MEASUREMENT OF THE LOCAL VALUES OF THE ION TEMPERATURE IN A TOKAMAK USING CHARGE EXCHANGE OF PLASMA IONS WITH A JET OF HYDROGEN ATOMS

V. V. Afrosimov, M. P. Petrov, and V. A. Sadovnikov
A. F. Ioffe Physico-technical Institute, USSR Academy of Sciences
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We describe a method for measuring local plasma-ion energy distribution, based on injection of a stream of hydrogen atoms into the plasma and using this stream as an artificial target for resonant charge exchange of the ions. The first results of the use of this method with the Tokamak-6 installation are presented.

One of the most important problems of plasma diagnostics is the measurement of local energy distributions and temperatures of the plasma particles. While this problem has been solved for electrons by using Thomson scattering of laser light by the electrons, the situation with ions is much more complicated. There have been practically no measurements of the local parameters of the ion component in a hot plasma to this day. Yet it is these parameters which are needed to determine the mechanisms whereby ions are heated or lose heat.

We describe here briefly one of the possibilities of measuring local ion parameters in a plasma (energy distributions, ion temperature T_i, ion density n_i) and the first results of its realization with the Tokamak-6 installation [1]. The experimental setup is shown in Fig. 1. A special injector 3 was used to inject into the plasma a collimated jet of fast hydrogen atoms 4. The main process of interaction between the jet and the hydrogen plasma is resonant charge exchange of the plasma ions with the atoms of the jet. The atoms produced by the charge exchange come from a small plasma volume 5 and enter a five-channel atomic analyzer 7 equipped with a narrow collimator 6. The energy distribution of the charge-exchange atoms entering the analyzer when the atom jet interacts with the plasma corresponds to the energy spectrum of the ions; in the case of a Maxwellian distribution it corresponds to the ion temperature T_i in the small volume 5. By rotating the analyzer axis relative to the equatorial plane of the toroidal chamber, as shown in Fig. 1, one can measure the values of T_i along the jet of the atoms, i.e., obtain the distribution of T_i over the cross section of the plasma filament.

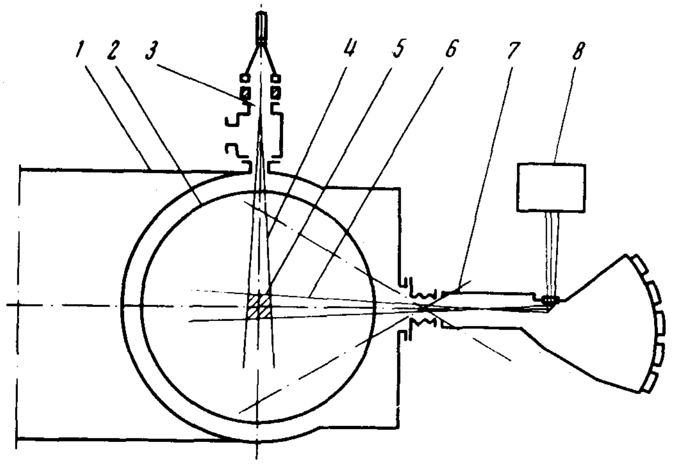

Fig. 1. 1 – Toroidal chamber of Tokamak, 2 – plasma boundary, 3 – injector, 4 – atom jet, 5 – investigated plasma volume, 6 – collimator of atomic analyzer, 7 – five-channel atomic analyzer, 8 – optical monochromator. The dash-dot lines show the limiting positions of the analyzer axis.

We used a pulsed plasma injector of the conical type [2]. During the preliminary tests performed by us at the A. F. Ioffe Institute, we found that such injectors produce under specially chosen conditions not only dense plasmoids but also intense streams of hydrogen atoms. We obtained and investigated atomic jets with average energy 30 – 150 eV and hydrogen atom concentration $n_a \simeq 10^{11}$ cm^{-3}. The jet lifetime was $\tau \simeq 5$ µsec. Tests had shown that there were no impurity atoms in the fast atomic jet; the impurities started to flow from the injector only several dozen microsecond later, and in negligible amounts.

During the first phase of the experiments on the injection of atomic jets into the plasma of the Tokamak 6, we investigated the effect of injector operation on the plasma. The strong longitudinal magnetic field of the Tokamak prevented the plasmoid that accompanied the stream of atoms from the injector from penetrating into the plasma. Experiments have shown that the rapid atomic jet from the injector exerts no influence on the plasma stability, on its concentration, on the conductivity, and other measureable plasma parameters. Only the stream of cold gas from the injector, which reaches the plasma several hundred microseconds after the fast atomic jet, leads to a noticeable increase of the plasma concentration, to a decrease of the conductivity of the plasma filament, and sometimes to an instability of the "breakdown" type [1]. None of this, of course, interferes with correct measurements during the instant of passage of the fast atomic jet.

During the principal phase of the experiments, we injected into the Tokamak-6 plasma a jet of hydrogen atoms of average energy 30 — 50 eV. The five-channel atomic analyzer registered simultaneously the flow of charge-exchange atoms at five different energies. This made it possible to obtain in one injector pulse the energy distribution of the plasma ions in the volume 5 (Fig. 1) for five points. Simultaneously with the charge-exchange atoms we measured the absolute intensity of the spectral line H_β produced as a result of excitation of the jet atoms by the plasma electrons and emitted from the same volume. The measured light passed through the analyzer collimator and was directed to monochromator 8 by a prism located at the end of the analyzer (Fig. 1). Oscillograms of the intensity of the H_β line and of the flow of atoms of five different energies, obtained during one injector pulse, are shown in Fig. 2.

The diameter of the atomic jet in the plasma on the axis of the plasma filament was determined by registering the intensity of the H_β line following displacement of the analyzer collimator axis in the equatorial plane of the toroidal chamber, and found to equal ~ 5 cm, so that the measurements can be regarded as local. The absolute intensities of the H_β line have made it possible to estimate for each injector pulse the concentrations of n_a of the jet atoms in the investigated volume 5, which amounted under the given geometrical conditions to $V \simeq 10$ cm^3. The value of n_a was calculated by the method described in [3], with allowance for the plasma-electron concentration n_e on the axis of the plasma filament, which was measured with a radio-interferometer. The optical measurements have shown that the atom concentration in volume 5 was $n_a = (2 - 4)\times 10^{10}$ cm^{-3} when the jet passed through the plasma.1)

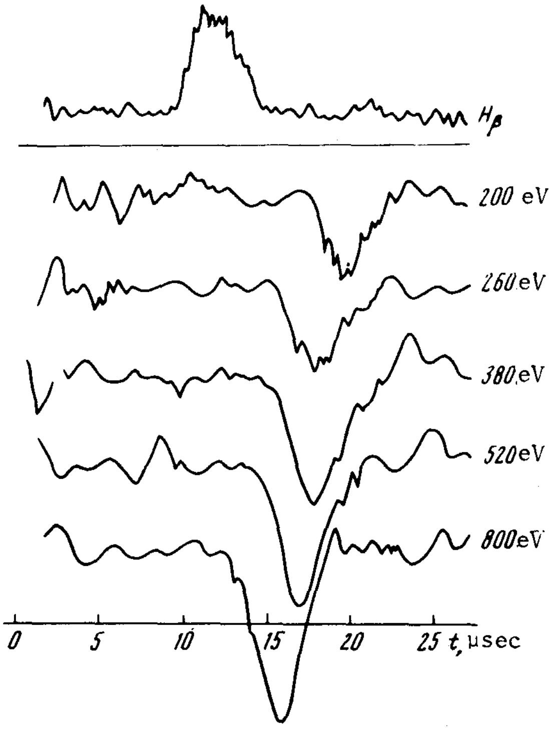

Fig. 2. Oscillograms of the intensity of the H_β line (top trace) and of the flow of charge-exchange atoms of five different energies, obtained by passage of the atomic jet through the plasma.

The energy distributions of the atoms emitted from the plasma interacting with the atom jet was measured in the energy range 200 - 800 eV. The distributions turned out to be Maxwellian in this range, with $KT \leq 200$ eV. Unfortunately, the regions of lower atom energies, where the maxima of the Maxwellian distributions should be observed, have not yet been investigated in detail. However, a comparison of the calculated flux of the charge-exchange atoms from volume 5 with the experimentally registered flux gives grounds for assuming the plasma ion energy distribution in this volume to be Maxwellian in the entire energy range. Indeed, under this assumption the number of charge-exchange atoms entering the analyzer when the jet passes through the plasma is given by

$$N = n_i n_a < \sigma v >_c V \frac{\omega}{4\pi} \tau . \qquad (1)$$

Here n_i is the concentration of the ions in volume 5 (we have assumed $n_i = n_e$ in the calculation), $<\sigma v>_c$ is the product of the resonant-charge exchange cross section by the ion velocity, averaged over the

Maxwellian distribution, and ω is the solid angle of the analyzer collimator. At $n_i = 2\times10^{13}$ cm^{-3} (radio-interferometer measurements), $n_a = 3\times10^{10}$ cm^{-3} (optical measurements)[1], $\langle\sigma v\rangle_c = 5\times10^{-8}$ cm^3/sec (for T = 200 eV), V = 10 cm^3, $\omega = 3\times10^{-5}$ sr, and $\tau = 5\times10^{-6}$ sec the number of atoms calculated from formula (1) is $N \simeq 4\times10^6$ atoms/discharge. This value agrees well with the number of atoms registered by the analyzer, when allowance is made for extrapolation of the Maxwellian distribution over the entire energy range. This agreement makes it possible to use the measured energy distribution of the atoms to determine the local value of the ion temperature T_i. Figure 3 shows the values of T_i obtained by rotating the analyzer axis upward in the direction toward the injector; these values characterize the distribution of the ion temperature for the upper part of the plasma-filament cross section. We note that the value of T_i on the plasma-filament axis agrees well with the ion temperature determined from the Maxwellian "tail" of the energy distribution of the charge-exchange atoms emitted from the plasma of the Tokamak-6 in the absence of an atom jet [4].

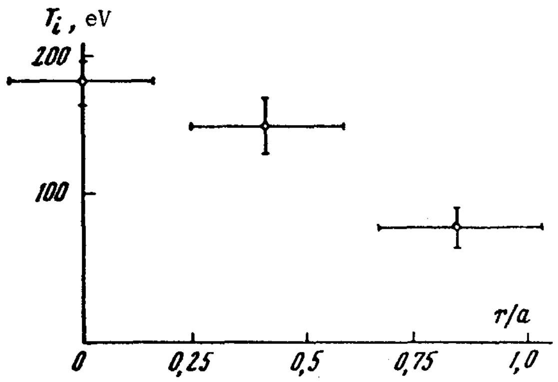

Fig. 3. Distribution of the ion temperature over the cross section of the plasma filament in the Tokamak-6: r — distance from the analyzer axis to the plasma-filament axis, a — radius of opening in diaphragm. Discharge conditions: longitudinal magnetic field 8.7 kOe, discharge current 45 kA, average electron concentration 1×10^{13} cm^{-3}, a = 14 cm.

The experiment described here is preliminary and constitutes mainly a demonstration of the possibilities afforded by the procedure of measuring the local parameters of the ion component of the plasma. These experiments with the Tokamak will be continued. We propose to measure the energy distributions of the charge-exchange atoms in a wider range of energies and to investigate in greater detail the distribution of T_i over the cross section of the plasma filament. In addition, we can hope that when sufficient accuracy is attained in the measurement of the absolute flux of the charge exchange atoms and of the absolute intensity of the H_β line it will be possible to use formula (1) to determine the local ion concentration n_i. In turn, comparison of the local values of n_i and n_e will yield information on the average charge of the plasma ions, i.e., a quantitative idea of the impurities in the plasma.

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[1] The measurements of the H intensity and the calculations of a n_a in these experiments were performed by V. M. Leonov.

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