Self-organization of high current-carrying plasmas: dynamics of forming toroidal plasmoids in plasma columns and tubes

Abstract In the report the dynamics of the Toroidal Plasmoids formation in a Cavity of the Neck (TPCN) of plasma columns and tubes is described. The study was carried out within the MHD (magnetohydrodynamics) frames and by using the particles method. It was shown that in the fast forming neck of plasma pinch, some observed orthogonal to the current structures could be H-filaments (at the equilibrium state they are $\theta$-pinches). These filaments are supported due to the interaction of the induced (secondary) current with magnetic field of the Z-pinch.

Key words plasma dynamics • plasma focus • plasma structures • self-organization • Z-pinch • $\theta$-pinch

Introduction

As it follows from experimental investigations of plasma focus (PF), the axial-periodical structures in the pinch are formed in a few operating regimes of PF devices (Fig. 1) [1, 4–6]. However, until now, there was no unambiguous explanation of such structures. On the other hand, in the $\theta$-pinch experiments of I.F. Kvartskhava [9], the structures called H-filaments were observed. Such filaments were shown to be self-organizing plasma creations extended along the external magnetic field and distributed periodically in azimuth. Finally, in the experiment done by E.Yu. Khautiev [2], the plasmoid of the toroidal type was created in the cylindrical square section chamber stringed on the central current (Fig. 2).

The question arises: do all the above-discussed phenomena have a similar physical nature? As shown in [2, 3], the cited above structures in the fast pinching plasma may be TPCN.

The topological model of TPCN is presented in this work; more detail is given to the dynamics of its formation, as well as the influence of the relative density of near wall plasma on the structure of the necking cavity.

Model of Toroidal Plasmoids in the Cavity of the Neck (TPCN)

We suggest the following model of the TPCN (Fig. 3), where the cavity forming in the neck of plasma column is a toroidal quasi-closed volume of coronal plasma and where the fast increase of the electric field vortex takes place. We assume that the values of $E_r$ and $E_z$ components of this electric field should be about several hundreds volts.
In case of occurrence of these two conditions, this fast changing electric field can induce the toroidal magnetic field $B_{\phi}$. The creation formed in such a way is the same as $\Theta$-pinch and has all its properties. In particular, it can consist of local H-filaments [9]. The collisions of such filaments could cause the formation of the plasma streams (Fig. 3b) ejected from their contact area (eruption instability [8]). In case of the much softer interaction of filaments, one can expect the turbulent mixtures of plasma.

We could expect TPCN generation in any plasma column with corrugated boundary or with $\Omega$-like current configuration. In this case the reconnection of the narrow “stem” of the neck can lead to the separation of the vortex of induced electrical field and to the creation of H-filament in the discharge space [11].

Is it possible to induce the necessary field in an experiment? As a comparison, we will calculate its value by using this formula $\partial \Phi / \partial t = E_z = E/L$, using parameters of the model experiment in Fig. 2. Naturally, we should use the average value for the decreasing magnetic field $H = (8+1.3)/2 = 4.7$ Tl. Then, the magnetic field flux $\Phi = H S = 4.7$ Tl$ \times 5 \times 10^{-3}$ m$^2$ $= 2.4 \times 10^{-2}$ Tl m$^2$. EDF, E, along the contour $L = 30$ cm will be equal to $E = 2.3 \times 10^{-2}$ Tl m$^2$/4$ \times 10^{-6}$, $c = 6 \times 10^3$ V.

Accordingly, the electric field strength is $E_z = E/L = 6 \times 10^3$ V/30 cm $= 2 \times 10^2$ B cm$^{-1}$. This value of field strength provides the gas break-down in the chamber wall presence and the transformation of created plasma in toroidal plasmoid.

**Dynamics of the forming of TPCN**

We do not have an experimental proof of the TPCN occurrence; therefore, the dynamics of the forming of TPCN structures is studied in this work by two methods – the MHD approximation and the method of particles. The detailed description of programmes and areas of application is contained in works [10, 11], thus not discussed here.

**MHD approximation**

Fig. 4 presents the results of the numerical calculation of the plasma discharge dynamics done for the configuration and characteristic values of the experiment conducted in [2] (also see Fig. 2). Fig. 5 presents the calculation results of plasma dynamics in a cavity. They show that the structure of the cavity depends on the ratio of densities in corona and in...
pinch and could have the necessary quasi-closed Ω-like form under the small ratios of the above-mentioned values. The calculations show also the influence of TPCN on the redistribution of current between the core and the peripheral part of plasma column or tube. Such redistribution of the current can play an important role in plasma focus and liner discharges.

Discussions

The presented results show the following: the experimentally observed current-plasma structures, forming at the
necks of fast pinching plasma columns and tubes, can be a
toroidal plasmoid or else – complex H-filaments (in the
quasi-state case they are local θ-pinches – quasi-equilib-
rium). Because at some period of time the plasmoid can be
in the quasi-equilibrium state, and if TPCN has a small
radius, \( k_H^{-1} \), significantly smaller than its large radius, \( R \), so,
the radial distribution of physical parameters in the cavity
can be calculated by the use of formulae of the accuracy
analytical solution received in [7]:

\[
(1) \quad p(r) = p_0 (1 + \gamma)^2 \frac{\exp \left( k_H^2 r^2 \right)}{[1 + \gamma \exp k_H^2 r^2]^2},
\]

\[
(2) \quad B(r) = 2\pi (1 + \gamma) c^{-1} \frac{1 - \gamma \exp k_H^2 r^2}{1 + \gamma \exp k_H^2 r^2} - H^* =
4\pi c^{-1} \frac{1 + \gamma}{1 + \gamma \exp k_H^2 r^2} + H_a = B_a (r) + H_a,
\]

where:

\[
\gamma = \frac{8\pi B^2 (0)}{B_a^2 (0)} = \frac{8\pi \Sigma n_i m_i v_r^2}{(4\pi c^2)^2};
\]

\[
k_H^2 = (1 + \gamma) \lambda^2 = \frac{B_a^2 (0) + 8\pi \Sigma n_i m_i v_r^2}{8\Sigma N_i m_i v_r^2} = \frac{(1 + \gamma) (4\pi c^2)}{8\Sigma N_i m_i v_r^2}.
\]

Field \( H^* \) can be calculated by using this formula:

\[
(3) \quad H^* = -H_a - \frac{1 + \gamma}{2} B_a (0), \quad B_a (0) = 4\pi I/c.
\]

Here: \( B_a (r) \) is the own magnetic field of plasma cavity; \( H_a \)
is the external magnetic field (field of the neck); \( H^* = m_i c e^{-1} \omega_0 \) is the strength of magnetic field (parallel to neck
field), forming due to the rotation of the plasma compo-
nents as one with constant frequency \( \omega_0 \) (at the small radius
\( r \) in the plane of the cavity); \( I = (2\pi)^3 \Sigma e \omega_0 N_i \) is the
azimuthal current per length of plasma toroid (along the
side of the neck magnetic field); and \( N_i \) is the corre-
sponding line particle density of i-sort; the rest parameters are
commonly accepted parameters.

The dynamics and characteristics of such filaments depend
on the plasma parameters such as the ratio densities in plas-
ma corona and in pinch, current and others. Therefore, the
smaller the ratio of densities, the larger is the size volume
of the cavity, and its form approaches \( \Omega \)-like structure.

The study of plasma structures may give the possibility to
develop a method based on the topological properties of
the high current discharges. The subsequent development
of this method can lead to creation of methods of control-
ling plasma parameters. The comparative analysis and cal-
culations done in this work by the different methods
demonstrates that the ability of high current-carrying plas-
mas to form the structures like TPCN is independent of the
used approximation and could be a common property for
both laboratory and galaxy plasmas.

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