*34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007 ECA Vol.**31F**, O-2.015 (2007)*

Magnetized Dust Filaments-to-Skeleton Transition in Electric Discharges (Numerical Modeling)

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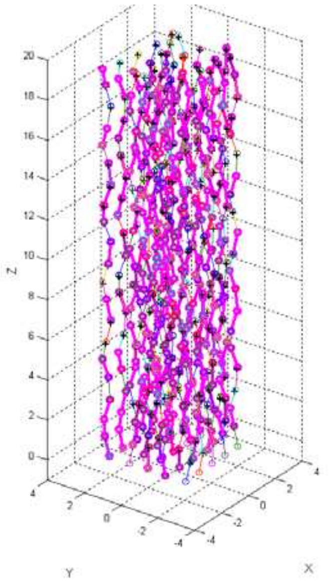
1. Introduction. Formation of a skeleton composed of a fractal condensed matter was suggested [1] to explain unexpected longevity of filamentary structures observed in laboratory electric discharges. A simple 3-D model [2(a)] of many-body system of magnetized, electrically conducting thin rods (1-D magnetic dipoles, in particular, magnetized nanotubular dust [1]) managed to describe the integrity of a hypothetical, "manually-assembled" tubular skeleton under the action of external forces, and the trend toward electrodynamic (magnetic and electric) self-assembling of coaxial tubular skeleton in a system of ~500 magnetic dipoles, which are initially arranged as 25-50 linear electric current filaments with a fraction of the dipoles with uncompensated magnetic flux [2(b,c)]. Here, in the frame [2(a-c)] we show the possibility of (i) transition from 3D quasi-homogeneous ensemble of initially linear filaments of electric current to a coaxial tubular skeleton, and (ii) formation of 1-D magnetic dipole of a bigger size on the basis of the above skeleton, that may provide a mechanism of generating the self-similarity. The problem of plausibility of the above initial conditions is considered in [2(d)] in the frame of modeling the self-assembling of linear filaments in a random ensemble of dipoles within a plasma electric current filament.

2. Main features of transition to a skeleton. We consider *a bunch of linear filaments between biased electrodes.* The filaments are composed of successively connected blocks (Fig. 1) with the properties [2(a)], namely static lengthy (i.e. 1D) magnetic dipoles, which possess longitudinal electric conductivity and electric charge, screened with dipole's own plasma sheath. The filaments are magnetically connected to the biased electrodes (a half of magnetic flux on the tip of each boundary block is trapped by the boundary surface, and these tips may move freely along this surface), each filament carry a constant electric current J_0. Such an ensemble may also describe, to certain extent, a part of much longer bunch of electric current filaments (e.g., closed filaments (loops) in a toroidal system). Numerical modeling of ~10^2-10^3 such dipoles demonstrates main features of self-assembling [2(b,c)]: (a) self-reduction of spatial dimensionality of structuring, due to counterbalance of ponderomotive attraction and the close Coulomb repulsion of filaments,

(b) magnetic coupling of neighboring filaments within the formed cylindrical structure, due to a fraction of dipoles with uncompensated magnetic flux within the filaments, and formation of tubular skeleton via such a "magnetic threading".



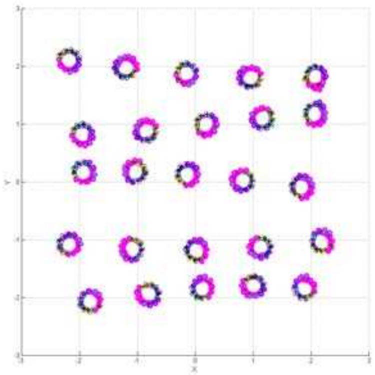


Fig. 1. The 3-D (left) and top-on (right) views of the initial position of a bunch of filaments composed of 1-D magnetic dipoles [2(a)] for the following parameters: total number of blocks N_{dip} = 500, number of blocks in filament = 20, number of filaments = 25, magnetic charge Z_M=2Z_{M0} (thick magenta blocks) and Z_M=Z_{M0} (others), electric charge Z= Z_{M0}, screening length r_D=1, space coordinates are given in the units of dipole's length *L*. Here fraction of magnetically double-charged blocks f_{2ZM0}= 1/2 with their aperiodic location, similar pictures for f_{2ZM0}= 1/3 and 2/7 with periodic location (and all other conditions the same) are given in [2(c)] and [3], respectively.

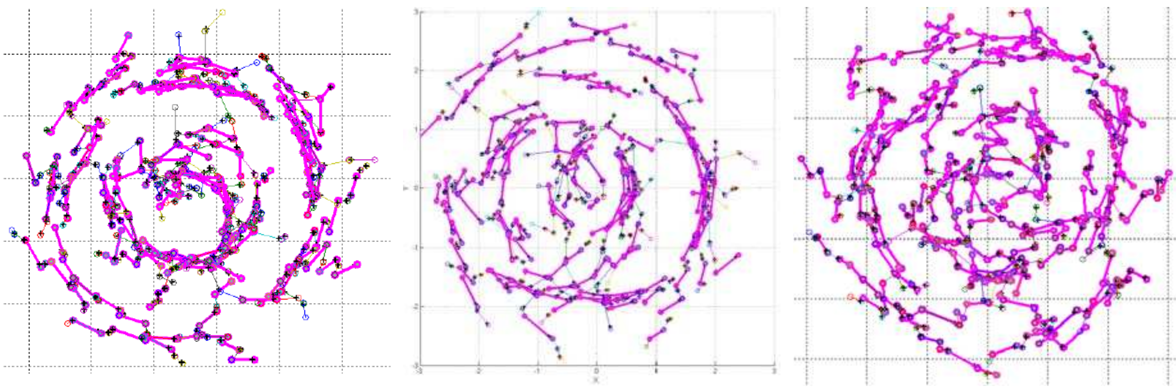


Fig. 2. Top-on views on a bunch of filaments in Fig. 1 at quasi-stationary stage of evolution (t ~ 10$(mL^3)^{1/2}(Z_{M0}e)^{-1}$) for electric current force coefficient $F_{0JJ} \equiv (J_0 L / cZ_{M0} e)^2$=0.25, brake coefficients for tip's collision, $(k_{br})_{dd}$ =100, and for brake in the ambient medium, $(k_{br})_{dm}$ =3 (all the forces are in the units $(Z_{M0}e/L)^2$, see [2(a)]), for f_{2ZM0}= 1/3 (periodic), 2/7 (periodic), 1/2 (aperiodic), from left to right picture, respectively. Mesh size is *L*.

Comparison in Fig. 2 illustrates the effect of the fraction of 1-D magnetic dipoles with doubled magnetic flux and of their distribution within initial linear filaments on the final structuring. It follows that capability of magnetic treading of neighboring filaments (namely, periodic location of a "magnetic valence" in the case of initially perfectly-linear filaments) is important already at intermediate stage [2(c)] when coaxial tubular structuring is formed due to azimuthal symmetrization and radial layering. Skeletal structure of outer wall and the less systematic magnetic threading in the inner part are shown in Figs. 3,4.

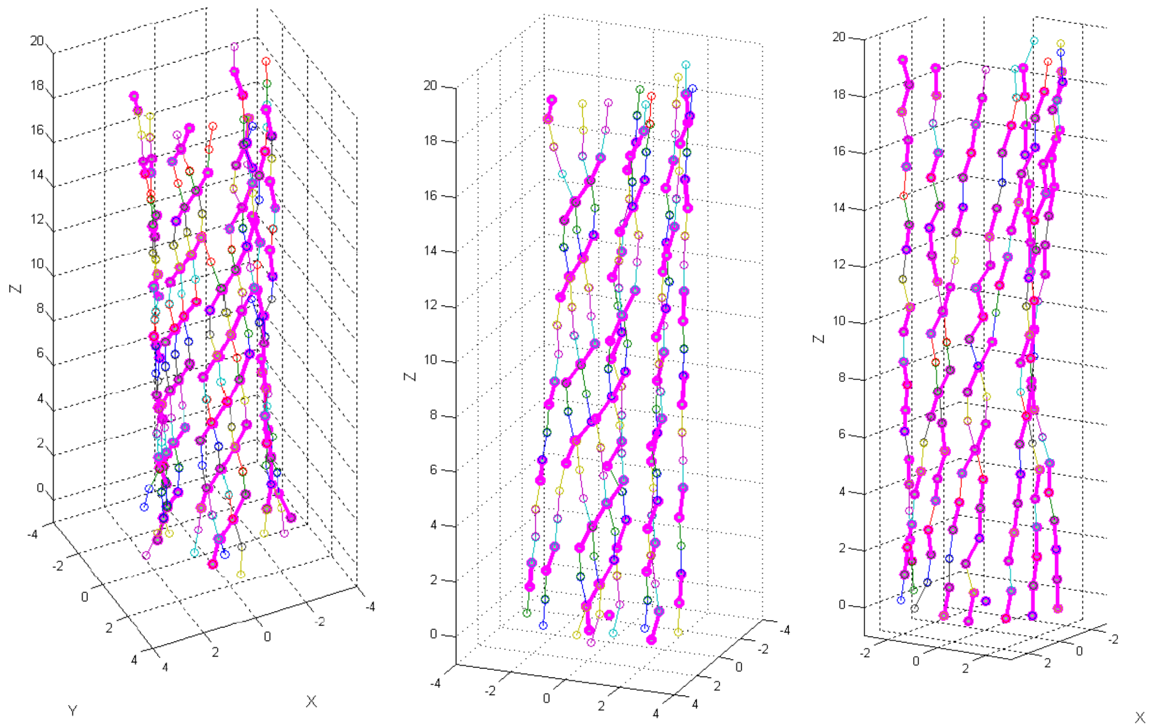


Fig. 3. A part of the outer shell of coaxial tubular structures in the respective pictures in Fig. 2, as seen from upper right direction in all those pictures.

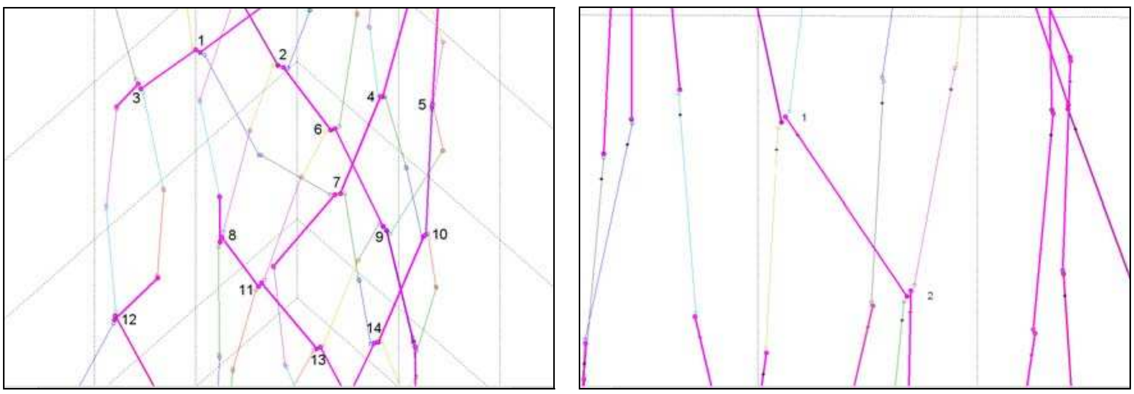


Fig. 4. The 3-D view of a part of the inner tubular skeletal wall in the left and right pictures in Fig. 2. The weaving of a network via magnetic coupling of uncompensated magnetic flux in the dipoles within initially linear filaments is indicated in the numerated crosses (14 such in the left and only 2 in the right), that provides a “magnetic threading” of the network.

The results of numerical modeling agree with approximate scaling law [2(c)], analytically derived for typical radial size of tubular structuring in such a system of filaments.

3. A trend towards self-similarity of magnetic-dipole structuring. The above results illustrate the trend towards self-similarity of structuring. Indeed, formation of a lengthy (i.e. 1-D) magnetic dipole of a bigger size on the basis of the above skeleton provides possible mechanism of generating the self-similarity. The new magnetic dipole is produced by (i) magnetic flux on the tips of the dipoles in the butt-end of tubular skeleton, (ii) uncompensated magnetic flux in the dipoles within the filaments, (iii) poloidal electric

current in the walls of the skeleton, produced by the declination of filaments due to action of azimuthal magnetic field of (initially purely longitudinal) electric current through the filaments on the dipoles with uncompensated magnetic flux. Here the latter contribution is illustrated with Fig. 5, which shows that for conditions of Figures 1,2 the magnetic flux, produced that way and trapped in the resulted skeletal, networked structure, is ~ $(J_0 L / cZ_{M0}e)$ in units of magnetic flux of individual dipole with $Z_M = Z_{M0}$.

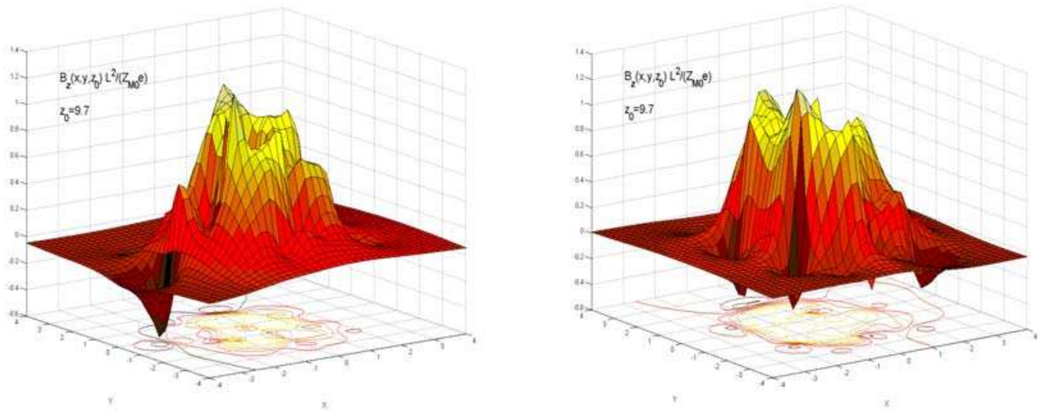


Fig. 5. The 2-D distribution of longitudinal magnetic field $B_z(x,y,z_0)$ (in units $Z_{M0}e/L^2$) in the median cross-section of the skeleton shown in the left and central pictures in Fig. 2. The outer shell of the skeleton corresponds to (azimuthally non-smooth) transition to negative values of B_z.

4. Conclusion. The above numerical modeling gives a (non-unique) solution to a significant part (namely, transition from 3D quasi-homogeneous ensemble of initially linear filaments of electric current to a coaxial tubular skeleton) of the entire inverse problem of reconstructing the electrodynamic parameters of blocks which may provide (i) electrodynamic self-assembling of a tubular structure in a many-body system and (ii) a trend towards self-assembling of macroscopic tubular skeletons which were identified [1(b)] in a broad range of length scales.

Acknowledgments. This work is supported by the Russian Foundation for Basic Research (project No. 05-08-65507).

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