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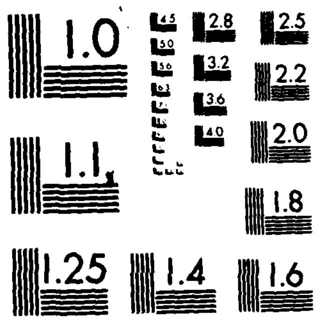
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On the Plasma Physics of the Beam Plasma Discharge

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Abstract

The scaling for the ignition of beam plasma discharge ~~(BPD)~~ observed in many laboratory experiments is consistent with the requirement for triggering an absolute instability near the plasma frequency (ω_e). The transition in the scaling with pressure can be attributed to transition from Bohm to classical diffusion losses.

omega sub e.

I. Overview and Observations

Although the phenomenon of beam plasma discharge (BPD) was experimentally observed 20 years ago [1,2], it has recently received particular attention in view of its importance to vehicle neutralization and the physical phenomena expected in ionospheric electron beam injection experiments from rockets and the space shuttle [3-6]. While the early experiments[1,2] injected pulsed keV beams into high neutral pressure ($p \gtrsim 1$ mT) high magnetic field (.2-1. KG) devices, more recent laboratory experiments[7-11] performed at the large tank at Johnson Space Center (JSC), injected steady state keV beams in ionospheric like pressures ($p \approx 1$-100 μT) and magnetic fields ($B \sim .5$-1.5 G). An empirical scaling law was found for the threshold current I_c required for ignition of BPD as shown in Fig. 1 and given by

$$I_c \approx \frac{E_b^{3/2}}{B^{\lambda} L} f(p) \qquad (1)$$

where E_b is the energy of the beam and L the length of the chamber. The value of $\lambda \approx .5$-1 and the function f(p) has a minimum at a pressure value $p_o \approx 15\mu$T and varied roughly as $p^{\pm .5}$ to $p^{\pm 1}$ above and below p_o (Fig. 1). This experiment coupled with our improved understanding of the nonlinear physics of beam plasma interactions in the strongly turbulent regime [12-15] allowed us to make major progress in the physics of BPD. The interdisciplinary nature of the phenomenon makes it an appropriate subject for a comment, whose purpose is to delineate the plasma physics of the BPD and provide a simple model for the incorporation of the relevant atomic physics and transport processes.

To orient the reader we describe first the observations of BPD at the JSC chamber, since they are rather typical of similar experiments. An energetic electron beam ($E_b \approx .7$-1.5 keV, $I \approx 1$-100mA) was injected parallel to an ambient magnetic field ($B \approx .8$-1.5 G) in a chamber of axial length $L \approx 20$ m and approximately equal diameter, filled with neutral gas with pressure $p \approx 1$-$30\,\mu$T. For beam currents below a critical value I_c, which is a function of p, L, B and E_b given by Equ. (1) the beam, as seen optically, follows the scalloped trajectory expected from single particle dynamics, accompanied by the emission of weak whistler and cyclotron waves. For beam currents above I_c there are many phenomena indicative of strong collective plasma interactions, such as:

(i) The beam expands radially filling its radius while any sign of single particle dynamics disappears.

(ii) Photometric measurements indicate a large increase in the 3914-A volume emission, accompanied by jumps in the plasma density by a factor between 5-10.

(iii) Electron heating to 1-2 eV, accompanied by large fluxes of suprathermal electrons in the region between 5-

100 eV.

(iv) Large localized electrostatic waves near the plasma frequency (ω_e) confined inside the beam region, while broadband featureless whistler emissions are measured outside.

II. A Simple Physical BPD Model:

On a superficial level BPD can be thought as an RF discharge at the critical density (i.e. $\omega_{rf} \approx \omega_e$) but with the rf fields being electrostatic in nature and driven by a beam plasma instability (BPI). In probing deeper into the BPD observables we discover many important characteristics different from RF discharges. Some of the key plasmaphysics issues of BPD can be identified by refering to the diagram of Fig. 2. In the absence of any collective effects the system will follow the path marked by 1 - 2 - 3. Namely the beam will ionize the neutral gas and a steady state will be established by balancing the rate of ionization with the rate of plasma loss, i.e.

$$\frac{dn}{dt} = n_b N \langle \sigma V_b \rangle - \frac{n}{\tau} \tag{2}$$

where n_b, n, N are the beam, plasma and neutral density, σ the ionization cross section and τ the confinement time. Although we will neglect recombination here, it can be included by taking $\tau \approx \frac{1}{\beta n}$ where β is the recombination coefficient. The expected steady state density from equ.(2) is then

$$\frac{n_o}{n_b} = N \langle \sigma V_b \rangle \tau \tag{3}$$

If $\tau \sim f(n)$, then n_o will be given by the solution of equ. (3) for n. In order to have BPD the path marked in Fig. 2 by 4 - 5 - 6 should be allowed on a time scale faster than

τ, and the rate of ionization due to 6 should be larger than due to 1. If we assume that the path 4→5→6 is allowed Equ. (2) should be modified to read

$$\frac{dn}{dt} = n_b N\langle\sigma V_b\rangle + n_s N\langle\sigma V_s\rangle - \frac{n}{\tau} \tag{4}$$

where n_s, V_s are the density and thermal speed of electrons with energy above the gas ionization energy E_i. Assuming that the confinement time is not affected, the steady state density after BPI will be

$$n_1 = n_o\left(1 + \frac{n_s\langle\sigma V_s\rangle}{n_b\langle\sigma V_b\rangle}\right) \tag{5}$$

If $\frac{n_s\langle\sigma V_s\rangle}{n_b\langle\sigma V_b\rangle} < 1$, the process can account for observations (i), (iii) and (iv) above. Namely we will have a BPI but not a BPD. If $\frac{n_s\langle\sigma V_s\rangle}{n_b\langle\sigma V_b\rangle} > 1$, then observation (ii) can be accounted for and we will have a BPD. The above considerations can be easily extended to include the possible effects of BPI to the plasma confinement (e.g. electron heating) by following the path marked 7→8 in Fig. 2. Based on the above considerations we can state a generic criterion for BPD triggering. "BPD will be triggered if the value of the pre-BPD density n_o combined with the other parameters (i.e. n_b, E_b, L, B, N) is such that it can produce on a time scale shorter than τ a flux of energetic electrons such that

$$\frac{n_s\langle\sigma V_s\rangle}{n_b\langle\sigma V_b\rangle} > 1\text{"}$$

It is also easy to see that if the plasma confinement during BPI is not affected or it improves we can reach stationary state. However if the confinement deteriorates the final state will have relaxation oscillations with time scale the new confinement time. Therefore the plasma physics input to the problem involves the computation of conditions for BPI, the energy transfer efficiency from the beam to electrons with ionizing energy, and the plasma confinement time.

III. JSC Scaling of BPD: The Papadopoulos Conjecture:

Guided by the measured plasma physics quantities near BPD threshold at the JSC experiment, Papadopoulos[4] conjectured that the BPD threshold is associated " with the value of the plasma density n_o required to produce an absolute instability near ω_e. The reasons for the conjecture were the following:

(i) The value of the electron neutral collisions was large enough to stabilize kinetic BPI. The hydrodynamic BPI can, however, be excited due to its larger growth as well as the fact that it is a negative energy wave instability.

(ii) Convective hydrodynamic instability has group velocity $v_g \gtrsim V_b$. Since the system size L is short, in the sense that $\frac{L\omega_e}{V_b} \gtrsim 6-8$, and the instability growth $\gamma << \omega_e$ convective amplification cannot produce substantial energy deposition. Only an absolute instability can do it.

(iii) The reason for insisting on an instability near ω_e, is not only the experimental evidence, but also the requirement for fast (collisionless) energy transfer of the energy to suprathermal particles. The spiky turbulence associated with ω_e waves automatically provides for this.[14-15]

(iv) An assessment of the overall efficiency of energy deposition by the beam (i.e. 6-8%) in the experiment was consistent with stabilization by trapping.

In a finite size system an instability can be produced by the coupling of the upper or lower hybrid plasma wave with the negative energy (i.e. slow) wave of the beam. In the weak coupling approximation an absolute instability requires[16]

$$v_1 v_2 < 0 \tag{6a}$$

$$\gamma^2 > \nu_1 \nu_2 \tag{6b}$$

$$L > \frac{(|v_1 v_2|)^{1/2}}{\gamma} \equiv L_c \tag{6c}$$

where (v_1, ν_1), (v_2, ν_2) are the group velocity and damping rate (collisional and collisionless) of the plasma and slow beam wave. The first criterion comes from the requirement that the unstable wavepacket encompasses the origin at all times. The second is the need to overcome the damping, while the third is the requirement for positive feedback. L_c corresponds to the critical length at which an amplifier becomes an oscillator (i.e. oscillator break length). Condition (6a) dictates that the instability should be produced at the upper hybrid wave (ω_o) which is a backward wave. For $\omega_o \approx \omega_e$ we require $\omega_e >> \Omega e$. The growth rate (γ) and v_1, v_2 for the upper hybrid-beam wave intersection are qiven by

$$\gamma = \frac{1}{2}\left(\frac{\omega_b^2 R \cos^2\theta}{\omega_o^2}\right)^{1/2} \omega_o \tag{7a}$$

$$v_1 = V_b \tag{7b}$$

$$v_2 = -2V_b \frac{\Omega_e^2}{\omega_e^2} \cos^2\theta \sin^2\theta \tag{7c}$$

where R is a geometric factor[17] connected with the finite radius of the beam (a) and the plasma (b), ω_b is the beam plasma frequency and

$$\omega_o^2 = \frac{1}{2}(\omega_e^2 + \Omega_e^2) + \left[\frac{1}{4}(\omega_e^2 + \Omega_e^2) - \omega_e^2\Omega_e^2\cos^2\theta\right]^{1/2} \tag{8a}$$

$$\sin^2\theta = \frac{k_\perp^2}{k_z^2 + k_\perp^2} \tag{8b}$$

The value of $k_\perp$ is given by the first root of $J_o(k_\perp b)=0$, i.e. $k_\perp = \frac{2.4}{b}$. Criterion (6a) is trivially satisfied for ω_o, as well as (6b); the condition for absolute instability is basically (6c). From (6c) and (7) we find

$$\omega_b^2 \geq \frac{2\sqrt{2}}{L}\left(\frac{n_b}{n}\right)^{1/2} \frac{\Omega_e V_b}{R^{1/2}} \sin\theta \tag{9}$$

The beam density is given by

$$n_b = \frac{I}{eV_b \pi a^2} \tag{10a}$$

$$a = \frac{V_b \sin\theta_d}{\Omega e} \tag{10b}$$

where $_d$ is the accelerator divergence angle. Noting that in the experiment a<b, the denisty n_o collisionally produced by the beam should be given by the steady state solution for a line source of the diffusion equation, i.e.

$$n_o = \frac{IN\sigma}{2\pi eD} \tag{11}$$

where D is the diffusion coefficient. In comparing Eqs. (11) and (3), we find that they are equivalent if the confinement time is diffusion controlled, i.e. $\tau = \frac{a^2}{D}$.

From Eqs. (9-11) using the fact that $\sigma \sim E_b^{-1/2}$, we find the threshold condition as

$$I \geq I_c = K_1 \frac{E_b^{3/2} D^{1/2}}{p^{1/2} L} \tag{12}$$

where K_1 is a constant including the term $\left(\frac{\sin\theta \sin\theta_d}{R^{1/2}}\right)$, which is very weakly (i.e. less than logarithmically) dependent on the system parameters. It was shown[10] that in the low pressure regime $p < p_o$ the diffusion is consistent with Bohm diffusion so that

$$D = D_B \sim \frac{1}{B} \qquad p < p_o \tag{13}$$

Therefore the scaling predicted by the Papadopoulos conjecture will be

$$I_c \sim \frac{E_b^{3/2}}{p^{1/2} B^{1/2} L} \qquad p < p_o \tag{14}$$

If p_o is the pressure value above which classical diffusion dominates (i.e. $D_B = D(p_o)$), we find that

$$D = D_{c\ell} \sim \frac{p}{B^2} \qquad p > p_o \tag{15}$$

in which case the scaling of I_c is

$$I_c \sim \frac{E_b^{3/2} p^{1/2}}{BL} \qquad p > p_o \tag{16}$$

Eqs. (14) and (16) are consistent with the experimental scaling. In fact[18] even the numerical coefficients, which are omitted here, accurately reproduce the numerical values of I_c. Notice that the relationship $D_B = D_{c\ell}(p_o)$ gives $p_o \sim B$ which seems to agree with Fig. 1.

IV Concluding Remarks

We proceed next to discuss the applicability of the above to other situations, especially the ones involving stronger magnetic fields. We first notice that as discussed before $p_o \sim B$; we therefore expect that for situations where $\omega_e > \Omega_e$ increasing the magnetic field will increase the value of p_o at which the transition to the high density regime occurs. Namely

$$P_o = 15 \left(\frac{B}{G}\right) \mu T$$

This has been observed by Konradi et al[19]. and Bernstein[20], where for $B \approx 38G$ $\frac{1}{p^{1/2}}$ behavior was observed up to the maximum pressure which was 500 μT. Notice that the observed scaling in the experiment was consistent with $\frac{1}{B^{.5}p^{.5}}$ as given by our conjecture[19]. Similar overall scaling was found in Lyakhov et al[21]. For even stronger magnetic fields when $\omega_e < \Omega_e$ at threshold, we would expect different scaling for two reasons. The first is that in this case the ω_e instability lies in the lower hybrid branch and is convective. The second is the possiblility that the beam radius as given by (10b) is too short and other effects (e.g. cathode size, charge neutralization etc.) will control it. To our surprise a recent experiment by Kawashima[22] with $B \gtrsim 1$-1.5 kG, not only shows scaling close to Equ. (14), but also the observed values of I_c are to within less than a factor of two from the predicted ones. The only explanation we can provide is the possibility that reflections from boundaries allow for oscillator behavior under conditions given by Equ. (9). This was actually observed in a BPI experiment by the Steven's group.

Is it possible to spark BPD with a convective instability near ω_e? The answer to this question is an unqualified yes, as long as the system size has many growth lengths for sufficient energy deposition. This would be the case for ionospheric injection. In most of the regions of interest to ionospheric injection $\frac{\omega_e}{\Omega_e} > 1$ without beam ionization. Currents much smaller than in the laboratory will be sufficient to trigger BPD if the Towsend condition is fulfilled since the system is long enough not to require absolute instability. To trigger BPD in the laboratory for $\frac{\omega_e}{\Omega_e} < 1$ with convective amplification would probably require very strong growth in the sense of $\frac{n_\omega}{n_o} \gtrsim O(1)$.

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FIGURE CAPTIONS

Fig. 1 Critical current for BPD ignition as a function of neutral gas pressure for three values of the magnetic field (from Ref. 7).

Fig. 2 Diagram of physical process controlling BPD phenomena.

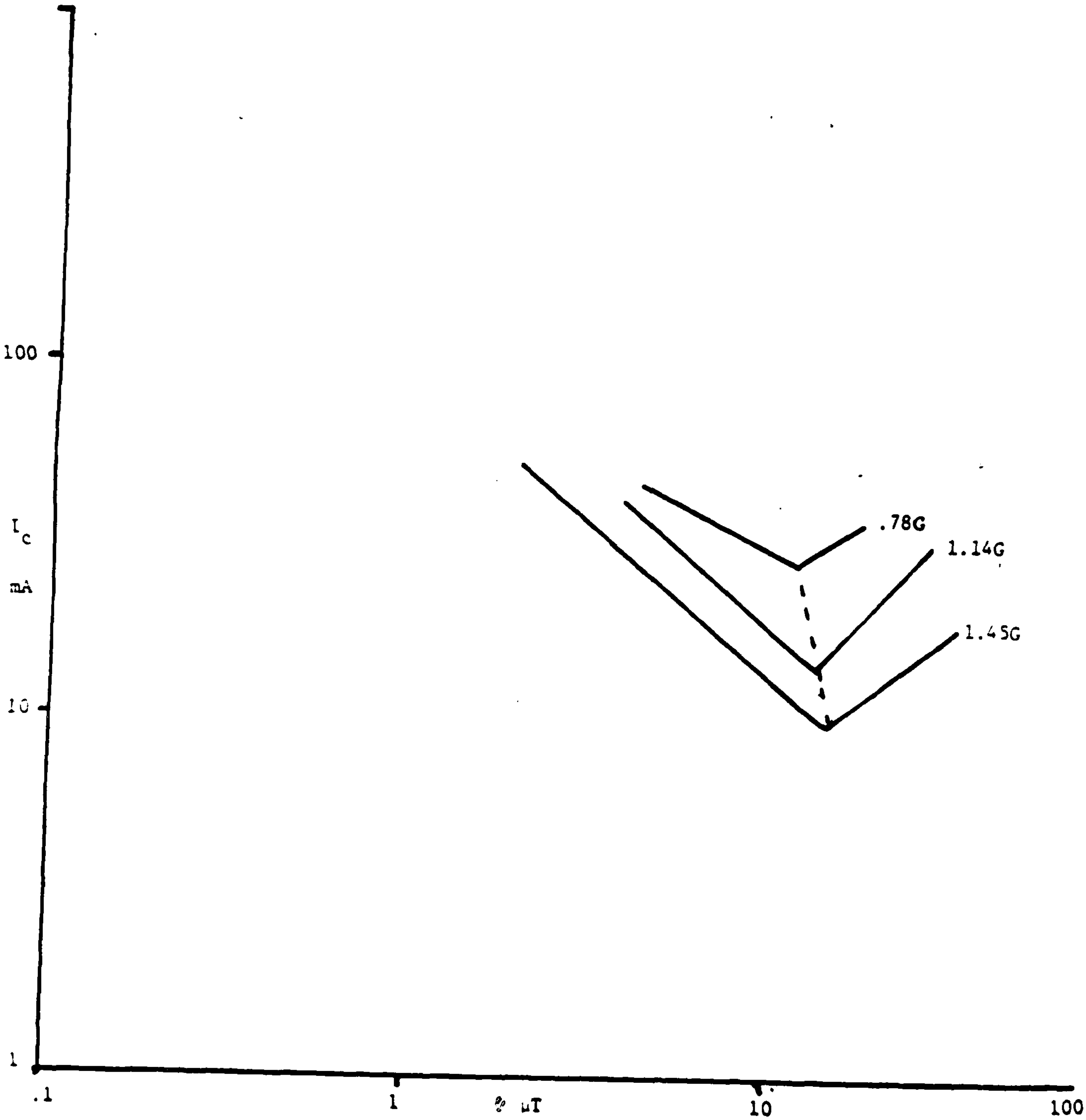
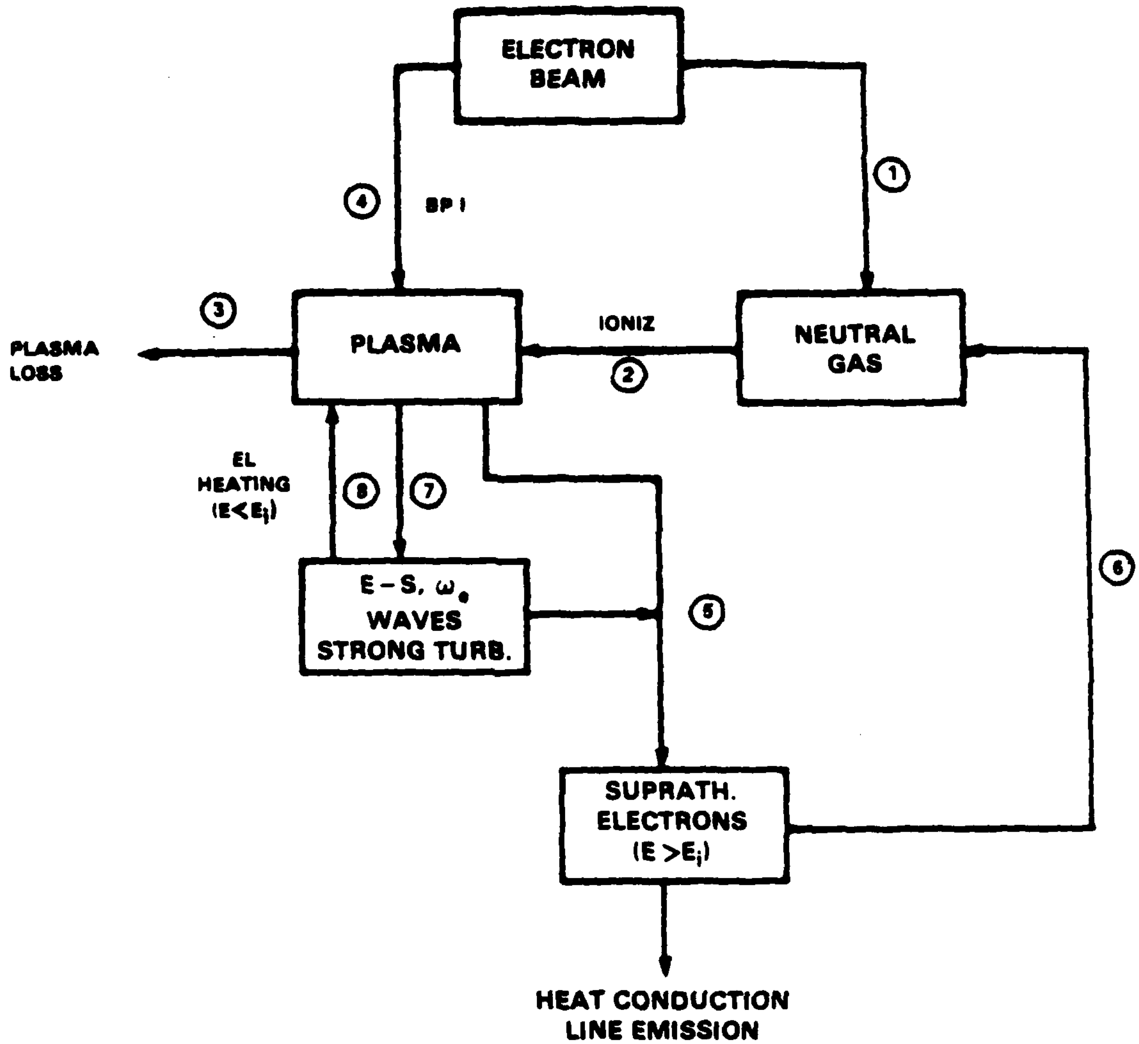


FIGURE 1


ELECTRON
BEAM
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4
BP I
3
PLASMA
LOSS
PLASMA
IONIZ
2
NEUTRAL
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(E<Ei)
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E – S, ωe
WAVES
STRONG TURB.
5
6
SUPRATH.
ELECTRONS
(E >Ei)
HEAT CONDUCTION
LINE EMISSION

FIGURE 2.