

OPTICAL DIAGNOSTICS OF LIQUID NITROGEN VOLUME PRE-BREAKDOWN EVENTS

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Abstract

An increased need for compact pulsed power systems requiring new switching technologies combined with the benefits of cryogenic properties, such as higher energy density and miniaturization, has lead to increased interest in liquid nitrogen as a switching medium. High hold off voltage, low dielectric constant, and low environmental impact are further advantages of liquid nitrogen. Characterization of breakdown is investigated using high-speed (temporal resolution < 1 ns) optical and electrical diagnostics in a coaxial system with 52Ω impedance. Experiments are done in self-breakdown mode in super-cooled liquid nitrogen with a temperature near 70 K. Discharge current and voltage are determined using transmission line type current sensors and capacitive voltage dividers. Discharge luminosity is measured with photomultiplier tubes (risetime \approx 800 ps) that are focused on the negative electrode tips and the center of the channel. Optical investigations of breakdown and pre-breakdown events on a nanosecond time scale will provide a better understanding of the fundamental physics of breakdown formation. Detailed optical and spectroscopic diagnostics combined with high-speed electrical diagnostics are aimed at clarifying the overall breakdown mechanisms, including electronic initiation and bubble formation. The breakdown initiation/development will be discussed.

I. INTRODUCTION

Electrical breakdown in dielectric liquids is of high technical interest and has been studied for several years. Cryogenic liquids are of unique importance and have several advantages over other dielectric liquids. These advantages include their direct usefulness for cryogenic and super-conducting applications, especially in conjunction with semiconductors where low temperatures increase power handling capabilities and reduce losses.

Recent investigations of liquid breakdown have shown that it is based on complex interactions between hydrodynamic and electrical phenomena. These interactions lead to a complex temporal and spatial structure of the development of the conducting channel. Basic investigation of streamers and breakdown initiation in liquid dielectrics is described in [1]. Field emission of electrons from the cathode into the liquid causes local heating of the liquid

leading to the development of electron avalanches [2]. The effects of area and volume on breakdown in liquid nitrogen [3] as well as the role of thermal bubbles and surface structures have been discussed in [4]. It is generally accepted that the application of a voltage to a gap in a liquid dielectric leads to pre-discharge events, consisting of discrete current and light emission spikes. These spikes are associated with streamer-like structures which propagate not continuously, but stepwise.

In this paper an attempt is made to further characterize the breakdown phenomena using high speed optical and electrical diagnostics, with resolutions in the sub-nanosecond regime. The use of high-speed optical measurement techniques such as photomultiplier tubes and spectroscopy in conjunction with electrical measurements of the voltage and current across the gap provide further insight into the pre-breakdown events.

II. EXPERIMENTAL SETUP

The setup incorporates a fast coaxial system with a matched impedance of 52Ω . It consists of two RG-19 transmission lines that connect at feedthroughs on either side of a cylindrical, stainless steel chamber. The inner conductor of each transmission line can be charged independently to 100 kV. This allows either a bipolar configuration or single sided charging of the transmission lines. The test gap is connected to either side of the transmission lines center conductor. A cylindrical grid inside the container connects the outer conductors, maintaining constant impedance. A point-plane geometry using a tungsten needle with a micrometer radius of curvature was placed 7 mm away from a 1 cm diameter copper plane electrode.

To minimize high voltage stress on the feedthroughs, both lines are charged slowly with opposite polarities until breakdown occurs. Therefore the breakdown voltage is twice the single line charging voltage. The matched coaxial setup facilitates fast electrical diagnostics which include a transmission line current sensor [5] and up to four capacitive voltage dividers with risetimes of less than 300 ps [6].

Luminosity measurements were performed with 3 Hamamatsu H6780-04 photosensor modules. The photomultiplier tubes (PMT) have risetimes of 780 ps, a sensitivity of 3×10^4 A/W and a gain of 5×10^5 . Two of the

PMT's were focused on the gap region. One observed the tip of the needle and the second was focused 5 mm away in the gap near the plane. The third tip was 5 mm away from the tip PMT observing the shaft of the needle. A cylindrical lens 5 mm long and 3mm in diameter focuses the light from each location onto a fiber optic cable that is connected to a PMT. This configuration allows a determination of the starting location for the pre-breakdown pulses as well as an estimate of the speed of propagation across the gap. Figure 1 is a sketch of the cylindrical lens setup for the optical diagnostics. The areas imaged onto the fiber are approximately 1 mm wide by 10 mm long.

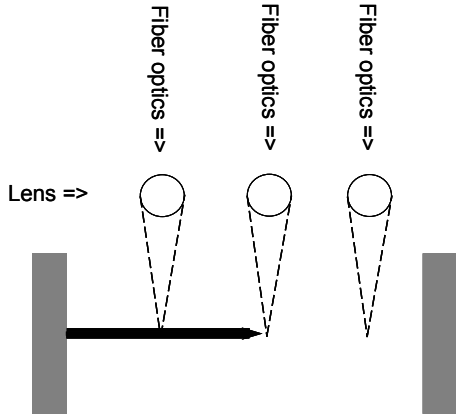


Figure 1. Sketch of cylindrical lens setup and point-plane gap for optical diagnostics. Gap 7mm.

Spectroscopic measurements were made using an Oriel MS257 optical spectrograph. The spectrograph uses an iCCD camera that is triggered with an 80 ns electrical gate pulse. The spectrograph connects to the same cylindrical lens configuration as the PMTs allowing the collection of spectral data at the tip of the needle and gap. Figure 2 is a diagram of the experimental setup.

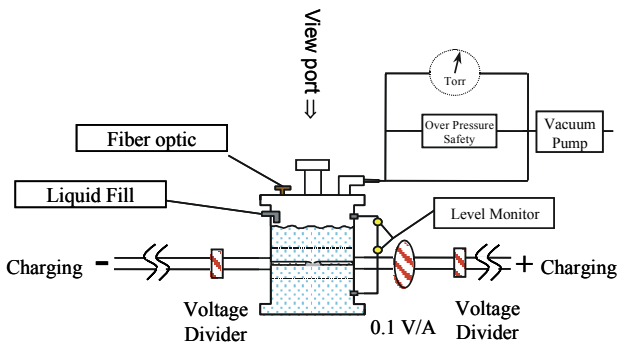


Figure 2. Experimental setup for LN₂ pre-breakdown tests with coaxial charging lines, and diagnostic devices.

The chamber is filled with liquid nitrogen and then evacuated to a pressure of about 0.50 atm. Evacuating the chamber will reduce the temperature of the liquid nitrogen (LN₂), after about 15 to 20 minutes, to a calculated value of approximately 70 K, as determined using the Clausius-

Clapyron equation, where it is assumed that the vapor can be described as an ideal gas [7].

$$\ln \frac{P_1}{P_2} = \frac{H_{vap}}{R} \left(\frac{1}{T_1} - \frac{1}{T_2} \right) \quad (1)$$

(P = pressure, T = temperature, H_{vap} = latent heat of vaporization per mole, R gas constant).

When the chamber is returned to atmospheric pressure the LN₂ stops boiling and will remain “quiet” until the liquid reaches the boiling point due to thermal conduction and radiation, after approximately 10 minutes.

Six inches of Styrofoam on the sidewalls and 4 inches on the top and bottom insulate the chamber. The amount of heat transported through the walls of the container is approximately 40 watts. The heat transport into the chamber from the inner and outer conductor of the transmission lines and radiation from the walls is approximately 150 watts.

III. RESULTS

A. Emission Spectra

The spectrograph is triggered as early in the breakdown as possible. Figure 3 represents the timing of the spectrograph gate relative to final breakdown for a typical shot taken during the early stage of main breakdown. The observed experimental spectrum taken during the early stage of main breakdown, see Fig. 4, lacks the distinct line features of the same spectrum taken in N₂ at atmospheric pressure, see Fig. 5. However, we are able to identify the following broadband band structures of N₂ and N₂⁺ [8]. The B²Σ_u⁺ → X²Σ_g⁺ transition of N₂⁺ with the band head at 391 nm and with the direction of the shading of the band system primarily to the red. For N₂, the m¹Π_u → a¹Π_g transition at 275 nm and possibly the d^r → a¹Π_g transition at 280 nm both shaded towards the red.

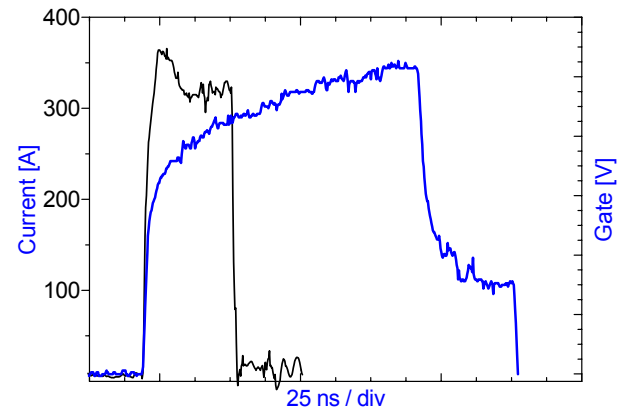


Figure 3. Graph of gate location during main breakdown. Gate = 80 ns.

The position of these bandheads explains the sharp drop in intensity around 275 nm. Other possible bands are ei-

ther outside the measured wavelength region or shaded into the violet and are excluded.

The spectrograph was configured with a 150 lines/mm grating blazed at 300 nm to observe a large spectral range from 200 nm to 800 nm. Tests were performed using a 10 micron slit and average light intensity was very close to the maximum levels at the needle tip for every test while the intensity was much lower in the gap near the plane. The same 150 lines/mm grating was used for the atmospheric tests as for the LN₂.

It should be noted that the transition of N₂⁺ goes into the ground state from the upper electronic level at ~ 3 eV, whereas the upper electronic level for both N₂ transitions is at about 13 eV. Assuming some kind of thermal distribution for the energy levels in N₂ and N₂⁺ it is clear that the upper energy level for N₂⁺ is relatively much more densely populated than the upper levels of N₂. Despite this, the observed bands exhibit similar intensity, which we attribute mainly to the larger number of non-ionized N₂ molecules in the discharge.

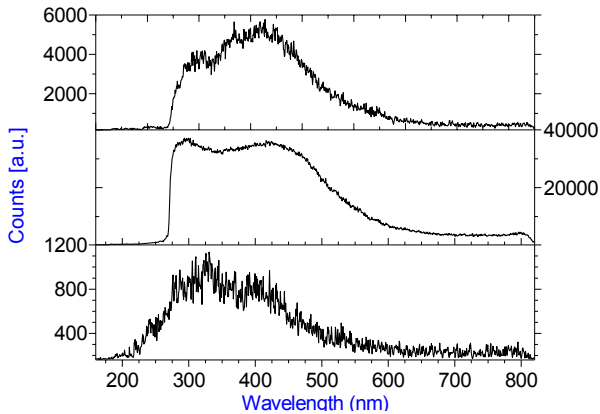


Figure 4. Spectra of Liquid N₂ during self-breakdown. Top is in the channel near the plane. Middle is electrode tip. Bottom is the needle shaft (see Fig 1).

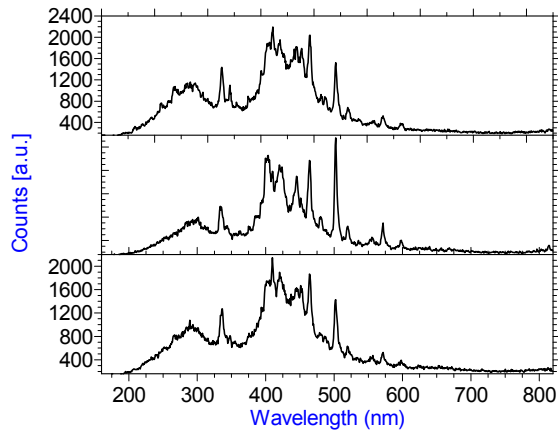


Figure 5. Spectra of atmospheric N₂ for DC self-breakdown. Top and bottom are electrode tips. Middle is center of channel. Gap = 1 cm. Hemispherical electrodes.

Of the several broadening mechanisms that could cause the observed broadband character of the LN₂ spectrum, we consider Stark broadening as most dominant, mainly due to the high degree of ionization and thus the high electron density in the discharge. We exclude pressure broadening due to collisions with nitrogen molecules in the liquid, as radiation from the liquid is not expected in any significant amount. Other broadening mechanisms such as Doppler and natural linewidth are estimated to be minor as well.

Besides being much more intense, the spectral shape of the spectrum taken at the tip is different from the one at the plane, indicating a different population of the energy levels and thus a variation of the electronic temperature. The third fiber, which was not directly aimed at the breakdown volume but rather 5 mm away from the needle tip, exhibits a somewhat different spectrum, which distinctly extends beyond the bandhead at 275 nm. It indicates the formation of a diffuse plasma that is located outside of the gap. Hence, the radiating volume linked to this spectrum must be subject to a different plasma background, favoring the population of additional energy levels followed by radiation from, for instance, the second positive group of N₂ (bandhead at 337 nm, shaded into the violet).

B. Pre-breakdown Current and PMT

Fast current and optical diagnostics allow measurement of current and luminosity from pre-breakdown events. There could be many pulses prior to the final breakdown that occur several hundred nanoseconds prior to the final breakdown event. Pulses usually increase in magnitude as they approach final breakdown. Figure 6 represents a typical test with several pre-breakdown events occurring prior to the formation of the conducting channel during final breakdown. Full breakdown in liquid nitrogen is very fast, reaching 50% of the final impedance limited current in approximately 2 ns. A comparison between liquid nitrogen and bio-degradable, transformer oil indicates that

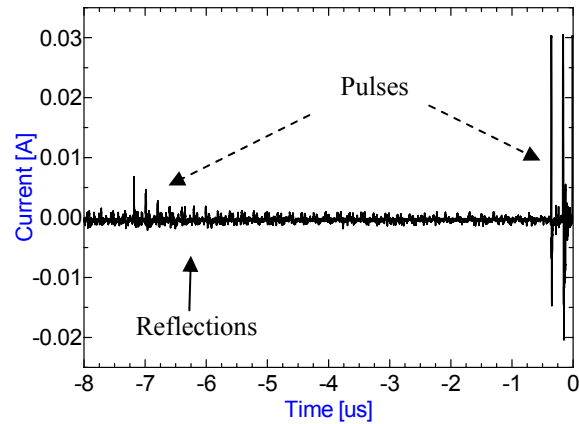


Figure 6. Graph of pre-breakdown current pulses in liquid nitrogen (point-plane geometry). Negative tip. Positive plane.

LN₂ is a faster medium. Liquid nitrogen risetime is approximately 5 ns and transformer oil has a risetime of about 20 ns. [9]

Since there are two PMT's that measure the discharges at different spatial locations it is possible to estimate the overall speed of the excitation wavefront as it passes through the liquid and determine the origin of the event. Light emission is first observed at the negative tip and then propagates rapidly across the gap. Figure 7 and 8 are two examples of current and light emission from pre-breakdown events. Variations in the discharge path can allow the light to pass near the edge of the lens allowing less light to be collected at the PMT.

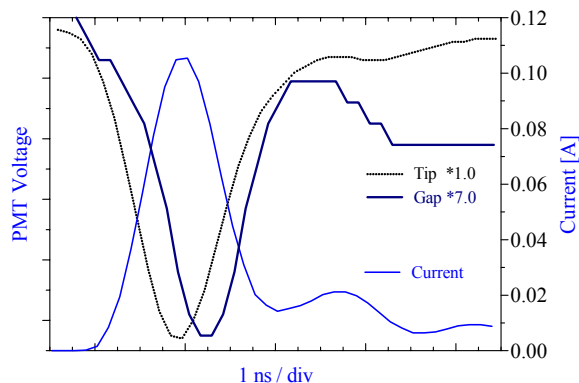


Figure 7. Graph of pre-breakdown current pulse and PMT pulses 460 ns before final breakdown. Pulses normalized to negative PMT. Negative tip. Positive plane.

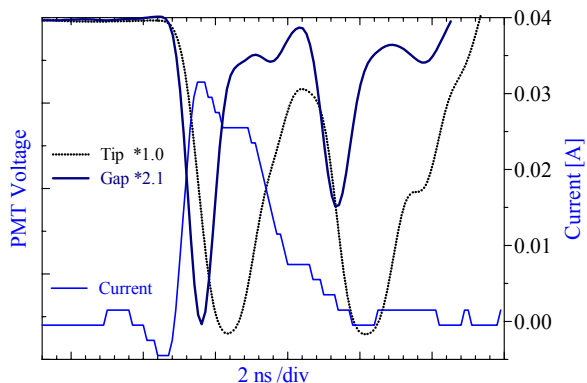


Figure 8. Graph of pre-breakdown current pulse and PMT pulses 200 ns before final breakdown. Pulses normalized to positive PMT. Positive tip. Negative plane.

IV. SUMMARY

Results presented in this paper describe the formation of pre-breakdown pulses in liquid nitrogen. The use of fast optical and electrical diagnostics demonstrates the presence of pre-breakdown phenomena. Light emission measured in the gap, near the plane, is significantly lower than light output at the tip. The nanosecond current pulses and localized light emission was measured up to

several hundred nanoseconds prior to final breakdown. The formation of bubbles by field emitted electron injection into the liquid causes localized heating and vaporization of LN₂. The gas discharges within the bubble most likely cause the pulses to form. Electron multiplication and light emission can occur within the gas phase of the bubble which has a locally lower density compared to the surrounding liquid.

Spectroscopic data has the same general structure as the data collected for N₂ gas at atmospheric pressure; however, the lines are broadened so that it is difficult to identify individual peaks. The presumed broadening mechanism is Stark broadening, due to the high degree of ionization and thus the high electron density in the discharge. Other mechanisms such as Doppler and pressure broadening are assumed to be less significant. Differences between spectra at the tip and the plane can be explained by difference in population densities of the various energy levels corresponding to different electronic temperatures.

V. ACKNOWLEDGEMENTS

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VI. REFERENCES

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