Characterisation of the ERAM detectors for the High Angle TPC of the T2K ND upgrade

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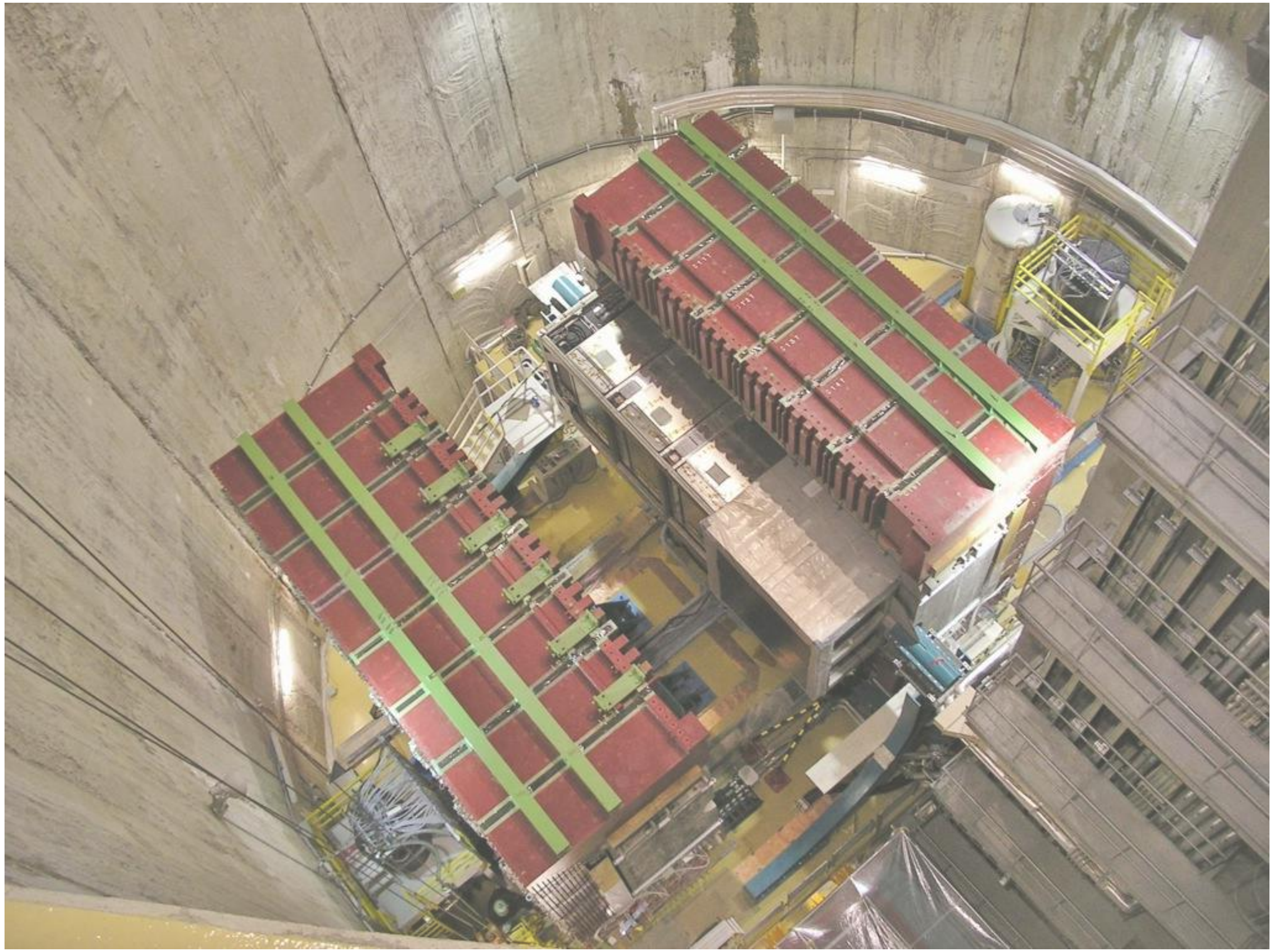
T2K

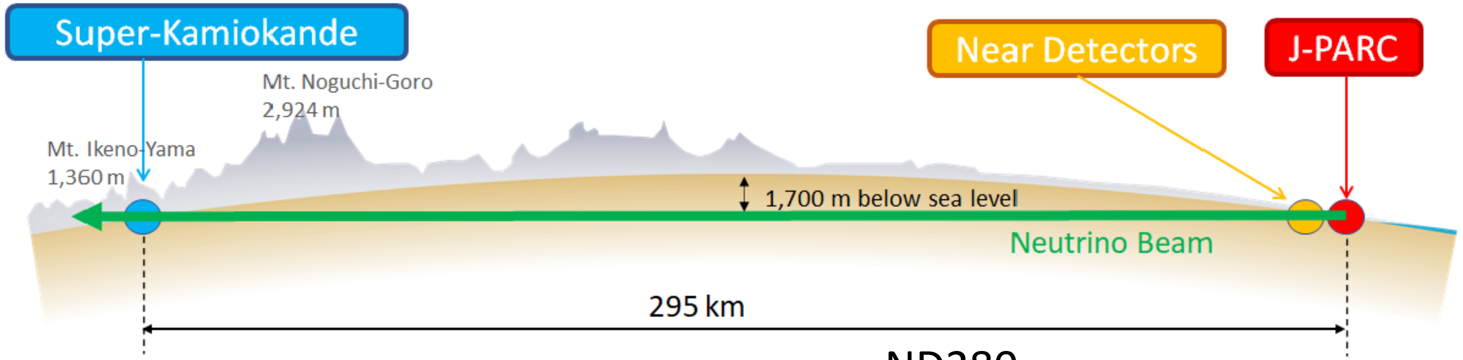
Overview

1. Introduction to T2K Experiment
2. ND280 Upgrade
3. HA-TPC
   - Field Cage
   - ERAM Sensors
4. ERAM Characterization
   - Test Bench
   - Test Beams
5. Conclusions



The T2K Experiment

T2K is a long-baseline neutrino experiment from J-PARC to Super-Kamiokande



Main goals and results:

- ν_μ disappearance

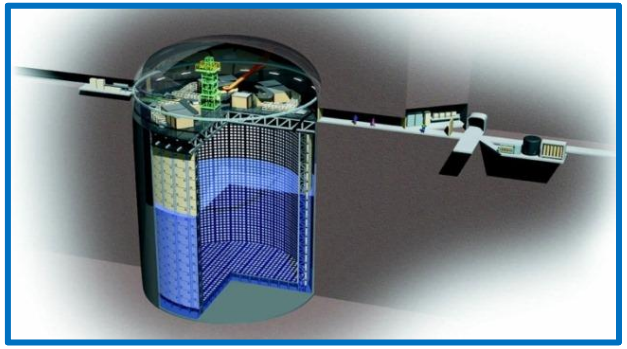
  $\boldsymbol{\theta_{23}, \Delta m^2_{23}}$

- ν_e appearance

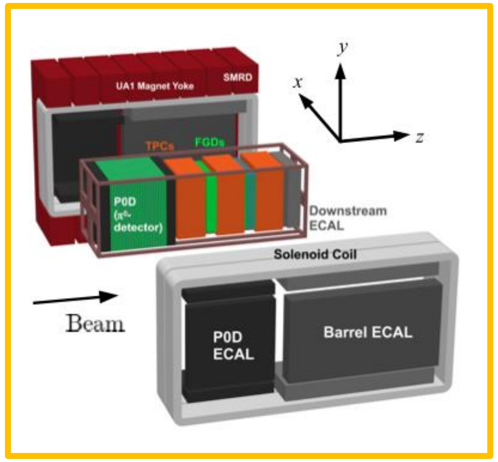
  $\boldsymbol{\theta_{13}, \delta_{CP}}$

$$\sin\delta_{CP} \propto \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu_\mu} \to \overline{\nu_e})}{P(\nu_\mu \to \nu_e) + P(\overline{\nu_\mu} \to \overline{\nu_e})}$$

Super-K



ND280



J-PARC

$$p + \text{graphite} \to \mu + \nu_\mu$$

Muon neutrino beam (~ 600 MeV) is detected at near and far detectors

T2K Phase II

- **MR** beam power from 500 kW to 750 kW in 2022
- Upgrade of Near Detector **ND280** to decrease systematics

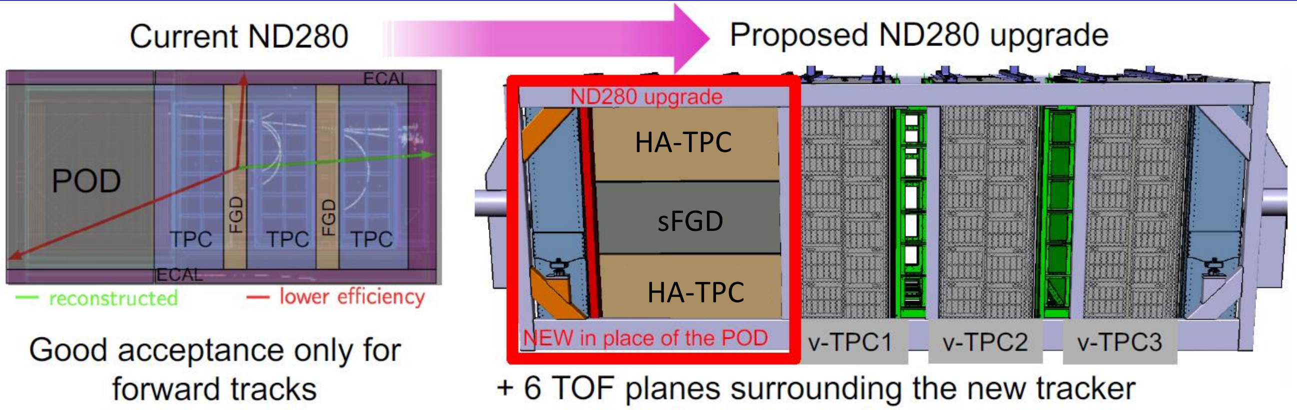
3σ C.L. on δ_{CP}

Near Detector ND280 Upgrade

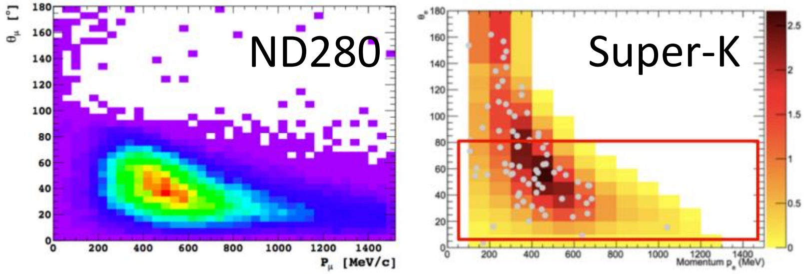
Current critical points:

1. **Low acceptance** for tracks with high angle ***"Forward Only"***
2. Low efficiency in reconstructing hadronic parts of interactions

Upgrade



Muon momenta reconstruction

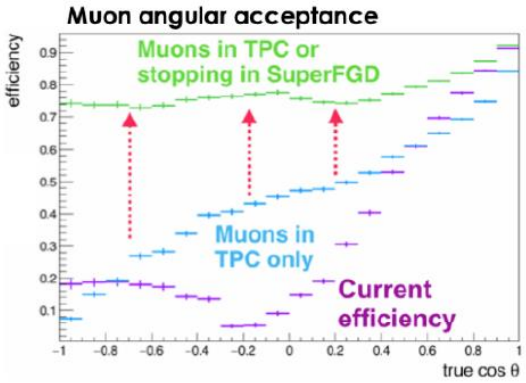


Upgraded Detector Configuration:

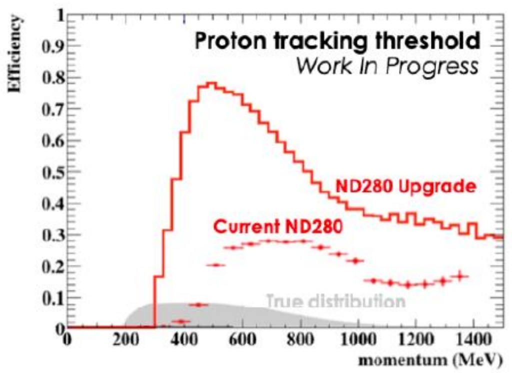
1. **Super Fine Grain Detector (sFGD):**
   Segmented target of cubic scintillators (1 cm side) for the improvement of hadronic part reconstruction
2. **Two High Angle TPCs (HA-TPC):**
   Placed at high angles respect to beam direction to improve Particle Identification for leptons
3. **Time of Flight (ToF):**
   Six planes of scintillators to reduce the background

ND280 Upgrade:

- Overall systematic uncertainty to **4%** (from 6%)
- Near detector for Hyper-K from 2027



Efficiency to select CC0pi events



The installation of ND280 Upgrade is expected to be completed in Fall 2023

High Angle Time Projection Chambers (HA-TPC)

Requirements:

- **Momentum resolution** $\frac{\sigma_p}{p} < 9\%$ at 1 GeV/c → neutrino energy estimation

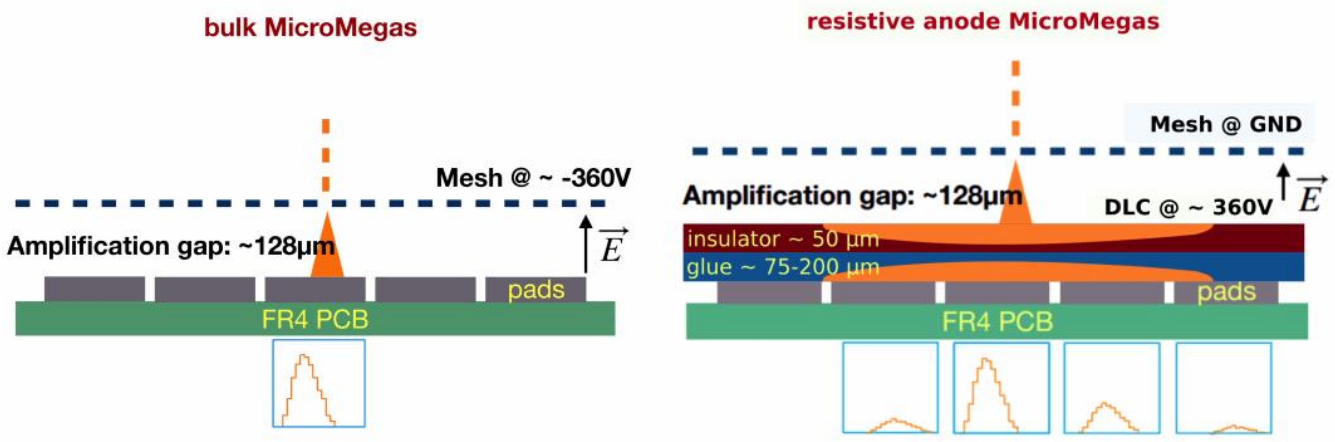
  ↓

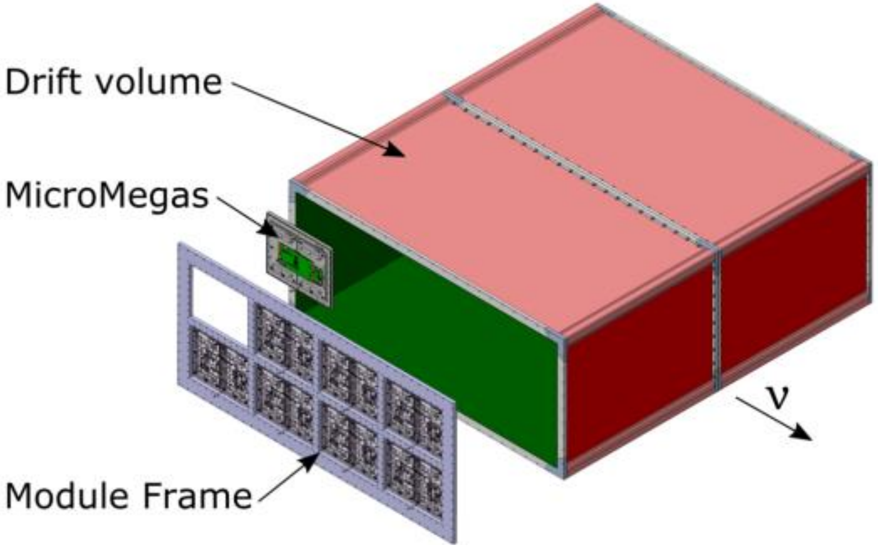
  Spatial resolution O(800 μm) → 3D track reconstruction

- **Energy resolution** $\sigma_{\frac{dE}{dx}} < 10\%$ → PID of electrons and muons
- **Low material budget walls**

1. **Field Cage**
   - Thin walls and less space subtracted to active volume
2. **Resistive MicroMegas**

   ERAM: Encapsulated Resistive Anode MicroMegas
   - Charge spread on resistive layer to enhance spatial resolution
   - Spark protection





Parameter	Value
Overall x × y × z (m)	2.0 × 0.8 × 1.8
Drift distance (cm)	90
Magnetic Field (T)	0.2
Electric field (V/cm)	275
Gas Ar-CF_4-iC_4H_{10} (%)	95 - 3 - 2
Drift Velocity $cm/\mu s$	7.8
Transverse diffusion ($\mu m/\sqrt{cm}$)	265
Micromegas gain	1000
Micromegas dim. z×y (mm)	340 × 410
Pad z × y (mm)	10 × 11
N pads	36864
el. noise (ENC)	800
S/N	100
Sampling frequency (MHz)	25
N time samples	511

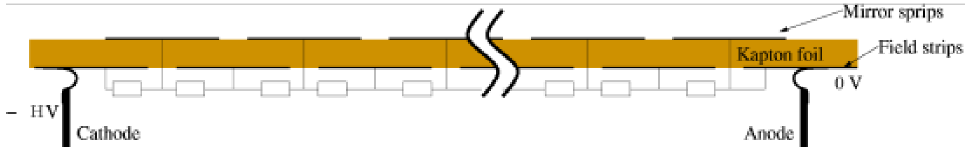
Field Cage Properties

Each TPC is composed by 2 Field Cages with a common cathode

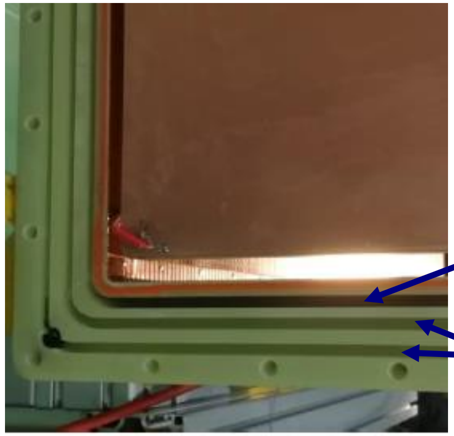
Field Cages are designed to:

- provide a **uniform Electric Field** $\frac{\Delta E}{E_z} < 0.1\%$

This is provided by two voltage dividers

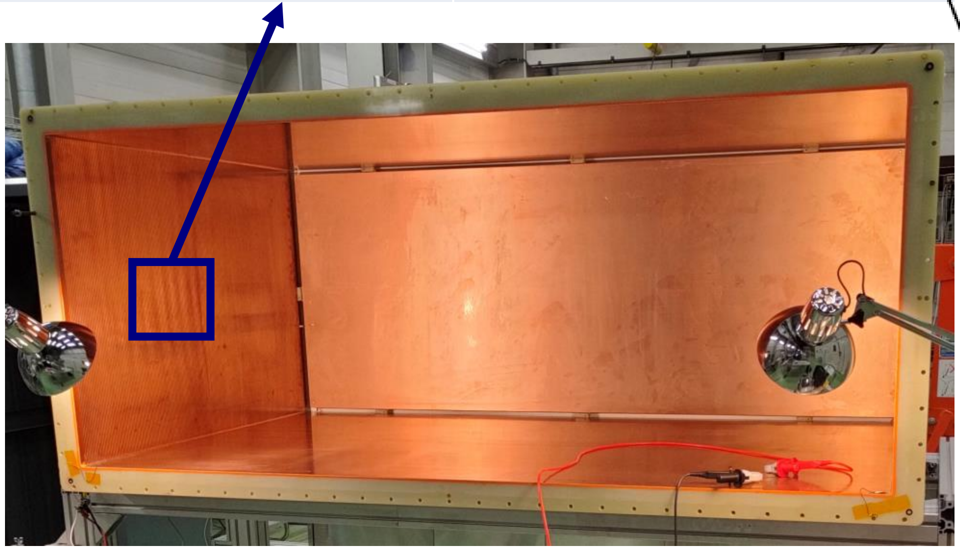


- be **gas-tight**

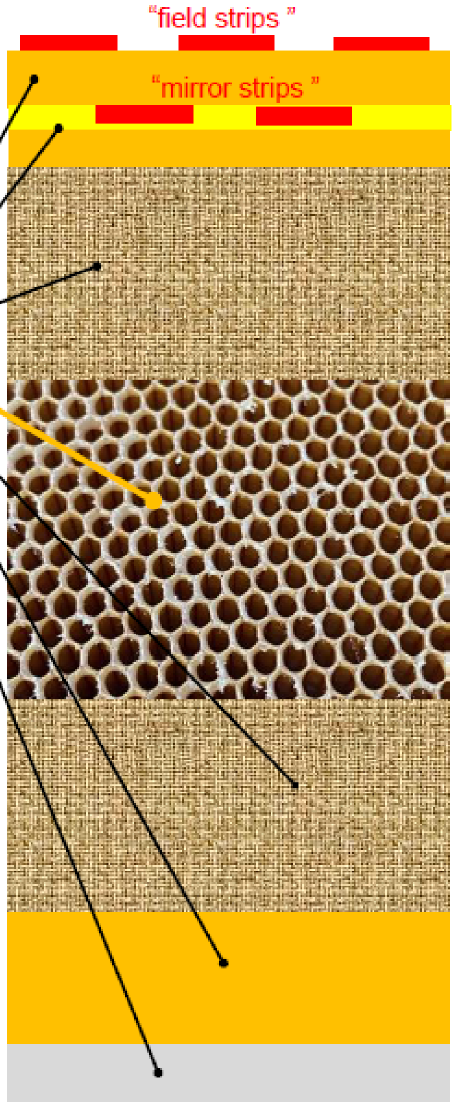


- Have optimal **mechanical properties** against deformation under several mbars of overpressure

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
Aramide HoneyComb panel	35mm
Aramid Fiber Fabric (Twaron™)	2mm
Kapton foil (insulation)	125µm
Aluminum foil (external shield)	50µm
Total	~40mm / ~ 6% radiation length



Inner part of Field Cage + Cathode



ERAM Sensors

The new Resistive technology allows a better spatial resolution respect to bulk MicroMegas

1. Electrons from ionization are **multiplied** thanks to an intense E field after the mesh

2. Charge will **spread** over the resistive layer

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

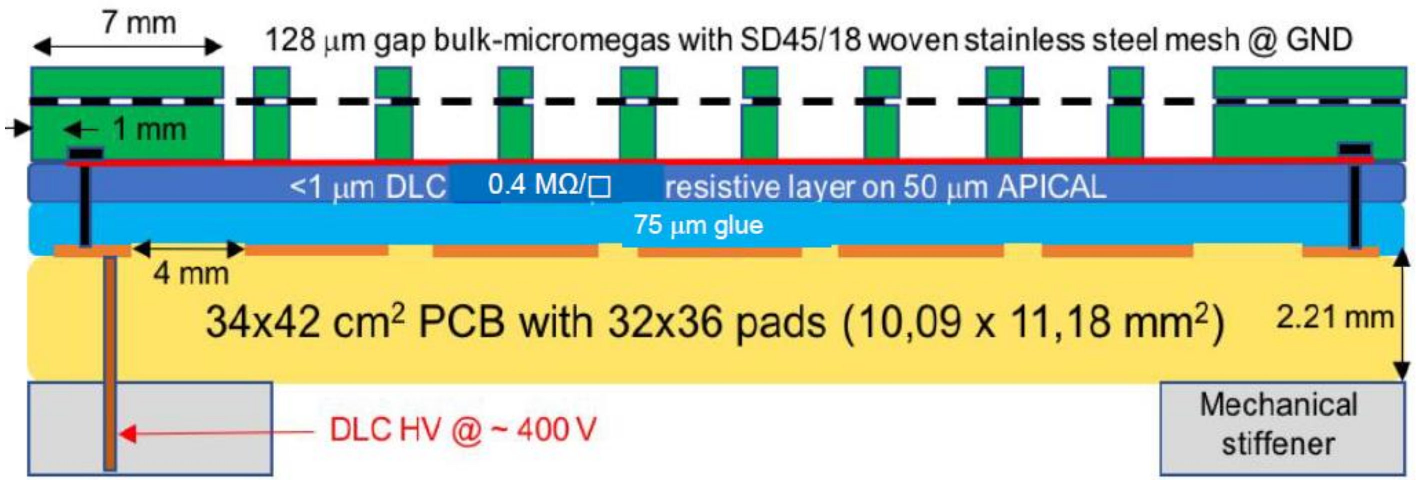
Solution to Telegrapher's equation

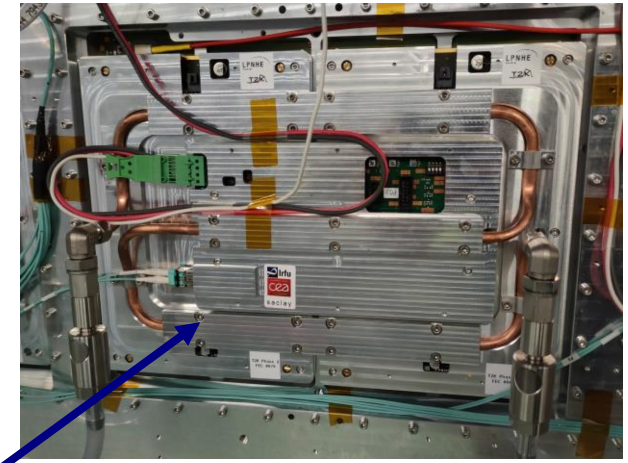
Gaussian spreading with $\sigma_t = \sqrt{\frac{2t}{RC}}$

3. **Induced** charge is collected by pads

ERAM characterization is performed via:
- Mesh pulsing
- X-Ray test bench

Detector characterization assessed by means of 5 test beams

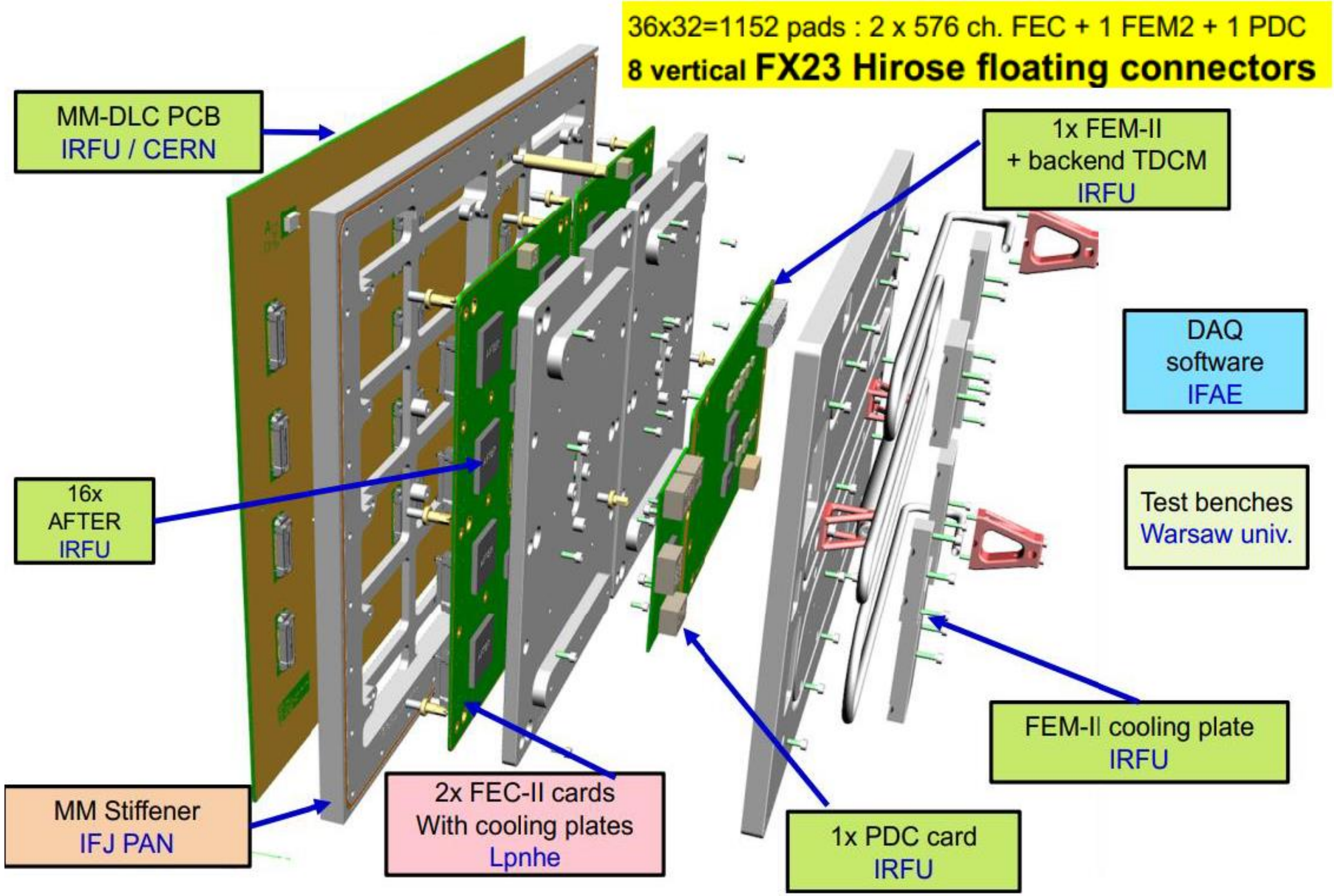


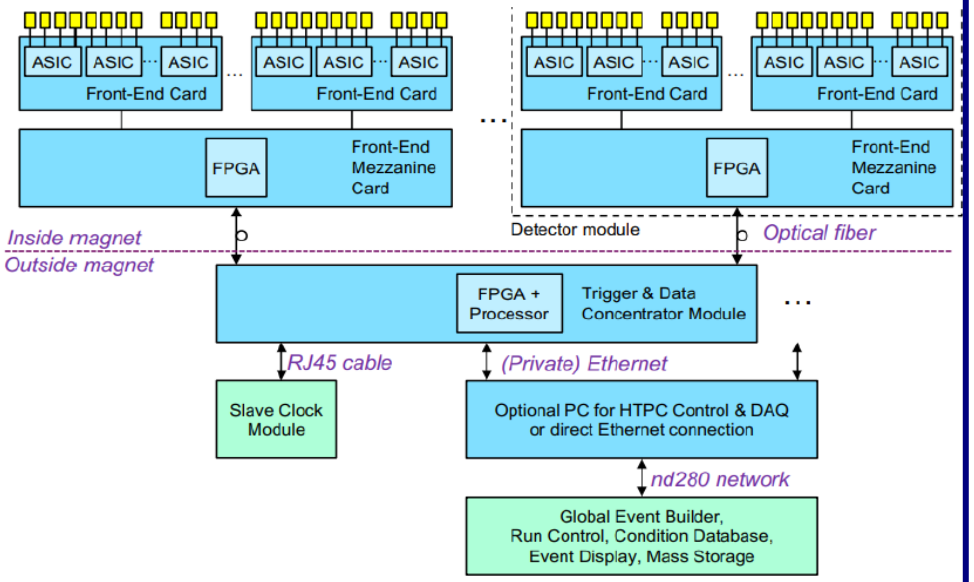


ERAM+Electronics

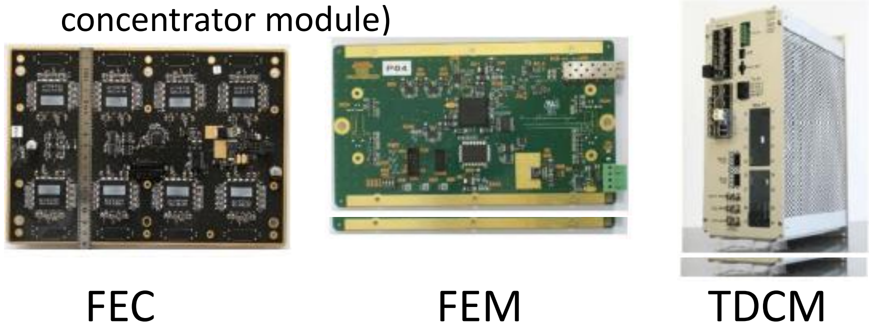
Dimensions: $340 \times 420\ \mathrm{mm}^2$
MM Gain: 1000
Pad size: $10 \times 11\ \mathrm{mm}^2$
Number: 1152 per module

ERAM Module + Electronics





- FEC with 8 AFTER chips→digitalization of pad signal
- FEM provide control, synchronization and data aggregation
- Each TPC is controlled by a single TDCM (trigger and data concentrator module)



- 8+8 modules per HA-TPC
- Minimization of dead volume

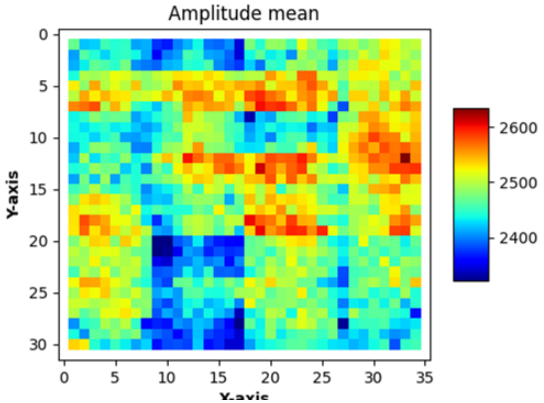
ERAM Test Bench

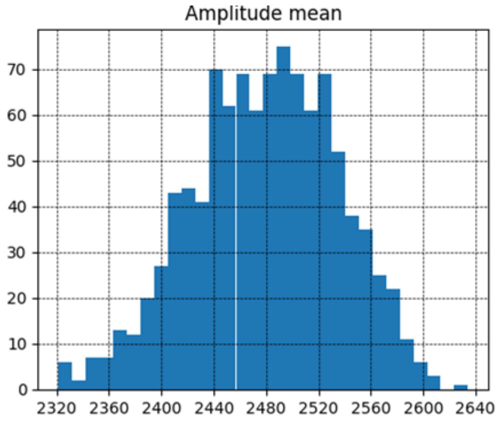
A test bench has been setup at CERN

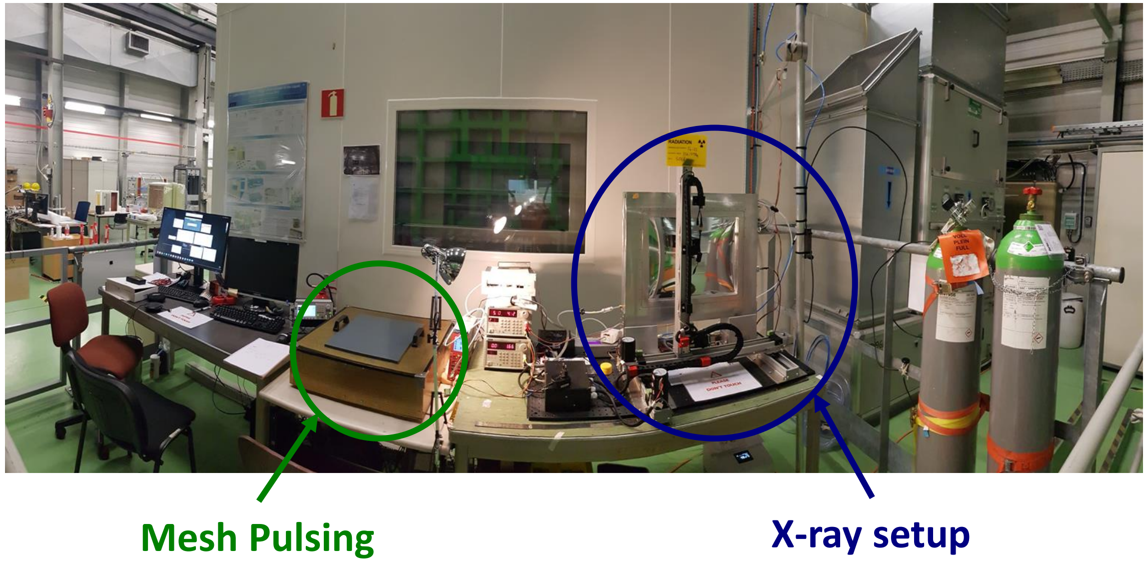
- **Mesh Pulsing**

The sensor is checked after the delivery with a **signal injection** before and after gluing to find **defects:**

- Uniformity of 15%
- Change in response after gluing



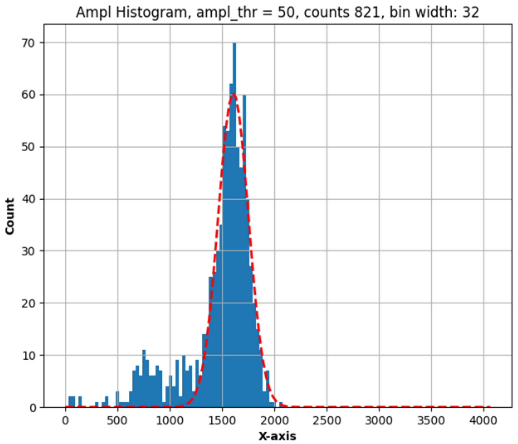


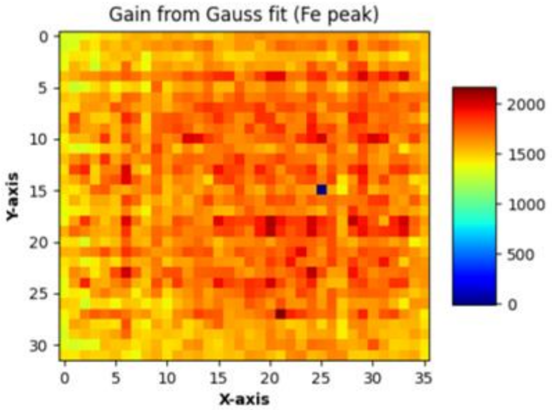


- **X-ray scan**

A collimated source of Fe-55 is used to estimate **gain** and **resolution**

A robotic arm places the source in front of **each pad**
Sensors are scanned with their electronic cards

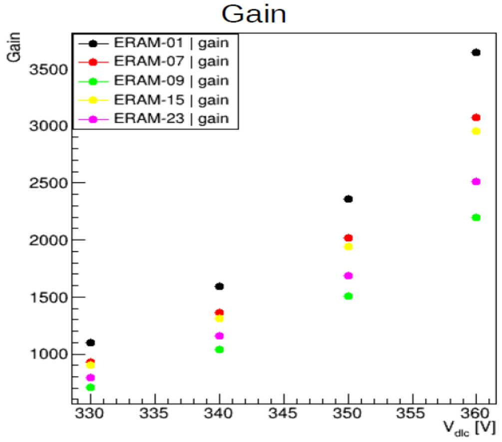


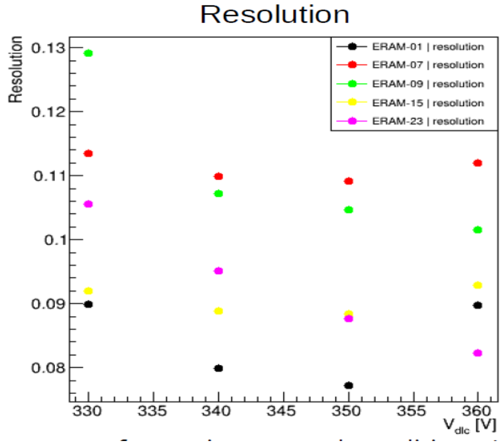


14 sensors are fully qualified

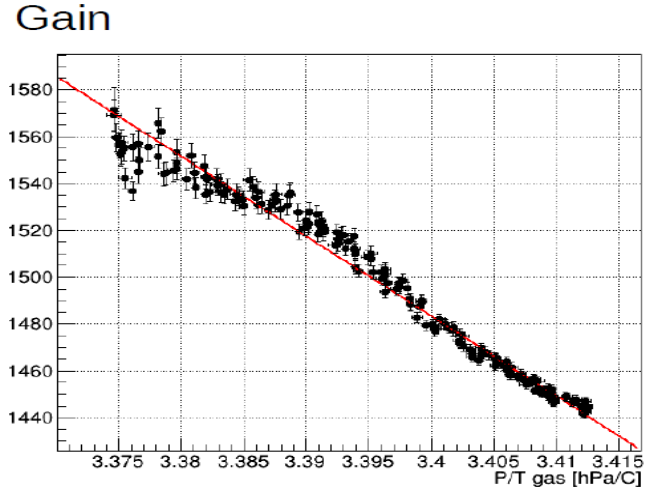
Results from Test Bench

A comparison among 5 detectors is reported for gain and resolution as a function of **DLC Voltage**





Environmental conditions are important!

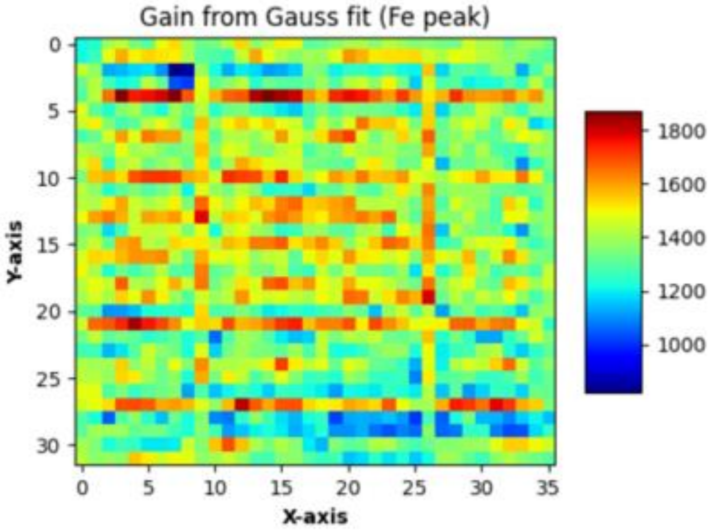


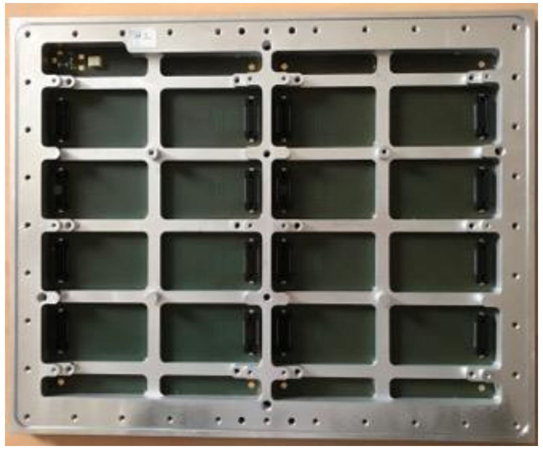
Pattern of pads with different gain and resolution were observed after production

Position is correlated with **mechanical structure** behind them

Non uniformity of PCB backside affects DLC side flatness and therefore **amplification gap** after pressing

(20% gain for 1-2μm gap change!)





Problem solved with modification of PCB features

Test Beams

Test beams provide crucial information on ERAM response for different track parameters:

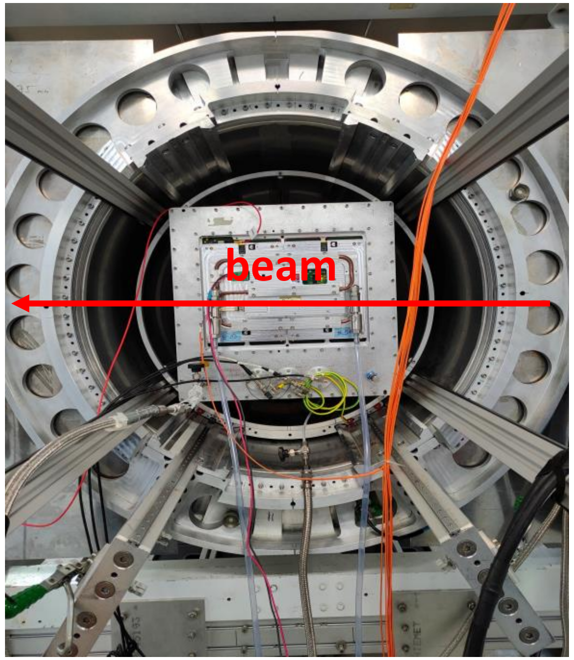
- ϕ and θ scan
- Incoming particle energy

→ Comparison with test bench for low level variables

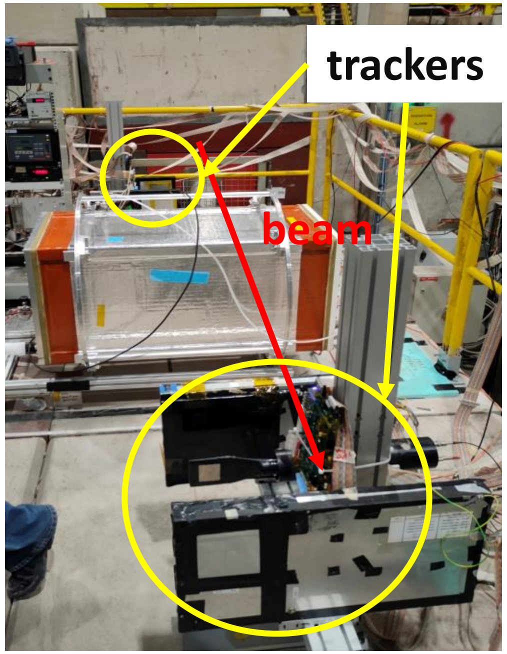
CERN 2018 →10.1016/j.nima.2019.163286 → Performance of **spreading** for right pad dimensions

DESY 2019 →10.1016/j.nima.2021.166109 → Performance of foil of 400 $k\Omega$/sq but not final electronics

DESY (July 2021)
Electron beam with energy 0.5-5 GeV
Superconductive magnet (B up to 1 T)

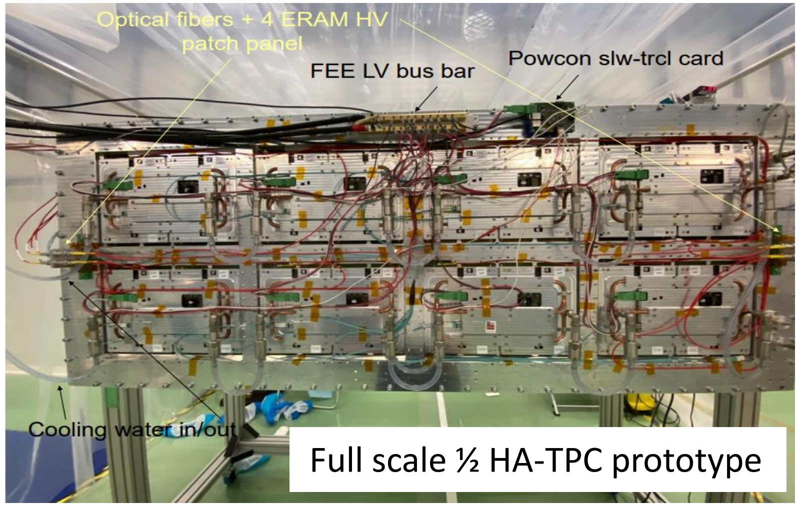


CERN (November 2021)
Muon beam
No Magnetic field
External tracker



CERN (September 2022)
8 ERAM detectors at same time
No magnetic Field

Rescheduled from May 2022



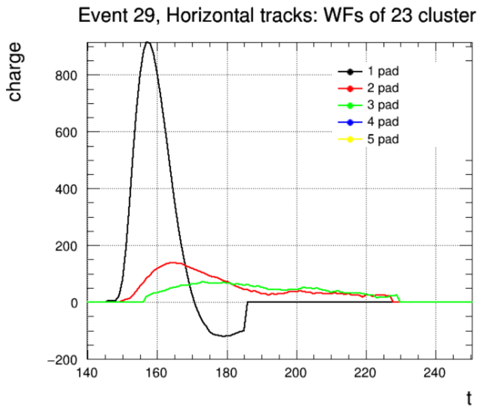
Methods for Data Analysis

dEdx Reconstruction

- Tracks are divided in **clusters**
- **Sum of waveforms** in a cluster is computed
- **Maximum** is taken

Truncated Mean: $\boldsymbol{\alpha = 0.7}$

$$\frac{dE}{dx} = \frac{\sum_{i=1}^{i<\alpha \cdot N_{cluster}} Q^i_{cluster}}{\alpha \cdot N_{cluster}}$$



Spatial Reconstruction

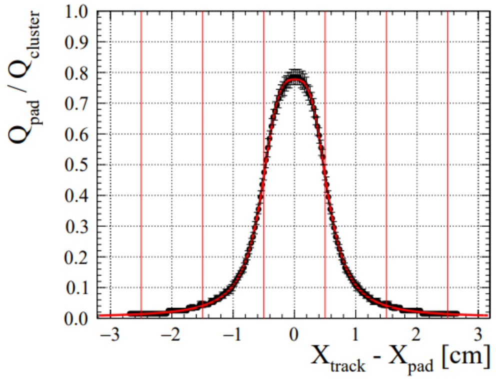
- Tracks are divided in **clusters**
- **Iteration 0:** Centre of charge is computed
- Fit of **Pad Response Function** (PRF)

$$PRF(x_{track} - x_{pad}) = \frac{Q_{pad}}{Q_{cluster}}$$

$$\downarrow$$

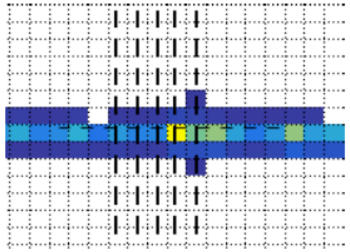
$$\chi = \frac{\frac{Q_{pad}}{Q_{cluster}} - PRF(x)}{\sigma}$$

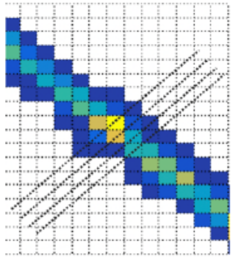
$$\sigma = \sqrt{\frac{Q_{pad}}{Q_{cluster}}}$$



- Fit is **iterated** with improved parameters

Type of Clustering



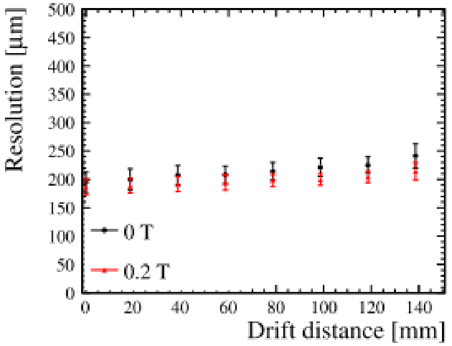


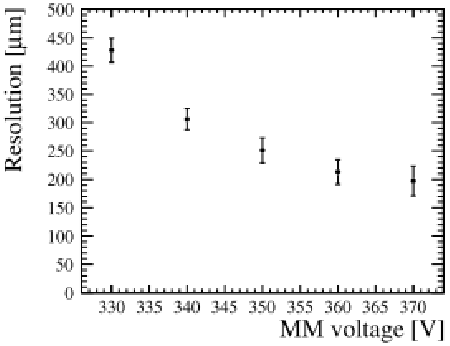
Results from DESY 2019 Test Beam

The prototype **satisfies the requirements** for ND280 Upgrade for every trajectory parameter for:

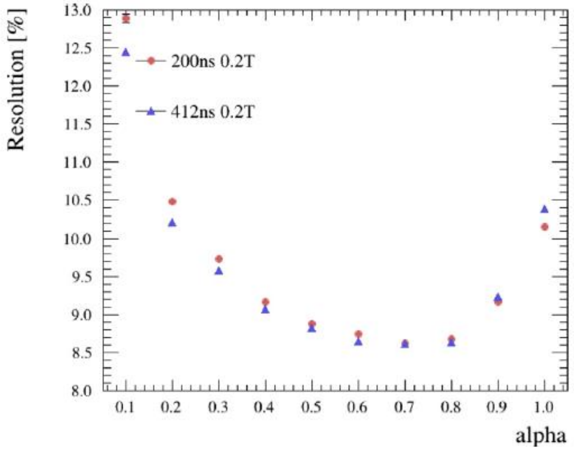
1. **Track Position** Reconstruction
2. **Energy Loss** Reconstruction

Spatial Resolution



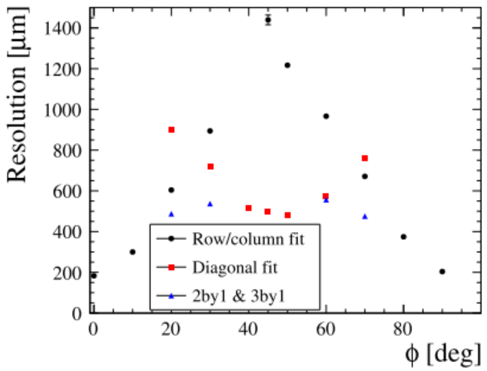


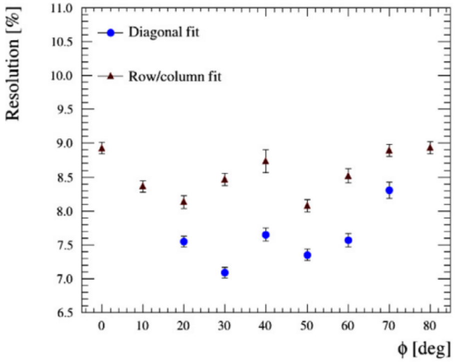
Energy Resolution



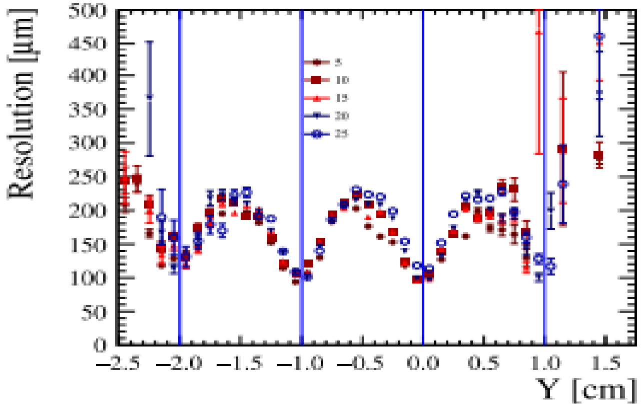
Critical Aspects

1. **Angle of track projection** (ϕ) on anode plane





2. **Track** horizontal position



Currently working on a global reconstruction method

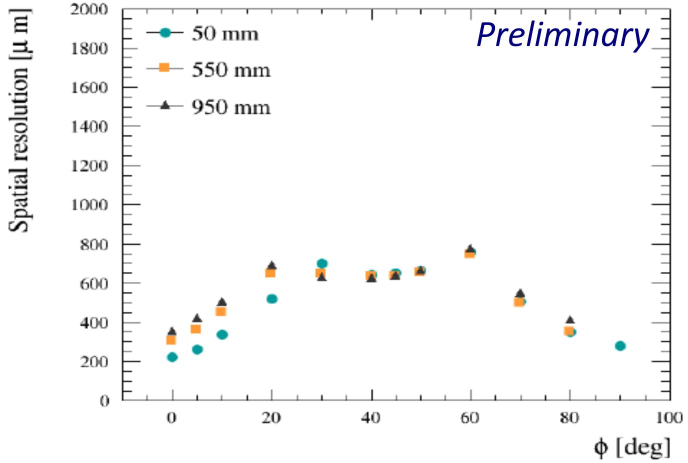
Results from DESY 2021 Test Beam

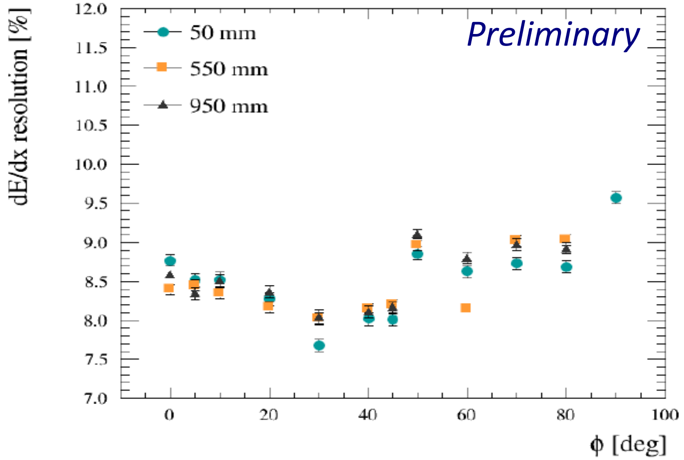
The prototype **satisfies the requirements** for ND280 Upgrade for every trajectory parameter for:

1. **Track Position** Reconstruction
2. **Energy Loss** Reconstruction

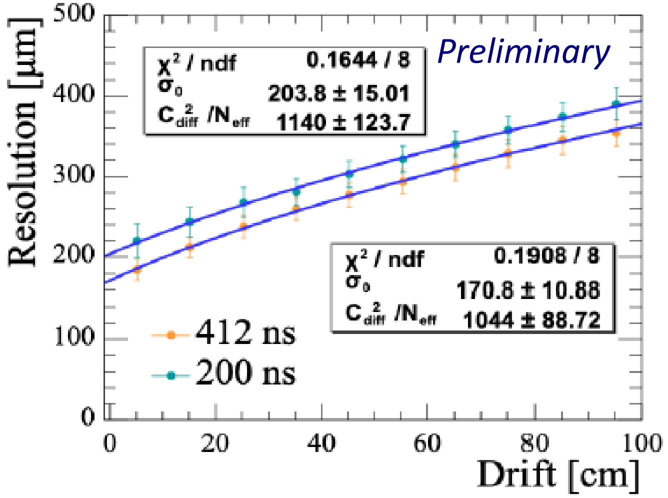
Critical Aspects

1. **Angle of track projection** (ϕ) on anode plane

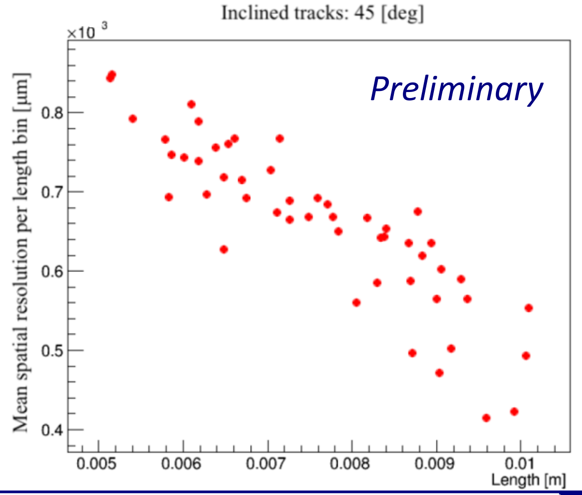




2. **Drift distance**



3. **Track projection length** on ERAM plane



The presence of a magnetic field distortion does not critically affect high level variables

ERAM Response Simulation

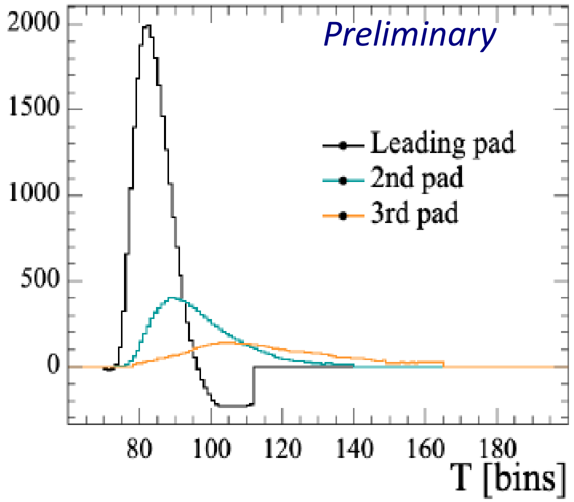
A simulation of detector response has been developed
The model has been compared with data from test beams

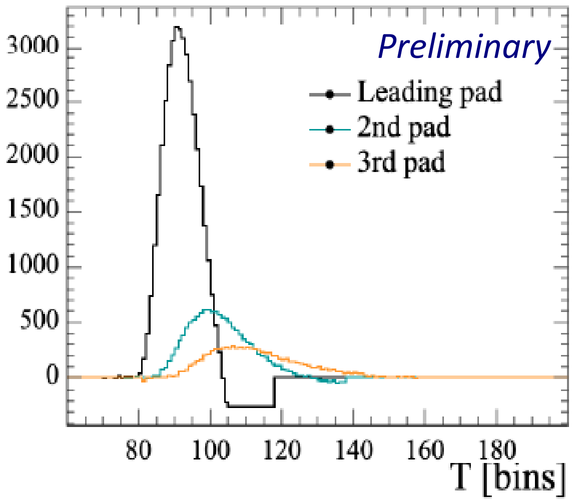
$$WF(t) = Q(t) \star \frac{dE}{dt}$$

Charge spreading from Telegraph equation

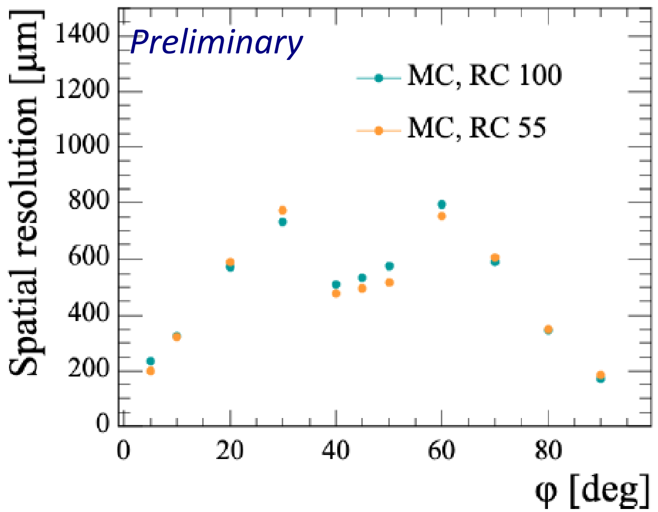
Derivative in time of Electronic response

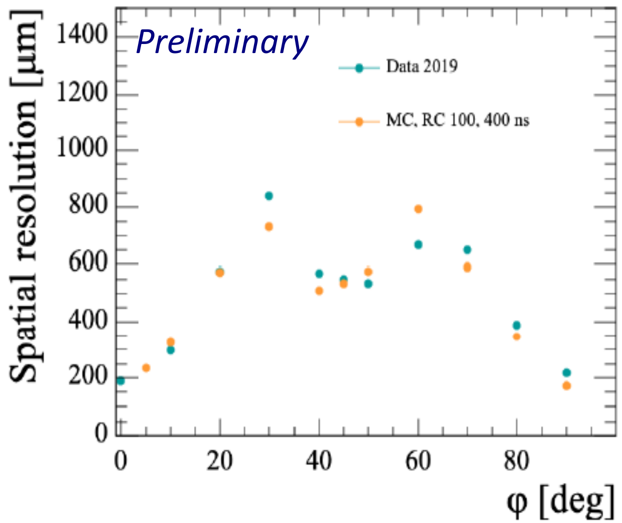
$$E(t) = \frac{e^{-\frac{3\tau}{t_{peaking}}} \tau^3 \sin \frac{\tau}{t_{peaking}}}{t_{peaking}^3}$$

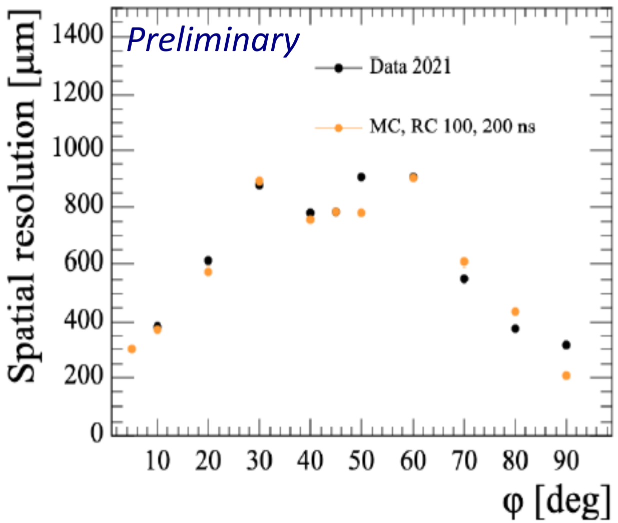




Comparison between **signal waveforms** in data and simulation







Performances from data and MC simulations

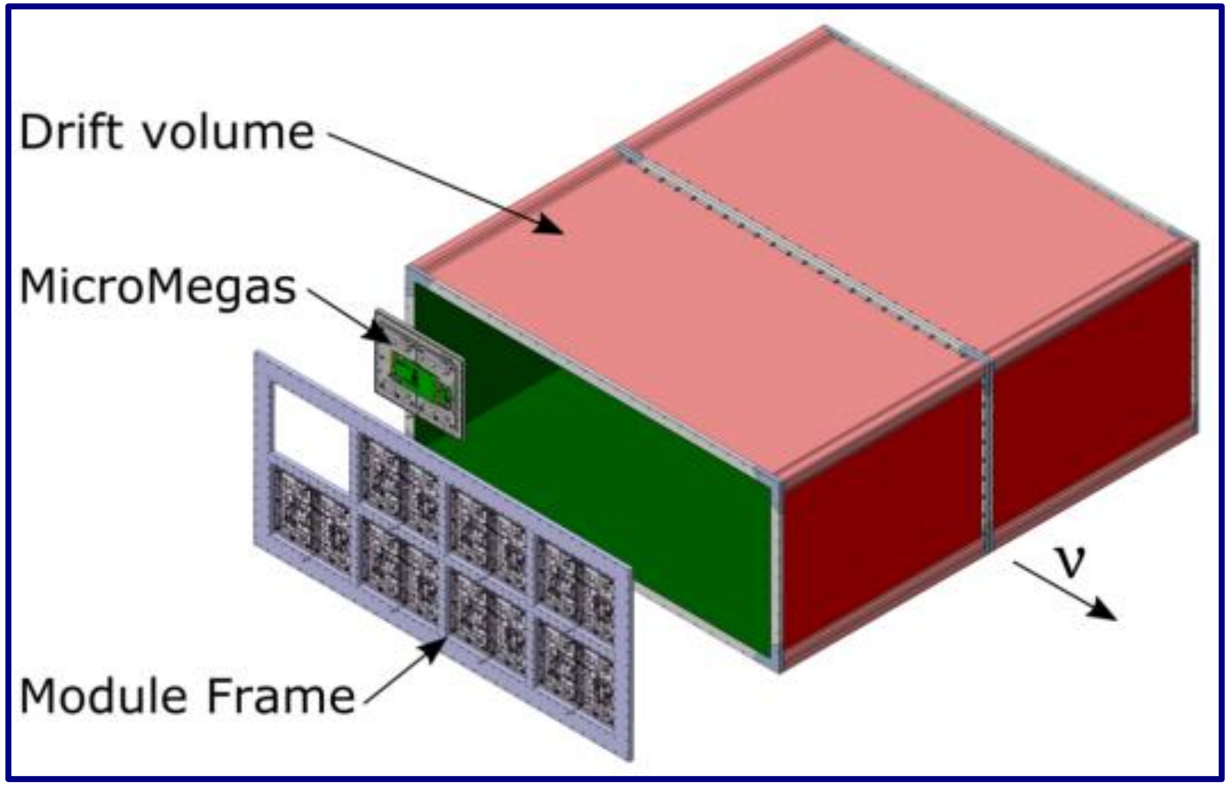
RC does not change critically the results

Conclusions

ERAM Sensors

Resistive technology studied in high detail for the first time

Production and validation is continuing



ERAM Performance

X-ray scan with Test Bench is going on

Gain and RC studies have been performed

Production is well on track

Spatial and Energy Loss resolution satisfy the upgrade requirements!

Currently working on a global reconstruction

Future Steps

Test beam in September 2022 with:

- 8 ERAM modules
- Full scale prototype as Field Cage

The installation of ND280 Upgrade is expected to be completed in Fall 2023

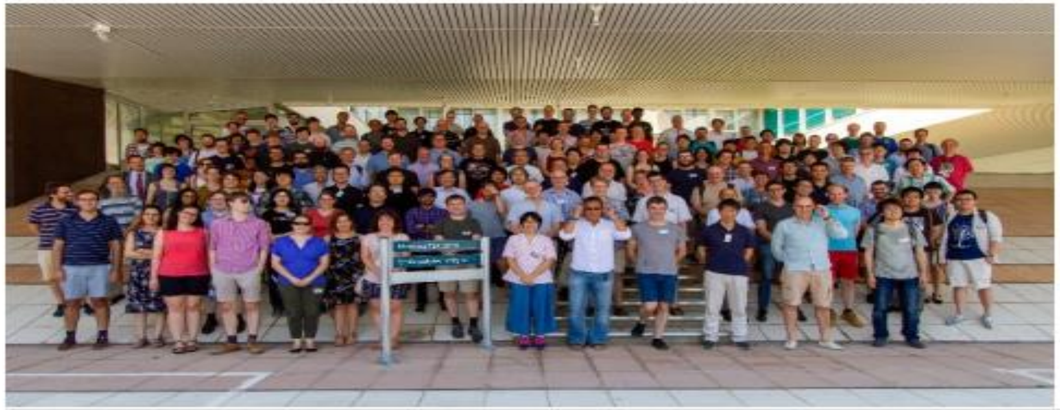
Thanks for your attention!

The T2K Collaboration (2022)

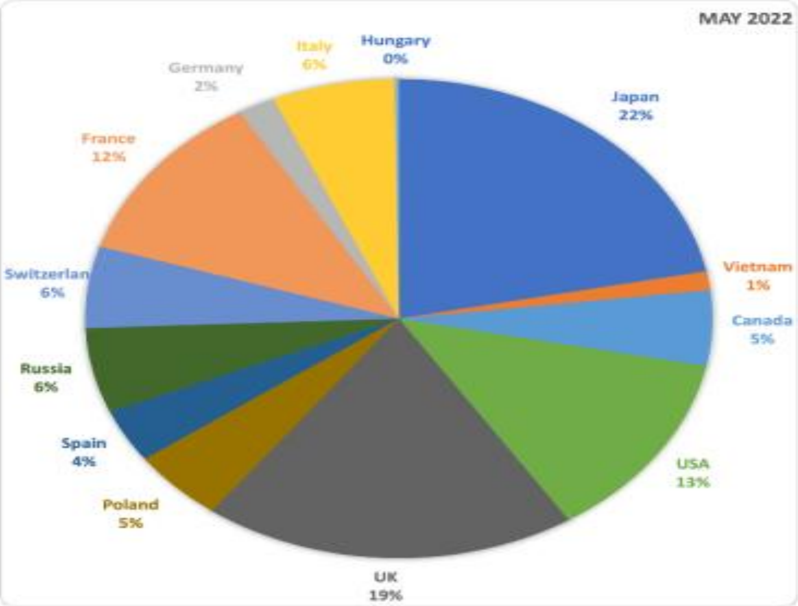
~528 members, 76 Institutes, 14 countries

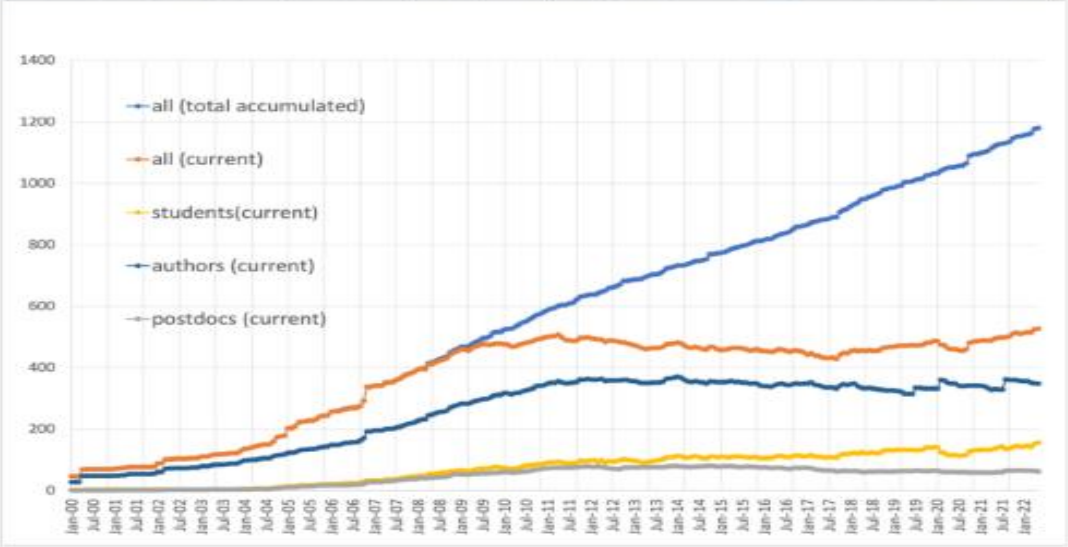
Asia	109
Japan	103
Vietnam	6

Americas	84
Canada	24
USA	60

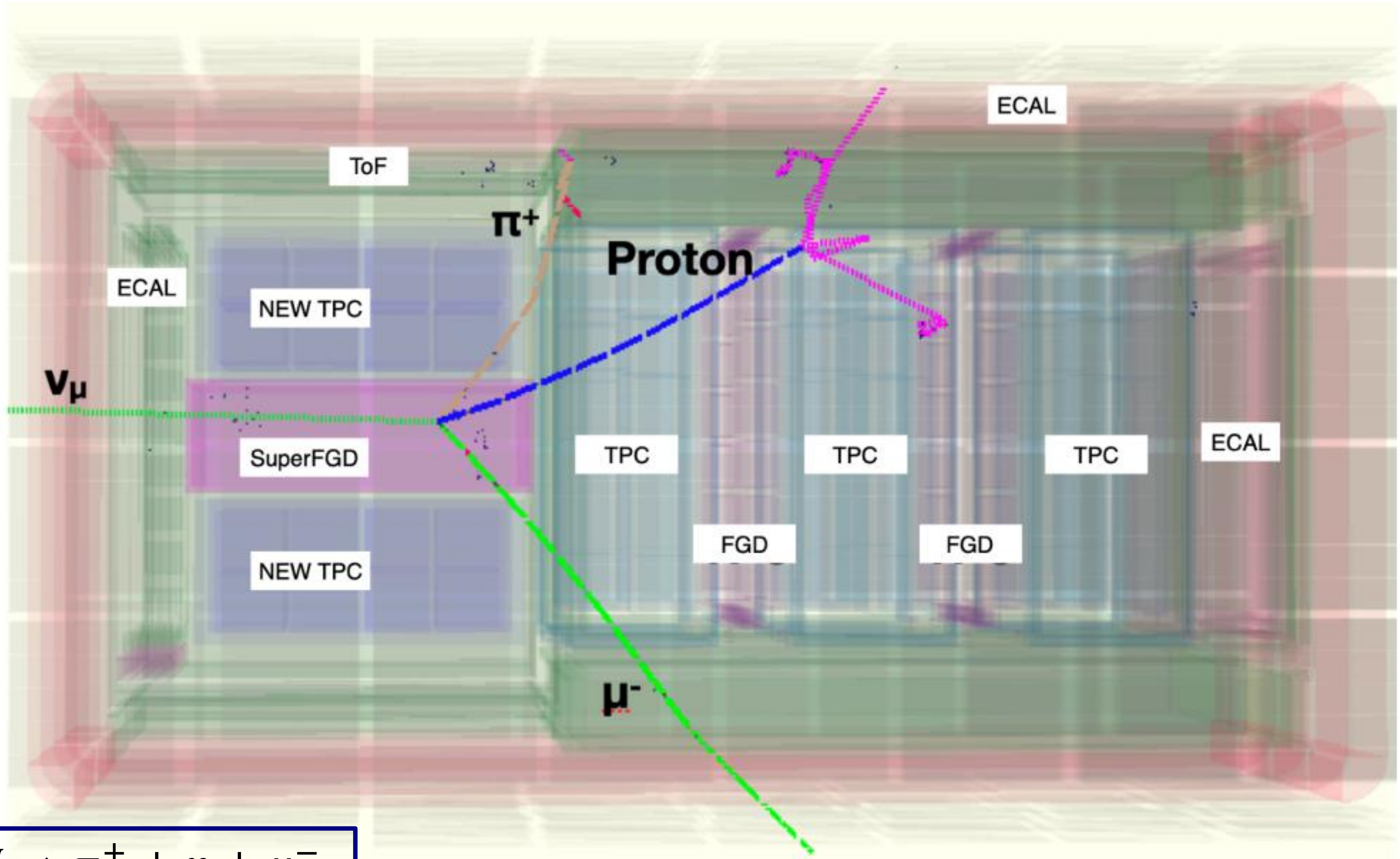


Europe	279
France	55
Germany	9
Hungary	1
Italy	30
Poland	23
Russia	27
Spain	17
Switzerland	26
UK	91





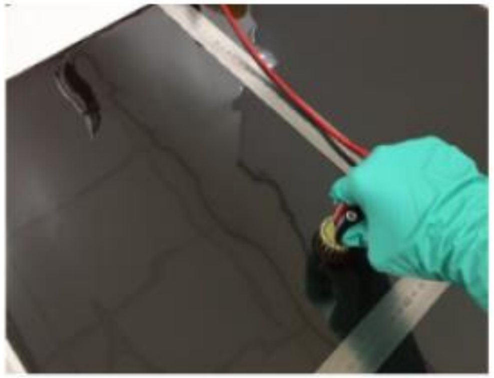
Event Display



$$\nu_\mu + N \rightarrow \pi^+ + p + \mu^-$$

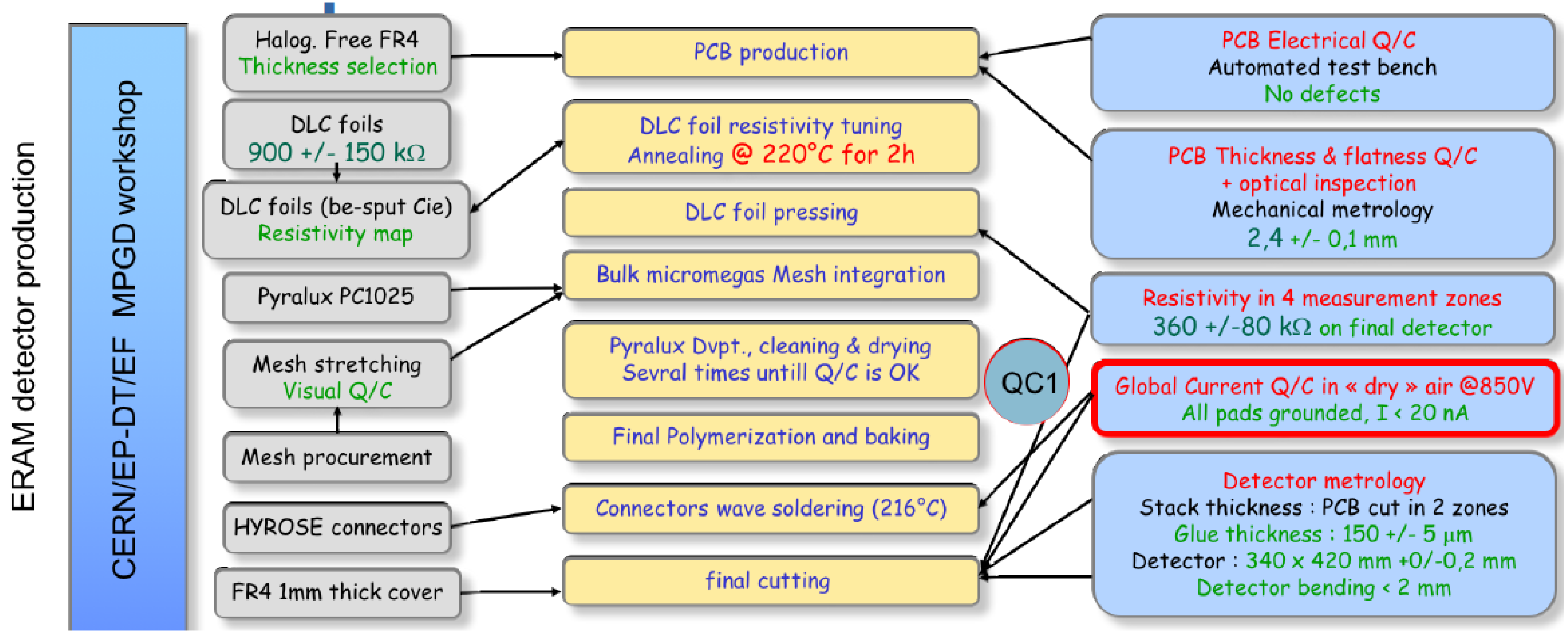
ERAM Production

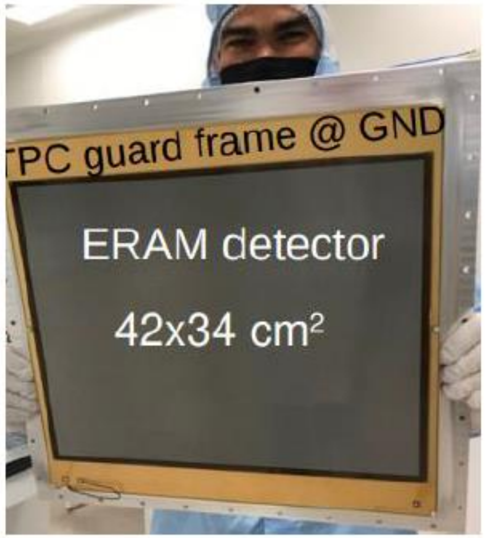
DLC foils are produced in Japan → Large area with controlled resistivity $\mathbf{R \sim 400k\Omega/sq}$
Value is allowed to change up to 10%



R&D first tests and validation procedure at **Saclay**

Other steps of production are performed at **CERN**



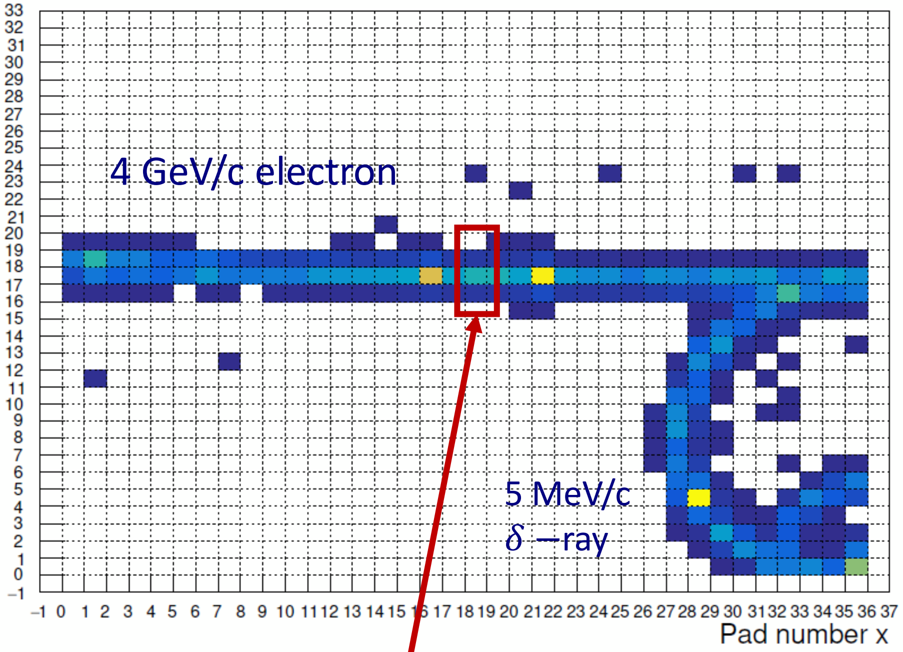


DESY Test Beam Setup in 2021

DESY II test beam facility area T24/1

13 days of beam time→many different setups:

- Scan on **Magnetic field** intensity (0-1 T)
- Scan on entrance position along **drift distance**
- Scan on **Phi** and **Theta** entry angles

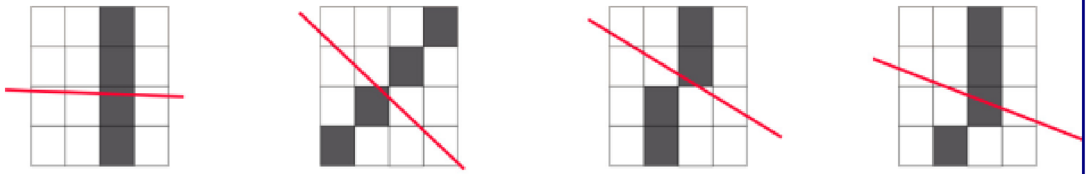


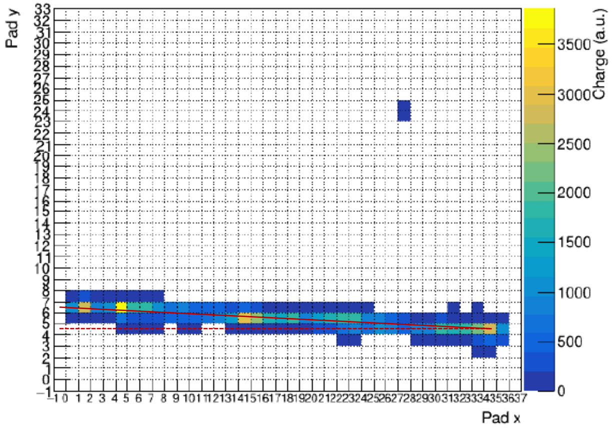
A study on **ExB Effect** has been performed to study the bias in particles trajectory reconstruction

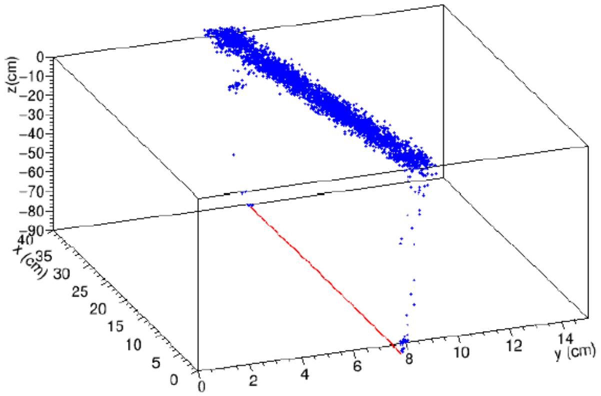
↓

Prototype in 2021 was **too long** for the Magnet

Energy loss and Position estimations start with a ***clustering procedure***







Data and simulated events due to ExB Effect