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Testbed for high voltage characterization of gaseous helium cooled hts power cables for electric transport systems

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Abstract. The design and implementation of a novel testbed for high temperature superconducting (HTS) power cables operating at cryogenic temperatures are described. The testbed features custom-designed electrical and thermal breaks, as well as a dual grounding scheme, to protect the cryogenic, vacuum, data acquisition, and other auxiliary equipment in an HTS cable system in the event of an electrical breakdown or arc formation. A successful characterization of an HTS cable was demonstrated, and partial discharge data was acquired. As expected, the noise levels and threshold of apparent charge measurements are higher than those achieved in controlled measurements in a Faraday cage. The test resembles field tests of an HTS cable on an electric transport platform. There is a need for further work in developing data analysis techniques, including machine learning tools, to separate data from noise sources. The testbed represents a much-needed high-voltage and high-current characterization of HTS cable systems to support the development of superconducting technology for hydrogen-fueled electric aircraft and electric ships.

1. Introduction

The urgent need to decarbonize the global transportation sector including maritime, aviation and rail transport, is driving intensive research into electric propulsion systems as sustainable alternative to conventional fossil fuel-based internal combustion engine technologies. Among the emerging technologies, high-temperature superconductor (HTS) technologies are promising for enabling the next generation of electric transportation systems [1]-[3]. The development of electric ships, hybrid wing body (HWB) electric aircraft concepts such as NASA's N+3 configuration, and high-speed electric trains represent a paradigm shift in transportation engineering [4]-[7]. HTS devices offer compelling advantages, including power rating tunability, increased efficiency, and high power densities of 3-5 times higher than conventional systems [6], [8].

The cooling methodology for HTS devices critically impacts system performance and operational flexibility. While liquid nitrogen (LN_2) cooling at 65-77 K has been used for HTS power cables, gaseous helium (GHe) cooling in the 50-80 K range offers distinct advantages for transportation applications [9]. GHe eliminates two-phase flow instabilities of LN_2 and supports compact cryogenic systems essential for marine and aerospace environments. Furthermore, the lower operating temperatures achievable with GHe enhance the current-carrying capacity of HTS conductors compared to LN2, providing additional design margin [10]. Despite these advantages, challenges remain in characterizing the high current and high voltage behaviour of GHe-cooled HTS power cables. Detailed characterization of electrical insulation performance for partial discharge (PD) is important for HTS cables. PD, which serves as a precursor to insulation failure, is the localized discharge within the voids of the electrical insulation. Understanding the discharge mechanisms enable the development of insulation designs that maintain reliability throughout the cable's operational lifetime.

The available HTS cable testing infrastructure presents a significant gap between laboratory-scale demonstrations and the requirements for cables for real-world transportation applications. At the Center for Advanced Power Systems (CAPS) at Florida State University, we have extensively investigated HTS cables in static cryogenic environments within electromagnetically shielded enclosure. However, long integrated HTS cable systems present unique challenges in electromagnetically noisy environments. These systems require coupling to both cryogenic and vacuum systems for proper operation. Due to their extended length and the need for auxiliary systems, HTS cable assemblies cannot be accommodated within conventional electromagnetically shielded enclosures for qualification tests. Hence, reliable methods for characterizing HTS cables to mimic field testing are necessary. Additionally, testbeds must protect the cryogenic and vacuum equipment during the high voltage tests that might lead to breakdown and/or arc formation. PD measurements present unique challenges in cryogenic circulation systems due to their inherent sensitivity to electromagnetic interference, vibration, and temperature variations. Traditionally, PD measurements in HTS systems have been conducted using Faraday cages for electromagnetic shielding. The integration of a cryogenic circulation system introduces additional complexity due to the electromagnetic noise of the compressors, circulation systems, and vacuum pumps, that interfere with precise PD measurement. This dynamic environment necessitates the implementation of different measuring techniques and noise filtering strategies beyond conventional shielding methods. At the same time, the cryogenic and vacuum systems must be protected from electrical breakdown and arc formation risks.

This paper presents the design and implementation of a comprehensive testbed developed at CAPS for high voltage characterization of GHe-cooled HTS power cables. Supported by NASA University Leadership Initiative funded Integrated Zero Emission Aviation (IZEA) program and the Office of Naval Research funded program, this facility enables testing of integrated HTS cable systems up to 30 meters under field-like conditions, including circulating GHe system at 50-80 K and operating pressure up to 2 MPa. A critical innovation in the testbed design is the implementation of thermally and electrically decoupled couplings through custom-designed cable terminations and electrical breaks. The testbed prevents cascading failures during fault conditions while maintaining the integrity of both the cryogenic and electrical measurement systems. The terminations incorporate bayonet connections for rapid cable changeout and integrated vacuum spaces for thermal isolation. Furthermore, the dual grounding system ensures proper electrical isolation between the high voltage circuit and the cryogenic circulation system, addressing safety concerns during the high voltage characterization of HTS cable systems.

The paper discusses the detailed design of the testbed, mechanical and electrical system integration, and measurement techniques. Section 2 describes the experimental setup, including cable termination and electrical breaks. Section 3 discusses the partial discharge measurements and Section 4 has the discussion. Section 5 summarizes the key achievements and outlines future work to expand the testbed capabilities.

2. Experimental Setup

2.1 Cable Terminations

The cable termination design was governed by two principal engineering considerations: thermal isolation to maintain cryogenic integrity and high voltage bushing selection for both electrical performance and mechanical compatibility. Two bushing configurations were implemented, a 30 kV rated 2.75" Conflat (CF) and a 60 kV rated 4.5" CF assembly. The larger 4.5" bushing was specifically chosen to accommodate the mechanical requirements of the model HTS cable. Its robust construction provides sufficient structural support to suspend the cable weight, thereby preventing the high voltage pin from contacting or resting against the ceramic insulator. This design approach ensures that proper electrical clearances are maintained throughout operation while eliminating potential discharge paths.

Thermal isolation between the cryogenic cable environment and ambient conditions is essential to maintain stable operating temperature while preventing excessive heat ingress that could compromise the superconducting state. To achieve the requisite isolation, a modified male bayonet design incorporates an 8" CF blank plate machined directly onto the bayonet assembly. This configuration enables connection to an 8" CF tee with a 6-inch inner diameter, providing sufficient internal volume for the integration of the 4.5" CF HV bushing and cable interconnection. The larger tee geometry ensures adequate clearance for assembly operations while maintaining the vacuum space necessary for effective thermal isolation.

Figure 1 illustrates the complete cable termination assembly. These design criteria collectively ensure that the termination provides both electrical and thermal performance necessary for high voltage characterization while maintaining operational flexibility for diverse cable geometries and testing protocols.

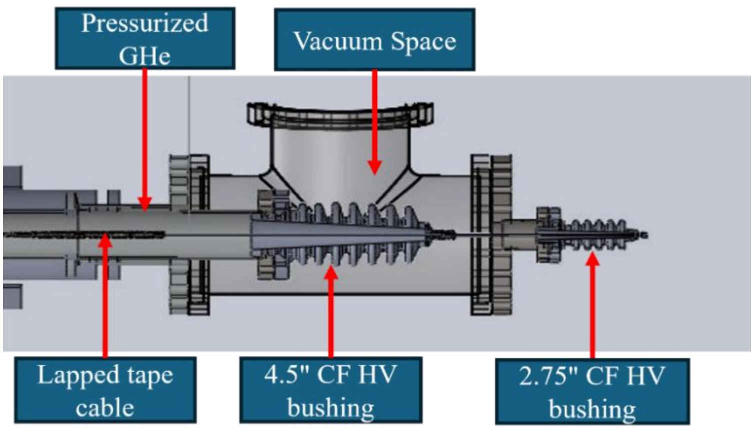

Figure 1. Cable termination design

2.2 Electrical Break System

The electrical break system serves to decouple the high voltage circuit from the cryogenic circulation loop, preventing ground faults from damaging both the cooling system and data acquisition equipment. This design implements a dual-break configuration, comprising inner and outer assemblies, that ensure electrical isolation while maintaining thermal stability of the cryogenic environment. This architecture enables a dual grounding scheme, establishing separate ground references for the high voltage system and the cryogenic plant. By isolating these ground paths, the system prevents fault currents from propagating between the electrical and cryogenic subsystems.

The outer electrical break assembly utilizes 8" CF components including a flexible bellows to accommodate thermal contraction, a 4-way cross that serves as both the mounting point for the inner break and connection port for vacuum pumping, a 75 kV-rated CeramTec ceramic isolator providing the primary electrical barrier, and a full nipple for system integration. The inner break employs 2.75" CF components comprising a tee section that houses a Cernox® temperature sensor, a 65 kV-rated electrical isolator, and a technifab transfer line that maintains cryogen flow while preserving electrical isolation. Figure 2 shows the electrical break assembly.

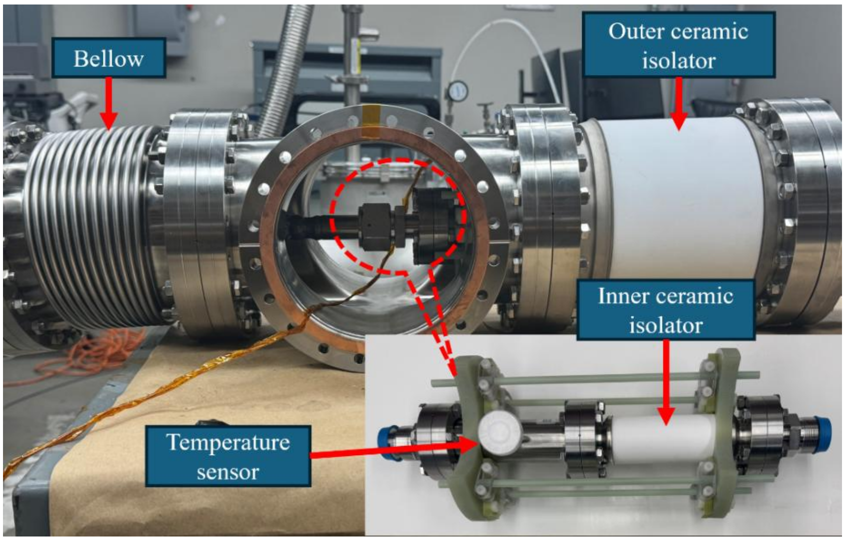

Figure 2. Electrical break assembly

This multi-barrier design creates a novel dielectric environment where high-purity vacuum, ambient air, and cryogenic helium coexist, forming multiple triple-point interfaces at their boundaries. These interfaces represent potential weak points for electrical breakdown, as electric field enhancement occurs at such junctions. To address this concern, finite element analysis (FEA) was conducted to evaluate the electric field distribution throughout the assembly ensuring the design maintains adequate safety margins under all operating conditions [11].

2.3 Testbed Design

The high voltage characterization testbed integrates multiple subsystems to enable testing of GHe-cooled HTS cable systems integrated with cryogenic, vacuum, and data acquisition components. Figure 3 shows a photograph of the experimental setup, illustrating interconnections of the major components.

The cryogenic system consists of a closed-loop GHe circulation system equipped with two Cryomech AL330 cryocoolers and two R&D Dynamics helium circulation impellers (HCF S803). The system provides up to 2 kW of cooling capacity at 60 K. The cryogen flows through vacuum-insulated transfer lines to the cable cryostat, where it directly cools the model HTS cable. A measurement tee positioned next to the cryogenic chamber enables real-time monitoring of temperature, pressure, and mass flow rate of circulating GHe.

The electrical system employs a 0-10/50 kVAC, 300/60 mA, 3 kVA Phenix transformer capable of generating test voltages up to 50 kV at power frequency. The transformer output connects to the cable termination through a coupling capacitor that detects and transmit PD signals to a measuring device. An Omicron MCT120 high-frequency current transformer (HFCT), clamped around the cable ground connection also allows for PD detection. An isolation transformer provides galvanic isolation between the high voltage circuit ground and the ground reference for sensitive equipment including the data acquisition system (DAQ) and vacuum pumps. The seperation of the grounds prevents ground loops and protects instrumentation from transient overvoltages during an electrical fault. The vacuum pumping system, comprising turbomolecular and scroll pumps, maintains ultra-high vacuum within the electrical break and termination assemblies. The system achieves a vacuum of 10^{-8} mbar at the pump inlet, while the average system pressure is maintained at approximately 10^{-6} mbar, representing a two-order-of-magnitude pressure gradient across the system.

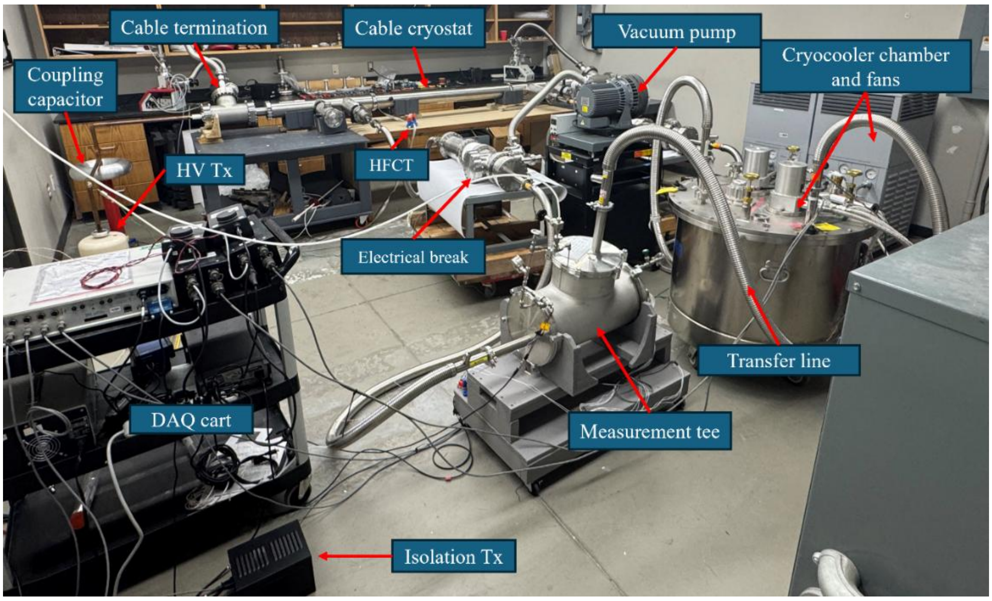

Figure 3. A photograph of the testbed for high voltage characterization of GHe-cooled HTS power cables

The electrical break assembly provides the critical isolation between high voltage and cryogenic circuits while maintaining mechanical stability and thermal performance. To evaluate the dielectric properties of the cable, the configuration utilizes a 6.35 mm copper conductor wrapped with 30 layers of lapped Kapton tape, creating dimensions equivalent to those of a CORC cable. No HTS material was used in the setup, as the primary objective is to assess the dielectric insulation performance of the cable structure. All measurement and control functions are integrated through a centralized DAQ system.

3. Partial discharge measurement technique

The testbed employs two complementary partial discharge measurement techniques to ensure characterization under varying experimental conditions, as illustrated in Figure 4. Both

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configurations utilize an MPD 800 PD detector coupled with an MCU2 control unit for signal processing and phase-resolved analysis.

Configuration (a) implements the conventional coupling capacitor method, widely recognized for its high sensitivity and standardized calibration procedures. In this method, the high voltage transformer energizes the device under test (DUT) through a measuring capacitor that provides the reference ground connection. A coupling capacitor, typically rated at 1 nF, extracts high-frequency PD signals. The coupling device, often referred to as a quadripole, containing an integrated impedance matching network, conditions the signals before transmission to the MPD 800 detector. Additionally, it often includes fast overvoltage protection and some filtering features that separate the test voltage to allow for synchronization [12]. This configuration achieves detection of apparent charge measurement sensitivity below 1 pC in electrically quiet environments, making it ideal for laboratory-grade measurements within a Faraday cage setup.

Configuration (b) utilizes an Omicron MCT120 HFCT for PD detection in electromagnetically noisy environments. The Omicron MCT120 HFCT, positioned around the ground connection of the DUT, detects the high-frequency current pulses associated with partial discharge events. This method proves particularly valuable for field tests and for our testbed outside the Faraday cage where the testbed has coupled GHe circulation. The setup encounters multiple electromagnetic noise sources, including cryocooler compressors and vacuum pumps.

Both measurements terminate at the MCU2 control unit, which converts optical signals into standard USB electrical communication signal. The processed data streams to a PC-based analysis system for real-time visualization of phase-resolved partial discharge (PRPD) patterns and long-term trending. The idea of incorporating both systems to record PD measurements is to enable direct comparison of the detection methods and develop and validate and field-line measurements useful for HTS cable installations in practical applications such as electric ships and aircraft.

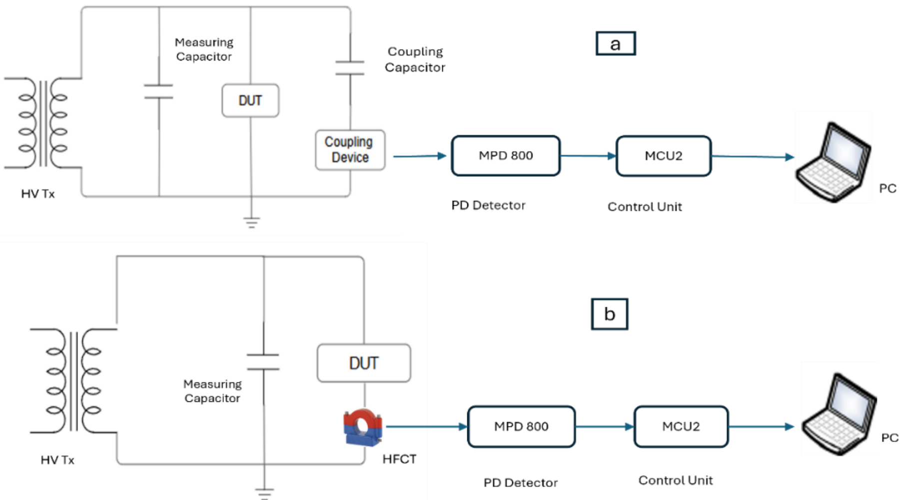

Figure 4. A schematic of the two PD measurement techniques, (a) Coupling Capacitor (b) MCT120 HFCT

4. Discussion

The noise levels in the open laboratory significantly exceed those achieved in the controlled Faraday cage environment. While the Faraday cage maintains an exceptionally low noise floor of 500 femtocoulombs, the noise levels in the open laboratory space with multiple pieces of

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equipment can be as high as 55 pC, an increase of over two orders of magnitude. This elevated noise floor stems from multiple electromagnetic interference sources operating within the test facility, including two cryocoolers with their associated compressors, impellers, various vacuum pumps, and a large power transformer. These sources generate electromagnetic interference that spans frequencies overlapping with typical partial discharge signatures, creating a challenging measurement environment encountered in a field test. The inclusion of the coupling capacitor enables system calibration and quantitative assessment of these noise levels, providing a baseline for distinguishing genuine partial discharge events from background interference.

With the baseline noise floor established at 55 pC, the detection threshold for partial discharge events is inherently limited to values exceeding this level. This constraint presents a fundamental challenge for determining the partial discharge inception voltage (PDIV), which by standard definition requires detection of discharges above 10 pC. The inability to resolve discharges in the 10-55 pC range effectively masks the true inception point, potentially leading to overestimation of the dielectric integrity.

Despite this limitation, the successful detection of partial discharges above 55 pC provides valuable diagnostic information for cable design. These higher-magnitude discharges typically indicate more advanced degradation mechanisms or significant defects that pose immediate reliability concerns. The presence of such discharges serves as a clear indicator that design modifications or manufacturing improvements are necessary. Furthermore, this measurement capability in noisy environments better reflects the actual operating conditions where cables must function reliably despite electromagnetic interference. The experimental technique is useful in developing a health monitoring system of an HTS cable system on an electric transport platform.

To enhance detection sensitivity and potentially recover partial discharge signatures below the current noise floor, advanced post-processing techniques incorporating sophisticated noise filtering algorithms should be employed. These methods, including wavelet denoising, adaptive filtering, and machine learning-based pattern recognition could effectively separate genuine discharge pulses from repetitive noise patterns. Implementation of such techniques would enable extraction of lower-magnitude discharge events from the noisy background, potentially approaching the sensitivity required for true PDIV determination even in electromagnetically challenging environments. This approach shifts the focus from laboratory-ideal measurements to practical assessment under realistic conditions.

5. Summary

A cryogenic high voltage testbed for comprehensive characterization of HTS cable systems is designed and established. A successful operation of the testbed under realistic operating conditions was demonstrated. The testbed is designed to test HTS cables integrated into a cryogenic helium circulation system, vacuum equipment, and data acquisition system. The testbed protects the auxiliary equipment in the event of an electrical breakdown or arc formation. The protection is achieved using carefully designed electrical breaks and separating the cable ground and equipment ground systems. The protection is achieved in the testbed by implementing a dual grounding system with custom electrical breaks that effectively decouple the high voltage and cryogenic circuits, ensuring both operational safety and protection of sensitive equipment. The specially designed high-voltage cable termination ensures stable operation in the cryogenic environment while allowing for rapid cable changeout and testing flexibility. Most significantly, the facility demonstrated the capability to perform partial discharge measurements in electromagnetically noisy environments that closely replicate field conditions, overcoming the limitations of traditional laboratory setups.

Acknowledgments
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