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Investigations of pulsed discharges show that the parameters of the plasma obtained by the implosion (pinching) of the current depend significantly on the initial stage of the formation of the plasma sheet, its structure and the dynamics of its motion.

Experimental investigations were carried out in a pinch chamber with metallic walls (shown in Fig.1) the operation of which has been described in detail in reference (1). A condenser bank (5) of capacitance 180 μF is charged up to 16-26 kV. The lid, side walls and the ring shaped base of the chamber (3) form the cathode, which is at zero potential. The high voltage, after breakdown of the ring shaped vacuum gap (4) is applied to the inner electrode (1). The diameter of the chamber is 70 cm, that of the inner electrode 48 cm, the height of the insulator (2) is 12 cm, and the distance from the lid to the surface of the inner electrode 8 cm. The voltage across the chamber is measured by an ohmic voltage divider (6) and the current by an integrating Rogovski coil.

The current reaches a maximum value of $\sim$ 1 MA in $\sim$ 3 μsec, rising initially at a rate of $(0.6-1.3) \times 10^{12}$ A/sec. The measurements were carried out at an initial deuterium pressure of 0.3-2 torr.

At the instant the high voltage is applied to the inner electrode, an electric field of 2-3 kV/cm fills the entire chamber volume and creates the initial conductivity of the gas. At this stage the discharge forms an ohmic load. Within 0.05-0.3 μsec (depending on the initial pressure) the ionization attains a level at which the ohmic resistance is very much smaller than the inductive impedance which causes a re-distribution of the voltage in the discharge circuit.

A qualitative theory of the ionization processes in fast pulsed discharges is developed in reference (2). By taking into account Coulomb collisions in determining the conductivity, a relationship is found between the thickness of the skin layer (the dimension of the current-carrying region) and time, its minimum value determined and the separation of the discharge from the insulator wall investigated. Calculations were carried out for a linear dependence of the current on time, assuming a uniform current distribution in the skin layer. The thickness of the skin layer then is

$$\delta = \delta_m \cdot \left[\left(\frac{t}{\tau} + \frac{\tau}{t} \right) \cdot \frac{1}{2} \right]^{1/4} \qquad \ldots (1)$$

where

$$\delta_m = 2.8 \times 10^5 \cdot \left(\frac{r_o}{\dot{I}_o} \right)^{1/2} \cdot p^{1/4} \qquad \ldots (2)$$

$$\tau = 1.8 \times 10^4 \left(\frac{r_o}{\dot{I}_o} \right) \cdot p^{1/2} \qquad \ldots (3)$$

is the instant in time when $\delta = \delta_m$.

In the above expressions r_o is the radius of the inner electrode in cm, $\dot{I}_o$ the initial current derivative (A/sec) and p the initial pressure in torr.

It follows from equation (1) that the current, initially distributed over the entire chamber volume, subsequently concentrates close to the insulator. Simultaneously a competing process takes place: under the influence of the self magnetic field, the current envelope as a whole moves away from the insulator. The displacement of the envelope,

$\Delta(t)$, starts directly the current is formed, and is expressed by

$$\Delta(t) = \Delta_m \cdot \frac{t}{\tau} \left[\frac{1}{2} \left(\frac{t}{\tau} + \frac{\tau}{t} \right) \right]^{-1/4} \qquad \dots (4)$$

where

$$\Delta_m = 2.6 \times 10^{-7} \left(\frac{r_o}{\dot{I}_o} \right)^{3/4} \cdot p^{-1/8} \qquad \dots (5)$$

is the displacement at $t = \tau$.

It can be shown that at this time the envelope becomes opaque to the neutral gas, and the "snowplough" mechanism begins to operate. For $t > \tau$ the expression for the displacement of the current envelope then takes the form

$$\Delta(t) = 34 \; \dot{I}_o \cdot t^2 \cdot r_o^{-1} \; p^{-1/2} \qquad \dots (6)$$

This law of motion is valid as long as the current can be considered a linear function of time, and $\Delta(t) \ll r_o$.

In discharges of this type the current envelope is cylindrical only over the section moving away from the insulator to the outer wall. As the distance between the envelope and the insulator increases, there is an increase in the components of the electrodynamic force near the edge of the inner electrode directed upward and toward the axis of the chamber, which leads to movement of the envelope in those directions.

Fig.2 shows streak photographs taken simultaneously through a radial slit in the lid of the chamber and vertically through a slit in the side wall. From the first, (b), the motion of the envelope in the radial direction can be studied (the upper part is moving away from the insulator toward the side wall, the lower part is moving away from the edge of the inner electrode toward the axis); from the second (c) the motion of the envelope away from the surface of the inner electrode toward the lid of the chamber can be examined. Because the optical axis of the photo-recording device is not parallel to the plane of the inner electrode, Fig.2c shows simultaneously the diametrically opposite boundaries of the envelope.

The positions of the current envelope, calculated from equations (4) and (6), at the corresponding instants in time, are plotted in Fig.2b. The calculations can also be verified from the voltage oscillogram. Equations (1), (4) and (6) yield information about the geometry of the current envelope in time and hence about its inductance. The value of the resistance of the envelope was determined from

$$R(o\mu) = 3 \times 10^{-3} \cdot \frac{h}{\delta_m \; r_o} \cdot \left[\frac{\tau}{t} \left(1 + \frac{\tau^2}{t^2} \right) \right]^{1/2} \qquad \dots (7a)$$

where h is the envelope height in cm. This dependence is only valid for $t \ll \tau$. For $t > \tau$ it can be assumed that

$$R(o\mu) = 5.2 \times 10^{-3} \frac{h}{\delta_m \; r_o} \quad . \qquad \dots (7b)$$

The voltage measured by the voltage divider is defined by

$$v = L \frac{dI}{dt} + I \frac{dL}{dt} + I \; R \; , \qquad \dots (8)$$

where I is the current recorded by the integrating coil.

The voltage values calculated from equation (8) are plotted as dots on the oscillogram (Fig.2a).

Satisfactory agreement is observed until the motion of the envelope upward and toward the chamber axis becomes significant.

One of the characteristic features of pulsed discharges is the azimuthal inhomogeneity of the current. However, the nature and moment of formation of the separate current fibres are still not sufficiently understood. The complex structure of the current was observed on photographs of a pinch[3] and confirmed by probe measurements[4]. In the present case the azimuthal inhomogeneity (fibrous structure) of the current envelope is distinctly visible, and can be studied in detail. As a result of numerous experiments it was established that the current fibres are distributed fairly regularly around the azimuth, and their period is not related to the arrangement of the electrical connections or to the design of the chamber but depends essentially on the initial pressure and voltage. Under similar initial conditions, the number (or pitch) of fibres in the discharge is practically constant. However, this picture is observed only for a positive polarity of the inner electrode. With the opposite polarity, there is no regular distribution of the fibres.

The breaking up of the current into separate fibres is energetically favourable. Any perturbations of the current density along the azimuth make it possible for the fibres to develop with time. However, when considering only the electrodynamic forces and assuming a fluctuational origin of the perturbations, it is difficult to account for the periodicity of the current structure and to relate it to the initial gas pressure. In an earlier paper by Klyarfeld et al[5], the qualitative assumption was made that the breaking up of the current into fibres is related to the existence of "anode spots". The distribution of the "anode spot" over the electrode surface is determined by the state of equilibrium between the Coulomb repulsion (an excess positive charge was found in the spot) and the electrodynamic attraction of the current fibres. If these assumptions are applicable to discharges of the type under investigation here, then the fibrous structure should originate from anode spots situated on a circle around the outer edge of the anode near which the current "skin" develops. Fig.3 is a streak photograph obtained through the slit IV. It shows, on a common bright background, several narrow, fairly regular current fibres (the instant of their formation is marked by an arrow) expanding with time. In this case the photo recording device is aimed exactly at the edge of the anode. Similar streak photographs, obtained when aiming at a point further away from the anode edge along the insulator (taken through the oblique slit IV′) show a rapid increase of the initial dimension of the fibre and a transition of the current into a continuous layer.

By developing the assumption put forward in reference (5) to include a relationship between the charge on the "spot" and its potential equal to the electron temperature (or the directed electron energy proportional to E/p), the dependence of the number of spots on the initial gas pressures p can be estimated.

It follows from these calculations that the total number of spots is proportional to $p^{2/3}$, which agrees with the experimental results.

The regular distribution of the fibres over the azimuth and the stability of their motion are sensitive to the surface condition of the anode edge. With an initial pressure of 1 torr, the discharge breaks up into fibres with a mean pitch of 1 cm. Since the later stages of the discharge depend significantly on the symmetry during the initial stage, it was decided to arrange the natural breaking-up of the current into an organised pattern with given pitch. For this purpose a "crown" was applied around the anode edge (7 on Fig.1) consisting of 154 small pieces of copper wire spaced at 1 cm pitch. Under these circumstances each current fibre is "attached" to a separate wire. Fig.4 is a streak photograph of the discharge, with the anode fitted with such a "crown", taken through slit I. A clearly defined azimuthal periodicity of the emitted light is observed, which is preserved as the envelope moves. It is interesting to note that the bright luminous strips observed in region (a) of Fig.4 do not coincide with the position of the current fibres but are located in between them. The explanation is that when a velocity of the order of the velocity of sound is reached, the current fibres set up diverging cylindrical shock waves with readily observable bright fronts (Fig.5). As the fronts of two adjacent shock waves merge, the intensity increases rapidly, which leads to the appearance of the bright strips on the streak photographs. It is quite probable that these bright strips were formerly taken to be the current fibres, whilst the actual fibres were in fact not observed because of their comparatively low intensity.

Fig.6 is a shadow photograph of a region of the current envelope, taken by the Schlieren technique with an exposure time of ~70 nsec, in the light of a ruby laser. The photograph gives a good illustration of the periodic structure of the envelope. The cylindrical shape of the divergent shock waves due to the current fibres, and the bands of increased density at the region of their merging, are clearly visible.

Should the periodicity imposed by the "crown" vary considerably from the natural periodicity of the fibres determined by the initial conditions, then the azimuthal periodicity during the motion of the envelope is upset.

Features of the development of the discharge related to the generation of shock waves can be studied in greater detail during a later stage when the current attains a value of ~1 MA. During this phase of the discharge the sideways and upward motion continues and a motion with large acceleration towards the axis of the chamber begins (compression stage).

If the velocity of the magnetic piston $u(t)$ varies with time according to the law

$$u(t) = a \cdot t^n \qquad \ldots (9)$$

where $n > 1$, we can use the solution of the problem of the development of shock waves, given in reference (6). The piston gives rise to a simple compression wave, propagating with the velocity of sound, C_0. The accelerated motion of the piston has the effect that at the time t_1, given by

$$t_1 = \left(\frac{2C_0}{a} \right)^{1/n} \cdot \frac{1}{\gamma + 1} \cdot \left[\frac{n+1}{n-1} \gamma + 1 \right]^{\frac{n-1}{n}} \qquad \ldots (10)$$

in the region bounded by the piston and the coordinate $C_0 t$, the compression wave 'breaks' and a shock wave develops. At this moment the velocity of the piston is greater than the velocity of sound in the unperturbed gas. The shock front propagates in the gas already heated by the sound wave and, at some instant in time, overtakes the front of the latter. The transition at the boundary between perturbed and unperturbed gas is accompanied by a decrease in the velocity of the shock wave and leads to an additional "reflection" of the compression wave in the direction away from the front toward the piston. In the region through which the shock wave passes, heating of the gas is intensified due to enhanced dissipative processes, and its conductivity increases.

For the operating conditions investigated here the coefficient in the expression for the velocity (equation (9)) is 2-3. The formation of the shock wave is shown on the voltage oscillogram (Fig.2a) by the development of a characteristic small peak, marked by an arrow. The voltage rise is related to the acceleration of the piston and the generation of the shock wave, the voltage drop to the retardation at the moment the shock front is being overtaken. At this moment streak photographs (Figs. 2b,c) show a bright flash caused by the increased temperature of the gas behind the shock front. The fluctuating character of the voltage, sometimes evident during the period immediately following the small peak, can be explained by successive reflections of an additional compression wave in the space between piston and shock front. The "freezing in" of the magnetic field, due to the heating and increased conductivity, increases the flexibility of the medium and thereby reduces the damping of the repeatedly reflected waves.

The voltage characteristic described above could be observed only when complete symmetry was achieved during the initial stage of the motion. Any azimuthal asymmetry obscures this effect. The instant of formation of the shock wave, calculated from equation (10), agrees well with the experimental observations. The measurements made in hydrogen showed that shock wave formation occurs later than in deuterium; this follows from equation (10).

Simultaneously with the formation of the shock wave the non-cylindrical structure of the pinch (curvature of envelope moving toward the chamber axis) becomes significant in the dynamics of the plasma envelope. The most extensive treatment of converging cylindrical waves in a plasma, including the structure of the wave front (i.e. taking into account the dissipative processes, the finite conductivity, etc.) has been published by Dyachenko and Imshennik[7].

For an effective comparison between the experimental results and theory it is convenient, with this type of pinch, to consider separately the motion of the cylindrical part of the current envelope away from the insulator toward the side wall, and the essentially non-cylindrical motion upward and toward the axis.

It was found that the motion of the cylindrical envelope is adequately described by the "snow-plough" model, and is in agreement with reference (7), whereas the behaviour of the non-cylindrical part does not fall within the framework of any theory. The measured velocity exceeds the calculated velocities (by a factor 2-2.5). According to one assumption, the compression is accompanied by the loss of a considerable proportion of matter (ejection of mass) attributable either to the fibrous structure during the early stages or, which is obviously the main reason, the curvature of the moving front. Since the curvature of the envelope is essentially a two-dimensional effect, it is unreasonable to expect agreement with the one dimensional calculations. From the appearance of an axial component of velocity in addition to the radial component one may assume that the ejection of mass will be proportional to the velocity of the shock wave front at a given instant in time. Such an assumption leads to a law of variation of the velocity which agrees well with the photographic results. It is then found that at the moment of implosion of the current over three quarters of the mass of gas initially present in the given cross-section, must have been ejected.

This type of motion is stabilized by the effect of the shock wave. Thus a small fraction of the mass of the plasma envelope may be accelerated to a velocity considerably greater than one would expect with purely cylindrical compression.

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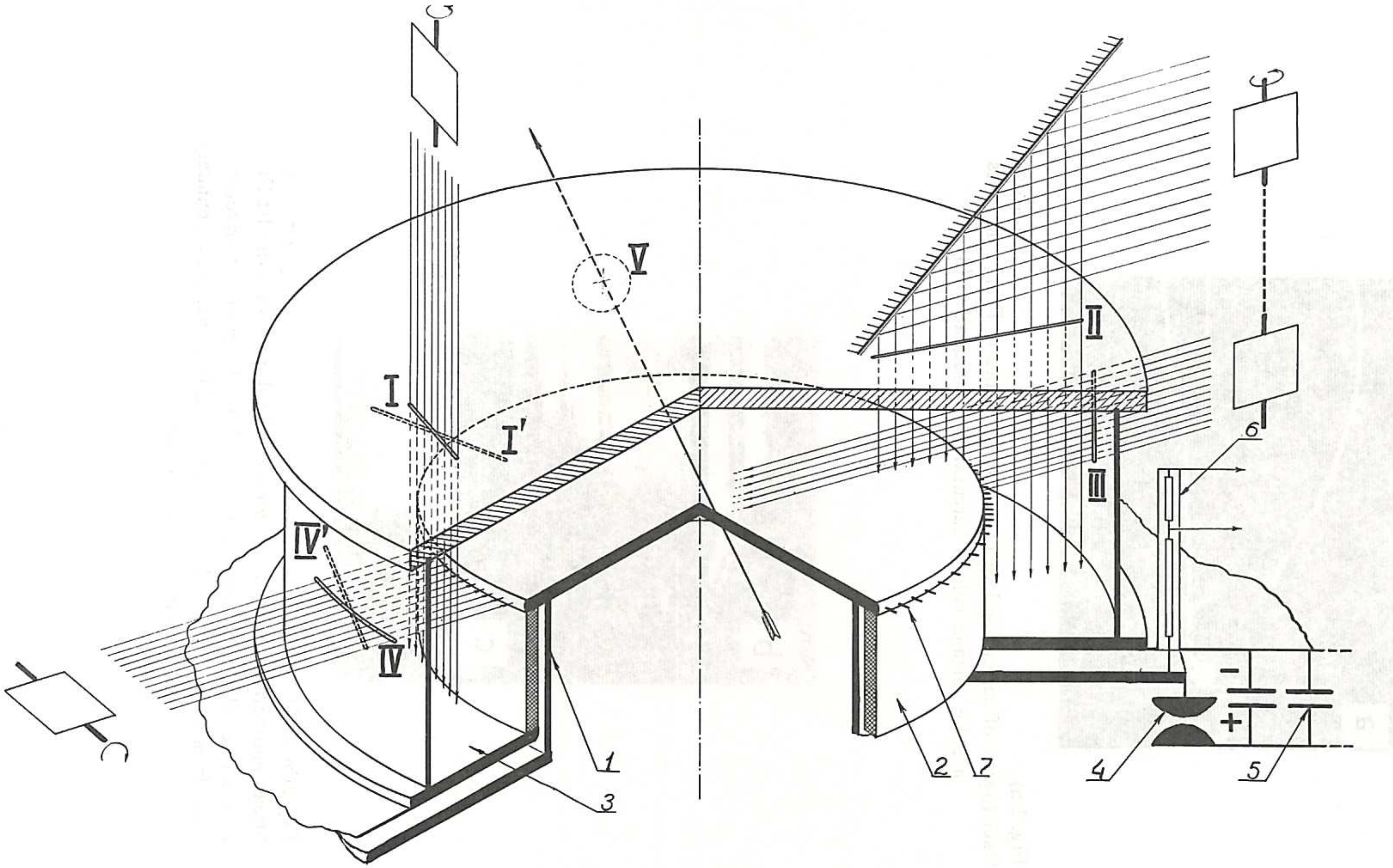

Fig. 1 Vessel and arrangement of photographic slits (CLM Trans 8)

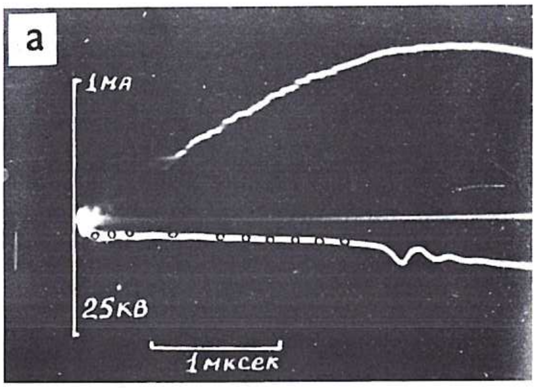

Fig. 2(a) (CLM Trans 8)
Oscillogram of current and voltage corresponding to Fig.2; the dots are the voltage values calculated from equation (8)

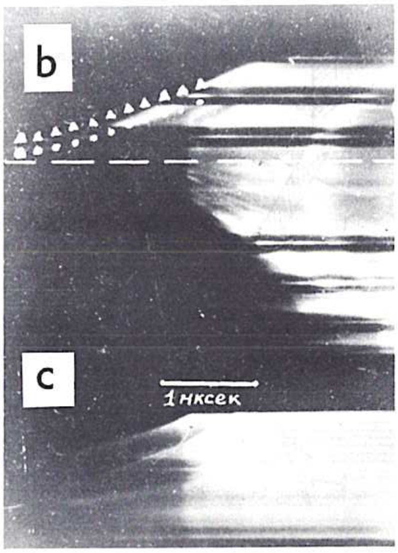

Fig. 2(b) & 2(c) (CLM Trans 8)
Streak photographs taken: b - through slit II ; c - through slit III; dotted line - electrode limit; dots - radial displacement of envelope away from insulator calculated from (4) and (6); triangles - boundary of the skin-layer, calculated from (1)

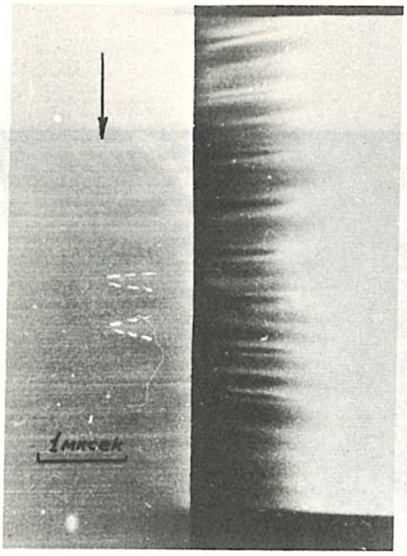

Fig. 3 (CLM Trans 8)
Streak photograph through slit IV; arrow - current fibres (low intensity); the L and the R half of the photograph printed with different exposures

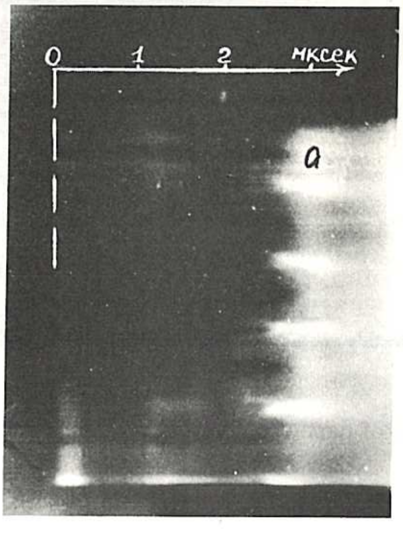

Fig. 4 (CLM Trans 8)
Streak photograph with 'crown' taken through slit I; a - regions of merging of cylindrical shock waves which are not the current fibres

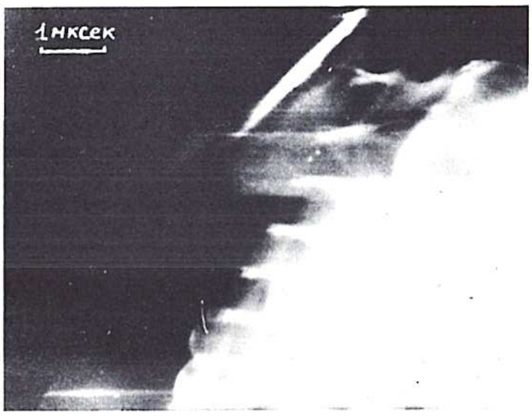

Fig. 5 Streak photographs through oblique slit I′ (CLM Trans 8)

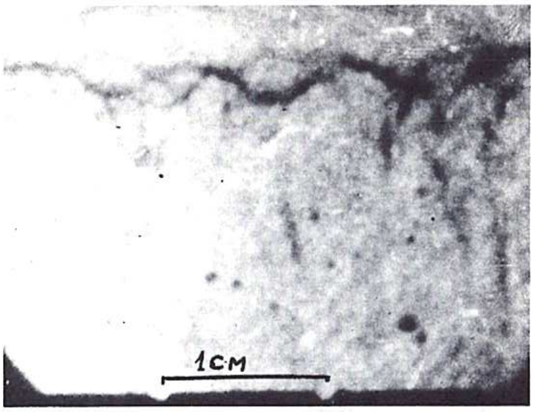

Fig. 6 (CLM Trans 8)
Shadow photograph of part of plasma envelope in ruby laser light

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