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THERMAL EXPLOSION INDUCED IN A COLLISIONLESS PLASMA BY A RELATIVISTIC ELECTRON BEAM

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Experimental investigations of the interaction between a relativistic electron beam and a plasma were performed with the setup whose scheme is shown in Fig. 1. A hydrogen plasma ($n_0 \sim 10^{11} - 10^{14}$ cm^{-3} was produced in cylindrical glass tube 1 of 20 cm diameter and 300 cm length, by discharging low-inductance capacitors through six "surge" turns 2 surrounding the outer diameter of the tube. The quasistatic magnetic field H_0 produced by the turns 3, with 30 cm diameter, was varied from 0 to 2.5 kOe.

The beam sources was the Rius-5 electron accelerator 4 developed in E.A. Abramyan's laboratory of our institute and described in [1]. The beam was introduced into the magnetized plasma by means of coil 5, which produced a magnetic field frozen into the cathode and was superimposed on the field H_0 so as to produce a magnetic-mirror configuration (such a configuration was produced on the opposite end of the plasma volume with the aid of doubled turns 12 having a smaller diameter). Under the experimental conditions, the maximum energy of the electrons in the beam reached 3 - 4 MeV, the maximum current was 10 - 15 kA, and the current duration was ∿50 nsec.

The initial density n_0 was registered by means of a microwave interferometer (λ = 8 mm, 3 cm, 6 cm). The heating of the plasma due to the passage of the beam was measured with external diamagnetic probes 7 in sections distributed along the tube axis z. The microwave noise was registered at several sections (9) in the 1.5 - 6 cm band. The beam current at the output of the accelerator and the total current in the plasma were registered with Rogowski

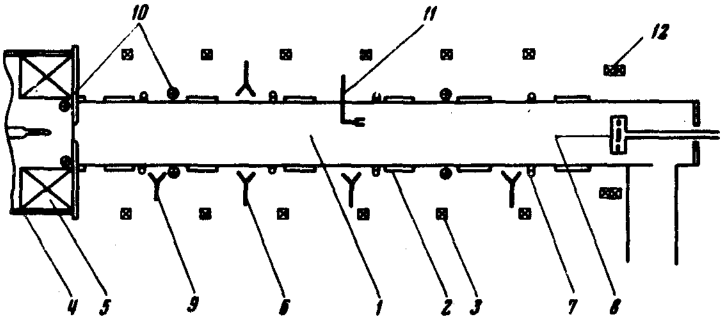

Fig. 1. Diagram of experimental setup.

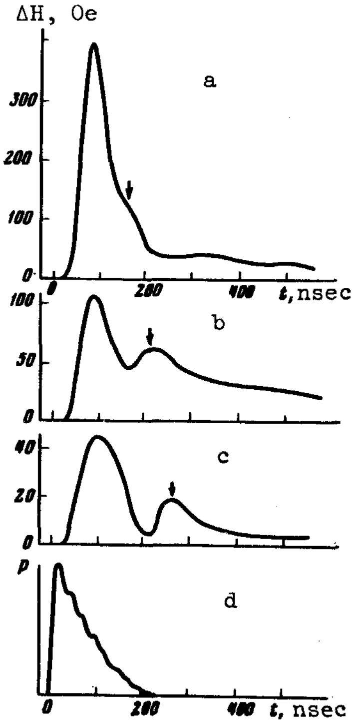

Fig. 2. Plasma heating by passage of beam and ensuing electronic thermal wave: a, b, c - signals from diamagnetic probes placed at distances z equal to 15, 155, and 240 cm, respectively; d - electromagnetic radiation from plasma in the $\lambda = 3$ cm band ($z = 15$ cm).

loops 10. The beam parameters (the radial distributions of the current and of the energy) after passage through the plasma volume was measured with a system of current collectors and thermocouple calorimeters (8) shielded against the thermal electrons and the plasma potential. The fast-electron currents in the different direction were measured with local collectors (11) placed inside the plasma volume. Simultaneous measurements with the aid of filters (Cu, Al) of different thickness (0.01 - 3 mm) make it possible to estimate the electron energy.

The main effects were determined by comparing the initial and perturbed states of the plasma, and also the beam parameters, after passage through the preformed plasma and through "vacuum" (without preionization; minimum pressure 10^{-6} mm Hg). The results point to a strong mutual interaction between the plasma and the relativistic electrons passing through it. The interaction effectiveness is such that the change of the beam input parameters (say the energy) is comparable with their initial values.

The main observed facts consist in the following:

1. A sharp rise in the plasma temperature, as follows from the readings of diamagnetic pickups placed in several sections (Fig. 2). The diamagnetic signal measured 50 - 100 nsec after turning the beam on reached, at the optimal parameters ($n_0 = 3 \times 10^{11} - 10^{12}$ cm^{-3}, $H_0 = 1.5 - 2$ kOe), a value corresponding to $nT \sim (1 - 5) \times 10^{16}$ eV/cm^3 (at a characteristic plasma-column diameter 7 - 10 cm).

2. The variation of nT along the tube, resulting from the action of the beam, was determined as a function of the parameters n_0 and H_0. Under optimal conditions, the bulk of the heat is released in the front layer of the plasma, of thickness much smaller than the length of the plasma column.

3. A consequence of the small relaxation length is the heat flow that is produced in this case from the initial strongly-heated plasma region towards the end of the plasma column, with a velocity ranging from 10^9 to 10^{10} cm/sec. On the oscillograms of Fig. 2, this corresponds to the second peak of the diamagnetic signal, marked by an arrow, which lags progressively in different sections. The measured pressure-transport velocity depends on the plasma heating and amounts in the mean to $(1/2 - 1/3)v_{Te}$. Such a high velocity excludes the possibility of transporting the entire plasma as a unit. This gives grounds for stating that the relaxation process following the initial heating is due to excitation of an electronic thermal wave [2]. As the wave propagates, its velocity decreases, a fact attributable to the decrease in the electron temperature upon expansion. It should be noted that, depending on the beam and plasma parameters, the ratio of the plasma heating by the beam directly and by the thermal wave at the end of the plasma volume may change considerably. In this case, the second diamagnetic-signal peak can greatly exceed the first in amplitude.

4. The relaxation of the beam is accompanied by a sharp burst (rise time $\sim$10 nsec) of electromagnetic radiation in the 1.5 - 6 cm band, of duration

100 nsec and more, in advance of the growth of the diamagnetic signal (Fig. 2d).

5. It has been established that the output beam parameters (energy, current) and their radial distributions depend on the plasma density, the other parameters remaining constant. Under optimal conditions, the decrease of the energy of the beam passing through the plasma reaches 50% and more (Fig. 3a). The maximum beam attenuation is observed under conditions when the strongest plasma heating takes place.

6. A current of fast electrons is observed in a direction opposite to the beam propagation, and reaches a maximum in the region of the optimal parameters. The use of filters with endpoint energy ∿200 keV has made it possible to eliminate the contribution of the hot plasma electrons and of the backward-current electrons, whose energy is $E \sim (m_e c^2/2)(n'/n_0)^2$. The existence of these currents can be attributed to the scattering of the beam electrons by the turbulent plasma fluctuations. This cannot explain the strong change in the radial distribution of the density n' of the beam electrons in the optimal range of parameters (Fig. 3b)1).

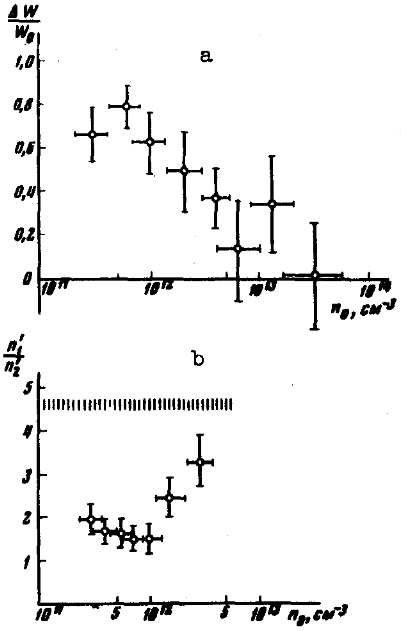

Fig. 3. a) Relative attenuation of the output beam energy $\Delta W/W_0 = (W_0 - W)/W_0$ in the plasma; W_0 is the output beam energy in vacuo. b) Ratio of density of high-energy electrons, registered by the central (n'_1) and peripheral (n'_2) current collectors (central: $0 < r < 25$ mm; peripheral: 27 mm $< r < 55$ mm); $n'_1/n'_2 = 4.3 - 4.7$ for vacuum.

It follows from the performed experiments that collisionless plasma can develop anomalous scattering properties, with a spatial scale $10 - 10^2$ cm, with respect to a relativistic electron beam, whereas the classical Coulomb mean free path of a relativistic electron is of the order of 10^{13} cm under the conditions of the experiments.

Thus, the investigated phenomenon has the character of a thermal explosion (T ∿ 10 - 100 keV) in a collisionless plasma, followed by secondary relaxation processes such as an electronic thermal wave and rapid equalization of the heat in the entire plasma volume.

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1) We note that plasma focusing of the beam is observed at higher concentrations n_0, but a discussion of this question is already outside the scope of the present paper.