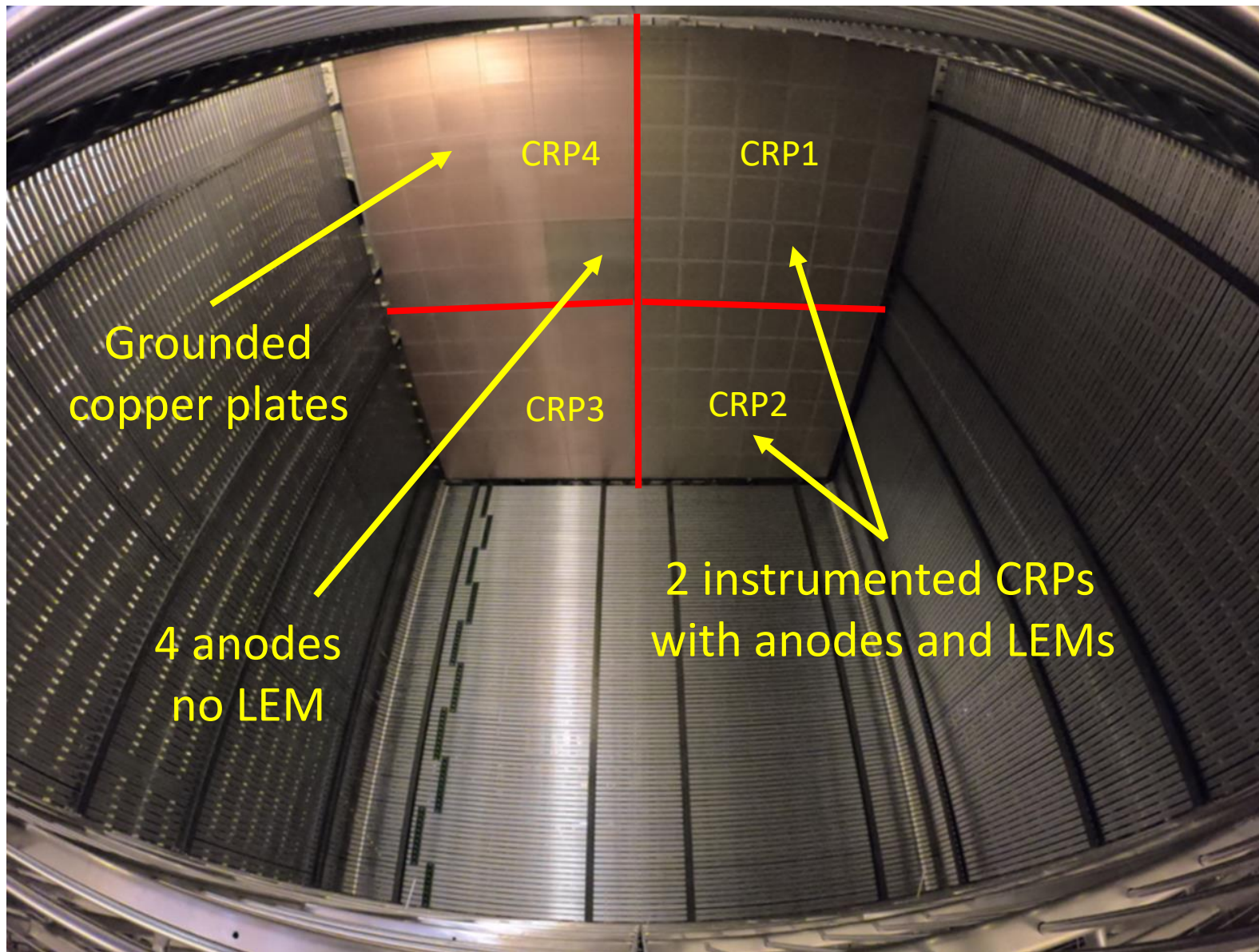


ProtoDUNE-DP: CRPs

Edoardo Mazzucato CEA/Irfu



- All 4 CRPs have a $3 \times 3 \text{ m}^2$ extraction Grid.
- Each instrumented CRP has 36 LEMs + 36 anodes ($50 \times 50 \text{ cm}^2$)

CRP Operations

- Data taking of cosmics from end of Aug. until Oct. 3rd and in Nov. with ΔV_{LEM} up to 3.2kV and high extraction efficiency (V_{Grid} : 5.5 – 6.5kV, tested up to 7.5kV).
- Since October, main effort in looking for stable LAr surface conditions (no bubbles) and keeping the detector at the same pressure in order to establish *long duration* and *stable* operation conditions.

Necessary condition to perform long-term HV stability tests of CRPs

- LAr surface with ripples (no bubbles) can also affect HV operation of Grids and LEMs (sporadic sparks).
- Effort also in HV stability studies of LEMs and Grids but this effort was hampered by frequent appearance of bubbles on liquid surface and by necessary cryogenic operations to clean clogged recirculation filter.

39 cryogenic operations in 17 weeks of ProtoDUNE-DP commissioning!

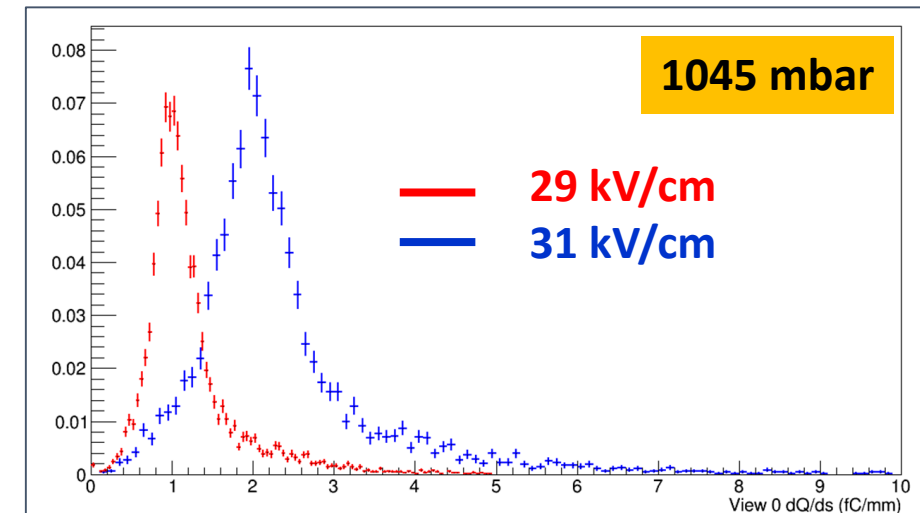
LEM + Grid Operation

- ΔV_{LEM} @ 2.9, 3.0, 3.1, 3.2kV and 3.3kV :
 - 67/72 LEMs operated so far with $\Delta V_{\text{LEM}} \geq 2.9$ kV.
 - G (2.9 kV) : ~ 2 @ 1045 mbar ($V_{\text{GRID}} = 6$ kV)
 - R_G (3.0 kV / 2.9 kV) = 1.4 (expected 1.3)
 - R_G (3.1 kV / 2.9 kV) = 2.0 (expected 1.8)
 - LEM gain @ $\Delta V_{\text{LEM}} = 3.2$ kV : ~ 12 @ 1010 mbar

To achieve higher LEM gains, stable cryogenic conditions over long periods of time are necessary to guarantee smooth LEM HV ramping up.

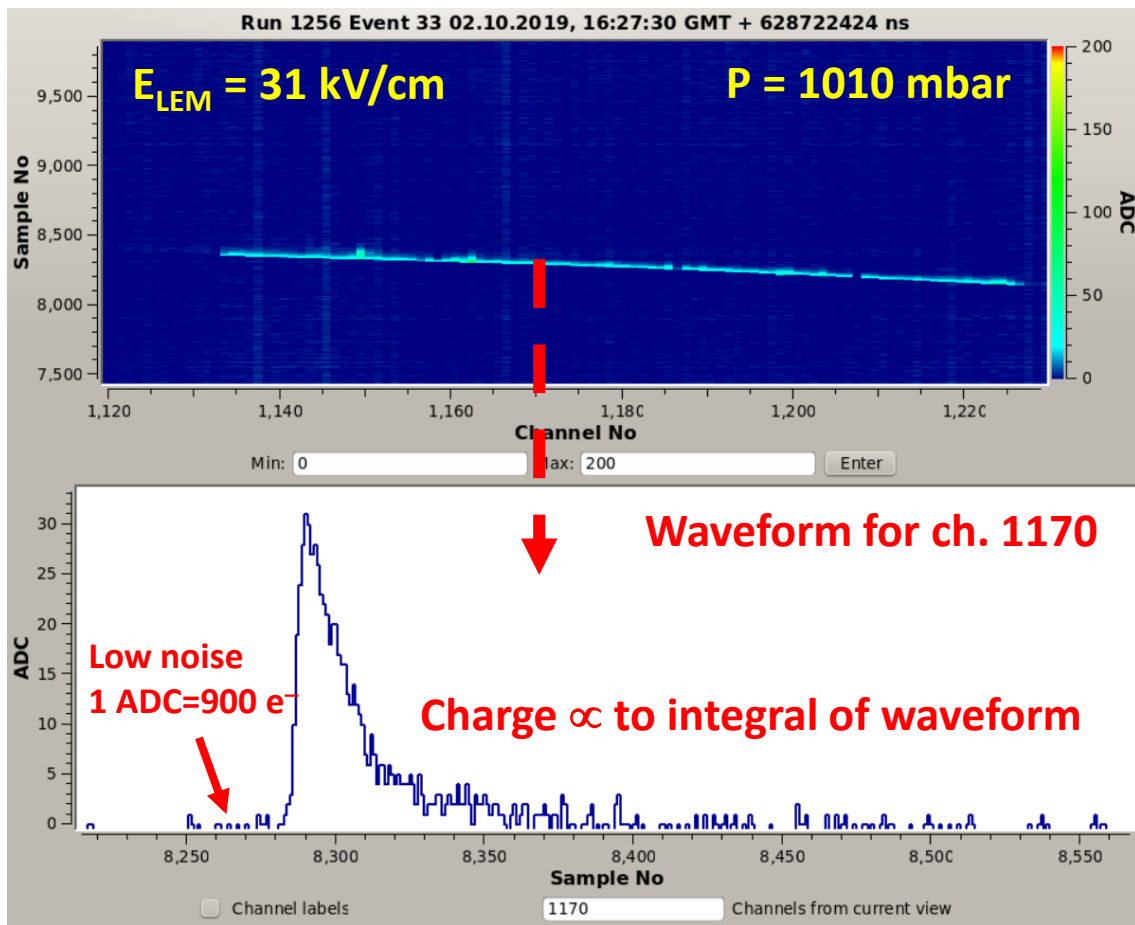
- LEM spark rates :
 - Goal : < 1 spark/h per CRP as achieved in the 2018 Cold Box tests at CERN.

dQ/dx in one of the two collection views

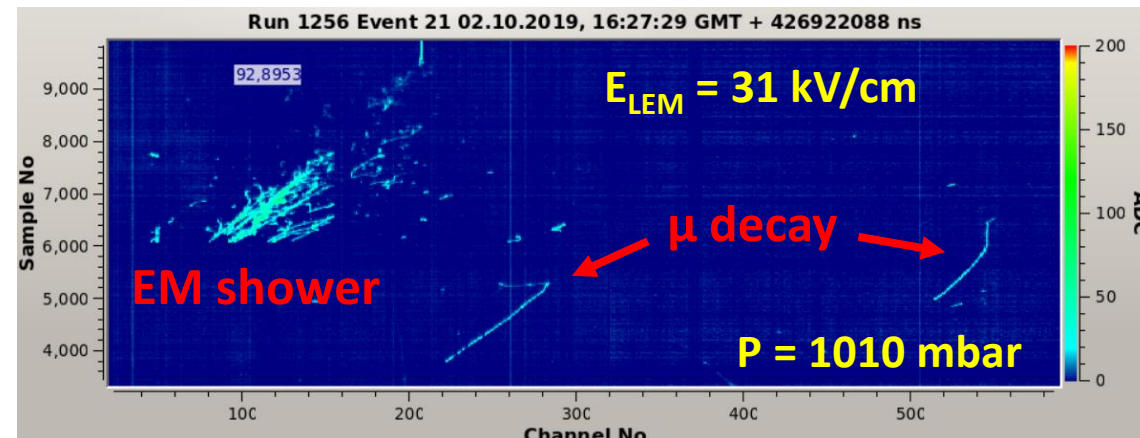


Event Gallery

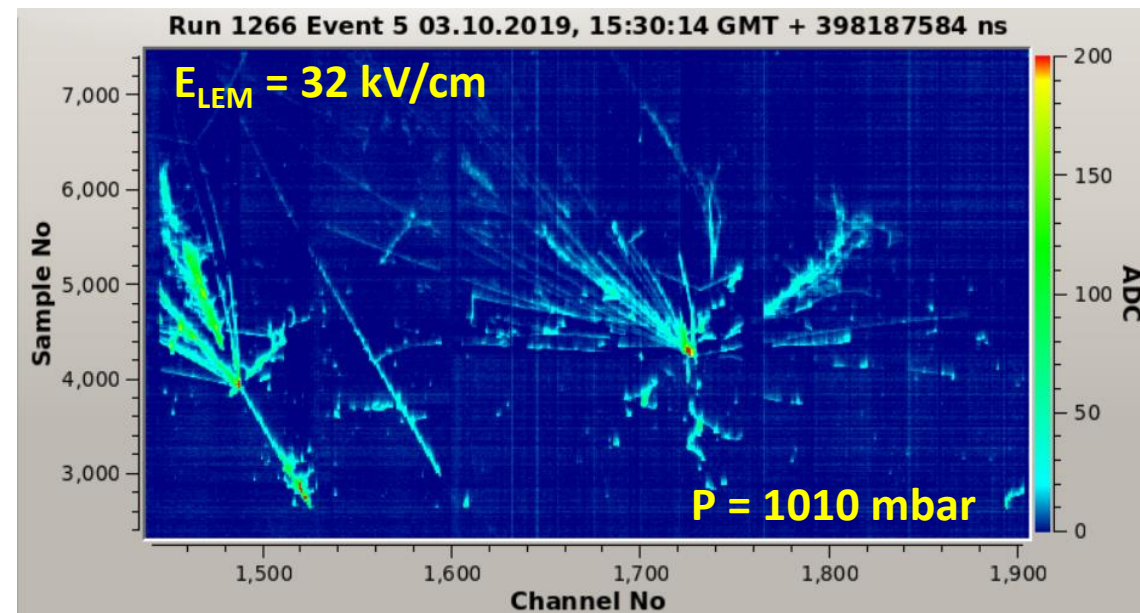
Horizontal muon track



Electromagnetic shower + two muon decays

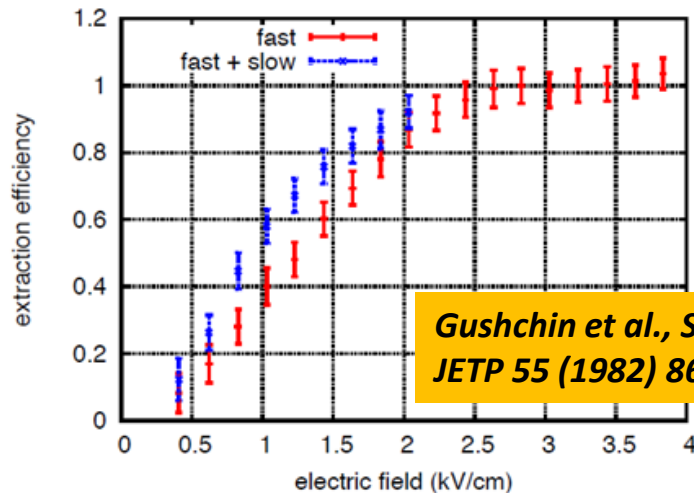


Multiple hadronic interactions in a shower



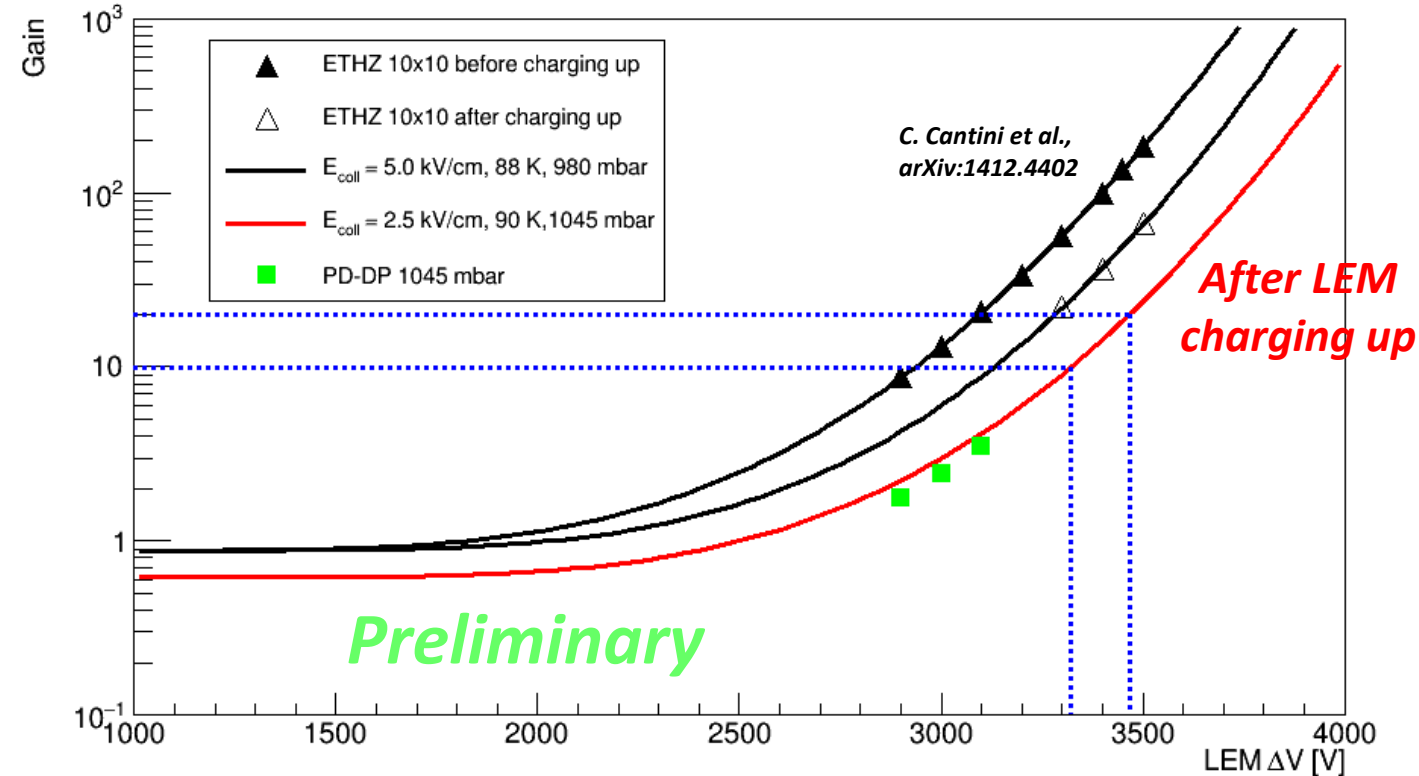
CRP Gain

$$G = \varepsilon_{\text{extr}} \times G_{\text{LEM}} \times \varepsilon_{\text{coll}}$$



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

- $V_{\text{TOP}} = 0.5 \text{ kV} \Rightarrow \varepsilon_{\text{coll}} \sim 70\%$
- $V_{\text{Grid}} = 6 \text{ kV} \Rightarrow \varepsilon_{\text{extr}} > 90\%$ for $\Delta V_{\text{LEM}} \sim 3 \text{ kV}$

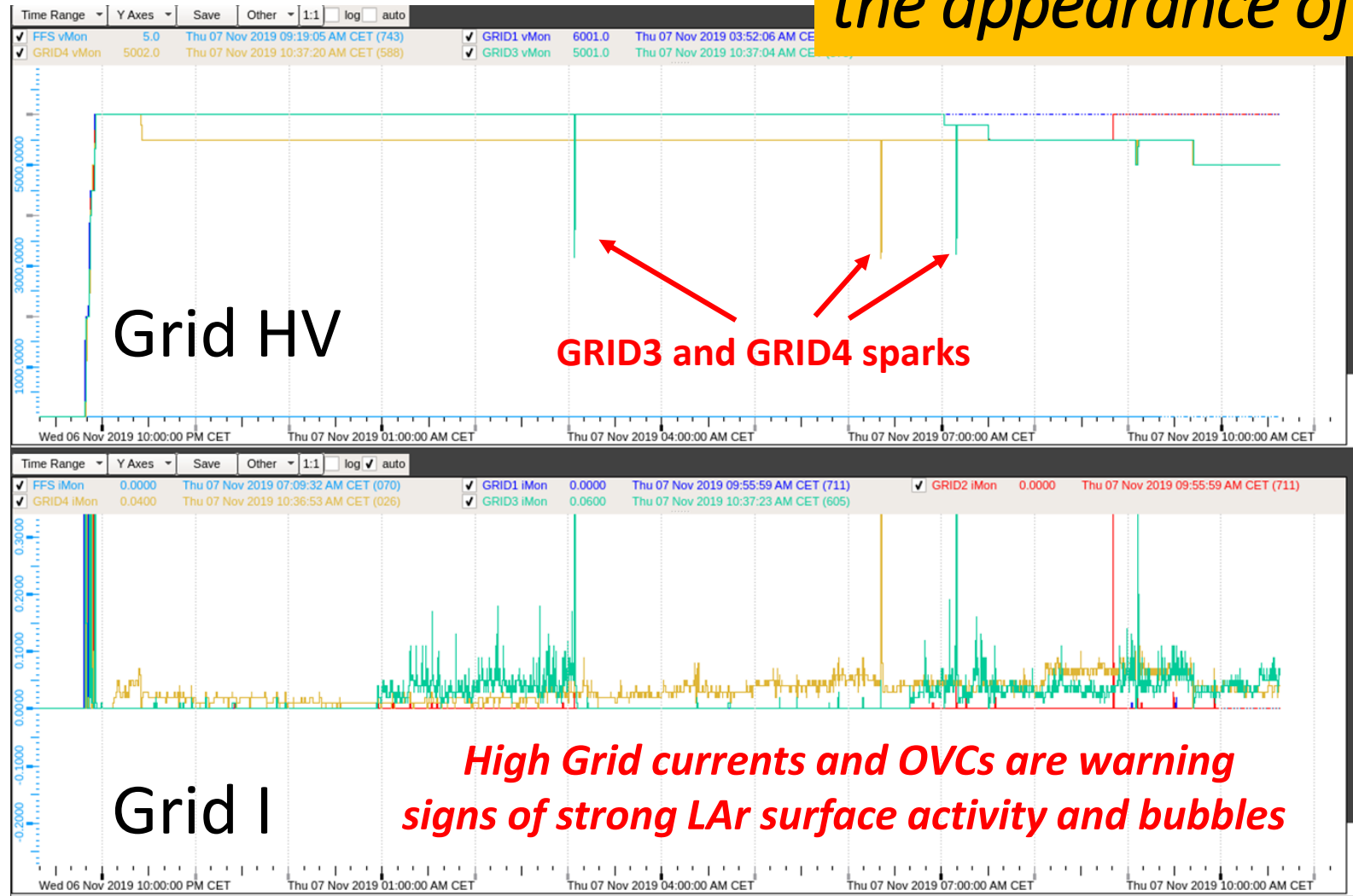


More data at 1010 mbar and 1045 mbar up to $\Delta V_{\text{LEM}} = 3.2 \text{ kV}$ being analyzed.

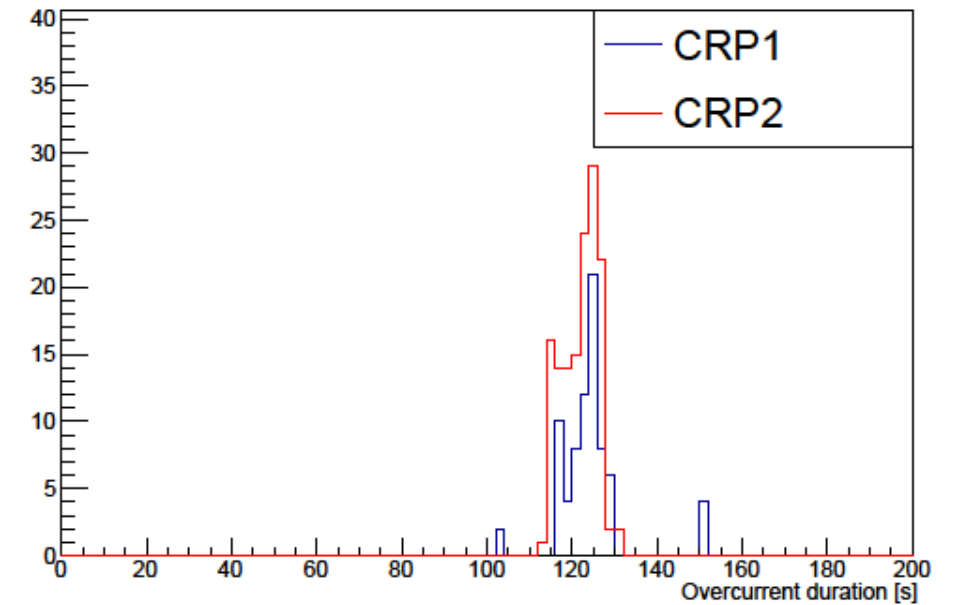
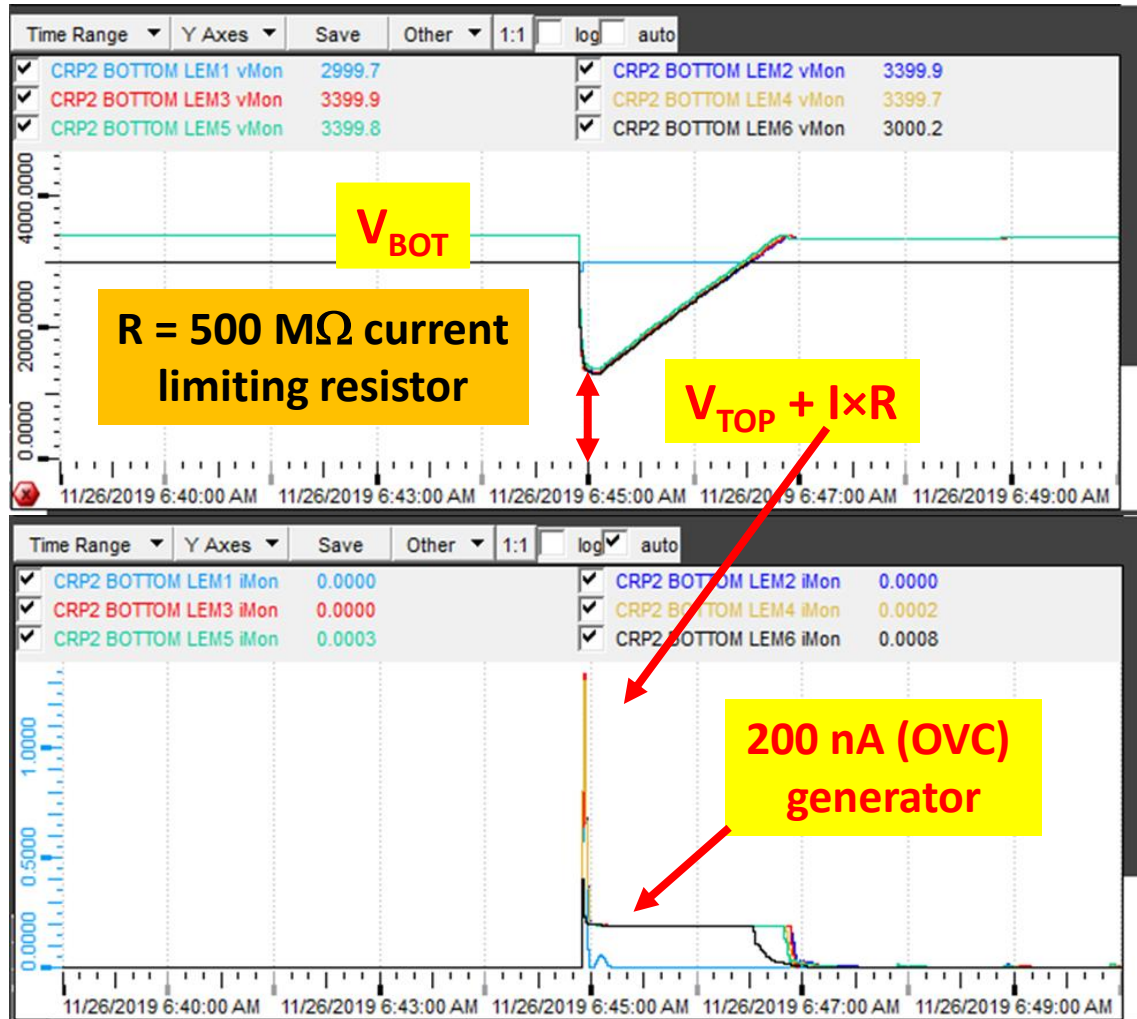
LEM and Grid OVC/Sparks

- Over Current (OVC) events are not necessarily sparks.
- OVCs occur when the power supply delivers a current above a maximum pre-set value to the electrical circuit in order to re-establish electrostatic conditions.
- $OVC_{LEM} = 200 \text{ nA}$ and $OVC_{Grid} = 1 \text{ }\mu\text{A}$.
- While a LEM discharge or spark in gas produces an OVC, a Grid may also produce an OVC event which is not necessarily a discharge. Grid sparks can damage the FE electronics.
- Since LEM and Grid are coupled capacitively, Grid and LEM OVC or spark events can occur in presence of rapid changes or ripples on the LAr surface.
- With a $500 \text{ M}\Omega$ current limiting resistor on LEM V_{BOT} ($RC \sim 5\text{s}$), reaction time not fast enough to compensate rapid voltage changes. Optimization of the electrical scheme under study.

Grid sparks correlated to the appearance of bubbles.



LEM Sparks

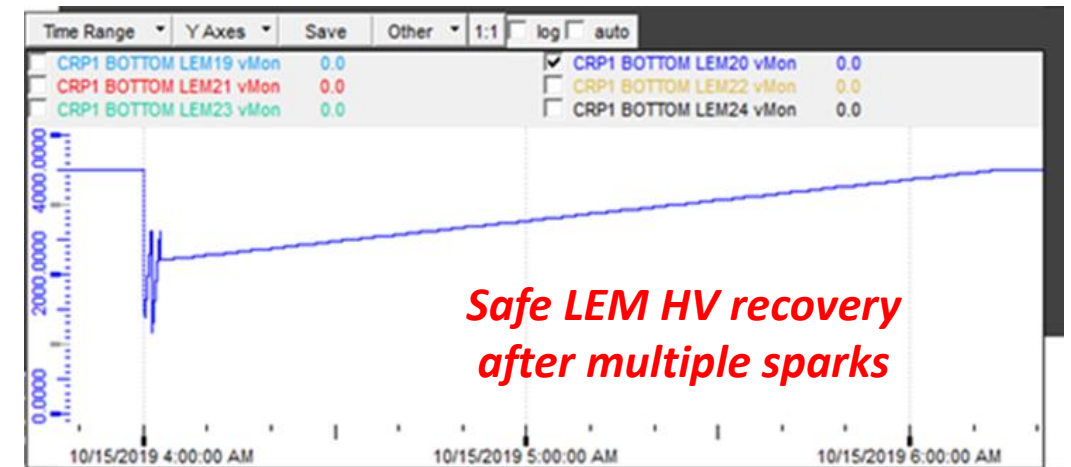
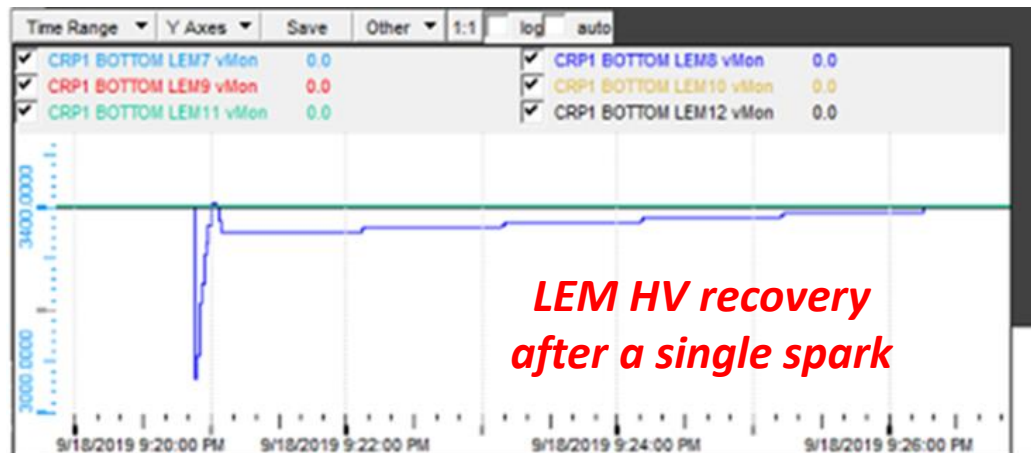
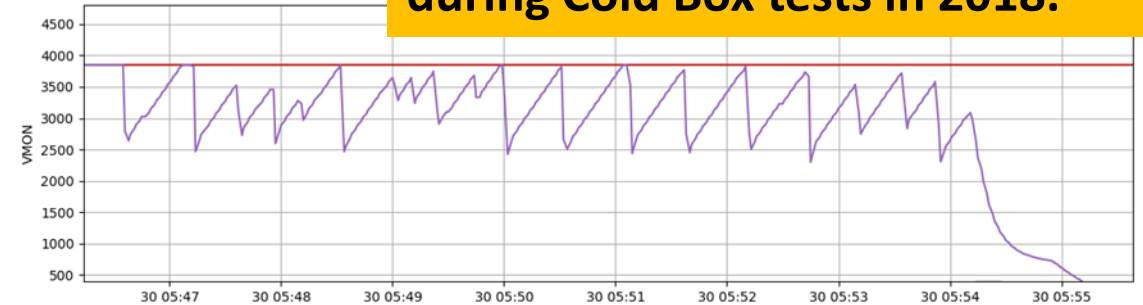


Dead time due to a LEM spark is set to 2 minutes. Not an issue for rates at the level of a several sparks per hour and per CRP.

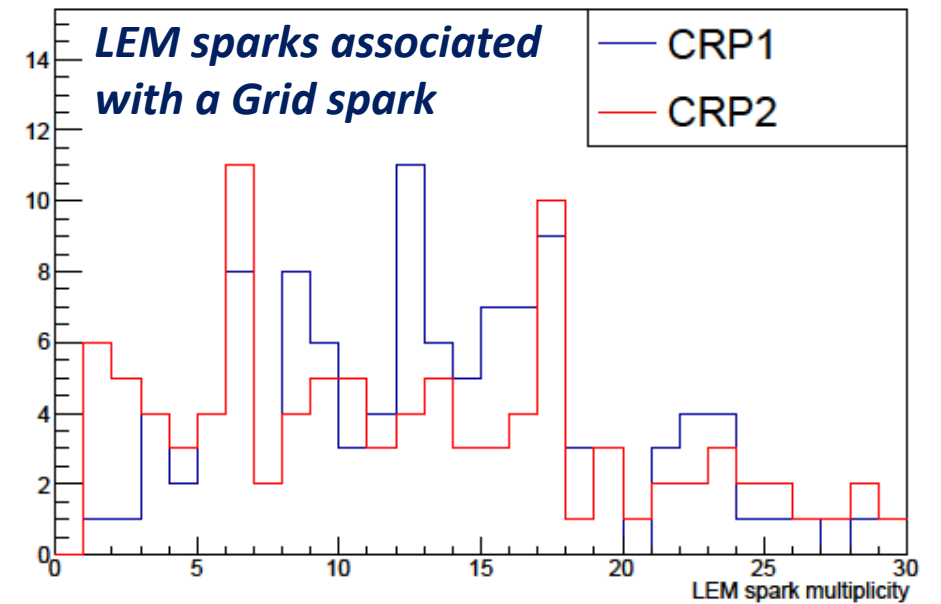
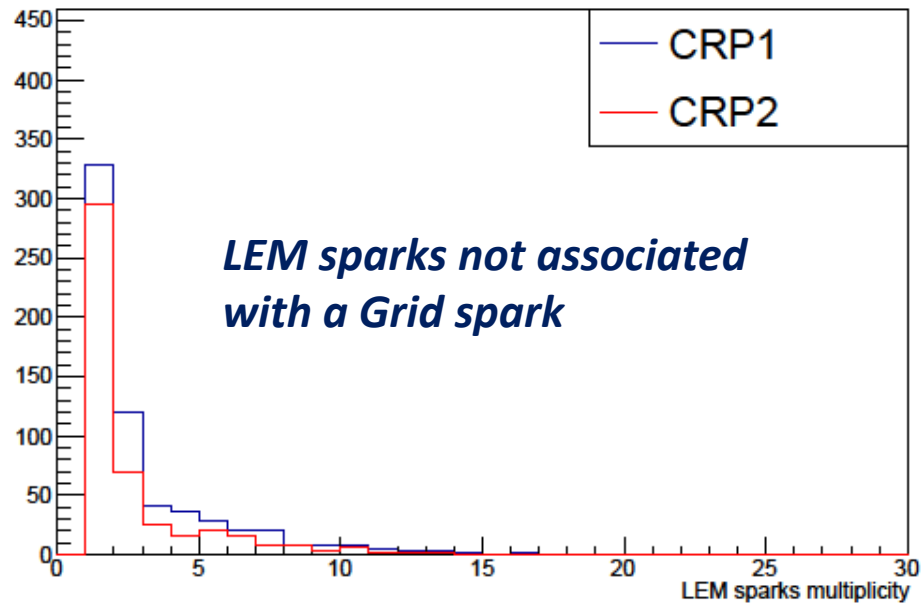
LEM HV Safe Recovery after a Spark

- Major SC improvement for safe operation of LEMs.
- Avoid power supply trips.
- Developed in collaboration with CERN EP-DT-DI.
- Being optimized to minimize dead-time (with a non-linear HV ramping up).

Reminder : continuous sparking that produced LEM carbonization during Cold Box tests in 2018.



LEM Spark Multiplicity



Correlation between LEM and GRID OVC

 No spark

 Spark

*Number of LEM sparking increases with Grid current
(~1s time resolution)*

01	02	03	04	05	06
07	08	09	10	11	12
13	14	15	16	17	18
19	20	21	22	23	24
25	26	27	28	29	30
31	32	33	34	35	36

$I_{grid} = 70 \text{ nA}$
 $\mathcal{M} = 1$

01	02	03	04	05	06
07	08	09	10	11	12
13	14	15	16	17	18
19	20	21	22	23	24
25	26	27	28	29	30
31	32	33	34	35	36

$I_{grid} = 230 \text{ nA}$
 $\mathcal{M} = 4$

01	02	03	04	05	06
07	08	09	10	11	12
13	14	15	16	17	18
19	20	21	22	23	24
25	26	27	28	29	30
31	32	33	34	35	36

$I_{grid} = 490 \text{ nA}$
 $\mathcal{M} = 8$

01	02	03	04	05	06
07	08	09	10	11	12
13	14	15	16	17	18
19	20	21	22	23	24
25	26	27	28	29	30
31	32	33	34	35	36

$I_{grid} = 650 \text{ nA}$
 $\mathcal{M} = 12$

01	02	03	04	05	06
07	08	09	10	11	12
13	14	15	16	17	18
19	20	21	22	23	24
25	26	27	28	29	30
31	32	33	34	35	36

$I_{grid} = OvC$
 $\mathcal{M} = 23$

01	02	03	04	05	06
07	08	09	10	11	12
13	14	15	16	17	18
19	20	21	22	23	24
25	26	27	28	29	30
31	32	33	34	35	36

$I_{grid} = OvC$
 $\mathcal{M} = 30$

Important to disentangle contributions to sparks from LEMs, Grids and perturbations on LAr surface

Grid and LEM OVC Rates

(*) CRP1, CRP2 LEMs not correlated to Grid OVC

Period	Duration (h)	Cathode	ΔV_{LEM} (kV)	V_{Grid} (kV)	Grid1 OVC (1/h)	Grid2 OVC (1/h)	LEM1* OVC (1/h/CRP)	LEM2* OVC (1/h/CRP)
30/10	15.0	OFF	2.9	3.4	0	0	0	0
12/11	21.0	OFF	2.9	6	0.2	0.05	0.3	0.3
01/11	19.8	OFF	3.0	6	0.2	0.3	0.3	0.6
05/11-17/11	38.0	OFF	3.1	6	0.2	0.4	1.0	1.3
05/11	18.8	OFF	3.2	6	0.4	0.1	0.4	0.3

Period	Duration (h)	Cathode (50kV)	ΔV_{LEM} (kV)	V_{Grid} (kV)	Grid1 OVC (1/h)	Grid2 OVC (1/h)	LEM1* OVC (1/h/CRP)	LEM2* OVC (1/h/CRP)
03/10-13/11	10.7	ON	2.9	6	0.09	0.09	1.0	1.0
14/11	11.5	ON	3.0	6	0.4	0.9	1.7	5.4
03/10-20/11	38.0	ON	3.1	6	0.5	0.9	3.8	7.7

- Grid OVC rate is < 1/h for both cathode OFF or ON.
- LEM spark rates are at the level of 1/h per CRP when Cathode is OFF but can increase significantly with cathode ON. Very likely due to ionisation from cosmics. Not an issue for DUNE.

Grid and LEM OVC Rates during « Pressure Cycle »

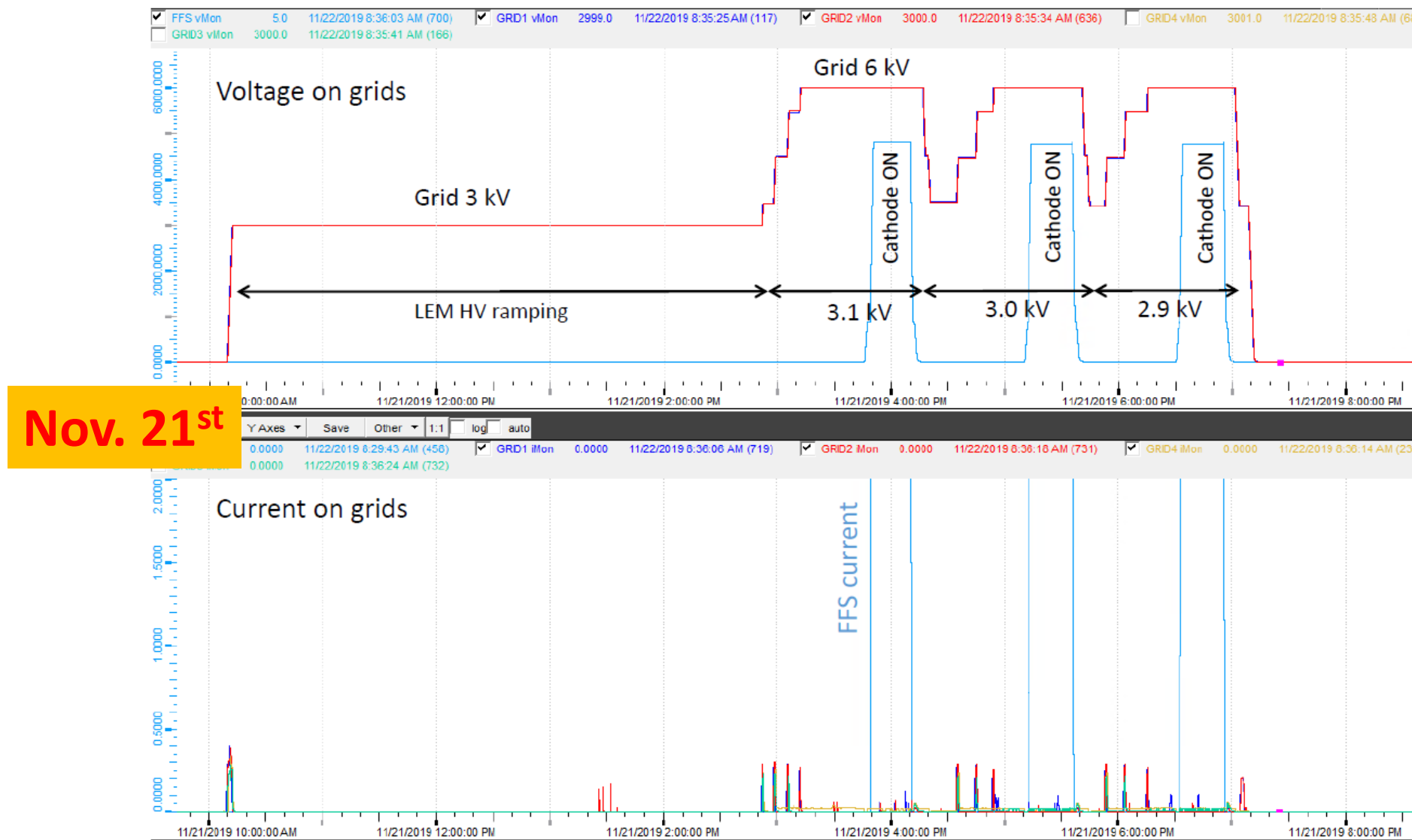
(*) CRP1, CRP2 LEMs not correlated to Grid OVC

Period	Duration (h)	Cathode	ΔV_{LEM} (kV)	V_{Grid} (kV)	Grid1 OVC (1/h)	Grid2 OVC (1/h)	LEM1* OVC (1/h/CRP)	LEM2* OVC (1/h/CRP)
04/09-18/09	11.5	OFF	2.9	6	0.4	0.2	1.3	1.2
16/09	4.8	OFF	3.0	6	0.4	0.2	0.2	0.2

Period	Duration (h)	Cathode (50 kV)	ΔV_{LEM} (kV)	V_{Grid} (kV)	Grid1 OVC (1/h)	Grid2 OVC (1/h)	LEM1* OVC (1/h/CRP)	LEM2* OVC (1/h/CRP)
04/09-18/09	23.3	ON	2.9	6	0.04	0.1	1.6	0.6
18/09	0.6	ON	3.0	6	0	0	1.6	1.6
18/09	0.5	ON	3.1	6	0	0	0	0

- During « pressure cycles » LEM spark rates close to the 1/h per CRP level even when cathode is ON.
- Supports the hypothesis that a calmer LAr surface during « pressure cycle » induces less sparks.

New HV Ramping Up Procedure



Grid and LEM OVC Rates

(*) CRP1, CRP2 LEMs not correlated to Grid OVC

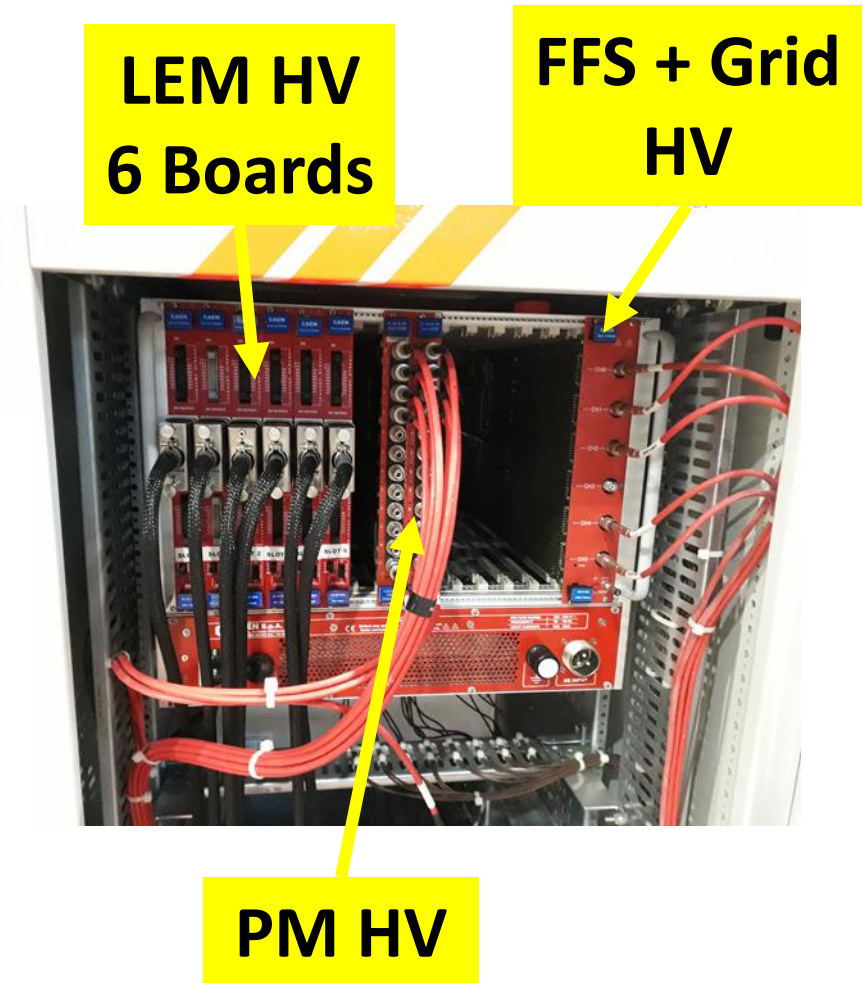
Period	Duration (h)	Cathode	ΔV_{LEM} (kV)	V_{Grid} (kV)	Grid1 OVC (1/h)	Grid2 OVC (1/h)	LEM1* OVC (1/h/CRP)	LEM2* OVC (1/h/CRP)
25/11-26/11	9.4	OFF	2.9	6	0	0	0.3	0.2
29/11	1.3	OFF	3.1	6	0	0	1.5	1.5
22/11-27/11	2.6	OFF	3.2	6	0	0	0.8	0.4

Period	Duration (h)	Cathode (50kV)	ΔV_{LEM} (kV)	V_{Grid} (kV)	Grid1 OVC (1/h)	Grid2 OVC (1/h)	LEM1* OVC (1/h/CRP)	LEM2* OVC (1/h/CRP)
25/11-26/11	18.0	ON	2.9	6	0.06	0.1	0.8	0.9
20/11	1.9	ON	3.1	6	0.5	0.5	2.6	2.6
27/11	18.5	ON	3.2	6	0.4	0.3	2.2	5.9

- No Grid spark \Rightarrow no damage to FE electronics.
- 0 spark on both Grid3 (5 kV) and Grid4 (4.5 kV) in 63 h.
- General trend with new HV ramping up procedure towards improvement. Need more observation time.

CAEN Power Supply Issues

- Since mid-October, frequent shutdowns of LEM and Grid HV Boards affected CRP operations (up to one per day).
- Several boards + mainframe replaced by CAEN experts.
- Re-distribution of power lines.
- Problem seems to be caused by power glitches (too sensitive HV boards?).
- Under investigation by experts.



Ion Feedback

- Positive ions due to ion feedback from avalanches in a LEM can accumulate on the LAr surface and create Grid + LEM instabilities leading to OVC and discharges.
- Instabilities have been observed a few times while taking data during the high pressure cycles with the cathode ON. They appeared in TPC operation mode within a few hours since the beginning of the high pressure period on a time scale of typically one hour while they were not observed in the same cycles when the cathode was switched on later (about 7 hours after the start of the cycle).
- If positive ions stick to the liquid surface due to electrostatic forces, they can be removed by LAr evaporation in normal conditions. Positive ions are then collected by the copper bottom faces of the LEMs where they are neutralized.
- During the last TPC operation with cathode ON in November, no instabilities were observed. Ion feedback in ProtoDUNE-DP needs to be further investigated.
- Positive ion accumulation will be largely suppressed in DUNE as the rate of cosmic rays is reduced underground by a factor 10^6 .

Summary

- Much progress has been made so far in the understanding of the CRP operation despite adverse cryogenic conditions (bubbles, ripples, filter clogging).
- More than 600 h of safe LEM operation achieved with new SC.
- Correlation between LAr surface quality and HV Grid + LEM stability observed.
- Clean cosmic events observed with LEM amplification gains ~ 10 achieved so far.
- Continuation of studies should address (assuming CAEN PS and filter clogging issues are solved):
 - Effects from LAr surface issues.
 - Long-term HV stability of CRPs.
 - Grid-LEM capacitive coupling effects.
 - Optimization of the CRP operation parameters.
 - Going to higher amplification gains.

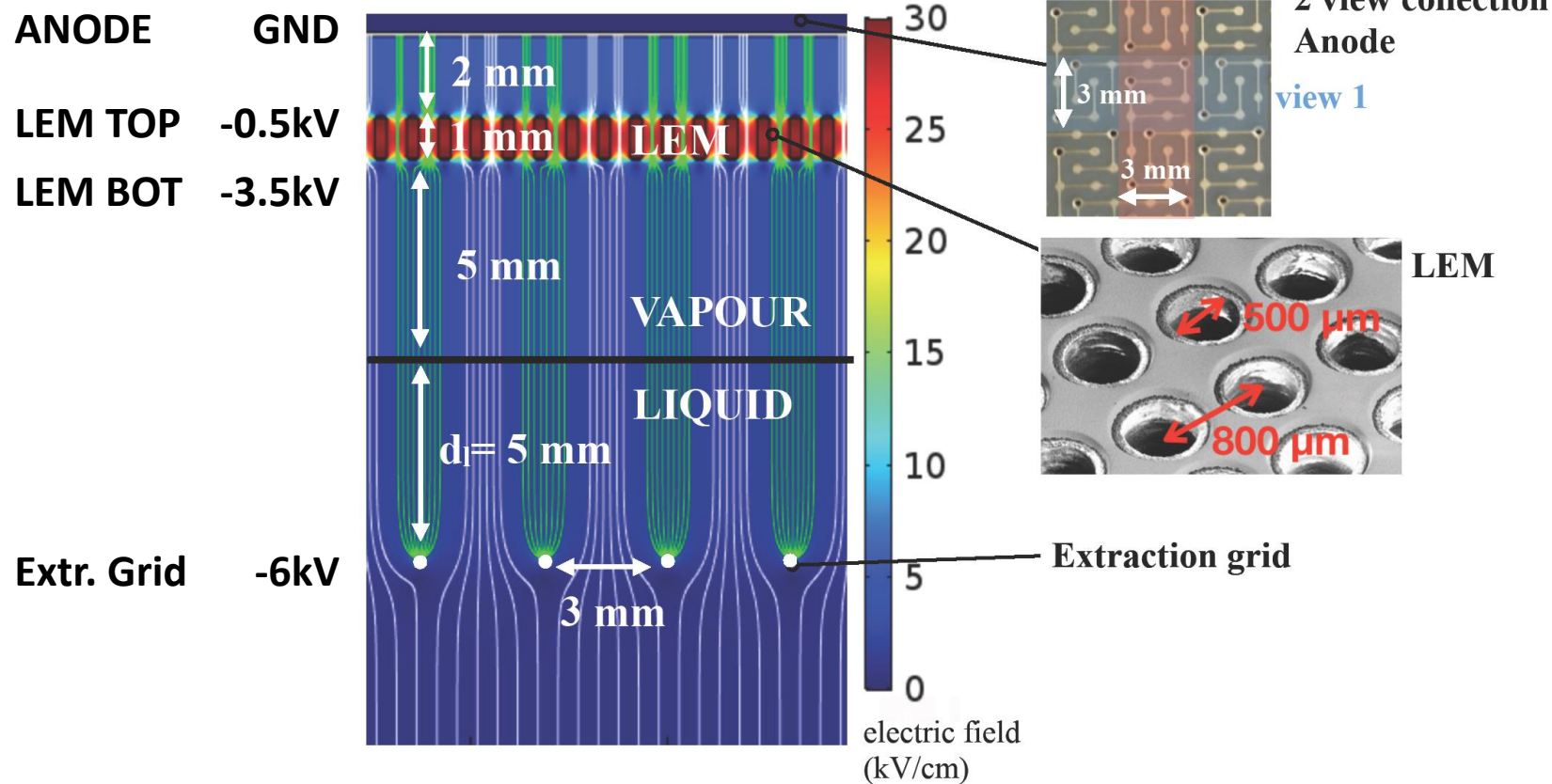
Backup Slides

Dual Phase Principle

Collection : 2.5kV/cm
Amplification : 30kV/cm

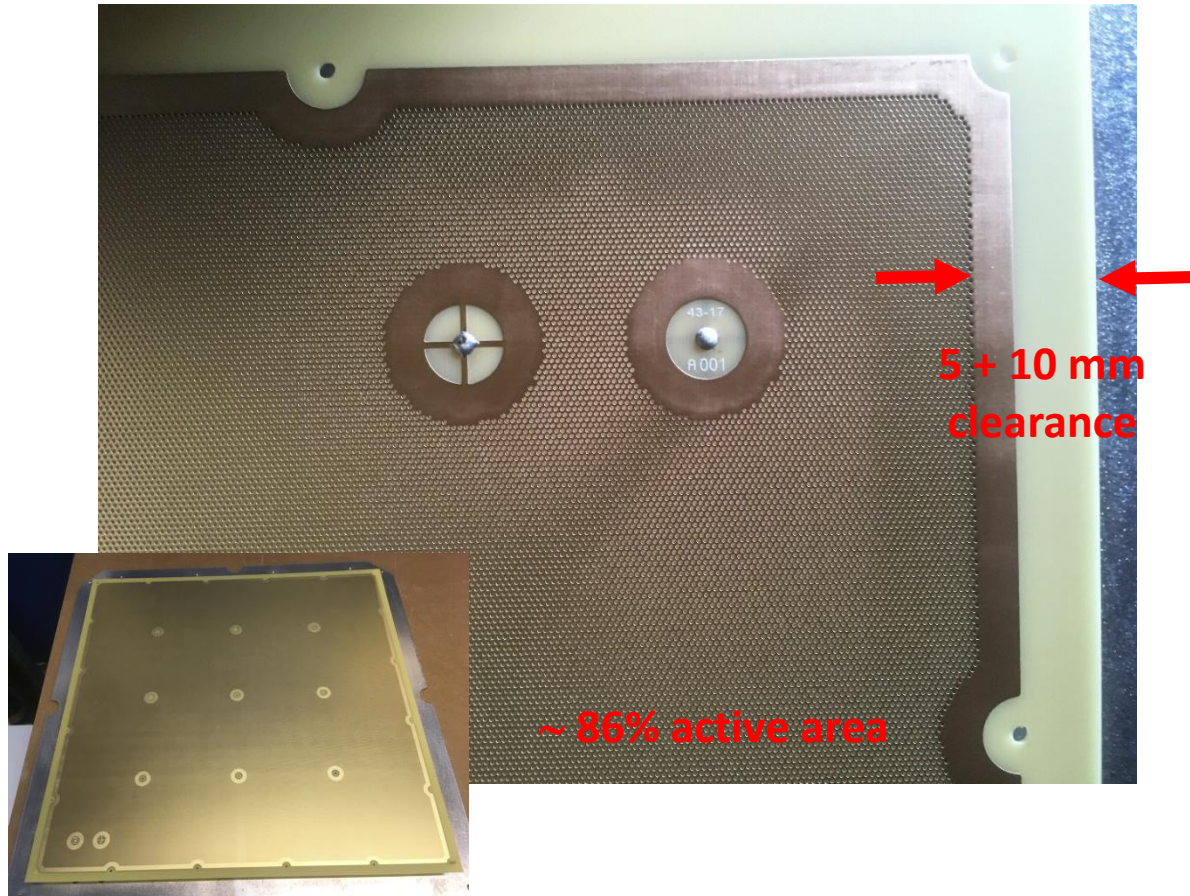
Extr. (GAr) : 3kV/cm

Extr. (LAr) : 2kV/cm

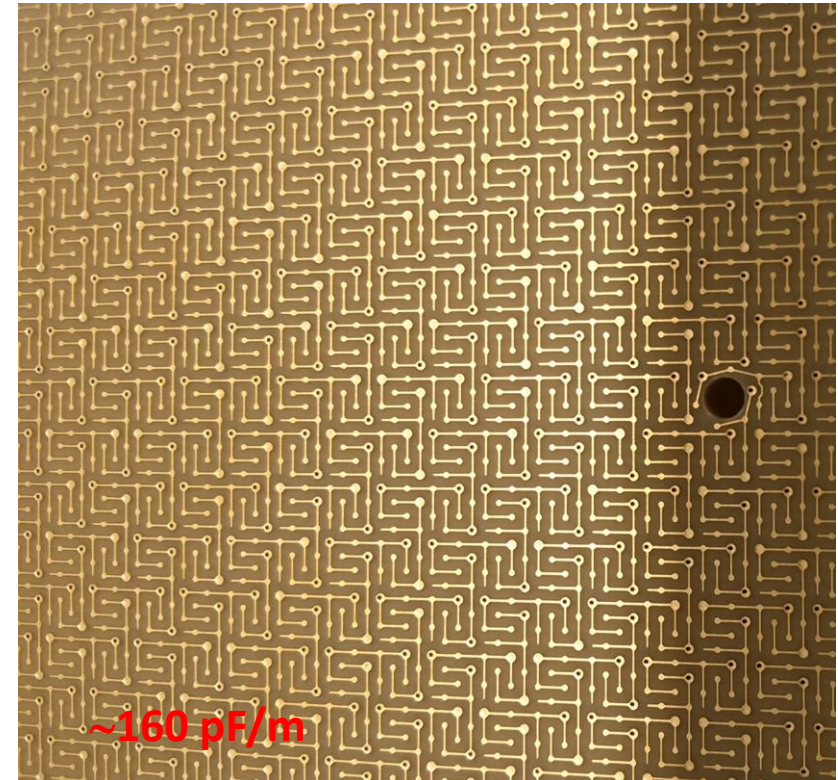


LEM and Anode

CFR-35 – NP02



Anode 2D RO



LAr surface in Cold Box Tests

