Snowmass2021 - Letter of Interest

High Voltage Cable Feed-through

Thematic Areas: (check all that apply ☐/■)

☐ (IF1) Quantum Sensors
☐ (IF2) Photon Detectors
☐ (IF3) Solid State Detectors and Tracking
☐ (IF4) Trigger and DAQ
☐ (IF5) Micro Pattern Gas Detectors (MPGDs)
☐ (IF6) Calorimetry
☐ (IF7) Electronics/ASICs
■ (IF8) Noble Elements
☐ (IF9) Cross Cutting and Systems Integration

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Collaboration (optional):

Authors: (long author lists can be placed after the text)

Abstract: (maximum 200 words)

Physics experiments featuring liquid noble gas time projection chambers (TPCs) are becoming larger in scale, and consequently so have their high voltage (HV) requirements, making conventional design HV feedthrough (FT) impracticable. A new concept for a HV cable FT usable in cryogenic environment is presented, which relies on the ability to fabricate a plastic material with tunable thickness and resistivity.

Liquid noble gas time projection chambers (TPCs) require the safe delivery of high voltage (HV) in a cryogenic environment. These TPCs work as particle detectors thanks to the presence of an electric drift field in their active volume formed by a field cage, an anode, and a cathode. HV is delivered to the cathode by a HV feedthrough (FT), a device penetrating the cryostat specifically designed not to cause an electric breakdown in the cryogen.

Conventionally designed HV FTs often couple a metal with an insulating polymer and have the strongest field strength located near the end of the ground ring[4;6]. If the field is higher than the electrical strength of the noble gas at liquid temperature, a spark could happen inside a bubble, that may have formed locally or elsewhere and drifted to the vicinity, causing an electrical breakdown. In order not to exceed the material's breakdown voltage, FTs are sized using the relationship $E \propto 1/r$, which describes the dependency of the electric field E, as a function of the distance r from the central conductor of the FT. The higher the biasing voltage (which determines E) the bigger the FT's outer diameter (OD) must be.

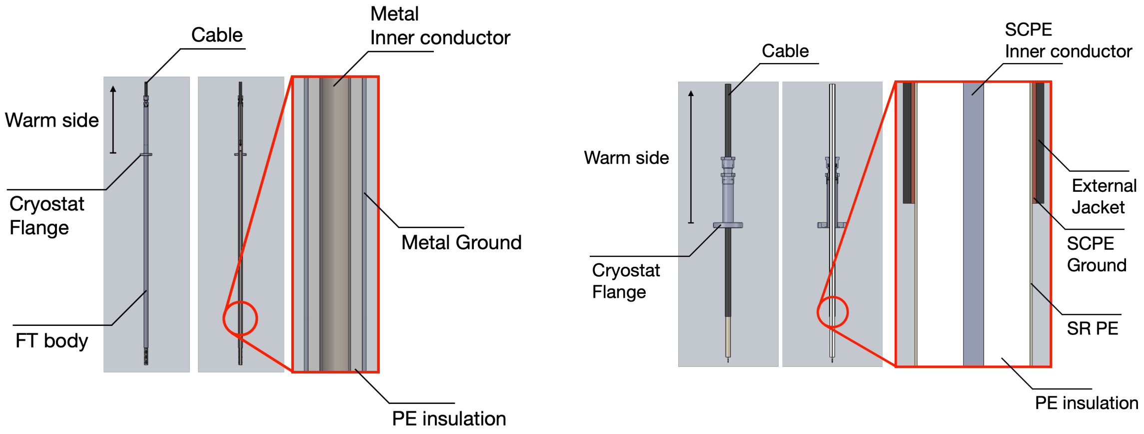
In the context of the ProtoDUNE experiment[2], a $4\,\text{in}$ OD HV FT able to deliver $200\,\text{kV}$ was successfully constructed[7]. Following the same design, a COMSOL[5] simulation of a HV FT immersed in liquid argon has shown that a $10\,\text{in}$ OD is required not to exceed the argon gas electrical strength limit[3] when a bias voltage of $600\,\text{kV}$ is applied. Even if constructing such a massive FT is feasible, it is not practical and still subject to failure. In fact, apart from the massive size, the mismatch in thermal expansion coefficients of the materials comprising the FT may create the conditions for the surrounding dielectric to infiltrate and reach regions of high electric field, where electrical breakdown would eventually occur.

A co-extruded multi-layered coaxial cable fabricated with a single material can overcome conventional design FT limitations. Being made entirely of a single material (i.e. of PE), the cable is not subject to the differing expansion rates of traditional FT's materials. This co-extruded nature of the cable guarantees leak-tightness within the cable while preventing out-gassing or bubble accumulation in a gap between the outer grounding and the insulator, which may form at cryogenic temperatures. Hermeticity at the FT is maintained by a room temperature plug between the cable and the cryostat. A cable composed entirely of PE is already commercially available. Its design features pristine PE as an insulator, with semi-conductive PE (SCPE) for the core conductor and ground layer. Adding carbon-black (CB) particles to pristine PE converts it to a semi-conductive material suitable for the core conductor and the ground layer of the cable. To preserve the cable's function as a HV FT, a semi-resistive (SR) layer must be added between the existing insulator and ground layers. The added SR layer will continuously confine the electrostatic field lines rather than letting them relax unconstrained.

Fig. 1 shows both the standard HV FT design and the new cable HV FT concept.

Fig. 2 shows the results of a COMSOL simulation for the allowed resistivity (ρ) and thickness (dt) of the SR layer in a PE HV cable FT biased at $70\,\text{kV}$ immersed in liquid argon. The allowed region reflects the requirements for the cable to function as a HV FT (which is not to exceed the argon electrical strength limit[3]) and not to produce bubbles (power dissipated by the SR layer must not exceed the safe threshold[1] of $1\,\text{mW/cm}^2$). As seen in Fig. 2 there are various combinations of ρ and dt, which can address the needs of the HV cable FT. The available parameters space allows different solutions to fabricate this layer. Three main avenues were identified: carbon black-doped polyethylene, ion implantation, and the usage of semi-resistive epoxies. Future work and R&Ds will focus on the feasibility of these different options.

This work, done in the DarkSide and DUNE collaborations, will benefit any future experiments that need to deliver high voltage into a cryogenic environment.



(a) (b)

Figure 1: Conceptual design of both a standard HV FT (1a) and the new HV cable FT (1b). Inscribed, is shown a detaile view of the vertical cross section of the HV FT.

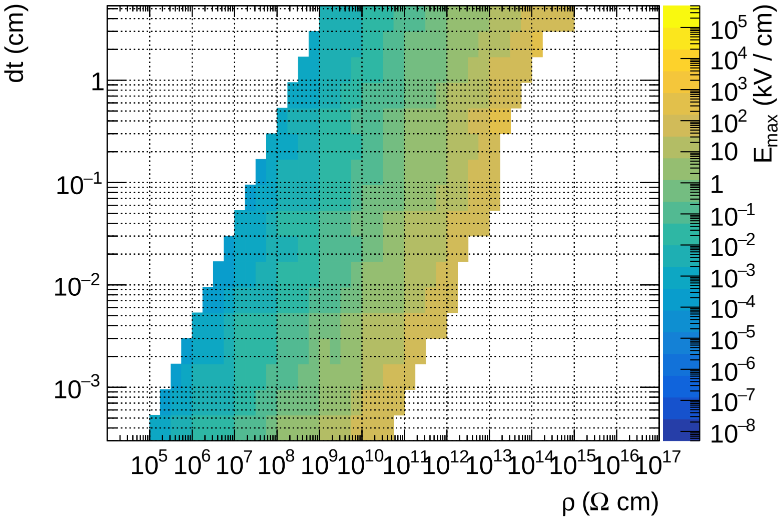


Figure 2: Results of a COMSOL simulation for the available parameter space in resistivity (ρ) and thickness (dt) of the SR layer in a PE HV cable FT. The cable is biased at 70 kV and immersed in liquid argon. The primary dimensions of the HV cable FT are taken from the commercially available version. This cable features a 0.08 in-thick SCPE core conductor, a 0.44 in diameter PE insulator, and a 0.01 in-thick SCPE wall ground. The length of the exposed SR layer (from ground to HV) is 5 in. The allowed region is determined requiring both that the maximum field does not exceed the argon gas electrical strength limit ($E < 108$ kV/cm)[3], and the dissipated power is below the safe bubbling formation threshold[1] of 1 mW/cm^2.

References: (hyperlinks welcome)

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