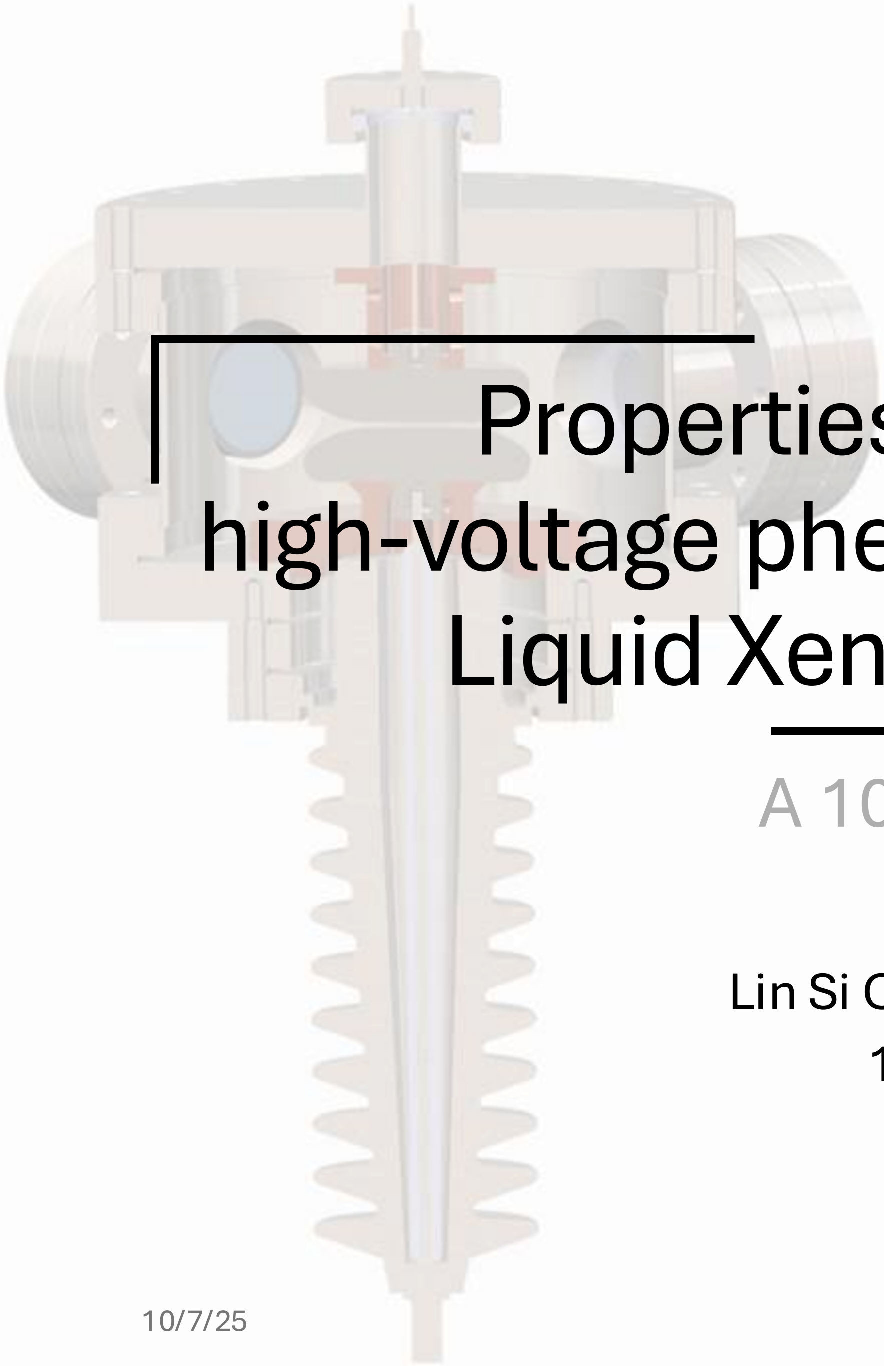
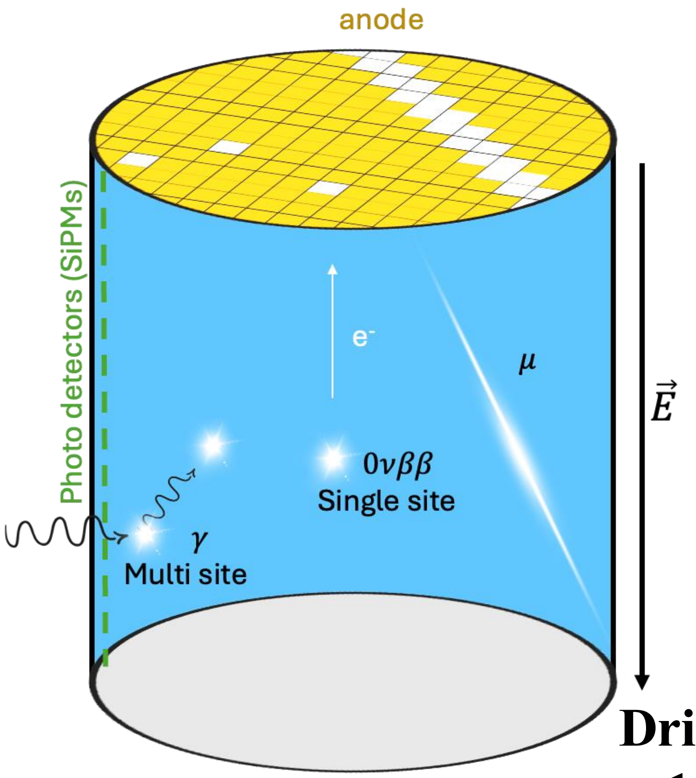


Properties and mitigation strategies of high-voltage phenomena measured at the Stanford Liquid Xenon High-Voltage Observatory

A 10 kg LXe Study of High-Voltage Phenomena with Electrode Surface Coatings

Lin Si On behalf of the nEXO collaboration
10/7/2025 CPAD Philadelphia

Why study High Voltage in Noble Liquids?



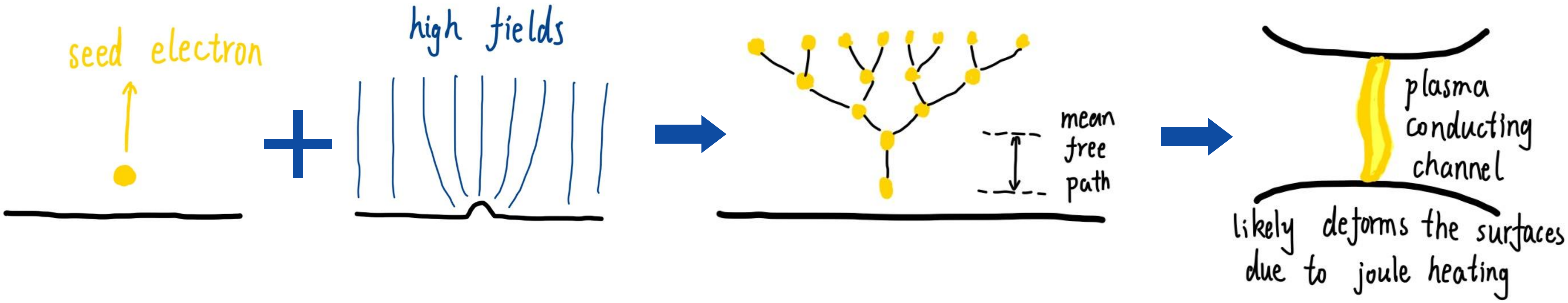
Drift fields :~100 V/cm

Xenon: XENONnT · LZ · PandaX · nEXO

Agron: DUNE · DarkSide

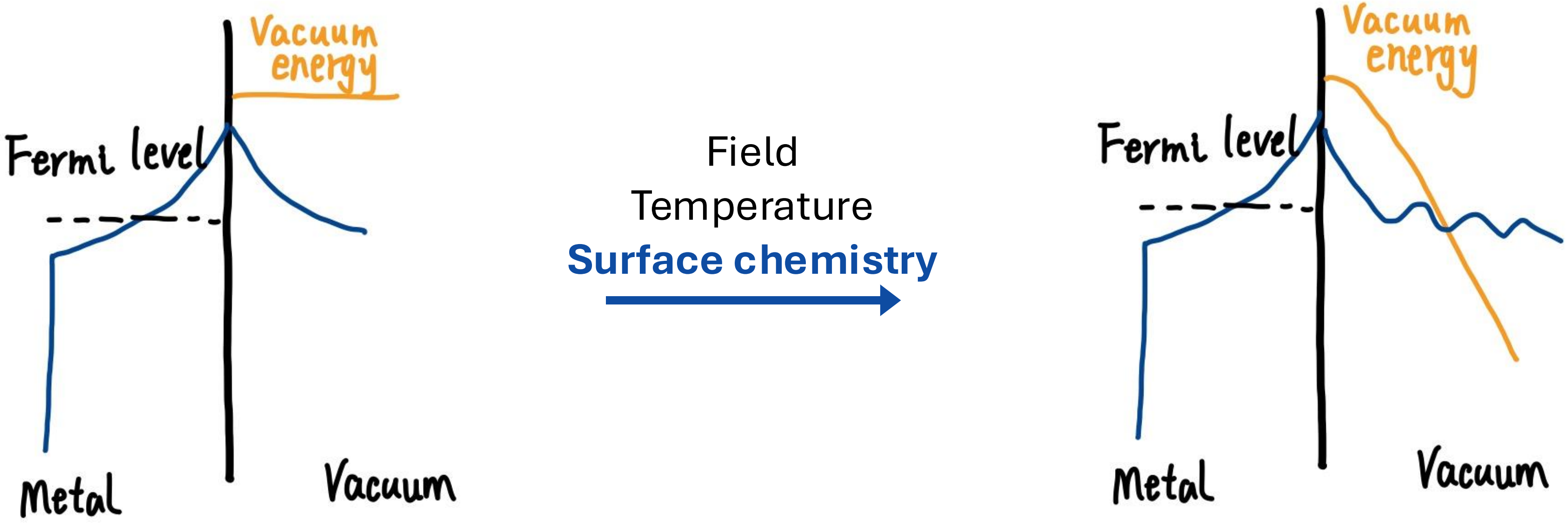
- Noble liquids enable rare-event searches (dark matter, neutrinos).
- Scaling to larger masses requires **hundreds of kV** for drift fields.
- No large-scale detector reached design field without high-voltage phenomena.

Breakdown and Pre-breakdown



- A breakdown starts from a seed electron in a strong field.
- In large detectors, we rarely reach full breakdown — but small bursts often appear on electrodes.
- These bursts emit light and electrons, disturbing data taking.
- They are short, random, and hard to reproduce.

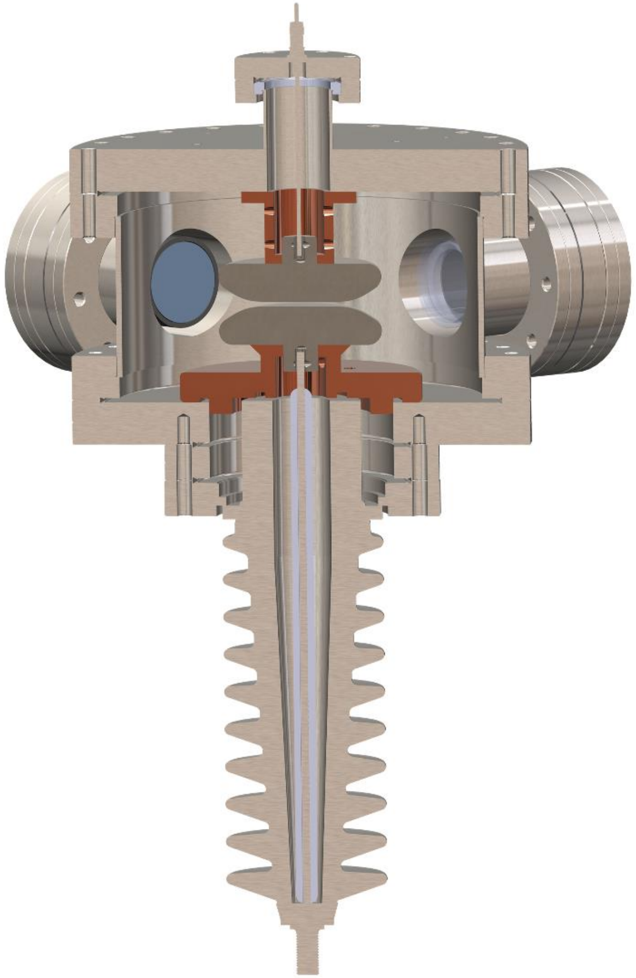
Where Do These Burst Come From?



Field
Temperature
Surface chemistry

- Bursts start with **seed electrons** emitted from electrode surfaces.
- Field emission: barrier tilts under strong field → electrons can tunnel through.
- Emission depends on **local field, temperature, and surface chemistry**.
- **Central idea:** if surface chemistry controls emission, **coatings may change HV behavior**.

Experimental Aims of the Stanford HV Test Chamber

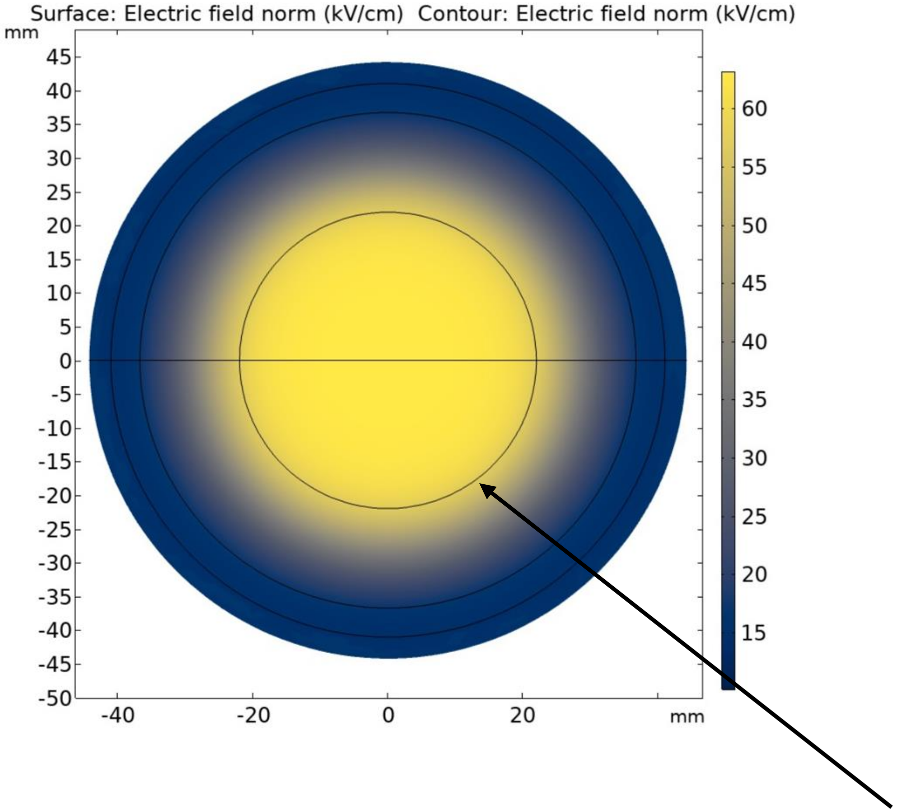


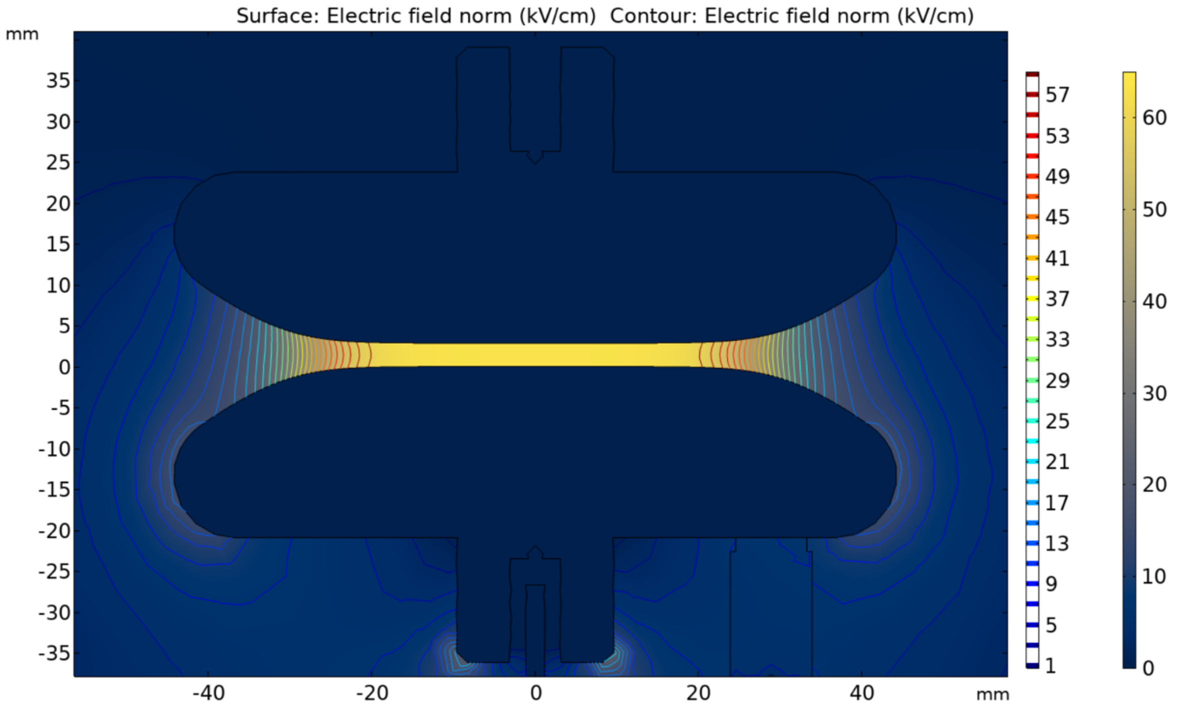
- Run liquid xenon tests where only the **electrode surface coating** changes.
- Observe **pre-breakdown** phenomena **without damaging breakdown**.
- Compare **thresholds** and features of pre-breakdown across coatings.
- Learn about the **nature of pre-breakdown in LXe**: how does charge evolve?

Not surface roughness, geometry scaling, pressure/purity effects

Chamber and Electrode Design

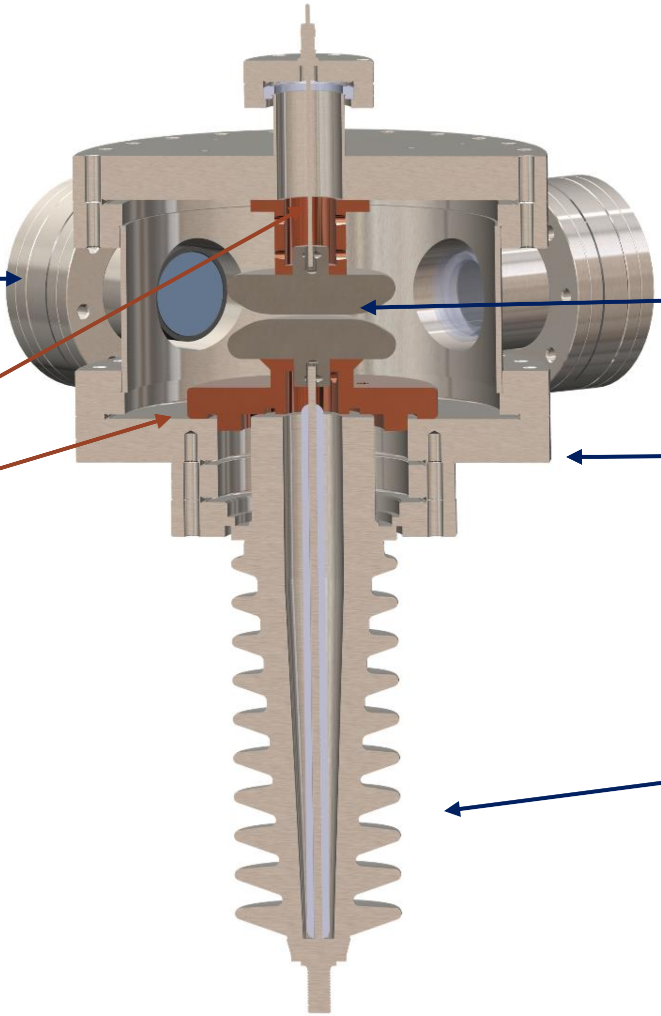
Rogowski electrodes: a shape that ensures field is **uniform and maximal** in the central region over a large area. No other region has field as high as the center





90% max field contour: 15 cm^2

Chamber and Electrode Design



Two re-entrant windows (80% at 175 nm) with VUV sensitive PMTs inserted
(provide by David Nygren, LBL/UT Arlingto)

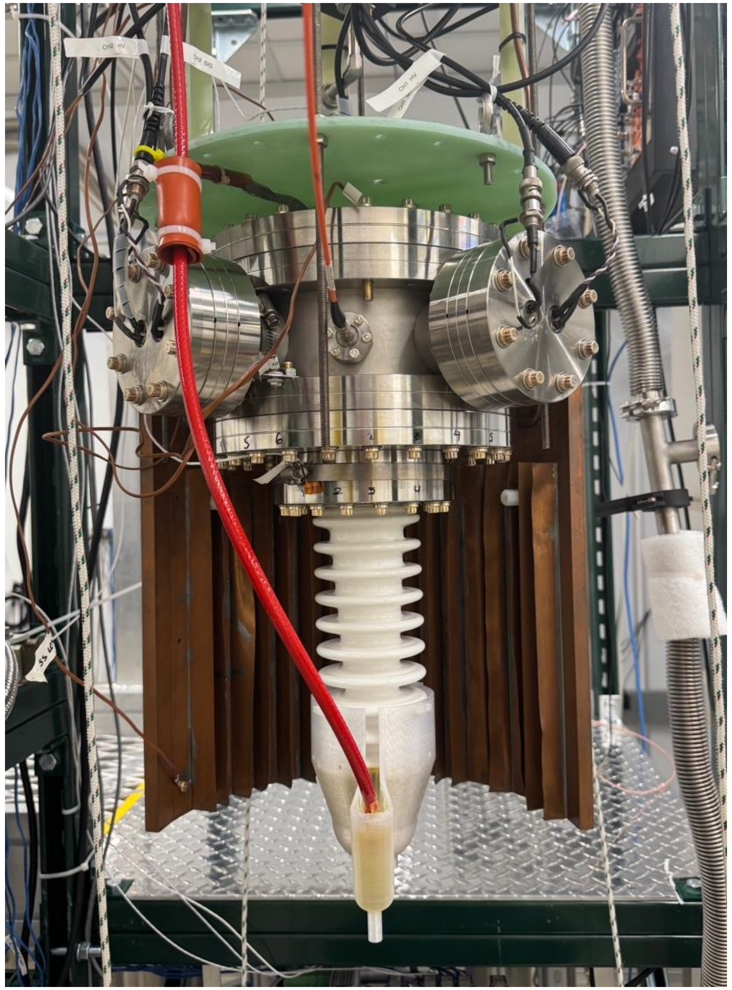
Electrodes set at a fixed distance using Ultem standoffs

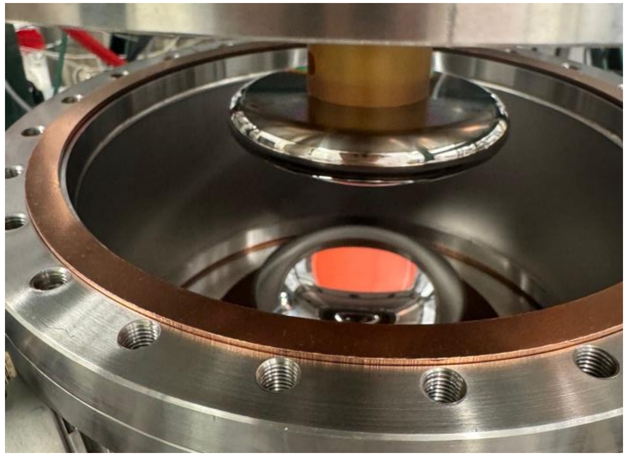
3.3mm Gap

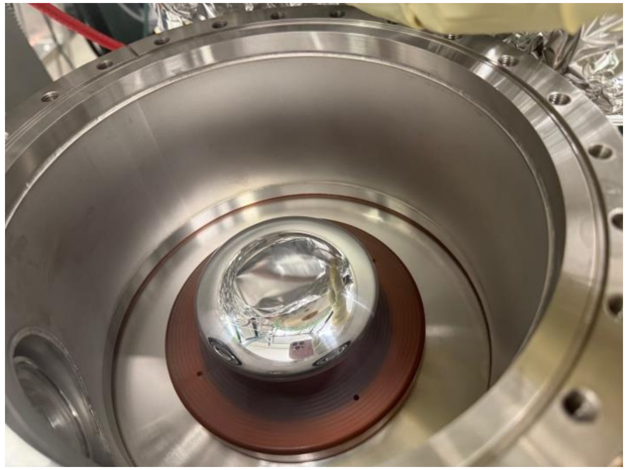
10” diameter CF cylinder holds ~11 kg (3.75 L) LXe

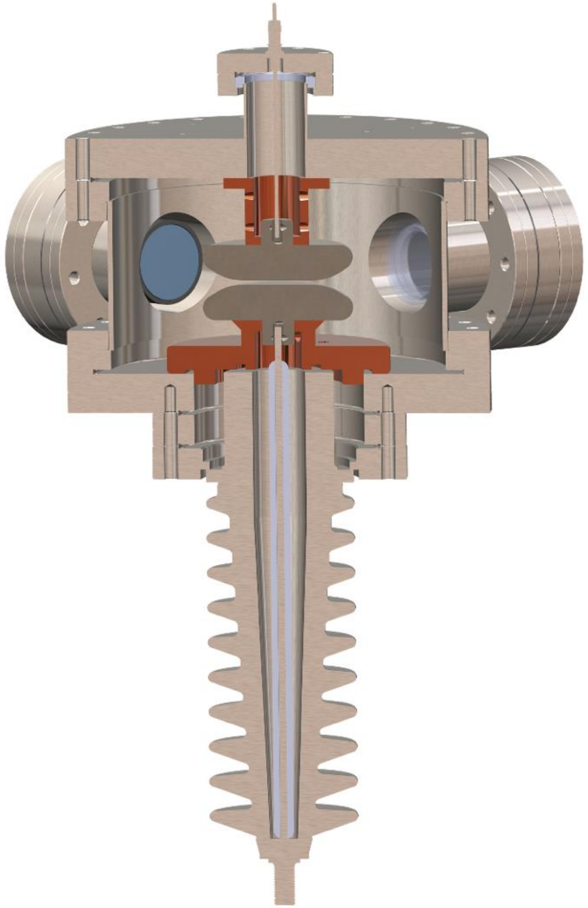
100kV feedthrough

Chamber and Electrode Design

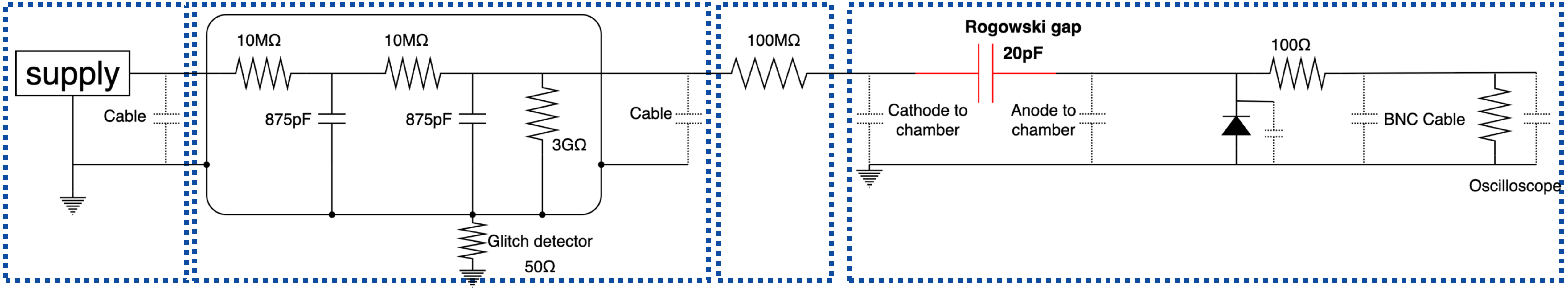








Electrical system



HV supply

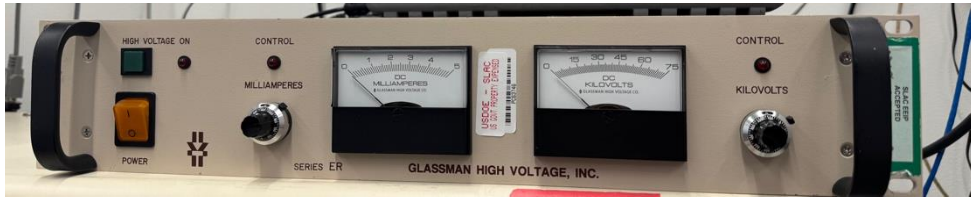
Oil insulation
Glitch pickoff

100MΩ
Resistor

Anode readout
Diode + digitizer

High Voltage Supply & Control

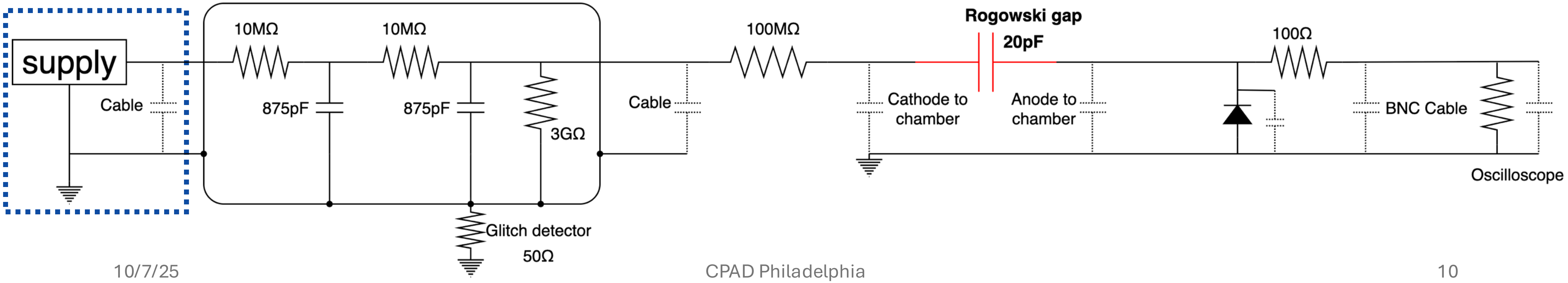
AD2



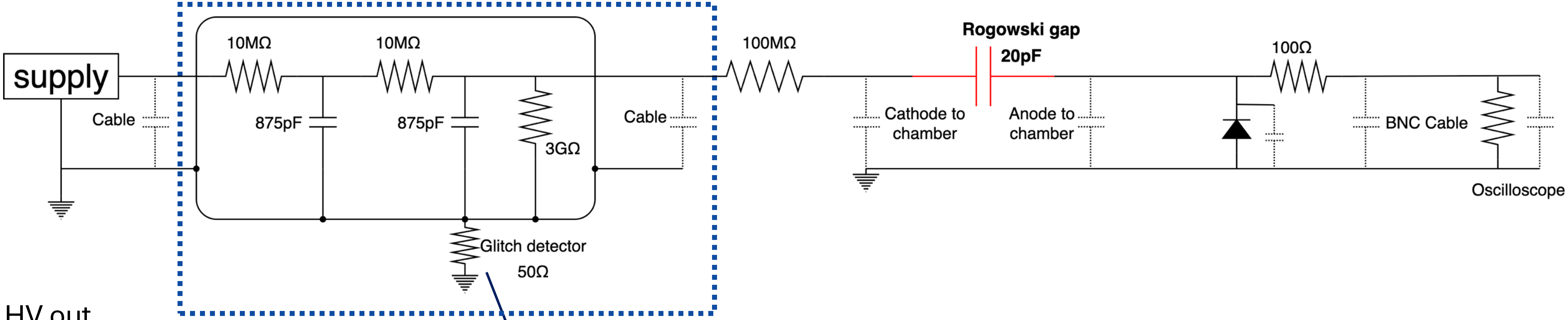
Glassman 75 kV supply

- Glassman ER series, up to 75 kV
- Controlled by AD2 DAC output
- Ramp rate: **2 V/s**
- Slow ramp avoids coupling into charge detection

Controller for HV and monitoring



Oil Filter & Cable Glitch Detector



HV out

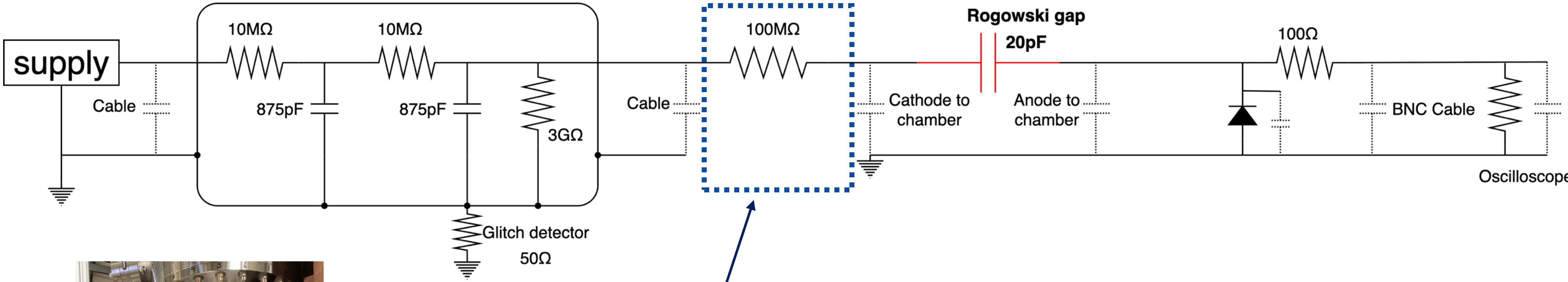
HV in

Oil insulation

Glitch detector

- Oil-filled low-pass filter smooths HV delivery
- Capacitive pickoff (“glitch channel”) senses transient pulses in cables/filter
- Digitized in parallel with anode → helps tag upstream signals

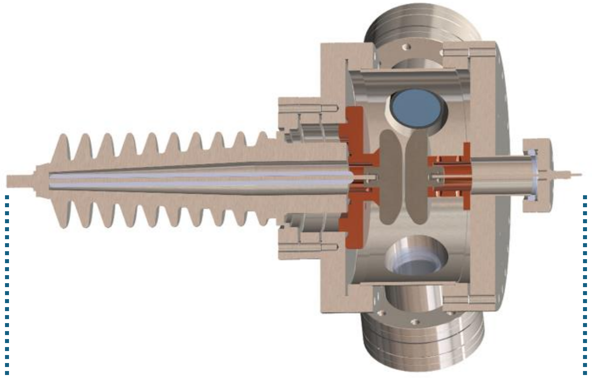
Charge-Blocking Resistor (100 MΩ)

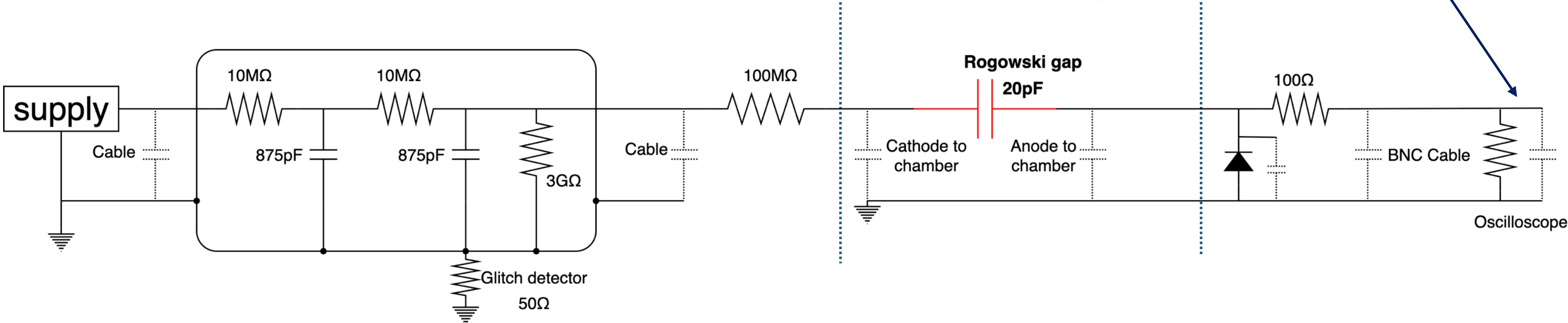


- 100 MΩ resistor in series with cathode
- Potted in epoxy for insulation in thermal bath
- Limits available charge in case of breakdown

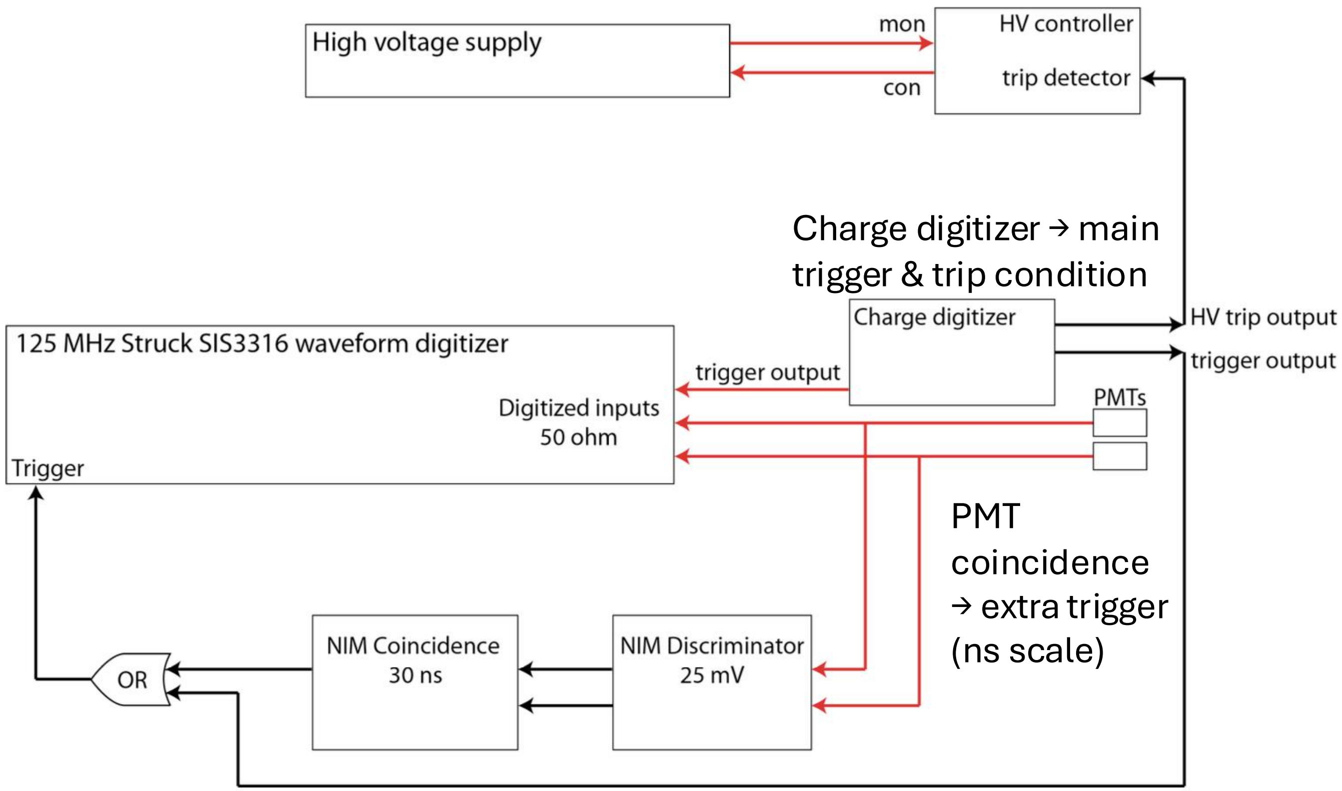
Anode Charge Detection

- Integrating readout at anode
- Circuit: anode → diode → cable capacitance → digitizer (1 MΩ)
- Sensitivity: 2.6 mV per pC (linear up to ~250 mV)
- Negative exponential pulses, τ ≈ 384 μs
- Protection diode conducts above threshold, prevents damage
- Measures total charge per event





Trigger and DAQ logic

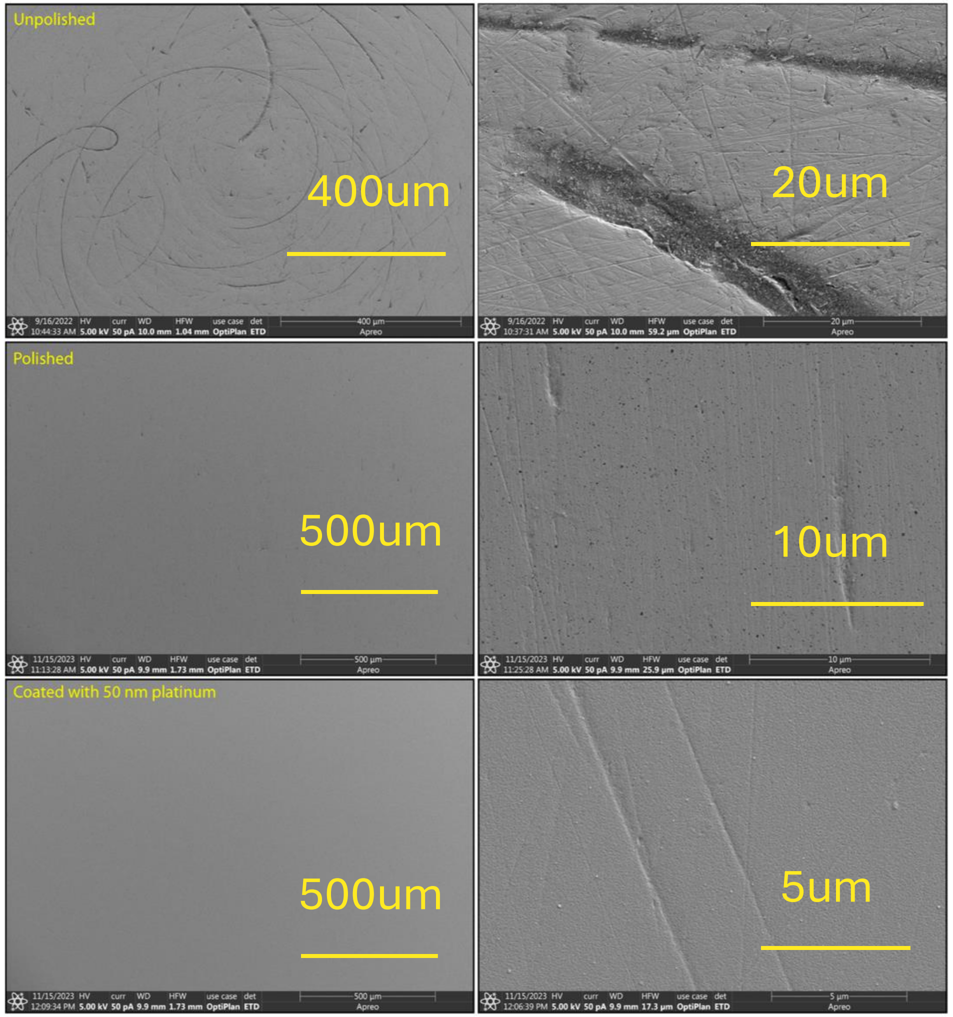


Charge digitizer → main trigger & trip condition

PMT coincidence → extra trigger (ns scale)

- Charge channel protects the system.
- Trips when it sees one big pulse or several small ones close together.
- PMTs are separate — they give fast timing but don’t control HV.
- Light and charge are combined offline to study pre-breakdown.

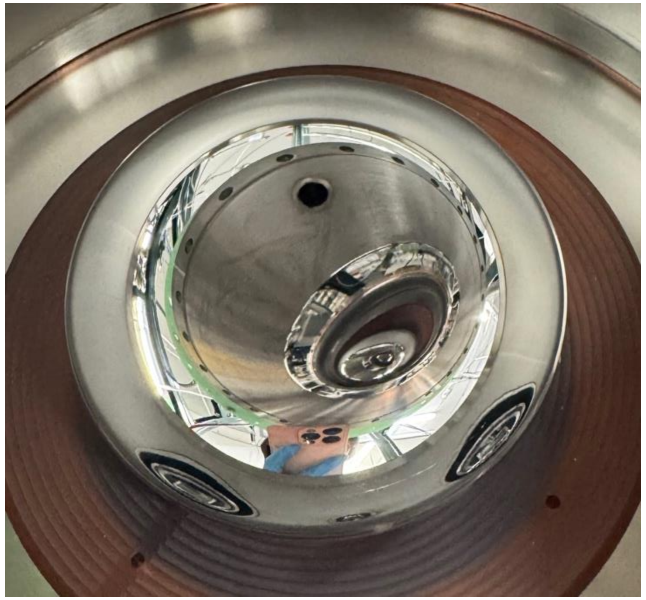
Electrode preparation and surface quality



Unpolished

polished

Coated



- Polishing improves smoothness, but residual dielectric particles remain
- All coatings applied on this polished baseline

Electrode Coatings: Process & Strategy

Stanford nano shared facilities electron beam evaporation chamber, run by Thomas Carver

- Deposited coatings on polished SS304 electrodes using e-beam evaporation.
- Layers include adhesion (Cr, Al) and functional coatings (Pt, MgF_2).
- Substrate kept cold, deposition begins at ~10^{-7} Torr.
- Goal: test if surface chemistry (metal vs insulator) changes pre-breakdown.
- So far: **Pt, MgF_2**.
- Next: **SiO_2, Parylene C**, and alternative methods / nano-coatings.

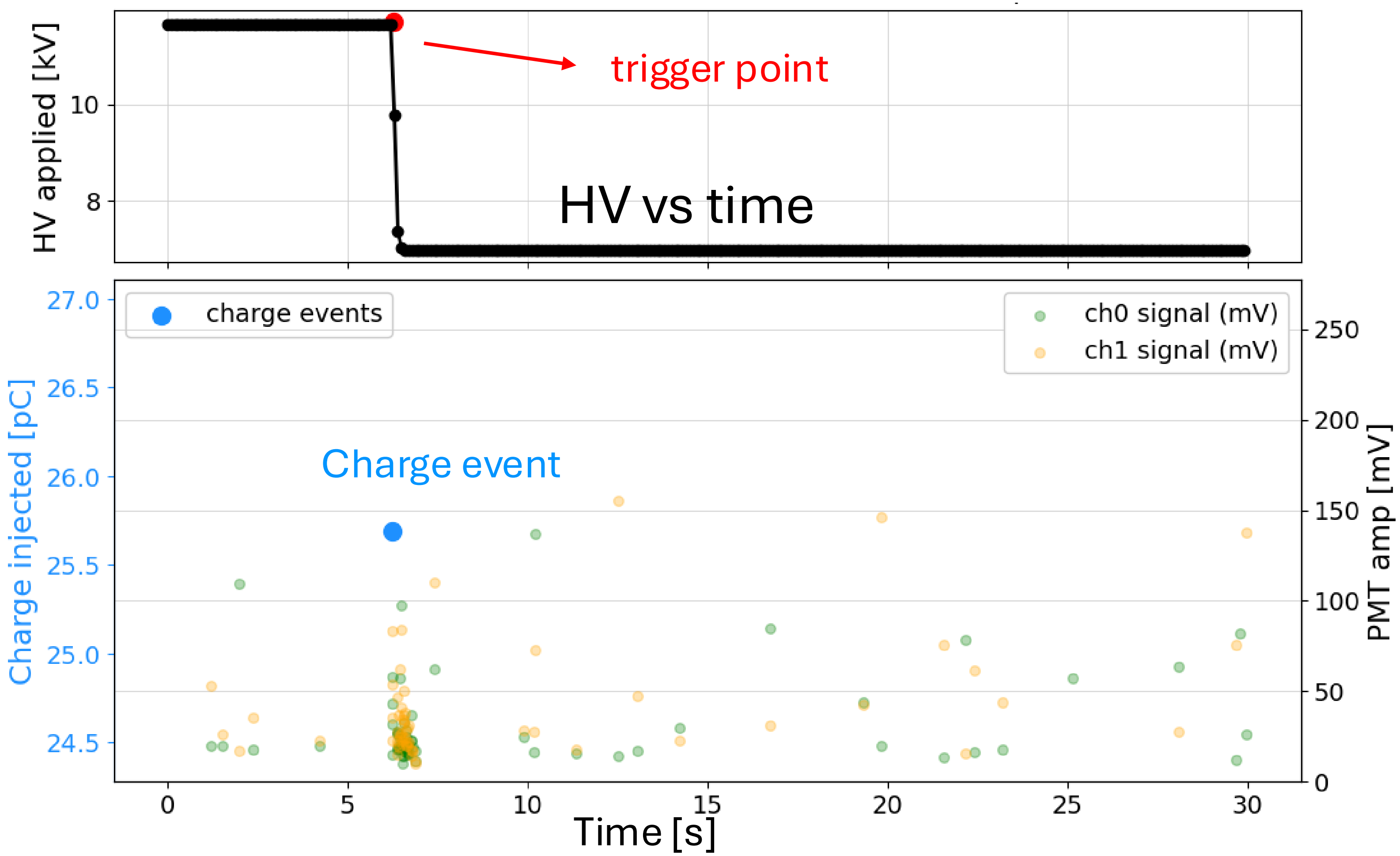
Layer of interest, in this case Pt (50 nm), MgF_2 (50 nm), MgF_2 (20 nm)

Al (100 nm)

Cr (5 nm)

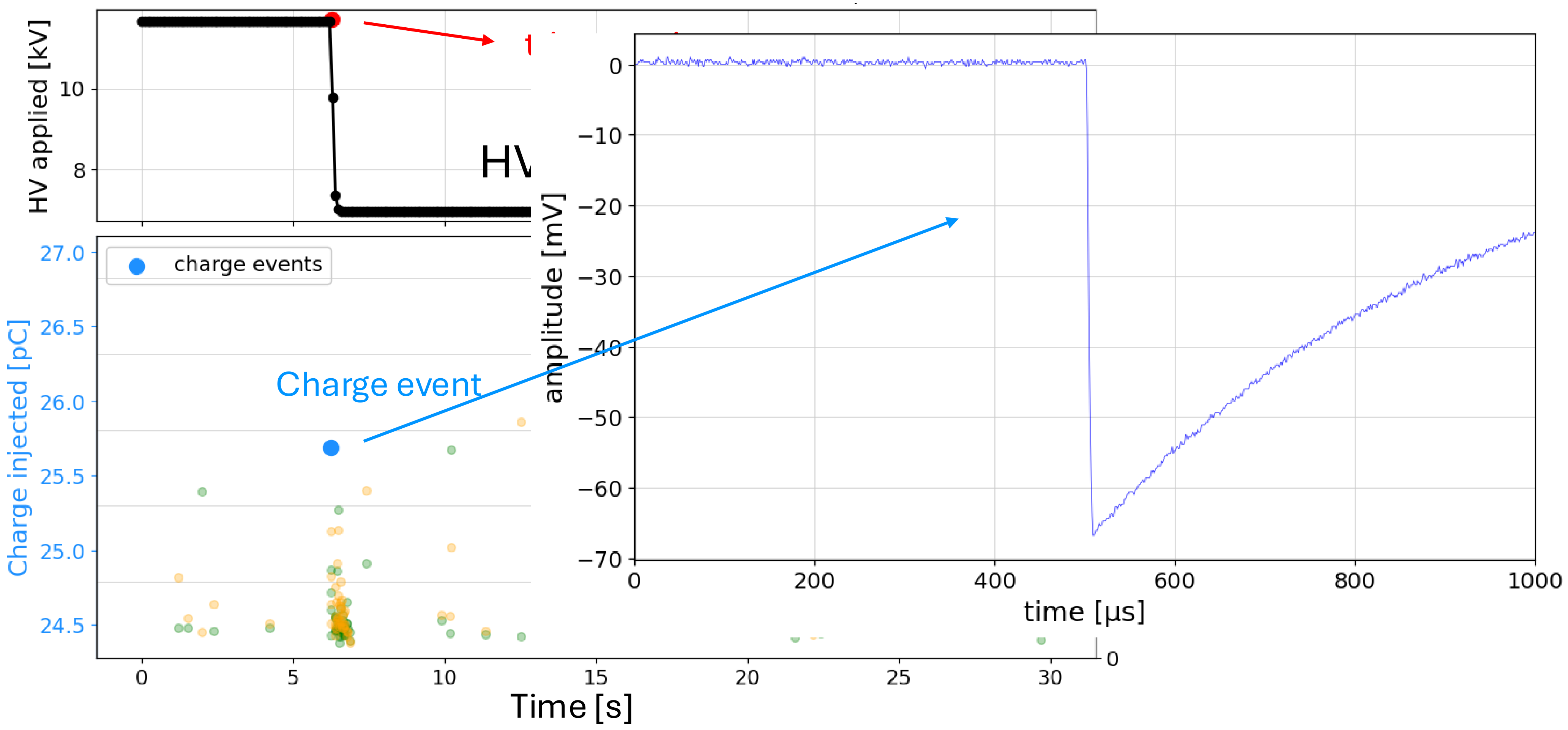
SS304 substrate

A Typical Pre-breakdown Event



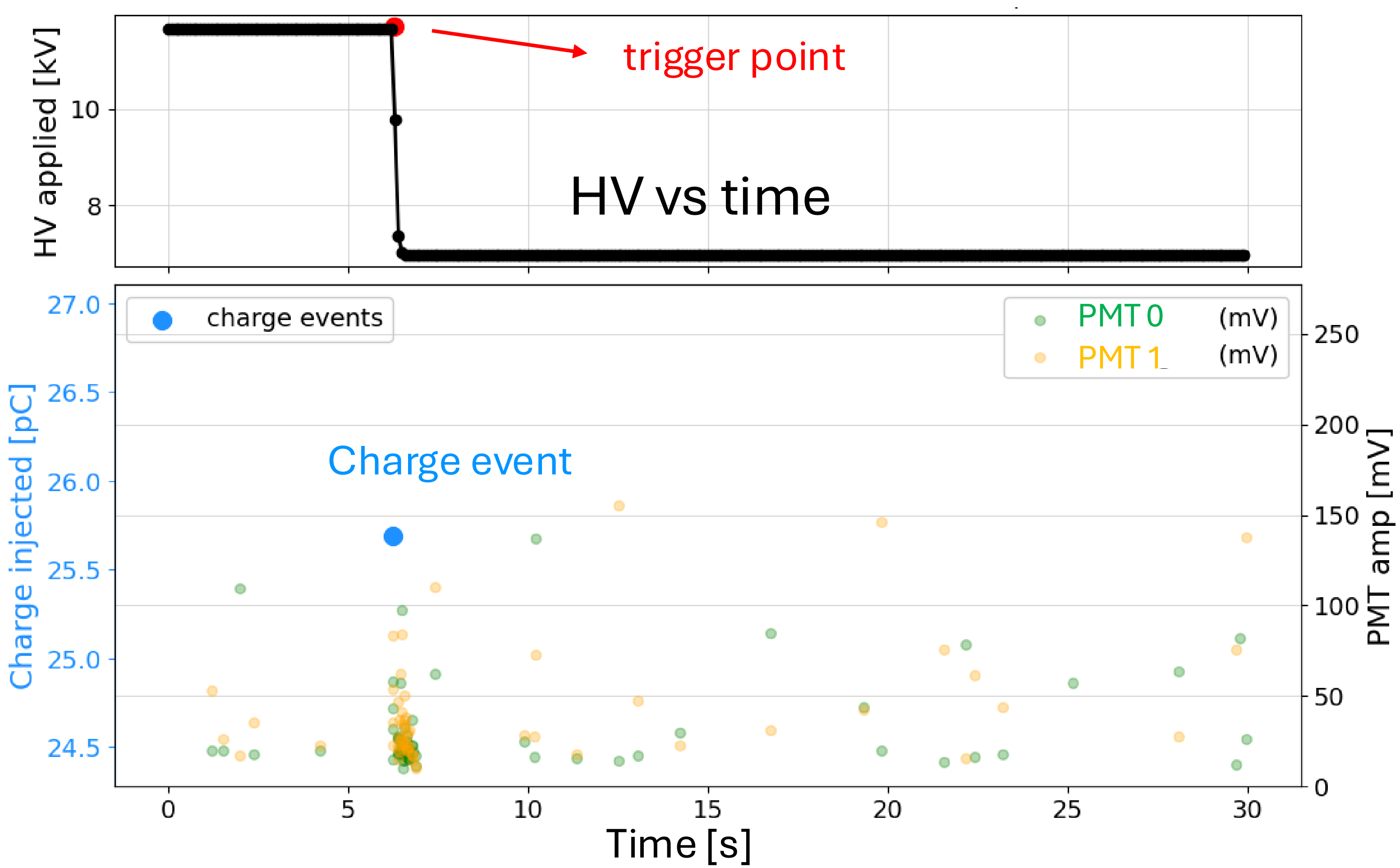
coincident charge and light signals

A Typical Pre-breakdown Event

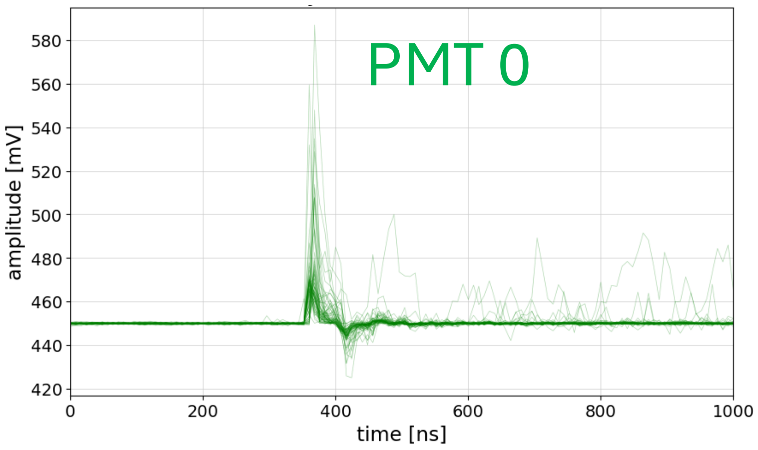


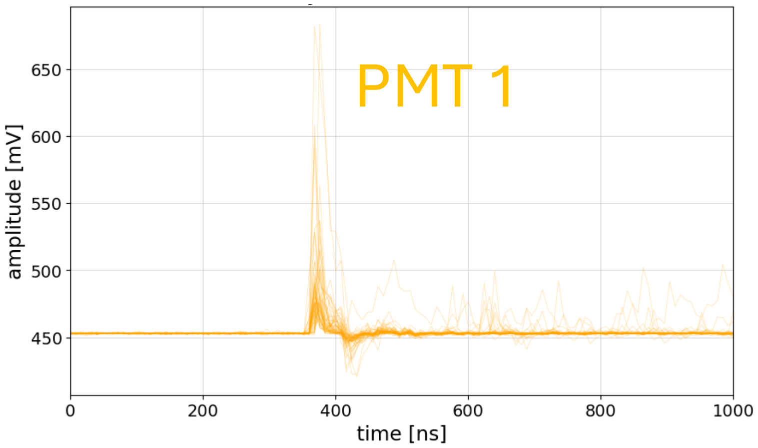
coincident charge and light signals

A Typical Pre-breakdown Event

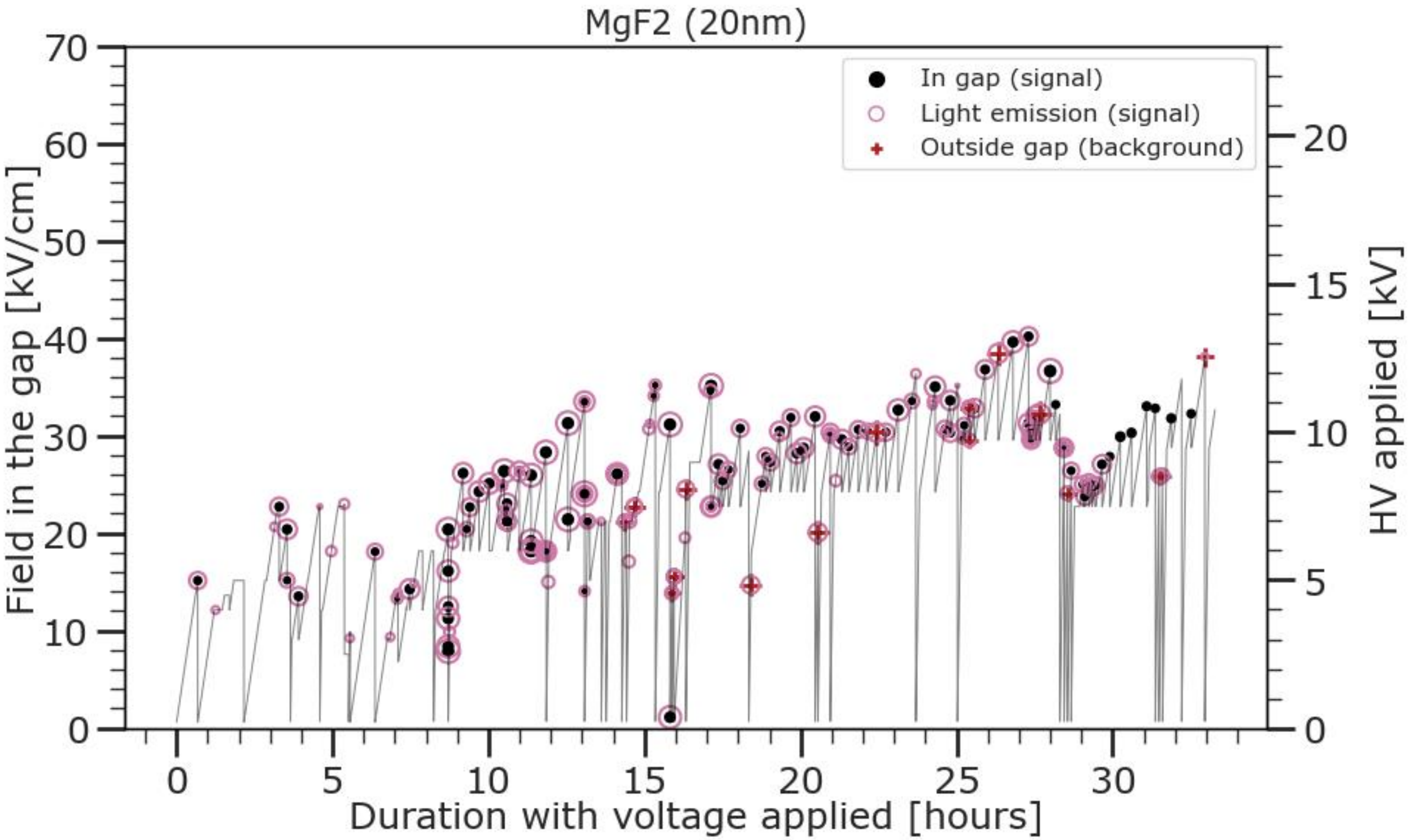


coincident charge and light signals

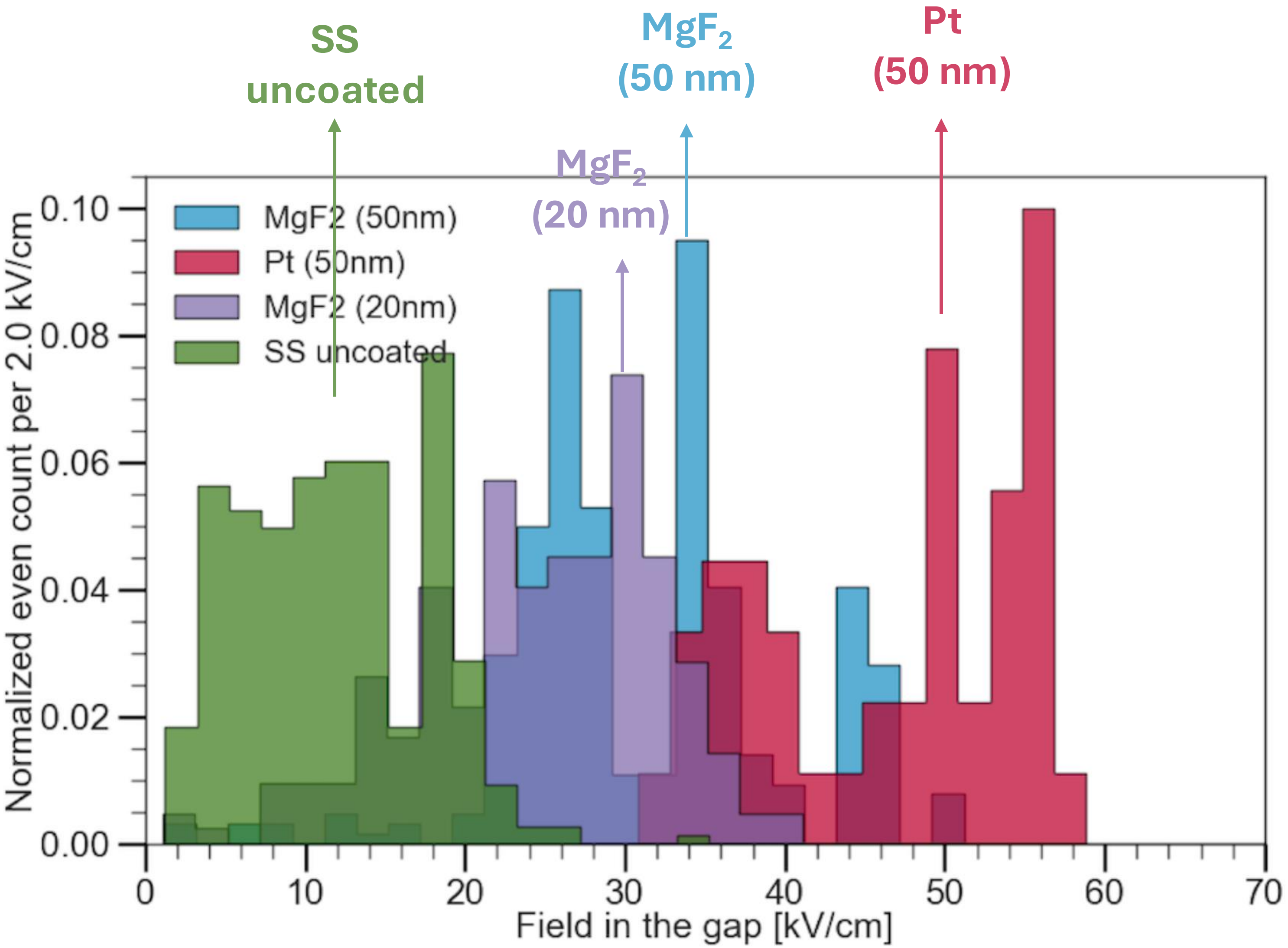




Trends for one coating (MgF_2 20 nm example)



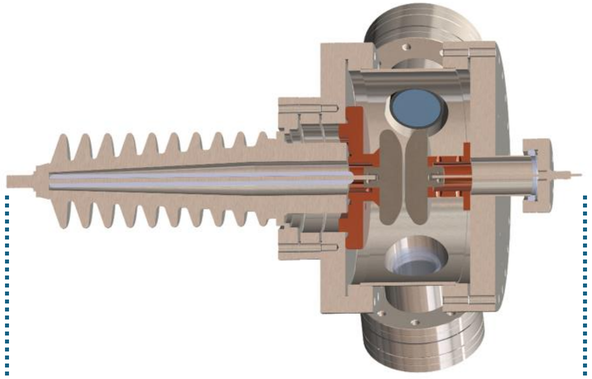
Statistics across coatings

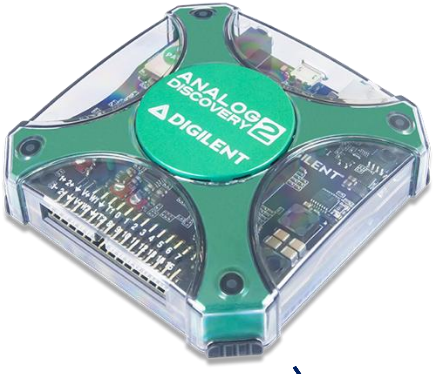


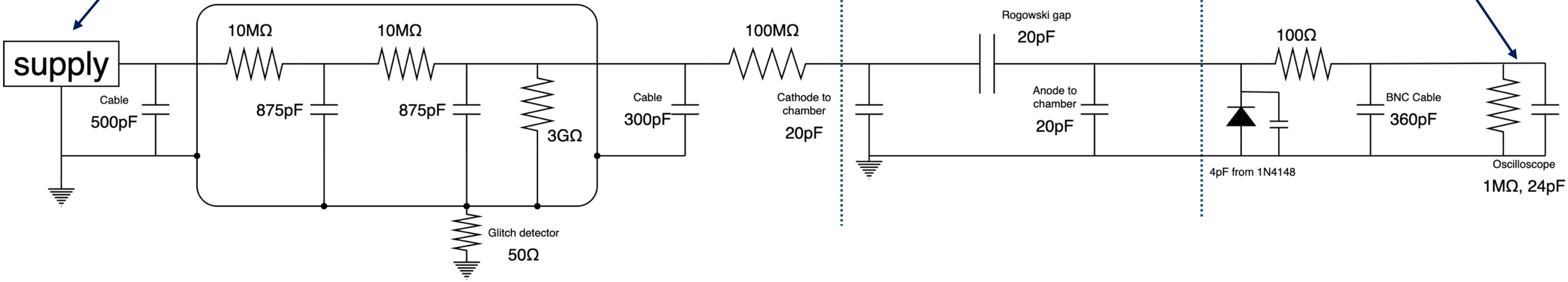
Summary

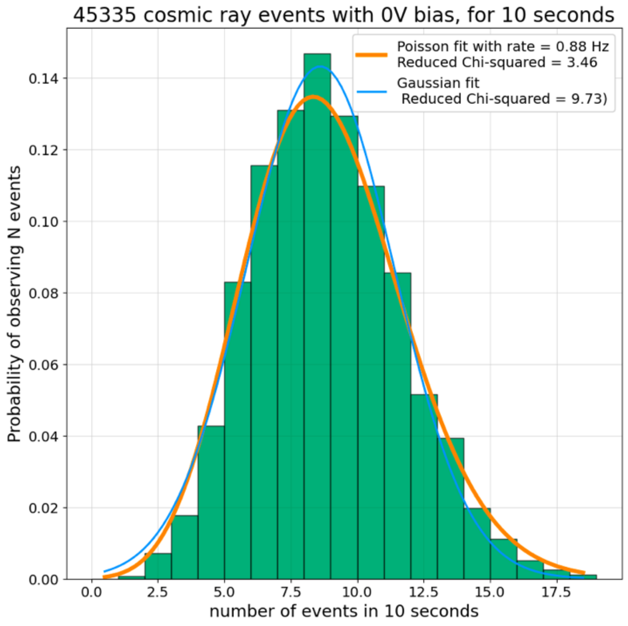
- We built a dedicated 10-kg LXe chamber to study these surface effects.
- Trip logic keeps the system safe and allows repeated conditioning.
- Surface coatings raise the pre-breakdown threshold compared to bare steel.
- Platinum gives the best improvement so far, and MgF_2 also helps.
- The study is still ongoing — we’re upgrading the detector, studying the origin of positive signals, and testing more coatings.

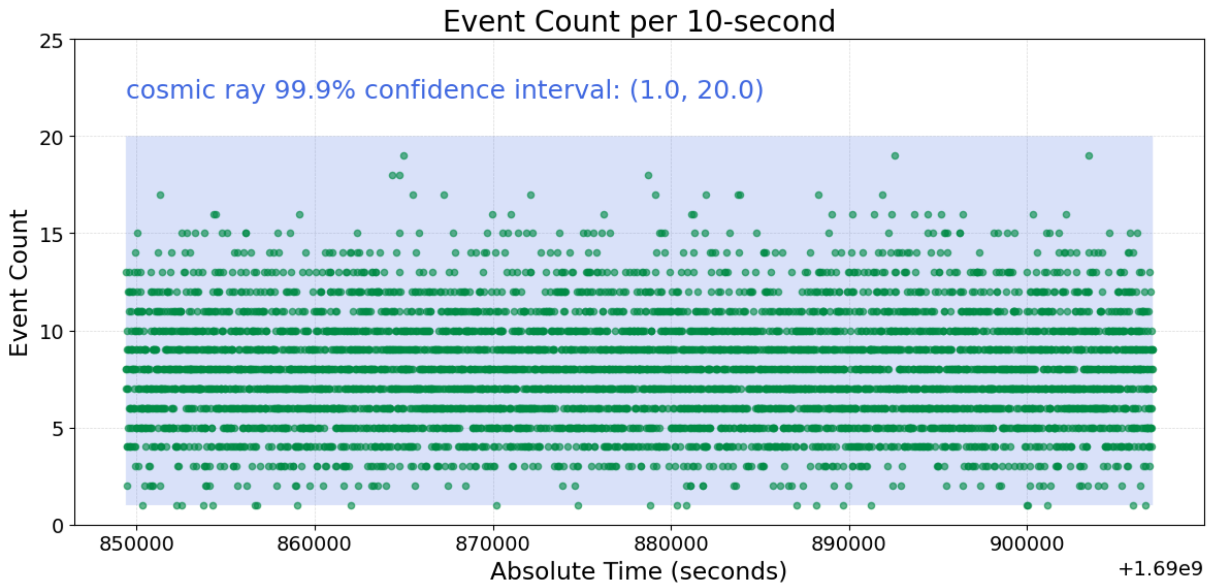
Controller for HV and monitoring



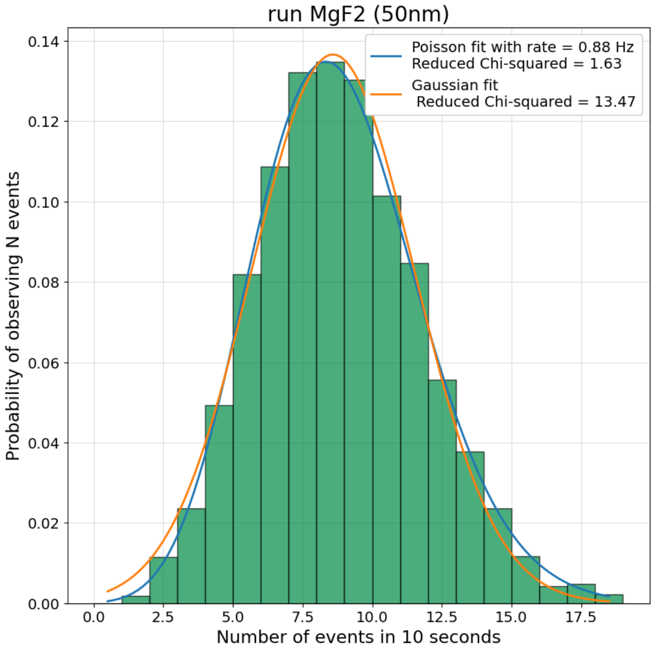


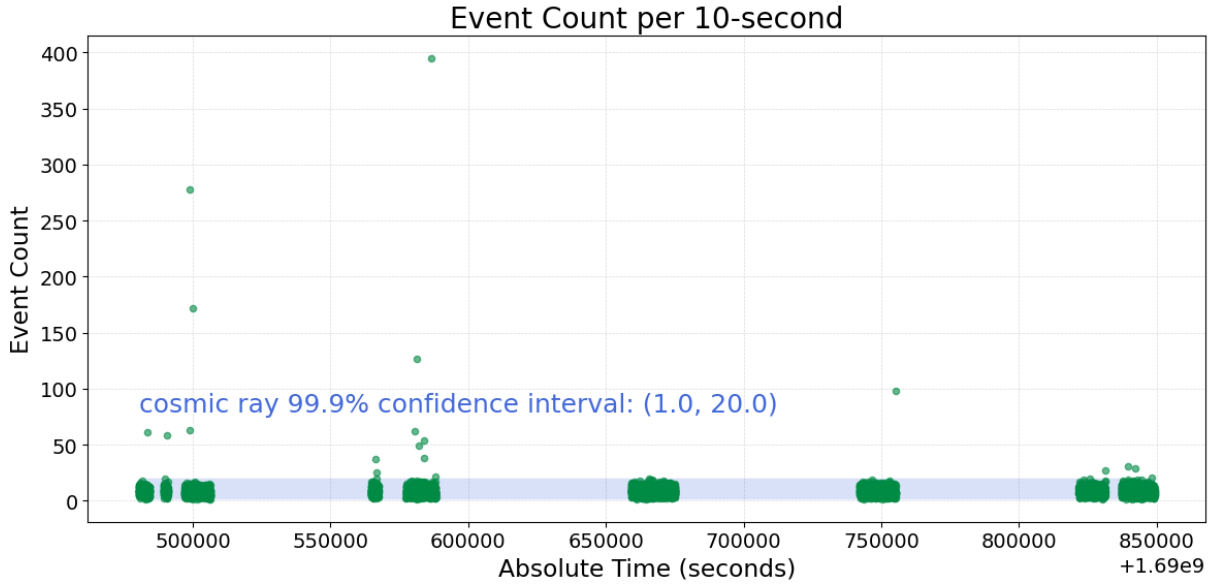




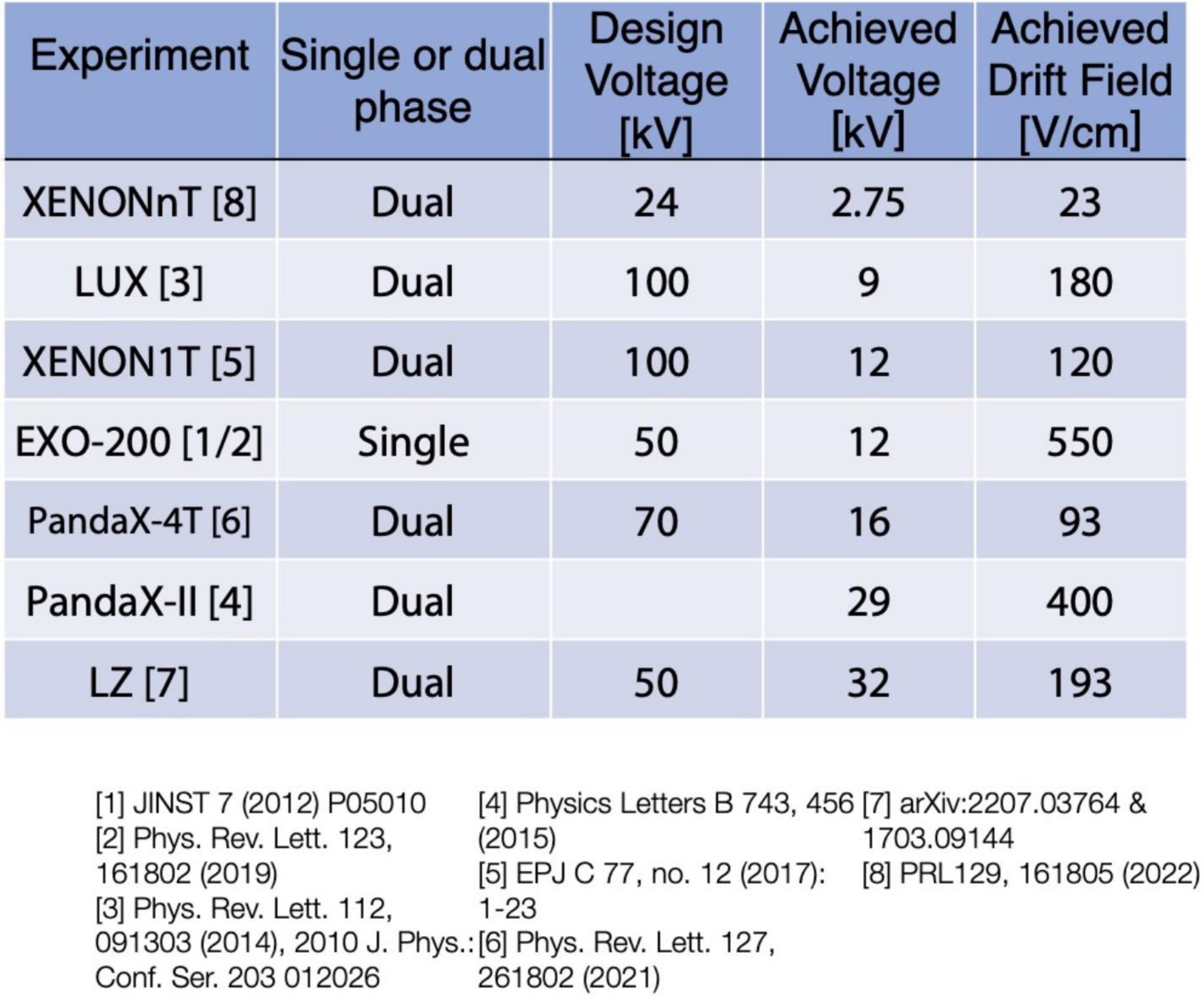


- **Cosmic ray**
- The number of events per 10 seconds follows Poisson distribution
- Within the 99.9% confidence interval, the number of events should be in the range of 1 to 20 per 10 seconds.





- **MgF2 (50nm)**
- Follows Poisson distribution too
- more than 20 events per 10 seconds should not be considered as cosmic rays.



Experiment	Single or dual phase	Design Voltage [kV]	Achieved Voltage [kV]	Achieved Drift Field [V/cm]
XENONnT [8]	Dual	24	2.75	23
LUX [3]	Dual	100	9	180
XENON1T [5]	Dual	100	12	120
EXO-200 [1/2]	Single	50	12	550
PandaX-4T [6]	Dual	70	16	93
PandaX-II [4]	Dual		29	400
LZ [7]	Dual	50	32	193

[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

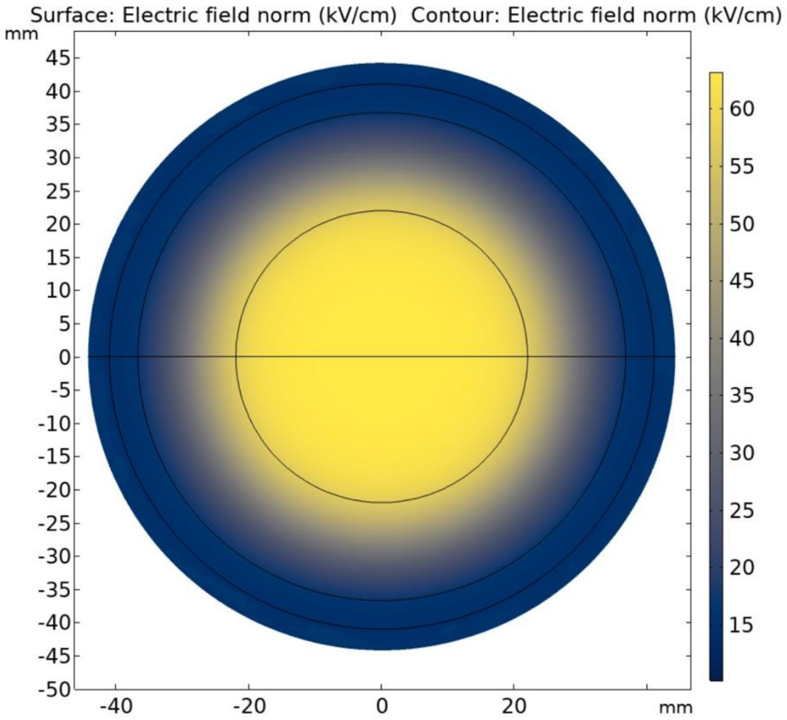
[4] Physics Letters B 743, 456 (2015)

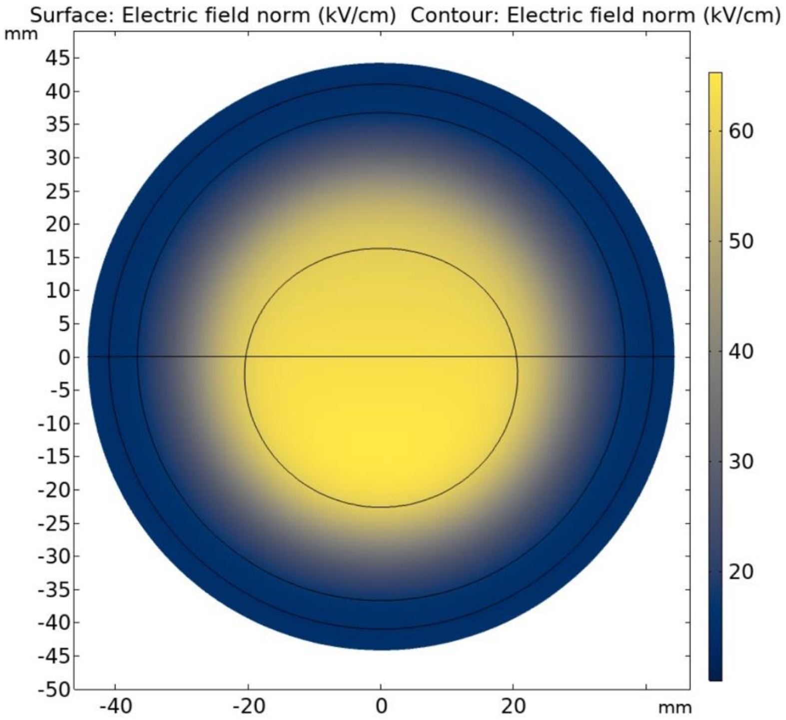
[5] EPJ C 77, no. 12 (2017): 1-23

[6] Phys. Rev. Lett. 127, 261802 (2021)

[7] arXiv:2207.03764 & 1703.09144

[8] PRL129, 161805 (2022)


Surface: Electric field norm (kV/cm) Contour: Electric field norm (kV/cm)
mm
45
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
-40
-20
0
20
mm
60
55
50
45
40
35
30
25
20
15


Surface: Electric field norm (kV/cm) Contour: Electric field norm (kV/cm)
mm
45
40
35
30
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20
15
10
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-5
-10
-15
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-45
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-40
-20
0
20
mm
60
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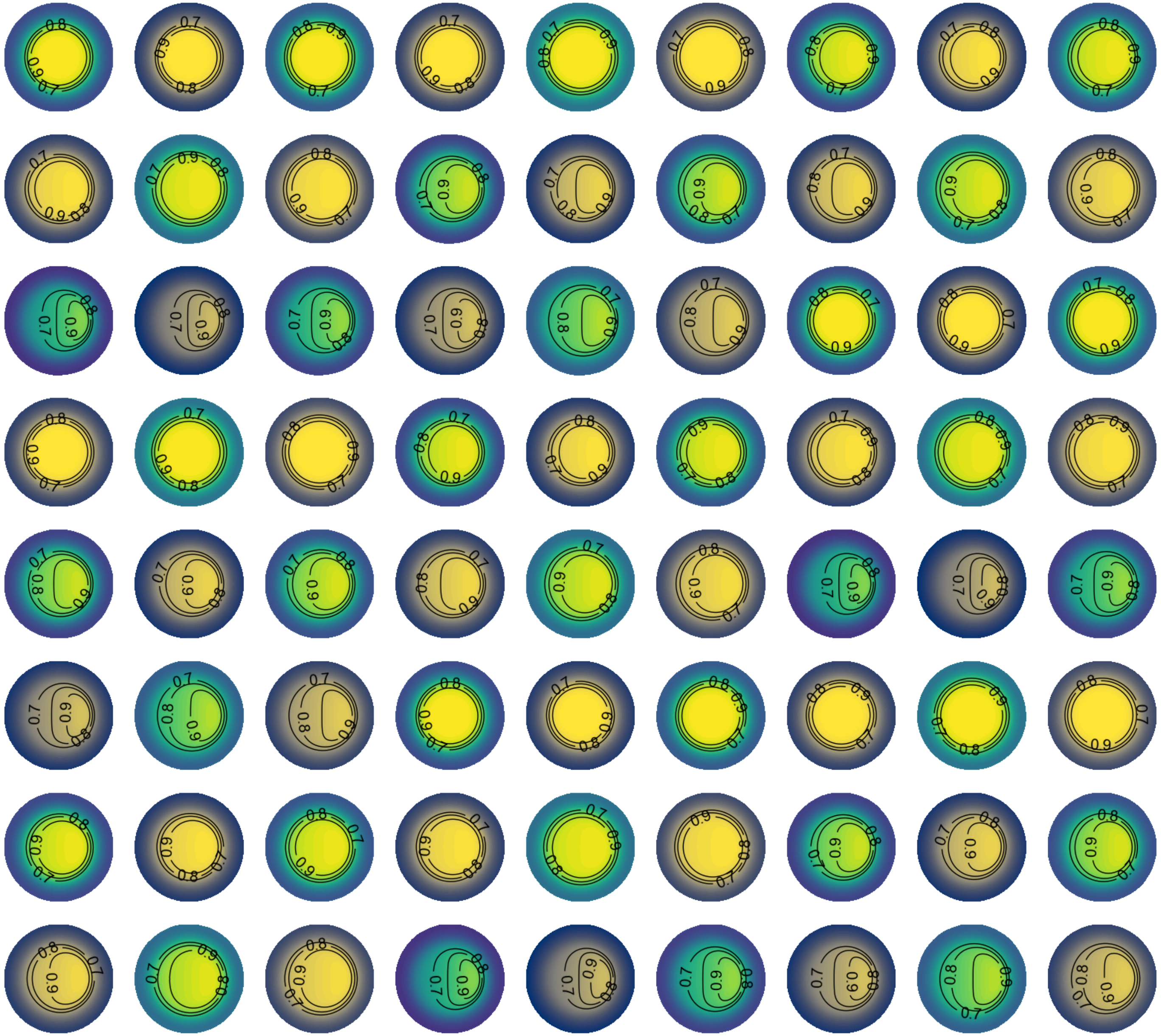
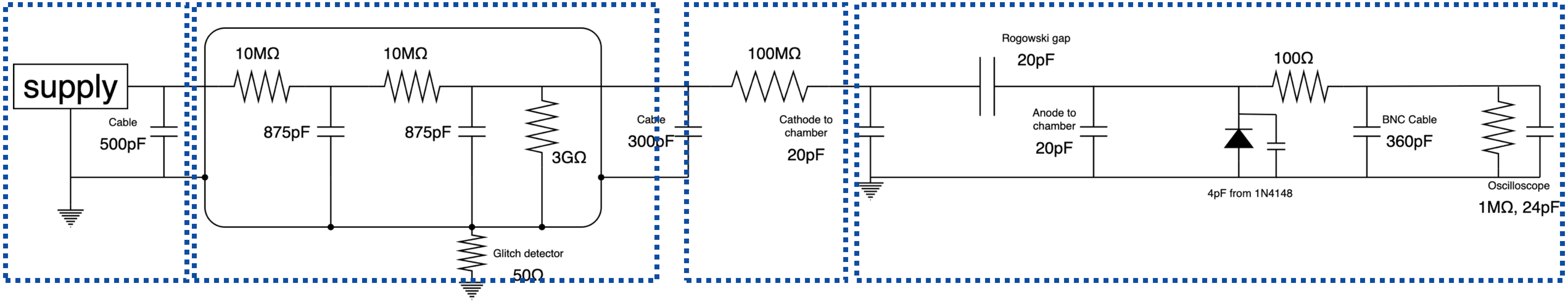
30
20


0.7
0.8
0.9

Electrical system

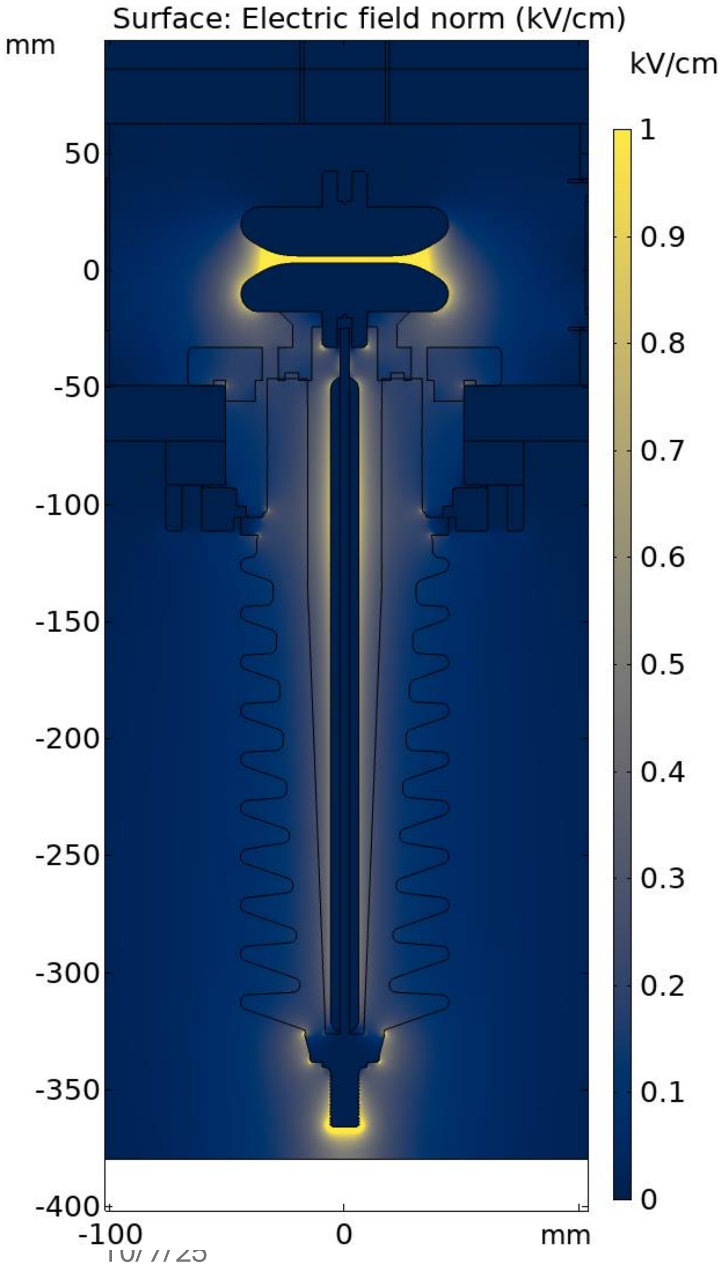


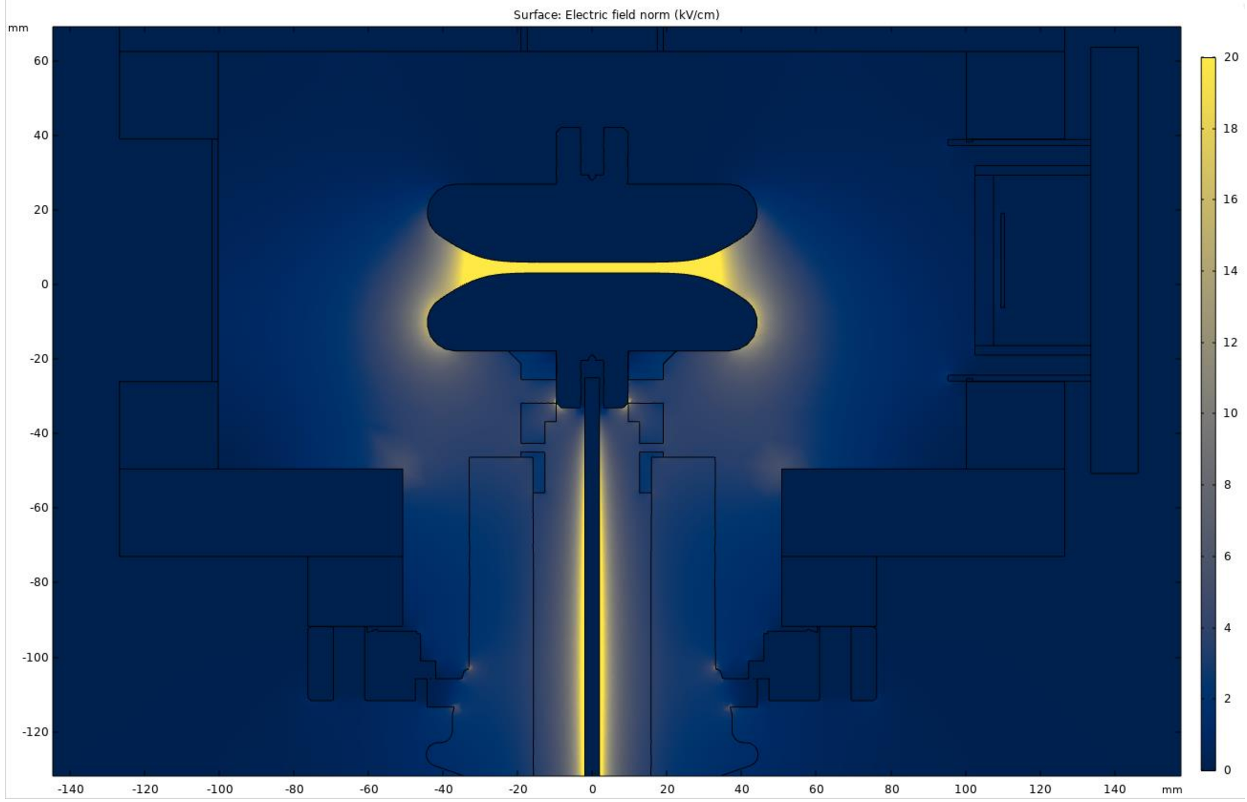
HV supply

Oil insulation
Glitch pickoff

100MΩ
Resistor

Anode readout
Diode + digitizer


Surface: Electric field norm (kV/cm)
mm
50
0
-50
-100
-150
-200
-250
-300
-350
-400
-100
0
mm
kV/cm
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0


Surface: Electric field norm (kV/cm)
mm
60
40
20
0
-20
-40
-60
-80
-100
-120
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
mm
20
18
16
14
12
10
8
6
4
2
0