PLASMOID STRUCTURE IN AN ELECTRODYNAMIC ACCELERATOR

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By means of a high-speed photorecorder it was observed that a plasmoid in an electrodynamic accelerator consists of separate sheets moving at approximately identical velocities. The following parameters of these sheets have been measured: velocity – $6 \cdot 10^6$ cm/sec, diameter – 0.2 cm, charged particle density in sheet – $2.5 \cdot 10^{17}$ cm^{-3}, temperature – $3.4 \cdot 10^4$°K, and average current in sheet – $4 \cdot 10^3$ a. It is shown that the sheets are pinches. The pinch plasma consists essentially of ions of oxygen O^+ and silicon Si^+, Si^{2+}, and Si^{3+}. The gas filling the tube is only slightly entrained. The existence of a limiting pinch radius is shown, and an expression agreeing closely with experiment is obtained for it.

The nonuniformity of plasmoids in electrodynamic accelerators has been reported on a number of occasions. Thus, Mawardi and Naraghi [1] observed a sheet-type structure in a coaxial accelerator using magnetic probes. They proposed a mechanism of internal instability of the plasma flux with a "frozen-in" magnetic field. A. M. Kovalev [2] attributed the formation of new current sheets to successive breakdowns behind the moving plasmoid.

In this article a more detailed experimental investigation of plasmoid sheets and the conditions under which they occur is described. Time resolution with a high-speed photorecorder (PR) was employed. From the Doppler shift of the spectral lines, data were obtained on the velocities of the different ions making up the plasmoid and the degree of entrainment of the gas filling the tube. The charged particle density in the sheets was determined from the quadratic Stark effect of the spectral lines of the oxygen ions. From the relative intensity of the lines of trivalent and univalent silicon ions, the plasma temperature in the plasmoid was measured. The experimental data obtained make it possible to propose another explanation of the origin of the sheets.

Description of Device and Experimental Results

The electrodes (Fig. 1) are two copper plates 1 located in the same plane between two plane walls 0.6 cm apart.

Parameters	
Electrode dimensions	20 × 1.5 × 0.15 cm
Distance between electrodes	2 cm
Capacitance of capacitors	C = 36 μF
Effective inductance of discharge circuit	L = 300 cm
Half-period	1/2 T = 10.5 μsec
Voltage across capacitors	U – up to 4.5 kV
Current amplitude in first half-period	I – up to 40 ka
Pressure in tube	p = 0.1-20 μ Hg

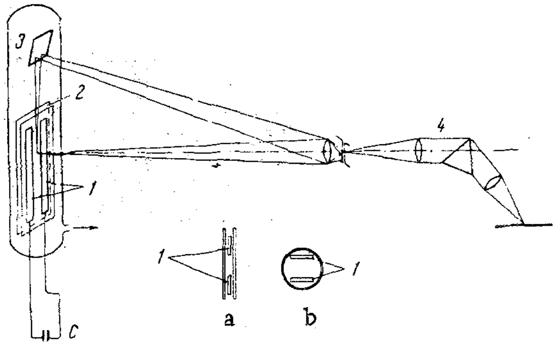

Fig. 1

Discharge was initiated at the beginning of the electrodes by a high-voltage pulse from an auxiliary device.

The time-resolved emission from the interelectrode gap was registered with the PR. The first PR-gram shows the entire discharge from the beginning to the end of the electrodes (Fig. 2a). The second PR-gram (Fig. 2b) shows the section of the discharge between the first and second marks to a larger scale. Distance between marks 5 cm; voltage across capacitors 4 kV. The slit of the PR was arranged parallel to the tube axis and cut out the emission from a narrow region between the electrodes (0.05-0.3 cm).

As is clear from Fig. 2b, the plasmoid corresponding to the first current half-period consists of narrow sheets moving at approximately the same velocity of $6 \cdot 10^6$ cm/sec. The distance between sheets at a voltage of 4 kV across the capacitors is 1.5-2 cm and their diameter, determined from the width of the bands in the PR-grams and their angle of inclination, is 0.15-0.2 cm. The first sheets are usually somewhat different from the rest with respect to both luminosity and velocity. Their diameter is of the order of 0.05 cm and their velocity is roughly 20% less than that of the other sheets. The velocity and diameter of the sheets are independent of the voltage across the capacitors (from 1.5 to 4.5 kV) and their number increases somewhat more rapidly than the voltage. The number of sheets may vary from discharge to discharge by 30%. In some cases their point of origin corresponds to a definite location on the electrodes (at this point a stationary discharge, from which the sheets separate, may be seen), while in others each successive sheet appears at a new point further advanced in the direction of motion behind the existing sheets.

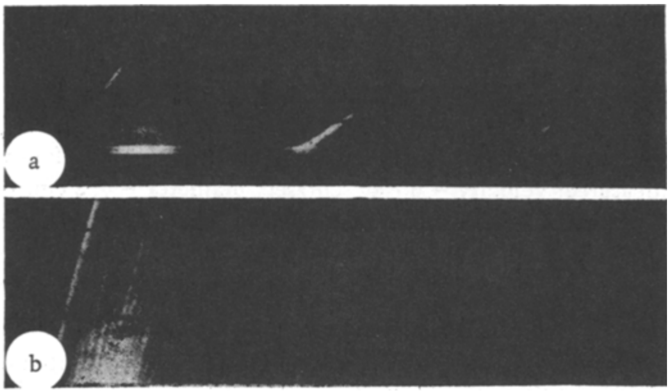

Fig. 2

Sometimes new sheets appear between existing ones. No accelerating process is observed, since the sheets already possess their limiting velocity when formed.

The velocity and diameter of the sheets does not vary within the pressure range 0.1-20 μ Hg and is independent of the type of gas filling the tube (air, neon, argon, krypton, or xenon).

To determine the velocity of the different ions making up the plasmoid, the Doppler shift of the corresponding spectral lines was measured. For this purpose both the direct emission and that reflected from a mirror (3, Fig. 1) located above the electrodes was focussed by a lens (f = 9 cm) on the slit of a ISP-51 spectrograph with a UF 84 camera (4, Fig. 1). The dispersion of the spectrograph in the investigated interval, 3900-4500 Å, varied between 6 and 12 Å/mm, while the resolving power in the 4000 Å region was 0.25 Å.

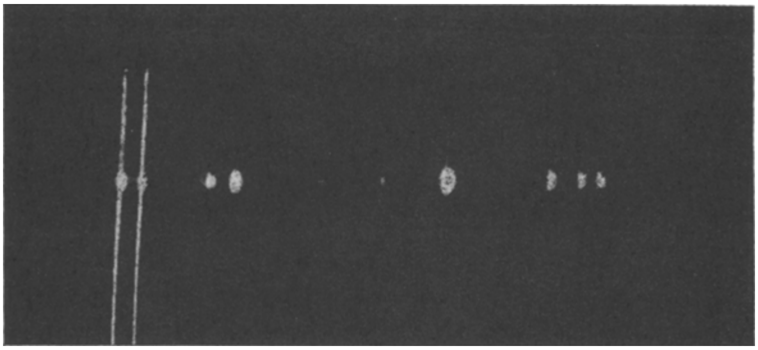

Fig. 3

Figure 3 shows part of the spectrum reflected from the mirror, in which bright shifted components are visible to the right of the unshifted narrow lines.

The brightest lines are, from left to right: SiII 4128 and 4131 Å, OII 4119 Å, SiIV 4116 and 4089 Å, OII 4076, 4072, and 4070 Å.

The discharge spectrum basically consists of the ionic lines of oxygen OII and OIII and silicon SiII, SiIII, and SiIV. With air ($p > 5\ \mu$ Hg) faint lines of the nitrogen ions NII and NIII apeared, and when the experimental tube was filled with inert gasses, the lines of univalent and divalent ions of the corresponding elements appeared.

Copper lines were sometimes present at the end of the electrodes. Nuclear lines were not observed.

The Doppler shift was studied for more than 40 lines of ionic oxygen. The shifted component of all the lines has a quite sharp intensity maximum corresponding to a velocity of $5 \cdot 10^6$ cm/sec, which coincides well with the sheet velocity determined with the PR. The velocities of O^{2+}, Si^{+} and Si^{3+} ions coincide, within the limits of error, with that of the O^{+} ions. The intensity of the shifted components of the SiIV lines is much greater and that of the SiII lines much less than the intensity of the unshifted components. The investigated lines for NII nitrogen, λ = 3919 and 3995 Å, have, in contrast to the oxygen lines, very faint shifted components, whose intensity falls smoothly without a maximum in the direction of smaller wavelengths. The maximum velocity for N^{+} ions coincides with the maximum velocity for oxygen ions. The lines of the inert gas ions do not generally have shifted components. This fact and the low intensity of the shifted nitrogen lines (although, as will be shown below, the temperature of the stationary plasma is less than the temperature in the sheets) indicate that the gas filling the tube is hardly trapped and entrained by the sheets at all.

The sheet plasma essentially consists of oxygen and silicon ions, i.e., the material of the glass walls. This follows from the fact that the line intensities of the oxygen and silicon ions do not depend upon the pressure and nature of the gas filling the tube and with air the intensity of the oxygen lines, whereas in a spark discharge channel the inverse relationship holds for the corresponding line intensities in air with charged particles at similar temperatures and concentrations.

The temperature of the sheet plasma was determined from the relative intensity of the shifted components of the lines for SiII $\lambda = 4128$ and 4131 Å and SiIV $\lambda = 4116$ and 4089 Å and the known electron density $T = 3.4 \cdot 10^{4}$°K. The low self-absorption of the corresponding lines was verified.

The presence of fixed components in the oxygen and silicon lines indicates that in the interelectrode space, in addition to moving plasma, there is an almost stationary component ($V < 1.5 \cdot 10^{6}$ cm/sec). From the ratio of the intensities of the fixed and shifted components of the oxygen and silicon lines one may conclude that the temperature of the "stationary" plasma is less than and the total mass greater than that of the moving plasma, i.e., for the sheets. The exposure times for the "stationary" and moving plasma are quite close.

The charged particle density was determined from the broadening of the ionic spectral lines of oxygen by the plasma microfields as a result of the quadratic Stark effect. At low pressures ($p < 2\,\mu$ Hg.) a considerable broadening of the lines of all the elements in the plasma was observed, particularly lines with high excitation potentials. The lines had a characteristic dispersion profile with broad wings. Assymmetrical broadening was observed in some cases.

	1		2		3	
	$\Delta\lambda$ (Å)	$N_e \cdot 10^{-17}$	$\Delta\lambda$ (Å)	$N_e \cdot 10^{-17}$	$\Delta\lambda$ (Å)	$N_e \cdot 10^{-17}$
Ar II 3928.62	0.32	2	0.60	4		
O II 3973.27			1.15			
O II 4069.90			2.2		0.65	1.4
O II 4075.87			1.6			
O II 4189.79			1.7			
Ar II 4266.5	0.35	2	0.85	4.9		
Ar II 4277.5	0.98	2	1.9	3.9		
Ar II 4282.9	0.33	2	1.05	6.4		
Ar II 4352.2	0.44	2	0.95	4.3		
O II 4414.89			1.8		0.7	1.85
O II 4416.98			2.0		0.7	1.66
			$N_e = 4.7 \cdot 10^{17}$ cm^{-3}		$N_e = 1.56 \cdot 10^{17}$ cm^{-3}	

According to theory (see, for example, [3]), for a quadratic Stark effect the line width is proportional to the charged particle density. Such quantities as the Stark effect constant, temperature, and the distance to the nearest perturbation terms are incorporated in the proportionality factor. The Stark effect constants for the ion lines are unknown; therefore, an additional study was made of the line broadening in a spark discharge in an air-argon mixture, which has been investigated for many lines by S. L. Mandel'shtam and M. A. Mazing [4]. The results of measuring the line width $\Delta\lambda$ (Å) and electron density N_e in three experiments are presented in the table: 1) spark in argon [4] ($U = 14$ kV, $C = 0.02\,\mu$F, $L = 10\,\mu$H); 2) spark in an air-argon mixture ($U = 3$ kV, $C = 0.25\,\mu$F, $L = 0.5\,\mu$H); 3) plasma accelerator.

Conversion is made much easier by the fact that the plasma temperature in the spark gap at atmospheric pressure is very similar to the plasma temperature in the sheets, while the charged particle densities are not very different. If it is assumed that in the sheet plasma, univalent oxygen ions and trivalent silicon ions predominate, then an electron density of $1.56 \cdot 10^{17}$ cm^{-3} corresponds to an over-all charged particle density of $2.5 \cdot 10^{17}$ cm^{-3}. The value obtained for the charged particle density is an average over several tens of discharges and all the sheets of each discharge. The same applies to the sheet plasma temperature. Toward the end of the electrodes, the mean charged particle density decreases.

Plasmoid structure for a different arrangement of the accelerator electrodes was also investigated (Fig. 1b). The same electrodes were turned to face each other. The diameter of the enclosing glass tube was 3.2 cm and the distance between electrodes was the same as before. With this electrode arrangement, the erosion of the glass walls and the quantity of gas liberated in one discharge were significantly reduced. The brightness corresponding to the first current half-period greatly decreased. At 4 kV, two or three blurred sheets are observed. Bright and narrow sheets occur as before during the second current half-period and sometimes at the end of the plasmoid of the first half-period. The velocity of the sheets did not change. The Doppler shift of the spectral lines also remained constant, but the intensity of the shifted components greatly decreased. At low pressures, a broadening of the spectral lines was observed as before.

Analysis of the Results

It follows from these experimental results that under our conditions the accelerated plasmoid separates into sheets which are compressed in a pinch.

The measured parameters of these sheets: mean charged particle density $N = 2.5 \cdot 10^{17}$ cm^{-3}, mean current in sheet $I = 4$ ka, obtained by dividing the maximum current of the first half-period by the maximum number of simultaneously existing sheets, sheet radius $r = 0.1$ cm, and mean temperature $T = 3.4 \cdot 10^{4}$°K are satisfactorily described by the formula relating the pinch parameters [5]

$$N = \frac{I^2}{2c^2\pi r^2 kT} = 6 \cdot 10^{17} \text{ cm}^{-3}.$$

The high plasma pressure in the sheets is natural, since the magnetic field of a current sheet with a radius much less than the electrode width must be much greater than the electrode field. Therefore such a current sheet must be compressed in a pinch. The reason why the mean charged particle density in the pinch is higher than the experimental value is that the plasma pressure is affected by the magnetic field of all of the preceding pinches. In the interval between pinches, there are no cathode spots on the electrodes and the luminescence of the plasma is very weak; therefore we may assume that the entire discharge current flows through the pinch.

The division of the plasmoid into a certain number of pinches of the same diameter becomes understandable, if one considers that the magnetic field is "frozen into" the plasma. The time required to displace a sheet of plasma through a distance equal to its radius $\tau_1 = r/V$ must be greater than the time required for the magnetic field to diffuse through the sheet [5],

$$\tau_2 = \frac{4\pi\sigma r^2}{c^2}.$$

Therefore the radius of a plasma sheet moving at velocity V may not be greater than

$$r_* = k\frac{c^2}{4\pi\sigma V}.$$

Here c is the speed of light, σ is the conductance, and k is a coefficient of the order of unity depending upon the geometry of the plasma sheet. At large pinch diameters, the interaction with different conductivity inhomogeneities, past which it moves, causes the current in the pinch to be redistributed. Substituting into the formula for r_* the values of the velocity and conductivity of the pinch plasma $\sigma = 1.5 \cdot 10^{14}$ CGSE units (conductivity of a completely ionized gas at $T = 3.4 \cdot 10^{4}$ °K), we obtain $r_* = 8 \cdot 10^{-2}$ cm.

As a result of the constraint on the pinch radius the strength of the electric field between the electrodes increases with increase in the current in the discharge circuit until breakdown occurs behind an existing pinch and a new one is formed.

In the second variant of the electrode arrangement, with sharply reduced erosion of the glass walls, the reduction in the charged particle density in the plasmoid leads to a reduction in plasma conductivity, since the plasma electrons become magnetized ($\omega\tau \gg 1$). Consequently, the limiting radius of the sheet and the current in it must increase:

$$I \sim \sigma r^2 \sim \sigma\left(\frac{1}{\sigma V}\right)^2 = \frac{1}{\sigma V^2}.$$

This explains the observed reduction in the brightness of the sheets corresponding to the first current half-period, together with the increase in diameter and decrease in number. At a sufficiently large radius, the sheets, generally speaking, should not contract into a pinch.

It follows from the spectroscopic data that the pinches composed of wall material (SiO_2) are preformed. They do not trap atoms of the stream of cold gas, but rather collapse. This follows from the low degree of entrainment of nitrogen and inert gas ions and the reduction in the brightness of the sheets and the charged particle density in them in the process of motion.

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