

Dielectric strength of insulating material in LN₂ with thermally induced bubbles

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Abstract. To realize a reliable and cost-effective application of high-temperature superconductive (HTS) equipment at high-voltage (HV) levels, the influence of thermally induced gas bubbles on the dielectric strength of different solid insulating materials in liquid nitrogen (LN₂) was investigated. A heatable copper tape electrode arrangement was developed simulating HTS tapes with insulation in between. AC breakdown measurements were performed without and with forced boiling on insulating papers, polypropylene laminated paper (PPLP) and polyimide (PI) films. Under nucleate boiling the influence of bubbles on the dielectric strength of all materials was not significant. However under film boiling the dielectric strength of the insulating papers decreased to a level comparable to their dielectric strength in air, demonstrating the insufficient impregnation of porous materials under film boiling. For PI there was no degradation at all. PPLP retained about 70% of its basic dielectric strength in LN₂.

1. Introduction

For mastering the challenge of a more efficient and reliable electrical energy transmission, the use of high-temperature superconductive (HTS) technologies is inevitable. With a fast-growing demand on electrical energy for instance to power electric vehicles or for the increasing automation of industrial processes, the increase of the capacity of existing electrical transmission and distribution systems must be taken into account as a superordinate goal. On top of that there is an increase of decentralised energy supply, causing a higher short-circuit power of the grid. HTS cables, transformers or superconductive fault current limiters (SFCL) are appropriate solutions for these challenges.

Most of these technologies have in common to be cooled with liquid nitrogen (LN₂). Additionally the liquid nitrogen is often used as electrical insulation medium in combination with solid insulating materials. Typically used insulating materials for HTS equipment are polyimide (PI) and polypropylene laminated paper (PPLP) [1, 2, 3, 4]. Due to the high costs of these materials alternative insulating materials for the application in LN₂ at high-voltage (HV) levels should be investigated in detail. Considering the material costs in detail, there is a price per square metre for a 125 µm PI insulating foil, which is a factor of 20 higher compared to conventional insulating papers with comparable material thickness commonly used in oil-insulated equipment like transformers [5]. Therefore insulating papers from Weidmann Technology AG are tested in detail concerning the AC breakdown behaviour in LN₂. Previous investigations [6, 7] already showed, that insulating papers have a dielectric strength in LN₂ comparable to their application in insulating oil. Additionally PPLP from Tervakoski Film, a



synthetic aramid insulating paper and a PI foil both from DuPont at comparable thickness are included in the present investigation.

Especially in a resistive SFCL the critical situation of a quench is expected, as this is the used principle of limiting the short-circuit current in a case of failure. A quench produces a huge amount of heat inside the insulation system of LN₂ and solid insulating material, so there is a significant amount of gas bubbles being generated. As a result of the significant lower dielectric strength of gaseous nitrogen compared to liquid nitrogen, a decreasing dielectric strength of the overall insulation system is expected [8]. Therefore an electrode arrangement is developed for performing breakdown measurements at simultaneous high-current (HC) injection to one electrode to achieve different boiling situations. The electrodes are based on the geometry of typical HTS tapes to get results, which represent the conditions in a real superconductor arrangement like in a bifilar HTS coil for SFCL e.g. developed in [9].

2. Investigated materials

A summary of all investigated materials and their main properties is shown in table 1. Three common insulating papers from Weidmann Technology AG [10] were investigated for their dielectric strength as alternative insulating materials in LN₂. First there is Grade 3, which is a mixture of 50 % sulphate wood pulp (cellulose) and 50 % cotton fibres. Grade 4 consists of 100 % cotton fibres and Grade K of 100 % cellulose.

Additionally PPLP of the type IPO by Tervakoski Film [11] with a thickness of 125 μm was investigated for detailed information concerning its dielectric strength at different boiling situations. PPLP IPO consists of about 50 % to 60 % of polypropylene (PP) and about 40 % to 50 % of insulating paper. Two outer insulating paper sheets and a central PP sheet are bonded together by extrusion process.

Nomex 410 [12] is a synthetic insulating paper consisting of aramid fibres. The material is already in use in a wide range of electrical equipment mainly impregnated with insulating oil. In comparison to conventional insulating papers, the use of Nomex is possible at significant

Table 1. Investigated insulating materials and their main properties including the nominal thickness t_n , density ρ , dielectric strength E_{BD} and the relative permittivity ϵ_r .

Type	Material composition	t_n (μm)	ρ (g/cm ³)	E_{BD} (kV/mm)	ϵ_r
Grade 3	Cotton & Cellulose	130	1.00	75 ^a	3.1/2.0 ^h
Grade 4	Cotton	130	1.10	75 ^a	3.8/2.2 ^h
Grade K	Cellulose	130	1.10	70 ^a	3.6/2.2 ^h
PPLP IPO	PP & Cellulose	125	0.91	95 ^b	2.3 ^d
Nomex 410	Aramid	130	0.88	28 ^c	2.4 ^e
Kapton 500HN	Polyimide	125	1.42	154 ^f	3.5 ^g

^aimpregnated with mineral oil for $t_n \leq 200$ μm at 23 °C [10]

^bimpregnated with synthetic oil (dodecylbenzene) at 25 °C [11]

^c60 Hz, ASTM D149, 50 mm electrodes [12]

^ddry at 50 Hz and 25 °C [11]

^e60 Hz, ASTM D150 [12]

^f60 Hz, 1/4 in electrodes, 500 V/s, 23 °C, 50 % RH, ASTM D-149-91 [13]

^g1 kHz, ASTM D-150-92 [13]

^h1 kHz, own measurement in air / LN₂ [14]

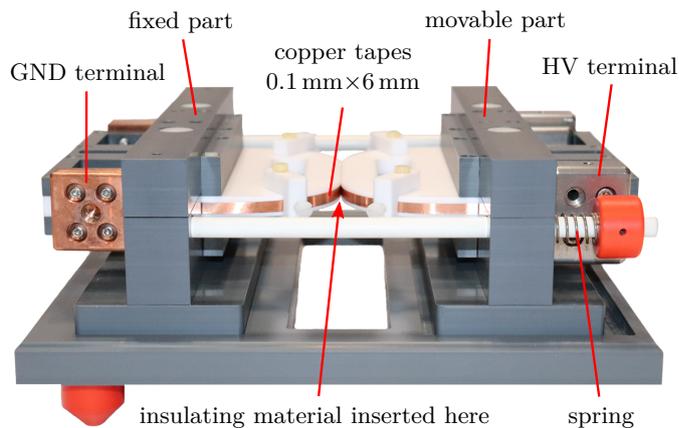


Figure 1. Copper tape electrode arrangement for performing breakdown measurements in liquid nitrogen with simultaneous heating of the ground (GND) tape conductor.

higher temperatures. At last Kapton 500HN (125 μm) [13] was investigated for comparison and to achieve knowledge on the behaviour of an insulating foil at different boiling situations in LN_2 .

All mentioned materials, excluding Kapton HN, have in common, that they gain their high dielectric strength through impregnation with a liquid insulating medium, mainly insulating oil. In the present study, after bringing the material test samples into the liquid nitrogen bath, the cavities inside the porous material were filled with LN_2 , analogue to the impregnation with insulating oil.

Before breakdown measurements all materials except for Kapton HN were conditioned according to ASTM D 2413-99 in an oven at 115 $^\circ\text{C}$ at an absolute pressure below 0.075 Pa for 16 hours. Dimensions of the specimens were 105 mm \times 50 mm.

3. Electrode arrangement

Figure 1 shows a photograph of the constructed electrode arrangement. The geometry of the electrodes is based on a real superconducting tape arrangement. Two copper tape conductors with a thickness of 0.1 mm and a width of 6 mm were used and arranged exactly parallel. The specimens of insulating material, not shown in the photograph, were positioned symmetrically between the two copper tapes vertically aligned, so that unwanted gas bubbles can rise up and do not accumulate under the tested insulating material. The complete length of the conductors is 370 mm, respectively, and the part, which has contact to the insulating material, has a length of 50 mm. Outside of the straight part, the tapes are bent towards the connection terminals with a radius of 50 mm. The HV terminals are made of stainless steel, containing a 4 mm bushing for the connection. The ground (GND) electrode connections are made of copper with a centred M10 thread for connecting the high-current (HC) source. Each ground terminal consists of two copper blocks. The ground tape conductor is clamped between these blocks on each side so that a sufficient small contact resistance is ensured.

The main parts of the electrode arrangement consist of unplasticized polyvinyl chloride (PVC-U). Only the white middle plate of the tape conductor arrangement is made of polytetrafluoroethylene (PTFE) for a higher heat resistance. Two glass-fibre reinforced (GFR) solid bars are used to realize a spring mechanism, which presses the movable HV side of the arrangement against the ground side, so the tested insulating material is being hold in position. By injecting a current into the ground copper tape, heat is generated and gas bubbles can be produced within the liquid nitrogen bath.

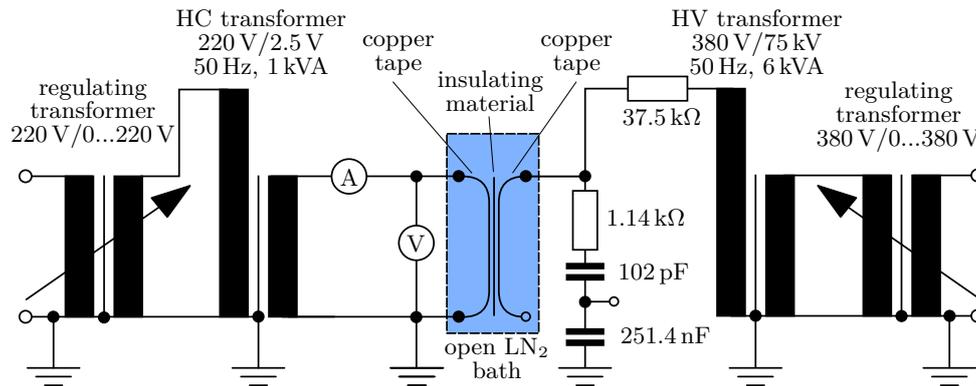


Figure 2. Measurement circuit for the breakdown measurements in liquid nitrogen without and with forced boiling. On the left side the high-current (HC) and on the right the high-voltage (HV) circuit.

4. Experimental setup, measuring procedure and evaluation

4.1. Experimental setup

For measurements in LN₂ a container made of expanded polypropylene (EPP) was used. The container was inserted into another EPP container filled partly with LN₂ used as thermal insulation for the inner one. All measurements were performed under atmospheric pressure in the open EPP container.

Figure 2 shows the HC and HV circuit used for the breakdown measurements. The HC side is fed by a 220 V/2.5 V 50 Hz transformer with a nominal power of 1 kVA. The secondary winding of this transformer has no internal ground connection, which allows the grounding of the connected copper tape electrode and the simultaneous current injection. Three 20 V varistors (not shown in the figure) connected to the transformer terminals were used for overvoltage protection. The current is measured by an analogue ammeter in combination with a current transformer, which are integrated in the current source. The voltage drop at the ground tape conductor is measured by a Fluke 187 True RMS digital multimeter directly at the copper terminal blocks.

The HV side is fed by a 6 kVA nominal power 380 V / 75 kV single-phase transformer at a frequency of 50 Hz. For current-stress protection there is a 37.5 kΩ resistor in series with the HV transformer. A measuring computer is connected to a capacitive voltage divider protected by a 1.14 kΩ resistor.

4.2. Measuring procedure

Before starting the measurements, the electrode arrangement was cooled down for 20 minutes after inserting into LN₂, so that the influence of unwanted gas bubbles on the measurements could be minimized.

For determination of the boiling phase, voltage drop measurements at the ground tape conductor at different current levels were performed to determine the resistance R_{gnd} of the conductor and the power P_{h} converted into heat. The measurements were started at a current level of 50 A. Based on the maximum allowed time to breakdown concerning the procedure described in [15], each measurement was taken for a time of 20 s to check, whether the values remain constant. After 20 s the voltage drop and current values were noted and the current was raised by 50 A. As soon as a current level was reached, at which the voltage drop started to raise significantly and the adjusted current dropped due to an increasing temperature of the ground conductor, no further 50 A step was performed to prevent damage of the electrode arrangement by too much heating.

After the voltage drop and current measurements, the digital multimeter was disconnected and the breakdown measurements were performed following [15]. The voltage rise rate was set to a value, by which the breakdown occurred after a time duration between 10 and 20 s. To determine the appropriate voltage rise rate for each material before starting the main test series, two additional samples were tested each time. Afterwards the measurements with the determined voltage rise rate were performed on 10 test samples. For Nomex 410 and Grade 3 a voltage rise rate of 0.5 kV/s was determined, for all other materials 1 kV/s was used.

In the measurements with forced boiling, the previously determined respective current for nucleate or film boiling (see section 5) was set and the high-voltage was turned on and raised immediately afterwards by using the same voltage rise rate as determined in the measurements without boiling. After breakdown, the current source was turned off and the material sample was replaced. Using a 10 mm GFR solid bar as lever, the HV electrode could be moved to exchange the test sample without taking the arrangement out of the liquid nitrogen. Therefore it was possible to start the measuring procedure again after a time of 30 s.

After the measurements in LN₂ additional measurements for comparison in air were performed for Grade 4, Grade K and Nomex 410.

4.3. Evaluation

The dielectric strength of a tested sample is given by

$$E_{\text{BD}} = \frac{V_{\text{BD}}}{t_{\text{n}}} \quad (1)$$

where $V_{\text{BD}} = \hat{V}_{\text{BD}}/\sqrt{2}$ is the measured breakdown voltage and t_{n} the nominal thickness of the sample. For each test series of 10 test samples the mean value and standard deviation were calculated. Additionally a fitting to the two parametric Weibull cumulative distribution function

$$F(x) = 1 - e^{-(x/\alpha)^\beta} \quad (2)$$

was performed. To determine the cumulative breakdown probabilities the Benard approximation [16] was used to estimate the median ranks by

$$MR = (j - 0.3)/(N + 0.4) \quad (3)$$

where j stands for the failure order number and N for the total number of measurements, in this case 10. The two parameters of the Weibull function were determined by linear regression. [16, 17]

For determination of the Weibull function parameters in test series, where the statistical spread was very high, only the values which fitted well to a regression line were included. The excluded values were plotted separately into the Weibull plot. However for calculation of the mean values all 10 measuring results were included resulting in higher standard deviation values.

5. Determination of the boiling phase

As described in 4.2 voltage drop measurements at the ground tape conductor at different current levels were performed to determine the resistance R_{gnd} of the conductor and the power P_{h} converted into heat. Till a current of 150 A the values remained constant over the measuring time of 20 s and a resistance $R_{\text{gnd}} = 1.7 \text{ m}\Omega$ and a power $P_{\text{h}} = 37.3 \text{ W}$ were calculated for the current value of 150 A.

At 200 A the current and the voltage drop were not constant. Therefore these values were measured over a time of 30 s and the power was calculated time-dependent. As can be seen in figure 3 the current decreases and the voltage drop raises immediately after switching on the HC source. After 30 s a current of 130 A and a voltage drop of 710 mV are reached, which represent a

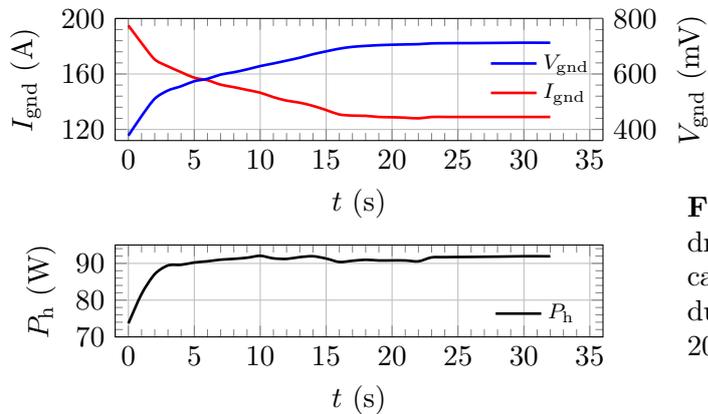


Figure 3. Measured current and voltage drop at the ground copper tape and the calculated heating power P_{h} over a time duration of 30 s after setting a current of 200 A.

resistance of $5.4 \text{ m}\Omega$. It can be assumed that the reason for this behaviour is film boiling around the copper tape, which prevents a direct contact between copper tape and liquid nitrogen. As a result the temperature and resistance of the ground conductor rise due to insufficient cooling. But the heating power remains nearly constant at a value of about 90 W after an initial time of 5 s because of the properties of the HC source. So for breakdown measurements with a set current of 200 A, where the breakdown occurs after 5 s, a heating power of roughly 90 W can be assumed.

At a current of 150 A, where current and voltage drop remained constant, it can be assumed that a sufficient cooling of the copper tape was sustained, which implies that no film boiling set in. So 150 A was defined as the current value for nucleate boiling measurements.

To confirm these assumptions for the respective boiling phase the characteristic boiling line of liquid nitrogen [18] is used. This line gives the boiling phase in dependence on the temperature rise ΔT and the respective heat flux \dot{q}_{h} of a heated surface in LN_2 .

In the present case the temperature rise of the ground copper tape is determined by the resistance calculated from the measured voltage drop and current using the linear temperature coefficient $\alpha_{20} = 0.00399 \text{ K}^{-1}$ in relation to room temperature. This temperature coefficient is determined by using the calculated resistance at 50 A ($1.5 \text{ m}\Omega$) as reference value for the resistance of the copper tape assuming a tape temperature of still 77 K (there was no boiling noticeable). The second value for linearisation is the measured copper tape resistance at room temperature (293 K, $10.8 \text{ m}\Omega$). Based on the determined resistances ($1.7 \text{ m}\Omega$, $5.4 \text{ m}\Omega$) a temperature rise of 3.8 K for 150 A and 90.6 K for 200 A in relation to the LN_2 temperature can be calculated.

Additionally the heating power is used to determine the heat flux concerning the surface of the copper tape, which has direct contact to LN_2 . The respective heat flux, assuming a copper tape surface of 21.7 cm^2 at the front side of the tape, is 1.7 W/cm^2 at 150 A and 4.2 W/cm^2 at 200 A. Comparing these values with the characteristic boiling line of LN_2 [18], nucleate boiling and film boiling at the determined heat flux values are most likely, confirming the assumptions above.

6. Breakdown measurement results and discussion

6.1. Dielectric strength without boiling

Figure 4 shows the Weibull probability plot of the measured breakdown values without forced boiling. In table 2 the 63 % values of the Weibull distribution and the calculated mean values with their standard deviations are compared. First of all the comparison of the 63 % values and mean values shows that there is no significant difference if the standard deviation of the values is small. Only for PPLP a very high standard deviation of 23 % is visible. So for determination of

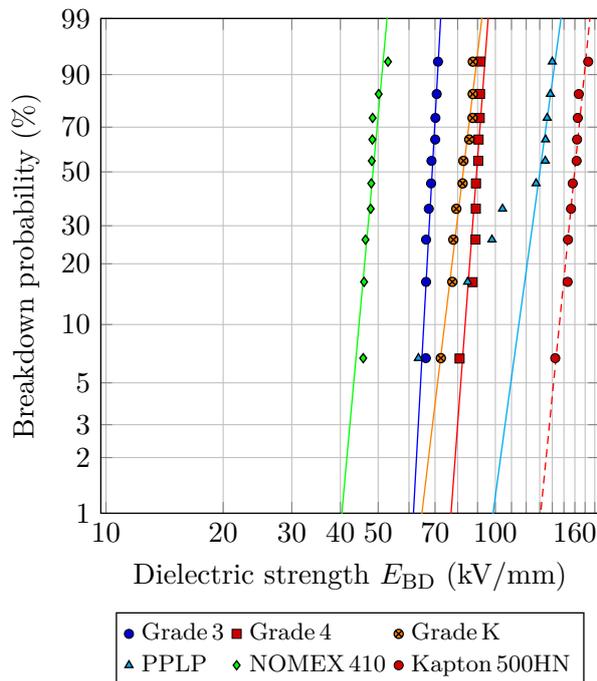


Figure 4. Weibull probability plot of the dielectric strength E_{BD} of the investigated insulating materials in LN_2 without forced boiling.

Material	E_{BD63} (kV/mm)	E_{BD} (kV/mm)	
Grade 3	69.5	68.6	± 1.9
Grade 4	90.7	89.0	± 3.1
Grade K	84.5	82.1	± 5.1
PPLP IPO	133.3	116.1	± 26.8
Nomex 410	49.3	48.2	± 2.1
Kapton 500HN	162.6	158.7	± 8.1

Table 2. Dielectric strength E_{BD63} at 63 % Weibull probability and mean values and standard deviations of E_{BD} in LN_2 without forced boiling.

the Weibull parameters for PPLP only the 6 values fitting well to the regression line in figure 4 are included. For the other four lower values, material defects especially in the PP layer could be a reason causing a significant lower dielectric strength.

Comparing the materials to each other, KaptonHN has the highest dielectric strength, followed by PPLP with a 27% lower E_{BD} value and by the Grade papers with values from 69 to 89 kV/mm. Nomex410 reaches the lowest dielectric strength. The determined value for KaptonHN is comparable to the data sheet value in [13] for the dielectric strength in air (154 kV/mm, see table 1). So it seems that the dielectric strength of Kapton HN is independent from the surrounding medium and the temperature.

The results for the Grade insulating papers are nearly identical to the determined E_{BD} values for the same material thickness in [7], 69 kV/mm for Grade 3, 89 kV/mm for Grade 4 and 78 kV/mm for Grade K. The 5% lower value for Grade K is within the standard deviation, so the difference is not significant. As 25 mm symmetric cylinder electrodes were used in [7] and the measuring procedure was very similar, the comparison shows that the used tape conductor arrangement delivers very well comparable values, though the geometry is much more inhomogeneous. In comparison to the dielectric strength values in insulating oil given in table 1, the insulating papers have in LN_2 a comparable (Grade 3) or even a slightly higher (Grade 4 and K) dielectric strength.

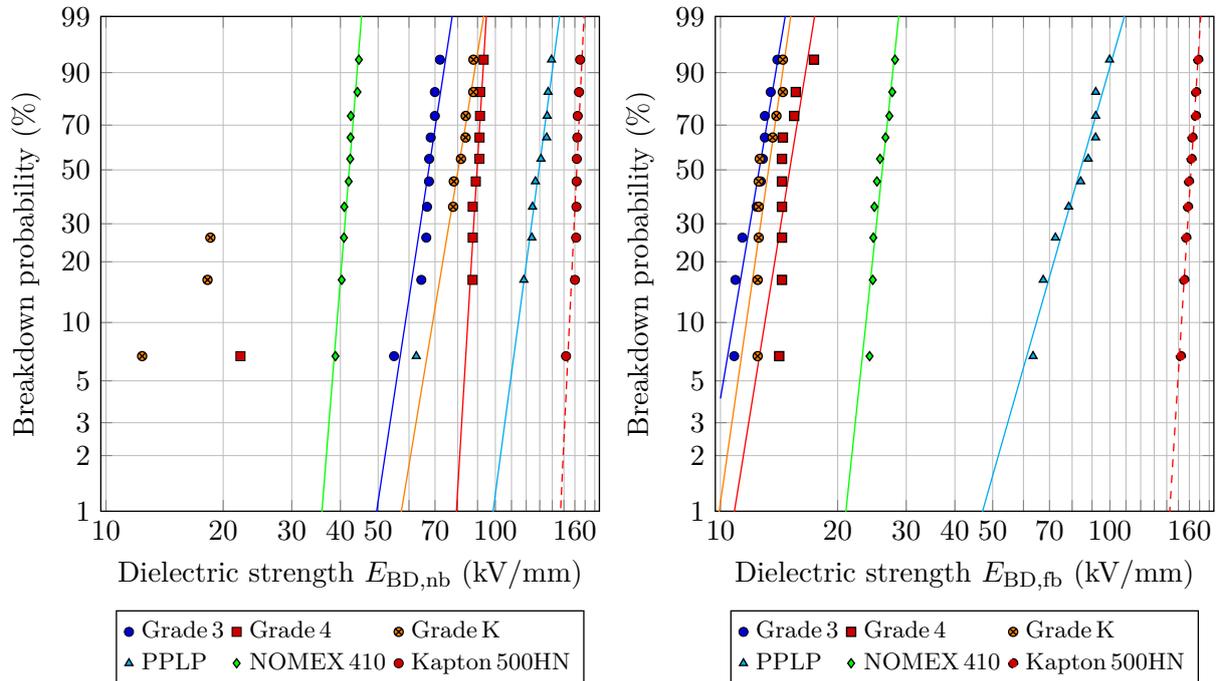


Figure 5. Weibull probability plot of the dielectric strength of the investigated insulating materials at nucleate boiling (left graph) and at film boiling (right graph). Significant lower values in the nucleate boiling graph for Grade 4 and Grade K are caused by a transition to film boiling after switching on the HC source.

6.2. Dielectric strength at nucleate and film boiling

Figure 5 shows the Weibull evaluation of the results at nucleate (left) and film boiling (right) in comparison. In table 3 the results are listed in detail with the respective degradation ΔE_{BD} of the dielectric strength in relation to the dielectric strength without forced boiling. Additionally figure 6 summarizes all mean values of the dielectric strength together with the standard deviations at all boiling conditions.

In the left Weibull plot it becomes apparent, that in comparison to the measurements without boiling, at nucleate boiling there are more significant low values for three materials, especially for Grade K but also for Grade 4 and PPLP. Comparable to the dynamic breakdown results in boiling LN₂ in [19], these lower breakdown values suggest, that there are two different mechanisms, which initiate the discharge. In each of the measurements, where the breakdown occurred at a significant lower value, the current dropped shortly after turning on the HC source. This implies that the resistance of the copper tape rose significantly due to a lower cooling of the copper tape. Subsequently in these cases film boiling occurred, the dielectric strength dropped immediately and the discharge was initiated. These results make clear that the nucleate boiling at a current of 150 A is not stable and can turn into film boiling when the cooling conditions slightly change.

This behaviour could be observed more clearly for Kapton HN, where no measurement with a constant current of 150 A was possible. In several tests the current dropped immediately after switching on the HC source and remained at about 130 A. The reason for this behaviour might be the high material density of Kapton HN, which downgrades the cooling of the conductor more than the porous materials do. After several tests with lowering the adjusted current a constant nucleate boiling state at 140 A was determined. This current value was defined for the breakdown measurements at nucleate boiling for Kapton HN.

Table 3. The dielectric strength $E_{BD63,nb}$ and $E_{BD,nb}$ at 150 A (Kapton HN at 140 A) with forced nucleate boiling and the degradation $\Delta E_{BD,nb}$ related to E_{BD} and the dielectric strength $E_{BD63,fb}$ and $E_{BD,fb}$ with forced film boiling at 200 A supplemented as well with the degradation $\Delta E_{BD,fb}$ related to E_{BD} .

Material	$E_{BD63,nb}$ (kV/mm)	$E_{BD,nb}$ (kV/mm)	$\Delta E_{BD,nb}$ (%)	$E_{BD63,fb}$ (kV/mm)	$E_{BD,fb}$ (kV/mm)	$\Delta E_{BD,fb}$ (%)
Grade 3	69.3	66.8 ±4.7	-3.0	13.0	12.5 ±1.1	-82.0
Grade 4	90.7	83.2 ±21.5	-7.0	15.5	14.9 ±1.0	-83.0
Grade K	82.6	63.0 ±32.4	-23.0	13.6	13.2 ±0.9	-84.0
PPLP IPO	132.5	123.5 ±22.4	+6.0	88.3	83.0 ±12.0	-29.0
Nomex 410	42.7	41.9 ±1.8	-13.0	26.5	25.9 ±1.4	-46.0
Kapton 500HN	163.1	161.2 ±3.6	+2.0	163.4	160.9 ±5.3	+1.0

Looking at the results for PPLP, this time there was only one lower value, which implies, that the results from the measurements without boiling were caused by material defects. A general degradation of the dielectric strength of PPLP at nucleate boiling is not noticeable. Only for Nomex 410 there is an overall decrease of about 13%, most likely caused by its lower density resulting in more gas bubbles inside the material. A comparable behaviour was also noticed in [20]. However in [21] a value of 34 kV/mm at nucleate boiling is given for Nomex 410 also with 130 μ m thickness. The 19% lower value in [21] compared to the 42 kV/mm determined in the present work, may be caused by the measuring procedure in [21], in which the material is stressed by the voltage over a time of 3 minutes.

Apart from the single lower dielectric strength values especially for the Grade K material, the dielectric strength of the Grade papers at nucleate boiling is nearly identical to the value determined without forced boiling. It seems that the produced nitrogen bubbles are not able to penetrate the insulating papers, so that they are still impregnated by LN₂. The reason for this might be the relative high density of the insulating papers in combination with the fine structure of the cotton and cellulose fibres within the material. In contrast to that the Nomex 410 paper has a lower density (see table 1) and the used aramid fibres might be coarse-grained.

At film boiling all results, excluding the ones for Kapton HN, show a significant degradation of the dielectric strength. For the conventional Grade papers the dielectric strength decreases by more than 80%, for Nomex 410 by 46%. The degradation of PPLP by 29% is considerably lower. This behaviour is caused by the PP layer, whose dielectric strength is not as much affected by the formation of gaseous nitrogen as the dielectric strength of the papers is.

The comparison to the dielectric strength of the insulating papers in air at room temperature, which is 18 kV/mm for Grade 4, 15 kV/mm for Grade K and 27 kV/mm for Nomex 410 (see figure 7), shows, that at film boiling the dielectric strength is very similar. This is caused by the significant lower dielectric strength of gaseous nitrogen compared to liquid nitrogen. Additionally the low permittivity of gaseous nitrogen near $\epsilon_r = 1$ in comparison to liquid nitrogen with $\epsilon_r = 1.44$ forwards discharges because of the increased electric field strength within the nitrogen bubbles. The slightly lower values at film boiling in LN₂, compared to the dielectric strength in air, may be caused by a locally higher gas temperature in comparison to room temperature, although the gas is cooled by the surrounding liquid nitrogen. For an exact evaluation of this aspect, a more detailed temperature monitoring of the volume is necessary.

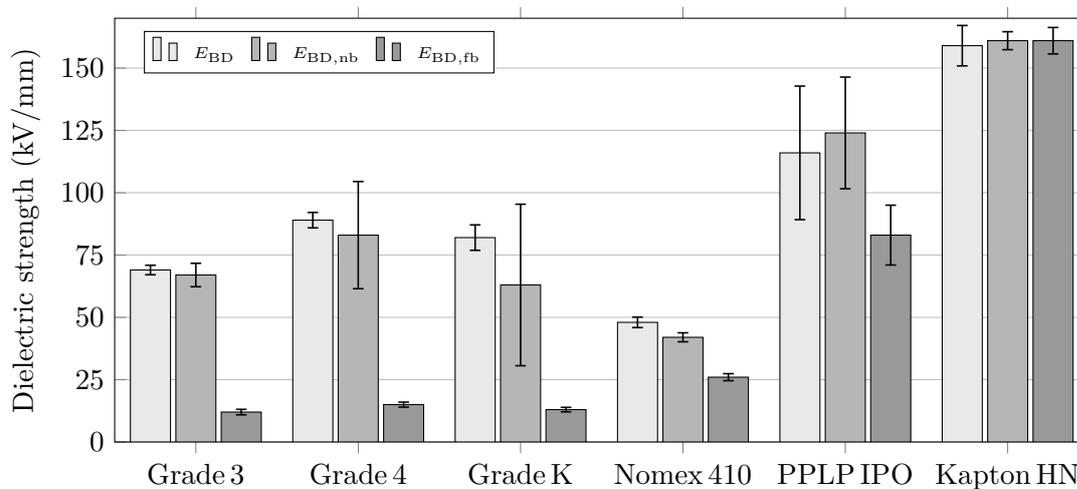


Figure 6. Determined dielectric strength values (mean values and standard deviations) of all investigated materials in LN_2 without forced boiling, at nucleate boiling and at film boiling in comparison.

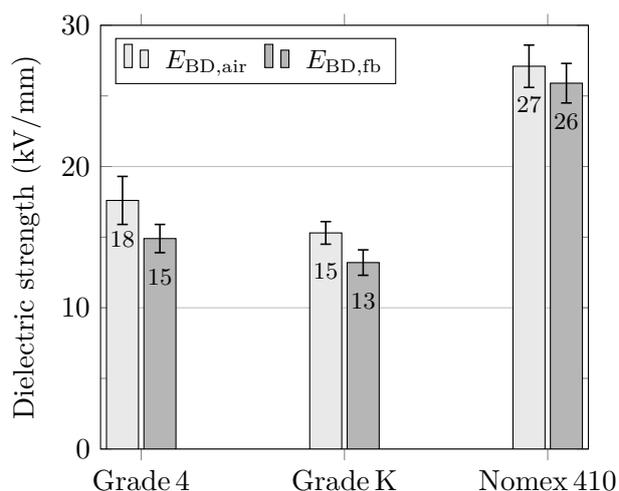


Figure 7. Comparison of the determined dielectric strength values (mean values with standard deviations) at film boiling in LN_2 of Grade 4, Grade K and Nomex 410 to the measurement results in air.

7. Conclusion

It becomes clear, that at film boiling the dielectric strength of materials, which gain their high dielectric strength through impregnation, decreases to a value very similar to the dielectric strength in air. Conventional insulating papers like Grade 3, Grade 4 and Grade K are affected by the gas formation the most. Indeed the degradation for Nomex 410 is lower, but the basic dielectric strength of Nomex impregnated with LN_2 is only about 50% compared to the Grade papers. For Kapton HN there is no change in the dielectric strength noticeable in all measurements, which shows its independence from the surrounding medium. The degradation of about 30% at film boiling for PPLP shows, that this material is basically an appropriate alternative to the very costly Kapton for an application in liquid nitrogen, also in a quench situation. Overall the results show that insulating foil materials or materials containing foil material like PPLP show a less influenced behaviour when a huge amount of gas bubbles is induced in liquid nitrogen. Conventional insulating paper seems to be not applicable for insulating HTS tapes in liquid nitrogen at normal pressure in consideration of a quench situation.

To find more alternative insulating materials for HTS equipment at high-voltage levels, an

investigation of different synthetic foil materials like PET, PP or PE would be reasonable. Furthermore investigations under higher pressure and long-term tests are necessary for more detailed information on the dielectric strength of appropriate materials in LN₂ under the influence of thermally induced gas bubbles. Additionally a more comprehensive measurement or monitoring of the temperature of the nitrogen volume and of the copper tape conductor can provide more accurate values for the determination of the boiling phase and the exact transition from nucleate to film boiling.

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