ON THE ELECTRIC CURRENT NETWORKING IN MAGNETICALLY CONFINED PLASMAS AND NON-LOCAL HEAT TRANSPORT IN A TOKAMAK

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Analyses [1,2] of the Z-pinches (and other magneto-inertially confined plasmas) allowed to resolve networking of filaments, thanks to resolvability of individual filaments and relative simplicity of their networking at implosion stage of Z-pinch discharge. An extension of approach [1,2] enables us to formulate probable principles of electric current networking in magnetically confined toroidal plasmas and suggest a qualitative picture for the non-local (non-diffusive) component of heat transport in a tokamak. The signs of networking are found in available data in visible light, soft X-rays, and magnetic probing.

1. Probable principles of networking in magnetically confined toroidal (MCT) plasmas

(1) Stair-step form of networking of filaments. It appears [1,2] 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* [3]), via toroidal and poloidal networking which incorporates first-generation filaments, with admixture of radial networking of a variable depth. In a tokamak this leads, within each magnetic surface, to a stair-step form of rotational transform which turns into canonical (i.e. smooth) one after respective spatial averaging.

(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. [2(b)]), in a tokamak there should be the regularly spaced bonds between the neighboring magnetic islands, which are directed roughly perpendicular to magnetic islands.

(3) A «two-component» approach to global structuring of plasmas. The electric current-carrying plasma can be roughly divided into (i) the non-filamentary plasma which is nearly a fluid described by the conventional MHD, and (ii) the strongest long-living filaments which penetrate the above, «fluid» component to form the percolating network(s) and, thus, to provide strong long-range bonds in plasmas.

(4) Radial sectioning of MCT plasmas. The MCT plasmas are suggested [3] to be composed of a finite-number set of the 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). 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 a 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 (cf. sawteeth, as initiated in the region $(q\text{-}1)\to -0$, and similar MHD activity, much less pronounced, around other, less strong stockings). Therefore the success of the reversed- or optimized-shear regimes looks, in this approach, like being caused by avoiding the appearance of the $(q\text{-}1)\to -0$ region, even at the cost of «refusing» from possessing the strongest, $q=1$ stockings whereas achieving the formation of the less strong, $q=2$ stocking (from the side of larger values of q) does make the discharge better [4].

(5) Non-local component of transport. With increasing accuracy of space-time diagnostics of perturbations in plasma, a lot of data is accumulated in recent years which identify a non-local component of heat transport in a tokamak (cf. [5]). The electric current networking opens unprecedented opportunities, as compared to «fluid» plasmas, for the various electromagnetic (EM) waves to carry the energy along filament throughout entire network, similar to EM energy transport in conventional wire circuits. Therefore, major contribution to the fast transport phenomena in plasmas is believed [3] to come from the non-local interactions of the «network» component with the EM fields (either directly pumped from external electric circuit or produced by the various plasma perturbations) whereas slow, diffusion-like transport is invariably associated with the «fluid» component. The strength of the transport processes associated with the network component strictly follows the hierarchy of radial sectioning (see item 4), ranging from the very strong transport within the stockings to its suppression in the internal transport barriers. For instance, the loss of the $q=2$ stocking, which is a strong transport barrier and a strong confining system for the MHD activity around it, leads as a rule to the disruption of discharge electric current.

The proposed approach opens new opportunities for developing the model [7] of the non-local heat transport in plasmas by the (non-specified) electromagnetic carriers of the long mean free path, of system's size and larger. In particular, more realistic seem now the high values of the coefficient of energy carriers' reflection from the plasma boundary, which have been obtained in [7(b)] when solving the respective inverse problem via numerical modeling of the initial stage of fast non-local transport of heat by the model waves in «cold pulse» experiments.

2. Signs of networking in a tokamak

(a) Visible light imaging. The hydrogen line emission from the inner wall region of the tokamak TFTR, Fig. 1(c) in [8], reveals the strata as a wide bands in nearly poloidal direction with the sub-islands seen as the bright parallel sections of filaments in nearly toroidal direction (according to [8], the respective average toroidal angle is approximately twice larger than that of local direction of total magnetic field). A detailed processing [3] shows that the neighboring strata are connected by a resolvable sequences of bright spots which follow a stair-step way, i.e. possess a certain shift in poloidal direction so that the statistics of these inter-strata links works just for diminishing the average toroidal angle of the individual stair-step filaments.

(b) Magnetic probing. Figures 1 and 2 are a (slightly) processed images (using the multilevel dynamical contrasting method [1]) of the pictures [9] resulted from «visualizing» the poloidal magnetic field perturbations at tokamak periphery. Figure 1 shows development of a predisruption in the T-11M tokamak (Fig. 1 in [9], perturbation mode {m=3/n=1}, vertical axis is poloidal angle, from -180° to +180°, horizontal is time, duration 1.25 ms). The weakening of the bonds between the neighboring islands is followed by a substantial weakening (probably, even destruction) of the islands themselves (and, consequently, of magnetic stocking at $q=3$ surface) at one side of the plasma. The same correlation is seen from a predisruption in TFTR tokamak in Fig. 2 (mode {m=2/n=1}, duration 0.5 ms, upper half of Fig. 3 in [9]) which shows that the strata are a periodic and common formation for the neighboring islands.

(c) Soft X-ray imaging. Figure 3 shows a processed image of the MHD-silent part (from 30.8 ms to 30.9 ms) of the SXR chord signal picture [10] taken at START tokamak in horizontal direction (see lower figure on page 87 in [10], the size in vertical direction, ±18 cm, is counted from toroidal axis). Dominant contribution to SXR images is believed to come from the strongest, and closest to the core, stocking. Note that unlike magnetic probing the SXR image contains a superposition of the images of the front and back sides of magnetic stocking. Analysis [3] of the SXR signal during the subsequent MHD activity (a chirping mode [10], around 31-st ms) shows that the islands survive only at one side of the stocking, quite similar to the same survival in the peripheral, $q=3$, stocking during the predisruption (cf. Fig. 1).

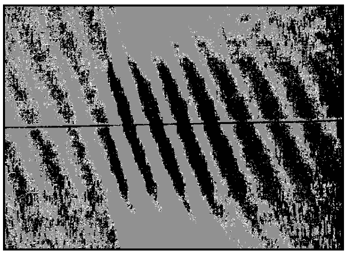

Fig. 1

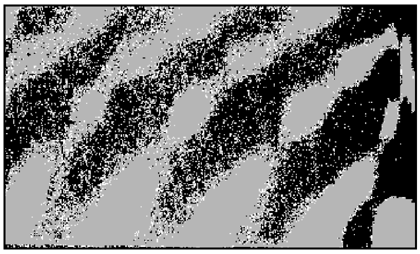

Fig. 2

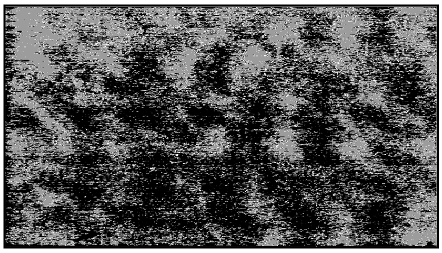

Fig. 3

(d) Thomson scattering. A number of electron internal thermal barriers and good-conduction zones in between these barriers have been found in the RTP tokamak experiments [6] on a highly-localized off-axis EC heating. It was shown that the barrier at $q=1$ surface, which has been identified thanks to a very localized power source in the center, does exist in the «silent» ohmic regimes and, therefore, is not a consequence of plasma perturbation but rather a sign of the intrinsic structuring of plasma (see Fig. 4 in [6] for more details).

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