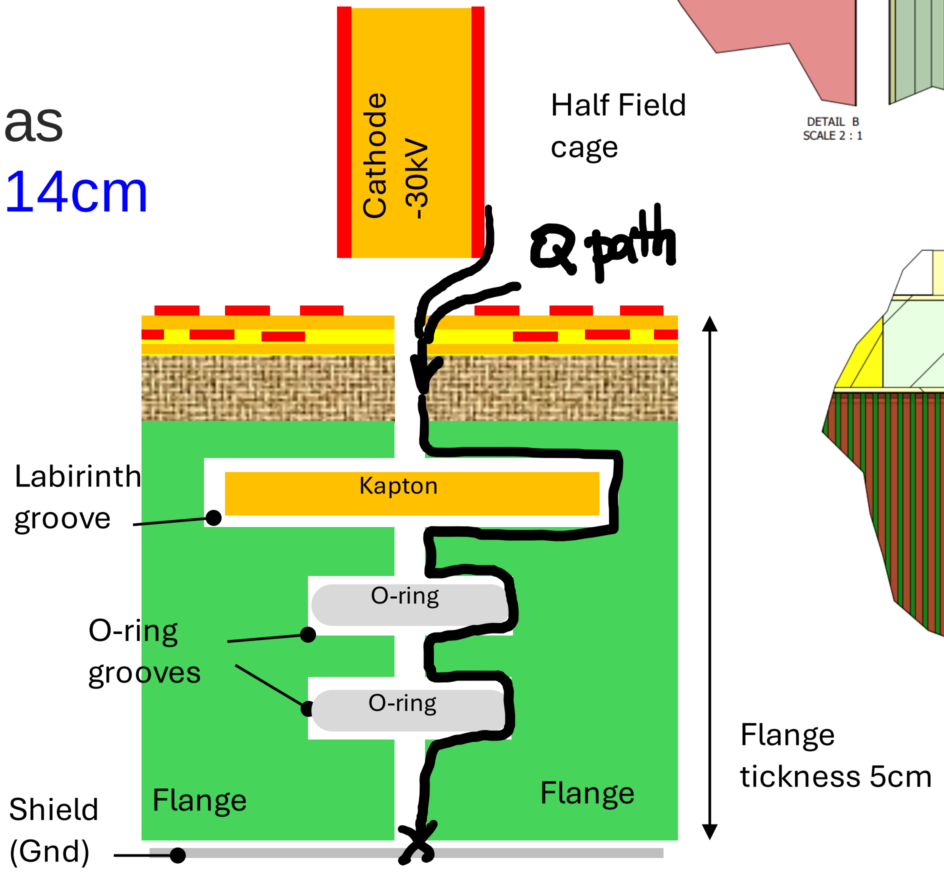
Field Cage mechanical details

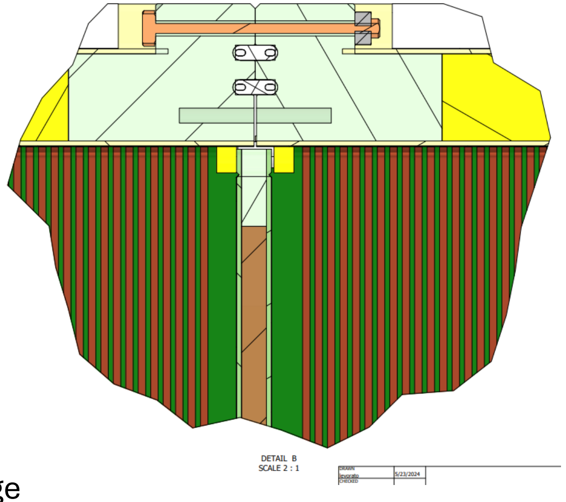
Flange thickness (5cm) too small for
degrading -30kV to GND over a flat surface

Three deep grooves
for enhancing the path from HV to GND
for charge moving on surface and with gas
flanges ~ 7cm thick vs labirinth lenght ~ 14cm

→ voltage drop / path length < 3kV/cm







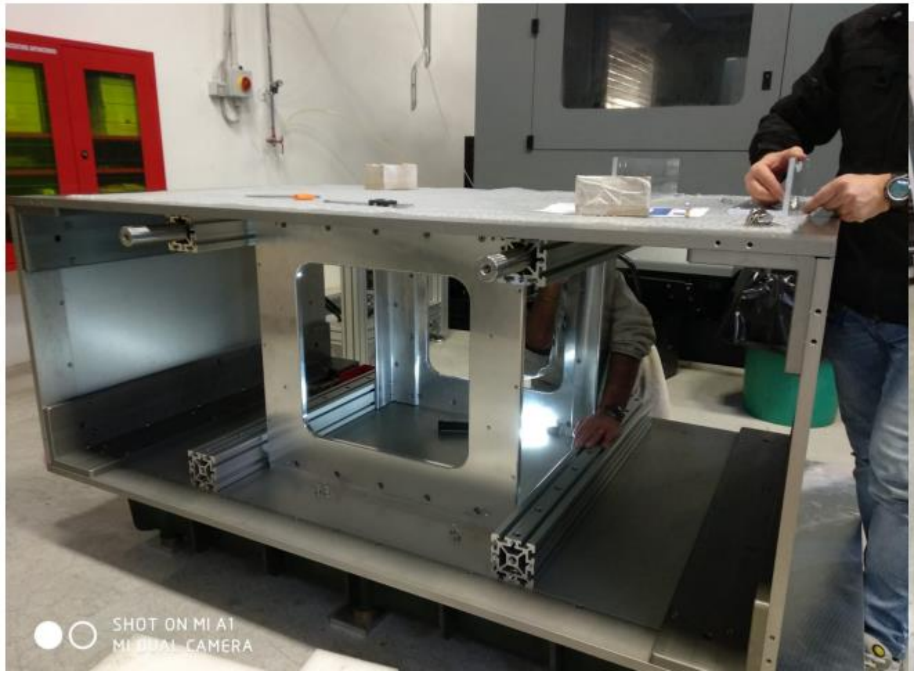
Field Cage building, assembling and characterization

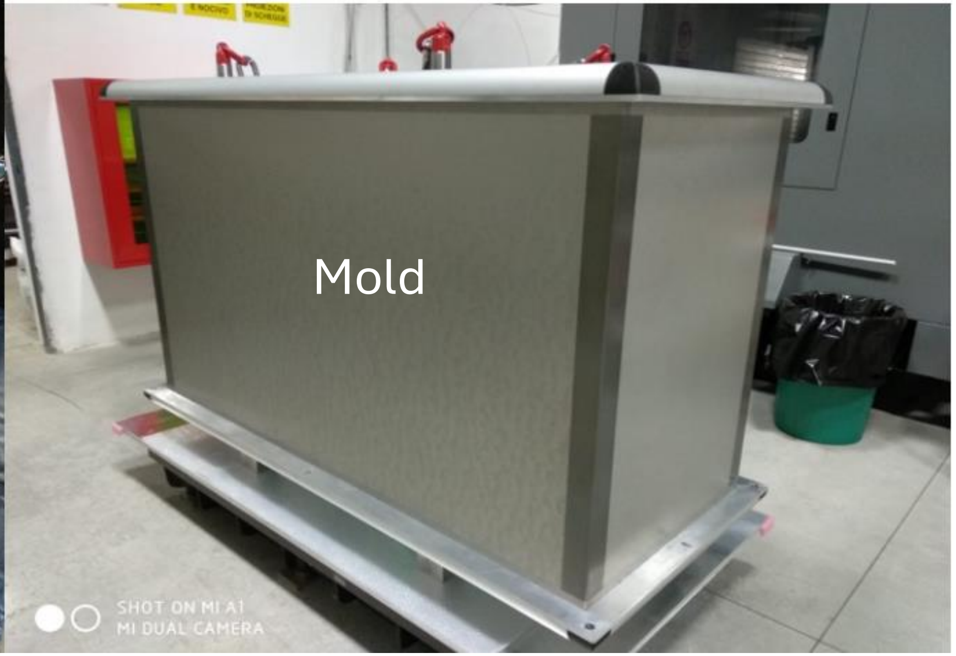
Production at NEXUS company (Barcelona) ~ 10 weeks
Validation, QC, electrical and mechanical assembly at CERN ~ 4 weeks

Field Cage building on a mould

Mold features

- 1cm thick Alu walls
- Anodyzd. Surfaces
- Waviness compl. iso1302 N8
- Surfaces ⊥ and ∥ better than 80μm/m
- Mount / unmount geom. reproducibility with high precision





Parts and materials

- Mold → INFN
- Double layer strip foil → CERN
- Structural parts = Flanges & Bars (G10 → ORVIM company (TV, Italy)
- Composite material & Production → NEXUS company (Barcelona)

Field Cage building, assembling and characterization

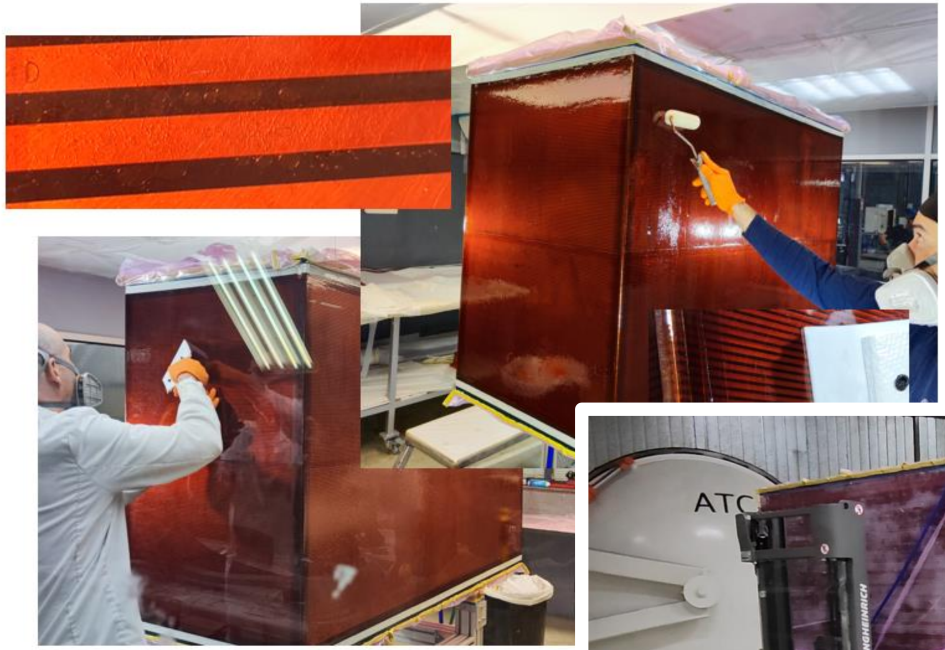
Production at NEXUS company (Barcelona) ~ 10 weeks
Validation, QC, electrical and mechanical assembly at CERN ~ 4 weeks

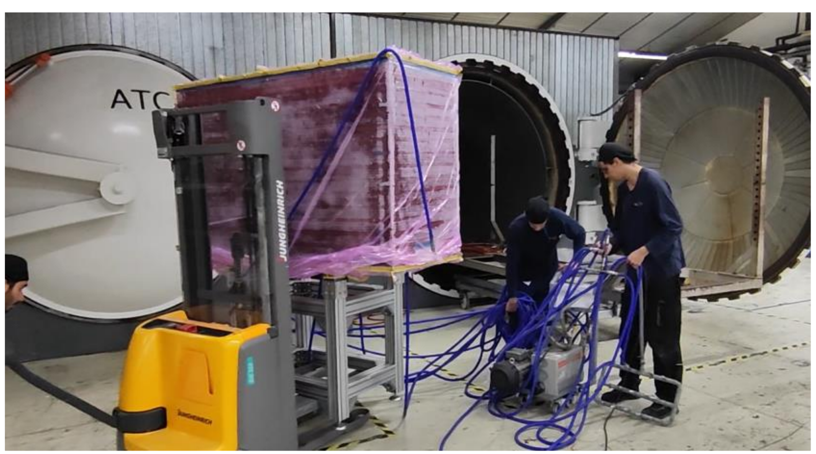
- Mold preparation
- Inner Vacuum bag
- Strip Foil positioning

- Thick corners w/ Kapton tape
- Eletrical tests on surfaces
- Resin samples electrical Tests

5 m perimeter x 1m height (drift length)

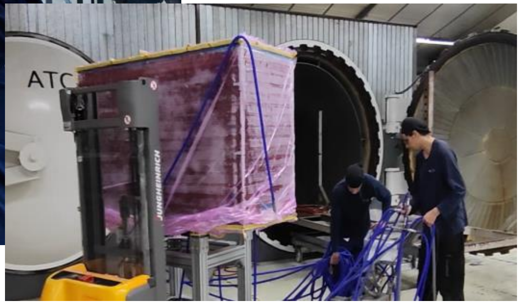
Strip foil alignment and lamination of 3 Kapton layers





- Kapton lamination
- Curing at 40C (fast)
- Eletrical tests on surfaces
- and resin samples

Field Cage building on a mould at NEXUS



- Kapton lamination
- Curing at 40C (fast = 12h) in autoclave
- Eletrical tests on surfaces and resin samples

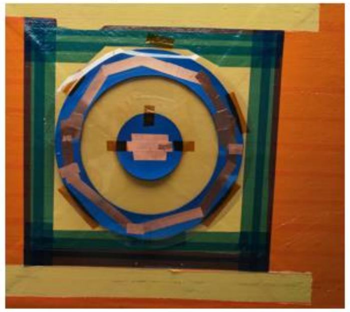
- First Twaron layer lamination
- Curing at 40C (fast) in autoclave

Inner Twaron peel lamination and electrical insulation QC

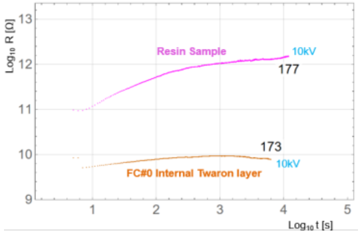
Quality controls – Resistivity of early Layers

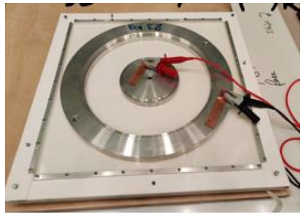
1) Resistance between mold and 40x45cm2 electrode
-> volume resistivity of layers

2) Surface resistivity
of last layer Twaron



3) Resistance between two 6x80cm2 electrodes
-> mix of surface and volume resistivity





Resin sample
(Resoltech Epoxy)

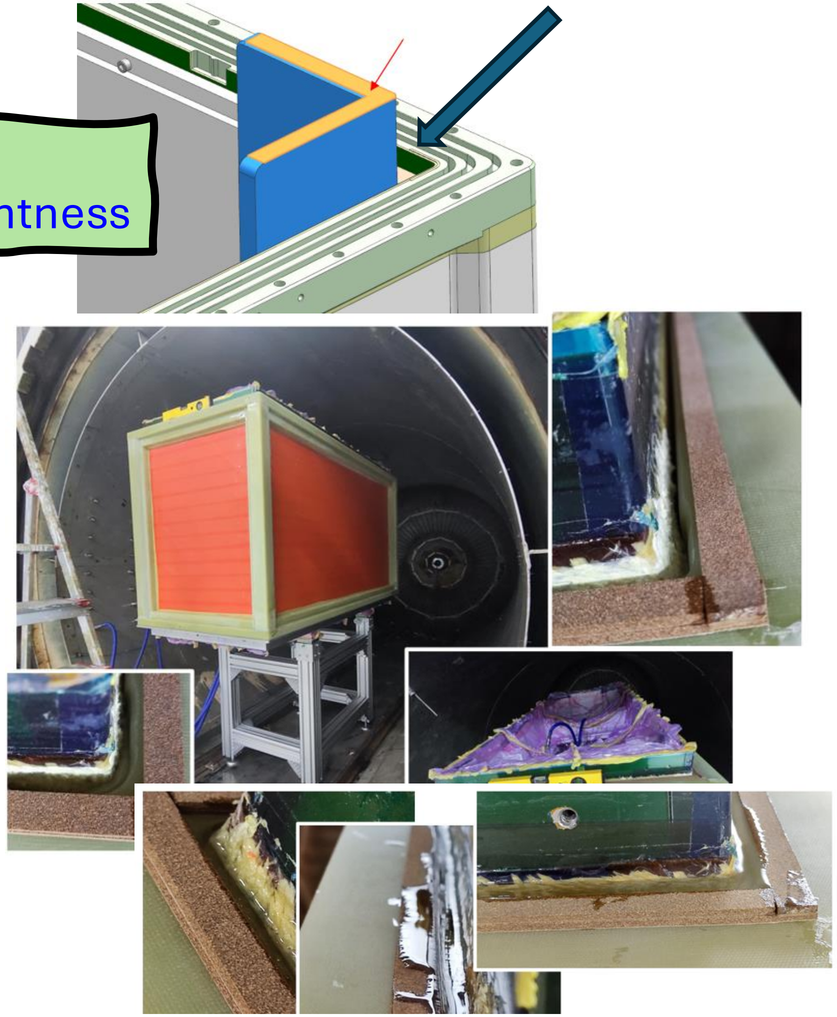
1) various methods and electrode types (optimizing contact)
→ consistent measurements

2) Resin sample ρ_S ~ 10 TΩ/□
→ very good

Field Cage building on a mould at NEXUS

Gluing G10 "skeleton"

Gluing G10 structural skeleton and
casting resin on flanges for ensuring gas tightness



- G10 skeleton gluing
- Curing 40C in clean room

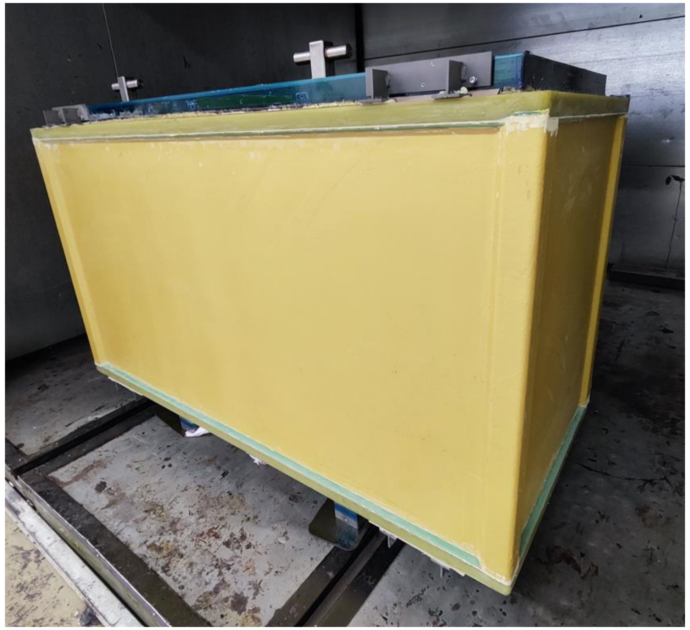
- Casting low viscosity resin on top flange
  (for sealing flange to laminated layers) ... in autoclave
- Curing at 40C in autoclave

Field Cage building on a mould at NEXUS

- Gluing Nomex Honeycomb
- Curing at 40C in owen

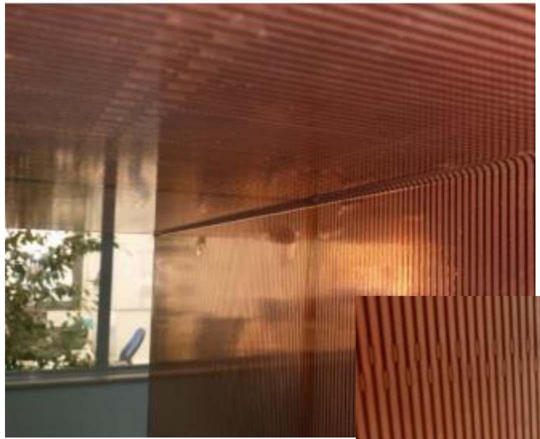
- Flipping the box top-bottom
- Resin casting on second flange
- Curing at 40C in autoclave
- Second Twaron peel lamination
- Curing at 40C in autoclave

Outer Twaron peel lamination

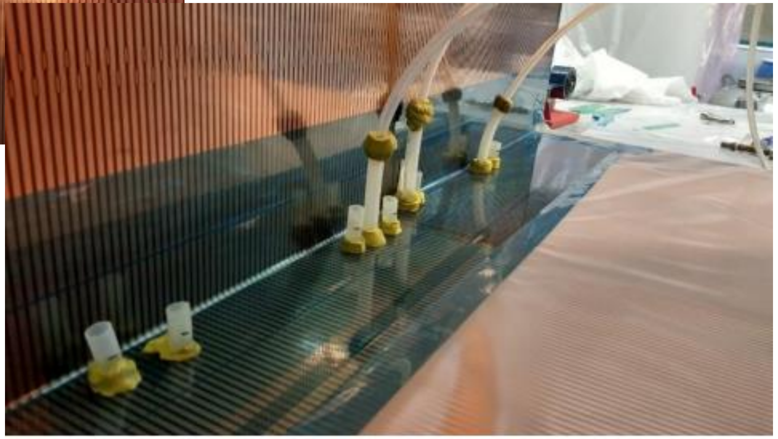


- Post-curing at 40C in owen (lasting as long as possible)
- Post-process machining (removing aramid and resin in ecxess)
- Packaging and shipping to external company (Vallmoll - Spain) for precision machining

Field Cage building on a mould at NEXUS



Back to NEXUS company for
- Mould removal
- Very fine polishing of flanges
- Correction of defects (eg bubbles)



precision machining
of cathode and anode
flanges

Precision machining of flages
and finishing surfaces (polishing)

Shipment to CERN

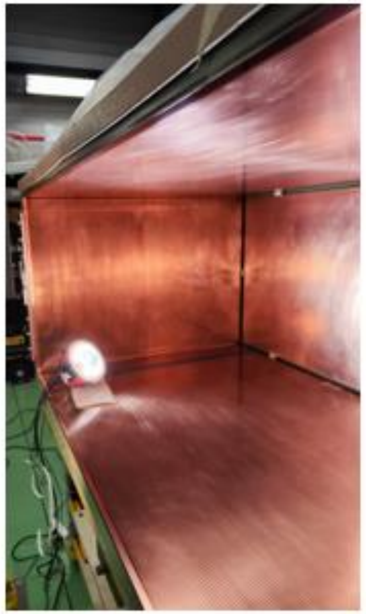
Field Cage assembling, characterization at CERN

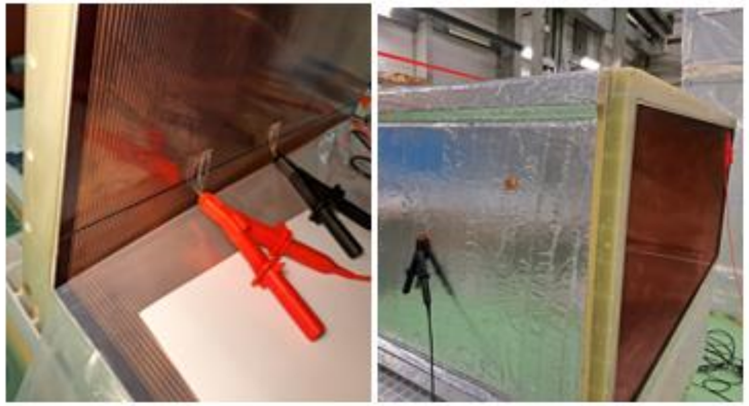
Inner cage surfaces polishing

Checking grooves for o-ring and for charge labyrinth on cathode flanges

Looking for defects on strips and strip-strip short-circuits and repairing them

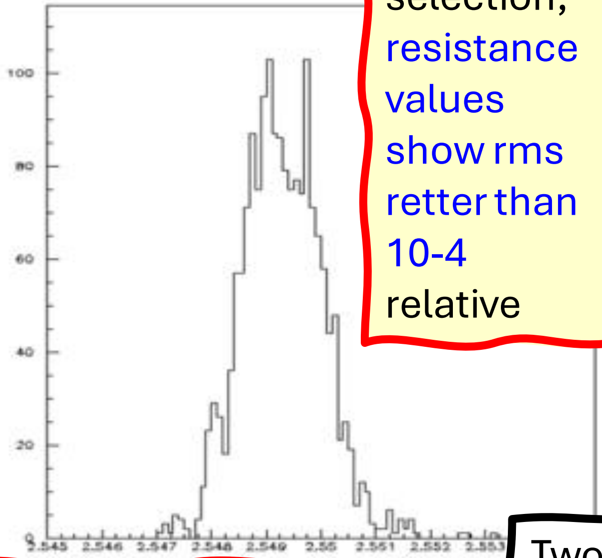
Soldering voltage divider resistors





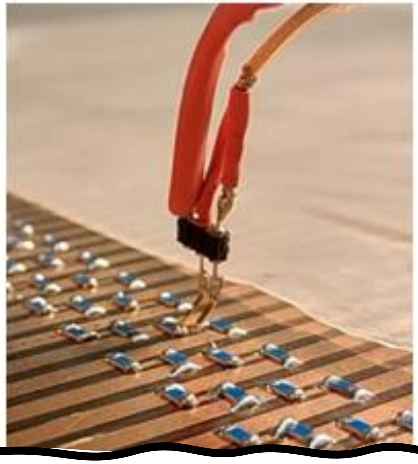
Measuring strip-strip and strip-shield insulation at high voltage

Mantle Resistance > 2TΩ ~ 2000 x voltage divider R



Due to resistor selection, resistance values show rms retter than 10-4 relative

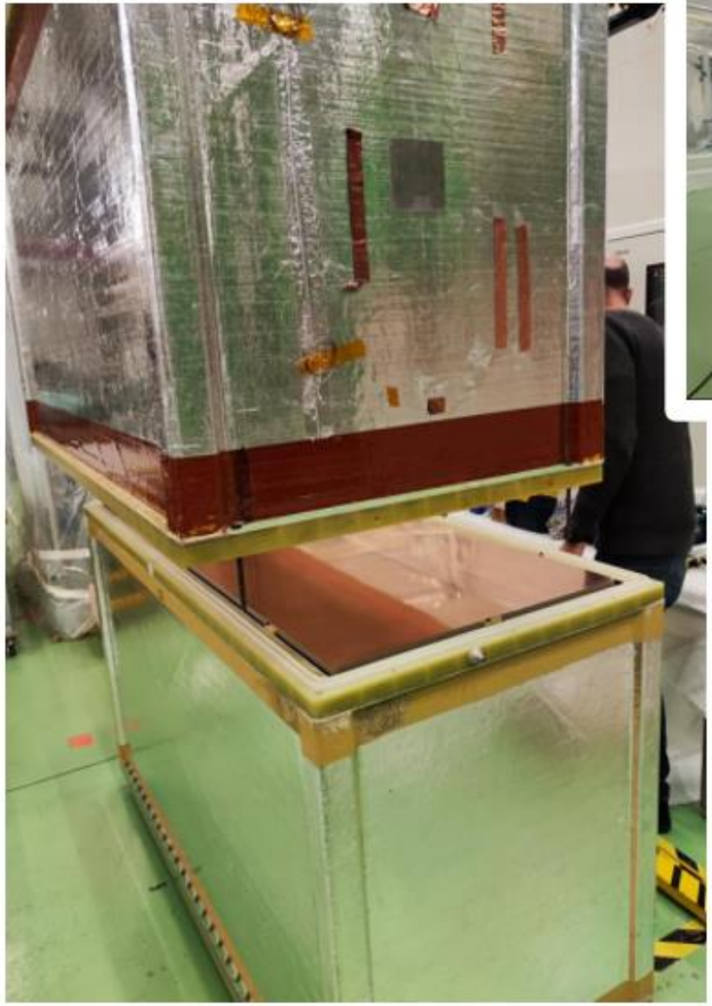
Measuring single resistors



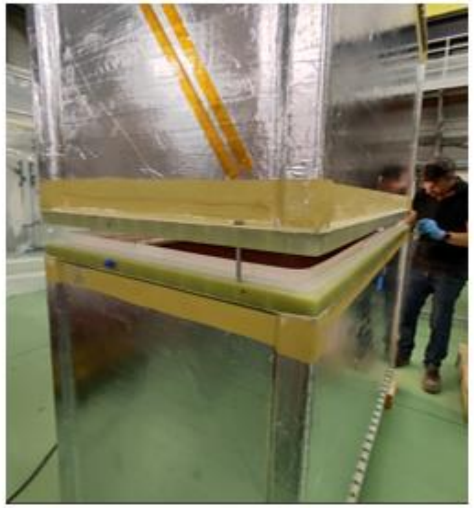
Two voltage dividers In parallel ~400 resistors each => Overall R ~ 1GΩ

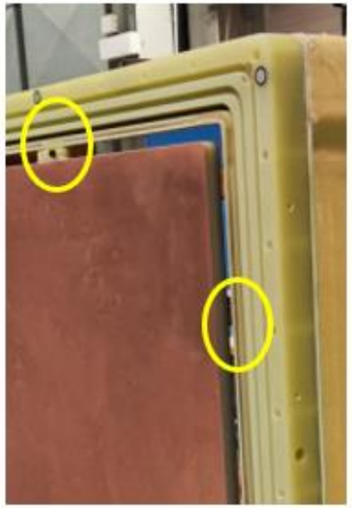
Field Cage assembling, characterization at CERN

Vertical assembly of
two Field Cages into HATPC



Cathode assembly



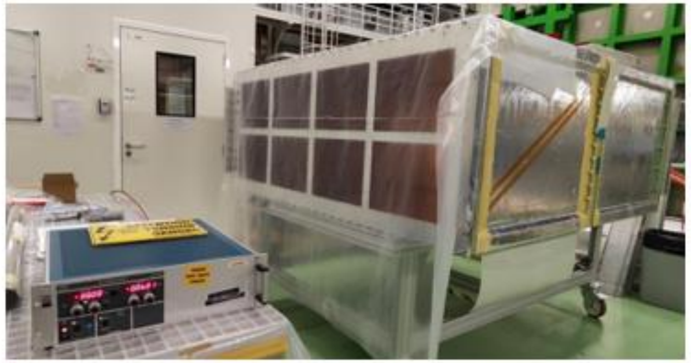


Cathode assembly

High Voltage feedtrough
external connection

Connection of last strips to cathode
and to high voltage feedtrough

High voltage tests after assembly



Field Cage assembling, characterization at CERN

Gas leakeage qualification

1) He leak tested w/ sniffer (air + 30mbar of He)

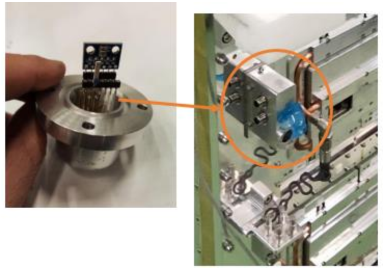
⇒ Local Leaks < 10^{-4} mbar L / s
(considering He ~ 1% gas)

2) Tested against gas density changes

- He Over-pressure (+20mbar)
- Air Under-pressure (-20mbar)

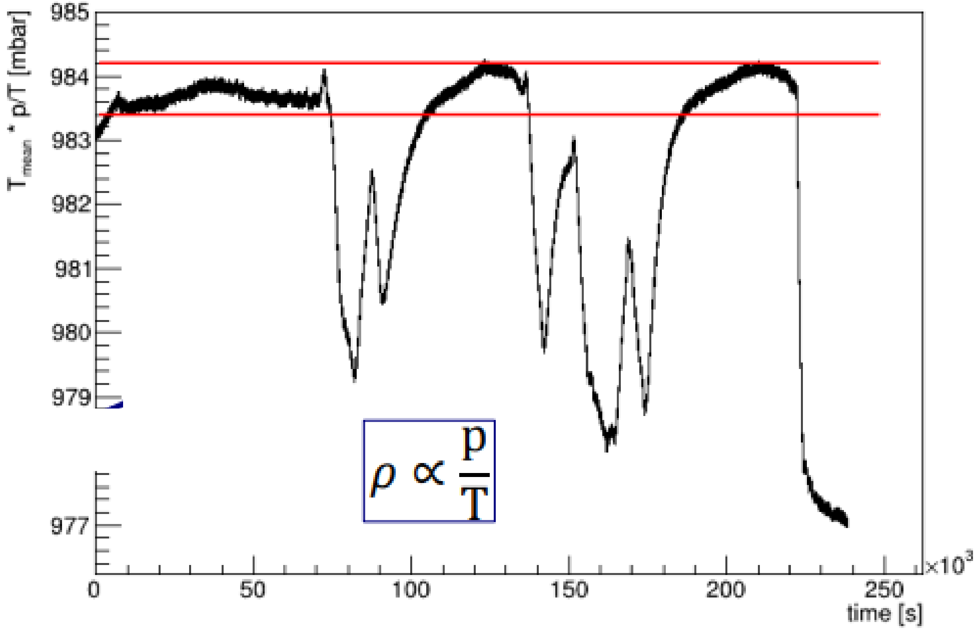
Several T,P,RH sensors
Inside FC

BME280 – T_{cage}, P, RH
IR sensor - T_{gas}
Thermocouple and Pt100
Voltage divider current meas.



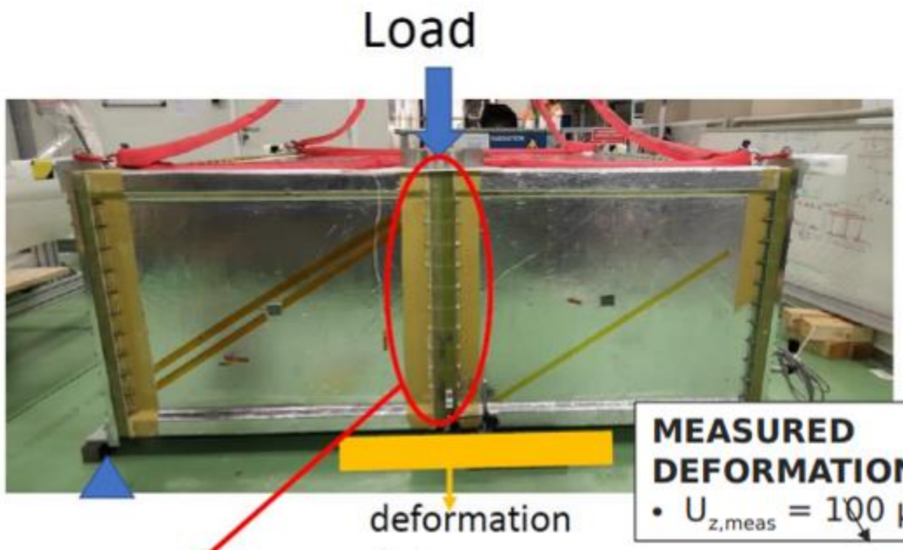
Gas density corrected
for Volume variation (due to Pin - Pout)

$$= \frac{Pin(t)}{Tin(t)/Tin(0)} \left(1 - \frac{\Delta V}{V0}\right) (\text{Pin} - \text{Pout})$$



=> Overall Leak < 10^{-3} mbar L / s

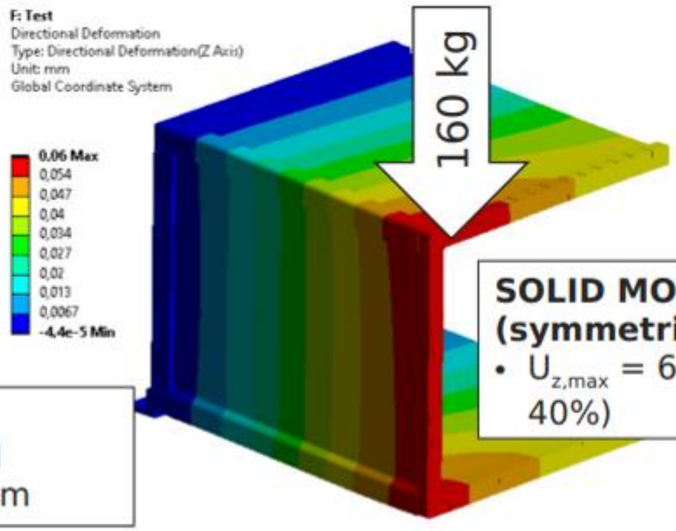
Field Cage assembling, characterization at CERN



G10 screws
(No metal near cathode)

MEASURED DEFORMATION

- $U_{z,meas}$ = 100 µm



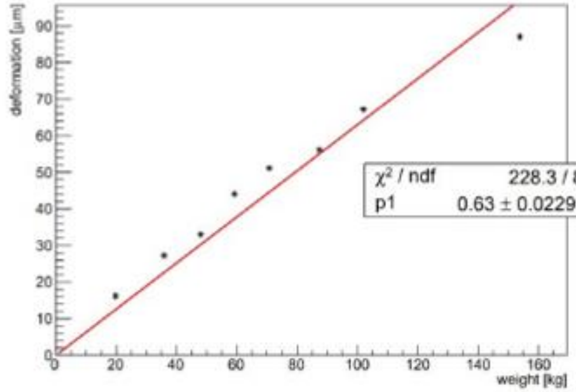
SOLID MODEL (symmetric)

- $U_{z,max}$ = 60 µm (Δ = -40%)

Mechanical qualification

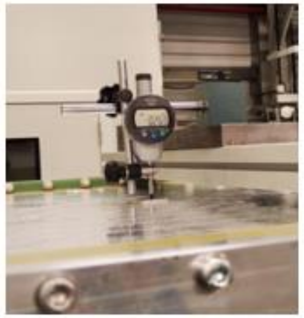
Comparison with FEM models in fair agreement with

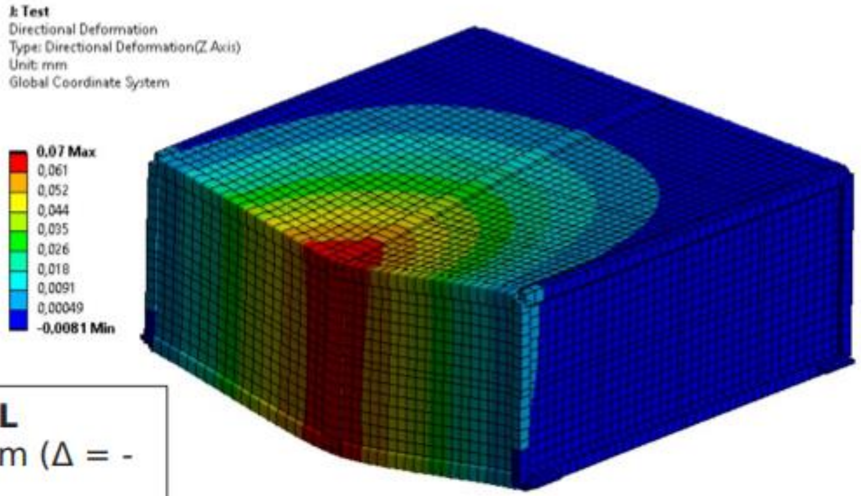
- load tests and
- deformation vs pressure



Load test performed up to 160 kg

Around ~ $0.6 \frac{\mu m}{kg}$ of deformation w.r.t. horizontal position



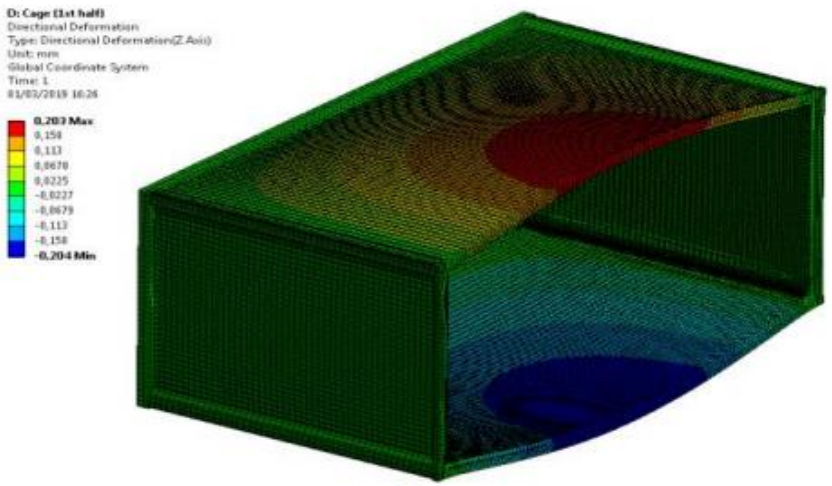


SHELL MODEL

- $U_{z,max}$ = 70 µm (Δ = -30%)

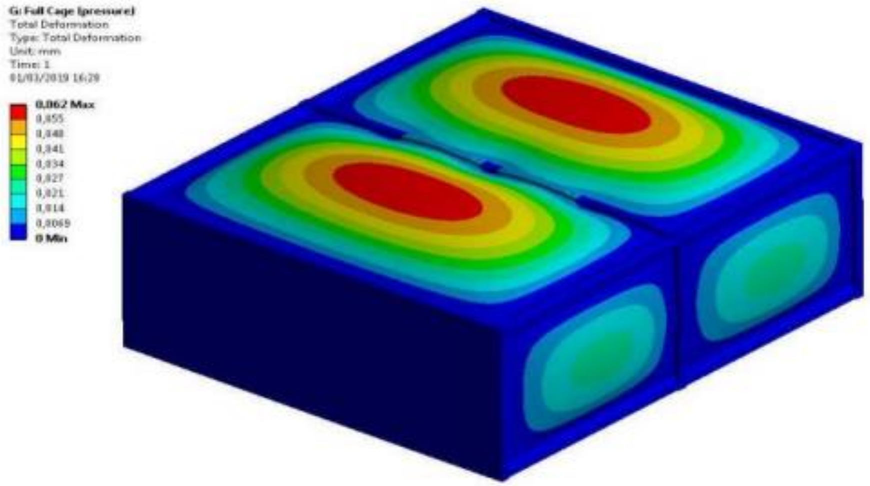
Field Cage assembling, characterization at CERN

ZERO axial contribution of the cathode panel



Max total deformation ~ 200 µm

FULL axial contribution of the cathode panel



Max total deformation ~ 60 µm

Mechanical qualification

FEM model of "Zero axial contribution from Cathode" in fair agreement with load measurements and measured deformations with pressure

Simulation:

Max deformation of large faces: $\sim 50\,\frac{\mu m}{mbar}$

Data:

Max deformation of large faces: $\sim 50\,\frac{\mu m}{mbar}$

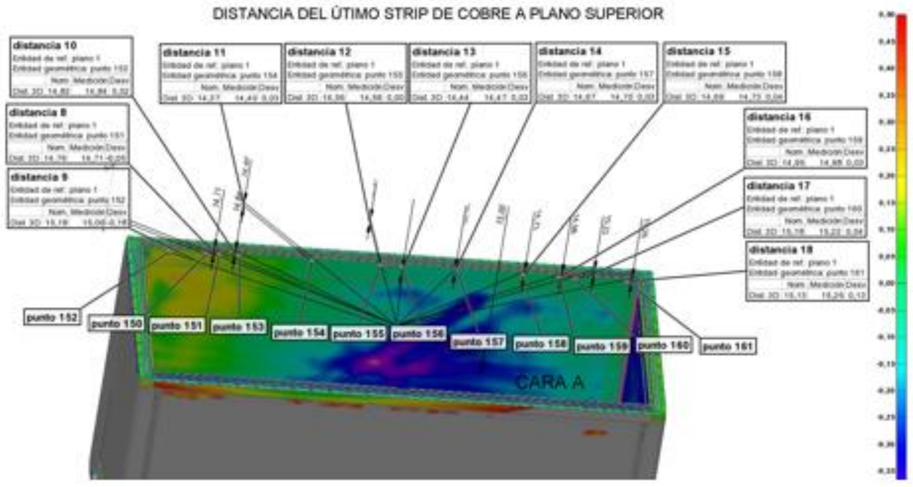
Max deformation of small faces: $\sim 8\,\frac{\mu m}{mbar}$

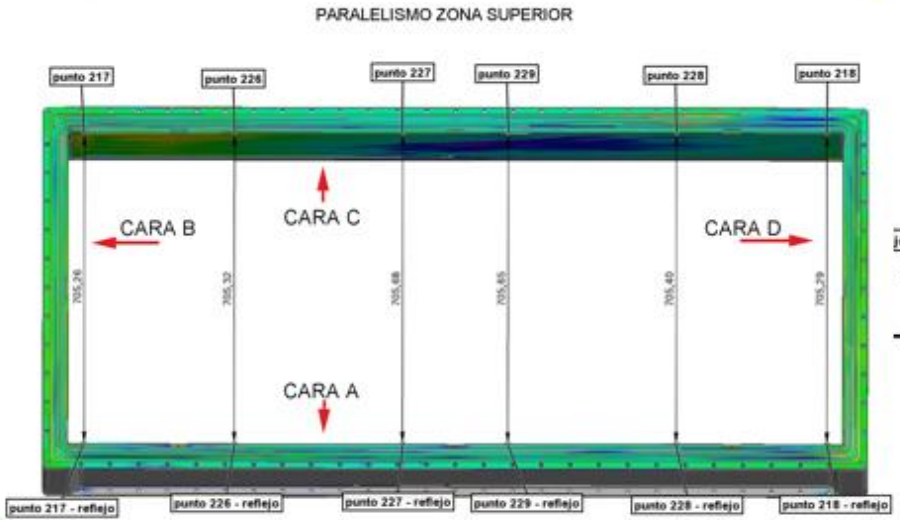
Almost linear in the studied pressure range

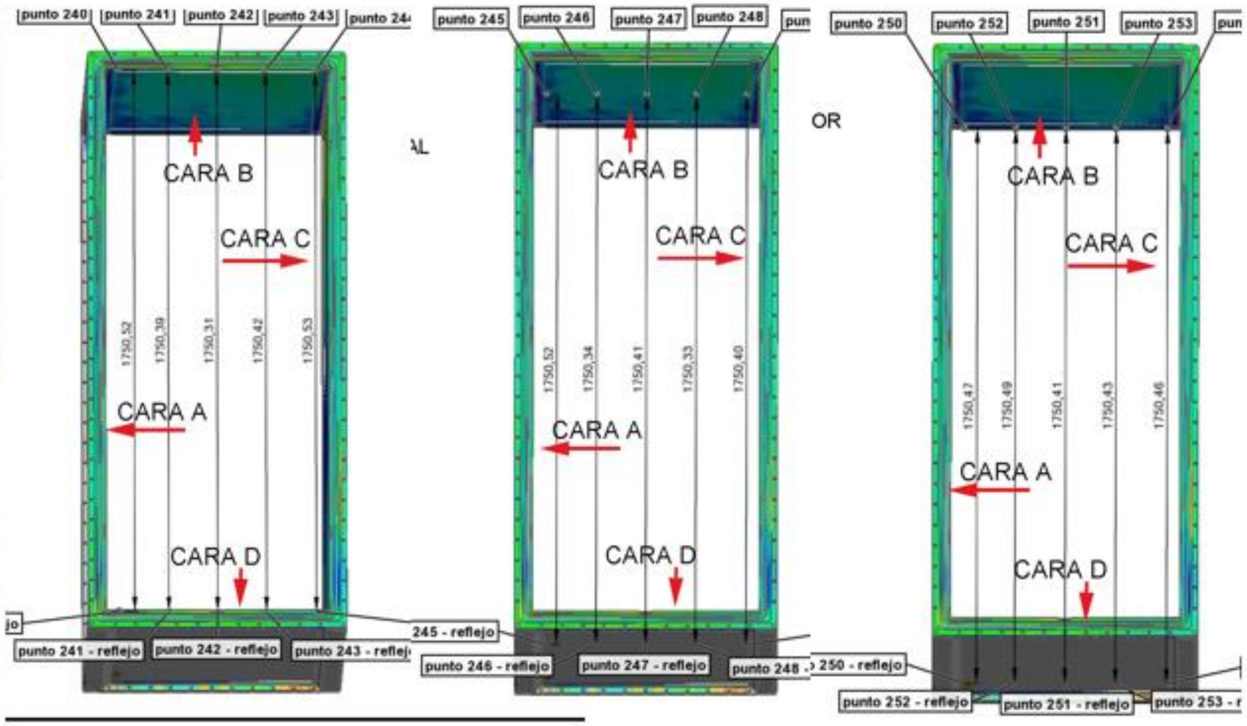
Cathode panel effect in constraining the flanges deformation is negligible

Field Cage assembling, characterization at CERN

Metrology NEXUS – single Field Cage box



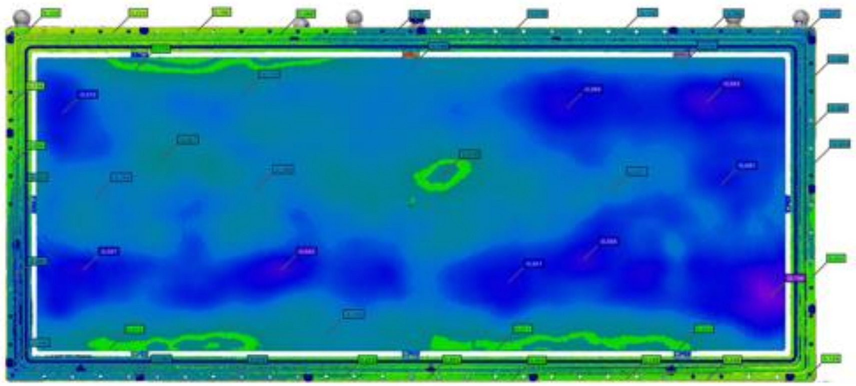




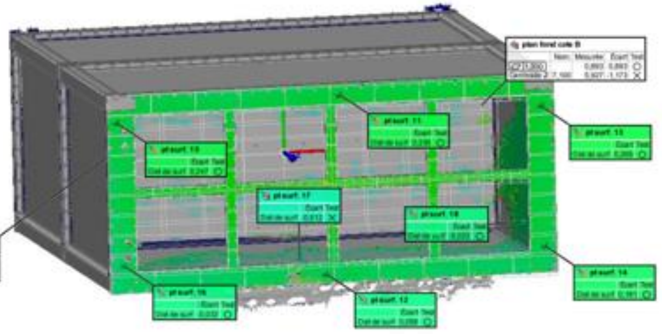
Reached limits of composite material technique
Large dimensions and hand lay-up

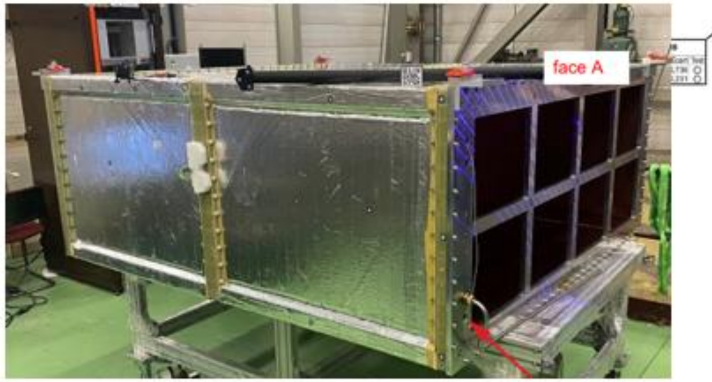
Tolerances and specifications at a level better than 300µm/m for planes parallelism and ortogonality and better than ISO1302-N8 for waviness are respected with few localized acceptable exceptions

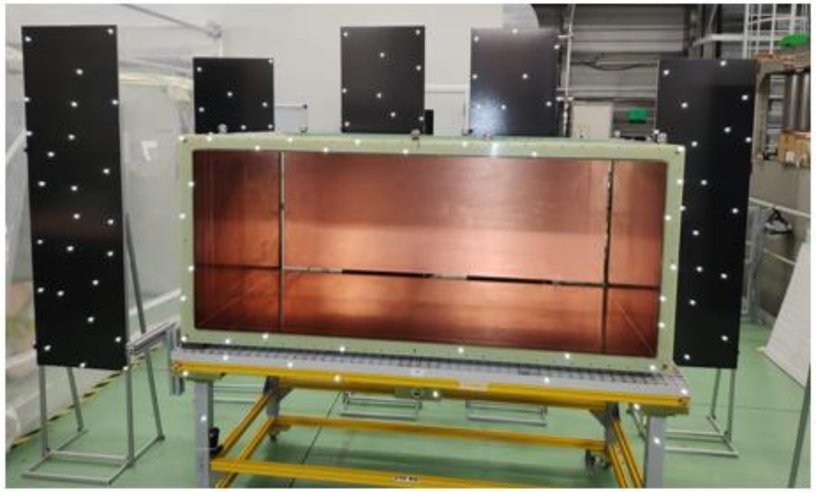
Field Cage assembling, characterization at CERN

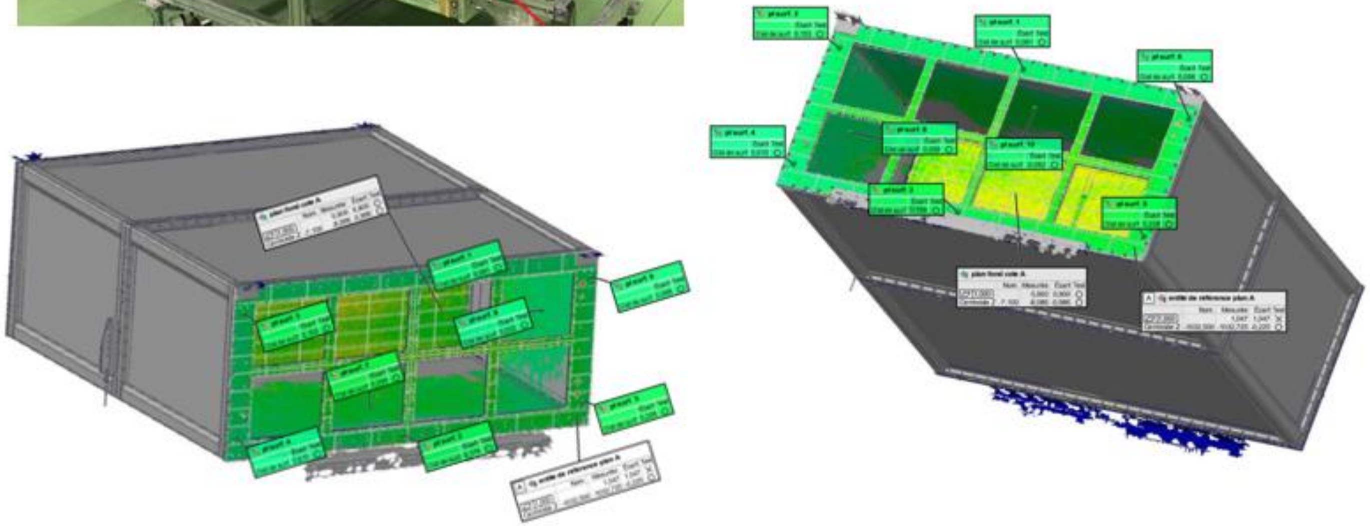


Metrology CERN – whole HATPC







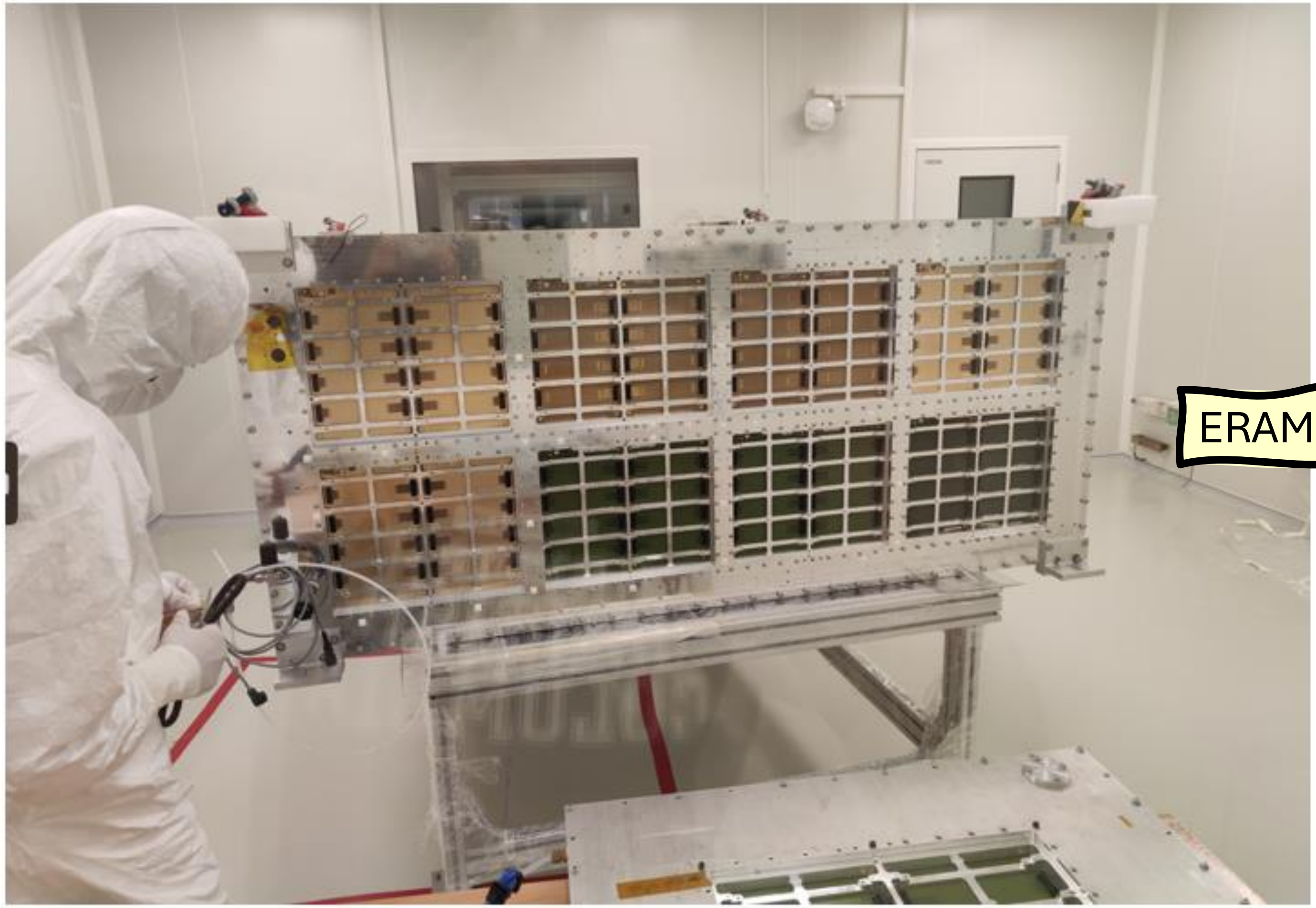


Metrology at CERN Bottom–HATPC (2023)
(Two separate cages and cathode)

Measured internal geometry after assemply agrees with nominal CAD with pull better than 300µm with few localized, acceptable exceptions

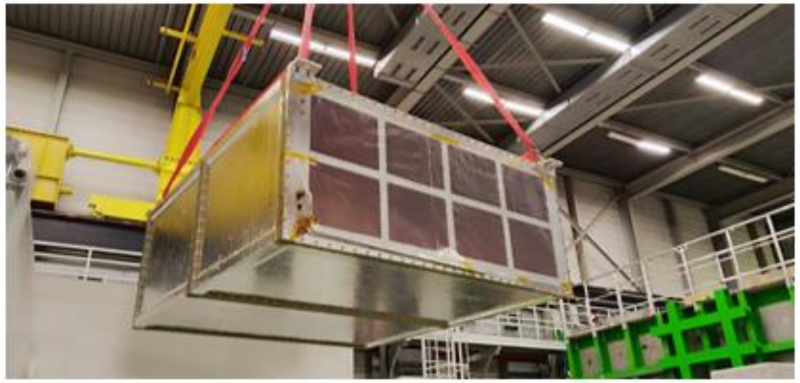
Field Cage assembling, characterization at CERN

Assembly 16 ERAMs in Clean room



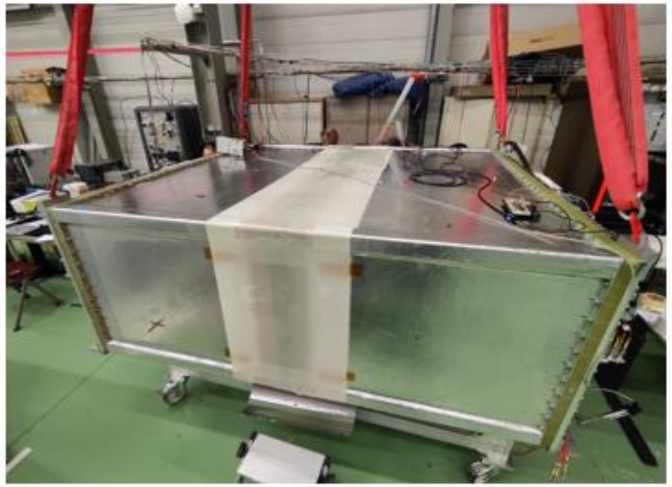
Grey tent area in front of Clean Room
large entrance for enhanced clean conditions

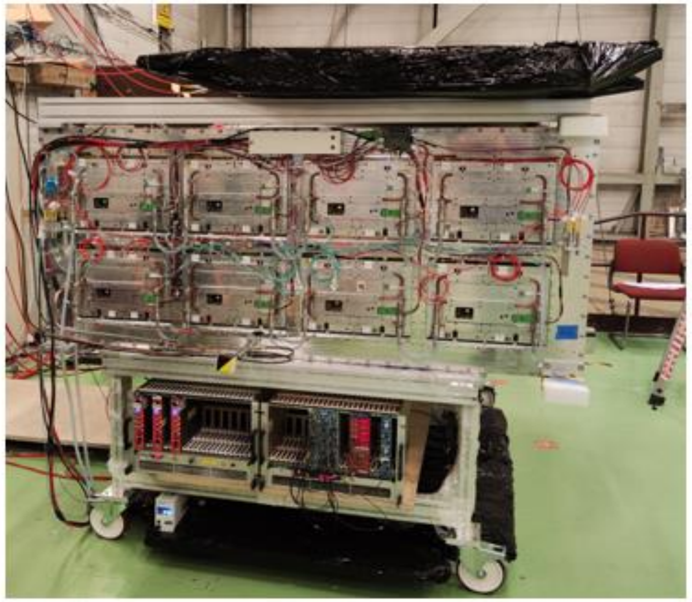
ERAMs very sensitive to dust ...

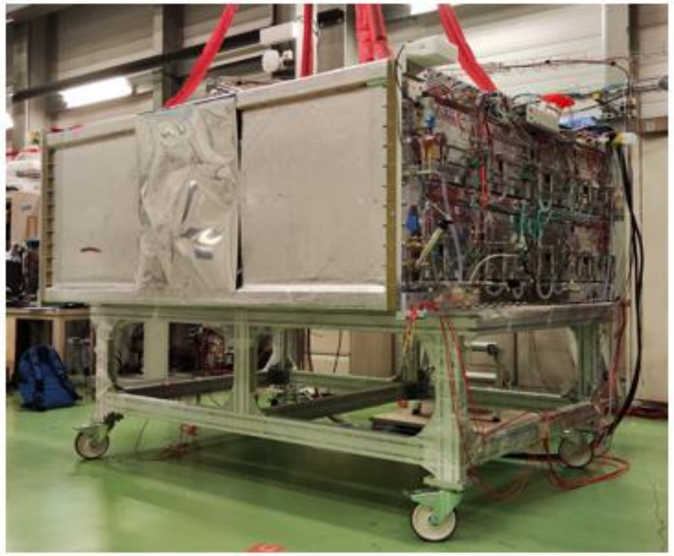


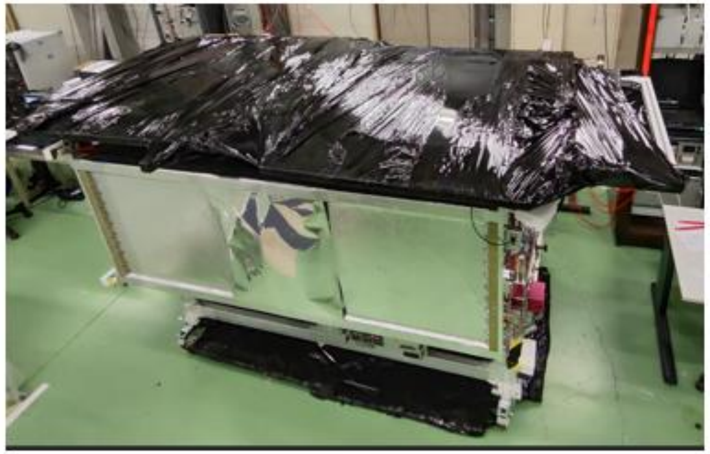
Field Cage assembling, characterization at CERN

Commissioning at CERN with Cosmic Rays



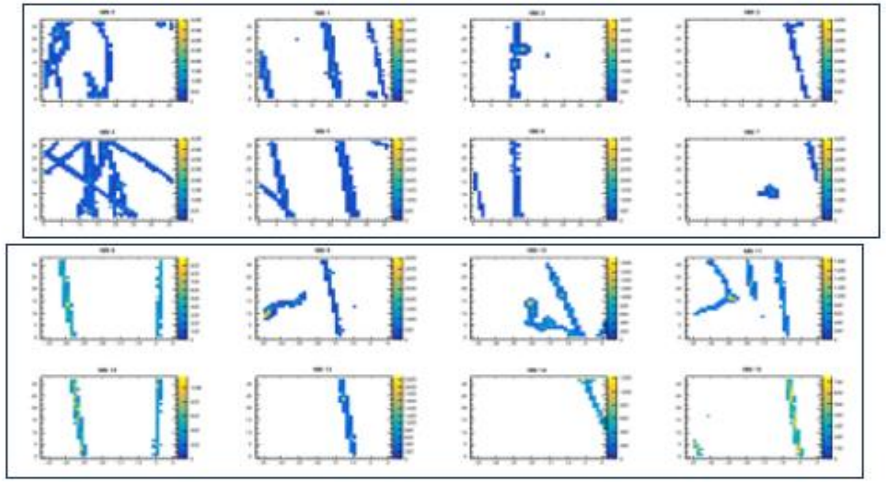




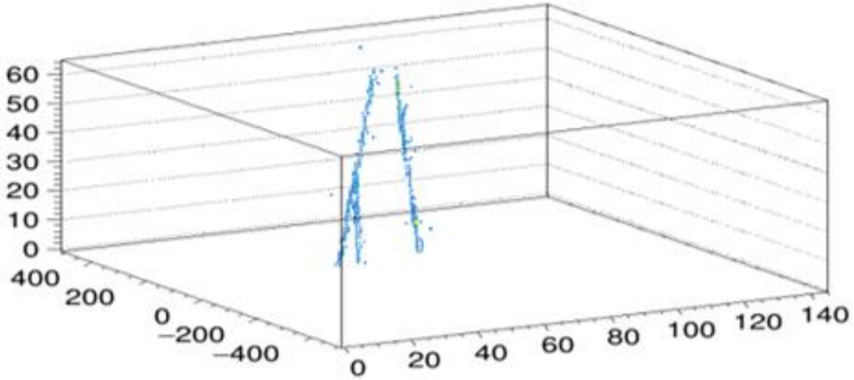


Cosmic shower evwnt

Projection on Anode End Plate 2



Projection on Anode End Plate 1



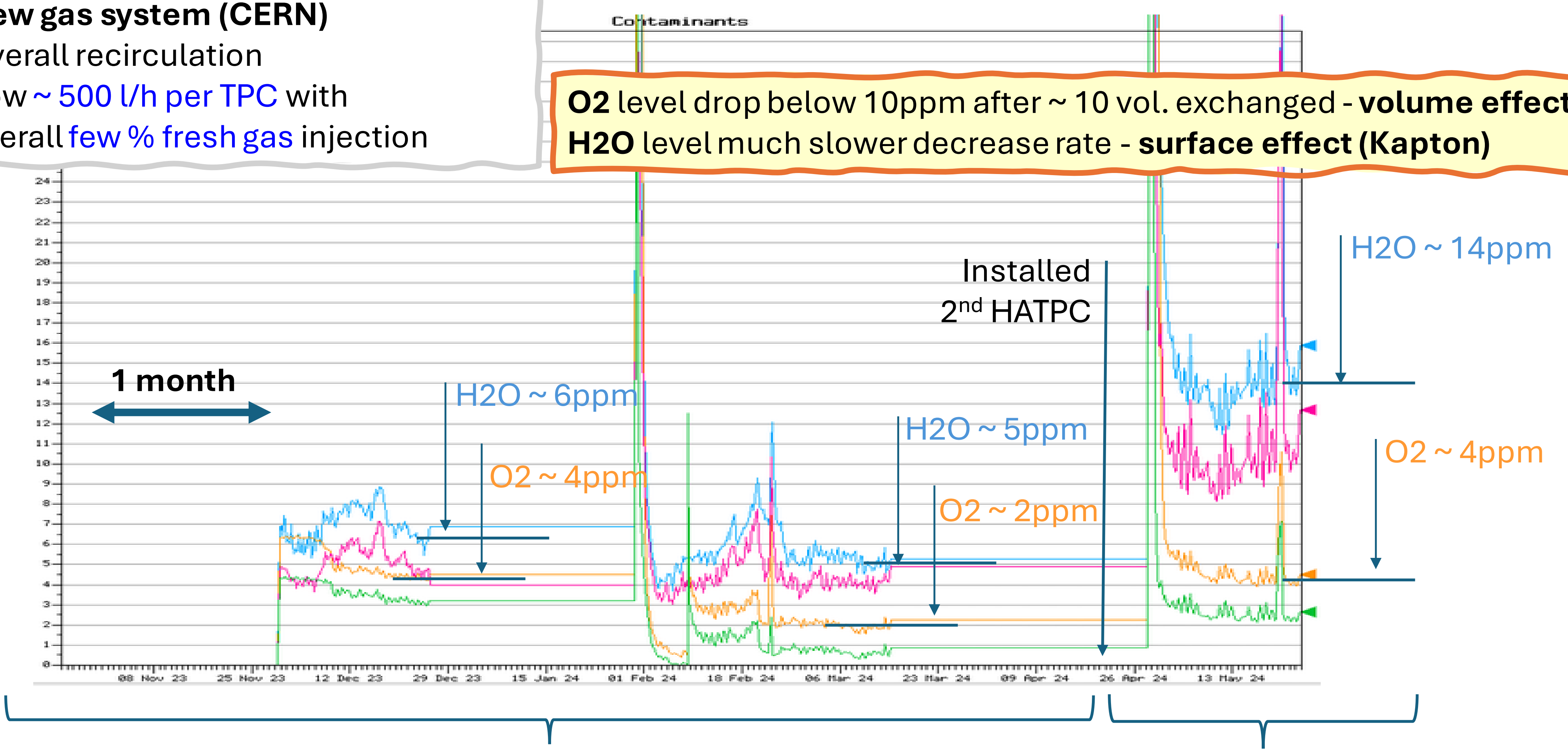
Cosmic tracks interaction evwnt

Field Cage assembling, characterization at JPARC

Gas contamination from Field Cage – O2 and H2O

New gas system (CERN)
Overall recirculation flow ~ 500 l/h per TPC with overall few % fresh gas injection

O2 level drop below 10ppm after ~ 10 vol. exchanged - **volume effect**
H2O level much slower decrease rate - **surface effect (Kapton)**



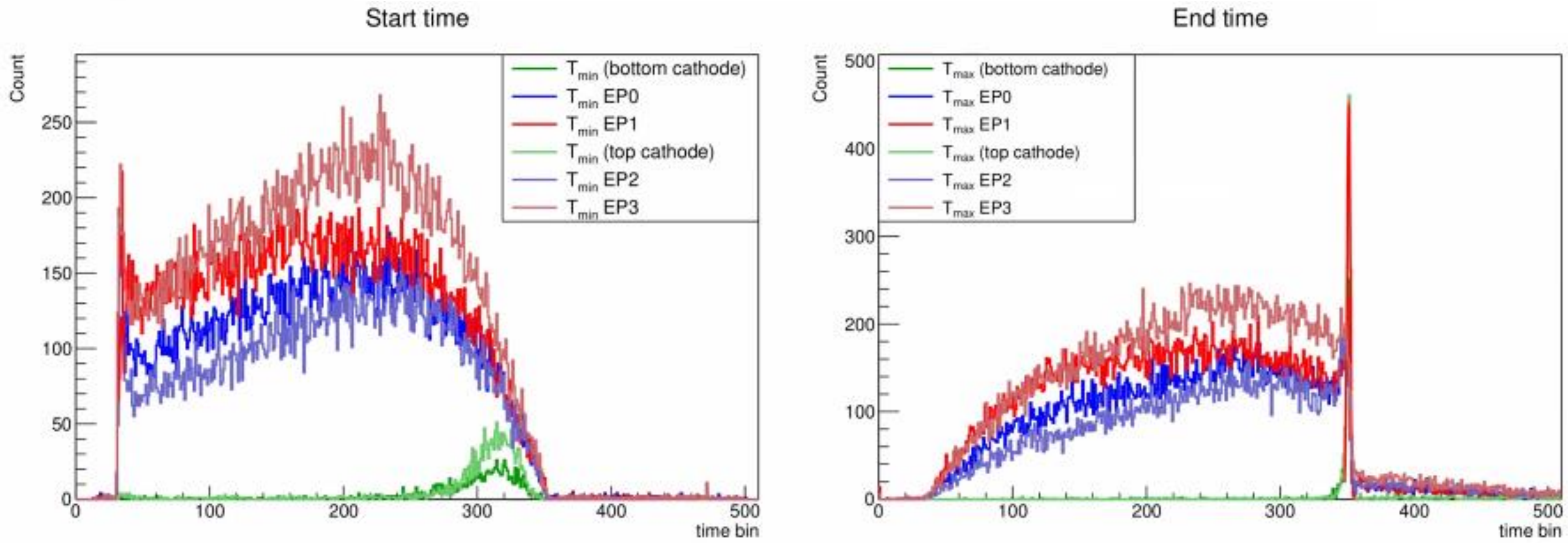
3 old TPC + 1 HATPC

3 old TPC + 2 HATPC

Field Cage assembling, characterization at JPARC

Gas contamination from Field Cage – O_2 and H_2O

Drift velocity




```
Drift velocity in bottom HATPC: 7.769 ± 0.005 cm/μs

Drift velocity in top HATPC:    7.772 ± 0.005 cm/μs
```

Perfect agreement with expectations

Highlights Field Cages

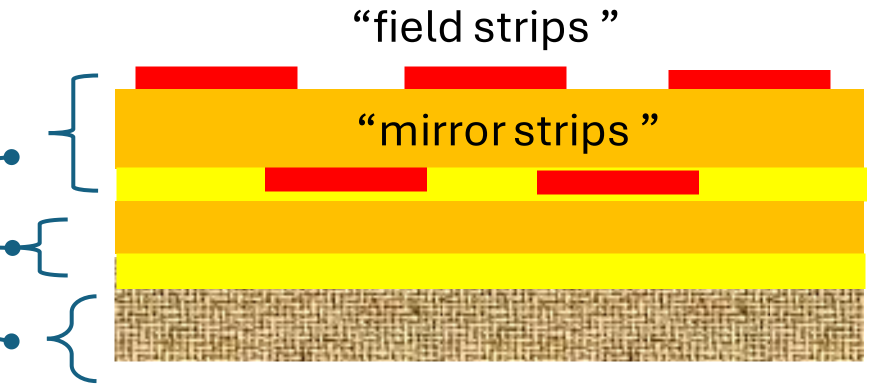
Mechanical - Building, assembly and characterization

➡ Electrical - High Voltage Insulation and Electric Field

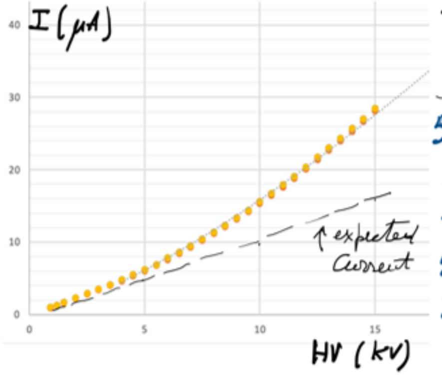
Insulation issue in full scale FC prototype

Innermost layers stack (first full scale FC prototype)

Material	Thickness
Cu Strips on Kapton foil (electrodes)	Cu 17μm / Kapton 50μm / Cu 17μm
“Coverlay” (strip insulation / protection)	Glue 20μm / Kapton 25μm
Aramid Fiber Fabric (Twaron™)	2mm



Current drawn by voltage divider starting in large excess wrt nominal at power on and slowly decreasing to lower value but still in excess

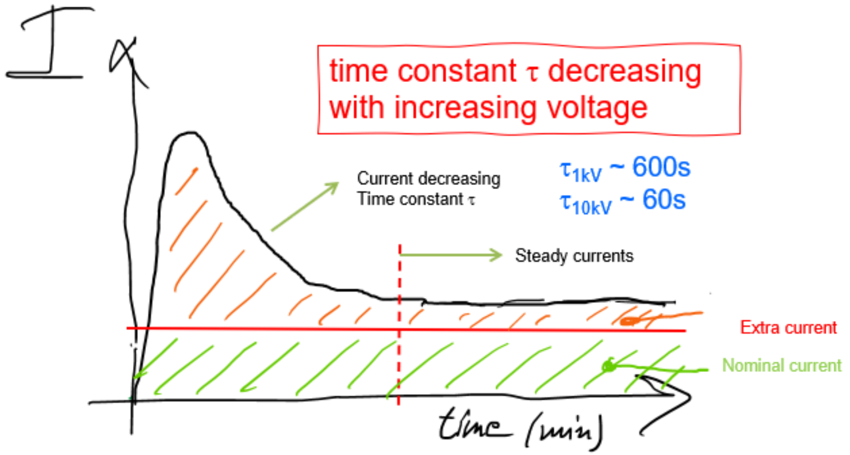


Divider R = 1GΩ

HV	I expected	I extra
5kV	5μA	0.8μA
10	10	6
15	15	18
20	20	30
25	25	45

I_{extra} increasing non linearly with voltage

Current drawn by voltage divider starting in large excess wrt nominal at power on and slowly decreasing to lower value but still in excess



Extra current is internal – flowing trough / in parallel to voltage divider
- Divide
- No le

Extra current is internal – flowing trough / in parallel to voltage divider
Divid... current same as delivered by Power Supply

Observed extracurrents in excess wrt expected from voltage divider

Reproducible I values (up to 25kV… when hysteresis happened)

Reproducible I values (up to 25kV… when hysteresis happened)

Insulation issue in full scale FC prototype

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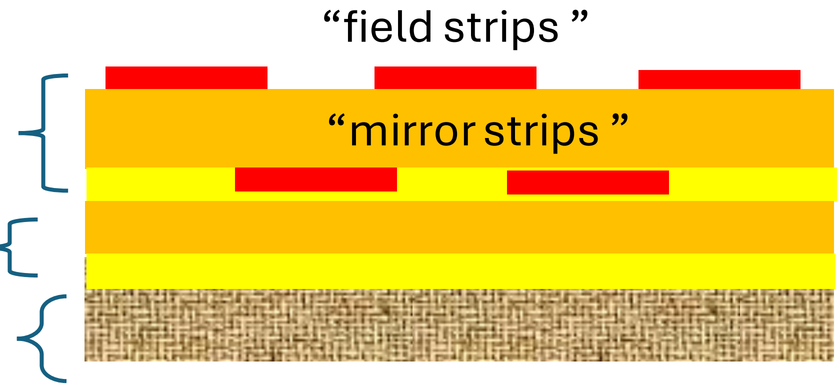
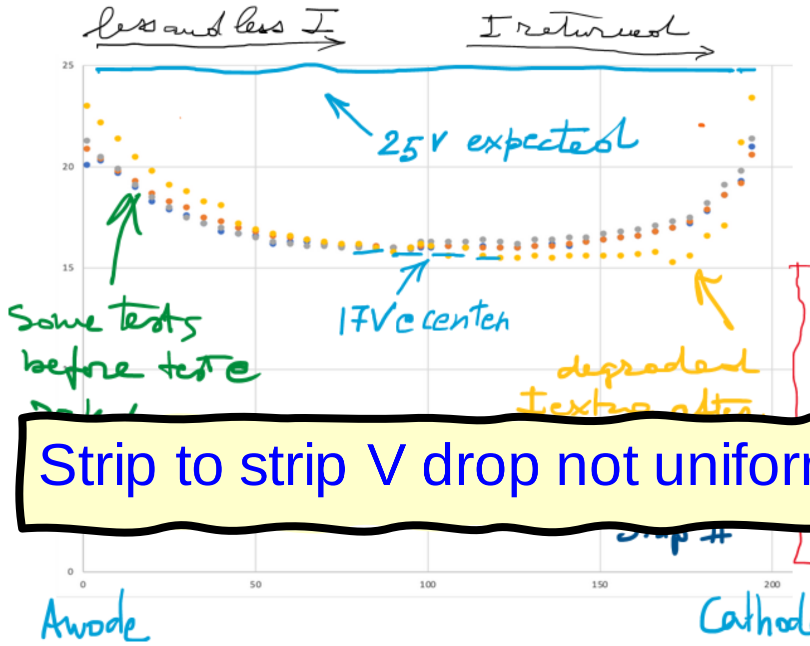


Strip-Strip Potential difference of the strips @ 5kV

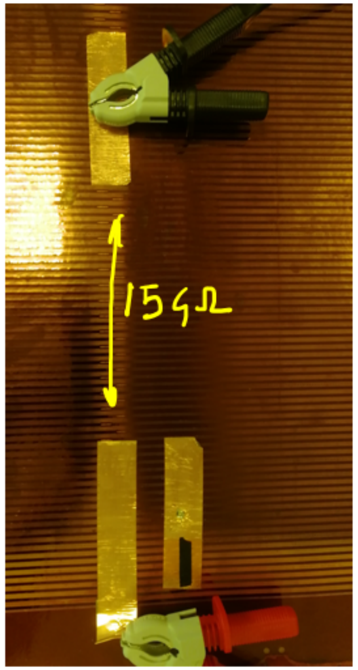
Voltage difference between Field strips (every 5 strips)
ie V_1-V_2, V_5-V_6, V_{10}-V_{11}, … V_1 = anode, V_{196} = cathode



Strip to strip V drop not uniform

Behaviour explained by either
1) ~~Voltage divider resistors values not uniform along the divider~~ ruled out
or
2) current diverted from voltage divider (drawn from strips) more and more along the 1st half of the cage
…om anode to
… returned to
…ler (pulled by the strips) in the 2nd half

Measurement of Surface resistance of strip foil (resistors removed)



Bad HV insulation of Strips

Example: measured R ~15 GΩ @ 1kV between two electrodes formed by 20Field+20Mirror strips each (surface of single electrode is huge ~ 0.5m²)
! No voltage divider there, ie all strips disconnected

Resistance is
- Independent of the distance between electrodes
- Linearly dependent of the number of the strips

→ not a surface resistance !

Measured R is rising with time (slow) up to saturation
- when repeating measurement, go faster to saturation
- when inverting polarity of electrodes, slow again

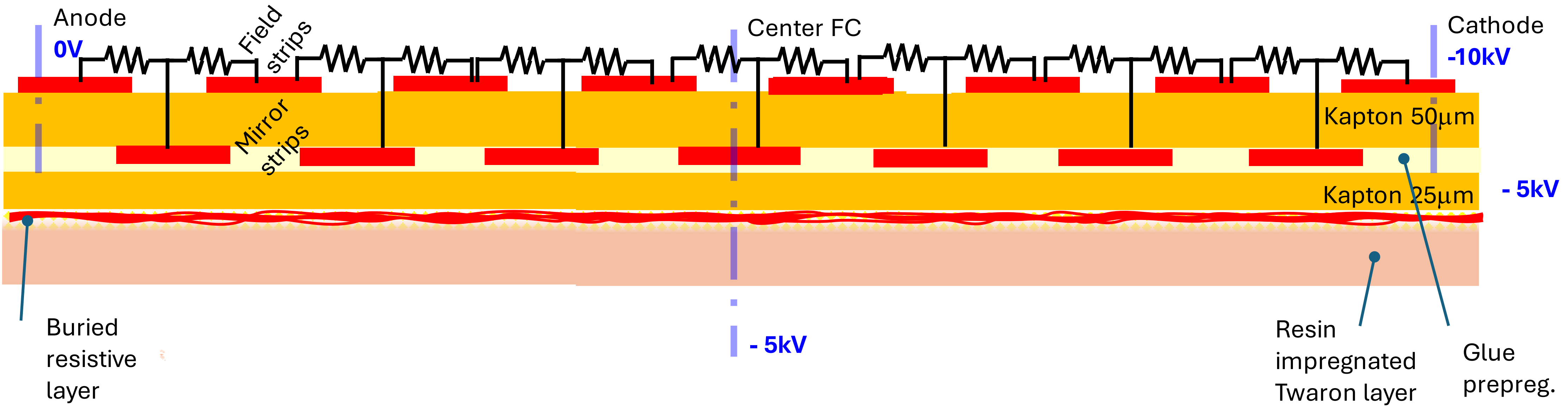
→ looks like due to dielectric polarization / relaxation
→ or capacitor charging trough high resistance

Find similar value of Resistance for same dimension electrodes formed in the Field Cage and on a strips foil when aluminum foil is placed underneath the foil → next

Buried resistive layer & electrical model

All observed features could be explained by the combination of two factors:

1) Presence of a resistive layer buried underneath the Kapton coverlay layer protecting the mirror Mirror strip
2) Low resistivity of the coverlay Kapton layer



Buried resistive layer & electrical model

In fact we **verified** the following

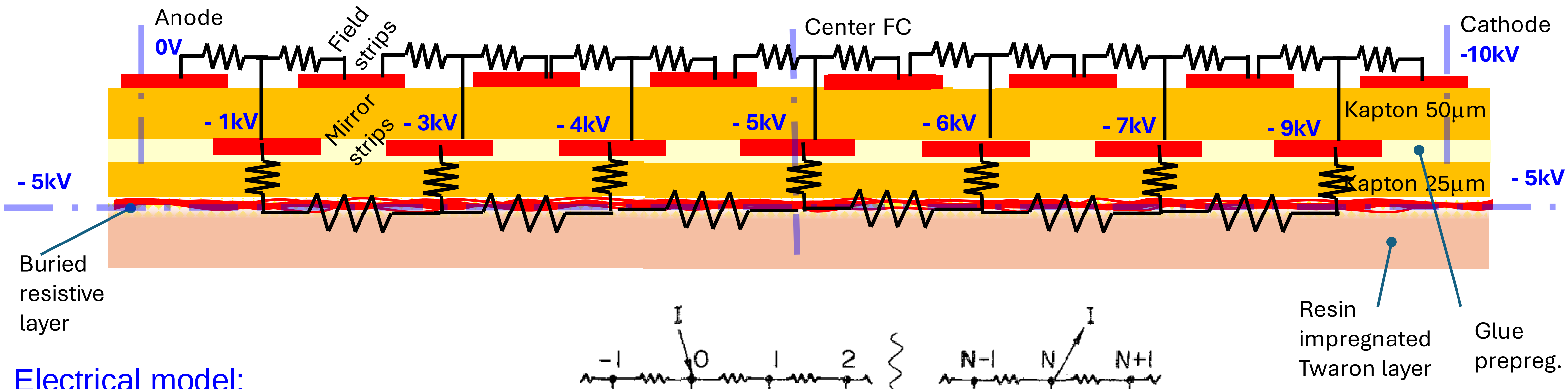
1) Coverlay Kapton volume resistivity was O(1GΩcm) (much lower than datasheet)
2) Twaron layer facing the coverlay featured surface resistivity O(1G/□)

Sources of “resistive” contamination

Both features could on turn be explained by the accidental use of antistatic spray (resistive) on the back of the strip foil (ie on the coverlay) after the strip foild was fixed on the mould, in order to keep the huge foil surface (5m2) clean from dust and other possible contaminants. The spray contaminated both the Kapton coverlay (being very easily adsorbed) and the innermost layer of the Twaron (being mixed with the resin which impregnates the fiber fabric, during the Twaron lamination phase)

We could not exclude alternative sources of contamination affecting the resin and making it resistive (eg presence of water if epoxy not treated in vacuum after mixing)

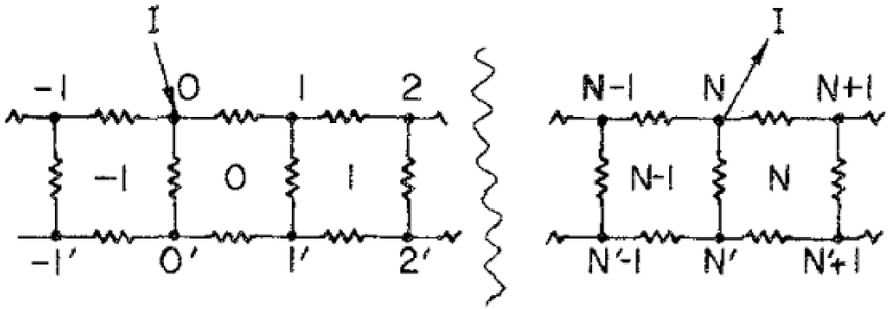
Buried resistive layer & electrical model



Electrical model:

resistor network

strip of mesh one loop wide

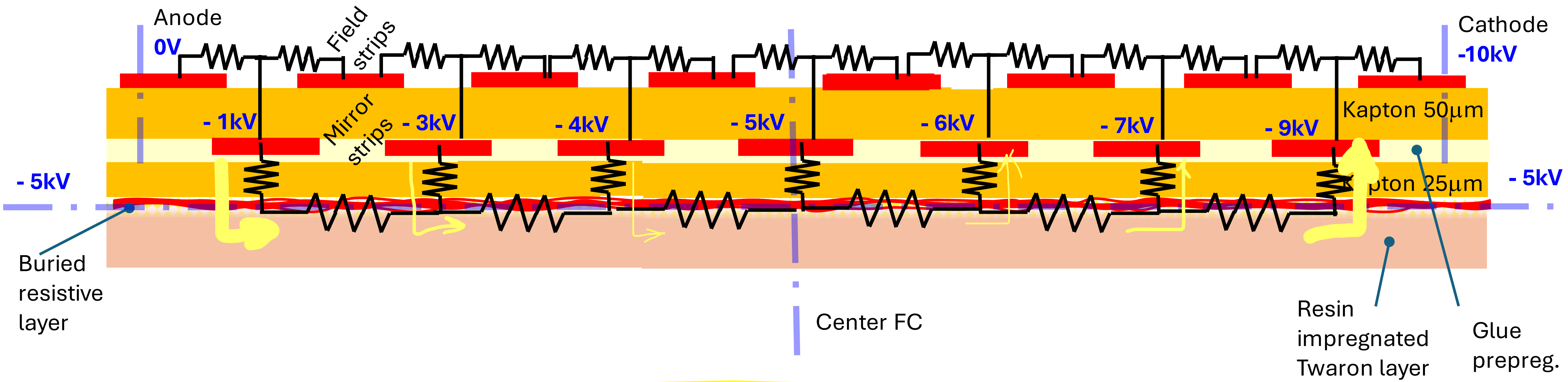


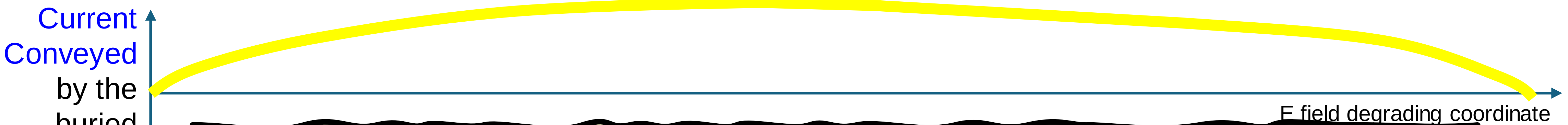
After appluing HV after applying HV (eg -10kV) to the cathode, two phases:

1) **Transient state**: in time scale depending of the contaminated layers resistivity (in our case very short O(10s) time scale) the buried resistive layer become equipotential (setting at intermediate potential -5kV) by drawing charge from the strips

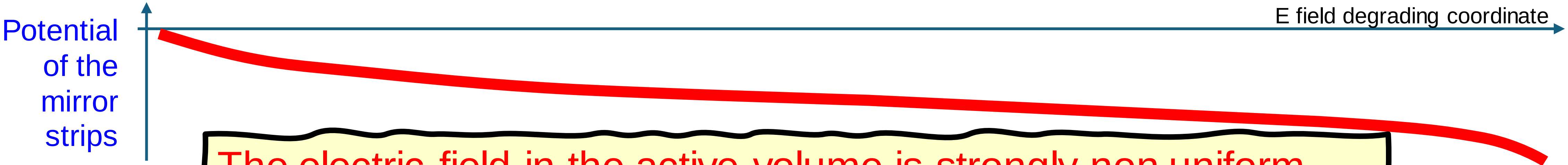
2) **Steady state**:Mirror strips on the Anode half convery current to the buried layer, while mirror strips on the Cathode side draw currents from the buried layer

Buried resistive layer & electrical model





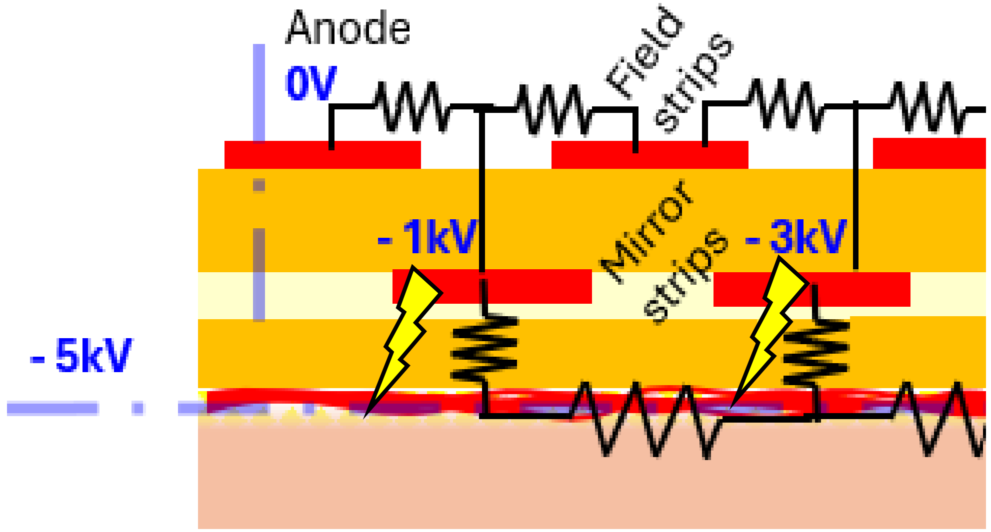
A spurious voltage divider is formed in parallel to the relgular one

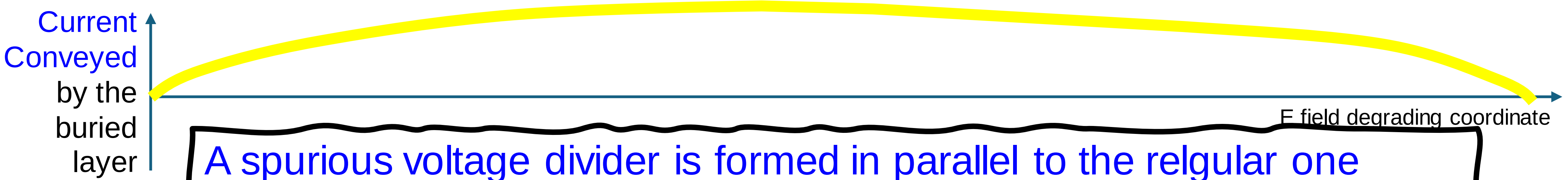


The electric field in the active volume is strongly non uniform

Buried resistive layer & electrical model

In addition, the coverlay Kapton layer may undergo dielectric breakdown especially in the Anode and Cathode regions (large potential gap wrt buried layer)





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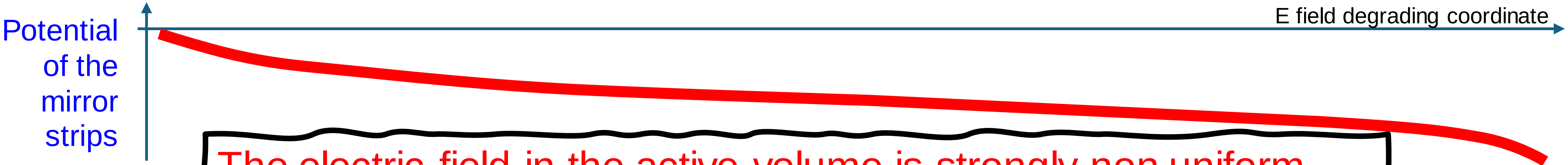
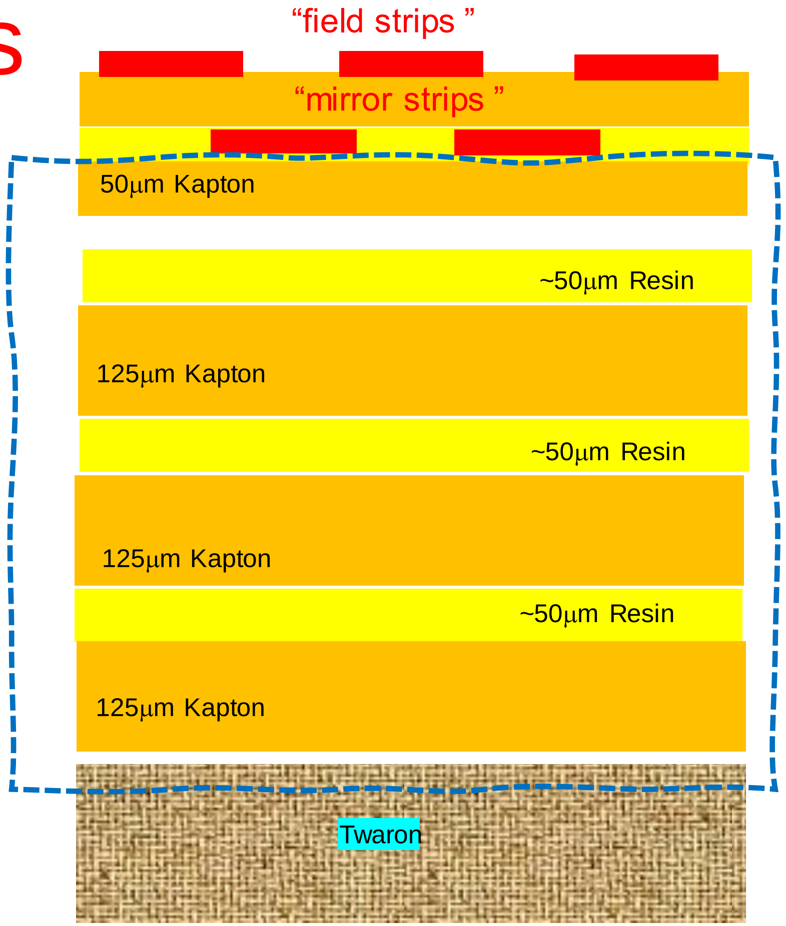


The electric field in the active volume is strongly non uniform

=> final layout, materials and procedures fixed for the series production



Key points to avoid failures

- no resin contamination !!! Note: susually glues and resins are the weakest points
- Interpose between strips and Twaron layers a “thick” layer of insulator featuring
    - High resistivity $\rho_V > 10^{15}$ Ωcm
    - Dielectric strength > 150kV/mm

Final layout of the stack: minimal changes to design

- new strip foil w/ thicker Kapton coverlay 50μm + 25μm glue (produced at CERN, gluing in vacuum with press)
- 3 layers of Kapton: 125μm + 50μm resin each (to be laminated on the back of strip foil on the mold)

→ thickness Kapton+Resin ~0.5mm → “vertical R” below 1 strip O(10TΩ) @ 10kV

Materials: Same insulating materials (Kapton + Aramide) and same resin (Resoltech)

Production procedure and enhanced QC

- Minimize moisture trapped in wall layers: drying in owen Kapton & Twaron just before use
- QC epoxy contaminaiton -> proper control of mixing and de-gasing process (new mixing / degassing tools and QC) and … avoid antistatic spray…
- QC electrical resistivity measurements after each early step in the production

Highlights ERAMs

➡ Production of 50 detectors and Operations experiences

Detector response, signal and impact on reconstruction

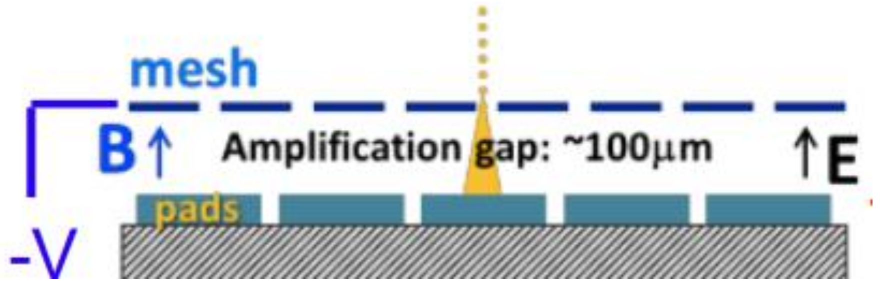
Charge readout – MicroMegas w/ resistive foil

Resistive layer enables Charge spreading
→ space resolution below 500µm with larger pads
→ less FEE channels (lower cost)
→ improved resolution at small drift distance
(where transverse diffusion cannot help)

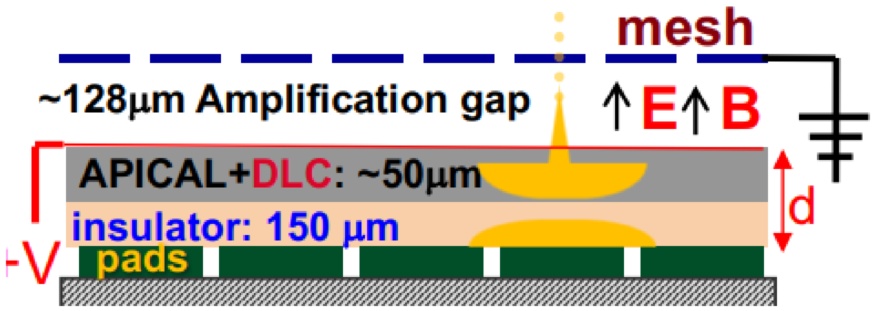
Resistive layer prevents charge build-up and hides sparks
→ enables operation at higher gain
→ no need for spark protection circuits for ASICs
→ compact FEE → max active volume

Resistive layer encapsulated and properly insulated from GND
→ Mesh at ground and Resistive layer at +HV
→ improved field homogeneity → reduced track distortions
→ better shielding from mesh and DLC → potentially better S/N

Standard bulk-MM



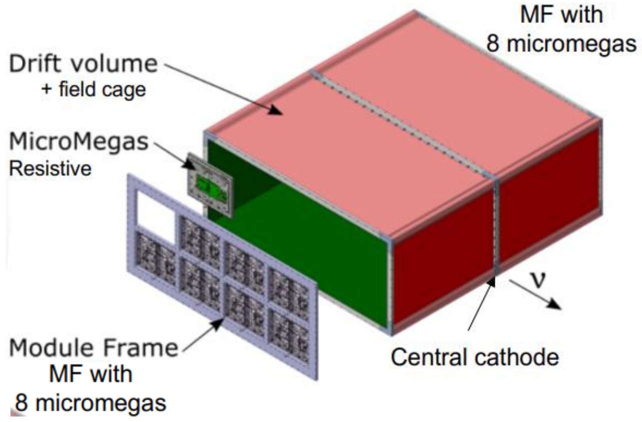
ERAM
= Encapsulated Resistive Anode MM

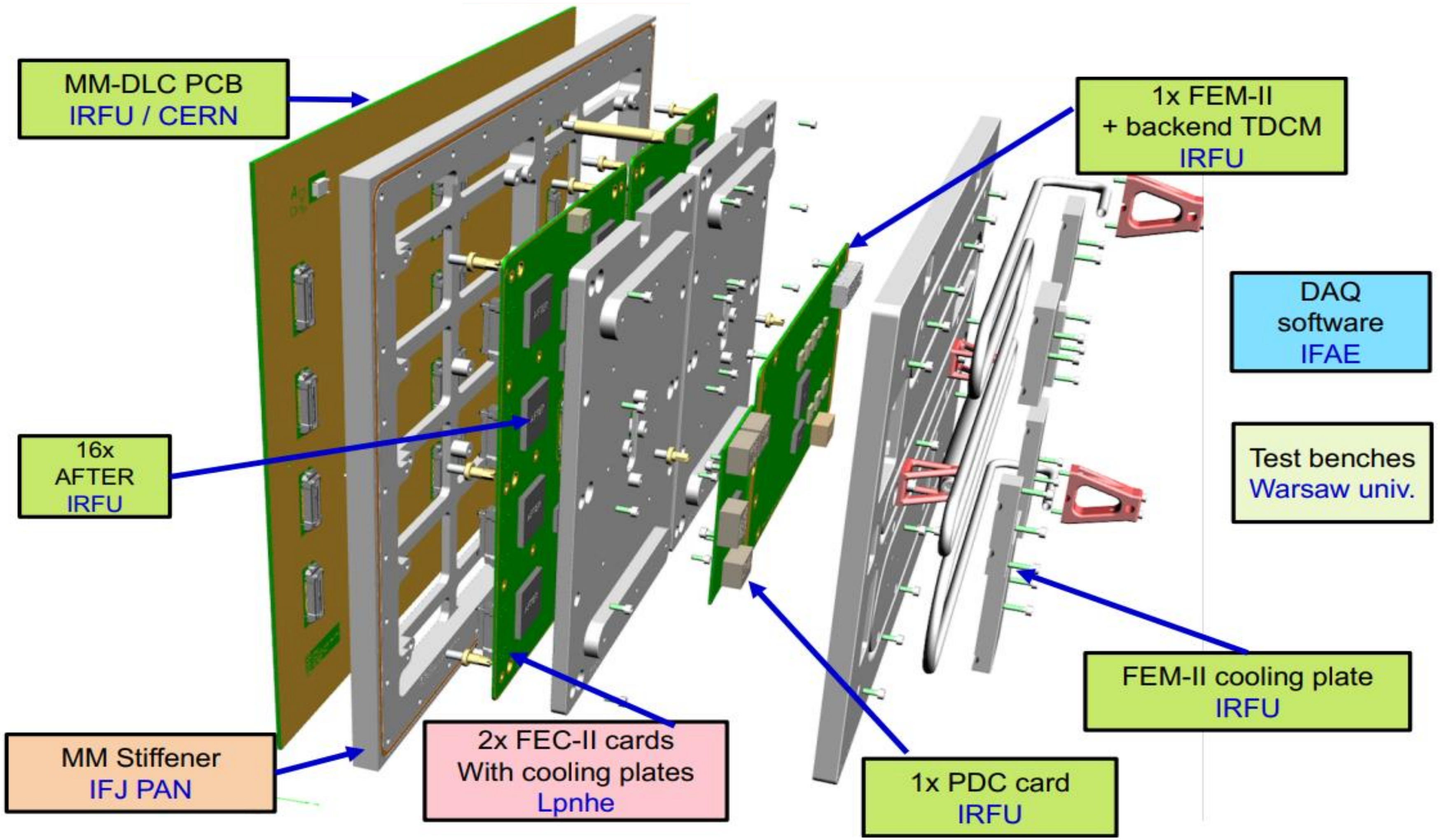


First use of Encapsulated Resistive foil in detector for regular experiment

ERAM module

8 + 8 ERAMs per HATPC





DAQ software IFAE

Test benches Warsaw univ.

Very compact electronics

36x32=1152 pads : 2 x 576 ch. FEC + 1 FEM2 + 1 PDC

Charge spread on low resistivity foil

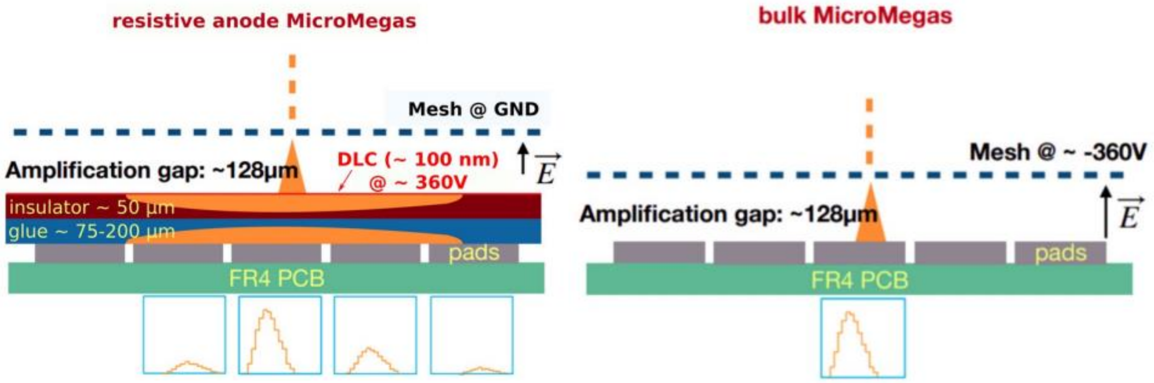
Charge Spreading 2D telegraph eqn. solution in O(RC) time scale

R- surface resistivity
C- capacitance/unit area

Gaussian spread

$$\frac{\partial \rho}{\partial t} = h\left[\frac{\partial^2 \rho}{\partial r^2} + \frac{1}{r}\frac{\partial \rho}{\partial r}\right] \Rightarrow \rho(r,t) = \frac{RC}{2t} e^{-r^2 RC/(4t)}$$

$$\sigma_r = \sqrt{\frac{2t}{RC}} \quad \begin{cases} t \approx \text{shaping time (few 100 ns)} \\ RC_{[ns/mm^2]} = \dfrac{180\, R_{[M\Omega/\blacksquare]}}{d_{[\mu m]}/175} \end{cases}$$

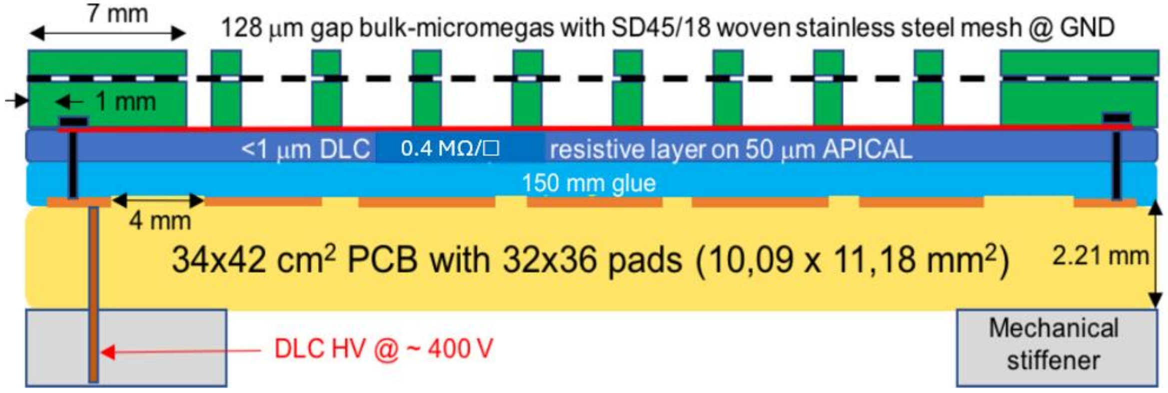


Final ERAM layout choice for series production:

Considering pads of 11x10 mm^2 parameters
- 400 kΩ/□ DLC resistivity – low resistivity
- 150 μm thickness glue – $C_{dlc\text{-}pad/gnd}$ ~ O(20pF)

⇒ RC ~ O(100ns/mm^2)

Trade-off optimal charge spread VS spark protection



Gain not affected by resistivity
(transparency to induced signals is guaranteed)

ERAM Production - about 50 detectors

Crucial steps in production
(CERN MPGD worksohp)

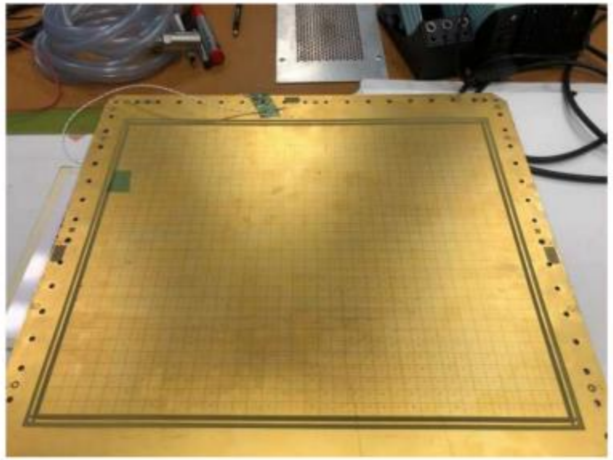
1) Selecting DLC foil resistivity
- Large variations from DLC provider
- Value stable after annealing

2) Gluing steps by Pressing
- DLC to PCB
- Stiffener to DLC-PCB

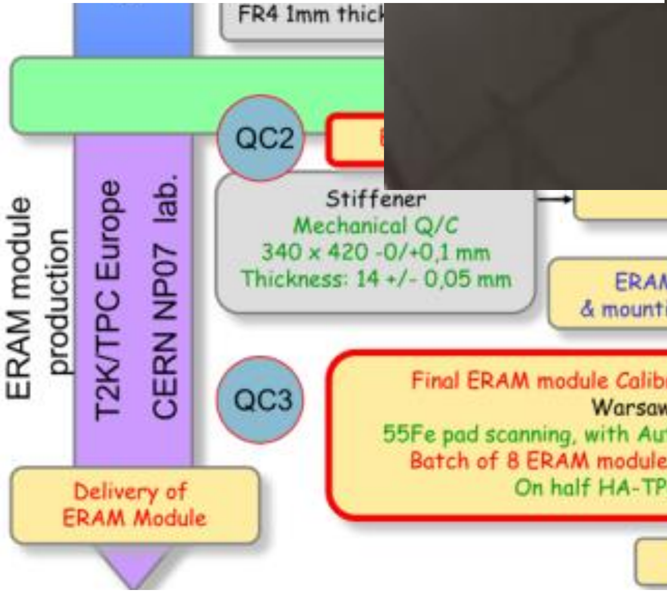
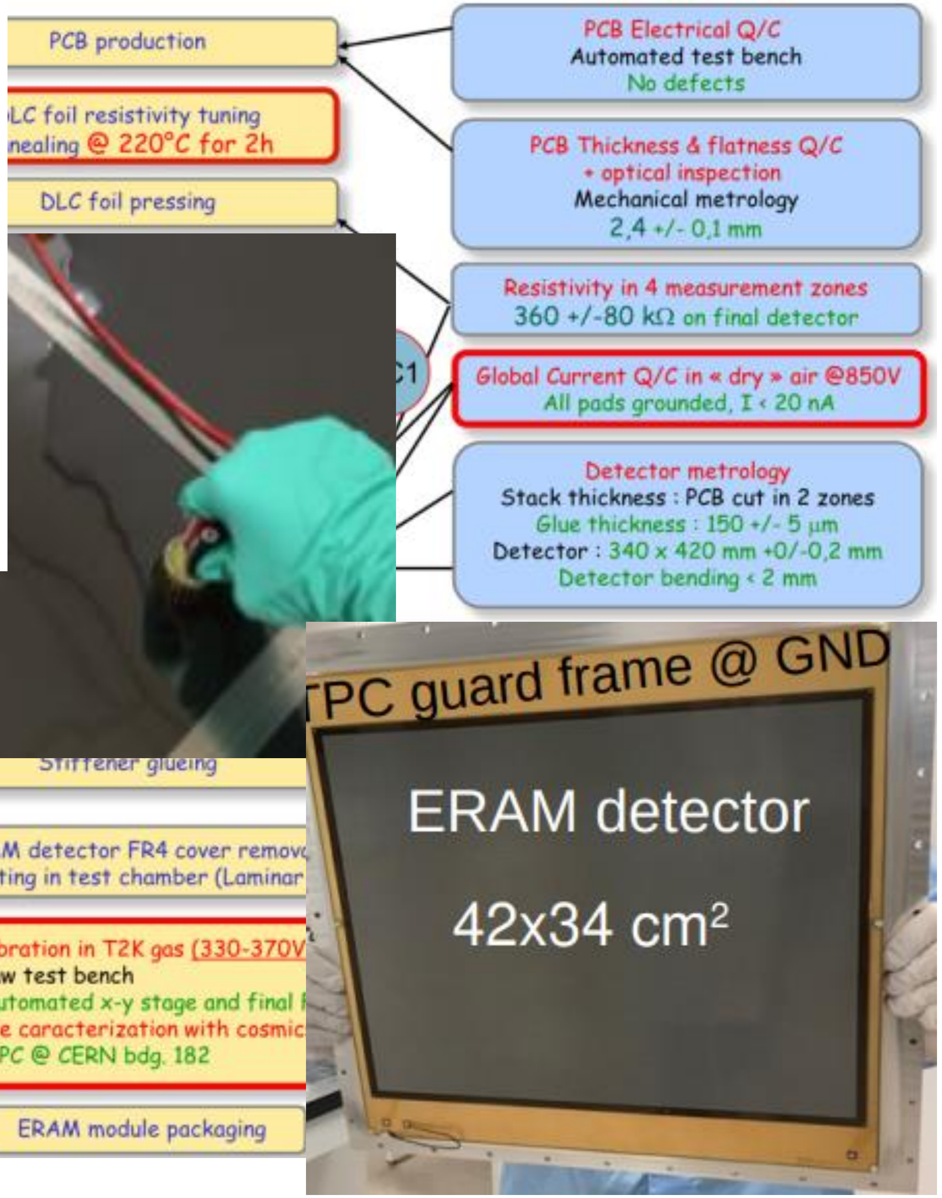
X-rays Test Bench
(CERN, bld 182)

1) Qualify, characterize and calibrate all prototypes and series ERAMs

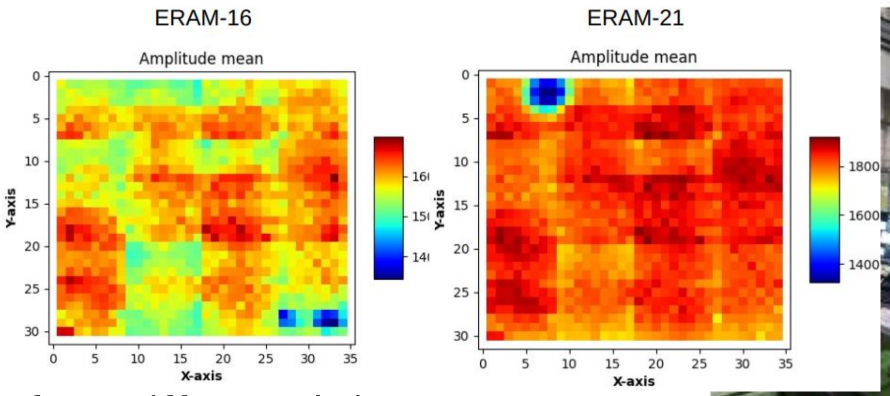
2) support the development of detailed ERAM response model

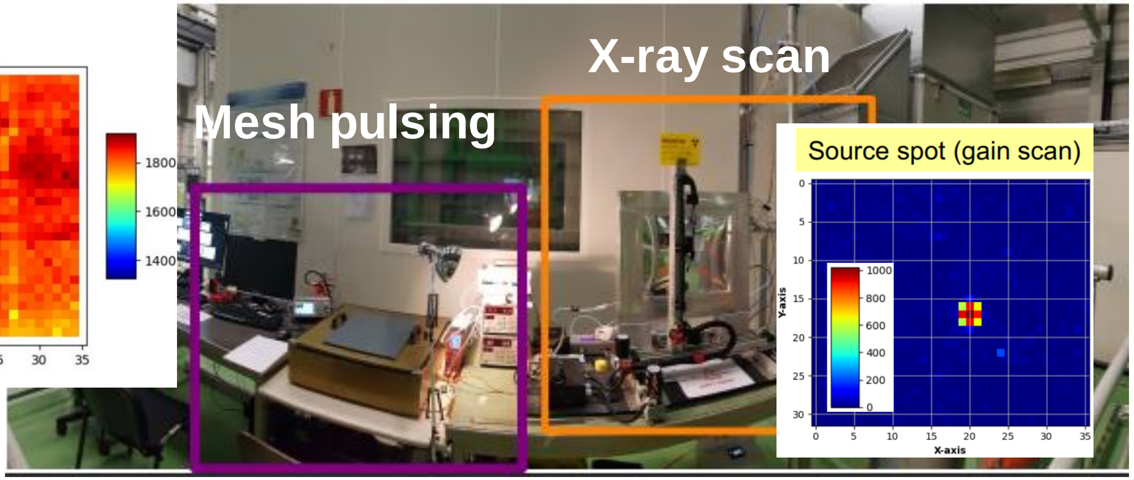


36 x 32 metallic pads
Pad size (mm²) : 11.28 x 10.19

ERAM Series Production experience





Mesh pulsing before and after stiffener gluing

Aim: detector geom, R, C, defects (eg pillar detach), stiffener gluing issues, electronic noise

X-ray scan of finalized detectors with final electronic modules

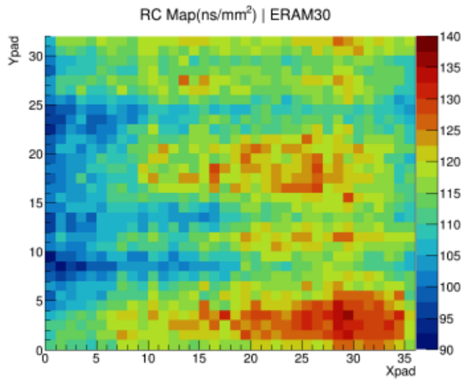
Remote controlled station for scannig with mm step fine steps

Aim: QC and fine calibration in terms of gain, resolution and RC

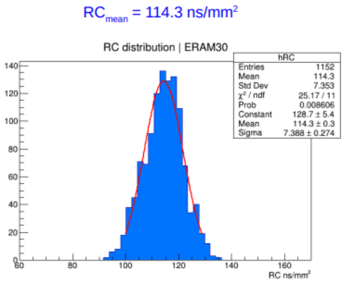
X-rays Test Bench at CERN was fundamental to

1) Qualify, characterize and calibrate all prototypes and series ERAMs

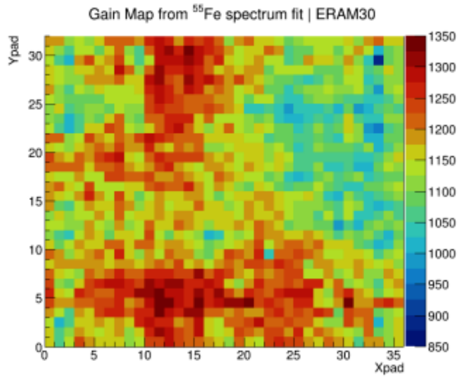
2) support the development of detailed ERAM response model



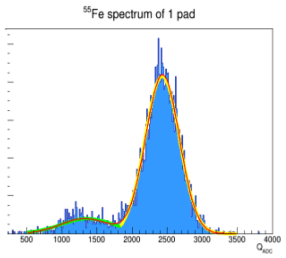
RC map of ERAM30



RC distribution of ERAM30



Gain map of ERAM30



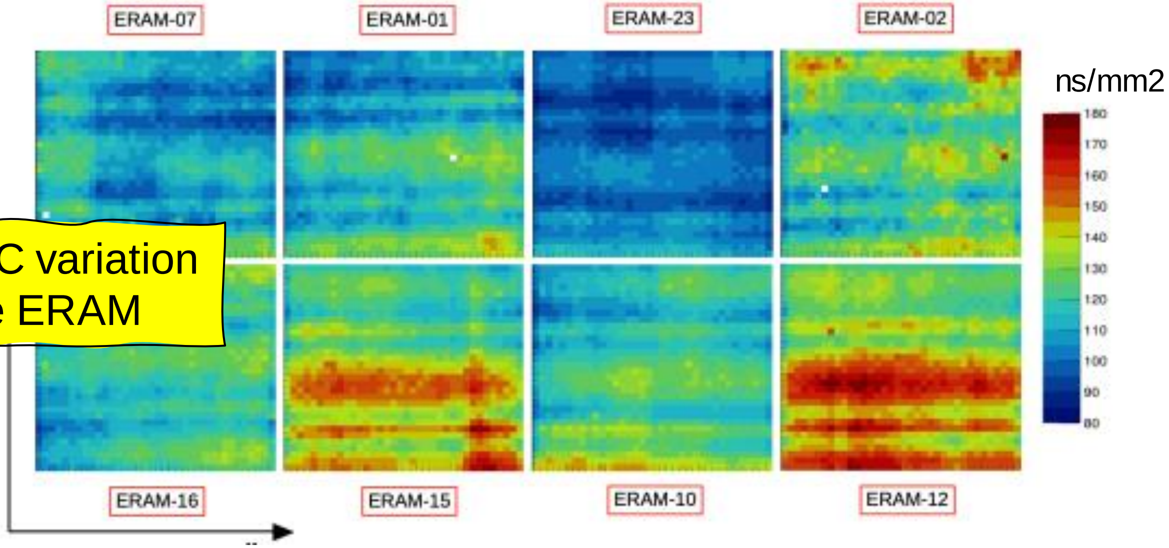
ERAM Series Production experience

Production steps most painful (needed long tuning)

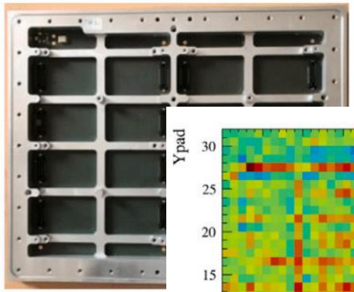
1) Selecting DLC foil resistivity
- Large variations from DLC provider
- Stable values only after annealing

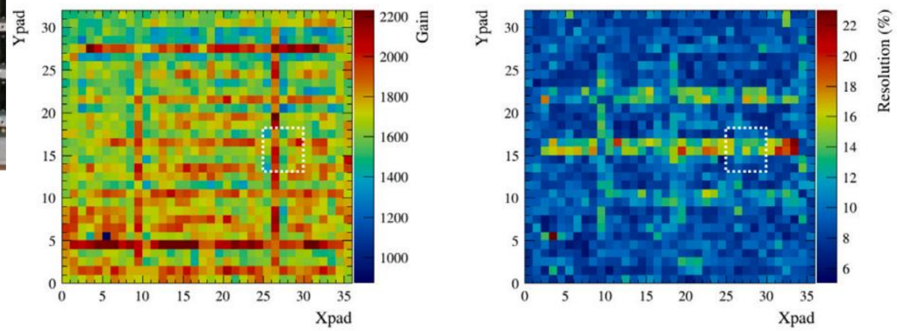
2) Gluing steps by Pressing
- DLC to PCB
- Stiffener to DLC-PCB

RC map of ERAMS on bottom HATPC EP1

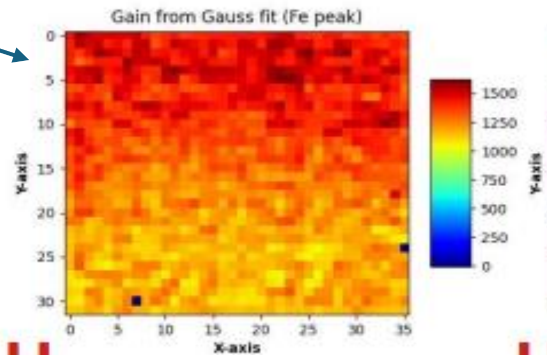


up 20% RC variation over same ERAM

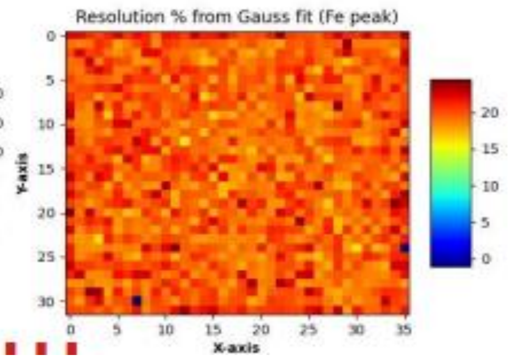




ERAM with DLC-PCB gluing issue

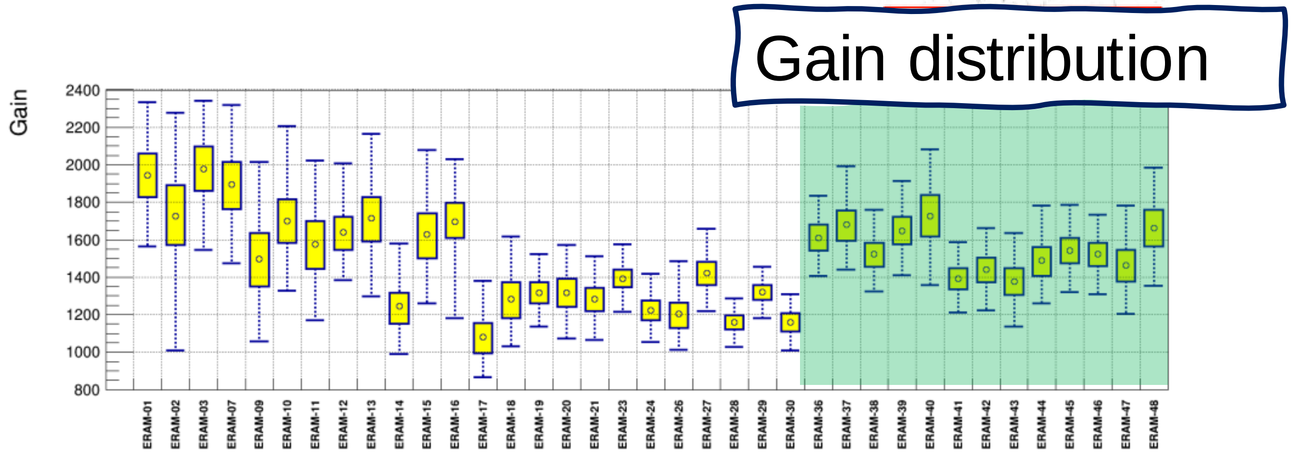


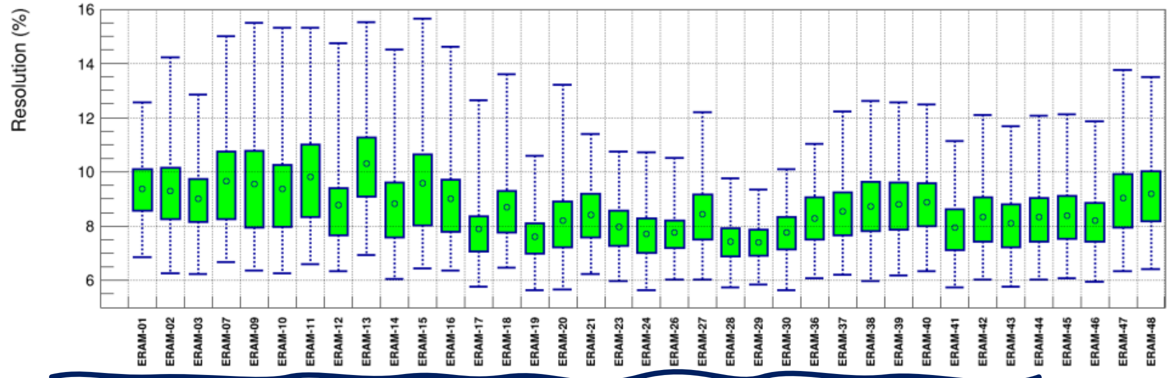
Gain map of ERAM OK

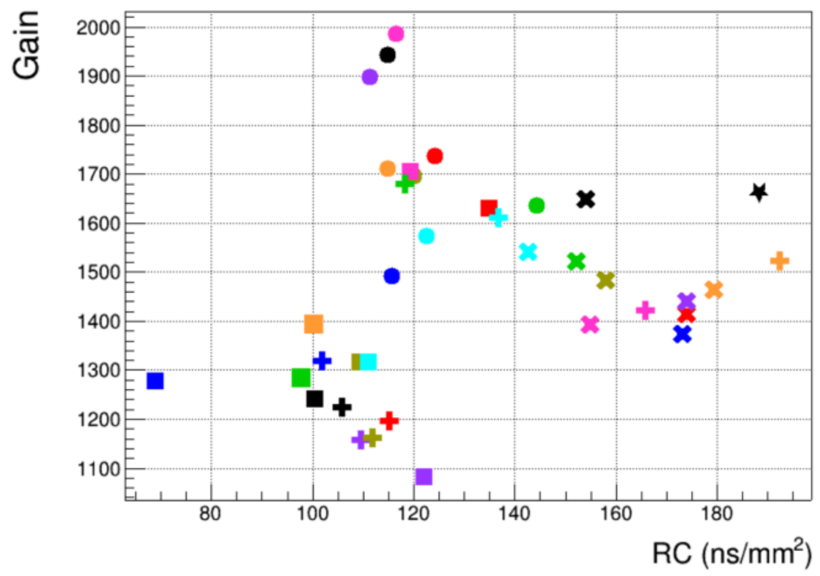


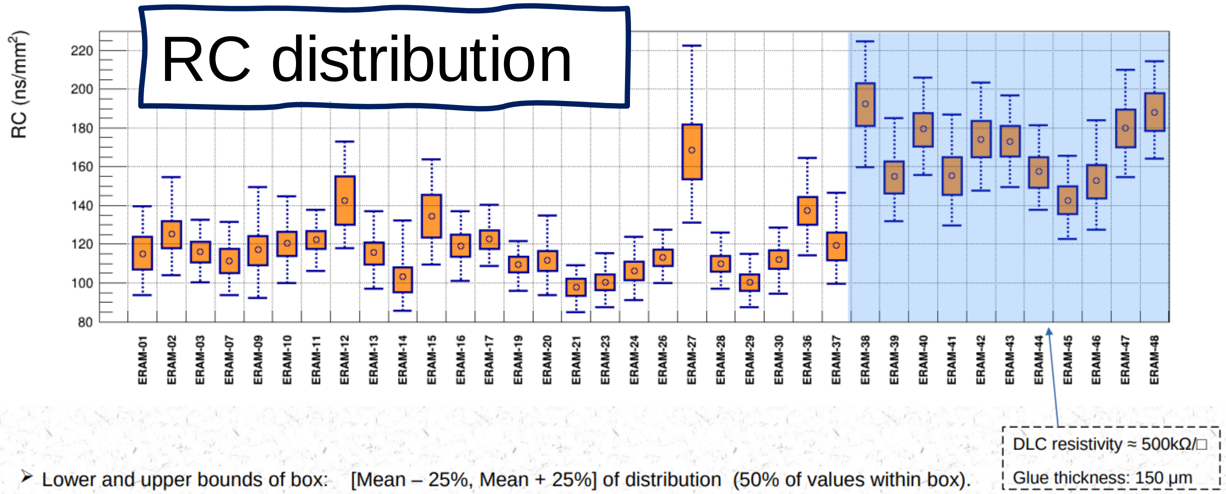
1µm mesh-DLC gap variation => 10% variation in gain

ERAM Series Production experience









- 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).

ERAM Assembly and Operation experience

Low resistivity DLC O(500kΩ/□) [after annealing] features
- Optimal charge spread → uniform response across pad (combined with C ~ O(20pF/cm^2))
- Fast Q removal and Effective Protection agains sparks included at moderate rates ~ O(1kHz) tracks crossin pads
- Leakage currents at level of few nA in normal conditions (no beam)

Annoying aspects

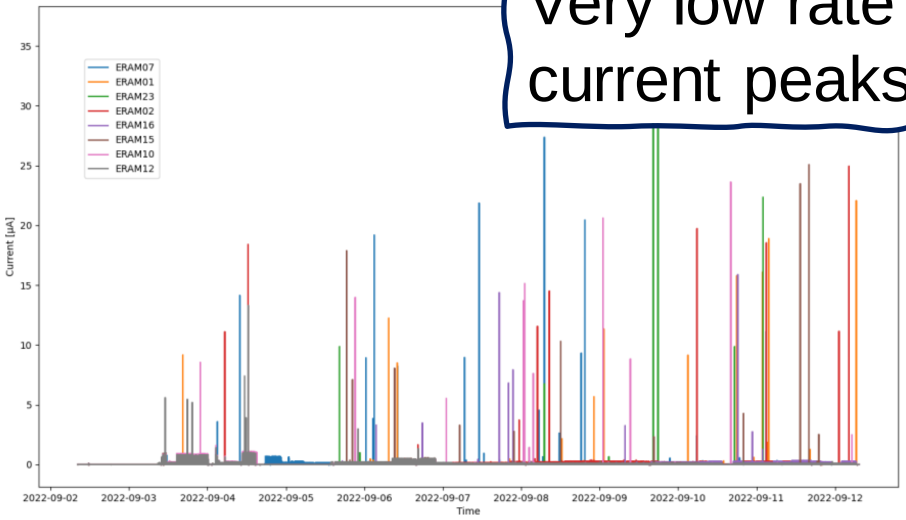
→ high sensitivity to dust
→ low H2O level (100ppm) before HV on

ERAM assembly (and storage) in Clean Room

Grey tent area in front of Clean Room
large entrance for enhanced clean conditions

ERAM @ test beam 2022

ERAM stability
- We have operated 8 ERAM modules during ~ 7.7 days @ CERN 2022
  - Intense beam activity
  - One ERAM module was not working during cosmic test (solved by hammering on it)
- **We have observed no major issue**
- The spark rate is between 0.8 and 1.7 per day (higher than 2uA)



Very low rate of current peaks

Highlights ERAMs

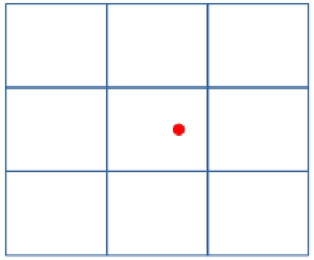
Production of 50 detectors and Operations experiences

→ Detector response, signal and impact on reconstruction

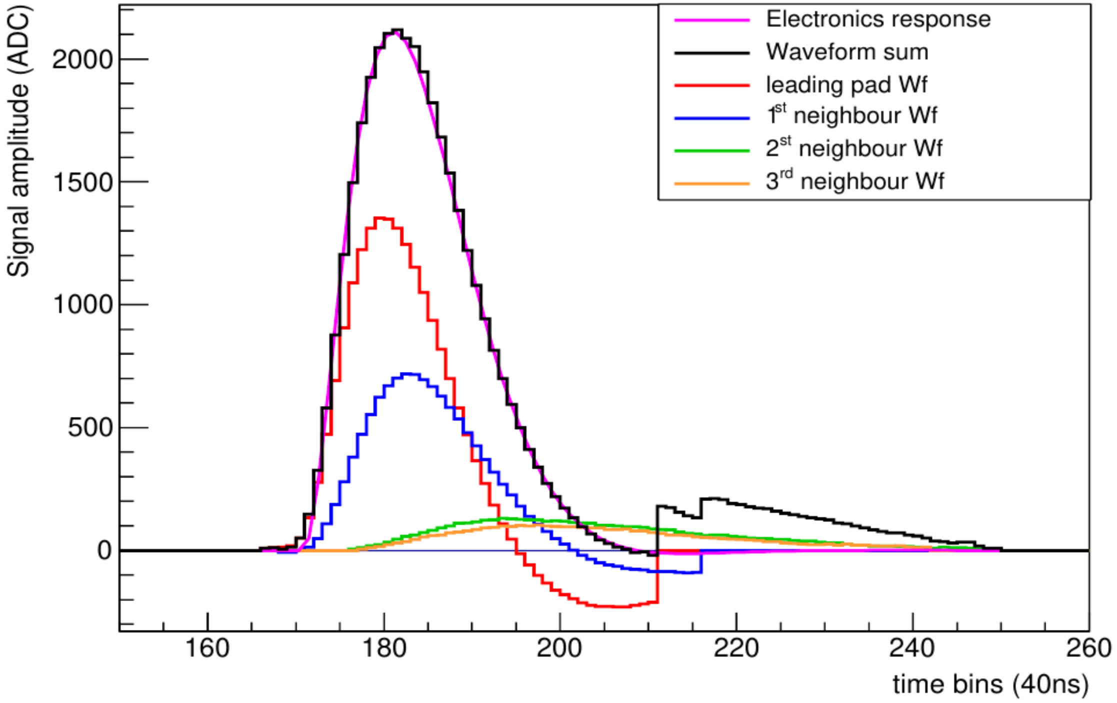
ERAM detector response – Signal formation

How does the signal look ? point deposition for example

Charge deposited punctually on a pad (X ray)



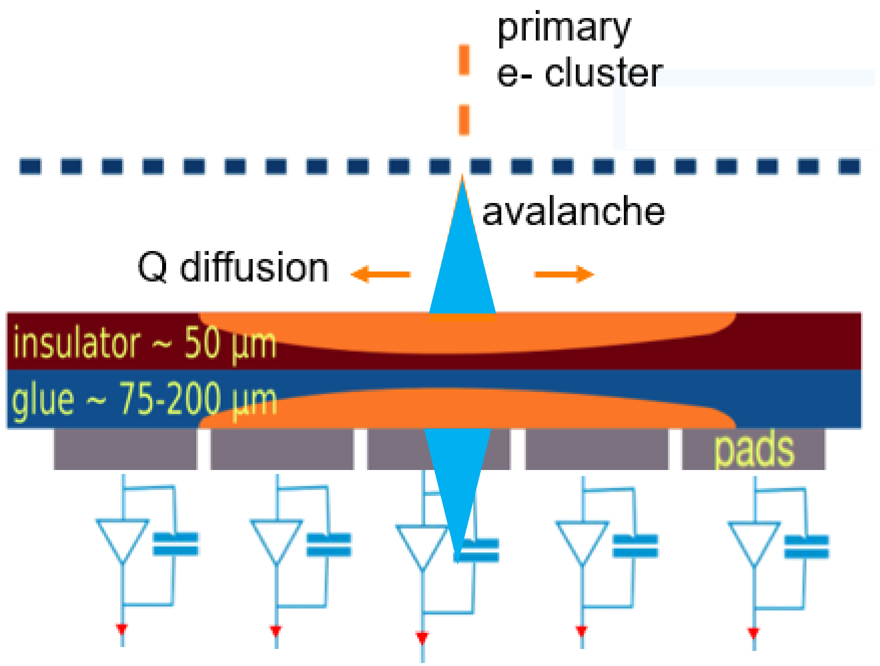
ADC signal : max 4096 counts
Time window of 511 time bins
Time bin (typ.): 40 ns (25 MHz sampling)
Peaking time (typ.) : 412 ns

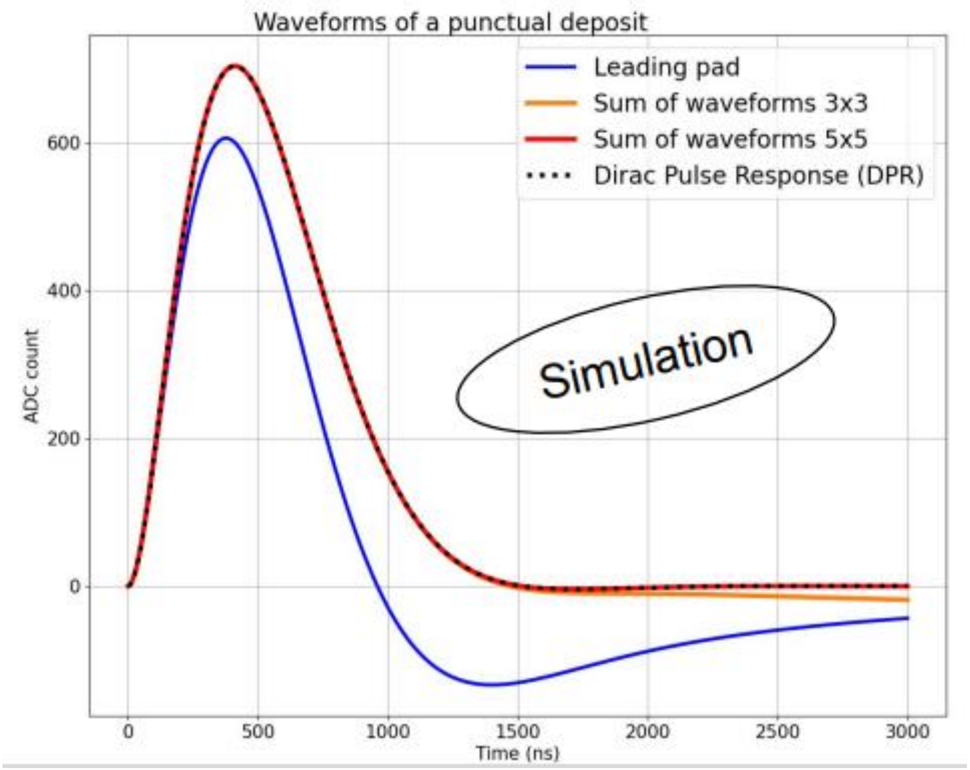


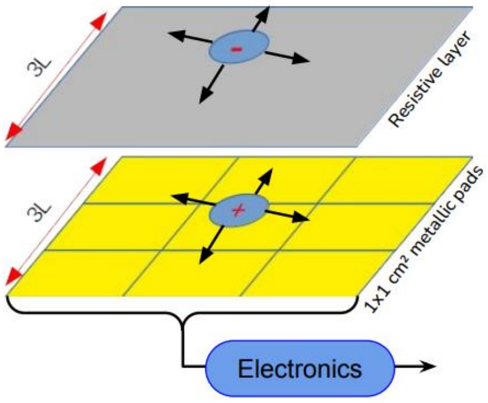
Leading pad: highest and earliest signal
⇒ current induced on pads from by avalanche, ie **ions** signal (as electrons' signal is too fast)

Adjacent pads: lower and later signals
⇒ current induced by potential field adjustments after **electrons** are collected by on DLC
(current induction by "charge spread on resistive layer")

Reconstruction of charge deposition



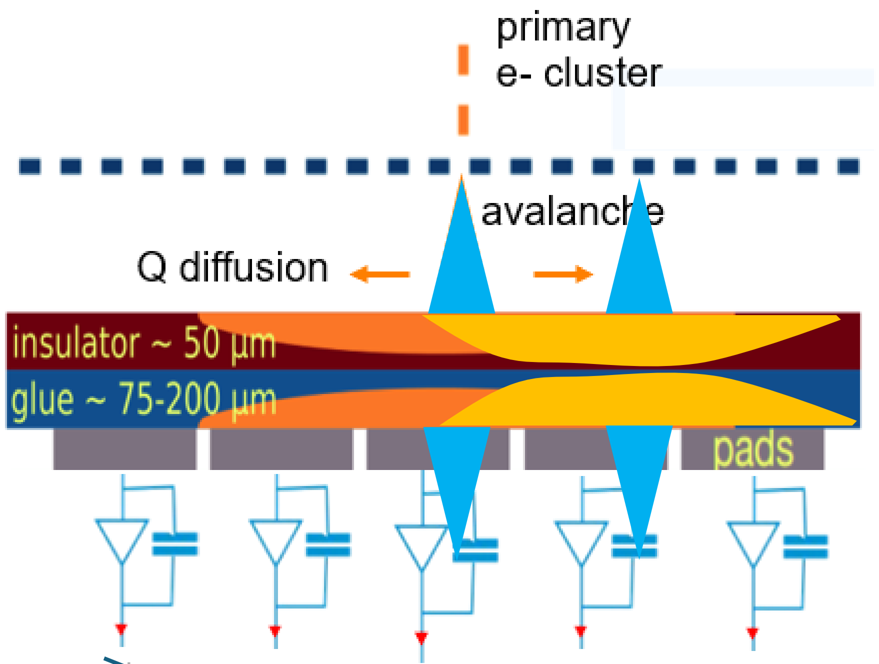


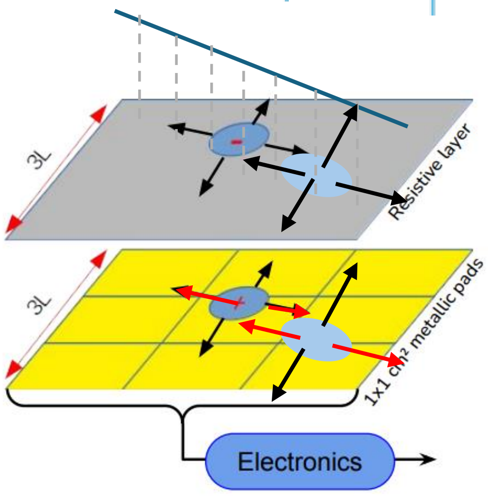


Recovering information about deposited Q is not trivial

Within our electronics shaping time scale
in primary pads, the signal of ions is «diluted» by the signal of charge spreading
=> Need combinig information of all pads (primary and secondary)

Reconstruction of charge deposition





Recovering information about deposited Q is not trivial

Charge on DLC spreads along any direction including track direction
«longitudinal correlation» across primary pads within our electronics shaping time scale

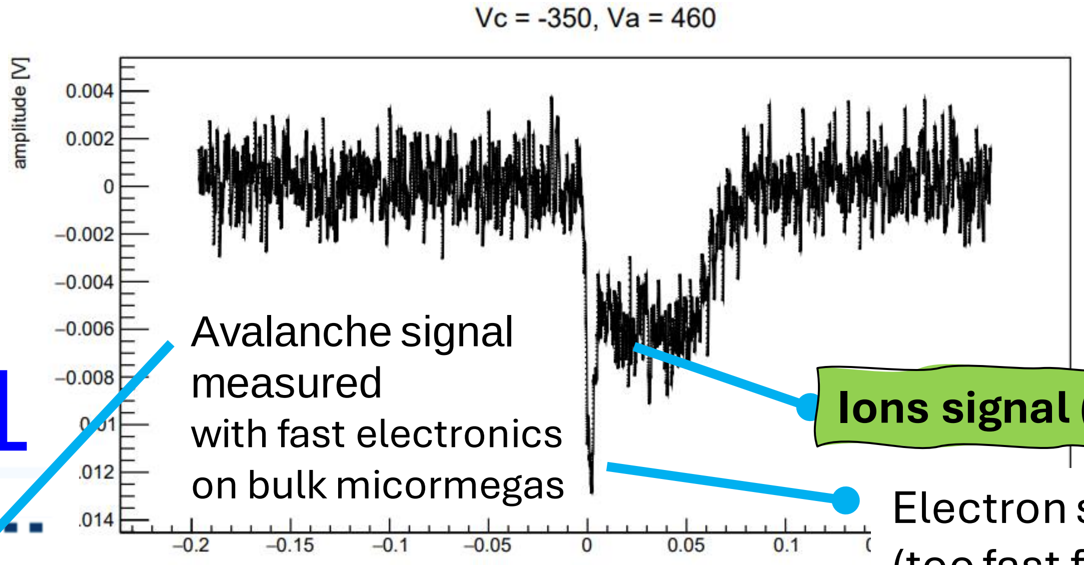
ERAM response – Signal formation model

Main ingredients

In the time scale ot our shaping time O(100ns)
Charge spread is properly described by

Solutions of 2D diffusion eqn.

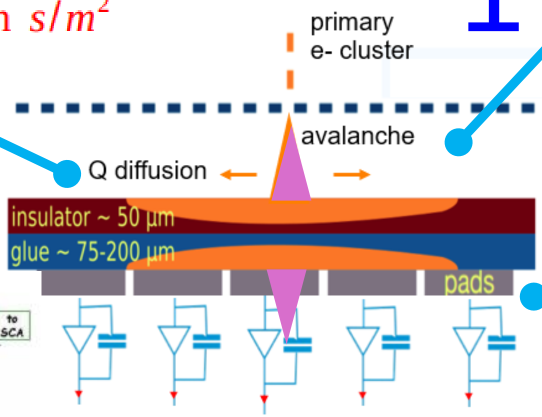
$$\Rightarrow \frac{\partial^2 \rho}{\partial^2 t} = \frac{1}{RC}\left(\frac{\partial^2 \rho}{\partial^2 x} + \frac{\partial^2 \rho}{\partial^2 y}\right) \quad \text{with } RC = \frac{C_S}{\sigma} \text{ in } s/m^2$$



1 Avalanche signal measured with fast electronics on bulk micormegas

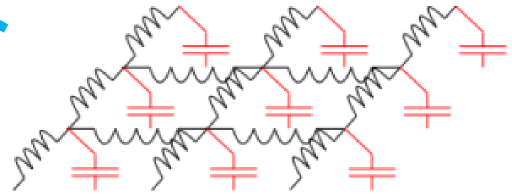
Ions signal (slow)

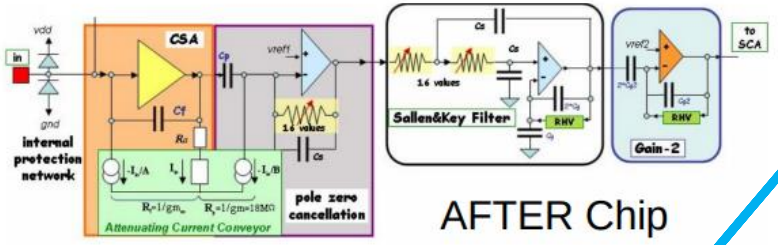
Electron signal (too fast for our shaping times)



2

3 **Electrical model of the sensor**





AFTER Chip

4

FEE Response Function

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

w_s~1/Peaking time and Q quality factor

Note: of course **gas transport properties** (L, T diffusion) have to be accounted for

ERAM detector response – Reconstruction

Use of the model for Reconstructing the charge deposition

Due to square shape of ERAM pads, the classical method (PRF+clustering) works OK only for tracks with horizontal or vertical direction (wrt pads coordinates)

Better methods use solutions of 1D or 2D telegraph equation in order to

1) diffuse template patterns charge on DLC
2) calculate the overall expected signal waveform per each pad and
3) find the best matching with the recorded waveforms

Its computationnaly heavy => different approximations are used for different analysis some examples → illustration algorithoms and TPC performances

1) X-rays analysis – ERAM characterization
2) Measurement of dE/dx – Particle Identification
3) Track reconstruction – momentum measurement

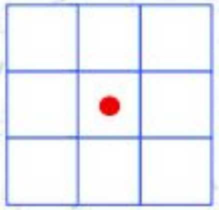
Reconstructing x-rays

Qpad(t) = Solution of 2D Teq. for diffusion of initital Qe deposited charge (point-like, delta-pulse initial conditions)

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

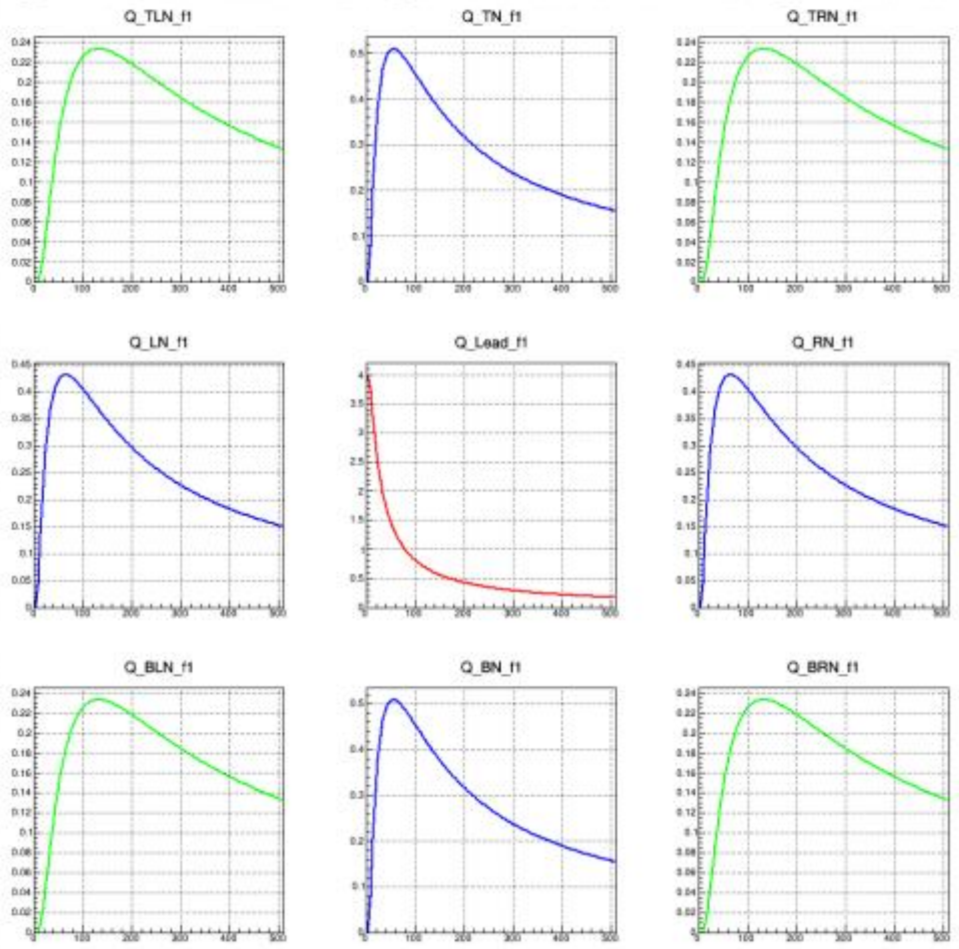
$$\sigma(t) = \sqrt{\frac{2t}{RC}}$$

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



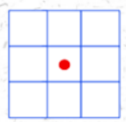
x_H, x_L: Upper and lower bound of a pad in x-direction
y_H, y_L: Upper and lower bound of a pad in y-direction

RC = 60 ns/mm²
$Q_e = 4\ e^-$

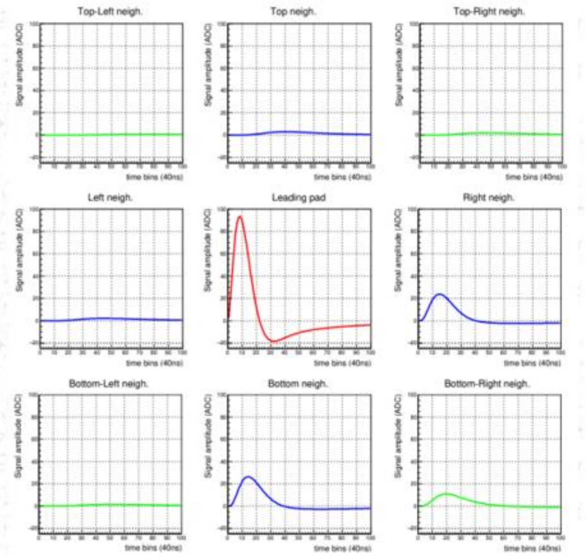


Reconstructing x-rays

Current induced on a pad dQpad(t) / dt
to be convoluted with
electronics transfer function R(t)
$dQ/dt \otimes R(t) = Q(t) \otimes dR(t)/dt$
$Q(t) \otimes dR(t)/dt$ is more practical



WF templates



Simultaneous fit of waveforms of
Leading pad + Neighbouring pads
to get the best 5 parameters

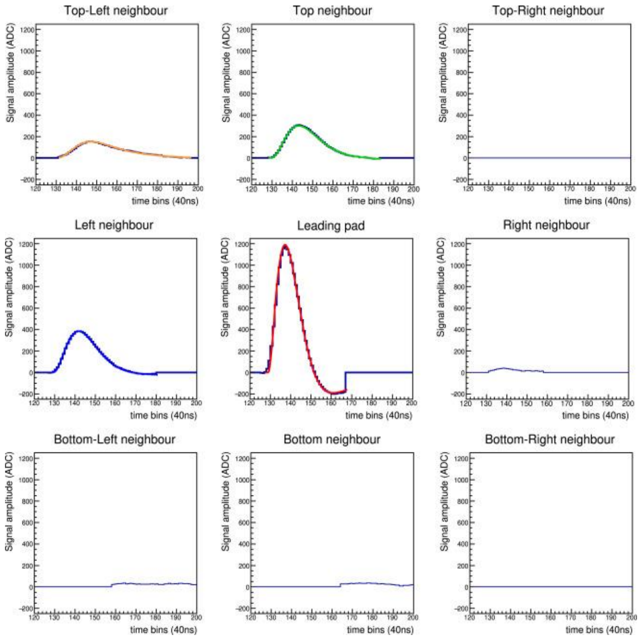
- x_0
- y_0

} Initial charge position

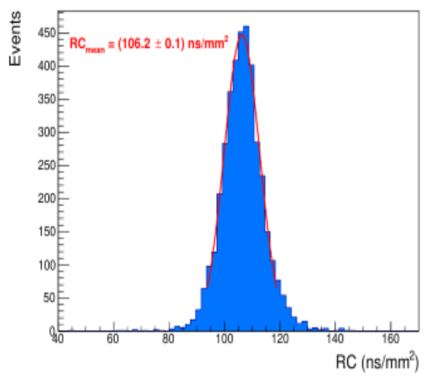
- t_0: Time of charge deposition in leading pad
- RC : Describes charge spreading
- Q_e : Total charge deposited in an event

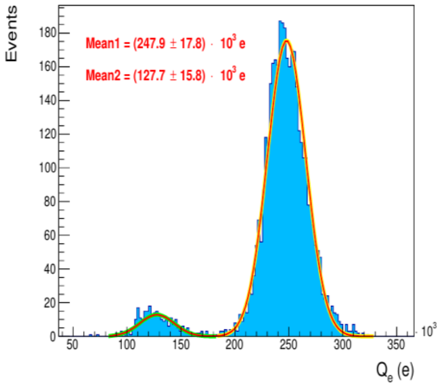
x_H, x_L: Upper and lower bound of a pad in x-direction
y_H, y_L: Upper and lower bound of a pad in y-direction

WF fit against templates



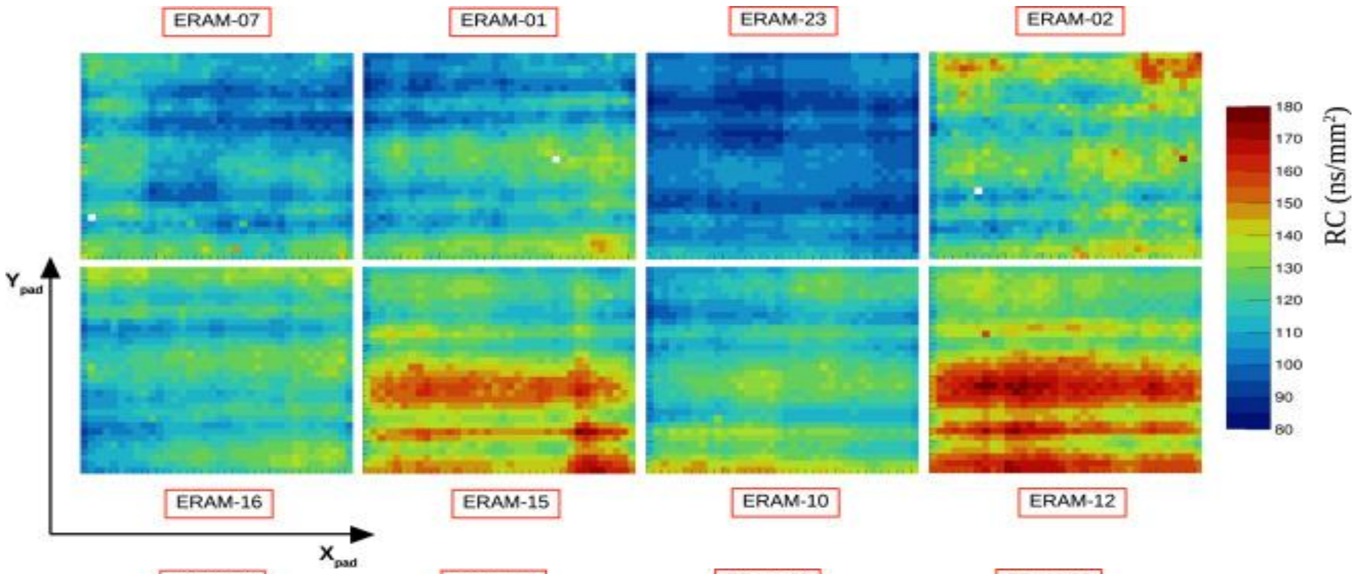
Results about Gain and RC

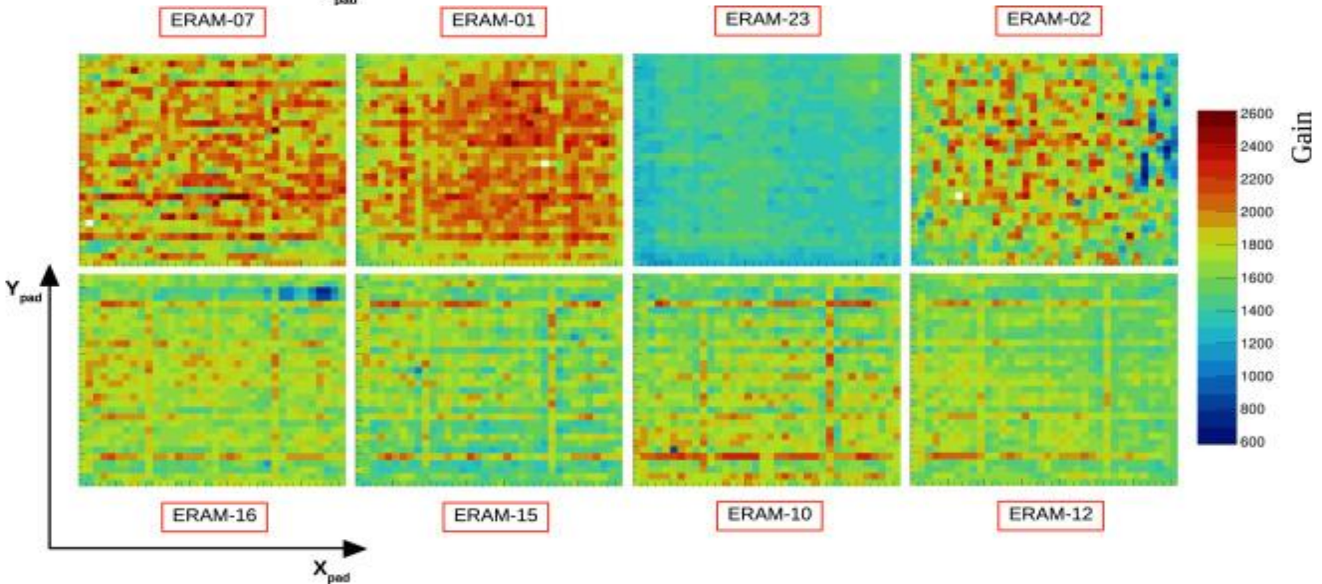




x-rays → RC & Gain maps

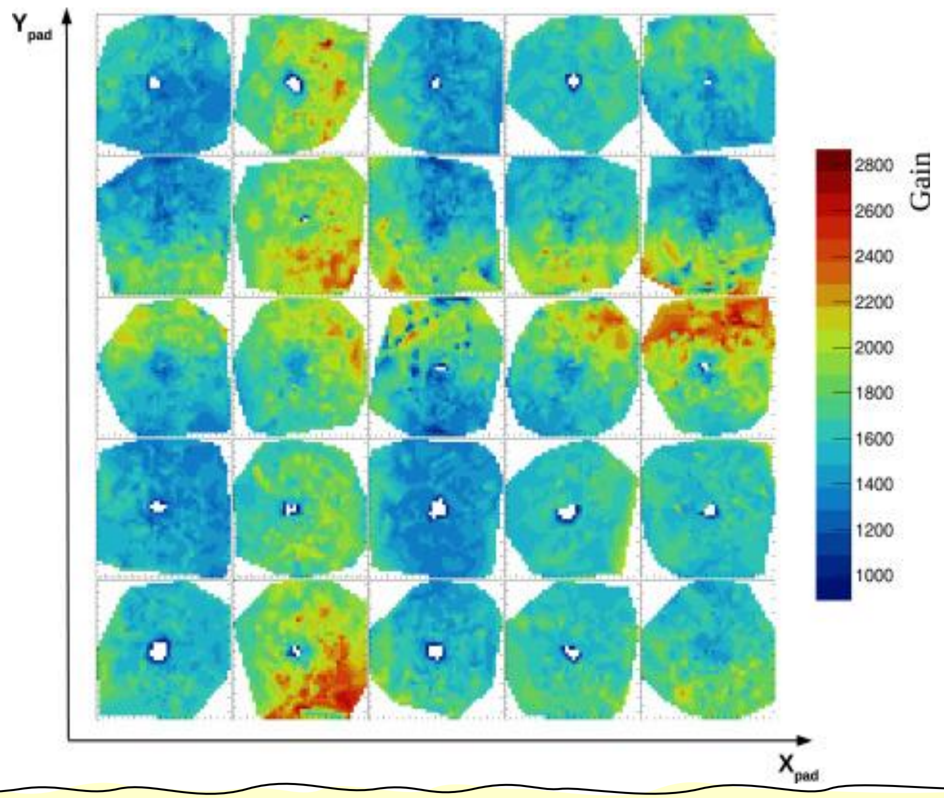
Use for calibrartion of top and bottom HATPC ERAM GAIN





X-ray conversion position is also fitted
=> accurate maps of Gain and RC

Use for detailed stiudies of charge diffusion and ERAM response at fine PAD position level



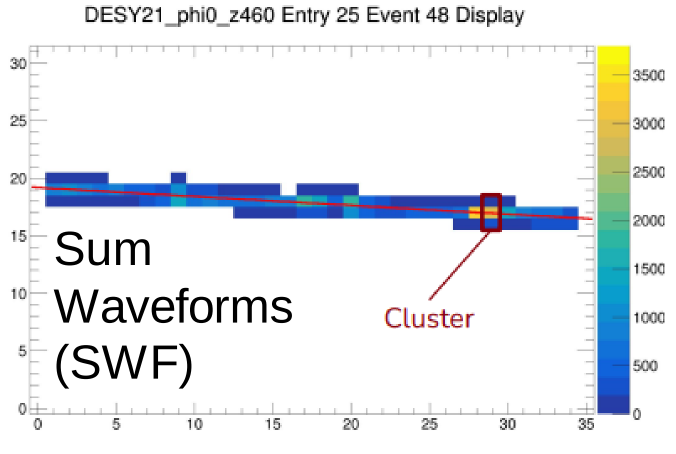
Indications are that the **lower resistivity** the **better performances** (eg space resolution)

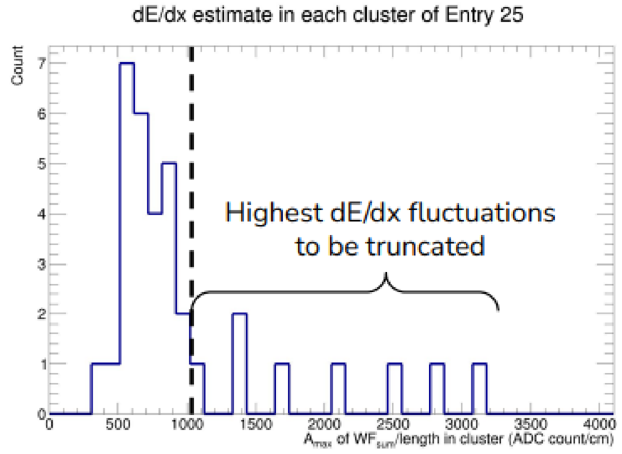
Reconstructing Q along tracks → dE/dx

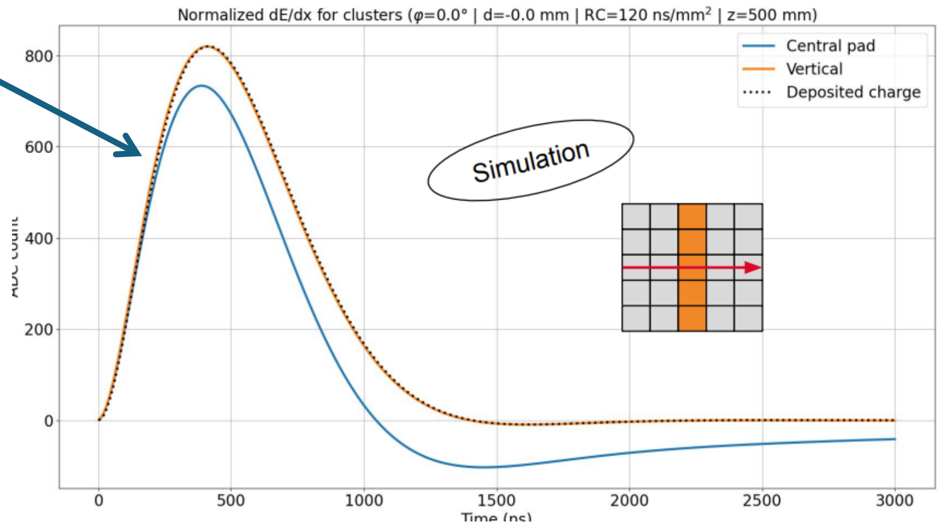
Simple method based on
Sum of waveforms(t) (SWF)
over pads in a cluster

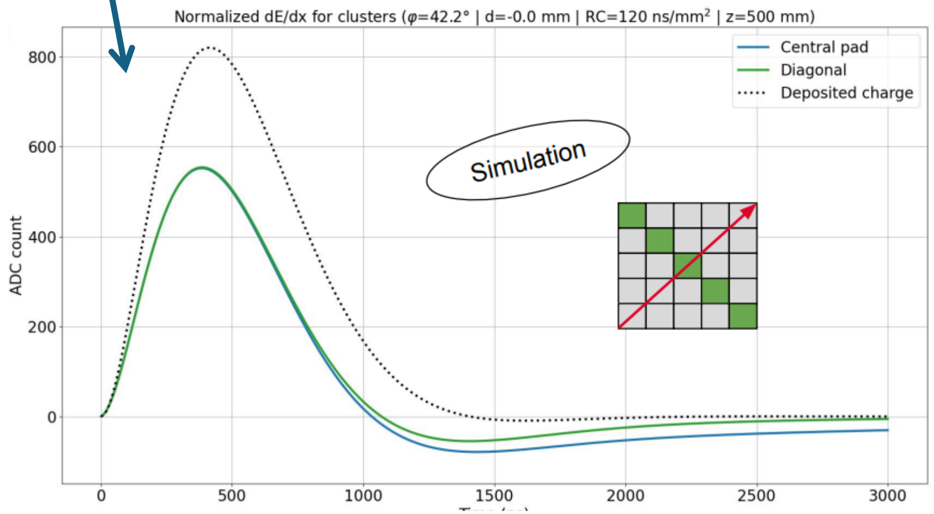
OK for almost H & V tracks

Q missing for inclinded tracks









1. Clusterize the pads into slices and sum the waveforms in each slice to get dE

2. Get the track length in each cluster to get dx

3. Truncate the clusters with the highest dE/dx (top 30%) to get rid of fluctuations

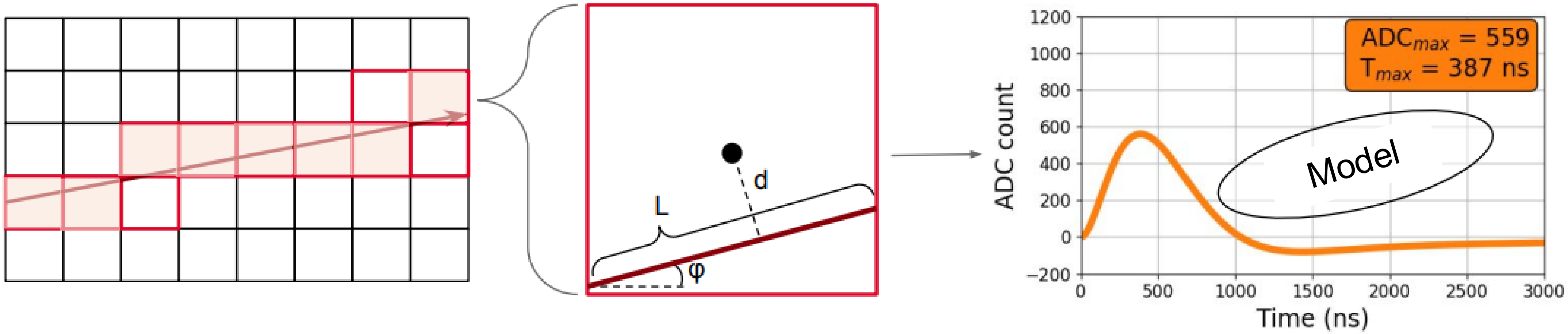
just like for vertical TPCs!

4. Get the mean over remaining estimates dE/dx

Reconstructing Q along tracks → dE/dx

Method of «crossed Pads» (XP)

1) Reconstruct tracks and consider only pads crossed (XP) by the track (primary pads)
2) Reconstruct original (ion induced) charge (Q) for each XP (given the track parameters there)
   by Q = A x (Q/A) – where A is recorded amplitude on XP and rescaling ratio (Q/A) from Look Up tables (LUT)
1) LUTs build from model: original Q is distrubuted linearly over the segment for each XP
   so that solutions of 1D diffusion equations can be used



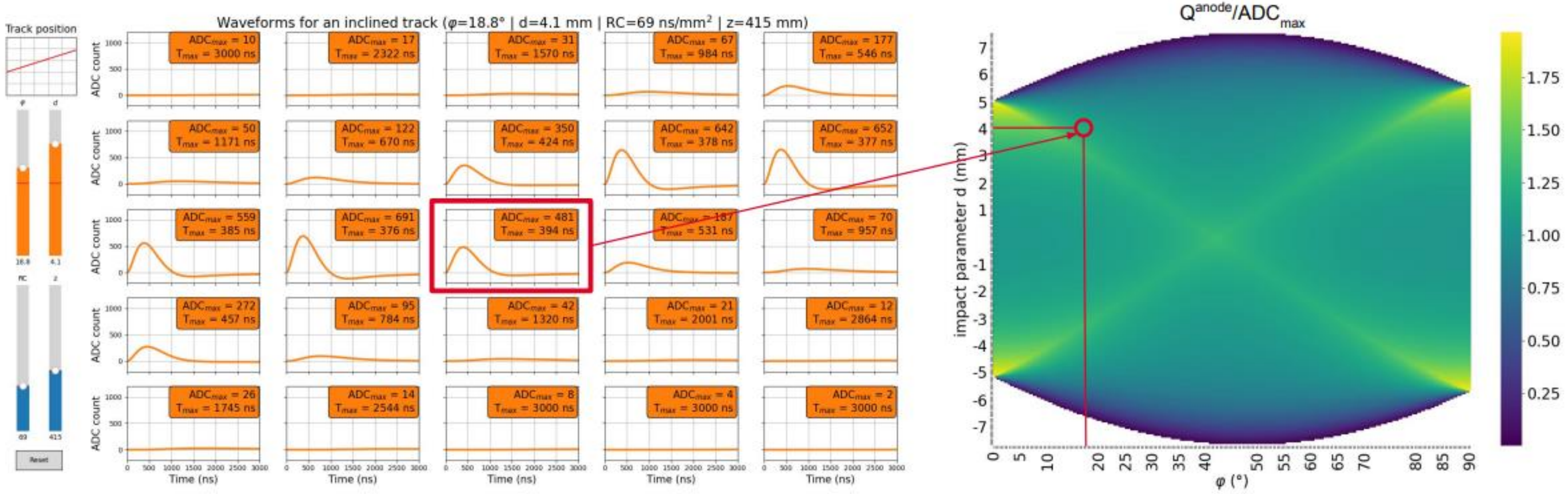
1) No clustering => potentially more accurate method because reconstructing full induced charge on primary pads
2) «dilution of ion signal» on a XP pad, due to charge spread over the pad is correctly taken into account
3) «longitudinal correlation» among adjacent XP pads, due to charge spread along track direnction, accounted for
4) Fast method though based on model templates (long time is to generate LUTs …)

Reconstructing Q along tracks → dE/dx

Building the rescaling ratio Q/A ratio 4D LUTs via model

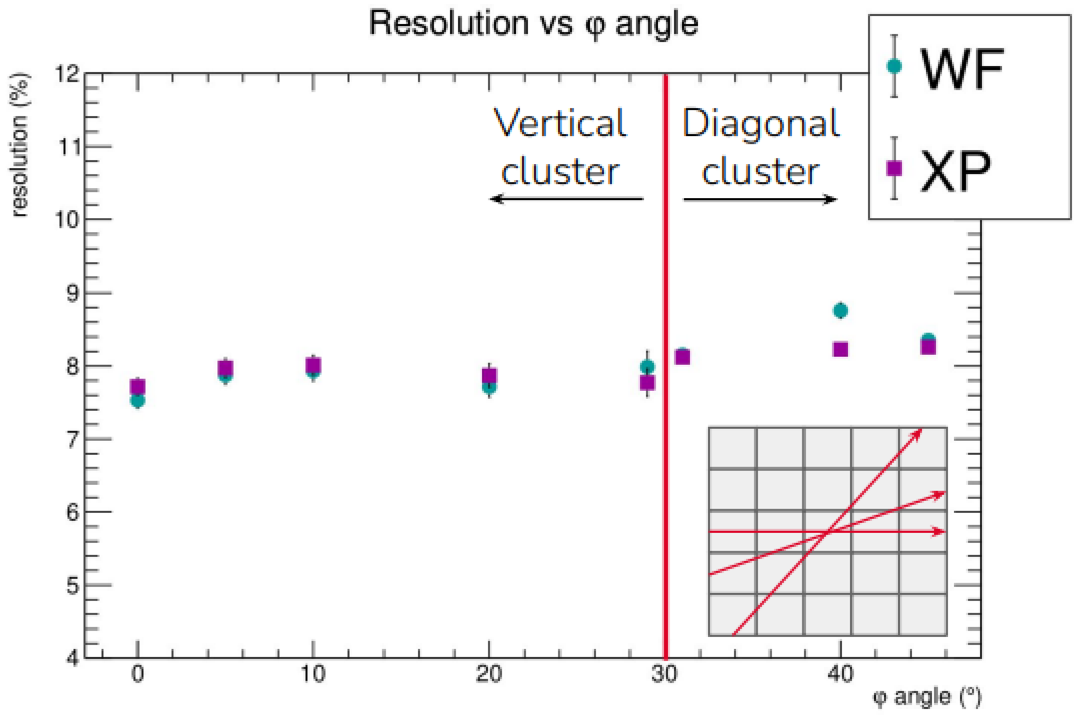
4D Look-Up Table (**LUT**):

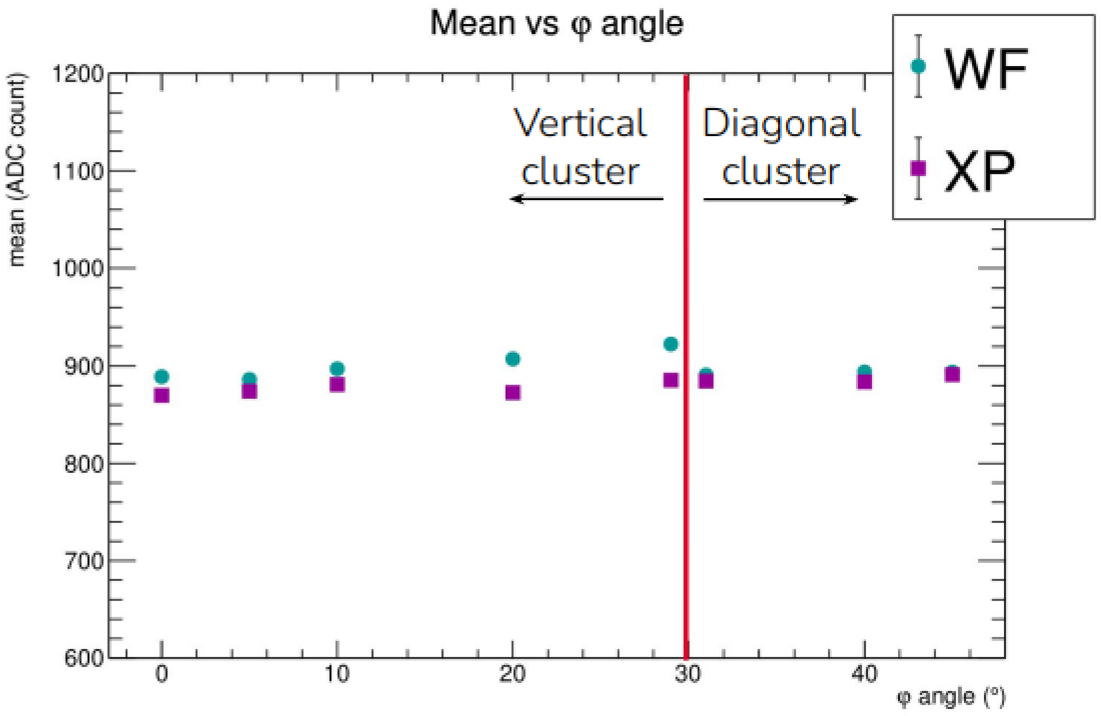
- Angle **φ**: 200 steps [0°, 90°]
- Impact parameter: 200 steps [-7.3, +7.3] mm
- Drift distance: 21 steps [0, 1] m
- RC: 21 steps [50, 150] ns/mm²



dE/dx preliminary results

dE/dx (4GeV electrons) – comparison of SWF and XP methods on Test Beam data (DESY)



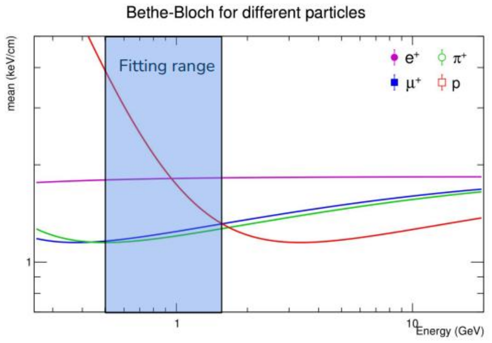


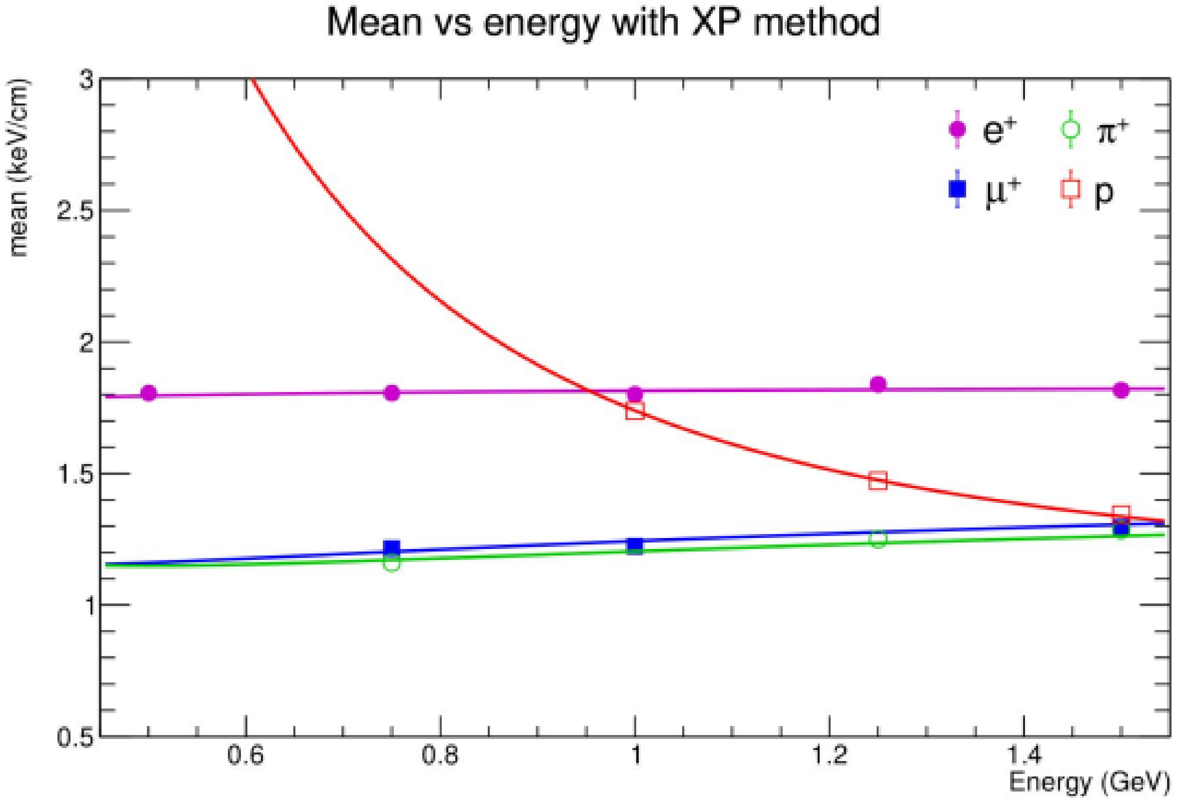
- Resolution σ/μ ~ 8% and stable
- XP gives better results at diagonal angle

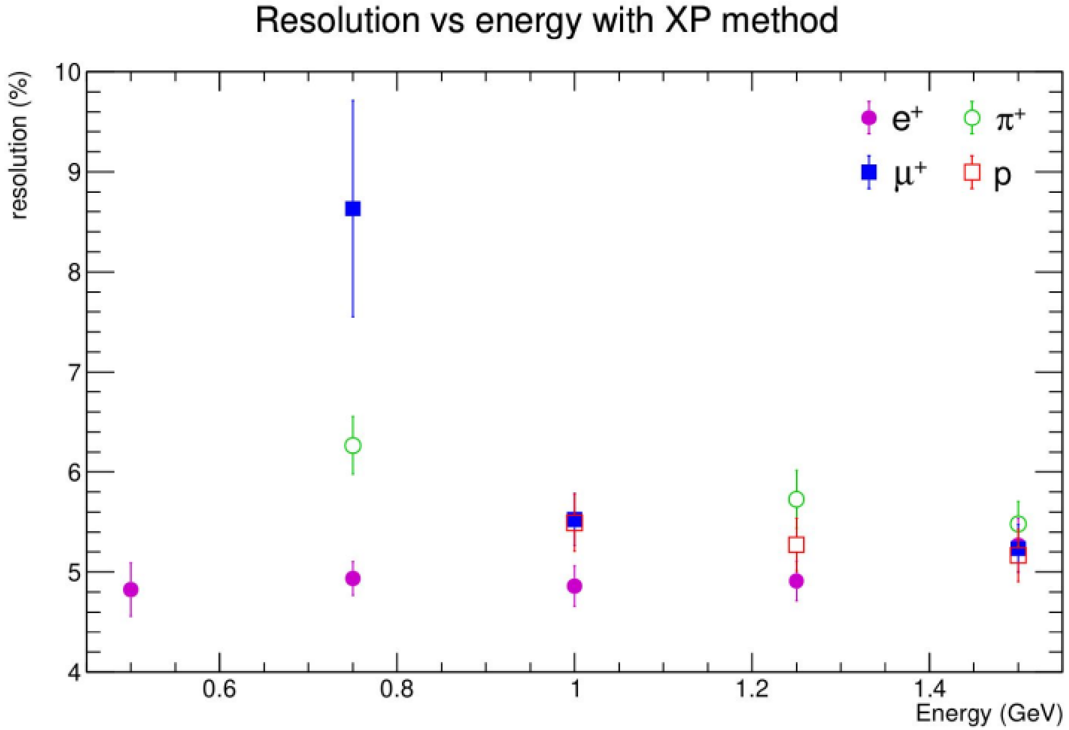
- Flat distribution of dE/dx across φ for XP
- Slight sink with WF_{sum} for diagonal clusters (compensated by correction function)

dE/dx preliminary results

dE/dx (160cm long tracks) – XP method on Test Beam data (CERN PS T10)





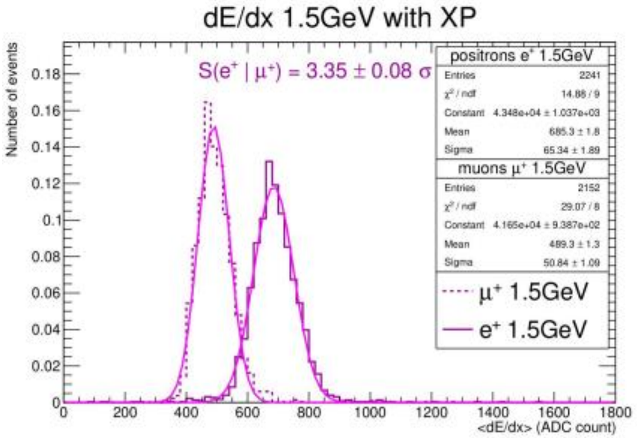


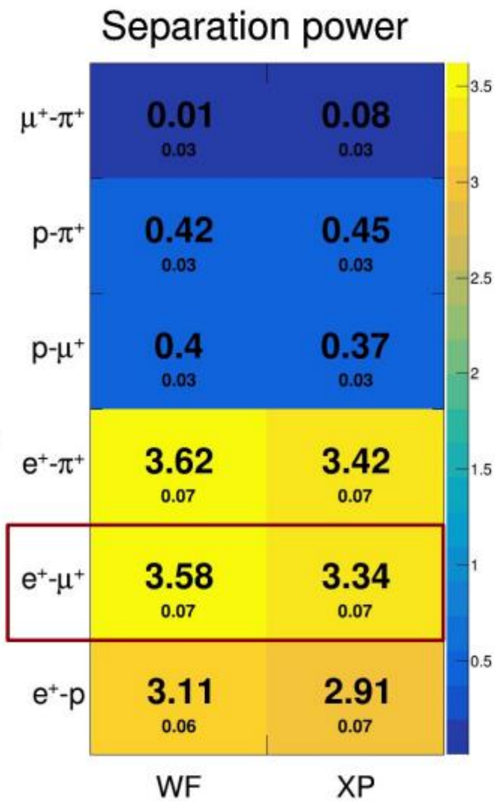
- Resolution < 6.5% (except low stat)
- e^+ stable < 5%

PID preliminary results

e/μ separation @ 1.5 GeV – Test Beam data (CERN PS T10)

Short tracks (~40cm)

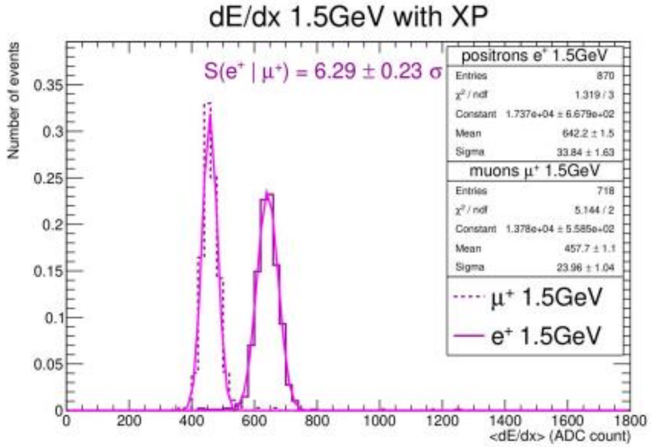


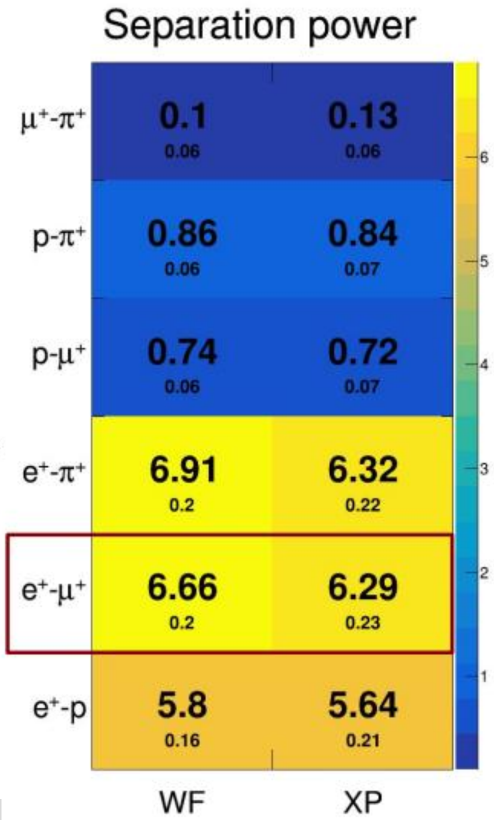


$$S(e^+, \mu^+) = \frac{|\mu_{e^+} - \mu_{\mu^+}|}{\sqrt{\left(\sigma_{e^+}^2 + \sigma_{\mu^+}^2\right)/2}}$$

- μ^+ & e^+ split by more than 3σ

Long tracks (~160cm)





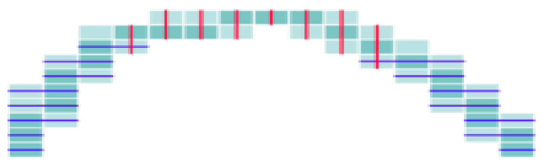
$$S(e^+, \mu^+) = \frac{|\mu_{e^+} - \mu_{\mu^+}|}{\sqrt{\left(\sigma_{e^+}^2 + \sigma_{\mu^+}^2\right)/2}}$$

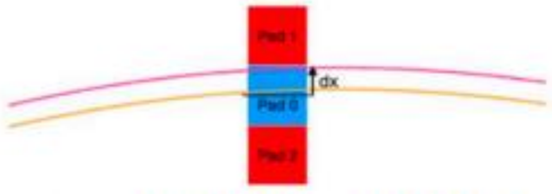
- μ^+ & e^+ split by more than 6σ

Reconstructing tracks – trajectory fitting

LogQ Method based on clustering & Log[Qprimary /Qsecondary]

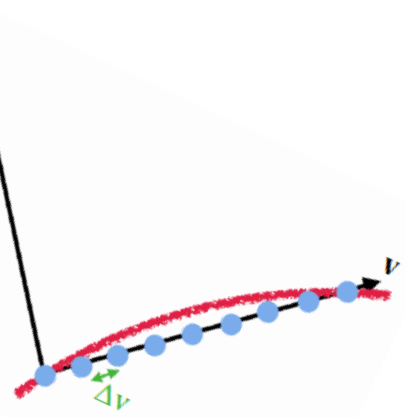
- logQ method to reconstruct position in each cluster
- Helix fit performed on those reconstructed positions





$$dx = f(\log(Q_1/Q_0) \text{ or } \log(Q_2/Q_1))$$

Full Waveform fit Method – based on model & no clustering



1) Use all the pads associated to a track (Qmax values) to define a (v,u) local frame

2) Distribute "arbitrary" point charges along v axis separated by Δv (5mm)
Q per each point is a free parameter

3) diffusion model to predict the waveform generated by point charges in surrounding pads

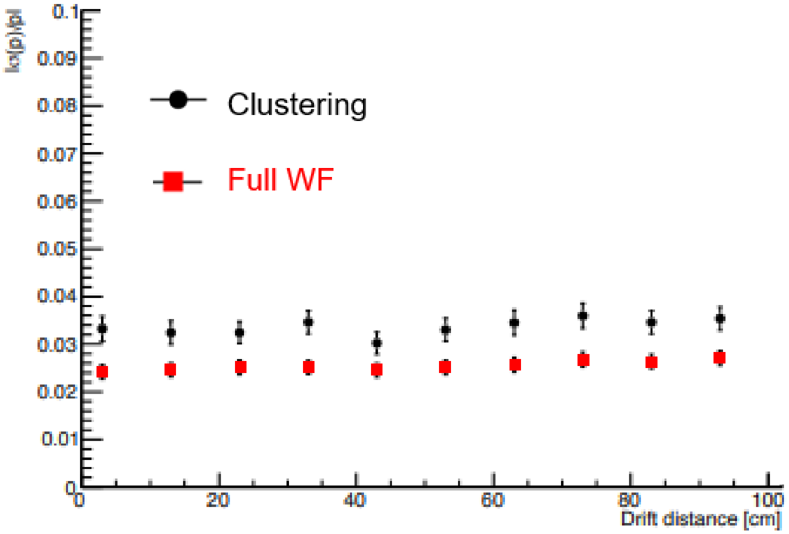
4) Move all points along the u axis to minimize the chi-square difference between measured waveforms and templates using RungeKutta method to fit (u0, du/dv, q/p, t0, dt/dv)

$$\chi^2 = \sum_{i(pad)} \sum_{j(timebin)} \frac{(Q_{i,j}^{obs} - Q_{i,j}^{Dixit})^2}{\sigma_{i,j}^2}$$

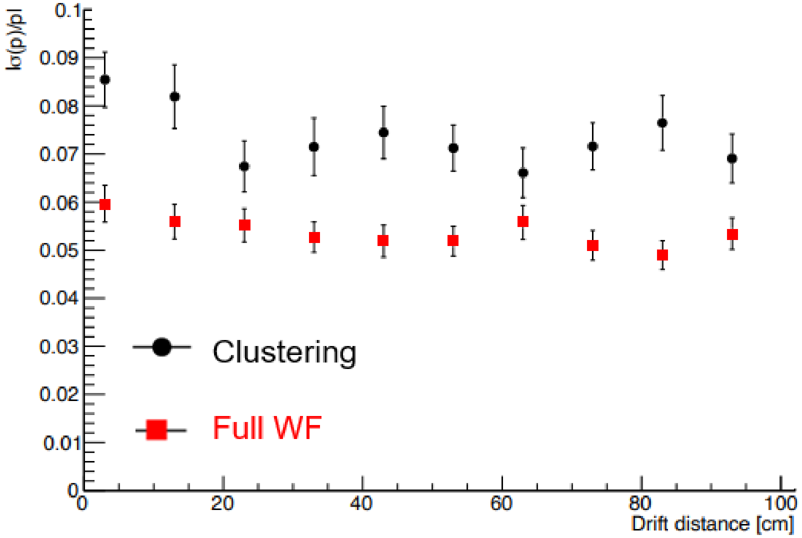
Reconstructing tracks – momentum resolution

σ_p/p Momentum resolution as a function of track drift distance -- simulated 700 MeV/c muons

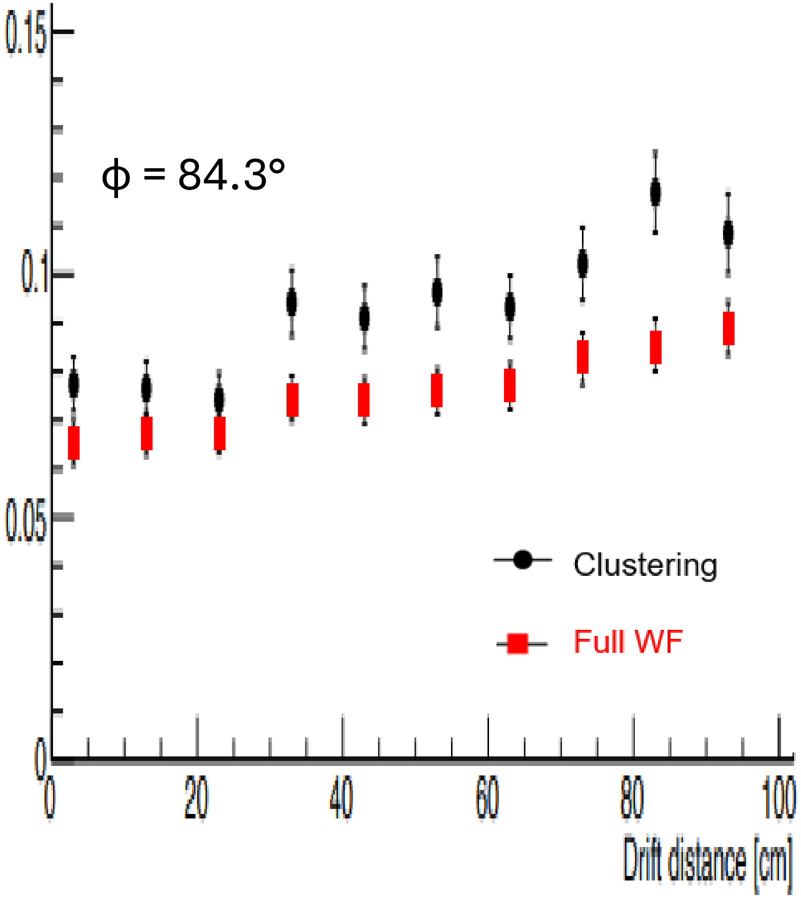
$\phi = 5.7°$



$\phi = 45°$



$\phi = 84.3°$



Conclusions

Two new TPCs have been just installed in ND280 at JPARC

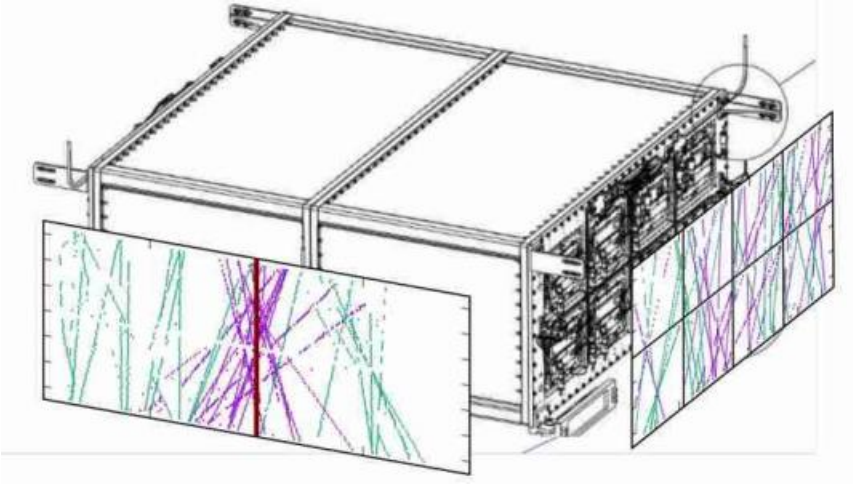
- Very stable operations in commissioning and technical runs
- Ready for neutrino beam … starting today

Field cages

- High ratio active/passive volume
- Highly effective insulation & E field uniformity

Resistive MM with encapsulated anode

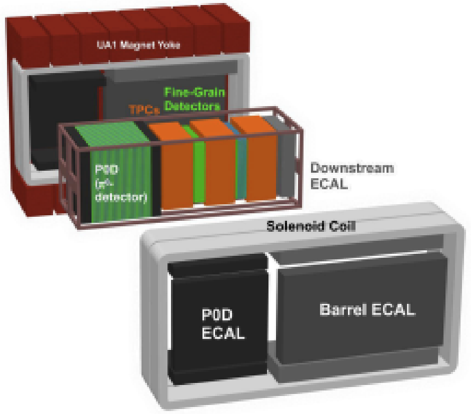
- Low resistivity & optimal charge spread & no sparks effects
- Series production allowed several detailed studies
- New algorithms for square pads exploiting detailed response model

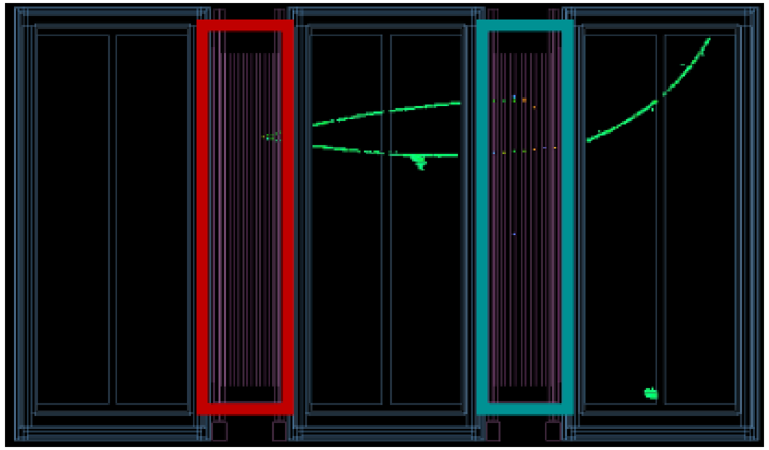


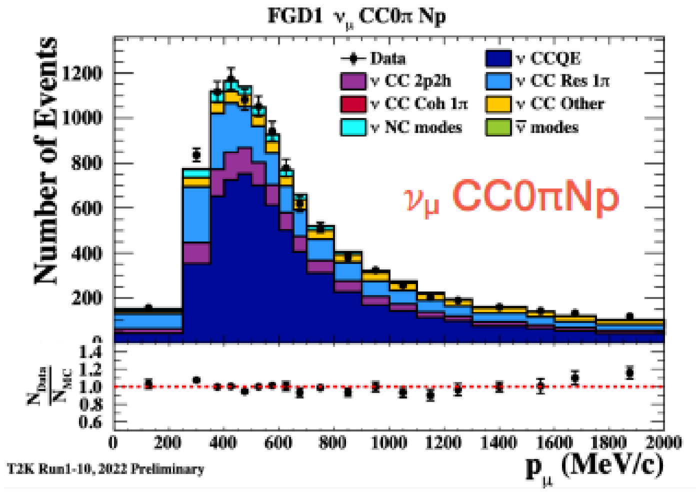
Additional Material

Near Detector impact on Oscillation Analysis

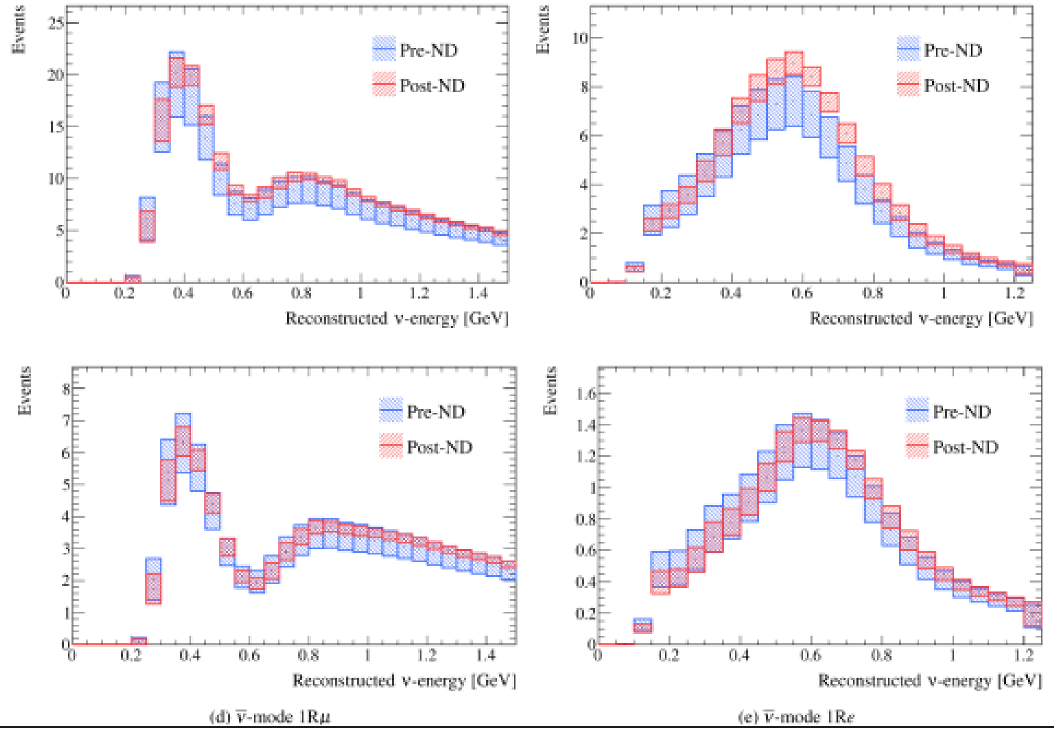
- ND280 magnetized detector
- Select interactions in FGD and measure muon kinematics in the TPCs
- Separate samples based on number of reconstructed pions (CC0π, CC1π, CCNπ), protons, photons, etc
- Factor of ~3 reduction on the uncertainty on the event rates at the Far Detector



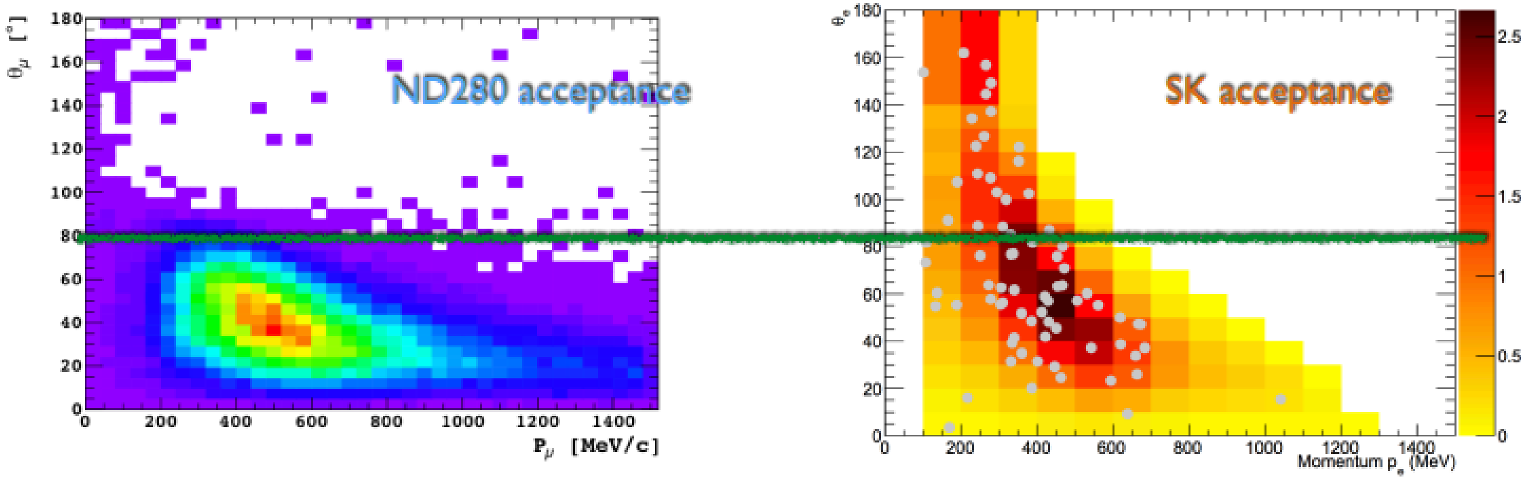


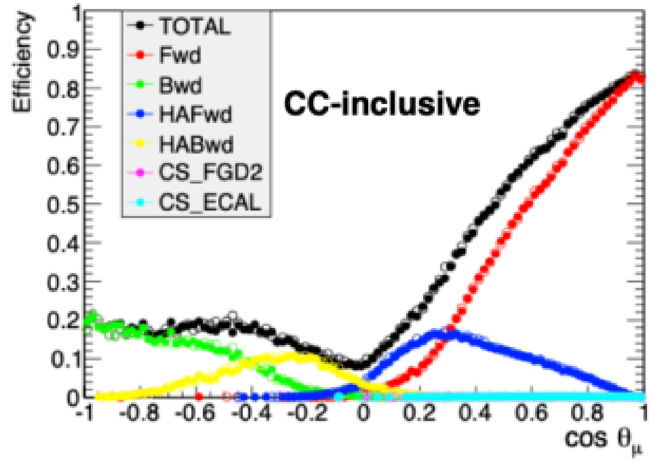


Sample	Pre-ND FIT error	Post-ND FIT error
FHC 1Rμ	11.1%	3.0%
RHC 1Rμ	11.3%	4.0%
FHC 1Re	13.0%	4.7 %
RHC 1Re	12.1%	5.9%
FHC 1Re 1d.e.	18.7%	14.3%

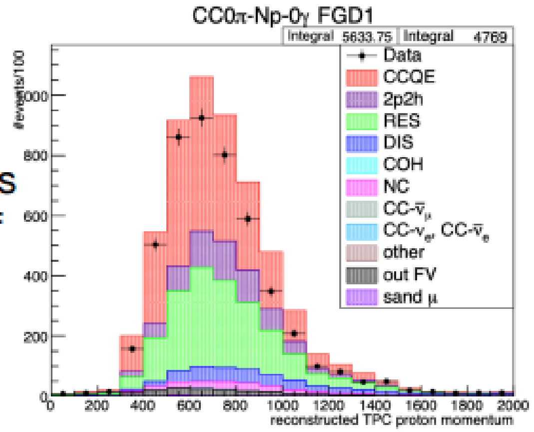


ND280 limitations

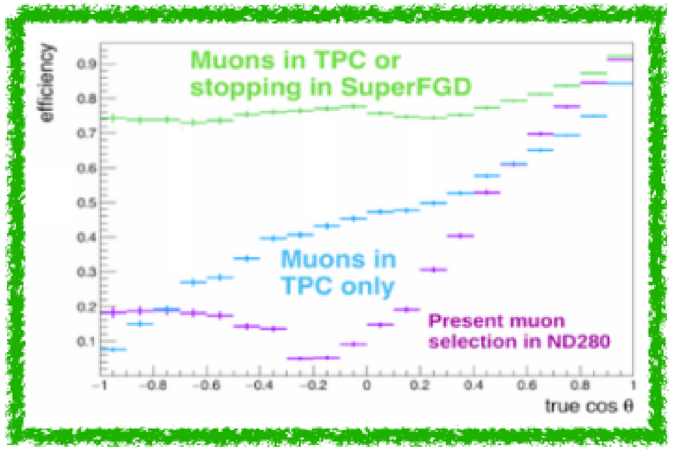


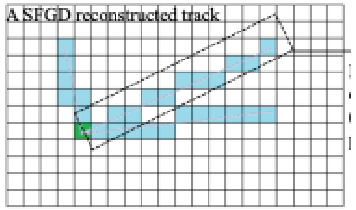


- Improve angular acceptance ν
- Better reconstruction and usage of the hadronic part of the interactions!
    - Currently samples are selected according to their topology (0π, 1π, 1p, Nπ, …) but the kinematics of the hadrons is not used in any way in the constraint on flux and x-sec systematics → plenty of additional information to be exploited
    - This is due to both, a low efficiency from ND280 to reconstruct hadrons and the difficulties in modeling the x-sec systematics for the hadronic part
        - With the upgrade we plan to improve the efficiency to reconstruct hadronic part

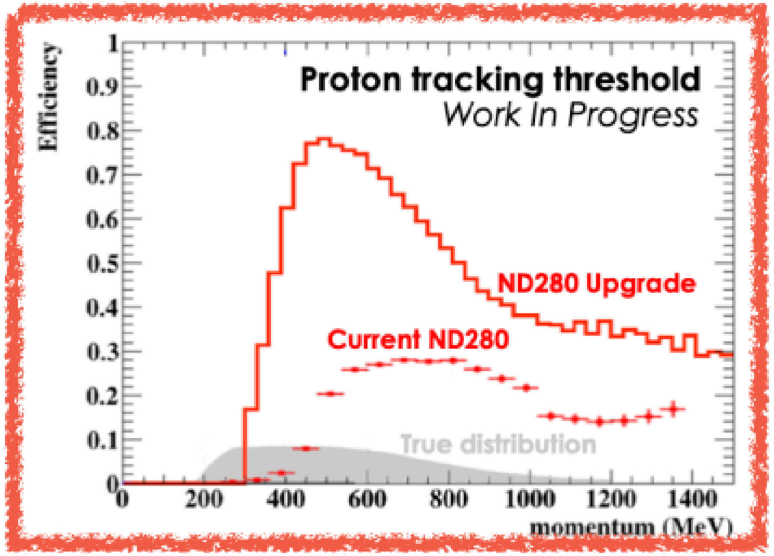


ND280 Upgrade improvements

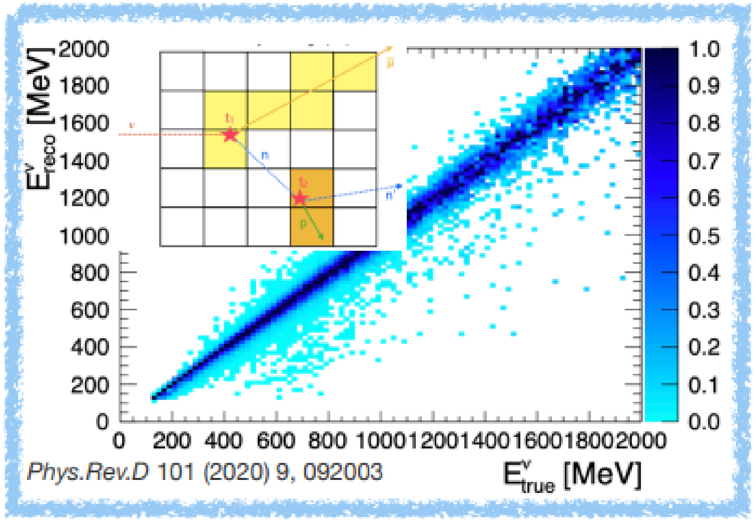




Protons → threshold down to 300 MeV/c
(>500/c MeV with current ND280)



- High-Angle TPCs allow to reconstruct muons at any angle with respect to beam
- Super-FGD allow to fully reconstruct in 3D the tracks issued by ν interactions →lower threshold and excellent resolution to reconstruct protons at any angle
  - Improved PID performances thanks to the high granularity and light yield
- Neutrons will also be reconstructed by using time of flight between vertex of $\bar{\nu}$ interaction and the neutron re-interaction in the detector



Mantle resistance

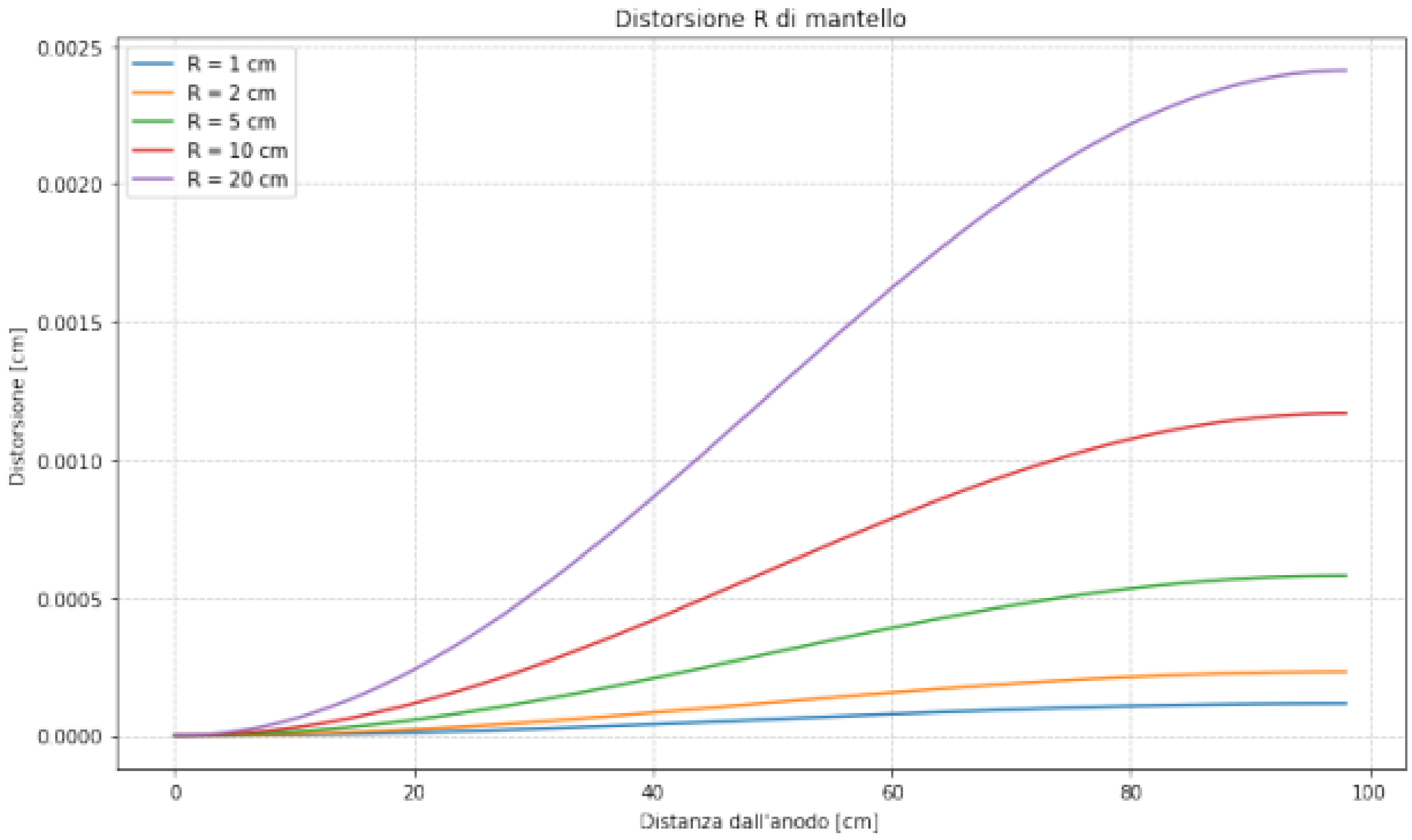


Figura 4.2: Spostamento lungo R del punto di arrivo di un elettrone causato da una resistenza R_{man} di un mantello isolante mille volte il valore della catena di resistori R. La distorsione é mostrata come funzione del punto di partenza z (Distanza dall'anodo).

ERAM Production - about 50 detectors

Crucial steps in production
(needed tuning)

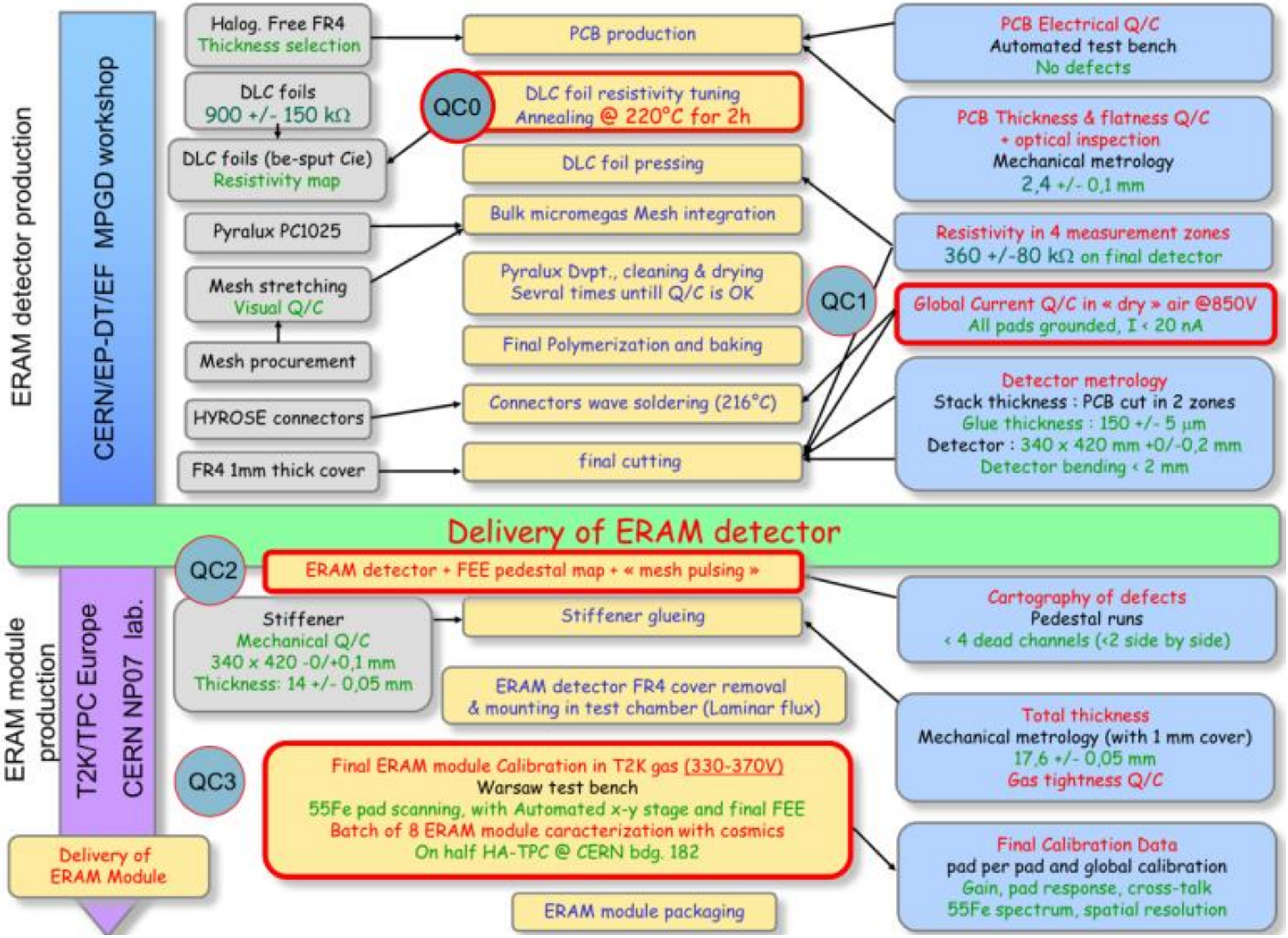
1) Selecting DLC foil resistivity
- Large variations from DLC provider
- Value stable after annealing

2) Gluing steps by Pressing
- DLC to PCB
- Stiffener to DLC-PCB

X-rays Test Bench at CERN
was fundamental to

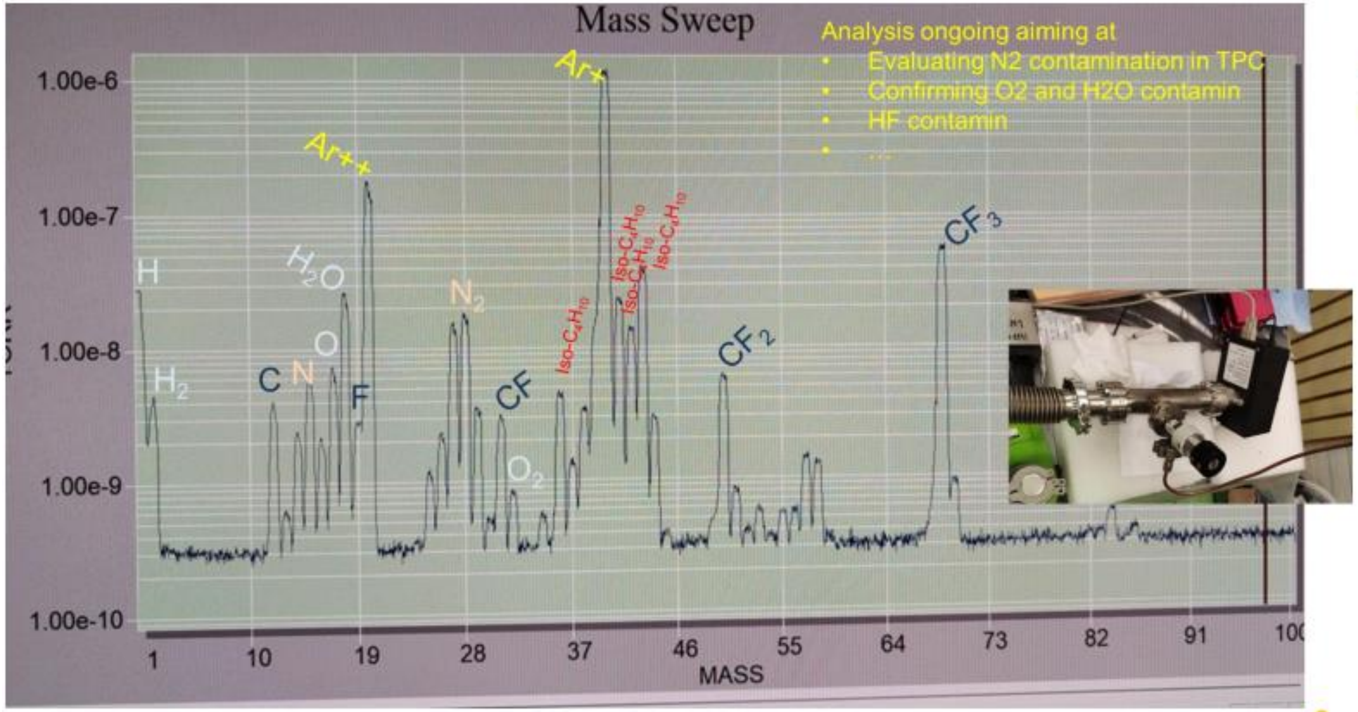
1) Qualify, characterize and calibrate
all prototypes and series ERAMs

2) support the development of
detailed ERAM response model



Field Cage assembling, characterization at CERN

Gas contamination from Field Cage – other contaminants



Analysis of gas composition during cosmics test in May

More accurate estimates ongoing

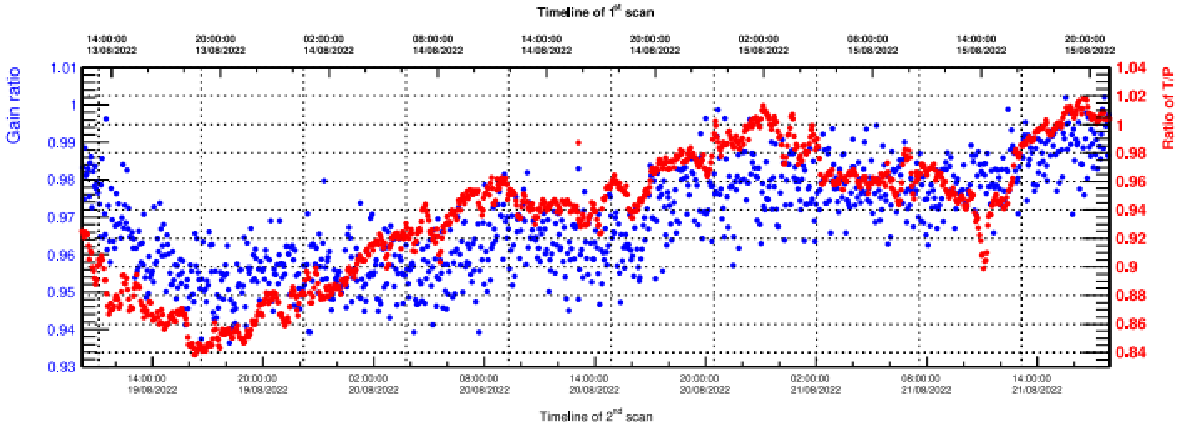
- N2 analysis
- HCl acid
- Evolution in time of components

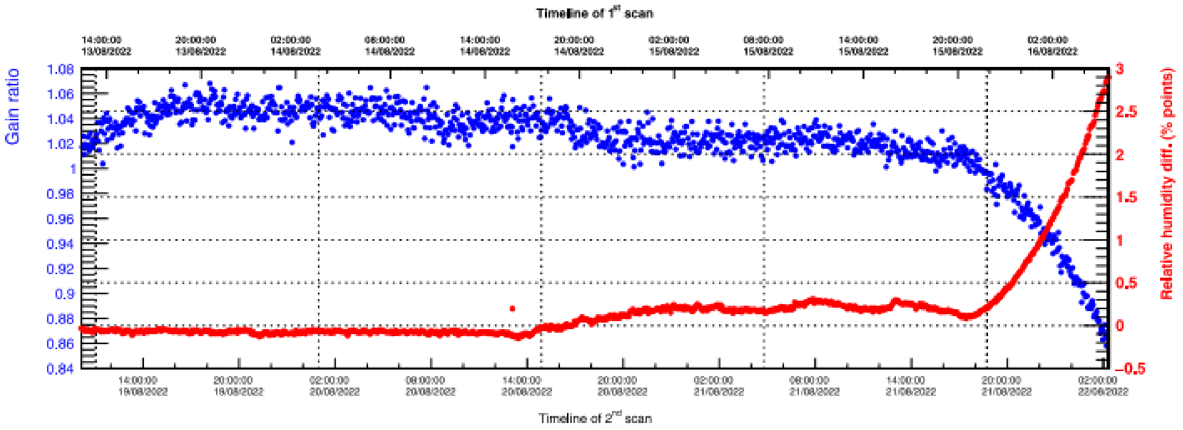
Main componensts → multi-peaks consistent with ratios found in literature

- H2O (+ HO) contamination ~2% → consistent with other sensors (Vaisala)
- O2 peak below sensitivity → consistent with ppm level → need further checks
- No HF acid apparently (below Ar++)

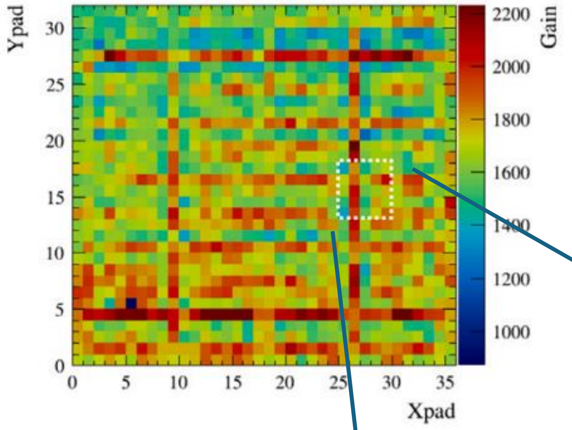
ERAM Series Production experience

Effect of gas density on (gas) GAIN



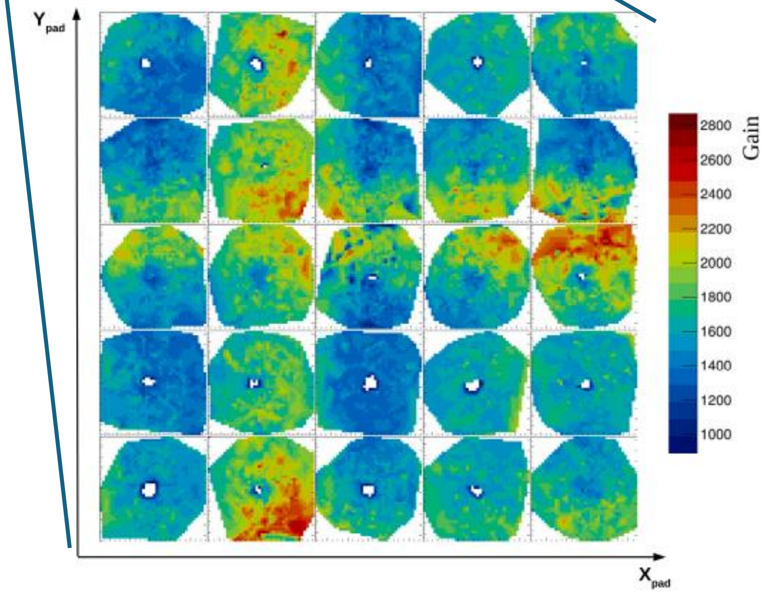


Effect of humidity on (gas) GAIN



Fine grain scan

GAIN as a function of Pad position



ERAM detector response – Simulation

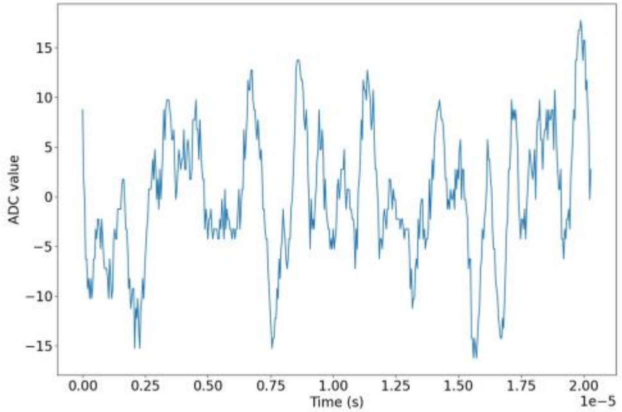
Use of the model for Simulation of charge deposition in events

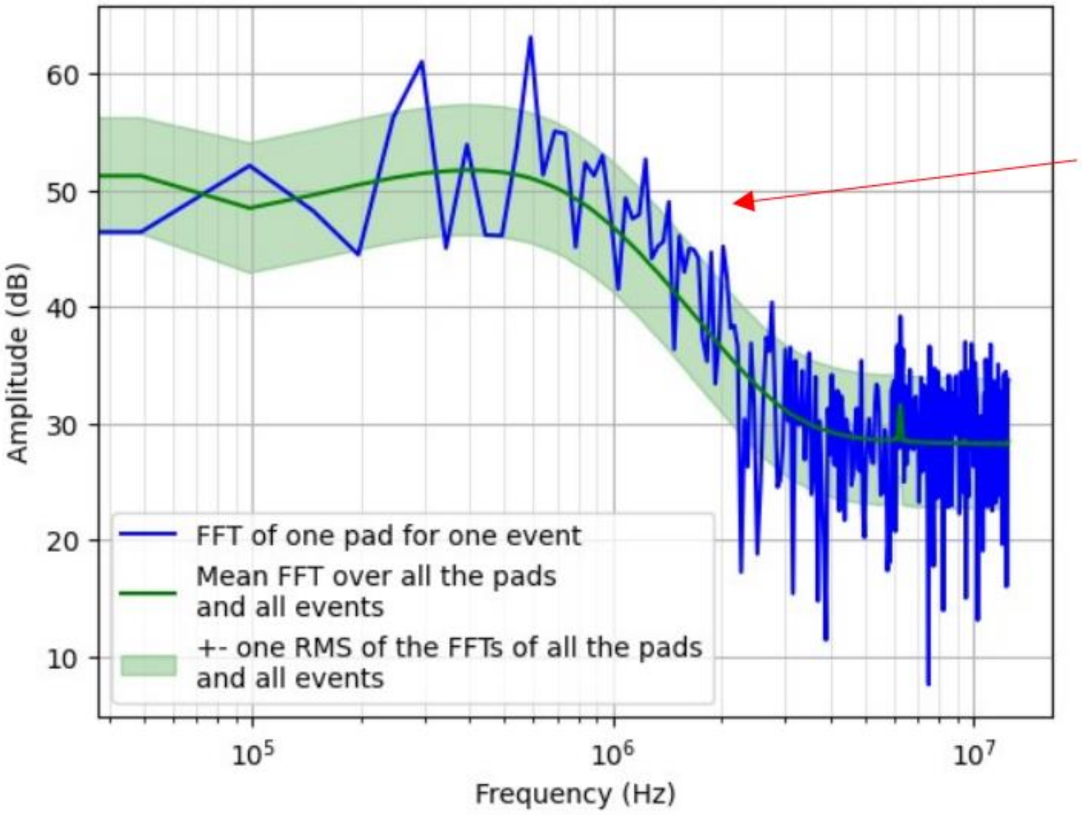
Where additoinal ingredient is noise detailed modeled

T_p= 412 ns
F_s = 25 MHz

Record of the baseline (no trigger) by D. Calvet

One record
T_p= 412 ns
F_s = 25 MHz





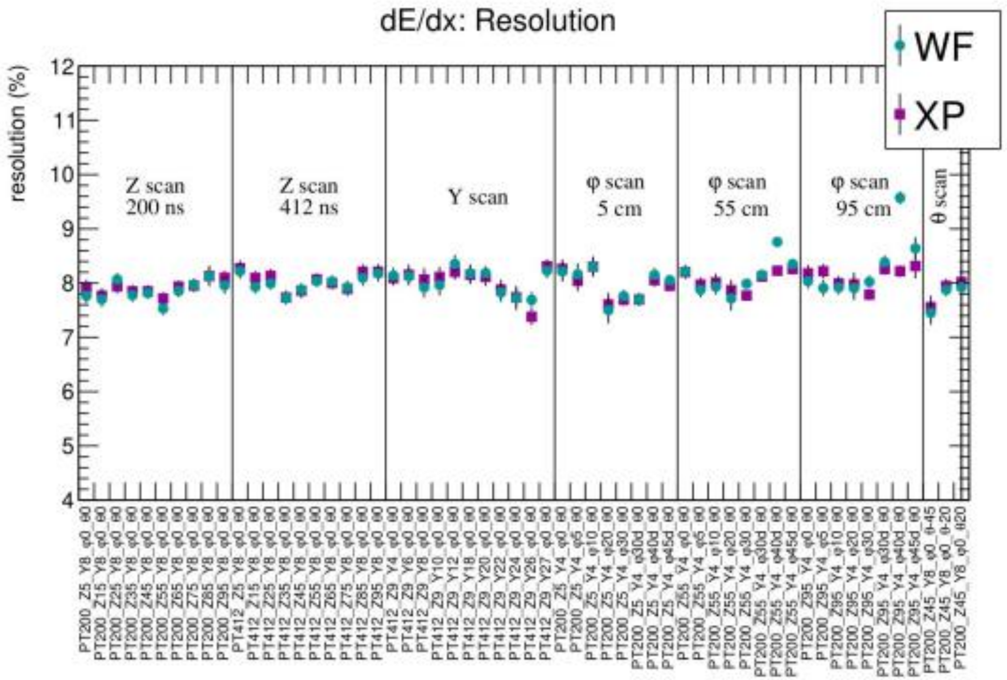
Dominated by frequencies lower than 1 MHz

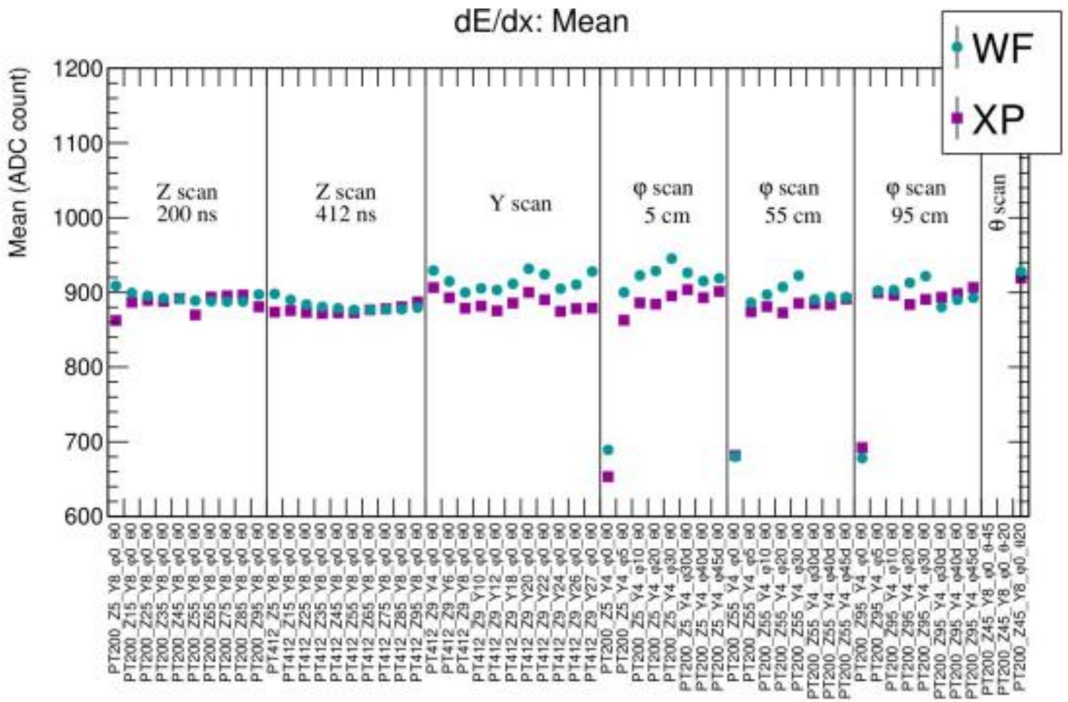
The spectrum can be fitted quite decently with a "simple" analytical function

$$\sqrt{\left[\frac{A_0}{f^2}\right]^2 + \left[A_1\sqrt{f}\,H_{after}(f)\right]^2 + A_2^2}$$

Reconstructing tracks dE/dx

dE/dx – comparison of SWF and XP methods on Test Beam data (4GeV electrons, DESY)

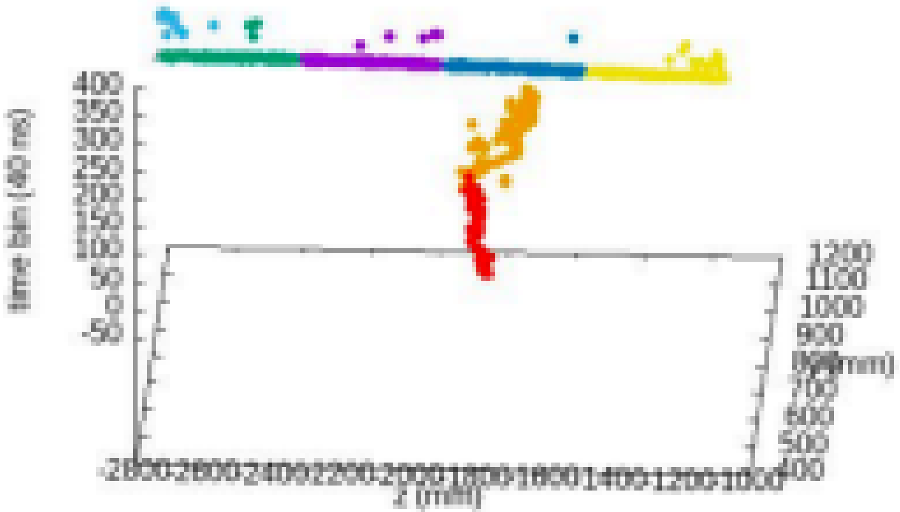


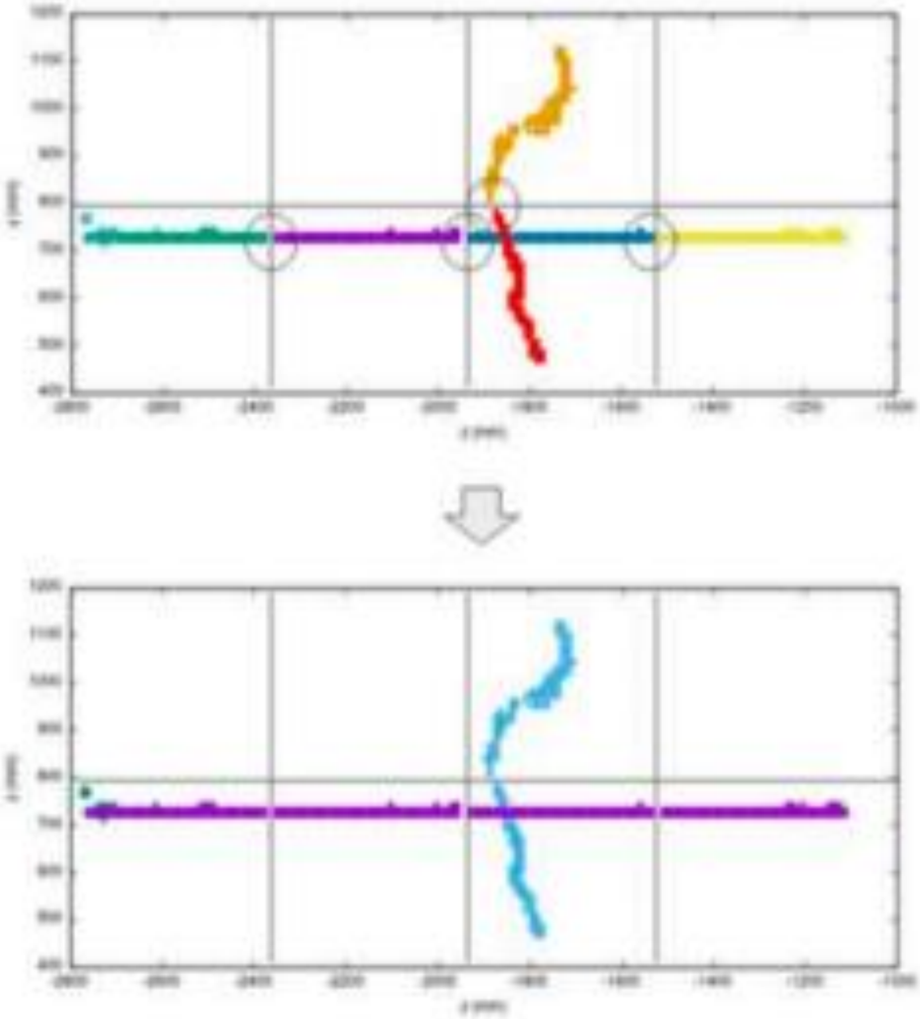


- Very good agreement overall
- Better resolution with XP with diagonal tracks

- Disagreement at small drift distance: reflects the track fitting quality
- Disagreement for Y scan: taken at small drift distance
- Disagreement for diagonal tracks: using only on correction function for WF_{sum} is not suitable

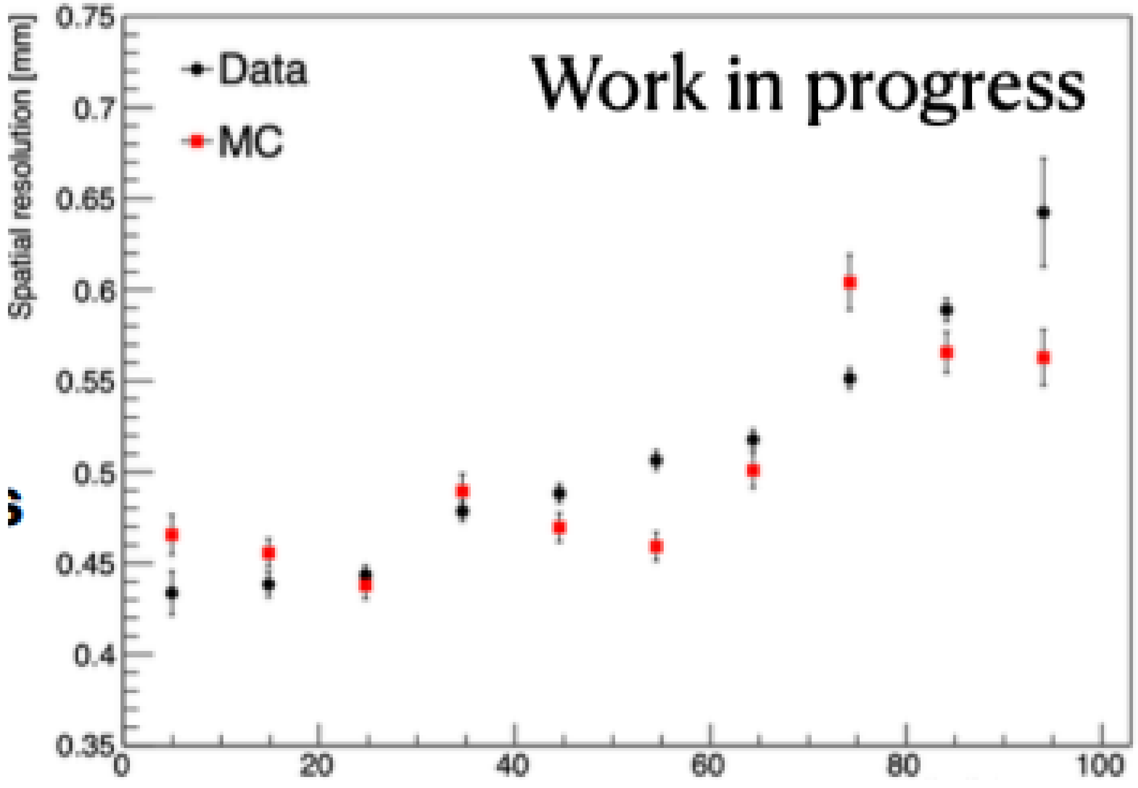
Reconstructing tracks – pattern recognition



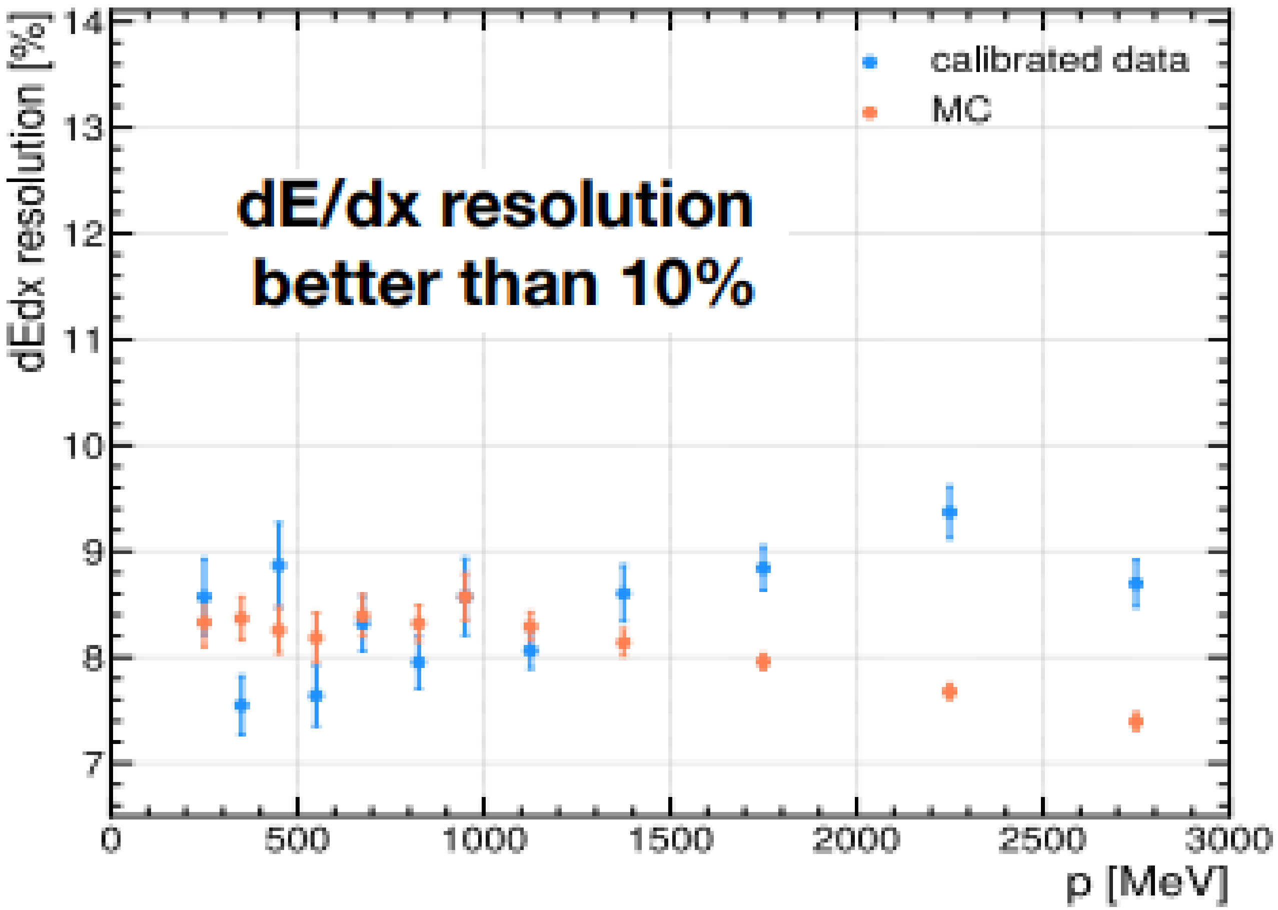


- Time and charge definition for each hit
- Waveform multipeak search in order to differentiate vertices and crossing trajectories
- Merging between different ERAMs and End Plates

Reconstructing tracks – trajectory fitting



Spatial resolution ~500 μm with muons



T2K gas properties