SELF-ORGANIZING CURRENT - PLASMA STRUCTURES AND THEIR EFFECT ON PLASMA DYNAMICS IN A PLASMA FOCUS

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1. Introduction

In recent studies of the plasmas more and more attention has been given to the study of one of the fundamental properties of plasmas - their ability for self-organisation, which is manifest, in particular, in the formation of various types of current-plasma structures. They exert a significant influence on the dynamics of the plasma leading to a number of positive and negative phenomena (in tokamaks, to disruptive instabilities and the ejection of plasma toward the walls; in plasma focus devices, to the division of the current envelope into a number of filaments, degrading the radiative characteristics but also resulting in very efficient acceleration). We have undertaken a series of studies concerning the experimental and theoretical investigation of current--plasma structures and their influence on the dynamics of a plasma focus (PF).

2. Experimental Installation

The experiments were conducted on two types of PF installations - Mather and Philippov - with energies from 30 to 1000 kJ [1]. The experiments included the use of high-speed laser techniques (shadow, Schlieren, and interferometric), X-ray pinhole methods, analyses of electrode surfaces by means of electron and optical microscopy, monitoring of soft and hard X-ray radiation, visible spectroscopy of the near-electrode plasma, and electrotechnical measurements.

3. Experimental Results

Our experiments indicated that a number of effects are observed at discharge currents exceeding 1 MA, including: azimuthal current--plasma structures (threads; see Fig. 1 [2,4,9]); layering of the near-anode cloud with a complex phase composition (Fig. 2) [1]; the "runaway" of the current envelope near the anode [1]; traces on the surfaces of the anode and isolator indicating the existence of regular periodic current structures near the anode (the contact zone) with sizes of the order of several microns [3] (Fig. 3).

4. Discussion

1. Azimuthal current-plasma structures (threads, filaments)

It seems to us that the formation of these filaments is connected with the creation at some time of conditions under which the magnetic pressure is appreciably higher ($m > 1$) than the gas-kinetic pressure. In this case, the formation of the filamentary structure of a plasma cord follows from the minimum energy principle. The magnetic field near the PF axis becomes multipolar, so that the generation of oppositely directed currents forming a quasi-equilibrium configuration with a filamentary structure is possible (Fig. 1). This disruption of the conditions for a Bennett equilibrium can form in a PF either as a result of a sudden lowering of the plasma temperature or during a sufficiently sharp growth of the discharge current in the stage preceeding the maximum compression.

Figure 1.

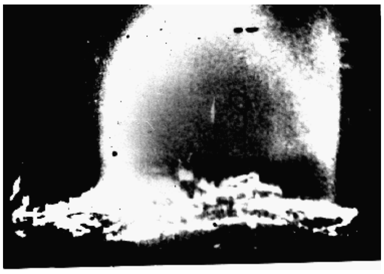

Figure 2.

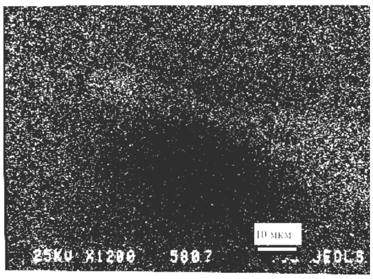

Figure 3.

We expect that such azimuthal structures should substantially alter the character of the discharge, and influence the final parameters of the plasma. There are weighty arguments suggesting that the "hot spots" observed at appreciable distances from the axis in radiative-compression experiments when strongly radiating impurities (Ar, Xe) are added to deuterium [5] could be the result of the evolution of such current--plasma filaments. Another effect that may be connected to the creation of filamentary structures is the growth of the minimum radius of the pinch (at the time of maximum compression) as the deposited energy is increased. Interpretation of this phenomenon in terms of shock--wave heating gives reasonable agreement with the experimental data. However, we note that this is not the only mechanism that can lead to a growth of the minimum pinch radius, which can, in particular, arise if the power of the plasma-focus installation is further increased. A mechanism associated with filament formation may be more important than shock-wave heating under certain conditions, in which case it will cease the compression of the pinch at an earlier stage.

The essence of this mechanism is the following. When the current already has a filamentary structure in the stage proceeding the initial compression, the magnetic field near the axis acquires a multipole character. In this case, oppositely directed current can be excited on the PF axis, which forms a current loop when it closes (as observed in the experiment of [6]). This leads to the deceleration of the plasma and to the formation of a quasiequilibrium "triax" configuration with a filamentary structure over some time (right up to the dissipation of this current). Let us consider the main characteristics of this equilibrium state. For an azimuthally inhomogeneous configuration, the average plasma temperature corresponds to the generalised Bennett condition: $\frac{I^2}{2c^2 N k_B T} = m$, where m is the number of filaments, I -the total current through the pinch, k_B- the Boltzmann constant, N - the linear plasma density, and T – the mean temperature.

Using the criteria established in [7-9] and experimentally observed values for T ≈ 100 eV, N ~ 5 x 10^{18} cm^{-3}, I_p = 1.5 MA, we can show that the filaments in Fig. 1 can, indeed, be elements of a tubular pinch structure (a Kvartshava structure) with the number of filament pinches $m = \frac{3.64 \cdot 10^{13} (1.5 \cdot 10^6)^2}{0.1 \cdot 10^3 \cdot 5 \cdot 10^{18} \cdot 1.1 \cdot 10^4} = 16$, which is close to the experimentally observed value. The magnitude of the current I_p is taken to be the fraction of the total current flowing through the pinch. Estimates of the other pinch-structure parameters (the scale of the structure, local pinching time, etc. [7-8]) are consistent with the proposed model. The results of [6], which was specially devoted to the dynamics of filament merging, indicates that a stabilising vortex current should appear between merging filaments.

Generation of a near-axial current may be accompanied by microbursts of hard X-ray radiation due to the appearance of beams of accelerated electrons at the points where counterflowing magnetic fields cross (nanosecond variations in the curve [2] representing the temporal behaviour of the hard X-ray radiation). The process of separation into threads may begin not long before the time of maximum compression not only due to the rapid growth in the current, but also during the disruption of a number of conditions necessary for the current flow. One of these conditions is the requirement that the ion component of the current be supported in accordance with the relation $J_i \approx J_e \sqrt{M_z / m_e}$ (M_z is the mass of the ions carrying current and J_e is the current through the plasma). During the increase in the current density, the normal regime for the flow of the ion current may be disrupted due to an insufficient supply of ions into the plasma-anode contact region. As a consequence, the erosion of the anode is sharply increased, leading to filamentary formations (micropinches) that flow in the same way as in the stage of maximum compression described above. This process could cause the plasma focus to make a transition to a regime with a breakdown of the current envelope (an X-ray regime). As a result, the magnetic field moves toward the axis, where a high-density (> 10^{19} cm^{-3}) micropinch with characteristic diameter 1-2 mm and height no more than 5-10 mm forms. (In contrast, the characteristic density in a pinch regime is an order of magnitude lower, and the dimensions an order of magnitude larger.) The formation and decay of this micropinch is accompanied by especially efficient generation of powerful electron and ion currents.

2. Layered structure

Layered transverse plasma structures near the anode (Fig. 3) can probably also be explained by the cessation of the current due to an insufficient supply of ions from the anode. This process results in a sharp decrease in the conductivity of the plasma in the plasma-anode contact region, increasing the energy deposition in this region, which, in turn, leads to a "burst" at the anode surface. The current layer that arises in this case can clearly be seen in shadowgrams (Fig. 3). One consequence of this "burst" is an increase in the emission of ions, and the conductivity of the plasma is re-established, with a subsequent decrease in the energy deposition. This process can repeat several times during the course of a single discharge, leading to the formation of a multi-layered plasma structure.

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