LEMs for ProtoDUNE-DP (PD-DP): design, QA/QC and tests

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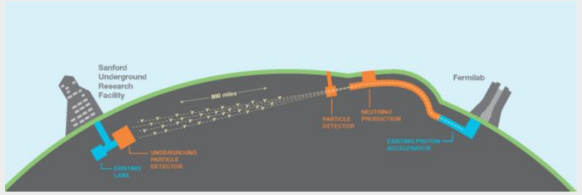
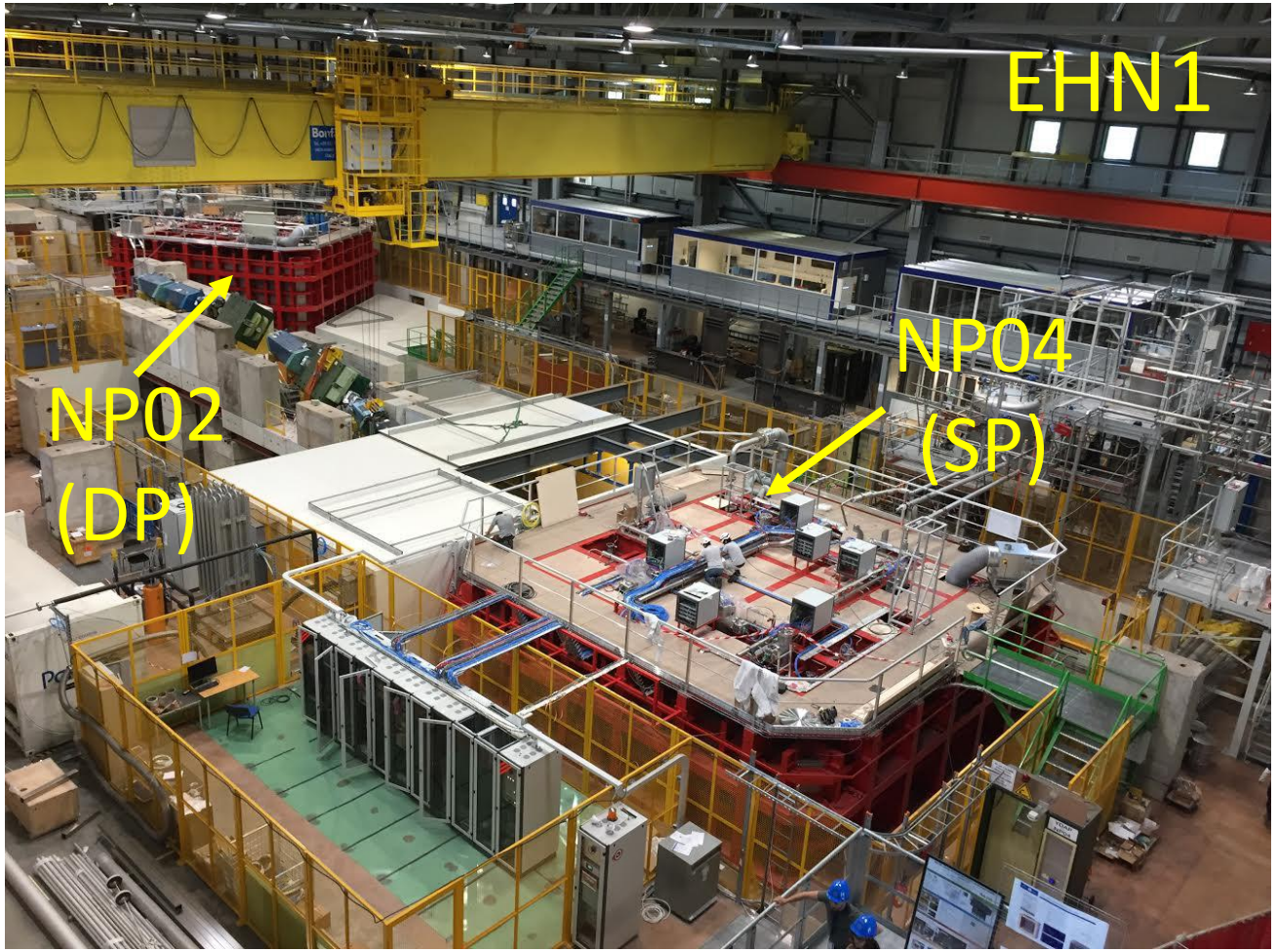
ProtoDUNEs @ the CERN Neutrino Platform

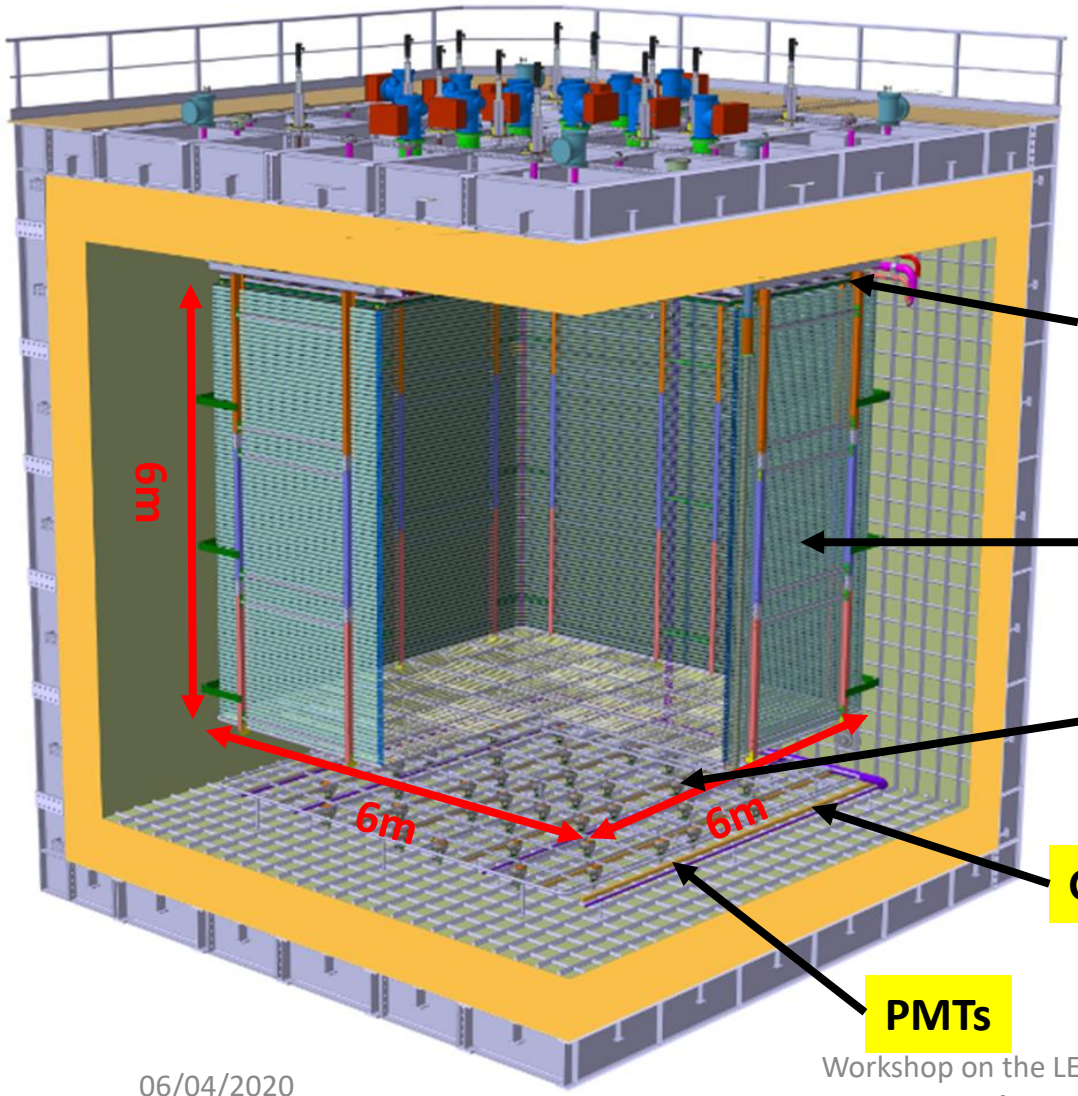
- Goal of ProtoDUNEs SP and DP :
  - *Validate the LArTPC technology scalable to O(10kt) modules of the FD for the future DUνE long-baseline ν experiment in USA.*



- ProtoDUNE-DP :
  - *Dual-phase LAr TPC*
  - *720t of LAr*
  - *300t fiducial mass*



ProtoDUNE-DP : a 300t LArTPC



Charge Readout Planes (CRP)

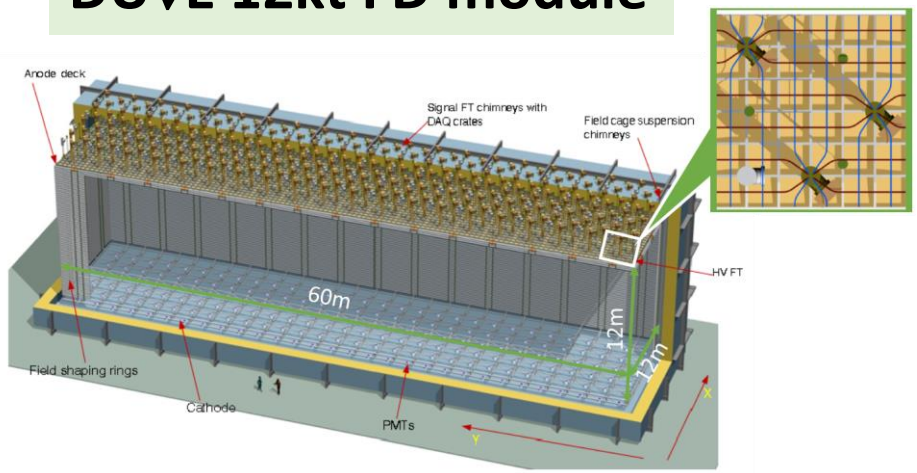
Field Cage

Cathode

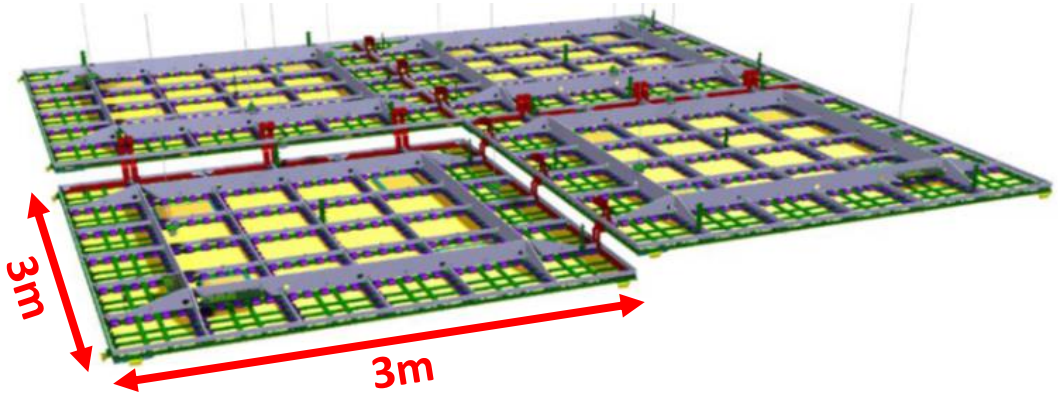
Ground Grid

PMTs

DUνE 12kt FD module



1 CRP = 36 Anodes + 36 LEMs (50×50 cm^2) + 3×3 m^2 Extraction Grid



Only 2 fully instrumented CRPs for ProtoDUNE-DP (see G.Eurin's talk)

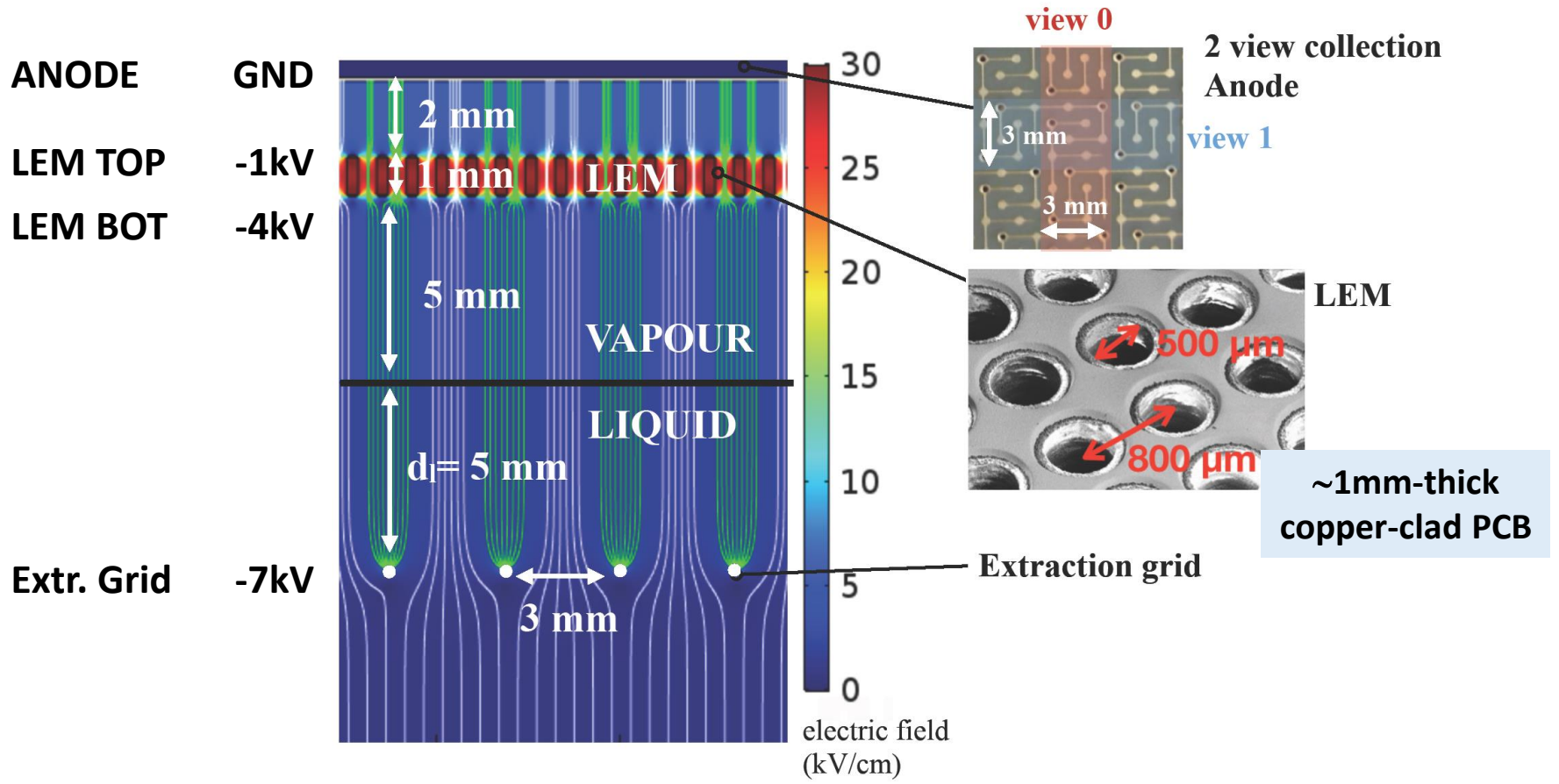
Dual Phase Principle: charge readout

Induction : 5kV/cm

Amplification : 30kV/cm

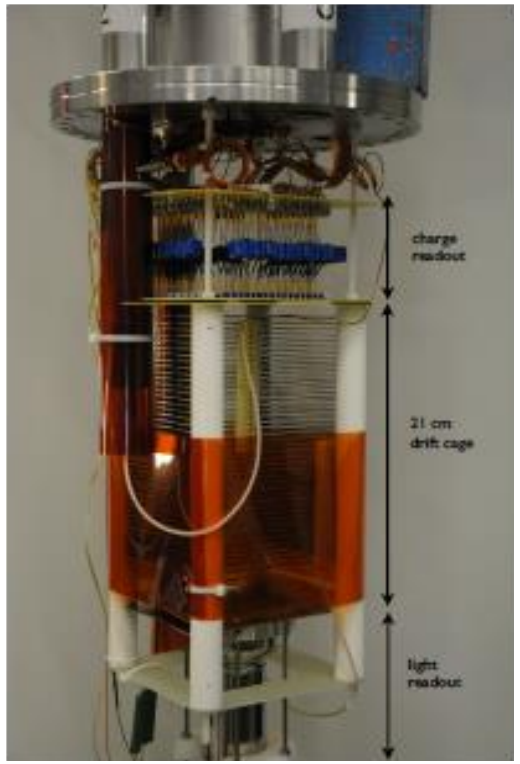
Extr. (GAr) : 3.6kV/cm

Extr. (LAr) : 2.4kV/cm



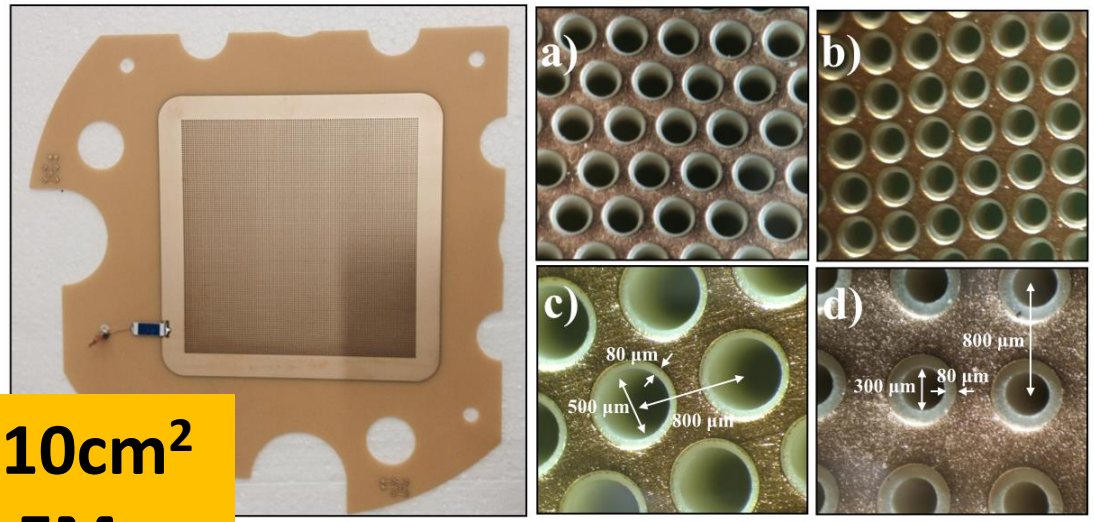
A bit of history …

Extensive studies performed at CERN by ETHZ (2008-2014) with a 3L DLAr TPC



C. Cantini et al., arXiv:1412.4402

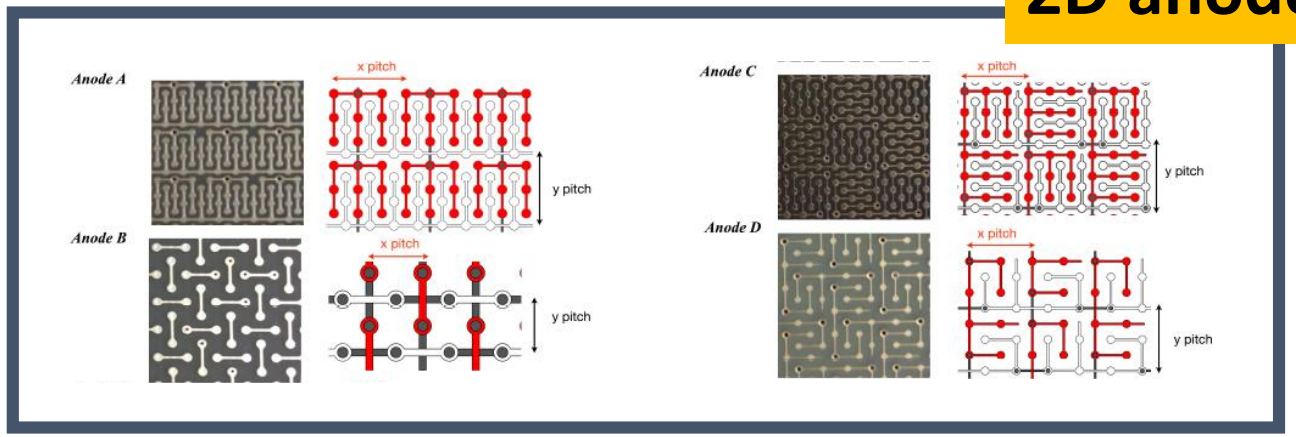
Different LEM and anode designs investigated



10×10cm² LEM

C. Cantini et al., arXiv:1312.6487

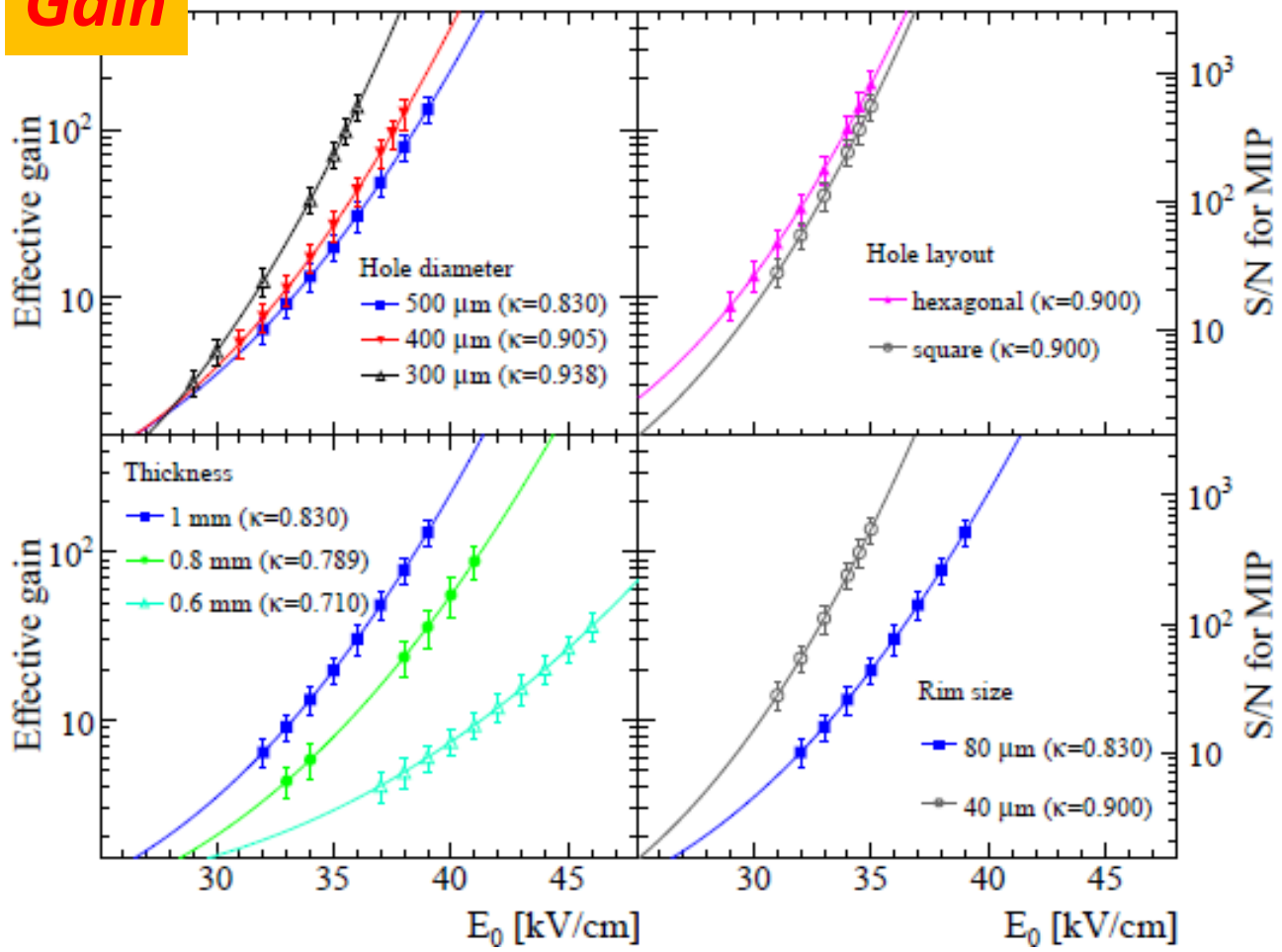
2D anode



Performance with the ETHZ 3L setup

C. Cantini et al., arXiv:1412.4402

Gain

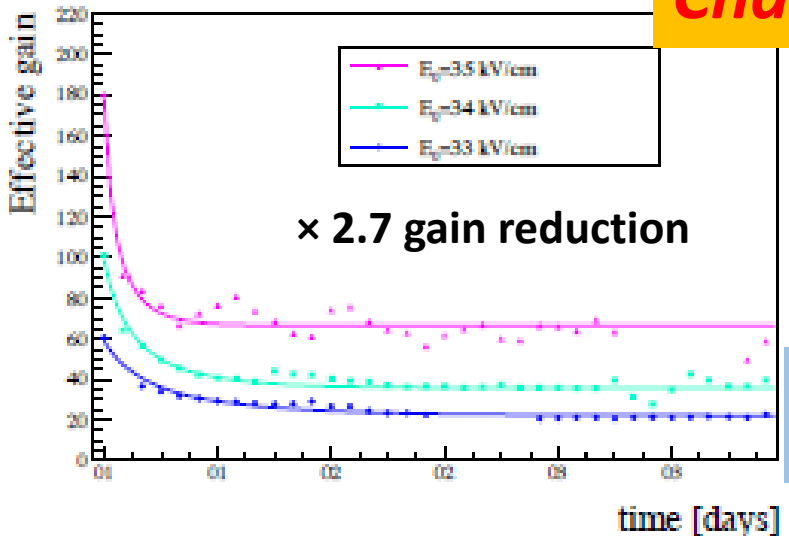


PD-DP LEM design

Maximal LEM gain achieved for:

- Hexagonal layout (800µm pitch)
- 1mm FR4 thickness
- 500µm diameter holes
- 40µm rim

Charging up

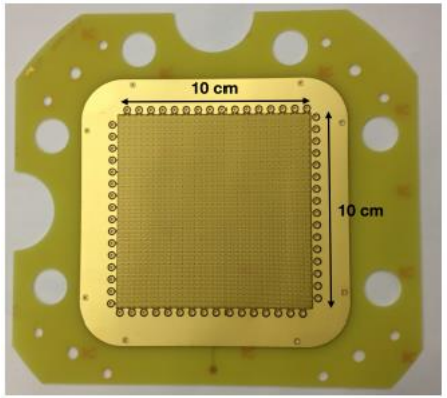


G=20@3.3kV PD-DP goal

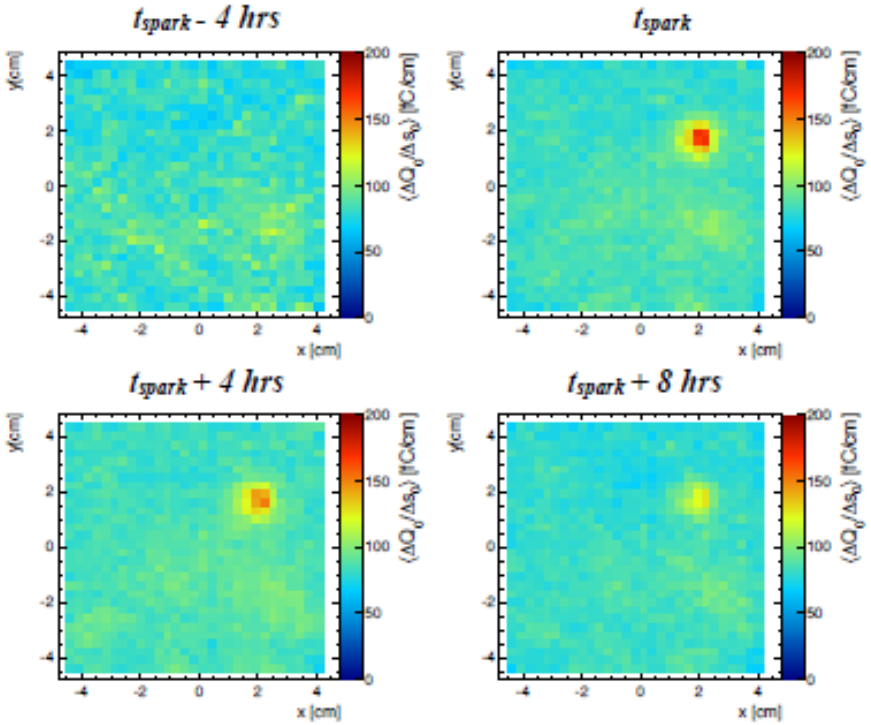
LEM charging up, sparks and long-term performance

C. Cantini et al., arXiv:1312.6487

ETHZ 10×10 prototype

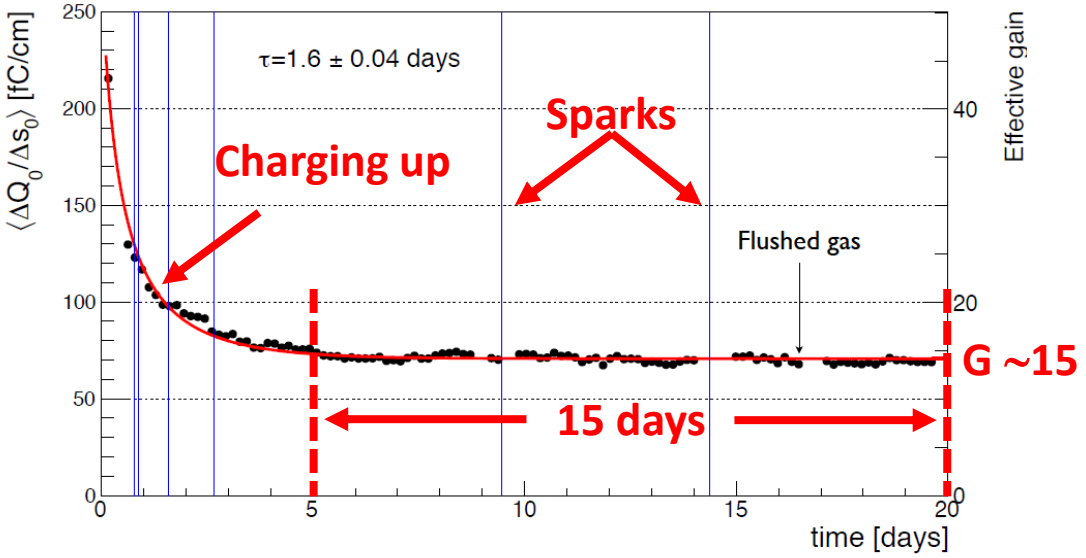


LEM spark history



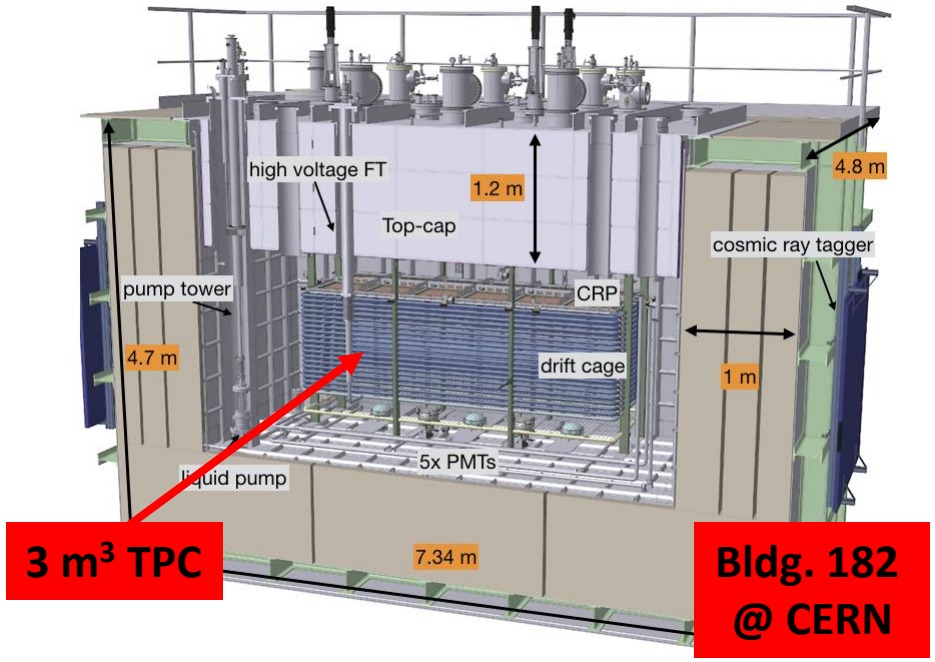
LEM charging up destroyed locally (~cm²) after a spark

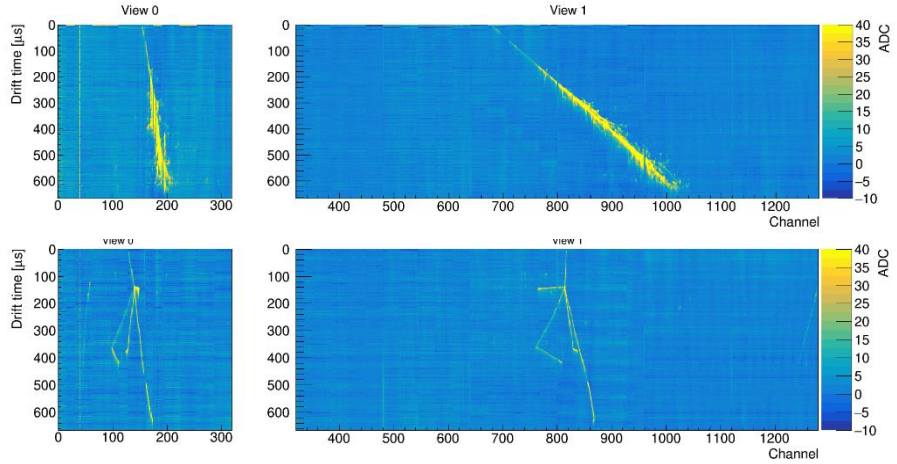
LEM dielectric charging up due to E-field lines crossing walls around holes



- ***2 sparks in 15 days after charging up***
- ***Extrapolation to 3m×3m : (5.0±3.5) sparks/h @ G~15***

The 311 prototype (2016-2018)

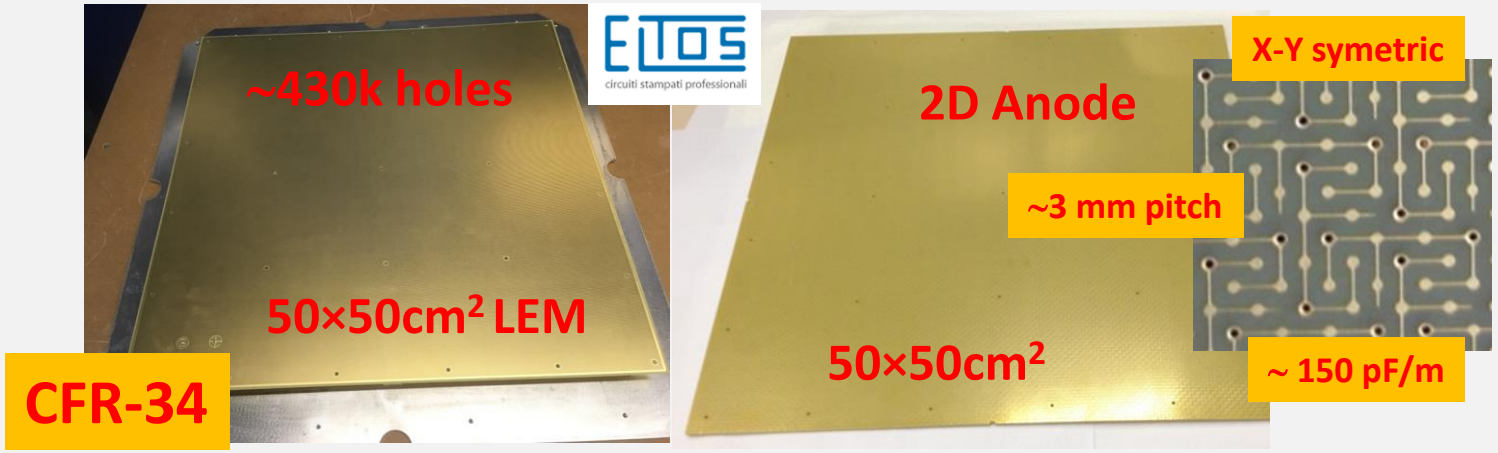




(B. Aimard et al., JINST 13 (2018) 11, P11003)

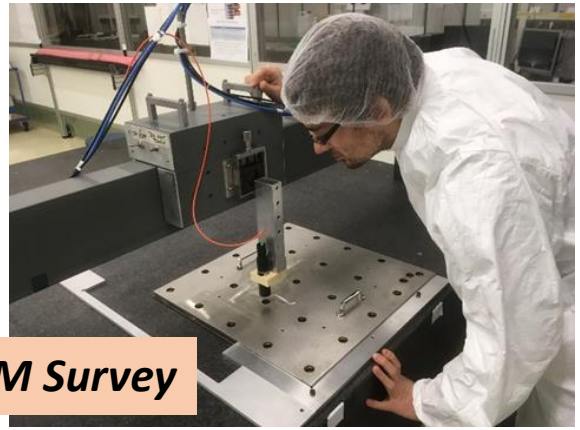
Dual phase concept demonstrated at the 4-ton scale. Several technical choices validated but also some CRP issues:

- Extraction grid could not be operated above 5kV
- Max. gain of 2-3 instead of goal value of 20
- Long-term operation not demonstrated (< 8h run), limited by power supply trips
- Max. E_{LEM} = 31kV/cm for short time (~1h) and < 3m^2



Meanwhile, @ CEA/Irfu ….

Development of the infrastructures needed at Saclay for the characterization and tests of the LEMs and anodes.

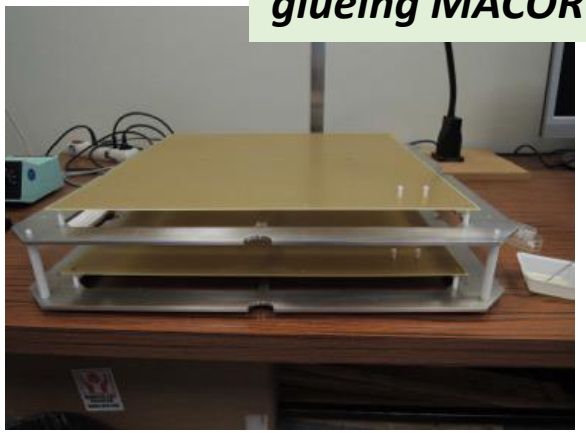


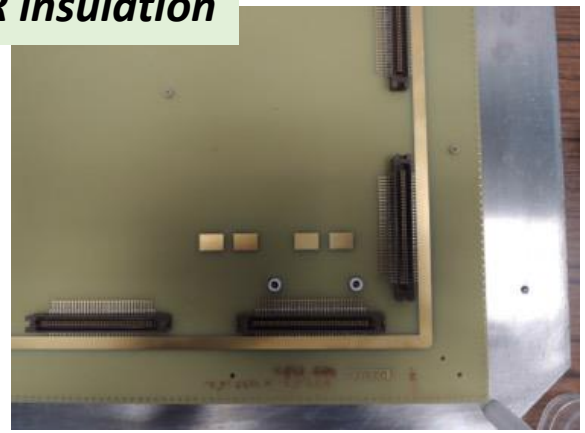
LEM Survey

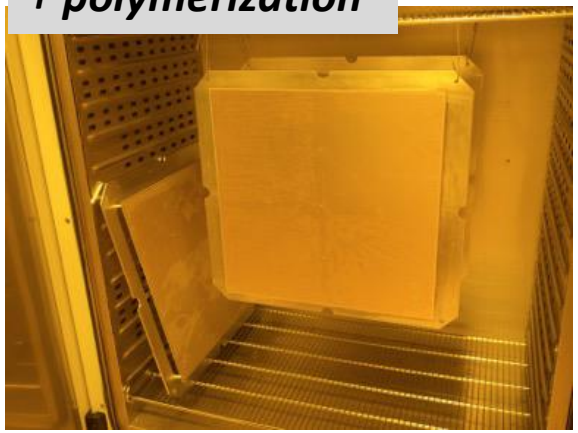
Soldering HV pins + glueing MACOR insulation

Ultrasonic bath

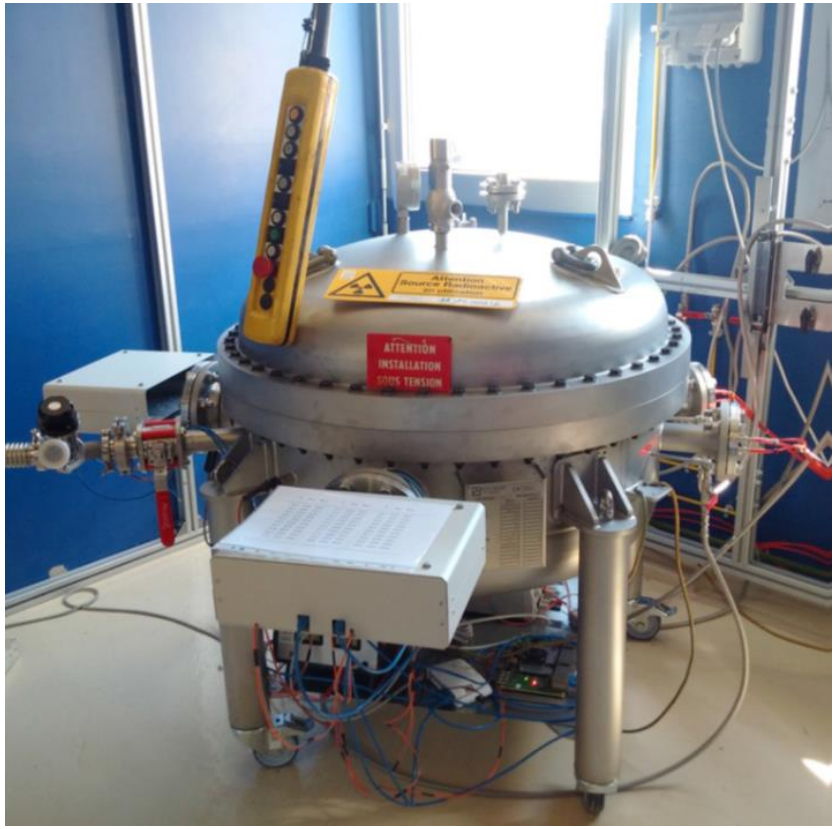
Cleaning + drying + polymerization

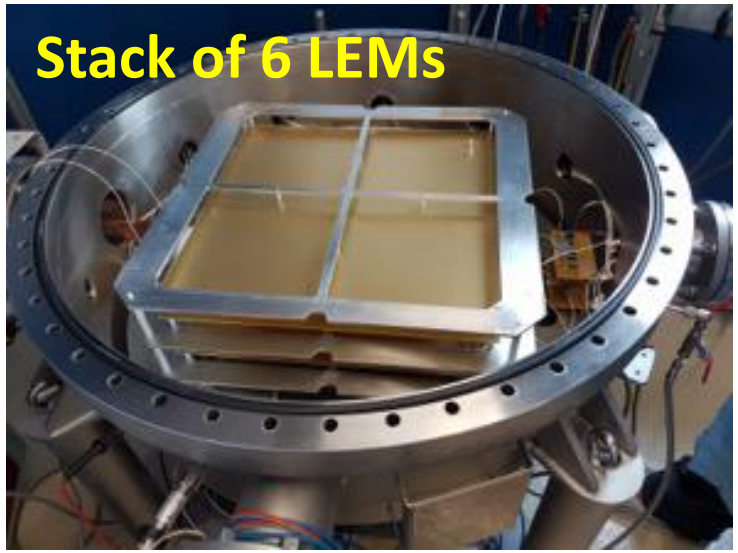


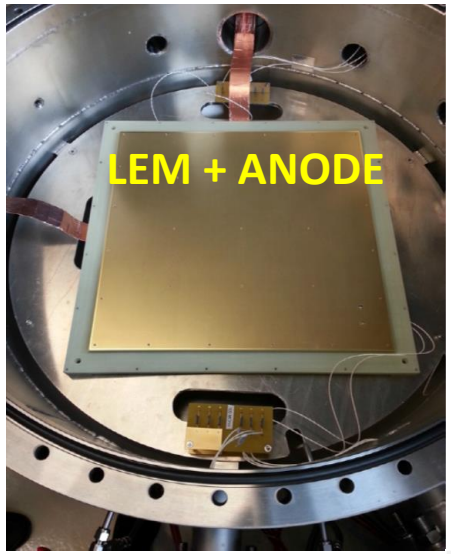




LEM HV Tests in a High Pressure Chamber



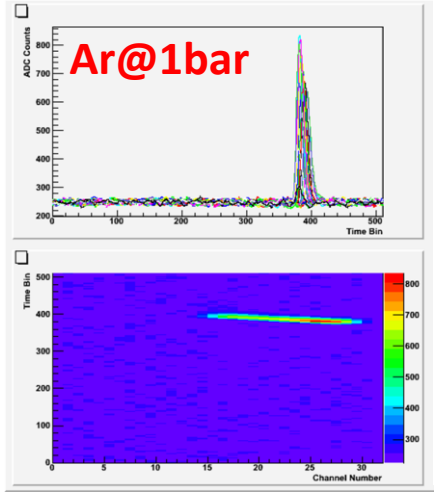


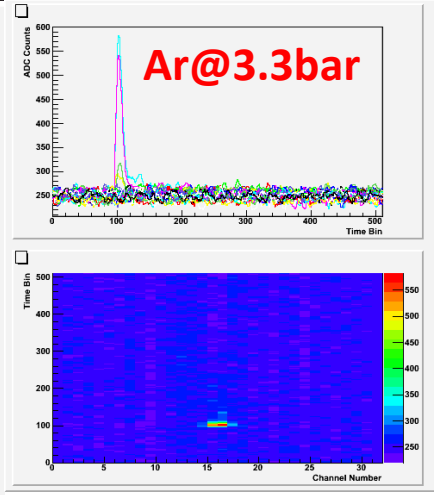


- Amplification gain inside the LEM depends on gas density ρ (or P/T) :

$$G = Ce^{\alpha d} \quad \text{with} \quad \alpha = A\rho e^{-B\rho/E}$$

- GAr @ 88°K and ~1 bar ⇔ T = 20°C and P ~3.3bar

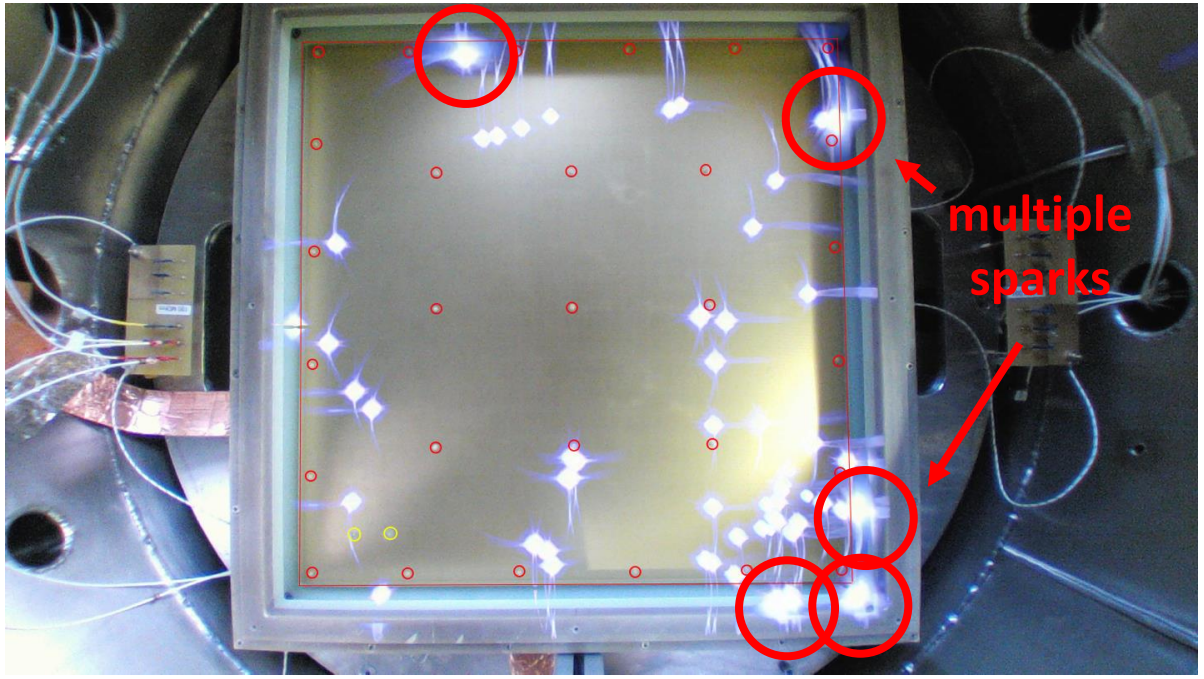


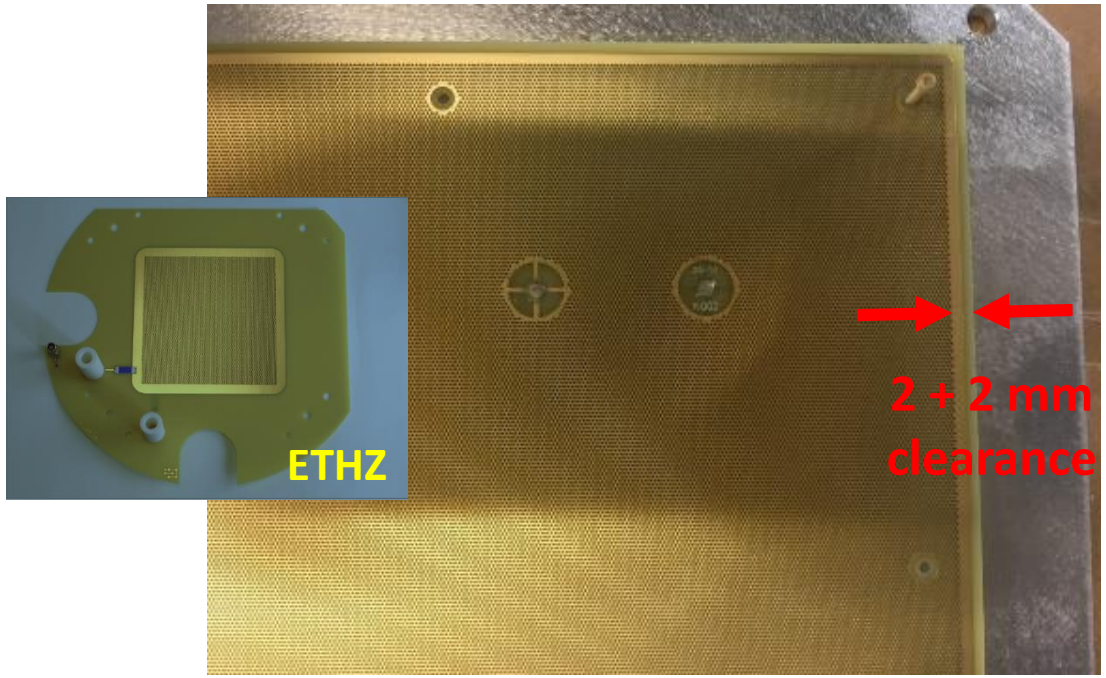


GAr purity in HP chamber :
> 1ppm O_2^{eq}

LEM HV Tests in Ar @ 3.3 bar

CFR-34 – 311 prototype



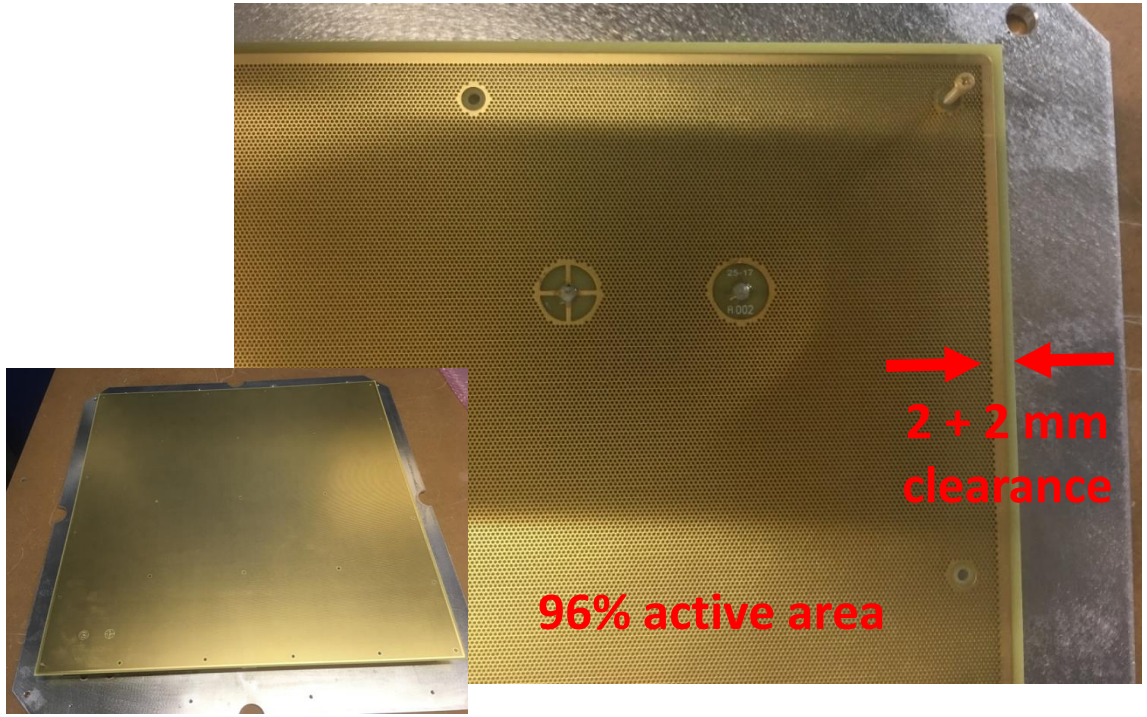


Spark rate : ~20/h for ΔV_{LEM} > 3.3kV in Ar @ 3.3 bar
(> 45% of sparks near edges or corners)

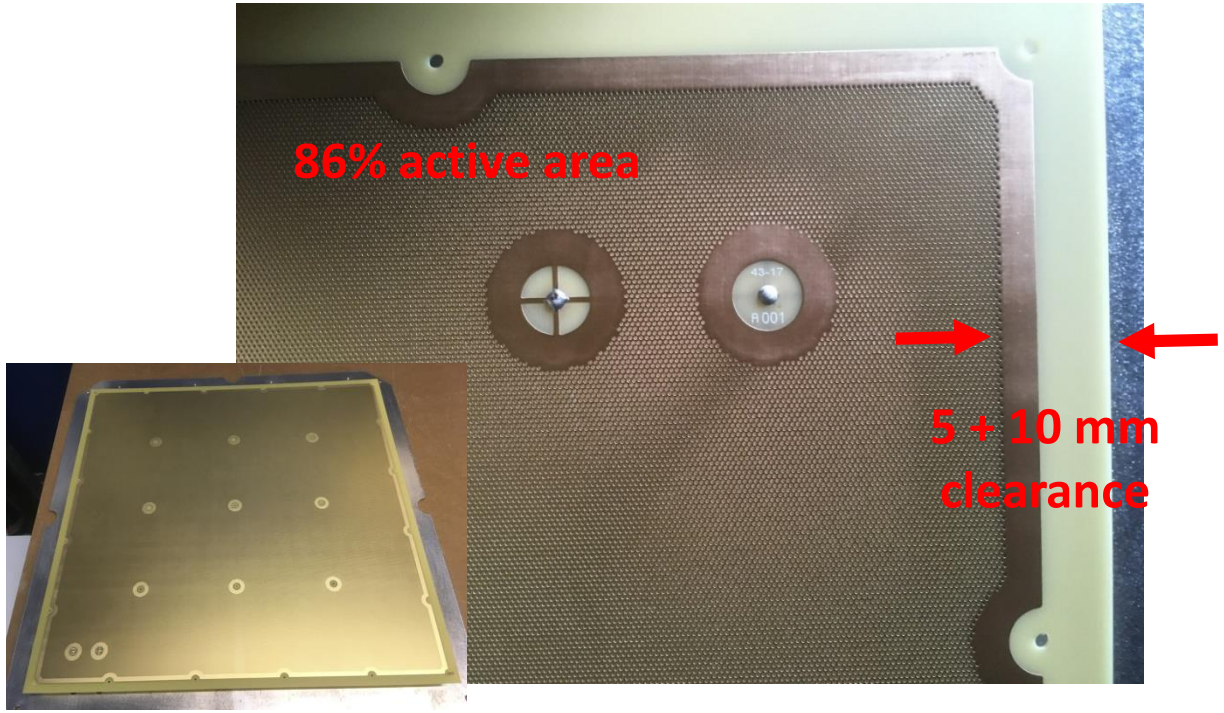
Building fully active LEMs is a challenge!

LEM Design for ProtoDUNE-DP

CFR-34 – 311 prototype



CFR-35 – ProtoDUNE-DP

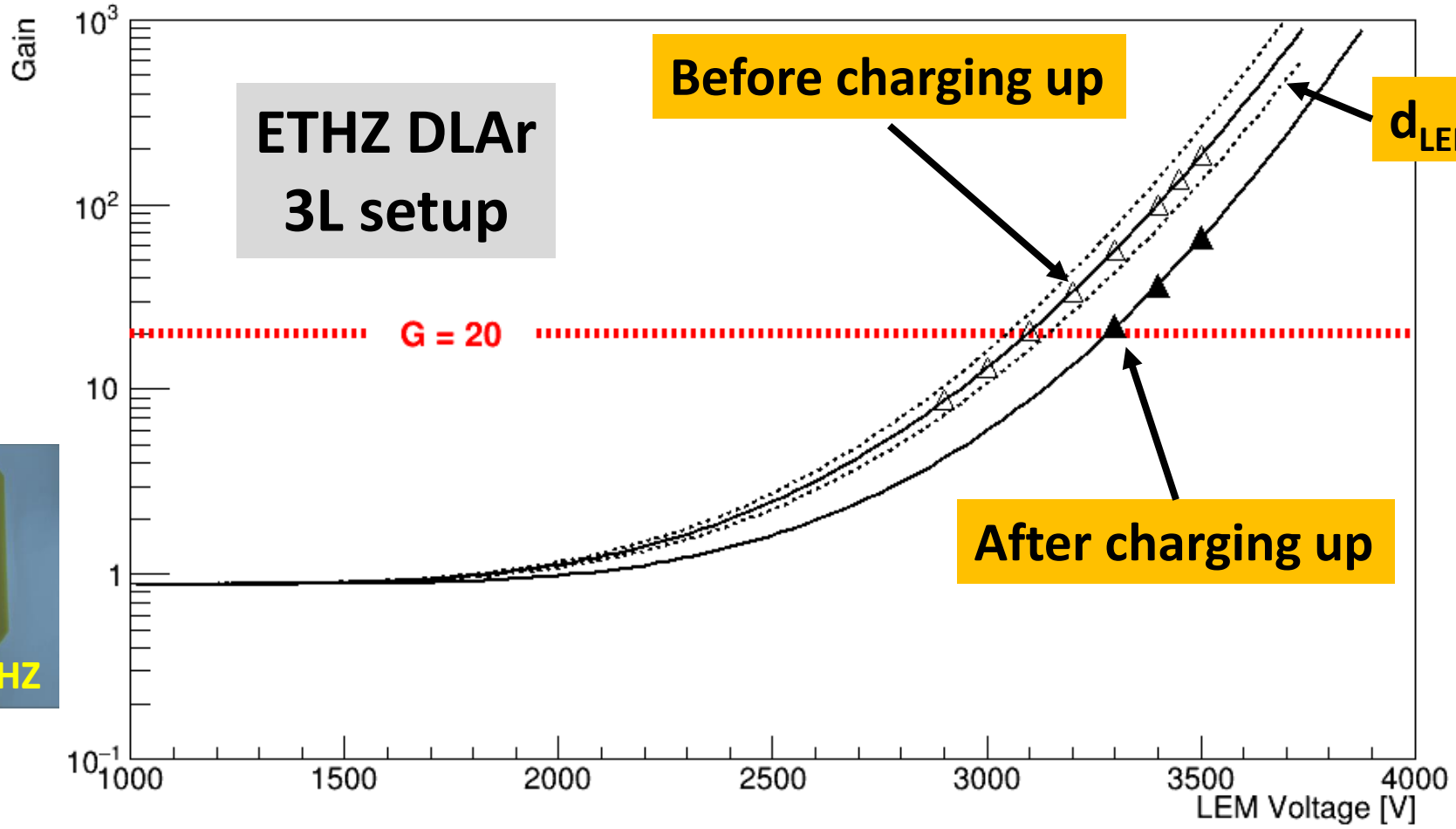


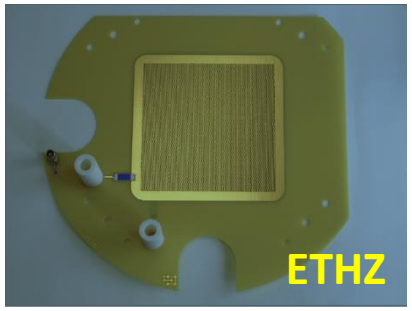
CFR-35 : LEM design for ProtoDUNE-DP production (74 LEMs) by ELTOS (Jan. – Oct., 2018)

Not the final one for a O(10kt) module! (see A. Delbart's talk)

Gain measurements (ETHZ)

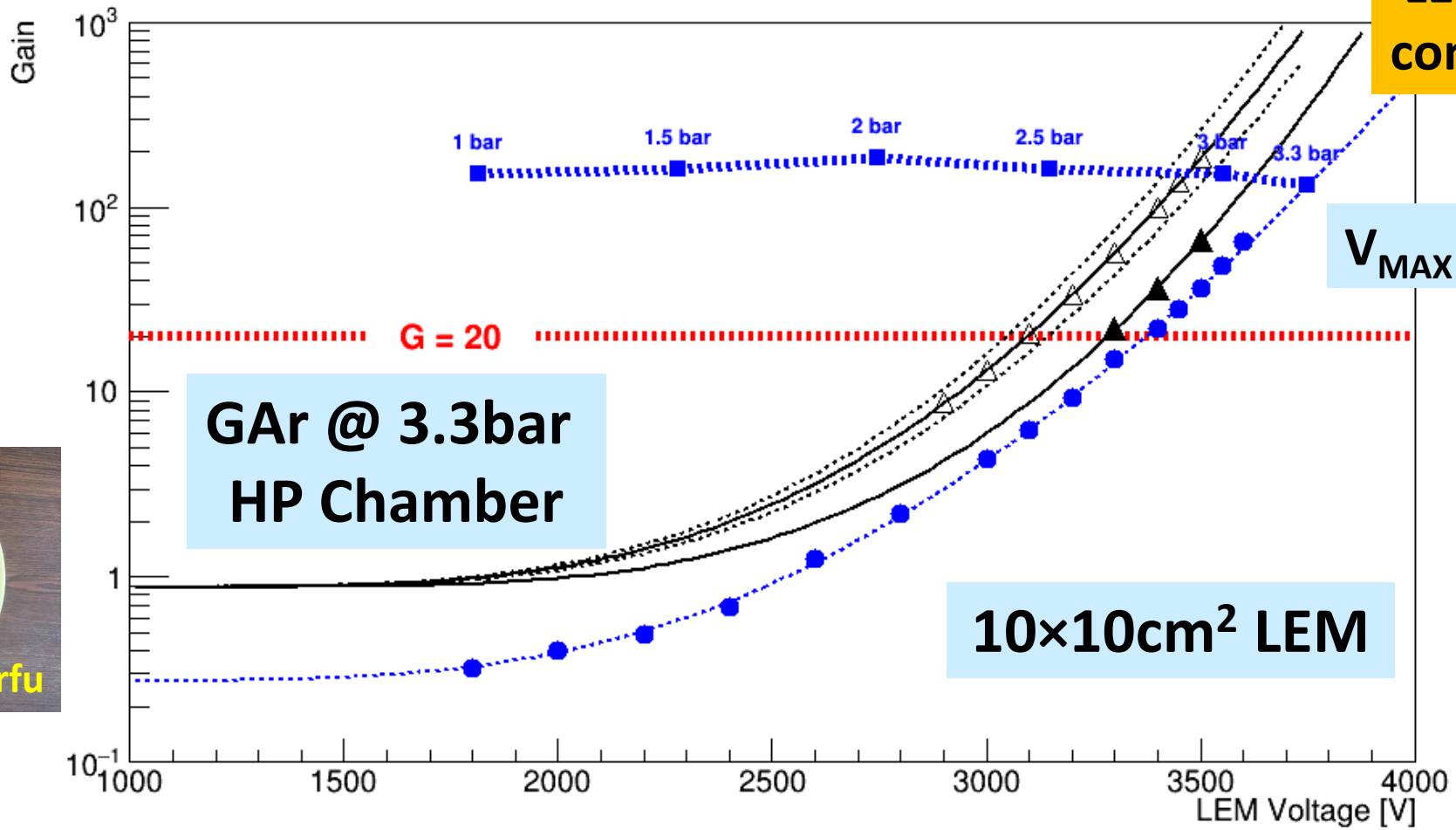
C. Cantini et al., arXiv:1412.4402





Cosmic rays

Gain measurements @ CEA/Irfu



LEM charging up completed locally

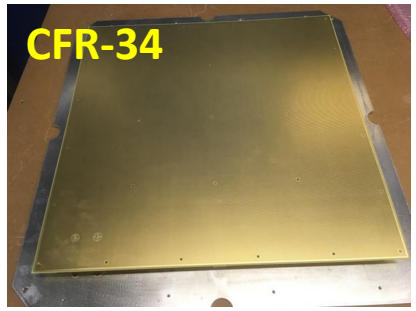
V_{MAX} ~ 3.7kV

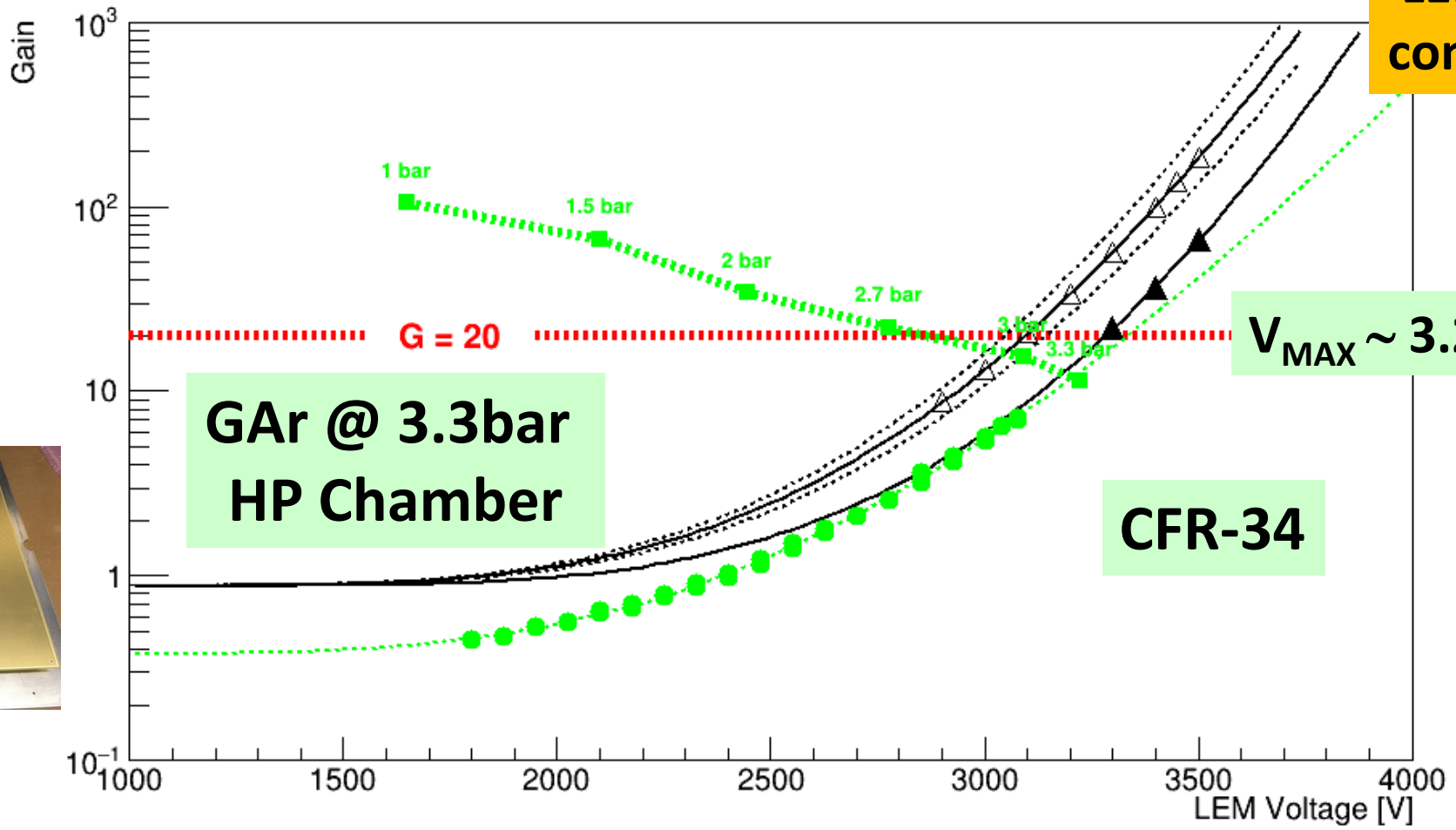
GAr @ 3.3bar HP Chamber

10×10cm² LEM

^{241}Am α source

Gain measurements @ CEA/Irfu



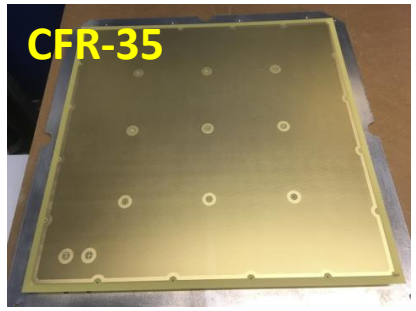


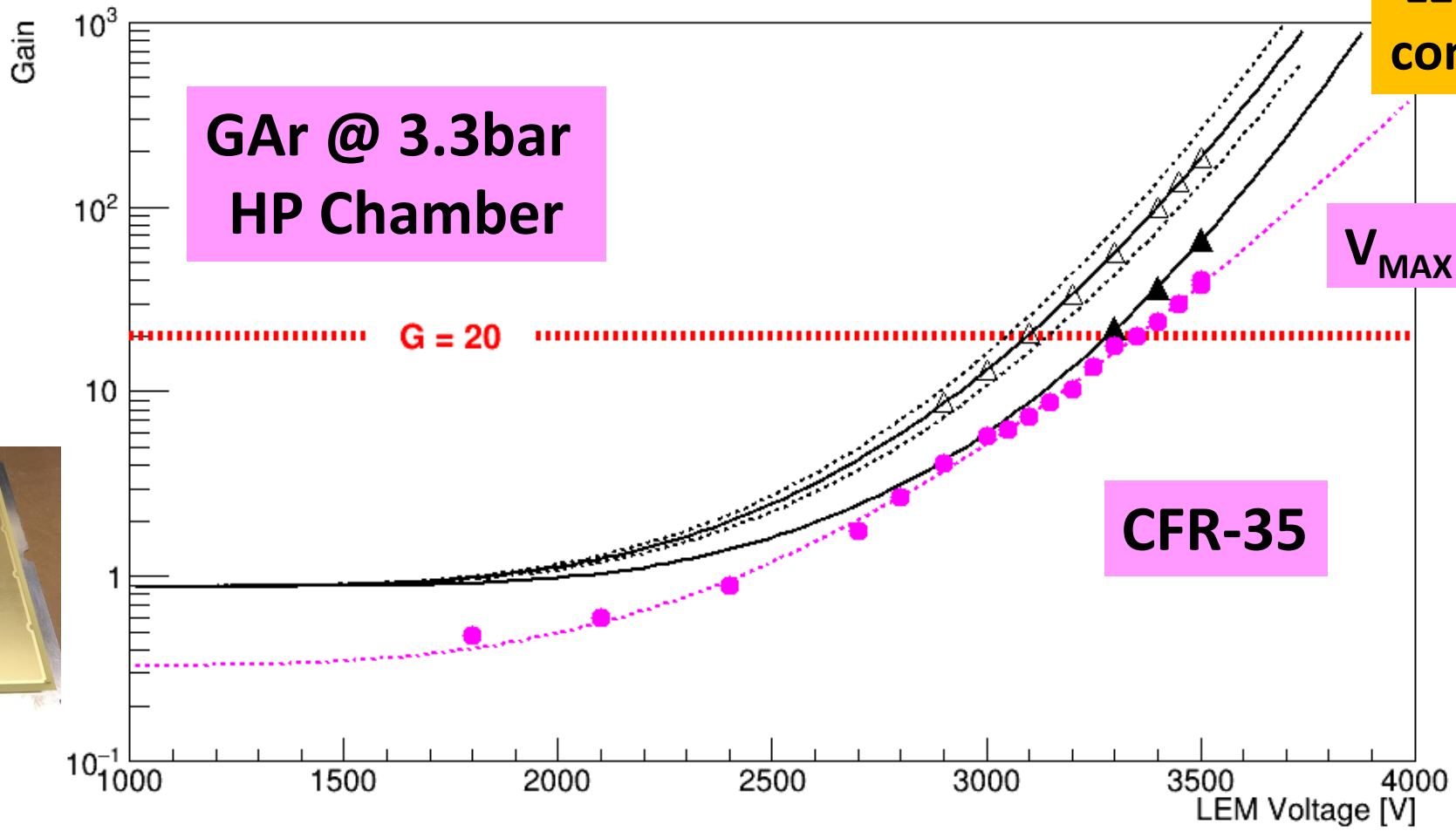
LEM charging up completed locally

V_{MAX} ~ 3.2kV

^{241}Am
α source

Gain measurements @ CEA/Irfu



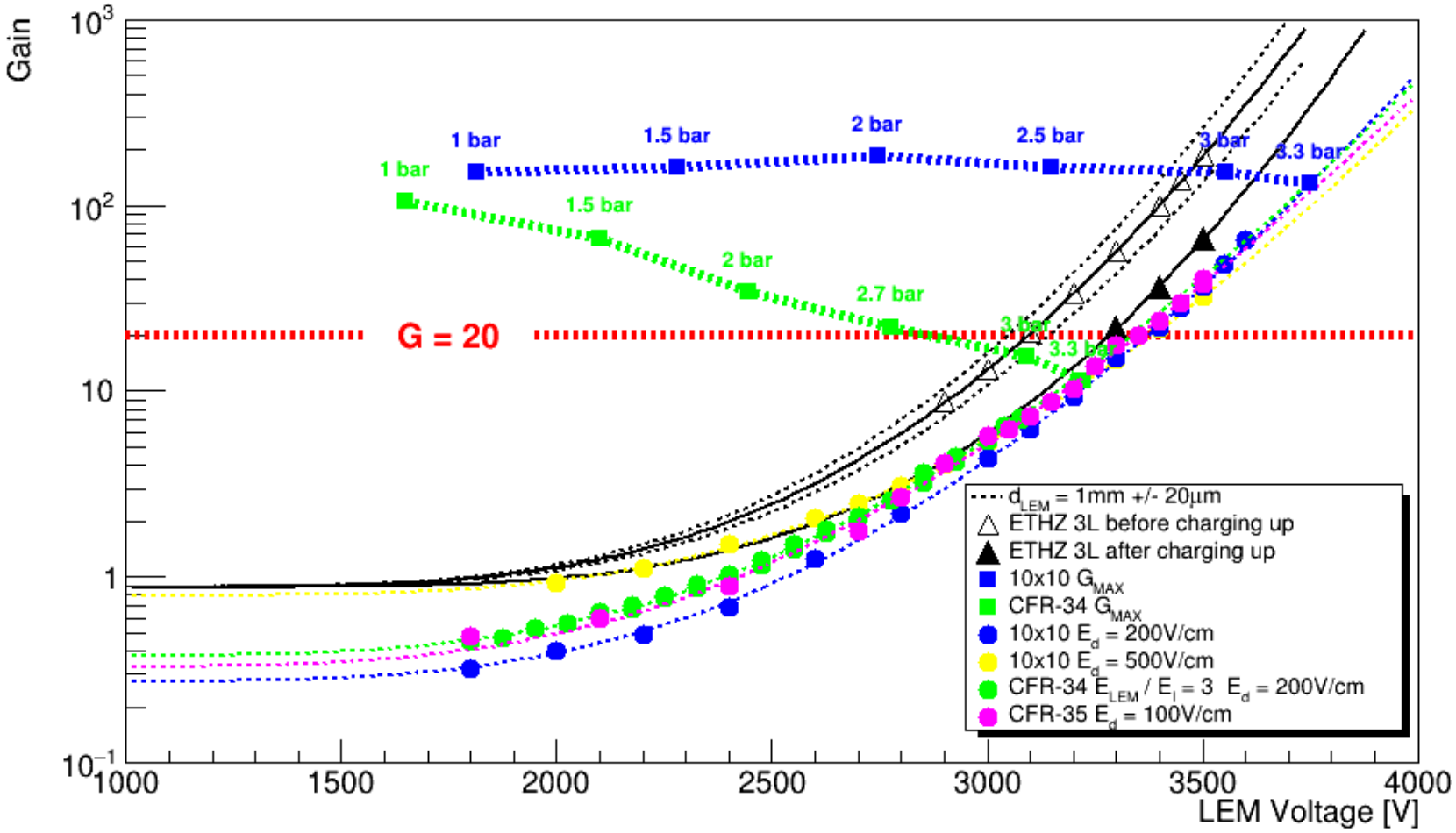


LEM charging up completed locally

V_{MAX} ~ 3.5kV

^{241}Am
α source

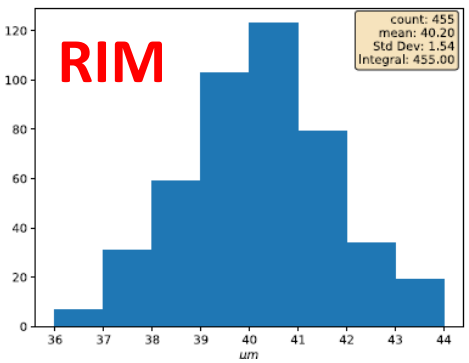
Gain measurements @ CEA/Irfu

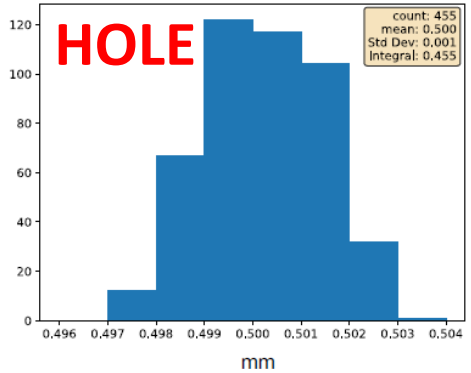


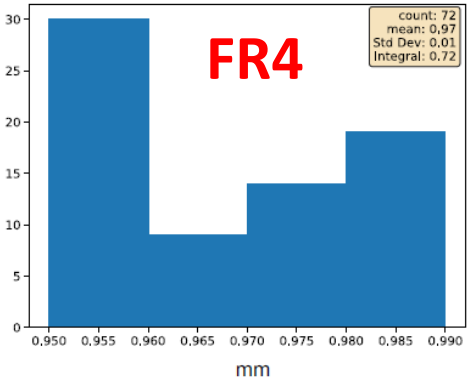
LEM QA/QC by ELTOS

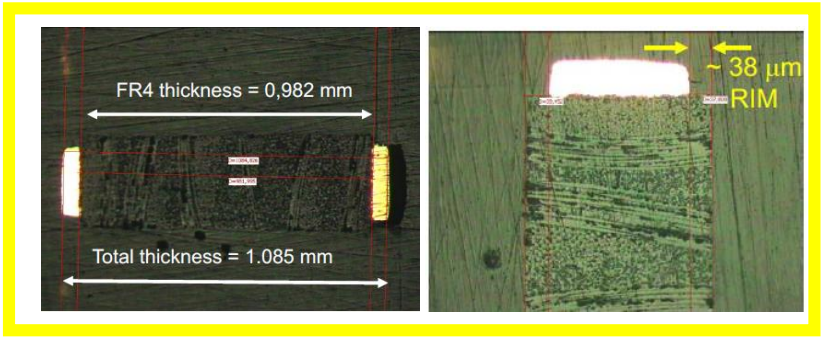
LEM Specifications

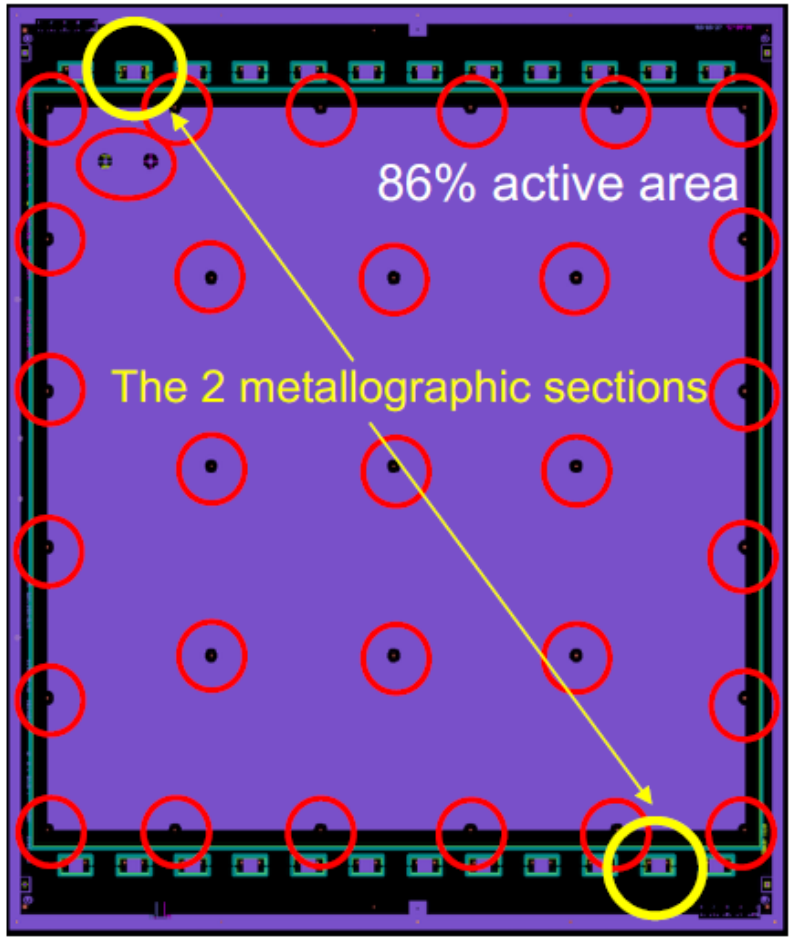
Laminate specifications	
Laminate	FR4 epoxy PANASONIC R-1566W
Dimensions	530 mm x 540 mm
Bare FR4 epoxy thickness	1 mm (-0.05 /+0 mm)
Copper thickness	105 µm
Mean thickness	1,20 (-0.06/+0) mm
Thickness uniformity	+/- 0.04 mm
final LEM specifications	
Dimensions	499.5 mm x 499.5 mm +0/-0.3 mm
Ni/Au	5 µm Ni + 0.1 µm Au
Final thickness	1.10 (-0.05/+0.02) mm
LEM holes	≈ 400 000 non-plated Φ=0.5 mm -0/+0.01 mm
RIM (with Ni/Au)	40 µm +/- 4 µm

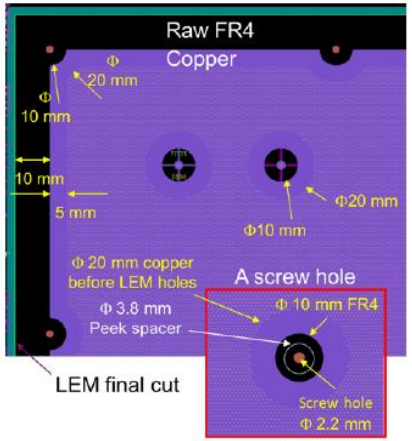


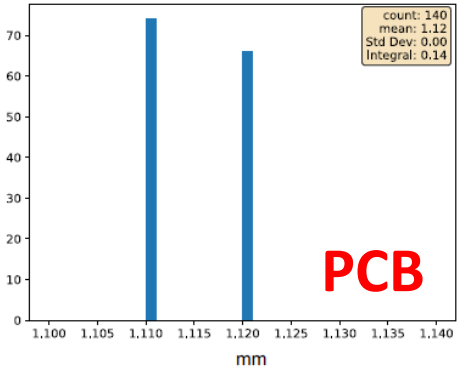




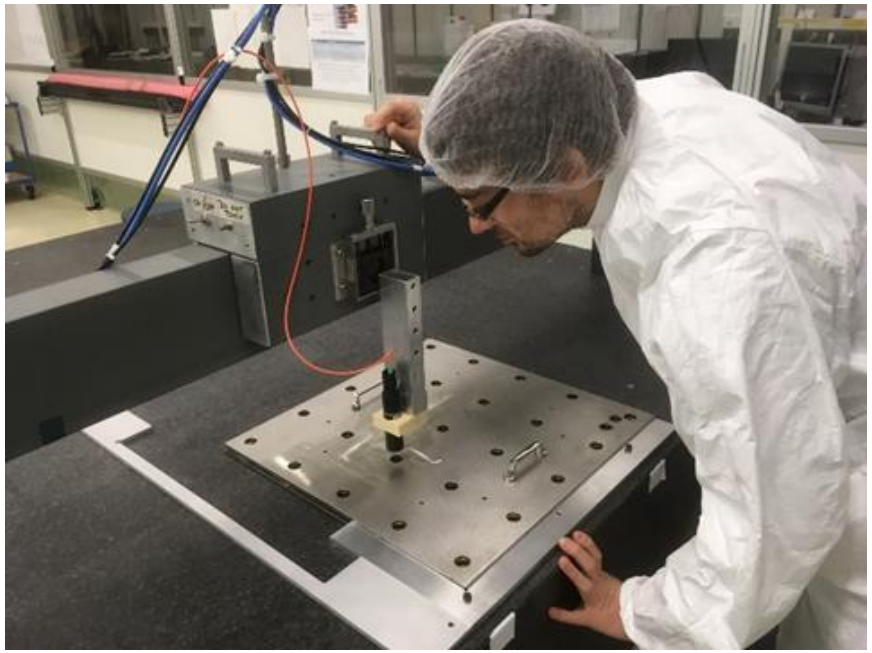


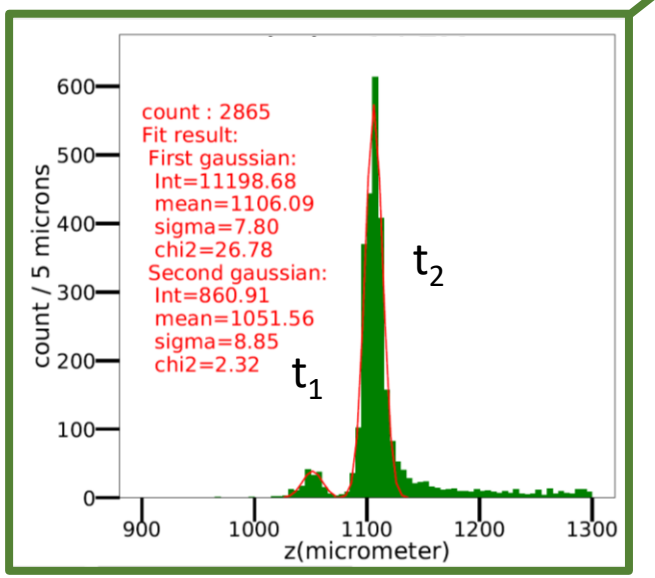


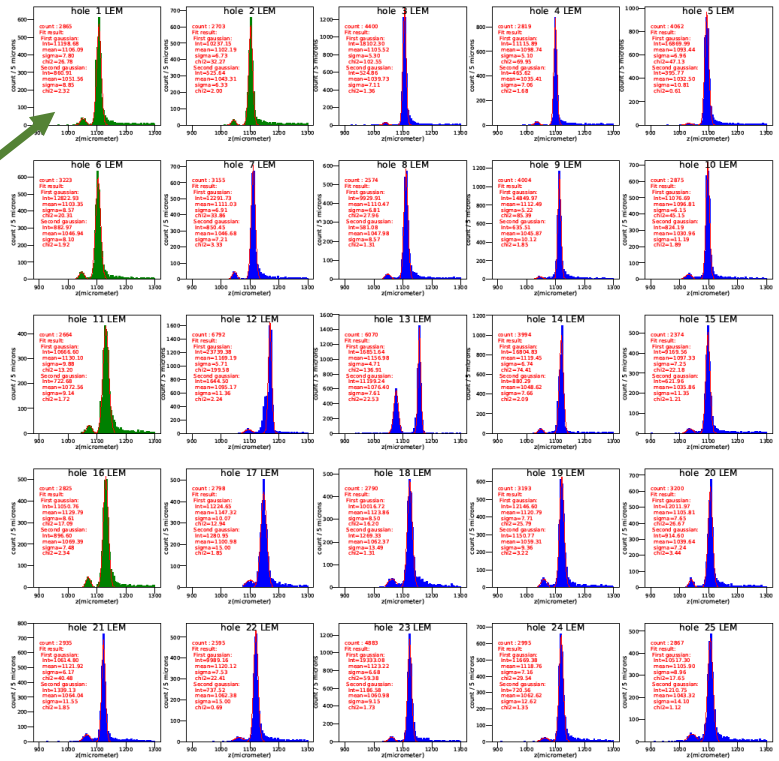




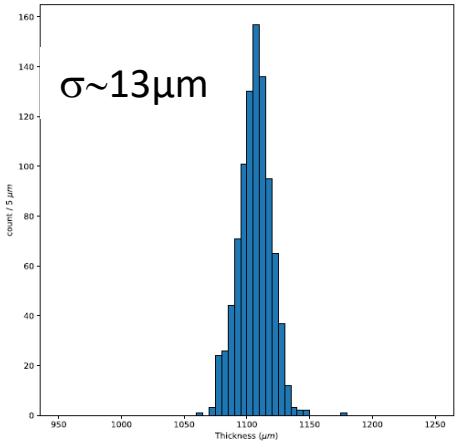
LEM Survey @CEA/Irfu



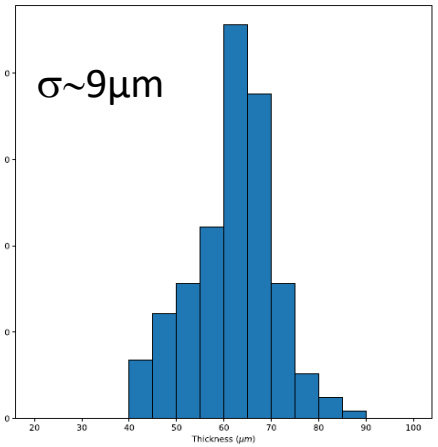




Mean LEM thickness : 1.106 mm

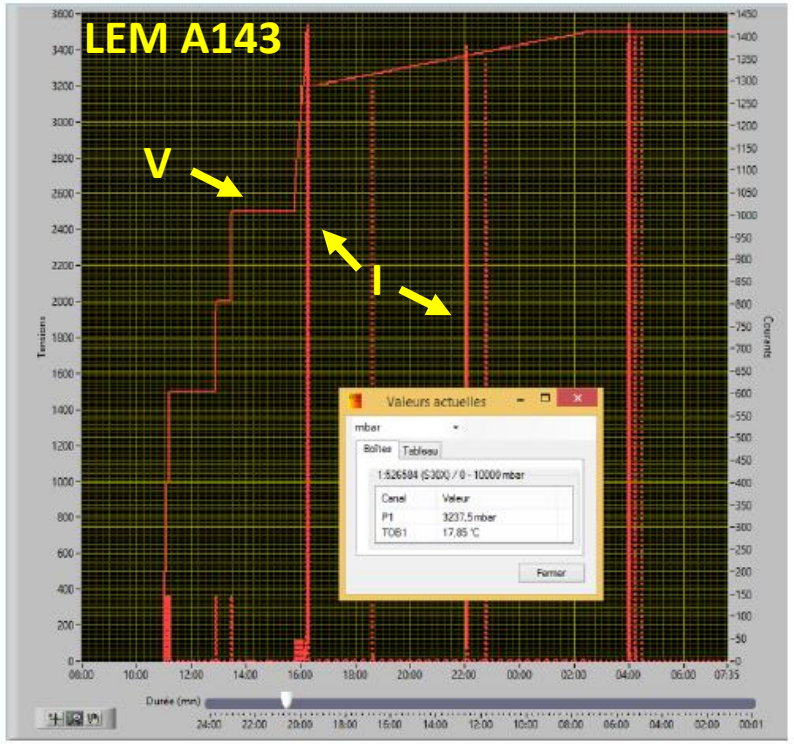


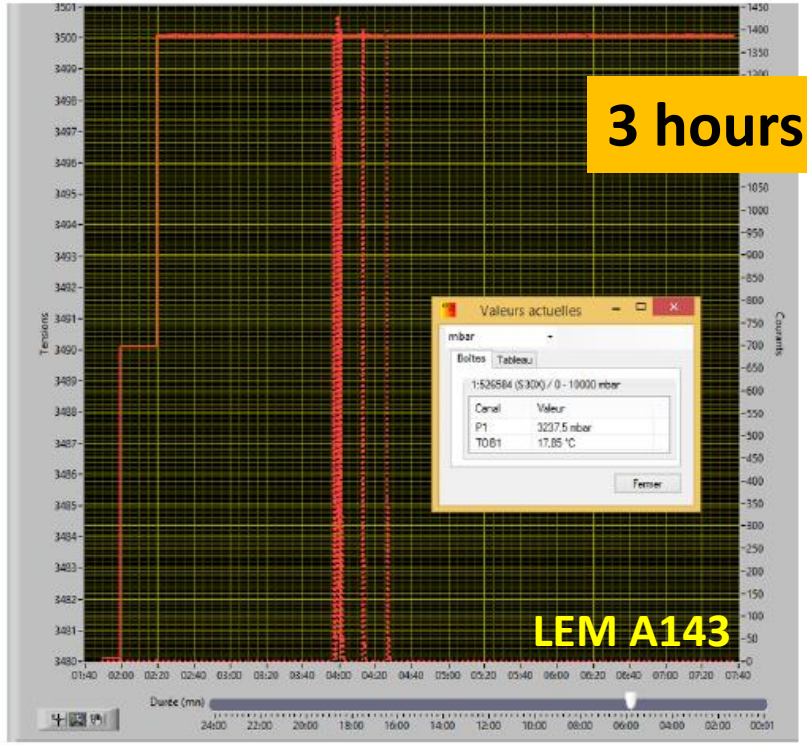
Mean copper thickness : 62 μm



LEM HV training in Ar @ ~3.3 bar

Fully automated HV training up to 3.5kV





All LEMs tested up to 3.4 – 3.5 kV (no charging up) with < 1 spark / 20 minutes. (1/74 LEMs discarded)

CRP assembly and Cold Box tests @ CERN

- Assembly of a CRP in clean room at CERN (2-3 weeks)
- 36 anodes, 36 LEMs, extraction Grid, cabling and instrumentation (temperature probes, level meters)
- CRP survey

- Tests in DLAr mode without drift field (no charging up!)
- LEM and Grid HV tests
- 4t of LAr, no purification (< 100 ppm O_2^{eq})
- GAr at atmospheric pressure : density not controlled

CRP1 and CRP2 LEM HV Test Results in CB (Oct. – Nov./2018)

- Liquid level in CB stable to within ~250µm; T_{LEM} ~ 91°K; $\Delta V_{LEM\text{-}GRID}$ = 3kV

CRP1

V_{TOP} (kV)	V_{BOT} (kV)	E_{LEM} (kV/cm)	Time (h)	Spark Rate (h^{-1})	P_{atm} (mbar)	Estimated Gain (no ch. up)
0.25	3.35	31.0	12	1.3	968 - 972	20
0.50	3.55-3.60	30.5-31.0	13	1.3	962 - 966	24 - 31
0.75	3.70	29.5	42	0.6	943 - 953	20
1.00	3.80	28.0	18	2 trips*	970 - 976	9
1.00	3.85	28.5	12	3 trips	936 - 947	15

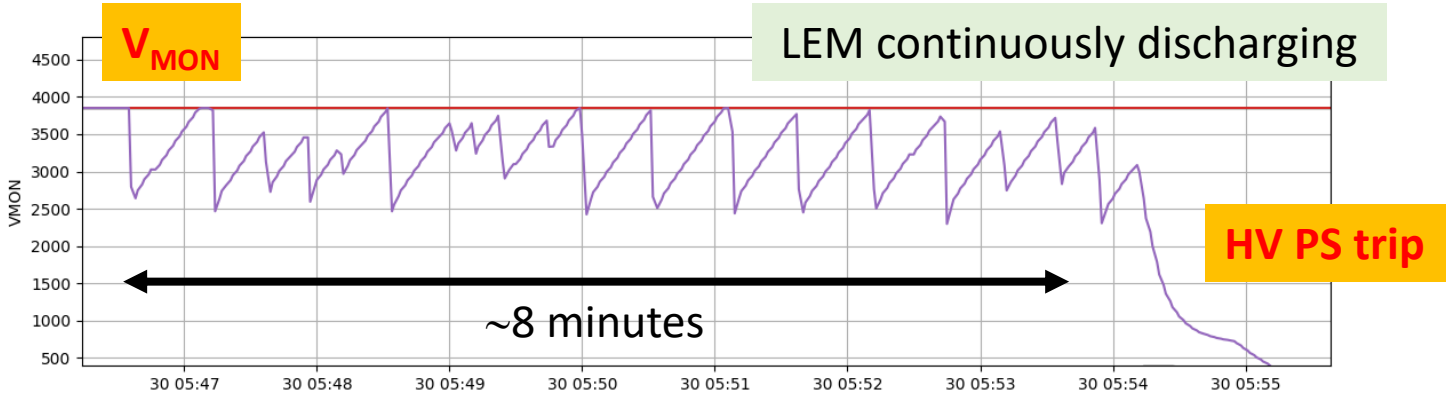
* PS TRIP time set too short

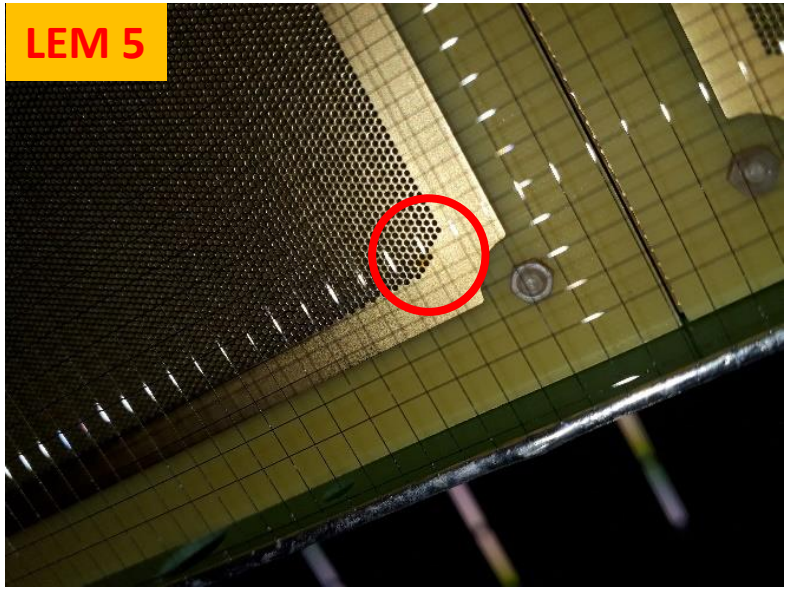
CRP2

V_{TOP} (kV)	V_{BOT} (kV)	E_{LEM} (kV/cm)	Time (h)	Spark Rate (h^{-1})	P_{atm} (mbar)	Estimated Gain (no ch. up)
0.10	3.15 – 3.20	30.5 – 31.0	17	0.8	969 - 973	9 - 11
0.25	3.34	30.9	16	1.3	968 – 970	19
0.50	3.55	30.5	11	0.9	957 – 965	24
0.50	3.555	30.55	42	0.5	962 – 964	25

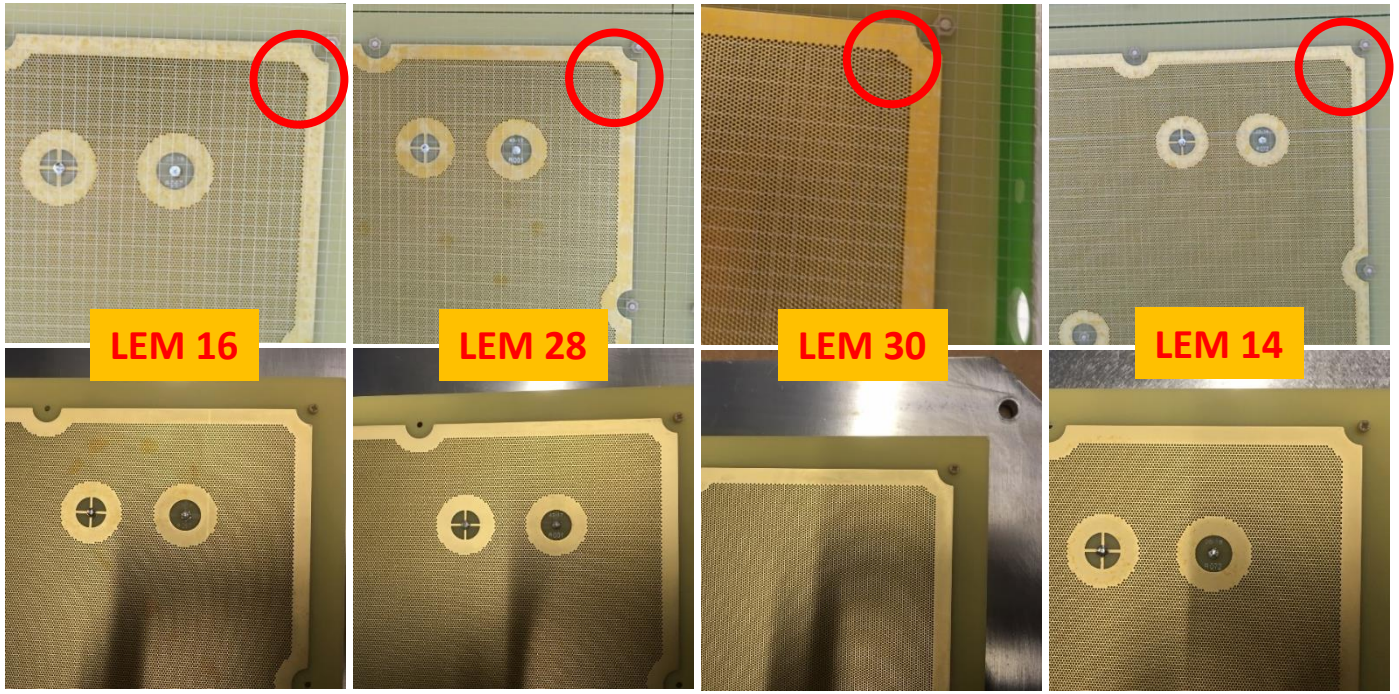
- ***Effective gain of 20 before charging up within range. Best HV configuration with V_{TOP} ~0.5kV.***
- ***For larger V_{TOP} values, need to decrease E_{LEM} to achieve stable operation.***

LEM Carbonization Issues



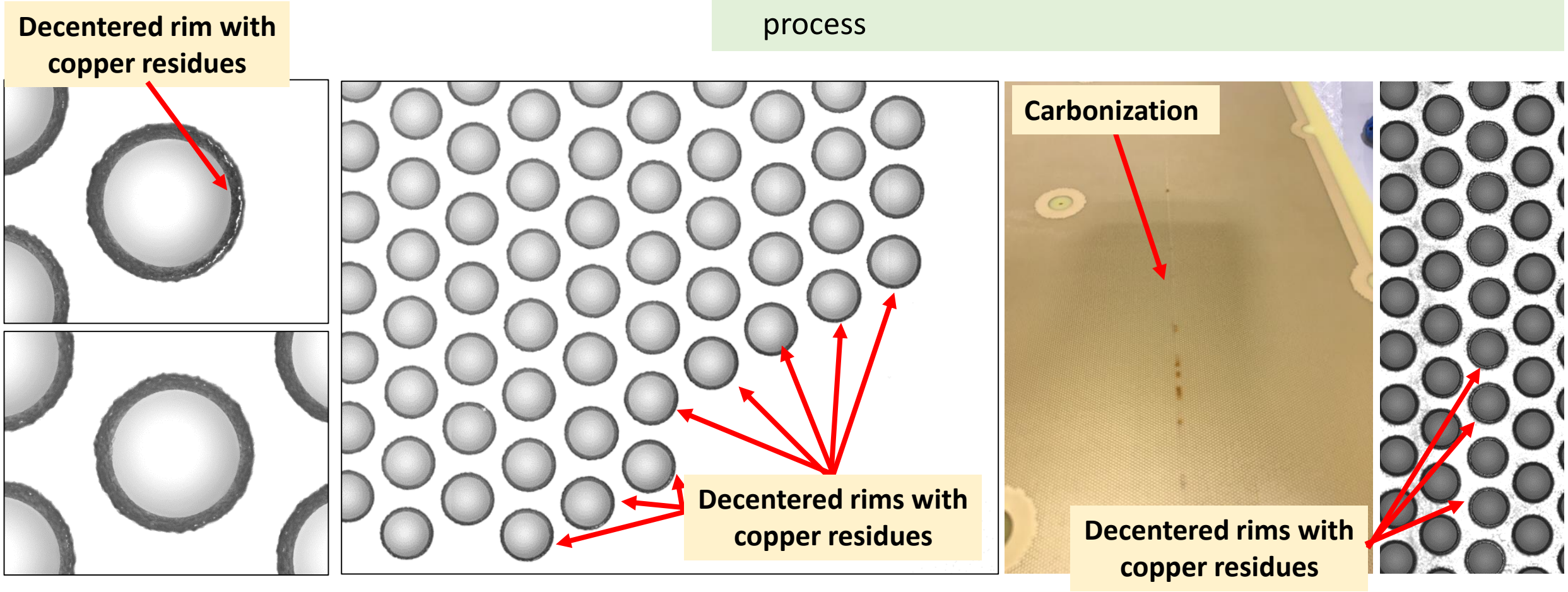


- Points to a LEM weaker region.
- 5/72 LEMs affected
- Treated with KMnO4 at CERN to remove carbonized FR4 inside holes. Copper surface unaffected.
- Cleaned at CEA/irfu and tested up to 3.2kV @ 3.3bar.



LEM rim defects

- Rims around holes near the LEM edges/corners appear to be decentered and containing copper residues
- Problem known by Rui de Oliveira (CERN EP-DT-EF)
- Due to method used by ELTOS for the micro-etching process



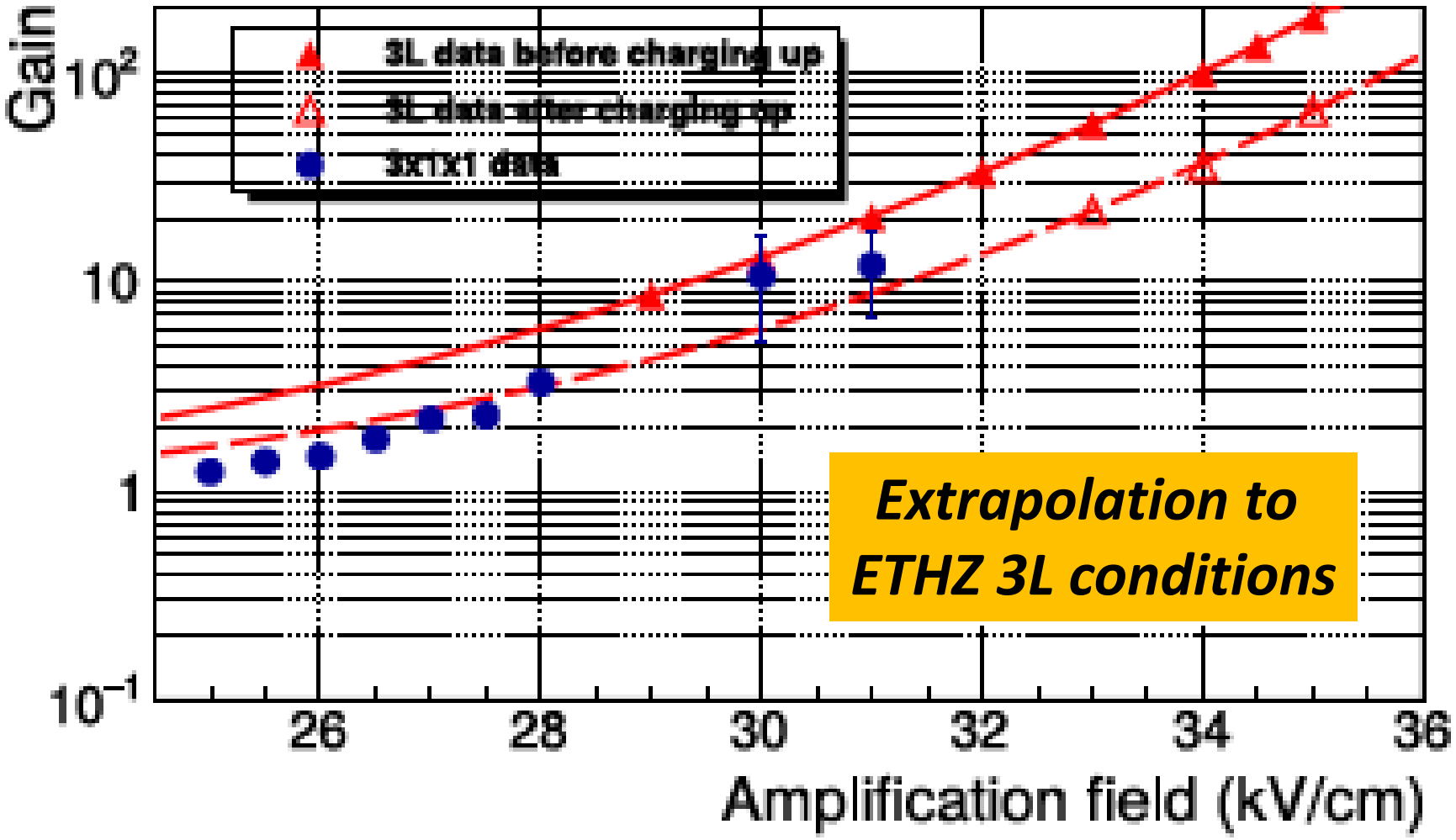
Problem addressed in collaboration with EP-DT-EF (see A. Delbart's talk)

Summary

- A lot of effort is being invested in the development of LEM detectors suitable for Dual Phase LArTPCs.
- Going from small prototypes to several m^2 detection systems, as needed in future ν experiments, is a real challenge.
- Collaboration with industrial partners, like ELTOS (Italy) for LEM and anode productions for ProtoDUNE-DP and ELVIA (France) for prototypes, has been very constructive.
- Carbonization issues observed during Cold Box tests clearly call for further improvements in the LEM design and in the manufacturing process.
- CERN EP-DT-EF is a key partner to achieve these goals.

The 311 prototype: gain measurements

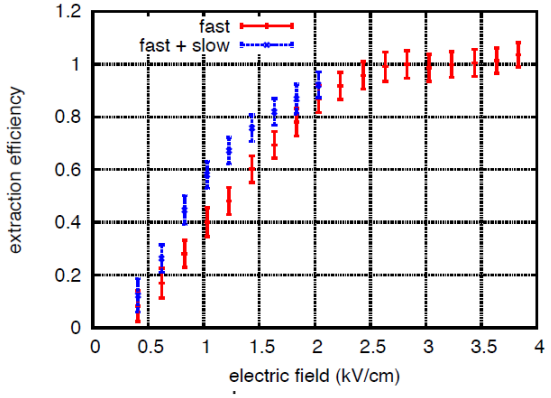
P. Cotte, Ph.D. thesis



Extrapolation to ETHZ 3L conditions

Effective gain

Gushchin et al., Sov. Phys. JETP 55 (1982) 860-862.



$$G_{eff} = \varepsilon_{extr} \times G_{LEM} \times \varepsilon_{ind}$$