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SLOWING OF AN INTENSE ELECTRON BEAM IN A DENSE PLASMA

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Slowing of an intense monoenergetic electric beam in a dense plasma is investigated for the case $\omega_p \gg \omega_H$. The longitudinal and total beam energy losses are measured experimentally. The mean beam energy at exit from the plasma decreases with the growth of beam density. Distributions in the beam are obtained for different initial densities. With increase of the beam density a continuous transition is observed from a plateau on the distribution function to a negative slope ($\partial f/\partial v_z < 0$). It is assumed that during the slow stage of relaxation, oscillations are excited which are inclined with respect to the magnetic field and which cause a transformation of longitudinal energy into transverse energy accompanied by upward curvature of the plateau at its low energy end.

PLASMA-plus-beam systems are used for the purpose of producing and heating plasmas in thermonuclear fusion investigations and in other fields of science and technology. The efficiency of the interaction in these systems depends on the magnitude of the loss of energy and the rate of its transfer from the beam to the plasma.

The energy loss of an electron beam passing through a plasma considerably exceeds the loss resulting from two-body collisions. The anomalously large energy loss that is observed experimentally can be explained only by taking a collective interaction mechanism into account.[1]

According to the quasi-linear theory of beam-plasma interaction with a Cerenkov excitation mechanism for oscillations propagating along the magnetic field, as the beam progresses through the plasma it is smeared out toward lower energies, forming a plateau on the distribution curve. The theory enables us to evaluate the time required to build up the plateau and to calculate the corresponding loss.[2-4] The formation of the distribution plateau has been observed experimentally.[5-9] The relative loss by an electron beam as a result of interaction with the plasma has been measured in [6, 9, 10].

The experimental results obtained heretofore have pertained to the interaction of an electron beam with a rarefied plasma in a magnetic field when $\omega_H \gg \omega_p$. It is of interest to measure the energy loss and to investigate the distribution function in a beam passing through a dense plasma ($n \approx 10^{13}$ cm^{-3}, $\omega_p \gg \omega_H$) as functions of the electron beam parameters.

The experimental apparatus, represented schematically in Fig. 1, comprises a conventional mirror trap in which the maximum magnetic field is 2 kOe at the center and 10.5 kOe at the mirrors. The two-electrode electron gun 1 with a lanthanum hexacarbide cathode of 17-mm diameter was located on the axis of the system, behind a mirror and parallel to the strong lines of the magnetic field; its anode was a tantalum grid 1 cm from the cathode. The electron gun was separated from the plasma chamber 6 by a long narrow channel which, with independent pumping from the chamber of the gun, provided for a pressure drop of two orders of magnitude. The rectangular pulses applied to the gun cathode were of 250-μsec duration with 20-kV maximum amplitude and 20-A maximum intrapulse current.

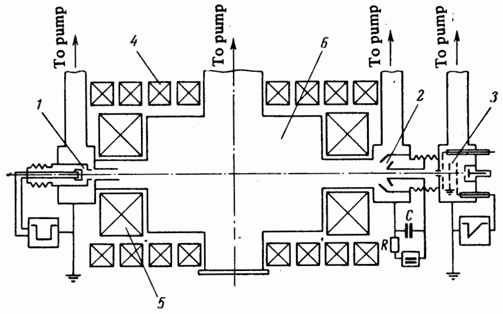

FIG. 1. Diagram of apparatus: 1—electron gun, 2—plasma injector, 3—grid probe, 4—coils of main magnetic field, 5—mirror coils, 6—vacuum chamber.

An electron beam was injected along the axis of the system into a hydrogen plasma ($T_e \approx 5$ eV) having 10^{13} cm^{-3} concentration that came from the titanium injector 2. (The electron temperature was determined from the diamagnetism of the plasma, and the concentration was measured with a microwave interferometer at 0.8 cm wavelength.) After traversing the channel of the plasma injector the beam passed through a 1-mm aperture in the thin front wall of an analyzer with a decelerating electric field. In this way we analyzed a small central portion of the electron beam as it left the plasma.

We used analyzers of two types: a multigrid probe and a probe in which the grids were replaced by diaphragms with slits. In the grid probe (which has four grids) it is impossible to exclude secondary emission from the analyzing grid and from the grid before the collector. However, secondary emission is completely eliminated in the four-slit analyzer. Here the beam can touch the edges of only the first slit in its path. The other slits are somewhat larger and their edges are in the shadow formed by the edges of the first slit. Secondary emission from the edges of the first slit was suppressed by the negative analyzing pulse applied to the diaphragm located close to the collector. Secondary emission from the collector was blocked by a positive (+200-V) bias. In order to remove the ion current to the entrance grid (or slit) a positive (+500-V) separating potential was applied relative to the front wall of the analyzer. Practically identical measurements were obtained with the two probes. Secondary emission in the grid probe produced no appreciable effect because of high grid transparency.

To record the energy spectrum of beam electrons as they left the plasma an oscillograph was used to register the beam current to the collector of the probe. A negative sawtooth pulse of amplitude equal to or greater than that of the cathode pulse was applied to the analyzing grid of the probe; in this way the spectrum in a single discharge was obtained. The sawtooth pulse of 150-μsec duration was switched on after a delay of about 70-μsec and terminated somewhat earlier than the cathode pulse. In this way the leading and trailing edges of the cathode pulse were excluded and the analysis covered the time during which a plateau existed in its oscillogram. The analysis of the oscillograms was not laborious because the beam current pulse was rectangular both upon entering the plasma (in the vacuum) and after traversing the plasma.

When a sawtooth pulse (Fig. 2a) of amplitude U_A equal to that of the cathode pulse was applied to the probe grid, the beam current oscillogram (Fig. 2b) in the vacuum was obtained. The monochromatic character of the undisturbed beam is shown graphically by this oscillogram. Figure 2c is the current oscillogram of a beam passing through the plasma in the absence of a sawtooth pulse on the analyzing grid of the probe. Small fluctuations of the signal are visible, but the shape and magnitude of the current remain practically unchanged. Figure 2d shows the beam current (5 A) at exit from the plasma when an analyzing pulse is applied to the probe grid. At the moment when this pulse is switched on the current to the collector drops almost to zero; as the grid potential diminishes the current is built up again until it reaches its initial magnitude at the termination of the sawtooth. Figures 2e and 2f are similar oscillograms for beam currents of 10 and 20 A, respectively. They show graphically that with increase of the current the spectrum of beam particles is shifted in the direction of lower energies.

In the oscillograms the region from the start to the end of a sawtooth comprises a retardation curve. Oscillograms of the sawtooth pulse and current to the probe were used to plot larger-scale retardation curves from which the relative loss of longitudinal beam energy was determined and energy distributions of the beam particles were constructed. The relative loss of longitudinal beam energy was calculated from

$$\eta_{\text{long}} = 1 - \frac{1}{I_0 U_0}\int_0^\infty I\,dU_A = 1 - \frac{S_1}{S_0},$$

where S_1 is the area of the retardation curve $I(U_A)$, which is proportional to the beam power at exit from the plasma, while S_0 is the area of the retardation curve of an undisturbed beam and is proportional to the beam power at its entrance into the plasma.

The total relative loss of beam energy in the plasma was measured with a thermocouple bolometer that consisted of a tantalum disk 30 mm in diameter and 0.2 mm thick with stainless steel suspensions. A sensitive thermocouple was fastened to the center of the back face of the disk, which was mounted behind the mirror on the axis of the system and intercepted the electron beam completely. Signals from the thermocouple were registered oscillographically (Fig. 3). The loss was determined from

$$\eta_{\text{tot}} = 1 - i_1 / i_0,$$

where i_0 is the amplitude of the thermocouple signal in the absence of the plasma and i_1 is the amplitude in the presence of the plasma. Experimental losses due to radiation from the disk and thermal conduction in the suspensions were insignificant and were neglected.

The measured losses are shown in the table, where we find that losses measured with the grid probe exceed the total losses that were determined with the bolometer. The differences for the 10-A and 20-A currents exceed the accuracy of the measurements and appear to have resulted from the transformation of longitudinal energy into transverse energy. This energy transformation is registered as a loss by the grid probe whereas the thermocouple responds to the total beam energy.

The total number of electrons in the beam is conserved, but the energy of most particles is considerably reduced, i.e., the beam is slowed down; this happens to an increasing degree as its current density is increased. From the difference between the beam energy at entrance into the plasma and the mean beam energy at exit from the plasma we calculated the mean absolute

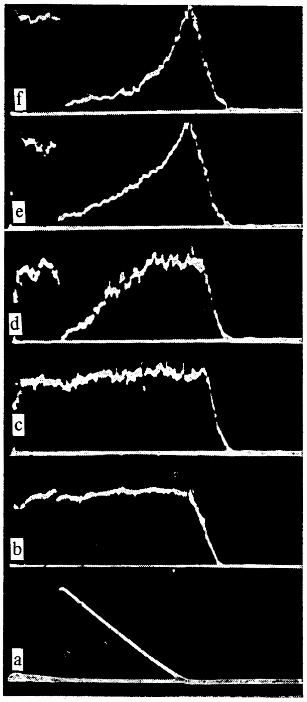

FIG. 2

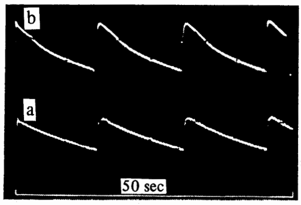

FIG. 3

FIG. 2. Oscillograms of the beam current to the grid probe under different conditions: a—sawtooth pulse applied to the analyzing grid of the probe; b—beam current (5A) at entrance into plasma (vacuum current); c—beam current (5A) at exit from plasma in the absence of a sawtooth pulse on the analyzing grid of the probe; d, e, and f—beam currents of 5, 10, and 20A, respectively, at exit from plasma when a sawtooth pulse was applied to the analyzing grid of the probe. For all oscillograms the sawtooth pulse had amplitude U_A = 20 kV and 150-μsec duration, the initial beam energy was 20 keV, and the magnetic field at the center of the trap was 1 kOe.

FIG. 3. Oscillograms of thermocouple signals: a—in the presence of a plasma; b—in the absence of a plasma. Initial beam energy 20 keV; beam current 10A; beam pulse duration 250 μsec; interval between pulses 15 sec; bolometer time constant 7.5 sec.

Beam current, A	Beam energy at entrance into plasma, keV	Relative loss of longitudinal energy, %	Total relative energy, loss, %	Mean longitudinal energy of beam at exit from plasma, keV	Mean loss of longitudinal energy,* eV/cm
5	20	34	29	13,2	85
10	20	57	36	8,6	142
20	20	67	41	6,6	167

*The length of the apparatus was 80 cm.

energy loss, which is given in the last column of the table. The mean beam energy was calculated from the relative loss coefficient:

$$U_m = U_0(1 - \eta_{long}),$$

where U_0 is the beam energy at entrance, η_{long} is the relative loss coefficient, and U_m is the mean longitudinal beam energy at exit from the plasma. The formula for U_m is valid when the total number of particles in the beam is conserved.

When the beam and plasma interact, while most of the electrons are slowed down it is observed that a small fraction of the beam particles are accelerated.[5] We also observed electrons having energies in excess of the initial beam energy. The presence of accelerated electrons at exit from the plasma is seen directly in the oscillograms 2f, e, and d (where the beam current is not zero for $U_A = U_0$). For the same reason the distributions shown in Fig. 4 do not reach a vanishing point at $U_A = U_0$.

The electron distributions at the exit of the beam from the plasma were obtained by graphic differentiation of retardation curves recorded for three values of the beam current. Figure 4 shows that the distribution is sensitive to beam current changes. In a current of 5 A a uniform energy distribution is established (curve a of Fig. 4). When the current is increased to 10 A or higher we observe a transition from the uniform energy distribution to a distribution having a negative slope ($\partial f/\partial v_z < 0$) that becomes steeper with increase of the beam density.

Similar transformations of the distribution, depending on the pressure in the chamber, were observed in experiments[9] where a high magnetic field was used ($\omega_H \gg \omega_p$) and the densities of the beam and plasma were lower by two orders of magnitude.

The mechanism of the transformation from a longitudinal velocity plateau to a distribution with a negative derivative was investigated theoretically in [11] for the case of a high magnetic field ($\omega_H \gg \omega_p$). Our experimental work was done in the opposite limit ($\omega_p \gg \omega_H$), so that we cannot use the conclusions in [11] for the purpose of interpreting our results.

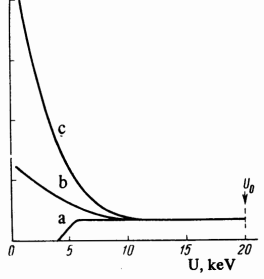

FIG. 4. Distribution of beam electrons with respect to longitudinal energy U = $mv^2/2$ for different beam current densities; beam currents: a–5A, b–10A, c–20A. The initial beam energy was 20 keV; the amplitude of the analyzing sawtooth pulse was 20 kV.

In a rapid relaxation stage, as in the case of a strong magnetic field ($\omega_H \gg \omega_p$), the beam is smeared out only with respect to longitudinal velocities, as is demonstrated by the plateau of curve a in Fig. 4. In this regime the difference between the longitudinal and total energy losses of the beam lies within the limits of experimental accuracy (see the table). Equality of the losses is a direct experimental argument for purely longitudinal slowing of the beam in a rapid stage of relaxation.

At high current densities (curves b and c in Fig. 4) the length within which the rapid relaxation stage occurs becomes shorter than the length of the apparatus. Figure 4 shows that the rapid relaxation stage does not lead to a stable state of the beam. In the case $\omega_p \gg \omega_H$ the beam is unstable if its directed velocity exceeds the mean thermal velocity of the plasma.[12] Slowing of the beam after the plateau has been formed is associated with the excitation of waves that propagate at an angle to the magnetic field. In our work the subsequent slower stage of beam relaxation can be associated with this process, which leads to smearing out of the transverse velocities and symmetrization of the distribution in the beam. As a result of the transformation from longitudinal to transverse energy the longitudinal energy spectrum is shifted toward lower values and a distribution with a negative derivative ($\partial f/\partial v_z < 0$) is built up. The presence of perpendicular energies at the beam exit from the plasma in the case of 10-A and 20-A currents is shown by the measurements of losses given in the table.

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65