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0.1 Description of Tokamak Plasma Basics

[referring to previous graphs.] ...The electron impact ionization and charge exchange cross sections have broad peaks at 60 eV and 30 KeV respectively. In the plasma edge region both the electron temperature (600 eV) and the electron density are an order of magnitude lower than in the core. The neutralization reactivity is an order of magnitude greater than that for ionization. As a result, the ionization-to-neutralization ratio for fast ions -- which are the only ones that contribute to plasma heating -- is essentially unchanged between the edge and the core. This is shown in Section 4 below.

From first principles (lateral dynamic stability), the electron density profile must equal the positive ion density profile. The published measured tokamak electron density profile [xx] is reproduced here in Figure xx.

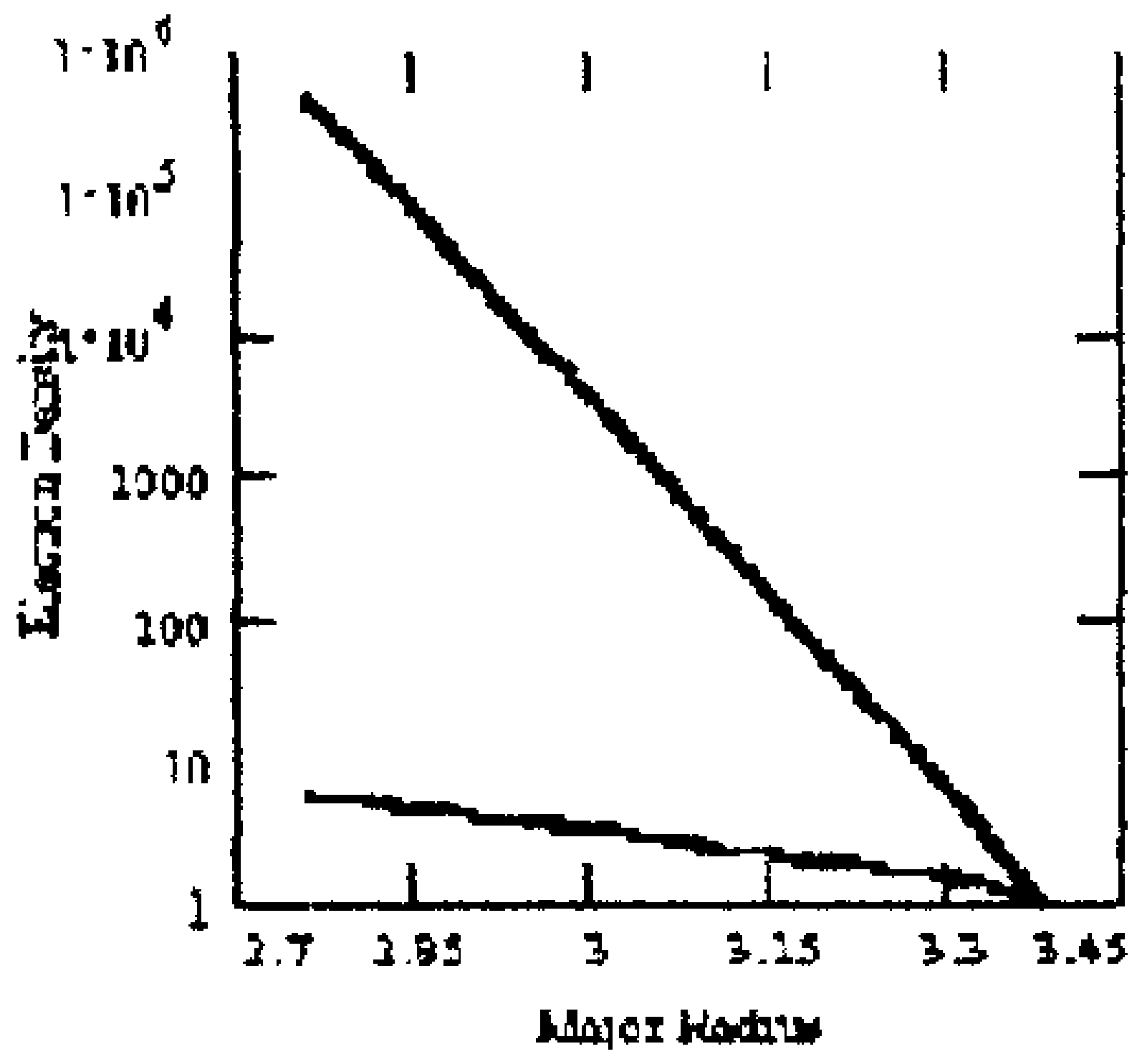

Figure xx. *Lower Curve.* Measured electron density profile [Fig. 8 Ref. xx]. *Upper Curve.* The required density profile for ionization pumping to a vacuum of 0.1 *nanotorr* (schmatic).

At any given point in plasma the ratio of neutralization rate (by charge exchange), I_{10}, to electron impact ionization rate, I_{01}, is *independent* of the slow atom density, n^0. That is, n^0 factors out of the ratio, giving

$$\begin{aligned} I_{10}/I_{01} &- (R_{10}n^{+}n^{0})/(R^{e}_{01}n^{-}n^{0}) \\ &- (R_{10}/R^{e}_{01})(n^{+}/n), \end{aligned} \tag{5}$$

which is independent of the slow atom density.

Let us derive quantitatively the true ratio for Eq.(4).

0.2 Beam dynamics

A neutral beam entering at the edge is a superposition of monatomic, diatomic, and triatomic deuterium and tritium beams. To illustrate the beam ionization dynamics, we will examine the interacting processes, ionization and neutralization, by treating the beam for simplicity as consisting of diatomic neutral deuterium molecules, $D_2{}^0{}_f$, having 100 KeV energy.[1] These molecules will be subject to ionization by electron impact:

$$D_2{}^0{}_f + e^- \rightarrow D_1{}^+{}_f + D_1{}^0{}_f + 2e^- . \qquad (6)$$

We follow first the fate of $D_1{}^+{}_f$. The $D_1{}^+{}_f$ ion will be subject to neutralization by electron capture (electron crossover) in impact with the fast atoms:

$$D_1{}^+{}_f + D_1{}^0{}_f \rightarrow D_1{}^0{}_f + D_1{}^+{}_f \qquad (7)$$

or with the slow atoms and molecules from wall outgassing, which will fill plasma with cold atomic and molecular ions, $D_1{}^+{}_s$ and $D_2{}^+{}_s$:

$$D_1{}^+{}_f + D_1{}^0{}_s \rightarrow D_1{}^0{}_f + D_1{}^+{}_s \qquad (8)$$

$$D_1{}^+{}_f + D_2{}^0{}_s \rightarrow D_1{}^0{}_f + D_2{}^+{}_s , \qquad (9)$$

while the fast neutrals, $D^0{}_f$, fly out or become re-ionized. As will be shown below, their mean free path for re-ionization is much longer than for re-neutralization.

We will calculate below the combined rates of Reactions (6) and (7).

Returning to the fast neutral atom, $D_1{}^0{}_f$ from Reaction (6): it will either fly out of the plasma or be ionized by electron impact:

$$D_1{}^0{}_f + e^- \rightarrow D_1{}^+{}_f + 2e^- \qquad (10)$$

Combined ionization - neutralization rate, Reactions (6 + 7).

Let λ_{01} and λ_{10} be the mean free path against ionization and neutralization, respectively and let L be the distance between the plasma edge and the core center. It can be shown that the ratio of fast ion density to fast atom density in the core is

$$\frac{n_f^+}{n_f^0} = \frac{e^{-\frac{L}{\lambda_{01}}} - e^{-\frac{L}{\lambda_{10}}}}{\lambda_{01} - \lambda_{10}} \lambda_{10} \qquad (11)$$

where

$$\lambda_{01} = \frac{v_f^+}{v_e \, \sigma_{01} \, n^-} \qquad (12)$$

and

$$\lambda_{10} = \frac{v_f}{\sigma_{10} \, v_f \, Z\left(n_f^0 + n_s^0\right)} \qquad (13)$$

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[1] We use here the subscript 'f' for denoting fast and 's' for denoting slow particles.

v^+_f and v^0_f are fast ion and fast atom velocities, respectively, $v_f = v^+_f = v^0_f$, *and* n^- is electron density. For tokamak, Z=2.3 .

	T_e	n^-	R_{01}	T_{D1}	$n_f^0 + n_s^0$	R_{10}	λ_{01}	λ_{10}	n_f^+/n_f^0
units	*KeV*	cm^{-3}	cm^3/s	*KeV*	cm^{-3}	cm^3/s s^{-1}	*cm*	*cm*	
multiply by...		$\times 10^{13}$	$\times 10^{-8}$		$\times 10^{13}$	$\times 10^{-8}$			
EDGE	0.6	1	2.3	50	4	13.2	830	12.6	0.014
CORE	10	6	0.2	35	4		1009	11	0.01

Table 1. Ratio of fast ions to fast atoms, n_f^+/n_f^0, at the edge and at the core center, calculated by evaluating Eq.(11) using cross sections from [13], n_e from [10], $(n_f + n_s) = 4\times10^{13}$, and other parametric values as indicated in the table. Distance from plasma edge to core center taken as $L = 70.$ *cm*.

Let us compute the ratio of fast ion density to fast atom density that results from the passage of neutral fast 100 KeV molecules from the edge to the core center. The medium consists of free electrons and slow and fast atoms, so that the neutral molecules are exposed to electron impact ionization along their path. We neglect the ion impact ionization.. We get the ion-to-atom ratio at the edge to be

$$(n^+_f/n^0_f) - 0.01 \quad . \qquad (14)$$

It can be shown that the contribution from Reactions (8) and (9) with the fast neutral atoms, n^0_f, that were produced in Reaction (6) will give a similar value for this ratio. The combined result is

$$(n^+_f/n^0_f) < 0.02 \qquad (15)$$

as compared to the ratio of 10^6 *asserted* by referee B (Eq.(4)).

Calculating λ_{01} for the core, using T_{D1} = 35 KeV, yields the same ratio as for the edge,

$$(n_f^+/n_f^0) < 0.02. \qquad (16)$$

0.3 Ionization Pumping

Developing the discussion of the previous section led us to learn of the misconceptions on the part of many tokamak physicists that gave rise to their uncritical belief in self-pumping by ionization. In surveying the literature, we find that the last time the problem was looked into was 30 years ago when the ion and electron temperatures considered were in the 100 eV region, the plasma density was low, and the influx from wall impurity influx was insignificant, so that Z=1 was reasonable to assume, compared with Z=2.3 for tokamak today. Under these conditions (comparing with the TFTR conditions) the electron impact ionization is 3 times as much and the charge exchange reactivity is less by a factor of 12.5. The neutralization-to-ionization ratio was then

$$I_{10}/I_{01} = 0.8$$

$$\text{for } T_e = T_{ion} = 100 \text{ eV}, \ Z = 1 \qquad (12)$$

While this is not sufficient for producing ultrahigh vacuum, it does provide some self-pumping. Historically, it gave hope that at greater densities this ratio would increase.

Lawson in 1954 originally derived a criterion for inertial nuclear fusion (the basis for fusion bombs), which is not affected by neutralization. The 'Lawson Criterion' does not contain or even acknowledge the existence of the neutralization (charge exchange) process, although its cross section is 10^8 times that for fusion and 10^3 to 10^5 times that of any other effect. Since that era, it appears that physicists have ignored the neutralization effect; no one has looked into the temperature and density dependencies of the effect. It apparently has not been relevant for inertial fusion.

The temperature and density dependencies of the effect *are* relevant for TFTR conditions, however. The neutralization cross section becomes larger by a factor of 36 at tokamak temperatures, compared with the 100 eV cross section.

It was shown in a series of papers [11, 12] that the Lawson Criterion, originally derived in 1950 for the evaluation and guidance of the inertial fusion project in the United States (the H bomb program), was not valid for magnetically confined thermonuclear fusion. The Lawson Criterion ignores the charge exchange rate term although it is 10^8 times the fusion term.

Based on a review of these papers, in 1976 the *Committee for Peaceful Utilization of Atomic Energy of the USSR* canceled the Soviet tokamak T-20. Since that time, no more tokamaks have been built by the Committee. The support of the Committee for tokamak development was thereafter only nominal, not actual. Construction of two other tokamaks by the USSR, still inoperative, was funded solely by the military, with plutonium breeding as the stated objective.

Citations

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