PARAMETERS OF THE ION COMPONENT OF PLASMA HEATED TURBULENT TURBULENTLY BY A LONGITUDINAL CURRENT IN THE MAGNETIC MIRROR TRAP

L. E. ARANCHUK and S. L. NEDOSEEV

Submitted April 20, 1971

Zh. Eksp. Teor. Fiz. 61, 1856–1863 (November, 1971)

The results are reported of an experimental study of the efficiency of turbulent heating by an ion current flowing through plasma in the direction of the magnetic field in a magnetic mirror trap. It is shown that this efficiency reaches 20% and that most of the energy is stored in the ion component during the confinement stage of the heated plasma. When the plasma density is 2×10^{13} cm^{-3} the mean ion energy is $\bar{\epsilon}_i \approx 3$ keV and the fraction of ions with energies in the range $0.5 \leq \epsilon_i \leq 20$ keV is about 30% of the total number of ions. The ion lifetime is determined by charge transfers to the neutral gas entering the plasma after turbulent heating, and amounts to 40–45 μsec.

EFFECTIVE heating of the ion component is of major practical importance in experiments on turbulent plasma heating by a longitudinal current. The aim of the present research was (1) to investigate the efficiency of turbulent heating of ions by a current flowing along the magnetic field of the magnetic mirror trap, (2) to determine the lifetime of the hot ions in the trap and their energy distribution, and (3) to determine the ratio of the energy densities stored in the electron and ion components of the heated plasma.

APPARATUS

The experiments were performed on the TN-5 magnetic mirror trap.[1] The principle of operation of this machine is not very different from that described in [2-8] but both the volume of the plasma and the energy stored in the capacitors in the longitudinal current circuit are greater. The main parameters are as follows: magnetic field in the trap 5–10 kOe, mirror ratio 2.2, distance between mirrors 3 m, diameter of the metal vacuum chamber 55 cm, total capacitance in the longitudinal current circuit $C_l = 0.4\ \mu$F, energy stored (at $V_l = 140$ kV) W = 4000 J. The titanium hydride injector produced hydrogen plasma with a density up to 2×10^{13} cm^{-3} and the plasma column diameter was 22–25 cm.

The plasma density n was measured with an 8-mm microwave interferometer, the longitudinal current I_l was measured with a Rogowski belt, and the potential difference V_0 between the electrodes was determined with the aid of potential dividers. The energy content U_V of the plasma was measured with a diamagnetic probe placed inside the metal vacuum chamber. X rays emitted by the plasma were monitored with a scintillation counter incorporating two small photomultipliers (FÉU-60) with plastic phosphors having a decay time of $\sim 10^{-8}$ sec. The amplifier resolution time for the photomultiplier signal did not exceed 10^{-7} sec. The recording surface of the phosphors was in the vacuum and was shielded from plasma radiation by carbon films with a transmission limit at $h\nu \approx 600$ eV. Absorbing filters were mounted in front of one of the phosphors. The counter was placed in front of an aperture in the opposite wall of the vacuum chamber and carried a collimator so that only x rays originating in the central part of the installation were recorded.

The parameters of the ion component of the turbulently heated plasma were determined by analyzing the neutral particles resulting from charge transfers. These particles were recorded in two ways. One has been referred to as the "capacitor microphone" method and was described in [3]. This method can be used to determine quite reliably the mean energy of plasma ions but provides no information about the distribution function or the lifetime of the hot ion component. To determine these quantities in our experiments we used the simplified version of the magnetic analyzer of neutral particles originating in charge transfers, in which they were ionized on a gas target. In a number of cases the magnetic analyzer was replaced by a time-of-flight analyzer and the velocity of the analyzed particles was estimated from the change in the shape of the current pulse of neutral particles over a flight path of 50 cm. Figure 1 shows schematically the principle of the apparatus and the disposition of the diagnostic equipment.

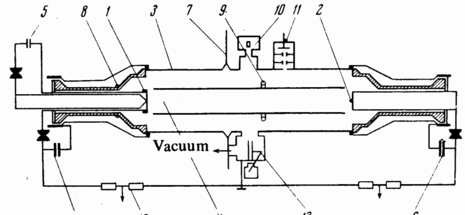

FIG. 1. Block diagram for the TN-5 installation and the disposition of diagnostic equipment. 1–Plasma injector, 2–longitudinal discharge electrode, 3–vacuum chamber, 4–plasma column, 5–injector capacitor bank, 6–capacitor bank in the longitudinal current circuit, 7–antennas of the microwave interferometer, 8–Rogowski belt, 9–diamagnetic probe, 10–capacitor microphone, 11–neutral particle analyzer or photomultiplier with optical H_β filter, 12–measuring voltage divider, 13–x-ray probe.

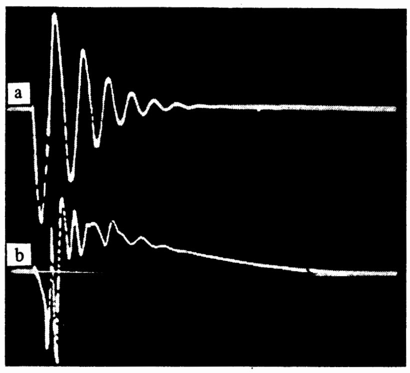

FIG. 2. Oscillograms of a) longitudinal current (V_1 = 140 kV, I_{max} = 35 kA, T = 5.5 μsec) and b) diamagnetic probe signal. Paramagnetic oscillations can be seen over the initial segment. $U_{V\,max}$ ≈ 900 J. Sweep time 70 μsec.

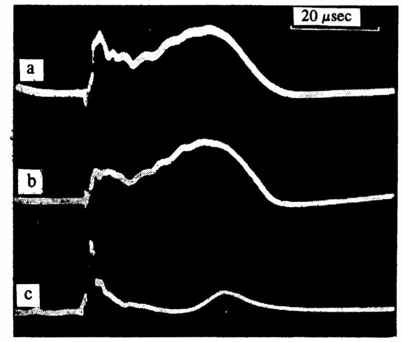

FIG. 3. Oscillograms of a) collector current $i_c(t)$ in the neutral particle magnetic analyzer, b) current to the distant collector of the time-of-flight analyzer of neutral particles, and c) H_β intensity.

EXPERIMENTAL RESULTS

The dependences of the anomalous resistance R, heating efficiency ξ, and energy input U_V into the plasma on the initial plasma density are in qualitative agreement with the results obtained for the TN-4.[2] The maximum turbulent heating efficiency in the TN-5 system corresponds to $n \approx 2 \times 10^{13}$ cm^{-3}, for which the anomalous resistance R of the plasma column is close to the wave resistance of the discharge circuit ($\rho \approx 2\Omega$). Under these conditions the heating power is $L_l^2 R \approx 10^9$ W, and the energy stored in the plasma is U_V = 900 J, which corresponds to a heating efficiency $\xi = 2U_V/C_1V_1^2$ ≈ 20%. Calorimetric measurements of the radial distribution of the energy flux along the magnetic field during heating and confinement of the plasma showed that the plasma diameter was 22–25 cm. Hence, the total volume of the hot plasma is $\sim 10^5$ cm^3 and the maximum pressure is $n(T_e - T_i) \approx 6 \times 10^{16}$ eV/cm^3. Oscillograms of the longitudinal current and the diamagnetic probe signal are shown in Fig. 2. It is clear that the hot plasma is confined to the trap for 35–45 μsec.

During maximum heating efficiency the mean ion energy measured with the "capacitor microphone" reaches up to $\bar{\epsilon}_i \approx 3$ keV. Comparison of these measurements with the diamagnetic probe measurements shows that the energy content of the ion component is close to the total energy content of the plasma

$$n_i\varepsilon_i \approx n(T_e + T_i)_{\text{diamag}}.$$

This enables us to conclude that the efficiency of turbulent heating of plasma ions in our experiments is at least as high as the electron heating efficiency.

The magnetic analyzer of neutral particles was capable of recording hydrogen atoms with energies in excess of 300 eV. The oscillogram showing the current i_c to the analyzer collector is given in Fig. 3a. The neutral-particle flux density has two peaks. The first is about 5 μsec long and appears roughly 1 μsec after the longitudinal current is introduced. The second, broader maximum appears after about 25 μsec. The shape of these oscillograms remains the same as the analyzing magnetic field is increased, but the height of the two peaks is reduced. The neutral-particle flux is recorded for 40–45 μsec, which is close to the duration of the diamagnetic signal.

Figure 4b shows the distribution function $f_i'(\epsilon_i)$ for hot ions in the energy range $0.5 \le \epsilon_i \le 20$ keV corresponding to the second peak on the neutral-particle intensity curve. For comparison we also give the Maxwell distributions with temperatures corresponding to 2.5 and 5.0 keV normalized so that the areas under the curves are equal. In contrast to the Maxwellian distributions, the function $f_i'(\epsilon_i)$ falls monotonically for ion energies in the range $0.5 \le \epsilon_i \le 20$ keV and the mean value is $\bar{\epsilon}_i' \approx 10$ keV.

In general, the magnetic analysis yields not the particle energy but the quantity $\delta_i M_i/Z_i$, which is a function both of the mass M_i and the charge Z_i of the ion. It may be supposed that in our experiments the charge of the analyzed particles was $Z_i = 1$ since the probability of formation of multiply-charged ions during the stripping of neutral particles in the gas target is very low. However, the mass of the neutral particles reaching the analyzer may be substantially greater than the proton mass. During the operation of the injector the plasma may contain titanium ions (M = 49). As a result of turbulent heating up to 50–100 eV, and rapid charge transfers, these ions may reach the analyzer with a velocity of about 2×10^6 cm/sec and form the second peak

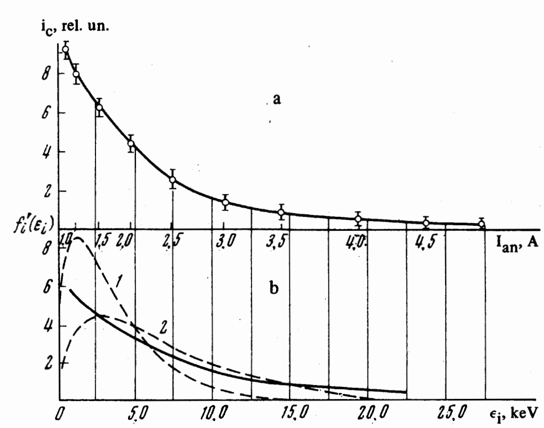

FIG. 4. Distribution function for turbulently heated plasma in the TN-5 installation (V_1 = 140 kV, I_1 = 32 kA, $n_i = 2 \times 10^{13}$ cm^{-3}, hydrogen). a) Collector current in the neutral particle analyzer as a function of the magnetic field H_{an} (kOe) = 0.141_{an} (A). b) Ion energy distribution function (relative units) ($\bar{\epsilon}_i'$ = 10 kOe). Broken curve shows the Maxwellian distribution functions for temperatures T_i = 2.5 keV and T_i = 5.0 keV (2).

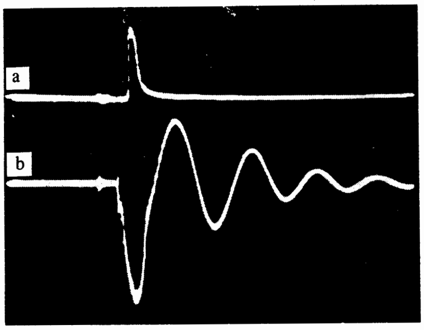

FIG. 5. Oscillograms of a) probe recording x-ray radiation from the plasma with $h\nu \gtrsim 600$ eV and b) longitudinal current. $I_{max} = 35$ kA, switching time 30 μsec.

on the collector current oscillogram. The time-of-flight analyzer was used to estimate the lower limit for the particle velocity. Figure 3b shows the current oscillogram for the collector placed at 50 cm from the electrode in the analyzing chamber. The analyzing magnetic field was switched off. The absence of appreciable time shift between the second maxima of i_c (a) and i_c (b) suggests that the velocity of the analyzed particles is not less than 10^7 cm/sec. Titanium ions with this velocity cannot be deflected by the magnetic field in the analyzer and produce a distribution analogous to $f_i'(\epsilon_i)$. This means that the amount of heavy impurities in the neutral-particle stream and hence in the plasma is quite small.

The H_β emission from the plasma volume seen by the neutral-particle analyzer also shows a nonomonotonic character (see Fig. 3c). The time of appearance of the second H_β intensity peak is practically simultaneous with the second peak on the i_c curve. Figure 5 shows the signal from the scintillation counter. High-intensity x-ray radiation with $h\nu \gtrsim 600$ eV is recorded only during the turbulent heating process, and the intensity of this radiation does not exceed 3–5% of the maximum value after a period of 3–4 μsec following the removal of the longitudinal current.

DISCUSSION

1. The fact that the neutral-particle flux is not monotonic may be explained by assuming that the density of the neutral gas on which hot ion charge transfers take place does not remain constant during the hot plasma confinement.

The first peak on the i_c curve is due to ion charge transfers to neutral particles in the plasma produced by the injector. When the turbulent heating is switched on, the density of these neutral particles should rapidly decrease as a result of ionization and charge transfers. However, the result of the influence of the longitudinal current on the injector is the appearance of a large quantity of cold plasma and neutral particles in the plasma. This increase in the neutral-particle density after a period of 15–20 μsec following the removal of the current corresponds to a velocity of entering particles of about 3×10^6 cm/sec and is responsible for the second peak on the i_c curve. This is confirmed by the nonmonotonic variation of H_β intensity. If we allow for the fact that at the time of appearance of the second peak of the i_c and H_β curves the plasma contains only a small fraction of the dissipated energy (about 3–5% of $\frac{1}{2}C_l V_l^2$) it may be concluded that the hot-ion lifetime is determined by ion-charge transfers in the cloud of neutral hydrogen which enters the plasma after heating.

2. As already noted, the duration of the neutral-particle bunch from the plasma is close to the duration of the diamagnetic signal, and the energy content of the neutral component is close to the total plasma energy content. To estimate the amount of energy carried by the electron component we note that the total intensity of x-ray bremsstrahlung emitted by the plasma can be described by

$$W_\gamma = \text{const}\cdot n_e n_{i\,\text{imp}} Z_{i\,\text{imp}}^2 \varkappa \sqrt{\langle \varepsilon_e \rangle},$$

where $n_{i\,\text{imp}}$ and $Z_{i\,\text{imp}}$ are, respectively, the density and charge of the impurity ions, $\langle \epsilon_e \rangle$ is the mean electron energy, and κ is a factor which depends on the electron-energy distribution function ($\kappa = 1$ for a Maxwellian distribution). It is readily shown that for other distribution functions which may be realized in practice the coefficient κ differs from unity by not more than a factor of about 1.5. For example, for a nonrelativistic electron beam of density n_1 and velocity v_1, flowing through plasma of density $n_2 = n - n_1$, and thermal electron velocity v_{Te} we have

$$\langle \varepsilon_e \rangle = \frac{m_e}{2}\left(\frac{n_1}{n} v_1^2 + \frac{3}{2}\frac{n_2}{n} v_{Te}^2\right), \quad 0{,}7 \leqslant \varkappa \leqslant 1{,}0,$$

when

$$1 \leqslant v_1 / v_{Te} \leqslant 10, \quad 0{,}1 \leqslant n_1 / n \leqslant 1.0.$$

This means that the above expression for W_γ can be used to estimate the electron energy content of plasma whatever the distribution function. In an open trap the cooling of the electron component occurs as a result of the escape of energetic electrons along the field lines. Consequently, the reduction in the intensity W_γ suggests that there is a reduction in the energy content of the electron component $n\langle \epsilon_e \rangle$.

It is clear from Fig. 5 that the x-ray intensity decreases much more rapidly than the diamagnetic signal. Even if we allow that at the time of the $W_\gamma(t)$ maximum the electrons carry all the energy stored in the capacitors in the longitudinal current circuit, we find that the electrons carry only 3–5% of this energy after a period of 3–5 μsec. The total energy content of the plasma at this time is about 20% of $\frac{1}{2}C_l V_l^2$, i.e., during the confinement stage the electrons do not contribute substantially to the energy content of the plasma and its diamagnetism is largely determined by the ions. This involves the assumption that the amount of impurity is not reduced during turbulent heating.

3. For ion energies in the range $0.5 \leq \epsilon_i \leq 20$ keV the distribution function $f_i'(\epsilon_i)$ is different from the Maxwellian distribution and the mean energy of the hot-ion component is $\bar{\epsilon}_i' \approx 10$ keV. According to the "capacitor microphone" measurements, the mean ion energy (taking into account the cold component) is $\bar{\epsilon}_i \approx 3$ keV. Assuming that $n_i\bar{\epsilon}_i \approx n_i'\bar{\epsilon}_i'$, we have $n_i'/n_i \approx 0.3$, i.e., about 30% of all the ions is associated with

the hot component n'_i. In these expressions n'_i is the density of the hot-ion component and n_i is the total plasma density.

4. Let us compare the above experimental results with certain deductions of the theory of turbulent plasma heating by a longitudinal current, as developed in [9].

In a plasma with anomalous resistance due to the ion-acoustic current instability, only resonance ions can be heated effectively, i.e., ions for which the velocity is $v_i \gtrsim c_s = \sqrt{T_e/M_i}$. In a nonisothermal plasma with $T_e \gg T_i$ there are very few ions with this velocity. However, according to [9], the nonlinear damping of the ion sound by cold ions ensures that some of these ions may assume velocities $v_i \gtrsim c_s$ and be subsequently effectively heated. The final ion distribution function may be written in the simplified form as the sum of two Maxwellian functions, one for the cold mass (n_i^X, T_i^X) and the other for the hot component (n_i', T_i'). The hot-ion group imposes a weak restriction on the existence of ion-acoustic oscillations so that

$$\frac{n_i'T_i'}{n_eT_e} < \left(\frac{T_i'}{T_e}\right)^{5/2}\left(\frac{m_eu^2}{T_e}\right)^{1/2},$$

where u is the electron drift velocity. Consequently, the energy of the hot-ion group may even exceed the energy of the electron component. It is assumed, of course, that $T_i^X \ll T_e$.

Our experimental results, i.e., the high efficiency of turbulent heating of ions, the non-Maxwellian ion energy distribution function, and the conclusion that the energy stored in the plasma is carried largely by the ion component, are in agreement with the theoretical predictions in [9].

We are greatly indebted to E. K. Zavoĭskiĭ for his constant interest in this work, and to K. I. Tarakanov, G. F. Zhalud', and their co-workers for enabling us to perform our experiments on this installation.

[1] E. K. Zavoĭskiĭ, S. L. Nedoseev, L. I. Rudakov, V. D. Rusanov, V. A. Skoryupin, and S. D. Fanchenko, Plasma Phys. and Controlled Nucl. Fusion Research **2**, Vienna, 1969, p. 679.

[2] M. V. Babykin, P. P. Gavrin, E. K. Zavoĭskiĭ, S. L. Nedoseev, L. I. Rudakov, and V. A. Skoryupin, Zh. Eksp. Teor. Fiz. **52**, 643 (1967) [Sov. Phys.-JETP **25**, 421 (1967)].

[3] E. K. Zavoĭskiĭ, S. L. Nedoseev, and L. I. Rudakov, ZhETF Pis. Red. 6. 951 (1967) [JETP Lett. 6, 367 (1967)] V. S. Grishin, G. I. Dolgachev, G. I. Kalinnikov, and S. L. Nedoseev, Vsesoyuznoe soveshchanie po diagnostike vysokotemperaturnoĭ plazmy (All-union Conference on High-temperature Plasma Diagnostics), Sukhumi, 1970, Paper K-10.

[4] V. A. Suprunenko, E. A. Suchomlin, and V. T. Tolok, Ninth Intern. Conf. on Phenomena in Ionized Gases, Bucharest, Rumania, 1969, Paper 4.4.1.3.

[5] L. V. Dubovoĭ and V. P. Fedyakov, Dokl. Akad. Nauk SSSR **167**, 553 (1966) [Sov. Phys.-Dokl. **11**, 239 (1966)].

[6] Yu. G. Kalinin, D. N. Lin, V. D. Ryutov, and V. A. Skoryupin, Zh. Eksp. Teor. Fiz. **56**, 462 (1969) [Sov. Phys.-JETP **29**, 252 (1969)].

[7] F. H. Jensen and E. R. Scott, Phys. Rev. Lett. **19**, 1100 (1967).

[8] N. K. Berger, V. S. Koĭdan, A. N. Papyrin, A. G. Ponomarenko, V. N. Stibunov, and B. A. Yablochnikov, ZhETF Pis. Red. **8**, 389 (1968) [JETP Lett. **8**, 241 (1968)].

[9] L. I. Rudakov and L. V. Korablev, Zh. Eksp. Teor. Fiz. **50**, 220 (1966) [Sov. Phys.-JETP **23**, 145 (1966)]. E. K. Zavoĭskiĭ and L. I. Rudakov, At. Énerg. **23**, 417 (1967).

Translated by S. Chomet
193