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ION LIFETIME IN THE TOKAMAK-3 MACHINE

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In closed magnetic traps of the Tokamak type, where the plasma loop is heated by current flowing through it and is stabilized by a strong longitudinal magnetic field, an important characteristic of the thermal insulation of the plasma is the average time of retention of the thermal energy in the ionic component, τ_{Ei}. By introducing this quantity, we can write down the equation of energy balance for the ions per unit volume, in the form

$$0{,}4 \cdot 10^{-17} \frac{n^2}{AT_i^{1/2}} = \frac{3}{2} nk \frac{dT_i}{dt} + \frac{3}{2} nk \frac{T_i}{\tau_{Ei}}, \qquad (1)$$

where A is the atomic weight of the material (hydrogen or deuterium), T_i the ion temperature in °K, and n is the plasma density. The left-hand term of the equation represents the energy transferred from the electrons to the ions by Coulomb collisions per second and per cm^3. This term does not include the electron temperature T_e, since the heat flux from the electrons to the ions depends very little on T_e in the range $T_e/T_i = 1.6$ to 10. Under the conditions of the experiment, the ratio T_e/T_i always lies in this interval. Equation (1) is valid in the case when the ions are heated mainly by heat exchange with electrons vial Coulomb collisions. Many experimental facts indicate that this assumption is valid if the plasma density is not too low (cf., e.g., [1]).

The figure shows the variation of the quantities T_i, n, and τ_{Ei} during the time of the discharge pulse in the T-3 Tokamak, for the central zone of the plasma pinch. The values of τ_{Ei} were calculated with Eq. (1), in which we substituted the ion temperature measured by analyzing the energy spectrum of the charge-exchange atoms, and the density was determined from radio-interferometry data. It follows from (1) that in the stationary state, i.e., in the time interval when the temperature is close to the maximum, we have

$$\tau_{Ei} \approx 50A(T_i^{3/2})/n.$$

It follows hence, in particular that the ratio of τ_{Ei} to the average time interval between two Coulomb ion-ion collisions is a constant quantity for the given species of ions, and is independent of T_i or of n.

The loss of thermal energy from the ionic component of the plasma are due to (i) thermal conductivity, (ii) diffusion, and (iii) charge exchange of the ions with the residual gas. Consequently

$$\frac{1}{\tau_{Ei}} = \frac{1}{\tau_t} + \frac{1}{\tau_d} + \frac{1}{\tau_c}, \qquad (2)$$

where τ_t is the energy conservation time due to the thermal conductivity, τ_d is the diffusion lifetime (or the lifetime of the charged particles, and τ_c is the lifetime of the ions relative to charge exchange. A comparison of the times entering in (2) characterizes the contributions of the foregoing three processes to the ion heat losses. τ_c and τ_d are given by

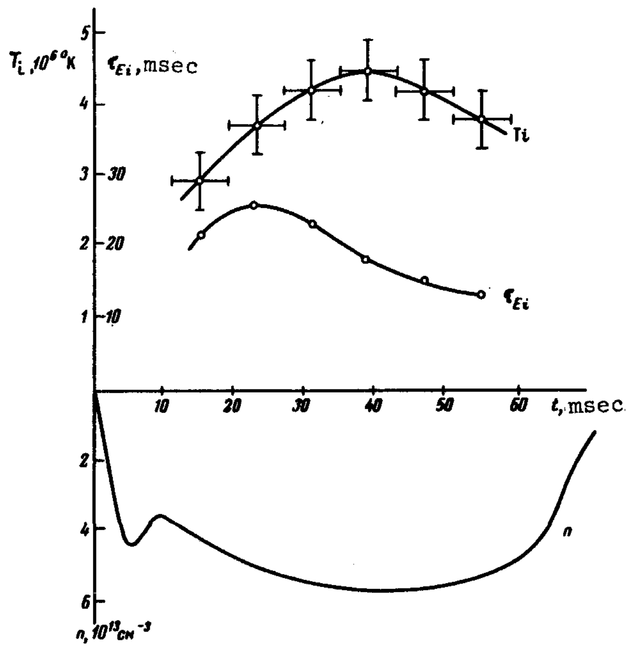
$$\tau_c = \frac{1}{n_a < \sigma v >_c},$$

$$\frac{dn}{dt} = n n_a < \sigma v >_i - \frac{n}{\tau_d}$$

(for a purely conducting plasma). In the stationary case we have

$$\tau_d = \frac{1}{n_a < \sigma v >_i}$$

In these expressions, n_a is the density of the hydrogen or deuterium atoms in the axial region of the plasma, $<\sigma v>_c$ and $<\sigma v>_i$ are the products, averaged over the Maxwellian distributions of the velocities, of the cross sections for resonant charge exchange and ionization of the atoms by the electrons, by the velocities of the ions and electrons, respectively.



Ion temperature T_i, energy lifetime of the ions τ_{Ei}, and plasma density n as functions of the time in the Tokamak-3 (all the parameter pertain to the axial region of the plasma). Discharge conditions: deuterium, discharge current 120 kA, longitudinal magnetic field 36 kOe.

The quantity n_a, which enters in (3) and (4), was measured in the Tokamak TM-3 machine by registering the absolute intensities of the hydrogen Balmer lines [2]. No such measurements were made with the T-3 machine; However, it is possible here to estimate the value of n_a from the absolute flux of the charge-exchange atoms emitted from the axial region of the plasma. Indeed, the flux of charge-exchange atoms emitted isotropically from 1 cm^2 of the surface of a plasma cylinder of radius a_0 is equal to

$$I_0 = \frac{1}{2} n n_a < \sigma v >_c a_0 \quad . \tag{5}$$

The energy distribution dn_0/dE of the charge-exchange atoms emitted by the interior regions of the plasma can be obtained with the aid of an atomic analyzer in an absolute scale in the energy range from 500 - 700 eV to several keV. It has a Maxwellian form with a temperature T_0 close to the maximal ion temperature of the plasma, and equal, under typical experimental conditions, to 300 - 400 eV for deuterium and to 500 eV for hydrogen. Extrapolation of such a distribution to zero energy after Maxwell, integration by the formula $\int_0^\infty (dn_0/dE)\, v \, dE$, and allowance for the geometry of the input collimator of the atomic analyzer make it possible to determine the value of I_0. As to a_0, it is equal to the radius of that axial zone of the plasma, which emits the measured flux of atoms I_0. The value of a_0 is thus defined by the fact that the ion temperature of the plasma within this radius must be close to the maximum temperature. Recent measurements performed with the T-3 of the plasma temperature distribution over the cross section of the plasma loop, using Thomson scattering of light by the electrons, have shown that a noticeable temperature drops occurs at distances larger than 10 cm from the loop axis [3]. At closer distances from the axis, the temperature decreases towards the periphery by less than 10%. This fact gives grounds for assuming the value $a_0 \approx 10$ cm for estimates of n_a by means of formula (5).

The values of n_a obtained in this manner for typical T-3 regimes in the period of time when $dT_i/dt = 0$ fall in the range $n_a \approx (1.5 - 3) \times 10^8$ atoms/cm^3. We note that for the TM-3 machine, calculations of this kind yield $n_a \sim 10^9$ atoms/cm^3, which is in good agreement with the corresponding quantities obtained by spectroscopic methods. Using the values $\langle\sigma v\rangle_i = 1.5\times10^{-8}$ cm^3/sec (for T_e = 1000 eV) and $\langle\sigma v\rangle_c = 4\times10^{-8}$ cm^3/sec (for T_{deut} = 300 - 400 eV) we obtain from formulas (3) and (4) a value of τ_d in the range (0.22 - 0.45) sec, and a value of τ_c in the range (0.085 - 0.17) sec. A comparison of these quantities with the value of τ_{Ei}, which amounts to ~17 nsec near the maximum of T_i, shows that the diffusion and charge exchange in the axial region of the plasma pinch in the T-3 accounts for not more than 20% of the total thermal loss, and that the bulk of the heat is lost by the ions through heat conduction.

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EXPERIMENTS WITH LARGE VALUES OF β_I IN TOKAMAK-3

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Experiments aimed at studying the plasma in the Tokamak devices have usually been performed under discharge conditions when β_I, the ratio of the mean gas-kinetic pressure of plasma $\bar{P}$ to the pressure of the magnetic field of the discharge current, $H_\phi^2/8\pi$, is much smaller than unity.

The only exception is a narrow region on the decreasing section of the current, where it turns out that H_ϕ^2 decreases more rapidly than $\bar{P}$ and regimes with $\beta_I > 1$ become possible.

One such regime of the T-3 apparatus was presented, for example, in [1].

There is nonetheless a widely held opinion that all the experimental results obtained with Tokamaks pertain to regimes with $\beta_I < 1$, and that when $\beta_I > 1$ the plasma pinch should be magnetohydrodynamically stable.

On the other hand, the existing magnetohydrodynamic theory of the equilibrium of a plasma pinch [2, 3] imposes limitations on the value of β_I only at the level of R/a (R is is the major radius and a the minor radius of the torus), amounting usually to 7 - 10.

A check on this assumption was of interest and was undertaken with the Tokamak-3 apparatus [4] with r = 10 - 15 cm and R = 100 cm.

Attention was paid to the fact that, strictly speaking, the theory imposes a limitation not on β_I, but on the sum $L/2 + \beta_I$ (L - inductance of plasma pinch per unit length), which in this case plays the role of the effective β_I^*. On the other hand, L breaks up into two parts, external $L_{ext} = 2\ln(b/a)$ b - radius of copper jacket) and internal, ℓ_i, characterizing the fraction of the energy of the magnetic field of the current, contained in the volume of the plasma pinch.

If the change of current I occurs within a time shorter than its skinning time in the plasma pinch ($\tau_{sk} = 4\pi\sigma a^2/c\mu_1^2$, $\mu_1^2 = 3.83$), in other words, if the magnetic energy is frozen in its volume, then the new value of the inductance **is** $L' = L_{ext} + \ell_i(I_1/I_2)^2$; ($I_1$ is the initial value of the discharge current, and I_2 is its value after the change).

On the other hand, if the plasma internal energy does not have time to change in this case, then the new value is $\beta' = \beta_1(I_1/I_2)^2$, and the effective value is

$$\beta_I^* = L_{BH}/2 + (l_i/2 + \beta_I)(I_1/I_2)^2.$$