Experiments on the collective interaction of a microsecond relativistic electron beam with a plasma in the GOL-3 facility

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A considerable collisionless slowing of a beam in a plasma (a decrease in the mean electron energy by ~25%) and transfer of a significant portion of the beam energy to the plasma are achieved as a result of the collective interaction of a microsecond relativistic electron beam with a plasma in the GOL-3 facility. A beam with a duration up to 5 μs and an energy up to 100 kJ is injected into a hydrogen plasma with a density $\sim 10^{15}$ cm^{-3} found in a 7-m solenoid with a field equal to 5.5 T. The specific energy content of the plasma remains longitudinally inhomogeneous during the heating period with a maximum near the point where the beam is injected. The parameters of the superthermal electrons born during the collective interaction are also determined. The features of the heating process and heat transfer in the plasma are discussed. © *1996 American Institute of Physics.* [S1063-7761(96)01206-1]

1. INTRODUCTION

Until recently, investigations on the collective interaction of high-power relativistic electron beams (REB) with a plasma were performed using beams of nanosecond duration, whose energy content did not exceed a few kilojoules (see, for example, Ref. 1). The physics and technology for generating high-power REB's of microsecond duration with a pulse energy content of 100 kJ or more were developed in the last few years in several laboratories, including the Institute of Nuclear Physics of the Siberian Branch of the Russian Academy of Sciences (see, for example, Ref. 2). These efforts created the foundation for setting up new experiments to investigate the interaction of such beams with a plasma, especially as applied to the problem of heating plasmas to subthermonuclear temperatures.[3] The GOL-3 facility was constructed for this purpose, and investigations of the collective interaction and heating of a dense plasma (with a density up to 10^{17} cm^{-3}) using an REB of microsecond duration have until now been carried out primarily in it.[4]

In this communication we report the results of experiments designed to study the collisionless relaxation of a microsecond beam when it is injected into a plasma with a density $\sim 10^{15}$ cm^{-3}.

2. THE FACILITY AND DIAGNOSTICS

A schematic representation of the facility is shown in Fig. 1. It consists of a U-3 electron-beam generator, a plasma chamber within a solenoid with a uniform field up to 6 T along a length of 7 m and 12 T in the separate mirrors at the ends, and a capacitor bank with a nominal energy content of 10 MJ for supplying the solenoid, as well as control, monitoring, and diagnostic systems. The main elements of the facility and their possibilities were described in Refs. 4 and 5. In the experiments discussed in this paper the facility operated with the following parameters: the magnetic field in the uniform part of the solenoid was 5.5 T, the magnetic field in the mirrors was 11 T, and the hydrogen plasma column had a length of 7 m and a diameter of 8 cm.

An electron beam with an energy of 0.8–0.9 MeV and a duration of 3–5 μs was generated in a quasiplanar diode with a graphite cathode having a diameter of 20 cm. The distance between the cathode and the anodic foil (aluminum-coated Mylar with a thickness of 10 μm) was 5–8 cm. The beam was generated in the diode with a longitudinal magnetic field strength up to 0.6 T, the beam current density reaching 200 A/cm^2. To increase the current density the beam was compressed in a magnetic field of the mirror configuration and injected into the plasma chamber. As a result, the current density of the beam in the plasma was equal to 1–2 kA/cm^2 when its diameter was 6 cm, and its typical energy content was 70±20 kJ.

Various methods were used to diagnose the parameters of the beam, the plasma, and the interaction of the beam with the plasma. The initial energy of the beam electrons was determined from the diode voltage U_d, which was measured by an ohmic divider. The beam current I_b at the entrance and exit and the total currents flowing in the plasma in different parts of the facility were measured by Rogowski loops. The energy content of the beam which traversed the plasma was determined using a graphite calorimeter, as well as by calculating the integral $\int U_d I_b dt$. The energy lost by the beam as a result of the interaction with the plasma was determined from the difference between these two values. The energy spectrum of the REB was measured using multifoil and magnetic analyzers, which were installed at the exit from the facility.

Two optical interferometers with $\lambda = 3.39$ μm, several

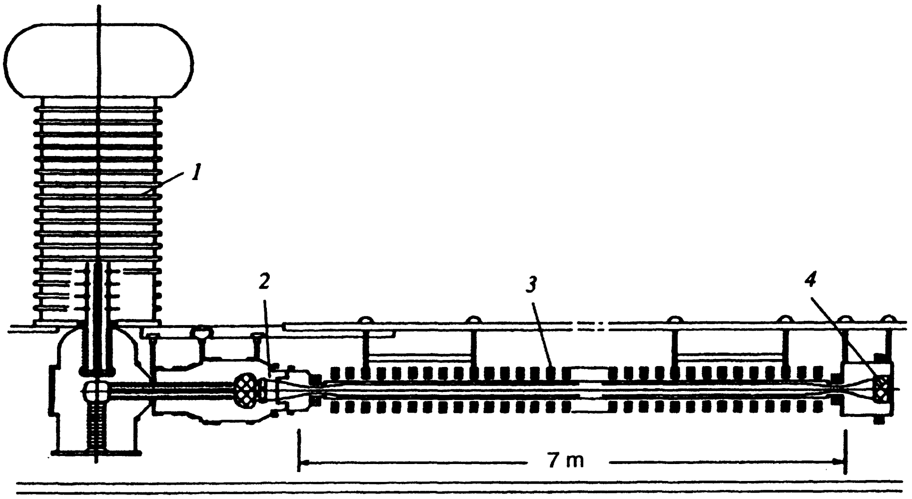

FIG. 1. Schematic representation of the GOL-3 facility: *1* — megavolt electron beam generator; *2* — vacuum diode; *3* — solenoid plasma chamber; *4* — exit (collecting) unit.

diamagnetic sensors, multichannel detectors of x and vacuum-ultraviolet radiation, two systems for determining the Thomson scattering of laser radiation, and several spectroscopic methods were used to measure the plasma parameters.

The main focus in this paper will be the results of the measurements performed by the diamagnetic sensors, which were located at several points along the facility, and the data from diagnosing the Thomson scattering of light from a ruby laser. One of the laser systems (25 ns, 20 J) was used to measure the density and temperature of the heated electron component in the center of the plasma column at a distance $x=270$ cm from the point of entry of the beam into the plasma. The other system (20 ns, 3 J) was intended to measure the radial profile of the plasma density and was positioned at a distance of 360 cm from the point of entry. The use of narrow-band light filters in this system also makes it possible to draw qualitative conclusions regarding the radial distribution of the temperature in the heated plasma.

3. EXPERIMENTAL PROCEDURE

At first the experiments were carried out only with injection of the beam into an initially prepared preliminary plasma,[5] but a series of experiments, in which the beam was injected into neutral hydrogen and the latter was ionized by beam electrons, was subsequently also carried out. The main attention in these experiments was focused on elucidating the following issues:

1. transporting the electron beam over the entire length of the vacuum chamber without losing particles;
2. finding the conditions for effective relaxation of the beam in the plasma;
3. determining the parameters of the electron beam after interacting with the plasma;
4. measuring the parameters of the electron component of the heated plasma (the main component and the superthermal electrons).

The main process resulting in a loss of energy by the beam in the range of experimental parameters under discussion is the excitation by the beam of Langmuir oscillations with a growth rate under kinetic conditions

$$\Gamma=\omega_p\frac{n_b}{n_p}\frac{1}{\gamma}\frac{1}{\Delta\theta^2},$$

where ω_p is the plasma frequency, n_p and n_b are the plasma and beam densities, $\Delta\theta$ is the angular straggling of the beam electrons, and γ is the relativistic factor. This and several attendant processes have been treated theoretically in detail in many publications (see, for example, Ref. 6–10). Despite the fact that highly efficient relaxation of a beam in a plasma with a density up to 10^{15} cm^{-3} has been achieved by several teams in experiments with nanosecond beams (see, for example, Refs. 4,11–15), the possibility of obtaining similar results with a beam of microsecond duration was far from obvious before the experiments were begun, since a microsecond beam has an appreciably smaller current density in the plasma and poorer angular characteristics due to its compression in the magnetic field before injection into the plasma.

In a typical experiment, after the magnetic field is switched on, a preliminary hydrogen plasma with a diameter of 8 cm and a length of 7 m is created at its maximum (10 ms) by a dc discharge. The plasma density can be varied in the range from 10^{14} to 10^{16} cm^{-3}. When the current of the dc discharge is terminated, the electron beam is injected into this plasma. The beam can also be injected into an unionized gas and into a preliminary plasma with incomplete ionization. The density of the preliminary plasma was quite uniform over its cross section.

4. GENERAL RESULTS

Macroscopically stable passage of the beam through the facility (7 m) was observed in the range of plasma and gas densities investigated (3×10^{14} to 5×10^{15} cm^{-3}). The diameter of the beam in different parts of the facility, which was determined from the sizes of holes in thin foils, corresponded to the calculated course of the magnetic field lines. In addition, the fluorescence of the plasma in the vacuum-ultraviolet range was observed using a multichannel pinhole camera

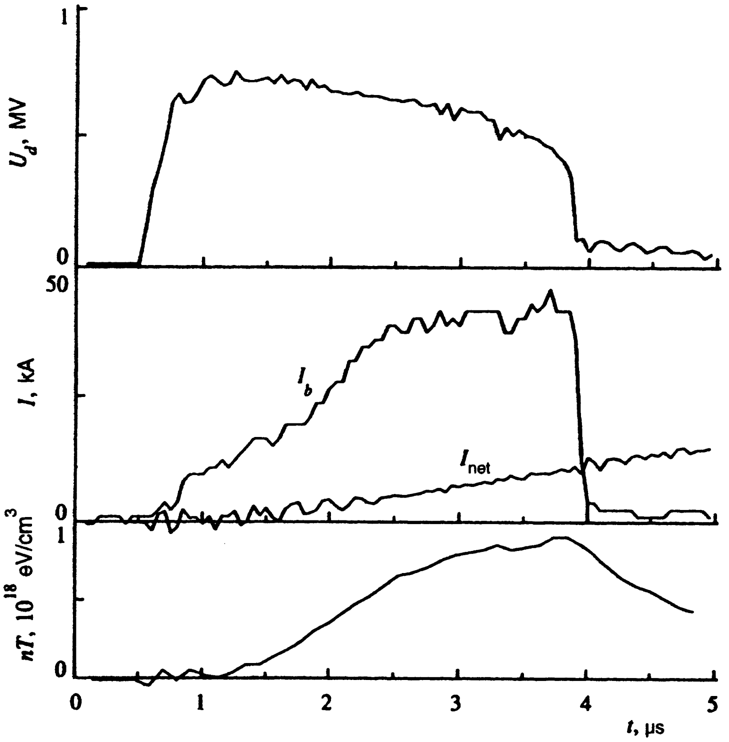

FIG. 2. Typical oscillograms of the voltage on the diode U_d, the beam current I_b, the total current in the plasma I_{net}, and the plasma pressure nT.

from a region, whose dimensions corresponded to the calculated diameter of the beam in the plasma. The beam current passing through the plasma was approximately an order of magnitude greater than the value of the limiting vacuum current (5 kA when the beam energy was $E_b = 600$ keV) for the geometry of the chamber in the facility.

According to the data from chordal vacuum-ultraviolet measurements, the intensity of the radiation from the region not occupied by the electron beam is insignificant. This indicates that there is no heating of the plasma due to the transfer of energy by the Langmuir oscillations into this region and that there are no appreciable macroscopic displacements of the beam as a whole as it is transported along the plasma.

One special feature of the operation of the microsecond diode in the experiments described here is the earlier termination of the beam current in comparison with the case in which a diode operates directly on a beam collector located behind the anodic foil of the generator. Up to the moment of diode breakdown (the abrupt decrease in voltage in Fig. 2) the dynamics of the beam current and the voltage on the cathode differ only slightly from the operating regime on a container–collector. One result of this breakdown is an appreciable decrease in the energy content of the compressed beam injected into the plasma. The reason for the earlier short-circuiting of the diode may be the additional "operating time" of the anodic plasma under the action of oscillating electrons appearing as a result of the reflection of some of the beam electrons back into the diode from the region of magnetic compression.

When a beam is injected into a preliminary plasma, partial current neutralization of the beam by the reverse plasma current is observed from the very beginning of the pulse (see Fig. 2). The total current increases practically linearly to 8–12 kA by the end of the pulse. When a beam is injected into a neutral gas, current neutralization begins later, ~ 0.5 μs after the beginning of the pulse, and the total current at the end of the pulse can reach 20 kA (when the beam current is 40 kA). In this case some displacement of the beam is sometimes observed at the exit from the facility when the total current is large, possibly indicating the appearance of a screw instability. At a certain time after the beginning of beam injection, heating of the plasma begins and can be detected by the increase in the pressure (diamagnetism) of the plasma, which remains approximately linear over the course of the injection pulse.

The temporal course of the plasma line density nl (l is the mean transverse dimension of the plasma) according to the data from interferometric measurements at a wavelength of 3.39 μm is illustrated in Fig. 3. At the time $t = 0$ the preliminary plasma is switched on, and injection of the electron beam is begun after 45 μs. In the interferogram in Fig. 3 the plasma preliminarily created using a dc discharge was not completely ionized. The mean plasma density after termination of the beam is 1×10^{15} cm^{-3}. The increase in the plasma line density after beam injection is completed corresponds to ionization of the hydrogen remaining in the chamber. As the experiments showed, an operating regime with incomplete ionization of the hydrogen by the dc discharge generally provides somewhat more stable and higher values of the plasma pressure at the time when beam injection is completed. This circumstance can be attributed to the ratio between the beam and plasma densities, which is more favorable for the development of Langmuir turbulence (see the formula for the growth rate presented above), especially in

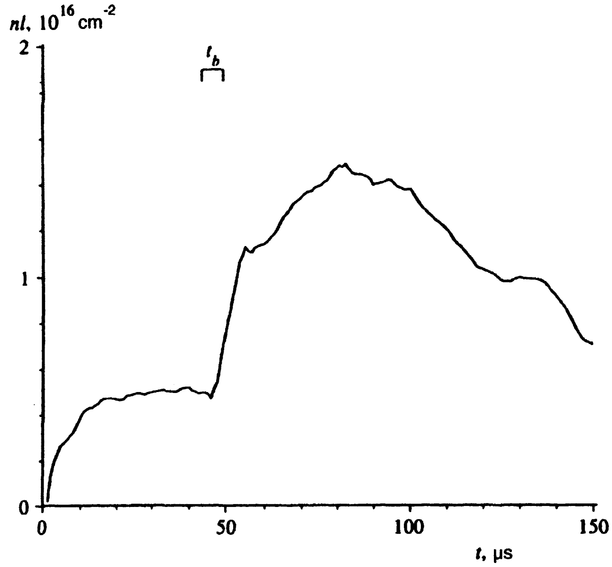

FIG. 3. Interferogram (regime with incomplete initial ionization). The beam injection time t_b is noted.

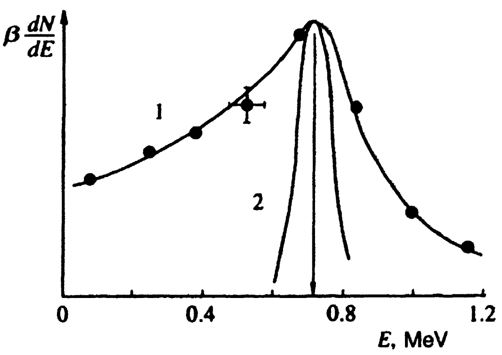

FIG. 4. Spectrum of the beam after traversing the plasma (*1*) at a time equal to 1.4 μs (the initial energy of the beam electrons eU is also indicated by the arrow) and instrumental function of the analyzer (2); β is the ratio of the electron velocity to the velocity of light.

the initial stage of injection, while the beam current density is small.

The dependence of the energy lost by the beam on the plasma density was obtained in the experiments from the results of calorimetric measurements. When the plasma density is high, the relative loss of beam energy is small, but it increases with decreasing density and reaches a value of 25% when the density is 5×10^{14} cm^{-3}. At the previously indicated kinetic energy of the beam electrons and plasma density this loss can be caused only by collective slowing of the beam in the plasma as a result of the development of beam instability (control experiments, in which the interaction efficiency and the heating of the plasma decreased considerably when the plasma density decreased and/or the angular characteristics of the beam worsened, were performed). We note that the loss of beam energy is practically identical when it is injected into hydrogen with an identical atom density, but with a different degree of preliminary ionization.

5. SPECTRUM OF THE BEAM ELECTRONS

The results obtained using the multifoil and magnetic spectral analyzers are consistent with one another; therefore, only the data from the measurements using the magnetic analyzer will be discussed below (the results obtained using the multifoil analyzer were presented in Ref. 5). The magnetic analyzer operates on the principle of separating the electrons according to the length of their Larmor "step" when they nonadiabatically enter a transverse magnetic field. To minimize the error associated with the angular straggling of the beam electrons, the analyzer was positioned outside the exit plug in a weak magnetic field. The spectrum was measured in the axial portion of the beam. The analyzer was preliminarily calculated with respect to the energy by injecting a beam with a current much smaller than the limiting vacuum current into a vacuum.

Figure 4 presents a typical spectrum of a beam at the exit from the plasma column in the strong-interaction regime. The figure also shows the instrumental function of the analyzer and presents the value of the voltage on the cathode of the beam generator at the time of measurement. It is seen that the spectrum of the beam broadens on the low-energy side, and an appreciable number of particles with an energy significantly exceeding the initial energy is observed. We note that accelerated beam particles were also observed in other facilities.[16,17] The mean energy of the beam electrons after traversing a plasma with a varying starting extent of ionization and a density equal to 0.3×10^{15} to 1.0×10^{15} cm^{-3} is equal to $0.7eU_d$, which corresponds to a 30% loss of beam energy. The magnitude of the loss varies weakly during a pulse.

Control experiments with injection of a beam into a plasma having a higher density of $\sim3\times10^{15}$ cm^{-3} showed that most of the electrons maintain an energy close to the energy determined by the diode voltage, although there are slow electrons with energies down to the minimum detectable values (~100 keV). The mean loss of beam energy in this regime is small. The beam can lose a small amount of energy in this case, since some heating of the plasma is already noted in this regime when the integral loss of beam energy is less than 5%.

In general, the energy loss on the axis of a beam with the optimum density can be determined as $dQ/Q\sim25$–30%. The magnitude of the loss varies weakly during a pulse, and the form of the spectrum of the beam is maintained, tracing the diode voltage (after a period of ~0.5 μs, when the currents in the analyzer channels are sufficient for reliable measurement).

As in some other experiments using microsecond REB's, each beam exhibits a characteristic microstructure, which is manifested in the form of short (~100 ns) current surges on the signals of collectors with dimensions corresponding to a diameter smaller than 1 cm on the cathode surface. In the experiments under discussion this microstructure was also noted in measurements employing an electro-optic x-ray converter that detects radiation with an energy above 3 keV from the surface of a thin foil immersed in a plasma.

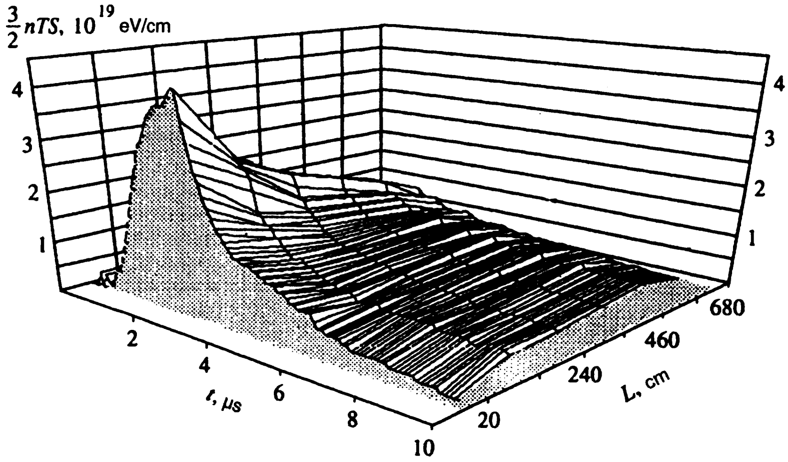

FIG. 5. Distribution of the diamagnetic signals along the facility and its dynamics with time.

6. HEATING THE MAIN COMPONENT OF THE PLASMA

We recall that the typical distribution function of the heated electrons in experiments involving the heating of a plasma by a high-current relativistic beam has a complicated form[18] (the ionic component of the plasma remains cold in such experiments). Along with the Maxwellian electrons (the main component), there are also superthermal electrons, which (depending on the experimental conditions) can hold most of the energy lost by the beam in the plasma. For REB's of microsecond duration most of the fast electrons manage to leave the plasma while the beam is being injected and thus carry off a considerable part of the energy transferred by the beam to the plasma. We note that there are, in principle, ways to "recover" the energy of the superthermal electrons in a plasma, for example, by creating dense plasma clouds near the mirror (see, for example, Ref. 19). Nevertheless, the energy remaining in the main component of the plasma has a value which is of interest in itself on both the absolute and relative (in comparison with the energy of the REB) scales.

Let us examine the overall picture of the release of energy by an REB in a plasma. Figure 5 presents the distribution of the diamagnetism (the plasma pressure) along the facility [in units of $(3/2)nTS$, where S is the cross-sectional area of the plasma column]. Integration of the local energy content of the plasma along the facility obtained from these measurements gives the total energy stored in the plasma column.

Figure 6 presents how the energy stored in the plasma column at the time of completion of an REB pulse, which was determined from diamagnetic measurements, varies with the energy of the injected beam. The beam energy was varied mainly by varying the beam duration while maintaining its instantaneous parameters. It is seen from the figure that the energy in the plasma column (its volume is about 20 liters) reaches 3 kJ and increases with increasing beam energy.

It should be noted at once that the values of the plasma energy content obtained cannot be attributed to Joule heating by the reverse beam current flowing through the plasma. Simple estimates show that the temperature to which a plasma can be heated by the reverse current and by the attendant current instabilities under the conditions of the experiments in the GOL-3 facility is less than 15–20 eV for a density of 10^{15} cm^{-3}. The absence of appreciable heating of the plasma by these mechanisms was experimentally confirmed when a beam having a large angular straggling and unaltered values of the remaining parameters was injected into the plasma and the conditions for the development of beam instability were thus absent. As in experiments with nanosecond beams, the release of energy in the plasma dropped sharply in this case.

Let us move on to the results of the laser-scattering measurements. The delay in triggering the laser relative to the beginning of beam injection could be varied, making it possible to obtain information on the dynamics of the temperature and the plasma density with time. The initial temperature of 1–3 eV increases by two or three orders of magnitude after beam injection. The plasma density at which these measurements were performed was $(1.0\pm0.2)\times10^{15}$ cm^{-3}. The information on the density obtained by the two laser-scattering systems is consistent with the data obtained by interferometry at a wavelength of 3.39 μm. The temperature obtained from the laser measurements ($x=270$ cm) amounts to 0.6 ± 0.2 keV at the heating maximum when the density is $(1.0\pm0.2)\times10^{15}$ cm^{-3}, and the values of the "laser" and "diamagnetic" temperatures agree with one another to within the measurement error in the plasma-cooling stage

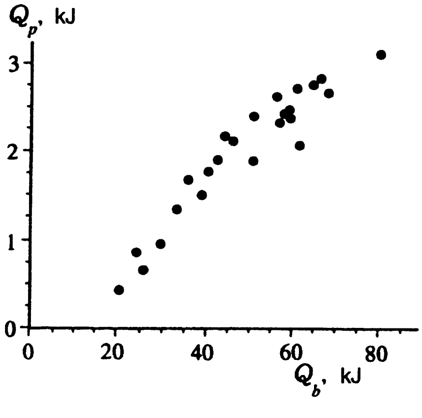

FIG. 6. Dependence of the energy content in the plasma Q_p on the injected beam energy Q_b.

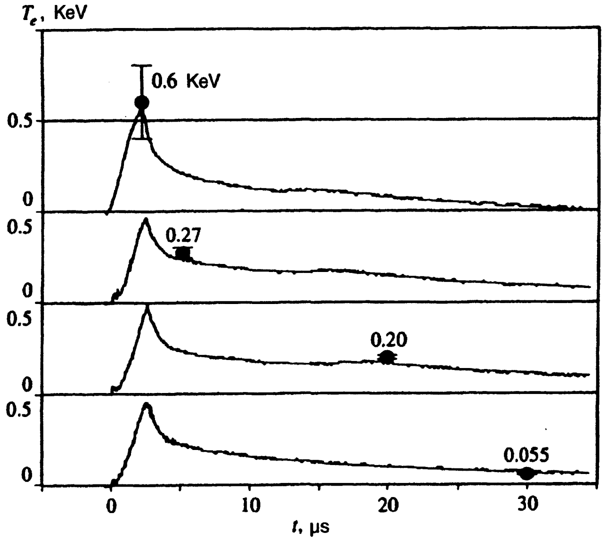

FIG. 7. Comparison of the plasma temperature obtained from diamagnetic measurements (solid lines) and laser-scattering measurements (points) at a distance of 270 cm from the entrance. Four successive shots are shown. The numbers are the values determined from the Thomson-scattering measurements.

(see Fig. 7). Such agreement shows that most of the energy remaining in the plasma after the heating is completed corresponds to thermal electrons. These measurements were performed in the central portion of the vacuum chamber of the facility, where the amplitude of the diamagnetic signals is appreciably smaller than at the site where the beam is injected into the plasma. The maximum value of the diamagnetic signals along the chamber corresponds to a mean electron–ion pair energy equal to 1.0–1.3 keV at the plasma density indicated in the best shots.

The results presented in Fig. 7 also indicate that, as in the experiments with nanosecond beams, the fraction of the energy transferred to the plasma ions is small. The ionic component of the plasma was not investigated in greater detail in the experiments under discussion.

The measurements using the Thomson-scattering system were performed under conditions such that the plasma density varied only slightly, but the results obtained could be extrapolated to a plasma of another density. As the plasma density increases, the efficiency of the interaction and the absolute value of the energy content in the plasma decrease fairly rapidly, but at small densities the energy content of the plasma varies only slightly. This enables the mean energy of an electron–ion pair from the diamagnetic measurements to exceed 2 keV near the point of beam injection already for $n \approx 5 \times 10^{14}$ cm^{-3}. Since, all other conditions being equal, the nonequilibrium nature of the electron distribution function observed during the beam heating of a plasma becomes stronger as the plasma density decreases, this provides some basis to assume that the diamagnetism of the plasma also has a thermal character at densities $n > 10^{15}$ cm^{-3}. At the same time, there is not yet sufficient experimental data for such an assertion regarding a low-density plasma.

7. SUPERTHERMAL ELECTRONS AND PLASMA RADIATION

The fairly high temperature of the Maxwellian component of the plasma obtained in the experiments has a significant influence on the parameters of the superthermal electrons. The mechanisms for generating such electrons usually considered in theory (see, for example, Ref. 10) presume stabilization of the energy W by Langmuir oscillations approximately at the level of the modulation-instability threshold:

$$\frac{W}{nT} \sim \left(\frac{\omega_H}{\omega_p}\right)^2,$$

where ω_H and ω_p are the cyclotron and plasma frequencies, respectively. Accordingly, the estimate of the characteristic energy E of the superthermal electrons is found to depend on the temperature of the plasma:

$$\frac{E}{T} \sim \left(\frac{L}{r_D}\right)^{2/3} \left(\frac{\omega_H}{\omega_p}\right)^{4/3},$$

where r_D is the Debye radius. This formula was obtained in Ref. 10 for a regime in which the limiting energy is determined by the escape time of an electron from the plasma and is applicable when the energy of the "hot" electrons is small compared with the energy of the original beam.

In our experiments the energy formally attainable for the superthermal electrons is equal to the beam energy; therefore, there is virtually no distinction between the slow beam electrons and the accelerated plasma electrons, and the energy lost by the beam is imparted to more energetic (compared with the electrons in experiments with nanosecond beams[18]) electrons. The superthermal electrons were studied using both a system for recording the soft x radiation of the plasma and an electron-spectrum analyzer (for energies above 14 keV).

The radiation of the fast electrons in the x-ray range was analyzed by the filter method using the eight-channel silicon surface-barrier detector fabricated in the Institute of Plasma Physics of the Academy of Sciences of the Czech Republic for the GOL-3 facility. Both beryllium filters with thicknesses of 8 μm or more and thin polymer films with and without a metal coating were used.

The dependence of the amplitude of the signal on the cutoff energy of a filter is presented in Fig. 8 (filled circles; the points below 0.9 keV refer to polymer filters, and their positions on the energy axis are hypothetical due to the nonmonotonic character of the transmission coefficient below 1 keV). The observed slope of the attenuation curve can be attributed to the presence in the plasma of a group of superthermal electrons with a mean energy above 10 keV and a density amounting to several percent of the plasma density at the end of the heating pulse (it was shown in special experiments with a weak beam–plasma interaction that the direct contribution to the signal from the REB electrons is insignificant). Individual calculations give a certain spectrum of permissible solutions, one of which is represented in the figure by the dashed line. The open points in the figure show the data obtained with an altered set of filters for another shot, in which the heating efficiency was lower. It is seen

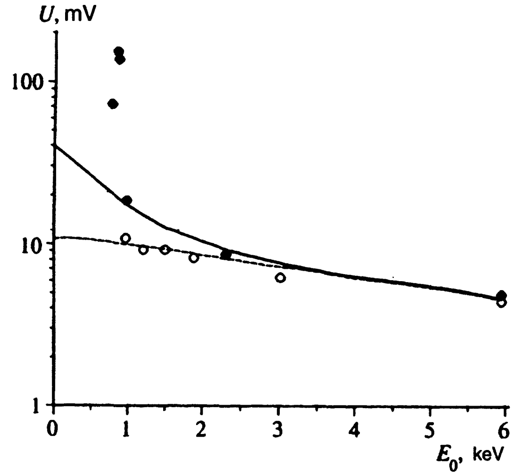

FIG. 8. Reconstruction of the attenuation curve (the dependence of the signal amplitude U on the cutoff energy of the filter E_0) at the heating maximum. The calculation was performed for the following parameters: $n_e = 1.0 \times 10^{15}$ cm^{-3}, $Z_{\text{eff}} = 1.5$, $T_e = 0.8$ keV, and a mean energy and a density of the superthermal electrons equal to 10 keV and 7×10^{13} cm^{-3}, respectively. Dashed line — radiation of the superthermal electrons alone, solid line — together with the radiation of the main component of the plasma.

from the figure that in the case of the lower interaction efficiency the measured dependence of the signal amplitude on the filter thickness for cutoff energies greater than 1 keV agrees well with the dependence calculated for the superthermal electrons. We also note that the density of the superthermal electrons cited in the caption to Fig. 8 corresponds to the maximum of the signal and that the mean density of this component during the injection period is approximately half as large.

Changes occur in the spectrum at the end of the heating in the region corresponding to radiation of smaller energies. Near the end of the heating pulse the point corresponding to the channel with an 8-μm beryllium filter has an amplitude that is 50% greater than could be expected for radiation from the superthermal electrons alone and thus corresponds approximately to the expected addition from the radiation of the main component of the plasma, whose parameters (a temperature equal to 0.6–0.8 keV and a density equal to 1×10^{15} cm^{-3}) are taken from other diagnostic data.

In the channels which are sensitive to softer radiation, the level of the signal is determined by the line emission of the ions of the light impurities (carbon, nitrogen, and oxygen). A rough estimate of the density of the impurities gives a total concentration of the light ions in the plasma equal to 2–3%. Experiments with identical filters in all the channels revealed the presence of regions in the plasma with increased brightness in the soft x-ray range with a characteristic spatial scale for these regions of at most a few millimeters. The increased fluorescence brightness can be attributed to various phenomena, viz., a local increase in the plasma density, "hot spots" with corresponding changes in the effective charge Z_{eff} and intensity of the line emission, and spatial inhomogeneity of the superthermal electrons. These phenomena can be a consequence of the observed microstructure of the electron beam.

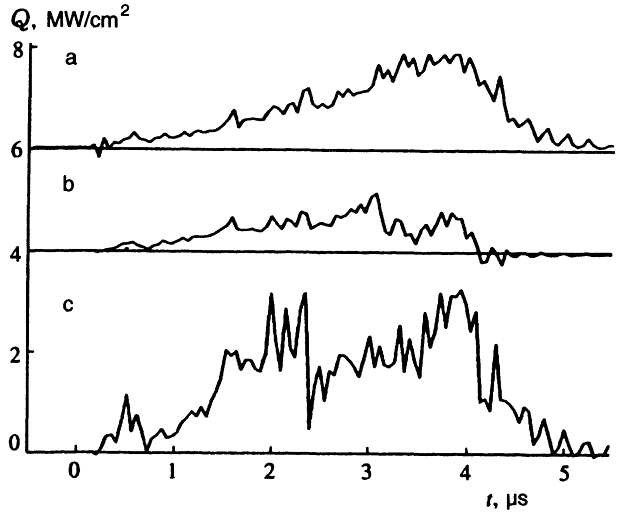

FIG. 9. Specific power of the flow of fast electrons leaving the facility in the ranges 18–21 keV (a), 21–24 keV (b), and 24– 36 keV (c); the density of the plasma was 1.1×10^{15} cm^{-3}.

The x-ray measurements performed when a beam is injected into unionized hydrogen reveal a strong increase in the hard radiation, which may indicate a larger number of superthermal electrons in the magnetic mirror. This is possible, for example, if in the initial stage of heating, when the plasma still has an insignificant extent of ionization and a very small density, there are differences in the level of Langmuir turbulence in comparison to the case of injection into a preliminarily ionized plasma.

The energy spectrum of the flow of electrons with energies above 14 keV at the exit from the trap was measured directly by a specially designed multifoil analyzer, which can be used to determine the spectrum from the laws governing the absorption of the superthermal electrons leaving the magnetic mirror in a set of nine thin conducting foils. The measurements showed that the current of absorbed electrons in the channels corresponding to energies equal to 14–36 eV increases by more than order of magnitude upon passage from the weak-interaction regime to the optimum regime. Figure 9 presents the power, calculated from the absorbed currents, of the flow leaving the plasma. The specific power in the strong-interaction regime reaches a value of ~ 10 MW/cm^2 for electrons with energies up to 50 keV (recalculated for a magnetic field of 5 T).

The data from the measurements performed by the x-ray method and the multifoil analyzer permit estimation of the energy imparted by the beam to the superthermal electrons. Their lifetime in the trap is small compared with the time of Coulomb scattering into the loss cone. Therefore, the instantaneous number of hot electrons in the trap, even at the heating maximum, is much smaller than the total number of such electrons born during the heating pulse. Accordingly, the superthermal electrons can carry off a large part of the energy lost by the beam in the plasma from the plasma.

8. TRANSFER PROCESSES AND WAVES IN THE PLASMA

We turn our attention to the characteristic features of the distribution presented in Fig. 5. First, the temperature rise

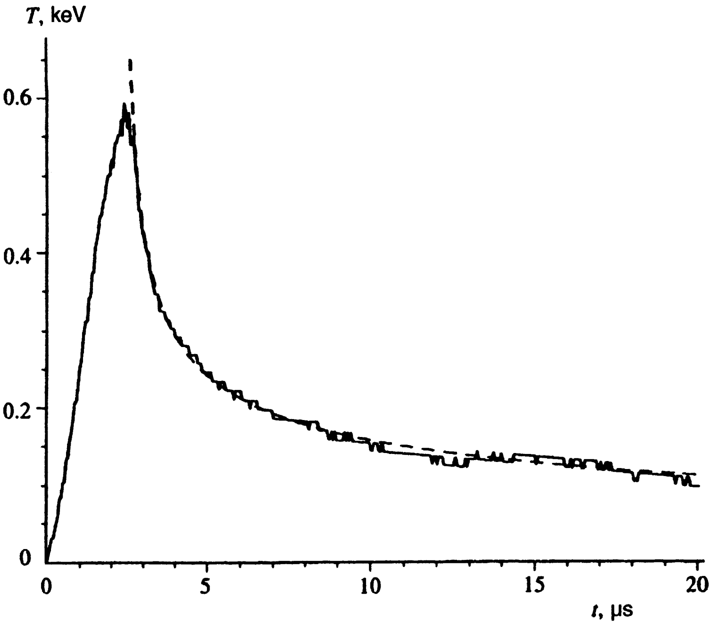

FIG. 10. Plasma cooling. Solid line – diamagnetic measurements at a distance of 240 cm from the point of beam injection, dashed line – calculation.

continues monotonically over the course of the entire beam-injection period. Second, the electron temperature distribution in the system varies, and this nonuniformity is maintained over the course of the entire heating period. Third, immediately after the heating is completed, the electron temperature quickly equalizes, and stronger cooling of the plasma occurs near the ends. Bolo-metric measurements show that the heat loss across the magnetic field (mainly due to radiation) is insignificant; therefore, the cooling of the plasma is due to the losses at the ends.

Near the mid plane of the column parallel to the chamber, where the most detailed Thomson-scattering measurements of the diamagnetism of the plasma and the temperature were performed, the temporal course of the temperature in the decay stage in the case of classical thermal conduction can be described by the approximate formula

$$T=\frac{T_{\max}}{(1+\alpha t)^{2/5}},$$

where the value of $\alpha=f(n,Z_{\text{eff}})$ is determined from a numeral calculation for the particular point in the facility. The only parameter which cannot be measured directly in an experiment is Z_{eff}, which must have a value of 1.3–1.6 in our case in order for the calculated curve to coincide with the measured plot. Figure 10 presents the temporal course of the diamagnetic temperature of the plasma and compares it with the calculation of the cooling. As is seen, the cooling of the plasma is described well by classical electronic thermal conduction through the ends.

On the other hand, simple evaluations already show that in the plasma-heating stage the thermal conduction must be significantly smaller than the classical value. Otherwise, the rate of the longitudinal losses calculated from the measured temperature profile of the plasma would become unacceptably large for the existing rate of beam heating. In the case of classical thermal conduction for temperatures above 0.3–0.5 keV, it is likewise not possible to obtain the observed longitudinal distribution of the plasma temperature in a calculation for any law governing the release of energy along the magnetic mirror (in this case thermal conduction requires the temperature maximum to be in the middle of the plasma column).

The calculations in Ref. 20, which were performed with consideration of the anomalous thermal conduction in the stage of heating by the beam, showed that an increase in the effective collision frequency of the Maxwellian electrons by two to three orders of magnitude in comparison with the classical frequency is needed for an acceptable level of agreement with experiment. Direct measurements of the spectrum of Langmuir oscillations performed on the GOL-M facility[21] confirmed the presence of a high level of turbulence during the injection of a nanosecond beam into the plasma. Since the resonant Langmuir oscillations excited directly by the beam have a phase velocity close to the velocity of light, a decrease in thermal conduction is possible when thermal electrons are scattered on slower electric fields of large amplitude. Such fields can appear on the density fluctuations formed when the turbulence level approaches the modulational-instability threshold.

The presence of a high level of turbulence in the plasma also naturally accounts for the short lifetime (at most or few transit times) of the superthermal electrons.

The anomalously low thermal conduction in the heating stage, which is longitudinally inhomogeneous, leads to the appearance in the plasma of large longitudinal pressure gradients. Under some regimes these gradients result in the appearance of pressure waves of large amplitude in the plasma, which propagate with the velocity of local ion sound. Such waves are detected in the diamagnetic measurements (Fig. 11), as well as in the diagnostics of the plasma radiation. It is seen from Fig. 11 that a wave (a second signal maximum) is generated near the point of entry of the beam into the plasma and propagates along the system in the direction of decreasing plasma pressures.

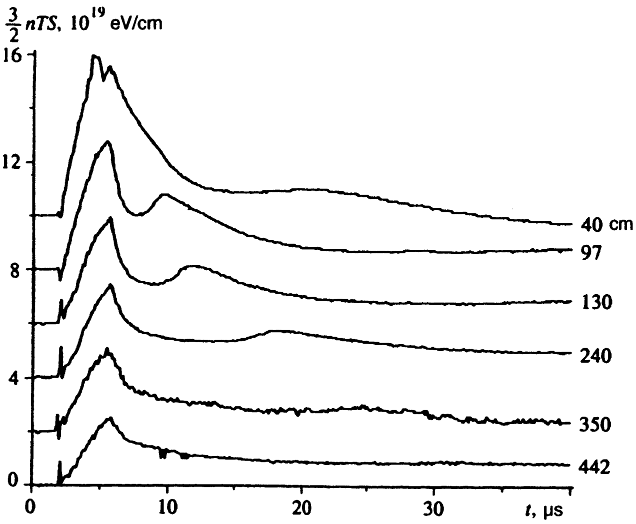

FIG. 11. Distribution of the pressure wave in the plasma (diamagnetic measurements; the distance from the point of beam injection to the diamagnetic sensors is indicated).

9. CONCLUSIONS

Effective relaxation of a relativistic electron beam of microsecond duration having a total energy content up to 100 kJ has been achieved during the beam heating of a plasma with a density of $\sim 10^{15}$ cm^{-3} in the GOL-3 facility. The total integral energy loss from the electron beam in the plasma reaches 25–30%, i.e., is comparable to the best results obtained in facilities with nanosecond beams (which have significantly higher values for the beam brightness and quality). The decrease in the mean energy of the electron beam measured in the axial region is of the same magnitude.

A plasma electron temperature as high as 1 keV has been obtained. It has been established that most of the energy lost by the beam is transferred to superthermal plasma electrons; however, a fairly considerable (up to 5% when the density is $\sim 5 \times 10^{14}$ cm^{-3}) part of the original energy stored in the beam remains at the end of the pulse in the main, Maxwellian component of the plasma electrons. The flows of electrons with energies of 10–50 keV measured at the exit from the facility have a specific power as high as ~ 10 MW/cm^2 in a magnetic field equal to 5 T when the duration is comparable to the beam duration.

In the plasma-decay stage the cooling is described well by the classical electronic thermal conduction through the ends. At the same time, when there is fully developed Langmuir turbulence in the plasma, the longitudinal thermal conduction observed during beam injection is anomalously low compared with the classical value. One of the consequences of this is the formation of large-amplitude ion-sound waves, which propagate along the plasma, in some regimes.

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