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PLASMA DIFFUSION IN A SPACE-SIMULATION BEAM-PLASMA DISCHARGE.(U)

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Plasma Diffusion in a
Space-Simulation Beam-Plasma Discharge

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E. P. SZUSZCZEWICZ, D. N. WALKER, and J. C. HOLMES

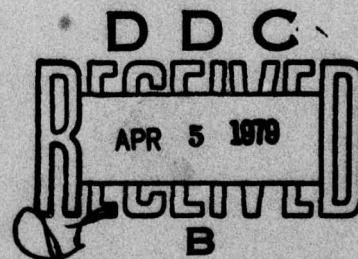*E. O. Hulburt Center for Space Research*

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Electron density and temperature profiles have been measured in a large-facility beam-plasma-discharge ($V_B \sim 1.3$ KeV, $I_B \sim 63$ ma) at low pressure ($P \sim 2\text{-}4(10^{-6})$Torr) and low magnetic fields ($B \sim 1.2$ G). The results follow an exponential behavior and are found to be in good agreement with a simple diffusion model. The favorable comparison between theory and experiment yields the first estimate of cross-field electron diffusion ($D_e^\perp(\text{nom}) \sim 2.2(10^6)$cm^2/sec) under conditions intended to simulate Spacelab-borne beam-plasma investigations. This value for $D_e^\perp$

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20. Abstract (Continued)

is orders of magnitude larger than would be expected for a cross-field collisional diffusion process, a result which is identified with the turbulent state of collective beam-plasma interactions.

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PLASMA DIFFUSION IN A
SPACE-SIMULATION BEAM-PLASMA-DISCHARGE

I. INTRODUCTION

Beam-plasma interactions have received increased
attention in recent years largely as a result of consid-
erations bearing on vehicle neutralization during space-
borne accelerator experiments, enhanced beam-plasma
ionization processes, and in general, collective phenomena
initiated by beam injection into neutral gas and charged-
particle environments. With plans for Shuttle-borne
experiments directed at controlled beam-plasma interactions
and the use of beams to probe ionospheric/magnetospheric
electric and magnetic fields, it became important to
conduct laboratory simulations which supported the Shuttle
plans and helped establish definitive Shuttle-borne experi-
ments.

As part of just such a plan involving a continuing
investigation of large-facility beam-plasma interactions
(Bernstein, et al, 1975,1977,1978) the Naval Research
Laboratory (NRL) participated in a recent series of experi-
ments at the NASA Johnson Space Center (JSC). The NRL

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contribution involved the direct measurement of electron density and temperature under varying conditions of beam-plasma   and neutral gas parameters. Reported here are the first large facility profiles of electron density and temperature under conditions of enhanced beam-plasma ionization...conditions which have come to be known as the BPD, the "beam-plasma-discharge" (Getty and Smullin, 1963; Bernstein et al.,1978). The observed density profile is found to be in good agreement with a two-dimensional diffusion model and this result makes possible the first estimate for the cross-field electron diffusion coefficient in a large facility BPD. In the following Sections the experiment is described, the theoretical model is defined, and the diffusion coefficient is derived.

II. EXPERIMENTAL RESULTS

The Experiment. The technique of the pulsed-plasma-probe (P^3) was employed to measure the beam-plasma profile. The P^3 provides simultaneous measurements of N_e, T_e, V_∞, and $\delta N_e(\rightarrow P_n(k))$ and is particularly useful under dynamic plasma conditions and in environments that can contaminate electrode surfaces   (Holmes and Szuszczewicz, 1975; Szuszczewicz and Holmes, 1975,1976,1977). Both these conditions prevailed to various degrees in the JSC experiments.

The experimental configuration (similar to that described by Bernstein et al.,1978) is illustrated in

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Figure 1. The P^3 was mounted on a traversal mechanism positioned at approximately 8 m above the injection point of the beam. The tungsten cathode gun was operated at 63 ma and 1.3 KV DC with the chamber pressure in the $2-4(10^{-6})$ torr range. A combination of coil current and the Earth's field established vertical and horizontal component B-fields at $B_z=1.21$ gauss and $B_{x-y}=0.27$ gauss, respectively. Under these conditions a BPD was established and the probe traversal mechanism was exercised to determine the plasma's radial profile out to 4.6 m. The resulting measurements of T_e and N_e are presented in Figure 2.

Following the diffusion-model density-profile predictions (discussed below) the experimental curves were fit with exponential distributions found to be

$$T_e \; [10^3 \; {}^\circ K] = \; 6.93 \; \exp \; (-r/1.99) \tag{1}$$

$$N_e \; [10^6 \; cm^{-3}] = 7.01 \; \exp \; (-r/2.49) \tag{2}$$

III. THEORETICAL CONSIDERATIONS

For purposes of comparison, a simple two-dimensional diffusion model is developed which follows the approach used in the study of small laboratory arc plasmas by Bohm et al., (1949a). The approach suggests the consideration of a differential plasma element of thickness dr and of length h parallel and equal to the length of the beam as depicted in Figure 3. The differential element is taken outside the domain of the primary beam and is assumed to be homogeneous

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along its length. The equilibrium density then arises from the balance of charge accretion by differential drift across the element, i.e., $j_e(r) - j_e(r+dr)$, and end losses ($Z=0$ and h) due to axial diffusion. Requiring $dN_e/dt = 0$ and assuming an axial diffusion loss directly proportional to density (i.e., differential end losses = $2\alpha_z^e N_e dr$), the balance between production and loss requires

$$(dj_e/dr) \, h \, \delta r = -2\alpha_z^e \, N_e \, \delta r \tag{3}$$

which is rewritten as

$$dj_e/dr = -2\alpha_z^e \, N_e/h \quad . \tag{4a}$$

Similar arguments for the plasma's ion component yield

$$dj_i/dr = -2\alpha_z^i \, N_i/h \tag{4b}$$

Independent of Eqs. (3) and (4) the diffusion currents j_e and j_i can be described by their respective mobility equations

$$j_e = -D_e^\perp \left\{ \frac{dN_e}{dr} - \frac{eN_e}{kT_e} \frac{dV}{dr} \right\} \tag{5a}$$

and

$$j_i = -D_i^\perp \left\{ \frac{dN_i}{dr} + \frac{eN_i}{kT_i} \frac{dV}{dr} \right\} \tag{5b}$$

where V is an electric potential and $D_e^\perp$ and $D_i^\perp$ are the perpendicular electron and ion diffusion coefficients, respectively. Taking the one-dimensional space-derivative d/dr of Eqs. (5) and substituting (4) yields

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$$T_e \left(\frac{\alpha_z^e}{hD_e^{\perp}} \; N_e - \frac{d^2N_e}{dr^2} \right) = - \frac{e}{k} \; \frac{d}{dr} \left(N_e \; \frac{dV}{dr} \right) \qquad (6a)$$

$$T_i \left(\frac{\alpha_z^i}{hD_i^{\perp}} \; N_e - \frac{d^2N_e}{dr^2} \right) = \frac{e}{k} \; \frac{d}{dr} \left(N_e \; \frac{dV}{dr} \right) \qquad (6b)$$

when $N_e \equiv N_i$ and the terms have been rearranged. Addition

of Eqs. (6) eliminates the potential-dependent term and

results in

$$\frac{d^2N_e}{dr^2} = 2 \, h^{-1} \left\{ \frac{\alpha_z^e D_i^{\perp} T_e + \alpha_z^i D_e^{\perp} T_i}{D_e^{\perp} D_i^{\perp} (T_i + T_e)} \right\} N_e \equiv \beta^2 N_e \qquad (7)$$

with a solution

$$N_e = \left\{ N_e^O - \frac{(N_e^O \exp(\beta R) - N_e^R)}{(\exp(\beta R) - \exp(-\beta R))} \right\} \exp(\beta r)$$

$$+ \left\{ \frac{N_e^O \exp(\beta R) - N_e^R}{(\exp(\beta R) - \exp(-\beta R))} \right\} \exp(-\beta r) \qquad (8)$$

In the limit $R \to \infty$, the solution becomes

$$N_e = N_e^O \exp(-\beta r) \qquad (9)$$

where

$$\beta = \left\{ \frac{2(\alpha_z^e D_i^{\perp} T_e + \alpha_z^i D_e^{\perp} T_i)}{D_e^{\perp} D_i^{\perp} (T_i + T_e) h} \right\}^{1/2} \qquad (10)$$

IV. COMPARISON BETWEEN THEORY AND EXPERIMENT

The agreement between theoretical prediction (Eq.(9)) and experimental results is found to be good (see bottom panel, Fig. 2) and provides the opportunity for determining the effective electron diffusion perpendicular to the magnetic field, i.e., the radial diffusion in the model of Fig. 3. To accomplish this, consider

$$\lim_{T_i/T_e \to 0} \beta^{-1} = \left(D_e^{\perp} h \Big/ 2 a_z^e \right)^{\frac{1}{2}} = 2.49 \tag{11}$$

where the value on the right side is taken from the exponential in Eq. (2). In addition, consider a_z^e as the effective velocity of axially diffusing electrons which have sufficient energy to overcome chamber sheath potentials and be completely lost to the system. In this case,

$$a_z^e = \sqrt{\frac{kT_e}{2\pi m}} \ \exp \ (-eV_c/\bar{k}T_e) \tag{12}$$

where V_c is the chamber-sheath potential. With $V_c = (4.8^{+0.5}_{-1.4}) \ kT_e/e$ (Chen, 1965; Szuszczewicz, 1972) and $T_e = 3 \ (10^3) \ ^oK$ Eq. (12) yields

$$\alpha_z^e (nom.) = 7.0 \ (10^4) \ cm \ /sec \tag{13a}$$

$$\alpha_z^e (max) = 2.8 \ (10^5) \ cm \ /sec \tag{13b}$$

$$\alpha \frac{e}{z} \text{ (min)} = 4.3 \ (10^4) \text{ cm /sec} \tag{13c}$$

Substituting the α_z^e values into Eq. (11) provides

$$D_e^{\perp}\text{(nom)} = 2.2 \ (10^6) \text{ cm}^2/\text{sec} \tag{14a}$$

$$D_e^{\perp}\text{(max)} = 8.8 \ (10^6) \text{ cm}^2/\text{sec} \tag{14b}$$

$$D_e^{\perp}\text{(min)} = 1.3 \ (10^6) \text{ cm}^2/\text{sec} \tag{14c}$$

as the first experimental estimate of the effective electron
diffusion coefficient perpendicular to the magnetic field
in a BPD.

The values for $D_e^{\perp}$ are orders of magnitude larger than
would be expected for cross-field collisional diffusion.
This result in itself is not surprising since a variety
of observations indicate that the diffusion of plasma
across magnetic lines of force can be substantially enhanced
above the collisional diffusion rate when fluctuating
fields are present in the plasma (Spitzer, 1962; Kadomtsev,
1965). This is indeed the case in a BPD which has as one of
its characteristics the presence of fluctuating electric
fields that are associated with large amplitude plasma
waves. The enhancement of diffusion in turbulent plasmas
goes back to Bohm et al. (1949b) who semiempirically de-
scribed the rate by what has come to be known as the Bohm
diffusion coefficient

$$D_B = 6.25 \ (10^6) \ T_e B^{-1} \text{ cm}^2/\text{sec} \tag{15}$$

where $[T] = eV$ and $[B] = $ gauss. For our nominal
temperature of $3(10^3)$ $^\circ K$ and a total field $B_z = 1.2$ gauss
Eq. (13) yields $D_B = 1.3(10^6)cm^2/sec$. This calculation
has not been intended to confirm or deny the validity
of Eqs. (14) but has been presented as the only possible
comparison with an existing concept of turbulent diffusion.
While the Bohm formula appears to apply to a surprising
number of different experiments, care must be exercised
so that the illusion of universal validity does not auto-
matically develop. It is evident that a first-principles
derivation of the coefficient of turbulent diffusion can-
not be obtained without a detailed investigation of the
plasma, particularly the fluctuation power spectra and
associated instability processes (Kadomtsev, 1965;
Papadopoulos, private communication 1978). The experi-
mental and theoretical aspects of these details, as they
relate to the JSC experiments, are currently underway
at NRL (Szuszczewicz and Papadopoulos, private communi-
cation 1978).

V. SUMMARY

The first experimental radial profiles of electron
density and temperature in a large facility beam-plasma-
discharge are found to fit exponential functions defined by

$$T_e \ [^\circ K] = 6.93 \ (10^3) \ \exp \ (-r[\,m\,]/1.99)$$

and

$$N_e[cm^{-3}] = 7.01 \ (10^6) \ exp \ (-r[\ m\ ] \ /2.49).$$

While the present stage of research does not provide a theoretical basis for the temperature distribution, the electron density results do agree with a two dimensional diffusion model which predicts

$$N_e = N_e{}^O \ exp \left\{ -(2 \bullet_z^e/D_e^\perp h)^{\frac{1}{2}} r \right\}$$

in the limiting case of large chambers with $T_i/T_e \longrightarrow 0$. With $\bullet_z^e$ taken as the effective velocity of axially diffusing electrons (assigned a nominal value of $7 \ (10^4)$ cm/sec) the identity of the experimental profile with the theoretical prediction yields

$$D_e^\perp(nom) = 2.2(10^6) \ cm^2/sec$$

for the radial electron diffusion across a superimposed magnetic field. This is the first such determination in a large-facility BPD and points to a process substantially faster than cross-field collisional diffusion. The reason for this is identified with the presence of large amplitude plasma waves and their associated electric fields.

While enhanced cross-field diffusion appears to be a characteristic of many turbulent plasma environments, the observations reported here are particularly unique in that the applied magnetic field is at best 10^3 times weaker than in any other turbulent diffusion investigation. This points to the importance of an unequivocal determination

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of the turbulence spectra and the associated instability processes. This work is currently underway at NRL.

ACKNOWLEDGEMENTS

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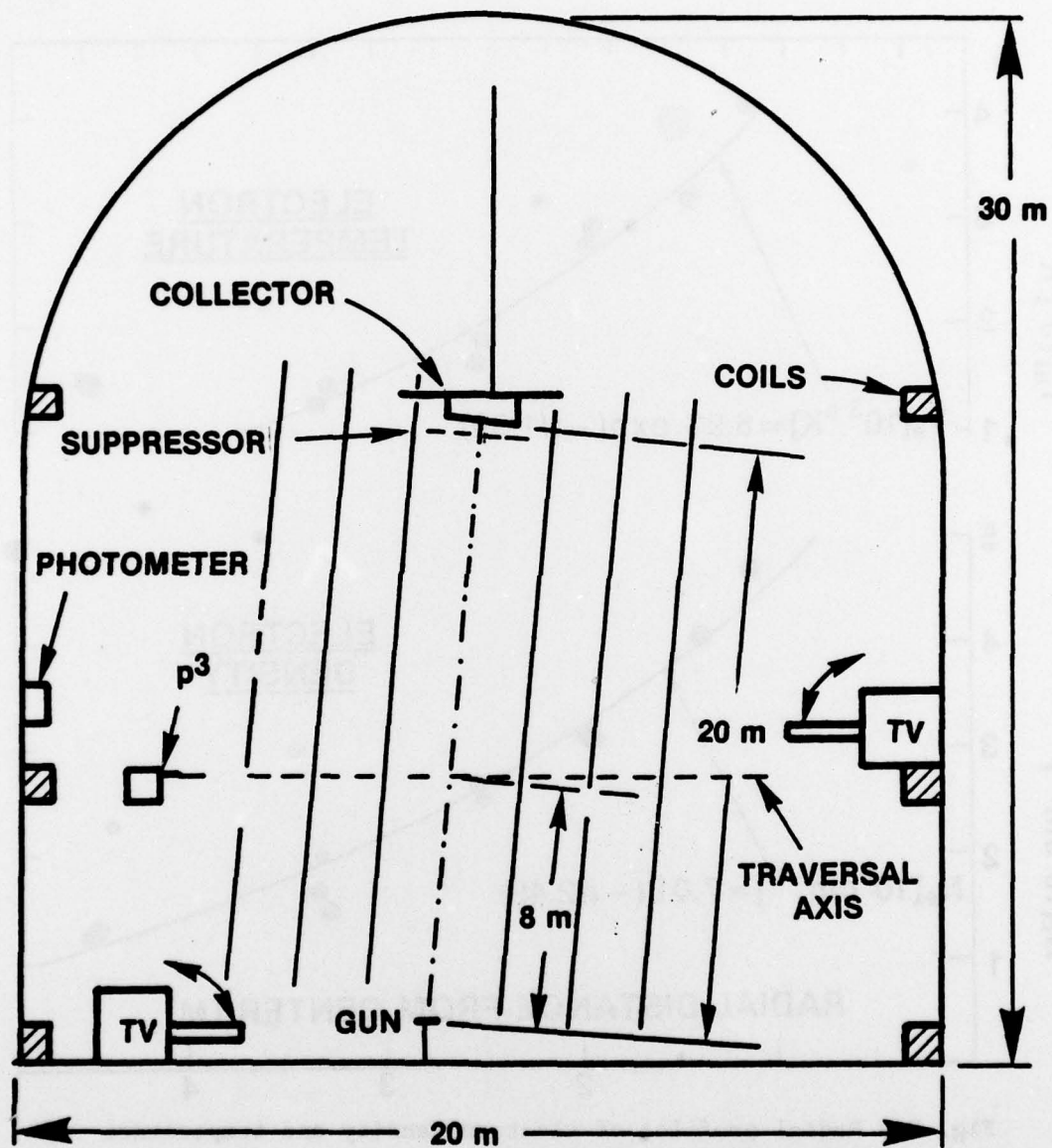layers", J. Geophys. Res. <u>82</u>, 5073, 1977.

Fig. 1 - Experiment configuration utilized in the large-facility
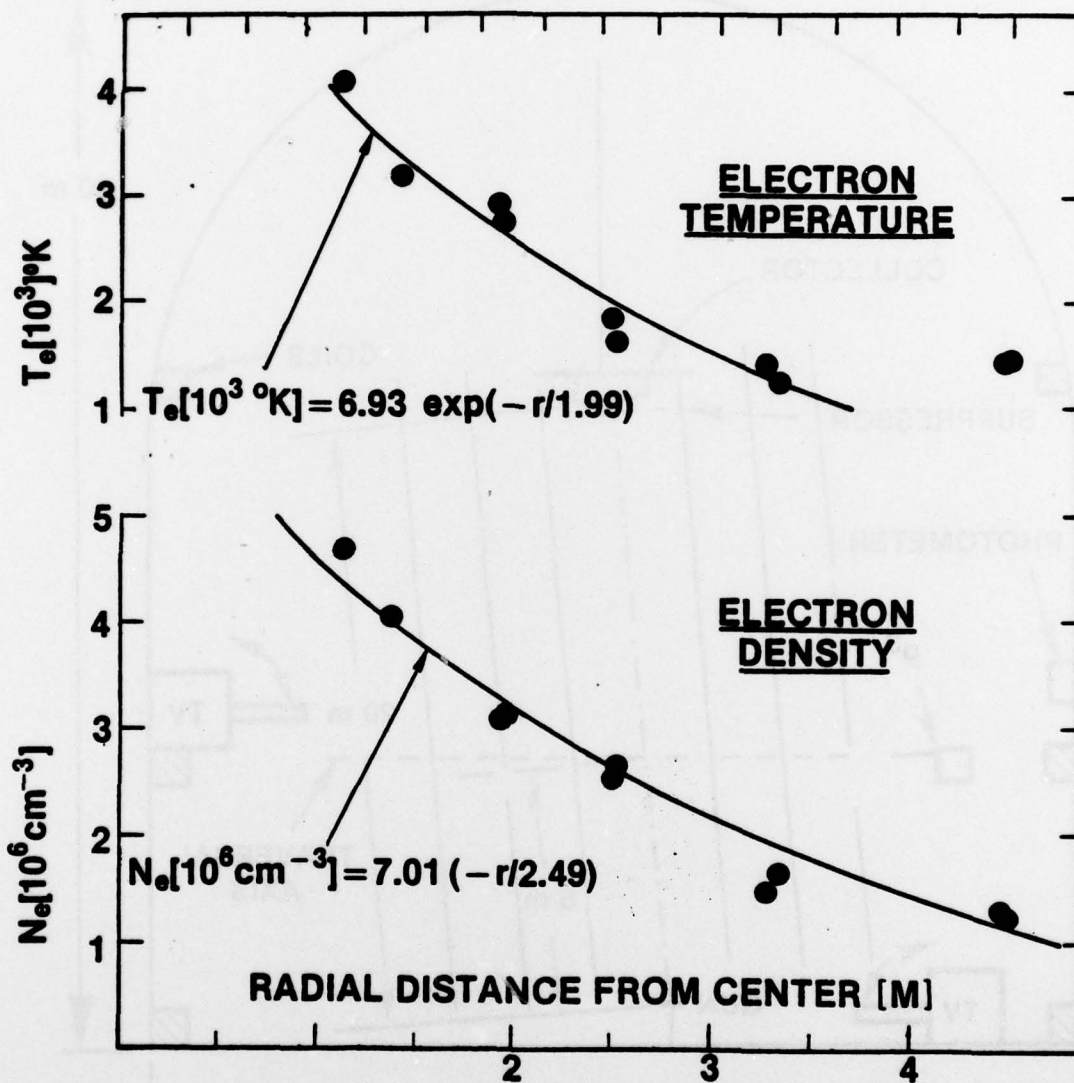beam-plasma investigations at the Johnson Space Center.

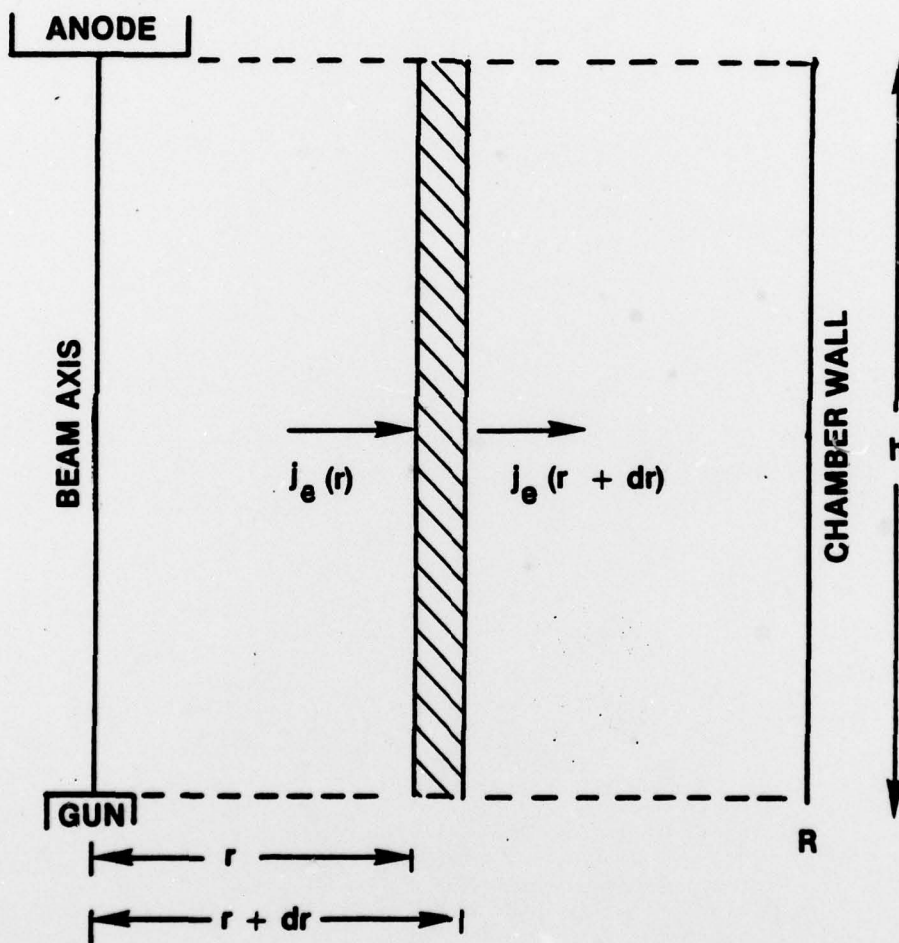Fig. 2 - Radial profiles of electron density and temperature under conditions of the beam-plasma discharge.

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Fig. 3 - Assumed configuration for diffusion-
model calculations.

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