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Electrical Breakdown in Gaseous Nitrogen at Cryogenic Temperature with a Heated Tape Electrode

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Abstract- With the objective to better understand and design the electrical insulation of resistive superconducting fault current limiters (r-SCFCL), breakdown experiments were performed in liquid (LN₂), and gaseous (GN₂) nitrogen. Conditions relevant to the extreme case of severe boiling, occurring during superconducting/resistive transition, were chosen. A tape-shaped electrode rapidly heated by impulse Joule effect is used to closely represent the specific conditions occurring during the transition. Comparisons with previous experiments carried out in LN₂ show that the reduction of breakdown voltage during transition results from the replacement of LN₂ by GN₂, and from heating of GN₂. Breakdown voltages in GN₂ with divergent tape-plane geometry can be modelled using the streamer criterion.

Keywords: Breakdown, Tape Electrode, Nitrogen Gas, Liquid Nitrogen, Transient Heating, Streamer Criterion

I. INTRODUCTION

Resistive superconducting fault current limiters (r-SCFCL) constitute promising solutions to increase the number of interconnections within power grids without increasing the short-circuit current, and also ease the current breaking function in HVDC networks [1 – 4]. Among the challenges to overcome to increase the technology readiness level of r-SCFCL, the insulation design is a major one. The insulation of a r-SCFCL strongly differs from well-known standard oil-insulated systems. Liquid nitrogen (LN₂), that can provide both proper cooling of superconducting wires and electrical insulation, is considered. Second generation superconductors are usually tape-shaped due to epitaxy manufacturing processes, which in turn causes a strong electric field reinforcement at the sharp tape edges. In addition, during the current limitation the superconducting / resistive transition (also known as “quench”) induces a sudden and massive amount of Joule energy dissipation in LN₂, inducing strong transient boiling conditions, and heavy convection movement. Moreover, during practical operation within a grid, a transient overvoltage similar to the standard Switching Impulse is applied to the r-SCFCL at the end of the limitation process, due to the interruption of current by external circuit breakers.

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This combination of such stresses is known to decrease significantly the withstand voltage of LN₂, and a significant number of papers already investigated this issue with either some or all these stresses applied together [5 – 8]. A severe unfavorable case for the insulation occurs when LN₂ is pushed away from the superconducting tape by the fast growth of vapor bubbles. LN₂ is hence replaced by GN₂ of lower breakdown strength, in a critical region where a very high field is present. This case was seldom investigated, especially when this phenomenon is coupled with the transient heating of the electrode (that occurs during superconductive to resistive transition). In order to investigate this rather specific situation, an experimental study aimed to record breakdown voltage in gaseous nitrogen with a heated tape was carried out.

II. EXPERIMENTAL SETUP AND PROCEDURES

A. Experimental Setup

The experimental setup, presented in Fig. 1, was already used to perform experiments in liquid and boiling nitrogen [9 – 11]. A grounded C276 Hastelloy[®] tape, 100 μm in thickness, is facing a stainless steel plan connected to high voltage.

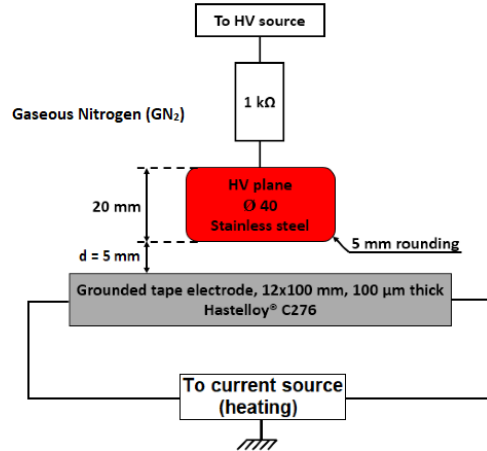


Figure 1: Tape-plane electrode system used during experiments.

Cross-section images of the tape show that its edges have a curvature radius ranging from 5 to 10 μm. Transient heating of the tape is achieved by the application of a 160 A, 40 ms duration current impulse through it. The tape temperature

rapidly increases from 77 K to 400 K within 40 ms, simulating the superconducting tape heating in a real r-SCFCL during transition.

Cold nitrogen gas GN₂ was obtained by cooling the cryostat high voltage test enclosure with LN₂, and then replacing it by GN₂. Thanks to the LN₂ reservoir surrounding the test enclosure, cold GN₂ at $T = 77$ K remained for several days. Some experiments were performed at 293 K (ambient temperature of the lab), without cooling the cryostat. All results were performed at atmospheric pressure $P = 0.10$ MPa, and the gap distance was fixed to $d = 5$ mm.

A. Experimental Procedures

A minimum 1-minute waiting time between two consecutive breakdown measurements with tape heating was observed, i.e. much longer than the time required for GN₂ and tape to stabilize back to 77 K. This was ascertained by GN₂ and tape temperature measurements [12].

For measurements without heating, 20 breakdown tests with DC ramps (1 kV/s rate of rise) were done. Bets fits of these results to the Weibull distribution are then compared to the raw results, and the fit is then used to compute 10 % probability breakdown voltages V_b , and associated confidence intervals.

For measurements with tape transient heating, a constant DC voltage was first applied to the tape, and then transient heating was triggered. If no breakdown occurred after 10 seconds, the result was categorized as “Withstand”, and conversely as “Breakdown” when breakdown occurred. The “10 % Up and Down” protocol, as specified in IEC 60060-1 standard, provides the mean 10 % breakdown voltage V_b^H . In order to compare these results with V_b obtained with a different procedure, Bayesian statistics was used to compute the confidence intervals associated with this breakdown voltage. The confidence intervals were usually small, due to the low scattering of recorded breakdown voltage.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Breakdown distribution with non-heated gaseous nitrogen

Breakdown measurements for both polarities in non-heated GN₂ at $T = 77$ K and 293 K are shown in Fig. 2, also showing best fits to Weibull distribution and confidence intervals. It can be seen that the data and the fit are in good agreement over the whole probability range, both at 77 K and at 293 K.

Breakdown voltages are much higher at $T = 77$ K compared to 293 K. This was expected since GN₂ density at $T = 77$ K is almost 4 times that at 293 K. However the 10 % breakdown voltage V_b only increased by a factor from 2 to 2.5 depending on polarity (from 9.0 kV to 19.9 kV in negative tape polarity, and from 9.4 kV to 25.7 kV in positive polarity). Also, the scatter of data was very small at 77 K (hence inducing a steep probability plot), while at 293 K breakdown voltages could vary by almost 50 % during test series.

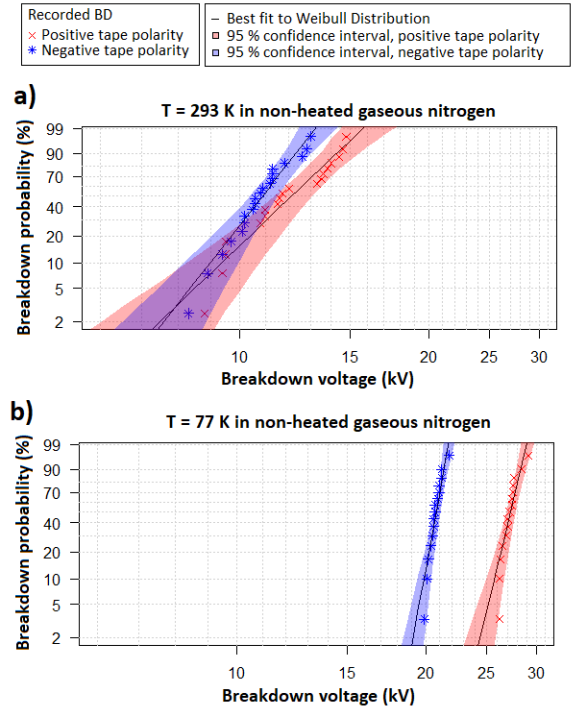


Figure 2: Breakdown voltage measurements in non-heated GN₂ at a) 293 K, and at b) 77 K, with best fit to Weibull distribution and 95 % confidence intervals

B. Breakdown voltage measurements at $T = 77$ K

The comparison between breakdown voltages V_b obtained for both tape polarities, in liquid and gaseous nitrogen, with and without transient heating of the tape, is presented on Fig. 3. In all investigated conditions, lower V_b are recorded in negative polarity. Non-heated LN₂ logically shows the highest breakdown voltage V_b . Heating LN₂ induces a very large drop of V_b (by a factor of nearly 10 in negative polarity). In such conditions, the tape becomes entirely surrounded by N₂ vapor [10]. V_b then compares with that recorded with either heated GN₂, or with non-heated GN₂ at high temperature (293 K, Fig. 2a). In non-heated GN₂ at 77 K, V_b is more than twice that in heated GN₂.

This illustrates the large deleterious impact transient heating has on LN₂ insulating capability. Replacing liquid by gaseous nitrogen at 77 K already induces a large drop of V_b , but a further degradation is attributable to tape heating.

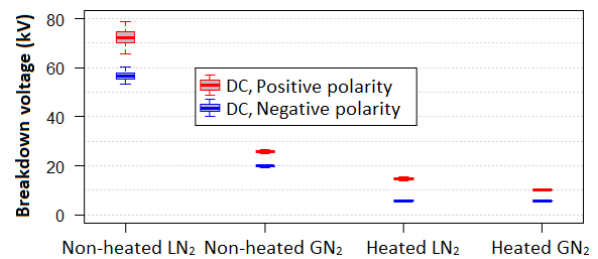


Figure 3: 10 % probability breakdown voltage in non-heated LN₂, heated LN₂, non-heated GN₂ and heated GN₂, for both tape polarities ($T = 77$ K).

C. Breakdown delay in heated GN₂

Breakdown delays t_D were measured from the start of transient heating up to the voltage drop induced by breakdown. They were recorded at 77 K both in heated LN₂ and in heated GN₂ (Fig. 4).

In GN₂ (Fig. 4a), breakdown in positive polarity never occurred before $t_D = 50$ ms, even at high voltage. Some correlation can be postulated with the propagation of a heat wave from the tape to the plane. It was observed on fast video recordings via the blurring induced by hot gas (variation of the gas optical index with temperature). The heat wave reaches the plane after about 50 ms, i.e. when breakdown with positive tape polarity starts occurring. Conversely, with negative tape breakdown occurred at lower voltage, and with a much-reduced delay t_D .

In liquid nitrogen at $P = 0.10$ MPa and $T = 77$ K (Fig 4b), breakdown in both polarities depends on the growth of vapor bubble induced by transient heating: t_D roughly corresponds to the time required for vapor bubbles to bridge the gap. This case is very similar to breakdown in positive polarity of Fig. 4a.

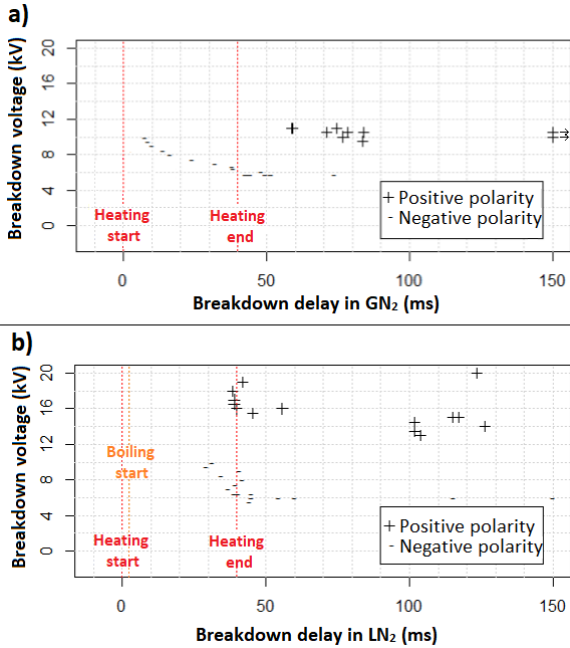


Figure 4: Breakdown delays t_D versus applied voltage in a) heated LN₂ and b) heated GN₂. $T = 77$ K.

D. Comparison with Paschen's law and application of the streamer criterion.

Electrical breakdown in gases such as nitrogen was extensively investigated for decades, especially with simple electrode geometry and in conditions relevant to HV apparatus (e.g. uniform and quasi-uniform electric field). Data in specific conditions such as the tape-plane configuration are scarce. In such divergent field, a lowering of breakdown voltage occurs due to the electric field reinforcement at the sharp edges of the tape.

A comparison between available data in GN₂ in uniform and quasi-uniform electric field at various temperatures, and the results obtained here is presented in Fig. 5. On this graph, the pressure x distance parameter of Paschen's graphs is normalized versus temperature following Eq. 1, to take into account gas density variations. Such adaptation is common for cryogenic gases that experience large density variations, well modeled by the perfect gas law [14] [15].

$$V_b = \frac{A * (P * d * \frac{T_0}{T})}{B + \ln(P * d * \frac{T_0}{T})} \quad (1)$$

Where V_b : breakdown voltage, P : gas pressure, T : temperature, d : gap distance, T_0 : reference temperature (usually room temperature), A and B : constant parameters depending on the gas nature and electrode set.

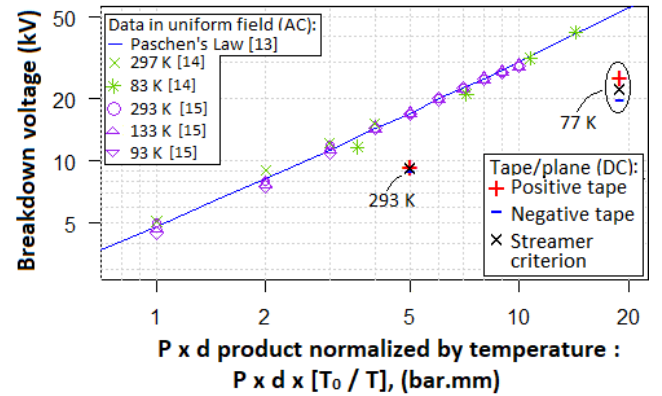


Figure 5: Comparison between Paschen's Law in GN₂ under uniform field at different temperatures, results obtained here with tape-plane geometry (non-heated GN₂, Fig. 2), and calculated with the Streamer Criterion. Data are normalized to temperature $T_0 = 293$ K.

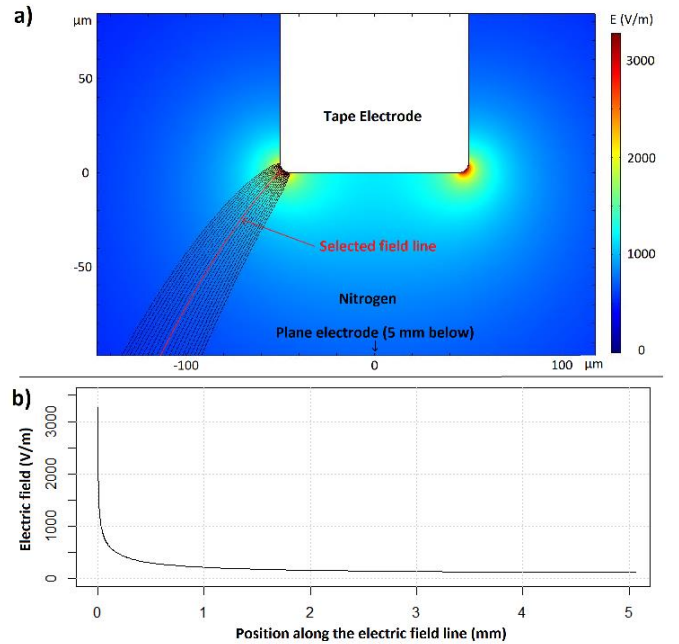


Figure 6: 2D Electric field simulation of the tape-plane electrode setup used for the Streamer Criterion computation. a) field map (applied voltage: 1 V) and selection of the most critical field line. b) Electric field intensity along the selected field line

Data obtained under uniform field over a wide range of temperatures are well fitted by the adapted Paschen's law. Conversely, the results obtained here in non-heated GN₂ at 77 K and 293 K in tape-plane geometry are logically lower, by a factor about 2. The field enhancement factor, calculated from the actual tape geometry, is close to 16.

To account for the divergent field used here, a calculation using the classical "streamer criterion" was carried out. Such criterion is usually modelled by the integral equation:

$$\int_0^{x_{cr}} \alpha(E) dx = K \quad (2)$$

where x_{cr} : distance at which the electric field drops to the critical field E_{cr} , α : ionization coefficient, K : ionization integral parameter [16]. Fig. 6 shows a plot of electric field calculated in the tape-plane geometry used here. Starting from the tape edge, 20 field lines were computed, and the line with the most intense electric field was selected as the most critical. Values of the ionization coefficient α versus electric field in GN₂ can be obtained from [17]. The value of the parameter K allowing proper modelling of breakdown voltages in N₂ depends on the " $P \times d$ " product [16], and hence slightly change versus temperature ($K = 5.22$ at $T = 77$ K and $K = 6.3$ at $T = 293$ K). Breakdown voltages predicted by the streamer criterion are 9.3 kV at 293 K and 22.5 kV at 77 K. As shown in Fig. 5, these computed breakdown voltages fit quite well with experimental results at 77 K and 293 K. Since the practical case of heated LN₂ is close to that of heated GN₂ (Fig. 3), this computation provides useful guidelines to predict the DC breakdown voltage of LN₂ when a superconducting / resistive transition occurs.

IV. CONCLUSION

Breakdown measurements were performed in gaseous nitrogen, using a tape-plane electrode system representative of a real superconducting current limiter, and different conditions of temperature and tape heating. The results obtained help better understanding breakdown phenomena occurring in liquid nitrogen, during the current limitation involving a superconducting – resistive transition. In LN₂, the breakdown voltage is strongly reduced during the transition due to transient heating of the superconducting tape that induces the fast development of a vapor bubble. This reduction is primarily due to the replacement of LN₂ by GN₂ of lower breakdown strength, but also by the fact that GN₂ is heated and has a lower density compared to the case at 77 K. From breakdown delay measurements, it is observed that for both heated GN₂ and heated LN₂, the propagation of hot GN₂ from the heated tape to the facing electrode weakens the breakdown voltage once hot GN₂ bridges the gap. Breakdown voltages of GN₂ in the divergent tape-plane geometry can be computed at different temperatures, using the classical "streamer criteria". A good agreement between measured and computed breakdown voltages is obtained.

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