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Abstract

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On the Generation of Superfast Plasma Clots in Railgun-Type Accelerators

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Despite the significant successes achieved in the field of electrodynamic acceleration of plasma clots, most of the designs described to date ($^{1-3}$) make it possible to impart to the plasma velocities not exceeding 0.1—$1.0 \cdot 10^6$ m/sec; however, for experiments with plasma injection into magnetic traps, for example, velocities of the order of 10^6—10^7 m/sec are desirable.

In accordance with the theory (^{4}), for given dimensions of the capacitor bank feeding the accelerator and for its optimum design, an increase in the velocity of plasma clots can be achieved by reducing the mass of the accelerated substance. However, as experience shows, this gives rise to a number of specific technical difficulties associated with the process of creating a plasma clot intended for subsequent acceleration, which must possess sharply defined boundaries and sufficiently high conductivity at a comparatively low concentration of the initial neutral particles.

In connection with preliminary studies of gas ionization at reduced pressures, in designing the system it was considered expedient to abandon the generally accepted scheme of injecting the accelerated substance in the form of neutrals, when the ionization and acceleration functions are assigned to one and the same current. In the experiments described, highly ionized plasma, created outside the acceleration space, was injected into the accelerator.

Figure 1 gives a schematic representation of the installation with spark gaps and capacitor banks. The length l of the coaxial electrodes is 0.9 m, and their diameters are 0.06 and 0.1 m, respectively. The self-inductance L_0 of the bank with the spark gap, at a capacitance $C = 48\ \mu$F, did not exceed $35 \cdot 10^{-9}$ H. The vacuum spark gap made it possible to switch the bank in the voltage range 1-50 kV in times of less than 50 nsec. The spark gap present in the installation for crowbarring the bank was not used in the experiments described.

The design of the plasma source is analogous to (^{5}). Normal operation of the source was ensured by the discharge of a low-inductance capacitor of capacitance 17 μF. The discharge current through the source had the form of an aperiodic pulse of duration 2.5 μsec. Varying the discharge current from 25 to 200 kA made

Fig. 1. Diagram of the setup.

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it possible to change the number of particles injected into the accelerator from approximately 1 to 60 μg. The plasma composition consisted of highly ionized products of evaporation of the surface of the insulating insert of the source, made of Plexiglas. The particle spectrum in the injected plasma, measured by the retarding-potential method (6), corresponds to an average electron and ion energy of 10–15 eV. The calculated value of the Coulomb conductivity of the plasma ensures insignificant diffusion of the accelerating current layer in the clot during the entire time of its motion along the coaxial line.

Plasma injection was carried out 30 cm from the separating insulator of the coaxial line. The measured velocity of propagation of the front of the injected plasma from the inlet was $5 \cdot 10^3$ m/sec and depended only weakly on the regime

source. The moment for switching on the main spark gap after operation of the plasma-injection system was determined experimentally from the maximum velocity of the bunch at the accelerator exit. The optimal delay time found in the experiments coincides with the time required for propagation of the front of the injected plasma from the injection point to a point 25 cm away from it. The velocity of motion of the bunches in the accelerator and the spatial

Fig. 1. Diagram of the setup. 1 —main spark gap, 2 —spark gap for short-circuiting the current battery, 3 —igniting electrodes, 4 —gun electrodes, 5 —plasma source. *a* —organic glass, *b* —rubber, *c* —metal

distribution of their density was determined with the aid of directed particle-flow probes (7), Langmuir probes, and magnetic probes.

As became clear in the process of tuning the accelerator, the optimum operating conditions of the design are very critical with respect to the spatial distribution of the plasma injected into the accelerator at the instant immediately preceding the switching on of the main battery. Stable operation of the accelerator was ensured only in the case of a sharply defined current-carrying end face of the bunch. The thickness of the diffusion layer of the end face measured in the experiments, defined as the distance over which a tenfold decrease in the density of charged particles in the injected bunch from the maximum value occurs, did not exceed 3–5 cm for a well-adjusted system, with an average length of the homogeneous part of 30 cm.

Figure 2 shows oscillograms of signals from a pair of electric probes located beyond the accelerator exit at a distance of 68 cm from one another. The signal amplitude is proportional to the particle concentration in the bunch; the characteristically weak spreading of the longitudinal dimensions of the plasma formation indicates a small spread in the longitudinal component of the particle velocities. The average value of the particle density in the bunch is 10^{14} cm^{-3}.

Fig. 2

Figure 2: Fig. 2

Fig. 3

Figure 3: Fig. 3

Fig. 2. Oscillogram of signals from probes.
1 div. = 1.65 μsec.

Figure 3 gives the experimentally obtained dependences of the propagation velocity of the leading front of the bunches, v_0, on the battery voltage V_b for different values of the discharge current in the plasma source. For a quantitative characterization of the curves obtained, at the points $V_b = 10$ kV the mass m_0 of the substance accelerated in the bunch was estimated with the aid of a ballistic pendulum. The figure clearly shows a pronounced increase in the velocity of the bunches with decreasing mass of the injected substance. The measurements showed that, under the experimental conditions, over the entire range of variation of m_0, with V_b unchanged, the product $m_0 v_0$ remains approximately constant.

When working with amounts of accelerated substance smaller than 1 μg, bunch velocities of $3\text{-}5 \cdot 10^6$ m/sec were achieved in the experiments; however, because of the instability of operation of the plasma source under these conditions, the reproducibility of the results obtained was unsatisfactory from one experiment to another.

It should be noted that, despite the large v_0 values attained in the experiments, the system described, like all the others (1-4), has a very small value of the efficiency of the acceleration process,

$$\eta = \frac{m_0 v_0^2}{C V_b^2},$$

which in the present design did not exceed a few percent. This is not unexpected, since with an average acceleration time $t \sim l/v_0 \simeq 10^{-6}$ sec, the time of complete discharge of the battery θ, made up of standard industrial capacitors with a large value of intrinsic inductance, is of the order of tens of microseconds; consequently, the efficiency of current utilization in this case is very small.

Fig. 3. Dependence of the velocity of plasma bunches on the battery voltage.
At the point $V_b = 10$ kV, the bunch mass on the curve is:
1—20 μg, 2—18 μg, 3—5 μg, 4—3 μg, 5—less than 1 μg.

Our attempt to increase the interaction time of the bunch with the current accelerating it by increasing the length of the accelerator did not lead to positive results. As measurements on a 3-meter model of the accelerator showed, the velocity of the bunch increases only at the beginning, over a distance of 0.6–1.0 m, and then, after saturation, begins to decrease slowly. The calorimetric and probe measurements that we carried out of the rate of energy losses and of diffusion in a freely moving bunch showed that the cause of this somewhat unexpected effect is the radial breakup of the bunch, in which the plasma particles, colliding with the electrodes of the ac—

of the accelerator, rapidly lose their energy. The effect is equivalent to a sharp increase in the dissipative losses in the bunch, compensating, in the final analysis, the work done by the current. At the same time, an intense process of cooling of the bunch and deterioration of its conductivity takes place, leading to the anomalously rapid diffusive spreading of the current layer observed earlier in (^{3}).

The decay time of the bunch τ may be estimated as a quantity of order $\delta R/v_\perp$, where δR is the difference of the radii of the coaxial system, $v_\perp \simeq 10^4$ m/sec is the transverse component of the ion velocity in the bunch. Since the radial component of the particle temperature in the bunch, which provides the plasma conductivity required by the skinning conditions, cannot be made less than 10—20 eV, the absence of methods for preventing radial diffusion of particles in railgun-type accelerators fundamentally limits the duration of acceleration processes to times of order 10^{-6} sec.

In this connection, together with the Computing Center of the Siberian Branch of the USSR Academy of Sciences, the problem was solved of optimizing the parameters of the accelerator that ensure the minimum time t_0 for transfer of the energy stored in the capacitor bank to the bunch. Numerical calculations carried out on the basis of the theory (^{4}) showed that for $q = C^2V_0^2L_1^2/2m_0L_0 \simeq 12$—20 this quantity has a minimum equal to approximately $3/\omega_0$, where L_1 is the inductance per unit length of the coaxial electrodes, $\omega_0 = 1/\sqrt{L_0C}$. Taking the lifetime of the bunch to be 10^{-6} sec, for the natural period of the accelerator power-supply bank we obtain the condition, quite stringent from the technical point of view, $\omega_0 \lesssim 3 \cdot 10^6$ sec^{-1}, which is satisfied only in the best examples of capacitor banks used in thermonuclear research in the study of fast processes in plasma. Processing of the data available in the literature shows that not one of the currently existing installations for electrodynamic acceleration of plasma satisfies the stated conditions, either simultaneously or separately.

In our experiments, with $m_0 \simeq 5$ μg, q is optimal; however, ω_0 is 4 times smaller than the maximum permissible value. In one of the most advanced modern installations (^{2}), $q \simeq 0.1$, and ω_0 is 3 times smaller than the optimal value.

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CITED LITERATURE

[1] V. F. Demichev, V. D. Matyukhin, DAN, **150**, 279 (1963).
[2] D. M. Wetstone, Phys. Fluids, **5**, 981 (1962).
[3] L. C. Burckhardt, R. H. Lovberg, Phys. Fluids, **5**, 341 (1961).
[4] L. A. Artsimovich, S. Yu. Luk' yanov et al., ZhETF, **33**, 3 (1957).
[5] Yu. S. Azovskii, I. G. Guzhovskii, B. G. Safronov, V. A. Churaev, ZhTF, **32**, 1050 (1962).
[6] D. G. Budilinskii, B. V. Galaktionov et al., ZhTF, **33**, 183 (1963).
[7] Plasma Eater Measurer Flow, Nukloniks, **20**, 58 (1962).

Note: Figure translations are in progress. See original paper for figures.