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

Vladimir M. Fadeev,
Edil'girej Yu. Khautiev,
Victor V. Vikhrev,
Valerij Ya. Nikulin,
Vladimir P. Tarakanov

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 θ-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 • θ-pinch

V. M. Fadeev
NPP VNII Electro-Mechanics,
101000, P.B. 496, Moscow, Russia

E. Yu. Khautiev, V. V. Vikhrev
Institute of Nuclear Fusion of RNC "Kurchatov Institute",
Kurchatov sq. 1, Moscow, Russia

V. Ya. Nikulin✉
P.N. Lebedev Physical Institute,
117924, Leninsky pr. 53, Moscow, Russia,
Tel. +7095/ 1326931, Fax: +7095/ 1357995,
e-mail: vnik@sci.lebedev.ru

V. P. Tarakanov
Institute of High Temperatures,
127412, Izhorskaya 13/19, Moscow, Russia

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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 θ-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.

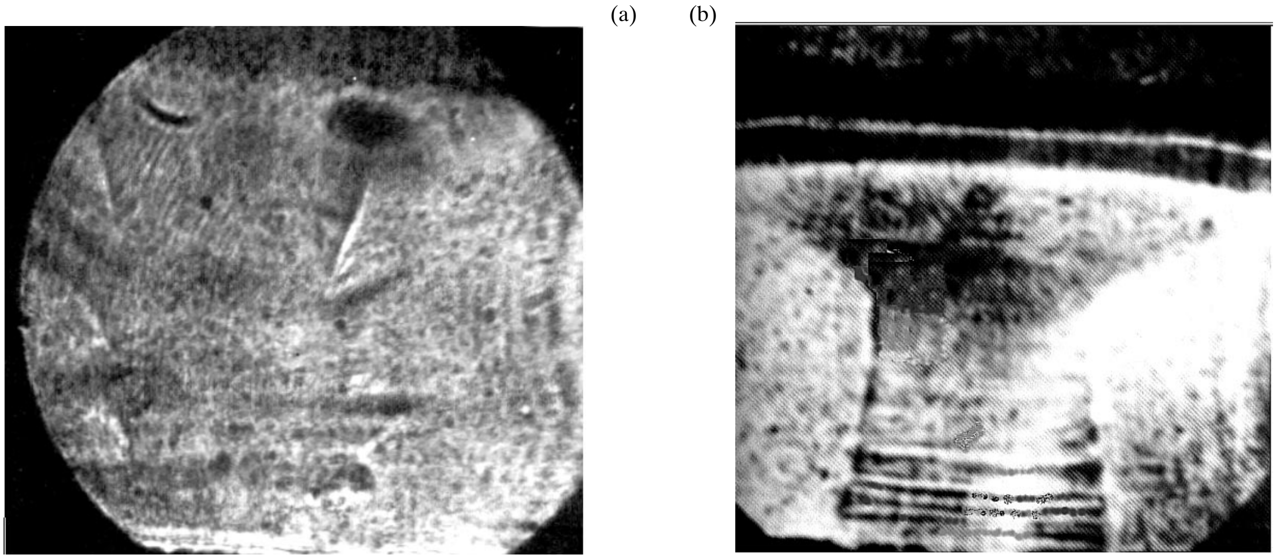

Fig. 1. The current plasma structures in PF for different conditions. (a – thick CPS for p = 1 Torr; b – narrow CPS, p = 3 Torr).

In case of occurrence of these two conditions, this fast changing electric field can induce the toroidal magnetic field B_φ. The creation formed in such a way is the same as θ-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 Ω-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 $\overline{H} = (8+1.3)/2 = 4.7$ Tl. Then, the magnetic field flux $\Phi = \overline{H}\,S = 4.7\ [\mathrm{Tl}]\times 5\times10^{-3}\ [\mathrm{m}^2] = 2.4\times10^{-2}$ Tl m^2. EDF, E, along the contour L = 30 cm will be equal to $\varepsilon = 2.3\times10^{-2}$ Tl m$^2/4\times10^{-6}$, c = 6×10^3 V. Accordingly, the electric field strength is $E_z = \varepsilon/L = 6\times10^3$ V/30 cm = 2×10^2 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. In PF-discharges, much greater fields often occur, therefore, only the second question is left – the possibility of occurrence of the quasi-closed cross section of the Ω-like cavity.

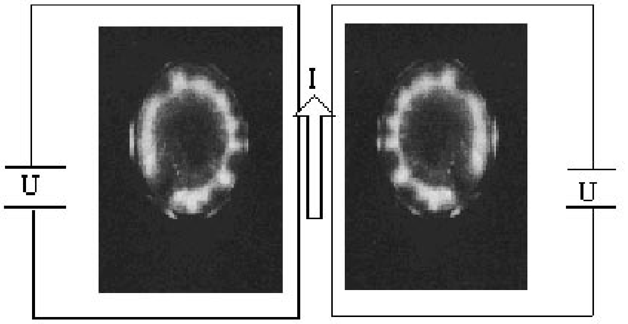

Fig. 2. Scheme of the model experiment. Parameters of the experiment (p = 0.01–0.1 Torr, U = 30 keV, I = 424 kA, B = 13.3–80 kGs, T = 16 μs; diameter of the chamber D = 12 cm, diameter of the electrode d = 1.4 cm, length of the chamber l = 10 cm).

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

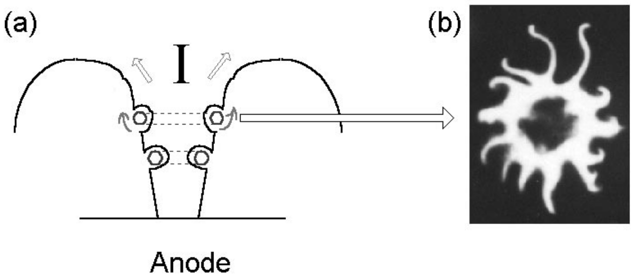

Fig. 3. (a) The model of the TPCN in Z-pinch. (b) The plasma streams from TPCN.

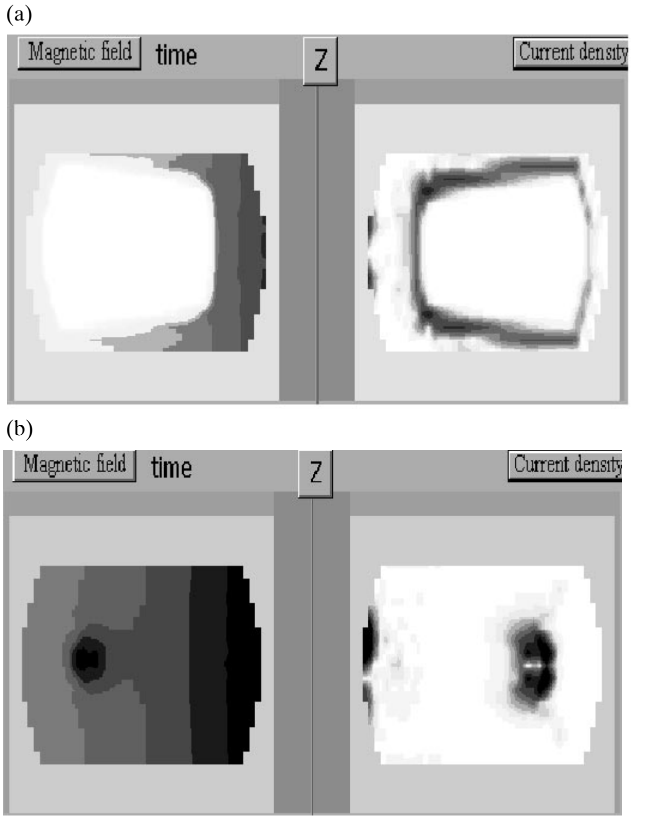

Fig. 4. The successive stage of the discharge of the model experiment (Fig. 2): (a) – for the beginning of the compression (t = 888 ns, I = 145 kA); (b) – for the maximum of the compression (t = 2154 ns, I = 318 kA).

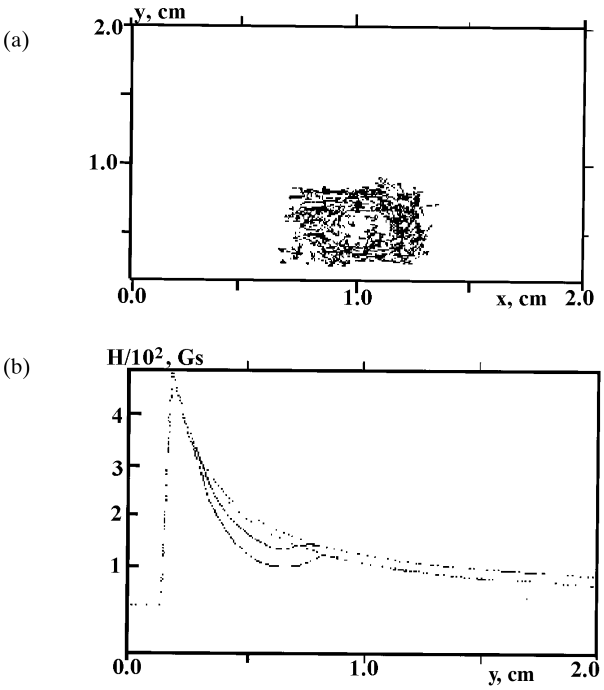

Fig. 6. The velocity field in the plasmoid – (a), and the radial distribution of magnetic field – (b).

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.

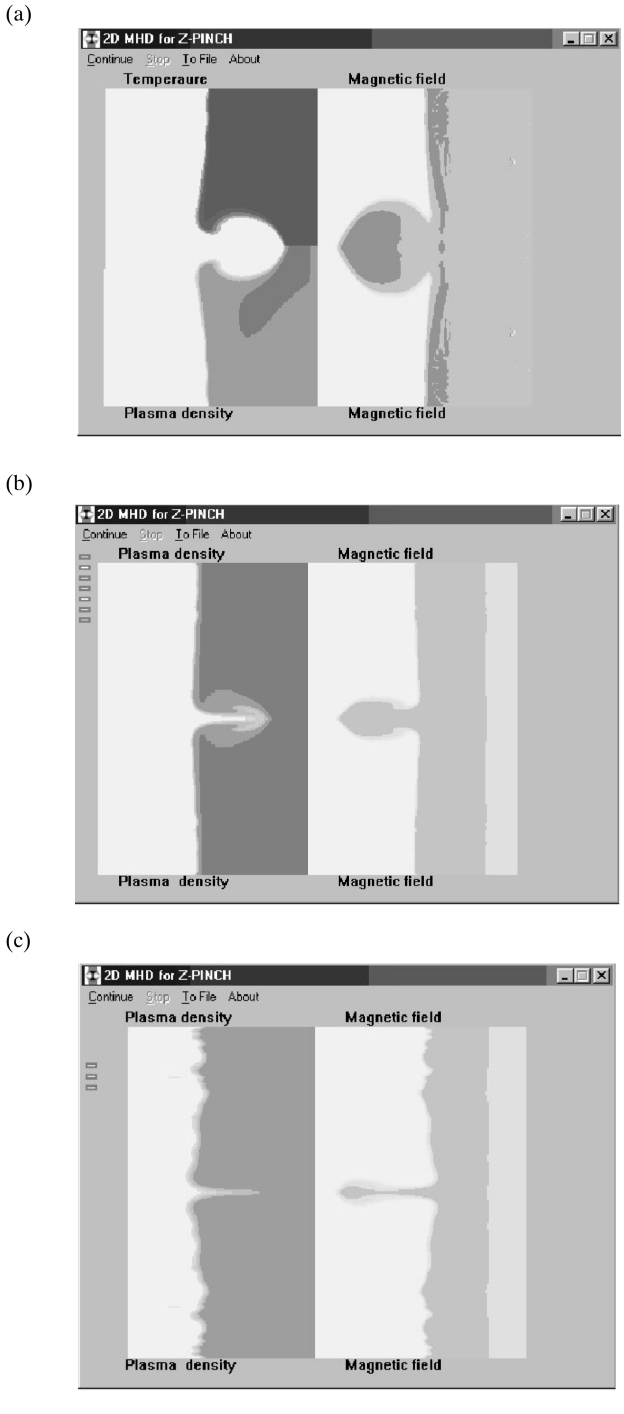

Fig. 5. The TPCN structure in dependence on the ratio n_c/n_p (a – $n_c/n_p = 10^{-3}$, b – 10^{-2}, c – 5×10^{-1}).

Method of particles

Numeric simulation [10] in the different region of the physical conditions by this method confirms the possibility of the existence of the closed discharges of TPCN type (Fig. 6). In this case, calculations are made for the following main parameters values: $n = 10^{12}$–10^{13} cm^{-3}, gas – N_2, $U = 10^3$–10^4 B. This method permits also to determine the conditions of the optimal TPCN development.

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-equilibrium). 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]:

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

$$(2)\qquad B(r) = 2\pi I(1+\gamma)c^{-1}\frac{1-\gamma \exp k_H^2 r^2}{1+\gamma \exp k_H^2 r^2} - H^* =$$

$$= 4\pi I c^{-1}\frac{1+\gamma}{1+\gamma \exp k_H^2 r^2} + H_\infty = B_p(r) + H_\infty,$$

where:

$$\gamma = \frac{8\pi P(0)}{B_p^2(0)} = \frac{8\pi \Sigma n_{0i} m_i v_i^2}{\left(4\pi I c^{-1}\right)^2};$$

$$k_H^2 = (1+\gamma)\lambda_H^{-2} = \frac{B_p^2(0) + 8\pi \Sigma n_{0i} m_i v_r^2}{8\Sigma N_i m_i v_r^2} = \frac{(1+\gamma)\left(4\pi I c^{-1}\right)^2}{8\Sigma N_i m_i v_r^2}$$

Field H* can be calculated by using this formula:

$$(3)\qquad H^* = -H_\infty - \frac{1+\gamma}{2}B_p(0),\quad B_p(0) = \frac{4\pi}{c}I.$$

Here: $B_p(r)$ is the own magnetic field of plasma cavity; $H_\propto$ is the external magnetic field (field of the neck); $H^* = m_i c e_i^{-1} \omega_i$ is the strength of magnetic field (parallel to neck field), forming due to the rotation of the plasma components as one with constant frequency ω_i (at the small radius r in the plane of the cavity); $I = (2\pi)^{-1}\Sigma e_i \omega_i N_i$ is the azimuthal current per length of plasma toroid (along the side of the neck magnetic field); and N_i is the corresponding 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 plasma 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 Ω-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 controlling plasma parameters. The comparative analysis and calculations done in this work by the different methods demonstrates that the ability of high current-carrying plasmas 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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