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ELECTRODYNAMIC ACCELERATION OF PLASMA BUNCHES

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An electrodynamic method of accelerating plasma bunches is proposed. The results of preliminary experiments are described. The data obtained are in qualitative agreement with the elementary theory of the phenomenon.

THE flow of an electric current is always accompanied by the formation of electrodynamic forces tending to deform the individual circuit elements. If one of the elements of a current circuit can be displaced freely, it acquires kinetic energy from the electromagnetic field energy. The force F acting on a mobile element is defined by the expression

$$F = \partial U / \partial x = {}^1/_2 J^2 dL/dx.$$

The acceleration of an electrically neutral substance has a number of advantages over the usual method of obtaining high-speed charged particles. The acceleration of a quasi-neutral gas discharge plasma (or of metal formations) affords the possibility of bypassing the difficulties relating to beam defocusing under the action of the space-charge force and permits, in principle, a gigantic number of accelerated particles per pulse to be obtained. The method proposed is especially suitable for production of heavy high-energy particles since the energy of the guided motion of each of the atoms is proportional to its atomic weight if a circuit element of fixed mass is to be accelerated.

This article explains the principle of electrodynamic acceleration, analyzes the elementary theory, and describes the results of preliminary experiments.

1. THEORY

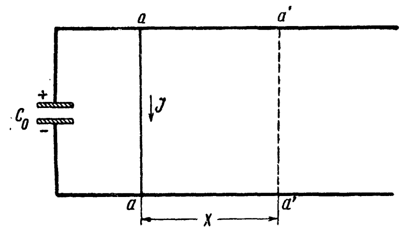

FIG. 1. Circuit diagram

Let us consider a circuit (Fig. 1) consisting of a capacitor bank and two parallel rigid conductors along which a piece of metal wire (a — a), serving as the mobile circuit element, can be freely displaced without friction. Understandably, such a simplified circuit cannot be the design of a new kind of accelerator. For simplicity, however, we shall consider in this section the idealized problem of the motion of a mobile wire.

The process of accelerating a mobile circuit element is described completely by the system of equations

$$mx'' = {}^1/_2 c^{-2} J^2 dL/dx, \quad (1)$$

$$J = - C_0 dV/dt, \quad (2)$$

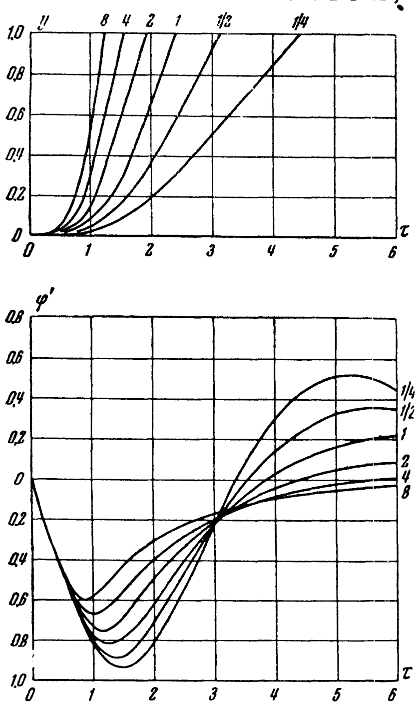

FIG. 2. Results of the numerical solution of the equations of motion for various values of the parameter q. The upper graph shows the time dependence of the distance traversed by the wire. Shown below is the time dependence of the discharge current. The quantities are plotted in nondimensional units.

$$V = c^{-2} d(LJ)/dt, \tag{3}$$
$$L = L_0 + bx, \tag{4}$$

where m is the mass of the wire to be accelerated, J the current in the circuit, C_0 the capacitance of the capacitor bank, V the capacitor voltage, L_0 the initial circuit inductance, and b the increment in the system inductance as the wire moves 1 cm.

The initial conditions at $t = 0$ are:

$$V = V_0, \quad x = 0, \quad J = 0, \quad x' = 0.$$

Let us introduce the nondimensional variables

$$y = bx / L_0, \quad \varphi = V / V_0, \quad \tau = \omega_0 t,$$

where $\omega_0 = (L_0 C_0)^{-1/2}$. After substituting L and J into (1) and (3), we obtain:

$$y'' = q\varphi'^2, \tag{5}$$
$$\varphi = -(d/d\tau)[(1+y)\varphi'] \tag{6}$$

The initial conditions become

$$y(0) = 0 \text{ and } y'(0) = 0; \quad \varphi(0) = 1 \text{ and } \varphi'(0) = 0.$$

The part of the dimensionless parameter is played in these equations by

$$q = b^2 C_0^2 V_0^2 / 2 mc^2 L_0.$$

Without solving the equation in general form, let us analyze two limiting cases.

1. Initial stage of the process ($y \ll 1$; $\tau \ll 1$)

$$\varphi = -d\varphi' / d\tau. \tag{7}$$

Integrating (7) and substituting the result in (5), it is easy to see that

$$y = {}^1\!/_4\, q\, [\tau^2 - {}^1\!/_2 (1 - \cos 2\tau)], \tag{8}$$

from which, because $\tau \ll 1$

$$y = q\tau^4 / 12.$$

2. The following asymptotic equation is obtained in the other limiting case ($\tau \to \infty$):

$$\varphi = B\tau^{-1/4} \cos((8/q)^{1/4} \sqrt{\tau} + \alpha). \tag{9}$$

It follows from this expression that as the wire is accelerated the amplitude of the voltage oscillations gradually attenuates but the period of the oscillations is increased. However, such a variation of the period and amplitude could be predicted on the basis of simple qualitative reasoning (it is explained by the growth in circuit inductance as the wire moves).

A numerical solution of (5) and (6) was obtained by G. A. Mikhailov and G. A. Bykov using the TsEM-1 electronic computer. The solutions obtained for various values of the parameter q are plotted in Fig. 2.

2. APPARATUS

A gas discharge plasma generated by the electric explosion of a fine metal wire was the mobile circuit element in all the experiments to be discussed. The electric circuit consisted of a 75 μF capacitor bank connected through a spherical discharge gap to massive copper electrodes ("rails"). These latter were placed in a continuously evacuated glass cylindrical chamber. Figure 3 shows schematically the arrangement of the fundamental elements of the apparatus.

An elementary analysis shows that in order to obtain high-speed plasma bunches the operation should be carried out with small values of the initial inductance. Hence, the capacitor-bank wiring described by Komel'kov and Aretov[1] was used.

The vacuum in the discharge chamber at the moment preceding the explosion of the wire was $1 - 2 \times 10^{-6}$ mm Hg.

High-speed photography was used to measure the speed of the plasma and the variation in the magnetic field intensity along the path of the plasma was recorded. The magnetic field was measured by using small coils in which an electromotive force proportional to $\frac{\partial H}{\partial t}$ was induced. The turns of the magnetic pick-off were oriented so that they recorded only the magnetic field intensity component parallel to the rails. This magnetic field intensity component should not change sign when the plasma bunch (current filament) passes the pick-off. The pulses from the magnetic pick-offs K_1 and K_2 are integrated by an RC network and fed to a two-beam pulse oscillograph OK-17M. The second beam of the oscillograph recorded the current in the circuit or the pulse from another magnetic pick-off placed at a definite distance from the first. The loop locations are shown in Fig. 3.

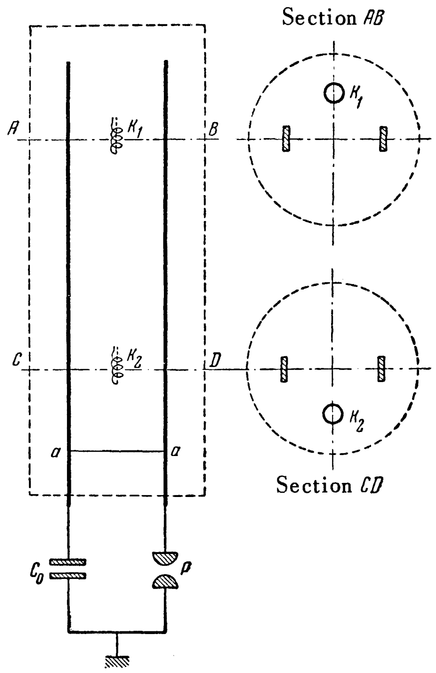

FIG. 3. Schematic diagram of the elements of the apparatus and the locations of the magnetic pick-offs K_1 and K_2.

3. MEASUREMENT RESULTS

High-speed photographs of the glow of the gas discharge plasma which occurs in the explosion of a wire moving along rails are given on Fig. 4. The film speed was 2×10^6 frames per second with a 0.2 μsec frame exposure. The capacitor bank was discharged in these experiments through copper wires of varying diameters. The initial capacitor voltage was 30 kv. By determining the position of the luminous front on each frame, the displacement of the plasma along the rails could be plotted as a function of time. Figure 5 shows a family of curves plotted by the method indicated (see the dashed curves).

The oscillographs of the pulses from the magnetic loops are shown in Fig. 6. The upward swing

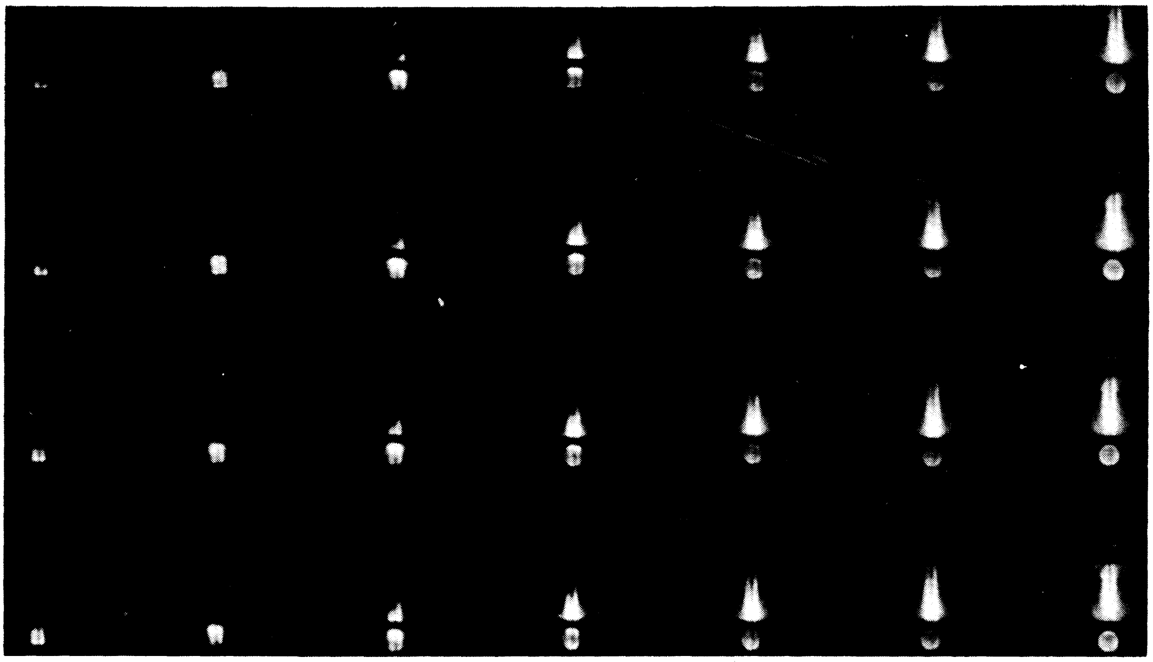

FIG. 4. High-speed photography frames. Lower part of the discharge chamber is metallic, consequently, part of the rails near the original position of the wire is not seen on the photographs. Frames are obtained during burning of 0.02 mm copper wire ($C_0 = 75$ μF, $V_0 = 30$ kv). Rails enclosed between vitreous plates.

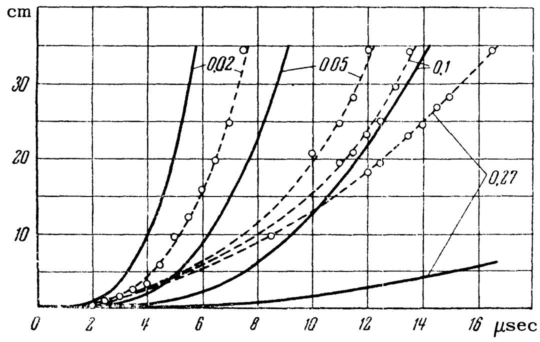

FIG. 5. Theoretical and experimental (dashed) curves of the time-dependence of the distance traversed by the plasma bunch. The different curves correspond to the burning of copper wires of different diameters (diameters indicated in mm).

corresponds to that direction of the magnetic field component which must occur when a hypothetical current filament passes the pick-off. In reality, as is seen from the figure, the magnetic field intensity is seen to change sign during the first current half period. The reason for this change is analyzed below. The speed of the plasma along different sections of the path was determined by the relative time shift between the pulses from two pick-offs located in a suitable manner. The value of the velocity obtained by processing sufficiently clear photographs is in satisfactory agreement with the results obtained from magnetic measurements. Thus, for example, at 30 kv the maximum value of the velocity in experiments with a copper wire of 0.02 mm diameter at a 30 cm distance from the initial position of the wire is 1.1×10^7 cm/sec by magnetic measurements and 1.2×10^7 cm/sec by photographic measurements.

The set of experimental results obtained indicates the

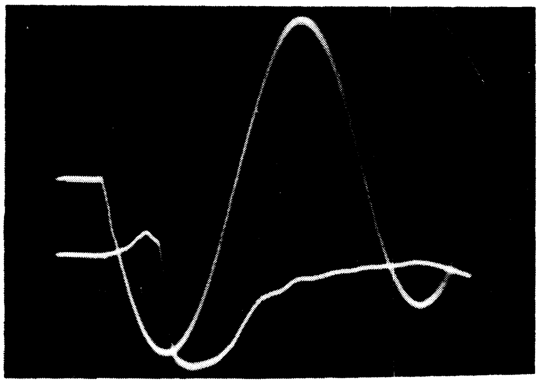

FIG: 6. Oscillogram of a pulse from the magnetic pick-off in phase with the discharge current.

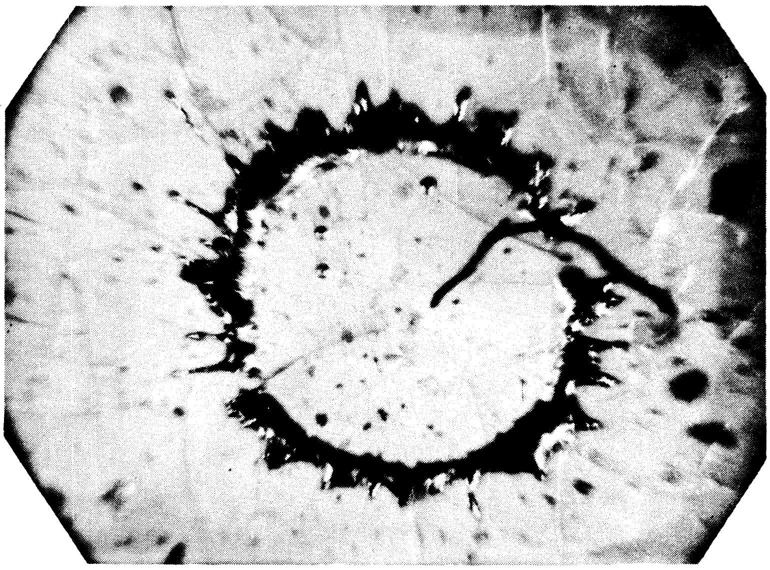

FIG. 7. Microphotograph of the deposit on a vitreous target obtained during the explosion of an 0.07 mm iron wire. Amplification 130×.

obvious inadequacy of the elementary theory given in Sec. 1 in at least two respects.

First, it is assumed in the theory that the mass m in the equation is the same as the mass of the evaporating wire. In reality, not all the material of the wire can be transformed into a cloud of ionized gas during an electric explosion. On the other hand, the plasma bunch interacts with the surface of the rails and with the inner chamber walls as it moves. This interaction can lead to an increase in the number of ionized particles participating in the acceleration process. Hence, the real mass of the substance to be accelerated can be either greater or smaller than m. The second inadequacy of the theory developed is the assumption that the shape of the plasma formation is invariant during the acceleration.

It follows from an analysis of the experimental results, that both assumptions of the theory do not correspond to reality. Actually, as is seen from Fig. 5, the experimental values of the transit time appears to be larger than the theoretical for fine wires while the reverse picture holds for thicker wires. The slower motion of the plasma bunches than results from the theoretical formulas is apparently due to the change in the shape of the plasma bunches and, therefore, to the current distribution therein during acceleration. Analyzing the individual frames of Fig. 4, it is easy to be convinced that what moves along the rails is not a sharply delimited luminous cloud but a rapid increase in the longitudinal size of the luminous region. If it is assumed that the distribution of the current density is in agreement with the distribution of plasma luminescence then the electrodynamic forces accelerating the leading edge of the plasma will be less than computed, resulting in slower motion. Photographs obtained by burning thicker wires show that the broadening of the plasma bunch is retained when the wire diameter changes. However, the influence of another factor seems to be more essential in the explosion of a wire of relatively large diameter, namely the incomplete evaporation and the incomplete ionization of the wire material. A direct proof, confirming the validity of this assumption, has been obtained by a microscopic investigation of the metallic deposit on vitreous targets situated at the end of the path of the plasma motion. The electric explosion of the wire is accompanied by the appearance of metallic formations, occasionally of very startling shape (Fig. 7), on the surface of the vitreous targets, such formations could not result from condensation of the vaporized material on the cold target.

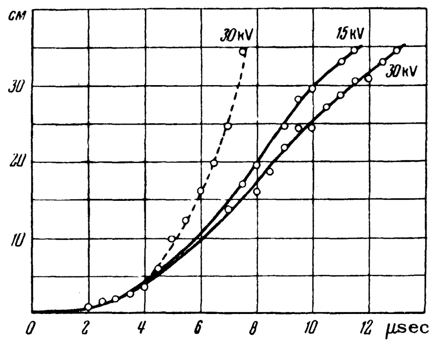

FIG. 8. Time-dependence of the distance traversed by the plasma bunch along the rails. Solid curves are obtained by processing photographs with accessory glass. Dashed curve is obtained for the same parameters but without the accessory glass and is given for comparison purposes.

Measurements of the magnetic field distribution during the plasma acceleration along the rails completely confirm the abovementioned assumption of the absence of any clear localization of the discharge current. At the very instant when the magnetic pick-off located at the end of the rails starts to indicate passage of current, the pick-off located at the beginning of the rails still continues to indicate a current flow in that region.

The results obtained with magnetic pick-offs indicate also a lateral broadening of the region occupied by the discharge current. Actually, as has already been said, the direction of the magnetic field recorded by the magnetic pick-offs changes sign while the discharge current direction remains invariant. A natural explanation of the character of the oscillograms obtained would be the assumption that the discharge current flows around the measuring coil (hence, the sign of the magnetic field at the coil location must become reversed). The similar character of the oscillograms of the pulses from the magnetic pick-offs located relative to the rails as shown in Fig. 3 indicates that an approximately symmetrical broadening of the region occupied by the dishcarge current occurs in a number of cases as the plasma bunch accelerates. In reality, as numerous investigations of the electric explosion of a wire in a vacuum indicate,[2] the propagation velocity of the explosion products can reach $10^5 - 10^6$ cm/sec and, therefore, the plasma bunch broadens in all directions in addition to having its center of inertia accelerate along the rails. The electromagnetic contraction appears to be inadequate to prevent broadening of the plasma ($\frac{H^2}{8\pi} < nkT$). Moreover, it should be kept in mind that the presence of the pick-off can itself cause additional distortion of the shape of the plasma bunch.

In order to confirm the assumption made about the lateral broadening of the bunch, the rails were enclosed between glass plates so that the discharge current could not flow around the magnetic pick-offs. An oscillographic investigation of the impulses of the magnetic field along the path traced by the plasma indeed disclosed that no negative excursions in this case. However, the plasma acceleration process appears to be a complicated, new, troublesome phenomenon. The discharge current is not a thin current filament moving along the rails but it occupies a sufficiently extended section of the rails. Consequently, the plasma reacts violently with the vitreous surface and heats it, which leads to a continuous growth in the mass of the moving substance. Such a continuous increase in the mass of the gas is equivalent to friction in certain respects and it must lead to a decrease in the plasma velocity, as is observed in experiments both during oscillographic measurements and during processing of the given high-speed photographs (Fig. 8).

Hence, on the basis of the preliminary experiments conducted, the conclusion can be made that the electrodynamic acceleration of a plasma is really observed, but that the acceleration process is characterized by considerably more complex laws than could be assumed a priori.

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[1] V. S. Komel'kov and G. N. Aretov, Dokl. Akad. Nauk SSSR 110, 559 (1956).

[2] W. Conn, ZS. angew. Physik 7, 539 (1955); I. F. Kartskhava, V. V. Bondarenko, et al., J. Exptl. Theoret. Phys. (U.S.S.R.) 31, 737, 745 (1956), Soviet Phys. JETP 4, 623, 637 (1957).

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