Measurement of the local ion parameters in the Tokamak-4 plasma

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An active corpuscular diagnostic method involving injection of an atomic beam into a plasma was used, for the first time, to show the possibility of measuring a local ion temperature by the scattering of atoms on ions. Temperature and ion density distributions along the plasma radius are obtained by means of ion charge exchange on an artificial target consisting of beam atoms.

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An atom injector,[4] multi-channel atomic particle analyzers[5] and several beam detectors were used for measurement using a method involving charge exchange on an artificial target[1,2] and scattering of an atomic beam by the plasma ions (Fig. 1). The design provides for independent scanning of the plasma pinch cross section by an atom injector 1 and atomic particle analyzers 2 and 3. This permitted experimentation on the scattering of an atomic beam by the plasma ions over a range of angles θ_{scat} from 0 to 16°, and other experiments involving charge exchange on an artificial target over practically the entire cross section of the plasma pinch (the pertinent portion of the latter is shown cross-hatched in Fig. 1). We used He^0, H^0 and D^0 atomic beams with the following parameters: energy $E_a = 8$–11 keV, pulsewidth $\tau_\pi = 200$ μsec, equivalent current density at the center of Tokamak-4 $j_a = 10$–30 mA/cm^2.

In the case of small-angle θ scattering of a monoenergetic atomic beam by the plasma ions, for which the atomic velocity v_a is much greater than ion thermal velocity v_{iT}, the ion temperature T_i is related to the broadening of the energy profile of scattered atoms at half maximum ΔE as follows[3]

$$T_i = \frac{1}{16\ln 2}\,\frac{m_2}{m_1}\,\frac{(\Delta E)^2}{E_a\theta^2}, \tag{1}$$

where m_1 and m_2 are masses of the beam atoms and plasma ions, respectively. If, however, condition $v_a \gg v_{iT}$ is unfulfilled, the relationship between T_i and ΔE becomes more complex and the dependence of T_i on ΔE must be evaluated numerically.

To measure T_i from scattering we used a He^0 atomic beam. This is more convenient than H^0 and D^0 beams since it generates practically no background associated with reverse charge exchange of ions formed from an atomic beam, and it has a higher scattering cross-section. In addition to this, a helium beam produces a better separa-

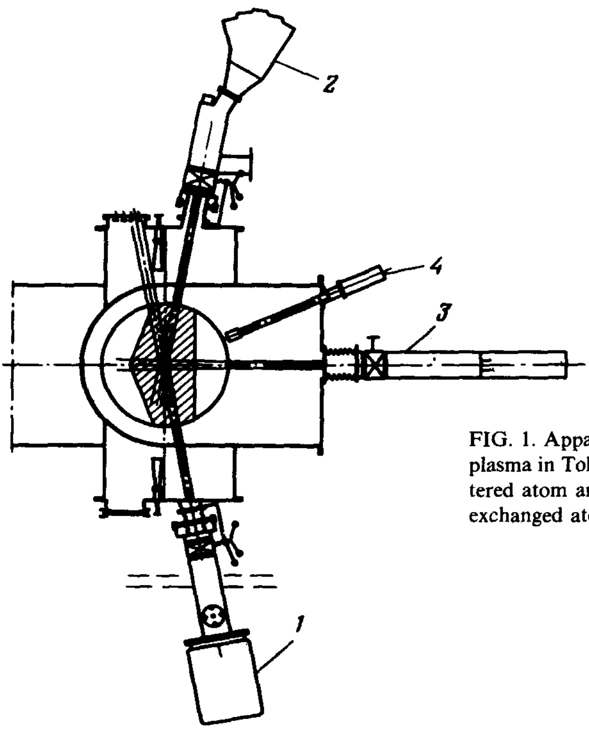

FIG. 1. Apparatus for the corpuscular diagnostics of a plasma in Tokamak-4. 1—atom beam injector, 2—scattered atom analyzer, 3—analyzer of artifically charge-exchanged atoms, 4—moveable beam detector.

tion of peaks that correspond to scattering on hydrogen and impurity ions.[6] Figure 2 shows the results obtained from scattering. Evidently, the increased temperature of the target-particle leads to curve broadening and increased average energy of scattered atoms. The latter is due to the fact that is our experiment v_a was just 3 times greater than v_{iT}. The experimental curve is in a good agreement with the calculated one corresponding to $T_i = 210$ eV. The error in determining T_i—based on the best fit of calculated and experimental curve—is not greater than ± 15 eV. Clearly, no significant signal that corresponds to impurity scattering is present.

In the experiments on the charge exchange of plasma ions due to the injected atomic beam, the resultant flux of atoms J_{act} is recorded against the background of a flux of atoms J_0 which occur due to ion charge exchange on atoms that are naturally present in a plasma. The ratio of the two fluxes for an energy of recorded atoms E is as follows:

$$\frac{J_{\text{act}}}{J_0} \sim \frac{n_\Pi(s_1)N(s_1)\sigma_\Pi(E_a)E_a^{1/2}\,\phi_i(E_1 s_1)L_\Pi \exp(-\tau(s_1, a))}{\int_0^L n_0(s)N(s)<\sigma_\Pi v_{\text{rel}}>\phi_i(E,s)\exp(-\tau(s,a))\,ds}, \quad (2)$$

where n_π and n_0 are atom concentrations in the beam and plasma, N is the proton concentration in the plasma, ϕ_i is the proton energy distribution function, s_1 is the coordinate of a plasma test volume, L_π and L are dimensions of the beam and plasma

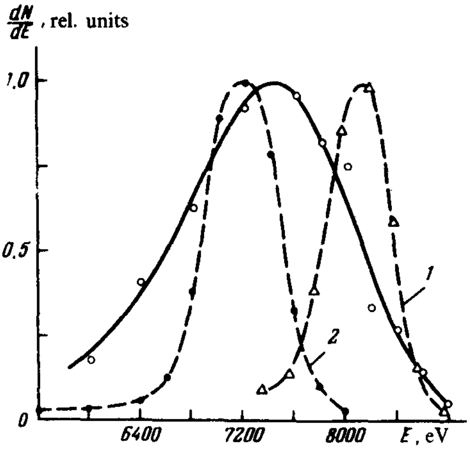

FIG. 2. Energy profiles for the scattering of He° atomic beam in a hydrogen plasma at a point 8 cm from the chamber center. 1—$\theta = 0°$ (initial beam profile); 2—$\theta = 9°$—scattering in a gas prior to discharge; 0—$\theta = 9°$—scattering in a plasma; solid curve—calculated for $T_i = 210$ eV. For convenience of comparison, line maxima were normalized.

in the direction of observation, $\tau(s,a)$ is the "optical thickness' of the plasma that confronts the atoms along a path from point s to the plasma boundary, a is the radius of the cross section of the plasma pinch, σ_π is the cross section of resonant charge exchange, $v_{\rm rel}$ is the relative velocity of ions and atoms, and $\langle\sigma_\pi v_{\rm rel}\rangle$ is the rate of charge exchange averaged with respect to the Maxwellian energy distribution of plasma ions.

The method in question provides that the beam atoms are used only as targets for the charge transfer of the plasma ions and are not to be recorded by the atom analyzers. Thus, a deuterium beam was injected into the hydrogen plasma and a five-channel

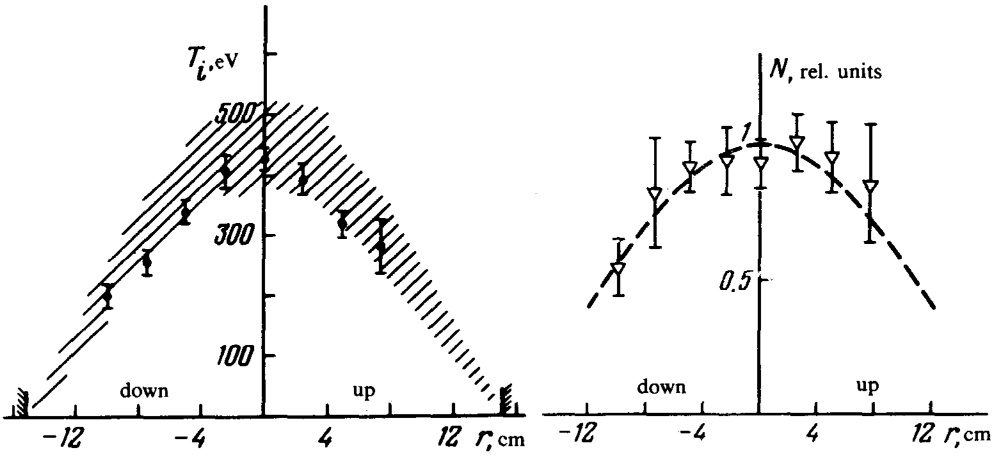

FIG. 3. a—Distribution of ion temperature T_i along plasma pinch radius r in the case of scanning with respect to equatorial plane of test chamber. ●—experimental results of charge transfer at an artifical target, cross-hatched area—results of calculations. Discharge conditions: current $I = 90$ kA, electron concentration $\bar{n}_e = 2\times10^{13}$ cm^{-3}, longitudinal magnetic field $H = 31$ kOe, electron temperature in center of a plasma $T_e(0) = 1$ keV; b—proton density distribution N along plasma pinch radius r under the same conditions, dotted curve—the $(I-(r/20)^2)^2$ parabola.

atom analyzer was used to provide for mass analysis and separation of the H^0 charge-exchange atoms from D^0 beam atoms.

In the experiment [with the foregoing beam parameters and a relatively-high (2–3×10^8 cm^{-3}) atom concentration in the Tokamak-4 plasma] the J_{act}/J_0 ratio attained a value of 2. Figure 3a shows the experimental radial profile of T_i and the calculated distribution $T_i(r)$. Coulomb heating of the ions and their cooling due to neoclassical heat transfer was assumed in the calculations. The foregoing range of results of calculations of $T_i(r)$ is associated with uncertainty in the value of the effective charge of the plasma, margin of plasma stability, and atom concentration at the plasma pinch boundary. Satisfactory agreement between experimental and calculated results indicates the classical nature of the ion energy balance in Tokamak-4.

Measurement of the beam intensity and flux of hydrogen atoms that occur in the course of proton charge exchange in the beam, provides a method of determining the proton density distribution $N(r)$ in the plasma. Figure 3b shows an example of the experimental profile of $N(r)$.

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