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PLASMA HEATING IN CLOSED MAGNETIC TRAPS BY INJECTION OF FAST NEUTRAL ATOMS

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One of the methods of heating plasma ions in modern closed magnetic traps is by injecting into the plasma fast hydrogen atoms with energies of several tens or hundreds of keV [1, 2, 12, 13]. The fast neutral atoms are produced by neutralization of an ion beam in a charge-exchange gas target. When these neutral atoms enter the plasma they are ionized, captured in a trap, and transfer energy to the plasma particles, which maintain this energy during a characteristic time τ_e. It is shown in the present article that replacement of the hydrogen atoms by lithium atoms having the same energy makes this plasma heating method much more effective and preferable for use in existing experimental setups and in those under construction. Let us consider the main factors that determine the effectiveness of this method of plasma heating.

1. The rate of energy transfer from a fast ion with energy W to ions and electrons of a plasma is given by the relations [3, 4][1)]

$$\frac{dW}{dt_{ii}} = -1.8\cdot 10^{-7}\,\frac{A_1^{1/2} Z^2 n L}{W^{1/2} A_2}\ \text{eV/sec}, \qquad (1)$$

$$\frac{dW}{dt_{ie}} = -3.2\cdot 10^{-9}\,\frac{Z^2 n W L}{A_1 T_e^{3/2}}\ \text{eV/sec},\ ^{2)} \qquad (2)$$

where A_1 and Z are the mass number and charge of the fast ion, A_Z is the mass number of the plasma ions, L is the Coulomb logarithm, M and m are the masses of the proton and of the electron, n is the plasma concentration in cm^{-3}, and T_e is the electron temperature (we assume below that $A_2 = 1$ and $L = 15$ [3]). The limiting energy at which $dW/dt_{ii} = dW/dt_{ie}$ is [4]

$$W_2 \approx 16 T_e A_1 \ . \qquad (3)$$

When $W < W_2$, the fast ions transfer energy predominantly to the plasma ions, and when $W > W_2$ to the electrons. The time of cooling of the fast ion to $W \approx T_j$, T_e is [12]

$$\tau = -\int_0^W \frac{dW}{dW/dt} \approx 2.6\cdot 10^7\,\frac{A_1 T_e^{3/2}}{Z^2 n}\ln[1 + (W/W_2)^{3/2}] \qquad (4)$$

It is necessary to substitute in (1) - (4) $A_1 = Z = 1$ for protons, and $A_1 = 7$ and $Z = 3$ for lithium ions (it is easy to see that the time that the lithium

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1) The relations used in [2] are in error, since they determine the relaxation time of the translational momentum of the fast ion, and not the energy relaxation time.

2) $W < A_1 M T_e/m$.

atom loses the entire electron shell in a plasma with $T_e \simeq 1$ keV is negligibly small compared with the cooling time; the cross section for the detachment of the first electron by the plasma electron is $\sigma_e \simeq 6 \times 10^{-17}$ cm^2, that of the second is $\sim 3 \times 10^{-18}$ cm^2, and of the third is practically the same as of the second [5, 6]).

2. The range of the neutral atoms prior to ionization in the plasma is

$$\lambda = \left(n\sigma_i + n\sigma_e \frac{v_e}{v_0} \right)^{-1}, \tag{5}$$

where σ_e and σ_i are the cross sections for the ionization of the atom (velocity v_0) by the plasma electrons (velocity $v_e >> v_0$) and ions. The values of σ_i and σ_e for the lithium atoms are 3 - 6 times larger than for the hydrogen atoms [5, 7], and the velocity v_0 (at equal energy) is smaller by a factor 2.7. The lithium atoms have therefore a much lower value of λ.

3. The efficiency of neutralization of the ion beam in the charge-exchange target is $(1 + \sigma_{01}/\sigma_{10})^{-1}$, where σ_{10} and σ_{01} are the cross sections for the neutralization of the ion and stripping of the atom by the target atoms. σ_{01} amounts to $\sim 10^{-16}$ cm^2 [8 - 10]. σ_{10} decreases rapidly with increasing ion velocity [8 - 10], as a result of which the neutralization efficiency at W = 100 keV does not exceed 0.2 in the case of the hydrogen ion [8] and amounts to ~ 1 in the case of the lithium ion (on K, Na, and Li vapor) [9 - 10].

Let us consider now a typical trap of the Tokamak type [11] ($n \simeq 5 \times 10^{13}$ cm^{-3}, $T_i \lesssim T_e \simeq 1$ keV, $\tau_e \simeq 10$ msec, minor diameter of the torus $d \lesssim 40$ cm. It is required to heat the plasma ions to a much higher temperature, but naturally under the following conditions: the ion heating time is smaller than or equal to τ_e, the range of the injected atom prior to ionization in the plasma is $\lambda \lesssim d$ (it is assumed that the productivity of the ion source, if utilized fully enough, is sufficient to heat the plasma). Let us consider first the "lithium" variant of heating at $W = W_2 \simeq 110$ keV. In this case, according to (4), the lithium ions will transfer within a time $\tau \simeq 8.5$ msec $< \tau_e$ the greater part of their energy to the plasma ions. According to (5), the length for ionization (capture in the trap) of the lithium atoms ($v_0 \simeq 1.8 \times 10^8$ cm/sec, $\sigma_i \simeq 4 \times 10^{-16}$ cm^2 [7], $\sigma_e \simeq 6 \times 10^{17}$ cm^2 [5]) is $\lambda \simeq 20$ cm $< d$. In the "hydrogen" variant of heating, at the same energy $W \simeq 110$ keV, it is the electrons that are mainly heated, according to (1) - (4) (with a characteristic time $\tau \simeq 50$ msec $>> \tau_e$). The rate of plasma ion heating will be smaller in this variant by a factor 24, and within the energy time τ_e only about 4% of the energy of the fast protons captured in the trap will be transferred to the plasma ions. The coefficient for the capture of these particles in the trap also turns out to be small, since (at $v_0 = 4.7 \times 10^8$ cm/sec, $\sigma_i \simeq 1.4 \times 10^{-16}$ cm^2, $\sigma_e \simeq 1 \times 10^{-17}$ cm^2) [7], according to (5), $\lambda \simeq 110$ cm $>> d$. In addition, the coefficient of neutralization of the ion beam in this variant amounts to only ~ 0.2. Consequently, the efficiency of the "hydrogen" variant of heating in a typical experimental situation is quite low.

Thus, the main factors that determine the efficiency of the considered plasma-heating method turn out to be much more favorable in the "lithium" variant of the method. This variant is therefore preferable for use in the existing installations of the Tokamak type and those under construction.

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