Production of dense cloud of oscillating relativistic electrons

A. V. Arzhannikov, A. V. Burdakov, V. S. Koĭdan, and D. D. Ryutov

Nuclear Physics Institute, Siberian Division, USSR Academy of Sciences

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The possibility of trapping an appreciable fraction of the electrons of a large-current relativistic beam in a plasma volume bounded by thin foils is experimentally demonstrated. The density of the accumulated electrons exceeds by more than one order of magnitude the density of the initial beam.

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When a relativistic electron beam (REB) with a supercritical current is injected in vacuum, a cloud of oscillating electrons should be produced at the anode foil.[1,2] As shown in[1], the density of this cloud can greatly exceed the initial beam density, and the total number of trapped electrons can be appreciably increased by producing on the outer side of the anode foil a plasma gap with length L significantly larger than the anode-cathode gap.

To verify experimentally the possibility of obtaining a dense cloud of relativistic electrons, we used the INAR installation.[3] The experimental setup is shown in Fig. 1. A relativistic electron beam of energy 0.8 MeV, current up to 14 kA, and 4 cm in diameter was injected through the entrance (anode) foil 2 into a hydrogen plasma pinch of 6.5 cm diameter, length $L = 20$ cm, and density $\sim 10^{14}$ cm^{-3}, which was produced by a Penning discharge. The exit foil 5 separated the plasma from the vacuum volume, in which a graphite collector 7 could move. An additional foil 6 was placed behind the foil 5, at a distance much shorter than the cathode-anode gap. This foil was connected with foil 5 through a noninductive shunt. We used in the experiment foils of aluminum 5–50 μ thick. The entire system was in a magnetic field of 12 Oe; the field in the diode region was 1.3 times stronger. The bremsstrahlung gamma rays from foil 2 were registered with a scintillation detector 9, which was constructed and mounted so as to receive the gamma rays traveling from the center of the anode foil at an angle 45° to the anode surface.

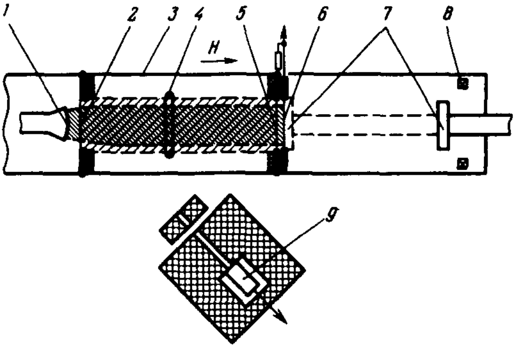

FIG. 1. Experimental setup: 1—accelerator cathode, 2—entrance foil, 3—return leads, 4—Penning-discharge anode, 5—exit foil, 6—exit measuring foil, 7—graphite collector, 8—Rogowski loop, 9—x-ray detector in lead shield.

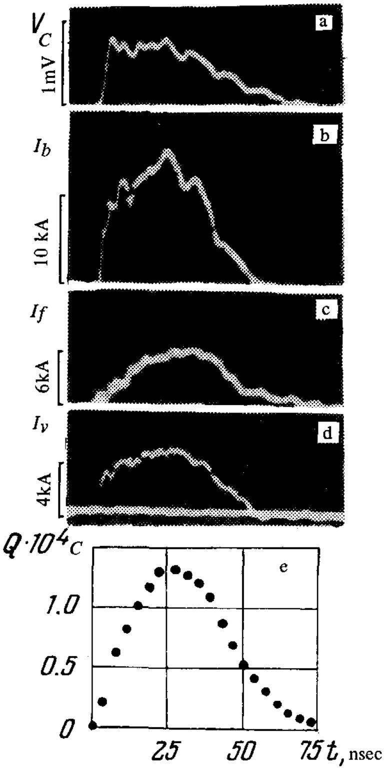

FIG. 2. Oscillograms demonstrating the accumulation effect at $d_2 = d_5 = 10\ \mu$, $d_6 = 50\ \mu$; a—accelerator-cathode voltage, b—injected-beam current, c—current in measuring foil 6, d—current flowing off into the vacuum, e—charge of accumulated relativistic electrons.

The results of the experiments are shown in Figs. 2 and 3. If the collector 7 is in contact with foil 6, then the shunt in the circuit of this foil registered the beam current passing through the plasma (this current practically coincides with the diode current), there is no signal in the Rogowski loop 8, and the signal from the detector 9 corresponds to single passage of the REB through foil 2. On the other hand, if the collector 7 is moved 50 cm away from foils 5 and 6, then the greater part of the electrons is reflected backwards, inasmuch as the injected current (Fig. 2b) is much larger than the vacuum current (Fig. 2d), and conditions are produced for oscillations of the relativistic electrons between the cathode of the accelerator and the "virtual" cathode in the vacuum, behind foils 5 and 6. In this case the current in the measuring foil 6 (Fig. 2c) grows slowly (it is due mainly to absorption of oscillating electrons in the foil), and the x-ray signal is increased by many times.

Generally speaking, a contribution to the signal from the foil 6 can be made also by the induced current due to the change in the charge of the electron cloud at this foil. It was established experimentally that the contribution of the induced current could be neglected when foil 6 has a thickness $d_6 \gtrsim 50\ \mu$; at a smaller thickness, this current was taken into account in the subsequent reduction of the oscillograms. In addition, by varying the thickness of the foil 6 at a fixed total foil thickness $d = d_2 + d_5 + d_6$, it was established that the current

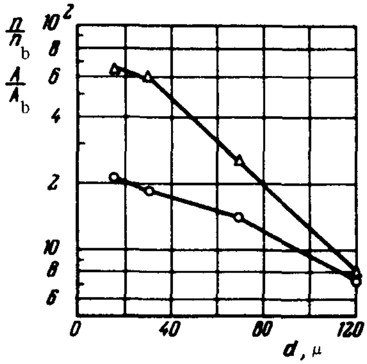

FIG. 3. Dependence of the accumulation effect on the combined foil thickness: ○—ratio of maximum density n of the accumulated electrons to the maximum density n_b of the initial beam ($n_b = 2.3 \times 10^{11}$ cm^{-3}); △—ratio of the amplitude A of the x-ray signal in the accumulation regime to its amplitude A_b for a single passage of the beam.

of the absorbed electrons is proportional to the foil thickness. This has made it possible to determine the total current to all the foils $\Sigma I_f(t)$ from the current flowing off to foil 6.

From the oscillograms of Fig. 2 it is seen that within approximately 25 nsec the injected current $I_b(t)$ exceeds the sum of the currents to the foils $\Sigma I_f(t)$ and to the vacuum $I_v(t)$, that is, relativistic electrons are accumulated in the plasma volume. The change of the total charge of accumulated electrons can be calculated with the aid of the equation $\dot{Q} = I_b(t) - I_v(t) - I_f(t)$. Graphic integration of this equation makes it possible to find the function $Q(t)$ (Fig. 2e). In our case, the maximum charge of accumulated electrons is 1.3×10^{-4} C, which is approximately 14 times larger than the charge of the initial beam in the plasma gap following a single passage.

With decreasing combined thickness d of the foils, the density of the accumulated electrons increases (Fig. 3), inasmuch as prior to the absorption by the foils the beam electrons execute a large number of oscillations between the turning points. We note that at $d \lesssim 30$ μ a decrease of the diode current is observed; at $d = 15$ this decrease reaches 30%. This effect can be attributed to the action of the space charge of that part of the cloud, which is located in the diode.[1]

With decreasing d, the x-ray signal increases more rapidly than the density of the accumulated electrons (Fig. 3). The reason is that the increase of the x-ray signal is due not only to an increase in the number of the electrons crossing the foil 2, but also to a broadening of the directivity pattern of the bremsstrahlung as a result of the angular scattering of the electrons after multiple passage through the foils. It should be noted that at $d = \text{const}$ the x-ray signal is approximately proportional to the thickness of the entrance foil, both in the case of single passage of the beam and in the accumulation regime. This means that the observed x rays come actually from the foil and not from the accelerator cathode.

The maximum charge of the accumulated electrons is reached at a minimum combined foil thickness ($d = 15$ μ) and amounts to 1.9×10^{-4} C, corresponding to a total number of relativistic electrons 1.2×10^{15} and to their volume density 5×10^{12} cm^{-3}; the pressure of this cloud is equal approximately to 1 atm.

This electron cloud is of interest from two points of view. First, the density of the energy stored in it is much higher than in the initial beam, and the time during which this energy can be released is very short ($\sim L/c$). Second, under conditions when plasma can be produced on the outer side of the foil 6, it is possible to effect collective acceleration of a large number of ions (their density will be of the order of the density of the accumulated electrons), to an energy exceeding by many times the accelerating voltage in the diode.[4] The results of the experiment offer evidence that these applications are realistic.

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