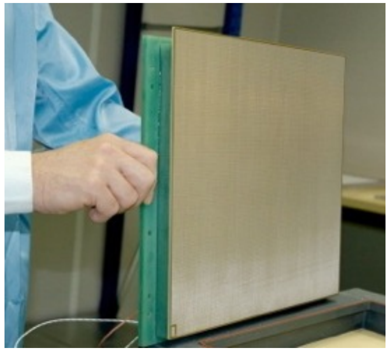
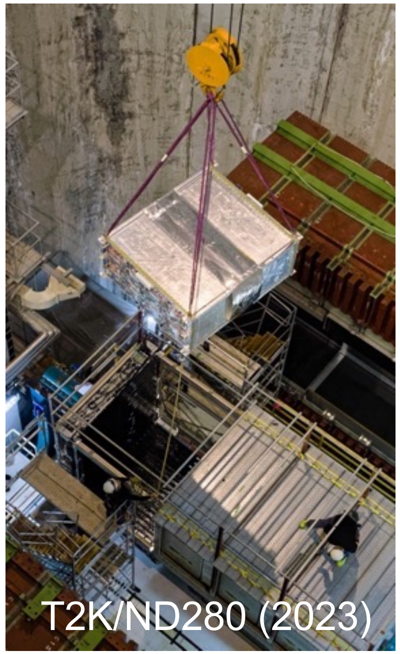
Production of Encapsulated Resistive Anode Micromegas (ERAM) for the T2K High-Angle TPCs

Alain Delbart, CEA/IRFU - Univ. Paris-Saclay, for the ND280/HA-TPC group

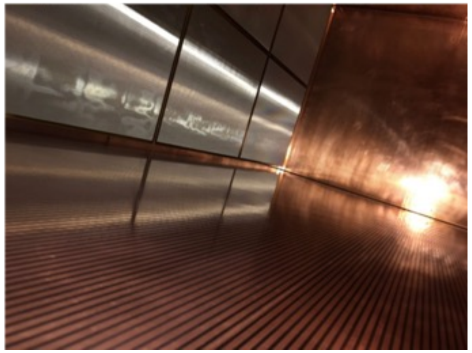
Vertical TPC (2004-) for ND280

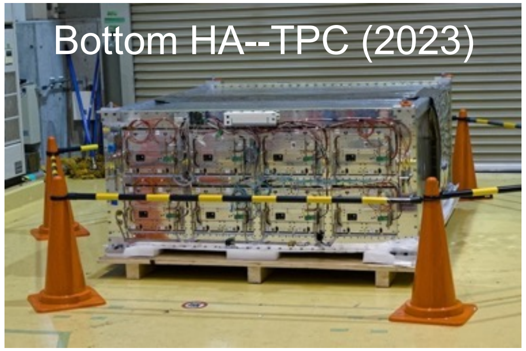


ND280 @ JPARC (Japan)



High-Angle TPC (2018-) for ND280 upgrade

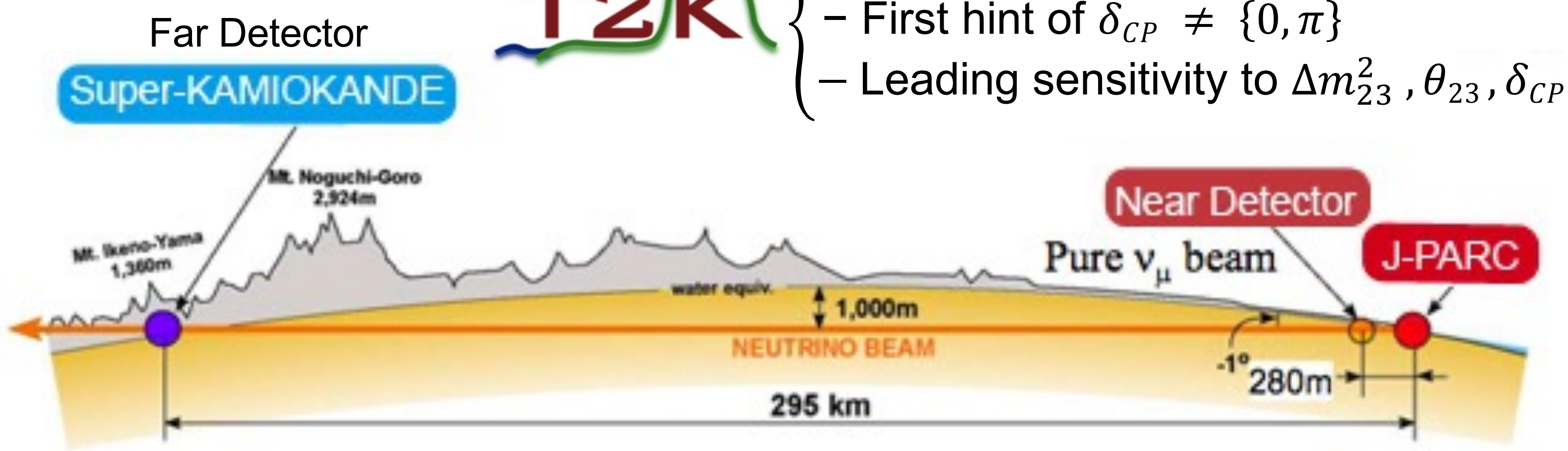




RD51 collaboration meeting, 4-8 december 2023

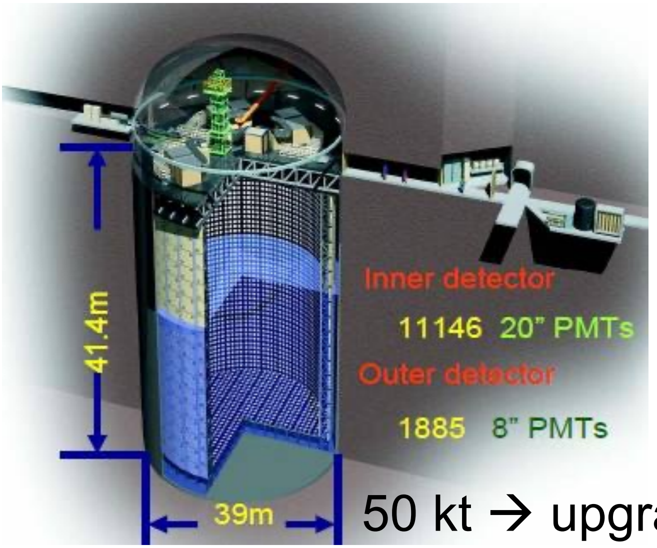
THE T2K EXPERIMENT: TOKAI TO KAMIOKA
FROM T2K TO T2K-II AND T2-HK

T2K
- Discovery of $\theta_{13} > 0$
- First hint of $\delta_{CP} \neq \{0, \pi\}$
- Leading sensitivity to Δm^2_{23} , θ_{23} , δ_{CP}

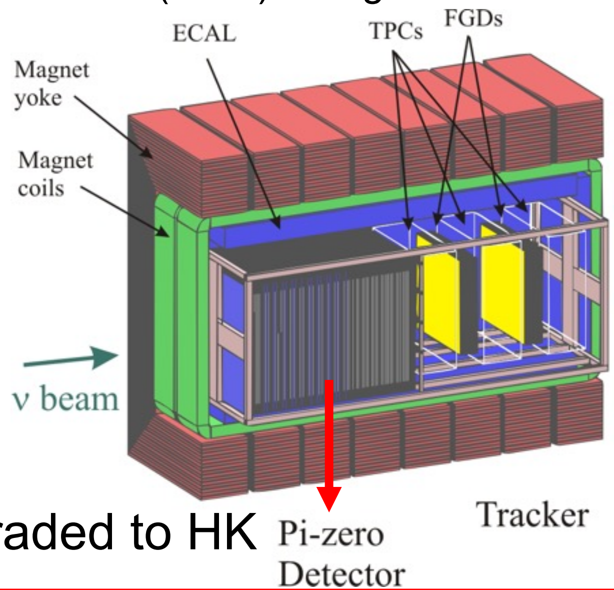


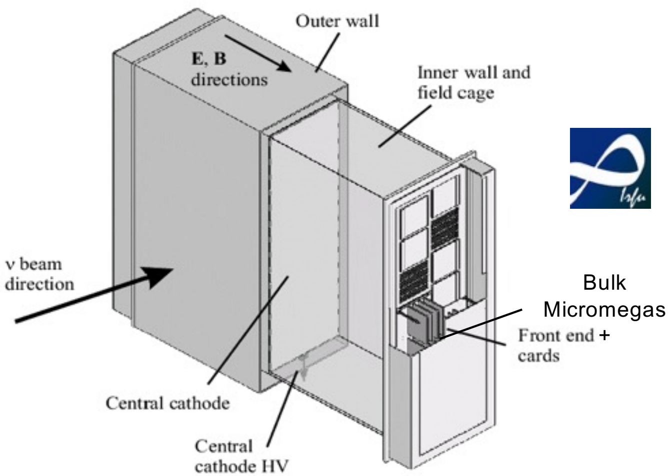
Volume 580 Issue 7803, 16 April 2020

Upgraded beam power : 560kW (2023) with gradual increase to 1.3 MW goal for HyperK



50 kt → upgraded to HK



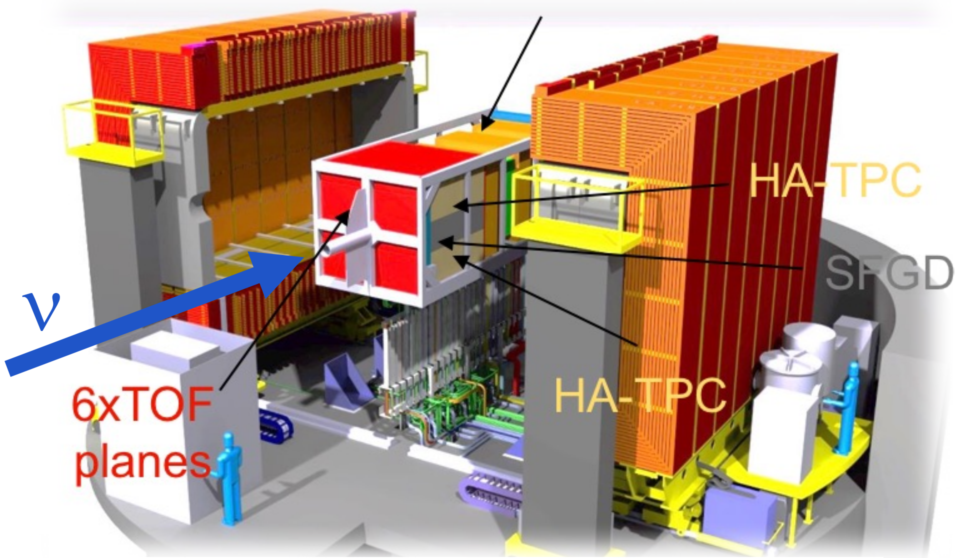


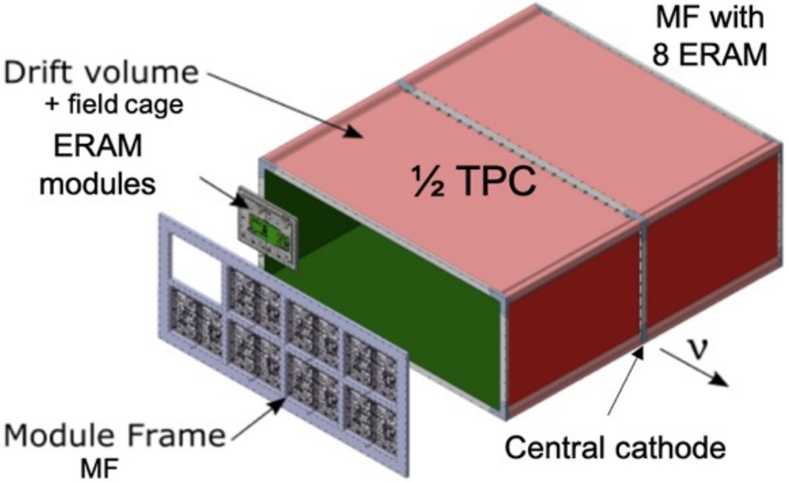
ND280 upgrade goal : reducing systematic uncertainties on beam characterization …

THE DEVELOPMENT OF THE UPGRADED NEAR DETECTOR OF T2K
THE HA-TPC (2018-2024)

... with 2 new TPCs with better final state muons acceptance from new SFGD target and from downstream events

2009 TPCs (x3) + T2K Gas system by CERN (mixing, filtering, gas properties monitoring)





Parameter	HA-TPC Value	v-TPC
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

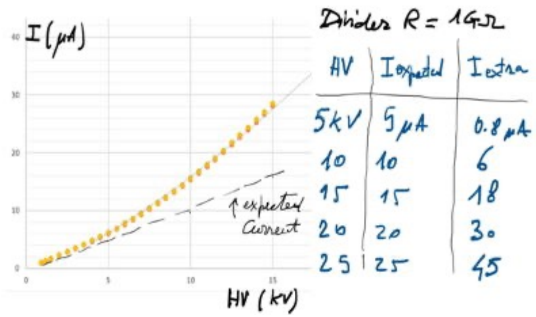
ND280 upgrade TPCs achievements

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

The HA-TPC field cage Original design modification

I$_{extra}$ increasing non linearly with voltage

May 2022 : first scale 1 ½ field cage exhibits a non-linear V-I behaviour
→ Leakage current flow through the wall structure

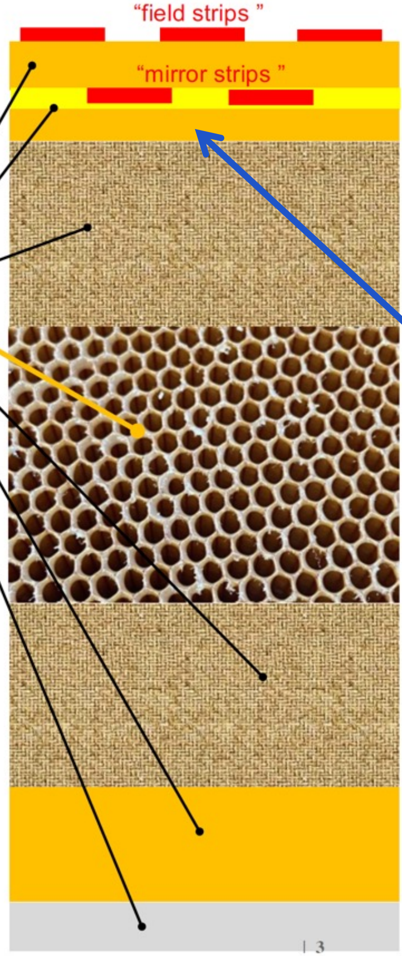


Field Cage – layers

See G.C. talk at
15th Pisa Meeting on Advanced Detectors
La Biodola, Isola d'Elba, May 22-28, 2022

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	~ 4 cm / ~ 2% radiation length

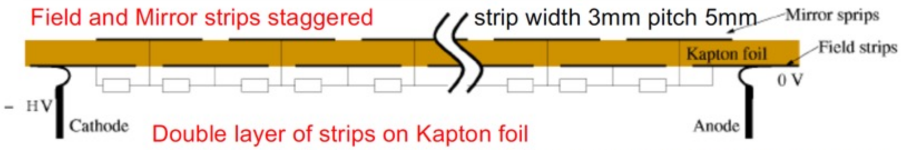
Note: V-TPC ~ 12cm / ~ 3.4% radiation length



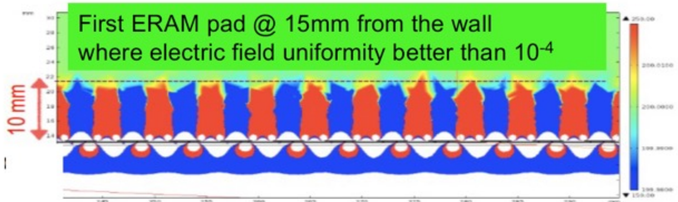
Electric field shaping

Field and Mirror strips staggered

strip width 3mm pitch 5mm

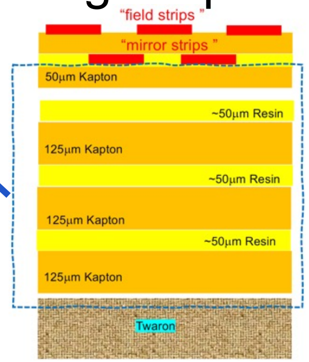


Double layer of strips on Kapton foil
Dimensions = 5m (inner surface cage perimeter) x 1m (drift distance)



Simulation Electric Field near walls

New design & procedures



- Keep same raw materials
- Avoid resin contamination
- Add thick insulator below strip foil (O(10 TΩ) @ 10 kV) :
    - a 50 μm kapton foil pressed on strip foil at MPGD workshop
    - 3x125 mμ Kapton foils wrapped at NEXUS

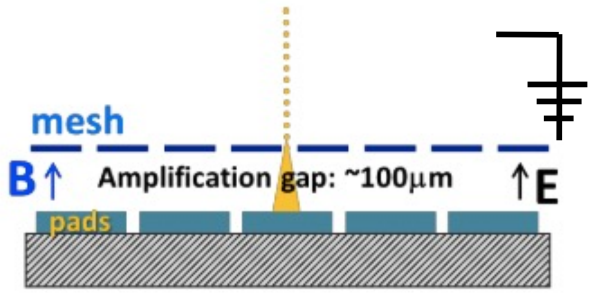
Ref: G. Collazuol (INFN/Padova)

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

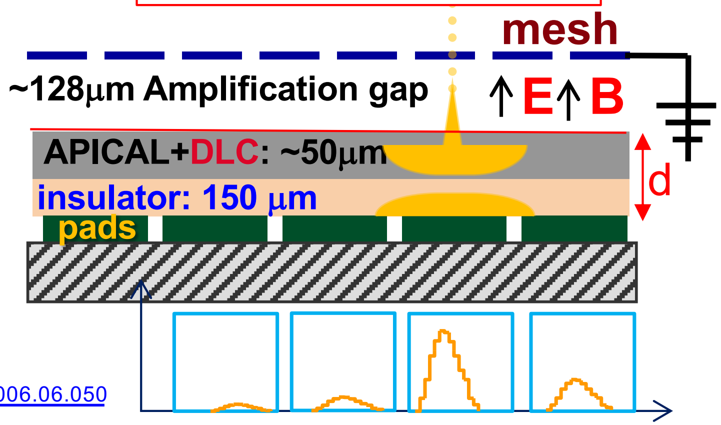
Choice of the Resistive foil technology for the HA-TPC micromegas readout

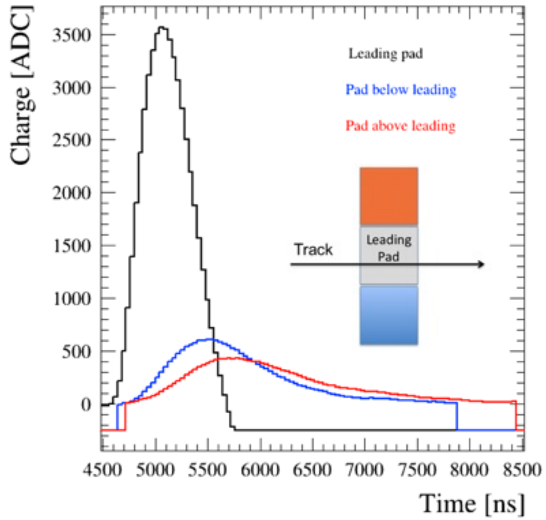
- Charge spreading which should enable keeping the ~600 μm spatial resolution with larger pads and improves it at short drift distance → less electronic channels, cost reduction
- ASIC spark protection no longer needed → more compact FEE, maximize HA-TPC acceptance
- Encapsulated mesh @ GND + insulating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

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

R- surface resistivity
C- capacitance/unit area

Gaussian spreading as a function of time with :

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

ε_r [APICAL]~3,3 and ε_r [glue] ~4,8

For ~11x10 mm² pads, DLC R is chosen $\sim 0.5\ M\Omega/\blacksquare$ 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~750 ns/mm² σ_r<2 mm

ERAM DEVELOPMMENT

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

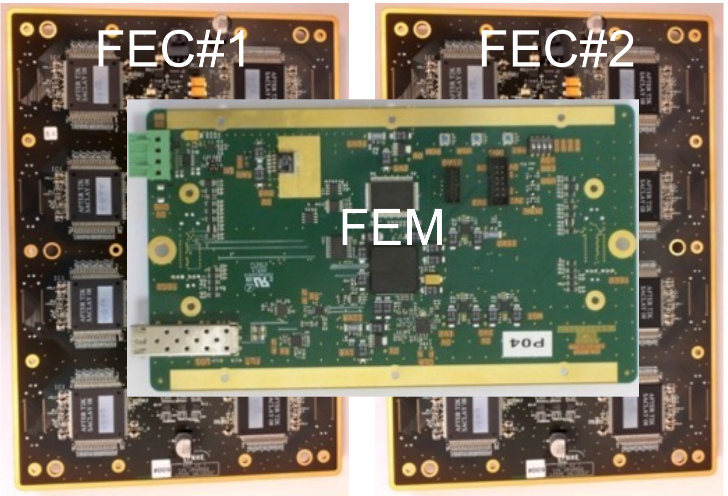
ILC-TPC heritage — 2018 — 2019 — 2020 — Nov. 12 PRR — Pre-series To series production — 2021

CERN/T9 test beam
DESY test beam
ERAM-01 @ DESY 2021
½ TPC @ CERN/T10 sept. 2022

	2018 MM0-DLC#	2019 MM1-DLC1 & 2	2020 ERAM-P1 & P2	Production ERAM-xx (ERAM-01-28)
Readout PCB	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

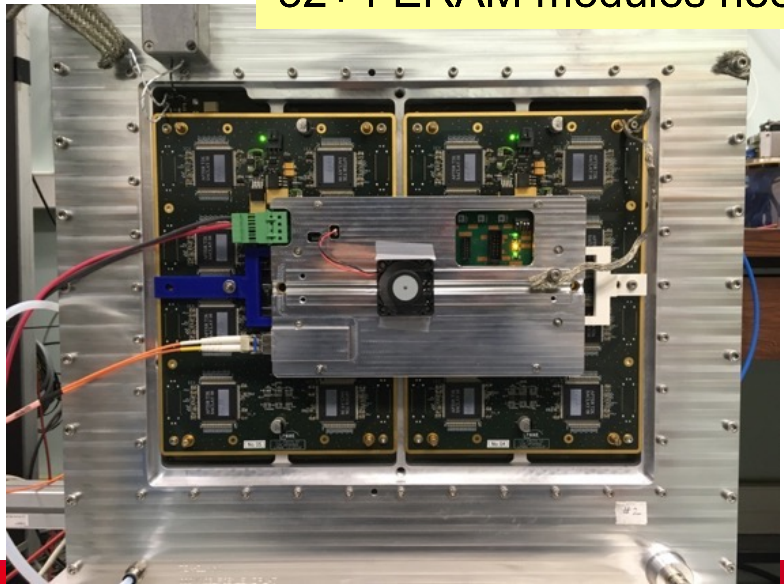
THE HA-TPC ERAM MODULE
A COMPACT TPC READOUT SYSTEM

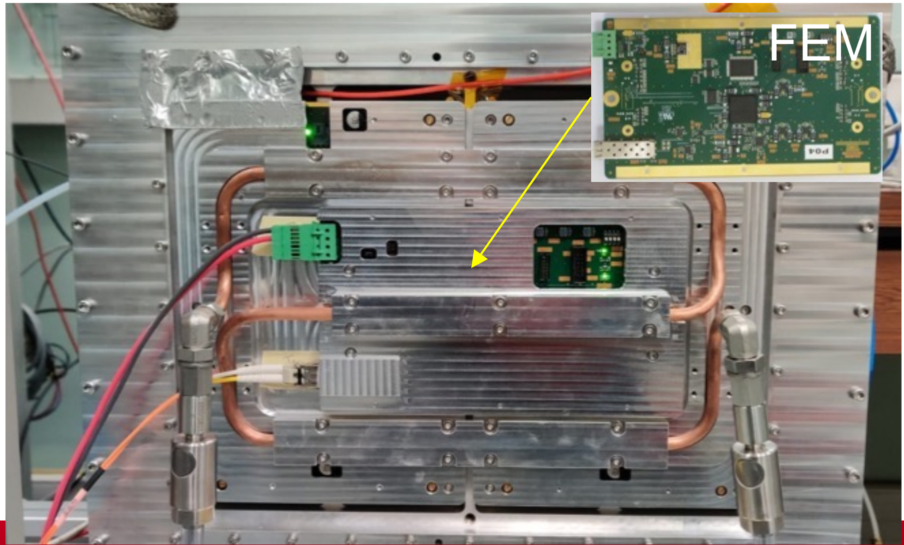
ERAM FEE : 2 x 576 ch. FECs (8xAFTER ASICs)
+ 1 digital FEM (~500 cm^2 cards)



T2K/ERAM detector (CERN MPGD workshop

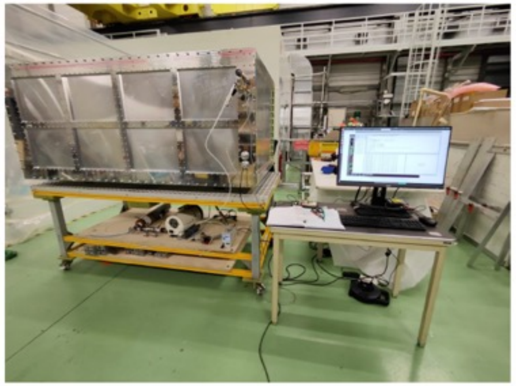
32+4 ERAM modules needed (detector + FEE + cooling mechanicals)



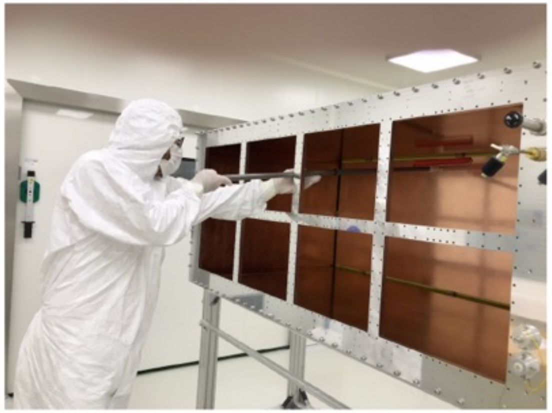


INTEGRATION OF ERAM DETECTORS IN CLEAN ROOM (~ISO 7-8)

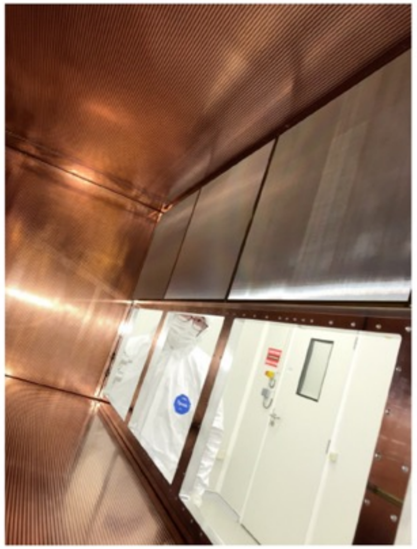
ref: D. Henaff (CEA/IRFU)
Coordination @ CERN bdg. 182



Final leak test of FC1 with Helium



Last cleaning inside the cage



First row of ERAM installed

Last ERAM installation

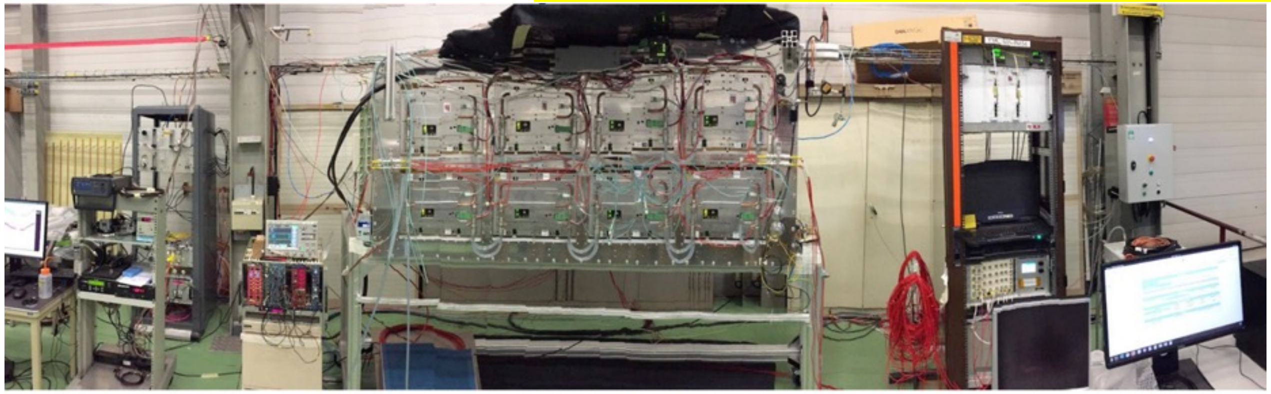
Leak test after ERAM installation

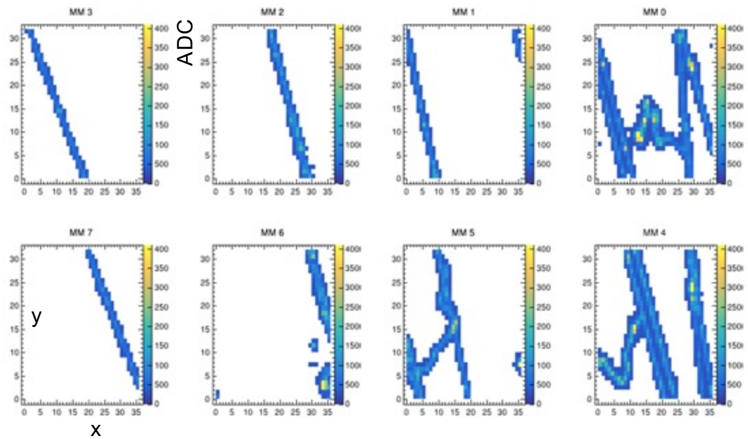
Field cage ready!

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

Final validation with cosmics at CERN

after 10 TPC vol. exchange





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

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

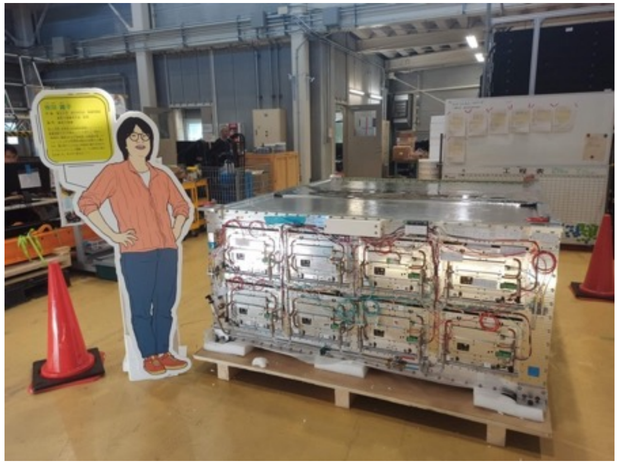
Half HA-TPC:
27.5kV and 350V on ERAMs

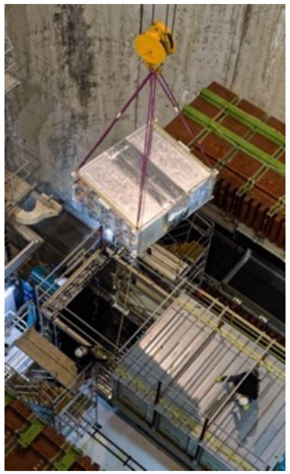
Electronic rack:
DAQ, ERAM & electronic power supplies

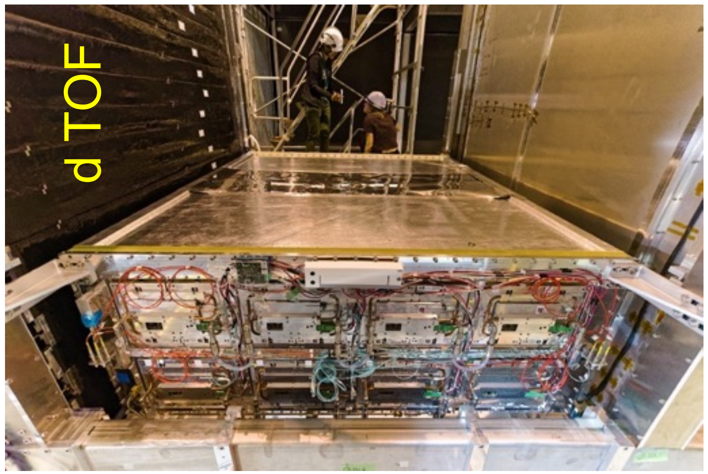
10 ppm O_2/~300 ppm H_2O

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

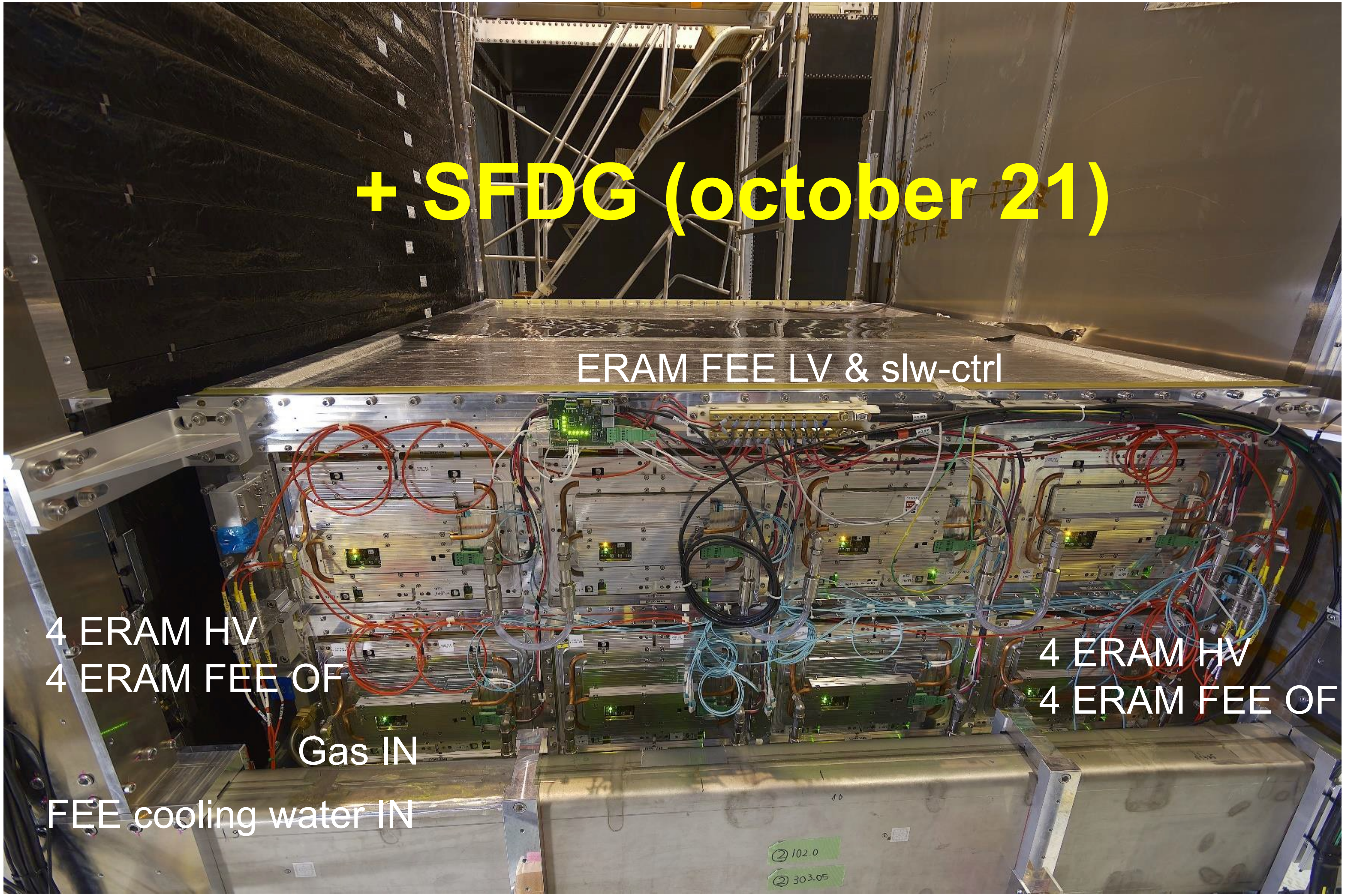
ref: T. Lux (IFAE)



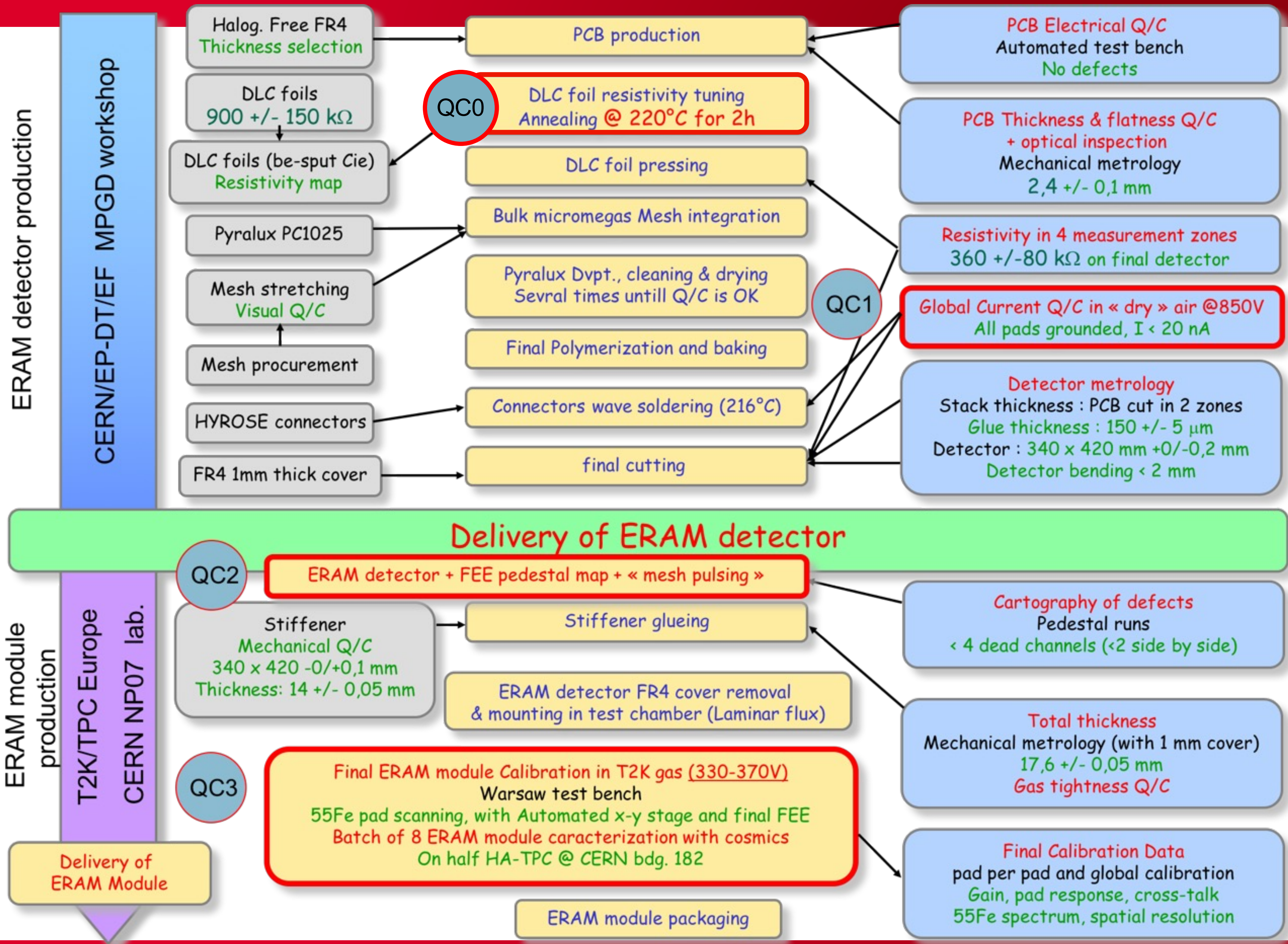




THE HA-TPC READOUT PLANE IN ND280 BASKET @ JPARC (SEPT 8)



ERAM MODULE PRODUCTION SEQUENCE

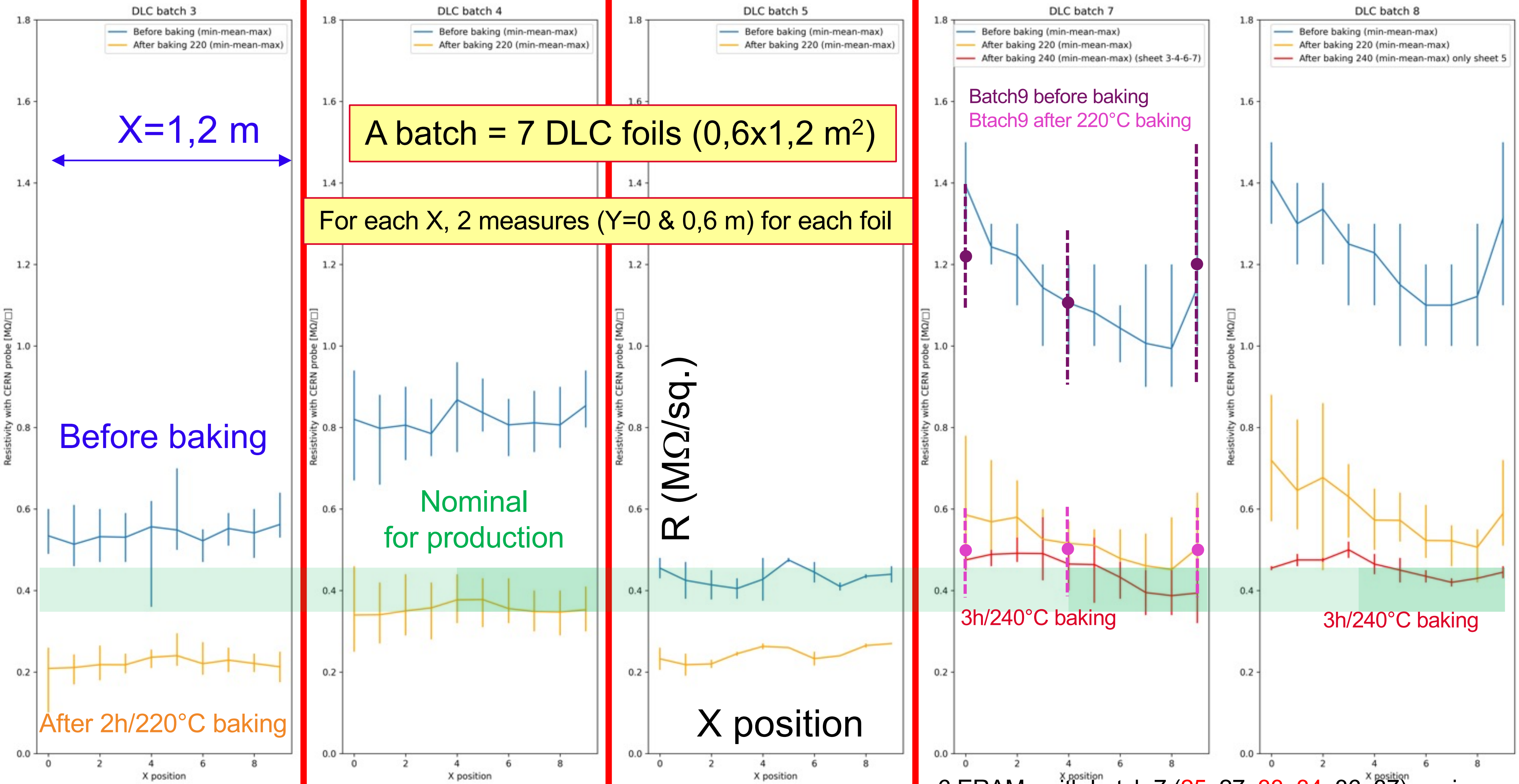


QC0: DLC RESISTIVITY : FOIL SELECTION

production (batch 1,2,4) → 21 ERAM

Top. TPC production →

½ RC prototype	Production	prototype	Restart of production for Top TPC



½ R, ½ RC	nominal R, RC	½ R, ½ glue thick. Nominal RC	6 ERAMs with batch 7 (~~25~~, 27, ~~33~~, ~~34~~, 36, 37) : gain gradient & spreading issues
→ ERAM-18		**→ ERAM-29**	**→ 11 last ERAMs done with batch 9 (R~0.5 MΩ/sq.)**

QC0: CONTROL OF GLUE THICKNESS
EX: 200 MICRONS GLUE PROTOTYPE

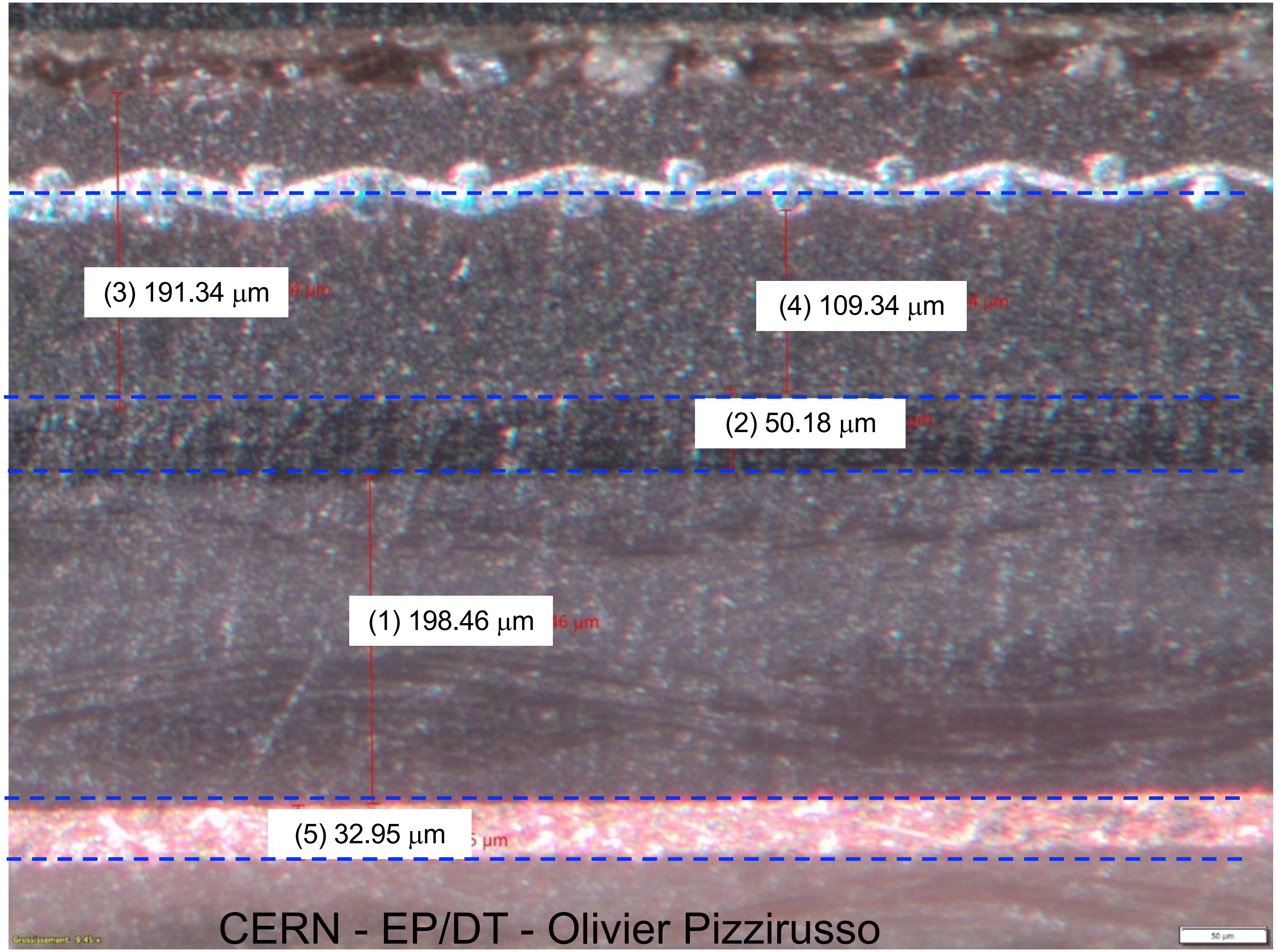
Amplification Gap

Apical (+DLC)

FR4 Prepreg (glue)

copper

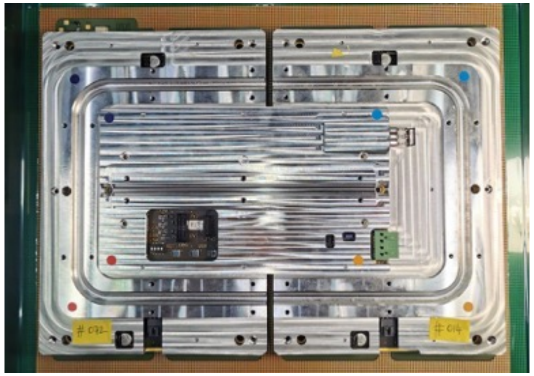
FR4



QC2 : ELECTRONIC MESH PULSING

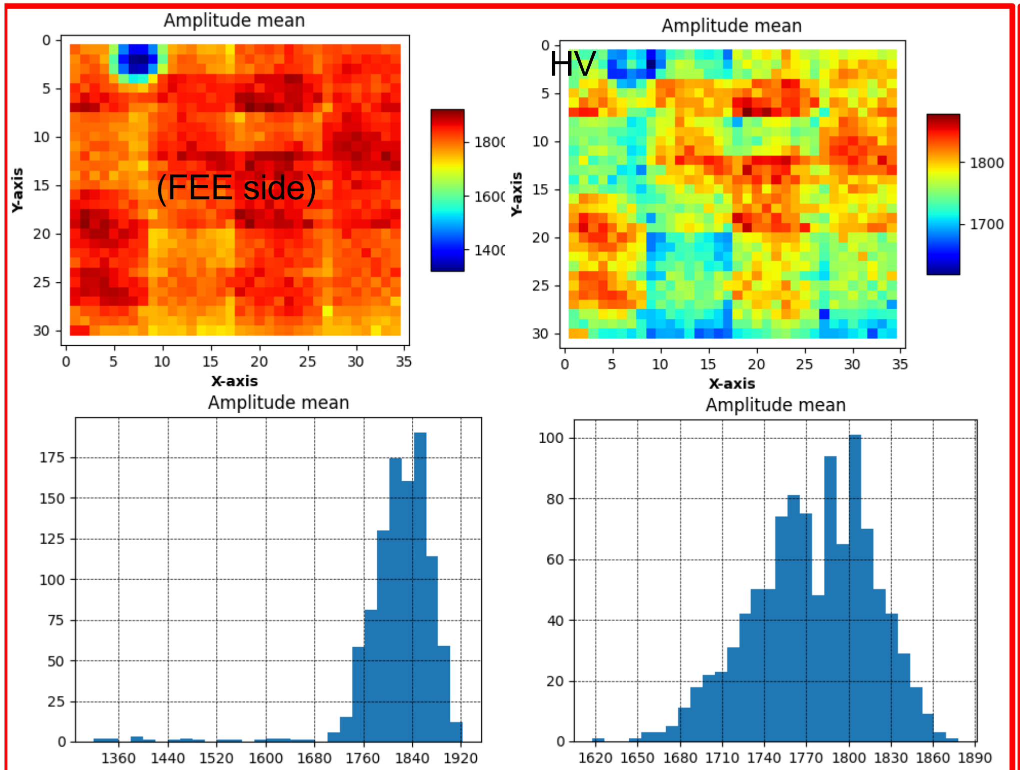
DETECTING DEFECTS BEFORE GLUING THE ALUMINUM STIFFENER

EXAMPLE OF A DEFECT ON ERAM-20

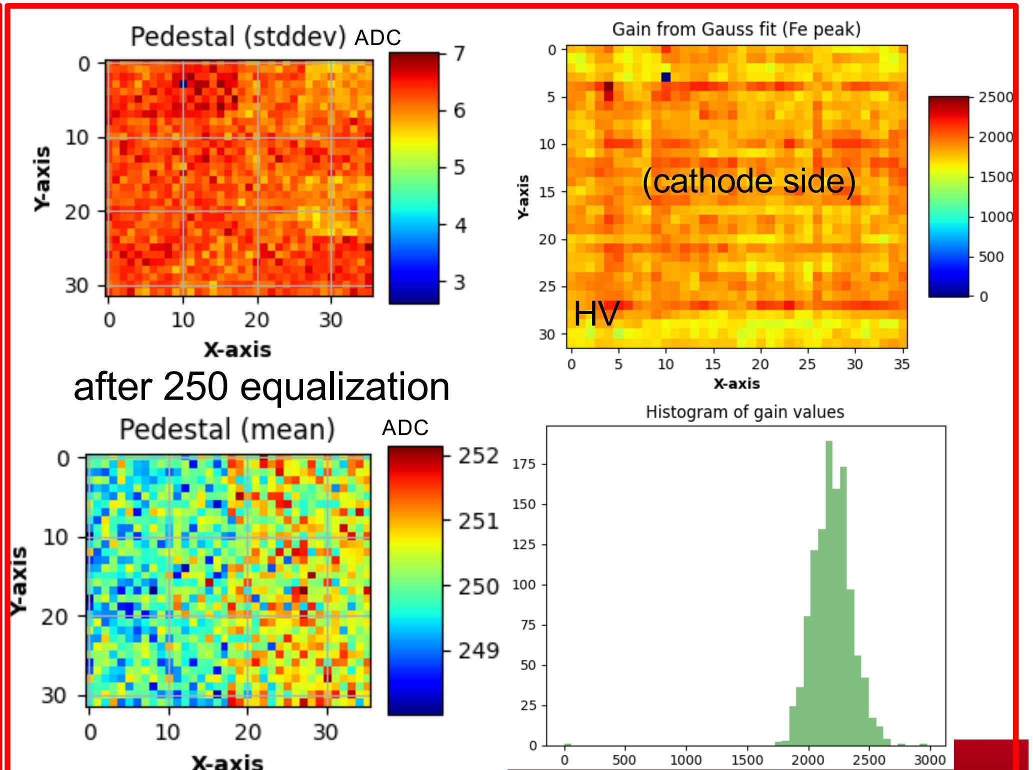


- ✓ The "mesh-pulsing" is a QC used before & after gluing of the mechanical stiffener to detect major defects
- ✓ A 1kHz, 300 mV square signal is pulsing the ERAM mesh through a 50 Ω adapted cable
- ✓ The readout electronics DAQ is triggered with a NIM signal synchronized with the mesh pulsing (~5 mn run).

QC2: mesh pulsing before & after « repair »

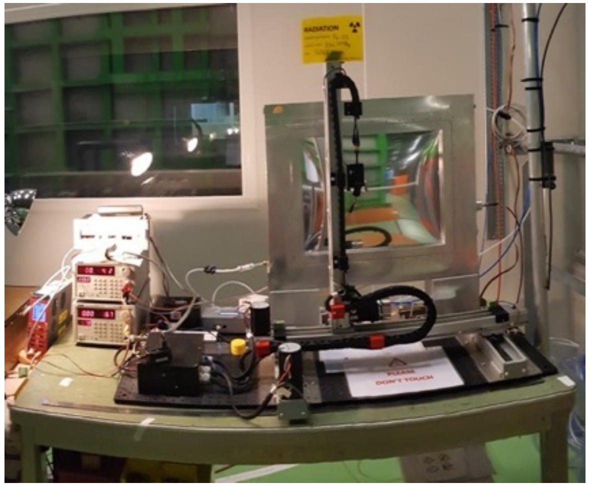


QC3: X-ray scan gain

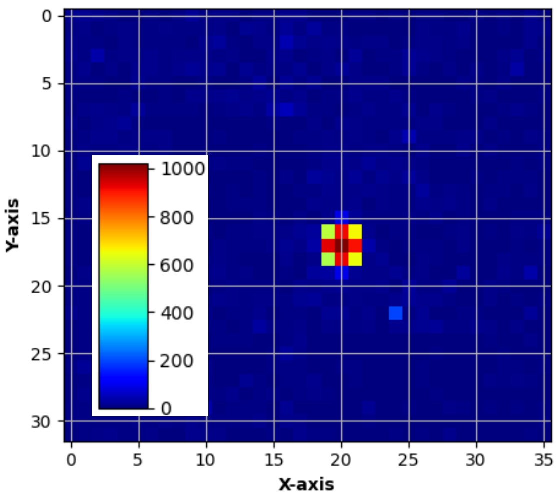


QC3: FINAL VALIDATION OF A MODULE
THE ERAM ^{55}FE X-RAY TEST BENCH @ CERN

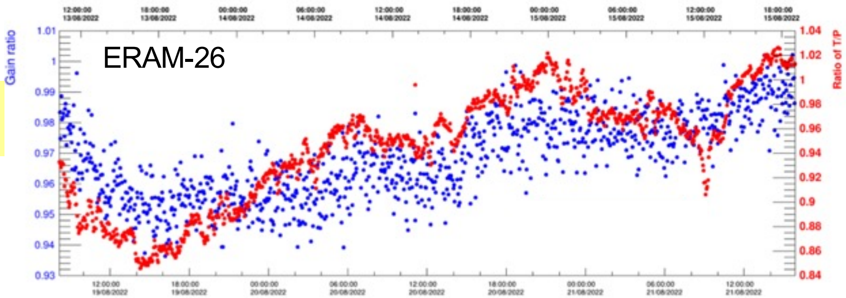
- ✓ Each ERAM is paired with 2 Front-End cards and "calibrated" for the use in the experiment
- ✓ Effective gain (ERAM * FE) and energy resolution @ 5.9 keV measurement on each pad with ERAM DLC layer at 350 V (nominal HV)
- ✓ The 280 MBq ^{55}Fe X-ray source is collimated in a Φ7 mm spot in the center 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

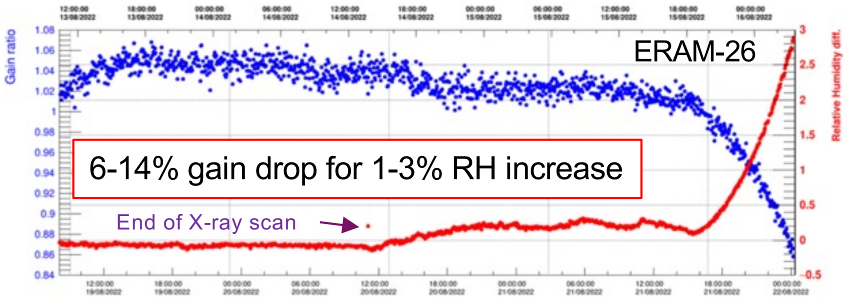


Source spot (gain scan)



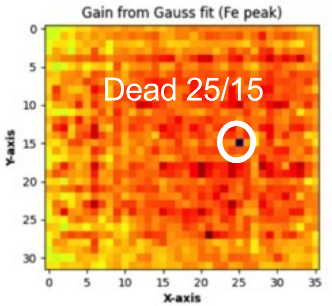
Gain correlation with T/P



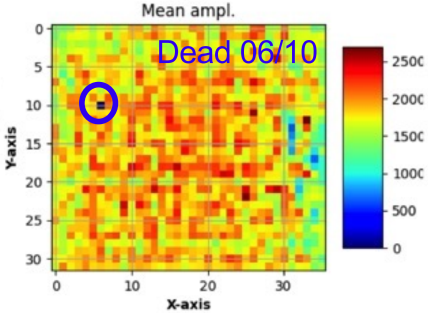


THE UNEXPECTED EFFECT OF THE ERAM PCB BACKSIDE LAYER DESIGN ON GAIN

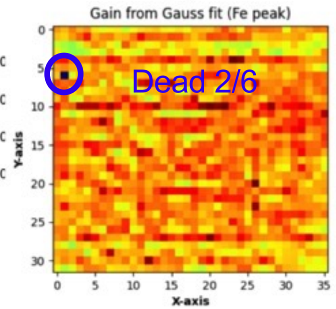
01 81L / 33R



02

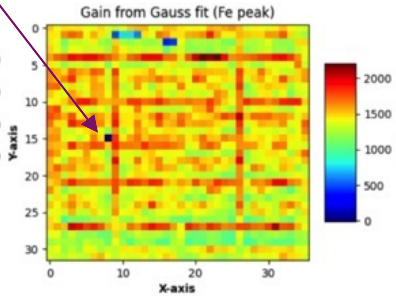


38L / 43R 07

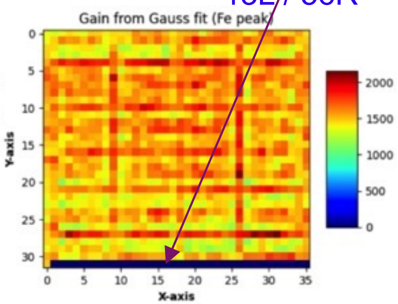


Not on pedestals

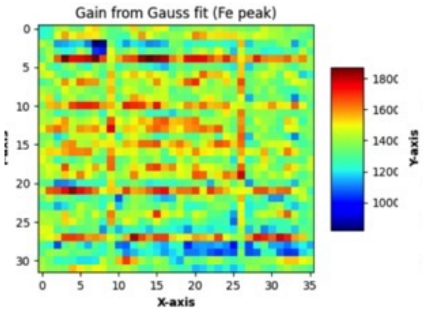
09 29L / 41R



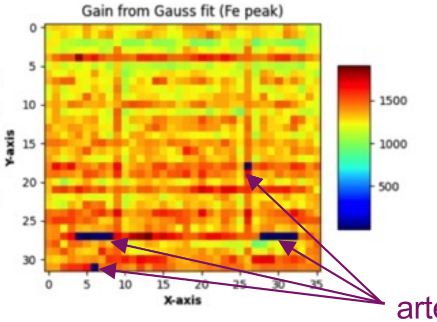
10 artefacts 13L // 56R



11 72L / 14R ?

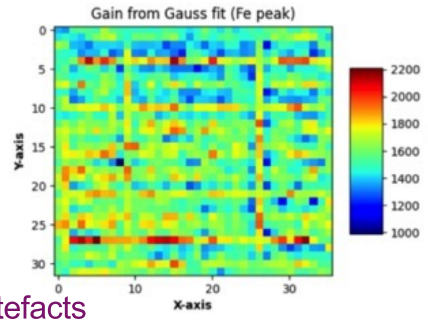


13

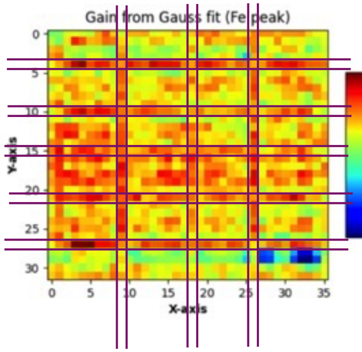


artefacts

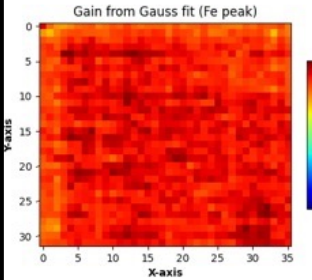
15 44L / 24R



16 65L / 36R

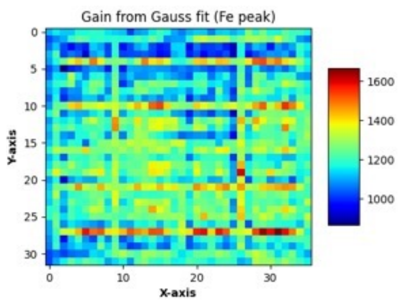


23 70L / 63R



Bare FR4 areas on PCB backside
= location of Al stiffener ribs gluing

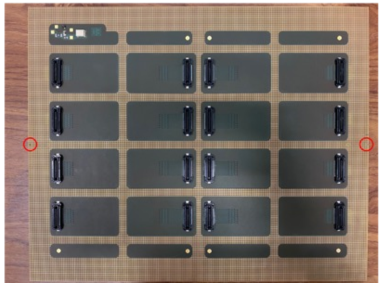
14 82L / 57R



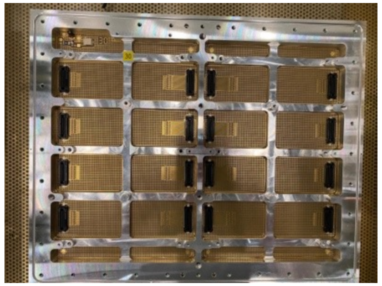
+ 03, 12, 18 (200 kΩ/sq.)

ERAMs up to S/N 23 : higher gain below stiffener ribs
This seems to be due to local extra thickness of copper & soldermask on the backside of the PCB which affects the micromegas amplification gap after DLC foil pressing.

ERAM-10 & 13: low gain pads are due to data analysis artefacts



ERAM detector

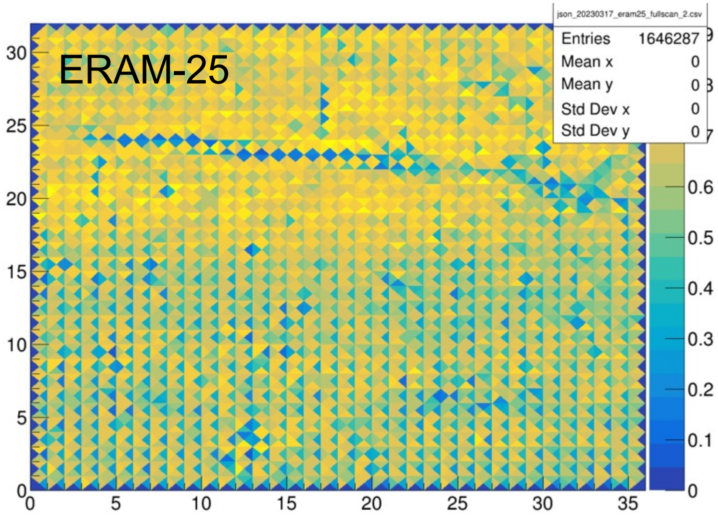


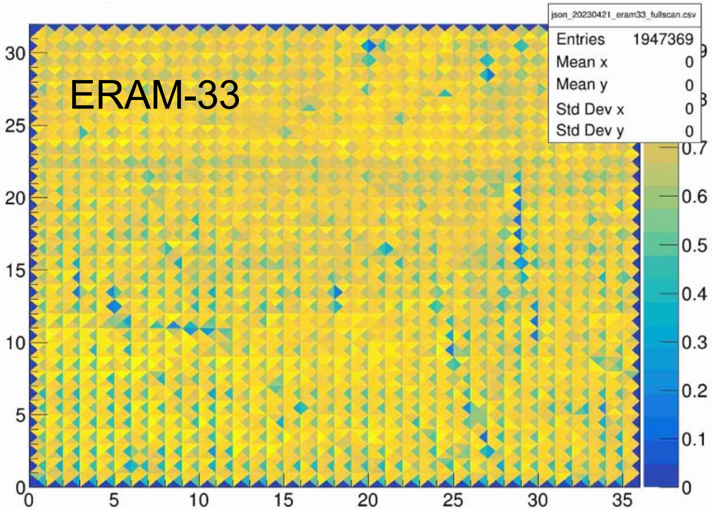
ERAM stiffener

ISSUES WITH BATCH 7 OF DLC FOILS
CHARGE SPREADING MAPS

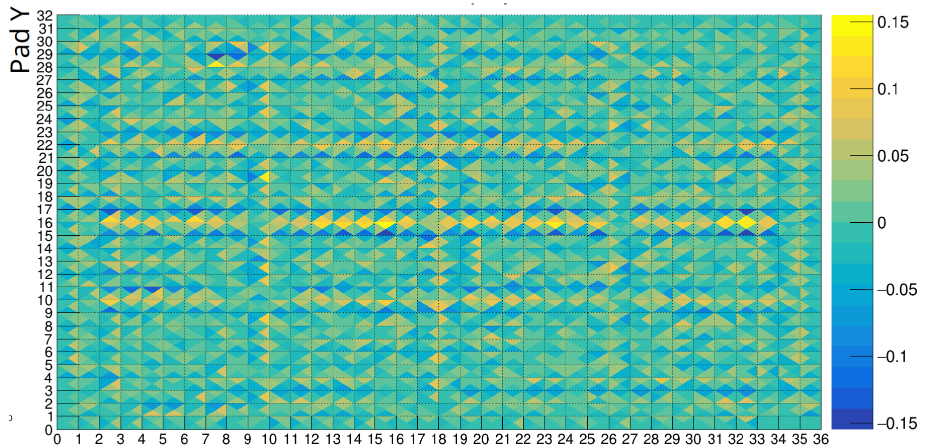
Ref: D. Henaff (CEA/Irfu)

Charge sharing maps extracted from X-ray scan pad waveforms

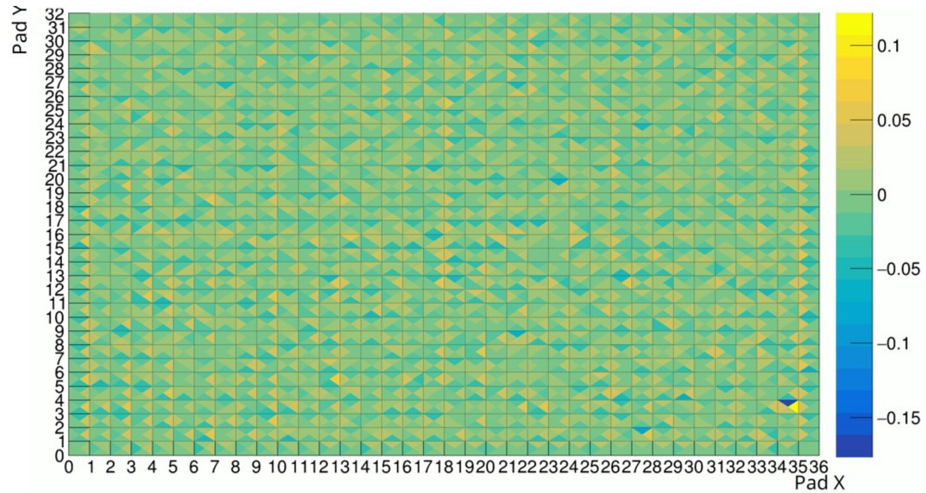




An ERAM **before** PCB backside layer modification

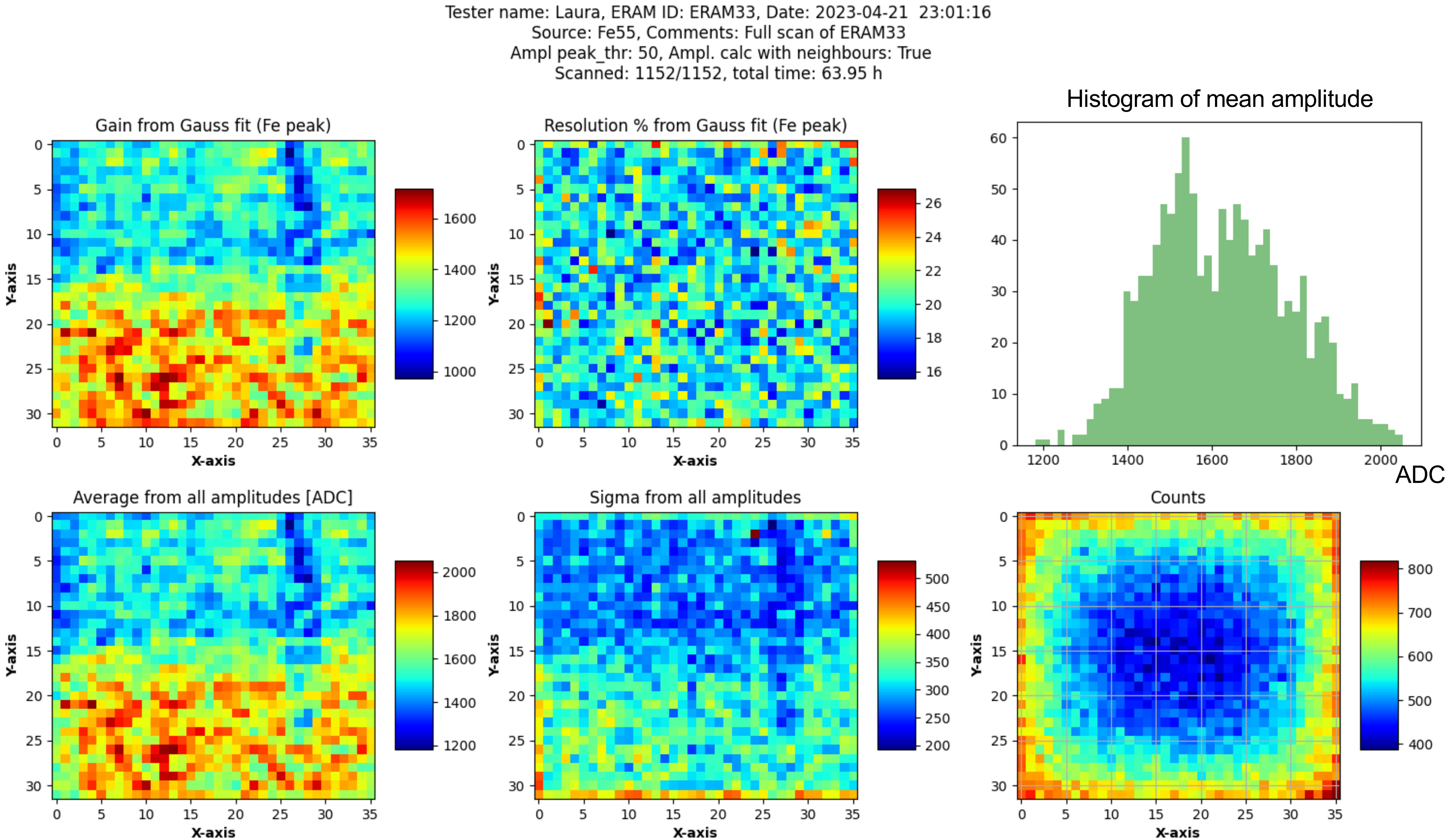


A « good » ERAM (after S/N 23)



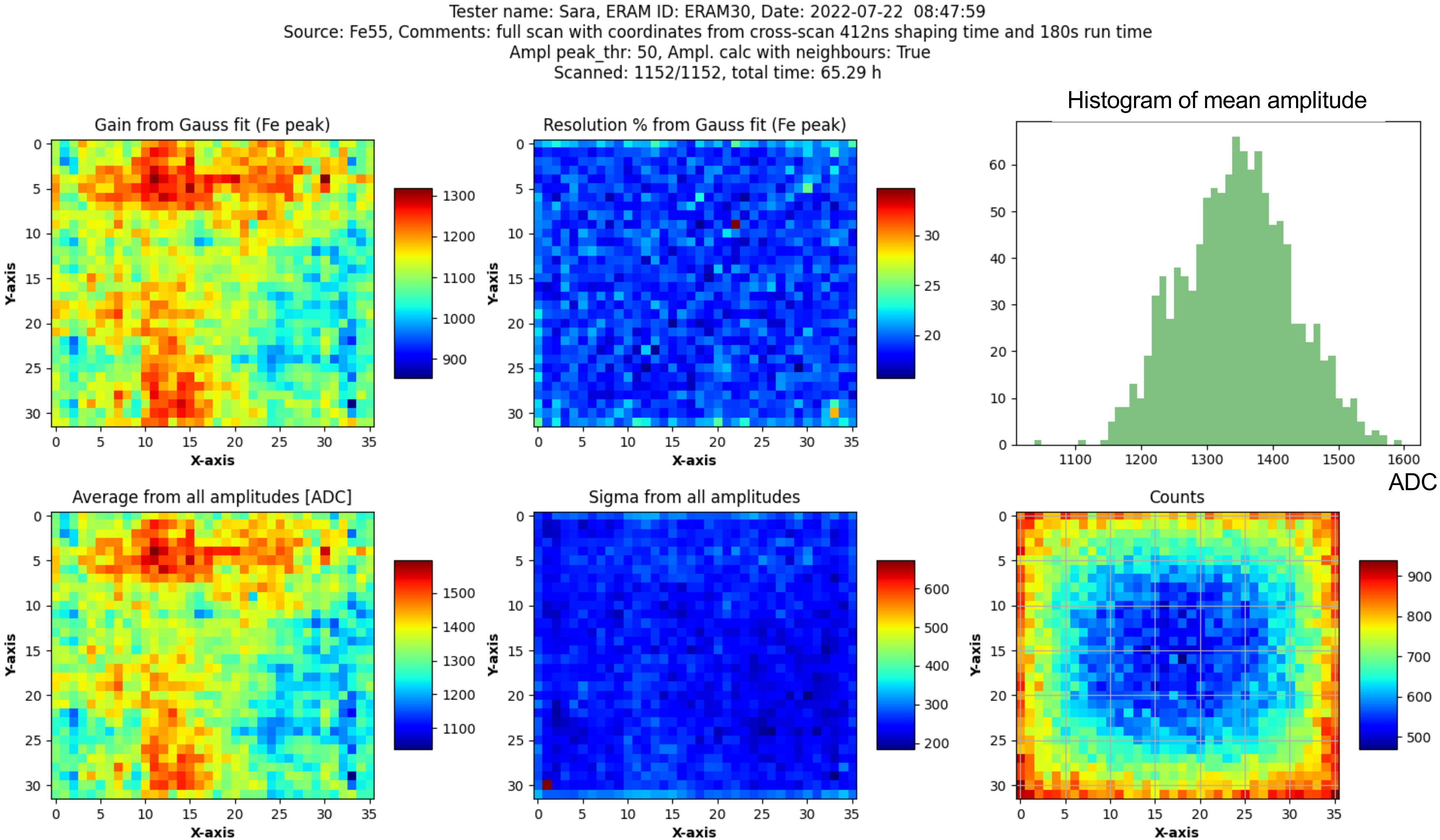
These defects may be correlated with DLC layer defects ... possibly because of too many baking treatments of the DLC foils

Issues with batch 7 of DLC foils
gain gradient on ERAM-25, 33, 34



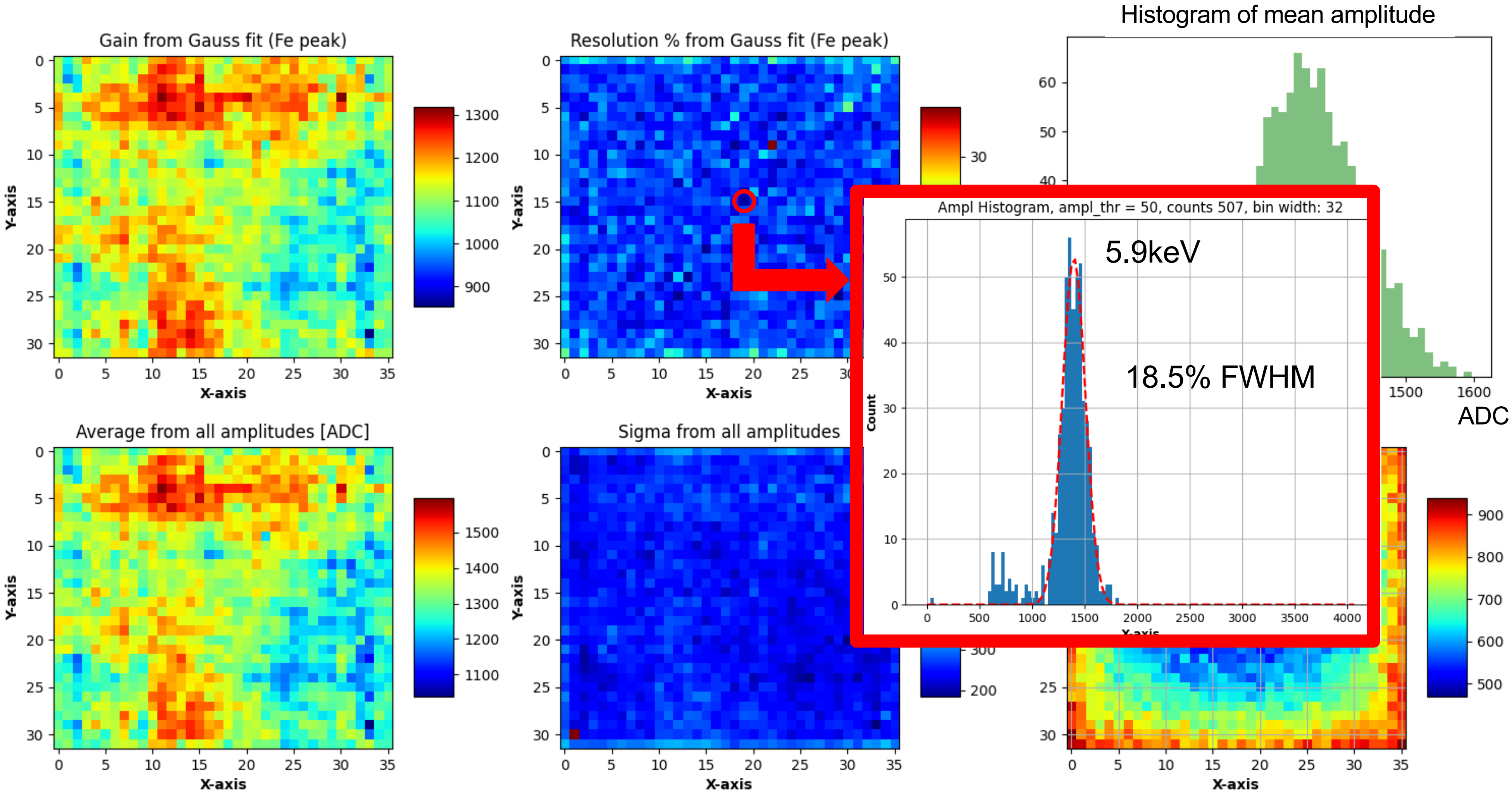
Problem at DLC pressing or mesh integration steps, not fully understood

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



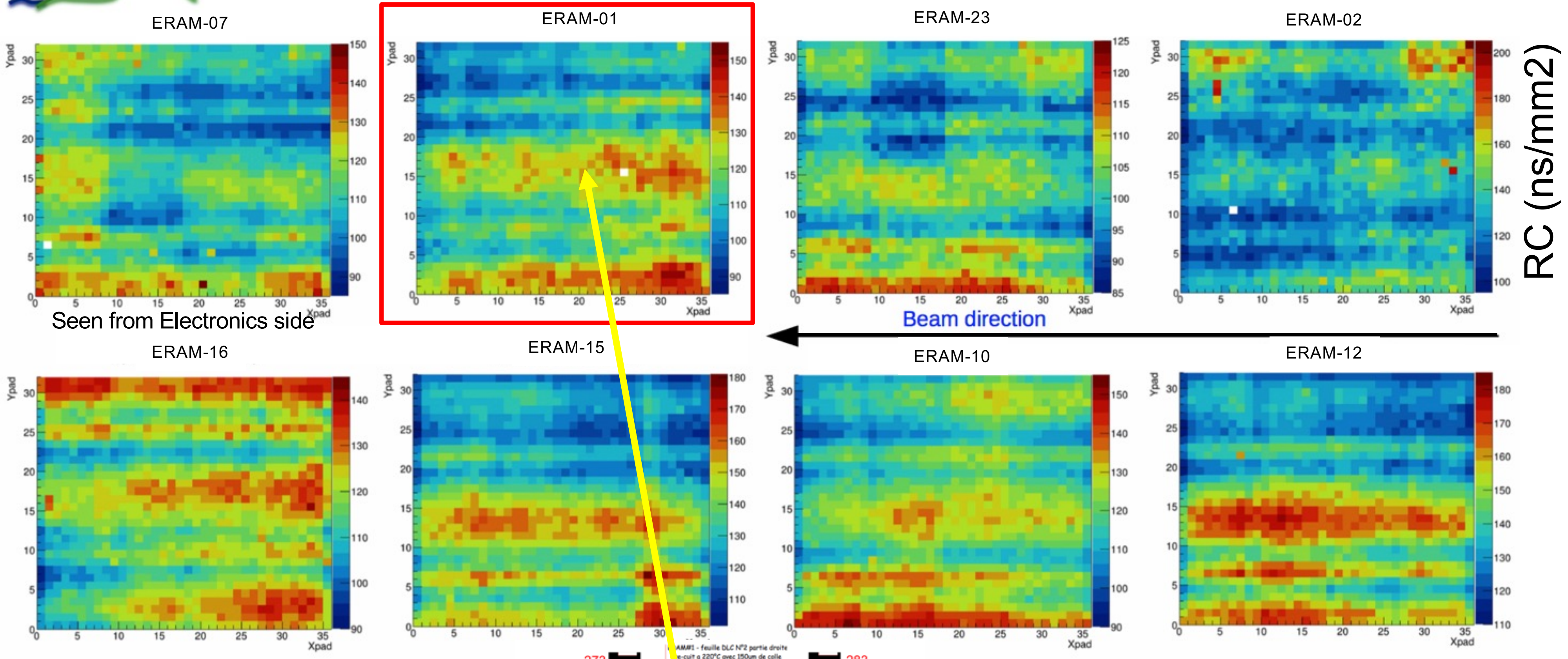
AN EXAMPLE OF A ^{55}FE X-RAY SCAN ERAM-30

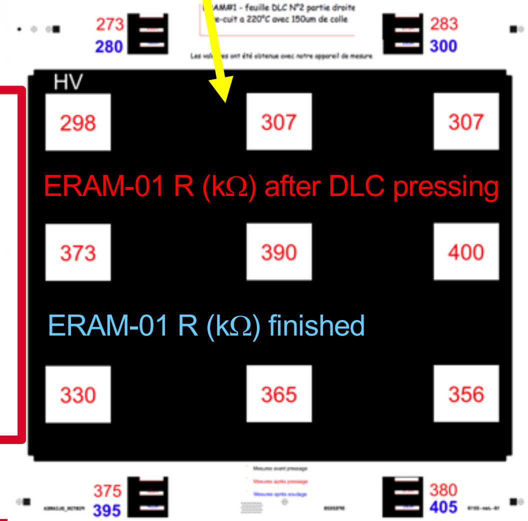
Tester name: Sara, ERAM ID: ERAM30, Date: 2022-07-22 08:47:59
Source: Fe55, Comments: full scan with coordinates from cross-scan 412ns shaping time and 180s run time
Ampl peak_thr: 50, Ampl. calc with neighbours: True
Scanned: 1152/1152, total time: 65.29 h



RC MAP DERIVED FROM X-RAY SCANS

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





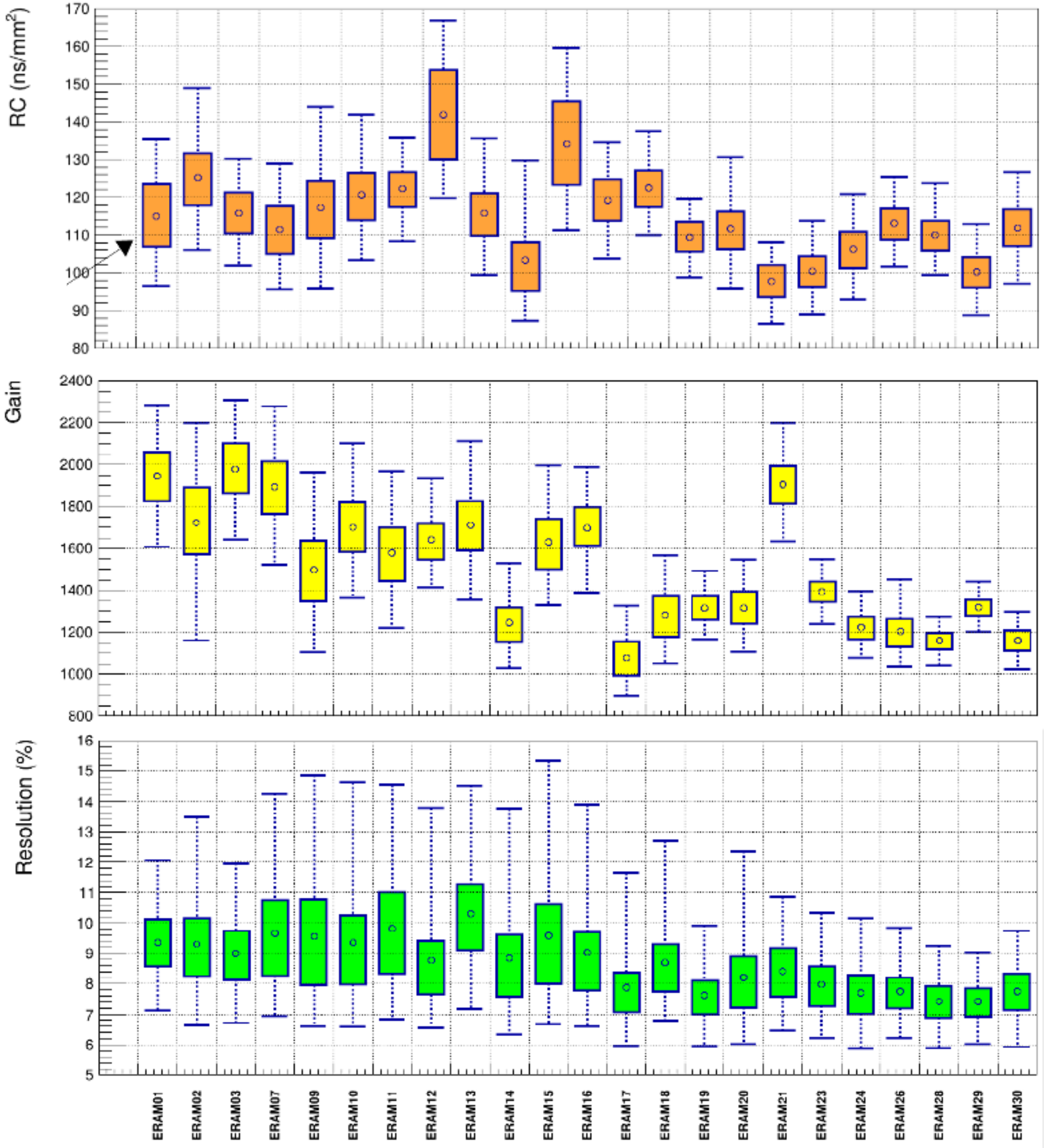
Detailed model of pad signals

- Primary electrons diffusion 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	

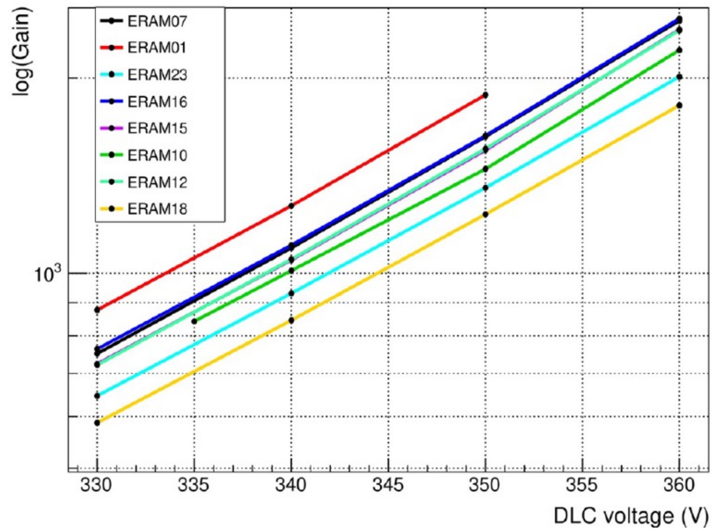
RC is quite well correlated to the measured DLC resistivity

STATUS OF ERAM PRODUCTION (06/23) TO BE COMPLETED WITH THE LAST ERAM SCANS

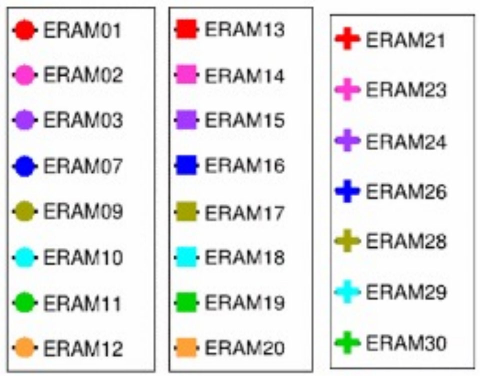


ref: D. Attié et al, Nucl.Instrum.Meth.A 1056 (nov 2023)
Doi: 168534

Gain v/s DLC voltage



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

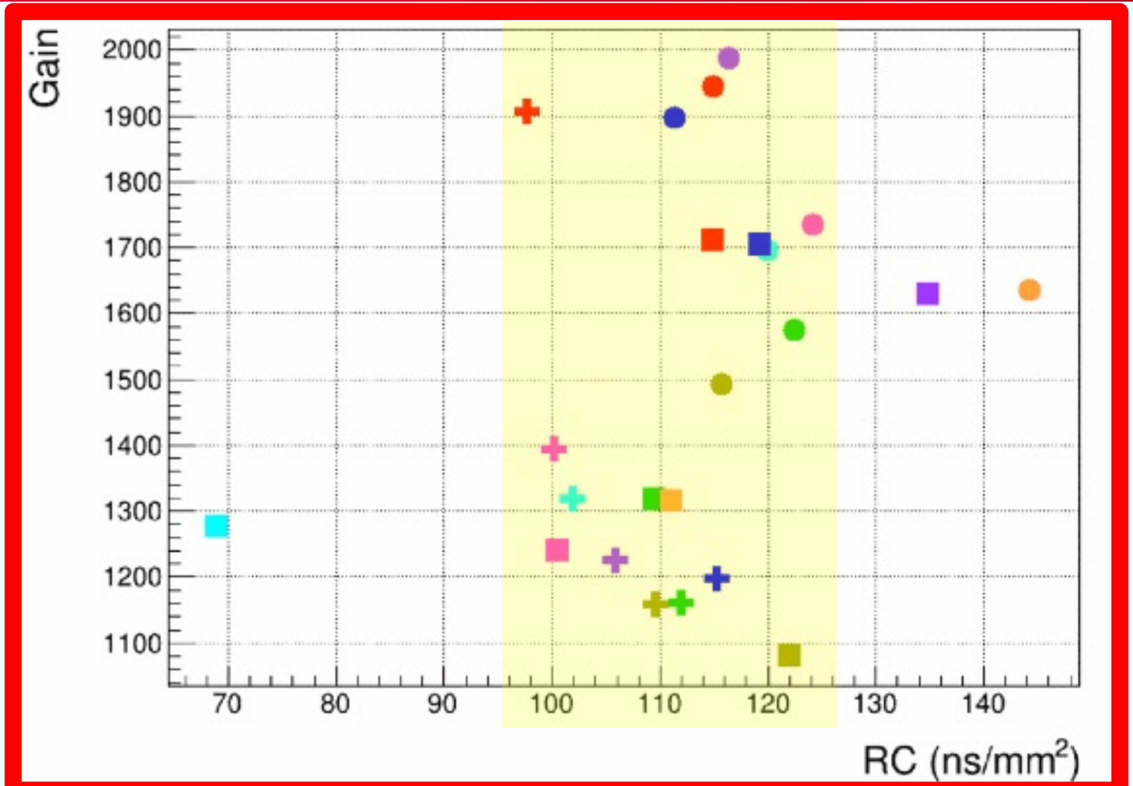


Except

ERAM-18 : ~1/2 R (½ RC)

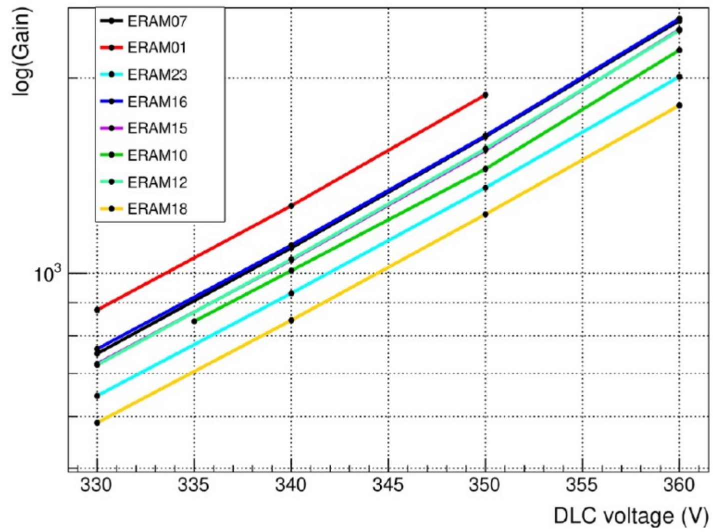
ERAM-29 : ~1/2 R
½ Glue thickness
same RC

STATUS OF ERAM PRODUCTION (06/23)
TO BE COMPLETED WITH THE LAST ERAM SCANS

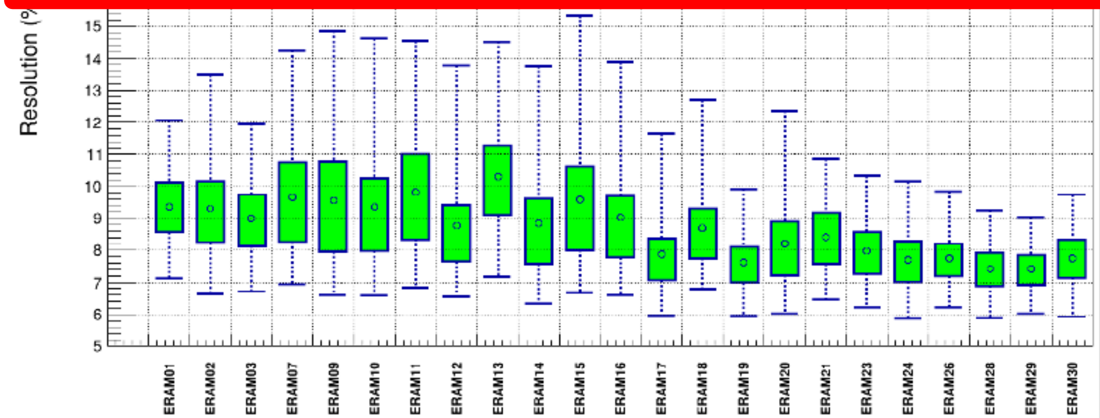


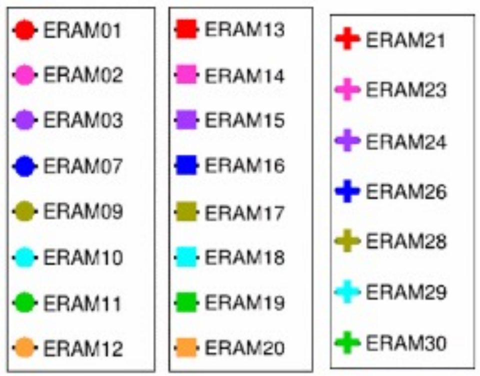
ref: D. Attié et al, Nucl.Instrum.Meth.A 1056 (nov 2023)
Doi: 168534

Gain v/s DLC voltage



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



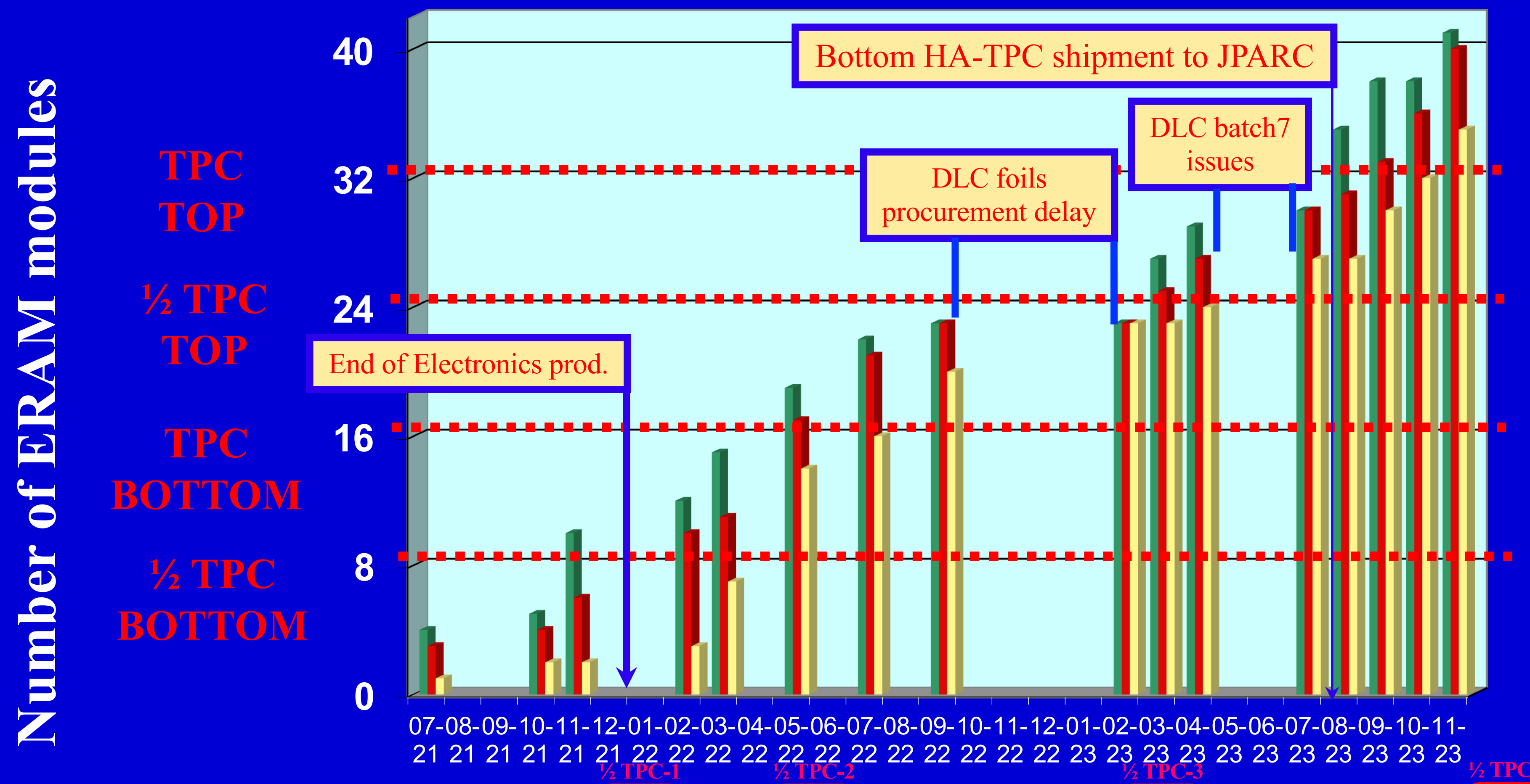


Except

ERAM-18 : ~1/2 R (½ RC)

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

ERAM PRODUCTION SUMMARY



	07-21	10-21	11-21	02-22	03-22 (½ TPC-1)	05-22	07-22 (½ TPC-2)	09-22	02-23	03-23	04-23 (½ TPC-3)	07-23	08-23	09-23	10-23 (½ TPC-4)	11-23
ERAM detectors	4	5	10	12	15	19	22	23	23	27	29	30	35	38	38	41
ERAM modules	3	4	6	10	11	17	21	23	23	25	27	30	31	33	36	40
Validated ERAM modules	1	2	2	3	7	14	16	20	23	23	24	27	27	30	32	35

Number of ERAM validated at each step of the production (11/23)					
Total nb of PCB	QC0 (PCB)	QC1 (bulk-MM)	QC2 (mesh-pulsing)	QC3 (x-ray scan)	For HA-TPC
48	45	41	36 recovered to 41	35	33

+3 last QC3 in dec 23

CONCLUSION AND PERSPECTIVES

- The T2K/HA-TPC ERAM detector module was designed to be a compact 34 x 42 x 4 cm^3 unit suitable to pave large readout endcaps of TPCs.

- The production is finished with a total of 36 detectors qualified for use in the two HA-TPCs. A lot was learnt from this 2 years production and difficulties were overcome for an overall very good quality of the detectors : less than 1/1000 “dead” pads and no major issues to operate the detectors.

- The detector response modelization is consolidated and the performances of the detectors, driven by the RC constant of the charge spreading DLC stack, are within the specifications for the readout of the ND280/HA-TPCs.

- The use of the bottom HA-TPC in the T2K ND280 detector just began and its commissioning is on-going smoothly.

- The TOP HA-TPC will be equipped with its 16 ERAMs in February next year for an installation of the TPC in the basket of ND280 in April, finalizing the upgrade of the Near detector of T2K.