Ion acceleration in the interaction of a strong-current relativistic electron beam with a spatially-periodic magnetic field

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We present the results of experiments on the acceleration of argon and nitrogen ions in a relativistic plasma generator of the "ubitron" type. It is shown that at an electron-beam current 2–3 kA, an energy 0.3 MeV and $\tau = 1\times10^{-6}$ sec, a current 2–3 A of accelerated ions is observed with energy up to 1.0 MeV and $\tau = 1\times10^{-6}$ sec.

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We present here the results of experimental investigations of the acceleration of ions in a microwave plasma generator based on the interaction of a strong-current relativistic beam of electrons of microsecond duration with a spatially-periodic magnetic field.[1]

The experimental setup is shown in Fig. 1. The accelerator produced an annular

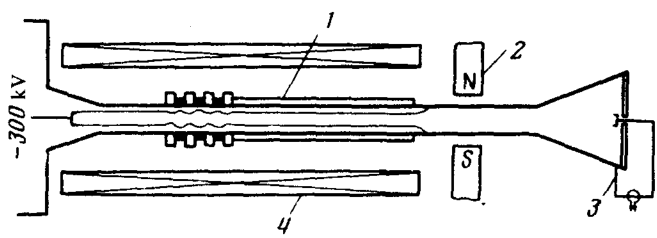

FIG. 1. 1) Electron accelerator, 2) permanent magnet, 3) Faraday cup and Rogowski loop, 4) solenoid.

electron beam with current up to 3 kA and particle energy ≈ 280 kV at a pulse duration 1×10^{-6} sec. The outside diameter of the beam was 32 mm and the width of the ring was 3.5 mm. The electron beam was injected in a round waveguide with inside diameter 49 mm, placed in an axial magnetic field modulated in accordance with the law

$$H = H_0\left[1 + \sin\frac{2\pi}{L}z\right].$$

In our experiments, H_0 could reach 10 kOe, the modulation depth was $\epsilon = 8\%$, and the period $L = 6$ at a total length of the modulated section 18 cm. This was followed by a region of homogeneous magnetic field, 20 cm long, and finally by a section with decreasing field, intended to break up the beam. The round waveguide was filled with gas, which was ionized by the beam to produce a plasma with density sufficient for

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charge cancellation. The plasma made it possible to decrease the beam velocity spread due to the Coulomb scattering, and this in turn led to an increase of the power of the microwave radiation.

When a beam having the indicated parameters interacts with a spatially-periodic magnetic field, whether in a vacuum waveguide or in a waveguide filled with plasma, intense microwave radiation is observed if the condition $(k+K)V_{\parallel} = n\omega c$ is satisfied, where k is the wave vector of the transverse wave; $K = 2\pi/L; V_{\parallel}$ is the longitudinal beam-particle velocity; $\omega_c = eH_0/mc\gamma$ is the cyclotron frequency; γ is the relativistic factor. In the vacuum case, the generation was observed at frequencies 10.5 and 11.5 GHz with a radiation bandwidth 3%, generation power 7–8 MW, and $\tau = 1\times 10^{-6}$ sec. The generation had a resonant dependence on the magnetic field intensity and reached a maximum at $H_0 = 3.7$ kOe. When the waveguide was filled with a plasma with $\omega_p < \omega_0$ (ω_0 is the generation frequency) the generation power increased to 20 MW without a change in the spectrum and duration of the radiation.

When the installation operated under conditions that yielded maximum microwave radiation power and the waveguide was filled with gas, an acceleration of the ions of this gas was observed. The accelerated ions were registered at a distance 60 cm from the end of the magnetic field of the generator, by a pickup located in the plane of the exit horn of the generator. The pickup was a Faraday cup combined with a Rogowski loop, whose signal was registered with an oscilloscope. In addition, the ions were registered with the aid of cellulose-nitrate films, whose surface was subsequently photographed with an electron microscope and used to obtain the parameters of the accelerated ions. In our experiments we investigated the acceleration of argon and nitrogen. Our measurements have shown that the total current of the argon ions is 2–3 A at a particle energy as high as 1 MeV and at a pulse duration 1×10^{-6} sec. We registered simultaneously a group of ions of low energy, with a current of about 10 amperes, but with an energy not exceeding 100 keV. The area of the obtained ion beam was 13 cm^2, i.e., the ions were accelerated over a total cross section of the waveguide, with the exception of a narrow region next to the wall.

The character of the dependence of the radiation power and of the current of the accelerated ions on the intensity H_0 of the external magnetic field is illustrated in Fig. 2a. Fig. 2b shows plots of the radiation power and of the ion current against the pressure in the waveguide. It is seen that there is a distinct correlation between the microwave radiation and the presence of acclerated ions. Thus, to our knowledge, acceleration of ions in a system of the type of plasma relativistic ubitron has been observed experimentally for the first time.

It appears that in our experiments the ion acceleration is due to the mechanism considered theoretically in Ref. 2. Following Ref. 2, we can present the following picture of the acceleration process. The interaction of the beam with the spatially periodic magnetic field leads to an effective conversion of the longitudinal component of the beam velocity into a transverse component and, if the condition $(k+K)V_{\parallel} = n\omega c$ is satisfied, results in powerful generation. As a result, the beam breaks up into bunches, which we have observed experimentally on the targets. This is followed by capture of the plasma ions by the field of the bunches, whose longitudinal velocity decreases as a result of the interaction with the spatially periodic magnetic

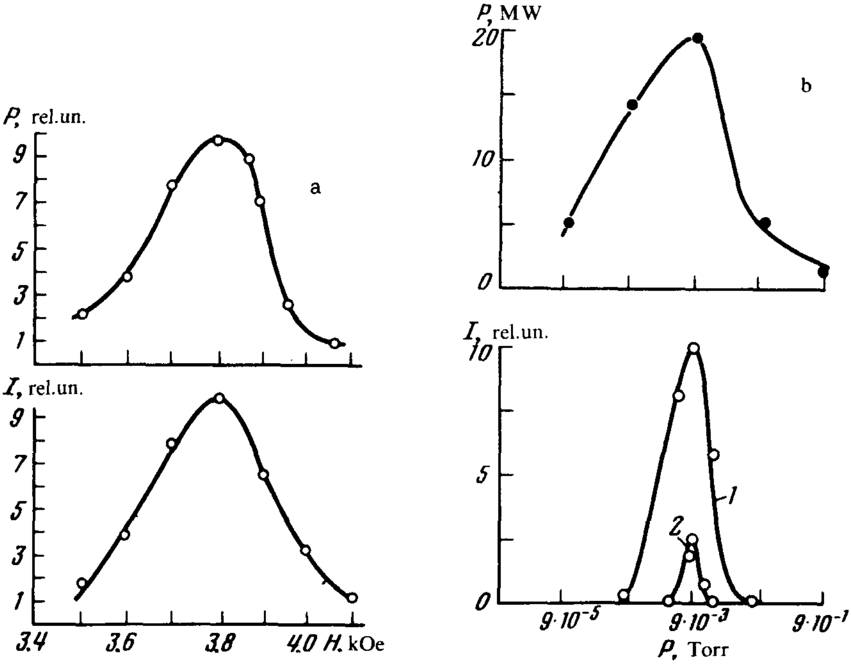

FIG. 2. a) Dependence of the radiation power and of the accelerated-ion current on the intensity of the external magnetic field; b) dependence of the radiation power and of the ion current on the pressure in the waveguide: 1) low-energy ion current; 2) high-energy ion current.

field to a value

$$V \lesssim 10^{-2} c \sqrt{eZ/A},$$

where eZ is the ion charge and A is the atomic weight of the ion.

FIG. 3. Oscillogram of microwave radiation and of the ion current.

Another effect that can lead to acceleration of the ions in our system is acceleration by waves with negative energy.[3,4]

In our installation we reached an ion-acceleration efficiency $\sim 3 \times 10^{-3}$ relative to the electron-beam power and $\sim 1 \times 10^{-1}$ relative to the microwave radiation power. An oscillogram of the microwave radiation and of the ion current is shown in Fig. 3. Further increase of the generator efficiency, which can reach $(2–3) \times 10^{-1}$, will make it possible to increase substantially the current and the energy of the ion beam.

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