COLLECTIVE PROCESSES IN THE PASSAGE OF HIGH-CURRENT RELATIVISTIC BEAMS THROUGH A GAS AND A PLASMA

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The purpose of the present paper is to report preliminary results of experiments on the interaction of high-current relativistic beams with a plasma. The experiments were performed with the setup illustrated in Fig. 1. An electron beam (current up to 60 kA, electron energy up to 1.0 MeV, energy spread $\sim$20%, pulse duration 3×10^{-8} sec) was produced with the aid of a cylindrical dual shaping line (DSL) filled with distilled water. The line was charged with a pulsed Marx generator designed for an output voltage up to 0.5 MV with a steep leading front of the voltage pulse [1]. The electron source used in the experiments was a needle-point cathode whose geometry ensured good matching of the electron gun with the DSL.

We investigated the passage of a relativistic beam through a chamber 3 m long filled with nitrogen at pressures 10^{-2} - 20 mm Hg. When the beam passed through the gas, a plasma of density 10^{12} - 5×10^{13} cm^{-3} was produced, and the electron beam was compensated both in charge and in current. The return current in the plasma was 70 - 80% of the current in the beam. The pressure range corresponding to the best passage of the beam was 5×10^{-2} - 8×10^{-1} mm Hg. At pressures lower than 5×10^{-2} mm Hg, the beam was blocked, since no gas focusing took place. At pressures above 2 mm Hg, the scattering of the electrons of the return current in the gas becomes appreciable. The formation of plasma following passage of a high-current relativistic beam is apparently due to collective effects, namely ionization in the fields and the beam-excited oscillations [2, 3]. At the same time, a characteristic periodic structure is observed and constrictions (necks) are observed along the beam (Fig. 2a). Under the conditions of optimal gas focusing, the minimum beam radius in the neck region reached 3 mm. The relaxation period in the beam is of the order of 40 - 50 cm.

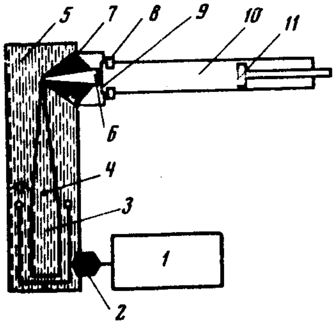

Fig. 1

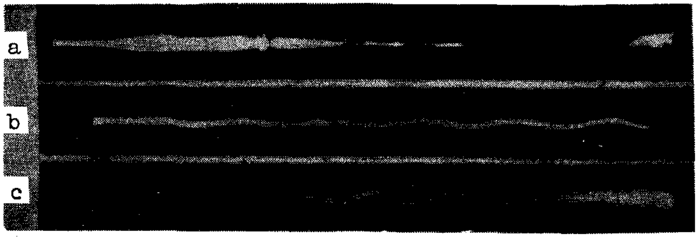

Fig. 2

Fig. 1. Experimental setup: 1 - Marx generator, 500 kV, 2 - charging insulator, 3 - coaxial double shaping line, 4 - coaxial transformer, 5 - liquid dielectric (distilled water), 6 - cathode of vacuum diode, 7 - bushing insulator, 8 - shunt-type current meter, 0.1 ohm resistance, 9 - anode (aluminum foil 40 μ thick), 10 - drift chamber, 11 - movable collector.

Fig. 2. Passage of relativistic electron beam through a gas under different conditions: a - beam current 30 kA, pressure 2×10^{-1} Torr; b - beam current 50 kA, pressure 4×10^{-1} Torr; c - beam current, 55 kA, pressure 1 Torr.

At large beam currents, $I \gtrsim 40$ kA, and at an energy $\mathcal{E} = 1.0$ MeV, we observed development of a macroscopic beam instability of the "hose" type [4]. The instability leads to a transverse displacement of the beam and to the occurrence of perturbations of the flat "snake" type (Fig. 2b). The instability increments are [5]

$$\delta_h = \left(\frac{n_1 m}{n_0 M}\right)^{1/2} \frac{c}{r_0} < \theta > \tag{1}$$

(n_1 and n_0 are respectively the beam and plasma density, m is the electron mass, M is the ion mass, $c<\theta>$ is the average spread of the transverse velocities, and r_0 is the initial beam radius).

Under the conditions of the experiment, δ_h is equal to $3 \times 10^8 - 10^8$ sec^{-1}, i.e., $\delta_h \tau_p \simeq 10 - 3$. The instability can therefore be observed only at the maximum currents attainable in this experiment. The wavelengths of the excited oscillations are bounded by the condition $\lambda > 2\pi r_0/<\theta> \simeq 20 - 40$ cm. The experimentally measured values of λ in the case of the "hose" instability are $\sim 40 - 50$ cm.

Experiments were performed on the generation of microwave radiation by interaction of the relativistic beam with the plasma. In view of the small angle scatter in the beam, $\theta \lesssim (n_1/n_0)^{1/3}$, and the small longitudinal-energy spread, $\Delta\mathcal{E}/\mathcal{E} < (n_1/n_0)^{1/3}\gamma_0$ (γ_0 is the relativistic factor), the instability resulting from the interaction of such a beam with the plasma is hydrodynamic, with an increment equal to

$$\delta = \omega_p \left(\frac{n_1}{n_0 \gamma_0}\right)^{1/3} \left(\frac{k_z^2}{k^2}\,\frac{1}{\gamma_0^2} + \frac{k_\perp^2}{k^2}\right)^{1/3}, \tag{2}$$

where ω_p is the plasma Langmuir frequency, and $k_\perp$ and k_z are the transverse and longitudinal components of the wave vector. It is known that a changeover to relativistic beam energies leads to a considerable increase of the energy of the microwave oscillations excited in the hydrodynamic instability ($\sim\gamma_0^2$) [6]. At the same time, at large γ_0 the growth lengths of the oscillations increase appreciably, and to obtain noticeable effects at short lengths it is necessary to use modulated beams. Owing to the difficulty of modulating high-current beams at relativistic energies, a highly promising procedure is to use the self-modulation resulting from the interaction of the beam with a periodic structure having a resonant frequency close to the plasma frequency.

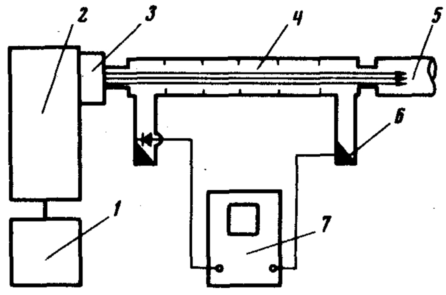

Fig. 3. Diagram of experiment on the interaction of a beam with a periodic structure: 1 - charging Marx generator, 2 - double shaping line, 3 - vacuum diode, 4 - iris-loaded waveguide, 5 - drift chamber, 6 - matched calorimeter load, 7 - OK-19M oscilloscope.

To obtain this effect we used a slow-wave structure comprising a section of an iris-loaded waveguide 1 m long, designed for a frequency 2500 - 2800 MHz and a slowing-down factor $\beta \simeq 0.7$ (Fig. 3). In the future we hope to use waveguides of higher frequency, in order that the beam self-modulation occur at frequencies close to the plasma frequency. At pressures 0.1 - 1 mm Hg, the beam passing through the section produced a plasma of density

$10^{12} - 10^{13}$ cm^{-3}, and this led to an increase of the slowing down in the section to a value 0.3 - 0.5 in the frequency range under consideration.

During the course of the pulse, the beam energy ranged from 0.3 to 1.0 MeV. The width of the resonance between the beam and the excited waves with frequency ω and wave number k_z is

$$\left|\frac{\omega}{k} - v_0\right| \sim \left(\frac{\omega_b}{\omega_0}\right)^{2/3} \frac{v_0^{4/3}}{v_g^{1/3}} \sim v_0 \tag{3}$$

where v_0 is the beam velocity, ω_b is the Langmuir frequency of the beam, v_g is the group velocity of the wave, and ω_0 is the resonant frequency of the section. Under the conditions of the experiment, the beam is at resonance with the excited waves during the entire pulse.

The length ℓ over which the oscillations build up is of the order of $\ell \sim 10 v_0^{2/3} v_g^{1/3} / \omega_b^{2/3} \omega_0^{1/3} \simeq 20 - 30$ cm, i.e., much less than the length of the section.

Thus, self-modulation of the beam produces a noticeable effect. The self-modulation is accompanied by generation of intense microwave oscillations at the resonant frequency ω_0. The microwave power was measured by two methods, with a calibrated detector and with a calorimeter matched to the waveguide channel (SWR = 1.35). The power reached 10^7 W. The generation of radiation was observed in the entire range of waveguide frequencies, with a maximum at 2600 MHz, and its duration was 3×10^{-8} sec.

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COHERENT GENERATION OF THE $2\pi^-\pi^+$ SYSTEM ON NUCLEI

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We have obtained new data on the coherent generation of a triad of pions ($\pi^+ 2\pi^-$) on light nuclei (C, F, Cl) by a π^- meson having a "momentum" ~3.9 GeV/c. Some experimental details can be found in [1].

An increase of the statistics has enabled us to study a group of reactions (202 events) with $t' = |t - t_{\min}| < 0.03$ (GeV/c)^2, in which the fraction of the coherent events, according to the most rigorous estimates, is not lower than 40%. The general characteristics of this group can be seen in Fig. 1. The presented mass distributions agree qualitatively with the corresponding distributions observed in similar experiments at higher energies.