First measurements of plasma parameters with the Tokamak-10 setup

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A plasma of density 6×10^{13} cm^{-3}, electron temperature $\sim$1 keV, ion temperature $\sim$ 0.7 keV, and neutron yield 3×10^{9} per discharge was obtained from the Tokamak-10 setup at a magnetic field 35 kOe, current 0.4 MA, and duration up to 1 sec. The energy containment time was $\sim$80 msec, and the plasma conductivity reached 7×10^{16} cgs esu.

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1. The T-10 setup is a Tokamak with round cross section and copper jacket and continuous bellows liner. The major radius of the torus (R) is 150 cm and the minor radius of the liner (a_L) is 39 cm. The diaphragm aperture radius (a) is 36.7 cm. After startup of the setup, in 1975, measurements of the main plasma parameters were performed during the course of the comprehensive shakedown. The experiments were performed at half the power input to the supply system of the toroidal field, corresponding to a magnetic-field intensity (H_z) 35 kOe on the system axis (the nominal value is 50 kOe). The maximum discharge-current amplitude reached 100 kA, and most experiments were performed at currents up to 400 kA, corresponding to a stability margin coefficient $q = (H_z/H_\phi)(a/R) \sim 4$ (H_ϕ is the field of the current).

Mathematical simulation of the processes of thermal insulation and heating of the plasma in the T-10 setup has shown that at the expected values of the concentration of the plasma and of the neutron atoms the value of the energy-release time at a current 400 kA will be approximately 100 msec.[1] The calculated value of the maximum attainable ion temperature on the pinch axis turned out to be less than expected from the Artsimovich formula.[2] The deviations from this formula for the T-10 are attributed to the small difference between the ion temperature and the electron temperature at a density above 4×10^{13} cm^{-3} (Fig. 1), and also to effects connected with the additional cooling of the ions by charge-exchange processes and by the presence of corrugation of the toroidal field.

The experiments were performed with hydrogen and deuterium. We registered the electrotechnical parameters of the discharge, namely the current, voltage, and displacement of the center of the plasma pinch relative to the center of the copper jacket. The electron density was measured with a microwave radio interferometer at wavelengths 2.3 and 0.9 mm. The electron temperature in the center of the plasma pinch (T_e) was determined by measuring the spectrum of the scattered light of a laser, and the ion temperature (T_i) was determined from the spectrum of the fast charge-exchange atoms in the energy range $(2-8)kT_i$. In addition, in discharges in deuterium the temperature of the ions at the center of the plasma pinch was calculated from the intensity of the yield of the thermonuclear reactions and from the measured plasma density. We measured also the intensity of the hard x rays.

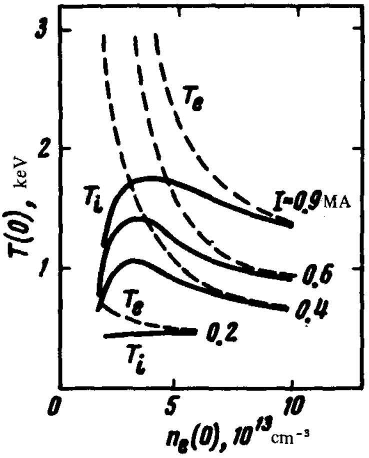

FIG. 1. Calculated plots of the maximum electron and ion temperatures vs. the electron density for different currents in hydrogen.

It should be noted that in discharges, both in deuterium and in hydrogen, neutral radiation was observed at the instant of the break of the current, due apparently to the (γ, n) reaction with the material of the diaphragm.[3] This radiation was correlated in time with the hard x-ray flash. Figure 2 shows an oscillogram of the current and of the neutron-counter signal for two discharges in deuterium. In case (a), where the abrupt break of the current at the end of the process causes the accelerated electrons to go off to the diaphragm, hard x-rays are produced together with a burst of intensity of neutrons of nonthermonuclear origin. In case (b) there is no break in the current and there is no neutron-radiation peak at the end of the process. In this case we attributed the entire neutron flux to $(d-d)$ reactions.

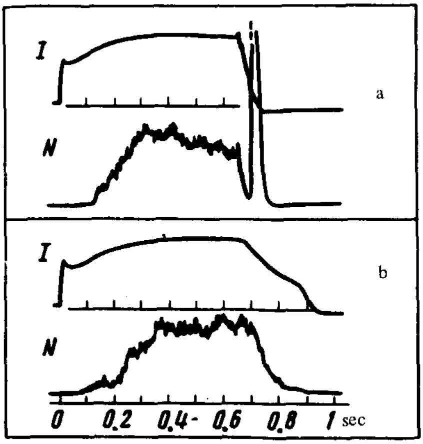

FIG. 2. Oscillogram of the current and of the neutron radiation: a) discharge with break in the current, b) discharge without break.

A comparison of the ion temperature as determined from the spectrum of the charge-exchange atoms (T_i) and from the neutron yield (T_{iN}) were made under the following assumptions: effective charge $T_e = 1$—3, radial distribution of the concentration $n_e(0)(1-(r/a_L)^2)$, ion temperature distribution in the form $T_i(0)(1-(r/a)^2)$ or $T_i(0)(1-(r/a)^4)$, based on the data obtained by simulation an by experiments with other Tokamak installations.

Absolute measurements of the flux of the charge-exchange atoms have shown that the neutral-particle density at the plasma center is $\sim 3\times 10^7$ cm^{-3}.

To obtain high plasma density, additional neutral gas was injected in certain experiments during the stationary stage of the discharge. The instant of injec-

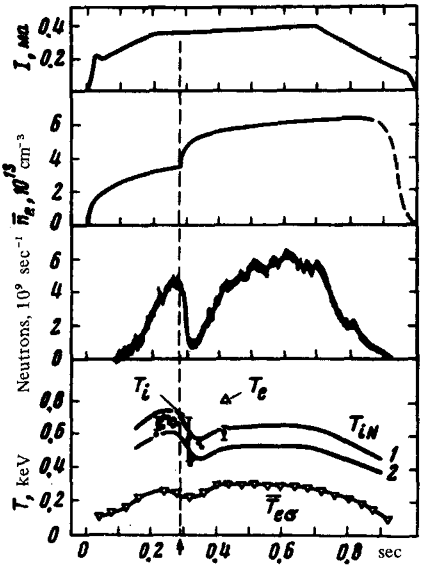

FIG. 3. Plasma parameters in the regime with additional injection of deuterium.

ion is marked by an arrow on Fig. 3, which shows oscillograms of the cur-
ent, electron density, neutron yield, and time dependence of the plasma tem-
erature. After the injection, a jump was observed in the electron density, and
lso a decrease in the plasma temperature and in the intensity of the neutron
lux. The second growth of the intensity is due to the increase of the deuteron
lensity and to the rise in the temperature. The scatter of T_{iN} shown in the
igure corresponds to different assumptions concerning the character of the
listribution of $T_i(r)$ and the value of $Z_{\rm eff}(T_i(r)=T_i(0)(1-r^2/a^2)$, $Z_{\rm eff}=3$—curve
, $T_i(r)=T_i(0)(1-r^4/a^4)$ and $Z_{\rm eff}=1$—curve 2).

It is easily found that in the case of a parabolic distribution of the electron emperature over the pinch cross section the temperature T_e at the center of he pinch is connected with the temperature $\overline{T}_{e\sigma}$ calculated from the electron onductivity averaged over the cross section by the relation

$$T_e=1.85\,Z_{eff}^{2/3}\,\overline{T_{e\sigma}}\,.$$

or the values of T_e and $T_{e\sigma}$ shown in Fig. 3, $Z_{\rm eff}$ turned out to be equal to 1.8. he values of $Z_{\rm eff}$ for different discharges lie in the range 1—3.5.

The energy containment time τ_E can be estimated within the framework of the ssumption of a parabolic distribution of T_e, T_i, and n_e and the available data oncerning the average plasma density and temperature at the center, we can stimate. Figure 4 shows the dependence of the energy time on a^2H_Φ, in the -10 installation as well as data for other installations. The scatter of the alues of τ_E at a given a^2H_Φ in the case of T-10 is due to the assumptions con-erning the different distributions of the plasma parameters over the pinch ross section and the uncertainty in the allowance for the inductive component f the voltage. The straight line corresponds to the empirical relation $\tau_E=3.6$ $10^8a^2H_\Phi$ obtained in[4].

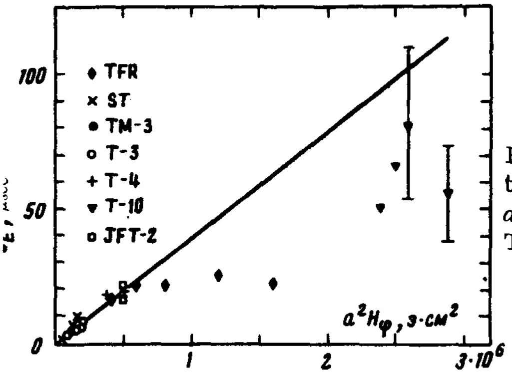

FIG. 4. Dependence of the energy containment time τ_E on the parameter a^2H_Φ for different installations of the Tokamak type.

In conclusion, the authors are sincerely grateful to the large group of co-orkers for starting the setup and performing the experiments, and to Academ-cians E.P. Velikhov and B.B. Kadomtsev for numerous discussions and help ith the work.

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