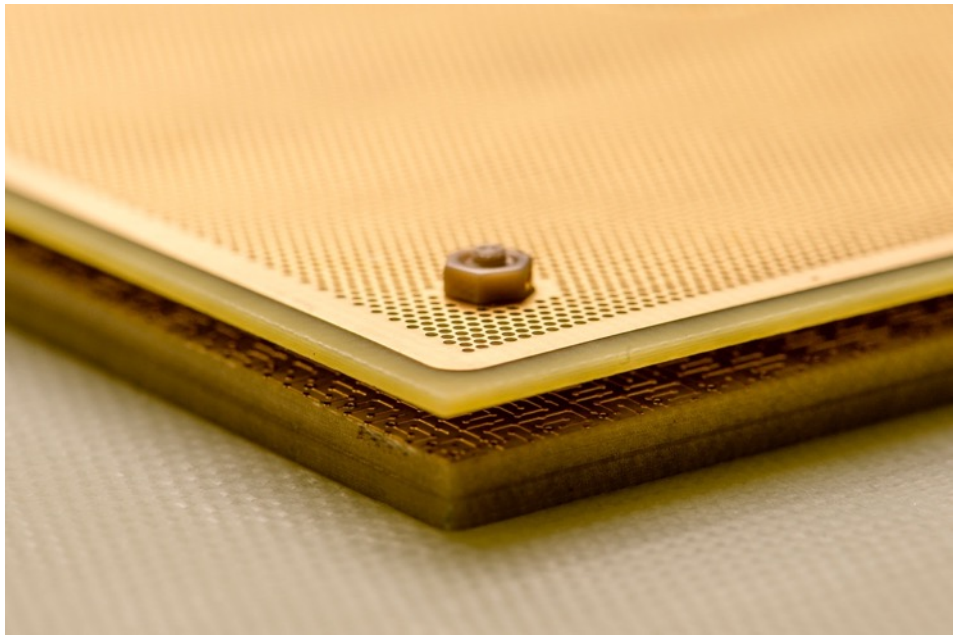
Discussion on LEM performances in ProtoDUNE-DP



LEM production & qualification tests

- ✓ Room T + high pressure Vs cryogenic DLAr conditions
- ✓ Where do the 50x50 cm^2 limitations Vs 10x10 cm^2 come from : borders, LEM imperfections scaling with surface, higher C, others ?
- ✓ Need of LEM HV qualification by HV burn-in ?
- ✓ What LEM controlled burn-in procedure to use ?
  - In air (with O_2) Vs in pure Ar ?
  - How does gas purity affects the process ?
  - How to prevent the LEM from irreversible damages ?
  - Use experience of carbonized LEM corners recovered from potassium permanganate cleaning for an iterative procedure ?
- ✓ Need of final qualification test of CRP in coldbox like setup : 4 x LEMs at least, Ar purity, extraction grid, TPC drift E ?, ….

LEM performances

- ✓ Observation of spark rate dependence on collection electric field
→ secondary sparks in induction gap ? How to mitigate this effect ?
→ need of Electric field simulations for further optimization

- ✓ Positive ions feedback and accumulation on Lar surface ?

- ✓ LEM ageing but no hint of resistive current between LEM sides ?

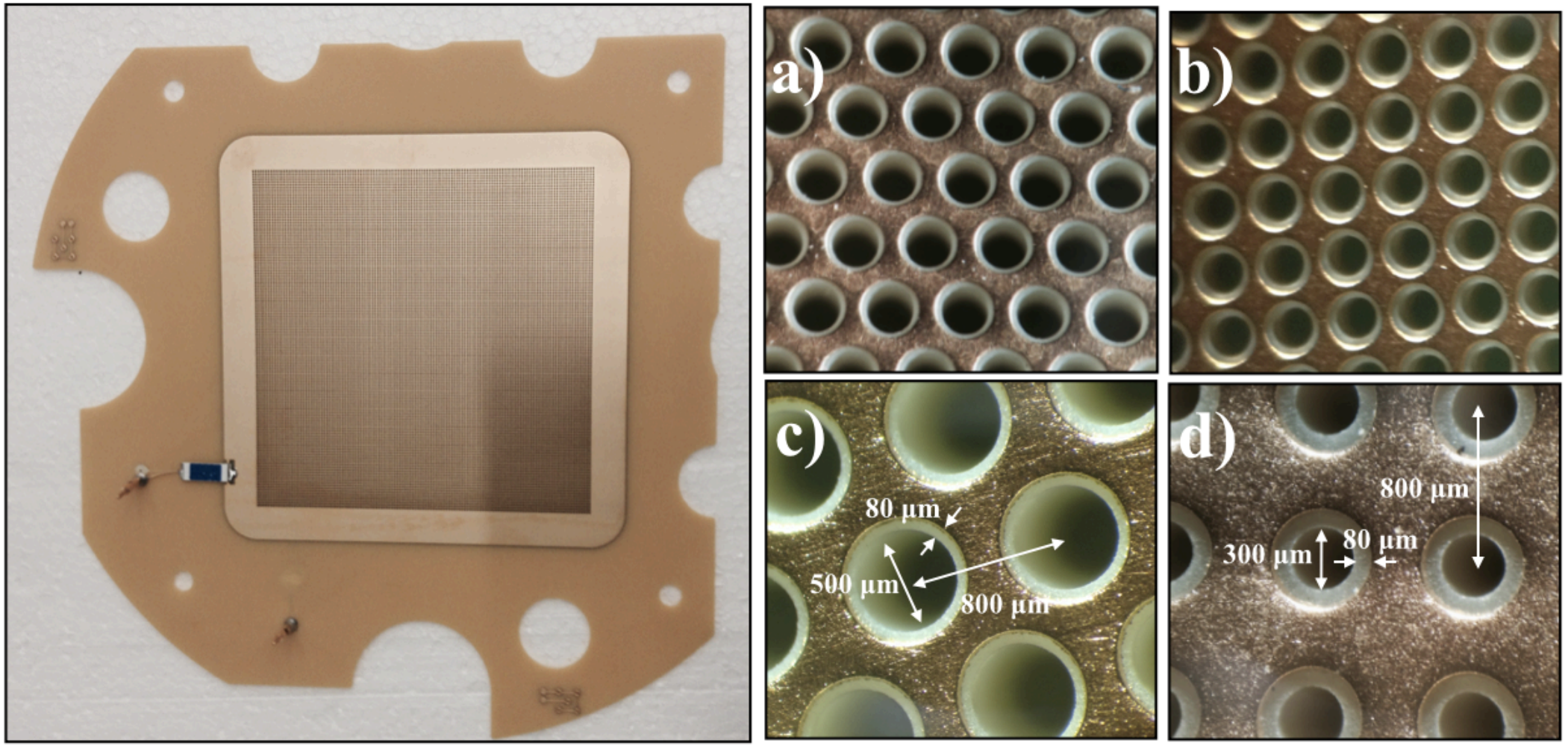
- ✓ LEM – Grid capacitive coupling depending on LAr stability
  - The quenching resistor does not affect LEM & grid the same way
  - Introduction of a coupling capacitance between LEM & Grid ?

- ✓ Explanations for 2 times lower gain derivation from cosmic tracks deposition compared to extrapolation of 3L ETHZ DLAr gain ?

Backup slides for discussion

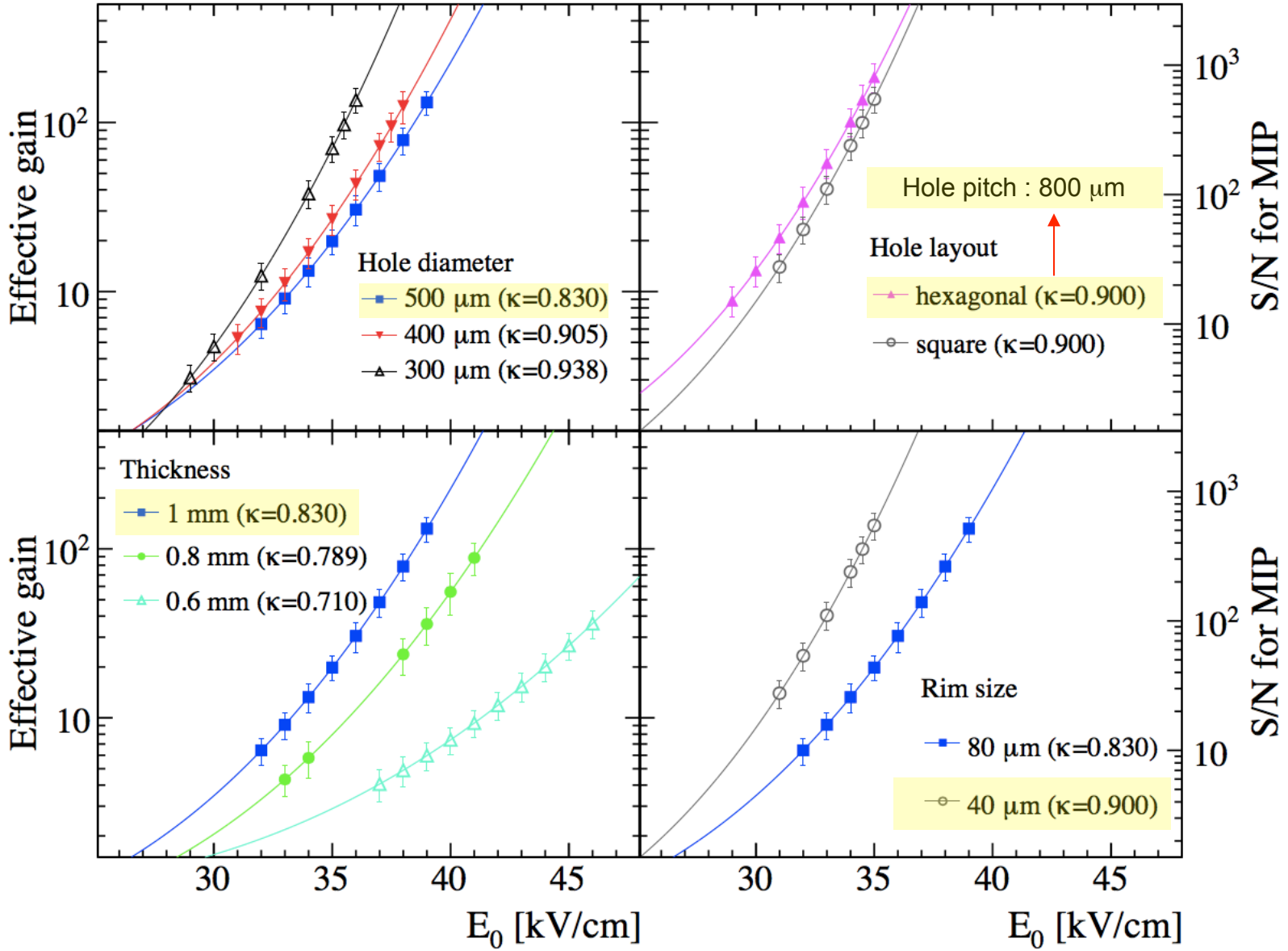
LEM structural parameters

10x10 cm^2 with large FR4 border



C. Cantini et. Al, « Performance study of the effective gain of the double phase liquid Argon LEM Time Projection Chamber, JINST **10** (2015)

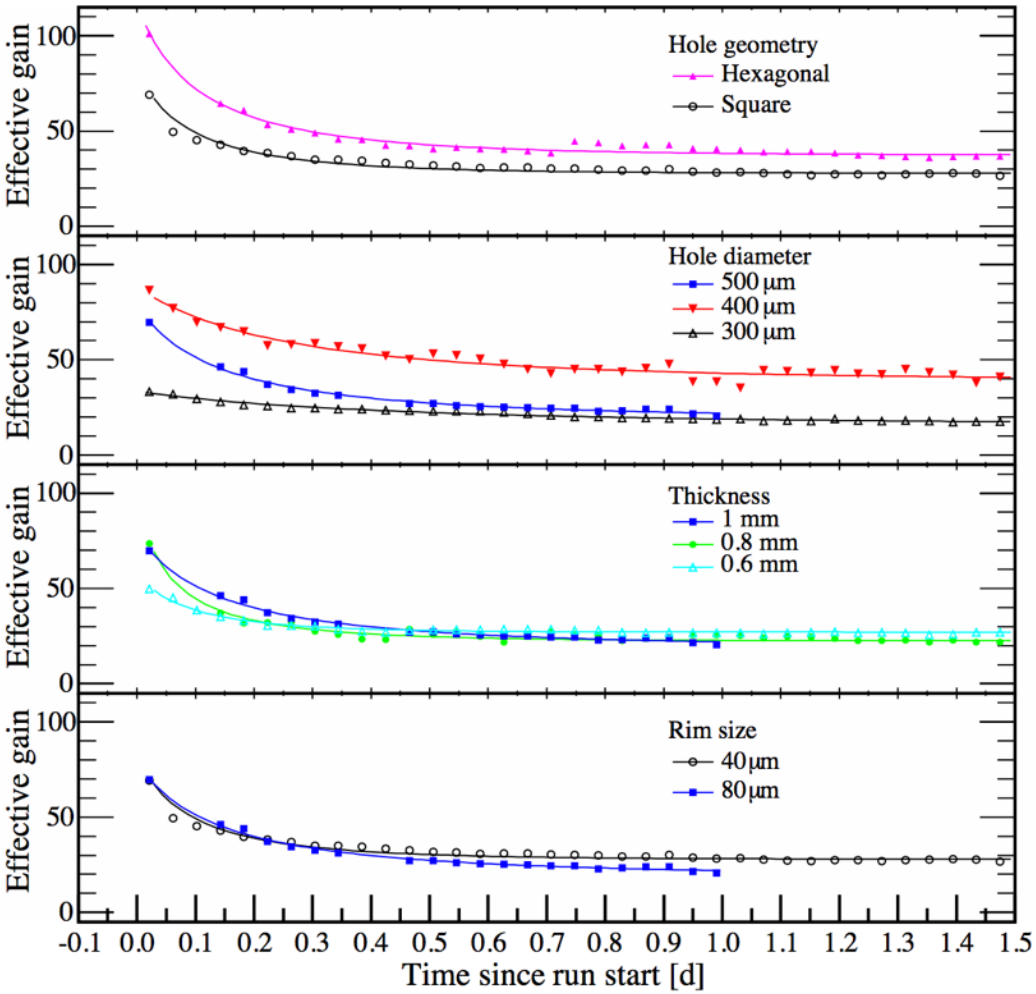
LEM structural parameters

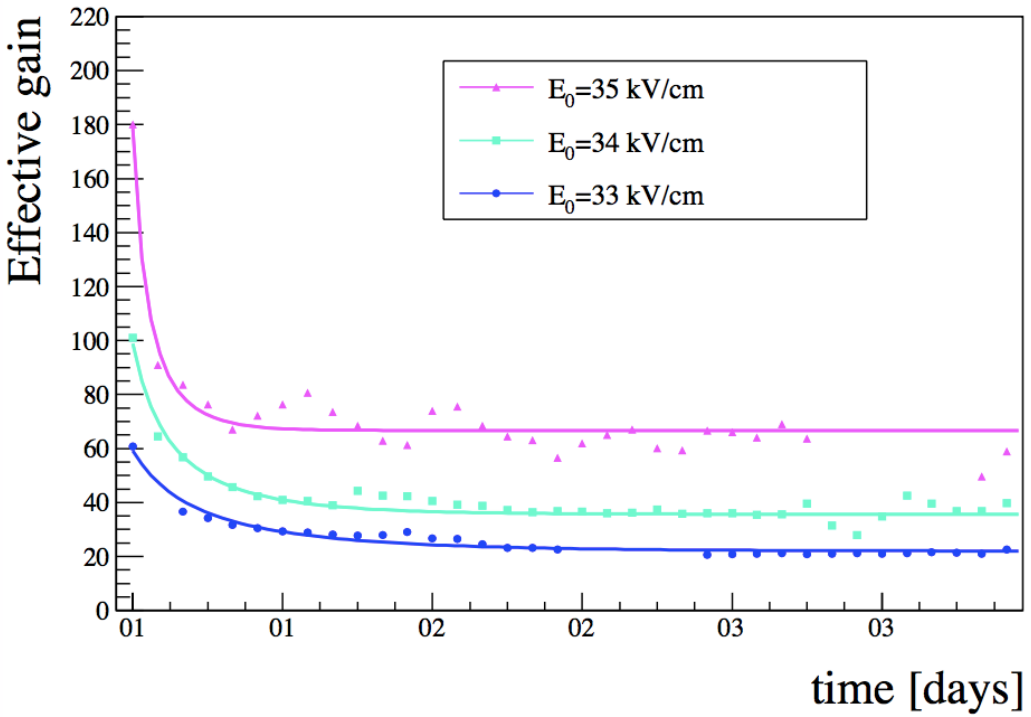


C. Cantini et. Al, « Performance study of the effective gain of the double phase liquid Argon LEM Time Projection Chamber, JINST **10** (2015)

10x10 cm^2 LEM charging-up

C. Cantini et. Al, JINST **10** (2015)





Charging-up effect on gain drop value & time behaviour depends on amount of FR4 material : RIM size, hole diameter, LEM thickness, density of holes

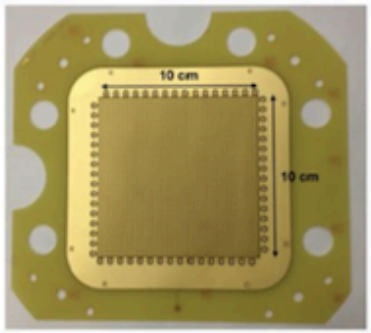
measured ~3.3 in 2-3 h for ProtoDUNE-DP LEMs at Saclay with ^{251}Am α source

10x10 cm² LEM sparking rate

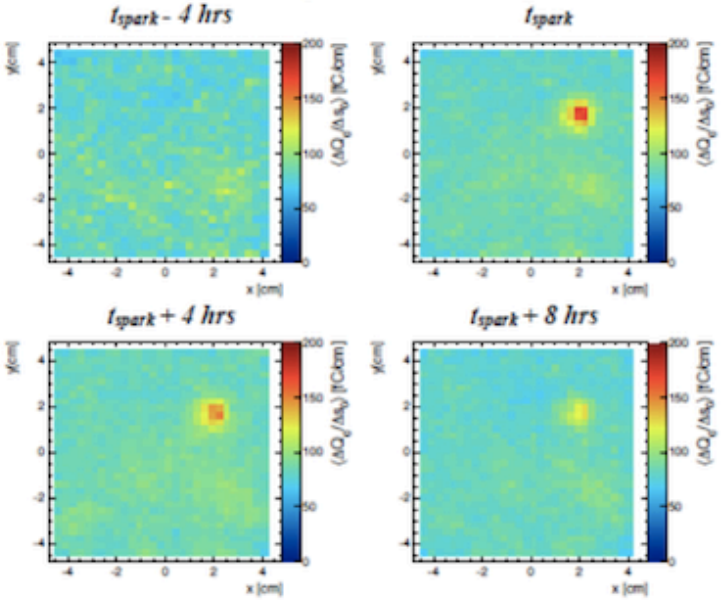
LEM charging up, sparks and long-term performance

C. Cantini et al., arXiv:1312.6487

ETHZ 10×10 prototype

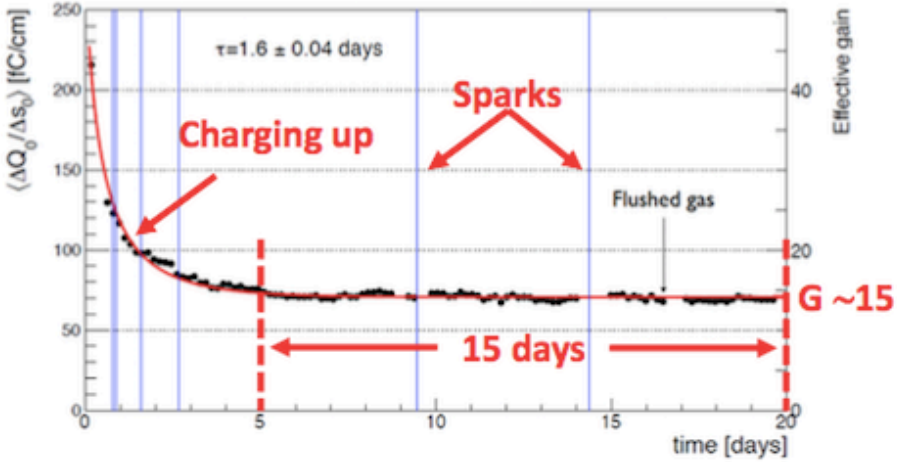


LEM spark history



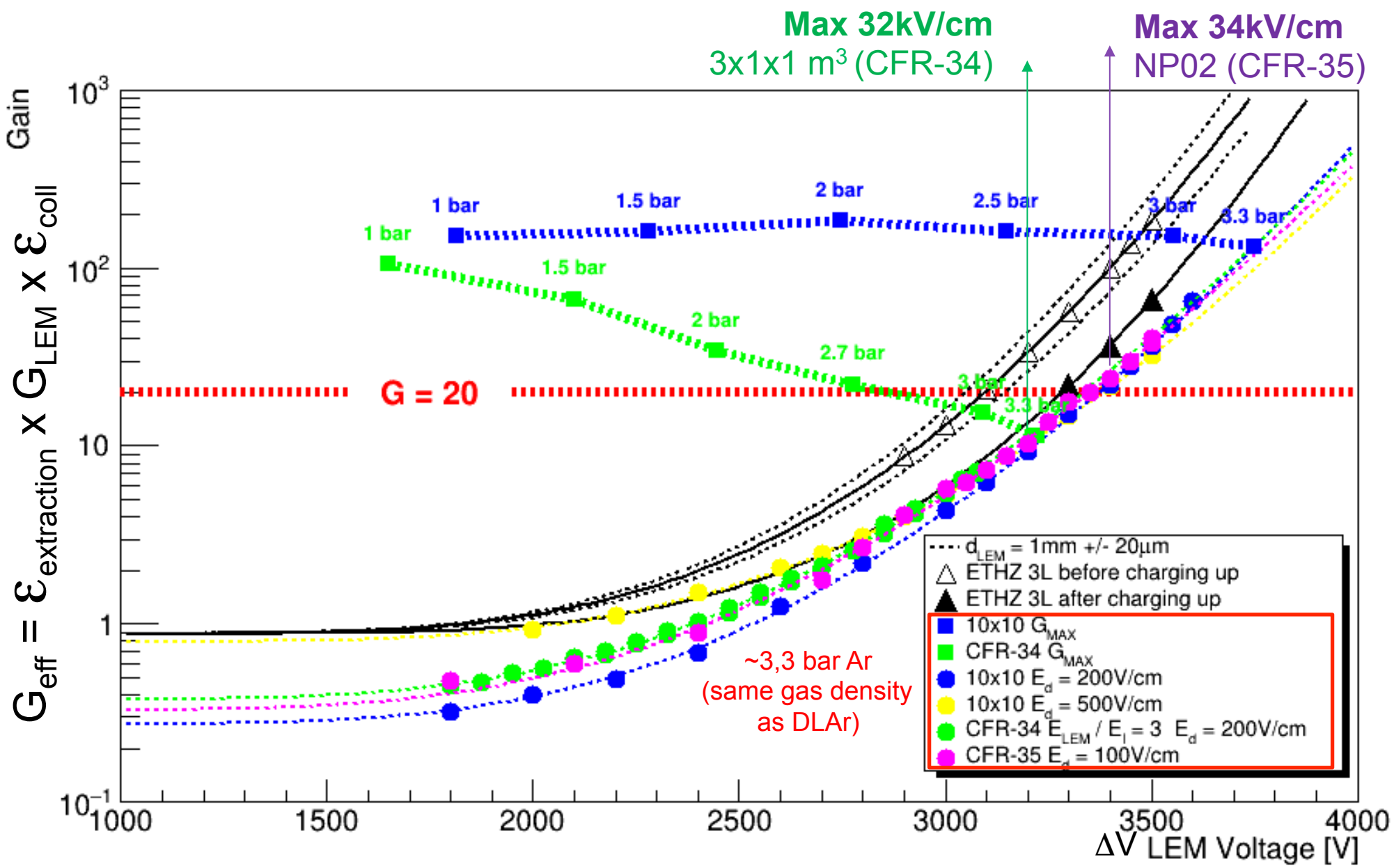
LEM charging up destroyed locally (~cm²) after a spark

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**

LEM Gain compilation



LEM manufacturing & QA/QC

By LEM manufacturer

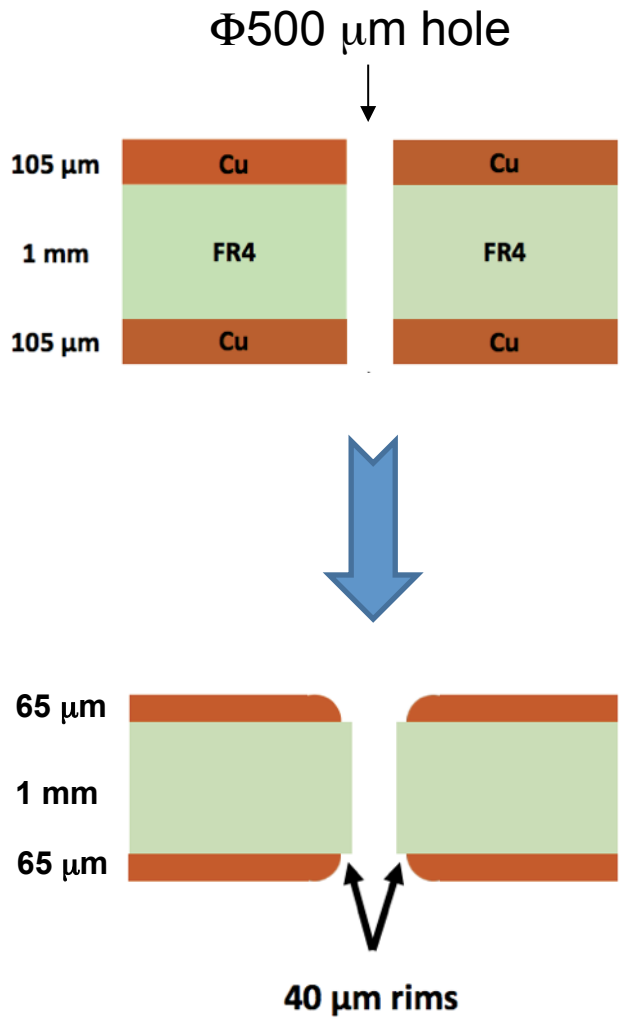
- CNC drilling — Change drills every 1000 holes; Drilling of stack of PCBs is forbidden
- mechanical polishing — with pumice powder; 4 steps (+/- 90°, top/bottom)
- permanganate bath +rince — *removes glass fiber from holes*
- Rims by global etching
- passivation (Chromic acid)
- Ni/Au plating

By WA105

- 3 mn Ultrasonic bath in 65°C NGL 17.40 ALU — *removes grease*
- Karcher Normal + DM water — *removes dust/dirt in holes*
- 3h Baking @ 80°C — **+ final 160 °C polymerization**
- HV test synth. Air & 3,3 bar Ar

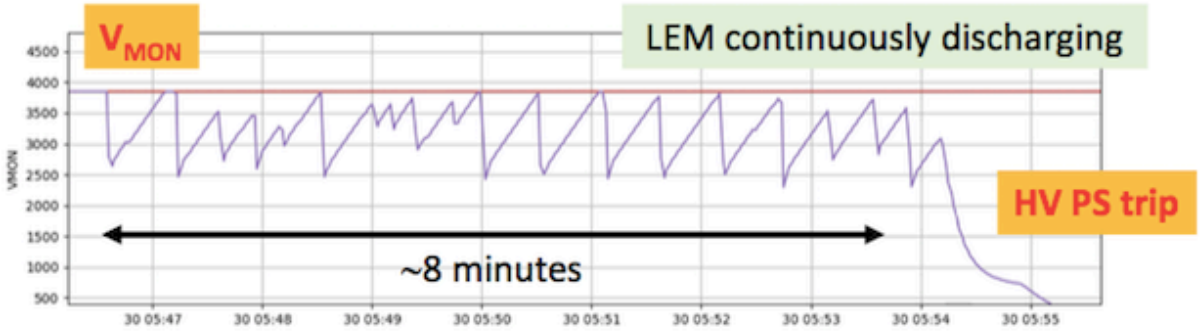
HV test not ok | **HV test ok** → storage + test

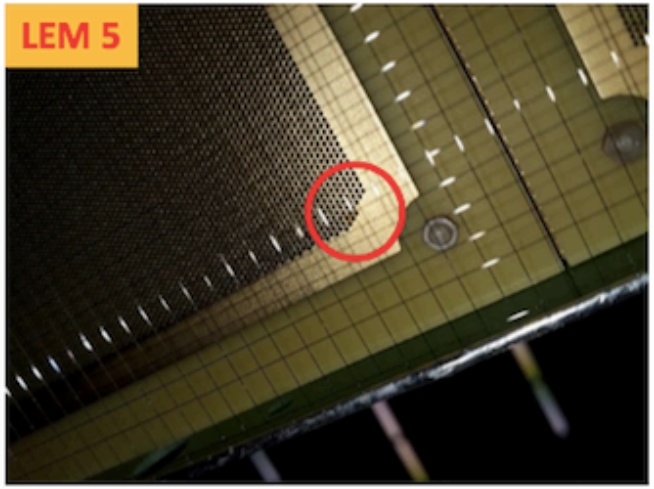
« standard »
global RIM micro-etching
(CERN-ELTOS)



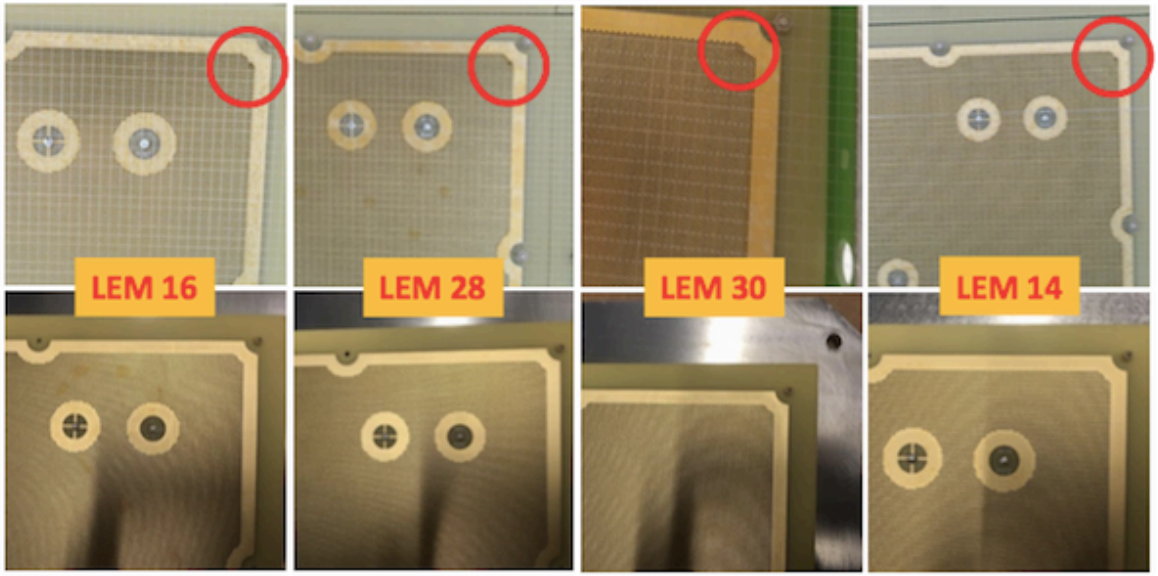
CFR-35 LEM carbonization
In coldbox

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.



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Coldbox tests of CRPs

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

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

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 $V_{TOP} \sim 0.5kV$.***
- ***For larger V_{TOP} values, need to decrease E_{LEM} to achieve stable operation.*** $\Diamond\ \varepsilon_{coll} \sim 0,7$

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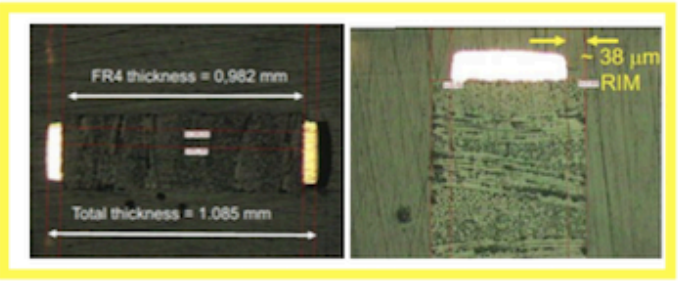
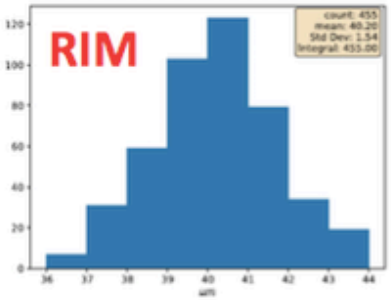
CFR-35 NP02 LEM QC

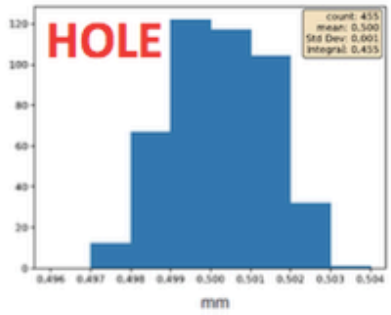
LEM QA/QC by ELTOS

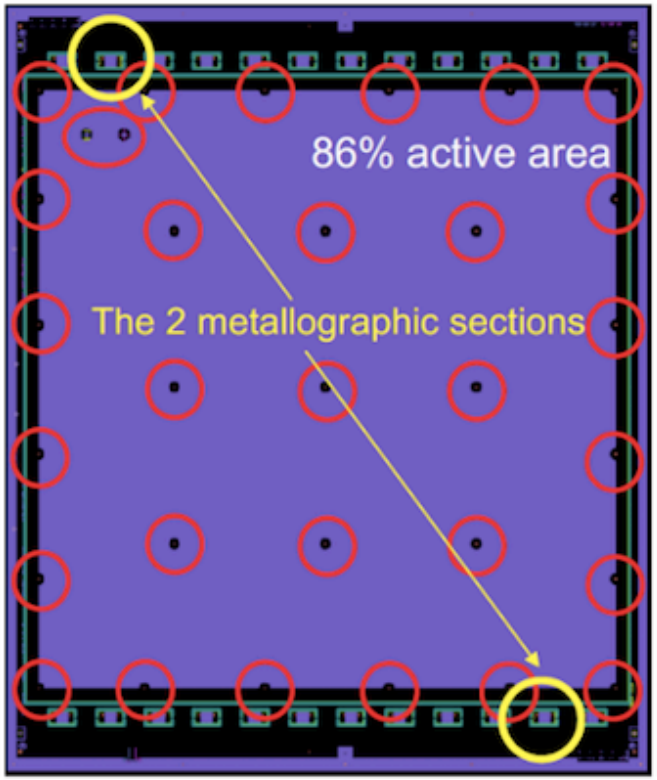
LEM Specifications

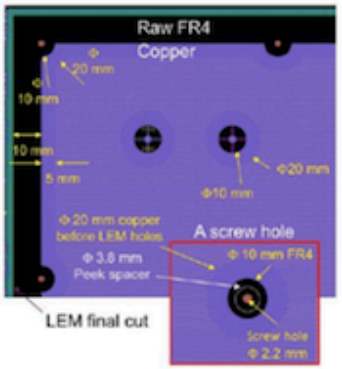
Laminate specifications	
Laminate	FR4 epoxy PANASONIC R-1566W
Dimensions	530 mm x 540 mm
Bare FR4 epoxy thickness	1 mm (-0.05 /+0 mm)
Copper thickness	105 µm
Mean thickness	1,20 (-0.06/+0) mm
Thickness uniformity	+/- 0.04 mm
final LEM specifications	
Dimensions	499.5 mm x 499.5 mm +0/-0.3 mm
Ni/Au	5 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

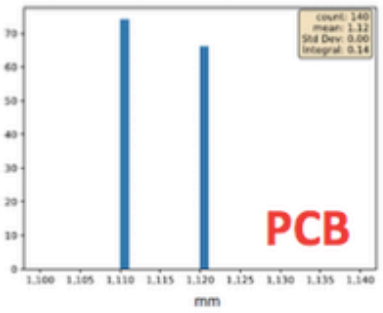


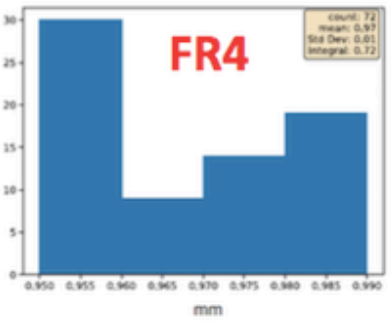












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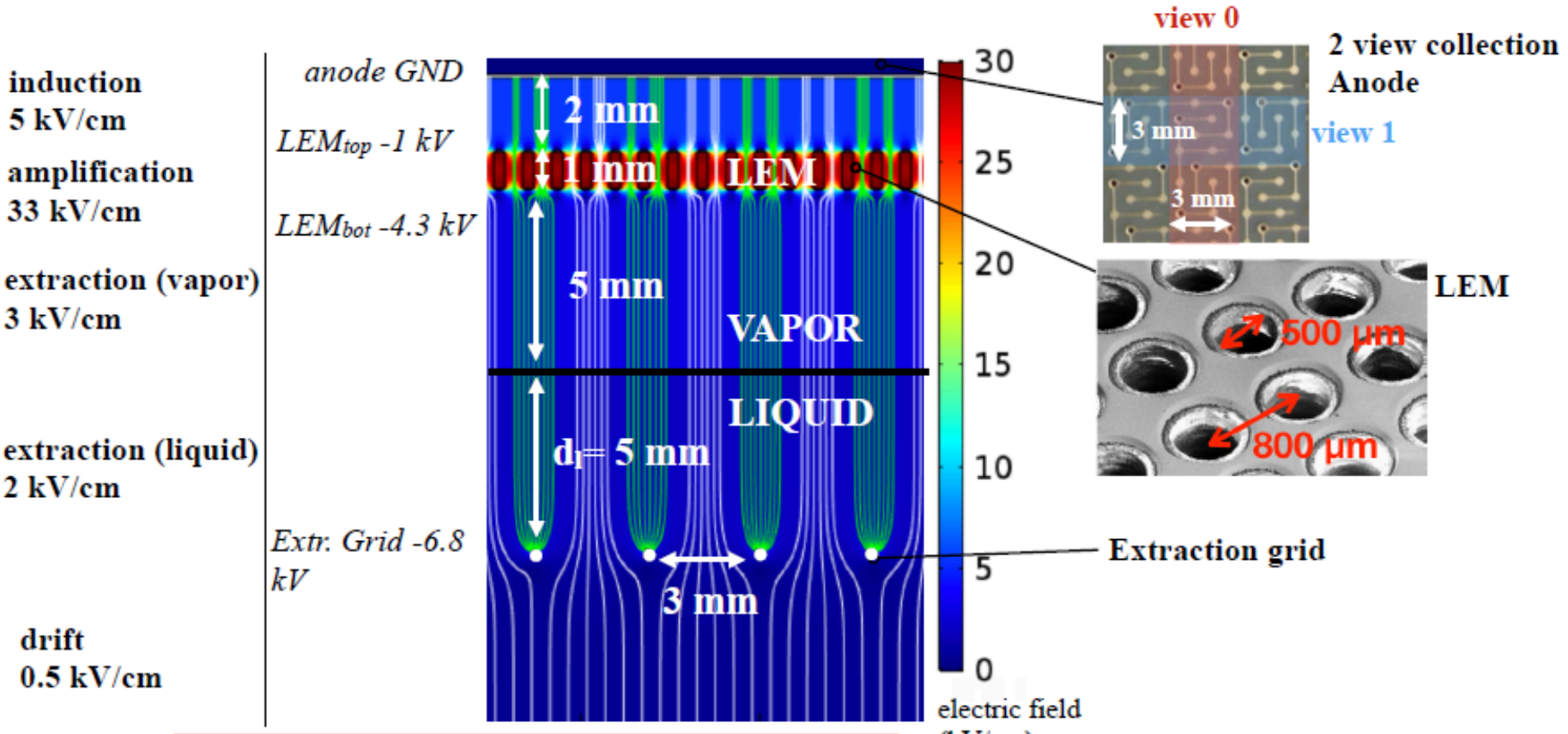
Electric field configuration

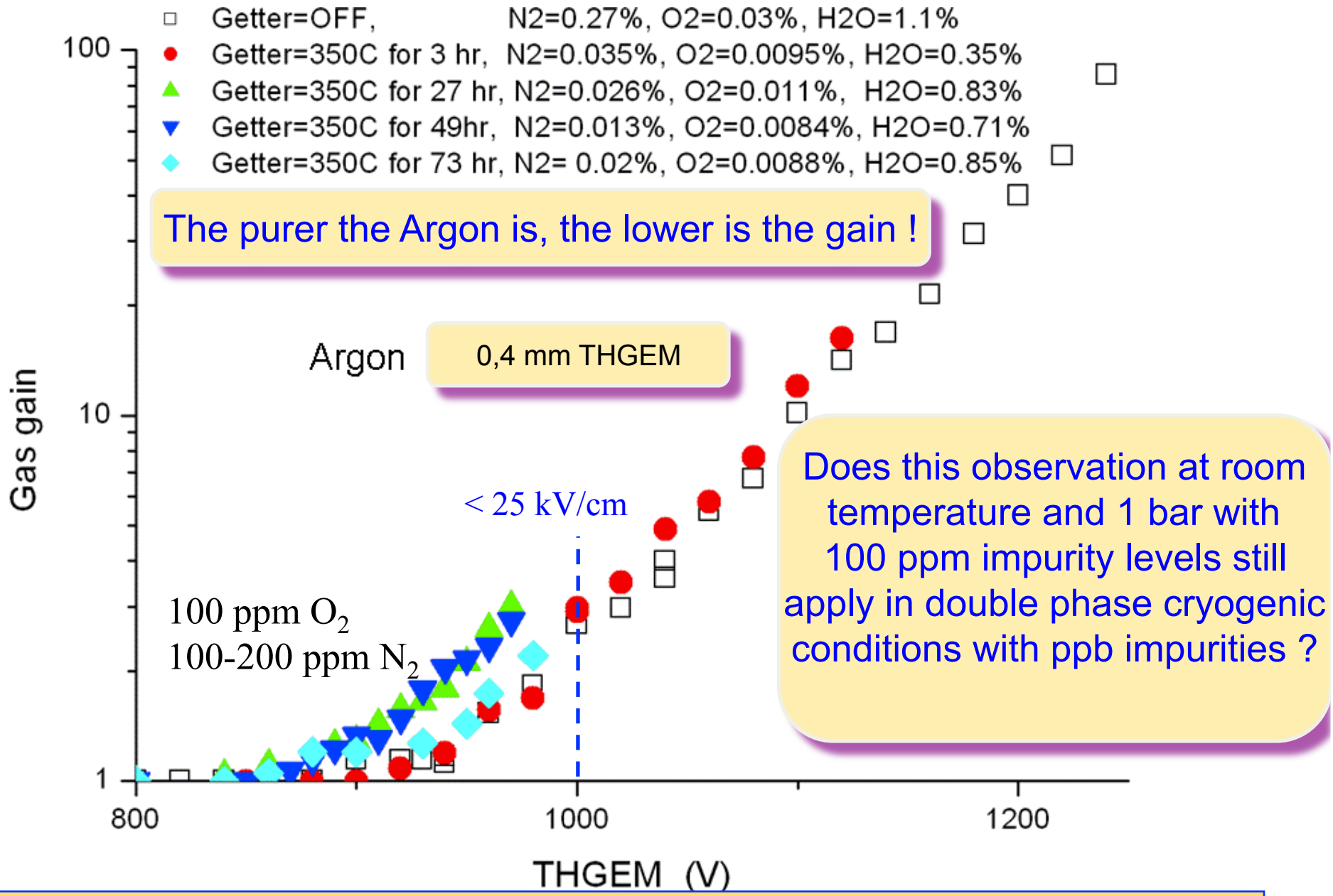


$$G_{eff} = \varepsilon_{extraction} \times G_{LEM} \times \varepsilon_{coll}$$

Effect of the collection electric field E_{coll} : 5 kV/cm is the baseline for maximum collection

Have to lower E_{coll} to 2,5 kV/cm in Dlar NP02 conditions for stability (ε_{coll} ~0,7)

Gain limits in pure Argon : a possible explanation ?

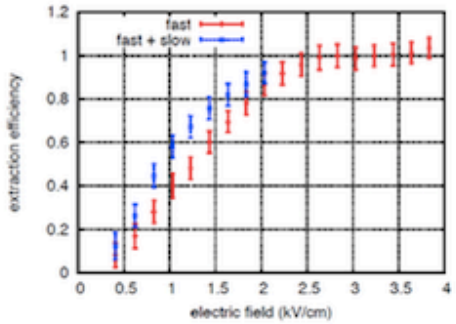


Ref: J. Miyamoto, A. Breskin and V. Peskov, JINST 2010, doi:10.1088/1748-0221/5/05/P05008

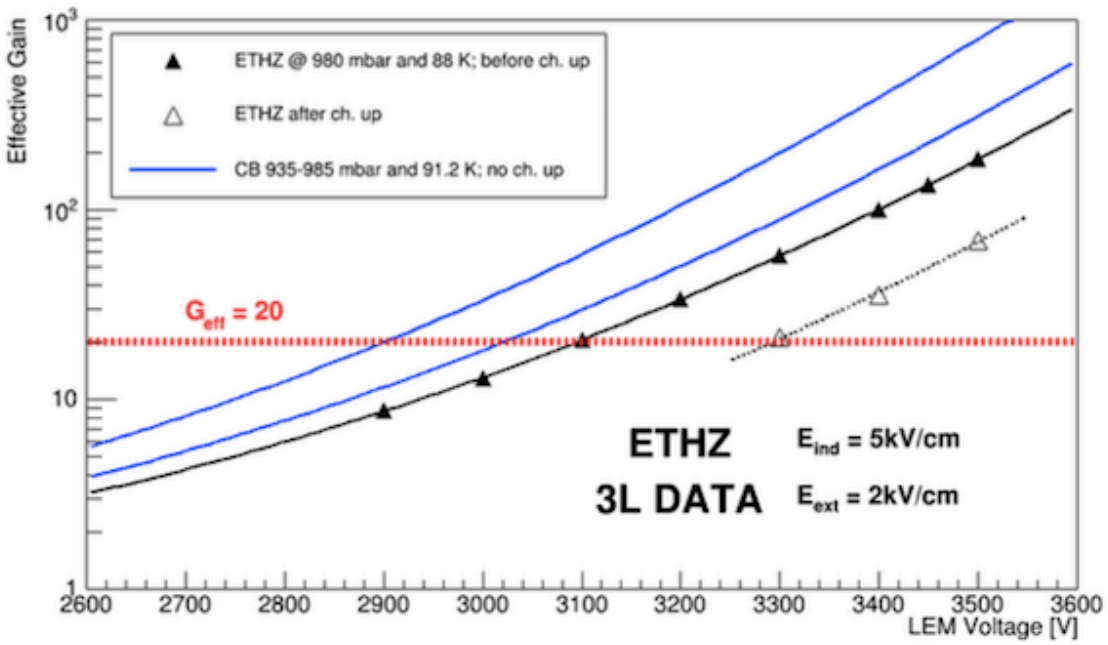
Effective gain

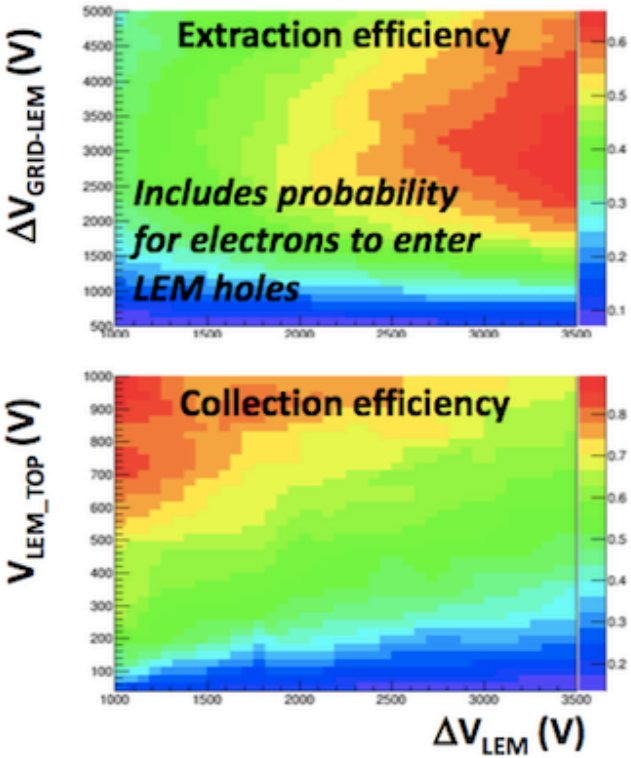
Effective gain

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



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





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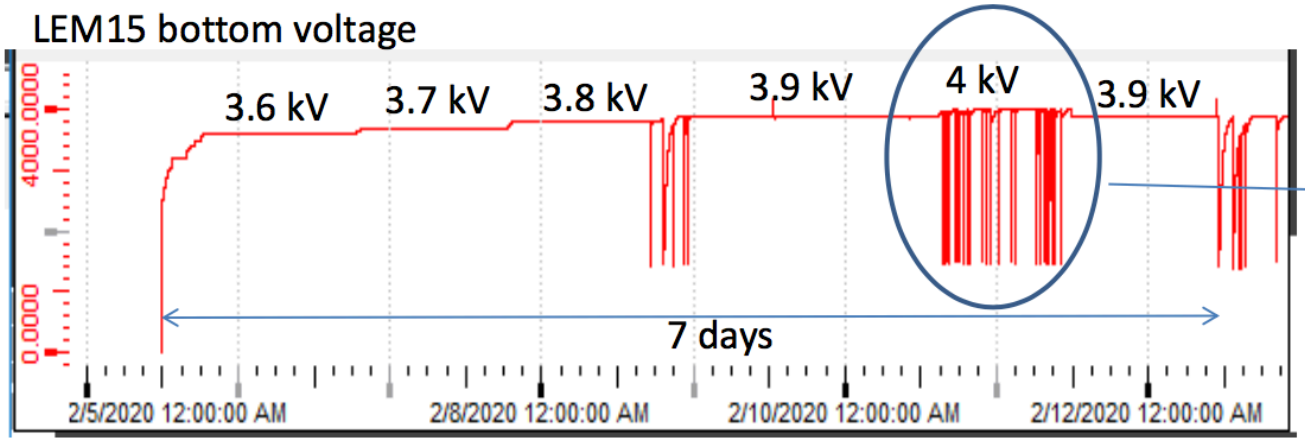
LEM stability & maximum High-voltage

CRP Stability tests

maximal LEM operation voltage

CRP2 LEM slow ramping to highest HV:



Spark rate at ΔV = 3.5 kV
corresponds to about 5 /h/CRP

G. Eurin, P. Granger

From tests done on February:

With more than 20 hours between 100 V step

CRP2 grid HV was set equal to LEM bottom HV
=> No extraction field for the high voltage LEMs

ΔV	duration	Single	Multiple	Total
3100 V	20.83 h	0.16 ± 0.16	0.00 ± 0.00	0.16 ± 0.16
3200 V	23.00 h	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
3300 V	23.42 h	0.98 ± 0.37	0.28 ± 0.20	1.26 ± 0.42
3400 V	60.50 h	0.39 ± 0.15	0.54 ± 0.17	0.93 ± 0.23
3500 V	18.33 h	1.07 ± 0.44	4.11 ± 0.86	5.18 ± 0.96

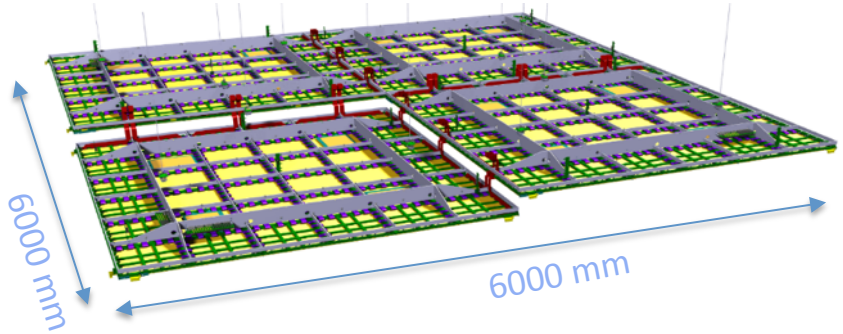
Result:

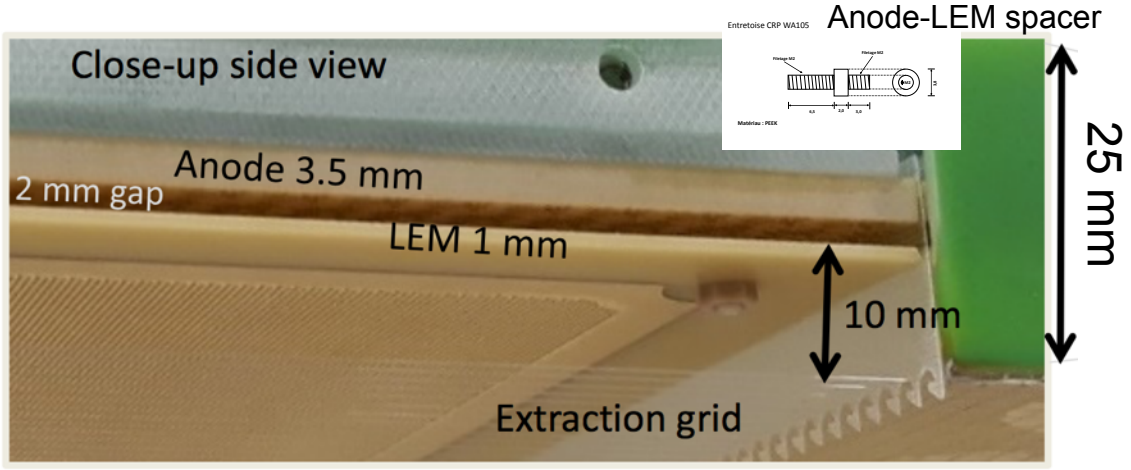
The maximal LEM operation voltage that can be achieved in stable conditions with the LEMs acting as an isolated system in absence of extraction is **3.4 kV across**

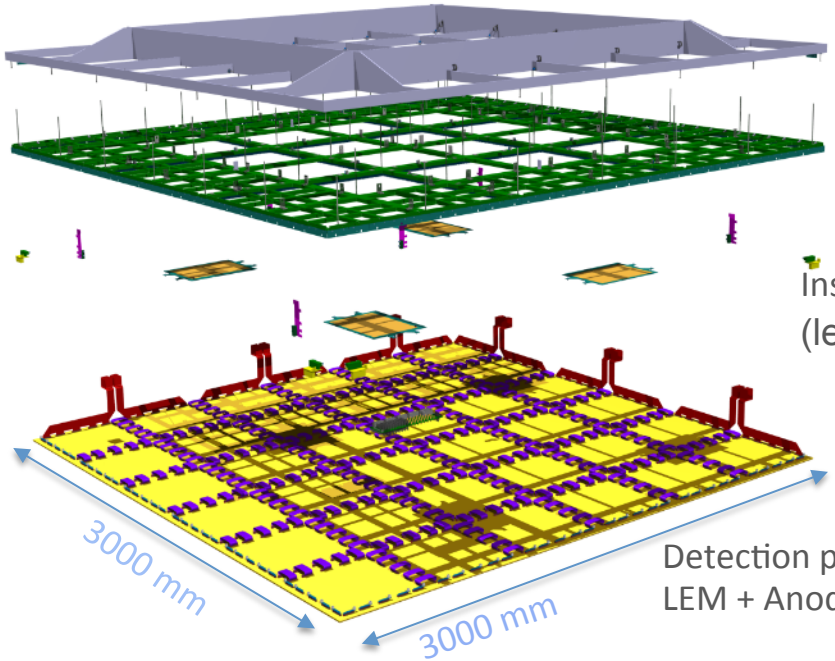
No large effect when the extraction and drift field are turned on
=> no instabilities related to the accumulation of positive ions over long time periods
μάξιμαλ γαιν

The LEM arrangement on CRP

ProtoDUNE-DP / 4 independant CRPs







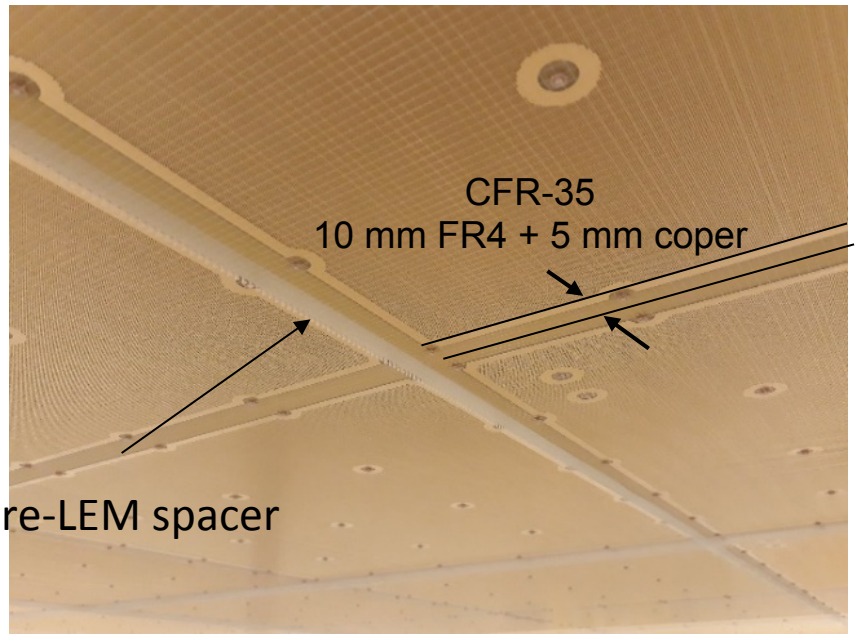
Invar Frame

G10 Frame +
Extraction Grid

Instrumentation
(level meters)

Detection plane
LEM + Anodes

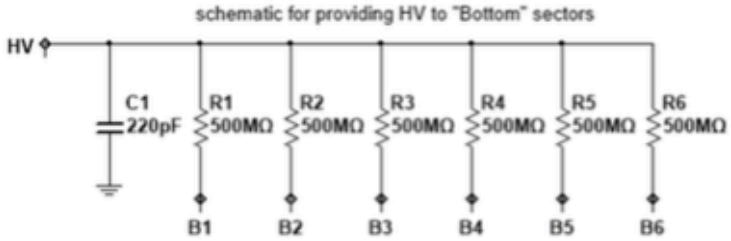
64 wires/module - 1.5N tension (3.5N @ 87K)

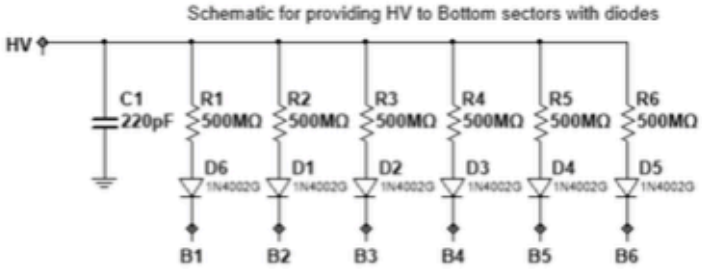


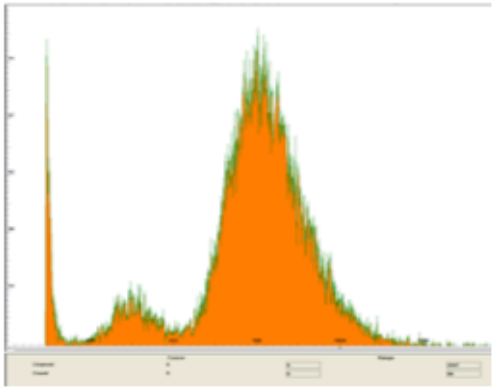
INFN/COMPAS-RICH THGEM
HV distribution

HV distribution to the THGEM, the issue of discharge propagation between sectors, a possible wayout

Discharge effect propagation from one sector to others (also non adjacent ones!) lowering voltage and reducing the neighboring sectors efficiency
HV distribution suspected.

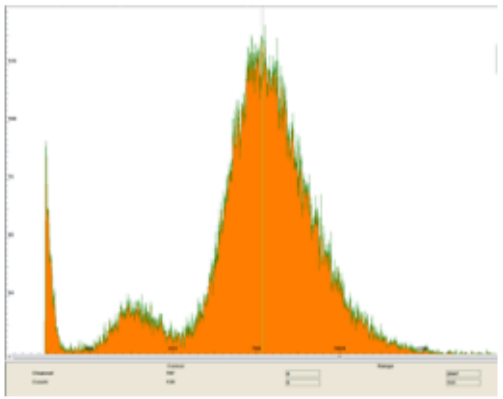




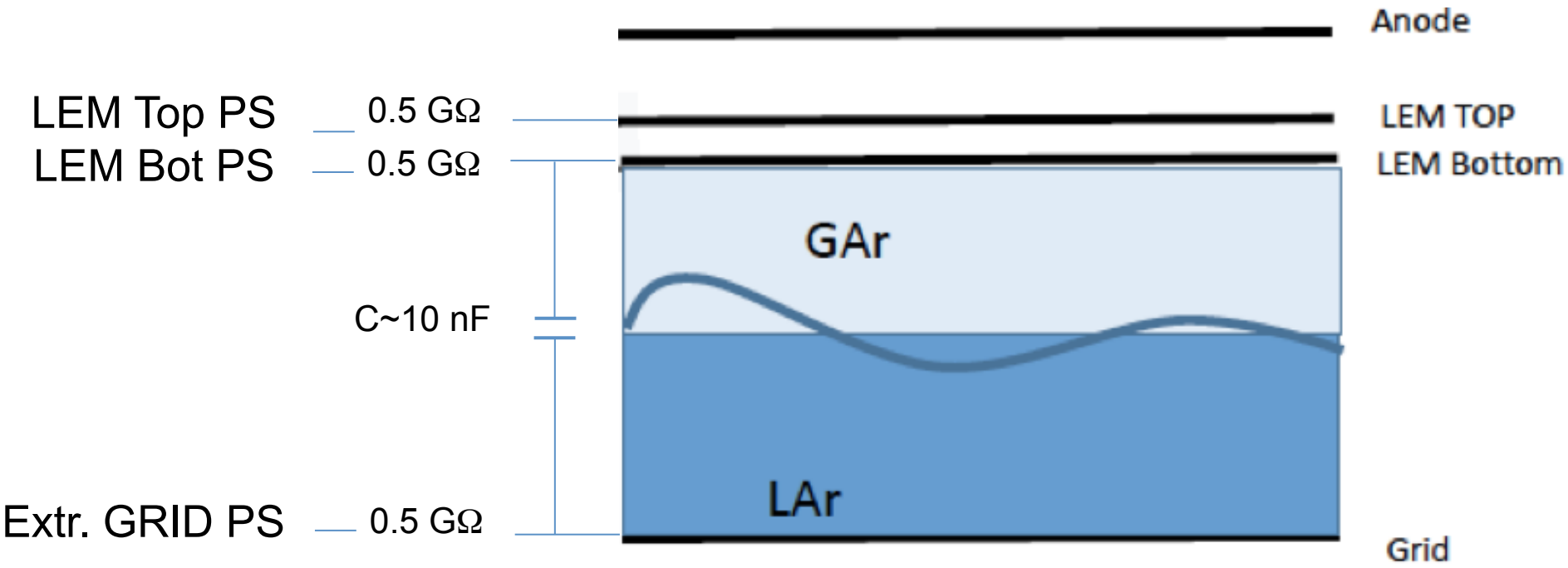


Collect spectra on one sector before and after a trip occurs in another sector (induced)
Comparison of the two spectra just before and after a trip in next to it sector.

Analogous scheme also
for the top
Diode: VS-20ETS High Voltage, Input Rectifier Diode

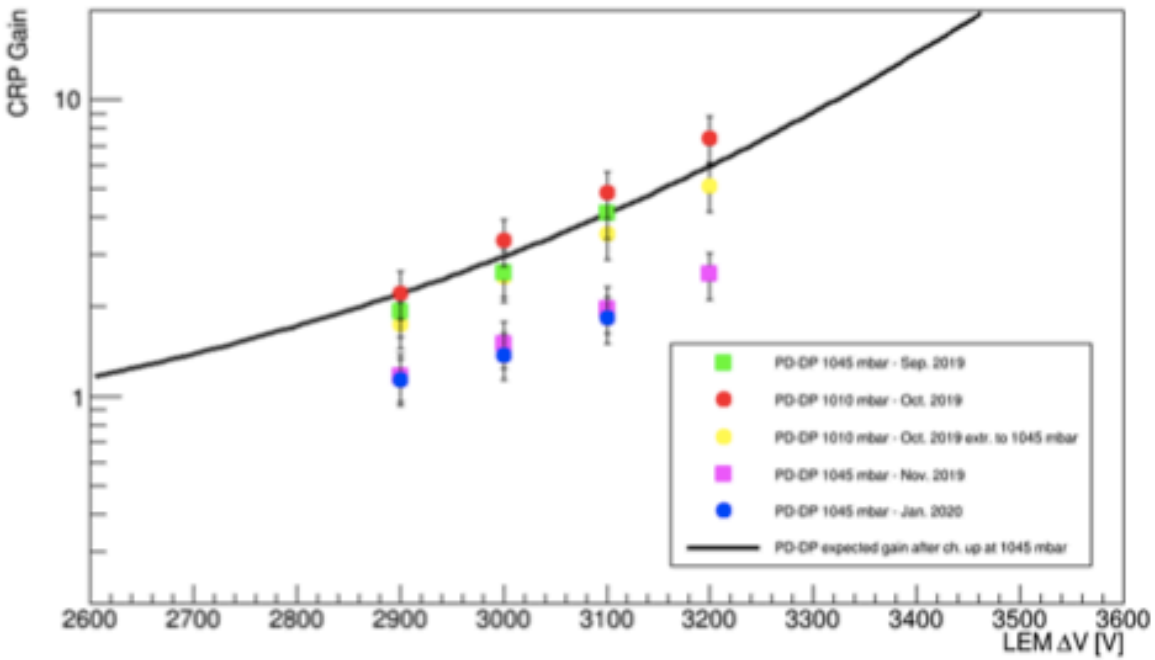


LEM – extraction Grid coupling



CRP gains

- Measurements between September 2019 and January 2020 with cosmics
- Operating conditions: 1045 mbar and $\sim$ 90 K
- CRP gain: $\epsilon_{\text{extraction}} \times G_{\text{LEMs,amplification}} \times \epsilon_{\text{Q collection}}(E_{\text{induction}})$
- $\epsilon_{\text{extraction}}$ estimated to be well above 90%

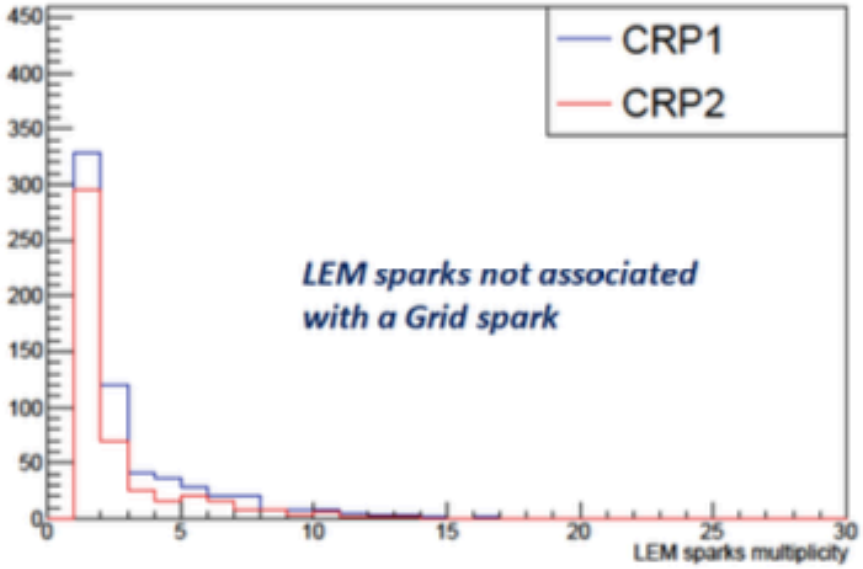


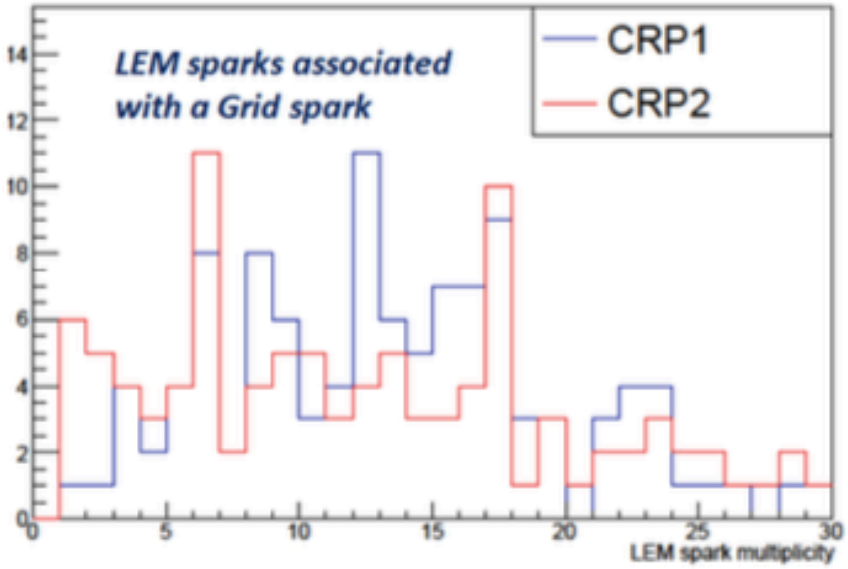
- November $\rightarrow$ January: very small reduction
- September $\rightarrow$ November: Reduction by at least a factor of 2
- Reductions due to charging up effects for designs with rims around holes

- Gain a factor of 2 lower than extrapolated from ETHZ measurements
- Discrepancy not yet understood, dedicated measurement planned in the near future

Sparking events during CRP operation

- Two types defined: grid+LEMs and LEMs-only
- LEM multiplicity: number of LEMs sparking simultaneously





- Grid sparking events: can reach very high multiplicities
- LEMs-only sparking events: limited to a few LEMs, mostly neighbouring ones
- Discrepancy points toward different origins for both types

Grid sparking

- Grid sparking analysis during long-term stability tests

	Extraction	Cathode	R = 0	R = 10 MΩ	R = 500 MΩ
CRP1 $\Delta V = 3.1\,kV$	ON	ON	0.63 ± 0.08	0.37 ± 0.06	*0.38 ± 0.11*
		OFF	0.26 ± 0.05	0.24 ± 0.03	0.20 ± 0.05 — *0.24 ± 0.09*
		ON - OFF	0.37 ± 0.09	0.13 ± 0.07	*0.14 ± 0.14*
	OFF	ON		*<0.07 @ 90 % C.L.*	*<0.06 @ 90 % C.L.*
		OFF		*<0.10 @ 90 % C.L.*	*<0.10 @ 90 % C.L.*

	Extraction	Cathode	No resistors	10 MΩ resistors	500 MΩ resistors
CRP2 $\Delta V = 3.4\,kV$	ON	ON		0.47 ± 0.06	0.89 ± 0.15
		OFF		0.39 ± 0.07	0.86 ± 0.18
		ON - OFF		0.08 ± 0.09	0.03 ± 0.24
	OFF	ON			0.02 ± 0.02
		OFF			0.00 ± 0.00
		ON-OFF			0.02 ± 0.02

- Extraction field OFF ⇒ rate consistent with zero, independent from LEMs ΔV, current limiting resistors and drift
- Extraction field ON ⇒ rate ∈ [0.2, 0.9] spark per hour
- With extraction, sparks due to LEMs-grid coupling
- No evidence for an impact of the drift field
- Factor of 2 reduction with resistors from 500 MΩ to 10 MΩ

Sparking rates analysis

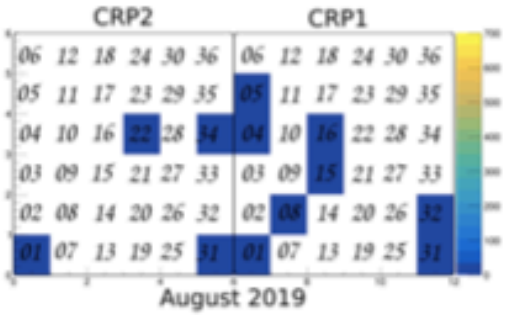
- LEMs sparking rates per hour normalised to a full CRP
- Numbers in grey given as an indication (different ΔV or number of LEMs, earlier period)

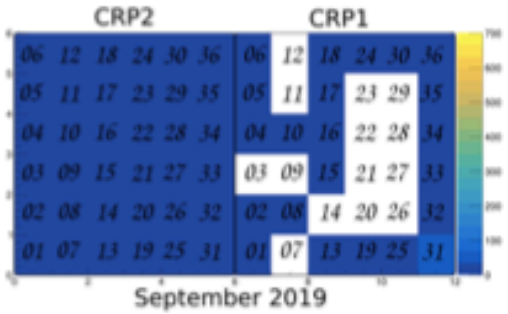
	Extraction	Cathode	R = 0	R = 10 MΩ	R = 500 MΩ
CRP1 $\Delta V = 3.1$ kV	ON	ON	1.4 ± 0.2	2.9 ± 0.3	*4.6 ± 0.5*
		OFF	1.9 ± 0.2	2.6 ± 0.2	1.0 ± 0.2 — *1.6 ± 0.2*
		ON - OFF	-0.5 ± 0.3	0.3 ± 0.3	*3.0 ± 0.5*
	OFF	ON		*1.2 ± 0.3*	*1.3 ± 0.3*
		OFF		*0.4 ± 0.2*	*0.3 ± 0.1*
		ON - OFF		*0.8 ± 0.3*	*1.0 ± 0.3*

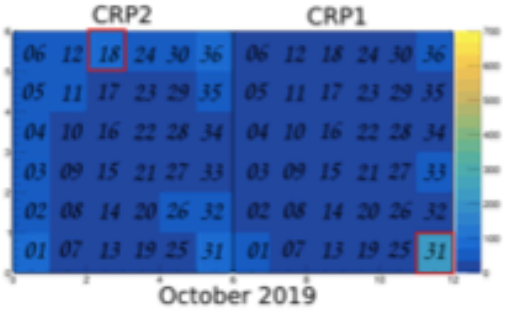
	Extraction	Cathode	R = 0	R = 10 MΩ	R = 500 MΩ
CRP2 $\Delta V = 3.4$ kV	ON	ON		5.9 ± 0.5	4.7 ± 0.6
		OFF		6.2 ± 0.6	3.9 ± 0.7
		ON - OFF		-0.3 ± 0.8	0.8 ± 0.9
	OFF	ON			5.4 ± 0.5
		OFF			0.9 ± 0.2
		ON - OFF			4.4 ± 0.6

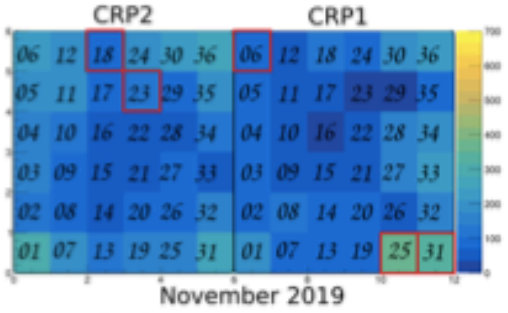
- Larger ΔV across the LEMs $\Rightarrow$ higher sparking rate
- With extraction: no visible contribution of drifted ions
- Current limiting resistors value impact sparking rates
- The extraction field seems to increase the sparking rate

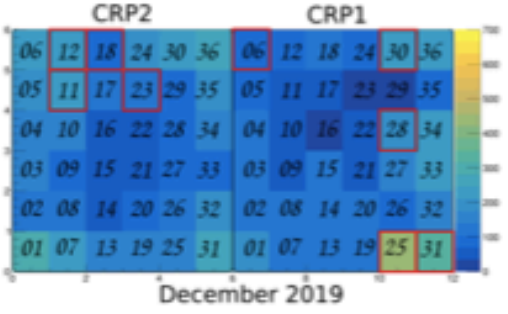
LEMs aging during ProtoDUNE-DP operations

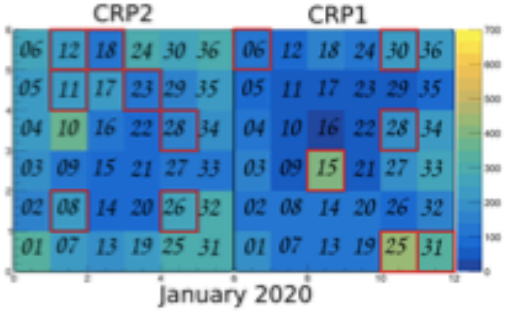


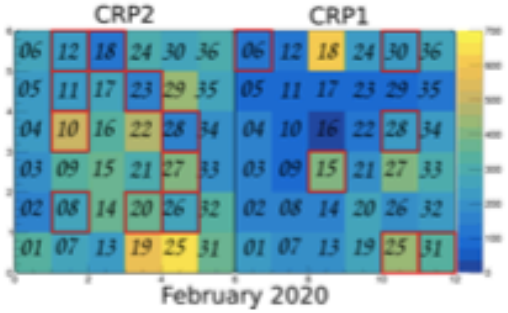


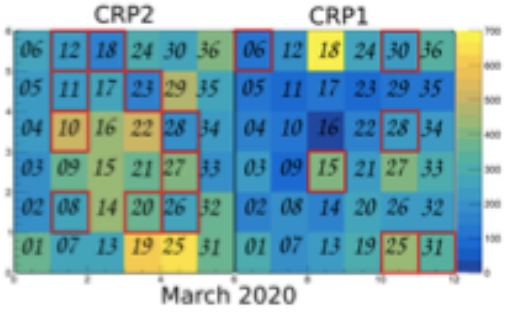






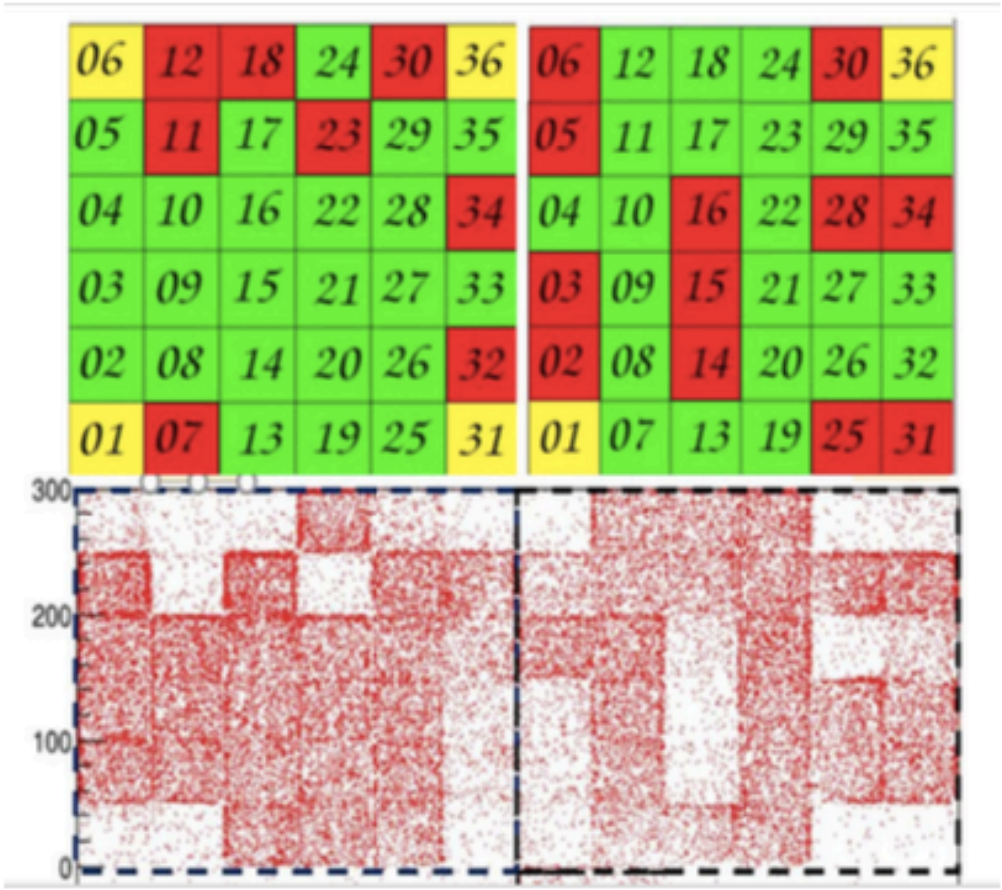






- Absolute number of sparks per LEMs
- Cumulative for each month of operations
- Large sparking rate on a LEM requires a reduction of the nominal HV
- Red squares highlight LEMs with a nominal $\Delta V \leq 2\,\mathrm{kV}$: 22 % of LEMs as of March 2020
- LEM 18 CRP1 probably aging faster since February
- Close to 50 000 sparks since beginning of operations

LEMs with reduced HV



E. Pennacchio

Cross-check of reduced LEM gain with the point of origin of tracks

- LEMs with reduced HV in red (1 to 3.2 kV on bottom electrode)
- LEMs set to lower HV as a precaution in yellow
- Lower HV implies reduced amplification on LEMs
- Reduces the active surface of the CRPs
- Mostly LEMs on the edges of the CRPs