# LEMs operation in ProtoDUNE-DP

*Workshop on the LEM/Thick GEM cryogenic utilization in pure Argon over large detection surfaces*

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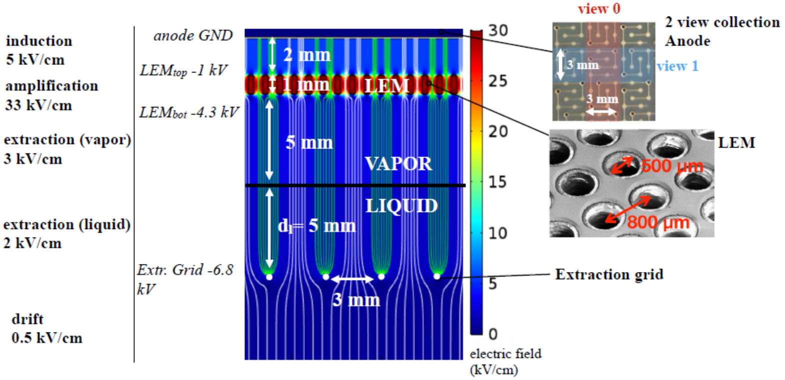
CEA-Saclay/IRFU

2020/04/06

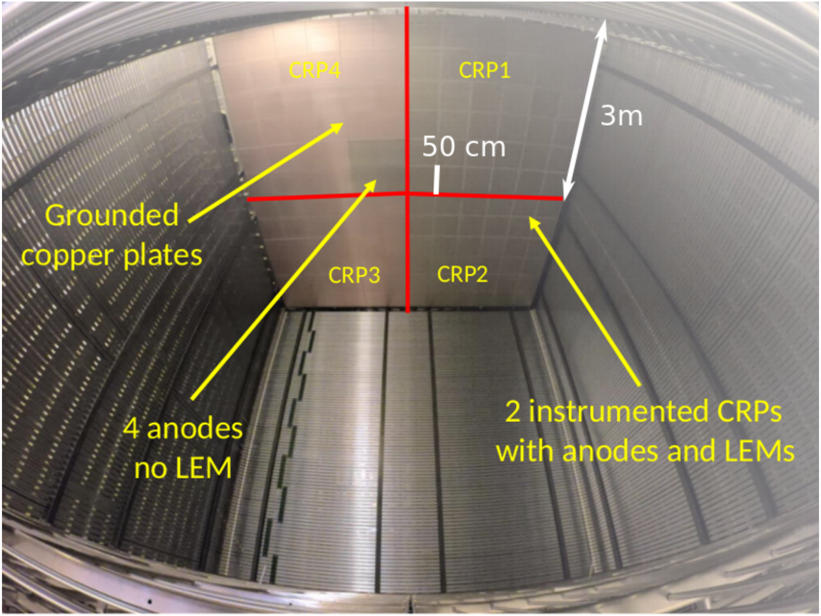
# ProtoDUNE-DP CERN

# Operating principle of ProtoDUNE-DP

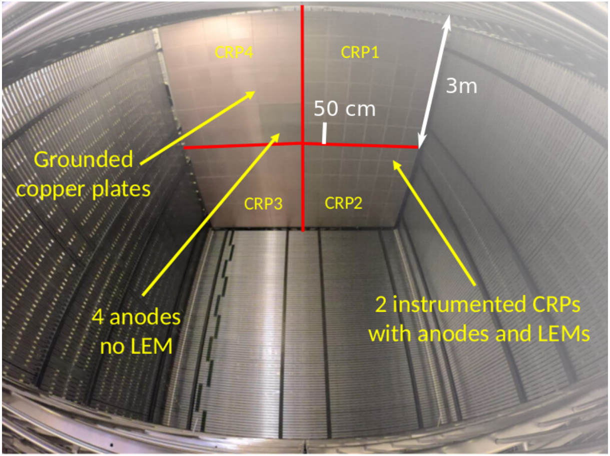



- Homogeneous drift field thanks to cathode and field cage
- Extraction field between grid and LEM bottom electrode
- Amplification in LEMs holes
- Readout in two directions by induction on the anode by field between LEM top electrode and anode

# LEMs in ProtoDUNE-DP



# Commissioning of ProtoDUNE in 2019

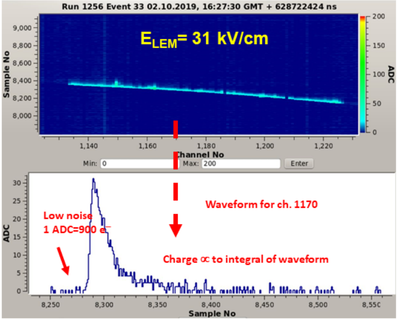



- 13/06:
  Cryostat closure
- 14/06 - 30/06:
  Air removal with GAr
- 01/07 - 04/07:
  Cooling down
- 05/07 - 09/08:
  LAr filling
- 12/08:
  Start TPC commissioning
- 29/08:
  First tracks from cosmics

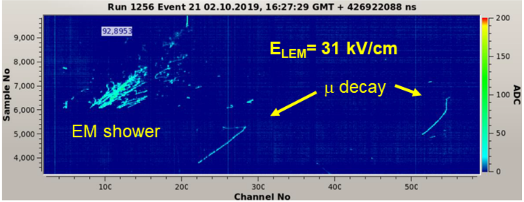
# Cosmic ray events recorded in ProtoDUNE-DP

Cosmic ray events at higher gains (3.1/3.2 kV) in protoDUNEdual-phase (October 2019)

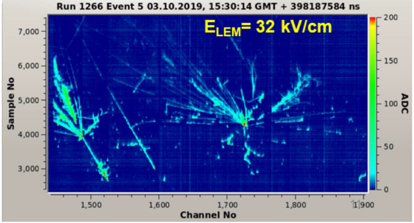
Horizontal muon track



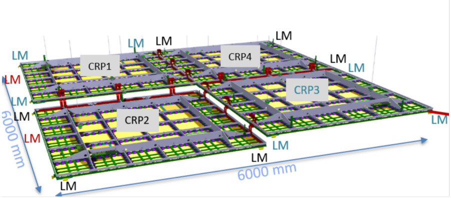

Electromagnetic shower + two muons decay



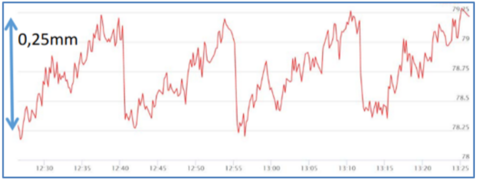

*Multiple hadronic interactions in a shower*



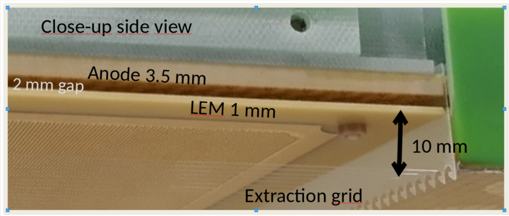
# Charge Readout Planes (see talks by D. Duchesneau and B. Aimard)



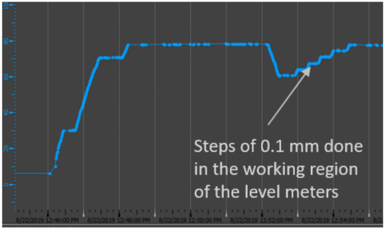

Planarity of ± 1 mm (after metrology at room temperature)




Automatic tracking of the liquid level

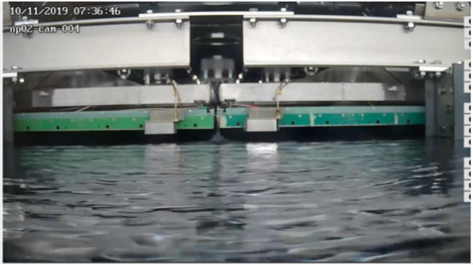


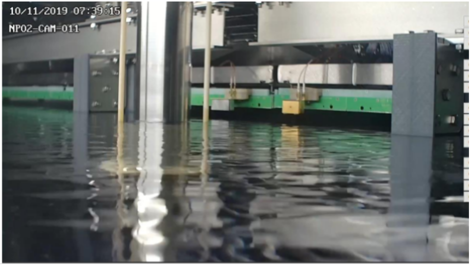

Planarity of ± 2 mm (observed during comissioning)

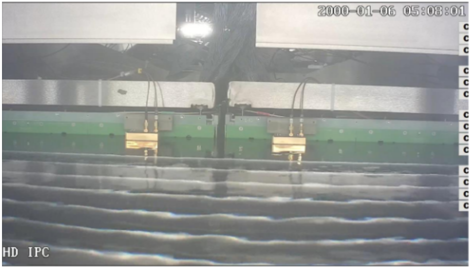


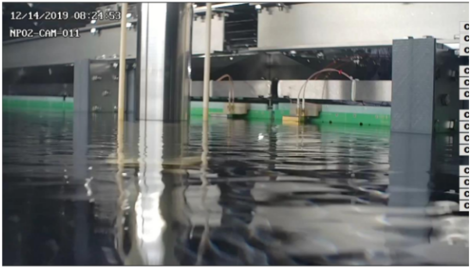

Tracking precision of 100 $\mu$m

# Cryogenics conditions and liquid argon surface



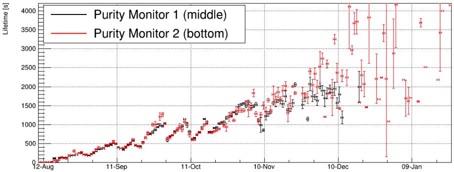



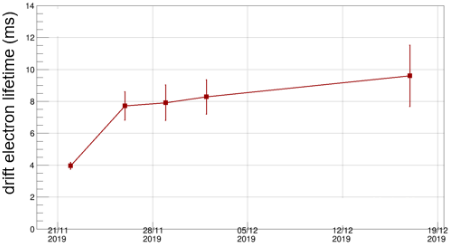



# Argon purity in ProtoDUNE-DP

Purity measurements from short purity monitors




Purity measurements from long purity monitor



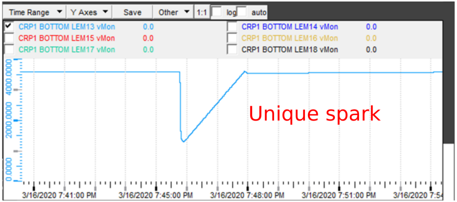

- 3 purity monitors (two *short* 17-cm long and one *long* 48cm-long)
- Since November 2019, short purity monitors sensitivity reached
- Long purity monitor more sensitive
- Discrepancies between long and shorts under investigation
- According to long monitor, electron lifetime larger than 7 ms since November and increasing

# Technical issues

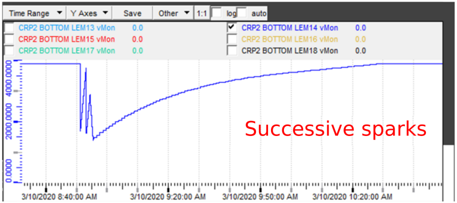
- Short-circuit between VHV cable and 21st ring of field cage
  $\Rightarrow$ Inhomogeneous electric field
  $\Rightarrow$ maximum 150 kV
  (50 kV standard, 70 & 90 kV recently tested)
  $\Rightarrow$ Should be fixed soon but challenging
- Surface instabilities:
  - Short pressure increase of 35 mbar performed every few days
  - Eliminates bubbles from top of field cage and HV feedthrough
  - Briefly eliminates waves on liquid surface
- Cryogenics instabilities could correlate with CRPs instabilities
- Cold filters clogging initially requiring cleaning every 10 days
  $\Rightarrow$ No more clogging after last intervention in November 2019
- Purity level systematics to understand
- Several electronics channels damaged by grid sparks

# Slow control and LEM sparking

- Cold box: no automated protection of LEMs
  $\Rightarrow$ carbonization on several LEMs from continuous discharges
- Two types of LEMs spark events: unique and successive
- In ProtoDUNE-DP, automatic reduction of HV from slow control:
  - $\sim$ 50 V for unique sparks
  - up to 2.5 kV + slow ramping up for successsive sparks (carbonization)



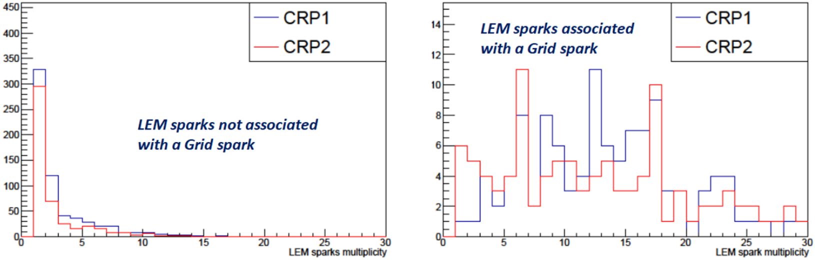

- Recovery time for a unique spark $\simeq$ 2 minutes
- Dead time for successive sparks of up to 2 hours




- $\sim$ 8 % of sparking events are successive sparks in standard operation

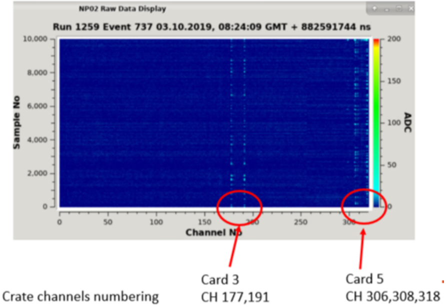
# Sparking events during CRP operation

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




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

# Grid sparking




- Problematic due to damages to front-end electronics
- Origin unclear since grids should be immersed most of the time by 4-5 mm inside LAr:
  - part of the grid temporarily in GAr due to large bubbles, waves
  - local charge build-up on some PCB parts or elements?
  - capacitive effects or induction on grid system
- Front-end cards put in a safe position (disconnected from cold flanges) for most tests
- Long-term stability tests performed to find operations conditions limiting grid sparking
- Test planned: increase total capacitance of LEMs-grid system to reduce sensitivity to capacitive variations

# Grid sparking

- Grid sparking analysis during long-term stability tests

| Sparks/h | Extraction | Cathode | R = 0 | R = 10 MΩ | R = 500 MΩ |
|---|---|---|---|---|---|
| CRP1 | 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 |
| $\Delta V = 3.1\,kV$ | 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 | 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 |
| $\Delta V = 3.4\,kV$ | OFF | ON | | | 0.02 ± 0.02 |
| | | OFF | | | 0.00 ± 0.00 |
| | | ON-OFF | | | 0.02 ± 0.02 |

- No evidence for an impact of the drift field
- Extraction field OFF $\Rightarrow$ rate consistent with zero, independent from LEMs $\Delta V$, current limiting resistors and drift
- Extraction field ON:
  - Sparks probably due to LEMs-grid coupling
  - Rate $\in$ [0.2, 0.9] spark/h (LEM $\Delta V > 3.1$ kV)
  - Larger rate with larger LEM $\Delta V$
  - Factor of 2 reduction with resistors from 500 MΩ to 10 MΩ

# LEMs HV scan

- Sparking rates with HV scan on CRP2
- LEMs sparking rates are normalised to a full CRP
- No extraction field on 9-11 LEMs chosen for their stability
- Rest of the CRP at $\Delta V = 2.0\,\mathrm{kV}$
- *Single* sparks with LEM multiplicity of 1
  *Multiple* sparks with multiplicity $\geq 2$

| $\Delta V$ [kV] | Duration [h] | Single [$CRP^{-1} \times h^{-1}$] | Multiple [$CRP^{-1} \times h^{-}1$] | Total [$CRP^{-1} \times h^{-1}$] |
|---|---|---|---|---|
| 3.1 | 21 | $0.2 \pm 0.2$ | $0.0 \pm 0.0$ | $0.2 \pm 0.2$ |
| 3.2 | 23 | $0.0 \pm 0.0$ | $0.0 \pm 0.0$ | $0.0 \pm 0.0$ |
| 3.3 | 23 | $1.0 \pm 0.4$ | $0.3 \pm 0.2$ | $1.3 \pm 0.4$ |
| 3.4 | 43 | $0.5 \pm 0.2$ | $0.8 \pm 0.3$ | $1.3 \pm 0.3$ |
| 3.5 | 18 | $1.1 \pm 0.4$ | $4.1 \pm 0.9$ | $5.2 \pm 1.0$ |

- Maximum operation HV is $\Delta V = 3.4\,\mathrm{kV}$

# LEMs sparking rates analysis

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

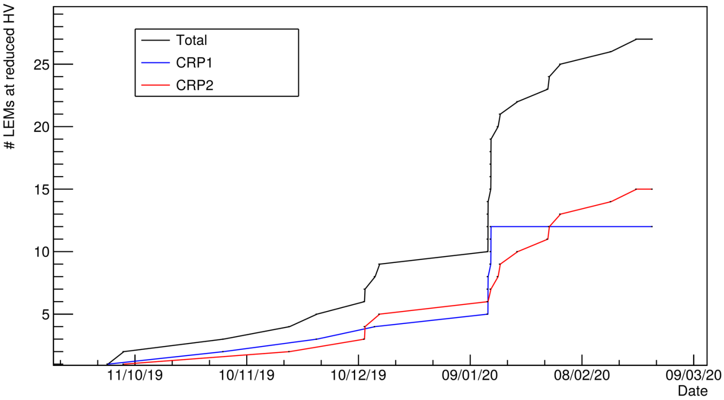
| Spark/CRP/h | Extraction | Cathode | R = 0 | R = 10 MΩ | R = 500 MΩ |
|---|---|---|---|---|---|
| CRP1 $\Delta V = 3.1\,kV$ | ON | ON | 1.4 ± 0.2 | 2.9 ± 0.3 | *4.6 ± 0.5* |
| | | OFF | 1.9 ± 0.2 | 2.6 ± 0.2 | 1.0 ± 0.2 — *1.6 ± 0.2* |
| | | ON - OFF | -0.5 ± 0.3 | 0.3 ± 0.3 | *3.0 ± 0.5* |
| | OFF | 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 $\Delta V$ across the LEMs $\Rightarrow$ higher sparking rate
- With extraction: no visible contribution of drift field
- Current limiting resistors value impact sparking rates
- The extraction field seems to increase the sparking rate

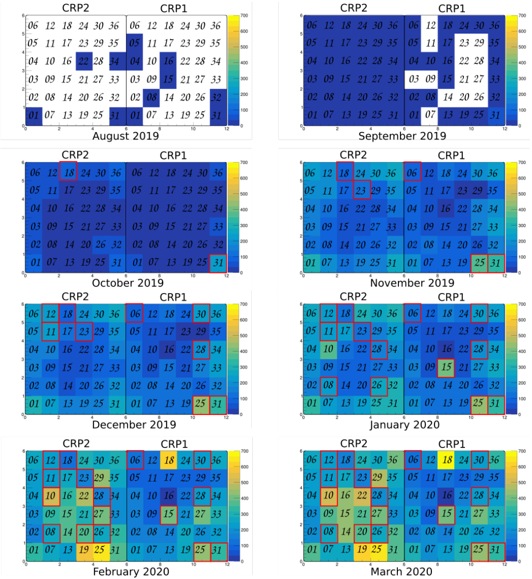
# LEMs aging during ProtoDUNE-DP operations

- Increasing number of LEMs with nominal ΔV below 2.9 kV

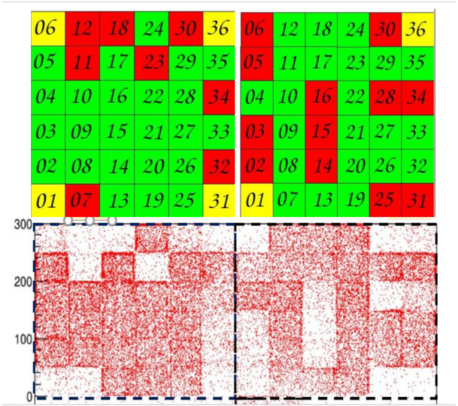



- To this date, 27 LEMs limited to $\Delta V = 2.9$ kV or less

# 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 $\Delta V \leq 2\,\text{kV}$: 22 % of LEMs as of March 2020
- LEM 18 CRP1 probably aging faster since February
- Close to 50 000 sparks since beginning of operations

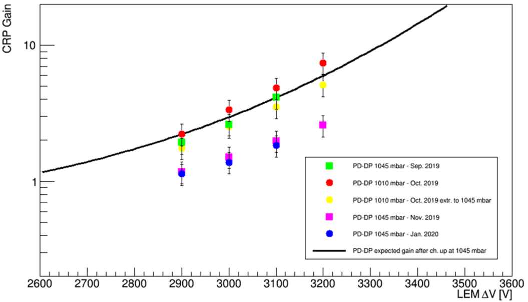



Cross-check of reduced LEM gain with the point of origin of tracks

- 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

# 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%



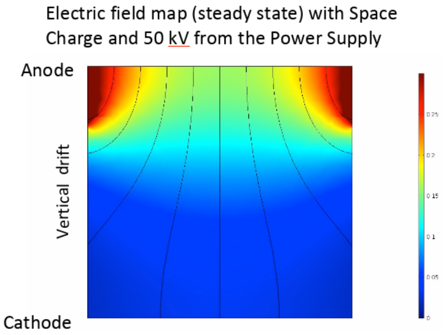

- November $\rightarrow$ January: very small reduction
- September $\rightarrow$ November: Reduction by at least a factor of 2
- Reductions due to charging up effects for designs with rims around holes

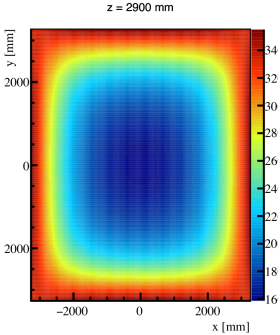
- Gain a factor of 2 lower than extrapolated from ETHZ measurements

  (https://arxiv.org/abs/1412.4402)
- Discrepancy not yet understood, dedicated study to come

# Electric field inhomogeneity in ProtoDUNE-DP

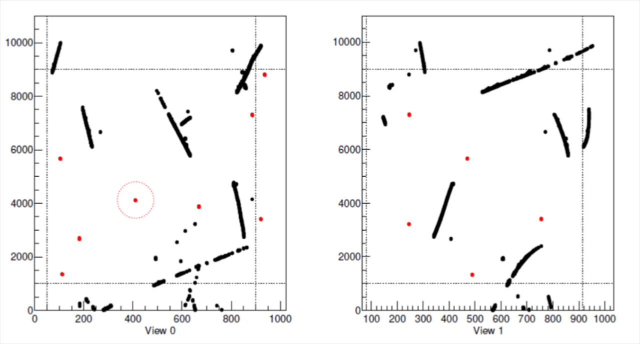
- Due to the HV feedthrough incident, electric field very inhomogeneous
- Different electric field could lead to different CRP gains depending on the position in the detector
- Dedicated study to be carried out to help understanding if this can explain the observed CRP gains



# $^{39}$Ar analysis with ProtoDUNE-DP

- $^{39}$Ar naturally and homogeneously present in Ar: decay rate per CRP $= 1.5 \times 10^4$ Bq
- Charge deposition constant with time $\Rightarrow$ calibration of LEM gain and monitoring of space charge effects

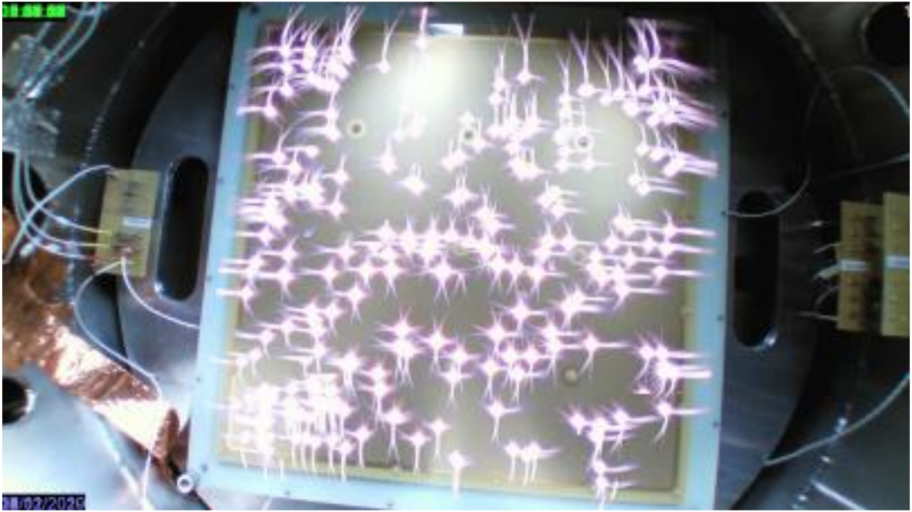



- Events selected as isolated hits matched in the two independent views
- Charge sharing between views evenly centered around 50 %

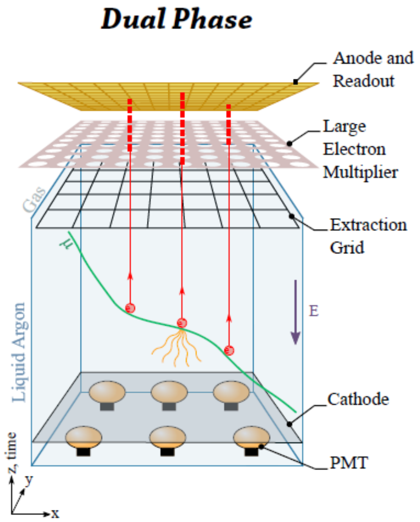
# Conclusions

- Extensive LEMs sparking rate studies carried out, and continuing
- Promising CRP gain calibration with $^{39}$Ar
- CRP gains lower than expected, needs to be understood
- Proof of principle of 300 t DPAr TPC made
- LEMs R&D in progress for ProtoDUNE-DP Phase II to improve HV stability, prevent carbonization, increase active area (see talk by A. Delbart)
- System to be upgraded to prevent grid sparking damaging the electronics (see talks by D. Duchesneau & B. Aimard)
- Several difficulties identified and developments in progress to mitigate them (waves, bubbles, filter clogging)
- These improvements should help demonstrate the feasibility of a DP module as far detector for DUNE

# Thank you for your attention!

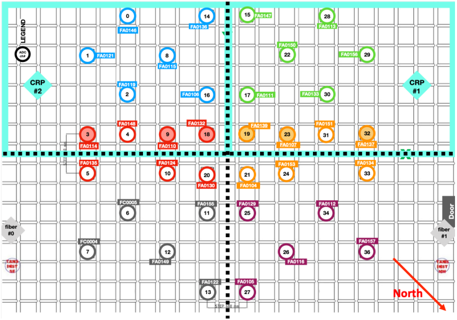


# Operating principle of ProtoDUNE-DP




- 720 t of LAr in a cryostat
- Scintillation light read out at the bottom of the cryostat
- Vertical drift of electrons
- Electrons extracted from liquid into gas phase
- Charge signal amplified and readout
- Dual phase TPC allows 3D reconstruction of tracks in detector

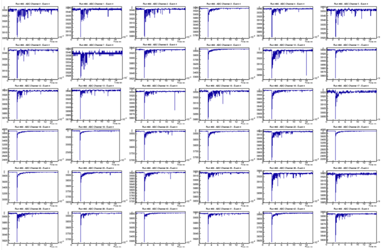
# Photodetection system in ProtoDUNE-DP



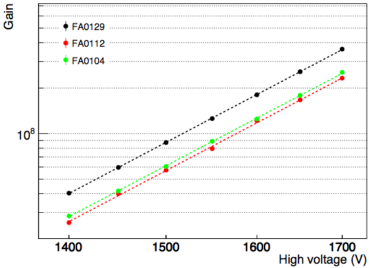

- 36 × 8” cryogenic PMTs Hamamatsu R5912-02-mod
- 7 m below collection plane
- Below cathode and ground grid
- Position optimized for light collection in cosmic rays events
- Wavelength shifter: 30 × PEN and 6 × TPB
- Light Calibration System for PMT stability estimation using blue LEDs and optical fibers

# Photodetection system operation

Coincident scintillation in 36 PMTs



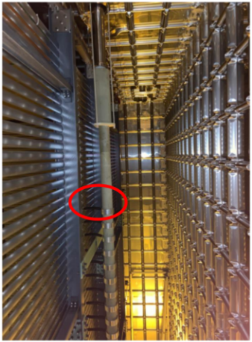
Gain linearity with HV

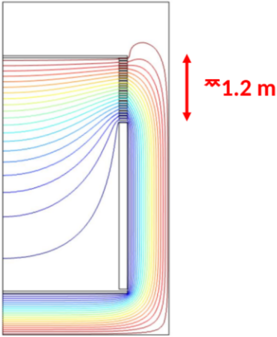



- Scintillation light measured since June 2019
- Data taken almost every day (86 MEvents)
- Very low noise level at $0.6 \pm 0.1$ ADC
- $S/N > 11$ for SPE at $G = 10^7$ (requirement of $S/N > 5$)
- Baseline (individual fibers + LED) and alternative calibration (top fibers) validated

# HV short cut

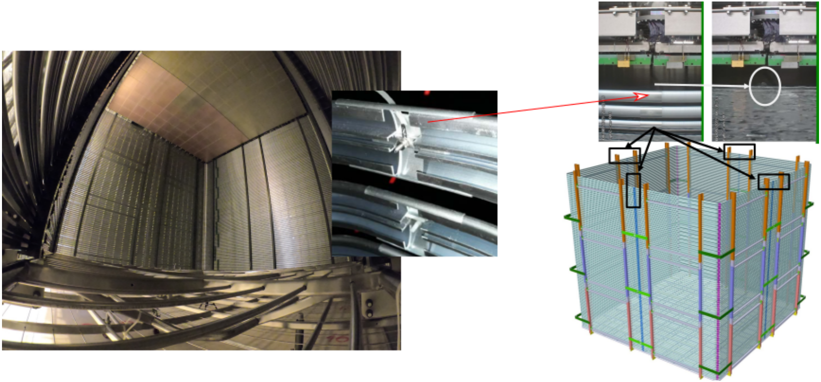
- Short cut between VHV feedthrough and 21st field cage ring
- HV limited to 150 kV, operated at 50 kV currently



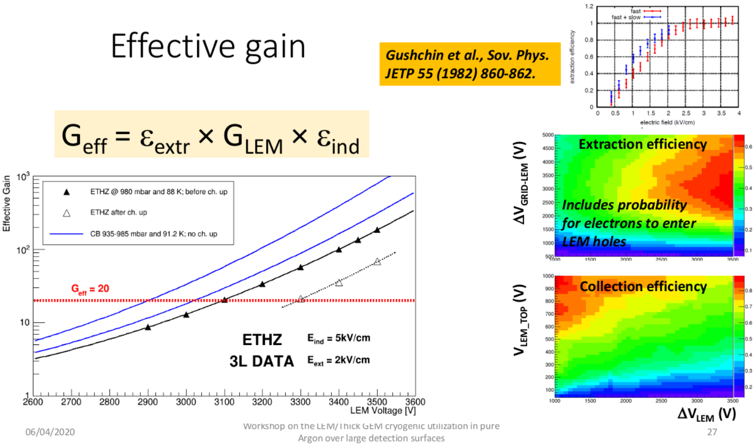


# Bubbles in ProtoDUNE-DP

- Bubbles appear above clips of field cage and VHV extender
- Origin of the bubbles still unknown

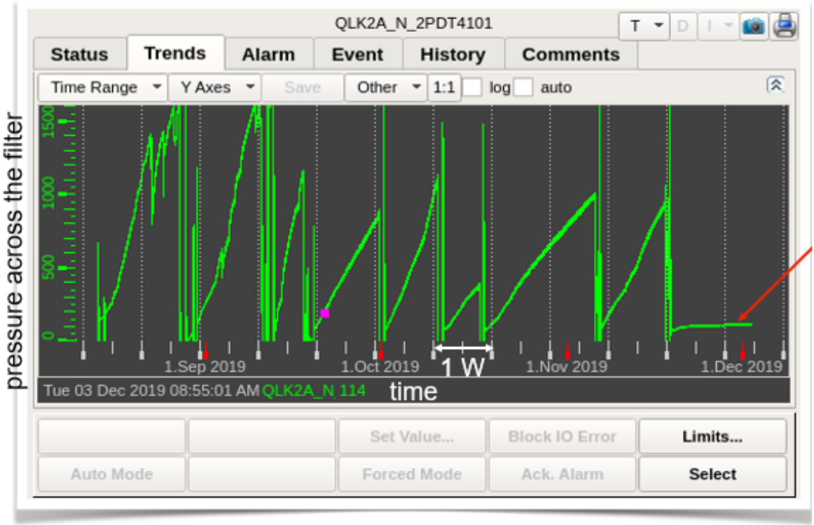


# Effective gain




E. Mazzucato

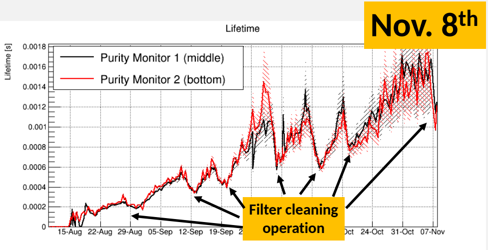
# Cold filters clogging



# Purity measurements

## Liquid Argon Purity

- LAr purity monitored so far by two 17 cm long PMs located at the bottom of the cryostat and in the middle.
- Recirculation should improve $e^-$ lifetime by factor 2.7 every ~4.5 days (1 volume recirculated).
- LAr purity limited so far to about 1.5 ms $e^-$ lifetime by several filter clogging and cleaning operations.





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