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ELECTRON BEAM SWITCHING EXPERIMENTS IN THE HIGH CURRENT GAIN REGIME

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INTRODUCTION

High energy switch technology for fast switching times has been dominated by spark gap type switches. There is however a need for switches which can handle high energies on a repetitive, long term basis and, even more important, can also switch off large energies. One of the more promising candidates for such applications is a gas discharge ionized by an external electron beam which can rapidly and repetitively be switched on and off. Selecting the proper operating conditions, the externally ionized gas volume then can be used as the on/off switch element. Initial experimental studies utilized equipment inherited from electrical discharge laser experiments, in particular, the electron guns used were of the high to very-high current density cold-cathode type[1,2]. This resulted in very fast switch rise times and the ability to work with gases containing sizeable amounts of attaching species, which in turn produced rapid switch-off times. On the other hand, the energy invested in the E-beam was almost of the same order or even the same magnitude as the energy to be switched. Since with these cold-cathode type E-beams the full E-beam voltage has to be switched, usually with spark gaps, the net gain in switched energy was quite small or nonexistent. If the E-beam current density is lowered, the ratio of discharge current to E-beam current can become much larger, as was already recognized by Koval'chuk et.al.[1]. Recently a quantitative assessment of this operating regime, using experimentally and theoretically derived values for the relevant gas characteristics such as breakdown voltage and electron transport data has been made[3]. Desired operating parameters included a current gain of up to 1000, discharge voltage of 1 to 2 kV, rise and fall times of a few microseconds, hold-off voltage to 100kV, repetition rates to hundreds of pulses/sec and a lifetime of 10^6 pulses or more. Using a small E-beam controlled closed-cycle flow discharge system, this operating regime has been investigated experimentally.

Experiment

The electron-beam gun used is a hot matrix cathode type[4] and can operate at pulse-repetition rates to 1000Hz at peak current densities to 5mA/cm^2 into the 5x15cm foil-aperture and at energies to 200keV. The transmission efficiency is less than 30%, pulse rise and fall times were approximately 1 μs. The discharge section had a grid structure, collinear to the foil support structure as anode and an insulated cathode with the spacing adjustable from 0 to more than 3cm. The electrode insulation was machinable glass-ceramic, the chamber walls had a fused quartz lining. The discharge section is part of a stainless steel ultra-high vacuum flow loop, the gas flow being produced by an externally driven vane-axial fan. After prolonged baking, the system reached base pressures as low as 10^{-9} Torr. The switch circuit consisted of the high voltage power supply, a 1 μF storage capacitor and copper sulfate load resistors of various values. The pulse repetition rate was limited mainly by the thermal characteristics of the load resistors.

Results

Current-Voltage Characteristics. Considering the externally ionized discharge as a circuit element, its I-V-characteristics are of most interest during the conduction phase. It was found that these characteristics have some similarities to those of transistors, with the E-beam current density replacing the transistor base current as a parameter. In particular, 3 distinct regions can be observed. At low voltages the current generally rises slowly with voltage, according to the increase of the electron drift velocity with increasing E/N (electric field/neutral density) and decreasing recombination losses. When a certain threshold voltage is exceeded, the current suddenly switches to much higher values at lower voltages (fig. 1).

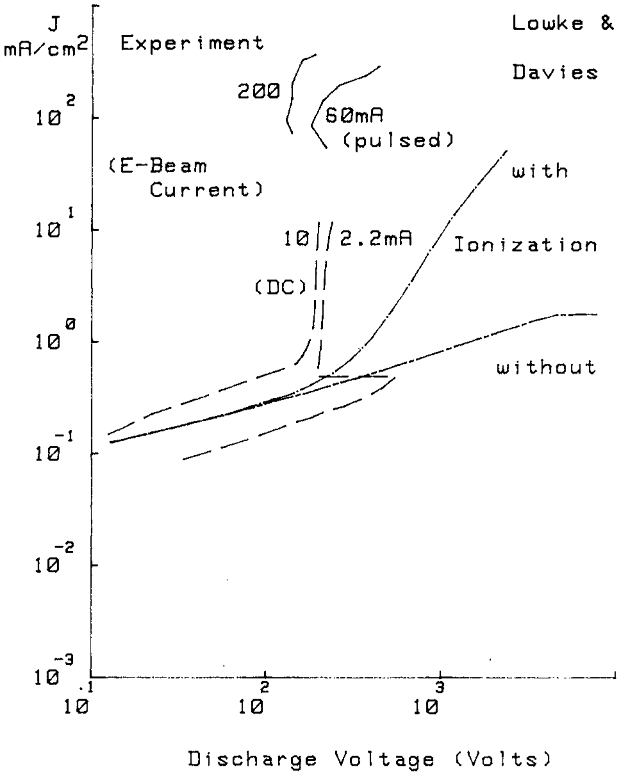

Figure 1. Experimental and theoretical I-V curves in Argon

This high conductance region is probably caused by the establishment of a cathode sheath which produces additional ionization, as has been calculated by Lowke and Davies[5] and has been observed also[6]. The calculations[5] result in a somewhat slower rise, probably since additional ionization sources (2-step and secondary ionization at the cathode) have been neglected. In Argon, in this region the voltage drop can be less than 200 volts across the switch gap, in Methane and Nitrogen the drop can be lower than 1 or 2 kV respectively. From the limited number of measurements it appears that the discharge voltage in this portion of the I-V characteristics is inversely proportional to the square root of the E-beam current. The voltage drop in this region is also an inverse function of pressure. At a certain discharge current, the I-V curve enters a much flatter, almost saturated region. It is this third region, where the discharge current is proportional to the square root of the E-beam current, a relation typical for externally ionized plasmas dominated

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by recombination losses. This also implies that the ratio of discharge current to E-beam current, or the current gain, is inversely proportional to $\sqrt{j_{E\text{-beam}}}$. For the measurements in Methane, the measured gain in this regime ranges from almost 1000 at 100mA E-beam current (after the foil) to over 3000 for a 6mA E-beam current. If attachment becomes more significant, then the discharge current becomes more a linear function of E-beam current (fig. 2),

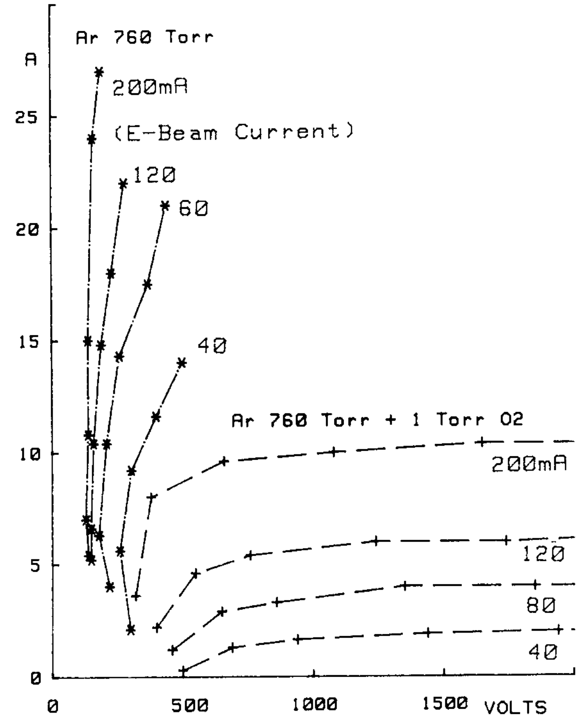

Figure 2. Experimental I-V curves in Argon with and without an attaching gas added

but of course, due to the increased losses, the magnitude of the discharge current is smaller. Methane, due to its very high drift velocity and high dielectric strength, is one of the more interesting gases for this application. Some improvement of its I-V characteristics, both in lowering the discharge voltage, increasing its conductivity and in extending the high conductivity region to larger currents by increasing the current gain, can be obtained by adding Argon (fig. 3). Unfortunately, the low breakdown

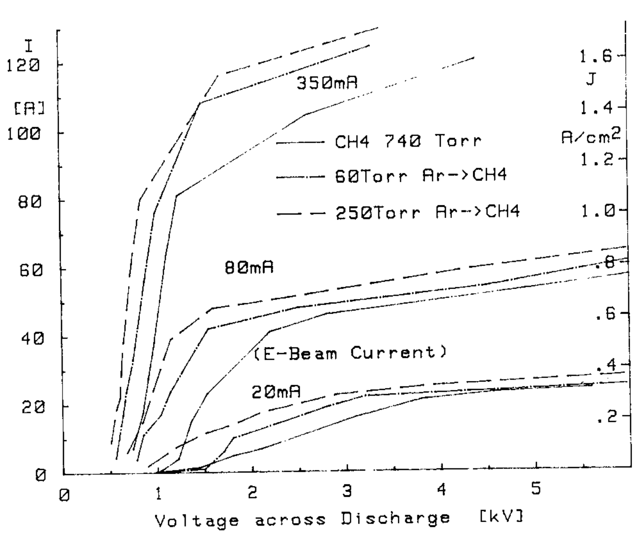

Figure 3. Experimental I-V curves in Methane and Methane mixtures. Due to foil losses, an E-beam current of 350mA before the foil results in 100mA into the discharge.

strength of Argon also will decrease the breakdown strength of Methane, at least at 250 Torr of added Argon. The saturation regime of Methane, as an example, can be modelled using available transport data, as shown in fig. 4. For these curves, the recombination data was increased by a factor of 10, as is also

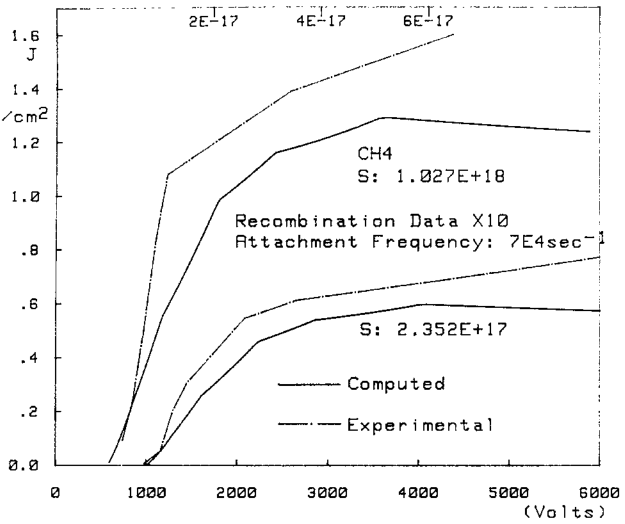

Figure 4. Experimental and theoretical I-V curves in Methane. The source terms (S) correspond to the experimental E-beam currents.

required to account for the measured decay times, to be discussed later. However, due to the neglect of boundary effects, agreement with experimental data in the technically important high conductance region as well as in the saturation region is only marginal. Another important quasi-static characteristic is obtained by measurements of the discharge voltage versus electrode distance. They indicate that a considerable portion of the voltage drop occurs at the cathode fall, corresponding to the intercept at zero distance. Also from these curves the voltage drop across a discharge of certain dimensions and operating parameters can be estimated.

Temporal Characteristics. Analytical relations for current rise and fall times for an E-beam ionized plasma have been derived by Douglas-Hamilton to obtain recombination rates at various, but constant E/N[7]. Even though for our case the electric field between off- and on-conditions varies over orders of magnitude, the basic trends indicated by his relations are still valid. These relations predict the following functional relationship between E-beam current density, recombination and attachment rates and current rise and fall times: An increase in E-beam current density will decrease rise time. Increase in attachment and recombination rates will both decrease rise and fall times. Fig. 5 shows the decrease of pulse rise-time with increasing E-beam current in a Nitrogen discharge, which has recombination losses only. The slow, recombination dominated decay is unaffected to first order by the E-beam current. Argon also has no attachment, a low recombination rate, and therefore a very slow decay (fig. 6). The effect of adding an attaching gas is shown in fig. 7 for 0.02 Torr of the very strong attacher SF_6. 1 Torr of Oxygen has about the same effect. As expected, both rise and fall of the

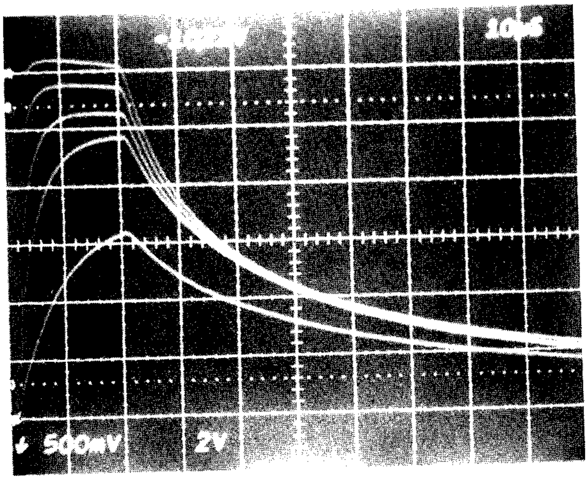

Figure 5
Measured switch current in atmospheric pressure Nitrogen (10 μs/div horizontal, 5 A/div vertical) E-beam currents 20, 50, 100, 200, 400 mA.

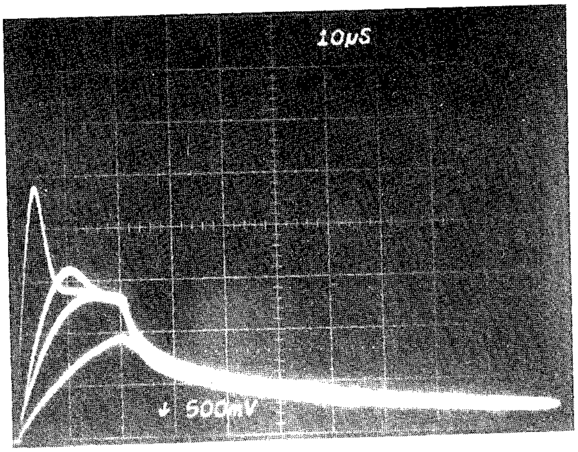

Figure 6. Measured Switch current in atmospheric pressure Argon. Same scale as Fig. 5. E-beam currents 20, 40, 80, 200 mA.

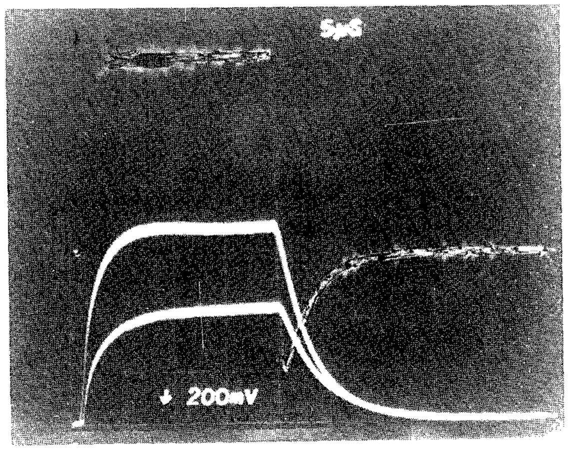

Figure 7. Measured switch current in atmospheric pressure Argon with 0.02 Torr of SF_6 added. (5 μs/div horizontal, 2A/div vertical) E-beam current 40, 80 mA.

current pulse are considerably shortened. The decrease of conductivity due to an added attaching gas has already been shown for Argon (Fig. 2). The measurements of the decay of current in Methane are compared in fig. 8 with decays computed using the transport data derived by L. Kline[3]. The best fit results from increasing the recombination rate data by a factor of 10 and also using a small, E/N independent attachment frequency of 7×10^4 sec^{-1}. For comparison, decay curves computed with the original recombination data, but increased attachment and with the increased recombination and no attachment are shown. As expected, recombination determines the initial current drop whereas the value of the attachment coefficient dominates the later portion. The details of the rise and decay wave shapes therefore reveal important information on the plasma loss processes. Presently it is not known whether the relatively large apparent recombination rates in Methane are due to the basic gas or some dissociation products. These higher rates however also result in a lower than expected current gain in methane.

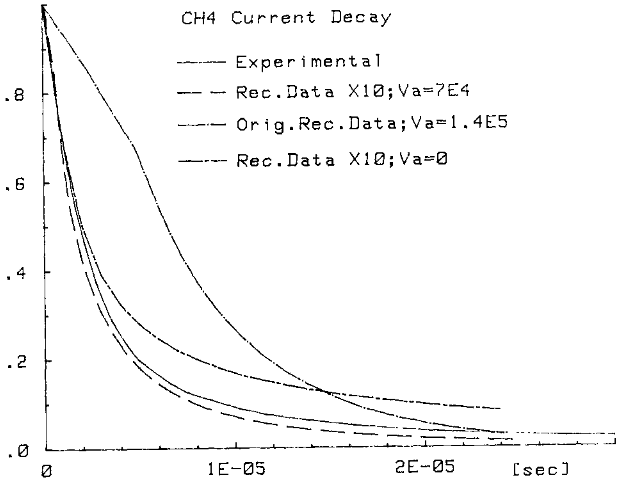

Figure 8. Comparison of experimental and theoretical current decay in atmospheric Pressure Methane.

Conclusion

For switch applications, the I-V curves can be used to estimate the current drop across the switch and maximum current density as a function of E-beam current density. The second region of the I-V curve has the highest conductivity and is therefore the preferred operating regime. Analogous to other nonlinear circuit elements, the switch operating point for a given load and operating voltage can be found by the crossing of the load line and the I-V curve. Since it combines low on-voltage with high die-electric strength, Methane is one of the more promising gases for this application and its conductivity and current gain can be improved further by the addition of Argon. Current gains of 1000 at voltage drops across the switch of less than 2kV and current densities of more than 1A/cm^2 have been measured. For higher current densities, the E-beam current density has to be increased, with an accompanying loss of current gain. The current fall time of Methane for 1A/cm^2 has been measured to be 10 μs (to 10% of the original value). If this decay time is too slow, attaching gases have to be added, reducing current gain and conductivity. However since under these conditions the discharge current is now a linear function of the E-beam current, at higher E-beam currents the negative effects of attachment become less significant. To be used as an off-switch, the discharge parameters have to be selected such that no plasma instabilities can occur. In particular postarcs and streamers, well known from electrical discharge lasers, have to be avoided. Thermal instabilities can be avoided by a closed-cycle cooled flow system, which also will be required for repetitive operation.

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