PINCHES OBSERVED IN PLASMA RAIL GUNS

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ABSTRACT: The decelerating mechanisms and existence conditions for the pinch structures obtained in plasma rail guns are considered. The plasma is confined by the magnetic field of the self-current. It is shown that under experimental conditions the predominant effect is induction deceleration of the pinches by plasma formed behind the pinches as a result of ionization of vaporized electrode and accelerator wall material. The expressions obtained for the limiting velocities and pinch radius are found to be in satisfactory agreement with experiment.

In [1] the author described narrow current layers 0.2 cm in diameter observed in a plasma rail gun with parameters: capacitance of capacitors—36 μF; voltage—up to 4.5 kV; maximum current during first half-period—up to 40 kA, electrode length—20 cm; distance between electrodes—2 cm. These layers had roughly equal luminescence intensity and diameter and moved at constant velocity at distances of roughly 2 cm apart. The velocity of the first layer was $(4-5) \cdot 10^6$ cm/sec, while the velocity of successive layers increased to $6 \cdot 10^6$ cm/sec. The voltage across the capacitors (1.5–4.5kV), the pressure ($p = 0.1-20$ μ Hg) and the type of gas filling the tube had no effect on the velocity or diameter of the layers. The number of layers existing simultaneously during the first current half cycle was roughly proportional to the voltage across the capacitors. The average density of the charged particles in the layer, measured using the Stark effect for OII oxygen ion spectral lines, was $2.5 \cdot 10^{17}\ \mathrm{cm^{-3}}$ for $p < 2$ μ Hg; with increase in gas pressure in the tube, the density dropped sharply. The average current in the layer was $4 \cdot 10^3$ A and the plasma temperature was $3.4 \cdot 10^{4\circ}$ K. It was shown that the layer parameters were well described by the usual pinch formula:

$$n = \frac{I^2}{2c^2 \pi r_1^2 kT}. \qquad (1)$$

Here n is the average density of charged particles in the pinch, r_1 its radius, I the pinch current, T temperature, c the speed of light, and k the Boltzmann constant.

Below, the conditions for separation of the current sheet in the plasma gun into pinches, and the processes determining the velocity and diameter of the pinches, and some other parameters are considered.

At constant velocity the electrodynamic force $F = (1/2)c^{-2}I^2 dL/dx$ accelerating the pinch must be compensated by the decelerating force. Experiment shows that in the pressure interval under investigation the residual gas pressure in the tube has no effect on the velocity. Using the above pinch parameters, we find that mechanical air-flow deceleration of the pinch only becomes noticeable at $p > 30$ μ Hg. It was also established that friction against the lateral glass walls was not a determining factor. An increase in the distance between walls by a factor of five or more did not affect the pinch velocity. If friction against the electrodes were a predominant factor, the pinches would either be deflected in the middle in the direction of motion or tilted, if the velocity depends upon near-electrode processes. High-speed photorecorder studies with the slit perpendicular to the velocity vector showed that the pinches were not bent but perpendicular to the electrode surfaces and the velocity vector.

Let us consider the effect on the moving pinches of plasma formed by ionization of vaporized material from the electrodes and walls. The presence of glass and metal vapor behind the moving pinches is indicated by the significant erosion of the glass walls along the entire electrode length and the deposition of copper on them. As a result of spectroscopic analysis [1], it was found that, in addition to the pinch plasma, there exists in the interelectrode space another practically "static" plasma ($V < 1.5 \cdot 10^6$ cm/sec), whose temperature is less than the pinch temperature but whose degree of ionization is considerable, since only ion lines were observed. It is also known that cathode spots are not observed between pinches, i.e., the discharge current flows only through the pinches.

In accordance with the experimental data, we shall assume that the pinches leave a plasma "wake" which is formed in the immediate vicinity of the pinch surface and fills a large part of the interelectrode space. When it is formed, the wake plasma has a velocity component in the direction of motion, which is much less than the pinch velocity, although the absolute velocity of the plasma fluxes from the electrode surface may be higher (up to $2 \cdot 10^6$ cm/sec [2]). The thickness of the plasma wake is of the order of the pinch diameter, and the wake is attracted to the next pinch.

In the wake plasma moving away from the pinch surface the magnetic field will decrease. This induces circulating currents which lead to acceleration of the wake plasma and the formation in the pinch region of a magnetic field opposite to the electrode field, i.e., to a decrease in the electrodynamic force accelerating the pinches. The figure shows the lines of force of the magnetic field (a) in the xoy plane near the moving pinch: 1) Pinch cross section, 2) wake plasma. The z-axis coincides with the pinch axis, while the x-axis is opposite to the pinch motion. The effect of the wake plasma induction currents on the magnetic field of the pinch in the zox plane is shown by the broken line (b) in the figure.

In the subsequent calculations it will be assumed that the wake plasma velocity is constant. This is valid when the induction deceleration time $\tau = c^2\rho/\sigma_2 H^2$ [3] is much greater than the time it takes the pinch to move through a distance equal to its radius

$$\frac{c^2\rho}{\sigma_2 H^2} \gg \frac{r_1}{V} \qquad \text{or} \qquad n \gg \frac{r_1 \sigma_2 H^2}{c^2 m V}. \qquad (2)$$

Here ρ is the wake plasma mass density, n is the particle density, H the pinch magnetic field, σ_2 the wake plasma conductivity, m the ion mass, and r_1 the pinch radius. Substituting the pinch parameters into this formula and setting the wake plasma conductivity equal to the conductivity of the completely ionized gas with $T = 3 \cdot 10^{4\circ}$ K, $\sigma_2 = 1.2 \cdot 10^{14}$ CGSE units, we obtain $n \gg 3 \cdot 10^{15}\ \mathrm{cm^{-3}}$.

We obtain an estimate for the limiting velocity of the first pinch from the condition that the magnetic field of the wake plasma induction currents at the pinch axis is equal to the electrode magnetic field. To simplify the calculations, we shall assume that the electrode magnetic field is constant along the pinch axis and equal to $1/2c^{-1}Il^{-1}dL/dx$, while the magnetic field of the pinch at its surface is much greater than the electrode field

$$\frac{2I}{cr_1} \gg \frac{1}{2c} I \frac{1}{l} \frac{dL}{dx}. \qquad (3)$$

Here I is the pinch current, r_1 its radius, l the distance between electrodes, dL/dx the inductance per unit length of electrode (dL/dx = = 10 cm/cm). For condition (3) to be satisfied, the pinch radius must satisfy the inequality $r_1 \ll 4l\,(dL/dx)^{-1} = 0.8$ cm; this is valid for the observed pinches.

In these conditions, the direction of the current in the wake plasma may be assumed to coincide with the z-axis, and the current density is

$$j_z = c^{-1}\sigma_z V H \sin\varphi + C_1, \qquad H = \frac{2I}{cr}.$$

Here σ_2 and V are the conductivity and velocity of the wake plasma, H is the pinch magnetic field, φ is the angle between the direction of motion of the pinch and the pinch magnetic field vector at a given point in the wake plasma, and C_1 is a constant determined from the condition that the currents in the wake plasma are closed

$$\iint j_z ds = 0,$$

where the integration is performed over the section of the wake plasma cut by a plane perpendicular to the z-axis. The condition of constant pinch velocity is written in the form

$$\frac{1}{2c} I \frac{1}{l} \frac{dL}{dx} = \iint \frac{2j_z}{cr} \sin\varphi \, ds. \quad (4)$$

Upon integrating we obtain an expression for the limiting velocity of the first pinch:

$$V_* = \frac{c^2}{6.65\sigma_2} \frac{1}{l} \frac{dL}{dx}, \quad (5)$$

i.e., for the decelerating mechanism under consideration the pinch velocity depends only upon the electrode configuration and the wake plasma conductivity. It follows that only the numerical factor in the expression for the velocity is affected by assumptions about the geometry of the wake plasma. Substituting numerical values for σ_2, l, and dL/dx, we obtain $V_* = 5.6 \cdot 10^6$ cm/sec. This is close to the observed velocity of the first pinch.

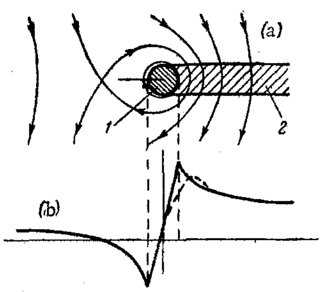

Fig. 1

In the same way we can obtain the limiting velocity of successive pinches; however, it is not possible to compare these values with experimental ones, since the density of the wake plasma of the first pinches and its decelerating effect on the pinch in question is not known.

So far, we have regarded the wake as a stationary plasma flux with respect to the pinch. Nonstationarity in the supply of plasma to the wake should impose a constraint on the pinch radius. The time during which the induction currents of some fixed volume of wake plasma act on the pinch is of the order of $\tau_1 = r_1/V$. This is explained by the fact that the wake plasma moves away from the pinch surface and the induction currents are attenuated. The nature of the deceleration of the pinches by the wake plasma depends upon the relationship between the time during which the magnetic field of the wake plasma acts on the pinch τ_1 and the time it takes to diffuse into the pinch volume $\tau_2 = 4\pi c^{-2}\sigma_1 r_1^2$.

Here σ_1 is the pinch plasma conductivity, and r_1 its radius. If $\tau_1 > \tau_2$ or $r_1 < c^2(4\pi\sigma_1 V)^{-1}$, the entire pinch volume is decelerated. When $\tau_1 < \tau_2$, only part of this volume, having a thickness of the order of $c^2(4\pi\sigma_1 V)^{-1}$, is decelerated; this thickness is equal to the depth to which the magnetic field of the wake plasma manages to diffuse into the pinch. Thus, the pinch dimension may increase owing to trapping of new gas until its radius is equal to the limit value

$$r_* = \frac{c^2}{4\pi\sigma_1 V}. \quad (6)$$

The numerical value of the limit radius obtained $r_* = 0.08$ cm is in good agreement with experiment.

New pinches may be formed by the moving current layer separating into two. This probably explains the fact that the acceleration process of newly formed pinches is not observed, although according to estimates the acceleration time must be considerable.

With an induction deceleration mechanism a pinch moving at velocity V_* has no external magnetic field, since the electrode field is compensated for by the wake plasma induction current field. Therefore, the pressure gradient in such a stationary pinch moving as a unit at constant velocity must be perpendicular to the magnetic field. This means that the pinch must have a cylindrical geometry, and its parameters must not differ from the parameters of the static pinch (1). The interaction of the moving pinches with the electrodes, walls, and freestream gas limits the time during which the pinch can exist. Thus, the region of existence of pinch structures is associated with predominance of the induction pinch deceleration mechanism.

The current sheet does not separate into pinches when there is only slight liberation of gas from the electrodes and walls. Then a single broad weakly-luminescent current sheet is observed during the first current half-period. A plasma wake with low particle density, irrespective of its conductivity, can not have a deceleration effect on the pinch; therefore in this case some other decelerating mechanism must predominate.

Likewise, in a poorly aged plasma accelerator, pinches are not formed. This is probably due to the fact that an increase in particle density in the wake plasma lowers the voltage at which the glow discharge across the wake plasma goes over into an arc discharge. The appearance of a high-current discharge across the wake plasma must cause the pinch to break down.

The pinches will also be decelerated by the induction currents of the plasma through which they move, and in some region of pressures this pinch deceleration mechanism may predominate if the conductivity of the surrounding gas is fairly high. This region is limited on the high-pressure side when the drag of the freestream gas begins to predominate and on the low-pressure side when the mass of all the gas flowing past the pinch is insufficient to decelerate it. In accordance with the foregoing, pinch structures may exist in plasma accelerators in this pressure region. This is a possible explanation of the observed separation of the convergent current cylinder in a Z-pinch into a network of filaments [4, 5].

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