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Self-Organization Phenomena in Dense Plasma Focus Experiments

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Abstract. *Experimental results are presented for the formation of complicated 3D structures, both disordered and ordered ones, in plasma focus gaseous discharges. This includes (i) self-formation and self-compression of a closed, spheromak-like magnetic configuration, (ii) intense short-scale mixing of the plasma and magnetic field, and (iii) cell-like structures built of plasma filaments and magnetic flux ropes, in particular, a heterogeneous magnetic flux rope.*

1. INTRODUCTION

The formation of a linear dense Z-pinch as an essentially axis-symmetric 2D structure was the major goal of experimental research programs on Dense Z-Pinches, both in cylindrical geometry and non-cylindrical one, like e.g. plasma foci. Here, all the deviations from axial symmetry were considered as a serious threat to concentrating the energy. However, a lot of data is accumulated that exhibit importance of the essentially 3D behavior of the plasma and magnetic field in the case of successful enough driving the load in high-current discharges. In particular, formation of a closed, spheromak-like magnetic configuration, of several cm size, in Filippov-type plasma focus gaseous discharges takes place thanks to (i) strong filamentation of helical electric currents and (ii) enhanced propagation rate of magnetic field (and current sheath) along the anode, due to Hall effect in plasmas (see [1]). So, the question does exist: to what extent does the 3-D 2-fluid MHD govern the high-current discharges?

Here, we present a number of experimental results which have been accumulated in earlier studies carried out at the Filippov-type plasma focus facility [2]. Such a presentation is focused at illustrating the coexistence and interaction of complicated structures, both disordered and ordered ones, of various space scale, in plasma focus gaseous discharges at conditions typical for the high current discharges.

2. SELF-FORMATION AND SELF-COMPRESSION OF A CLOSED, SPHEROMAK-LIKE MAGNETIC CONFIGURATION

The model [3] and the analysis of experimental results obtained from earlier experiments in various high-current gaseous discharges has allowed the identification of the following characteristics of the spheromak-like magnetic configuration (SLMC) formation [1]: (1) The self-consistent generation of a poloidal magnetic field (the dynamo effect), solely by the internal dynamics of the magnetic field in the discharge. (2) Strong filamentation of electric currents, which occurs both in the inner region of the SLMC (i.e. in the combined Z-ϑ-pinch) and in its periphery. (3) SLMC formation is stimulated by the enhanced propagation rate of the magnetic field along the anode, due to the Hall effect in plasmas. (4) A magnetic field reconnection process leading to the formation of the SLMC as a closed configuration, appears to occur before the current sheath converges on the axis. (5) In its final stage, the SLMC takes the form of a squeezed spheromak configuration, confined and driven by the pressure of the residual magnetic field of the plasma focus discharge. (6) Large space scale (vs. “hot spot”) determined by the geometry (and capacitance) of the facility. (7) The power density in the combined Z-ϑ-pinch at the major axis exceeds the peak power density of a force-free fluxconserver-confined spheromak by several orders of magnitude. (8) The SLMC exhibits a cyclical, evolutionary tendency to form, be compressed and eventually repelled away from the anode, and reform repeatedly. (9) Self-organization of the discharge plasma (non-monotonic dependence of input vs. output parameters; "quantization" of the discharge energy).

A great deal of experimental data obtained in earlier neon gas studies carried out at the Filippov-type plasma focus facility [2] supports the SLMC model [3]. Some of the results presented here and in [1] have not been previously published, as they were not fully understood before. Significantly, the identification of the SLMC formation appears to be available essentially from *combining* the results of the following diagnostics with different (and complementary to each other) spatial and spectroscopic scales: namely, (i) motion picture of the evolution of SLMC formation, taken with the help of a ruby-laser-based interferometer operating in the Bates regime (0.01-J laser pulse energy; 2-ns duration) [1]; (ii) visible light photographs taken with the help of an electronic optical converter which is synchronized with the current to an accuracy of <50 ns [1]; (iii) time-integrated SXR spectra from a pinhole camera.

The results are presented for the following discharge conditions: mushroom-shaped anode (11-cm diam.) inside a coaxial metallic chamber 80-cm long and 30-cm high, which acts as the cathode; capacitance, 180 μF; initial inductance, 55 nG; initial voltage, 16 kV; discharge energy, 20 kJ; maximum current, 530 kA; neon gas pressure, 3 Torr. Time zero (t=0) corresponds to the major peak of the time derivative of the current.

3. SHORT-SCALE MIXING OF THE PLASMA AND MAGNETIC FIELD

The Hall effect in plasmas [4], which is caused by the frozenness of the magnetic field into electron plasma and by the resulting transfer of magnetic field with electric current velocity, manifests itself in the enhanced rate, as compared with ordinary diffusion, of magnetic field propagation in plasmas in the case of electric current moving along the gradient of plasma density. The major physical mechanism is the "scattering" of magnetic field, which is transferred by the electric current, at positive gradient of electron density. Such a phenomenon is identified in full in the case of steep electron density gradients at plasma-conductor boundaries. For instance, the current sheath slipping along the anode at initial stage of the discharge in plasma focus facility [2] has been reproduced in the 2-D 2-fluid numerical modelling [5] with allowing for the Hall term (see also the database presented in [1]). Contrary to ideal MHD instabilities, this mechanism gives regular, highly reproducible dynamics that agrees quite well with numerous experimental data. Similar phenomena may take place in plasma interior as well. Here, the enhanced propagation rate leads to penetrating the domain of the lower plasma density and subsequent superseding the plasma by the magnetic field. Such a mechanism leads to a stochastic short-scale (as compared with space scales of the current sheath) mixing of the plasma and magnetic field, being thus an alternate for the snow plough regime of current sheath formation and driving.

The pictures shown in Fig.1 (t= -90 ns) and Fig.2 (t= +174 ns), for deuterium gaseous discharge of initial pressure 163 Torr, are the shadowgrams taken with the help of a ruby laser (0.01-J laser pulse energy; 15-ns duration; pulse direction perpendicular to the system axis). The anode is at the bottom of the diagnostic window (4 cm diam.), the plasma focus major axis coincides with the vertical axis of the window.

A great deal of experimental database exhibit cell-like structure of the plasma. Such a phenomenon may be interpreted as the formation of a thin volumetric (three-dimensional) net-like structure of the magnetic field penetrating the plasma. The local values of magnetic field inside this net may substantially exceed its values averaged over several cells, up to the order of magnitude. Therefore this mechanism of plasma-magnetic field interaction doesn't need

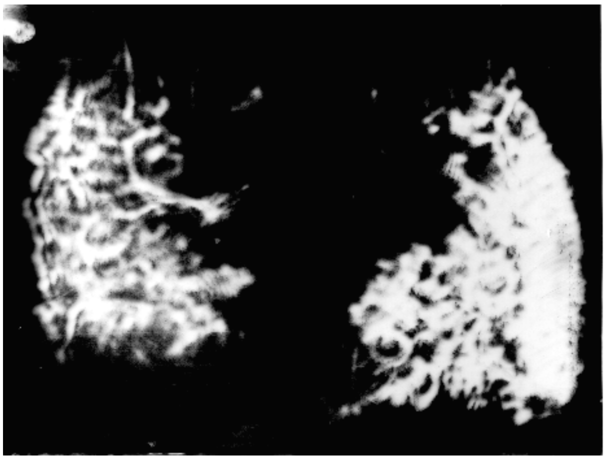

Figure 1

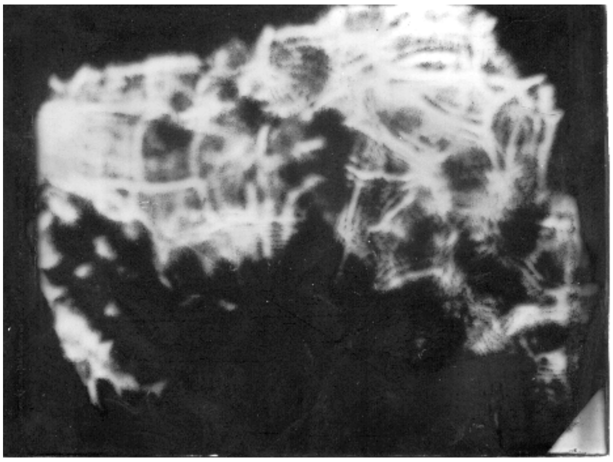

Figure 2

large spatially averaged values of the parameter $\omega_e \tau_{ei}$, thus suggesting that the criterion for the onset of the 2-fluid effects may be strongly dependent on the local values of density fluctuation level of the appropriate space scale. Such a 2-fluid instability being developed in a certain small volume, can propagate in space and interact with conventional ideal-MHD instabilities, e.g via triggering the current sheath breakthrough by the Rayleigh-Taylor instability.

4. FILAMENTS AND MAGNETIC FLUX ROPES

The complexity of short-scale structure of the magnetic field penetrating the plasma, leads to existence of a rich background for short-scale self-organization processes. This results in forming the strongly inhomogeneous plasma structures, with the filaments of electric current and the magnetic flux tubes (magnetic flux ropes, according to the space plasma language, see e.g. [6]) being the building blocks of these structures. The filaments are characterised by the enhanced plasma density, due to pinching effect, whereas magnetic flux ropes exhibit substantially lower plasma density, with force free-like configuration of magnetic field. It is combination of these two substructures, under condition of appreciable helicity, that supports long-range, essentially three-dimensional correlations of electric currents and magnetic field.

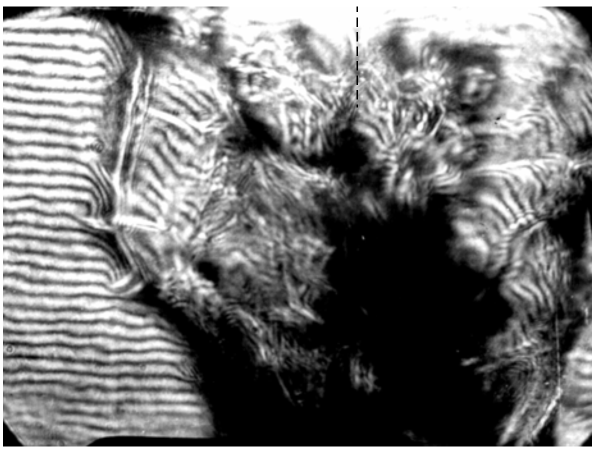

Figure 3.

The filamentation of electric current is well known to characterize plasma behavior at initial stage of gaseous discharges. Being driven by the inflated magnetic field toward system's axis, the filaments may form a quasi-uniform current sheath of a cylindrical/linear Z-pinch. However, this may not be the case when filamented structures form essentially 3D plasma structure as it happens, in particular, in a certain type of plasma focus discharge resulted in the formation of a closed, spheromak-like magnetic configuration of several cm size [1]. Here, filamentation of electric currents is needed for the production of the poloidal magnetic field and the respective 3D large-scale ordering of both the plasma incorporated in a closed configuration and the plasma carrying the current of external circuit. Figure 3 (interferogram, Bates scheme, ruby laser, 2ns pulse duration) shows fine structure of the filamented inner, closed magnetic configuration and the current sheath formed by the residual magnetic field (D_2, 6 Torr, 24 kV, -150 ns; system's axis is indicated,- space scale the same as in Figs.1,2). The interferogram of Fig. 4 (negative; 20 ns; discharge type similar to that of Fig.3) illustrates the braidedness of the twisted filaments.

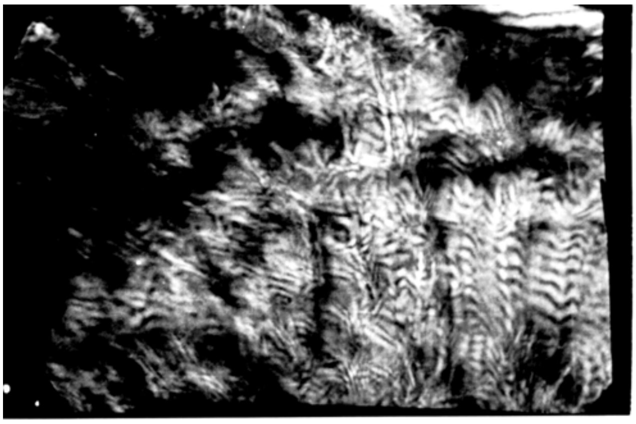

Figure 4

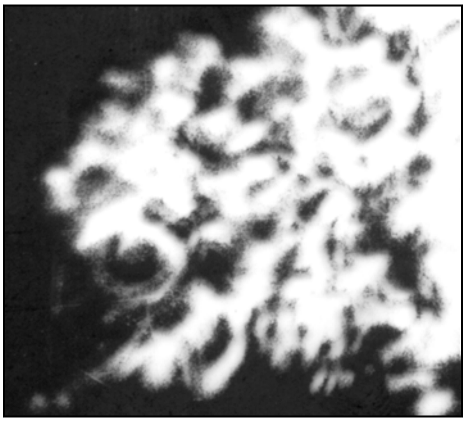

Figure 5

Interaction of filaments and magnetic field lines, via twisting, winding and interweaving, leads to formation of the heterogeneous force free-like magnetic configurations. Such a structure may form a heterogeneous magnetic flux rope. Separate section of the (teared to pieces) rope forms a stick-like, heterogeneous plasma formation embedded into a closed, spheromak-like magnetic configuration. Typical formation of this type is shown in Fig. 9 (see left upper part of the Figure) which is extracted from the right lower part of Fig. 5.

CONCLUSIONS

Experimental results presented illustrate complexity of plasma and magnetic field behavior in high-current discharges. It follows that the 2-fluid effects (the Hall effect in plasmas) may produce more intense (short-scale) mixing of the plasma and magnetic field, as compared with that predicted by the ideal MHD. This, in turn, leads to formation of essentially 3D structures of space scale of the above mixing. Interaction of these processes with electric current filamentation leads to long-range 3D correlations and strong local self-organization. The latter results in formation of closed, strongly inhomogeneous magnetic configurations of various space scale, up to several cm size formations reported in [1].

The results suggest the necessity to allow for the effects of the 3-D 2-fluid MHD in numerical modelling of plasma radiation sources.

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