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Electrode Surface Engineering for Stable High-Voltage Operation in LXe TPCs: Mitigating Pre-Breakdown Phenomena

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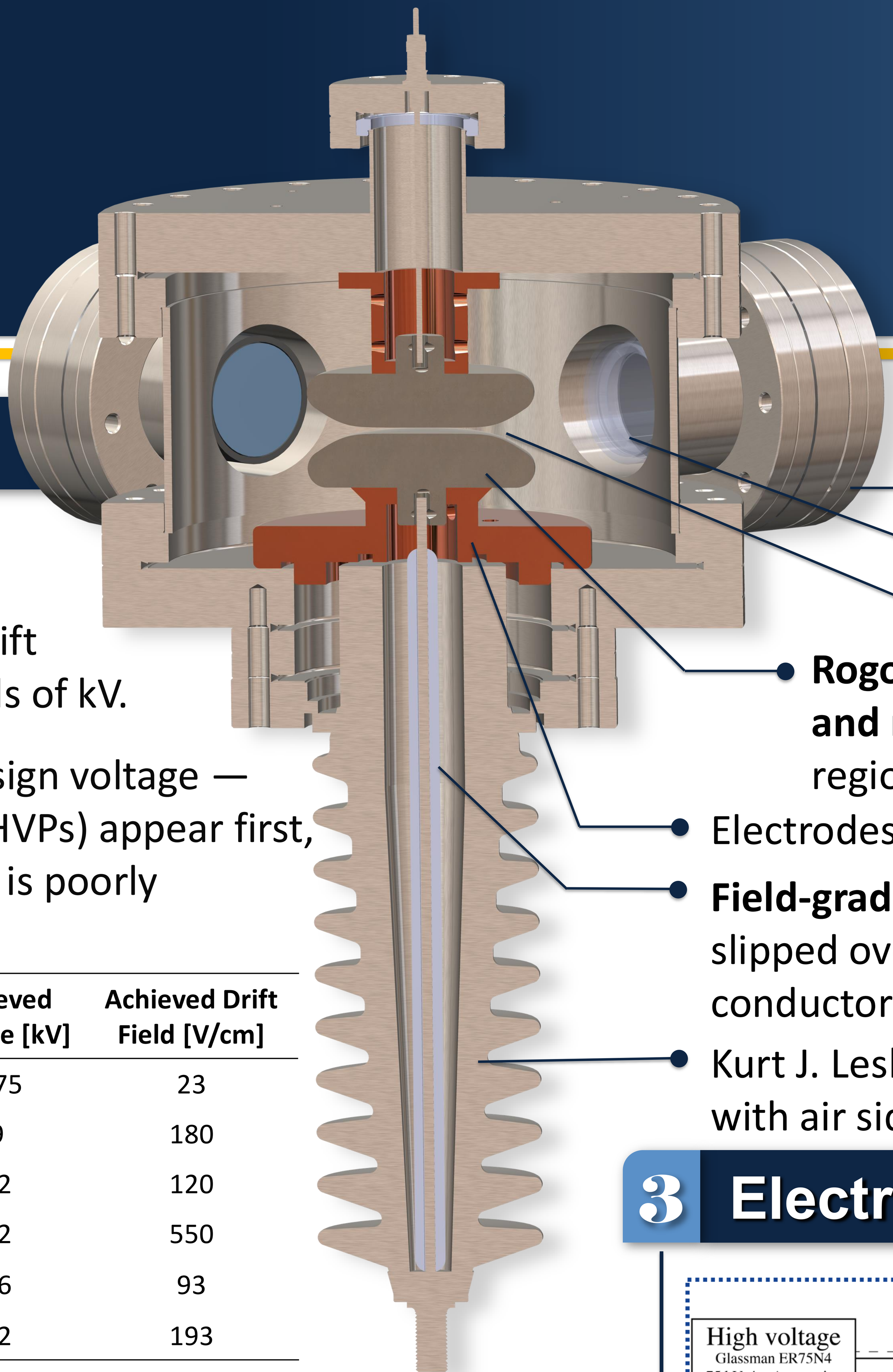
1 HV Challenge

Noble-liquid TPCs lead the searches for 0νββ and dark matter; scaling up needs drift fields held at tens–hundreds of kV.

No detector reached its design voltage — high-voltage phenomena (HVPs) appear first, and their nature varies and is poorly understood.

Experiment	Design Voltage [kV]	Achieved Voltage [kV]	Achieved Drift Field [V/cm]
XENONnT [7]	24	2.75	23
LUX [3]	100	9	180
XENON1T [4]	100	12	120
EXO-200 [1/2]	50	12	550
PandaX-4T [5]	70	16	93
LZ [6]	50	32	193

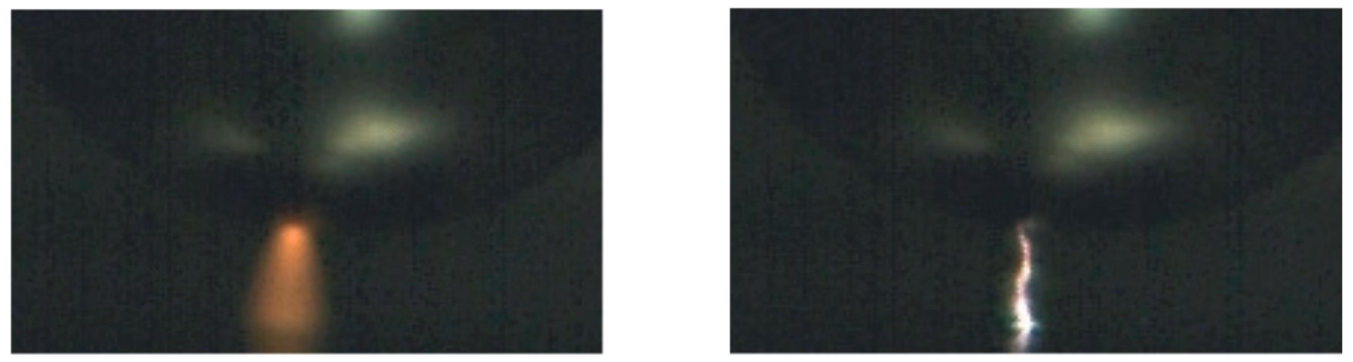
Stanford High-Voltage Test Chamber



- 10" diameter CF cylinder holds ~10kg LXe.
- Photomultiplier tubes in re-entrant windows.
- Fixed gap of 3.3mm
- **Rogowski** electrodes: a shape that ensures field is **uniform and maximal** in the central region over a large area. No other region has field as high as the center.
- Electrodes set at a fixed distance using Ultem standoffs
- **Field-grading sleeve** *(arXiv: 2606.10232)*: a 316L stainless sleeve slipped over the 100 kV feedthrough pin enlarges the center-conductor radius, lowering its peak surface field.
- Kurt J. Lesker model EFT1C12156A 100kV CF-flange feedthrough with air side potted in RTV656

2 What Controls HV Phenomena?

Pre-breakdown vs. Breakdown



Images of high voltage phenomena in liquid argon from reference [8]

Pre-breakdown: observed as small, **nondestructive** light or charge depositions that build over the last ~30–60 s before breakdown, spiking sharply in the final second [8].

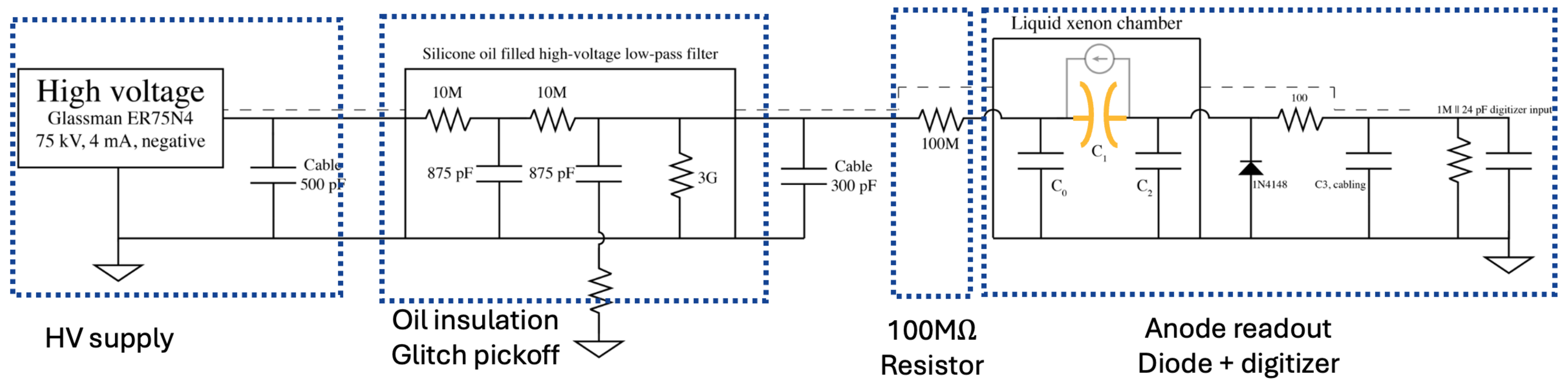
Breakdown: a low-resistance plasma channel between cathode and anode — can deposit enough energy to **hysteretically change the system.**

Goal: characterize pre-breakdown and avoid breakdown.

- Surface defects: points, edges, craters (scale with area)
- Electronegative purity of the liquid
- Temperature, pressure, proximity to phase transition
- **Chemical nature of the electrode surface, photoelectric work function ← *the knob we turn***

What are the characteristics of pre-breakdown in LXe?
Can the electrode's surface chemistry change the likelihood of HV phenomena?
How does an insulating thin film compare to a metal?

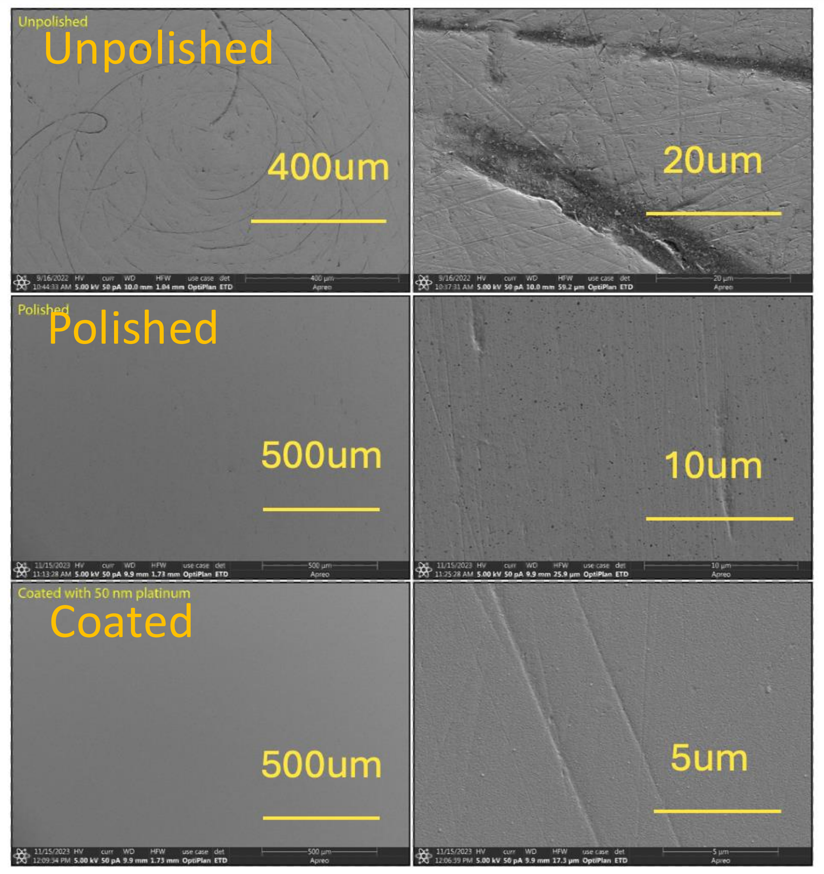
3 Electrical System

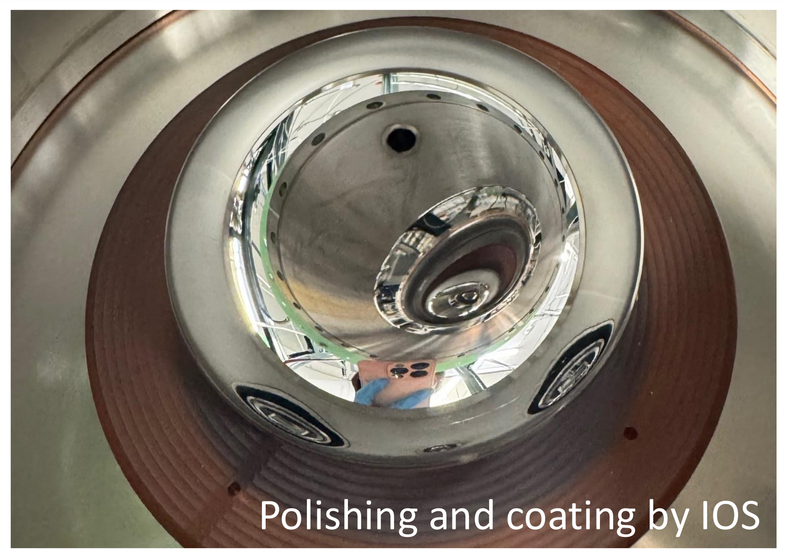


Goal: observe tiny high voltage phenomena that are non-destructive, avoiding breakdown

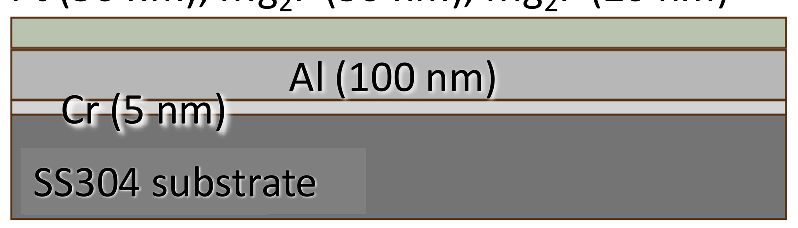
• Typical energy stored in the gap:	1 mJ
• Typical charge stored in the gap:	200 nC
• Typical charge events detected:	2 pC = 1e7 e⁻
• Energy carried in typical events from U= Q(dQ)/C:	20 nJ

4 Electrode Preparation and Surface Quality

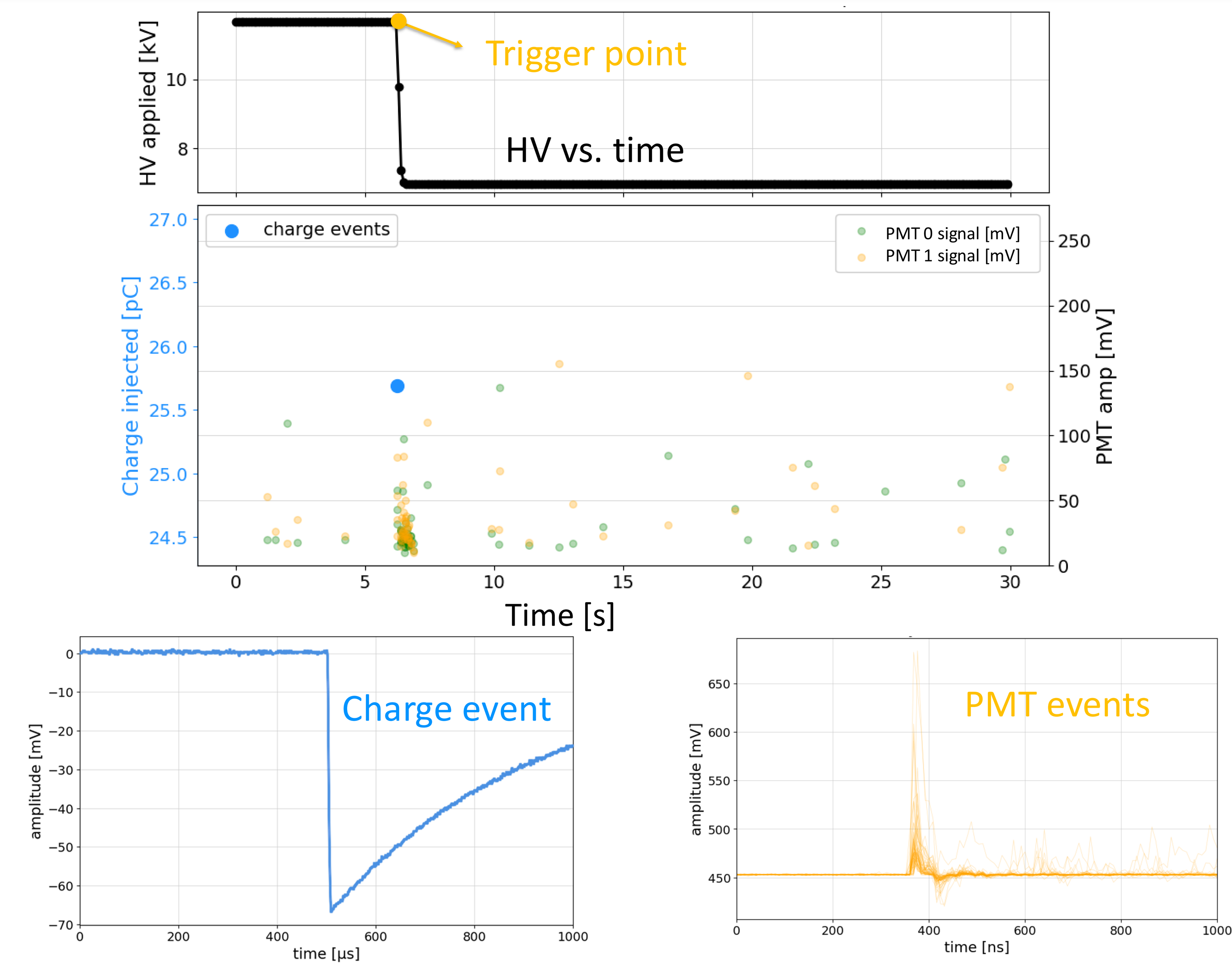




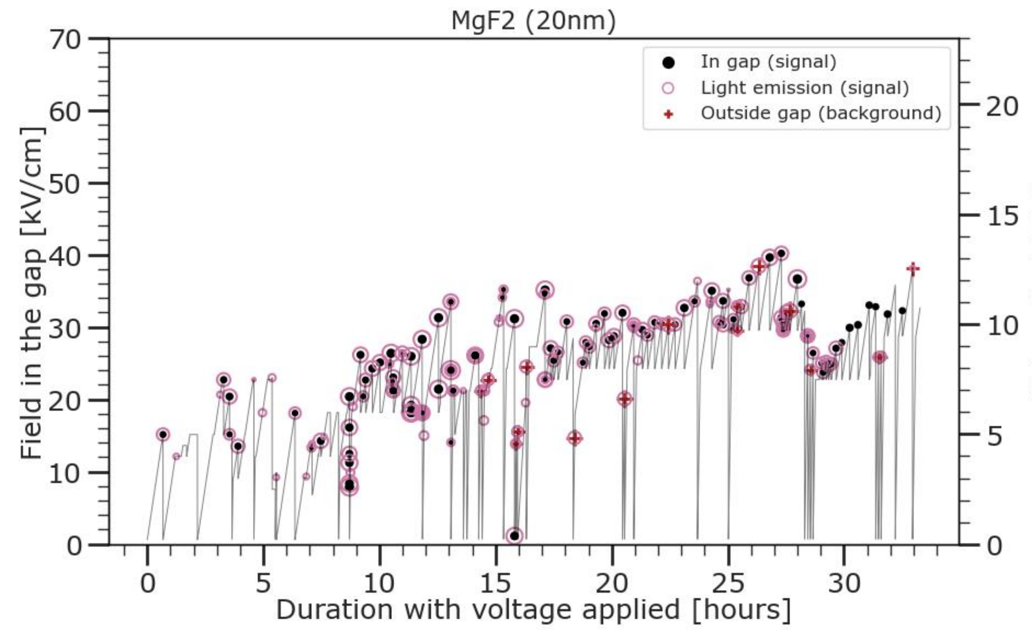
Layer of interest
Pt (50 nm), Mg_2F (50 nm), Mg_2F (20 nm)



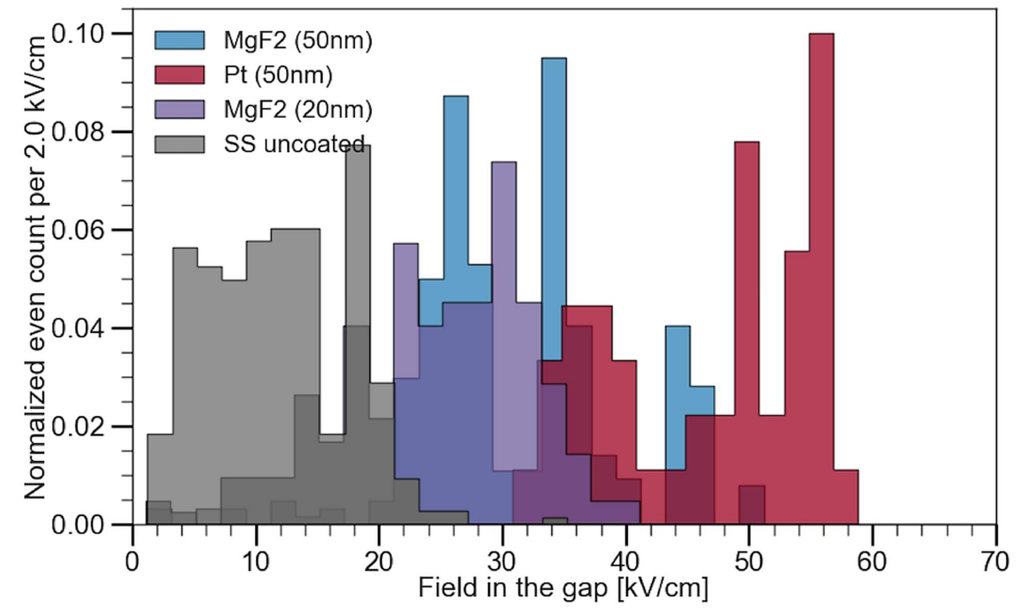
5 A Typical Pre-breakdown Event



6 Conditioning Over Time



7 Coatings Raise Threshold



Surface **coatings raise the** pre-breakdown **threshold** compared to bare 304 steel.

Platinum gives the best improvement so far, and MgF_2 also helps.

The study is still ongoing

[1] JINST 7 (2012) P05010
[2] Phys. Rev. Lett. 123, 161802 (2019)
[3] Phys. Rev. Lett. 112, 091303 (2014), 2010 J. Phys.: Conf. Ser. 203 012026
[4] EPJ C 77, no. 12 (2017): 1–23
[5] Phys. Rev. Lett. 127, 261802 (2021)
[6] arXiv:2207.03764 & 1703.09144
[7] PRL 129, 161805 (2022)
[8] JINST 11(2016) P03017