May 1987

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Influence of photodetachment on the switching characteristics of diffuse discharges containing oxygen

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(Received 5 January 1987; accepted for publication 10 March 1987)

Externally sustained discharges can be used as opening and closing switches in pulsed power systems. Admixtures of attachers allow rapid opening when the external sustaining source is terminated; however, they will increase losses in the closing phase. Photodetachment has been proposed as an additional control mechanism to overcome these losses. This letter presents measurements on photoionization sustained discharges in argon and nitrogen containing admixtures of oxygen under the influence of laser radiation. Strong changes of the voltage-current characteristics have been observed. The influence of parameters such as percentage of O_2, laser power, laser pulse width, and circuit impedance is presented. Additionally, it is shown that photodetachment can enhance the stability of diffuse discharges.

Externally sustained diffuse discharges can be used as opening and closing switches in pulsed power systems. To achieve short opening times with electron densities in the range $n_e \leqslant 10^{14}$ cm^{-3} electron attachers have to be used. Attachers with high attachment rates at high values of reduced field strength E/N and low attachment rates at low values of E/N will allow fast opening when the electron beam is turned off and low losses in the conduction phase.[1,2] Such attachers, however, increase the closing time and increase the loss during switch closure, especially if closure has to be performed in a high impedance system. This effect has been demonstrated in calculations[3] on discharges in N_2 containing N_2O and in experiments[4] on discharges in Ar containing C_2F_6.

It has been proposed that photodetachment can be used to overcome these losses during closure.[3,5] The influence of photodetachment will mainly influence the discharge characteristics in an intermediate E/N range. At low values of E/N, attachment will not dominate the discharge if the attacher used has the properties as mentioned above. At high values of E/N—above self-breakdown—ionization through the discharge electrons will dominate.[6] For applications as a repetitive closing and opening switch the discharge therefore has to be operated at low values of E/N not influenced by attachment in the conduction phase, and at intermediate values of E/N well below self-breakdown and subsequently dominated by attachment in the nonconducting phase, and the transitions between these two phases. The influence of photodetachment can subsequently be demonstrated by measuring the current density (J) versus reduced field strength (E/N) characteristics under the influence of photodetachment.

The experimental setup[7] used for our experiments is shown in Fig. 1. The major component is the discharge chamber with a transverse laser electrode configuration (variable gap distance, $d = 3.5$–10 mm, active electrode width $w = 20$ mm, electrode length $l = 200$ mm). The electrodes of this chamber are connected to a 125-Ω line which is charged to a voltage below self-breakdown of the discharge gap. A resistor in series is used to vary the system impedance. A spark array ultraviolet (UV) light source is located behind a screen in one of the main electrodes. This UV source can produce light pulses with 5 ns rise time and nearly constant emission over several 100 ns. When the UV source is fired, an externally sustained discharge will be initiated in the discharge chamber. Current and voltage probes in the main line allow the evaluation of the time dependence of current, voltage, and impedance of the discharge. Side windows at the discharge chamber allow the illumination of the discharge volume with a flashlamp pumped dye laser. This laser produces pulses of approximately 1000 ns length and nearly constant power of ~1 MW over the central 400 ns at 590 nm. With a Pockels cell chopper, short pulses of 50 ns

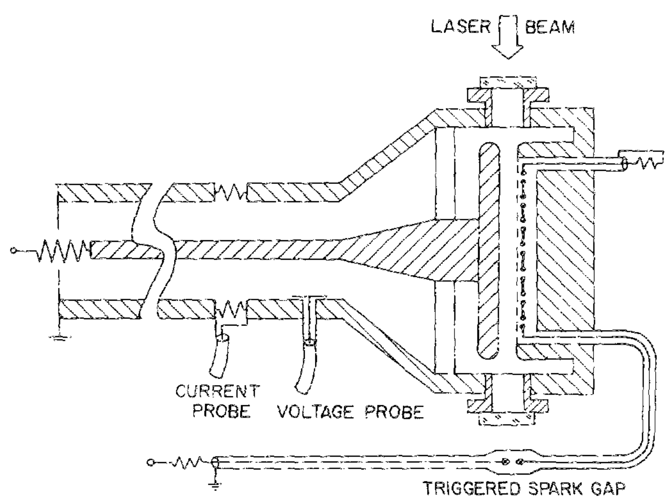

FIG. 1. Experimental setup for UV-sustained, photodetachment-controlled discharge.

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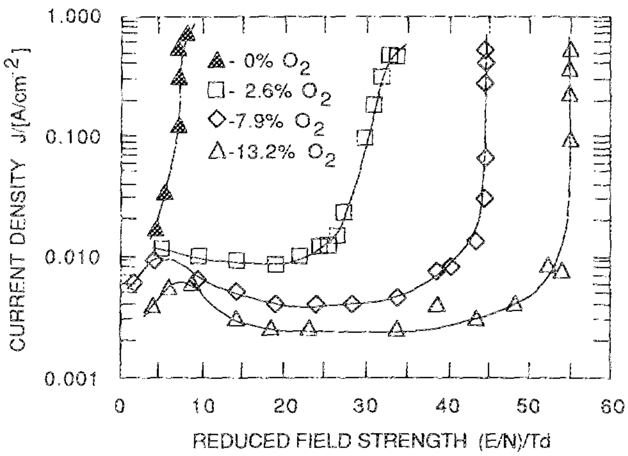

FIG. 2. J-E/N characteristics of UV-sustained and UV-initiated discharges for several concentrations of O_2 with 2.6% N_2, 350 ppm dimenthlaniline, and balance of Ar at 1 atm.

length and ~ 500 kW power can be obtained. The time-dependent measurements of current and voltage across the discharge, with and without laser, allow the evaluation of the influence of photodetachment on the J-E/N characteristics and on the transient behavior of the discharge.

Measurements were performed in mixtures of argon and nitrogen with an admixture of oxygen as the attacher. Attachers producing O^- as the dominant negative ion are good candidates for photodetachment experiments, since O^- has a relatively high photodetachment cross section[8] for photons of approximately 2 eV. The mixture of Ar and N_2 optimizes the ionization efficiency of the UV source. Nitrogen increases the UV yield of the spark sources[9] while the admixture of Ar increases the penetration depth of the ionizing radiation. The ionization efficiency was further enhanced by using N,N dimethylaniline as an additive with a low ionization potential.[10]

The first set of experiments was performed to evaluate the influence of attachment on the steady-state J-E/N characteristic of the discharge. For these experiments the system

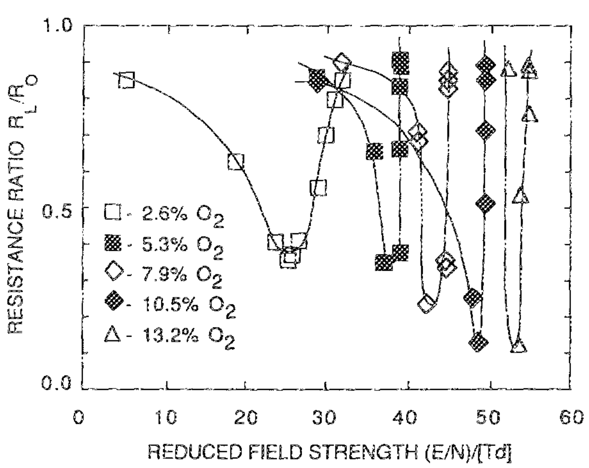

FIG. 3. Influence of the laser on the discharge resistance R_L/R_0, where R_L is the resistance with laser illumination and R_0 is the resistance without laser illumination vs E/N for 125-Ω system impedance. Gas mixtures contained various concentrations of O_2, 2.6% N_2, 350 ppm dimethylaniline, and balance of Ar at 1 atm.

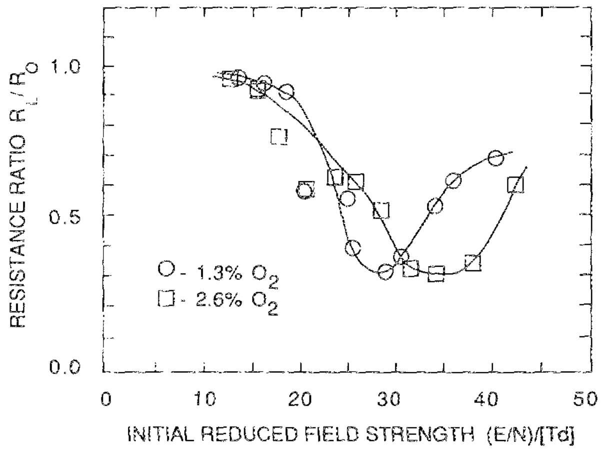

FIG. 4. Influence of the laser on the discharge resistances R_L/R_0, where R_L is the discharge resistance with laser illumination and R_0 is the discharge resistance without laser illumination vs initial E/N for 13-kΩ system impedance. Gas mixture contained varying concentrations of O_2, 2.6% N_2, 350 ppm dimethylaniline, and balance of Ar at 1 atm.

impedance was kept small compared to the impedance of the discharge (with nearly constant discharge voltage). One set of data was taken without the laser. Figure 2 shows the J-E/N characteristics for gases with varying concentrations of O_2. The mixtures used with higher O_2 concentrations generated regions of negative differential conductivity in intermediate E/N ranges of the characteristics. This effect is the consequence of an attachment coefficient that strongly increases with E/N. At high values of E/N the currents increased drastically. In this E/N range internal ionization through discharge electrons becomes significant and, therefore, represents the transition to self-sustained discharges.

Figure 3 shows the influence of photodetachment for varying concentrations of O_2 in a low impedance circuit (constant E/N). For these experiments, the UV source was triggered at the peak power of the 1000 ns laser pulse. The laser power density in the discharge chamber was 8×10^5 W/cm^2. Discharges that did not contain oxygen showed no change in resistance when illuminated by the laser. No influence of the laser on the discharge characteristics was observed in the low E/N range where no dissociative attachment occurs. The influence of the laser starts in the range where the current density reaches a minimum. In this E/N range attachment is strong and the density of negative ions is

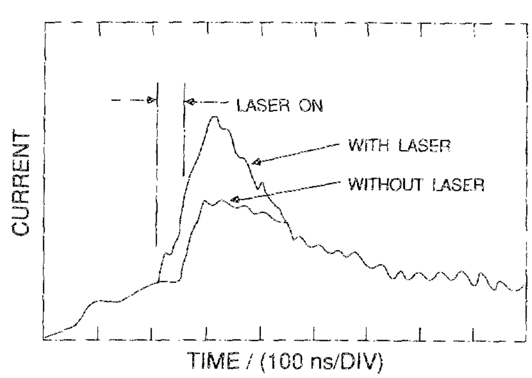

FIG. 5. Current vs time with and without short laser pulse for a gas composition of 13.2% O_2, 2.6% N_2, 84.2% Ar, and 350 ppm dimethylaniline at 1 atm, initial E/N = 50.2 Td, and a laser power density $\simeq 400$ kW/cm^2.

high. The strongest changes were observed in the transition regime to the self-sustained discharges. Increased electron density, due to internal ionization, along with the higher E/N caused a high density of negative ions. Also, the higher oxygen concentrations produced a more pronounced change in resistance, as a result of the higher negative ion densities.

The dependence of the resistance change on the laser intensity was also measured and was found to be linear up to the maximum intensity of our laser, 8×10^5 W/cm^2. This result indicated that only a fraction of the negative ions were being photodetached, and, that with higher laser powers, stronger resistance changes could have been attained.[5]

Further experiments involved determining the effect of photodetachment in a high impedance circuit. A 13-kΩ resistor was placed in series with the transmission line of the diffuse discharge circuit. In such a circuit the increase of current is associated with a decrease of E/N and, consequently, a reduction of the attachment rate. The effect of the laser is therefore expected to be smaller. The laser was operated again in the long pulse mode, and the UV source was triggered at the time of peak laser power. The results are shown in Fig. 4. The abscissa shows the value of E/N just before triggering of the UV source (i.e., the initial E/N). As in the low impedance measurements, the strongest changes in resistances occurred in the transition regime from externally to self-sustained discharges.

Schaefer *et al.*[3] have demonstrated through simulations that short laser pulses occurring soon after discharge initiation can strongly alter the J-E/N characteristics of the discharge for the remainder of the discharge pulse. Figure 5 shows similar results in our experiment in which the laser pulse was only on for ~ 50 ns soon after discharge initiation. Current density changes caused by short laser pulses occurring later in the discharge were smaller and more closely followed the laser in time.

As a final demonstration of the influence of photodetachment, laser enhanced stability experiments were performed in the 125-Ω system in a mixture of Ar with 5.3% O_2 and 350 ppm dimethylaniline at 1 atm. Sudden voltage collapse and current changes in the discharges indicated formation of arcs. As in the previous experiments, the laser was used with a peak intensity of approximately 8×10^5 W/cm^2. In five out of five cases where the discharges were not illuminated by the dye laser, arc development occurred anywhere from 350 ns to 1 μs after discharge initiation as previously demonstrated by Norris and Smith.[11] However, for five out of five cases where the discharges were illuminated, no arcs were observed. By increasing the electron density[12] and lowering the effective attachment rate, photodetachment enhances discharge stability.

The experiments presented demonstrate that externally sustained discharges in mixtures of Ar and N_2 containing admixtures of O_2 exhibit a negative differential conductivity in an intermediate E/N range. This effect is believed to be the consequence of the attachment coefficient for the dissociative process ($e + O_2 \rightarrow O^- + O$), increasing strongly with E/N. Photodetachment with a visible laser can be used to significantly change the discharge characteristics. Resistance changes at moderate laser powers (800 kW/cm^2) were strongest (factor of 8) in the E/N range where the ratio of the negative ion density to the electron density is highest. This E/N range corresponds to the regime just below the transition from externally sustained to self-sustained, which is the E/N range close to the initial E/N values that would be used for a diffuse discharge switch in a high impedance system. Short laser pulses during discharge initiation are sufficient to change the behavior of the entire discharge pulse.

From these experiments, we believe that discharges can be operated as opening switches with low loss in high impedance, burst mode systems, if photodetachment is utilized during discharge initiation. For both switches and lasers, photodetachment can be used as a mechanism to improve the stability of diffuse discharges.

The authors would like to thank R. A. Korzekwa for his assistance in the preparation of this letter. This work was jointly supported by the Air Force Office of Scientific Research and the Army Research Office under contract AFOSR 84-0032 and by the National Science Foundation under grant No. ECS-8318122.

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