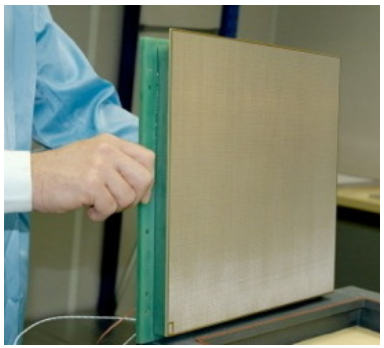
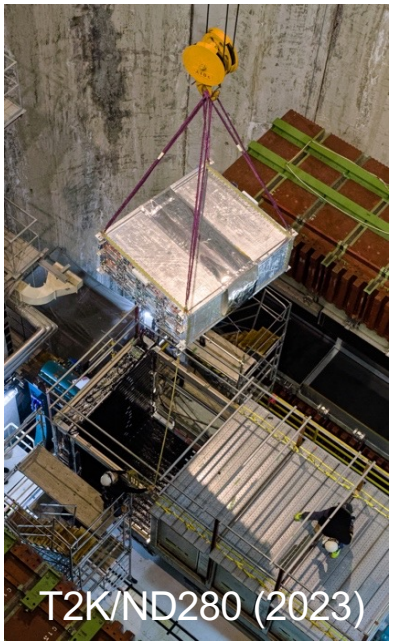
Time Projection Chambers for the T2K experiment

Alain Delbart, CEA/IRFU - Univ. Paris-Saclay

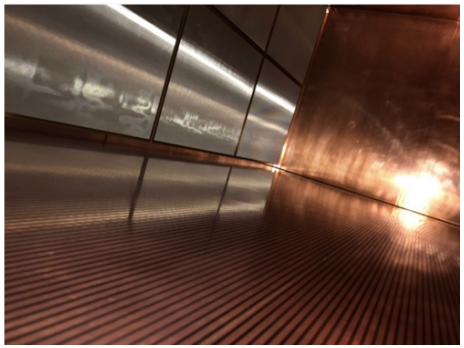
Vertical TPC (2004-) for ND280

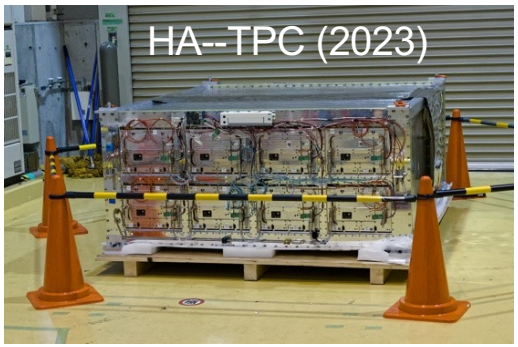


ND280 @ JPARC (Japan)

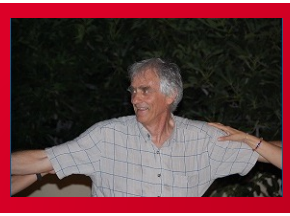


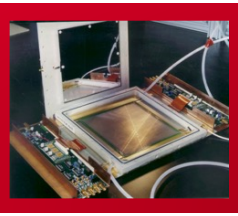
High-Angel TPC (2004-) for ND280 upgrade





cea irfu





Celebrating Ioannis Giomataris
CEA/Saclay, 5-6 october 2023

Me, Ioannis and Micromegas

CF4 in Gas for KABES

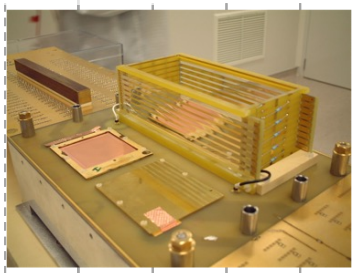
1995 2000 2005 2010 2015 2020

« Optical trigger »
PhD with Ioannis

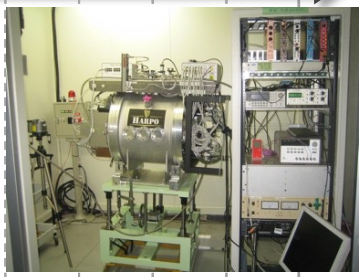
Micromegas R&D

NA48
Kabes
Compass

Neutron detect.



1999: PSI test beam / Sparks Vs gas
2000: PS + CENBG (nTOF) test beams
2001: 3 PS test beams (Kabes & GEM+MM)
CAST, ILC/FELICE, ion backflow, T2K gas, etc

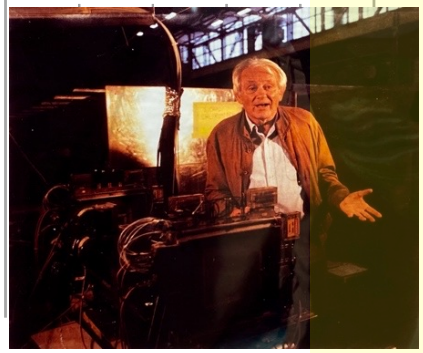


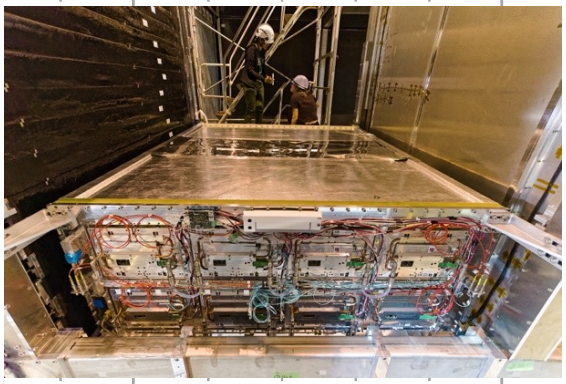
Minos
Compact annular TPC

T2K/ v-TPC
Large scale production of bulk-micromegas

High pressure TPC
Harpo

ERAM detectors
T2K/HA-TPC

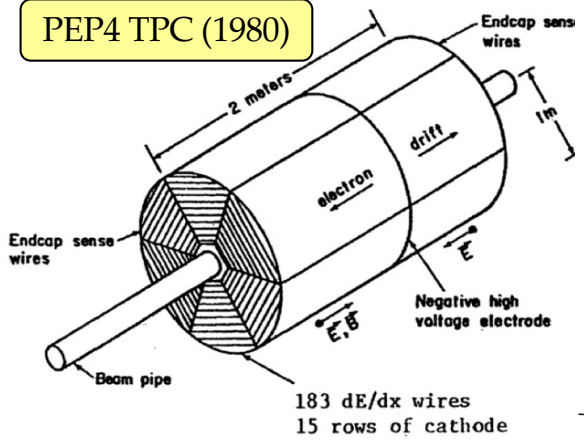




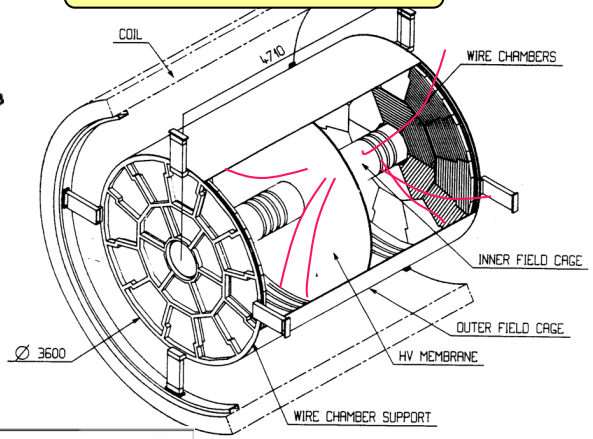
TIME PROJECTION CHAMBER (TPC)

Original proposal by D. R Nygren for the PEP4 experiment (LBNL internal report, 1974)

PEP4 TPC (1980)

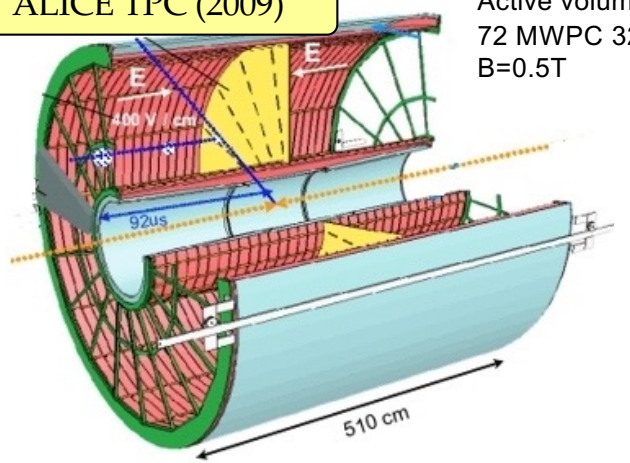


ALEPH TPC (1990)

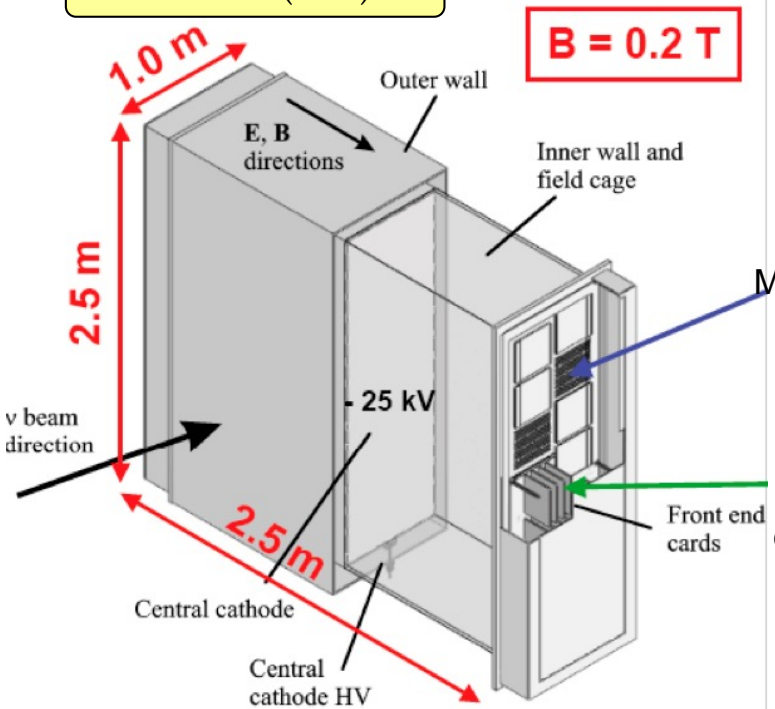


ALICE TPC (2009)

Active volume 88m^3
72 MWPC 32m^2
B=0.5T



T2K TPC (2009)



- ✓ Gas choice (Magbolz, Garfield), gas vessel & system
- ✓ Field cage for homogeneous electric field to provide an undeformed projection of the tracks (COMSOL)
- ✓ Magnetic field (for momentum measurement and B//E to lower diffusion of electrons)
- ✓ Readout plane with charge amplification for X-Y localization and dE/dx measurement (MWPC, MPGD)
- ✓ Gating grid (or else) to suppress the ion feedback
- ✓ Calibration system (field distorsions, gain, ...)
- ✓ Readout electronics : continuous sampling of induced charge on X-Y pad plane
- ✓ Event triggering system

T2K/ν-TPC IN TPC HISTORY

MPGD readout

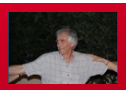
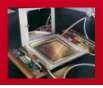
Table 3. Continued.

Parameter/Experiment cont.	NA35	EOS/HISS	NA49 VTX	NA49 MAIN	CERES/NA45	HARP	T2K[a]
Operation	1990	1992	1995	1995	1999	2001	2009/10
Inner/Outer radius or L/W (m)	2.4/1.25 (L/W)	1.5/0.96 (L/W)	2.5/1.5 (L/W); 2×	4/4 (L/W); 2×	0.6/1.3; $L = 2$	0.1/0.41	2.2/0.7 (H/L); 3×
Max. driftlength (L/2) (m)	1.12 vert.	0.75 (H)	0.67 vert.	1.1 vert.	0.7 rad.	1.6	0.9 W
Magnetic field (T)	0	1.3	1.5	0	$B_z < 0.7$; $B_r < 0.3$	0.7	0.2
Gas :	Ar/CH_4	Ar/CH_4	Ne/CO_2	$Ar/CH_4/CO_2$	Ne/CO_2	Ar/CH_4	Ar/CF4/i-C4H10
Mixture	91/ 9	90/ 10	90/10	90/ 5/5	80/ 20	91/ 9	95/ 3/ 2
Pressure (atm)	1	1	1	1	1	1	1
Drift field (kV cm^{-1} atm^{-1})	0.12	0.12	0.19	0.175	0.2-0.6	0.111	0.2
Electron drift velocity (cm μs^{-1})	5	5.5	1.3	2.3	0.7-2.4	5.2	7
$\omega\tau$ (see section 2.2.1.3)	0	0.5	1	0		3.3	0.7
Pads: size ($w \times L$, mm × mm)	5.5 × 40	8 × 12	3.5× (16 , 28)	(3.6, 5.5)×40	10 chevron	6.5 × 15	6.9 × 9.7
Max. no. 3D points	60 + 30	128	<150	90		20	72 × 3
dE/dx: Max. no. samples/track	60	128	<150	90		20	72 × 3
Sample size (mm atm); w or p	40; pads	12	16, 28	40		15	9.7
Gas amplification		3000	20 000	5000	8000	20 000	~1000
Gap a–p; a–c; c–gate[b]		4; 4; 6	3 , 2;	2,3; 3;6	3;3;6	5;5;6	0.128
Pitch a–a; cathode; gate	4; 1; 2	4; 1; 2	4; 1; 1	4; 1;1	6; 2; 2	4; 2; 2 stagg.	
Pulse sampling (MHz/no. samples)	12.5 /	10/256, SCA	/512	/ 512		10/>300, FADC	/512 SCA
Gating[c]		o. on tr.	o. on tr.	o. on tr.	o. on tr.	o.on tr.	none
Pads, total number	11 000	15 000	74 000	108 000	78 000	4000	125 000
Performance							
Δx_T (μm)-best/typ.	300–800	300	150	150	230/340	600–2400	600 (1m drift)
Δx_L (μm)-best/typ.	250–450				$dr = 400/640$	3.5	
Two-track separation (mm)	18	25		10			
$\partial p/p^2$ (GeV/c) $^{-1}$: TPC alone; high p		1			1	0.2/0.45–0.50	spec: <10;
dE/dx (%) : single tracks/in jets	/ 6	/ 4	<4 : VTX + Main			16	spec: <10 /
Comments	$B = 0$ only pad r.o.	only pad r.o.	Kr^m calibration only pad r.o.	up to1200 tr. only pad r.o.	Radial TPC No field wires	el. crosstalk	Micromegas r.o.

[a] Expected performance.
[b] a = anode, p = pads, c = cathode grid.
[c] o. on tr.: gate opens on trigger; cl.wo.tr. : opens before collision and closes without trigger; static : closed for ions only (see text).

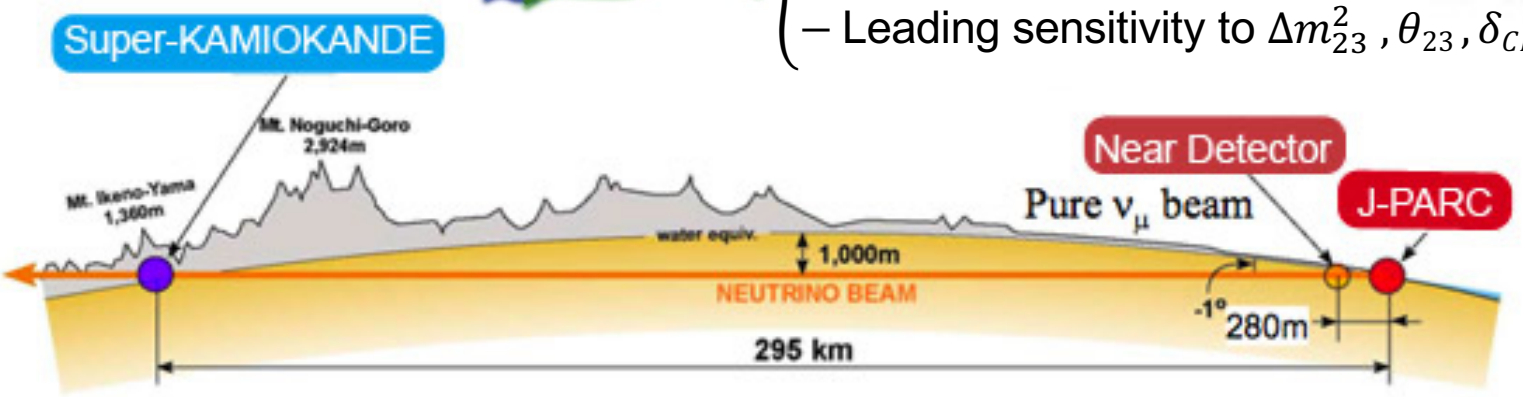
+ T2K/HA-TPC (ERAM readout) : 2023

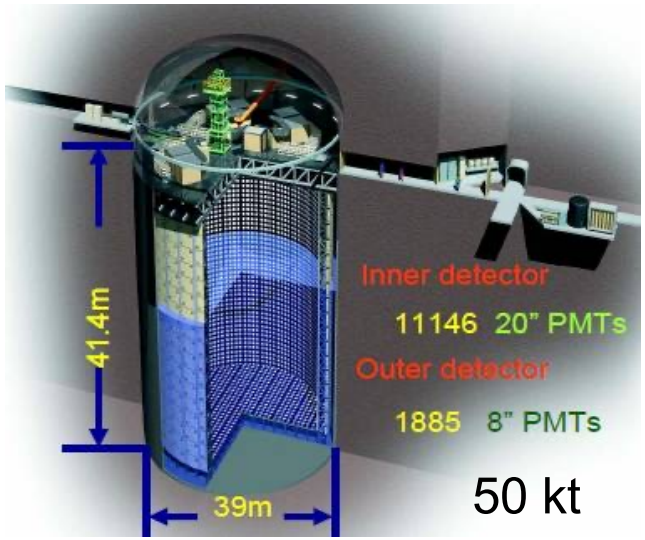
H. J. Hike, "Time Projection Chambers", Repot On Progress In Physics (2010) p73-109

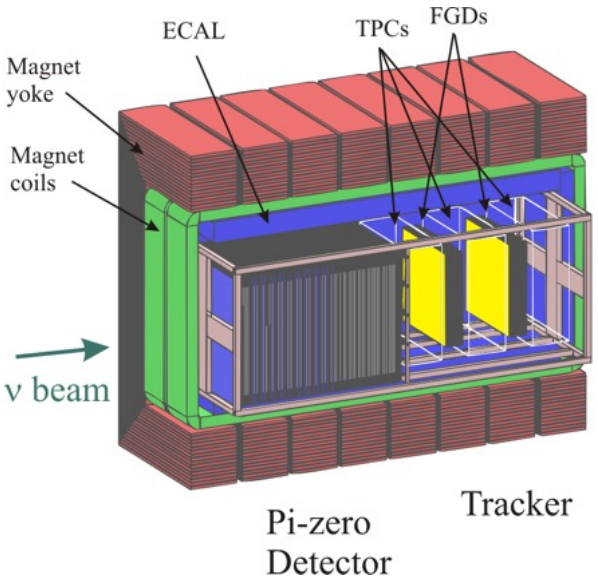



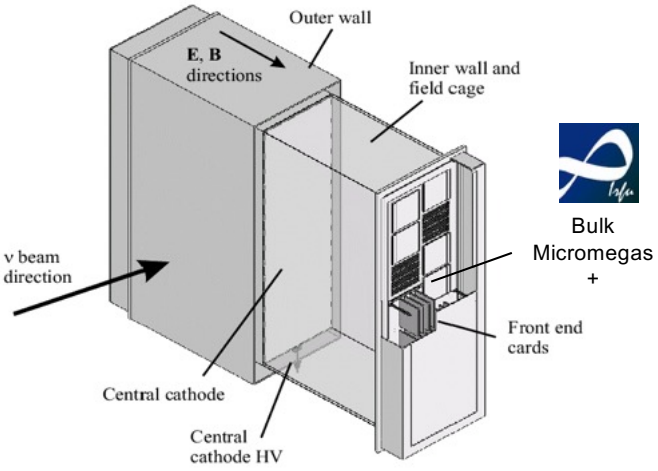
THE T2K EXPERIMENT: TOKAI TO KAMIOKA ND280 IN 2010

- Discovery of $\theta_{13} > 0$
- First hint of $\delta_{CP} \neq \{0, \pi\}$
- Leading sensitivity to Δm^2_{23} , θ_{23} , δ_{CP}









The T2K/ND280-TPC (2004-2007)

From the first ideas to the design choices

Gas mixture studies, readout segmentation, FEE readout

2004 — 2005 — 2006 — 2007

Yanis

Choice of Micromegas for the TPC readout by T2K

Ioanis major contribution and support

Proposition of a TPC for the T2K/ND280

Tests of first bulk-micromegas 10x10 cm^2

Beam test at CERN of 2 bulk-micromegas modules

T2K TPC Feasibility Report

December 6, 2004

T2K-TPC Group

Jacques Bouchez, Christian Cavata, Alain Delbart, Frédéric Druillole, François Pierre, Marco Zito
CEA/DAPNIA (SACLAY), France

Federico Sánchez
Universitat Autonoma de Barcelona, Institut de Fisica d'Altes Energies

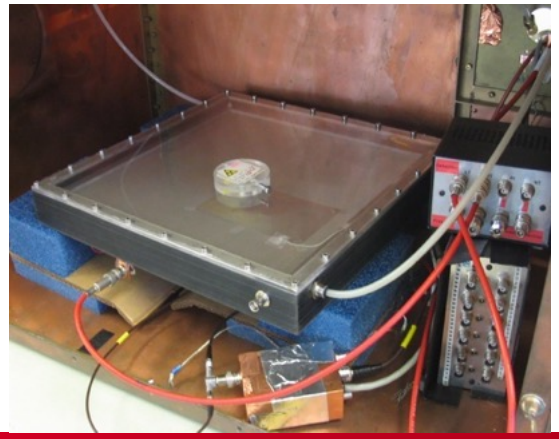
Alain Blondel, Anselmo Cervera, Edda Gschwendtner, Raphael Schroeter, J.-P. Richeux, Pierre Bene, Daniel LaMarra
University of Geneva, Switzerland

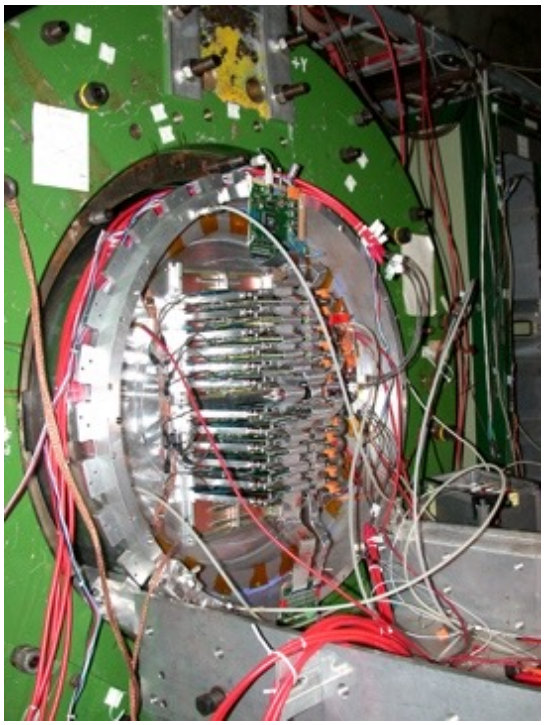
Wayne Faszer, Robert Henderson, Issei Kato, Akira Konaka, Konstantin Olchanski, Robert Openshaw, Fabrice Retiere
TRIUMF, Canada

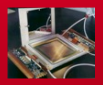
Juergen Wendland
University of British Columbia, Canada

J.P. Martin
University of Montreal, Canada

Paul Birney, Dean Karlen, Mark Lenkowski, Paul Poffenberger, Mike Roney, Gabe Rosenbaum
University of Victoria/TRIUMF, Canada







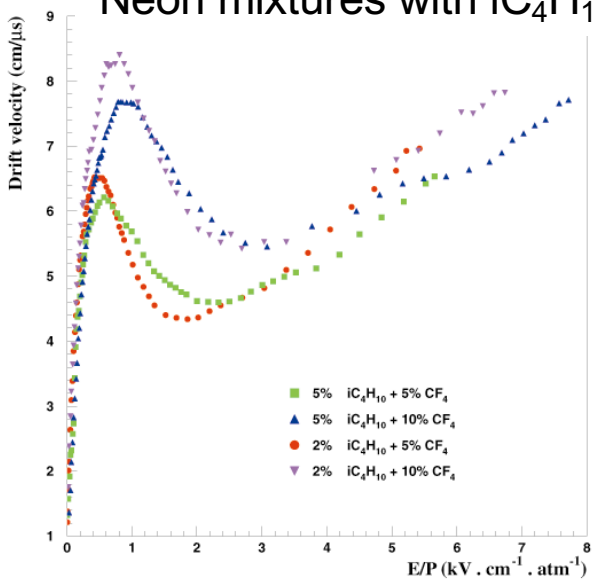
T2K/TPCs GAS CHOICE : THE T2K GAS MIXTURE ONE OF IOANNIS (et al.) CONTRIBUTION

The TPC gas mixture properties have to comply with many design and operating TPC parameters :

- ✓ Electron drift velocity Vs electronics sampling frequency Vs maximum drift length
- ✓ Electron transverse diffusion Vs pad size for optimal charge sharing between adjacent pads (X,Y)
- ✓ Gas gain (electron multiplication by avalanche) in the charge amplification
- ✓ Stability of gas parameters Vs P, T, impurities, electric field, …
- ✓ Electron attachment by electronegative components or impurities (Halogenides, oxygen)

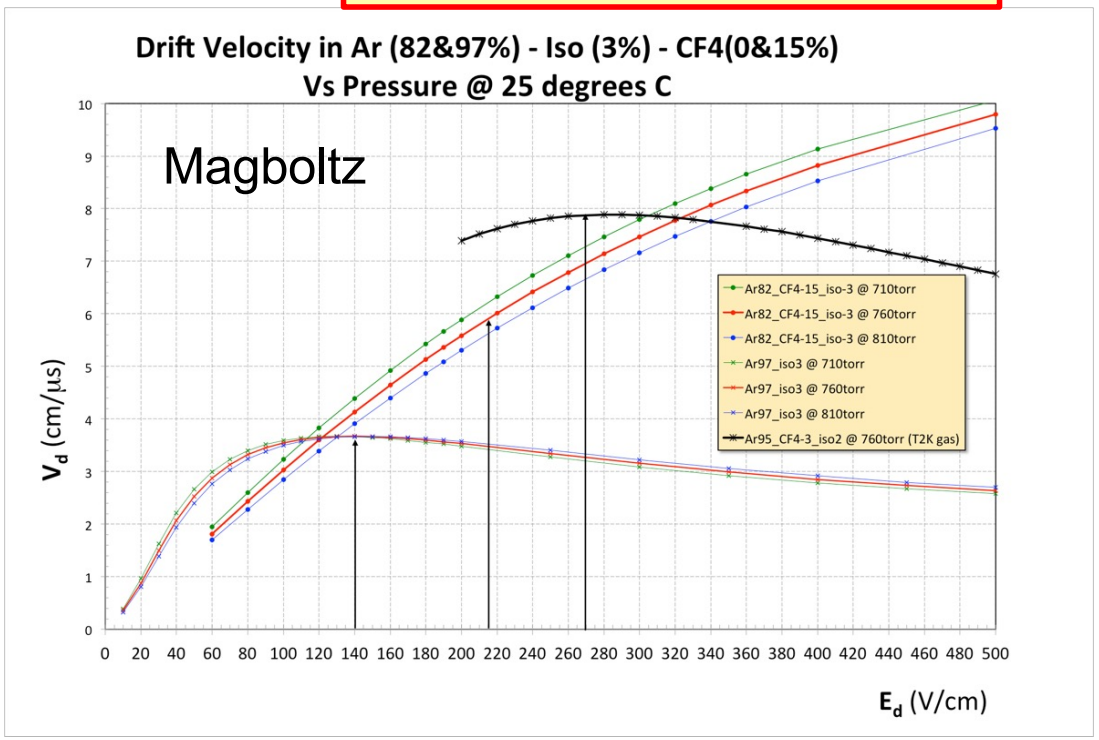
Ex: Ar(80)/CH_4(20) for PEP4, Ne(90)/CO_2(10)/N_2(5) for ALICE, **Ar(95)/CF_4(3)/iC_4H_{10}(2) for T2K**

Neon mixtures with iC_4H_{10} & CF_4



Ref: P. Colas et al, NIM A478, p215 (2002)

Shift to Ar (T2K gas)

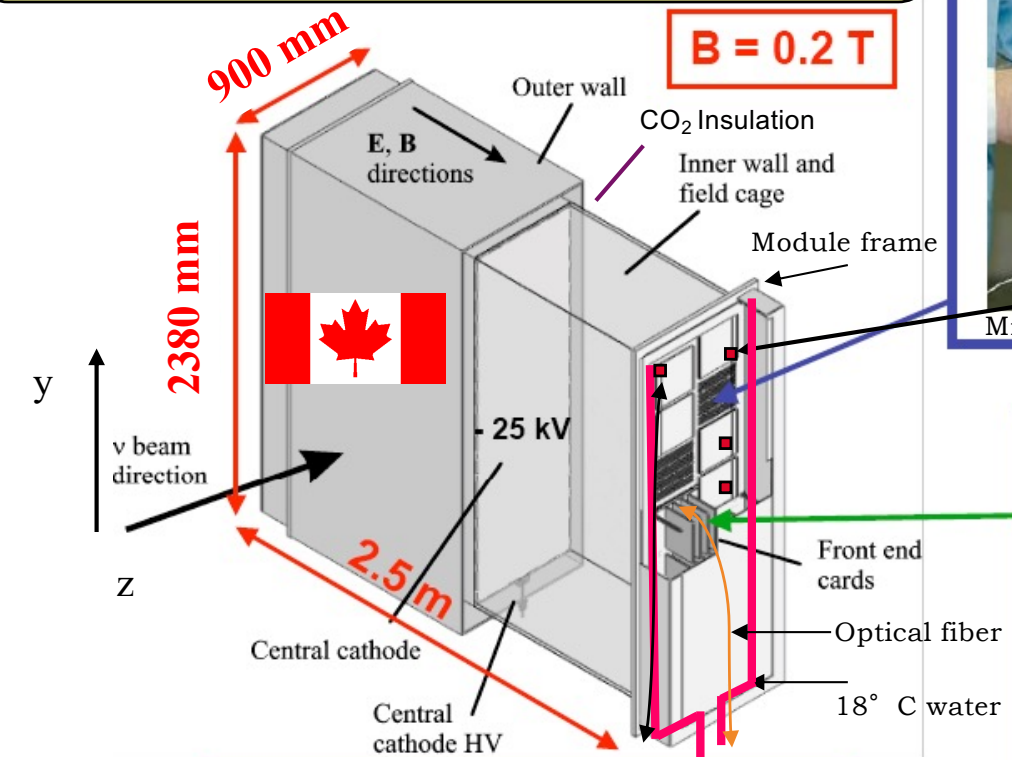


THE FINAL DESIGN OF THE T2K / ν-TPC

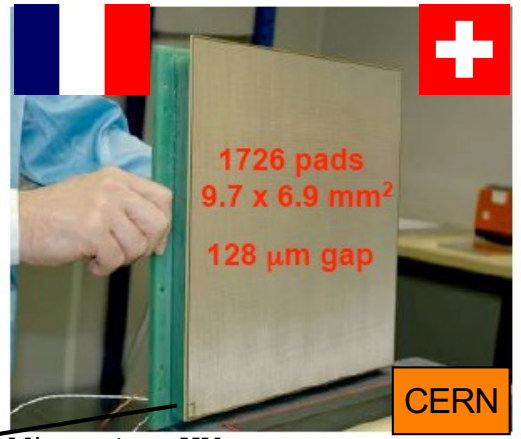
Specifications / performances

TPC PID : e^-/μ seperation

- ✓ dE/dx < 9% (MIP)
- ✓ Spatial resolution of 600 µm @ z=1m ($\Delta p/p < 10\%$)



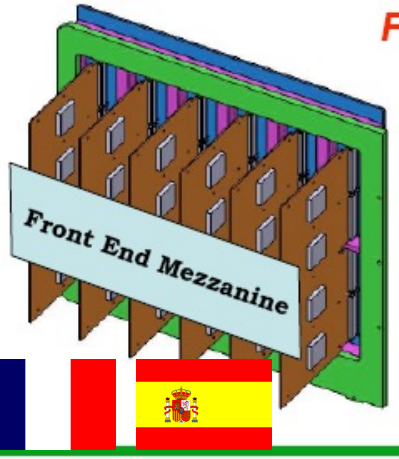
36 x 34 cm² « Bulk » MicroMegas



12 modules per Readout plane

Total of 72 modules

FEE based on the ASIC AFTER



6 FECs + 1 FEM per module

Total of
1728 ASICs
432 FECs
72 FEMs

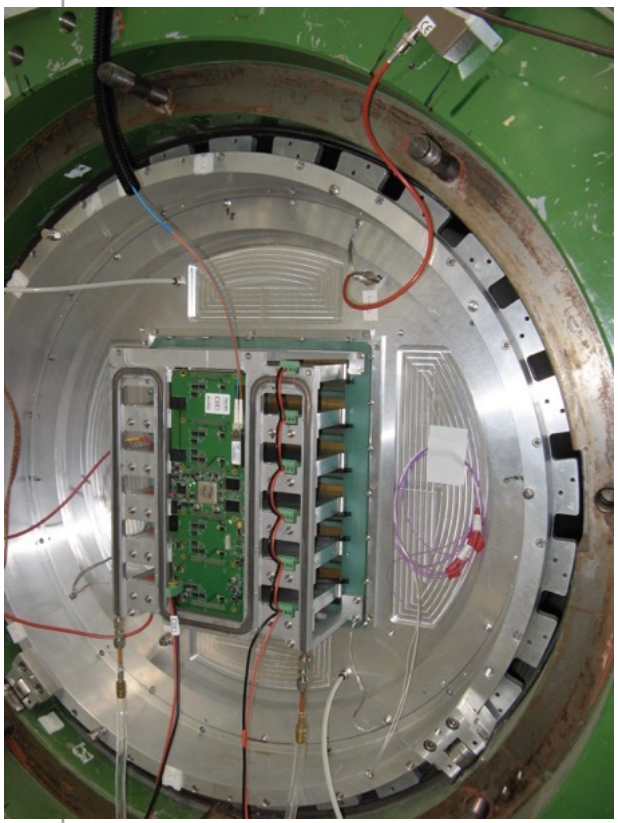
With On-detector FEE cooling mechanicals

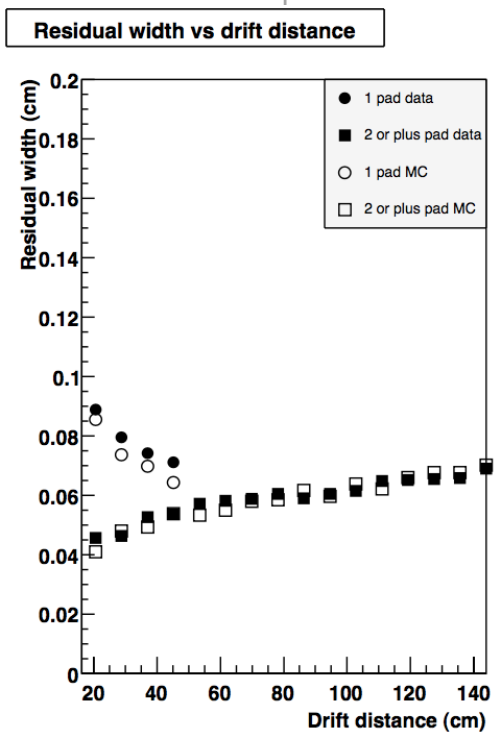
72 modules for ~9 m² active area
~120k electronics channels

The T2K/ND280-TPC (2007-2009)
From the pre-production prototype to the production

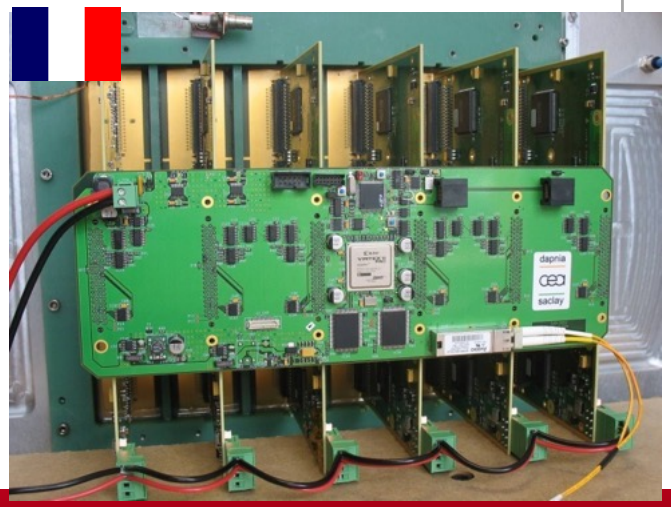
2007 — 2008 — Start of the production By the CERN MPGD workshop — 2009

Beam test at CERN of 1 scale 1 Micromegas module





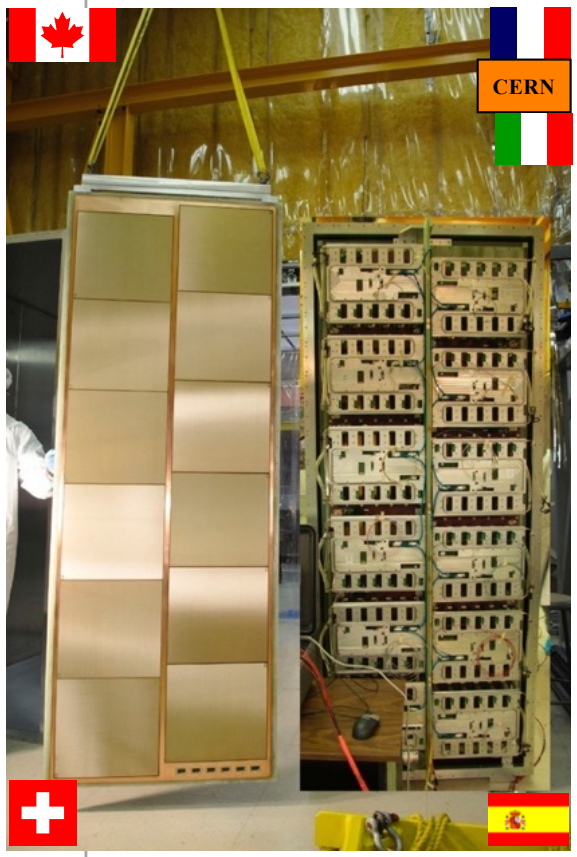
Production Readiness Reviews



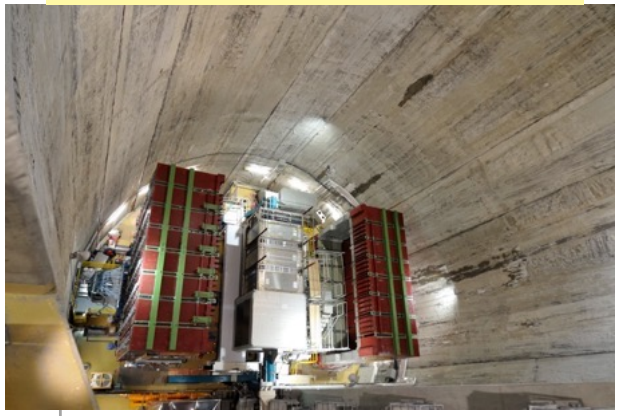
THE T2K/ND280-TPC (2009-2012)
FROM THE FINAL ASSEMBLY TO THE EXPERIMENT

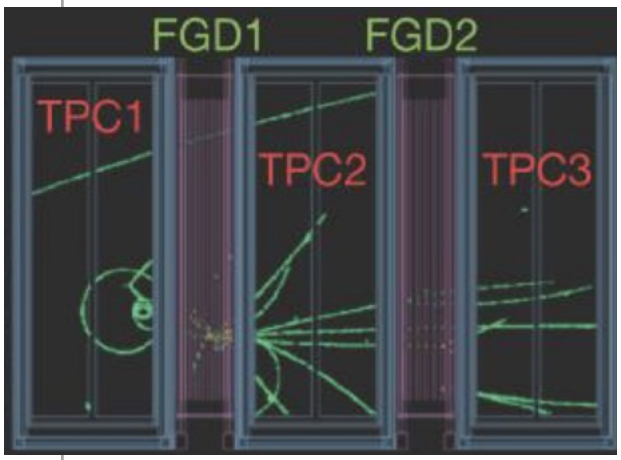
2009 — 2010 — 2010 - T2K experiment — 2011 — 2011 first publications — 2020

Assembly and Validation with beam of the first TPC at Triumf (vancouver, Canada)

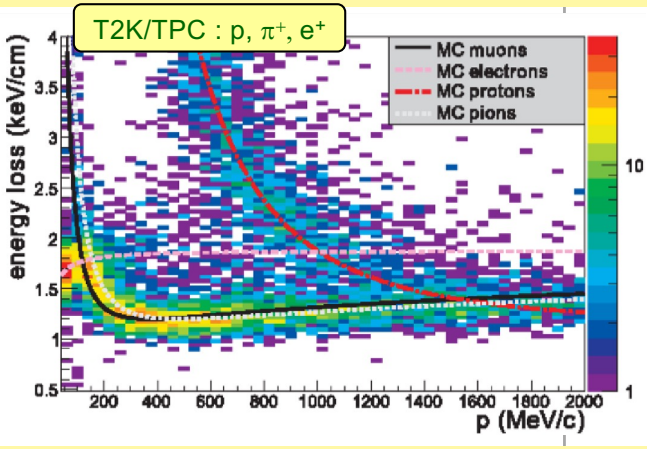


2010 - ND280 integration, commissioning & start of T2K





289 INSPIRE citations : N. Abgrall et al. (T2K/ND280 TPC Collaboration), "Time Projection Chambers for the T2K Near Detectors" Nucl. Instrum. Meth. A637, 25-46 (Dec 2010)
1001 INSPIRE citations : K. Abe et al. (T2K Collaboration), "The T2K Experiment" Nucl. Instrum. Meth. A659, 106-135 (June 2011)



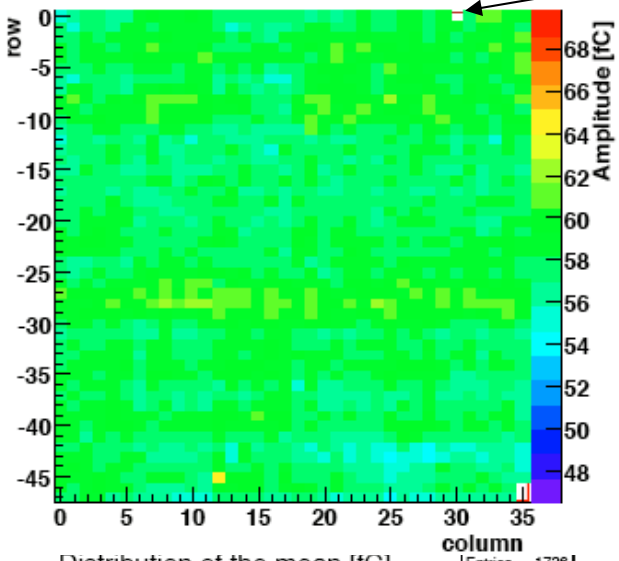
1765 INSPIRE citations : K. Abe et al. (T2K Collaboration), "Indication of Electron Neutrino Appearance from an Accelerator-produced Off-axis Muon Neutrino Beam" Phys. Rev. Lett. 107, 041801 (june 2011)
704 INSPIRE citations : K. Abe et al. (T2K Collaboration), "Observation of Electron Neutrino Appearance in a Muon Neutrino Beam" Phys. Rev. Lett. 112, 061802 (Nov. 2013)

THE T2K/V-TPC BULK MICROMEGAS PERFORMANCES

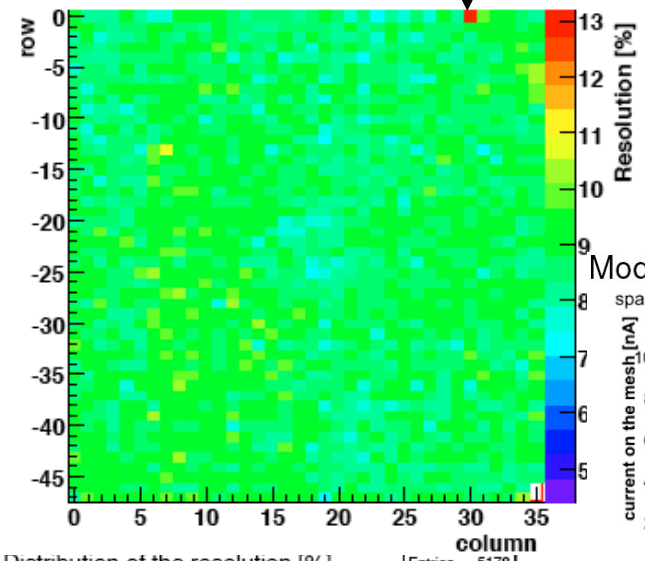
1726 pads scan @ -350 V

1 FEC dead ch.

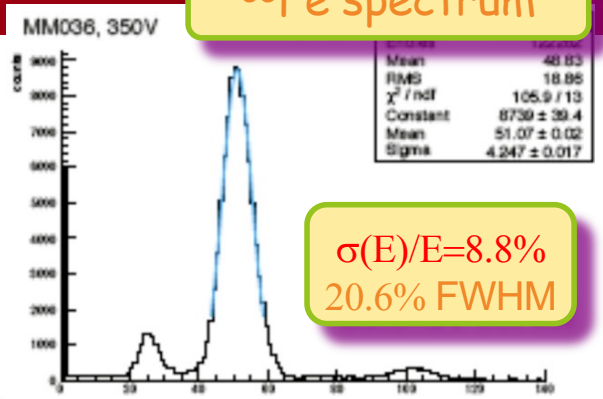
Map of the gain (mean value)



Map of the resolution (sigma)

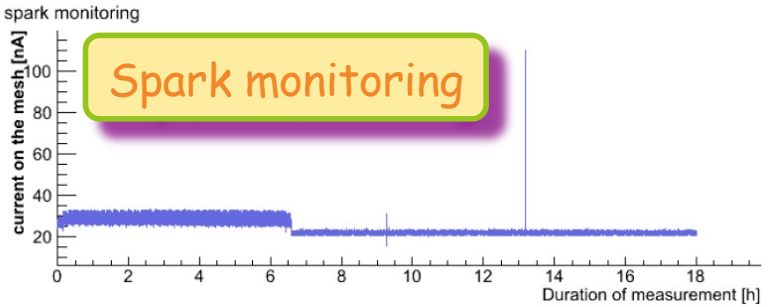


^{55}Fe spectrum



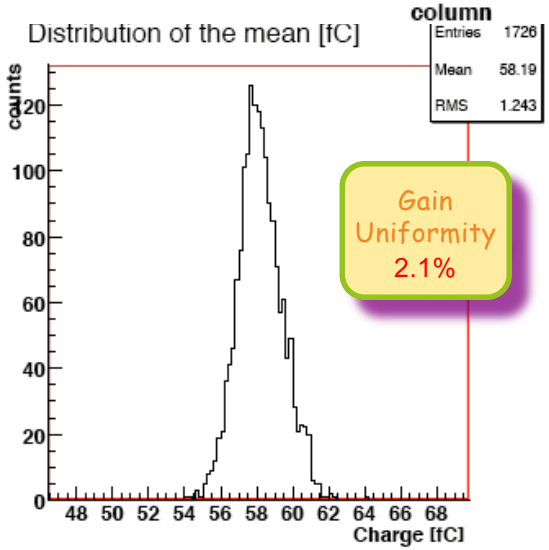
σ(E)/E=8.8%
20.6% FWHM

Mod_024
spark monitoring



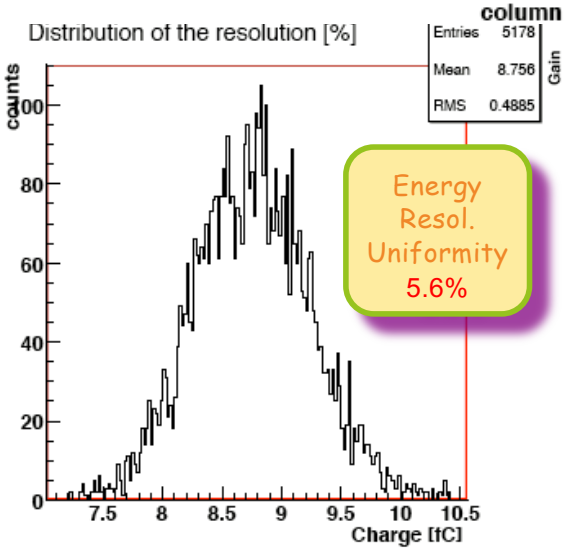
Spark monitoring

Distribution of the mean [fC]



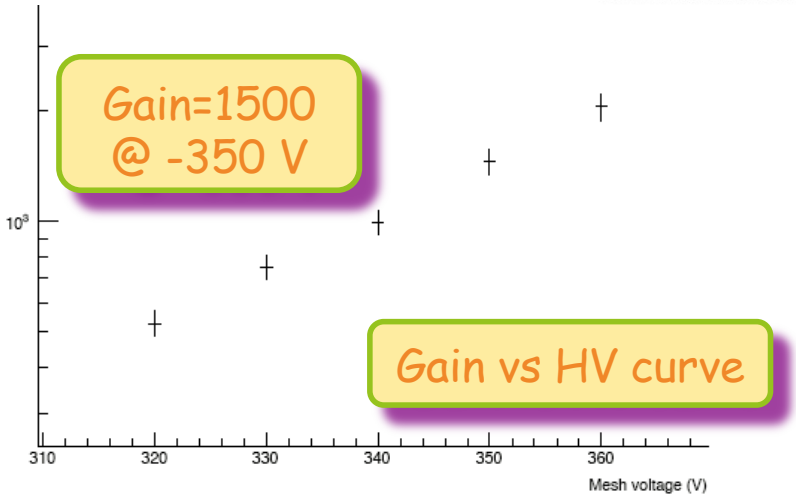
Gain Uniformity 2.1%

Distribution of the resolution [%]

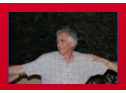


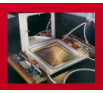
Energy Resol. Uniformity 5.6%

Gain=1500 @ -350 V



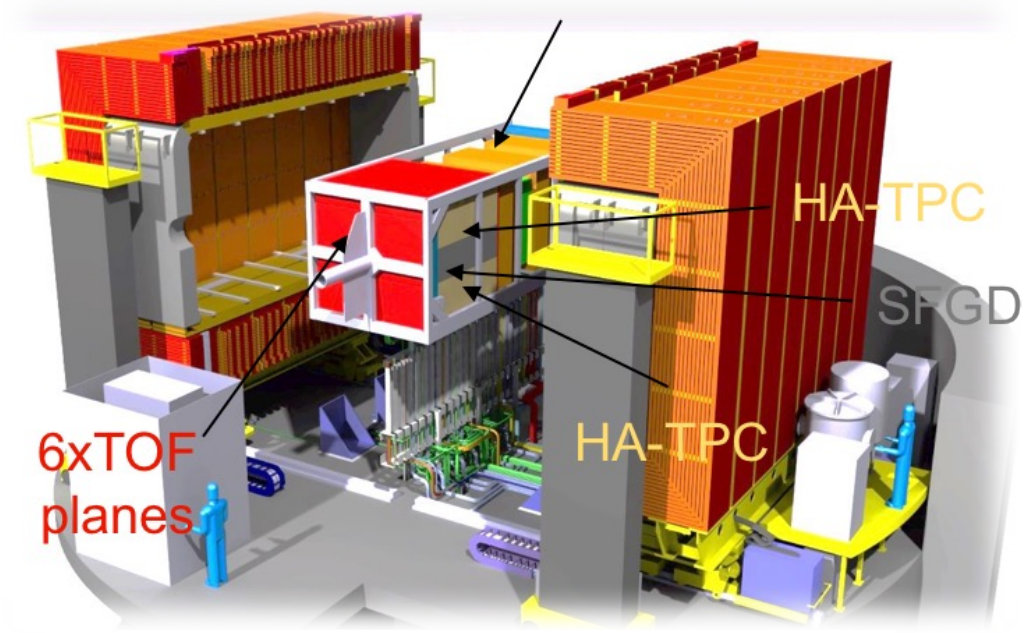
Gain vs HV curve

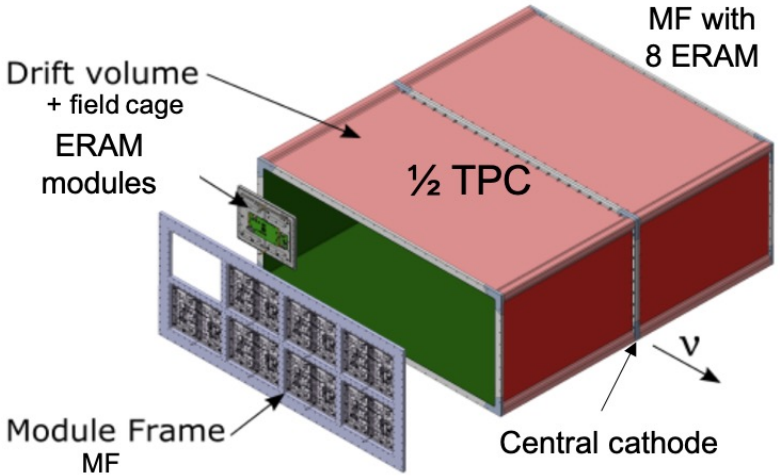




THE UPGRADE OF THE T2K NEAR DETECTOR DEVELOPMENT : 2017-2024

2009 TPCs (x3)





	HA-TPC	v-TPC
Parameter	Value	
Overall x × y × z (m)	2.0 × 0.8 × 1.8	0.85 x 2.2 x 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)	340x420	340x360
Pad z × y (mm)	10 × 11	7x10
N pads	36864	124272
el. noise (ENC)	800	
S/N	100	
Sampling frequency (MHz)	25	
N time samples	511	
Channel density (nb. / cm^2)	0.9	1.4

ND280 upgrade TPCs achievements

- First experiment to use ERAM detectors
- Performances similar or better than v-TPCs with ~1/3 less electronic channel density
- New innovative field cage design for high acceptance and dead volume reduction

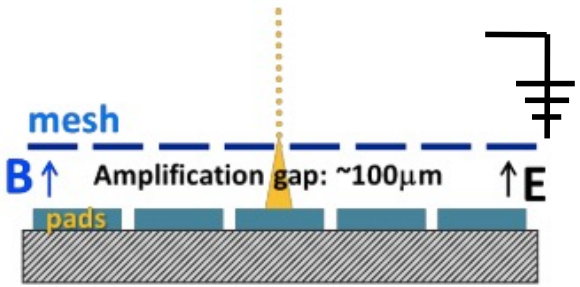
THE NEW MICROMEGAS MODULES FOR THE HA-TPC
THE ENCAPSULATED RESISTIVE ANODE MICROMEGAS

Ref: P. Colas/D. Attié ILC/TPC R&D (M.S. Dixit *et al. NIM* A518, p. 721, 2004

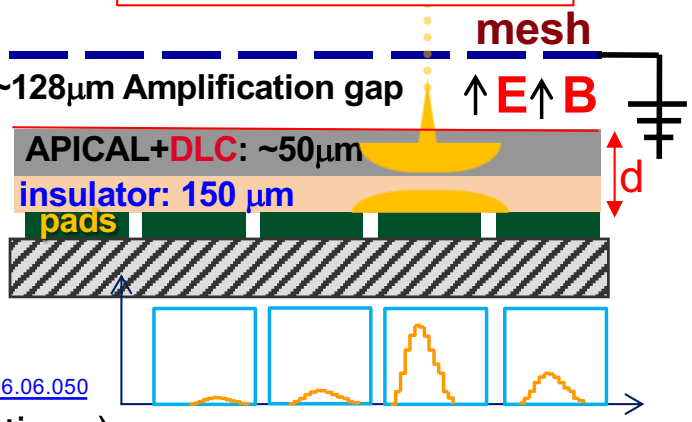
Choice of the Resistive foil technology for the HA-TPC micromegas readout

- Charge spreading which should enable keeping the ~600 μm spatial resolution with larger pads and improves it at short drift distance → less electronic channels, cost reduction
- ASIC spark protection no longer needed → more compact FEE, maximize HA-TPC acceptance
- Encapsulated mesh @ GND + insulating layer → potentially lower track distorsions & better S/N

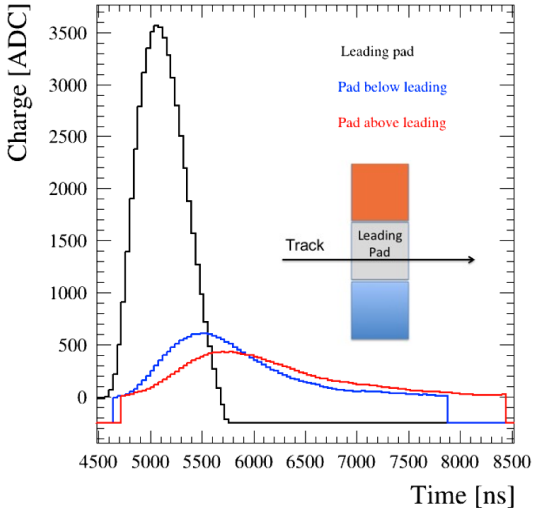
Standard bulk-mm



Resistive-bulk-mm



M. S.Dixit et al. NIM A566, (2006), 281–285. doi:10.1016/j.nima.2006.06.050



2-D RC network (telegraph equations)

$$\rho(r,t) = \frac{RC}{2t}\exp\left[-\frac{-r^2RC}{4t}\right]$$

R- surface resistivity
C- capacitance/unit area

Gaussian spreading as a function of time with :

$$\sigma_r = \sqrt{\frac{2t}{RC}} \qquad \begin{cases} t \approx shaping\ time\ (few\ 100\ ns) \\ RC_{[ns/mm^2]} = 10^3\,\varepsilon_0\,\varepsilon_r \dfrac{R_{[M\Omega/\blacksquare]}}{d_{[\mu m]}} \end{cases}$$

ε_r [APICAL]~3,3 and ε_r [glue] ~4,8

For ~11x10 mm² pads, DLC R is chosen ~0.5 $M\Omega/\blacksquare$ and the glue thickness ~150 μm, RC_{design}~100 ns/mm²

ILC/TPC R&D : 7x3 mm² / DLC R~2.5 Mohm for an RC~

FOCUS ON ERAM DEVELOPMMENT

D. Attié et al. NIM A1052, (2023), 164288. doi.org/10.1016/j.nima.2023.168248

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

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

Nov. 12 PRR | Pre-series To series production

ILC-TPC heritage

2018 2019 2020 2021

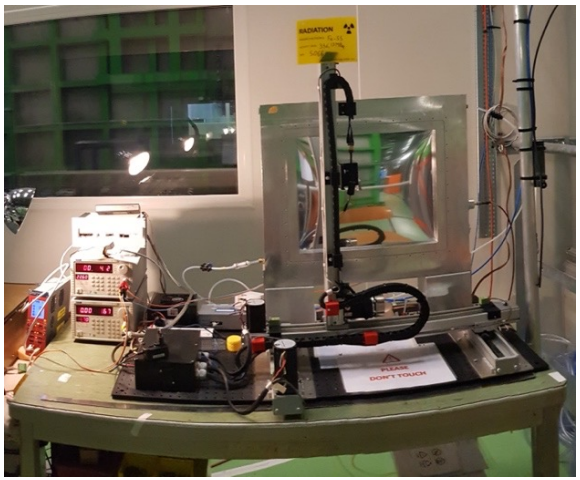
CERN/T9 test beam DESY test beam

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

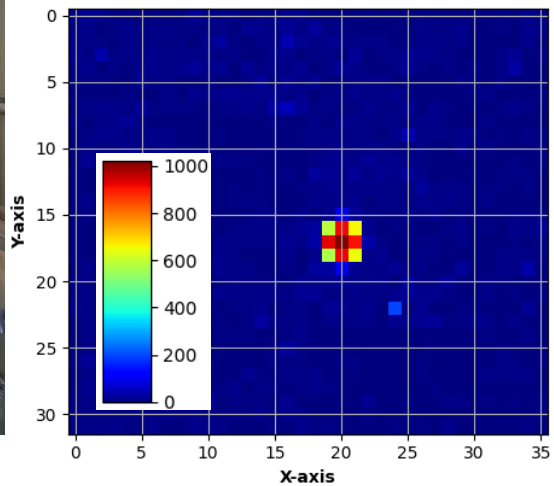
	2018 MM0-DLC#	2019 MM1-DLC1 & 2	2020 ERAM-P1 & P2	Production ERAM-xx (ERAM-01-28)
Readout PCB	v-TPC PCB	HA-TPC V1 + ARC FEE	HA-TPC V2 + final FEE V1	HA-TPC V2 + final FEE V2
Size	34 × 36 cm²	34 × 42 cm²	34 × 42 cm²	34 × 42 cm²
Pads	48 × 36 cm²	32 × 36 cm²	32 × 36 cm²	32 × 36 cm²
Pad size	6,85 × 9,65 mm²	10,09 × 11,18 mm²	10,09 × 11,18 mm²	10,09 × 11,18 mm²
Number of pads	1728	1152	1152	1152
DLC resistivity (MΩ/sq.)	~2,5 (original foil) Not meas.on detector ILC/TPC foil	0,32-0,44 (batch#P1 foils) 0,2-0,27 (meas. on detector)	0,28-0,40 (batch#P1 foils) 0,15-0,22 (meas. on detector)	**~1 (foils) / ~0.28-0,4 (det.)** Top TPC: 1-1.5 (foils) **After baking: 0,4-0,55**
RC_{design} [ns/mm²] RC_{data} [ns/mm²]	~260	50<RC<70	15<RC<23	**55<RC<78** **102<RC<145**
Insulation layer	200 µm glue + 50 µm APICAL	75 µm glue + 50 µm APICAL	200 µm glue + 50 µm APICAL	150 µm glue + 50 µm APICAL
Expected σ (mm) For 200 ns peaking t For 412 ns peaking t	 ~1,6 ~2,3	 ~4 ~5,6	 ~6 ~8,5	 ~3,8 ~5,4
dE/dX (measured 1 det.) Extrapol. to 2 detectors	9 to 9.5% (e- & p) <7%	9 to 9.5 % (e-) with 0.2T <7%	Energy resolution @5.9 keV ^{55}Fe :	Energy resolution @5.9 keV ^{55}Fe to be measured
Spatial resolution (µm) Beam (Horizontal tracks) cosmics	300 (0T)	MM1-DLC1 200 (0 or 0.2T, 200/400 ns t_p) 700 (MM1-DLC2, @370V)	300-350 (ERAM-Px @370V)	@ DESY 07/ 21 380-300 (ERAM-01) for 200ns & 412ns

THE ERAM ^{55}FE X-RAY TEST BENCH @ CERN

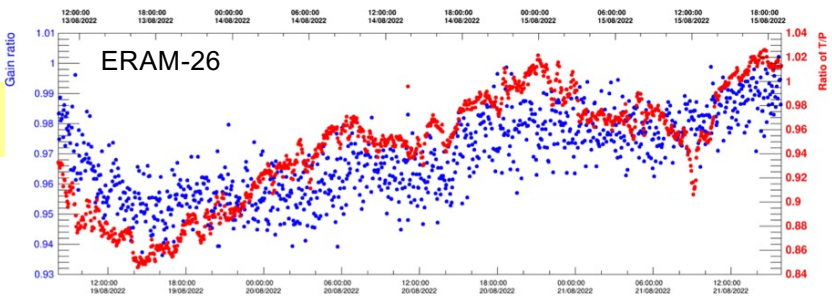
- ✓ Each ERAM is paired with 2 Front-End cards and "calibrated" for the use in the experiment
- ✓ Effective gain (ERAM * FE) and energy resolution @ 5.9 keV measurement on each pad with ERAM DLC layer at 350 V (nominal HV)
- ✓ The 280 MBq ^{55}Fe X-ray source is collimated in a Φ7 mm spot in the center of each pad
- ✓ The source is moved by an X-Y robot with respect to a reference pad which is "cross-scanned" with the source to locate its center (20 points every 1 mm in X&Y)
- ✓ Gas flow is 14l/h, the scan starts when RH<0.4 and stable, full scan duration 64h (3 mn/pad)
- ✓ Monitoring of "environmental conditions" : Gas composition (supplier certificate), T_{amb}, P_{atm}, $\Delta p_{chamber}$, T_{gas}, Relative Humidity $RH_{Gas\ out}$
- ✓ HV scan (330 - 360 V) on pad x20/Y17 (gain tuning)
- ✓ Remote shifting with local hardware support

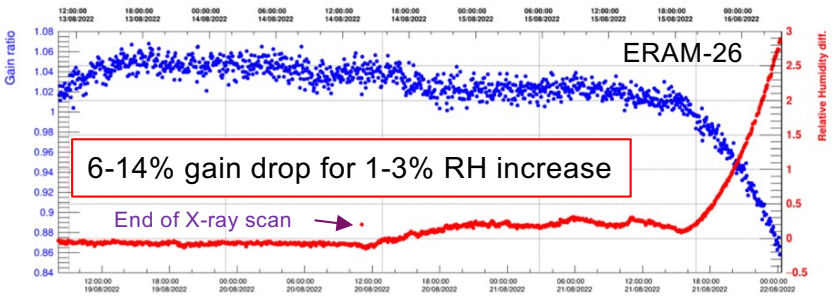


Source spot (gain scan)



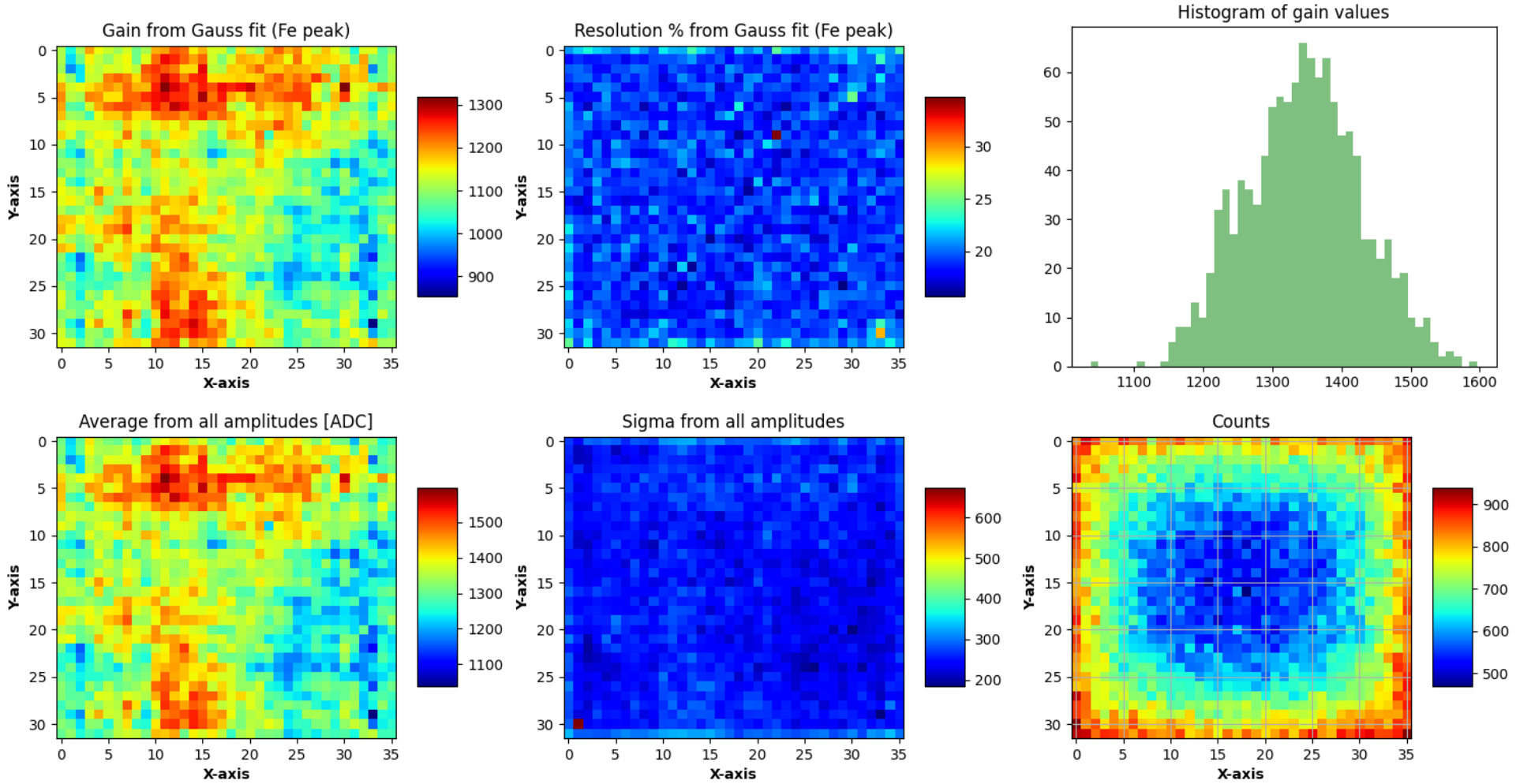
Gain correlation with T/P





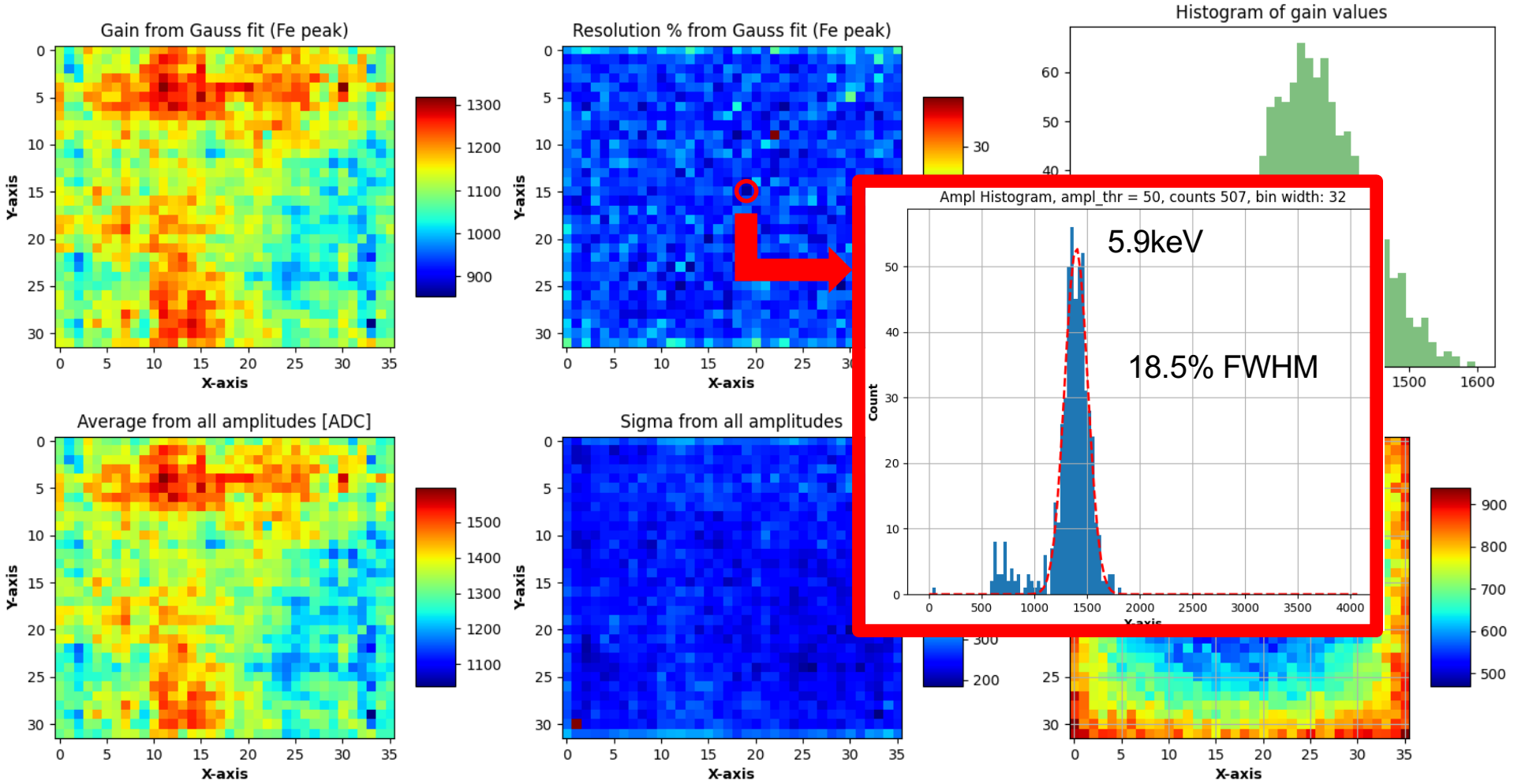
AN EXAMPLE OF A ^{55}FE X-RAY SCAN ERAM-30

Tester name: Sara, ERAM ID: ERAM30, Date: 2022-07-22 08:47:59
Source: Fe55, Comments: full scan with coordinates from cross-scan 412ns shaping time and 180s run time
Ampl peak_thr: 50, Ampl. calc with neighbours: True
Scanned: 1152/1152, total time: 65.29 h

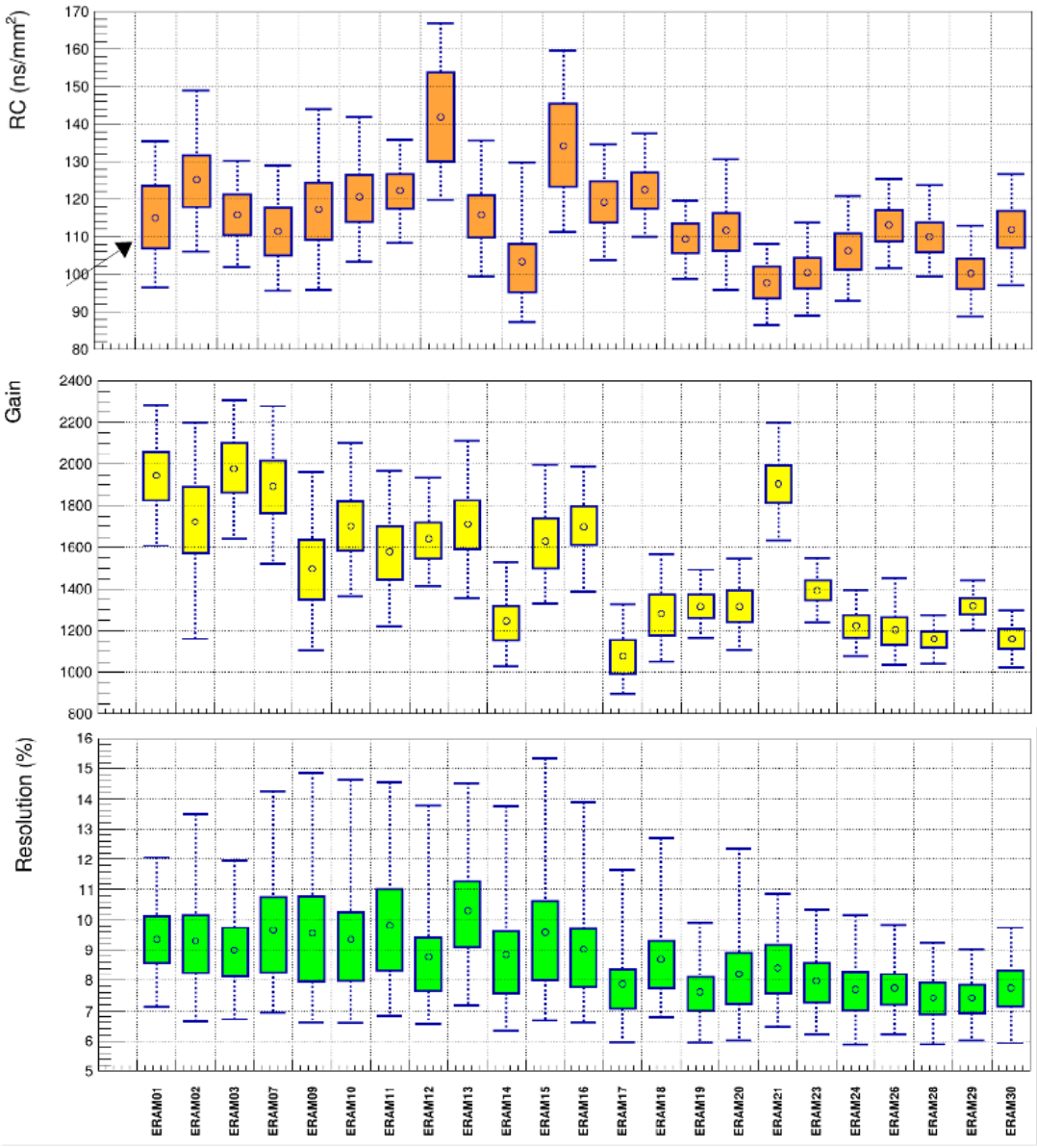


An example of a ^{55}Fe X-ray scan ERAM-30

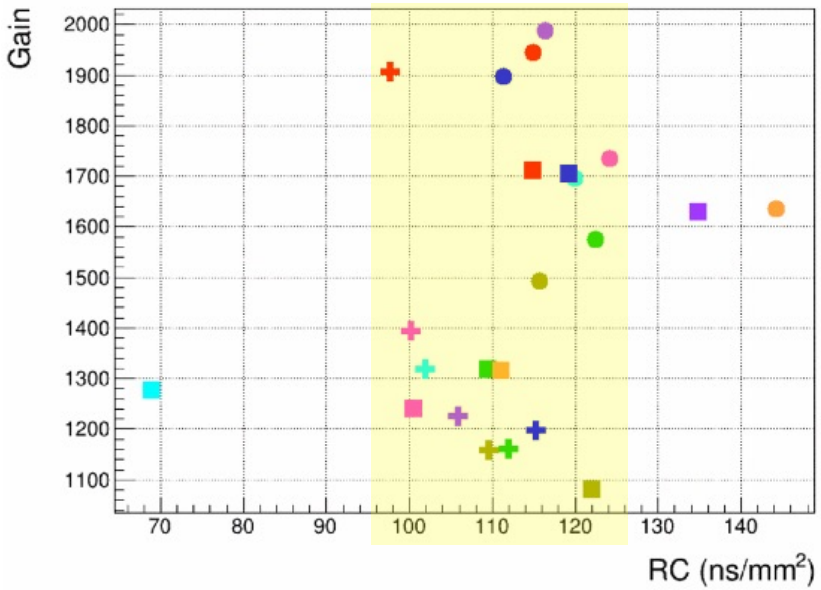
Tester name: Sara, ERAM ID: ERAM30, Date: 2022-07-22 08:47:59
Source: Fe55, Comments: full scan with coordinates from cross-scan 412ns shaping time and 180s run time
Ampl peak_thr: 50, Ampl. calc with neighbours: True
Scanned: 1152/1152, total time: 65.29 h



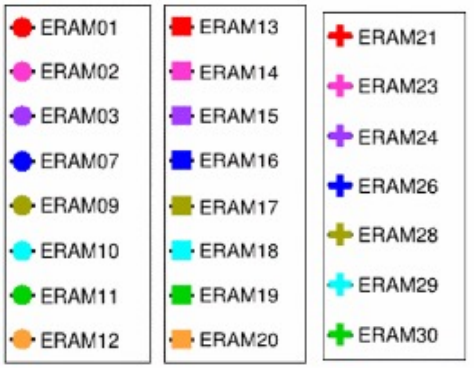
STATUS OF ERAM PRODUCTION (06/23)
CERN MPGD WORKSHOP



ref: D. Attié et al, Nucl.Instrum.Meth.A 1056 (nov 2023)
Doi: 168534



All ERAM with : 0.38 < R_{meas} < 0.56 MΩ/sq.
C fixed by 150 μm glue thickness



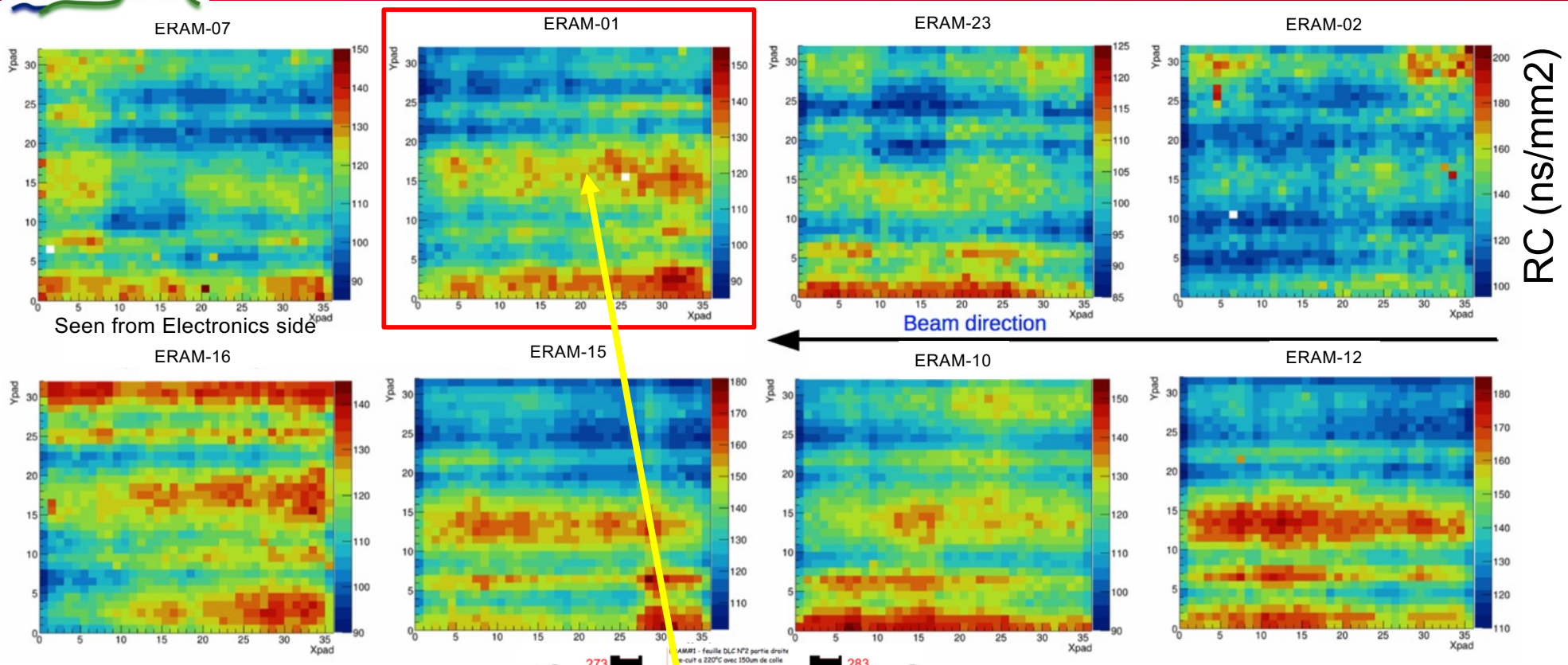
Except

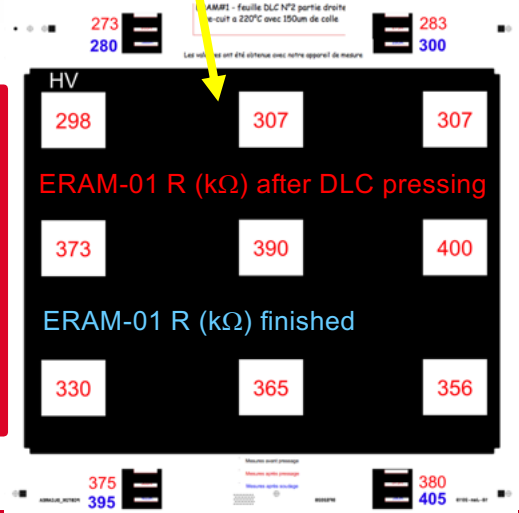
ERAM-18 : ~1/2 R
(½ RC)

ERAM-29 : ~1/2 R
½ Glue thickness
same RC

RC MAP DERIVED FROM X-RAY SCANS

ref: D. Attié et al, Nucl.Instrum.Meth.A 1056 (nov 2023)
Doi: 168534





Detailed model of pad signals

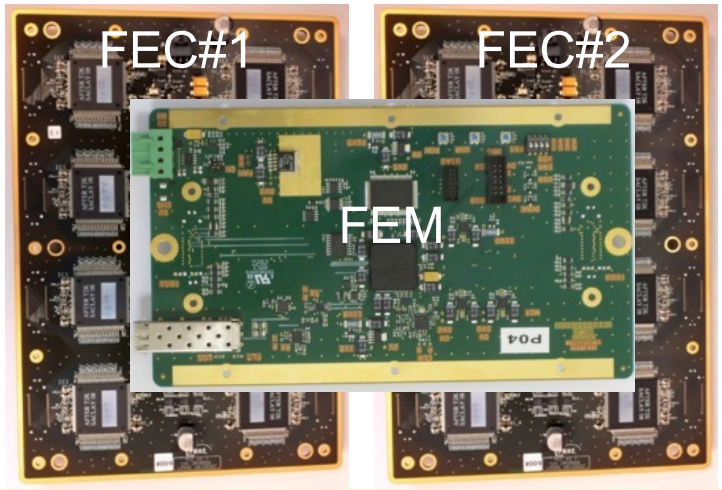
- Primary electrons difusion in gas and amplification in micromegas
- Charge amplifier response
- Charge dispersion on the DLC resistive anode Vs RC

ERAM	RC_{mean} (ns/mm²)	$Gain_{mean}$	
01	116.9	1944	
02	128.6	1736	
03	116.4	1987	
07	111.8	1898	
10	120.9	1697	
12	145.4	1635	
15	135.1	1629	
16	120.4	1705	
18	68.98	1277	~1/2 RC as expected
23	101.6	1393	
29	102	1318	~ RC as expected
30	114.3	1161	

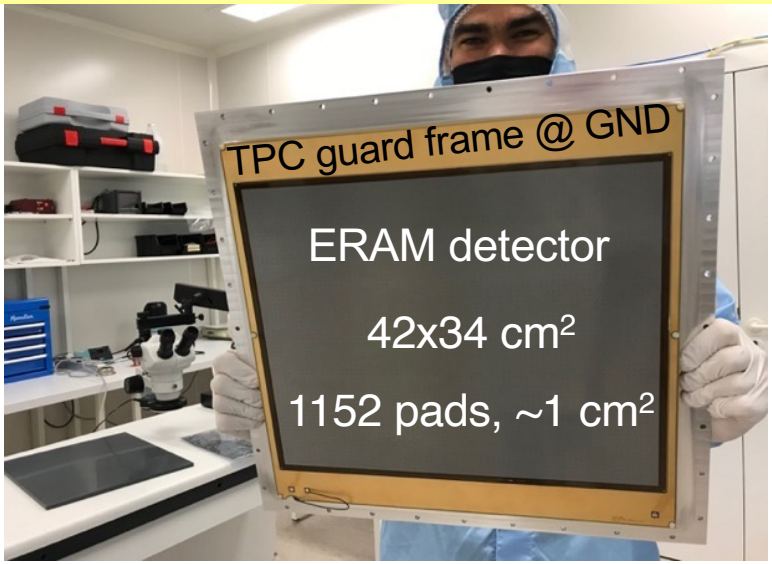
RC is quite well correlated to the measured DLC resistivity

THE T2K/ND280 UPGRADE HA-TPC
ERAM MODULE + FEE + MECHANICALS

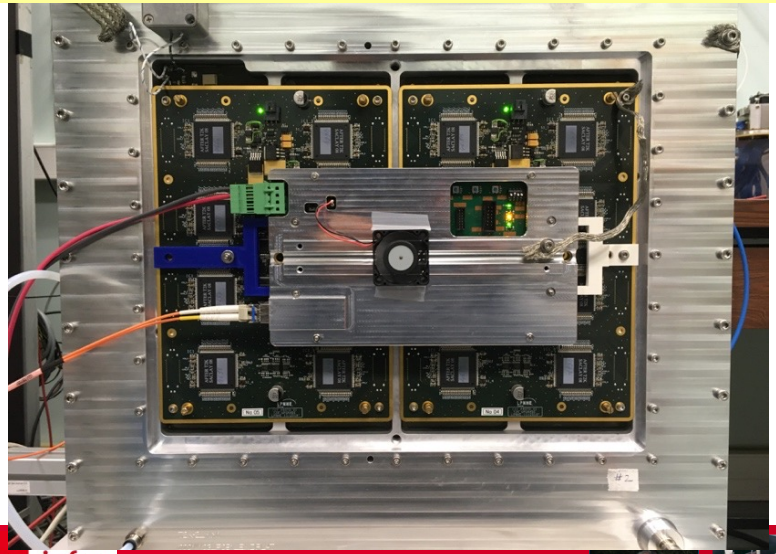
ERAM FEE : 2 x 576 ch. FECs
+ 1 digital FEM (~500 cm^2 cards)

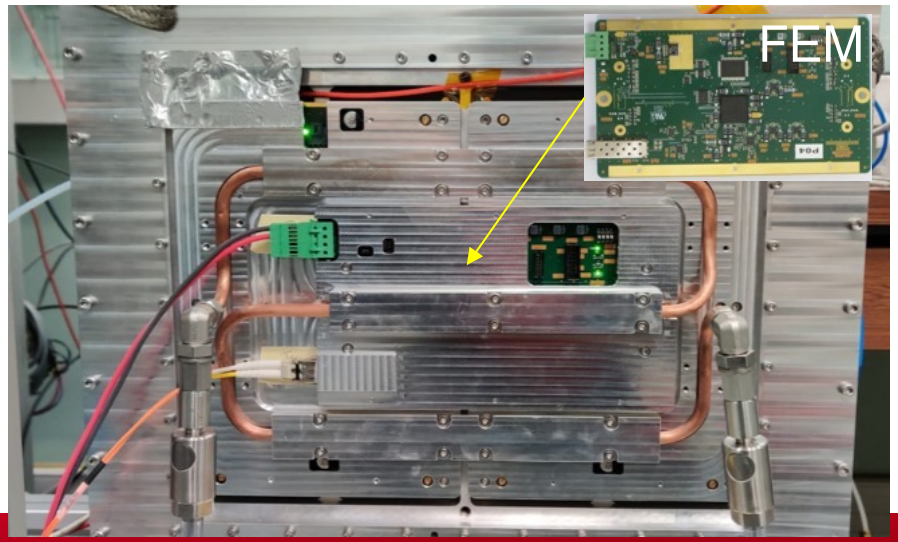


T2K/ERAM detector (CERN MPGD workshop



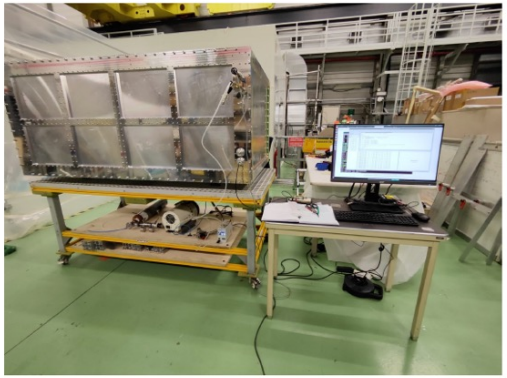
32+4 ERAM modules (detector + FEE + cooling mechanicals) to produce (03-21 to 11-23)



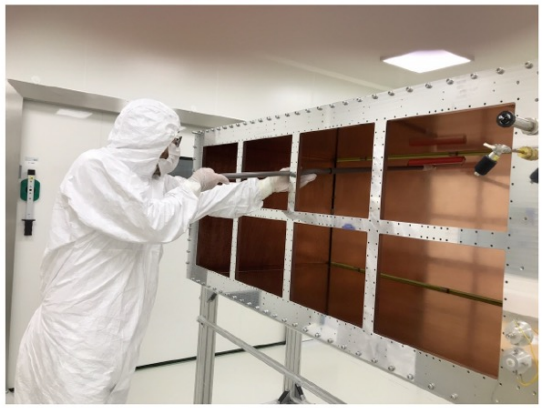


« BOTTOM » HA-TPC ASSEMBLY INTEGRATION PROCESS FOR ½ TPC

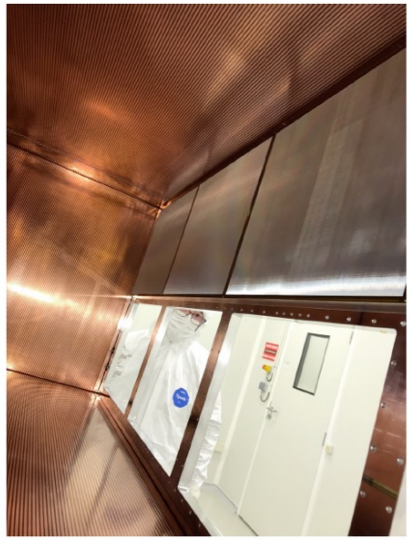
ref: D. Henaff (CEA/IRFU)
Coordination @ CERN bsg. 182



Final leak test of FC1 with Helium



Last cleaning inside the cage



First row of ERAM installed

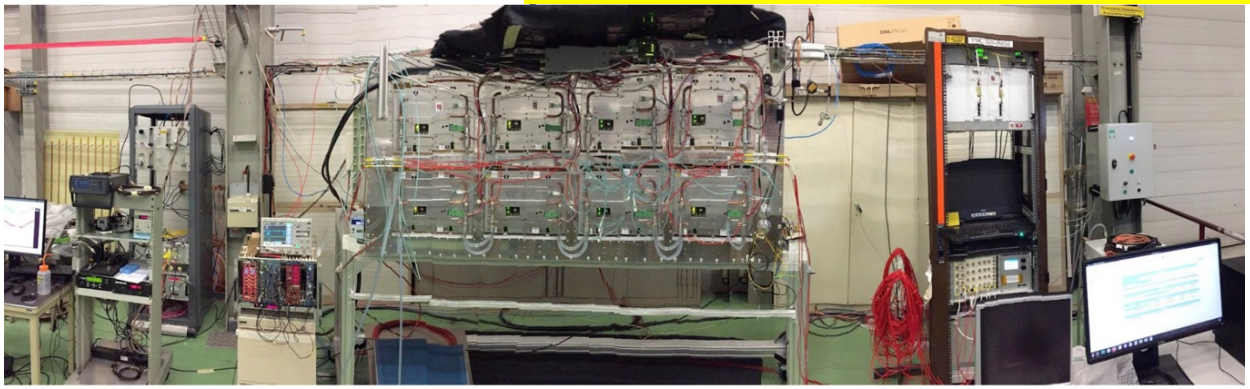
Last ERAM installation

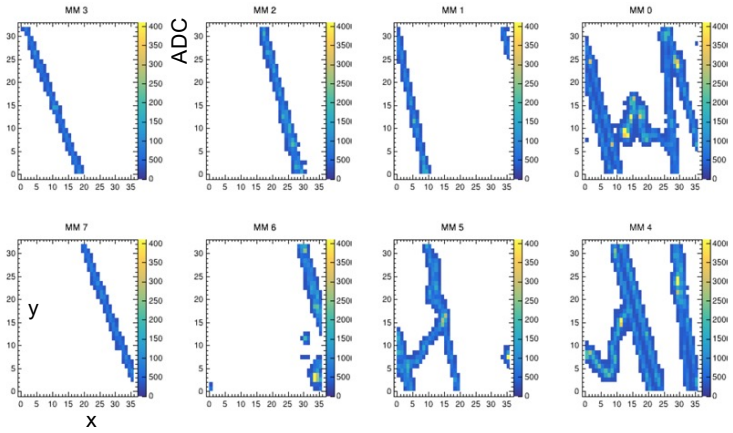
Leak test after ERAM installation

Field cage ready!

« BOTTOM » HA-TPC FROM CERN TO JPARC (JAPAN)

Final validation with cosmics at CERN





Gas rack:
Control flow and monitor gas quality (GMC+sensors)

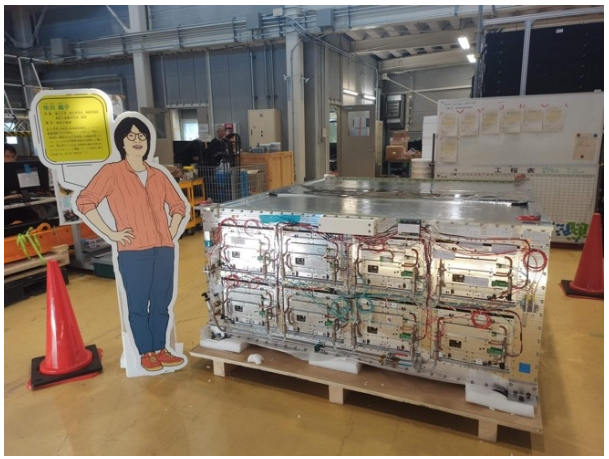
Trigger:
Readout of the two scintillator panels (1m²)

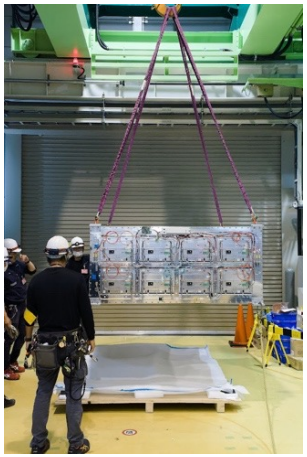
Half HA-TPC:
27.5kV and 350V on ERAMs

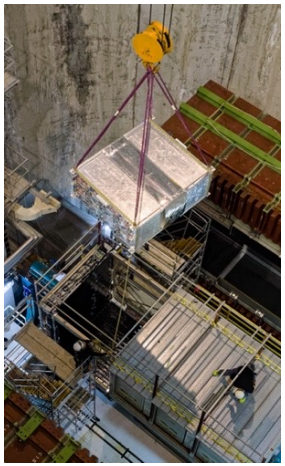
Electronic rack:
DAQ, ERAM & electronic power supplies

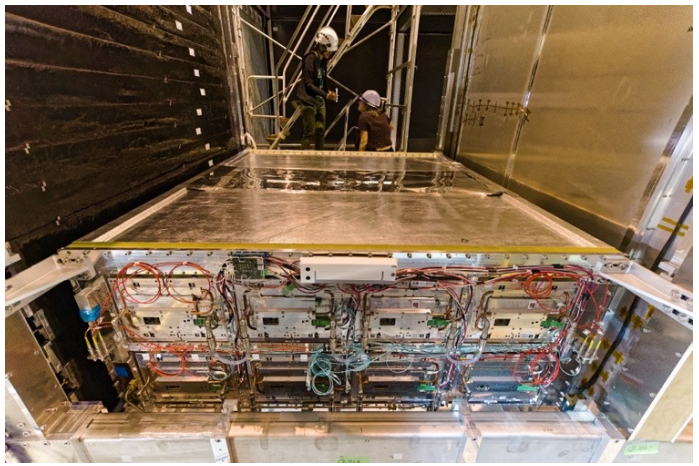
Integration in ND280 « basket » at JPARC (8 sept 2023)

ref: T. Lux (IFAE)









CELEBRATING IOANIS !

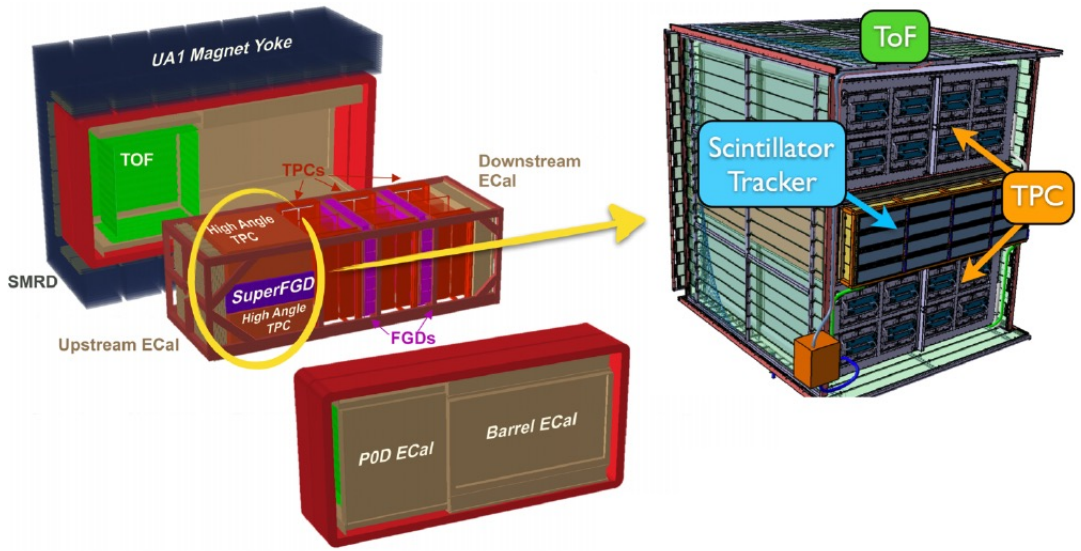
Celebrating …

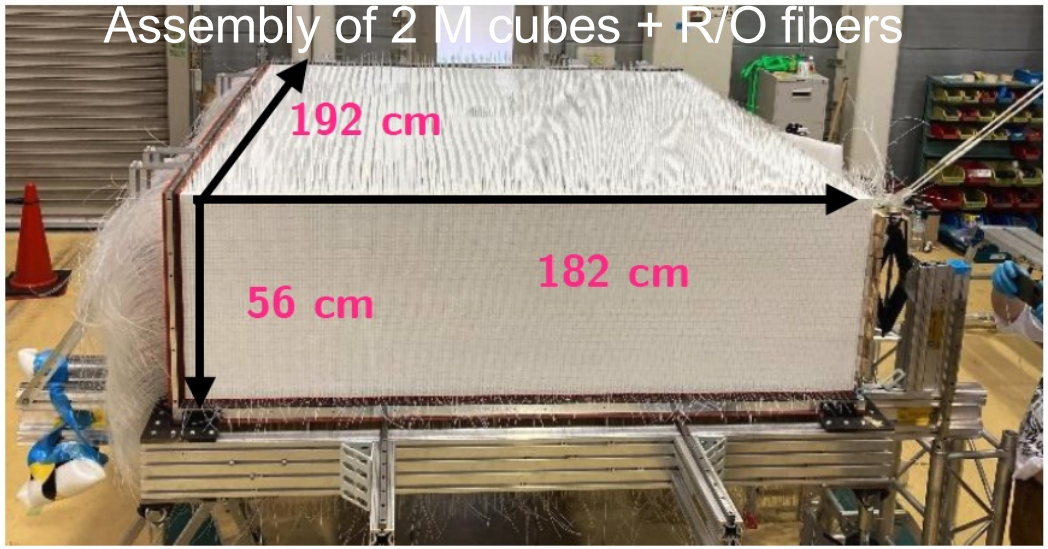
- Your scientific legacy in T2K, within the IRFU & worldwide « detector » communities (esp. RD51)
- Your kindness and constant availability, always with a smile, for discussions, help and support

Personal thanks for …

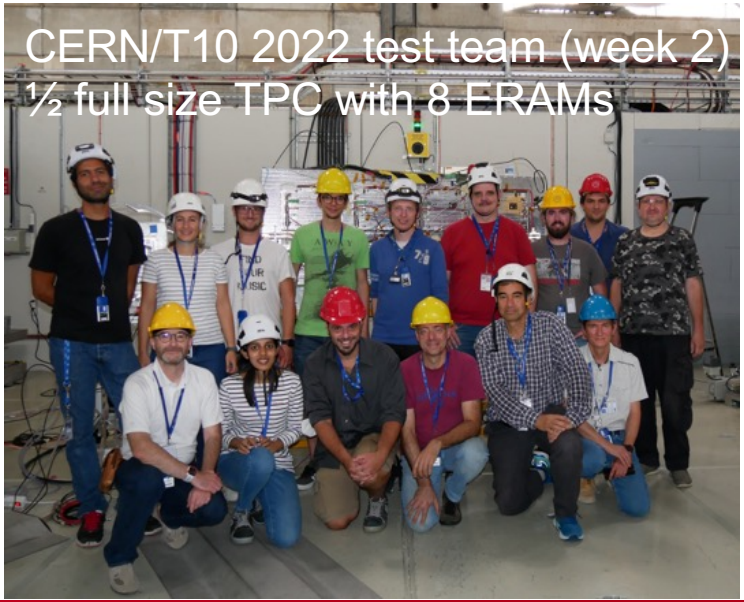
- Giving me the motivation for developping detectors for physics and enjoy it !
- Many souvenirs and stories to share of funny (and sometimes stressful !) situations that helped me build the way I manage the development of scientific instruments

NEXT WEEK @ JPARC
INSTALLATION OF THE SFGD TARGET



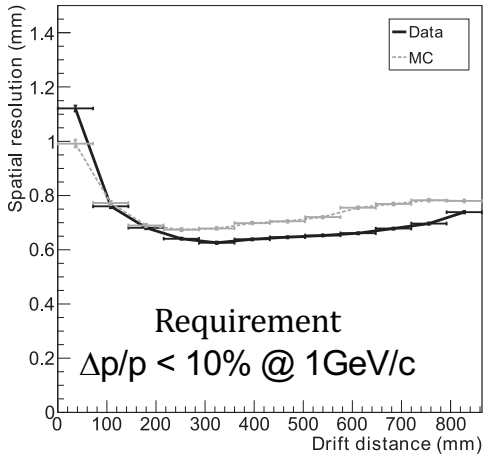


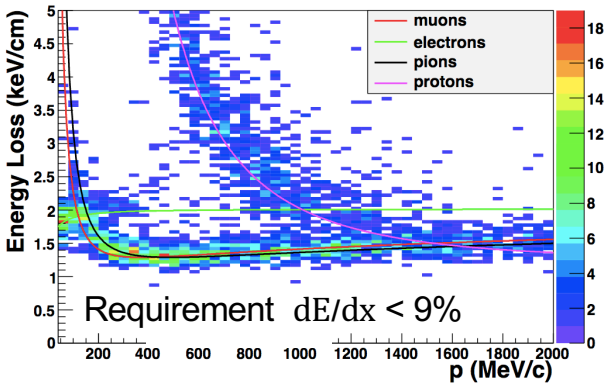
ABOUT THE IMPORTANCE OF TEST BEAMS



T2K TPCs PERFORMANCES

V-TPC performance and requirements
« metallic » anode bulk-micromegas





ERAM / DESY test beam 2021

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