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A Model of Magnetic Aggregation of Nanodust in Electric Discharges

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1. Introduction. We propose a simple model for magnetic aggregation of nanoparticles in electric discharges, based on the assumption of the possibility of nanotubular structures to acquire the static magnetic dipole moment (presumably, at the initial stage of discharge, e.g. during electric breakdown). Such an assumption was made [1(A,B)] to explain the unexpected longevity of straight filaments, and their networks, revealed [1(C)] in the Z-pinch gaseous electric discharges. This allowed the prediction of macroscopic fractal structures with basic topological building block of tubular form (with presumably carbon nanotube at nanometer length scales), which may be successively self-repeated at various length scales (see [1(D)] for summary of experimental evidences for self-similarity of skeletal structures in the range 10^{-5}cm-10^{23}cm). Indirect evidences for trapping of magnetic flux, and its slow dissipation, by nanotubular blocks (and their natural and artificial assemblies) have been reported in a number of experimental and theoretical papers (cf. [2]).

Capability of nanoblocks to aggregate towards self-assembling of macroscopic skeletons with the help of nanoblocks' magnetism may be demonstrated on the example of electrodynamic self-assembling of a tubular structure of the 2-nd generation (in terms of [1(A,B)]) under conditions peculiar to electric breakdown. Here we report on numerical modeling, in the framework of the approach [2], of dynamics of ~10^2-10^3 nanodipoles and discuss a qualitative comparison with experiments on the laser production of large carbon-based toroids [3], including the Q-shaped toroids.

2. The trends towards tubularity in a system of 1D magnetic dipoles.

The problem is treated within as simple framework as possible. We assume the elementary building block to possess the following electrodynamic properties: (i) the 1D static magnetic dipole moment (such a dipole may be represented as a couple of magnetic monopoles located on the tips of a long thin rod; elasticity of the rod gives repulsion of attracting monopoles at close distance); (ii) two point masses, *m*, on the tips of the rod are connected with a massless rigid bond; (iii) static electric charge, which is located in the center of the rod and may be screened by the ambient medium (e.g., positive electric charging may be caused by the field emission, at least thermal one, by the nanotubes), (iv) longitudinal electrical conductivity. These properties allow the modeling of many-body interaction of magnetic dipoles (i.e. of circular electric currents in the walls of 1D dipole), and longitudinal electric currents in the dipoles (for more detail see [2]).

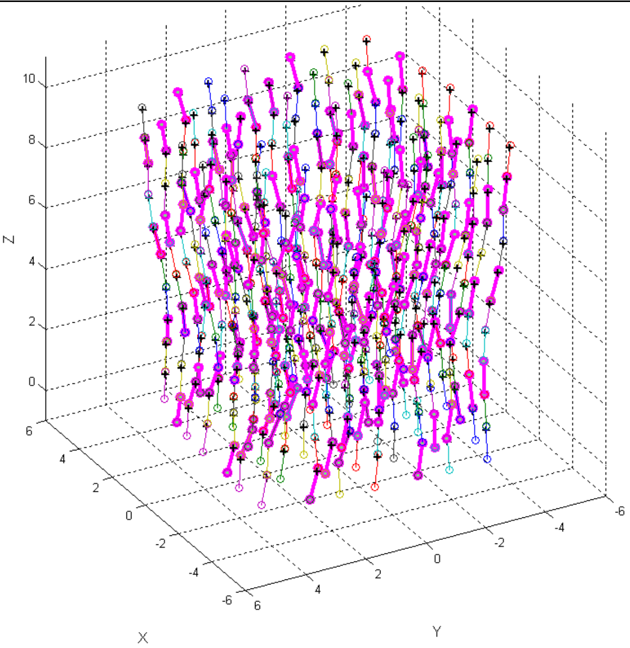

Fig. 1. A bunch of filaments composed of 1D magnetic dipoles at starting position (t=0). The filaments are placed nearly regularly in a square of (6 x 6) length units.

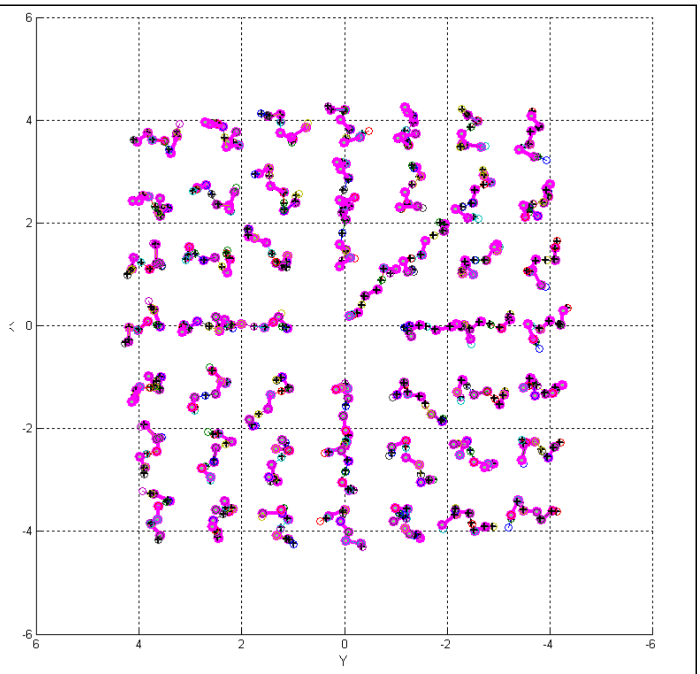

Fig. 2. Top-on view on a bunch of filaments in Fig. 1 at the beginning of self-assembling process (t ~ 0.1).

The trend towards self-assembling of a tubular structure we illustrate with the following example. A bunch of 49 filaments, with each being composed of 10 successively coupled magnetic dipoles, may carry a constant electric current in each filament (Figs. 1,2). The filaments' ends may move in the planes z = 0 and z ≈ 10. Such an ensemble may be considered as a part of much longer bunch of electric current filaments or as a bunch of filaments, which connect the biased electrodes.

Space coordinates, time and velocity are given in the units of dipole's length L, $t_0 = \frac{\sqrt{mL^3}}{Z_M e}$, and $v_0 = \frac{Z_M e}{\sqrt{mL}}$. $Z_M = \frac{\Phi}{4\pi e}$ is magnetic charge (in the units of electron charge e), Φ is magnetic flux, trapped in the dipole. The evolution of the system is governed by the attraction of electric currents, electric repulsion of blocks at distances less than the screening length, and spatial inhomogeneity of magnetic charging along the filaments. The latter effect corresponds to mutual interaction of uncompensated ($Z_M=2Z_{M0}$) magnetic dipoles, incorporated in the linear filaments, and their interaction with magnetic field of total electric current though the filaments (Fig. 3).

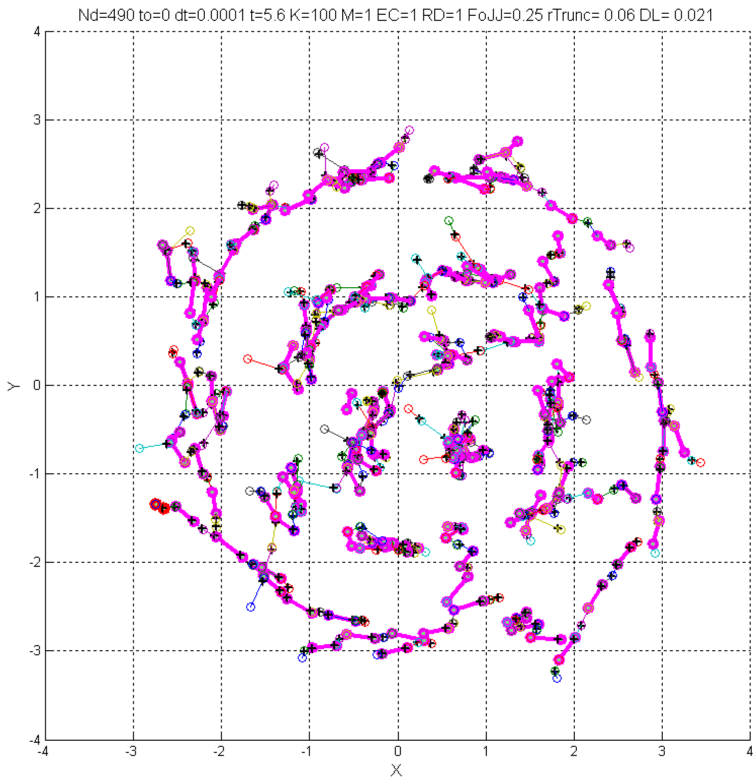

Fig. 3. Top-on view on a bunch of filaments of Fig. 1 at time t ~ 5.5 for the following set of parameters: $Z_M=2Z_{M0}$, for red thick blocks, and $Z_M= Z_{M0}$, for all the others; electric charge $Z = Z_{M0}$ for all the blocks; electric screening (Debye-like) radius $r_D=1$; brake coefficients for, respectively, close collisions of dipole's tips, $k_{br}=100$, and motion in the ambient medium, $k_{br}=1$; current-current force coefficient $F_{0JJ}=0.25$ (all the forces are in the units $(Z_{M0}e/L)^2$, see [2]).
The picture exhibits the signs of a trend towards coaxial tubular structuring. Note that radius of the outer rim (~3) is smaller than the mean radius at starting position (> 4.5).

3. Simple model of a skeletal matter, composed of 1D magnetic dipoles.

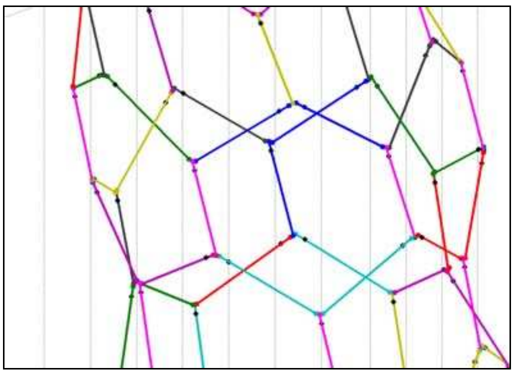

Fig. 4. The fragment of a perfect skeleton whose wall is "manually" assembled from hexagons composed, in turn, of 1D magnetic dipoles. The black crosses indicate the North pole part of the dipoles. Magnetic charging of blocks corresponds to the perfect magnetic threading of skeleton (specifically, magnetic flux in coaxial blocks is twice of that in the declined ones).

The capability of the model formulated in [2] is illustrated here with an example of dynamics of an ideal (here, "manually-assembled") tubular skeleton (see Fig. 4) subjected to the impact of magnetic field from distant electric current, similarly to the case of Sec. 3 in [2] but for a larger total number of the dipoles, N_{dip} = 582. The set of parameters is almost the same, except for the coordinates of distant external electric current: now the line of current, which flows in X direction, is located in the point {Y=-15, Z=25}. Also, at starting moment the center of the skeleton is pushed in Y-direction with a velocity v_y~ 1. Figure 5 shows skeleton's deformation caused by the above push and the bending force of magnetic field of external electric current.

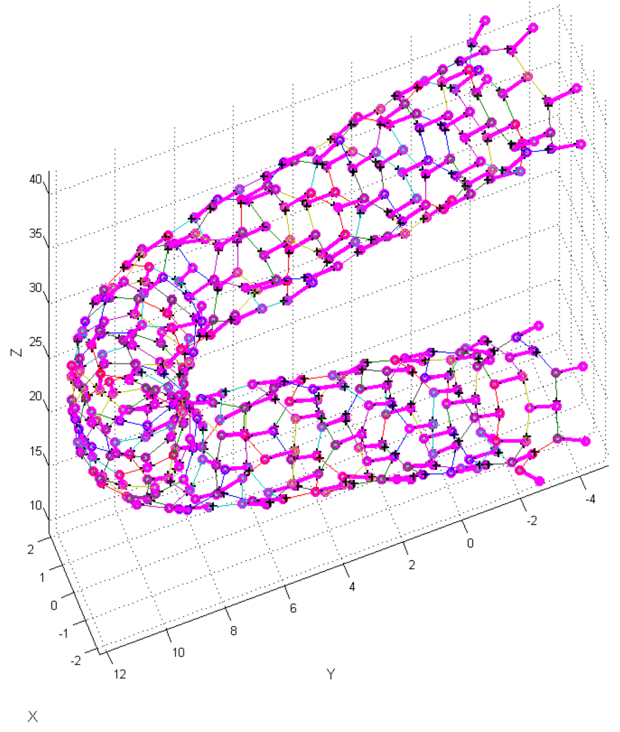

Fig. 5. The skeleton composed of 582 magnetic dipoles at time t=0 was directed vertically with z-axis at x=0, y=0. The figure shows the skeleton at time t=6.

Such a modeling is aimed at describing the trend towards production of carbon-based skeletons in the pulsed electric discharges of a high current density -- in particular, laser-induced production of submicron carbon-based toroids [3] (cf. Q-shaped hollow toroid in Fig. 3 in [3] and Fig. 7 in [2]). Our results suggest that toroids may form, e.g., thanks to the following succession: (a) formation of a tubular structuring, similarly to the case of Sec. 2; (b) declination of longitudinal electric currents (cf. Fig. 3) to produce internal coaxial magnetic flux and make a bigger magnetic dipole; (c) the close of such a tubular structure by the internal and external forces to make a hollow toroid, either the perfect one or not, e.g., a Q-shaped hollow toroid.

4. Conclusions. The model [2] of magnetic aggregation of nanodust is capable of describing (i) the trend towards production of coaxial tubular structuring in a bunch of linear filaments of electric current, composed of 1D magnetic dipoles (cf. Fig. 3), (ii) stability of ideal, “manually-assembled” skeletal matter [2] for a large number of dipoles ($\sim 10^3$), and (iii) the trend towards production of hollow toroidal structures by the external and internal forces (cf. Fig. 7 in [2] and Fig. 5).

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