COMPUTER CALCULATIONS OF THE TIME DEPENDENT BEHAVIOR OF DIFFUSE DISCHARGE SWITCHES

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Abstract

A computer code has been developed to describe the time dependent behavior of externally controlled diffuse discharges useful in various switching applications. The code is based on a set of rate equations which describe the densities of the dominant discharge species including the electron density and is used to calculate the discharge resistivity coupled to a circuit equation for the total discharge circuit. Previously Monte Carlo calculations for the electron energy distribution function were calculated parametrically with (E/N) to allow the calculation of the (E/N) - dependence of the different rate constants, starting from a initial set of cross sections. The present code has been applied to two opening switch models first an electron beam controlled device and secondly to an optically controlled one. Using these models, the influence of various attachers, each with their own (E/N) -dependence of the attachment rate constant, on turn-on and turn-off can be investigated and their consequences for each switch case drawn.

Introduction

Energy storage using inductive elements is attractive in pulsed power applications because of its intrinsic high energy density. However, the effective use of inductive storage requires a rapidly opening switch.[1] External control techniques of diffuse discharges seem to offer the best opportunity for the realization of fast, rep-rated opening switches.[2,3] Diffuse discharges are advantageous for switching because of their low inductance, small electrode erosion and heating rates, and moderate energy density which allows external control by means of e-beam and/or lasers of reasonable power. The practical knowledge of diffuse discharges has been drastically improved through the development of gas lasers. However, the operating conditions which the discharge has to fulfill, are different for switching applications. Other discharge properties and mechanisms of impact in the discharge have to be considered and their collective influence on the coupling between discharge and circuit optimized.

The final switch operation is determined by the control mechanism selected, by the gas mixture, and finally the external parameters of the circuit. Generally, admixtures of attachers are used to achieve fast opening of the switch. To achieve both low forward voltage drop and fast opening, the selected mixture should satisfy the following properties:[2,3]

a) at low values of E/N, i.e., during the condition phase, the gas mixture should have a high drift velocity and a low attachment rate.

b) at high values of E/N, i.e., during the open phase the gas mixture should have a low drift velocity and a high attachment rate.

With these gas properties and an adequate circuit it seems obvious that low loss operation is possible as well in the conduction phase (low values of E/N) as in the open phase (current density low or zero). However, any switch process will proceed through a lossy state, and these transitions are of major importance for any proposed switch performance.

To evaluate the time dependent impedance of an externally controlled discharge in a given circuit and to optimize the properties of the gas mixture and the circuit parameters a computer code was developed. To allow for fast calculation different parameters, the code uses two independent programs. In a first step all rate constrants of the significant processes are calculated as a function of E/N for a representative gas mixture. These calculations use the E/N-dependent electron energy distribution functions that have been previously calculated using a separate Monte Carlo code. In a second step a system of circuit equations and rate equations using the E/N dependent rate constants are solved. It is assumed that the E/N-dependence of the rate constants does not change significantly for small variations of the gas mixture. Additionally the electron energy relaxation is considered to be faster than any significant change in E/N, allowing for time dependent solutions.

It should be pointed out, that the set of processes considered in the Monte Carlo calculations and in the rate equation program are different. In the rate equation system only those processes are considered that, according to switching applications, contribute to the electron density balance. As the gas discharge is considered to stay relatively cold within the pulse, any thermal excitation or ionization, or more generally, any V,R,T TE collisions (transfer of energy from vibrational, rotational, translational energy to electronic excitation) is neglected and transitions into rotational and vibrational states are considered only as loss mechanisms. In the Monte Carlo code however, a set of cross sections, as complete as possible, is used. Such cross section sets unfortunately are only available for a few gases or gas mixtures.

The code is not spatially resolved. It does allow one to evaluate the influence of general gas properties and the circuit on the discharge. To also investigate the stability of certain discharges the code should allow a pertubation in one coordinate. Although such a change of the code is a minor problem, the computation time would increase unacceptively.

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14. ABSTRACT

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Results

The calculations presented here were performed for an e-beam sustained discharge in N_2 with admixtures of N_2O as attacher. N_2O in N_2 buffer gas exhibits an E/N-dependent electron decay rate as previously described as desirable gas requirements. The rate increasing by more than a factor of 20 in the E/N-range from 3 Ts to 15 Ts.[2,4] It should be noted however, that N_2 has an electron mobility increasing with E/N and therefore is not an optimum candidate for a buffer gas in diffuse discharge switches. N_2 was used because a complete set of cross sections for the Monte Carlo code was available.[5] Furthermore the plasma chemistry in a mixture of N_2 and N_2O appears to be simple. The transition set used in the rate equations is shown in Fig. 1.

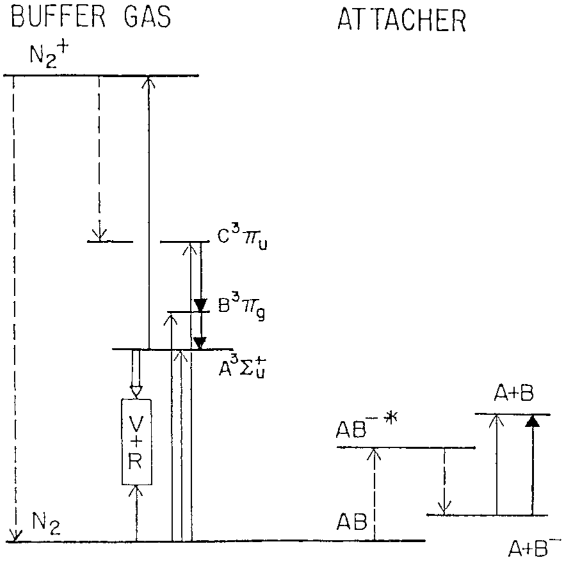

Figure 1. Transitions used in the system of rate equations.

The circuit used for the sample calculations is shown in Fig. 2. In the calculation the system was matched in the conduction phase a $R_D << Z$, $R_E = Z$, to fit our experimental arrangement. To adequately describe the switch characteristic only the value of $(Z + R_E)$ is important and therefore is given as the parameter of interest in each subsequent graph. The following parameters were kept constant at the value indicated $A = 100\ cm^2$, $d = 1\ cm$, $p(N_2) = 1\ atm$, $V_0 = 50\ kV$, e-beam electron generation rate $R_e = 8 \cdot 10^{21}\ cm^{-3}\ s^{-1}$ for $0 \le t \le 100\ ns$.

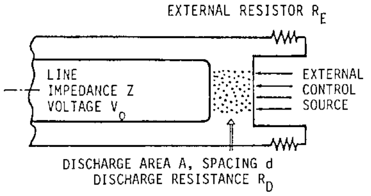

Figure 2. Setup with circuit parameters.

In the first set of calculations the line impedance was kept constant at $Z + R_E = 20\ \Omega$ and the concentration of N_2O was the variable parameter. Figure 3 shows from top to bottom the time dependence of E/N, current density J and loss power per unit volume. Three curves for 0.1, 0.5, and 0.75% of N_2O approach the same steady state value for E/N and J in the conducting phase, demonstrating that in this state the discharge is not strongly influenced by attachment. This also indicates that after turn off of the e-beam the discharge properties change very slowly until an E/N-value where attachment becomes effective is approached. However, in contrast for 1% N_2O the attachment is strong enough to prevent the discharge ever reaching a low E/N-state and the steady state is therefore attachment dominated. Thus when the e-beam is turned off, the values for E/N and J change immediately.

The loss power curves (Fig. 3, bottom) show, that if the discharge has a low E/N-steady state, strong losses only occur in the transition region. The half width of the first loss peak (closing phase) increases as one increases the attachment concentration, while the half width of the second loss peak decreases. The values in Table 1 show the energy input per volume for one switching cycle or for 300 ns if the discharge is still on at that time.

In Fig. 4 the admixture percentage of N_2O is kept constant (1.0%) and the total impedance of the system $(Z + R_E)$ is the parameter varied. For a value of 40 Ω for the total impedance, the discharge reaches the low E/N region where attachment is not dominant. In this state the system impedance alone and not the discharge limits the current. For lower impedances the discharge does not approach low E/N values and therefore remains attachment dominated during the closed phase. The loss curves also makes evident that only for the high system impedance can the losses be kept small. Unfortunately in this latter case the current amplification (discharge current density/e-beam current density) has its smallest value. Thus a compromise has to be struck between these two desirable features (low losses and high current amplification).

As is easily seen, both the impedance $(Z + R_E)$ and the N_2O-concentration can determine whether or not the discharge reaches the low E/N-region below 3 Ts where attachment is not effective, i.e., where the switch operates in the conduction phase at low losses. On the other hand the opening phase ($t \ge 100\ ns$) is controlled principally by the attacher concentration. The consequences of the specific E/N dependence of the attachment rate can be recognized, playing a role if the E/N value is still high when the e-beam is turned off, or becoming observable after some delay if E/N is below 3 Ts.

There are however other options for using additional control mechanisms to improve the performance of diffuse discharges for switching applications. A significant improvement could be achieved by operating at high attacher concentrations to achieve fast opening time and, or low system impedances to achieve high current amplifications while still operating in the low E/N-region in the conduction phase to achieve low losses. As seen in Fig. 3, (curves for 0.1% to 0.75% N_2O) the conducting phase is not strongly influenced by the attacher concentration. An increasing attacher concentration however inhibits or can even prohibit achievement of low values of E/N. One possibility to speed up or to enforce this transition would be to use an e-beam current density with an additional peak at the beginning of the controlling pulse, i.e., tailor the shape of the external control level.

Another possibility would be to use laser induced photodetachment to compensate for attachment during the closing phase, e.g., N_2O undergoes dissociative attachment producing O^-. Photodetachment of O^- has already been considered as a possible control

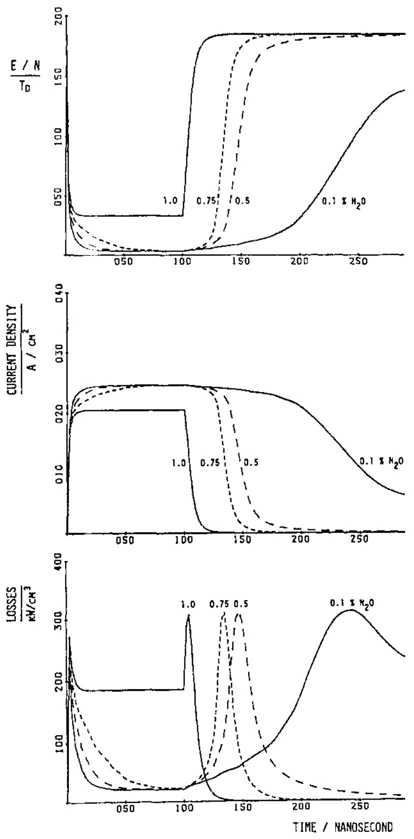

Fig. 3

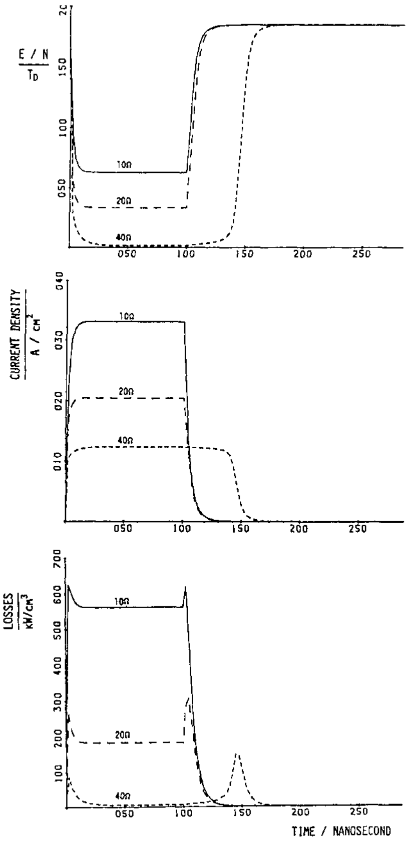

Fig. 4.

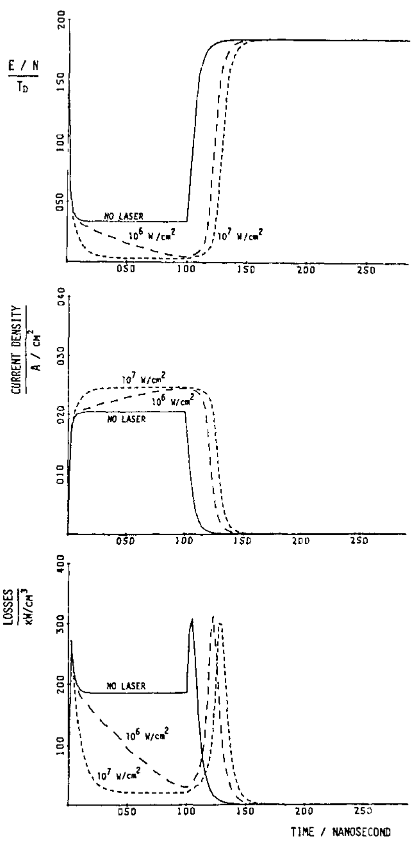

Fig. 5.

Time dependence of E/N (top), current density (middle), and loss power density (bottom) of an e-beam sustained discharge in 1 atm N_2. The e-beam is on for $0 \le t \le 100$ ns. Parameters see text.

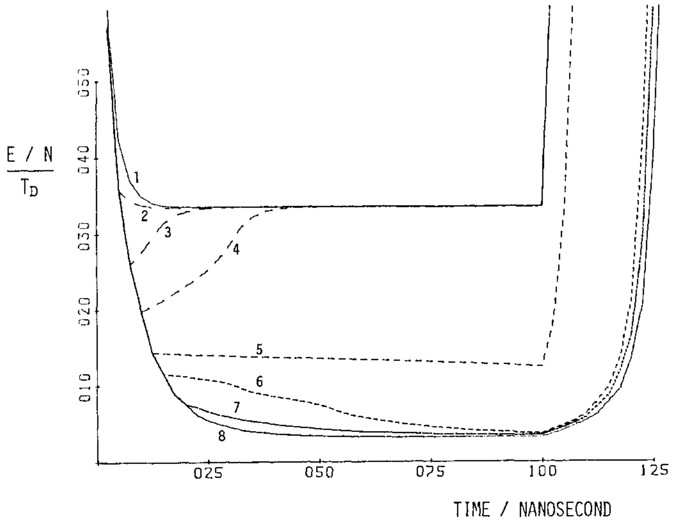

Figure 6. Time dependence of E/N of an e-beam sustained, photodetachment assisted discharge. Parameter is the laser pulse length as seen in table 2.

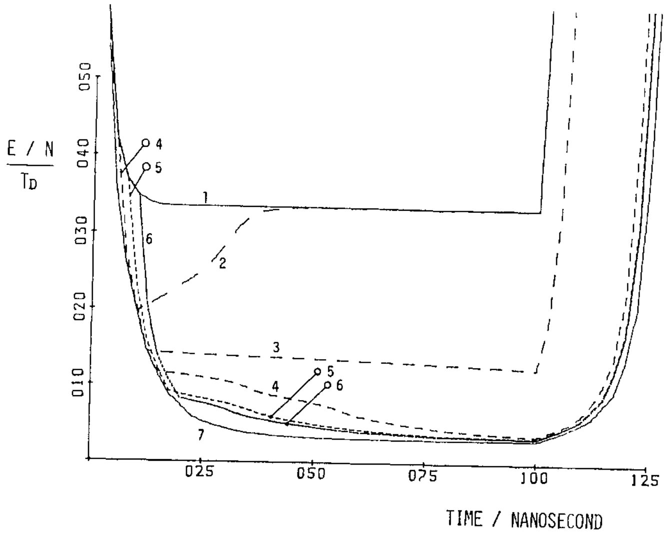

Figure 7. Time dependence of E/N of an e-beam sustained, photodetachment assisted discharge. Parameter is the delay of the laser pulse as seen in table 2.

mechanism for diffuse discharges.[6] The optimum photon energy is about 2eV. Figure 5 exhibits the time dependent behavior of such a controlled discharge. The total impedance is 20 Ω, the N_2O concentration is 1% and the parameter is the laser power areal density. The laser is on for the same duration as the e-beam. With a power density of 10^6 W cm^{-2} the discharge can be easily switched into the low E/N region, however this takes approximately 100 ns, on the other hand with 10^7 W/cm^2 the value of E/N drops very fast. The total loss energy for one cycle is the lowest of all operating conditions for the same impedance (compare Table 1 and Table 2).

After a discharge has reached the low value of E/N detachment does not strongly affect the electron balance and further laser irradiation to provide photodetachment is not warranted. Figure 6 depicts the time dependence of E/N for laser pulses of different length t_L, starting together with the e-beam at t = 0 ns. The laser power density is 10^7 W cm^{-2}. For short laser pulses ($t_L \leq 12.5$ ns) the discharge does not reach the region of low E/N values, while e.g., a laser pulse of $t_L = 20$ ns has nearly the same effect as a pulse during the full e-beam period ($t_L = 100$ ns). The loss energy density for these calculations is listed in Table 2.

At t = 0 ns no negative ions have been produced, here laser irradiation in the first few ns is probably also of little value. Figure 7 shows calculations of the time dependence of E/N for laser pulses of $t_L = 10$ ns length, but starting at different times. The power density is 10^7 W cm^{-2}, so the beam fluence is 100 mJ cm^{-2}. Note that with transverse illumination the illuminated area can be much smaller than the discharge area. For comparison the curves without laser irradiation and for laser irradiation during the full e-beam period (0 to 100 ns) are also shown. The values indicating the total energy input per cycle are shown in Table 2. It is assumed that for the early pulses the discharge does not proceed into the low E/N region. The lowest losses of the examples shown are achieved for laser pulses starting after 7.5 ns.

Conclusion

The calculations presented herein clearly show that the use of attachers with the proposed attachment characteristic allows operation of an e-beam sustained discharge with low losses in the conduction phase while enhancing short opening times. The requirement to operate the discharge under optimum conditions however limits certain parameters ranges such as attacher concentration and system impedance. Using additional control mechanisms such as photodetachment, operation with equally low losses can be extended to higher attachment concentrations and, or lower system impedances allowing shorter opening times and/or higher current amplifications.

References

1. Proc. ARO Workshop on Repetitive Opening Switches, Tamarron, CO (1981).
2. Proc. ARO Workshop on Diffuse Discharge Opening Switches, Tamarron, CO (1982).
3. K. H. Schoenbach, G. Schaefer, M. Kristiansen, L. L. Hatfield and A. H. Guenther, IEEE Trans. Plasma Sci., PS-10, 246 (1982).
4. L. C. Lee, C. C. Chiang, K. Y. Tang, D. L. Huestis, and D. C. Lorents, in Second Annual Report on AFOSR Sponsored Coordinated Research Program in Pulsed Power Physics, Texas Tech University (1981).
5. Provided by A. Phelps, JILA, Boulder, CO.
6. G. Schaefer, P. F. Williams, K. H. Schoenbach, J. Moseley, submitted to IEEE Trans. on Plasma Science.

Table 1. Loss energy density per switch cycle (300 ns) in mJ/cm^3.

	N_2O-Concentration			
System Impedance	0.1%	0.5%	0.75%	1.0%
10 Ω	92.9 *	57.5	58.1	61.4
20 Ω	37.1 *	15.8 *	13.0 *	22.0
40 Ω	12.4 *	6.8 *	4.4 *	3.6 *

For 0.1% N_2O and 0.5% N_2O the discharge was still on after 300 ns. At that time the loss power was still 70% of its maximum value for 0.1% N_2O and 3% for 0.5% N_2O respectively (see Fig. 3 bottom).

*In these calculations the discharge reaches low values of E/N.

Table 2. Loss energy density per switch cycle for the curves shown in Fig. 6 and Fig. 7, i.e., optically controlled discharges.

# in Fig. 6	1	2	3	4	5	6	7	8
Laser on from-to in ns	no laser	0-5	0-7.5	0-10	0-12.5	0-15	0-20	0-100
Loss energy in mJ/cm^3	22.0	28.9	21.65	20.7	13.2	10.5	9.4	9.0

# in Fig. 7	1	2	3	4	5	6	8
Laser on from-to in ns	no laser	0-10	2.5-12.5	5-15	7.5-17.5	10-20	0-100
Loss energy in mJ/cm^3	22.0	20.7	13.2	10.8	10.0	10.1	9.00

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