BREAKDOWN PHENOMENA IN ULTRA-FAST PLASMA CLOSING SWITCHES

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Abstract

An experimental investigation into the rate of voltage collapse in plasma closing switches has been undertaken. A transmission line test switch, using a radial/conical topology to minimise wave reflections, has been used for this investigation. The results described in this paper were obtained from experiments using hydrogen. The results show that there is a distinct difference in behaviour between low pressure (< ~5 bar) and high pressure (> 5 bar) breakdown. Comparatively high values of dV/dt were obtained at both low and high pressures, whereas a low dV/dt was observed at intermediate values of pressure.

I. INTRODUCTION

There is a significant amount of literature, published over many years, devoted to the experimental and theoretical descriptions of electrical breakdown of gaseous dielectrics, and associated phenomena, including plasma closing switches. The bulk of this literature relates to electrical breakdown in the tens of nanoseconds to microseconds range [1]. More recently, interest has arisen in breakdown in the nanosecond and sub-nanosecond regimes. This interest has been generated by the demands of commercial and military applications (pulsed laser drivers, high power microwaves etc.), and by the availability of diagnostics and measuring devices able to record information on these timescales. The conventional approach to fast breakdown is based on the work of R C Fletcher [2]. His concept for fast breakdown was to use transmission line technology, with the gas switch as an inline component of the transmission line system. His findings were that fast breakdown could be achieved with a short gap spacing and a step-like charging pulse. This concept has been developed to produce ultrafast voltage collapse times of under 100 ps, using short gaps and a highly pressurised gas (usually hydrogen) [3]. Other experimental work [4,5] has shown that it is possible to obtain comparable voltage collapse times at near atmospheric pressure.

The experimental work described in this paper investigates the influence of gas pressure on switch closure. Earlier work [4] has reported that when a plasma channel closes, a radial electromagnetic wave is generated and propagates outwards from the plasma channel axis. In a conventional high-pressure switch, this radial wave soon reflects off the switch walls. Depending on the location of the diagnostics, measurements of the output waveform normally include the superimposed effects of multiple reflections. In order to avoid this problem, the switch topology for the current work has been designed to allow for the transmission of this radial wave. Consequently, the breakdown results obtained during this study are clear of radial wave reflections for at least 1.5 ns.

II. APPARATUS

A. Test switch

The test switch has a radial/conical transmission line topology and is developed from a conical transmission line switch that was used in previous experiments [4]. The earlier switch was restricted to operating at pressures below 6 bar (absolute). To enable operation at pressures of up to 50 bar, the switch design was modified. This was achieved by reducing the diameter of the gas cell to 20 mm. The gas cell was cut in the centre of a profiled nylon cylinder, as shown in Figure 1. The inner portion of the cylinder has a parallel symmetry and forms a radial transmission line. At a radial distance of 43 mm from the centre of the cylinder, the profile changes to that of a conical form. The conical transmission line has a constant impedance of 11.6 Ω. The switch has been designed so that the impedance of the radial line matches the conical

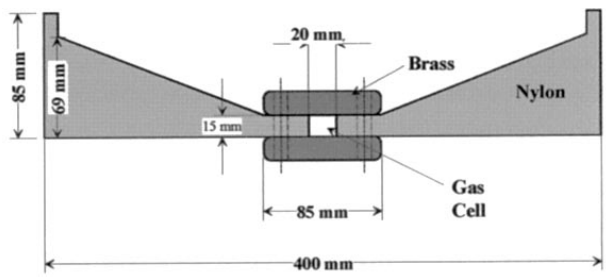

Figure 1: Sketch of test switch.

line at the radial line/conical line interface. This ensures that there are no reflections at this interface. There will, of course, be reflections at the inner gas-cell/nylon interface. However, computer simulations have shown that by

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14. ABSTRACT
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restricting the radius of the gas cell to 10 mm, there is no net, discernible, effect on a signal measured outwith this boundary.

The upper and lower surfaces of the profiled nylon cylinder have been covered with 0.08 mm thick copper foil. The foil thickness is greater than the skin depth of copper for frequencies greater than 673 kHz. The frequencies comprising the voltage collapse pulse are in the megahertz range. Flat brass plates of 16 mm thickness and 85 mm diameter are mounted above and below the gas cell. A high voltage pulse is applied to the upper plate, and gas is fed through the lower plate. Brass, hemispherical electrodes are mounted on these plates and fitting electrodes having a different thickness varies the gap spacing. The brass plates are clamped to the switch surface by specially constructed nylon bolts, which incorporate an 'o' ring and a collar to reduce the possibility of flashover occurring along the bolt thread. To reduce flashover at the outer edge of the switch, the upper conducting surface is terminated with a circular copper ring. This ring is embedded in a raised nylon wall, which forms the outer edge of the profiled nylon cylinder.

B. Pulser

The test switch is pulse charged from an inverting, single stage pulser, as shown in Figure 2. The energy store is a 25 m length of RG 218 coaxial cable, having a capacitance of 2.5 nF. The cable is discharged via a primary switch that is triggered pneumatically. Copper sulphate wavefront and wavetail resistors shape the

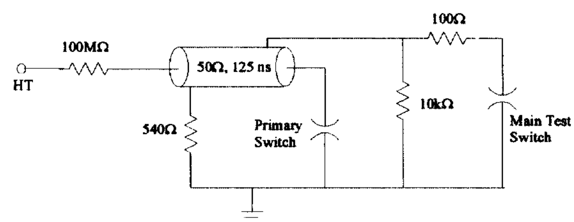

Figure 2: Circuit diagram of pulser

output pulse. This pulse has a 'loaded' 10%-90% risetime of 55 ns and there is a flat-top duration of 160 ns before a pulse reflection returns from the far end of the RG 218 cable. A 540 Ω resistor has been fitted to compensate for the effect of stray transmission line effects in the experimental enclosure.

C. Diagnostics

D-dot monitors, mounted on the base of the test switch, record the voltage collapse, which occurs as a result of breakdown in the gas cell. These monitors are situated 57 mm out from the central switch axis, and so measure the voltage pulse in the conical, constant impedance, section of the switch. These monitors are constructed using modified N-type panel adapters. They are attached to the nylon base prior to the copper foil being fitted. The signals measured by these monitors are recorded on Tektronix SCD5000 (bandwidth > 2 GHz) and TDS220 (bandwidth = 100 MHz) oscilloscopes. These instruments are, in turn, connected to a PC, where the data is stored for processing.

III. RESULTS AND DISCUSSION

A. Waveforms

D-dot monitors record a signal proportional to the rate of change of voltage (strictly, the rate of change of the normal component of the electric displacement, **D**). As well as recording the rate of voltage collapse at breakdown, the monitors also record the rate of rise of the charging pulse. Because this produces a prepulse effect, a procedure of baseline correction is required. One method of eliminating this prepulse is to ensure that breakdown occurs on the flat-top of the charging pulse. However, it is not always possible to obtain sufficiently long time lags to breakdown. In these cases a software algorithm is employed to remove the prepulse effects. It is more straightforward to measure the experimental parameters directly from the recorded (differential) waveform, rather than from a processed, numerically integrated waveform.

A typical measured waveform (1 bar hydrogen, 0.7 mm gap, 9 kV breakdown voltage) is shown in Figure 3. This

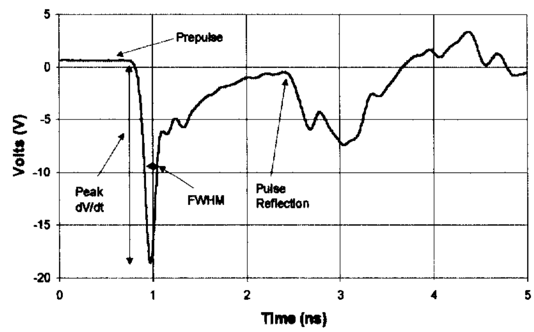

Figure 3: Typical recorded waveform

figure shows the presence of a prepulse prior to breakdown. It also shows wave reflections returning from the outer rim of the switch. The position of the D-dot monitor means that this reflection is recorded 1.76 ns after breakdown commences. It marks the limit of useful breakdown information. The parameters selected to characterise breakdown are the maximum amplitude of the pulse, which is the maximum rate of change of voltage (peak dV/dt), and the pulse width at half-maximum (FWHM). Peak dV/dt is a measure of the rate of voltage collapse and FWHM is a measure of the duration of the voltage collapse.

One D-dot monitor was used to measure the rapid voltage collapse. This signal was recorded on a SCD5000 digitiser. A second D-dot monitor was used to measure the slower prepulse. This monitor was connected to a TDS220 oscilloscope. When numerically integrated this prepulse signal formed the charging voltage pulse and thus provided the breakdown voltage.

B. *Variation of Breakdown Parameters with Pressure*

The trends that occurred as the pressure was varied are illustrated with a sequence of measurements, taken in hydrogen, when the gap spacing was 0.7 mm. For these conditions, breakdown occurred on the rising edge of the charging pulse. This also allowed an investigation of the effect of the rate of rise of the charging pulse. Altering the charging voltage on the pulser varied the effective rate of rise, since the normalised pulse risetime remained

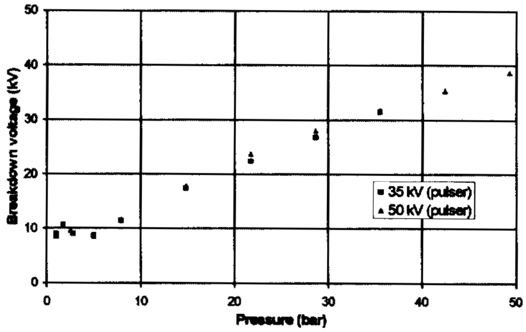

Figure 4: Breakdown voltage against pressure

constant. Figure 4 is a plot of breakdown voltage as a function of pressure. The data in this graph includes information from two sets of pulser charging voltages (35 kV and 50 kV). It can be seen that varying the rate of rise of the charging voltage is not a significant factor in determining the breakdown voltage under these conditions. This figure also shows that at low pressures (below 1.75 bar) the breakdown voltage increases with increasing pressure. At intermediate pressures (1.75–5 bar) the breakdown voltage decreases with increasing pressure. Above 5 bar, the breakdown voltage again

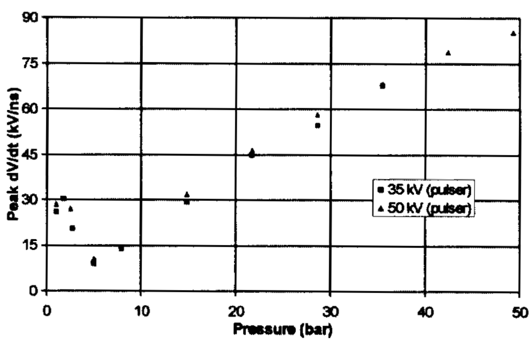

Figure 5: Variation of peak dV/dt with pressure

increases with increasing pressure.

Figure 5 is a plot of the variation of peak dV/dt with pressure, taken from the same data set as Figure 4. It can be seen that there is a trend similar to that in Figure 4. Below 1.75 bar, peak dV/dt increases with pressure. Between 1.75 bar and 5 bar, peak dV/dt decreases with increasing pressure. At high pressures, above 5 bar, peak dV/dt again increases with pressure. There is no significant effect on peak dV/dt due to the rate of rise of the charging voltage. The peak dV/dt data also shows a local maximum at 1.75 bar and a minimum at 5 bar. The relative changes are more pronounced in this figure than in the breakdown voltage graph. This is demonstrated more clearly in Table 1 and in Table 2.

Pressure (bar)	**Breakdown voltage (kV)**	**Peak dV/dt (kV/ns)**
1.75	10.7	30.3
5	8.75	9.07
35.5	31.5	67.8

Table 1: Measured data (35 kV charging voltage)

Pressure change (bar)	**% change in breakdown voltage**	**% change in dV/dt**
5 → 1.75	22.3	234
5 → 35.5	260	648

Table 2: Comparative changes in V and dV/dt

Table 1 shows data extracted from the breakdown measurements in hydrogen when the charging voltage was 35 kV. The data is the breakdown voltage and peak dV/dt measured at pressures of 1.75 bar, 5 bar, and 35.5 bar. Table 2 shows the relative change in breakdown voltage and peak dV/dt as the pressure is reduced from 5 bar to 1.75 bar and as the pressure is increased from 5 bar to 35.5 bar. This shows that peak dV/dt is much more sensitive to pressure change than the breakdown voltage for both low and high pressures. It can also be seen that whilst the relative change in peak dV/dt is an order of magnitude greater than the change in breakdown voltage at low pressure, it is only greater by a factor of 2.5 at high pressure. This further emphasises the difference between low pressure and high pressure behaviour.

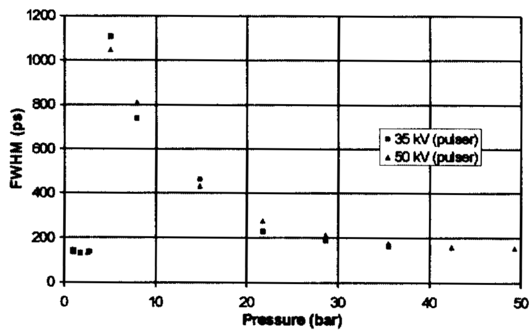

Figure 6: Variation of FWHM with pressure

Figure 6 shows the variation of FWHM with pressure, taken from the same data set as Figure 4. FWHM, as indicated in Figure 3, is the width of the dV/dt pulse at half-maximum value. This graph confirms the trends described earlier as it illustrates that the duration of the voltage collapse (FWHM) is short (< 200 ps) at low pressure. This duration lengthens sharply to greater than 1 ns at 5 bar, before shortening again as the pressure is further increased. Even though the results may be bandwidth limited at high pressure, the trend is clearly one in which the FWHM tends towards a limit.

C. Variation of Breakdown Parameters with Gap Spacing

To examine how the measured breakdown parameters vary with the gap spacing, results from larger gap spacings are combined with the previously shown data. Figure 7 is a plot of the mean breakdown field, *E*, against pressure. *E* is used instead of the breakdown voltage since

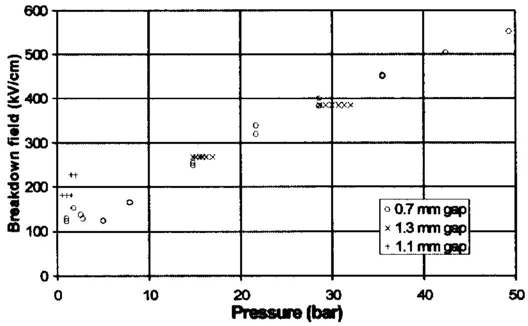

Figure 7: Breakdown field against pressure

the gap spacing is implicit in its definition. One of the additional data sets was taken from a series of experiments in low-pressure hydrogen when the gap spacing was 1.1 mm. The other additional set of data was taken in high-pressure hydrogen with a gap spacing of 1.3 mm. The same experimental apparatus was used for the acquisition of all three sets of data. However, it was

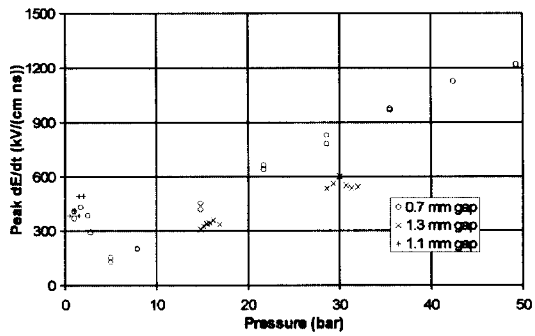

Figure 8: Variation of peak dE/dt with pressure

possible, for these additional gap spacings, to attain breakdown during the flat-top of the charging pulse. This was done for a discrete set of charging voltages, which explains the clustered nature of the data. It can be seen from this graph that at low pressure, increasing the gap spacing has increased the breakdown field for a given pressure. However, at high pressure, increasing the gap spacing has had little effect on the breakdown field.

Figure 8 is a plot of peak dE/dt against pressure for the same data sets that were shown in Figure 7. At low pressure, increasing the gap spacing has increased the peak dE/dt, but not by as much as the breakdown field increased. At high pressure, increasing the gap spacing has reduced the peak dE/dt, despite there being no change in the breakdown field. These findings are compatible with results from Fletcher [2] onwards, who found that faster voltage collapse was achieved with smaller gaps.

The behaviour of several other gases (nitrogen, SF_6, helium) is being examined currently. Preliminary results indicate a similar qualitative behaviour to that found with hydrogen.

IV. CONCLUSIONS

The experimental results have demonstrated a significant change in switching behaviour, in hydrogen, as the pressure is varied. There is a minimum in the breakdown voltage which, for the experimental conditions described in this paper, is at around 5 bar. At this pressure, the rate of voltage collapse is a minimum and the duration of the voltage collapse is a maximum. The profile of the breakdown voltage waveform is highly sensitive to the breakdown voltage, especially at low pressure. The rate of rise of the charging pulse does not appear to be a significant factor in these experiments.

The effect of changing the gap spacing was also investigated. These results show that, at high pressures, the breakdown field is dependant on pressure but not the gap spacing. However, increasing the gap spacing reduces the rate of voltage (electric field) collapse.

The results suggest that, at low pressures, breakdown is governed by *E/p*, whereas, at high pressures, a hydrodynamic, pressure dependant mechanism may be important.

V. ACKNOWLEDGEMENT

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VI. REFERENCES

[1] A R Dick and S J MacGregor, "Review of Published Literature", Sandia National Laboratories, Albuquerque, USA (UOS/PPG/SAN/9701), 1997

[2] R C Fletcher, "Impulse Breakdown in the 10^{-9}-Sec. Range of Air at Atmospheric Pressure", *Phys Rev.*, 76, pp 1501-1511, 1949

[3] C A Frost et al, "Ultrafast Gas Switching Experiments", *Proc. 9th IEEE Intl. Pulsed Power Conf.*, pp 491-494, 1993

[4] A R Dick et al, "An Investigation into High Speed Gas Breakdown", *Proc. 23rd Intl. Power Modulator Symp.*, pp 202-205, 1998

[5] W R Cravey, P Poulson and P A Pincosy, "A Picosecond High Pressure Gas Switch", *Proc. 23rd Intl. Power Modulator Symp.*, pp 387-390, 1992