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WITHSTAND IMPULSE VOLTAGE OF LIQUID NITROGEN IN THE PRESENCE OF GAS BUBBLES

S. Fink*, W.-S. Kim**, M. Noe*, and V. Zwecker*

* Karlsruhe Institute of Technology (KIT), Germany **KEPCO Research Institute (KEPRI), Korea

INTRODUCTION

Liquid nitrogen is often not only used as a coolant but also as an electrical insulation material for application in high voltage superconducting apparatus. A temperature increase, e.g. after the transition of the superconducting to the normal conducting state of a superconducting fault current limiter, may cause a considerable decrease of the breakdown voltage within the apparatus by generation of gas bubbles.
The test facility Fatelini 2 (FAcility for TEsting LIquid NItrogen) used permits examination of the dielectric strength of liquid nitrogen with and without bubbles by the use of a sphere to plane electrode configuration. The employed impulse generator allows us to create standard 1.2/50µs lightning impulse voltages up to 365 kV. This paper discusses the withstand voltage of liquid nitrogen for different gap lengths in the bubble generation case in comparison to the pure liquid phase.

TEST FACILITY FATELINI 2

The Fatelini 2 test facility shown in Figure 1 is the successor to Fatelini 1 which had allowed testing of liquid nitrogen with a heat-able plane with standard lightning impulses up to 365 kV and alternating voltages up to 200 kV rms [1]. The main disadvantage of Fatelini 1 was the missing observation possibility for liquid nitrogen. Hence with Fatelini 1, it had not been possible to decide if gas bubbles occurred during the heating time of the chosen 6 s with 500 W. This heating duration of 6 s had been found to be sufficient for bubble generation with the plane heated with 500 W in a flat open cryostat but it did not mean that this duration was sufficient to generate gas bubbles in the case of higher gas pressure values or other hydrostatic pressure. After starting the superconducting fault current limiter project of KEPCO in the 170 kV grid, tests showed that nitrogen gas bubbles were generated for each current limiting event due to an evaporation of about 50 kg of liquid nitrogen within a heating duration of 67 ms.
Hence several heating duration tests were performed with Fatelini 2 before starting the high voltage experiments. It turned out that a duration of 10 s is sufficient for generation of gas bubbles under the maximum pressure of 0.3 MPa (abs.) and at the maximum liquid nitrogen filling level above the plate. This creates an additional hydrostatic pressure in the space between plane and sphere.

Figure 1 Test facility "FATELINI 2" in the Cryogenic High Voltage Lab of KIT-ITEP with cryostat and cryogenic bushing (right side), high voltage divider (foreground, middle), Marx generator (left) and high voltage transformer (background, far left).

Direct bubble observation under high voltage application was not possible for safety reasons. Therefore a USB camera was installed on a remote controlled Laptop. A three stage Marx generator was available for the creation of standard lightning impulses up to 365 kV. A cryogenic bushing (manufacturer Hochspannungsgeraete Porz) can be used for standard lightning voltages up to 550 kV and alternating voltages up to 230 kV rms.
The voltage was measured with a broad band high voltage divider (Hilo-Test HVT 240 RCR special version) and a battery powered oscilloscope. This oscilloscope is only able to store up to 10,000 points per channel which means that 40 ns is the time between two samples for the selected signal storage duration of 400 µs. Although this time between two

samples and the divider bandwidth of 8.75 MHz do not fulfil standard measurement requirements of IEC 61083-1 it has been considered sufficient for the measured values which fit well in the allowed tolerances of the standard lightning impulse parameters (Figure 2).

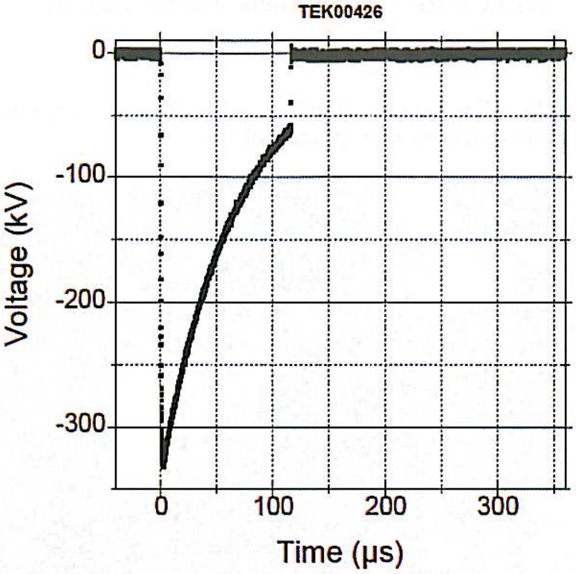

Figure 2 Negative high voltage waveform with breakdown. The crest value was 330 kV, virtual front time was 1.14 μs, time to half value was 48.5 μs, and time to chopping was 118 μs.

A temperature and relative pressure measurement system was programmed, based on C#. The heater voltage and current were measured with a second oscilloscope. The average power during the heating duration could be directly indicated by using the internal mathematical functions of this oscilloscope.
For the tests with the heater applied, the trigger impulse for the first stage of the Marx generator was synchronized by a home-made two channel fibre optic trigger system. In our tests, the final setting for the heating duration was 10.1 s and the Marx generator was triggered 10.0 s after starting the heating.
Electrode configuration observation and filming via USB camera was used to verify that bubbles appeared during the impulse voltage application.

PREPARATION, SWITCHING SEQUENCE AND MEASUREMENT

Firstly, the cryostat was filled up to the rated liquid nitrogen level. Then the pressure was increased in the case of tests above 0.1 MPa. Next, the temperature sensors were removed in order to avoid damage by electromagnetic pulses.
For each high voltage impulse test with heater operation, the following sequence was performed:
Firstly the Marx generator was charged. Then atmospheric pressure and relative pressure were measured. Next the USB camera film for bubble generation verification was started manually. When the time counter of the remote running video program showed 2s, the switching process was started (ramp down AC voltage of high voltage transformer, interrupt connection to transformer primary voltage supply, start fibre optic trigger system which triggers heater and Marx generator). Because this procedure generated a jitter in the range of one second between video starting and the switching process, the heating process was indicated by a red light reflected on the plane and the Marx generator trigger impulse was fired at a specific time by an acoustic signal on the film. The bubble appearance during voltage impulse was verified by viewing and the stored film was used for documentation and control purposes.
After the voltage impulse evaluation, the heating impulse power and duration were controlled.
After each experimental period, the temperature of the liquid nitrogen was measured before releasing the over pressure of the cryostat in order to determine the maximum temperature of the liquid nitrogen.

BUBBLE GENERATION DEPENDING ON PRESSURE

The heating of the plane created a pressure dependent boiling behaviour. Snapshots from the video films were used for the description of this different behaviour. Figure 3 shows a view of the electrode arrangement embedded in liquid nitrogen before starting the heater. The same gap distance of 8 mm between plane and sphere was kept in Figure 3 up to Figure 10 to exclude the minor effect of different gap distances for the boiling behaviour. No bubbles appeared without heating in Figure 3.

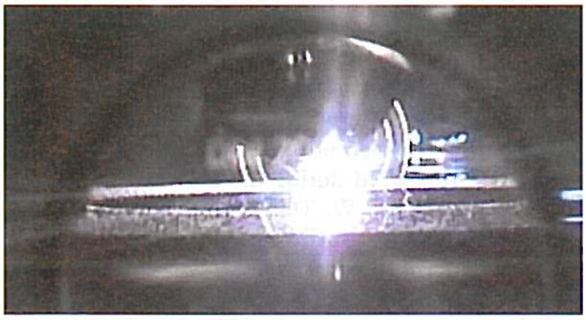

Figure 3 View through the cryostat windows on the sphere (top) to plane (bottom) electrode arrangement at t = 0 before starting the heating (t = 3 s) at 0.1 MPa (abs.). The space around the electrodes was completely filled with bubble-free liquid nitrogen. Light and reflections on the plane were generated by an LED behind the opposite cryogenic window (within vacuum shield of the cryostat) and not by a breakdown. Unclear visible text on the cryogenic front window (manufacturer, standard, maximum allowed overpressure) which partly covered the bottom view of the sphere is according to the standard DIN 7080.

After starting the heating process, convection started in the liquid nitrogen which was recognised by a shimmering effect above the plane (not shown here). Then small areas with streaming became visible in the liquid nitrogen. Figure 4 shows these areas. The subsequent start of the strong bubble generation occurred quickly i. e. superheating may have happened.

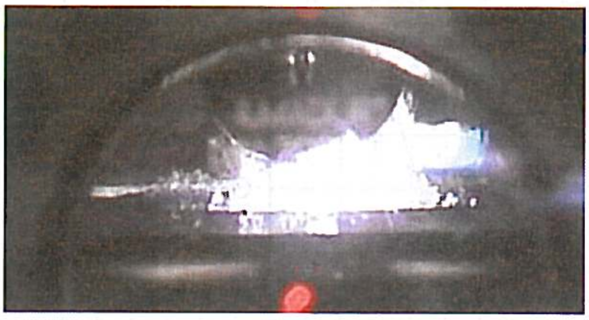

Figure 4 View of the sphere to plane arrangement a t = 8 s which means a heating duration of 5 s. The red signal near the base of the plane indicates that the heater is powered.

Figure 5 shows the situation one video frame later than Figure 4. Since about 14 frames per second are accessible by the used frame to frame viewing method, this means a duration of about 70 ms between Figure 4 and Figure 5. The bubbles can be found almost throughtout the window view of figure 5.

Figure 5 View of the sphere to plane arrangement at 0.1 MPa about 70 ms after Figure 4. The bubbles can be found almost throughtout the complete window view. The small red point above the plane is only a reflection and not an electric spark.

The strong boiling also continues during the time of the high voltage impulse (Figure 6) and for few seconds longer.

For the experiments at 0.2 MPa, strong boiling continued (Figure 7) but with a duration of less then 1 s which led usually to the presence of a covering with small bubbles above the heatable plane area during the high voltage impulse (Figure 8).

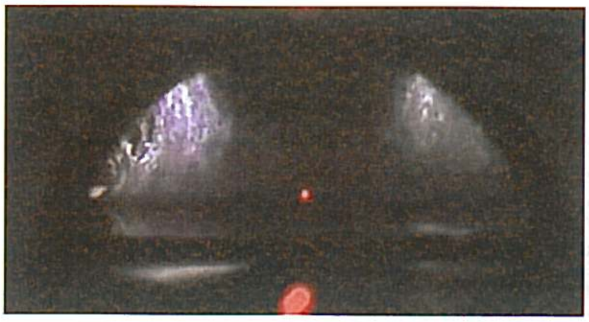

Figure 6 Sphere to plane arrangement at 0.1 MPa during the high voltage impulse (t = 13 s, which means after a heating duration of 10 s). The bubbles still can be found almost throughtout the complete space between sphere and plane. No breakdown happened during this test.

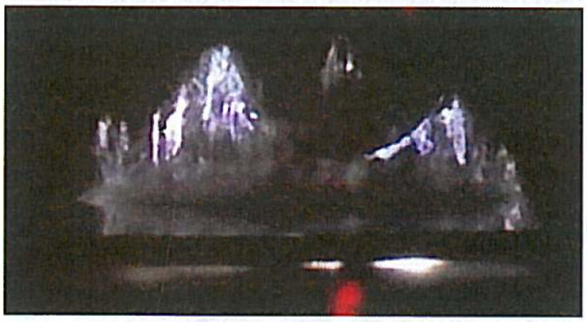

Figure 7 Sphere to plane arrangement at 0.2 MPa during strong bubble generation period.

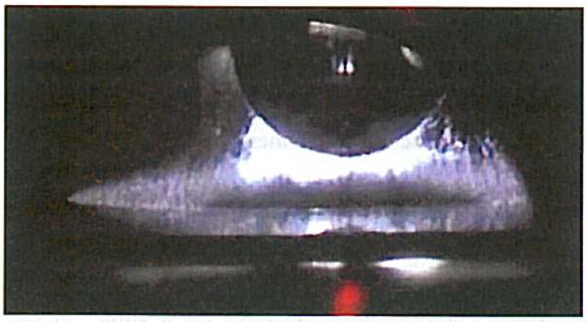

Figure 8 Sphere to plane arrangement at 0.2 MPa during the high voltage impulse. The bubble space is considerably smaller compared to the 0.1 MPa condition (Figure 6).

For tests with 0.3 MPa (absolute), the strong boiling affected only a small amount of the space around the plane and sphere (figure 9) but few turbulent paths may still bridge the gap between the electrodes, mostly starting on the boundary of the heat-able area to the surrounding not heat-able area of the plane. During the high voltage event, the amount of gaseous nitrogen was again reduced compared to the 0.2 MPa test (Figure 10).

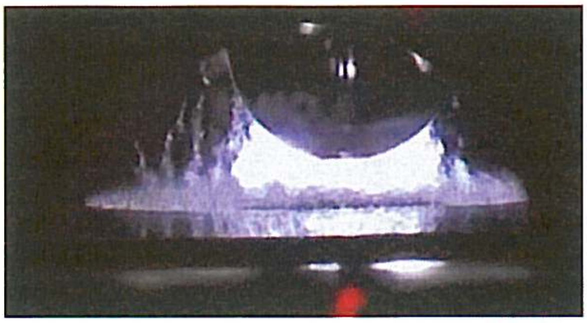

Figure 9 Sphere to plane arrangement at 0.3 MPa at the moment of maximum bubble generation. The amount of gas is considerably lower compared to the situation at lower pressure stages.

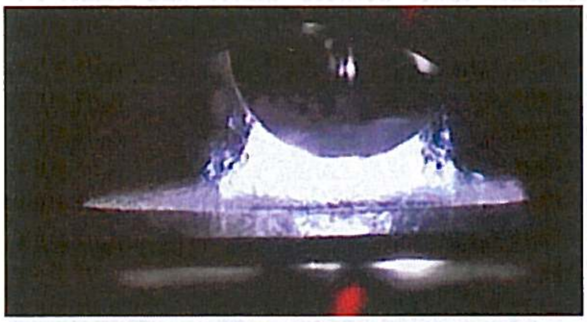

Figure 10 Sphere to plane arrangement at 0.3 MPa during the high voltage impulse. The amount of liquid is higher compared to the 0.2 MPa condition (figure 8).

For all heating impulses, the bubble generation started before or during the moment of the high voltage impulse. Pictures with electrical breakdown are not shown because the camera was not able to present it in an accurate manner.

HIGH VOLTAGE WITHSTAND BEHAVIOUR

The breakdown and withstand behaviour were examined in series of up to 20 standard 1.2/50μs lightning impulses with the same crest value. In the case of at least one breakdown, the voltage was decreased by about 10%. In the case of 20 impulses without breakdown, the voltage was increased by about 10% and a new series with 20 impulses was performed if the new value did not exceed 365 kV. Finally, this method resulted in a series without breakdown and the neighbouring series with breakdown. The voltage values of these series were defined as withstand and breakdown value respectively.

It is obvious that this special definition of a withstand voltage can only be used for a rough experimental approach to the dielectric strength behaviour investigation and is not sufficient for insulation co-ordination of a power engineering device.

The minimum waiting interval between 2 consecutive impulses was selected as 3 minutes.

Figure 11 shows the measured breakdown and withstand voltages for positive impulses (i.e. high voltage impulses with positive polarity on the sphere, plate is grounded) and figure 12 shows the results for negative impulses.

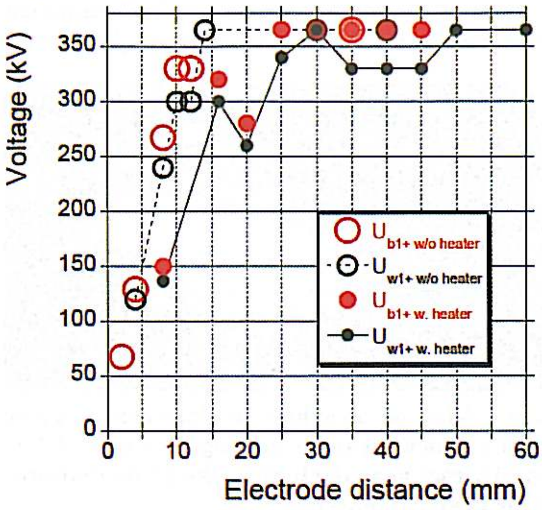

Figure 11 Breakdown (abbreviation "b", red colour) and withstand ("w", black colour) voltages with 500 W operation of the heater ("w. heater", filled markers) and without excitation of the heater ("w/o heater", unfilled markers) for a pressure of 0.1 MPa absolute (abbreviation "1") depending on electrode distance. Only positive polarity ("+") is shown, hence e. g. $U_{b1+w.heater}$ means:
U: voltage
b: breakdown
1: at 0.1 MPa
+: positive polarity
w. heater: with heater

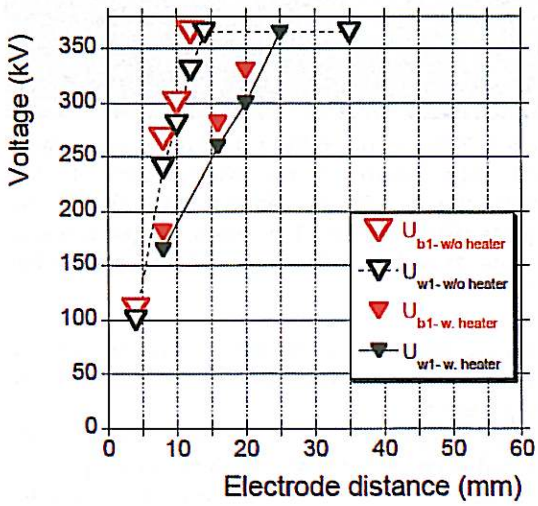

Figure 12 Breakdown and withstand voltages with heater and without heater for a pressure of 0.1 MPa absolute and negative polarity (abbreviation "-"). Other abbreviations are the same as in Figure 11.

Both figures present the data for the tests at 0.1 MPa (absolute) only.

A roughly linear increase through the point "0 V, 0 mm" of the withstand and breakdown voltage is shown in Figures 11 and 12 for the tests without heater operation (unfilled markers) up to an electrode distance of 14 mm. The withstand voltage of the maximum test value of 365 kV was reached for both polarities at a distance of 14 mm, hence the slope is about 26 kV / mm.

Randomly, one breakdown event for a high voltage impulse without heater was found at a distance of 35 mm by an un triggered discharge of the positively charged Marx generator (see Figure 11). Such uncontrolled discharges happened often with the simple Marx generator used under certain weather conditions (high humidity and warm). If no breakdown occurred, these impulses were ignored with the exception of considering the minimum waiting interval for the subsequent high voltage impulse.

After the breakdown at 35 mm the dielectric strength around these gap lengths was examined in detail with a series of 20 impulses of 365 kV with positive polarity at distances of 30 mm and 40 mm and additionally with negative polarity at 35 mm. No breakdowns occurred. The values can be found in Figures 11 and 12.

Due to the limitation of 365 kV, a withstand voltage at 365 kV in the figures makes no claim about a potentially higher withstand voltage for a 20 impulse series test, i. e. a withstand value marker at 365 kV means withstand value is ≥ 365 kV because the tests cannot be continued with higher voltages.

For the test with gas bubbles, a strictly monotonically increasing curve can be found for negative polarity (Figure 12) but the values are significantly lower than for the tests without heating and the curve is no longer linear through the point "0 V, 0 mm". For the negative polarity with gas bubble generation the withstand voltage value of 365 kV was reached for a distance of 25 mm.

The plot for the curve with positive polarity and bubble generation (Figure 11) illustrates similar behaviour to that for negative polarity up to 16 mm the next value at 20 mm shows significantly lower breakdown and withstand voltages. For larger distances, the curve is again increasing and the 365 kV value is reached at 30 mm. For this distance, one breakdown was found for 21 impulses (instead of 20 due to miscounting). Hence in Figure 11, the breakdown and the withstand markers for the tests with the heater are allocated to the same voltage for a distance of 30 mm. Between 35 mm and 45 mm, the withstand voltage was found to be 330 kV and the 365 kV withstand voltage value was again reached for 50 mm and kept for 60 mm distance as well.

Figure 13 shows the pressure dependence of breakdown and withstand voltages for a distance of 8 mm and the absolute pressure values 0.1 MPa, 0.2 MPa and 0.3 MPa. The temperature increase in the liquid nitrogen in the height of the plate caused by the pressure increase was ≤ 0.3 K.

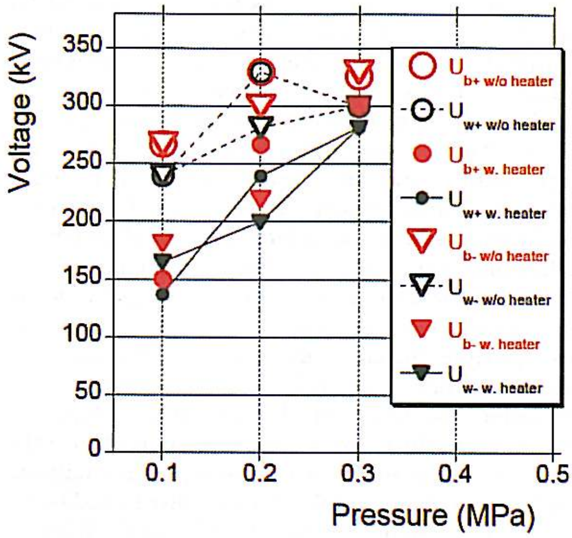

Figure 13 Breakdown and withstand voltages depending on absolute pressure for an electrode distance of 8 mm. Abbreviations are the same as in Figure 11.

All values in Figure 13 are below the 365 kV limitation and no distinct polarity effect can be found in the case of the 8 mm electrode separation.

Significant lower withstand and breakdown voltage values in the case of bubble generation (filled markers) compared to the results without heating (unfilled markers) can be seen for the 0.1 MPa pressure tests, e.g. the reduction of the withstand voltage by gas bubble generation is higher than 30%.

The dielectric strength gain by the pressure increasing is higher for the bubble experiments resulting e.g. at 0.3 MPa, in a reduction of the withstand voltage by gas bubble generation of only 6% for both polarities.

A special breakdown happened for a positive 330 kV, 0.2 MPa test without excitation of the heater. This breakdown showed a very short time to chopping (340 ns) and the operators had the impression of a strange sound. Hence it cannot be excluded that the breakdown happened outside the cryostat although all outer creepage distances were large. 20 further tests with 330 kV showed no breakdown and testing with 10% higher voltage showed breakdown for the first impulse. Hence it was decided to allocate to the combination "330 kV, positive polarity, 0.2 MPa" the breakdown and withstand marker also.

DISCUSSION OF THE TEST RESULTS

A remarkable outcome of the positive impulses at 0.1 MPa (Figure 11) was the appearance of a transition area with decreasing dielectric strength between a zone with a roughly linear increase of the

dielectric strength and a saturation area with a low increase of dielectric strength with distance.
Deviation from the Paschen curve on the right side of the Paschen minimum has already been reported for strongly non-uniform fields and electrode configurations with constant distance but increasing pressure, leading to a region with decreased breakdown voltage by increasing the pressure [2].
In the examined case, the pressure of 0.1 MPa was kept constant and the distance was varied with a sphere of 50 mm diameter. According to Figure 11, a local minimum was found for a distance of 20 mm. A utilization factor (or field efficiency factor) of η = 0.6 for a sphere to plane electrode configuration can be determined according to [3], assuming homogeneous dielectric material and neglecting the effect of the grounded cryostat cylinder wall (diameter 646 mm) for the electrode distance of 20 mm. This utilisation factor of 0.6 is far above the value which characterises a strongly non-uniform field in air around 0.1 MPa. Hence other or additional effects are responsible for the observed dielectric strength reduction.
It must also be recognised that, in a gas-liquid-mixture, the higher permittivity of liquid nitrogen creates a field enhancement within the gas bubbles.
A hint may be derived from a comparison of Figures 11 and 12 that there is a polarity effect for longer distances with lower positive withstand voltages but it is necessary to collect more experimental data for negative impulses to confirm this.
For the tests with the pressure steps, the equilibrium temperature would be 83.6 K for 0.2 MPa and 87.9 K for 0.3 MPa to reach saturation [4]. For the measured temperatures of $T \leq 78.4$K, the liquid nitrogen around the electrodes was supercooled. The increase of the dielectric strength of liquid nitrogen by increasing pressure can not only be explained by the increasing breakdown strength for a pressurised gas, assuming a cavity breakdown mechanism, but also by the cooling of the bubble especially in the super-cooled case, creating a lower gas temperature and a fast destruction of the bubbles. This explains the higher dielectric strength gain for the experiments with bubbles compared to the tests without operation of the heater. Due to limitations of the test facility, it was not possible to make tests with pressures higher than 0.3 MPa and it would have been too difficult to make high voltage tests at 0.2 MPa or 0.3 MPa at the equilibrium temperatures.
Another limitation was the maximum heater power of about 500 W which is far below the expected heating power during a quench of the planned KEPCO high voltage superconducting fault current limiter.
Simultaneous appearance of the high voltage impulse with special short time gas conditions, like superheating, is a statistical event and can only be considered by an adequate number of experiments where 20 seems not to be sufficient for insulation co-ordination purposes. On the other hand, the limited total test duration did not allow a larger number of experiments.

CONCLUSION

A series of 20 standard lightning impulses was performed to determine the withstand voltage of a 50 mm diameter sphere to plane electrode arrangement. Considerably lower withstand voltage values were found for saturated liquid nitrogen at 0.1 MPa in the case of gas bubble generation created by a 500 W heating compared to the unheated case. Strong non-linear behaviour was found for positive polarity in the case of bubble generation. A pressure increase to 0.3 MPa with super-cooled liquid nitrogen seems to be an effective method to improve the dielectric strength in case of bubble generation.
A random positive 365 kV impulse without heating for an electrode distance of 35 mm caused a breakdown, although a series of 20 impulses with 365 kV had already passed a 14 mm distance testing without breakdown. This event emphasis the need for selecting high safety factors or performing more tests in order to obtain sufficient data for making e. g. a Weibull distribution analysis.
Alternating voltage (50 Hz) tests with the same electrode arrangement with and without heating are planned with the test facility Fatelini 2.

REFRENCES

1 *Fink, S, Noe, M, "A facility for testing the dielectric strength of liquid nitrogen", 16th IEEE International Conference on Dielectric Liquids, Poitiers, France, June 30, (2008) http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=04622450*
2 *Kind, A, Feser, K, "High voltage test technique", Reed Educational and Professional Publishing Ltd, 2nd edition, pp. 208, (2001)*
3 *Philippow, E, "Taschenbuch Elektrotechnik – Band 6 Systeme der Elektrotechnik", Carl Hanser Verlag, München, pp. 253, 254 (1982)*
4 *"PHDiagramm", version 3.1.1 cjt Systemsoftware AG*