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DELAY TIME FOR THE ONSET OF BEAM PLASMA DISCHARGE

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Abstract—We consider the interaction of a non-relativistic electron beam with a neutral gas in a large chamber and study the time interval before ignition of beam plasma discharge (BPD). We find a new theoretical expression for the time delay before BPD ignition as a function of the critical current necessary for BPD to be established. There are two parameters in the theoretical expression, and both are derived from two different experiments. We use these parameters to write the time evolution equation for plasma density as a function of time.

INTRODUCTION

The interaction of electron beams with low pressure gases has been studied since the 1940s. These early experiments utilized high current density electron beams in relatively small containers. In more recent years experiments involving the emission of electron beams from rockets and satellites has prompted the use of large space simulation chambers to provide laboratory support for the space-borne experiments. Much recent laboratory work has used the large Space Simulation Chamber (SSC) at the Johnson Space Center (JSC) in Houston, Texas. This facility provides a cylindrical volume 30 m high and 16 m in diameter, with a controllable magnetic field from 0 to 2 g, and pressure as low as 10^{-6} T (Bernstein *et al.*, 1975, 1978, 1979; Raitt *et al.*, 1982; Banks *et al.*, 1982; Denig, 1982).

Both the early experiments and those later at the SSC have shown that ionization in vacuum chamber experiments does not occur through generation of electron–ion pairs from the neutral gas at a rate determined by the ionization cross-section for the energetic electrons. A much more intense interaction is often observed, producing greatly enhanced ionization, optical emissions, and a variety of plasma waves. This phenomenon is called Beam Plasma Discharge (BPD) and has been shown to occur when the beam current exceeds a certain threshold level dependent upon various parameters, including magnetic field intensity, neutral gas pressure, and chamber length.

Recently, Raitt *et al.* (1982) have observed from experiments in the SSC that, even when the threshold level of beam current has been exceeded, the BPD does not begin immediately, but shows a time delay. Typical onset times from these experiments are in the range of 1 to 10 ms. It is the purpose of this report to model this BPD time delay using observations made in the SSC at Johnson Space Center. We then use these observations to determine the parameters in a theoretical model for the time dependence of plasma density in the chamber prior to BPD.

Other investigators have generated models for BPD onset delay time. But, these other theories contain a fundamental mistake. The experimental data from both the Bernstein *et al.* experiment (Bernstein *et al.*, 1975, 1978, 1979) and the Raitt *et al.* experiment (Raitt *et al.*, 1982; Banks *et al.*, 1982; Denig, 1982) show that there is a linear relationship between the inverse of the time delay for BPD onset and the critical current required for BPD. We will clearly show this relationship. Papadopoulos (1986) and Szuszczewicz *et al.* (1982) have assumed that BPD onset delay time depends logarithmically on the critical current, and we will show that neither the Bernstein *et al.* nor the Raitt *et al.* experimental data support this assumption. The difference in these two theories can be traced to different loss mechanisms which describe the loss of plasma from the plasma chamber. Papadopoulos (1986) and Szuszczewicz *et al.* (1982) assume that the loss of plasma from the chamber is proportional to the plasma density. The theory developed in this report,

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which matches the data, evolves from a theory in which electrons lost from the system is a constant as in the Krook model. (The Krook model is usually thought of as describing simple scattering; however, we will show in a subsequent report, that loss of plasma from the plasma chamber is described by a different mechanism.)

EXPERIMENTAL OBSERVATIONS

Experimental studies of BPD onset times have been reported in the literature by Szuszczewicz *et al.* (1982) who discussed an experiment conducted by Bernstein *et al.* The same type of studies have been made by Raitt *et al.* (1982) and Denig (1982) describing a separate experiment. Two separate sets of experiments were involved in these observations, and the data collected provide the information needed to evaluate the slope and intercept of a straight line which describes the data when the data are plotted correctly. We note, however, that the definitions of BPD onset used in these experiments were not the same. As described by Bernstein *et al.* (1979), the results of Szuszczewicz *et al.* (1982) were based on the appearance of high frequency plasma oscillations, while Raitt *et al.* (1982) determined the delay time using a high time resolution electron detector. For our present purposes, we consider these criteria to be equivalent, even though some small, systematic differences may exist.

Szuszczewicz *et al.* (1982) proposed to describe their data with a theory in which the plasma loss from the chamber varied as the plasma loss rate ν times the plasma density N. Combining this with other assumptions lead to the formula for BPD delay time T_d:

$$T_d = -\frac{1}{\nu}\ln\left(1-\frac{I_B^c}{I_B}\right) \qquad (1)$$

where I_B is the electron beam current and I_B^c is the critical current needed to obtain BPD conditions.

In Fig. 1, we plot the data from the Bernstein *et al.* experiment. We plot the inverse of the time delay for BPD onset against critical beam current, for both the Raitt *et al.* and the Bernstein *et al.* experiment. Also shown are the error bars for the Raitt *et al.* experiment; the error bars on the bottom to data points do not lie outside the dot drawn as the data point. This figure shows that the data are described by a functional form of

$$\frac{1}{T_d} = P^* I_c - L^* \qquad (2)$$

between the BPD delay time and the BPD critical current I_c. P^* and L^* are the slope and intercept from the plot of data in the figure.

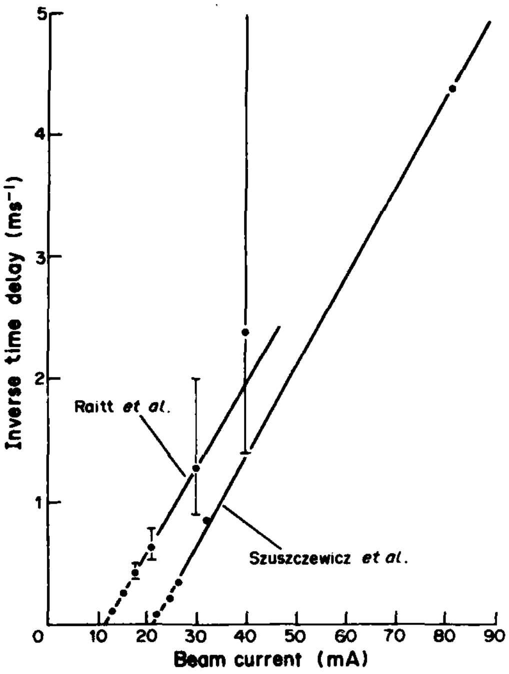

FIG. 1. INVERSE OF DELAY TIME VS CRITICAL BEAM CURRENT. Figure plots the experimentally determined values of inverse delay time vs critical beam current from the experiments reported by Szuszczewicz *et al.* (1982) and Raitt *et al.* (1982). The straight lines are least-square fits to each set of data; in the case of Raitt *et al.*, the top data point was not included.

Not only does the theoretical line given by (2) lie within the error bars, but it passes through the bottom five data points from the Raitt *et al.* experiment and passes very close to all the data points from the Bernstein *et al.* experiment. The functional form of the theory given by (2) describes the data of Bernstein *et al.* at the exclusion of the theory of Szuszczewicz *et al.* given by (1). We also note that the experiments of Raitt *et al.* and Bernstein *et al.* are quite different; a fact that gives credence to the validity of expression (2) as the correct representation of the data.

THEORETICAL MODEL

The model developed in this report considers the build-up of plasma density resulting from the passage of electrons from an electron gun through a low pressure gas contained in a large vacuum chamber. The purpose of the model is to estimate the time history of the plasma generation up to a defined level at which the instability known as BPD is triggered. We do not model subsequent effects once the BPD trigger level has been attained.

In order to simplify the analysis, we assume that positive ions exist as a stationary background which preserves neutrality; that is, we neglect dynamic effects associated with ion motions in the chamber. In this case, we are concerned with only the electron density $N_e(t)$.

From the equation of continuity, the time rate of change of plasma density can be written as:

$$\frac{\partial N_e}{\partial t} = P - L \tag{3}$$

where P is a production term which represents all processes which produce electron–ion pairs, and L is the loss term which represents all processes which result in the loss of plasma. We assume that P and L are independent of time and plasma density; for emphasis, we write

$$L = \text{constant}. \tag{4}$$

Integrating (3), we find

$$N_e(t) = (P - L)t \tag{5}$$

where we take $N_e(t = 0) = 0$. Expression (5) describes the time evolution of electron density from time zero when the beam current is switched on until and including time T_d when BPD starts.

The condition we have adopted for the BPD trigger is that given by Szuszczewicz *et al.* (1982) which uses the criterion that the plasma instabilities responsible for the BPD occur when the beam-generated plasma density reaches a value such that

$$\omega_p = 5.4\omega_c \tag{6}$$

where ω_p is the electron plasma frequency, and ω_c is the electron cyclotron frequency. The constant 5.4 varies slightly (Szuszczewicz *et al.*, 1982).

Solving the equation $\omega_p = \sqrt{Ne^2/(\varepsilon_0 m)}$ for the plasma density as a function of the plasma frequency and using (6) and $\omega_c = eB/m$, we may write $N_{ec} = (5.4)^2(\varepsilon_0/m)B^2$. ε_0 is the vacuum permittivity, and m is the mass of an electron. The criterion, given by (6), represents a critical plasma density N_{ec}. N_{ec} is given by

$$N_{ec} = 2.8 \times 10^{12} B^2 \quad \mathrm{m}^{-3} \tag{7}$$

where B is the magnetic field in gauss. With these assumptions, condition (7) says that the critical plasma density is known once the magnetic field in the chamber is given.

At T_d the plasma density has a critical value given by (7), and the delay time has been determined by the critical current I_c. Since expression (5) describes the plasma density at this time, we may write

$$\frac{1}{T_d} = \frac{P - L}{N_{ec}}. \tag{8}$$

From expression (2), we see that L is a constant; $L = N_{ec}L^*$, and we see that P varies proportionally to the beam current. We write the production term as $P = N_{ec}P^*I$. P^* is the slope of the curve in a plot of inverse delay time against critical beam current, and L^* is the inverse delay time intercept in the same plot. The values of the slope and intercept for the Bernstein *et al.* and the Raitt *et al.* experiments are given in Table 1.

Using the slope and intercept from a plot of the inverse delay time vs critical current, we may write equation (5) for time development of plasma density before BPD as

$$N_e(t) = N_{ec}(P^*I - L^*)t. \tag{9}$$

From the resulting linear fits and using equation (2), the parameters described in equation (9) have been determined and are listed in Table 1.

CONCLUSIONS

We have developed a theory which explains the observed time delay between switching on electron beam current and the occurrence of BPD. Beam electrons passing through a neutral gas create plasma, through primary and secondary collisions, at approximately a constant rate. Plasma builds up in time in a region around the beam, and when its density is high enough so that the local plasma frequency is about five times the electron gyrofrequency, BPD is ignited. The time delay is a result of the finite time it takes the beam to generate local plasma; this time is determined by competition between the production process described and loss processes.

A theoretical expression for pre-BPD time development of ionization in a neutral gas with an electron beam passing through it has been derived and has been shown to fit two experimental data sets of the time delay vs critical current. We have obtained a better fit to the observations than Szuszczewicz *et al.* (1982) by using a loss term independent of the plasma density in determining the time variation of plasma density after electron beam turn-on. We note that the slope in the plot of inverse delay time vs critical beam current is nearly the same for the Bernstein *et al.* and the Raitt *et al.* experiments. This indicates that the plasma production rate was nearly the same in the two experiments. The loss of plasma from the chamber in the two experiments was quite different, as we see from the difference in intercept values in the two plots.

The plasma density dependent loss term has been

TABLE 1

	B (gauss)	$N_{cc} \times 10^{12}$ (m^{-3})	P^* $(\mathrm{ms\ mA})^{-1}$	L^* $(\mathrm{ms})^{-1}$	$P \times 10^{11}$ $(\mathrm{m}^3\ \mathrm{ms})^{-1}$	$L \times 10^{12}$ $(\mathrm{m}^3\ \mathrm{ms})^{-1}$
Bernstein *et al.*	1.56	6.9	0.068	1.4	4.7 I	9.8
Raitt *et al.*	1.0	2.8	0.067	0.79	1.9 I	2.2

used by Papadopoulos (1986) in the time evolution equation for the plasma density. This equation forms the fundamental basis for the theory of Papadopoulos (1986) and since, as we have shown, this equation does not describe the correct behavior of plasma density in the beam chamber, it is unlikely that the results based on this equation describe the behavior of plasma in the chamber.

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