An investigation of ion heating by injection of a relativistic electron beam into a plasma

V. S. Koĭdan and A. I. Rogozin

Nuclear Physics Institute, Siberian Division, USSR Academy of Sciences, Novosibirsk
(Submitted May 3, 1976)
Zh. Eksp. Teor. Fiz. **71**, 1837–1848 (November 1976)

Experimental results are presented for the distribution function and number of heated ions appearing when a relativistic electron beam is injected into a plasma. An electron beam with energy 1 MeV, current 7–10 kA, and duration 70 *ns* was injected into a plasma of density 3×10^{12}–4×10^{14} cm^{-3} situated in a magnetic field 6–12 kOe. The ion heating was investigated by analyzing the fast neutral charge-exchange particles emitted from the plasma across the magnetic field. It was established that the form of the distribution function and the number of heated ions depend strongly on the density of the initial plasma. For a plasma density $n > 10^{14}$ cm^{-3} the distribution function of the ions in the range of energies under investigation is close to Maxwellian, and the density of heated ions is 10^{-3}–10^{-4} of the total ion density. As the plasma concentration decreases ($n < 10^{14}$ cm^{-3}) the distribution function begins to deviate from equilibrium and the number of heated ions increases and reaches 10–20% of the total number of ions. For lower densities the distribution function can be interpreted as a "two-temperature" distribution, but it is obvious that the distribution of all the ions of the plasma in all regimes has a form different from an equilibrium distribution. For high densities ($n > 10^{14}$ cm^{-3}) ion heating occurs in the volume occupied by the electron beam. As the plasma density is lowered ($n < 5\times10^{13}$ cm^{-3}) ion heating is observed in the whole volume of the plasma column. Possible mechanisms for ion heating are discussed.

PACS numbers: 52.50.Gj, 52.40.Mj

I. INTRODUCTION

When a high-power relativistic electron beam (REB) is injected into a plasma placed in a longitudinal magnetic field, one observes under certain conditions a collisionless heating of the plasma (cf., e.g., [1–4]). In the optimal case the efficiency of the heating, as determined by means of diamagnetic measurements, reaches values of 10–15%. In order to determine the physical mechanism of energy transfer from the beam to the plasma it is necessary to investigate the heating of both the electronic and the ionic components of the plasma.

In the present paper we describe the results of experiments carried out on the INAR installation,[2] where the heating of the ions was studied as a function of the initial parameters of the beam and the plasma. The experiments were carried out with initial plasma densities 3×10^{12}–4×10^{14} cm^{-3}, electron densities in the beam 1×10^{11}–5×10^{11} cm^{-3}, incident electron beam energy 1 MeV, and a transverse magnetic field 6–12 kOe. The heating of the ions was investigated by analyzing the fast charge-exchange atoms emitted by the plasma.[5]

II. APPARATUS AND MEASUREMENT METHODS

1. Description of the installation and of diagnostic methods

A schematic diagram of the experiment is given in Fig. 1. The initial hydrogen plasma 2 was produced by a pulsed Penning discharge in a glass pipe 1 placed in a longitudinal magnetic field. The diameter of the plasma column was bounded by ceramic diaphragms of inside diameter 8 cm. By regulating the instant of injection of the electron beam 3 relative to the time the Penning discharge is switched-on we could investigate the character of the interaction of the REB with the plasma at different densities. In the experiment the fundamental parameters of the plasma and of the electron beam were measured. The plasma density was measured in several ways: by the blocking of microwave signals, by the attenuation of an external probing beam of hydrogen atoms[6] as well as by means of an electric double probe. The electron temperature of the initial plasma was also determined by means of a double probe. The current of the electron beam, the total energy transferred by the beam per pulse, and the total current in the plasma were measured respectively by means of a shunt, a calorimeter, and a Rogowski belt (for more details, cf. [2]).

A study of the energy distribution of the charge-exchange atoms was done by means of an installation consisting of a gas stripping chamber, a Hughes–Rojansky charged-particle differential analyzer, and a detector based on the VÉU-1 secondary-electron multiplier. The charge-exchange atom analyzer was connected to the installation at a distance of approximately 70 cm from the anode foil of the electron accelerator. Part of the atom flux emitted by the plasma reached the stripping chamber 5 where a definite fraction of the neutral particles were stripped by air to form ions that were subsequently

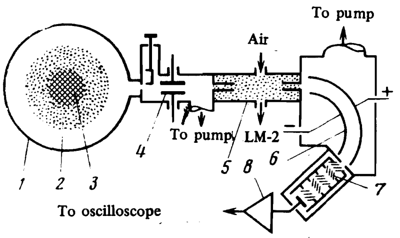

FIG. 1. Schematic diagram of experiment: 1—Glass chamber, 2—initial plasma, 3—relativistic electron beam, 4—deflection plates, 5—stripping chamber, 6—electrostatic analyzer plates, 7—secondary electron multiplier, 8—amplifier.

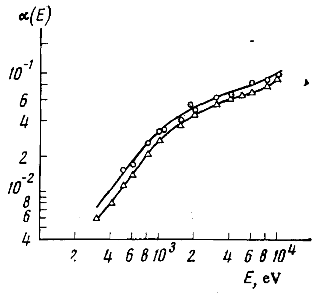

FIG. 2. The energy dependence of the conversion coefficient for hydrogen atoms in the stripping chamber. The upper curve has been obtained during the present experiment ($P=5\times10^{-4}$ Torr), the lower curve has been obtained in Ref. 7 ($P=4\times10^{-4}$ Torr).

analyzed in an electric field created by the plates 6. The distance between the analyzer plates is $\Delta r=1.8$ cm, the radius of the mean ion trajectory is $r_0=10$ cm, and the aperture angle of the cylindrical capacitor is 127°. The entry and exit gaps of the analyzer had a width $\delta=0.45$ cm and height of 1 cm. If the voltage on the capacitor plates is $\pm U$, the analyzed energy is $E=r_0qU/\Delta r$, where q is the charge of the ion. The energy resolution of the analyzer is determined by the expression:

$$\Delta E=2\delta E/r_0. \tag{1}$$

After the energy analysis the ions were recorded by the secondary-electron multiplier 7, in the voltage divider of which capacitors were soldered in parallel to the last ten dynodes, which allowed one to obtain from the anode of the multiplier current pulses up to 5 mA with a duration of $\lesssim10^{-5}$ s. A characteristic feature of the multiplier used is its low sensitivity to hard x rays produced by the accelerator and the high stability of the amplification factor after repeated exposure to air. The signal from the anode of the electron multiplier was transmitted into a shielded room, where after additional amplification by means of the amplifier 8 it was recorded in an oscilloscope with a bandwidth of 30 MHz. The whole apparatus and signal transmission line were thoroughly shielded against electromagnetic interference from the installation.

Before carrying out the measurements the neutral-particle analyzer was calibrated by the method described in[7,8]. During the first stage of calibration we determined the efficiency α of conversion of neutral hydrogen atoms into protons in the stripping chamber as a function of the energy E in the range 0.3–10 keV. Figure 2 shows $\alpha(E)$ for a stripping chamber of 25 cm length with pressure-drop channels of 0.8 cm diameter and 7.5 cm length. For a fixed energy of the hydrogen atoms the dependence of α on the pressure of the air sweeping the chamber is close to linear in the range 10^{-4}–7×10^{-4} Torr.

In the second stage of the calibration we have determined the dependence of the amplification factor of the electron multiplier on the supply voltage and on the energy of the protons to be recorded. For protons with energies 0.3–10 keV the amplification factor of the multiplier was subject to insignificant changes. This was due to the weak dependence of the secondary emission coefficient of the first dynode on the energy of the protons in the range 5–15 keV (the negative potential of the first dynode of the multiplier was 5 kV).

The temporal resolution τ_r of the analyzer is determined essentially[1)] by the length of the flight-path L of the particles from the plasma to the detector, and by the final energy resolution determined according to Eq. (1). It is easy to show that the temporal resolution is determined by the equation:

$$\tau_r=3.63\cdot10^{-7}L\Delta E/E^{3/2}, \tag{2}$$

where τ_r is in seconds, L in centimeters, and the energies are in electron-volts.

2. Reduction of the experimental data

In the experiment the analyzer is tuned to various energies, and signals proportional to the output current of the detector $I(E)$ are recorded.

The magnitude of the signal is related to the equivalent particle current I_H at the entrance of the stripping chamber by means of the following relation:

$$I(E)=k(E)\alpha(E)\Delta E dI_H/dE, \tag{3}$$

where $k(E)$ is the amplification factor of the electron multiplier, which has a weak energy-dependence, and $\alpha(E)$ is the stripping coefficient of the atoms in the stripping chamber. The temporal correspondence of the signals at different energies is determined with account taken of the flight time of the particles from the plasma to the detector.

The distribution function dn_i^*/dE of the hot ions in the plasma can be obtained taking into account the charge-exchange of these ions on neutral particles in the plasma and the possible weakening of the flux of fast atoms on account of ionization by electrons, charge-exchange with ions, and stripping on atoms and ions[9]:

$$\frac{dn_i^*}{dE}=\frac{I(E)e^{-\gamma l}}{BE^{1/2}\sigma(E)k(E)\alpha(E)}, \tag{4}$$

where l is the path-length of the charge-exchange atoms in the plasma,

$$\gamma=n_0\sigma_2^0+n_i(\sigma+\langle\sigma_e v_e\rangle/v_0+\sigma_2^i),$$

n_0 and n_i are the densities of cold neutral particles and ions, respectively, σ is the charge-exchange cross section, $\langle\sigma_e v_e\rangle/v_0$ is the effective ionization cross section of fast atoms by electrons, σ_2^0 and σ_2^i are the stripping cross sections on neutral atoms and ions, respectively, and B is a coefficient which does not depend on the energy.

In the case of an isotropic Maxwellian distribution of the ion energies one can find the ion energy from the slope of the line determined by the equation

$$\ln\frac{I(E)e^{-\gamma l}}{k(E)\alpha(E)E^2\sigma(E)}=-\frac{E}{kT_i}+\ln C, \tag{5}$$

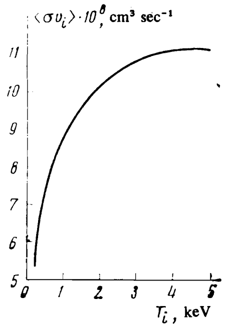

FIG. 3. The dependence of the charge-exchange rate of protons on atomic hydrogen on the ion temperature.

where C is a constant. For a plasma density $n \lesssim 10^{14}$ cm^{-3}, $l \sim 5$ cm, and an electron temperature $T_e \sim 10-10^3$ eV, the factor $e^{-\gamma l}$ in Eqs. (4) and (5) is close to unity, and can be omitted in the treatment of the experimental data.

We now discuss how one can determine the number of heated ions which have the measured energy distribution. The flux of atoms incident on the entrance slit of the analyzer is determined by the following expression:

$$I_n = \frac{n_i^* n_0 \langle \sigma v_i \rangle S}{4\pi R^2} V, \tag{6}$$

where n_i^* is the density of hot ions, n_0 is the density of atoms on which the charge-exchange takes place, $\langle \sigma v_i \rangle$ is the rate of charge exchange, averaged over the velocity distribution, S is the area of the entrance slit of the analyzer, R is the distance from the plasma to the entrance slit, V is the volume of hot plasma seen by the analyzer. At the same time (cf. Eq. (3))

$$I_n = \int_{E_{min}}^{E_{max}} \frac{I(E)\,dE}{k(E)\,\alpha(E)\,\Delta E} = \frac{r_0}{2\delta} \int_{E_{min}}^{E_{max}} \frac{I(E)\,dE}{k(E)\,\alpha(E)\,E}, \tag{7}$$

where E_{min} and E_{max} are the minimal and maximal energies of the atoms recorded in the experiment.

Comparing (6) and (7) one can find the density of hot ions in the plasma:

$$n_i^* = \frac{2\pi R^2 r_0}{n_0 \langle \sigma v_i \rangle S V \delta} \int_{E_{min}}^{E_{max}} \frac{I(E)\,dE}{k(E)\,\alpha(E)\,E}. \tag{8}$$

The quantities in the integrand are determined when the analyzer is calibrated and when the spectrum of the charge-exchange atoms is measured. The rate of charge exchange of protons on atomic hydrogen $\langle \sigma v_i \rangle$, which enters into Eq. (8) after averaging over the Maxwellian distribution, was calculated on a computer for ion temperatures 0.2–5 keV. The results of the calculation are represented in Fig. 3. In these calculations, which made use of known results, [10,11] the resonance charge-exchange cross section of protons on atomic hydrogen was represented analytically by the following expression:

$$\sigma[\text{cm}^2] = 10^{-16}(8.71 - 1.42 \log E\ [\text{eV}])^2.$$

As regards the density of atoms, n_0, in the conditions of our experiment it can be defined as follows:

$$n_0 = 1/\tau(E)\,\sigma(E)\,v_i(E), \tag{9}$$

where $\tau(E)$ is a characteristic time of decrease of the emission of charge-exchange atoms with energy E. Such an estimate of n_0 has good accuracy up to plasma densities $n \lesssim 10^{14}$ cm^{-3}, since in this case the ionization time of fast neutral particles by plasma electrons is significantly larger than the characteristic time of decrease of hot ions on account of charge-exchange.

The hydrogen atom density n_0 was estimated also from the ionization-induced increment in plasma density after passage of the electron beam.

The size of the plasma region in which ion heating occurs can be found from the rise time τ_a of the analyzer signals. This rise time is determined by the temporal resolution τ_r of the analyzer at a given energy, the heating time of the ions τ_{heat} and the time of collection of neutral charge-exchange particles from the region where the ion heating occurs:

$$\tau_a = [\tau_r^2 + \tau_{\text{heat}} + (d/v_i)^2]^{1/2}, \tag{10}$$

where d is the diameter of the region occupied by the heated ions and v_i is the ion velocity at the given energy.

III. EXPERIMENTAL RESULTS

1. Measurements of the plasma density by means of attenuation of the neutral beam

Figure 4a represents the oscilloscope trace of the attenuation of a beam of hydrogen atoms of energy 8 keV in the initial plasma. The plasma was produced at a hydrogen pressure ~ 2 mTorr in the chamber in a longitudinal magnetic field of 12 kOe. For the determination of the initial intensity I_0 the atomic beam was switched on 100 μs before the discharge was ignited. The attenuation of the atomic beam occurs mainly on account of charge exchange and stripping on ions. The electron temperature of the initial plasma, measured by means of a double probe, was 2–3 eV. Consequently one may neglect the ionization of the atoms in the beam by electrons. In these conditions the concentration of the plasma is determined from the following expression:

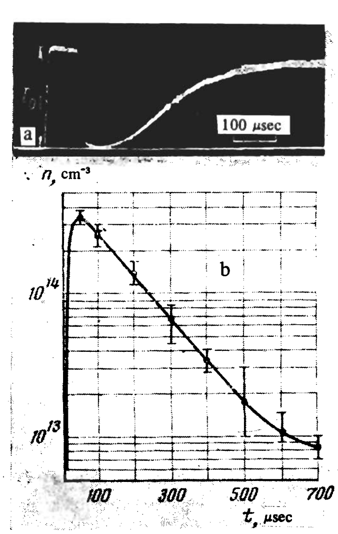

FIG. 4. a—Oscilloscope trace of the attenuation of the beam of hydrogen atoms with 8 keV energy in the initial plasma; b—the dependence of the ion concentration of the initial plasma on time.

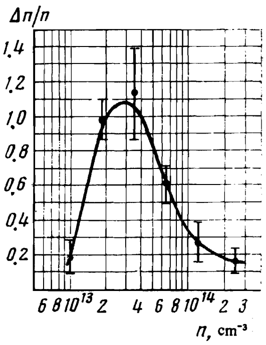

FIG. 5. The dependence of the relative change of plasma density which appears on account of the REB injection on the plasma density.

$$n(t)=\frac{\ln(I_0/I(t))}{\sigma_\Sigma D},$$

where I_0 is the initial beam intensity (before the production of the plasma, $I(t)$ is the intensity at time t, σ_Σ is the total cross section for charge exchange and stripping of the beam atoms on plasma ions, and D is the diameter of the plasma column. The probe measurements have shown that the density distribution of the plasma along the radius is close to homogeneous within the region bounded by the disphragms. At a radius larger than internal dimension of the diaphragm the density decreases rapidly. The variation of the concentration of the initial plasma as a function of time is shown in Fig. 4b. The plasma densities obtained by means of the neutral beam, the double probe and the cutoff of microwave signals differ from each other by less than 30%. At the time when the current of the Penning discharge is damped out, the plasma density attains its maximum $n_{\max}\approx(3-4)\times10^{14}$ cm^{-3}.

After the injection of the relativistic electron beam into the plasma the plasma density increases. Figure 5 shows the density dependence of the ratio of the maximal increment of plasma density to the density at which the REB is injected. The magnitude of the relative increment is determined by the density and temperature of the electrons, which are heated as a result of the passage of the REB, as well as by the quantity of neutral hydrogen present in the plasma. As can be seen from Fig. 5, the quantity $\Delta n/n$ has a maximum for $n\approx(3-4)\times10^{13}$ cm^{-3}.

We note that, as was shown earlier, [2] this is exactly the concentration for which one observes a maximum of the plasma diamagnetism. The decrease of $\Delta n/n$ at small concentrations is due to the fact that the plasma diamagnetism decreases, and also to the fact that the ionization time of neutral particles by electrons becomes larger than the characteristic time of confinement of hot electrons in the trap. The decrease of the quantity $\Delta n/n$ as the initial density of the plasma increases (for $n>4\times10^{13}$ cm^{-3}) is determined principally by the decrease of the quantity of neutral hydrogen in the initial plasma.

2. Investigation of the hot-ion distribution function

The main results on ion heating were obtained in two regimes of functioning of the electron accelerator. In the first the maximal beam current injected into the plasma was ≈7 kA, the diameter 4.3 cm, the electron density in the beam $n'\approx10^{11}$ cm^{-3}. In the second regime the measurements were carried out with a REB of 2.5 cm diameter and maximal current ≈10 kA. In this regime the electron density was $\approx5\times10^{11}$ cm^{-3}. In both regimes the energy of the REB was ~1 MeV and the pulse duration ≈70 ns. The transverse dimension of the beam was determined by means of astrolon plates situated in its path. By the autograph left by the beam in the astrolon one can reach the conclusion that the radial current distribution does not have clearly expressed inhomogeneities.

The first experiments have shown that as the electron beam passes through the plasma, a broad spectrum of fast hydrogen atoms is emitted from the plasma. For fixed parameters of the REB the range of observed energies of the fast atoms depends strongly on the density of the initial plasma. For a high density ($n\gtrsim10^{14}$ cm^{-3}) the neutral particle spectrum stretches to energies of 2.5–3 keV. In the low-density region ($n\lesssim10^{13}$ cm^{-3}) we have recorded neutral particle emission with energies up to 10–15 keV.

Typical oscilloscope traces of signals from charge-exchange atoms at different energies are shown in Fig. 6. The difference in the positions of the maxima is due to the fact that the flight time of the particles from the plasma to the detector depends on the energy. Taking into account the time-of-flight relations one can conclude that the appearance of fast charge-exchange atoms coincides with the instant at which the electron beam is injected into the plasma within an accuracy of 30 ns. The decrease of the duration of the front of the signal as the energy increases is due to the improvement of the temporal resolution of the analyzer, and in addition the collection time for charge-exchange atoms from the region occupied by the heated ions decreases. After the completion of the ion-heating phase there occurs a decrease of the emission of neutral charge-exchange particles. Since the rate of charge-exchange is higher at high energies, the emission of particles with high energies falls off faster.

We have constructed the distribution functions of the heated ions for the instant of time corresponding to the maximal signal of charge-exchange atoms at the highest energy. The change of the ion distribution function as a function of the initial plasma into which the REB is injected is shown in Fig. 7. For high plasma density ($n\gtrsim10^{14}$ cm^{-3}) the heated ions have a distribution function

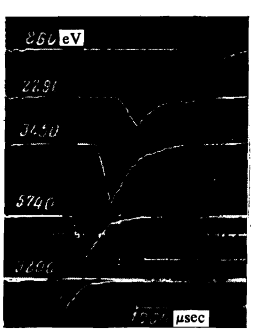

FIG. 6. Oscilloscope traces of signals from charge-exchange atoms with different energies for plasma density $n\approx10^{13}$ cm^{-3}.

close to Maxwellian. For $n \approx 2\times10^{14}$ cm^{-3} and $n' \approx 10^{11}$ cm^{-3} the ion temperature determined with the aid of Eq. (5) is ≈ 390 eV. For densities $n \lesssim (3-4)\times10^{13}$ cm^{-3} one observes a substantial deviation of the distribution function from Maxwellian. However, in this case the distribution function of the heated ions can be represented as a superposition of two Maxwellian functions with temperatures T_1 and T_2. Thus, for $n \approx 10^{13}$ cm^{-3} and $n' \approx 10^{11}$ cm^{-3} the ion distribution function obtained experimentally can be described by two Maxwellian functions with the temperatures respectively equal to $T_1 = 400$ eV and $T_2 = 2\times10^3$ eV. As can be seen from Fig. 7, as the plasma density decreases, the number of heated ions increases. But we will show below that in all regimes of operation not all ions are heated, but only part.

The interaction of a REB of particle density $n' \approx 5\times10^{11}$ cm^{-3} with a plasma leads to the observation of the emission of neutral charge-exchange particles to a maximal plasma density of $n \approx (3-4)\times10^{14}$ cm^{-3}, whereas for $n' \approx 10^{11}$ cm^{-3} there is no emission of charge-exchange atoms for this plasma density. The concentration n_0 of neutral hydrogen determined according to Eq. (9) and also from the results of measuring the increment in plasma density after the passage of the REB, turns out to be $n_0 = (5-6)\times10^{13}$ cm^{-3} for a plasma density $n = (2-4)\times10^{14}$ cm^{-3}, and $n_0 = (2-3)\times10^{13}$ cm^{-3} for $n = 3\times10^{12}-1\times10^{13}$ cm^{-3}.

We now consider the results of the determination of the number of heated ions. The dependence of the density of these ions on the plasma concentration was calculated according to Eq. (8), making use of the results of measurements of the spectrum of charge-exchange atoms, the quantity n_0 and the calibration data. This dependence is exhibited in Fig. 8. In the high-density region ($n > 10^{14}$ cm^{-3}) the fraction of heated ions is small ($10^{-3}-10^{-4}$ of the plasma density). For the "two-temperature" distribution of the ions ($n < 10^{13}$ cm^{-3}) the density of the "warm" ions ($T_1 = 400$ eV) exceeds that of the "hot" ones ($T_2 = 2$ keV) by a factor of 3–6. The total quantity of heated ions reaches a fraction of 10–20% of the total number of ions in the plasma. We note that the change in electron density in the REB from $n' \approx 10^{11}$ cm^{-3} to $n' \approx 5\times10^{11}$ cm^{-3} leads to an insignificant change of the average energy of the heated ions, whereas the quantity of heated ions (in the range $n = 2\times10^{13}-4\times10^{14}$ cm^{-3}) increases considerably.

Thus, when the REB is injected into the plasma only a fraction ($\lesssim 20\%$) of the ions is heated. The distribution

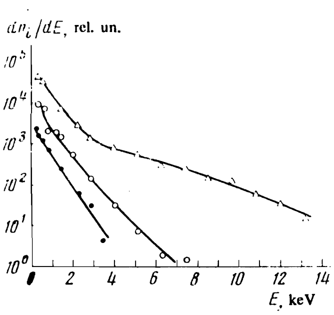

FIG. 7. The distribution function of heated ions for various plasma densities: Δ—$n = 10^{13}$ cm^{-3}, o—$n = 3.5\times10^{13}$ cm^{-3}, $\bullet$—$n = 2\times10^{14}$ cm^{-3}.

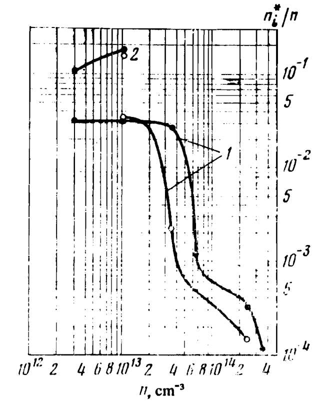

FIG. 8. The dependence of the density of heated ions on the plasma concentration: 1—the density of ions with temperature T_2; 2—the density of ions with temperature T_1, $\bullet$ beam diameter 2.5 cm, o—beam diameter 4.3 cm.

function of the heated ions differs from a Maxwellian in the energy range under investigation, particularly for not very large plasma densities. The main fraction of ions seems to remain cold. It was not possible to measure the distribution function of the cold ions by the described method (the sensitivity of the apparatus is limited from below by neutral particle energies of 200–300 eV). Taking into account the presence of the group of these cold ions, one can say that as a whole, the distribution function of the ionic component of the plasma after the passage of the REB has a form which differs substantially from an equilibrium distribution. In this case even the concept of a two-temperature distribution is only a matter of convention. In principle, for sufficiently lengthy confinement the heated ions will transfer their energy to the cold ions, leading to an equilibrium distribution of the ions. For this it is necessary first that the lifetime of the heated ions with respect to charge exchange should be long compared to the time of binary collisions. To this one must add that the time of escape of hot ions from the trap must be larger than the time of binary collisions.

In the course of the experiment we have also measured the emission of neutral charge-exchange particles from the peripheral region of the plasma column. In these conditions the analyzer scanned a plasma region with radius ≈ 0.7 cm situated at a distance of 1 cm from the boundary of the electron beam (the beam diameter was 2.5 cm). In distinction from measurements along the radius of the plasma column, the emission of neutral particles along chords was observed only when the plasma density was lowered to $n \lesssim (5-6)\times10^{13}$ cm^{-3}. This indicates that for a plasma density $n > 6\times10^{13}$ cm^{-3} the region where the heating of the ions occurs is close to the diameter of the REB. The distribution function of the ions at the periphery of the plasma column is a two-temperature distribution. Here the average energy of the ions is by 10–20% lower than in the central plasma region.

The size d of the plasma region where the ion heating occurs was also estimated by means of Eq. (10) (for the heating time τ_{heat} we have taken the duration of the REB pulse). As the plasma density varied in the range $4\times10^{14}-3\times10^{12}$ cm^{-3} the quantity d varied from the diameter of the electron beam to the diameter of the plasma column. Finally, we note that a decrease of the magnitude of the longitudinal magnetic field from 12 to 6 kOe does not lead to substantial changes in the ion heating.

IV. DISCUSSION OF THE EXPERIMENTAL RESULTS

Let us consider the possible mechanisms for the ion heating observed in the experiment: 1) nonlinear scattering of the ions by Langmuir oscillations excited by the electron beam, 2) acceleration of plasma ions in radial electric fields which appear when the electron beam is injected, 3) the interaction of the ions with small-scale oscillations excited by the reverse current. Let us consider each of these possibilities in more detail.

As the REB is injected into the plasma a beam instability may develop with increment $\mathrm{Im}\,\omega \sim (n'/n)\omega_{pe}$, leading to the appearance of Langmuir oscillations with phase velocity $v_{ph} \sim c$. Under the assumption that $\omega_{pe} \gg \omega_{He}$ (for $H = 12$ kOe this condition is met if the plasma density is $n > 10^{14}$ cm^{-3}), the dispersion relation for these waves has the form

$$\omega=\omega_{pe}\left[1+\frac{1}{2}\frac{\omega_{He}^2}{\omega_{pe}^2}\sin^2\theta\left(1-\frac{\omega_{pe}^2}{k^2c^2}\right)\right],$$

where θ is the angle between the wave vector $\mathbf{k}$ and the direction of the magnetic field. For such a dispersion law an effective heating mechanism may be the nonlinear scattering of the ions on Langmuir waves. The resonance condition for this interaction is $\omega - \omega' = (\mathbf{k} - \mathbf{k}') \cdot \mathbf{v}_i$ and is valid in a wide range of ion energies. The consideration of such a mechanism for heating shows that as a result of nonlinear scattering a distribution function of the ions must obtain which has a Maxwellian form with temperature dependent on the energy density of the Langmuir waves. Rough estimates of the ion temperature yield values at the level of the electron temperature, but unfortunately it is very hard to give a unique answer to the question what fraction of the ions is heated in this process. Therefore one cannot definitely say whether this mechanism manifests itself in our experiments.

The passage of the electron beam through the plasma may be accompanied by the appearance of a sufficiently strong radial electric field. This field exists in time less than the period of the cyclotron rotation of the ions and can lead to their acceleration. However, the distribution function of the ions under such an acceleration must differ substantially from the one observed experimentally, since the charge-exchange cross section changes only by a relatively small factor over the range of energies from 0.3 to 15 keV, and under our experimental conditions the charge-exchange process occurs only once. The absence of such a heating mechanism is also indicated by the fact that the heating character is not affected by the magnetic field. If the magnetic field is decreased one should observe a stronger radial acceleration of the ions, which does not happen experimentally.

In preceding experiments carried out on the INAR installation,[2,4] it was shown that when a REB is injected into a plasma a reverse current is excited, current which guarantees the current compensation of the electron beam. The degree of compensation is determined by the parameters of the REB and of the plasma and by the stability of the reverse current. For a plasma density $n > 10^{14}$ cm^{-3} the beam current is almost completely compensated by the reverse current which flows in the beam cross section. In this case the plasma has a high conductivity and the energy dissipation of the reverse current is small. The current velocity of the plasma electrons for complete compensation is relatively low and can be determined from the simple relation: $u = cn'/n$. In the range of concentrations $n \lesssim 10^{14}$ cm^{-3} the current velocity of the plasma electrons u is larger than the ion sound velocity v_s. Under these conditions an ion-acoustic instability may arise, with an increment $\mathrm{Im}\,\omega \sim \omega_{pi}$. The reverse current energy dissipation observed through electrical measurements for $n < 10^{14}$ cm^{-3} is apparently related to the appearance of an anomalous resistance for a sufficiently developed instability. The appearance of an anomalous resistance leads to an increase in the thickness of the skin-layer, and hence the reverse current in the plasma begins to flow in a cross section which exceeds the transverse size of the beam. For $n < 6\times10^{13}$ cm^{-3} the reverse current flows already in the whole cross section of the plasma column. If one compares the results of observation of charge-exchange neutral particles with the data obtained from measurements of the reverse current one can note the following two circumstances. First, the region in which the ion heating occurs coincides with the region where the reverse current flows. Second, as the current density of the beam increases and together with it the density of the reverse current, the concentration and temperature of the heated ions increase for fixed plasma density.

For a plasma density $n < 10^{14}$ cm^{-3} the described results on the heating of ions in a REB + plasma system have much in common with the experiments on turbulent plasma heating by a current. Thus, in a series of papers[12–15] a two-temperature character of the plasma ion distribution function was also observed. Thus, the ion heating when a REB is injected into a plasma in the conditions of our experiment seems to be related to the appearance of small-scale turbulence in the plasma as a result of reverse current instability, the reverse current being generated by the high-current relativistic electron beam.

The authors are sincerely grateful to D. D. Ryutov, V. V. Mirnov for useful discussions and to A. V. Arzhannikov and A. V. Burdakov for help with the experiment.

[1)]The temporal resolution of the secondary electron multiplier VEU-1 is $\tau_{\mathrm{VEU}} \lesssim 10^{-8}$s.

[1]V. S. Koĭdan, V. M. Lagunov, V. N. Lukyanov, K. I. Mekler, and A. P. Sobolev, Proc. 5-th Europ. Conf. Plasma Phys. and Contr. Nucl. Fusion Research, Grenoble, 1, 1972, p. 161.

[2]Yu. I. Abrashitov, V. S. Koĭdan, V. V. Konyukhov, V. M. Lagunov, V. N. Luk'yanov, K. I. Mekler, and D. D. Ryutov, Zh. Eksp. Teor. Fiz. 66, 1324 (1974) [Sov. Phys. JETP 39, 647 (1974)].

[3]A. V. Arzhannikov, B. N. Breĭzman, L. N. Vyacheslavov, V. S. Koĭdan, V. V. Konyukhov, and D. D. Ryutov, Plasma

Physics and Contr. Nuclear Fusion Research, IAEA, Vienna, 3, 257 (1975).
[4]A. V. Arzhannikov and V. S. Koĭdan, Proc. 12-th Intern. Conf. on Phenomena in Ionized Gases, Eindhoven, 1, 1975, p. 278.
[5]V. V. Afrosimov, I. P. Gladkovskiĭ, Yu. S. Gordeev, I. F. Kalinkevich, and N. F. Fedorchenko, Zh. Eksp. Teor. Fiz. 30, 1456 (1960) [*sic*].
[6]O. V. Kozlov, A. M. Rodin, V. D. Rusanov, Yu. A. Skoblo, and A. V. Chernetskiĭ, in: Diagnostika plasmy (Plasma diagnostics), Vol. 1, Atomizdat, 1963, p. 199.
[7]V. S. Koĭdan, Candidate's Dissertation, Inst. Nucl. Phys. Siber. Div. Acad. Sci. USSR, Novosibirsk, 1971.
[8]N. A. Koshilev and O. G. Parfenov, PMTF (Prikladnaya Matematika i Teoreticheskaya Fizika ?) No. 6, 40 (1974).
[9]N. I. Alinovskiĭ, A. T. Altyntsev and N. A. Koshilev, Prik. Mat. Teor. Fiz. No. 3, 132 (1970).
[10]L. A. Sena, Stolknoveniya élektronov i ionov s atomami gaza (Collisions of electrons and ions with gas atoms), OGIZ, 1948.
[11]W. L. Fite, R. F. Stebbings, D. G. Hummer, and R. T. Brackman, Phys. Rev. 119, 663 (1960).
[12]V. S. Koĭdan and A. G. Ponomarenko, Proc. 4-th Europ. Conf. Plasma Physics and Contr. Nucl. Fusion Research, Roma, 1, 1970, p. 63.
[13]E. K. Zavoĭskiĭ, B. A. Demidov, Yu. G. Kalinin, A. G. Plakhov, L. I. Rudakov, B. D. Rusanov, V. A. Skoryupin, G. E. Smolkin, A. V Titov, S. D. Fanchenko, V. V. Shapkin, and G. V. Sholin, Plasma Phys. and Contr. Nucl. Fusion Research, IAEA, Vienna, 2, 3 (1971).
[14]C. Wharton, P. Korn, D. Prono, S. Robertson, P. Auer, and C. T. Dum, *ibid.* 2, 25 (1971).
[15]H. de Kluiver, H. W. Piekaar, W. R. Rutgers, H. Schrijver, and B. de Groot, *ibid.* 2, 67 (1971).

Translated by M. E. Mayer

Thermalization of the directed motion of plasmoids by a turbulent skin-layer discharge

L. E. Aranchuk, Yu. G. Kalinin, A. S. Kingsep, V. A. Skoryupin, and V. V. Yan'kov

I. V. Kurchatov Institute of Atomic Energy
(Submitted May 17, 1976)
Zh. Eksp. Teor. Fiz. **71**, 1849–1862 (November 1976)

Slowing down of oppositely moving plasma streams is observed experimentally when a direct skin-layer current of density $j > en(T_e/M)^{1/2}$ is passed through them. The energy of the translational motion is transformed in this case into thermal energy. The plasma column is heated along the radius from the skin layer toward the axis at the velocity of ion sound; the heating is accompanied by intense noise with a frequency on the order of ω_{pi}. A theoretical explanation of the phenomenon is proposed, based on the nonlinear instability of a two-stream plasma to finite-amplitude perturbations originating in the skin layer.

PACS numbers: 52.25.Fi

The turbulent heating of a plasma by a current is one of the most effective methods of obtaining a dense high-temperature plasma. Since the trail-blazing work by Zavoĭskiĭ and co-workers,[1–3] this problem has attracted considerable attention in plasma research to this day (see, e.g.,[4–6]). For large-scale installations with a dense plasma, the condition of turbulent heating $j > ne(T_e/M)^{1/2}$ with allowance for the actually attainable total current is easiest to realize under conditions of a skin-layer discharge, when the current flows only in a thin plasma layer. The first investigation of turbulent heating of a plasma in a large-scale installation under conditions of a skin-layer discharge was carried out in[7].

The experiments described below were performed with the same installation but under conditions when there are opposing plasma streams. It was observed in these experiments that excitation of ion-sound instability in a two-stream plasma leads to effective deceleration of the plasmoids. The energy of the translational motion goes over in this case into thermal energy. A theoretical explanation is offered for this phenomenon on the basis of nonlinear instability of a two-stream plasma to perturbations of finite amplitude, the source of which is the skin layer.

1. INSTALLATION AND DIAGNOSTICS

The TN-5[8] installation constitutes an open trap with a mirror ratio 1.85 and a magnetic field up to 7 kOe in the central part. The metal vacuum chamber of 55 cm diameter was evacuated to 10^{-8} mm Hg. A plasma column of length 3 m and diameter ~20 cm was produced in the central part of the trap by two film-hydride sources placed in the mirrors, to which capacitors up to 0.7 μF pre-charged to 20 kV were alternately switched. A 0.83-μF capacitor charged to 10–45 kV in the different experiments was connected in the direct-discharge circuit. The time variation of the plasma density and its distribution along the radius could be evaluated from the readings of electric double probes operating in the saturation regime. The results were monitored against the cutoff of a microwave signal of wavelength 4 or 8 mm. The radial distribution of the azimuthal field $H_\varphi(r)$ of the current was measured with an array of seven magnetic probes, followed by RC integration, while the total current was measured with a