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# PPLP and Kraft Paper Under High Voltage in Liquid Nitrogen

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**Abstract** – liquid nitrogen impregnated PPLP and Kraft lapped papers are compared in terms of space charge distribution measurements for high voltage insulation in high power HVDC superconducting cables. Measurements with the pressure-wave-propagation method have shown that PPLP and Kraft paper samples behave similarly up to 30 kV/mm. No space charge has been observed in the insulation. Partial discharges at the interfaces of the carbon loaded paper electrodes are observed and produce an injection like phenomenon.

**Keywords:** impregnated paper, liquid nitrogen, space charge measurement, PWP, HVDC superconducting cable

## I. INTRODUCTION

Within the framework of the BestPaths European Project [1], a specific demonstration task called DEMO 5 aims to demonstrate high voltage direct current (HVDC) superconducting lines for transporting at least 3.2-GW electrical power through a single pole. Transporting such a high power requires high current and high voltage at the same time. The proposed cable structure of the BestPaths project is composed of a double cryogenic envelop to maintain with efficiency the cryogenic temperature required by superconducting materials [2]. The inner cryogenic envelop encloses a very small MgB<sub>2</sub> superconducting conductor which can transport at least 10-kA current at a temperature of about 20 K. The outer cryogenic envelop contains the insulating part of the cable which is subjected to 320 kV in liquid nitrogen, at about 77 K and under 5-bar pressure. The typical cable structure is presented in Fig. 1.

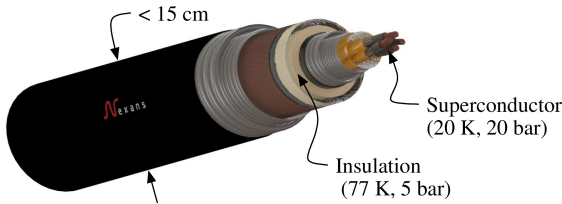


Figure 1. Typical cable structure for the BestPaths project. The inner cryostat contains the superconducting MgB<sub>2</sub> conductor and is held to high voltage. The outer cryostat contains the lapped paper insulation.

Though superconducting materials naturally work at low temperature, insulating materials are much more often used at room temperature. Indeed, superconductors are generally used for generating high amplitude magnetic fields (high current, low or zero voltage), thus no specific electric insulation is required. Using conventional synthetic insulating materials, such as polyethylene or cross linked polyethylene, is not appropriate at low temperature. Indeed any bending and shrinkage could undergo cracks and thus

impair insulation. Therefore lapped materials are more convenient as each slice can slightly slide on another giving mechanical compliance to the structure. Oil impregnated Kraft paper has been used for many years for undersea applications with good results and polypropylene lapped paper (PPLP) has shown good behavior at liquid nitrogen temperature [3,4]. However, space charge measurements in such lapped structures at liquid nitrogen temperature have never been studied.

In this contribution, space charge distribution in 2-mm-thick lapped paper under 20 and 30 kV/mm at liquid nitrogen temperature are presented. Two kinds of samples are compared, 16 layers of liquid nitrogen impregnated Kraft paper and 17 layers of liquid nitrogen impregnated PPLP. The measurements are carried out with the pressure-wave-propagation (PWP) method [5] using a high power piezoelectric pulse generator [6]. The hydro-static pressure is maintained at 5 bar. In the following section, the measurement setup is briefly presented and samples are described. In the last section before conclusion, results are presented, compared and discussed.

## II. MEASUREMENT SYSTEM AND PROCEDURE

### A. Measurement Setup

The measurement setup consists of a 2-m-high 25-cm inner diameter cryostat. Voltage up to 60 kV can be applied to the sample and the internal liquid nitrogen pressure can be adjusted from atmospheric pressure up to 5 bar.

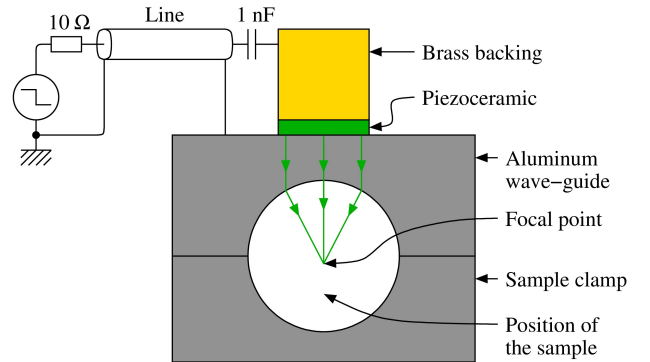


Figure 2. Sketch of the sample holder with the piezoelectric pressure pulse generator.

As lasers cannot be used to generate the pressure pulses required for the PWP method as it would generate nitrogen gas bubbles, a piezoelectric pressure pulse generator is used instead [6]. It is composed of a 15-mm diameter 200-μm thick Pz24 piezoelectric ceramic from Meggitt coupled on one side to brass and on the other side to aluminum. The aluminum is used as the wave-guide to transmit the pressure

pulse to the sample. As the velocity of sound in liquid nitrogen is very small compared to the one in aluminum, the aluminum wave-guide is also used as a lens to convert planar waves to coaxial waves, the geometry of the sample. The piezoceramic of the pressure pulse generator is fed through a 10- $\Omega$  cable and a 1-nF capacitor in order to limit the influence of its high capacitance. A sketch of the sample holder with the pressure pulse generator is presented in Fig. 2.

The signal generated by the pressure pulse is measured through a 500-pF high-voltage low-temperature capacitor and amplified by a 50- $\Omega$  input-impedance 40-dB amplifier before being acquire by a high speed oscilloscope.

### B. Samples

Two kinds of sample have been tested. All insulation layers are lapped on a 26.9-mm-diameter 70-cm-long steel tube that mimics the outer part of the inner cryostat. Carbon loaded paper is first lapped on the entire length of steel tube. Stripes are almost 50% overlapping. Then 16 layers of Kraft paper (Sample 1) or 17 layers of PPLP (Sample 2) are lapped, each stripe being separated by 5-mm gaps. Finally 10 cm of carbon loaded paper is lapped with almost 50% overlapping in the middle of the sample. The carbon back paper layer purpose is to smooth the electric field at the conducting surfaces. Both kinds of sample have an insulating thickness of 2 mm. A photography of one of the sample is shown in Fig. 3.

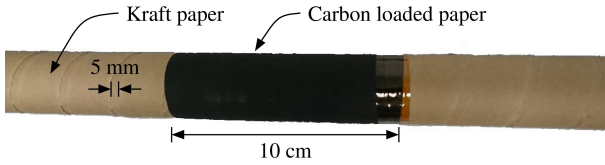


Figure 3. Photography of the Kraft paper sample (Sample 1).

## III. RESULTS AND DISCUSSION

Samples were stressed for 1h under 40 kV, then put under short circuit for 1h, then stressed for another 1h under 60 kV and finally put under short-circuit for 1h. During the volt-on cycles, measurements were taken under voltage and the voltage was turned off during less than a minute to carry out a measurement under short-circuit before reapplying the voltage stress. Therefore, small charge buildup can be easily detected even during the volt-on cycles.

Fig. 4 and Fig. 5 present the measurements under voltage and under short-circuit for the Kraft paper sample under 40 kV (Fig. 4) and 60 kV (Fig. 5).

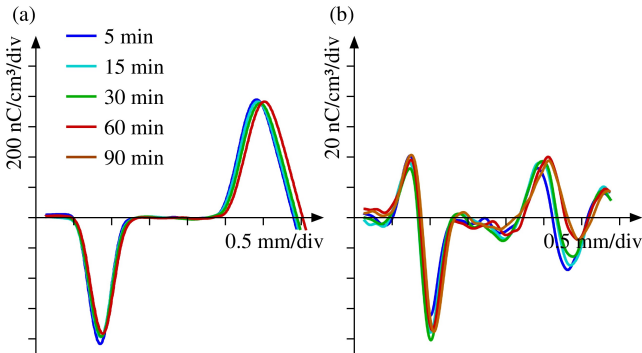


Figure 4. Measurements under voltage and under short-circuit for the Kraft paper sample (Sample 1). (a) 40-kV cycle, (b) measurements under short-circuit during 40-kV cycle and after.

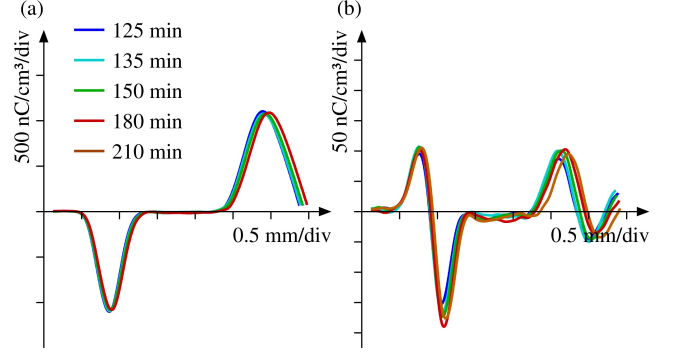


Figure 5. Measurements under voltage and under short-circuit for the Kraft paper sample (Sample 1). (a) 60-kV cycle, (b) measurements under short-circuit during 60-kV cycle and after.

Fig. 6 and Fig. 7 present the measurements under voltage and under short-circuit for the PPLP sample under 40 kV (Fig. 6) and 60 kV (Fig. 7).

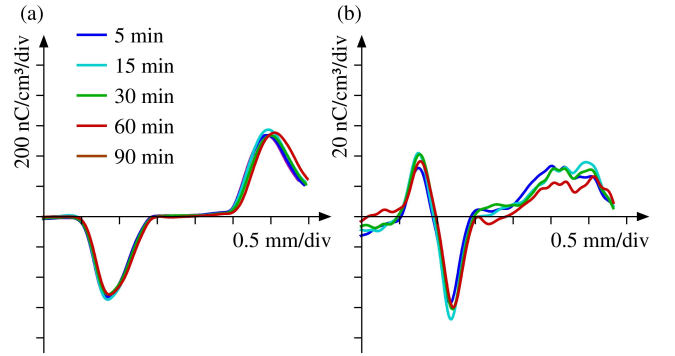


Figure 6. Measurements under voltage and under short-circuit for the PPLP sample (Sample 2). (a) 40-kV cycle, (b) measurements under short-circuit during 40-kV cycle and after.

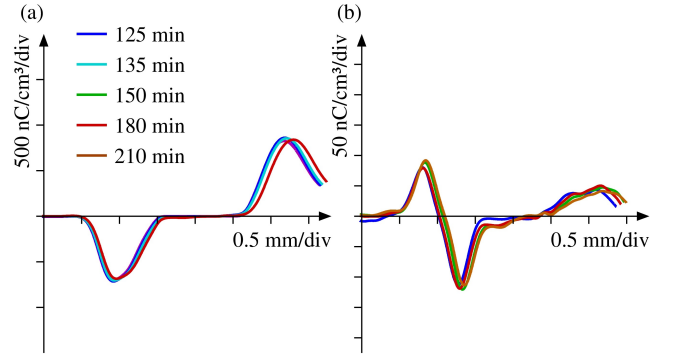


Figure 7. Measurements under voltage and under short-circuit for the PPLP sample (Sample 2). (a) 60-kV cycle, (b) measurements under short-circuit during 60-kV cycle and after.

Kraft paper and PPLP samples behave very similarly, that is to say that there is no significant difference under such electric field, i.e. up to 30 kV/mm. It can be noticed that though no evolution of the signal is observed during the volt-on cycles, measurements made under short-circuit clearly show injected charges at the interface for both kinds of sample. There is however no charge detected in the bulk of the insulation.

It is also clear that the injected charges are detected as soon as the voltage is applied and remain very stable during volt-off cycles as shown in Fig. 8.

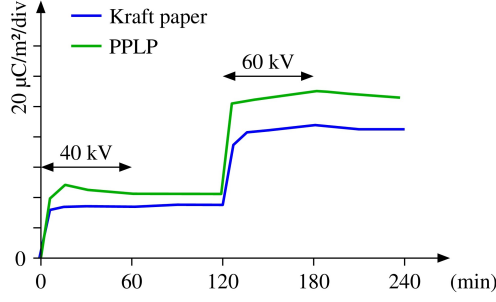


Figure 8. Evolution of the front electrode peak as a function of time for both kinds of sample.

These charges have not been injected into the insulator, but instead are only trapped at the interface of the carbon loaded paper. It indicates that insulator made out with liquid nitrogen impregnated papers is homogeneous and very well suited for safe HVDC operations. In the conducting carbon paper some carbon particles are not percolated with the others. These particles play the role of an electrostatic trap. When the voltage is turned on, partial discharges occur to equalize the voltage across all carbon particles. When the voltage is turned off, one part of the charges trapped into the isolated carbon particles goes back to the electrode through partial discharges while the other part remains trapped once the level for partial discharges is no longer sufficient. The discharge current shows indeed an increase at the end of the voltage drop certainly due to that later partial discharges. This is illustrated in Fig. 9.

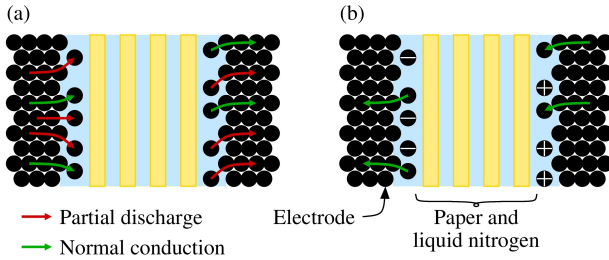


Figure 9. Explanation of the charges observed. (a) When the voltage turns on, the charges move in the electrodes (green arrows) and to the isolated carbon particles through partial discharges (red arrows). (b) When the voltage turns off, one part of the charges in the isolated carbon particles remains.

In order to check this assumption, the outer carbon loaded paper was removed from sample, thus the outer electrode is the aluminum wave-guide which has a polished surface. Results under voltage and under short-circuit are presented in Fig. 10. It can be noticed that the peak at the front electrode is sharper when there is not the carbon loaded electrode (Fig. 10a). This is due to the attenuation and dispersion of the pressure pulse through the carbon loaded paper electrode. As expected, the measurement under short-circuit (Fig. 10b) does not present any charge buildup at the front electrode. The carbon paper is thus at the origin of the charges observed.

Though charge injections lower the interface electric field for HVDC applications, they enhance it at voltage reversal. Moreover, the partial discharges occurring at the interface may lead to premature aging of the paper of the electrode and

thus carbon particles may be released into liquid nitrogen and can migrate through the sample structure by electrophoresis leading to more problematic charge buildup issues on longer time scales.

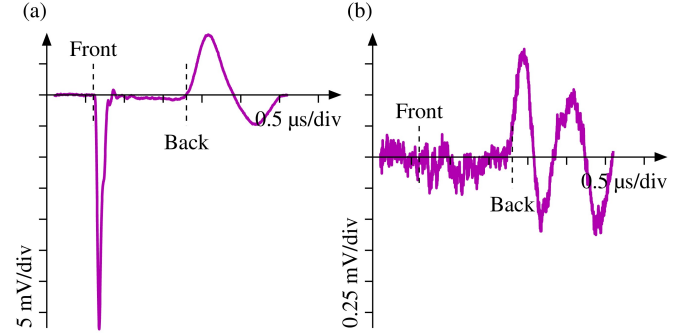


Figure 10. Explanation of the charges observed. (a) After 15 minutes under 60 kV. (b) Under short circuit. Charges are not visible at the front side.

#### IV. CONCLUSION

In this contribution we have shown that even under very low temperature, such as liquid nitrogen temperature, space charge phenomena can be locally observed on relatively short time scales only at the interfaces. No space charges are found into either Kraft paper or PPLP insulation indicating a very safe insulation for operating HVDC superconducting cables. The observed *space charges* phenomena have been attributed to the carbon loaded paper electrodes that contain carbon particles non in contact with the others at the interfaces with the insulator. The partial discharges occurring at these interfaces can lead to premature aging thus such carbon loaded paper should be avoided. The use of carbon paper at the interface in HVDC superconducting cables could be reconsidered.

In addition, there is no significant difference between PPLP and Kraft paper at an electric field up to 30 kV/mm. Kraft paper is thus an economical alternative to PPLP since PPLP is more expensive and less permeable to liquid nitrogen though having a higher breakdown voltage.

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