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TRANSFER EFFICIENCY OF INTENSE NEUTRAL BEAMS

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ABSTRACT

Intense energetic neutral beams are used for heating plasma in fusion experiments. Here we show that serious attenuation of the beam may occur during transfer of the beam from source to plasma. The critical region is where the beam passes through the input tube and this is immersed in the containment magnetic field of the plasma. For a given set of conditions there is a maximum beam which can be transmitted which is determined by the scale of the tube, the wall re-emission coefficient and the cross-section for ionization of the beam by the gas. Practical examples which are considered show that this limitation may be avoided by careful design.

(To be submitted for publication in NUCLEAR FUSION)

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INTRODUCTION

Intense energetic neutral beams are used for heating plasma in fusion experiments [1,2]. Here we show that serious attenuation may occur during transfer of the beam from source to plasma. The critical region, illustrated in Fig.1, is where the beam passes through the input tube and this is immersed in the containment magnetic field of the plasma. Beam atoms are ionized in collisions with gas molecules, and these ions are deflected onto the tube walls. Further gas is released by this bombardment and this in turn adds to the beam ionization [6]. We find that for a given set of conditions there is a maximum beam current above which the beam power reaching the plasma decreases. Below this value the beam power which can be transmitted is set by the acceptable loss to the walls, or the required overall efficiency. Angular scattering for a beam composed only of atoms is a small effect [3] and is neglected here.

THE MODEL

The fraction of the beam ionized in the tube is $f = 1 - \exp(-nL\sigma)$ where:

n (molecules cm^{-3}) is the mean gas density

L (cm) is the tube length and

σ (cm^{2}) is the cross section for electron loss by a fast atom, in the beam, in collision with a gas molecule, see Table 1.

The rate of change of gas density in the tube is

$$\frac{dn}{dt} = \frac{\gamma}{e}\frac{I}{V} f - \frac{n\,C}{V} + \frac{\phi}{V} \qquad \dots (1)$$

where I is beam intensity in terms of the equivalent current (A)

e is the electron charge, 1.6×10^{-19} coulombs

γ is the number of gas molecules released at the wall per incident ion

ϕ is the gas flow independent of beam current

V (cm^3) is the tube volume.

C (cm^{3}s^{-1}) is the effective pumping speed for removal of gas from the centre of the tube (we assume that the fast ions are deflected in this region).

TIME DEPENDENT SOLUTION

An approximate solution of (1) valid when $f \approx n\sigma L \ll 1$ is

$$n = n_o\left\{\left(\frac{I}{I - I_m}\right) \exp\left(\left(\frac{I}{I_m} - 1\right)\frac{C}{V}t\right) - \left(\frac{I_m}{I - I_m}\right)\right\} \qquad \ldots (2)$$

where

$$I_m = \frac{Ce}{\gamma L \sigma} \qquad \ldots (3)$$

and $n_o = \frac{\phi}{C}$ is the initial gas density. The slow gas flow ϕ is usually from the source or neutraliser. Clearly if $I \geqslant I_m$ the gas density will exponentiate to a high value and a large part of the beam will be ionized before reaching the plasma. I_m is the maximum possible beam intensity which can be transmitted.

EQUILIBRIUM SOLUTION

The time to reach an equilibrium gas density is $\sim \frac{V}{C}$(s), which is typically $\sim 10^{-3}$s and much shorter than the beam pulse length in most applications. Therefore it is the equilibrium solution of (1) that is needed. We set $\frac{dn}{dt} = 0$ in (1) and then

$$n = \frac{\gamma I f}{e C} + n_o \quad . \qquad \ldots (4)$$

Using this equation the fraction of the beam transmitted, $I_t/I = 1 - f$, and the transmitted beam intensity, I_t/I_m, are obtained and are shown in Fig.2(a) and (b) respectively as a function of $\frac{I}{I_m}$ and for various $n_o\sigma L$. The maximum beam that can be transmitted occurs at $I = I_m$ and for $I < I_m$ the gas density reached is $n = \left(\frac{I_m}{I_m - I}\right) \cdot n_o$. To keep the losses below some level f we require

$$I \leqslant \frac{I_m}{f} \cdot \ln\left(\frac{1}{1-f}\right) - n_o \sigma L \quad . \qquad \ldots (5)$$

If high efficiency is the main concern, ie. small f, then the system must be designed to have a large enough I_m for the required I_t, and also $n_o L \sigma$ must be small. Which of these is the more important factor depends on the type of application.

For the case where I_t is known and f is small then

$$f \simeq n_o L\sigma \ (1 - I_t/I_m + n_o L\sigma)^{-1} \quad .$$

PRACTICAL EXAMPLES

To illustrate the problems that can occur we consider two examples; 1) an injection system typical of those currently in use; 2) a system which might be appropriate to a toroidal reactor. The schematic arrangement is shown in Fig.1. In assessing the gas flow we will ignore the streaming component of the gas from the neutraliser and treat the problem using simple molecular flow theory [4]. The conductance of a circular tube of diameter D(cm), length L(cm) for hydrogen gas is

$$C_c = \frac{4.5 \times 10^4 \ D^3}{L} \quad cm^3 \ s^{-1} \quad . \qquad \ldots (6)$$

For rectangular tube of height h(cm), breadth b(cm),

$$C_R = \frac{1.2 \times 10^5 \ (hb)^2}{L(h + b)} \quad cm^3 \ s^{-1} \quad . \qquad \ldots (7)$$

For a short tube, fed by a larger one, we replace, L by L + 1.34D in the circular case, L(b + h) by L(b + h) + 2.67 hb in the rectangular case. Conductance is proportional to $m^{-\frac{1}{2}}$ where m is the molecular weight so that conductance falls for heavier gases.

Example 1. The source operates at 20 kV and a beam of H^+ ions is extracted. The ion beam is neutralized on gas from the source with 70% efficiency, and 20% of the beam is intercepted by apertures, the source gas efficiency is 40%, in consequence the total gas flow from the neutraliser is $\sim \frac{2I}{e}$ molecules per second. Following the neutralizer is a pump of speed S $cm^3 \ s^{-1}$ and the input tube has L = 100 cm, D = 10 cm. The conductance of this tube from pump to plasma is therefore $C_t = 4 \times 10^5 \text{ cm}^3 \text{ s}^{-1}$. The neutral density at the entrance to the input tube is:

$$n_p \simeq \frac{2\ I}{e(C_t + S)} \text{ cm}^{-3} .$$

If we assume that the gas density at the plasma is zero, i.e. the plasma is a good pump, then:

$$n_o = 0.5\ n_p \simeq \frac{I}{e(C_t + S)} \text{ cm}^{-3} .$$

The effective conductance of the tube for gas evolved in it at the centre may be calculated with both ends of the tube pumped, S >> C and plasma pumping, or with only one end pumped

$$C = (2 \rightarrow 4)\ C_c \simeq (0.9 \rightarrow 1.8) \times 10^6 \text{ cm}^3 \text{ s}^{-1}$$

From (3), $I_m = \dfrac{11.25 \rightarrow 22.5}{\gamma}$ (Amperes)

From (5), $I_t = \dfrac{I_m \left(\dfrac{1-f}{f}\right) \ell n \left(\dfrac{1}{1-f}\right)}{1 + \dfrac{C}{\gamma f (C_t + S)}}$ (Amperes)

In Fig.3, the neutral beam intensity reaching the plasma, I_t, is plotted for various values of f and $\dfrac{C}{(C_t + S)}$. The most optimistic value for $C = 1.8 \times 10^6 \text{ cm}^3 \text{ s}^{-1}$ was used in all cases, and $\gamma = 1$ molecule /incident ion.

It can be seen that quite a large pump must be used if transmitted currents of more than 10 amps are to be achieved. With good pumping the slow gas flow becomes unimportant compared to gas evolved from the tube and the result is then sensitive to the value of γ.

Example 2. For a toroidal reactor we can expect that the blanket and coil thickness will lead to L ⩾ 200 cm, and access between the coils will restrict the tube to a rectangular section with h ≃ 100 cm, b ≃ 50 cm. For these dimensions $C_R \simeq 5 \times 10^7 \text{ cm}^3 \text{ s}^{-1}$ for deuterium. We take the slow gas flow into the input tube as $\frac{\alpha I}{e}$ molecules/sec, then from (5) with α and $f << 1$,

$$I_t \lesssim I_m \Big/ \left(1 + \frac{\alpha C}{2\ f\ C_R \gamma}\right)$$

This assumes zero pressure at the plasma. With $C \sim 4\ C_R$, we can identify two regimes. Consider a 500 keV deuterium beam, $\sigma \simeq 10^{-16} \text{ cm}^2$ per molecule.

(i) High slow gas flow, $\alpha > 0.5\,\gamma f$, $I_t \leqslant \frac{2C_R ef}{\alpha L\sigma}$,

for example : $\alpha = 0.1$ $f = 0.01$ $\gamma = 1$ $I_t \leqslant 80$ A

(ii) Low slow gas flow, $\alpha < 0.5\,\gamma f$, $I_t < I_m$,

for example : $\alpha = 0.01$ $f = 0.05$ $\gamma = 4$ $I_t \leqslant 400$ A

Since the gas evolved from the walls may not be hydrogen, and may then have a larger cross section, we must allow that these are optimistic estimates.

Table I

σ for ionization of H^0 of energy E in hydrogen gas [5]. For D^0 multiply E by 2.

E keV	$\sigma \times 10^{-17}$ cm^2/molecule
5	8.2
11	9.2
20	12.8
30	16.0
40	16.0
50	15.8
70	13.8
100	11.6
200	7.2
500	3.2
1000	1.9

CONCLUSION

Re-ionization of neutral beams in the input tube of a fusion device can be a serious problem. We have assumed that none of the neutral beam impinges directly on the tube wall, the situation is clearly worse if this is not the case. Great care must be taken to ensure that adequate pumping is provided and that wall materials have a low gas secondary emission coefficient. For a given input tube and given fractional loss there is a limit to the neutral current which may be injected.

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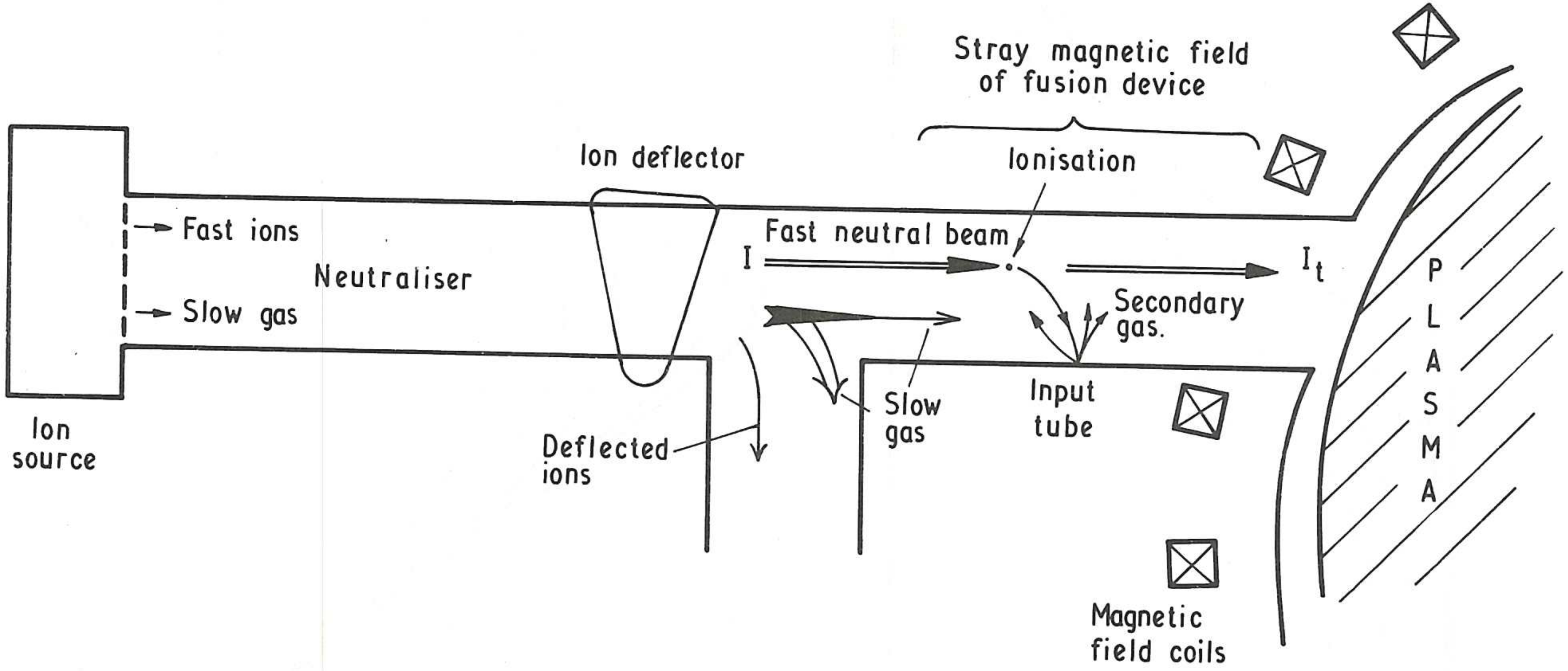

Fig. 1 Illustration of gas evolution in the input tube.

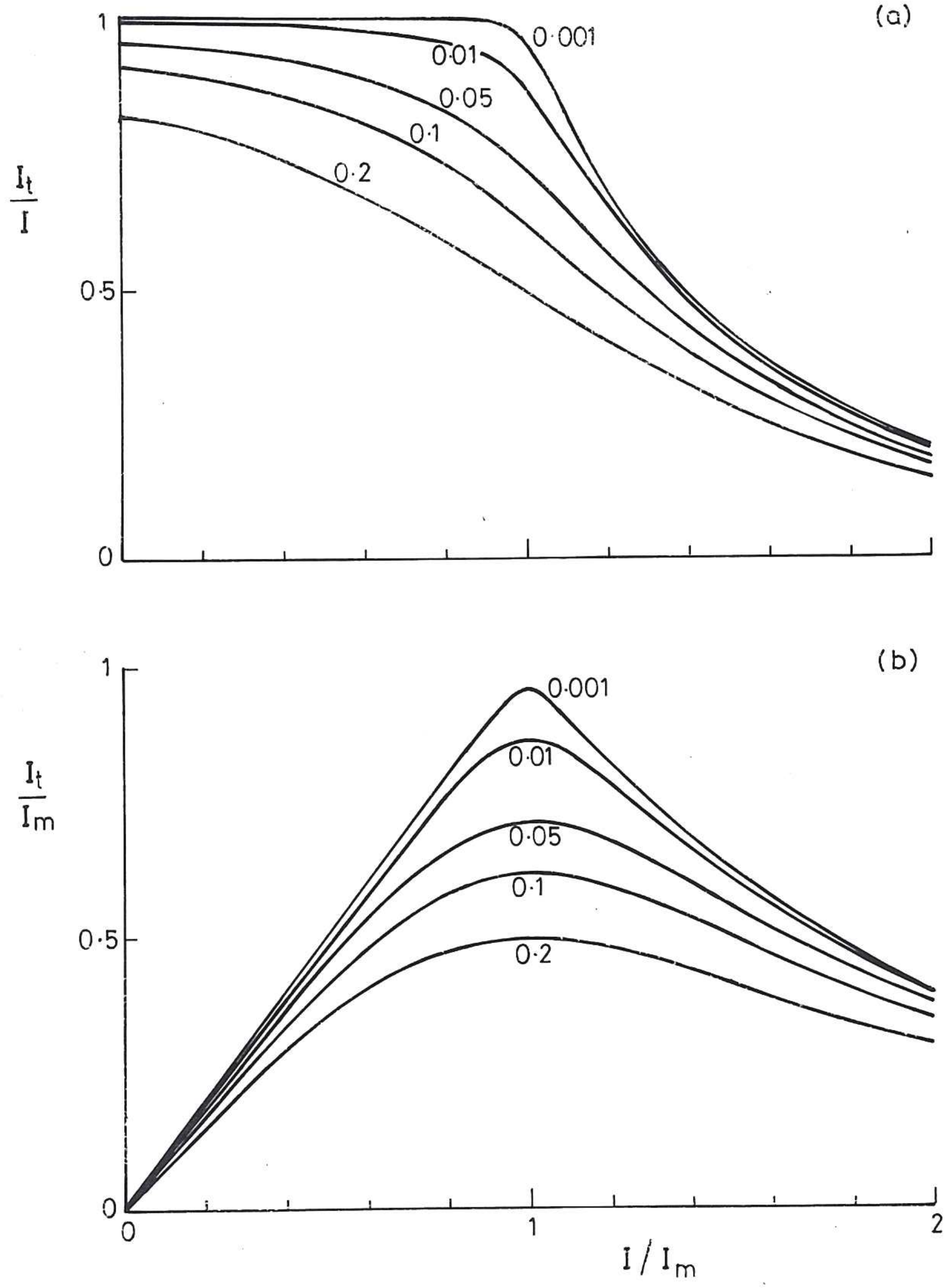

Fig.2 (a) Fraction of beam transmitted, and (b) ratio of transmitted beam to critical current I_m as functions of I/I_m. The parameter is $n_o\sigma L$, the initial background target density.

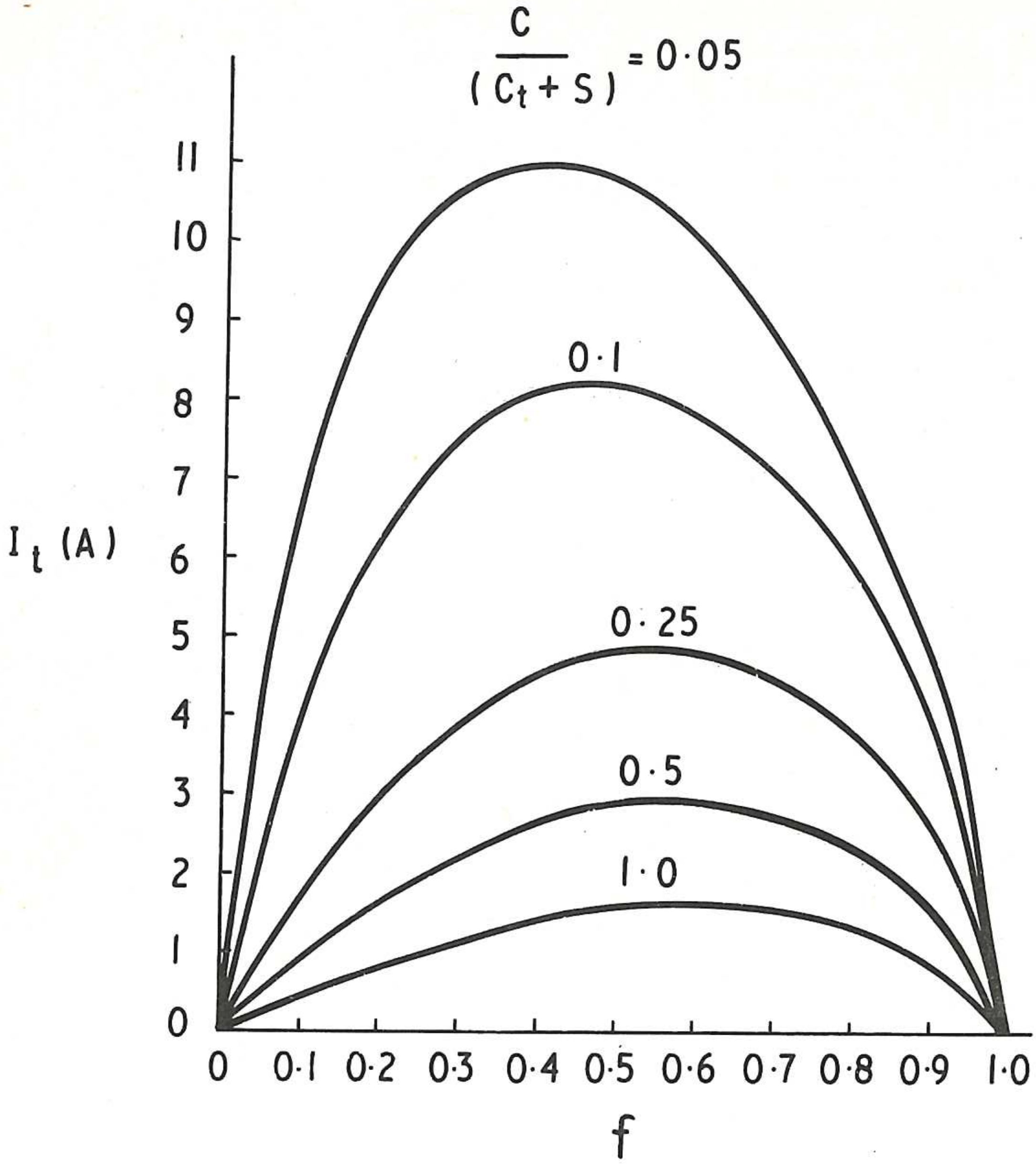

Fig.3 Neutral current I_t reaching the plasma, as a function of the fractional loss (f) and the fraction of slow gas reaching the input tube for example (1).