Resonant resistive instability of a relativistic electron beam in a plasma

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An instability of a relativistic electron beam in a plasma has been observed. This instability occurs in a time shorter than the scale time for changes in the magnetic field, $\tau_d = 4\pi\sigma a^2/c^2$, and results in a displacement of the beam as a whole to the side wall of the drift chamber.

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A macroscopic instability has been detected in a study of the transport of a relativistic electron beam in a plasma with a density $n_e \sim 10^{14}$–10^{15} cm^{-3} and a conductivity $\sigma \sim 10^{12}$ s^{-1} produced during the injection of a relativistic electron beam into a gas with a pressure in the range $2 < p$ (Torr) < 100. This instability sharply reduces the transport efficiency. It takes the form of a spontaneous deviation of the beam from its rectilinear path, which results in the beam's striking the side wall of the drift chamber. The observed beam displacement time is 5 ns, while the scale time for the change in the magnetic field of the beam and thus for the onset of the firehose instability[1] is about 100 ns.

The experiments were carried out on the Neptun accelerator,[2] which produced a beam of relativistic electrons with an energy $\epsilon \simeq 450$ keV, a current $I_b \simeq 20$ kA, a pulse length $\tau_p \simeq 40$ ns, and a radius $a \simeq 3$ cm. The beam electrons coming from a graphite cathode 4.8 cm in diameter through a titanium-foil anode, 20 μm thick, were injected into a drift chamber with an inside diameter of 17 cm and a length L up to 1.5 m. Multisection vacuum Faraday cups of various designs yielded information on the time evolution of the radial distribution of the beam current and on the beam current drawn by the side wall of the chamber. Framing photographs of the plasma emission were taken with image convertors with a 5-ns exposure time and an equal time interval between frames.

Measurements of the radial distribution of the beam current density j_b (r,z,t) taken 85 cm from the anode foil with a multisection Faraday cup showed that at pressures near 1 Torr j_b (r,z,t) remains symmetric with respect to the chamber axis. Beginning at 5 Torr, a multisection Faraday cup at the end detects an asymmetry in the radial distribution of the beam, showing a displacement of the beam as a whole away from the chamber axis. This asymmetry intensifies with increasing pressure. Above 10 Torr the radial displacements of the beam are comparable to the radius of the chamber, and most of the beam electrons strike the side wall (Fig. 1). This event is accompanied by a cutoff of the beam current. After the current signals vanish from the collectors of the multisection Faraday cup at the end, an electron current appears, after a 5-ns delay, at

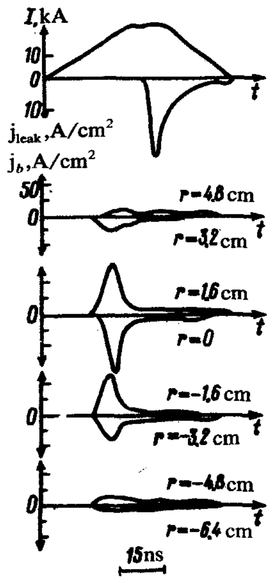

FIG. 1. Oscilloscope traces of the beam current I, the leakage current density (j_{leak}) drawn by a Faraday cup at the side wall of the chamber at a point 7 cm from the plane of the multisection Faraday cup, and the beam current density (j_b) drawn by the collectors of a multisection Faraday cup at the end of the chamber, 85 cm from the anode foil ($p = 25$ Torr). The multisection Faraday cup consists of nine collectors with a radius of 5 mm positioned along a diameter of the chamber in a plane perpendicular to the beam transport direction. The collectors are at distances $r = 0$, ± 1.6, ± 3.2, ± 4.8, and ± 6.4 cm from the chamber axis.

a

b

c

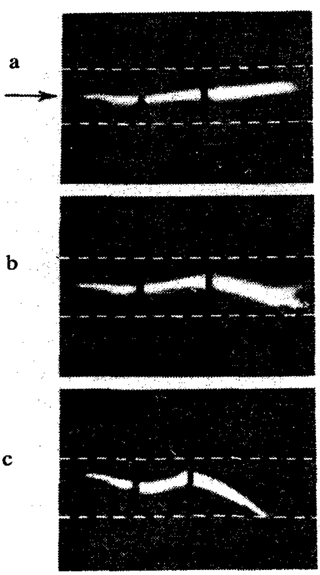

FIG. 2. Image-convertor photographs of the onset of the instability. a—10 ns; b—15 ns; c—20 ns. $L = 130$ cm, $p = 30$ Torr. The arrow shows the beam injection direction. The dashed lines show the contour of the drift chamber. The distance between dark bands (the markers) is 20 cm.

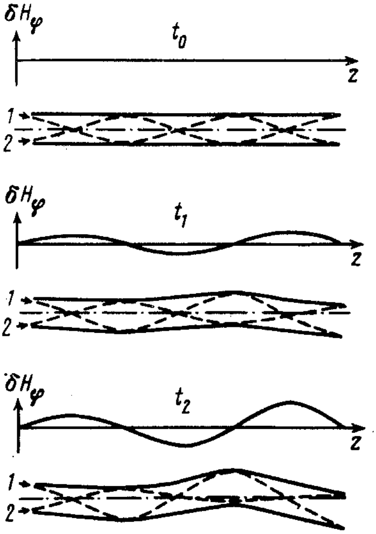

FIG. 3. Changes caused in paths 1 and 2 (dashed curves) and in the envelope of the beam particles (solid curve) by a magnetic-field perturbation δH_ϕ at three successive times (t_0, t_1, t_2). Dot-dashed curve—axis of the drift chamber.

a side vacuum Faraday cup. Photographs of the evolution of this fast instability confirm that it occurs and also yield information on the dynamics of the radial displacement of the bam (Fig. 2). Up to the time $T = 10$ ns, reckoned from the beginning of the accelerator current pulse, the beam is transported along the chamber axis. In 5 ns there is a significant radial displacement; the displacement velocity is 10^9 cm/s, in agreement with electrical measurements. On the third photograph, taken in the next 5 ns, we see the displacement of the beam to the side wall of the chamber. The wavelength in the developed stage of the instability is 30–40 cm.

We attribute the cutoff of the beam current to the onset of a resonant resistive instability. The mechanism for this instability can be described qualitatively as follows (Fig. 3): The motion of the beam electrons in the resultant magnetic field of the beam current, I_b, and of the return current of plasma electrons, $I_{\rm pl}$, in the unperturbed state is a motion along the chamber with superimposed transverse (betatron) oscillations at the frequency $\omega_\beta \equiv \omega_\beta(I_b - I_{\rm pl}/I_A)$ [$I_A = (mc^3/e)\beta\gamma$ is the Alfvén current]. Figure 3 shows two paths (1 and 2) which differ in oscillation phase by half a period. If the wave number k_z of the field perturbation $\delta H\phi$ satisfies the phase-resonant condition $k_z v_z = \omega_\beta$, the frequency of the betatron oscillations agrees with the frequency of the driving force, and the amplitude ξ of the displacement of the particle's path from the equilibrium path in the proper frame of reference increases in accordance with

$$\xi = \frac{\omega_\beta a}{2} \int_0^t \frac{\delta H_\varphi}{H_{0\varphi}} dt. \qquad (1)$$

Since $\delta j_b \sim (\xi/a) j_b$, the equation for the magnetic field,

$$\frac{\partial H_\varphi}{\partial t} = \text{rot}\left(\frac{c^2}{4\Pi\sigma}\ \text{rot}\, H_{\dot\varphi} - \frac{c}{\sigma} j_b\right)\ , \qquad (2)$$

yields

$$\gamma \sim \sqrt{\frac{\omega_\beta}{\tau_d}}\ \sqrt{\frac{I_b}{I_\Sigma}} >> \frac{1}{\tau_d}\ ; \qquad I_\Sigma = I_b - I_{pl}\ . \qquad (3)$$

Two of the present authors (V.V.G. and S.V.Z.) have carried out a systematic analysis of this instability, taking into account the anharmonicity of the betatron oscillations, the velocity spread, and the boundary conditions. This analysis leads to the following growth rate for this experiment:

$$\gamma \simeq \frac{1}{\tau_d}\ \frac{I_b\, I_A}{I_\Sigma^2}\ \ln\left(\omega_\beta \tau_d\, \frac{3}{16}\ \frac{I_\Sigma^3}{I_b\, I_A^2}\right). \qquad (4)$$

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