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PLASMA DIFFUSION IN A SPACE-SIMULATION BEAM-PLASMA DISCHARGE.(U)
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NRL Memorandum Report 3925

Plasma Diffusion in a Space-Simulation Beam-Plasma Discharge

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February 12, 1979

NAVAL RESEARCH LABORATORY
Washington, D.C.

SECURITY CLASSIFICATION OF THIS PAGE (*When Data Entered*)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS
BEFORE COMPLETING FORM

1. REPORT NUMBER
NRL Memorandum Report 3925

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (*and Subtitle*)
PLASMA DIFFUSION IN A SPACE-SIMULATION BEAM-PLASMA-DISCHARGE

5. TYPE OF REPORT & PERIOD COVERED
Interim report on a continuing NRL problem.

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
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8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Naval Research Laboratory
Washington, DC 20375

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
NRL Problem A02-11
Subtask RRD33-02-42

11. CONTROLLING OFFICE NAME AND ADDRESS
Office of Naval Research
Arlington, Virginia 22217

12. REPORT DATE
February 12, 1979

13. NUMBER OF PAGES
18

14. MONITORING AGENCY NAME & ADDRESS(*if different from Controlling Office*)

15. SECURITY CLASS. (*of this report*)
UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (*of this Report*)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (*of the abstract entered in Block 20, if different from Report*)

18. SUPPLEMENTARY NOTES

*NOAA/ERL/Space Environment Laboratory, Boulder, Colorado

19. KEY WORDS (*Continue on reverse side if necessary and identify by block number*)

Plasma physics
Energetic beams
Beam-plasma interactions

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

Electron density and temperature profiles have been measured in a large-facility beam-plasma-discharge ($V_B = 1.3$ KeV, $I_B = 63$ ma) at low pressure ($P = 2\text{-}4(10^{-6})$Torr) and low magnetic fields ($B = 1.2$ 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 ($D_e^{\perp}(\text{nom}) = 2.2(10^6)\text{cm}^2/\text{sec}$) under conditions intended to simulate Spacelab-borne beam-plasma investigations. This value for $D_e^{\perp}$

(Continues)

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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.

CONTENTS

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 considerations bearing on vehicle neutralization during spaceborne 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 experiments.

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 experiments at the NASA Johnson Space Center (JSC). The NRL

Note: Manuscript submitted December 11, 1978.

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

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

$$T_e\ [10^3\ ^oK] = 6.93 \exp(-r/1.99) \qquad (1)$$

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

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 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

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

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

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

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

where the value on the right side is taken from the exponential in Eq. (2). In addition, consider α_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,

$$\alpha_z^e = \sqrt{\frac{kT_e}{2\pi m}} \exp \left(-eV_c/kT_e\right) \qquad (12)$$

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

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

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

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

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 described 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] = e V and [B] = gauss. For our nominal temperature of $3(10^3)$ ^oK 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 automatically develop. It is evident that a first-principles derivation of the coefficient of turbulent diffusion cannot 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 experimental and theoretical aspects of these details, as they relate to the JSC experiments, are currently underway at NRL (Szuszczewicz and Papadopoulos, private communication 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

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

and

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

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

$$D^{\perp}{}_e(\mathrm{nom}) = 2.2(10^6)\ \mathrm{cm}^2/\mathrm{sec}$$

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

ACKNOWLEDGEMENTS

This work was supported by the Office of Naval Research under Program Element 61153N-33 in Task Area RR033-02. The authors would like to thank Drs. Owen Garriott and H. Friedman for suggesting and making possible the NRL participation in the JSC experiments. We also wish to thank W. Bernstein and Dr. D. Papadopoulos for their review of the manuscript, their support in the activities, and their helpful suggestions. Sincere thanks are also extended to the large number of people at JSC who helped rig the P^3 configuration and the traversal mechanism.

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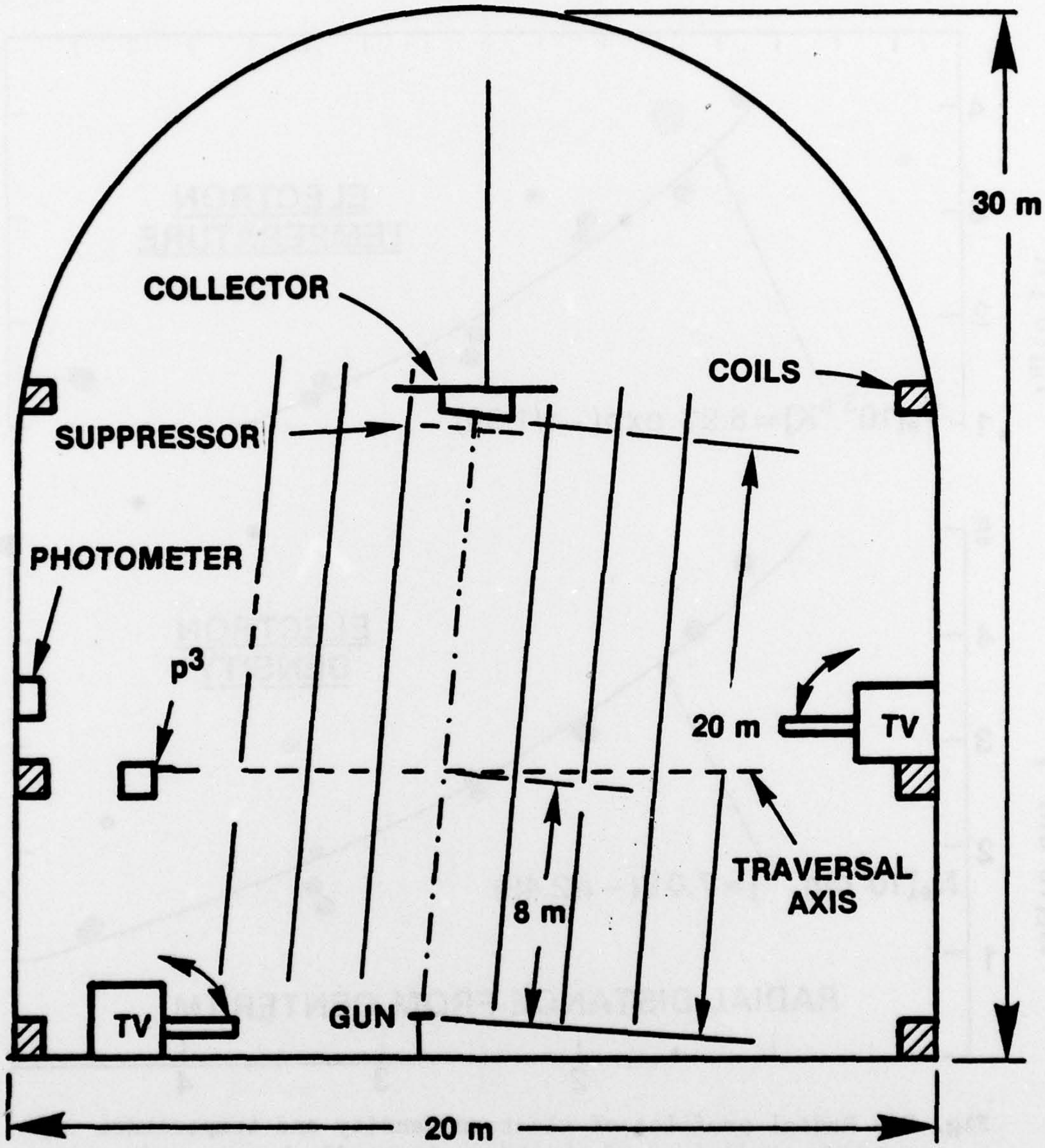

Fig. 1 - Experiment configuration utilized in the large-facility beam-plasma investigations at the Johnson Space Center.

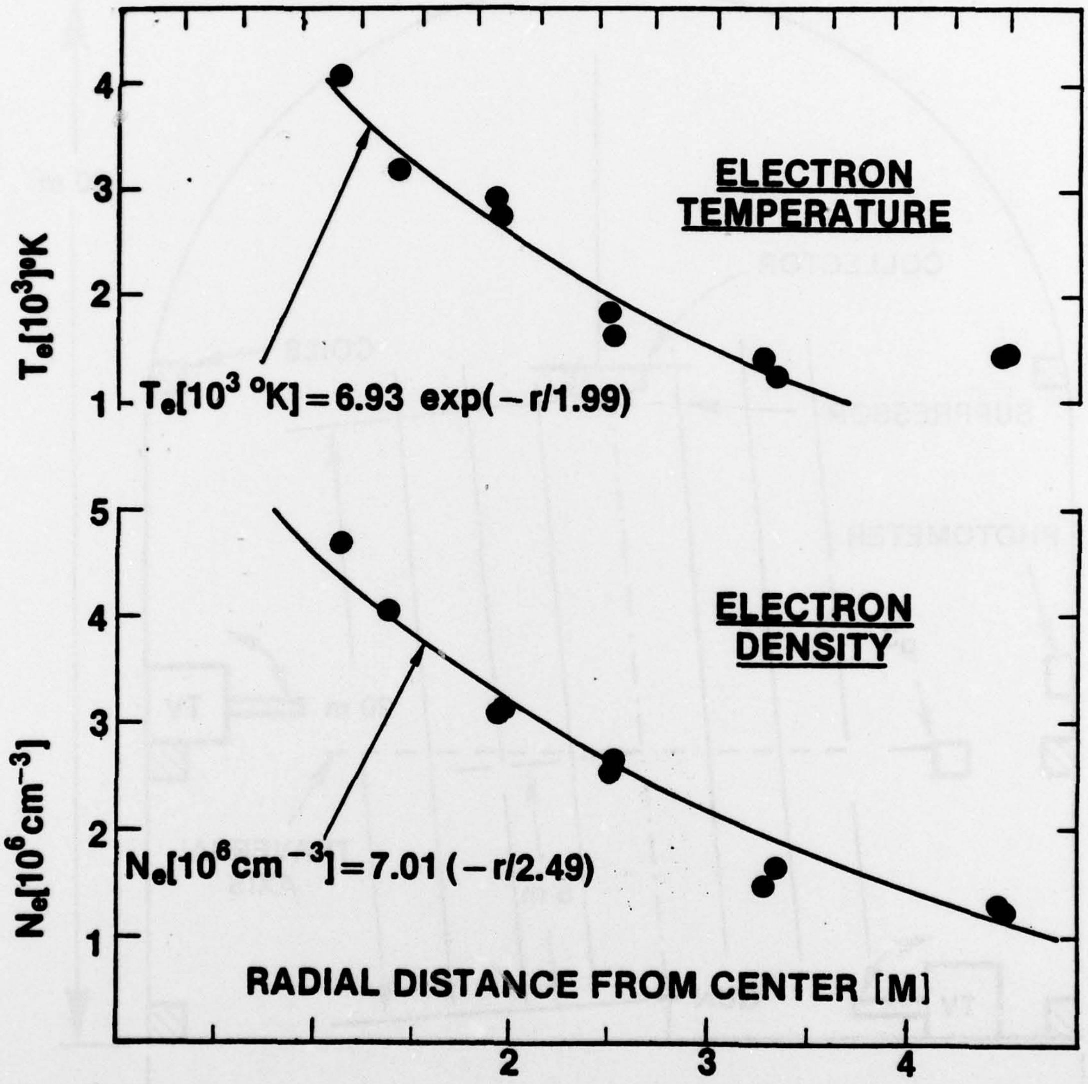

Fig. 2 - Radial profiles of electron density and temperature under conditions of the beam-plasma discharge.

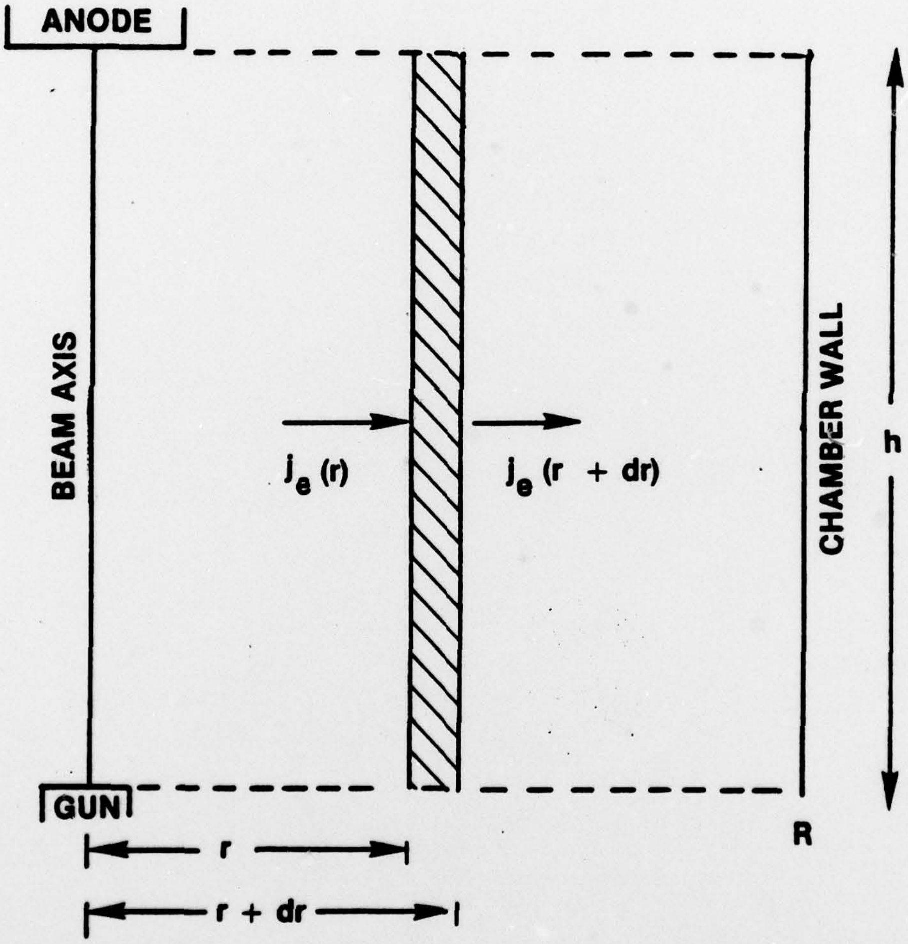

Fig. 3 - Assumed configuration for diffusion-model calculations.