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On the Networking of Long-Living Filaments of Electric Current in Magnetically Confined Toroidal Plasmas

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Abstract

The probable principles of the electric current networking in magnetically confined toroidal (MCT) plasmas recently formulated are applied to suggest a novel qualitative view on MHD equilibria in magnetically confined plasmas.

Keywords:

electric current filament, networking of filaments, magnetohydrodynamic equilibrium

1. Introduction

Recently the probable principles of the electric current networking in magnetically confined toroidal (MCT) plasmas have been formulated [1,2] which inferentially extend recently formulated concept of the formation of the non-fluctuative (i.e. unexpectedly long-living) filaments of electric current, and their networking, in *Z*-pinch plasmas [3] (and other magnetoinertially-driven plasmas) to the case of MCT plasmas (tokamaks, reversed field pinches etc.). This extension suggests a necessity to append conventional picture of the non-filamentary plasma (which is nearly a fluid described by the conventional MHD) with a "network" component which is formed by the strongest long-living filaments of electric current and penetrate the "fluid" component to produce a percolating network. A qualitative approach which treats long-living filaments as a classical plasma formation governed by the long-range quantum bonds provided, at the microscopical level, by nanotubes of elements of optimal valence (carbon) is outlined in [4]. The self-similarity of tubular structuring of magnetoinertially-confined and cosmic plasmas is suggested to sustain the self-similarity of the electric current networking in a broad range of length scales (see this conference proceedings).

An application [1,2] of the method of the multilevel dynamical contrasting [3] to analyzing available data from tokamak plasmas revealed the signs of networking in the visible light and soft X-ray images, and magnetic probing data. Also, implicit signs of networking have been found [1,2] in the Thomson scattering and correlation reflectometry.

The approach [1,2] opens new opportunities for developing the model of the nonlocal (non-diffusive) heat transport in plasmas by the electromagnetic carriers of the long mean free path – of the system's size and larger. In particular, observations of fast nonlocal responses to a localized perturbation and internal transport barriers (ITBs) in tokamaks exhibit qualitative correlation with the networking-based approach [1].

The present paper is focused at application of principles [1,2] to the problem of MHD equilibria in MCT plasmas. The results give a novel qualitative view on MHD equilibria and suggest a possibility to extend J.B. Taylor's approach [5] to the case of non-force-free equilibria in plasmas with a strong radial sectioning (or, equivalently, strong ITBs).

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2. Probable Principles of Networking

2.1 Stair-Step Form of Networking of Filaments

The data analyzed in [1-3] suggest that the networking starts along with filamentation from the very beginning of discharge. The first-generation filaments are directed toroidally (to give a nearly force-free magnetic configuration at low values of plasma pressure) whereas the second-generation filaments tend to weave the nested toroidal surfaces (called magnetic stockings [1]), via toroidal and poloidal networking which incorporates first-generation filaments, with an admixture of radial networking of variable depth. In a tokamak this leads, within each magnetic flux surface, to a stair-step form of the rotational transform which turns into canonical (i.e. smooth) one after spatial averaging within respective magnetic flux surface.

2.2 Selective Survivability and Large-Scale Structure of Magnetic Stockings

The individual stocking with simplest connection of its filaments is most stable to various perturbations. Therefore the strongest stockings in a tokamak should be located at low-order resonance magnetic flux surfaces. Correspondingly, magnetic island looks like a filamentary layer formed by the local pinching of filaments within respective magnetic stocking. Similarly to stratification of *Z*-pinch plasmas in transverse direction, with respect to *Z*-pinch axis (cf. Sec. 4 in ref. [3]), in a tokamak there should be the regularly spaced bonds between neighboring magnetic islands. These bonds reside within respective magnetic surface and are directed roughly perpendicular to magnetic islands. The latter is true of the large scale structuring which has been found [1,2] in processing available data in visible light (from tokamak periphery) and soft X-ray images (from core plasma), and magnetic probing data (from plasma surface).

2.3 Radial Sectioning of MCT Plasmas

The MCT plasmas are suggested [1,2] to be composed of a finite-number set of nested toroidal layers with strong (anomalous) radial transport of heat in their interior. The "network" components of these layers are decoupled from each other to form the internal transport barriers (the decoupling is self-consistently supported by the shear of plasma rotation velocity) whereas "fluid" component (partially or completely) washes out the jumps produced by the sectioning. The set includes:

(i) few/several relatively thin layers which are formed by the strongest stockings located at/around low-order rational magnetic flux surfaces;

(ii) the intermediate (thicker) layers with internal networking which is weaker than that of strongest stockings but still sufficient for the anomalous radial transport; and

(iii) the regions of poorest networking, in closest vicinity to strongest magnetic stockings, where the plasma to a largest extent resembles a fluid, because here the "defect of the resonance" prevents not only the self-closure of filaments but the good-quality networking as well. The latter makes these regions hydrodynamically most unstable (e.g. sawteeth seem to be ignited just in the region $(q - 1) \rightarrow -0$; similar MHD activity, much less pronounced, exists around other, less strong stockings [6]).

The success of the reversed- or optimized-shear regimes looks, in the networking-based approach, like being caused by avoiding the appearance of the $(q - 1) \rightarrow -0$ region, even at the cost of non-achieving (from the side of larger values of q) the formation of strongest stocking, at $q = 1$ surface. Note that achieving the formation of another strong stocking, at $q = 2$ surface, does make the discharge better [7].

The above picture is in agreement with observations in the RTP tokamak [6], with the best ever available resolution of T_e, of electron ITBs at low-order resonance magnetic flux surfaces. Therefore, it is not surprising that the ITB position is not necessarily coupled to q_{min} surface and may appear even outside this surface [8].

3. Networking-Based Picture of MHD Equilibria

3.1 Alternative View on Relaxed States

The analysis [1,2] enables us to treat, in unified frames, the mechanisms of the relaxation to a force free and non-force free magnetic configurations and to trace the links between these equilibria.

First, we suggest an alternative explanation to the success of J.B. Taylor's principle [5] of the relaxation to a minimum magnetic energy state (a relaxed state) under condition of the conserved magnetic helicity. From the viewpoint [1,2], the principle of helicity conservation may be treated as a consequence of the conservation of networking of long-living filaments of electric current.

The success of principle [5] may stem from the fact that magnetic helicity K characterizes the knottedness of magnetic field lines. In ideal MHD, the integral of the scalar product ($\vec{A}$, $\vec{B}$) (where $\vec{A}$ and $\vec{B}$ are vector potential and magnetic field, respectively) over each infinitesimal flux tube surrounding a closed field line is an invariant (i.e. if one closed field line initially link another N times then these two loops sustain this linkage during any ideal MHD motion). In order to assure the conservation of total magnetic helicity $K(V)$ (i.e. integrated over entire plasma volume V), one need the identity of magnetic flux tubes. Indeed, the identity leads to a force free configuration which is described by a single parameter rather than the infinity of parameters as in the general case of ideal MHD. In [6], the identity of flux tubes results from allowed magnetic reconnections (as they, on the one hand, conserve magnetic helicity and, on the other hand, destroy all other ideal MHD conservation laws). To make reconnections possible Taylor introduced finite conductivity of plasma. The respective Ohmic dissipation leads to the non-conservation of helicity, however the decay rate of the helicity in turbulent plasma has been estimated to be (much) less than that of magnetic energy (note that the case of negligible plasma thermal energy has been considered there).

The networking-based approach replaces the identity of reconnectable magnetic flux tubes with the identity of long-living (i.e. non-reconnectable) filaments. In the case of MCT plasmas this implies the integrity of network component of plasma in each radial section. The identity of filaments is provided by the intrinsic mechanisms of networking, namely by the symmetrization of sub-filaments within observed individual filaments and by the similar mechanisms of the symmetrization of networking processes in a broad range of length scales (see [2,3] for more detail).

3.2 On the Extension of Taylor's Principle

The networking-based view suggests the lines of extending the Taylor's approach [5] to the case of a finite particle pressure and stable plasma flows, with allowing for ITBs.

A number of solutions to the problem of plasma equilibria for a finite pressure gradient have been given in literature for the case of smooth profiles of plasma pressure and electric current (i.e. plasmas without ITBs). In tokamak case, a substantiation of the "profile consistency" phenomenon [9] has been independently given in [10-12]. All these schemes minimize magnetic energy W_m (of poloidal B_p [10,11] or total magnetic field [12] and thermal energy W_{th} [10,12] under condition of conserved total (toroidal) electric current [10-12] and one more constraint:

(i) in [10], a particular choice of the functional dependence of the current density j and plasma pressure on safety factor q (in variational procedure the quantities j and B_p have been decoupled, because of allowed reconnections, but the particular choice made them finally interrelated by the conventional MHD equation);

(ii) in [11,12], the number of variables is reduced by using the Grad-Shafranov equilibrium equation.

Interestingly, in [10], an extended scheme, with addition of helicity conservation, has also been considered in the variational procedure.

The fruitfulness of the principle of magnetic helicity conservation in describing a non-force-free equilibrium has been demonstrated in [13]. There the variational principle minimizes W_m and W_{th}, with conserved helicity (rather than total electric current), and introduces the Grad-Shafranov equation directly to variational procedure. The results for cylindrical geometry with the first-order toroidal corrections did manage to give a peaked profile of electric current for the analyzed there particular cases of the reversed field pinch, screw pinch and tokamak experiments.

An analysis, from the networking viewpoint, of the opportunities to extend the principle [5] suggests that the helicity conservation constraints could draw the most natural bridge between force-free and non-force-free cases. Specifically, an extension of approaches [5,13] to the case of allowing for the sectioning of the network component in MCT plasmas could be based on minimizing the magnetic, thermal (and stable plasma flow) energies with the following constraints in the variational procedure:

(a) Grad-Shafranov equation;

(b) conservation of helicities integrated over major radial sections of plasma, with a freedom for the plasma macroscopic parameters to loose their smoothness at the ITBs (i.e. at strongest stockings if they are considered as a "singular" surface layers).

We are to comment on the following two issues. First, introduction of additional constraints (conservation of partially-integrated helicities rather than total one) doesn't lead to the "overweighting" of the problem because this is compensated by the appearance of new parameters introduced by the sectioning of profiles.

Second, plasma flow effects should be introduced, strictly speaking, everywhere: in total energy, plasma equilibrium equation, probably even in the helicity to combine the fluid plasma and magnetic field behavior (cf. e.g. generalized helicity approach [14]). However, very preliminary analysis suggests that the role of plasma flows is maximal in sustaining the shear (or, more precisely, the jumps) of rotation velocity (and consequently, the existence of ITBs). Therefore, at the first step of analyzing the above scheme one could probably neglect plasma flow effects taking them into account only implicitly, via assuming the radial sectioning as itself.

4. Conclusions

The networking-based approach suggests a simple and transparent interpretation of the success of the approach [5] and opens new opportunities for extending major idea of the concept [5], namely the dominant role of the conservation of magnetic helicity, to much more complicated cases which are under investigation now in fusion systems with essential role of auxiliary heating, sheared plasma flows, and internal transport barriers.

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