

High-Voltage System control for the ICARUS experiment at Fermilab

A. Gioiosa^{1,2}, Linda Bagby⁷, Hector Carranza³, S. Donati^{1,4}, Alberto Guglielmi⁵, Anna E. Heggestuen⁶, Wooyoung Jang³, Claudio Silverio Montanari⁷, Promita Roy⁸, Geoffrey Savage⁷, Donatella Torretta⁷

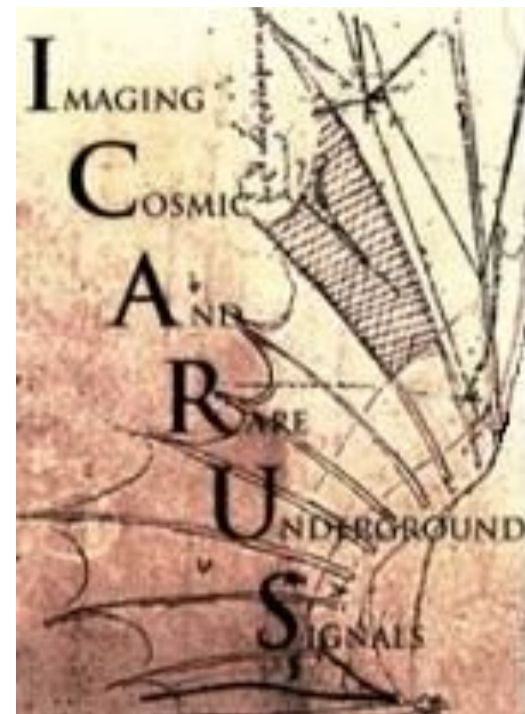
¹INFN Sezione di Pisa, Italy; ²Università degli Studi del Molise, Italy; ³The University of Texas at Arlington, USA; ⁴Università di Pisa; ⁵INFN Sezione di Padova; ⁶Colorado State University; ⁷Fermi National Accelerator Laboratory, USA; ⁸Virginia Polytechnic Institute and State University, USA

Abstract
The ICARUS-T600 detector is a large liquid argon time projection chamber (LAR-TPC) installed at Fermilab within the Short-Baseline Neutrino (SBN) program. Its operation depends on a highly stable and precisely controlled high-voltage (HV) system that generates the uniform electric field required for ionization charge drift and collection. The system supplies -75 kV to a central cathode, producing an electric field of 500 V/cm across a 1.5 m drift distance.

The HV infrastructure consists of an external power supply, custom cryogenic feedthroughs, and a resistive voltage divider chain that linearly distributes the potential along the field cage. A fully automated ramp-up and ramp-down capability is implemented through a remote PC-based control system using an Ethernet analog interface (EDAS-1000), allowing accurate configuration of voltage setpoints, ramp rates, and safety thresholds.

Continuous real-time monitoring ensures that voltage and current remain within operational limits, while automatic interlocks and logging guarantee safe operation. The system has demonstrated excellent stability, maintaining fluctuations within ± 25 V at -75 kV (about 3×10^{-4} relative variation) with no measurable leakage current. Controlled ramping and careful electrical design minimize stress and thermal load, ensuring reliable long-term operation under cryogenic conditions.

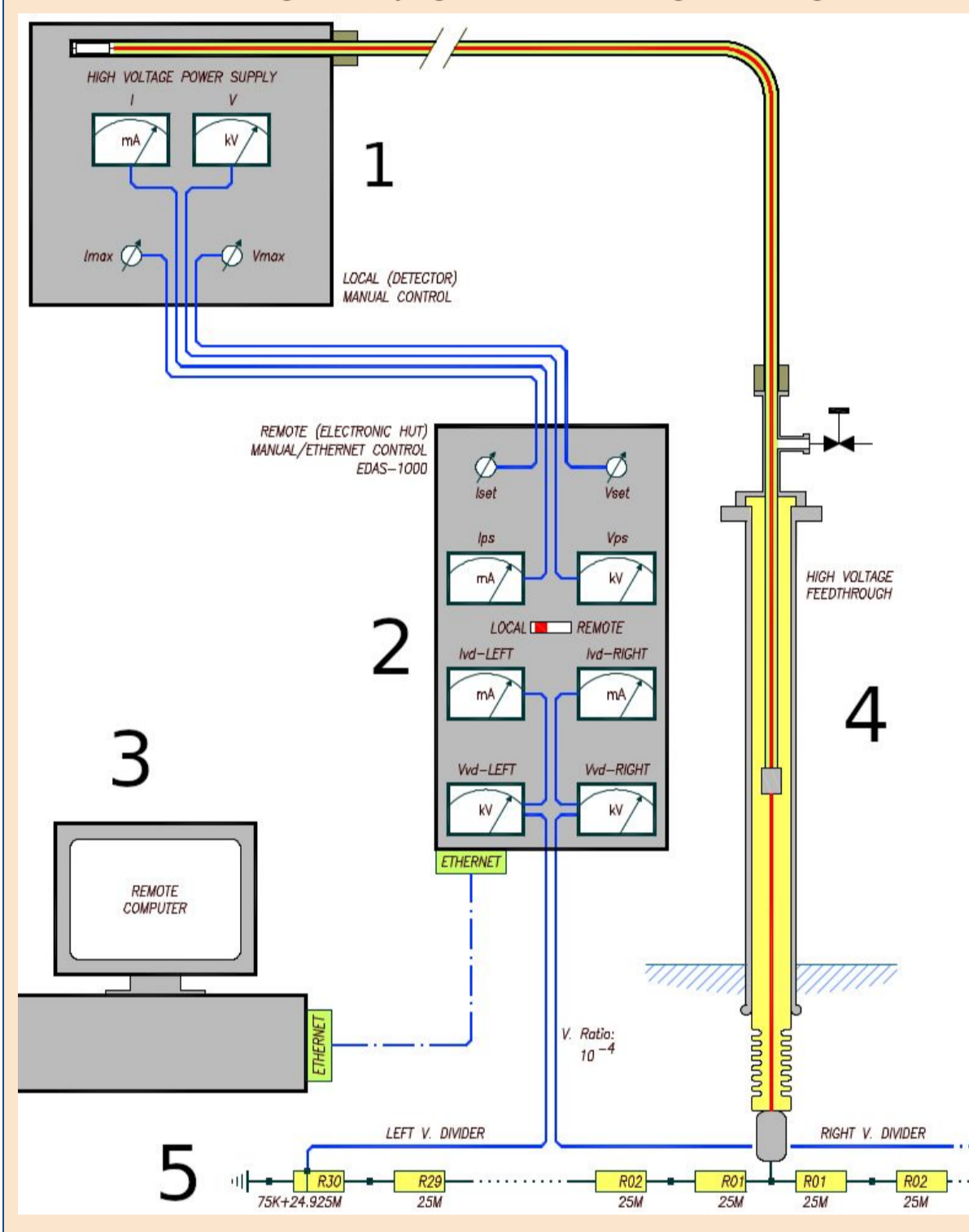
Since its commissioning in 2020, the HV system has supported cosmic-ray calibration and continuous neutrino data taking, achieving signal-to-noise ratios above 5 and electron lifetimes exceeding 3 ms. In late 2023, the control software was upgraded with an automatic emergency ramp-down triggered by power outages or interlock signals, a feature validated through extensive testing and stable GUI operation.



1. Hardware Infrastructure: HV Power Generation

Physical components responsible for generating and distributing the electric potential:

- HV Generation:** The primary voltage is supplied by a robust external power supply (Heinzinger).
- Distribution:** Potential is linearly distributed along the field cage via a resistive voltage divider (degrader) chain.
- Cryogenic Integration:** Connection to the internal detector components is achieved through custom-designed cryogenic feedthroughs, designed to minimize thermal load and electrical stress.



The diagram illustrates the complete signal and power path of the ICARUS High-Voltage system, from the external power generation to the internal detector components.

- High-Voltage Power Supply (Heinzinger):** The primary external hardware responsible for generating the drift potential. It features local analog displays for monitoring voltage (V) and current (I), along with manual control knobs.
- Custom Control & Monitoring Module:** A specialized interface unit that bridges the Heinzinger power supply with the remote control system. It utilizes the **Burr Brown EDAS-1000** analog-to-Ethernet interface to transmit front-panel controls and monitoring signals to a remote host.
- Remote Computer & Ethernet Link:** The system is operated via a host PC connected through a standard **Ethernet link**. This allows for fully automated ramp-up and ramp-down procedures and real-time data logging from the Electronic Hut.
- High-Voltage Feedthrough:** A custom-designed cryogenic component that safely penetrates the detector's vacuum-insulated vessel to deliver the -75 kV potential to the liquid argon environment.
- Cathode and Voltage Divider Chain:** Inside the detector, the high voltage is distributed to a central cathode. A chain of **resistive voltage dividers** (degraders) linearly steps down the potential along the field cage to maintain a uniform electric field of 500 V/cm across the 1.5 m drift distance.

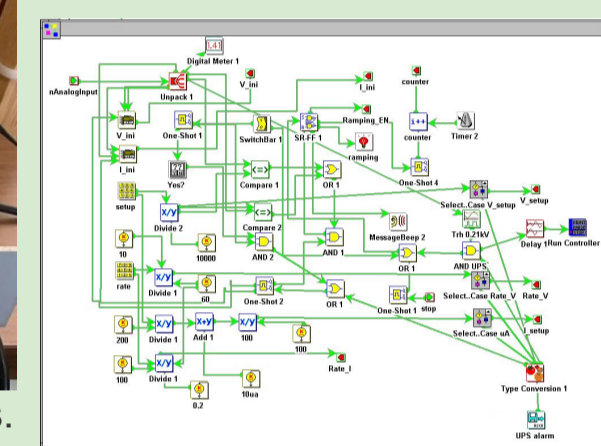
2. Control Architecture and Software Interface

The logic and hardware used to manage the system remotely:

- Interface Hardware:** Control is centralized on a remote PC connected via an Ethernet-based analog interface (**Burr Brown EDAS-1000**).
- Visual Designer Software:** The control logic is developed using Visual Designer, allowing for precise configuration of voltage setpoints and ramp rates.
- Automation:** The system supports fully automated ramp-up and ramp-down procedures, providing a user-friendly GUI for real-time operator oversight.



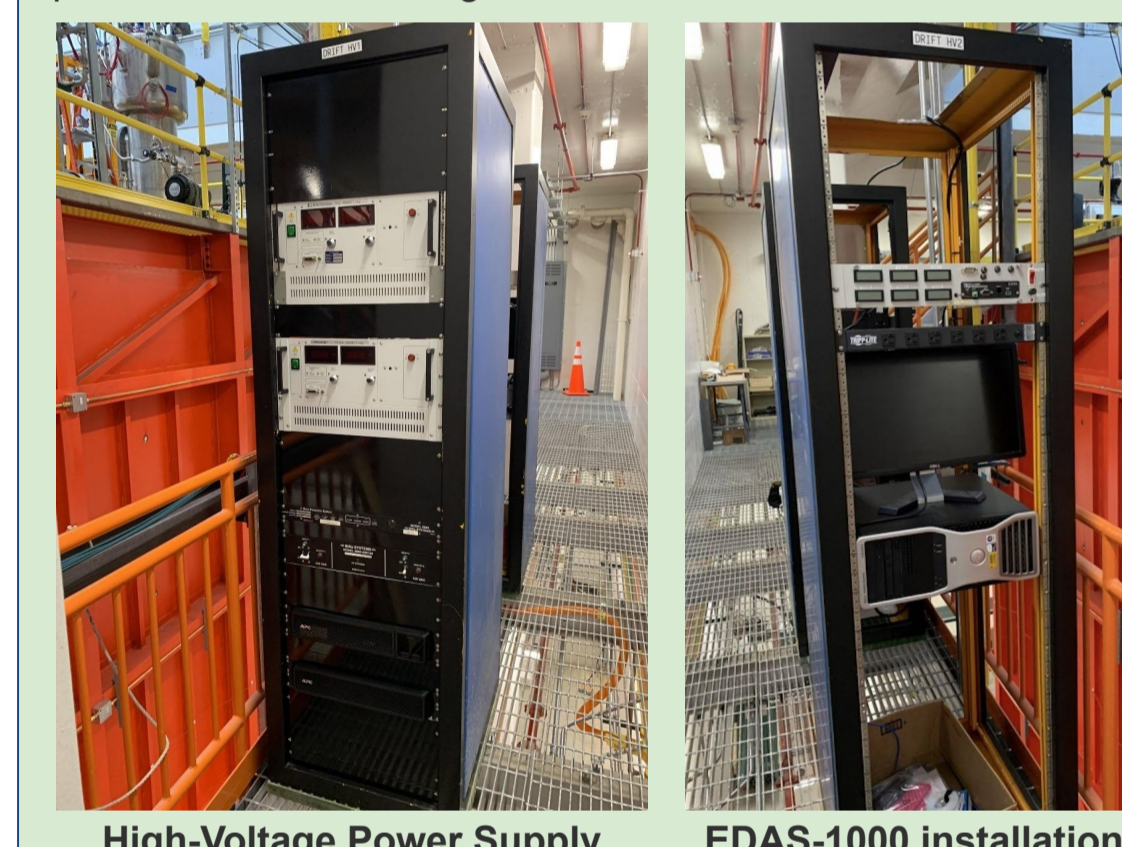
The EDAS unit installed inside the Monitor Chassis. The chassis open, revealing the EDAS module connected to a custom breakout board and the internal power distribution wiring.



Visual Designer Control Architecture Schema developed for the ICARUS HV system:

The HV control software is developed in a graphical environment where modular blocks define the system logic.

- Data Acquisition:** The **nAnalogInput** block acquires real-time monitoring signals (voltage and current) from the EDAS-1000 interface.
- Operational Logic:** The control subgram processes user-defined setpoints, safety thresholds, and ramp rates.
- Automation:** The **Ramping** module executes the automated voltage adjustment sequences, ensuring smooth transitions to the target potential.
- Safety Integration:** The diagram includes dedicated logic for **automatic emergency ramp-down**, which is triggered by UPS status files to safely de-energize the detector during power failures.

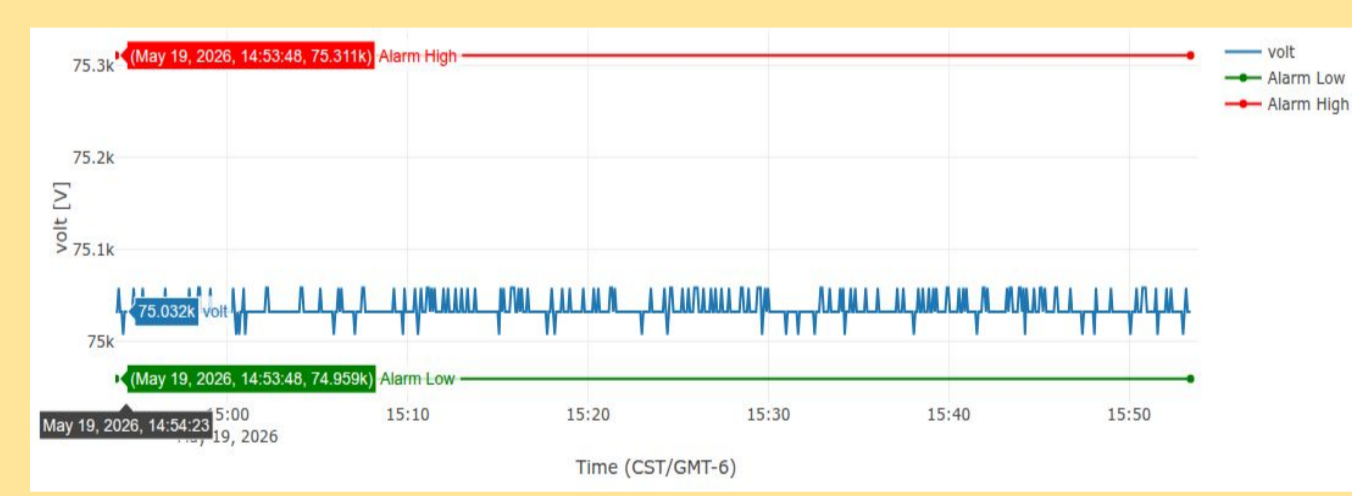


High-Voltage Power Supply EDAS-1000 installation

3. Continuous Monitoring and Performance Stability

Voltage Stability

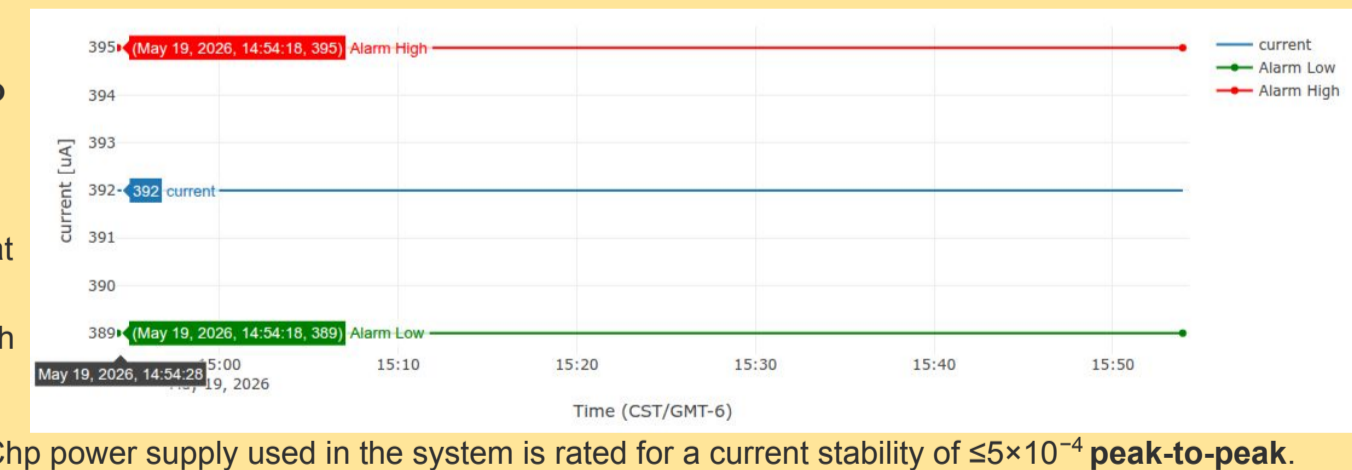
- Operational Stability:** A highly stable potential, with fluctuations kept within ± 25 V at a nominal operating voltage of -75 kV. This represents a relative variation of approximately 3×10^{-4} .
- Ripple Rejection:** The residual voltage ripple at 75 kV is roughly **150 mV peak-to-peak**. With a specialized three-stage rejection filter, the low-frequency ripple (50 Hz) is further reduced to approximately **29 mV peak-to-peak**, while high-frequency components are virtually eliminated.



- Impact on Data Quality:** This high level of stability is critical for detector performance, enabling **signal-to-noise ratios exceeding 5** and **electron lifetimes above 3 ms**, which are essential for high-fidelity event reconstruction.

Current Stability

- Leakage Current:** The system operates with **no measurable or significant leakage current** observed during standard operation at -75 kV.
- Operational Consistency:** During stable runs at 75 kV, the total current remains around **0.4 mA** flipping between 395 and 396 μ A, consistent with the unit's expected stable behavior.
- Hardware Specifications:** The Heinzinger PNChp power supply used in the system is rated for a current stability of $\leq 5 \times 10^{-4}$ **peak-to-peak**.



Monitoring and Averaging

- To ensure stable readings, the **Visual Designer** control software processes raw signals from the hardware through a "Monitor Subgram".
- Voltage Monitoring:** The software calculates the average of the last **10 to 20 samples** to provide a steady display value.
 - Current Monitoring:** The software averages over **30 samples** to filter out electronic noise and provide a stable monitoring output.
 - Data Logging:** The system's "Record Subgram" logs raw data for detailed stability analysis. Slightly higher variability (up to ± 5 μ A) may be observed compared to the smoothed display.

4. Safety Upgrades and UPS Integration

AC Power Distribution and UPS Integration: ICARUS Drift HV Rack 1

A visualized blueprint of the electrical power path, integrated safety layers, and UPS backup for critical high-voltage equipment and network hardware.

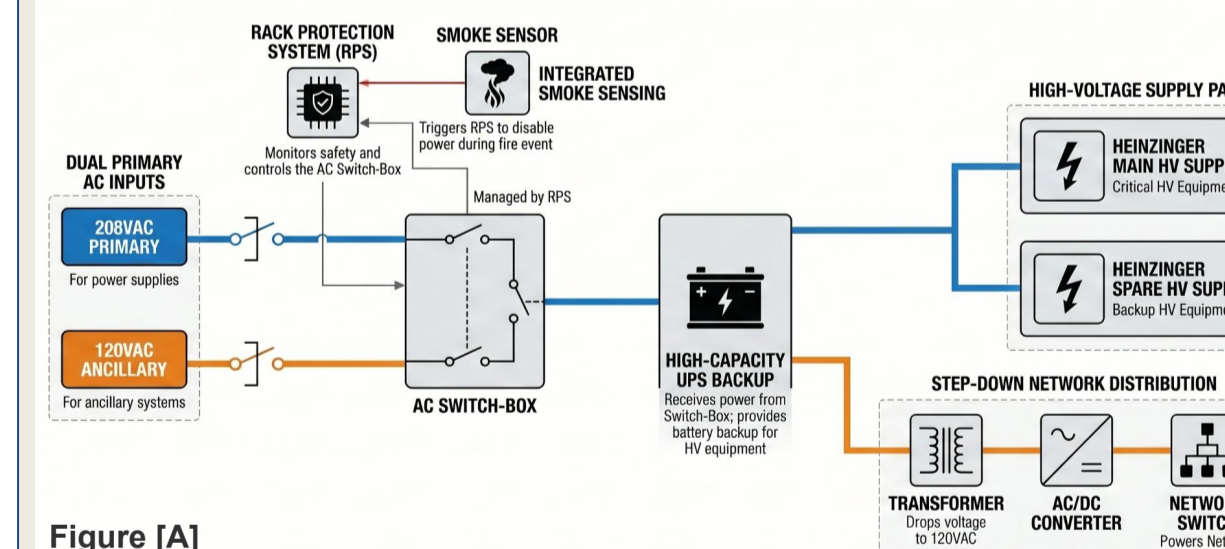


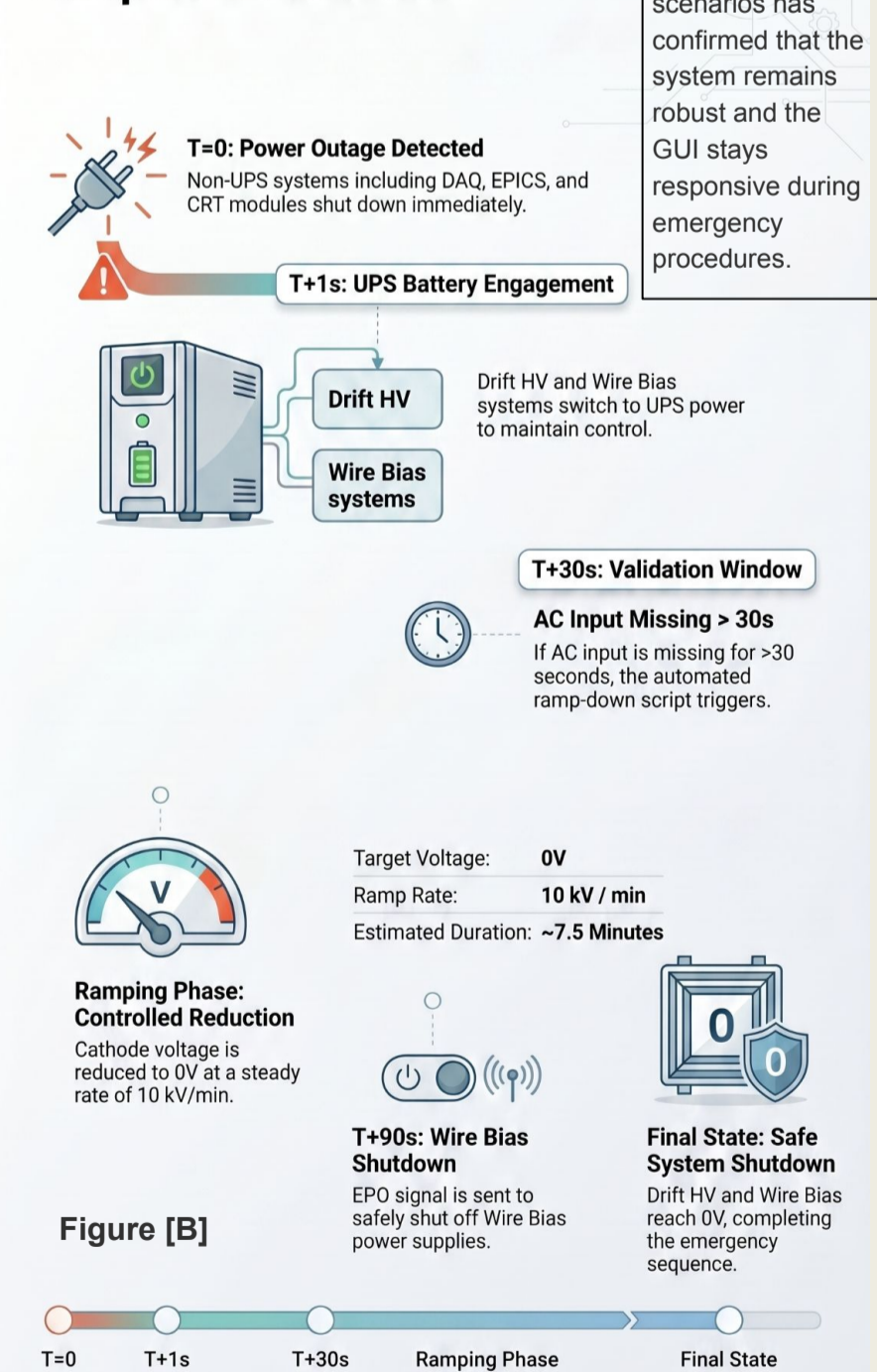
Figure [A]

Figure [A]: AC Power Distribution and UPS Integration. This schematic details the power path from the mains to the HV power supplies through the UPS and the Rack Protection System (RPS). It includes the smoke detection interlock that can trigger an immediate power interruption.

Figure [B]: Emergency Response Flowchart. Sequence of automated actions during a site-wide power outage. The system switches to UPS battery immediately and, after a 30-second validation period, executes the safe ramp-down sequence to protect sensitive LAR-TPC components.

- Visual Designer Emergency Logic**
Upon detecting a power failure, the system automatically latches the current voltage and initiates a controlled ramp-down to 0V at a rate of 10 kV/min.

ICARUS Drift HV Emergency Response Flowchart



Conclusions and Operational Impact

This final section summarizes the success of the HV system and its contribution to the SBN program.

- System Proven Reliability:** Since its commissioning in 2020, the HV system has demonstrated exceptional reliability and stability, maintaining a uniform electric field of 500 V/cm with minimal fluctuations.
- Data Quality Excellence:** The high stability of the -75 kV potential has been a key factor in achieving superior data quality, characterized by signal-to-noise ratios > 5 and electron lifetimes exceeding 3 ms.
- Enhanced Safety Standards:** The successful 2023 integration of automated emergency procedures provides a robust safeguard against power failures, ensuring the long-term protection of sensitive detector components.
- Fundamental Role:** These results affirm the HV system's essential role in supporting continuous neutrino data taking and enabling precise event reconstruction for the ICARUS-T600 detector.

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