15 min DC breakdown tests with pressurized liquid nitrogen

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Preface— **This publication is an extended version of the paper: S. Fink, V. Zwecker, "DC breakdown tests with pressurized liquid nitrogen," 2020 IEEE 3rd International Conference on Dielectrics (ICD), Valencia, Spain, 2020, pp. 93-96, doi: 10.1109/ICD46958.2020.9342003**

Abstract— **Liquid nitrogen is a widely applied cooling fluid for superconducting high voltage devices. The pressure dependence of the dielectric strength of liquid nitrogen is an important design issue in case of using liquid nitrogen for high voltage insulation purposes, too. The objective of the FASTGRID project is to support a liquid nitrogen cooled superconducting fault current limiter solution for DC grids. Occurrence of heat impulses, caused by transition from the superconducting to the normal conductive state, is an unavoidable feature of a superconducting fault current limiter and therefore the influence of such heat impulses were also investigated. The high voltage test facility Fatelini 2 allows DC testing of liquid nitrogen up to voltages of 325 kV and pressures up to 3 bar (absolute). A high voltage electrode with the shape similar to a bell and a ground plane electrode with an internal resistive heater were used. The pressurization causes subcooled conditions leading to a negligible sensitivity of the breakdown strength against heating which is different from the heat sensitive breakdown behaviour for the non-subcooled condition. The polarity effect changed after subcooling in case of testing the long gap setups. Calculated maximum field values based on the experimental withstand voltages for gap lengths between 10 mm and 96 mm are above 6.0 kV / mm.**

I. Introduction

DC power engineering for long distance application is a growing market [1]. An increasing demand of higher power leads also to rising prospective fault currents. Such prospective fault currents can be limited by using a Superconducting Fault Current Limiter (SFCL). Presently commercial projects exist for AC grids [2], [3], [4]. The objective of the FASTGRID project [5], [6] is to support a liquid nitrogen cooled SFCL DC solution. The rated voltage of the FASTGRID demonstrator is only 50 kV but experimental data are needed for higher test voltages and future DC SFCLs with higher rated voltage.

It is assumed that liquid nitrogen is used in future high voltage SFCL for cooling as well as for high voltage insulation purposes. Most existing SFCL projects operate under subcooled conditions because the operation temperature of the superconductor is selected below 78 K in order to reduce the amount of superconductor material because of its high price. Derived from Fastgrid project experience it is also discussed to select an operation temperature of 77 K. But even in the latter case subcooled conditions exist in case the operation pressure is above 0.1MPa. Hence the dielectric strength of liquid nitrogen was examined under subcooled conditions. The transition from the superconductive to the normal conductive state is an inherent feature of SFCL. Breakdown tests with and without bubble generation were therefore performed in order to examine a potential degradation of the dielectric strength by boiling. The described test series were focused on electrode distances of 10 mm and longer due to the intended breakdown value range.

II. Set-up And Test Procedure

The KIT facility "Fatelini 2" (FAcility for TEsting LIquid NItrogen) had already been used for investigation of breakdowns in liquid nitrogen for voltages up to 230 kV AC (rms) [7], [8] and standard lightning impulse [9] up to 365 kV with a sphere to plane setup under maximum pressure conditions of 0.3 MPa (absolute). DC tests up to 325 kV had also been performed but with a bell to plane electrode setup (Fig. 1a). The maximum gap length of the facility is about 100 mm. The shortest gap length examined in the described DC tests was 10 mm. The Schwaiger utilization factor η [10] varied therefore between 0.8 and 0.3. For the gap length of 30 mm a value of 0.6 can be calculated which is often considered as the limit between quasi uniform and weakly non-uniform field [11]. The high voltage experimental cabin with the cryostat is shown in Fig. 1b and described in detail in [12]. A partly self-made 400 kV high voltage divider in combination with a USB oscilloscope was used for breakdown voltage measurement. This divider shows strong oscillations synchronous to the ripple although the measurement cable was terminated with its surge impedance at the divider side. But the DC voltage itself is measured with a voltage dependent deviation between 0.0% and 0.8% compared to a commercial reference divider which is limited to 300 kV DC. The DC ripple factor of the generated voltage at 300 kV is measured as 0.5% with the commercial high voltage divider.

The prior DC experiments had been performed slightly above ambient pressure with and without heater activation and under saturated conditions for liquid nitrogen. For the new subcooled tests the pressure was increased and the temperature was kept at 78 K. For Fatelini 2 only this pressure increase method alone is used up to now. It is assumed that if there is an effect for the breakdown voltage by additional temperature reduction this will not cause a decrease of the breakdown strength because additional energy is needed to generate bubbles. Hence tests at 78 K will produce design data which are on the safe side.

The stainless steel ground plate has a diameter of 300 mm and a thickness of 10 mm. The heater is wounded in the shape of a spiral and integrated in the ground plate 1.7 mm below its top surface. The outer diameter of the spiral is 120 mm.

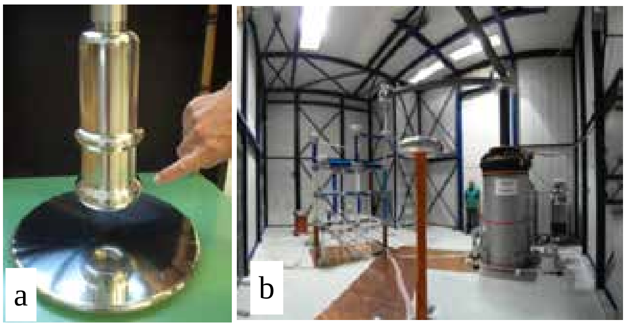


Fig. 1. a: Bell to plane electrode system. b: Experimental cabin with cryostat and DC supply.

In order to concentrate the energy transition to liquid nitrogen in a central area of the surface the spiral is surrounded by an internal groove between the diameter 126 mm and 130 mm where the upper steel thickness is only 1.5 mm. In addition thermal insulator material is placed below the spiral and within the groove.

Initial unipolar ramping tests had shown a conditioning effect for breakdowns in case of breaks of 3 min [12]. This conditioning effect had been found less incisive in case of heater activation. After waiting over night the conditioning effect had not been detected. Hence the test evaluation for the DC tests of this paper was restricted to the first breakdown of a day even in case more breakdown tests were performed. The DC test starts with an initial one-hour voltage step followed by a series of 15 min DC steps at increasing voltage levels (about 10% of the actual step voltage) until breakdown. In case the breakdown appears at step 3 or earlier the test was repeated another day with a lower initial step voltage. Five 500 W or 550 W heater impulses were generated within the ground plane during each 15 min step in case of heater generation tests. The heater impulses had a duration of 10 s and a break of 3 min, each. In an ideal case one test series is performed per day which consists of the 1 h conditioning voltage step, at least two 15 min voltage steps before breakdown, and measurement of one breakdown voltage and one withstand voltage.

The withstand voltage is specified as the 15 min step voltage before the breakdown. In the real experiments some deviations occur. In order to make still use of the time consuming and expensive measurements some simplifications are done. As one example in case no breakdown occurred during the voltage step with the maximum facility voltage of 325 kV (and also at least the 2 preceding steps) the test was stopped and the value of 325 kV was counted as withstand voltage of 325 kV although the real withstand value can be higher. Further simplifications are described in [13].

III. Testing and Results

A. Heater operation and boiling of liquid nitrogen

The heater activation causes a streaming of the liquid nitrogen within the cryostat with a rise of the fluid above the center of the plate. Boiling generation in Fatelini 2 is a random event. A webcam was used for heating process observation. A typical frame of a webcam video is shown in Fig. 2. The variation of the quality of the webcam frames is high because of the limited resolution, gap depending illumination quality, fast change of brightness for changing bubble density, reflections within the outermost plastic window, etc. Especially after a leakage of one rubber seal on the room temperature part of the vacuum shield the vacuum side of the inner glass was covered with ice which reduced the video quality. Nevertheless, some typical classes of boiling can be distinguished. Strong bubble generation was found for all tests at 0.1 MPa in case of heating the not subcooled liquid nitrogen with 500 W for 10 s. More heater power or longer heating was avoided in order to prevent heater destruction by overheating in case of the sudden appearance of film boiling.

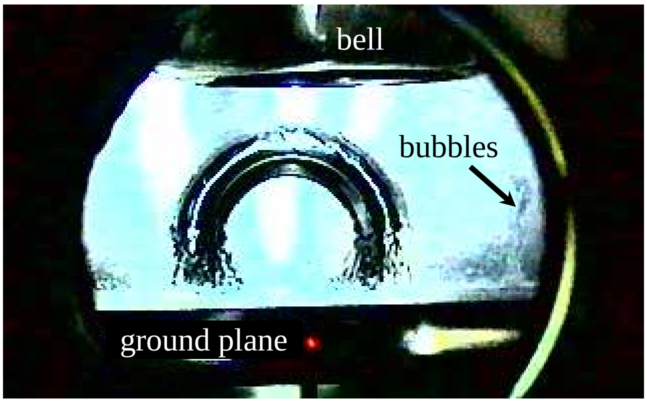
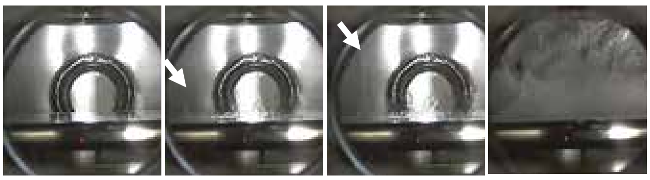


Fig. 2. Video frame showing the bell to plane electrodes through one observation window. The space is filled with saturated liquid nitrogen (p = 0.11 MPa, 78 K). The circle arc in the background is the edging of the opposite window system. Heater activation is indicated by a red display point on the plate. Gap length is 50 mm, applied positive voltage on the bell is 282 kV. Frame is captured 4 s after heater starting where convection has started above the plane and a chain of bubbles moved towards the bell. (AKZ 5 video 212-frame 179)

Sometimes the bubble generation at 0.1 MPa happened spontaneous above the complete heated steel surface (Fig. 3). In other cases bubbles started on discrete locations (Fig. 4) and built one or more chains of bubbles before bubbles appeared and detached from the complete steel surface of the plate above the heater spiral. The bubble chains were never observed to start in the center of the plate but on the outer boundary of the heated circular steel surface.

(a) t = 0 (b) t = 6.00 s (c) t = 6.30 s (d) t = 6.37 s

Fig. 3. Video sequence of boiling process generated by a heater impulse with 500 W for saturated liquid nitrogen at p = 0.1 MPa and a gap length of 60 mm (bottom part of bell is just visible on top). First frame (a) shows starting of 5th heater impulse (t = 0) during voltage step with +325.5 kV. (AKZ 6 2018 video 24)



(a) t = 0 (b) t = 3.68 s (c) t = 3,79 s (d) t = 4,58 s

Fig. 4. Video sequence under same conditions as in Fig. 3 but 3rd heater impulse (t = 0, (a)) during voltage step with +325.5 kV. A chain of bubbles developed on the left side from the plane (b) (c) before starting of strong boiling (d). (AKZ 6 2018 video 24)

Notable pressure dependence of gas bubble generation was found. The boiling was strongly reduced after increasing the pressure from 0.1 MPa to 0.3 MPa even after increasing the heater power to 550 W (Fig. 5). The heating duration was kept at 10 s. For few combinations of voltage and gap length bubble detection cannot be confirmed. It is not clear if in these cases bubbles did not occur or if they were just limited to a space outside the good visible range. At least natural convection can be confirmed in all cases.


(a) t = 0 (b) t = 2,47 s


(c) t = 4,93 s (d) t = 7,40 s

Fig. 5. Video sequence of boiling process generated by a heater impulse with 550 W for subcooled liquid nitrogen at p = 0.3 MPa and a gap length of 14 mm. First frame (a) shows starting of 1st heater impulse (t = 0) during voltage step with +201 kV. (d) shows the last frame before voltage breakdown. (AKZ 6 2019 video 169)

The quality of the video camera is not sufficient to recognize details of the 3-dimensional distribution of the bubbles. Although bubble ascension may be influenced by field distribution a relevant difference of the main behavior compared to the no voltage videos is not detected. Hence some pictures were taken with a camera with higher resolution compared to a single video frame in order to present a better view of the difference of the fluids behavior for the saturated condition at atmospheric pressure (Fig. 6) and at subcooled conditions caused by increase in pressure to 0.2 MPa (Fig. 7) and 0.3 MPa (Fig. 8). All three figures show a sharp boundary between the heated and the not heated volume above the central heated steel surface. The heated nitrogen ascends and finally forms a concave shape similar to a hyperbolic hyperboloid touching also the surface of the bell. Distinct gas bubbles can be seen for all 3 photos above the plate surface but not or only very limited in the subcooled space above.

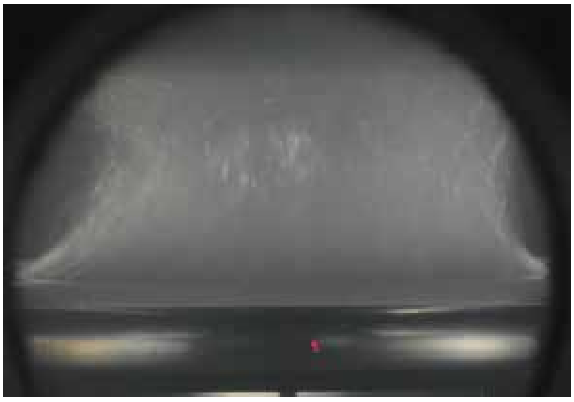


Fig. 6. Strong bubble generation of not subcooled liquid nitrogen (p = 0.1 MPa) and a gap length of 40 mm in case of heater operation with 500 W for 10 s. Strong bubble generation and detachment appeared typically after about 4 s. (SAM_2710)

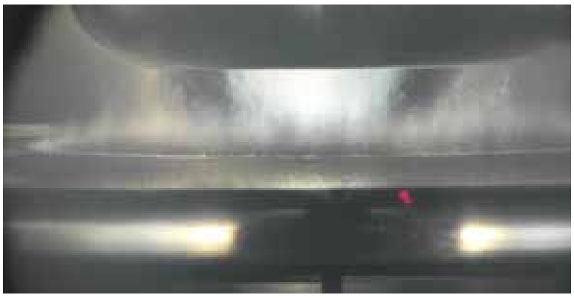


Fig. 7. Boiling within subcooled liquid nitrogen (p = 0.2 MPa) in case of heater operation with 550 W for 10 s and a gap length of 14 mm. Boiling is signifantly reduced compared to the not subcooled liquid at 0.1 MPa. (SAM_2595)

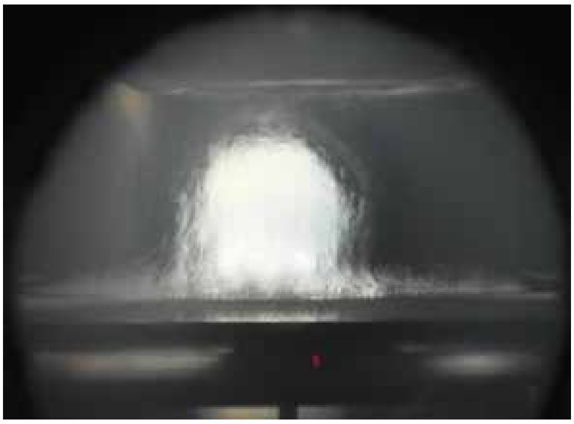


Fig. 8. Boiling within subcooled liquid nitrogen (p = 0.3 MPa) in case of heater operation with 550 W for 10 s and a gap length of 40 mm. (SAM_2686)

B. Voltage breakdown and withstand values

Fig. 9 shows the data for the breakdown and withstand values which are valid according to the test criteria. Most of the data for tests with saturated nitrogen at 0.1 MPa are taken from [13]. Some results at 0.1 MPa are added for a gap length of 14 mm. Experiments with subcooled liquid nitrogen at 0.3 MPa were started for gap lengths of 10 mm with different configurations of polarity and heater mode. Then the gap length for the 0.3 MPa tests was increased up to gap lengths of the last 325 kV withstand tests, each. Breakdown and withstand tests with subcooled nitrogen at 0.2 MPa were done for the gap length of 14 mm only. This relatively short value was selected because it was assumed to deliver breakdown data for 0.2 MPa below the facility limit of 325 kV for all configurations.

Only the withstand values for 0.1 MPa and 0.3 MPa are shown in Fig. 10 for better visibility.

For examination of the pressure effect pairs for the different pressures but with the same gap length, polarity and heater operation mode are compared. The data are not considered if both values of such a pair reach the facility limit. In 16 out of the total number of 19 cases the 0.1 MPa withstand voltage values are lower than the corresponding values for 0.3 MPa. For one case the value is the same and in two cases the withstand voltage values for 0.3 MPa are lower than at 0.1 MPa. These 3 special pairs can be found under positive polarity without heater operation for gap lengths between 20 mm and 40 mm (at 50 mm the 325 kV limit was reached for both pressure levels under these test conditions). An outlier with a noticeable low breakdown happened for positive polarity without heating at 0.3 MPa and 40 mm gap length.

Largest gap size with breakdown was 80 mm for 0.1 MPa (negative, with heater) and 40 mm for 0.3 MPa (positive, without heater). Hence it can be concluded that there is a pressure effect causing increase of dielectric strength with exception of positive polarity without heater for gap lengths from 20 mm on.

For examination of the effect of heating the measured data allow a total number of 22 comparisons of withstand voltage below the facility limit with same pressure and same polarity but for heated vs. not heated operation. 13 of these pairs can be compared for the pressure of 0.1 MPa. The withstand voltage for the heated case is only in one case at 0.1 MPa higher than the withstand voltage in the not heated case (14 mm gap length, positive polarity). For one case at 0.1 MPa and 10 mm gap length the withstand voltages occurred at the same voltage step. For all other combinations for 0.1 MPa the withstand data are lower in case of heater operation.

For the 9 combinations at subcooled (0.2 MPa and 0.3 MPa) conditions 4 combinations show even higher withstand voltages for heater operation and 3 withstand voltages happened at the same voltage step value. It can therefore be concluded that under subcooled conditions the heater activation had no decreasing impact on the DC dielectric strength of liquid nitrogen whereas for saturated liquid nitrogen conditions the bubbles reduce the dielectric strength significantly.

For the examination of the polarity effect 20 pairs according to the data from Fig. 10 with different polarity but same gap length, pressure value and heater mode can be compiled below the facility limit. At 0.1 MPa for 8 out of 12 pairs the positive polarity withstand values are higher than the negative ones. Hence there is a certain polarity effect but as already mentioned in [13] there is no general behavior at 0.1 MPa. For 0.3 MPa the negative polarity withstand values are in 7 out of 8 cases higher than for negative polarity. Only for the gap length of 10 mm with heater operation it is vice versa. Hence one can find a polarity effect for 0.3 MPa.

It should be noticed that for negative polarity and a pressure of 0.3 MPa the facility limit of 325 kV is already reached for a gap length of 20 mm, i.e. the largest gap where a breakdown happened was at 14 mm independent if the heater is activated or not.

Fig. 11 shows the same measured data as Fig. 10 but minimum lines where added. Note that in Fig. 11 the minimum lines are defined to meet zero and only one withstand value whereas the lines of [13] are defined to meet zero and the first withstand value with 325 kV where no further breakdown happened for longer gap lengths. Sometimes this new method results in a line with a lower slope in Fig. 11 for the same distribution compared to the method of [13] due to the higher sensitivity towards outliers.

The strong influence of bubble generation at 0.1 MPa can be found resulting in the two minimum lines with the lowest slope for the two cases (i.e. both polarities) with heater activation at 0.1 MPa. The minimum line with the next higher slope passes through the 0.3 MPa outlier. Then the lines with the next two higher slopes are the ones for the 0.1 MPa experiments without heater activation. The minimum lines with the highest slope were found for 0.3 MPa with negative polarity independent if the heater had been used or not.

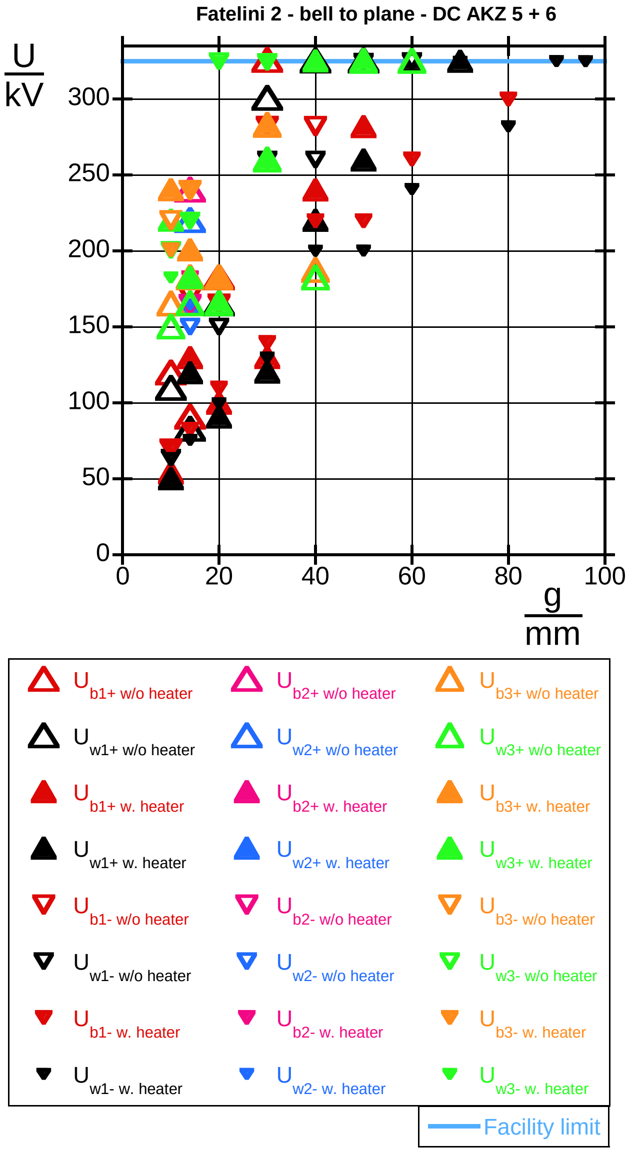


Fig. 9. Absolute DC withstand (abbreviation: "w") and breakdown ("b") values vs. gap length at 0.1 MPa ("1") up to 0.3 MPa ("3") for the bell to plane arrangement without heater ("w/o heater", open markers) and with heater activation ("w. heater", filled markers). Positive polarity is labeled as "+" (rectangle marker points upwards) and negative polarity as "-" (rectangle points downwards). The identitier "AKZ 5 + 6" in the header assignes the test series numbers.

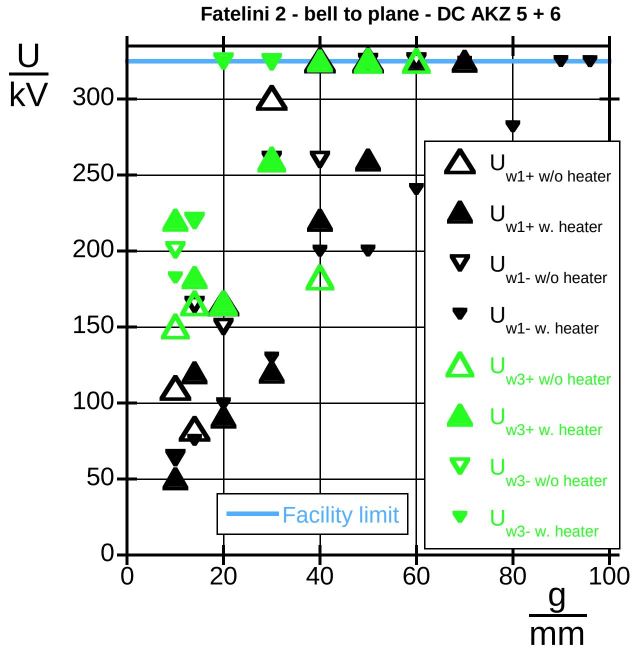


Fig. 10. Absolute DC withstand values at 0.1 MPa (black color) and 0.3 MPa (green) vs. gap length without heater and with heater activation. Abbreviations and polarity symbles are the same as in caption for Fig. 9.

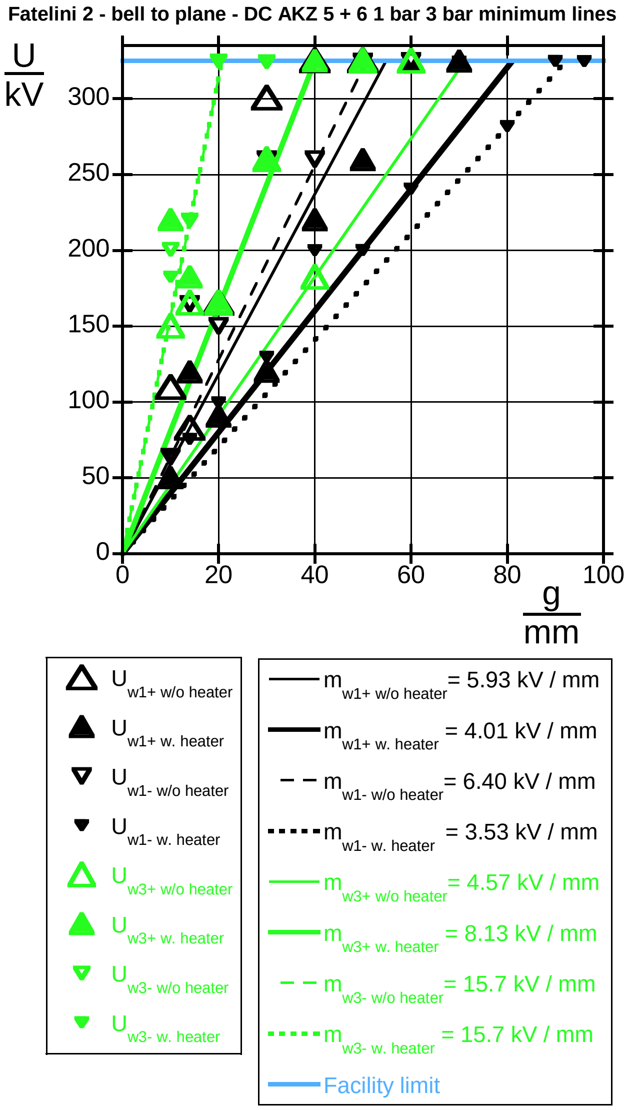


Fig. 11. Absolute DC withstand values vs. gap length at 0.1 MPa and 0.3 MPa for the bell to plane arrangement without heater and with heater activation. Abbreviations, polarity symbles and color code are the same as in caption for Fig. 10. Minimum lines start in the origin (0 mm, 0 kV) and have the lowest slope m to meet only one withstand value, each. Minimum lines for positive polarity are solid. Minimum lines for heater activation are thicker than for data without heater activation.

Fig. 12 uses the breakdown data of the 14 mm gap length from Fig. 9 for all 3 pressure levels but arranged as withstand voltage vs. pressure. All withstand voltages for the 14 mm gap length are below the maximum facility operation voltage of 325 kV. The withstand voltage values U_{w3} for 0.3 MPa are always higher than the corresponding withstand voltages U_{w1} for 0.1 MP. But only for the tests with heater operation there is a general linear increase with $U_{w1} < U_{w2} < U_{w3}$.

In Fig. 12 the withstand voltage at 0.1 MPa for positive polarity is higher for heater operation compared to the test without heater operation for the used 14 mm gap length. As already mentioned, this was the only case where such a breakdown behavior was observed under saturated nitrogen conditions and therefore this incident can be considered as not representative.

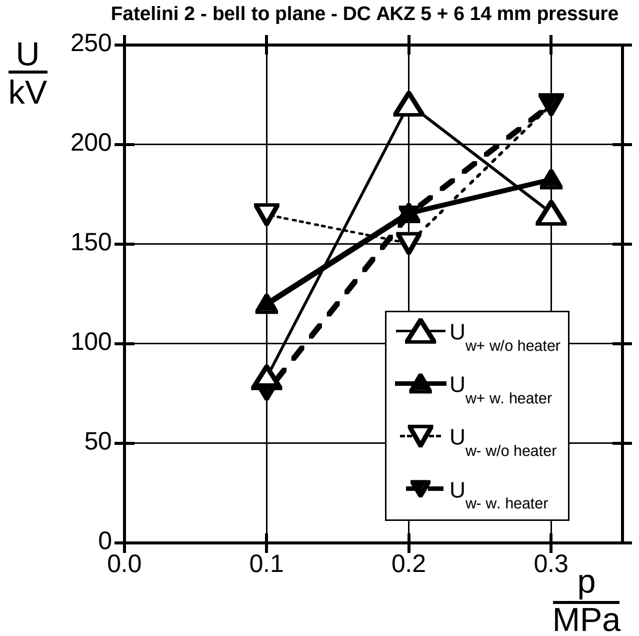


Fig. 12. Absolute DC withstand voltage vs. pressure for the bell to plane arrangement without heater and with heater activation. Abbreviations and polarity symbles are the same as in caption for Fig. 9. Lines are no minimum lines but connect directly the markers with same polarity and heater mode.

C. Electric field

For a more general approach the electric field strength is calculated vs. gap length. A mean field value can be calculated by dividing the voltage by the gap length only. But the maximum field value Emax seems to be more important because a high field region is assumed to be decisive for the breakdown process as described for liquid nitrogen under AC stress in detail in [14]. The maximum field Emax for the DC tests is calculated by the withstand voltage divided by the gap length and the field efficiency factor (Fig. 13). The field efficiency factors for the different gap lengths adjusted during the test series were received by 2D field calculation for the bell to plane setup including the cryostat wall [12].

For the interpretation of the field strength behavior it must be taken into account that for each gap length no field value for Emax is achievable higher than the one which is based on the facility voltage limit of 325 kV. The gap length depending highest field value concerning location ("max") as well as concerning voltage ("limit") is named $Emax_{limit}$. The field values $Emax_{limit}$ were calculated for all gap lengths and are illustrated in Fig. 13 as dashed (point to point) line without markers. Field values represented by markers on this limitation line do only show the possible maximum (related to the location) field values Emax based on the facility voltage limit of 325 kV. Such maximum field values Emax on the limit line may have been higher if a more powerful equipment would had been available providing test voltages above 325 kV.

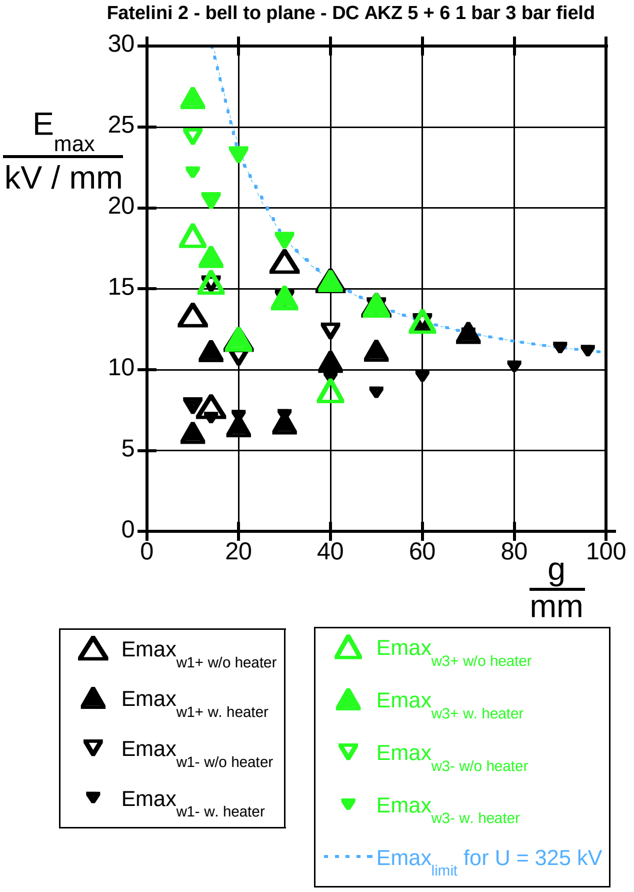


Fig. 13. Withstand DC field values vs. gap length at 0.1 MPa and 0.3 MPa for the bell to plane arrangement without heater and with heater activation. Emax means the maximum electric field value within the liquid space during withstand voltage application received by field calculation. Other abbreviations, polarity symbles and color code are the same as in caption for Fig. 10. $Emax_{limit}$ is the highest electrical field within liquid nitrogen space calculated for the test gap lengths with the facility voltage limit of 325 kV and connected by a dashed line with neighbouring values, each.

The field values for 0.1 MPa have an increasing slope for all 4 data sets with the same polarity and heater condition. All Emax data with heater activation are above 6 kV / mm. All data without using the heater are above 7 kV / mm.

For the 0.3 MPa values both data sets with negative polarity have only 2 values, each, before reaching the limit line because of the high withstand field values. All these four values are well above 20 kV / mm. Detailed description of the behavior is not useful with such a low test number. At least it can be concluded that no distinct decrease can be assessed for both data sets. For the data sets at 0.3 MPa with positive polarity the highest field values occur for the shortest gap length at 10 mm. All positive withstand values at 0.3 MPa are above 11 kV / mm with the exception of the outlier (8.7 kV / mm).

A minimum line for the maximum field strength (based on the lowest maximum field value for every test length independent of the test conditions) would start with a value of 6.1 kV / mm at 10 mm with a positive slope. Hence no general decrease of the maximum electric field value is found for increasing gap length.

IV. Discussion

A degradation of the DC dielectric strength of liquid nitrogen by heater generated gas bubbles had been published for nitrogen along the saturation line slightly above the ambient pressure (0.11 MPa, 78 K) with the bell to plane setup for gap lengths up to 96 mm [13]. Few experimental data for 14 mm gap length for 0.1 MPa were added to the data set of [13]. The positive breakdown value at 14 mm gap length with bubbles is higher than the breakdown voltage without bubbles which is an exception but the negative breakdown voltage with bubbles is the lowest breakdown value for this gap length. Hence the new data do not change the general statement of the pressure sensitivity for bubbles under saturated conditions. For all experiments at 0.1 MPa with heater activation the webcam observation allowed confirmation of strong nucleate boiling affecting also the bell surface for the used setup in Fatelini 2. Nucleate boiling is reported to occur in saturated liquid nitrogen at 77 K in case of a heated surface temperature of 77 K up to 88 K [15]. For the 78 K experiment the important surface temperature should be about 1 K higher.

In case a bubble is released from the plate it can be observed that a size reduction occurred during ascending under subcooled conditions. Hence the gas volume on the plate is larger than the gas volume around the bell. Photos of strong boiling for saturated liquid nitrogen and reduced boiling for subcooled liquid nitrogen are available for a heater wire with a thickness of 0.6 mm in [16] showing also a change of the shape of bubbles after subcooling. Change of bubble ascension caused by a DC electric field is reported for bubbles generated within the saturated liquid nitrogen space in a non-uniform field [17] with vertically arranged plate to rod electrodes with a distance of 16 mm. It is reported that the bubbles tend to move in the lower field region. The phenomenon is described to be valid for both polarities and it is explained by an electric field force mainly based on dielectrophoresis. Bubble movement towards low field region or bridging the electrodes by a long gas bubble are described for a 2.6 mm gap setup under DC use in [18] or described in a general scope in [19]. For the gaps used in Fatelini 2 it was not observed that bubbles do not ascend towards the higher field space of the bell electrode although the dielectrophoresis force can be assumed to act on the gas bubbles. An explanation may be that the heated surface in the shape of a circular disk in the middle of the ground plate generates a circulation with ascending fluid in the center and descending liquid nitrogen along the space near the cryostat wall whose force on the ascending bubbles is larger than the electrical force. Due to the large gap length an uninterrupted gas hose was also not observed in Fatelini 2.

In case of tests without heater activation no bubbles were observed before breakdown which confirms that the thermal insulation of the cryostat is sufficient and can therefore be compared with results of other researchers which do not work with heaters.

Literature for direct comparison for DC voltage breakdown and gap lengths above 10 mm is not found. But some comparisons will be made for other waveforms, distances and pressure conditions. Table I summarizes the DC experiment results of Fatelini 2 which will be discussed. Detailed lists are given in the appendix.

TABLE I. IMPACT ON WITHSTAND VOLTAGE FOR CHANGE OF PRESSURE, HEATING OR POLARITY (PLUS (+) OR MINUS (-)). WITHSTAND VOLTAGE INCREASED (Ý), DECREASED (ß) OR THERE WAS NO DIFFERENCE (**0**). SOMETIMES THE EFFECT OCCURS FOR LONGER GAP LENGTHS (**g**) ONLY.

1. Change of withstand voltage by increase of pressure (increase from 0.1 MPa to 0.3 MP)			
Uw+ w/o heater	***Uw- w/o heater***	***Uw+ w. heater***	***Uw- w. heater***
g ≤ 14 mm: **Ý** g = 20 mm: **0** g ≥ 30 mm: **ß**	**Ý**	**Ý**	**Ý**

2. Change of withstand voltage caused by heating (tendency)			
Uw1+	***Uw1-***	***Uw3+***	***Uw3-***
ß	**ß**	**0**	**0**

3. Polarity on bell which causes the lower withstand voltage (tendency)			
Uw1 w/o heater	***Uw1 w. heater***	***Uw3 w/o heater***	***Uw3 w. heater***
g ≤ 14 mm: **0** g ≥ 20 mm: -	g ≤ 30 mm: + g ≥ 40 mm: -	+	g = 10 mm: - g ≥ 14 mm: +

A. *Effect of pressure increase*

Increasing dielectric DC strength by pressure increase was experienced for Fatelini 2 with exception of positive polarity without bubbles for the gap length of 20 mm and longer. An increase of the dielectric strength by pressure increase had already been found for the Fatelini 2 cryostat with a sphere (50 mm diameter) to plane setup for AC [8] and lightning impulse [9] for unheated and heated case. For AC this behavior is already well known at least since the 1970s, e.g. described for a not heated rod to plane electrode and 4 mm gap length [20]. An increase of the AC and impulse breakdown voltage with increasing pressure for a gap length of 1 mm is reported in [21] for a not heated sphere (10 mm diameter) to plane setup.

Pressure impact for not heated non uniform AC fields was examined with different needle radii tips to a plane for gap lengths up to 50 mm in [22]. The largest needle radius was 2 mm. For this needle shape a pressure increase from 0.1 MPa to 0.3 MPa for 5 gap lengths between 10 mm and 50 mm was examined. The following AC voltage breakdown results for increasing pressure were found: 1 time a voltage decrease, 1 time about the same voltage, 3 times a voltage increase.

Increase for DC breakdown voltage by pressure increase for a heated and unheated horizontal rod to plane setup with a gap length of 1.2 mm was reported in [18].

No explanation can be given so far for the missing increase of the withstand voltage for positive voltage after increasing the pressure in the unheated case for gap lengths of 20 mm and longer which is not in agreement with literature. The withstand voltage increase by pressure increase for the three other cases is in good agreement with the literature mentioned above.

B. *Effect of heating at saturated condition*

A reduction of the breakdown strength of saturated liquid nitrogen (0.11 MPa, 78 K) by gas bubbles is usually reported for AC [7] [16] [19], DC [16] [18] [23] and standard lightning impulse [9] [19]. Only [24] stated no influence of bubbles for standard lightning impulse breakdown. But this suggestion is based on a comparison on data sets of different authors with only one paper with bubble generation [25] and even the authors of this paper with bubble generation had found influence of bubbles on impulse breakdown voltage within their data sets if one looks in detail (Fig. 8 in [25]). Voltage degradation due to bubble generation was found for AC, DC and impulse voltage for short gap lengths up to 1 mm in a cylinder (length 20 mm) to plane setup in [26]. Hence one can conclude that the result of a decrease of the withstand voltage for saturated liquid nitrogen caused by heating is in good agreement with literature.

C. *Effect of heating for subcooled conditions*

For subcooled liquid nitrogen (78 K, 0.3 MPa) no reliable reduction of the dielectric strength caused by heater generation is found for the DC tests with Fatelini 2 equipped with the bell to heatable plane setup. This result is in agreement with AC tests with Fatelini 2 using a sphere to heatable plane setup at 0.2 MPa with gap lengths of 8 mm and longer and with AC tests at 0.3 MPa for all gap lengths (starting with 2 mm) [8]. For the shortest examined gap length of 4 mm under 0.2 MPa a decrease of the AC withstand voltage caused by gas bubbles was reported. For lightning impulse tests with Fatelini 2 cryostat and a sphere to heatable plane setup a decrease of the dielectric strength by heater activation was found for both polarities for the fixed gap length of 8 mm [9]. Other researchers report breakdown voltage decrease for bubble generation under subcooled conditions, e.g. for uniform field and gap lengths below 5 mm [27] for AC and impulse and pressures up to 0.5 MPa (with one exception for AC at the longest gap length and highest pressure).

A decrease of the DC breakdown voltage after exceeding a certain heater power was reported for a horizontal rod to plane setup with a gap length of 1.2 mm in [18]. The maximum pressure was 0.5 MPa and the maximum temperature was 79 K.

Based on the different results of literature it can be concluded that there exists a certain heater power limit for triggering a degradation of the dielectric strength. The stable dielectric strength of Fatelini 2 in case of DC tests with subcooled conditions is therefore caused by dissipation of heater power below this limit for the tested gap lengths. Natural convection within the high field space is not sufficient to cause the degradation. The few number of bubble chains are also not sufficient to cause the degradation.

The balance between the cryogenic layout of a high voltage device and the dissipated energy is therefore a very sensitive issue for the dielectric design. Assuming a modular design for a high voltage device (e.g. fault current limiter) with a number of shells as field grading units which envelope the edged tapes it is important to know if bubbles also move in the outer long gap high field space. With this view it should be discussed if the energy of 5 kJ dissipated in Fatelini 2 related to the heater surface of about 129 cm^2 is comparable with realistic fault current limiter designs.

According to the fault current limiter simulation model proposed in [28], the energy dissipated in a high temperature superconductor tape with a width of 12 mm per length of 1 m is estimated as 3 kJ (a fault duration of 50 ms, a prospective current of 3 kA (peak) and a frequency of 50 Hz were assumed). For a DC simulation model the estimated energy was 3 kJ, too. Considering the surface of a tape of only one-meter length (2 times 120 cm^2) would lead to a lower ratio for the dissipated energy per surface compared to the ratio obtained for the Fatelini 2 experiments. But on the other hand this consideration would often be too optimistic because of several reasons, e.g. the much larger amount of superconductor in a fault current limiter. In addition, the 10 s dissipation time of Fatelini 2 allows longer time of gas bubble size reduction by condensation. Another important issue is that the heat is not generated near the high field region in the present Fatelini 2 setup. Facility specific investigation and measures for a balanced cryogenic high voltage design are therefore indispensable for large scale applications.

D. *Polarity effect*

Positive polarity for saturated conditions and negative polarity for subcooled conditions has higher breakdown voltages compared for the other polarity, each, for the DC tests with Fatelini 2 in case of considering the relatively longer gap lengths (details see Tab. 1). Higher DC breakdown voltage for positive polarity compared to negative polarity is reported for a tape to plane setup with 10 mm gap in [23] for saturated conditions with and without bubbles as well as for subcooled conditions with bubbles. This is in one mode not in agreement with the DC test results in Fatelini 2 for 10 mm (saturated conditions, bubbles). The difference may be explained by the different efficiency factors. For the Fatelini 2 setup the tendency for higher positive breakdowns is for these conditions more typical for longer gap length (with lower efficiency factor).

In [18] positive polarity shows higher or at least same breakdown voltage as negative polarity for all cases without heater and with the highest heater power. The difference of the breakdown voltage is decreasing with increasing pressure leading to almost the same values above 0.3 MPa for the not heated case.

It may be concluded that for medium products of pressure times gap length a positive polarity and for high products a negative polarity shows the higher breakdown voltage in case of weakly non uniform fields.

E. *Similarities to gas breakdown*

A general theory of the breakdown in liquid does not exist yet and sometimes one possible mechanism proposed in one experiment is inconsistent with observations in another set of device [29]. The model of an involvement of a gas breakdown is able to explain several of the properties found in the DC tests with Fatelini 2. Models like direct impact ionization or Auger process [29] require high fields which are not likely for the used bell to plane setup. Microbubbles can be assumed to exist or evolve within field stressed areas in case no gas bubbles are generated by a heater. This model was able to explain an increase of the breakdown voltage by increasing the pressure as well as the decreasing breakdown voltage for heater activation as described in [13].

The decrease of the breakdown voltage by heating is strong in saturated liquid nitrogen because nucleate boiling generation requires only relatively low amount of energy (latent heat of vaporization: 160 kJ / l; latent heat for water: 2255 kJ / l [30]). In addition, large amount of bubbles can ascend in the high field of the bell electrode. No relevant decrease of breakdown voltage by heating under subcooled conditions is found although the heater power has been increased for 10% compared to heater experiments under saturated conditions. This is caused by a lower bubble generation and a size reduction of the bubbles during ascending towards the high field space. It should be noticed that the energy which is needed for vaporization of liquid nitrogen under 0.3 MPa is calculated with [31] as 3% higher (20.84 kJ / kg from saturated conditions at 1.08 MPa to saturated conditions at 0.3 MPa, plus 183.96 kJ / kg for vaporization at 3.0 MPa) compared to vaporization at 0.108 MPa (198,47 kJ / kg).

Increasing pressure reduces the size of gas bubbles and increases the dielectric strength of the gas within the bubbles. Stronger impact for the copious bubble tests can also be explained but the model does not explain the complete missing of this kind of pressure effect for tests without using the heater, positive polarity and gap lengths from 20 mm onwards.

The various polarity effects measured for DC voltage in Fatelini 2 are not consistent. No or moderate polarity effect for the breakdown in liquid nitrogen was found for the shortest gap length of 10 mm which is in agreement with the breakdown in quasi uniform field in air for such a short gap length. But for the less uniform air breakdown in long gaps a distinct lower breakdown voltage for positive polarity can be expected which is only in agreement for the test results under subcooled condition. Indeed, for saturated conditions with long gaps the breakdown voltage at positive polarity is even higher.

Shielding for air breakdown can reduce the breakdown voltage and is also known to reduce or even practically eliminate the polarity effect for non uniform gaps (e.g. [32] for gap lengths between 10 mm and 50 mm). Reversal of polarity effect with changing gap length or pressure is reported for strong non uniform field and short gap lengths in air (e.g. higher breakdown voltage for negative polarity and 0.25 mm gap at 0.30 MPa (absolute); higher positive polarity for 1.5 mm gap at 0.30 MPa as well as for 0.25 mm gap at 0.05 MPa [33]). In case of the shielding of air gaps with solid barriers one may see certain physical analogies with long gap setups with partial gas discharge impeded by the liquid space assuming a kind of local varying shielding. But other effects seem to have only similar behavior without allowing to refer to similar physical background. Hence several observations exceed the possibilities of the gas breakdown model. Additionally, it must be taken into account that the discharge process in liquid is not just an "extension" of the gas breakdown but much more processes are involved, e.g. in case of contamination by ice.

F. *Literature of breakdown observation with high speed camera*

The used webcam in combination with the strong data compressive video mode allows only the investigation of slow macroscopic processes. Some literature is available with camera observations of voltage breakdown in liquid nitrogen.

In a sphere to plane setup with a gap length of 1 mm [21] lightning impulse breakdown pictures are presented for saturated liquid nitrogen conditions. For negative polarity on the sphere the negative streamers started on the sphere and for positive polarity the negative streamers started on the plate. Breakdown voltages at positive polarities had been higher than at negative polarity within this setup also under subcooled conditions.

Photos in a DC field of a tape to plane setup [23] with a gap length of 10 mm show breakdown in full gaseous bridges for both polarities under saturated conditions with boiling caused by a heater. For subcooled conditions at 0.25 MPa under no field conditions no full gas bridge occurred. Breakdown for negative polarity started typically in a partial gas bridge and for positive polarity in the liquid phase. Under subcooled conditions the difference between the polarity effect with the higher positive polarity is reduced for higher pressures.

The different breakdown mechanism observed by high speed camera may explain the change of polarity effect for subcooled conditions due to the impeded breakdown through the liquid phase for positive polarity.

G. Volume effect

With respect of size effects Fatelini 2 experiments have a limited significance for large scale DC apparatus but nevertheless these experiments are larger than most other fundamental breakdown voltage tests with liquid nitrogen with respect of volume and gap length. An extensive comparison of AC breakdown field values under saturated conditions of multiple authors [34] had shown that the Fatelini 2 AC experiments with unheated sphere to plane are on or even below the calculated lower confidence interval limit. The volume DC effect is not examined quantitatively in the present paper because of a too low number of comparable DC experiments and in addition, the bell to plane setup was selected to avoid distinct high field volume maxima within the examined gap range and has therefore only a relative low change of the high field volume.

For the AC tests of Fatelini 2 with bubble generation the calculated data in [34] are significantly lower than the other setups which can be considered as critical for large scale high voltage application. On the other hand, Fig. 13 had shown that no decreasing tendency for the DC field values was found for increasing gap length with the bell to plane setup.

A simple high field model is not sufficient in overlap situations of different breakdown mechanism. As an example in a not heated case the breakdown starts within the high field region of a non uniform field but in case of strong bubble generation the breakdown may be triggered in a lower field space located in a gas space attached to the plate. In case the gas distribution is time dependent in the range of the breakdown trigger delay the scattering of the breakdown voltage in the transition area of different breakdown processes can be increased.

V. Conclusions

The 15 min DC breakdown behavior of liquid nitrogen was examined in the pressure range between 0.1 MPa and 0.3 MPa for a temperature of 78 K with a bell to plane electrode setup. Local heating impulses in the grounded plane were generated for simulation of a superconductor quench in comparison to no heater activation. Strong bubble boiling occurred in the saturated case whereas no strong nucleate boiling occurs in the subcooled case.

Gas breakdown model can explain some of the changes in dielectric strength like its increase by pressure increase (for most cases) or decrease by heating in saturated conditions. In contrast the varying polarity effect cannot be explained sufficiently.

A lower limit of the withstand field strength seems to exist for tests with heater generation which may be an important information for large scale DC apparatus. For subcooled conditions no degradation due to heating is observed with the 550 W operation for 10 s which can be important considering that most commercial application like SFCLs are expected to be operated in subcooled conditions. The polarity effect allows size optimization by selection of higher negative field stress for large gap subcooled high voltage apparatus in case no high voltage fault case with pressure loss must be considered. In segmented large scale applications small size units may show opposite polarity effect e.g. for tape to surrounding grading shell unit within a fault current limiter compared to the higher large gap voltage.

Repetition of tests have shown strong scattering in some breakdown tests [13]. Hence the experimental DC withstand values give an orientation for gap lengths of few 10 mm but cannot be considered as safe in the sense of a 0% breakdown probability.

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Appendix - Fatelini 2 – DC tests with liquid nitrogen and bell to plane setup – results AKZ5 and AKZ6

D:\Fink\Energietechnik\Fatelini 2\6. AKZ DC 2018-19\Messungen\Auswertung\Fatelini 2 - AKZ 5 and AKZ 6 table.docx

Spacing	U\db1+ w/o heater	U\dw1+ w/o heater	U\db1+ w. heater	U\dw1+ w. heater	U\db1- w/o heater	U\dw1- w/o heater	U\db1- w. heater	U\dw1- w. heater	U\db2+ w/o heater	U\dw2+ w/o heater	U\db2+ w. heater	U\dw2+ w. heater	U\db2- w/o heater	U\dw2- w/o heater	U\db2- w. heater	U\dw2- w. heater	U\db3+ w/o heater	U\dw3+ w/o heater	U\db3+ w. heater	U\dw3+ w. heater	U\db3- w/o heater	U\dw3- w/o heater	U\db3- w. heater	U\dw3- w. heater
0																								
10	120.10	110.00	54.00	50.14	70.06	64.04	69.74	63.71									165.50	150.40	240.30	220.30	220.30	200.80	200.90	182.70
10			38.94																					
14	91.02	83.02	129.90	119.90	170.40	164.80	82.84	75.79	240.40	220.40	182.40	165.50	165.10	150.40	182.40	165.00	182.70	165.60	200.70	182.50	240.10	220.10	240.30	220.20
20	182.60	165.50	99.86	90.71	165.40	150.40	109.90	99.85									182.70	165.60	182.70	165.70		325.00		324.30
30	325.80	300.80	130.00	120.30	282.30	260.30	139.80	130.00									283.00	260.20	282.80	259.90		324.50		324.40
40		325.30	240.10	220.20	282.20	260.30	220.00	200.20									187.60	182.60		325.10				
50		325.30	281.80	259.90		324.70	220.00	200.30										325.10		324.80				
60				325.50		325.10	260.60	240.80										325.10						
70				324.80				324.50																
80							300.00	282.10																
90								325.00																
96								324.90																

Abbreviations:

“AKZ5” and “AKZ6” are names for test series derived from two different cool down cycles (AKZ is an abbreviation for **A**b**k**ühl**z**ykus which means cool down cycle).

“\d” is a control character expression that means “subscript” in the data analysis application “Kaleidagraph”

Appendix - Fatelini 2 – DC tests with liquid nitrogen and bell to plane setup – results AKZ5 and AKZ6

Pressure Influence

		A		C		B		D										A		C		B		D
Spacing	U\db1+ w/o heater	U\dw1+ w/o heater	U\db1+ w. heater	U\dw1+ w. heater	U\db1- w/o heater	U\dw1- w/o heater	U\db1- w. heater	U\dw1- w. heater	U\db2+ w/o heater	U\dw2+ w/o heater	U\db2+ w. heater	U\dw2+ w. heater	U\db2- w/o heater	U\dw2- w/o heater	U\db2- w. heater	U\dw2- w. heater	U\db3+ w/o heater	U\dw3+ w/o heater	U\db3+ w. heater	U\dw3+ w. heater	U\db3- w/o heater	U\dw3- w/o heater	U\db3- w. heater	U\dw3- w. heater
0																								
10	120.10	110.00	54.00	50.14	70.06	64.04	69.74	63.71									165.50	150.40	240.30	220.30	220.30	200.80	200.90	182.70
10			38.94																					
14	91.02	83.02	129.90	119.90	170.40	164.80	82.84	75.79	240.40	220.40	182.40	165.50	165.10	150.40	182.40	165.00	182.70	165.60	200.70	182.50	240.10	220.10	240.30	220.20
20	182.60	165.50	99.86	90.71	165.40	150.40	109.90	99.85									182.70	165.60	182.70	165.70		325.00		324.30
30	325.80	300.80	130.00	120.30	282.30	260.30	139.80	130.00									283.00	260.20	282.80	259.90		324.50		324.40
40		325.30	240.10	220.20	282.20	260.30	220.00	200.20									187.60	182.60		325.10				
50		325.30	281.80	259.90		324.70	220.00	200.30										325.10		324.80				
60				325.50		325.10	260.60	240.80										325.10						
70				324.80				324.50																
80							300.00	282.10																
90								325.00																
96								324.90																

Total number of data: 19

Uw3 > Uw1 16 times

Uw3 = Uw1 1 time

Uw3 < Uw1 2 times

=> Pressure increase increases withstand voltage value with 3 exceptions out of 19 data pairs. Exceptions occurrence for positive polarity, without heater, gap length ≥ 20 mm.

Appendix - Fatelini 2 – DC tests with liquid nitrogen and bell to plane setup – results AKZ5 and AKZ6

Heater Impact

		E		E		F		F		G		G		H		H		I		I		J		J
Spacing	U\db1+ w/o heater	U\dw1+ w/o heater	U\db1+ w. heater	U\dw1+ w. heater	U\db1- w/o heater	U\dw1- w/o heater	U\db1- w. heater	U\dw1- w. heater	U\db2+ w/o heater	U\dw2+ w/o heater	U\db2+ w. heater	U\dw2+ w. heater	U\db2- w/o heater	U\dw2- w/o heater	U\db2- w. heater	U\dw2- w. heater	U\db3+ w/o heater	U\dw3+ w/o heater	U\db3+ w. heater	U\dw3+ w. heater	U\db3- w/o heater	U\dw3- w/o heater	U\db3- w. heater	U\dw3- w. heater
0																								
10	120.10	110.00	54.00	50.14	70.06	64.04	69.74	63.71									165.50	150.40	240.30	220.30	220.30	200.80	200.90	182.70
10			38.94																					
14	91.02	83.02	129.90	119.90	170.40	164.80	82.84	75.79	240.40	220.40	182.40	165.50	165.10	150.40	182.40	165.00	182.70	165.60	200.70	182.50	240.10	220.10	240.30	220.20
20	182.60	165.50	99.86	90.71	165.40	150.40	109.90	99.85									182.70	165.60	182.70	165.70		325.00		324.30
30	325.80	300.80	130.00	120.30	282.30	260.30	139.80	130.00									283.00	260.20	282.80	259.90		324.50		324.40
40		325.30	240.10	220.20	282.20	260.30	220.00	200.20									187.60	182.60		325.10				
50		325.30	281.80	259.90		324.70	220.00	200.30										325.10		324.80				
60				325.50		325.10	260.60	240.80										325.10						
70				324.80				324.50																
80							300.00	282.10																
90								325.00																
96								324.90																

Considering all 22 data:

Uwithout heater > Uwith heater 13 times

Uwithout heater = Uwith heater 4 times

Uwithout heater < Uwith heater 5 times

Arrange results concerning pressure conditions:

Saturated conditions (0.1 MPa)	At 0.3 MPa only	Subcooled conditions (0.2 MPa and 0.3 MPa)	
Uwithout heater > Uwith heater 11 times Uwithout heater = Uwith heater 1 time Uwithout heater < Uwith heater 1 time	Uwithout heater > Uwith heater 1 time Uwithout heater = Uwith heater 3 times Uwithout heater < Uwith heater 3 times	Uwithout heater > Uwith heater 2 times Uwithout heater = Uwith heater 3 times Uwithout heater < Uwith heater 4 times	
=> For saturated conditions: Heater activation causes in most cases reduction of withstand voltage		=> For subcooled conditions: Heater activation has no relevant impact on withstand voltage	

Appendix - Fatelini 2 – DC tests with liquid nitrogen and bell to plane setup – results AKZ5 and AKZ6

Polarity effect

		K		L		K		L										M		N		M		N
Spacing	U\db1+ w/o heater	U\dw1+ w/o heater	U\db1+ w. heater	U\dw1+ w. heater	U\db1- w/o heater	U\dw1- w/o heater	U\db1- w. heater	U\dw1- w. heater	U\db2+ w/o heater	U\dw2+ w/o heater	U\db2+ w. heater	U\dw2+ w. heater	U\db2- w/o heater	U\dw2- w/o heater	U\db2- w. heater	U\dw2- w. heater	U\db3+ w/o heater	U\dw3+ w/o heater	U\db3+ w. heater	U\dw3+ w. heater	U\db3- w/o heater	U\dw3- w/o heater	U\db3- w. heater	U\dw3- w. heater
0																								
10	120.10	110.00	54.00	50.14	70.06	64.04	69.74	63.71									165.50	150.40	240.30	220.30	220.30	200.80	200.90	182.70
10			38.94																					
14	91.02	83.02	129.90	119.90	170.40	164.80	82.84	75.79	240.40	220.40	182.40	165.50	165.10	150.40	182.40	165.00	182.70	165.60	200.70	182.50	240.10	220.10	240.30	220.20
20	182.60	165.50	99.86	90.71	165.40	150.40	109.90	99.85									182.70	165.60	182.70	165.70		325.00		324.30
30	325.80	300.80	130.00	120.30	282.30	260.30	139.80	130.00									283.00	260.20	282.80	259.90		324.50		324.40
40		325.30	240.10	220.20	282.20	260.30	220.00	200.20									187.60	182.60		325.10				
50		325.30	281.80	259.90		324.70	220.00	200.30										325.10		324.80				
60				325.50		325.10	260.60	240.80										325.10						
70				324.80				324.50																
80							300.00	282.10																
90								325.00																
96								324.90																

Considering all 21 data:

Upositive > Unegative 10 times

Upositive = Unegative 1 time

Upositive < Unegative 11 times

Arrange results concerning pressure conditions:

Saturated conditions (0.1 MPa) without heater	Saturated conditions (0.1 MPa) with heater	Subcooled conditions (0.2 MPa and 0.3 MPa)	Subcooled condition 0.3 MPa
Upositive > Unegative 4 times Upositive = Unegative 0 Upositive < Unegative 1 time (for g = 14 mm)	Upositive > Unegative 4 times Upositive = Unegative 0 Upositive < Unegative 3 times (for g ≤ 30 mm)	Upositive > Unegative 2 times Upositive = Unegative 1 time Upositive < Unegative 7 times	Upositive > Unegative 1 time (10 mm gap) Upositive = Unegative 0 Upositive < Unegative 7 times
=> For saturated conditions without heater: Lower withstand voltage for negative polarity for gaps ≥ 20 mm Or in other words: Higher withstand voltage for positive polarity for gaps ≥ 20 mm	=> For saturated conditions with heater: Lower withstand voltage for negative polarity for gaps ≥ 40 mm Or in other words: Higher withstand voltage for positive polarity for gaps ≥ 40 mm	=> For subcooled conditions in more cases: Lower withstand voltage for positive polarity Or in other words: Higher withstand voltage for negative polarity	=> For subcooled conditions at 0.3 MPa: Lower withstand voltage for positive polarity for gaps ≥ 14 mm Or in other words: Higher withstand voltage for negative polarity for gaps ≥ 14 mm