High-Voltage Performance Testing in LAr of the PMMA Cathode Connection for the DarkSide-20k Experiment

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On behalf of the DarkSide-20k Collaboration

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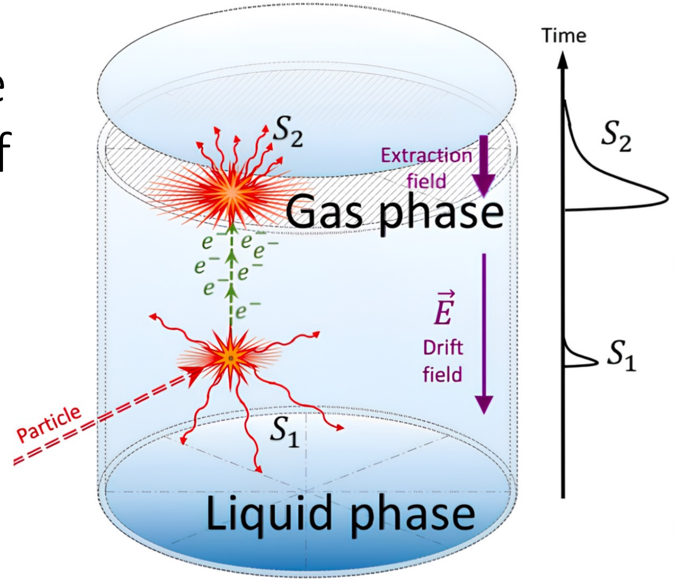
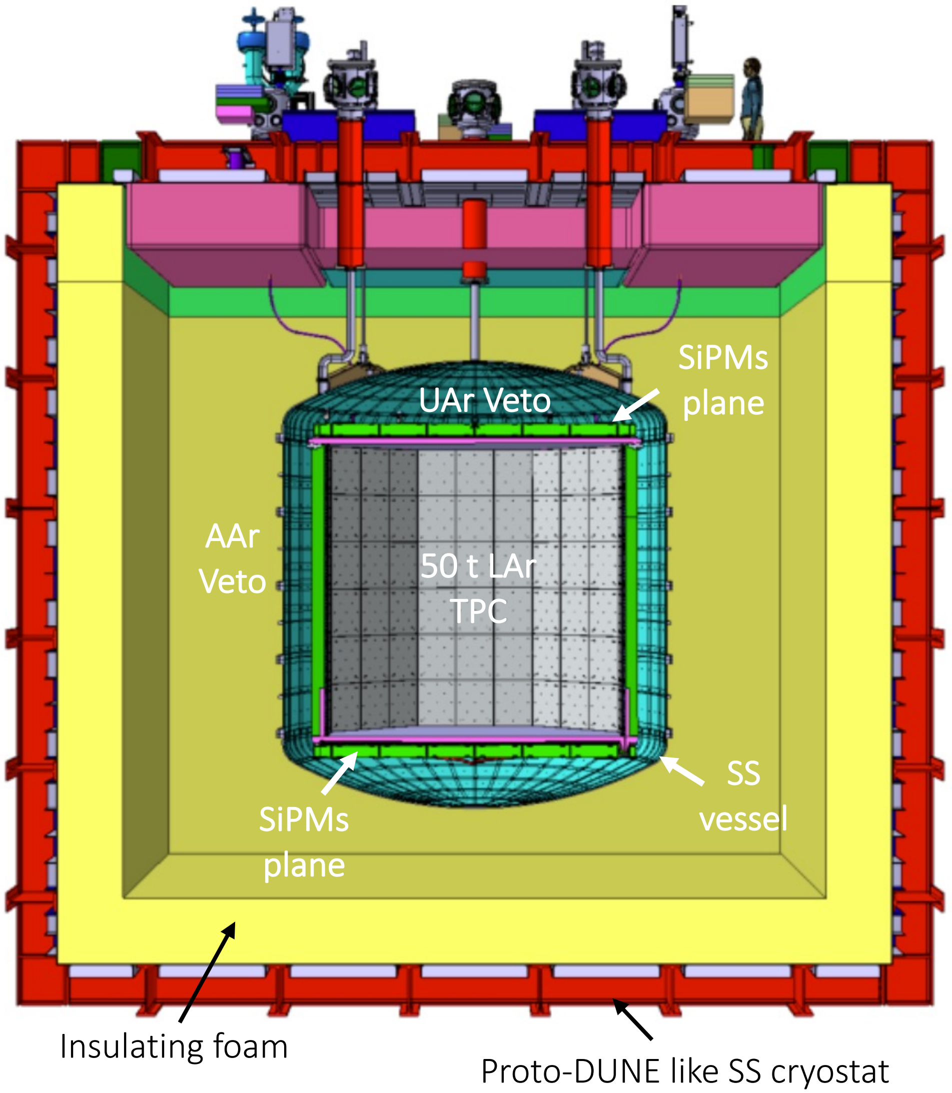
LIDINE 2025

The DarkSide-20k experiment

- Dual-phase LAr-TPC with an active (fiducial) volume of 49.7 t (20 t) of low-radioactivity underground argon (UAr)
- 32 t of liquid UAr serving as active neutron veto
- Wavelength shifters (TPB in the TPC, PEN, in the Veto)
- 21 m^2 of cryogenics SiPMs
- TPC and Veto housed within 700 t of liquid atmospheric argon cryostat, acting as a cosmogenic neutron veto





A. Jamil's talk

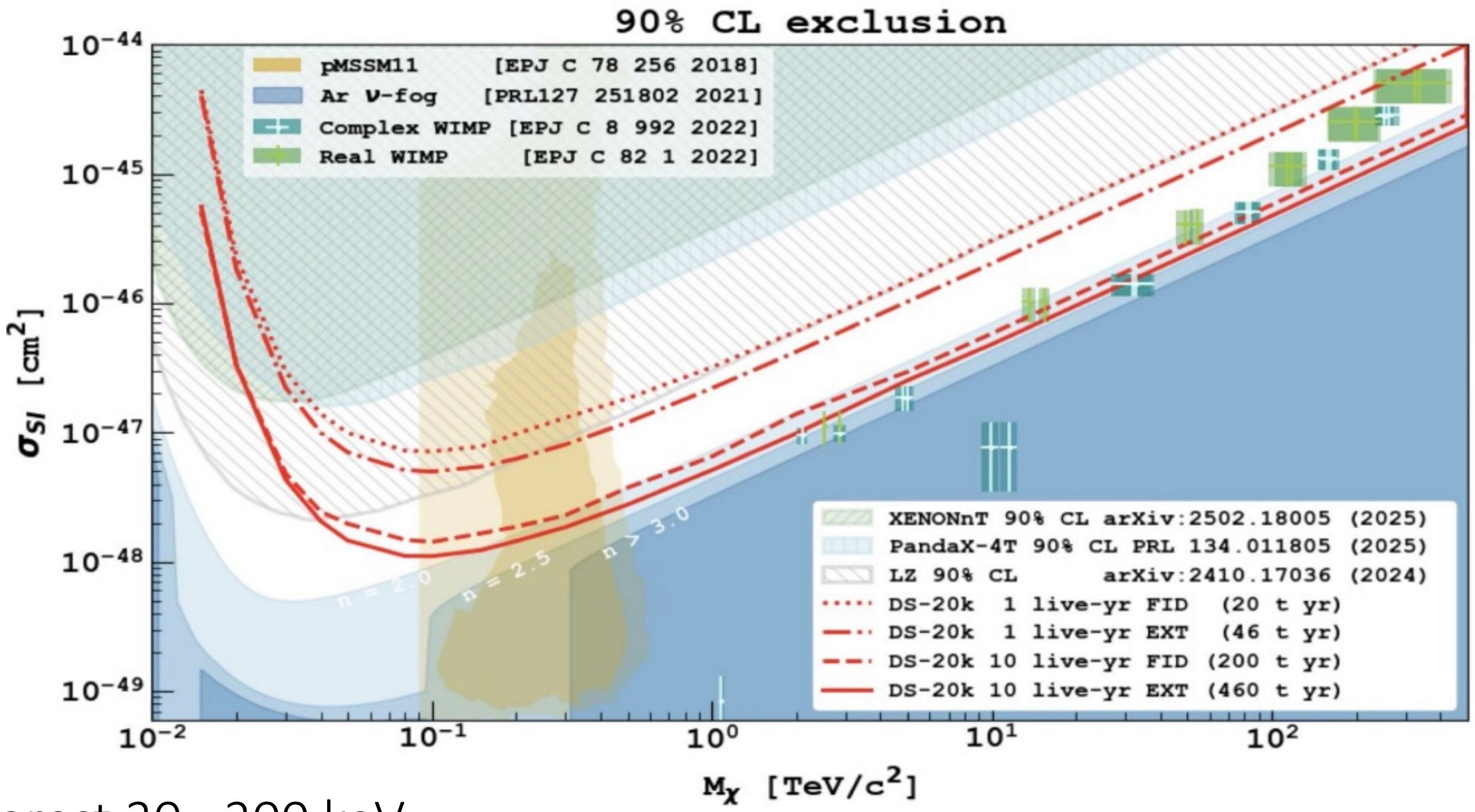
DarkSide-20k – Scientific Goals

- 10 y nominal exposure (200 t y)

- Energy threshold < 10 keV

- Spin-independent WIMP-nucleon cross section

- Background:
  - instrumental background
    <u>< 0.1 events</u> in the Region of Interest 30 –200 keV_{nr}
  - <u>3.2 CEνNS</u> events (dominant background)



Electric Fields in DarkSide-20k

- The choice of electric field strength has a direct impact on the experiment's sensitivity
- Electric fields in DS-20k are given by
    - Clevios™ conductive polymer coating on TPC PMMA anode, cathode and field cage rings
    - Resistor chains
    - Steel wire grid

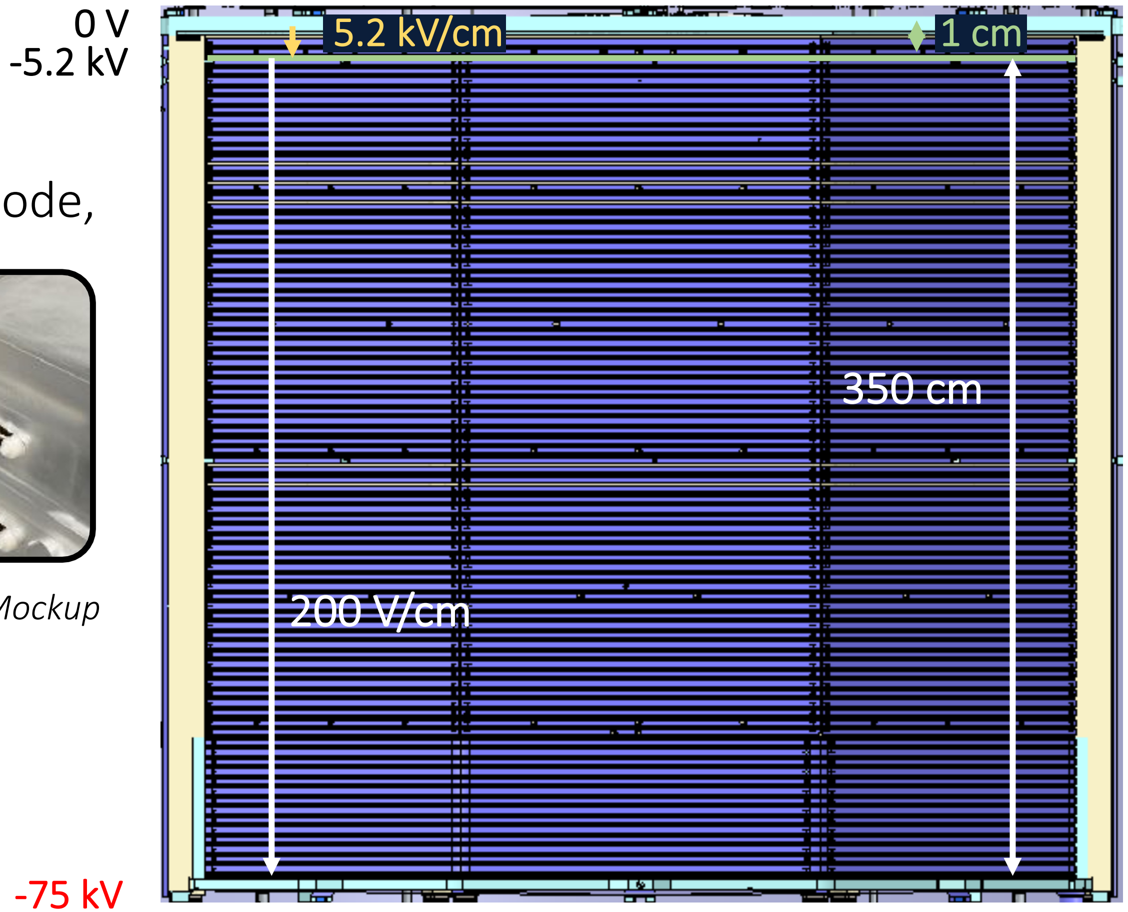
From DS-20k Mockup

- Drift field = 200 V/cm
    - LY = 8.5 PE/keV at 41.5 keV (^{83m}Kr decay)
    - maximum e^- drift time = 3.7 ms

➤ Nominal cathode voltage ≈ -75 kV

- Extraction/electrolum. field = 5.2 kV/cm
    - 20-30 PE/e- in the electrolum. region

DS-20k TPC

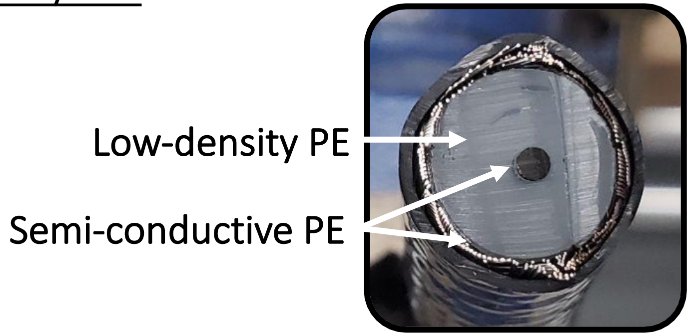


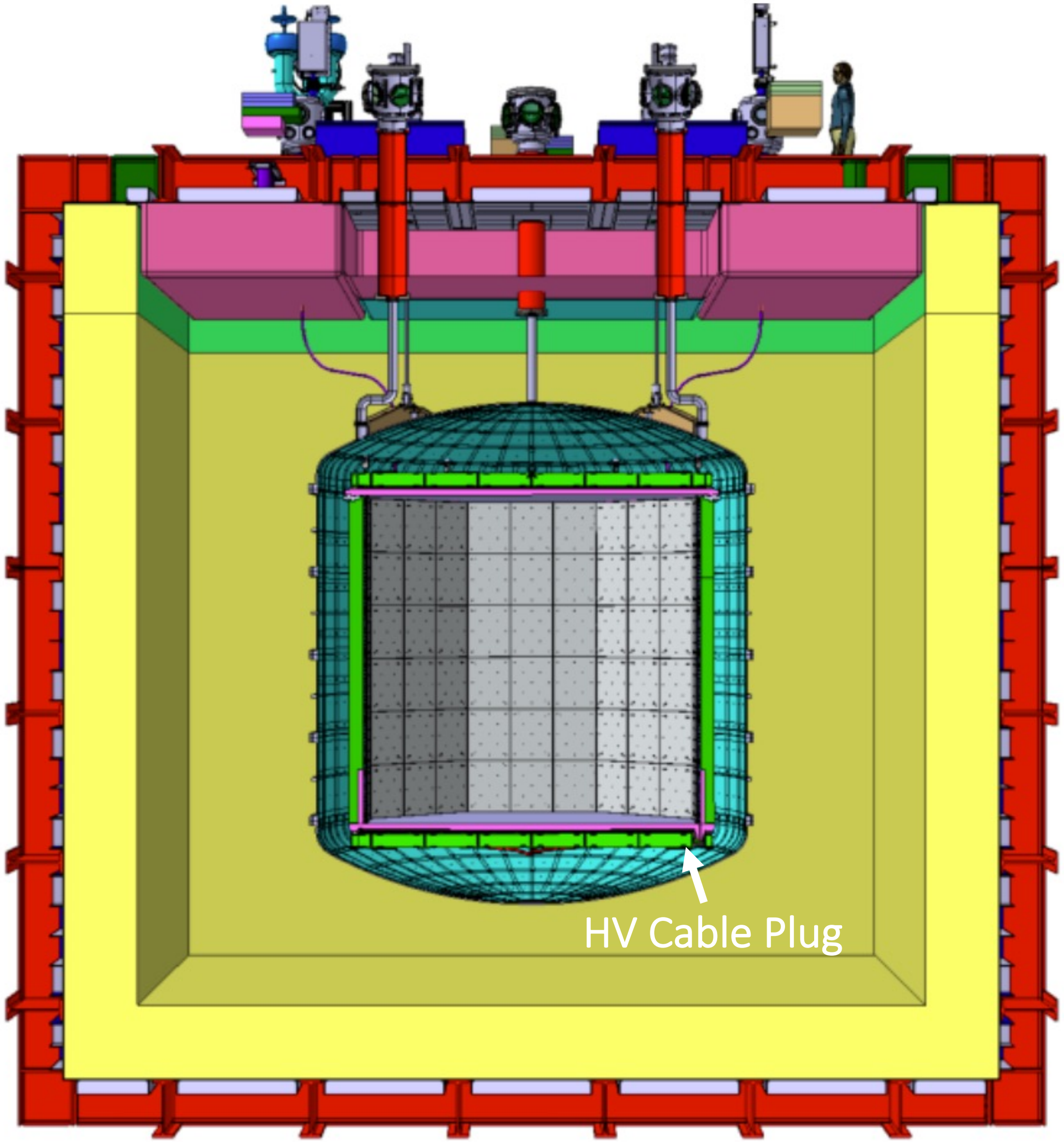
Cathode High-Voltage System in DarkSide-20k

- Nominal cathode voltage ≈ -75 kV

- HV supplied through ~15 m long cable
  - enters from outside the cryostat
  - through the stainless-steel vessel
  - plugged to a copper connector on the PMMA, in contact with the Clevios™ layer

- The HV cable consists of 3 polyethylene-based layers





HV Cathode Plug in DarkSide-20k

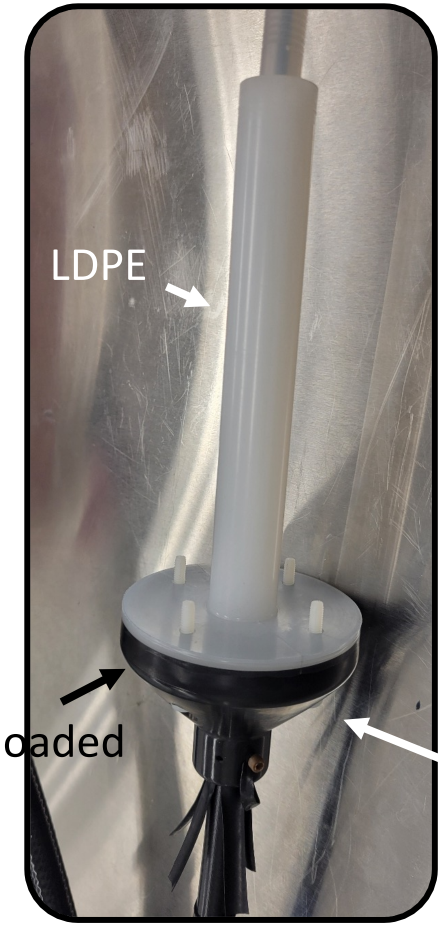
- At one end of the HV cathode cable, a cone consisting of two parts
  - LDPE insulating sleeve
  - carbon-loaded conductive PE outer shell

- HV cable cone assembly attached to Clevios-coated PMMA cone (better electrical insulation) and plugged into the copper connector

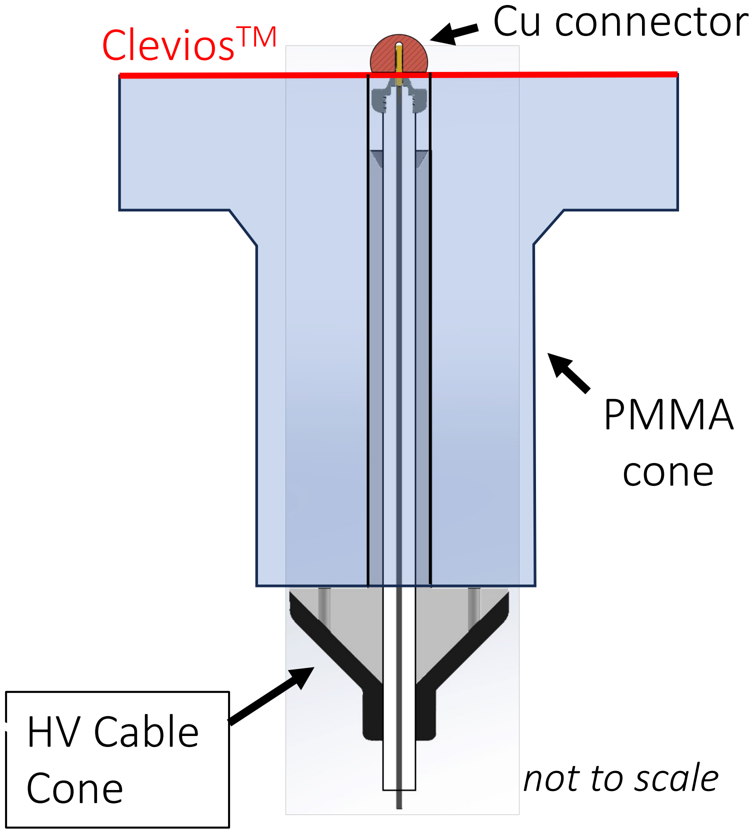
- Key challenges of the DS-20k HV cathode system:
  - delivering such HV (> -75 kV) while minimizing the risk of electrical discharges (breakdown in LAr ~ 40 kV/cm)
  - ensuring a reliable connection in such a confined space (< 1 mm)
  - ensuring the stability of the HV stress cone under cryogenic conditions

From DS-20k Mockup

Cathode Cable Plug



Carbon-loaded PE shell

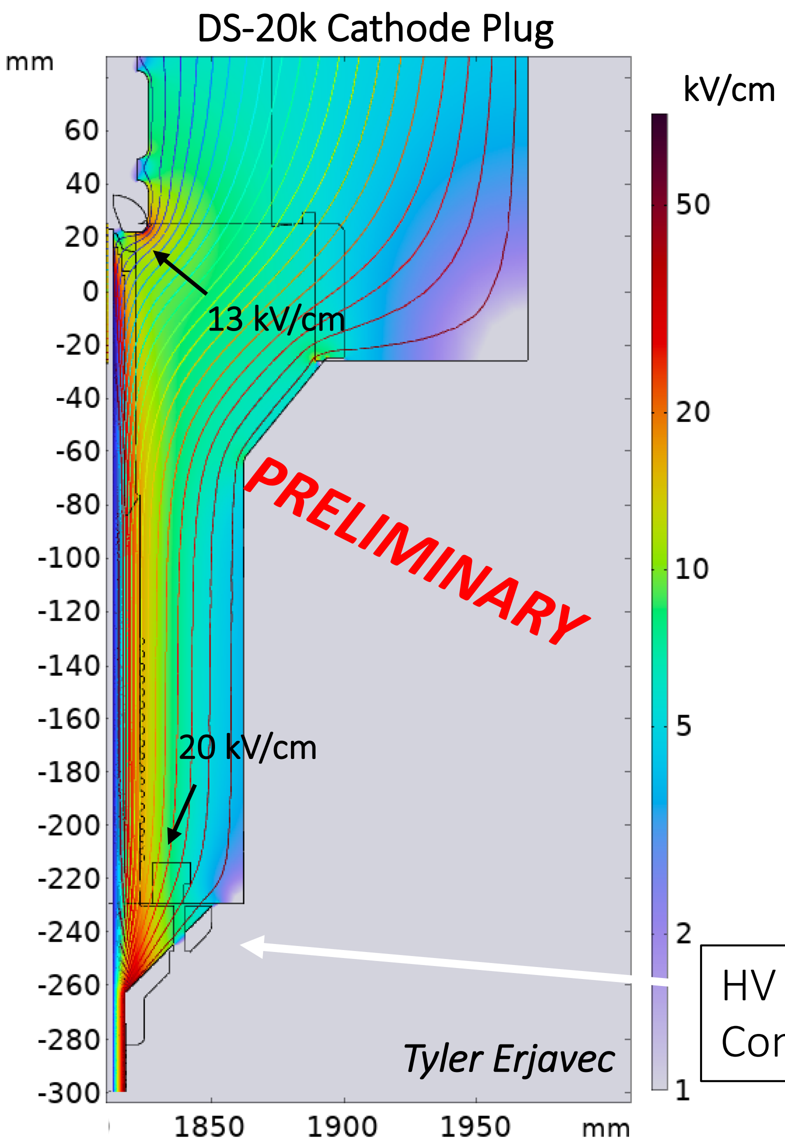


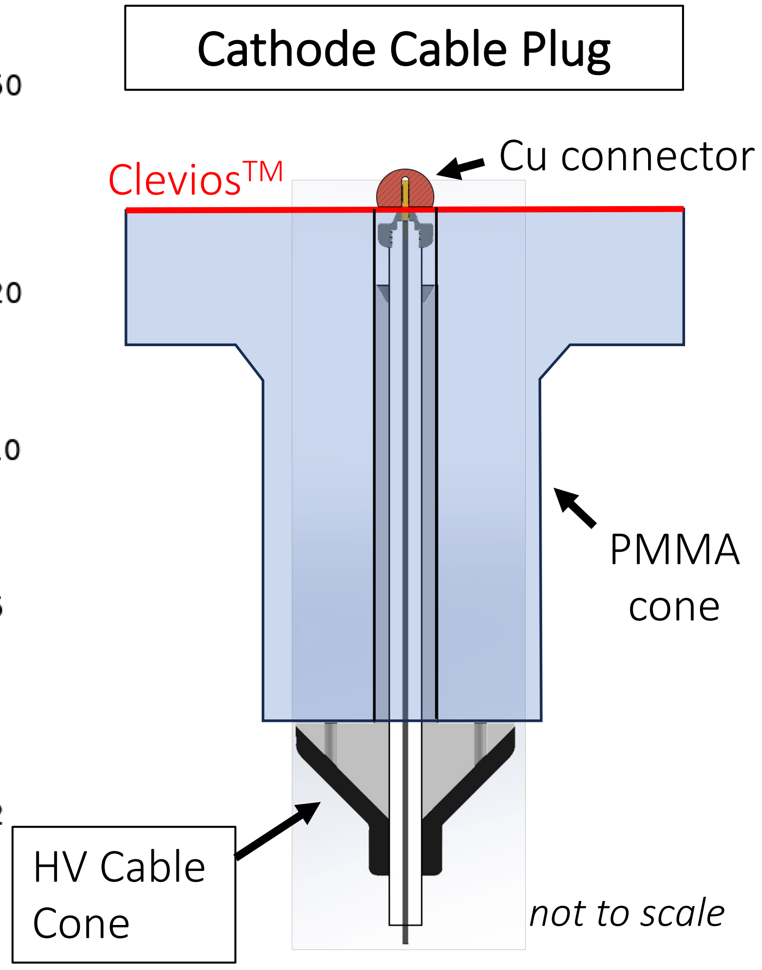
Cathode Plug in DS-20k – Local Electric Fields

- Critical areas are below the HV cone, the HV plug and inside the PMMA cone
- Local electric field estimation (*Comsol* simulation) with V_{cath} = -75 kV
  - ~15 kV/cm between cone and PMMA
  - 13 kV/cm below copper electrode
  - 20 kV/cm inside the corner of the HV cone

  Local electric fields < 40 kV/cm (breakdown in LAr)

- The safety margin is 45% of -75 kV above that value, at which E > 40 kV/cm in the critical regions





HV Cable Cathode Plug Test @UCDavis

- Two cathode HV cables with stress cones:
  - DS-20k Mockup (*P. Salomone's talk*)
  - @UCDavis in a dedicated setup (**this talk**)

Test the HV stress cone within a closed LAr system replicating — in terms of local electric fields — the HV connection to the PMMA cathode of DS-20k, operated at HV values (up to -100 kV)

- Specific goals:
  - reach DS-20k nominal voltage (-75 kV) and 33% higher (-100 kV)
  - test the stability of the system
  - test the operational procedures for ramp up and ramp down
  - implement the control and readout system via software
  - monitoring via cryogenic cameras
  - establish procedure for cool down of the setup

University of California, Davis – July 2025

Local Electric Fields – Cathode Plug in DS-20k vs HV Test

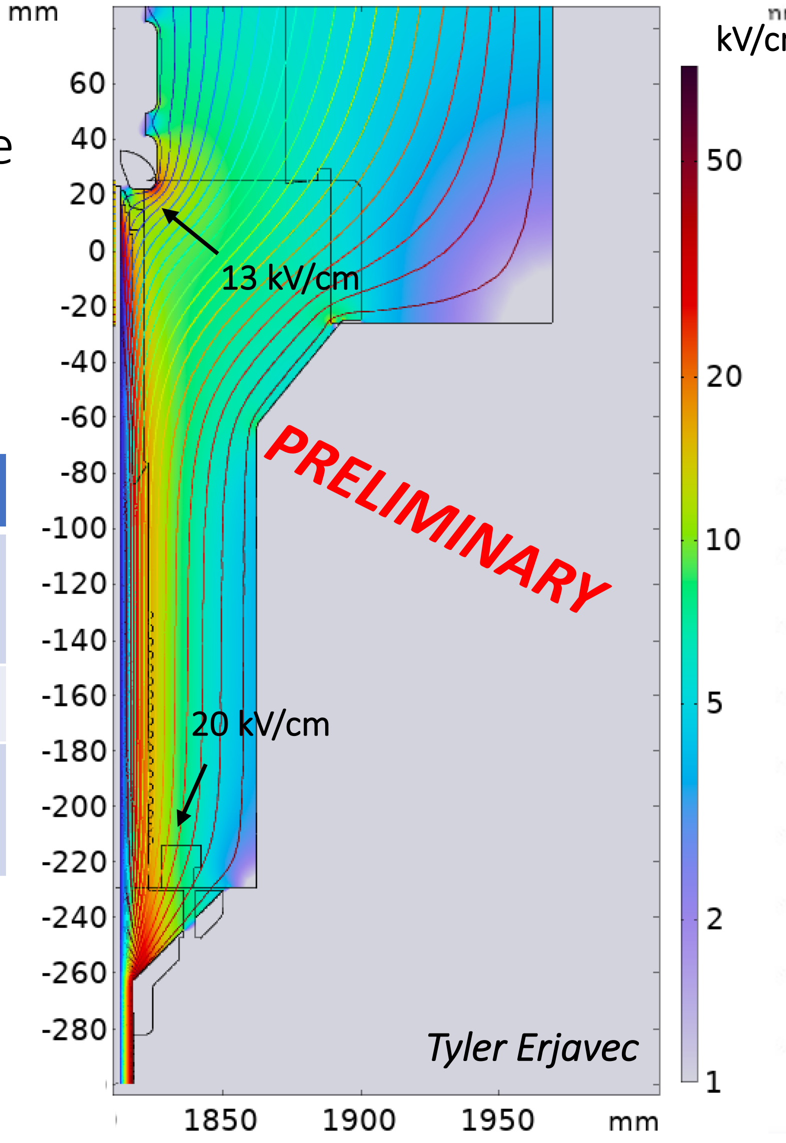
- <u>Idea</u>: HV cable and stress cone inserted in a PMMA cylinder and plugged into an aluminum sphere, within a closed LAr volume

- Comparison of local electric fields (*Comsol* simulation) *@V_{cath} = -75 kV*

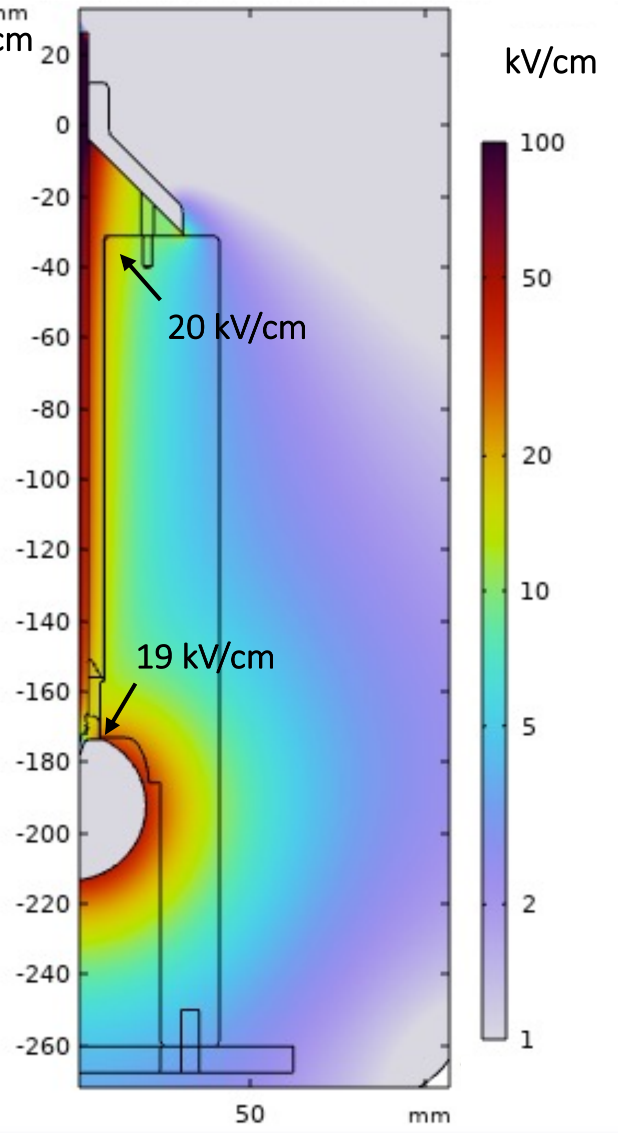
	Electric Field (kV/cm)		
	Inside the cone	Base of connector	Base of the cone
DS-20k	15	13	20
HV Test @UCDavis	15	18	20

We can replicate local electric fields in DS-20k cathode plug

DS-20k Cathode Plug

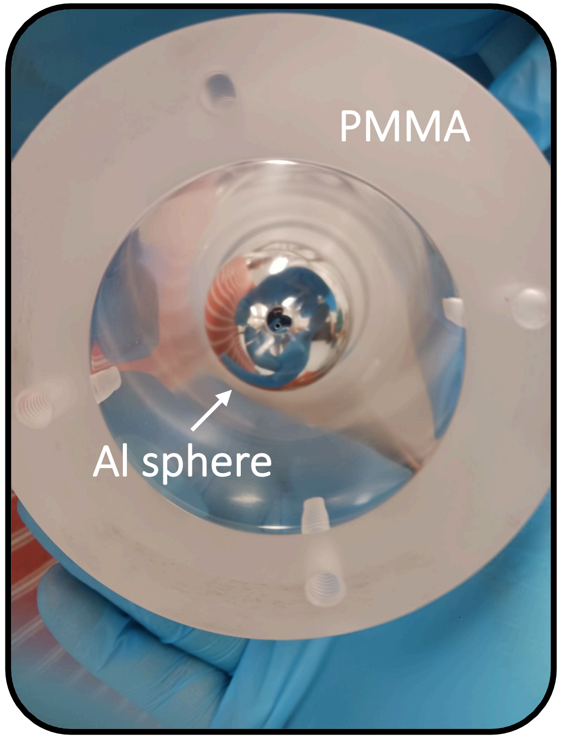


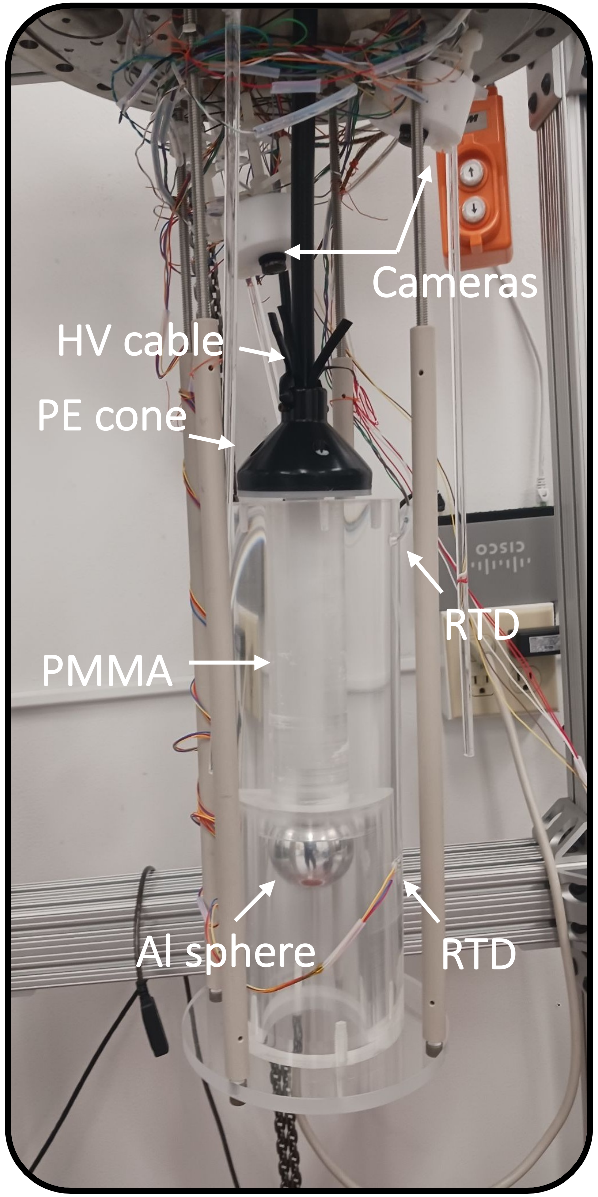
HV Cable Test



HV Cable Cathode Plug Test – Experimental Setup

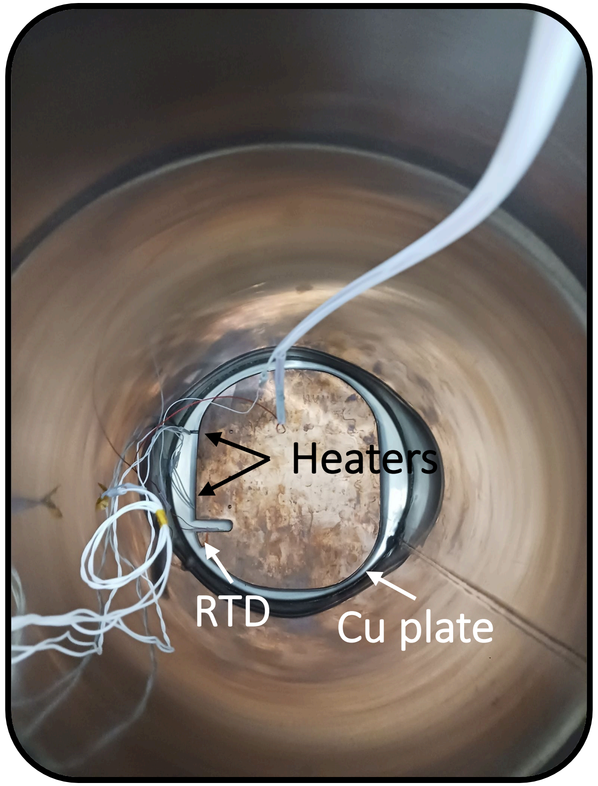
- HV cable and stress cone inserted in a PMMA cylinder and plugged into an aluminum sphere
- Two PT100 RTDs on the PMMA at different heights (19.5 cm apart) to measure PMMA temperature during the cooling down and filling stages
- Two cryo-cameras, to observe occurrence of sparks or/and bubbles (geometry upside wrt DS-20k)
- LEDs illuminate the inside of the dewar





HV Cable Cathode Plug Test – Experimental Setup

- The entire structure is inserted in a SS dewar
- Two heaters at the bottom of the dewar thermally coupled to a copper plate, to make more uniform cooling down
  - Minimize thermal stress on the PMMA and PE of the cone
- Temperature on copper is monitored by a PT100 RTD



Cooling down and LAr Filling

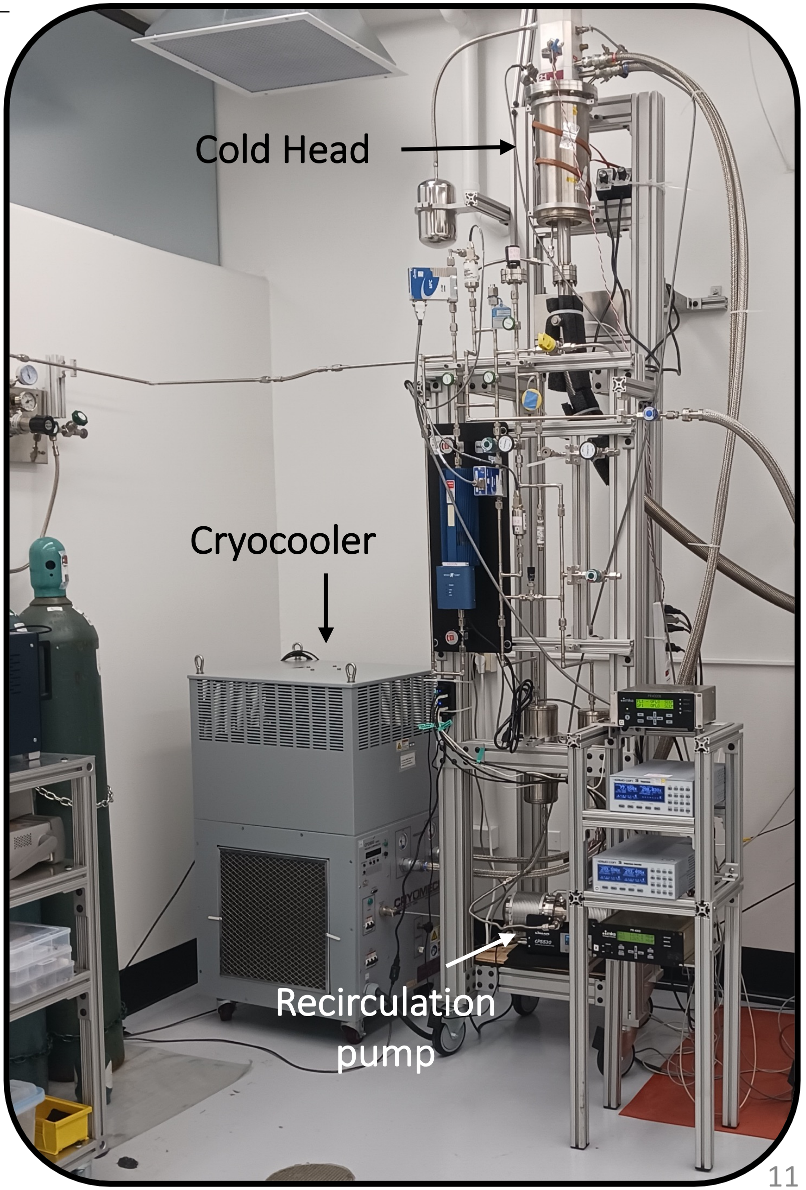
- Argon condensation using a cryogenic refrigeration system based on closed-loop helium expansion cycle

- Entire system pumped down before filling
  - $P_{vacuum} = 7.6 \times 10^{-3}$ *mbar*

- Industrial-grade Argon (99.997% purity) ⏵ Real purity unknown
  - purity monitor underway

- Temperature, pressure and flow rate monitored

- Gas circulation pump to help uniform temperature of GAr within the dewar



Cooling down and LAr Filling

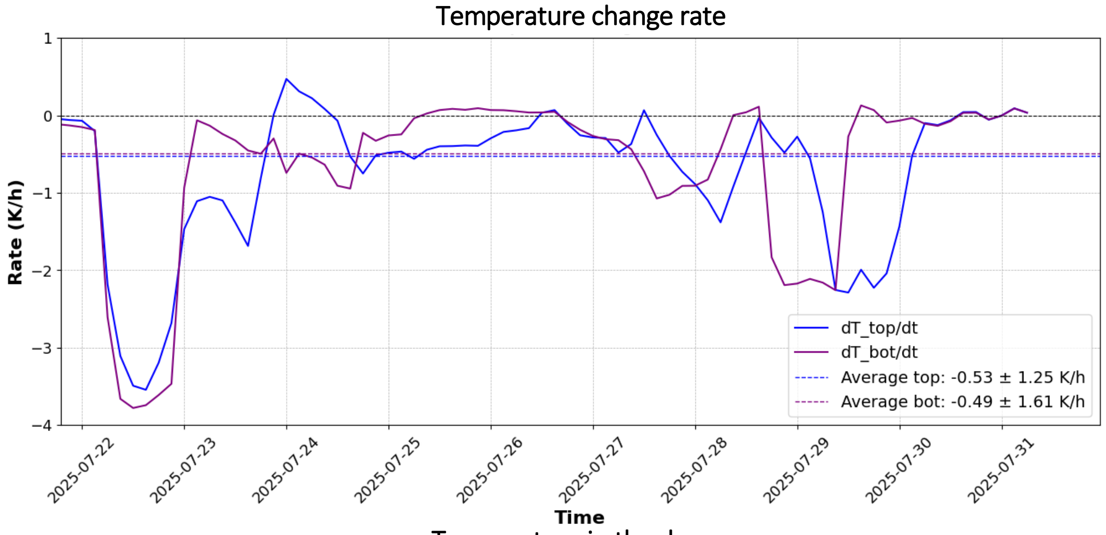
- To control the cooling rate speed and uniformity, two heaters + copper plate

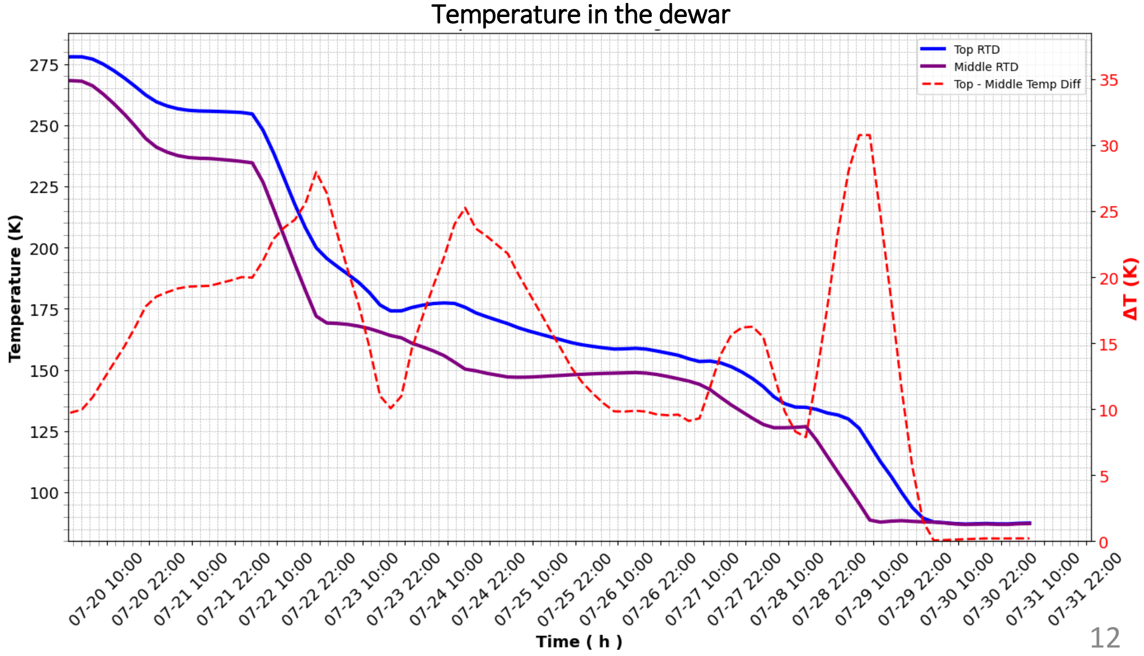
- About <u>11 days</u> to reach LAr level up to the cone
  - *~20 L of LAr*

- Average cooling down rate $dT/dt \cong -0.5\ K/h$ for both RTDs on the PMMA (< -4K/h limit for PMMA)

- Temperature difference between top and bottom PMMA RTDs $\Delta T\ (top - bottom) < 35\ K$
  - $< 1.8\ K/cm$ between the two RTDs

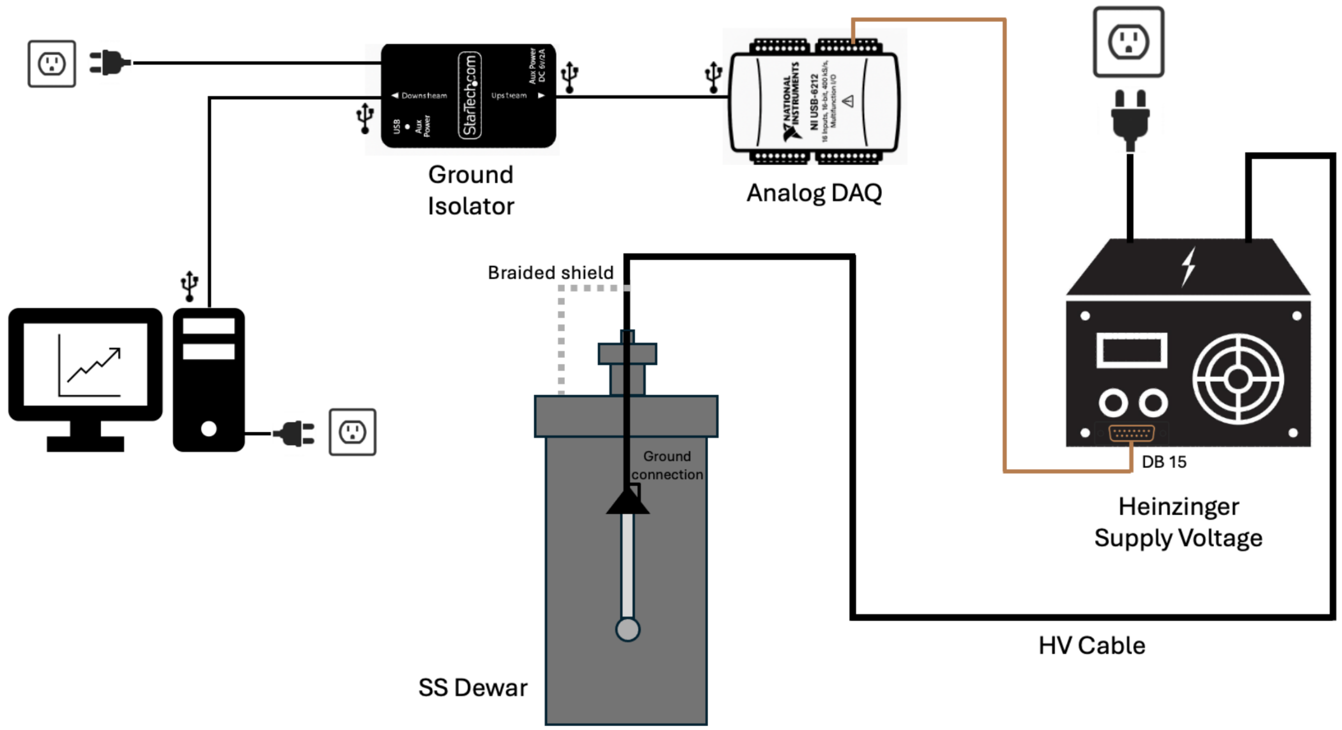
Reasonably controlled slow cooldown rate and thermal uniformity within the dewar

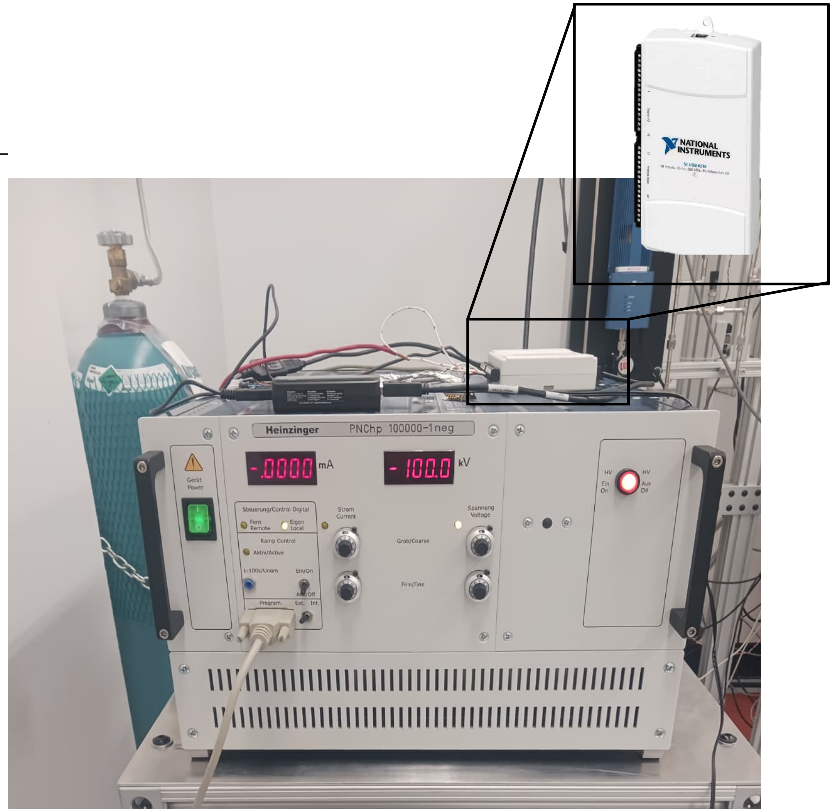




High-Voltage Supply

- Once the dewar was filled with LAr (above the HV cable cone), we powered the HV cable
- The HV power supply is a *Heinzinger PNChp 100000-neg* (Vmax = -100 kV, Imax = 1 mA) – same to be used in DS-20k





- Analog output connected to a USB DAQ device (NI-USB, 16 bit, 400 kS/s) to control and readout the output voltage and current

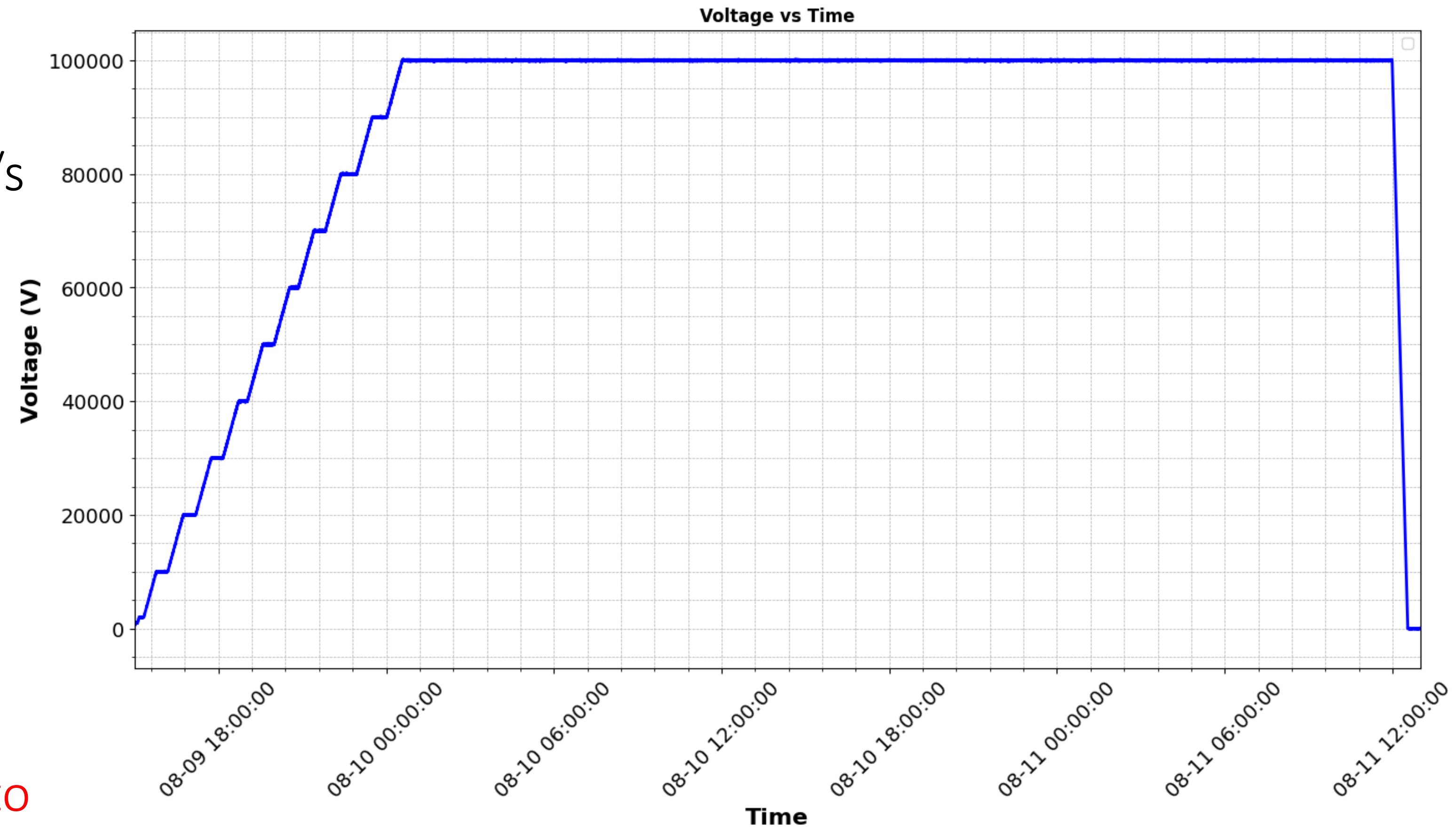
High-Voltage Run

- Ramp up until -100 kV, 5 V/s, in steps of 10 kV, with 30-minute pauses between each step:
    - ~10 h to reach -100 kV
    - ~14 d @-100 kV

- Ramp down from -100 kV to 0 V, 50 V/s

- System stable
    - no oscillations in the voltage

- Measured current O(100 nA), for ramp up and ramp down
    - no peaks in the current due to electrical discharges



We can supply the HV cable up to -100 kV with the system being stable during the test

High-Voltage Run – Hardware

- Recording with no LED light: no sparks due to electrical discharges observed from cameras view
- Bubble formation around the sphere could not be clearly determined
  - different bubbles sources within the dewar
- HV cable capacitance and resistance measured after test
  - $C = 376 \pm 4\ pF$ ($C = 380 \pm 4\ pF$ before test)
  - $R = 185 \pm 1\ k\Omega$ ($182 \pm 1\ k\Omega$ before test)

Electrical properties of the cable stable throughout the test

- No damages reported due to thermal stress, both on PMMA and PE of the cable and stress cone

HV cable and cone proved to be robust and reliable throughout the thermal gradients induced by the LAr cooldown process

Conclusions and Next Steps

- In DS-20k the electric field strength is critical for the sensitivity of the experiment, and E_{drift} = 200 V/cm means a cathode supply voltage of -75 kV

- With the HV test @UCDavis, we tested the HV cable and the stress cone in LAr, simulating the connection to the PMMA cathode of DarkSide-20k in terms of local electric fields

- Control cooling down rate and uniformity in the dewar through a copper plate + heaters at the bottom of the dewar and a recirculation pump

- Al sphere powered up to –100 kV:
  - system stable, with the output voltage free of oscillations
  - measured current O(100 nA)
  - no sparks and no evident bubbles formation around the sphere observed from cameras
  - HV cable C and R stable throughout the test

- The system was held at –100 kV for ~14 d, during which the voltage remained stable

This test provides key technical and procedural insights into the design, operation, and reliability of the cathode voltage supply and plug system for DS-20k

- Next step: add argon purity monitor

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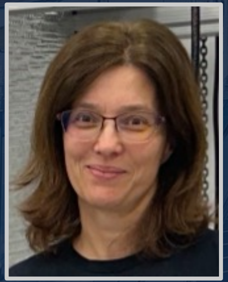
THANK YOU!


Emilija Pantic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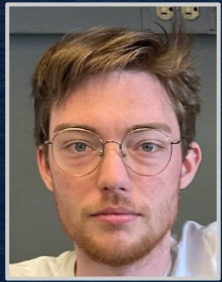
Tyler Erjavec


Aaron Elersich


Dylon Fleming

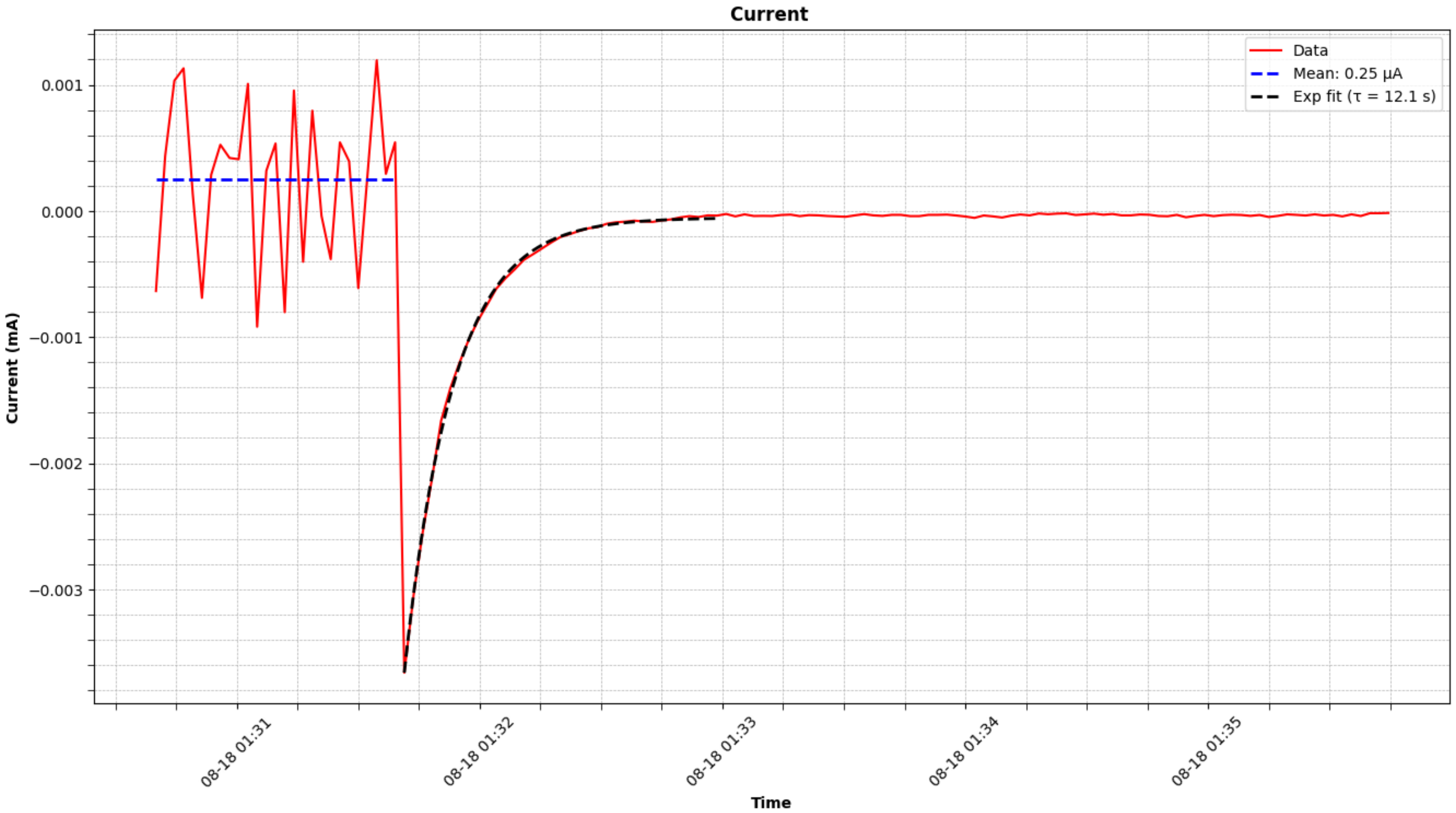
BACKUP

- At V = 40 kV, I_0 = 0.25 **μ**A
  - $R_{tot} = V/I_0$ = 160 GΩ

- Sudden shut off of the voltage supply:
  - $I(t) = I_0 e^{-t/\tau} \Rightarrow$ Negative exponential fit

- $\tau = 12.2\ \text{s} = R_{tot}C_{eff} \Rightarrow$ **$C_{eff} = \tau / R_{tot}$ = 76.3 pF,** which is the effective capacitance of the HV system

- Stored energy **E = ½ CV² ≅ 3 J**



Temperature difference
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ΔT (top − bottom) < 35 K