EXPERIMENTAL DETERMINATION OF DIELECTRIC PROPERTIES OF CRYOFLEX IN HIGH PRESSURE COLD HELIUM GAS

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Abstract: First tests on a novel high-temperature superconducting cable were performed to characterize its dielectric properties. The insulation system consisted of cold high-pressure helium gas and wound layers of Cryoflex™ tape. It was designed for applications where liquid nitrogen cannot be used. Three model cables each of length 1 m have been characterized regarding partial discharge (PD) inception voltage level as well as AC breakdown voltage level. The results are very consistent and promising for application in a 1000 V shipboard power system.

1 INTRODUCTION

With the advent of high-temperature superconductors (HTS) in many areas of power systems, there is a growing need for diverse methods of cooling. The standard technique used is liquid nitrogen (LN2). However, there are limitations with LN2, for example in a shipboard power system, where the risk of asphyxiation is high. LN2 could leak from storage tanks or the cable itself, evaporate and produce large quantities of nitrogen gas, which could accumulate on the lower decks of a ship, displacing breathable air. The United States Navy considers high pressure gaseous helium a viable alternative as it would quickly escape the ship hull due to its low density [1], [2]. Helium gas also offers additional benefits such as operation of HTS at lower temperature, which offers a higher critical current density. The ideal temperature for operation was determined to be around 55 K [1].

Insulation properties of gaseous helium are inferior to those of LN2. Breakdown field at room temperature and ambient pressure is only between 0.3 kV/mm to 0.7 kV/mm for gap distances between 100 mm and 1 mm [3]. This is two orders of magnitude lower than in LN2 [4]. Even so, the breakdown strength of gaseous helium considerably improves at higher gas density. At operating temperatures between 40 K and 70 K, the density is four to seven times higher than that under normal atmospheric conditions of temperature and pressure. In addition, at operating pressures between 0.44 MPa and 2.2 MPa (absolute) the gas density increases by another factor of between four and twenty [5].

In the past, single samples of Cryoflex™ have been tested in homogeneous field under various pressure conditions [6]. A small cryostat especially designed for this test series was used. It allowed characterization of Cryoflex™ in Helium gas at 77 K by AC, DC, and impulse breakdown tests. These results have guided the selection of appropriate design parameters for the cable such as the number of layers of Cryoflex™ tape. The performance of Cryoflex™ was also compared to that of Kapton™.

2 LAYOUT OF THE CABLE

The layout of this particular HTS cable (Figure 1) is typical for a 1-phase HTS cable except that it is not immersed in LN2 but in gaseous helium. A steel former in the center provides the necessary mechanical support. It is corrugated in order to allow to be bent. The former is also perforated to allow pressure equalization. A few layers of spirally-wound semiconductive tape are wrapped around it to provide a smooth surface. The actual HTS tape layers – coated with YBCO superconductor – are applied on top of the former and secluded by another few layers of semiconductive tape. The purpose of this semiconductive layer is to even out the electric field and to provide a smooth surface for the insulation tape. The electrical insulation is established by several layers of Cryoflex™ tape, a proprietary polymeric material used for cryogenic applications. The cable is completed by some more layers of semiconductive tape and an aluminum shield which is electrically grounded.

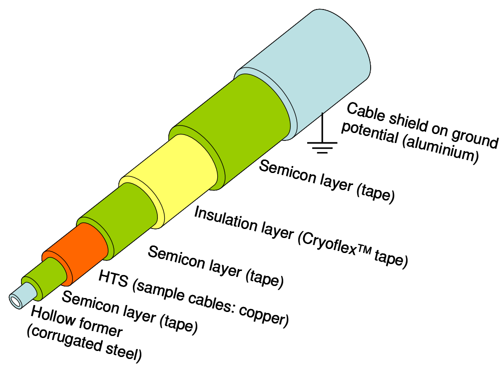

Figure 1: Layout of the superconducting cable (without cryostat)

For application in a shipboard power system, this cable is operated in a high-pressure cryostat. Terminations on each cable end provide electrical access to the HTS as well as ports to maintain a constant flow rate of cool helium gas. The helium is cooled externally to a constant temperature level.

The conducted dielectric tests focus on the properties of the insulation system consisting of Cryoflex™ tape in helium gas. Therefore, the cable was not positioned in its proper cryostat but in a vertical test vessel for laboratory purposes only. Also, the cable did not contain HTS tape but normal copper tape. The purpose of these experiments was to study the dielectric properties of cryoflex in a helium gas requirement.

3 TEST SETUP

3.1 Model Cable

In order to determine the key performance parameters of the insulation system, a model cable has been fabricated (Figure 2). The dielectric tests focused on the properties of the insulation system consisting of Cryoflex™ tape in helium gas. The cable did not contain HTS tape but was made from copper tapes of the same dimensions. The length of the cable sample was limited to 1 m because of the height restrictions in the test chamber. The cable was equipped with stress cones at both ends. The cones consisted of many layers of the same type of Cryoflex™ tape used for the cable insulation. Both ends were threaded to allow suitable attachment to the bushing (top end) and to the stress-control sphere (bottom end).

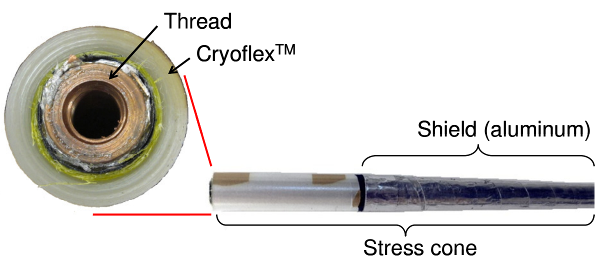

Figure 2: Photograph of the stress cone section of the model cable

The field distribution in the cones and on their surfaces was optimized by an FEA tool: Figure 3 shows the electric field for an early version of the stress cones at an applied voltage of 1 kV. The electric field on the surface to helium was kept below 0.5 kV/mm.

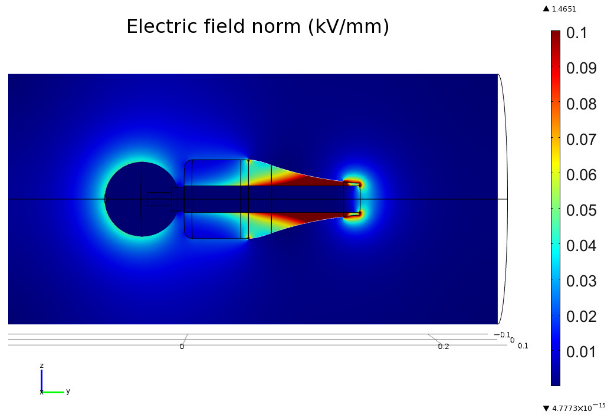

Figure 3: FEA simulation of the electric field on an early design of the bottom stress cone fixed to the test cable (applied voltage: 1 kV)

3.2 Pressure Cryostat

The model cable was not positioned in its proper cryostat but in a vertical pressure cryostat designed for dielectric characterization of the cable at pressure levels of interest. Figure 4 shows the basic layout.

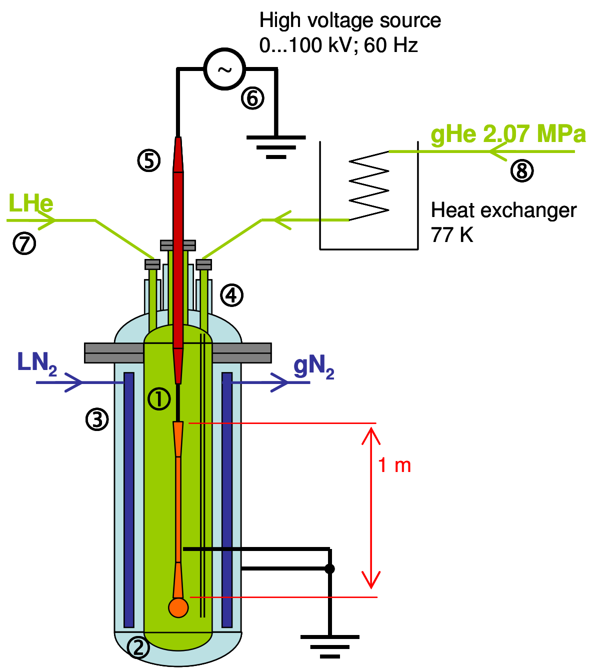

Figure 4: Schematic of the cryostat with pressure vessel (1), vacuum section (2), radiation shield (3), access flanges in the lid (4), high voltage bushing (5), external high voltage source (6), and infeeds for liquid (7) and gaseous helium (8)

The inner pressure vessel (1) can be evacuated or pressurized up to a static pressure level of 2.2 MPa. The pressure vessel is surrounded by a vacuum section (2). This section also contains a radiation shield (3) filled with LN2, which helps to maintain low temperature in the pressure vessel. The lid (4) contains one DN100 flange (6” ConFlat) in the center surrounded by six DN40 flanges

(2.75” ConFlat) for sample-, gas- and instrumentation access. The high-voltage bushing is introduced into the center flange. The peripheral flanges contain a feed line for liquid helium (7) and also a feed line for high pressure gaseous helium (8); the latter ends at the bottom of the vessel. Furthermore, there is a flange for a pressure relief valve, also used for evacuating the vessel, and a flange for a signal feedthrough for internal temperature sensing. Two more flanges are reserved for future use. The gaseous helium is pre-cooled by an external heat exchanger. It proved important to feed gaseous helium into the bottom section of the vessel since this substantially reduces the temperature gradient along the test object.

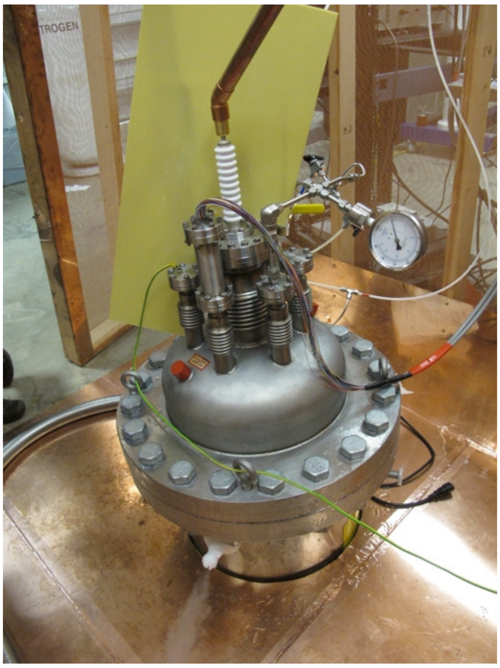

Figure 5: Photograph of the pressure cryostat, partially lowered into the laboratory floor; the G10 plate behind the bushing is for illustrative purposes only.

3.3 High Voltage Bushing

The requirements for the high voltage bushing are demanding especially when considering the limited space available. First and most important, it must be free of partial discharge (PD) up to at least the PD inception voltage (PDIV) of the test object. In addition to its dielectric properties it must bear significant mechanical stress due to the high internal pressure as well as a substantial temperature gradient and temperature fluctuations.

A hollow ceramic feedthrough with a DN40 flange (Figure 6 top) was used for the initial tests. It was designed to be operated in cryostats with nitrogen coolant. Our tests showed that its dielectric performance in helium was poor. The PDIV in helium at 0.5 MPa pressure was a low value of approximately 3.1 kV_{peak}. The explanation for these low PDIV levels was that the bare conductor was surrounded by helium gas near room temperature. The gap between the conductor and the inner wall of the ceramic insulator was 6.5 mm assuming the conductor was perfectly centered. The feedthrough in its original configuration could not be used for cable tests but needed modification.

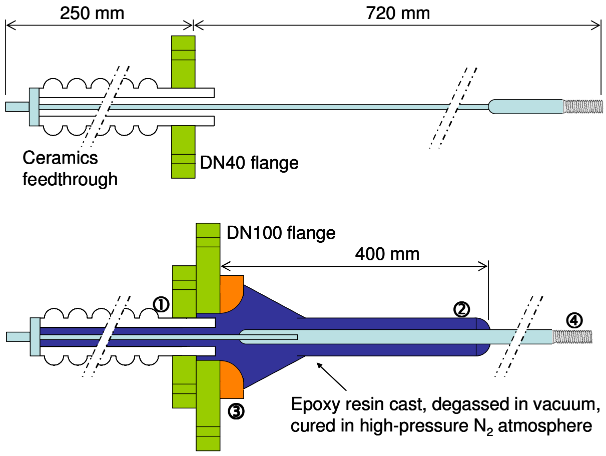

Figure 6: Original ceramic feedthrough (top) and modified feedthrough with all cavities filled with epoxy resin and extending the cast to increase creepage distance (bottom)

Figure 7: Photograph of the modified feedthrough

The basic idea for modification (Figure 6, bottom) was to eliminate the cavity between the ceramic part and the conductor. Therefore, the hollow part of a very similar type of ceramic feedthrough was filled (1) with epoxy resin (Stycast® 2850FT). The cast was extended by another 400 mm in order to get a long enough creepage distance to ground (2). A corona ring (3) was put in place and the diameter of the conductor (4) increased to 12.7 mm to further reduce the maximum electric field stress. A finite element analysis (FEA) tool was used to optimize the dimensions of each part. A photo of the modified HV bushing is shown in Figure 7. All of these modifications together increased the PDIV to 15.5 kV_{peak} at 2.17 MPa, which was good enough to perform the necessary PD tests on the cable samples.

3.4 High Voltage Setup

The inner conductor of the cable was connected to the HV bushing of the pressure cryostat while the cable shield was grounded. The High-voltage tests were performed in a shielded room divided into two cells. Figure 8 shows the high voltage power supply cell. The power supply consisted of a high voltage transformer (1), an in-line, low-pass filter (2), grounding circuit (3), capacitive voltage divider

(4), and two capacitors for PD instrumentation (5). A copper tube (6) connected the second cell containing the pressure cryostat. Figure 9 shows the circuit diagram.

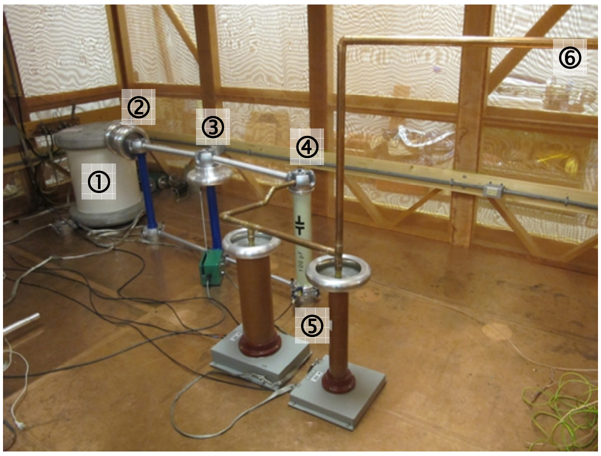

Figure 8: High voltage setup with transformer (1), filter (2), grounding switch (3), voltage divider (4), PD capacitors (5), and conductor to the cryostat (6)

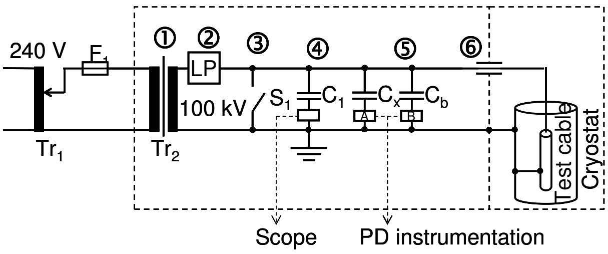

Figure 9: Circuit diagram of the high voltage setup

4 TEST PROCEDURE

The test procedure started by establishing a pure helium atmosphere in the pressure cryostat. It was of utmost importance to have a high-purity helium atmosphere for the dielectric tests on the test cables, otherwise complex effects from solid crystals (water moisture, carbon dioxide) or liquid drops (nitrogen, oxygen) could affect the dielectric properties of the insulation system. In order to accomplish the necessary purity, the pressure vessel was flushed first with nitrogen gas and later multiple times with helium gas. After each flush, the vessel was evacuated by a turbomolecular pump to 10^{-4} Pa (10^{-6} torr) and held at this vacuum level for several hours.

The initial cooling process started by filling the nitrogen jacket with LN2. While the surface temperature was normally 77 K, it could be further subcooled by a rotary vacuum pump to below 70 K. However, the improvement to the temperature distribution in the cryostat by subcooling of the nitrogen jacket was minimal since the most significant heat leaks were through the main flange and the high voltage bushing.

After releasing any significant overpressure, liquid helium was injected into the pressure vessel. During this process, a ball valve was opened to prevent build-up of overpressure in the vessel. This was a rather delicate process because any contamination of the helium atmosphere by air-influx had to be prevented. The liquid helium cooled the wall of the vessel as well as the test object and the lower part of the bushing to a temperature below 15 K. At that point the injection of liquid helium was stopped and the ball valve closed.

Subsequently, pressurized helium gas, pre-cooled by a heat exchanger, was fed into the pressure vessel. Practice showed that the temperature distribution was significantly more homogeneous if the gas was fed at the bottom of the vessel by a vertical tube. This process was stopped when a pressure of 2.17 MPa was reached. At this point, the temperature distribution along the cable was typically between 40 K and 60 K depending on the amount of liquid helium injected before pressurizing. Then the high voltage source was engaged and PD measurement started. Later, the pressure was reduced to 1.82 MPa by relieving some gas through the ball valve. This was followed by the next PD measurement and repeated for four more pressure levels. The temperature was kept constant at approximately 50 K.

AC breakdown tests were performed after complete PD characterization since they were of destructive type. The warm-up time before opening the cryostat was around two days. Three identical model cables were tested.

5 RESULTS

5.1 PD Level, Pattern and Inception Voltage

PD is considered a viable tool to characterize an insulation system for HTS application [7]. This is also in concert with international standards, which include cables with laminar dielectrics [8]. PD inception voltage (PDIV) must be well above the operating voltage to prevent deterioration of the insulation system. PD tests must be performed under AC (60 Hz) conditions even though the cables are intended to be used in DC systems. All AC voltage values are given as peak value. Three sample cables of identical type have been tested at six different pressure levels.

Figure 10 shows the PD activity as a function of both applied voltage as well as helium pressure. The three sample cables show very consistent levels of PD. This attests to a high degree of reproducibility for PD measurement and cable manufacturing. One important measure is the PD inception voltage (PDIV) level. Because of an omnipresent level of background noise, the threshold for the apparent charge was set to

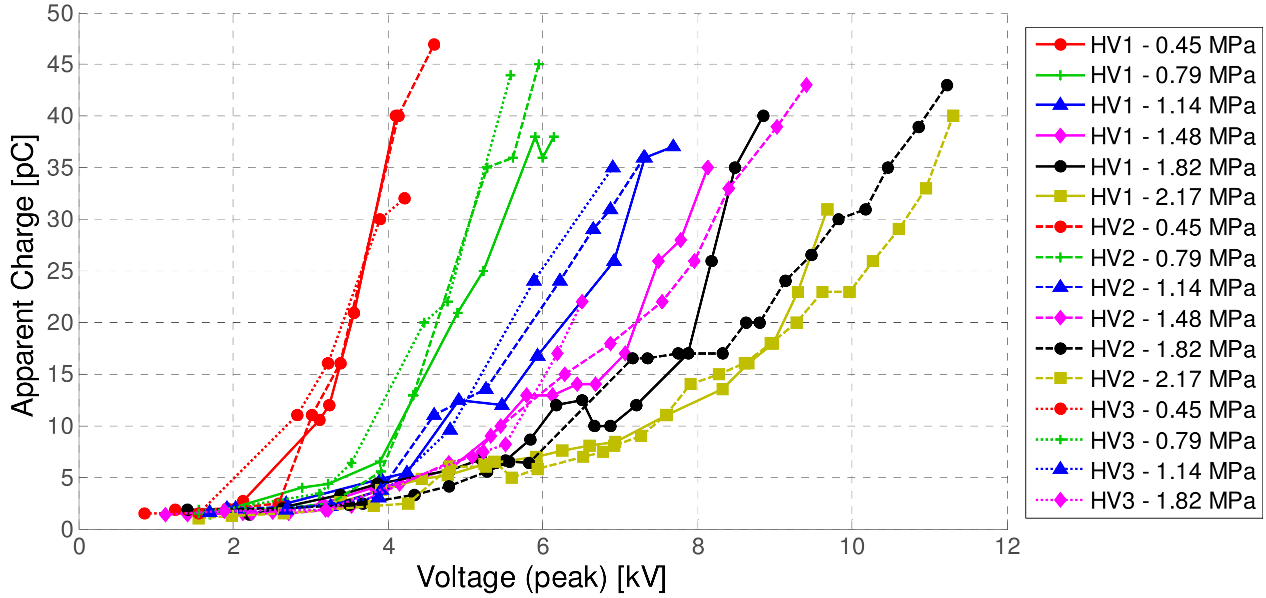

Figure 10: Partial Discharge activity as a function of applied voltage, measured at six different pressure levels

10 pC. The AC voltage was increased in small steps (between 0.3 kV_{peak} and 0.8 kV_{peak}) up to a PD level of approximately 40 pC. The exact value of PDIV was obtained by linear interpolation at 10 pC. Figure 11 shows PDIV as a function of pressure. The three model cables show very similar PDIV levels. Subsequently, the voltage was reduced in small steps to determine the PD extinction voltage (PDEV) level. However, no significant difference between PDIV and PDEV was observed and consequently the latter are not presented here. No PD data was obtained for cable 3 at the two levels of highest pressure.

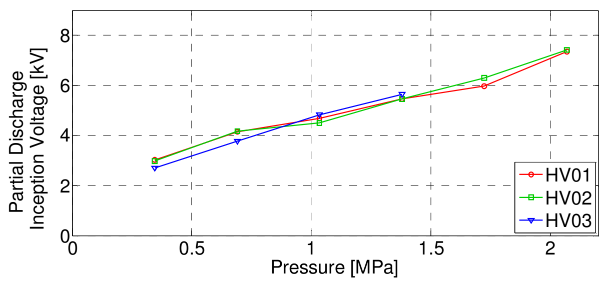

Figure 11: PD inception voltage levels as a function of pressure for all three test cables

The phase-resolved PD pattern shows a distinctive difference between the PD mechanisms at 1.82 MPa helium pressure (Figure 12 left) compared to 0.44 MPa pressure (right). While the pattern for the higher pressure shows PD activity mainly in the first quadrant, the pattern for lower pressure shows activity in both first and third quadrant. A possible explanation could be that at high pressure (and therefore at higher electric field) corona discharges dominate while at lower pressure, surface discharges dominate. However, this is an early hypothesis, which needs validation by future tests.

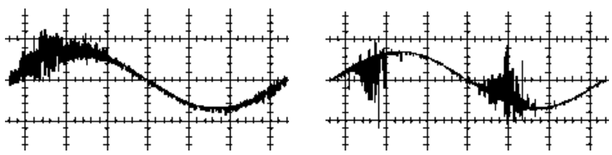

Figure 12: Phase resolved PD pattern (Phi-Q graph) at 1.82 MPa and 5.4 kV_{peak} (left) as well as at 0.44 MPa and 3.5 kV_{peak} (right)

5.2 AC Breakdown Test

Insulation breakdown was tested for each cable after completion of PD tests. The voltage was increased at a rate of 0.71 kV_{peak}/s until breakdown. The AC peak values were 39 kV, 45 kV, and 42 kV for cables 1, 2, and 3 respectively.

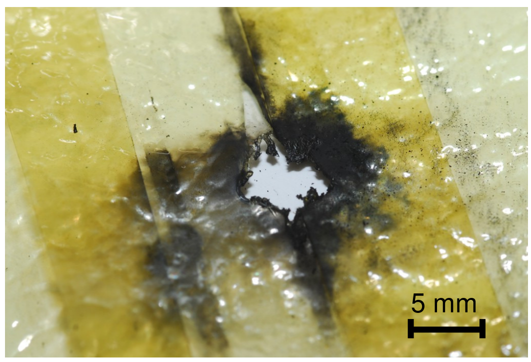

Figure 13: Marks from breakdown in unwrapped layers of Cryoflex^{TM} from cable 2

The cables were dissected after the breakdown tests to analyze the cause of breakdown. The location of breakdown for cable 1 was right at the point where one of the stress cones began. Cable 2 and 3 broke down in the straight section (40 cm and 48 cm from end, respectively) where no obvious cause for field enhancement was visible. This indicated that the test setup was adequate for resolving the intrinsic insulation properties. The holes had diameters of approximately 5 mm (Figure 13). Burn marks were visible straight through all layers, including the semiconductive tape layers. There were no visible tracking along butt gaps.

6 CONCLUSION

High pressure helium gas appears to be a promising candidate to serve as an alternative coolant and insulation medium for HTS cables where the risk of asphyxiation does not permit application of LN2. However, substantially lower dielectric strength considerably reduces the maximum allowed electric field in the cable insulation and consequently the maximum allowed voltage compared to LN2.

PD and breakdown tests have been performed on three short sample cables. More samples will be tested shortly in order to allow a comprehensive statistical analysis including Weibull plots. The characterization of this novel HTS cable type was limited to AC (60 Hz) tests. In the future, DC characteristics will also be tested. The authors currently consider to apply a test method based on Ildstad's work [9], which proposes abrupt DC voltage grounding. The intended use of the cable in shipboard power systems with short cable lengths, low impedances, high power density, high penetration of power electronics, and high-impedance grounding schemes [10] is expected to result in significant stress by fast voltage transients. Furthermore, preparations are under way to test a 30 m long cable with terminations on each side. This allows the study of the volume-scaling of the dielectric properties. The terminations are built to allow load currents of up to 6 kA, which also enables the analysis of the superconducting properties.

7 ACKNOWLEDGMENTS

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