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# Similarity of micro- and macrotubules in tokamak dust and plasma

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**Abstract**

The evidences for the structures of similar topology (a tubule with a cartwheel in the edge cross-section) and very different length scale are found in the tokamak dust and tokamak plasmas. In the dust deposit, such structures of 50–100 nm diameter are assembled from tubules of the size typical for multiwall carbon nanotubes. In the plasma, similar structures of centimeter scale diameter are observed in the visible light emission. These data are compatible with the hypothesis about microsolid skeletons, assembled from carbon nanotubes (or similar nanostructures), of the observed long-living filaments in plasmas. 

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## 1. Introduction

Recently the evidence for the rigid-body tubular long-living filaments (LLFs) of macroscopic size were found in tokamak and Z-pinch plasmas (few centimeters long LLFs, in a Z-pinch [1–3], and several times longer, in tokamaks [4;6]). The long-livingness of rigid-body straight filaments was proven in [1;2] in tracing their dynamics in a Z-pinch during almost entire discharge. The evidences came from the results of processing the visible-light images with the help of the method of multilevel dynamical contrasting (MDC) [7;8] (the originals were taken from experiments in various small and moderate-size tokamaks and a gaseous Z-pinch; sometimes the large scale structuring may be seen without MDC processing). The reliability of the results is based on the rich statistics, considerable similarity of the LLFs observed in various regimes and various facilities, as well as on the insensitivity to specific way of imaging.

Besides the probable importance of the phenomenon of rigid-body LLFs as itself, the above results gave some support to the hypothesis [1–3] about the presence of a microsolid skeleton in the LLFs (this hypothesis suggests the LLF's skeletons to be assembled from carbon nanotubes (NTs), or similar nanostructures, during electric breakdown; a mechanism of survivability of such skeletons in a high-temperature plasma environment is proposed in [4–6]). However, much more direct evidences are needed to make such an approach recognizable for the researchers. To this end it seems natural to seek

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for tubular structures in the dust deposits in experimental facilities where LLFs are observed, first of all – in tokamaks.

The problem of dust in tokamaks is of growing interest now. Experimental evidences for and characterization of dusty particles cover a range from $\sim 100\,\mu$m down to $\sim 100$ nm; see [9;10], for tokamak TEXTOR, and [11] (Section 3.A.2) for tokamaks DIII-D, ALCATOR C-MOD, and TFTR. The strongest evidence for a self-organized structuring of the tokamak dust is probably the fractal structures of a cauliflower-like form observed in [9;10]. The theoretical treatments of dust in fusion plasmas extend the approaches developed for low-temperature plasma processing devices to the case of the Scrape off Layer and divertor (see the survey [12]). These approaches are based on the kinetics of strongly coupled Coulomb systems in which the plasma non-ideality comes from high electric charge of dust particles.

The present Letter is aimed at demonstrating the topological similarity of *tubular* structures found in (i) various dust deposits in the tokamak T-10 [13] (in the range from few nanometers to few micrometers) and (ii) the structures in the plasma (at least, peripheral one) in small tokamaks (in the range from few millimeters to several centimeters) [4;6]. Despite this analysis covers only a part of the entire range of length scales which are of interest for the problem, this gives first explicit arguments in favor of the very possibility to draw a bridge between the nanoscale structures and the observable, macroscopic-size LLFs for particular (though very important) case of tokamak plasmas.

## 2. Microtubules in tokamak dust

An extensive analysis [13] of tokamak dust taken from various locations in the tokamak T-10 facility gives rich database on the size and abundance of dust particles. The figures presented here are the result of a search for those microstructures which are typical for multiwall carbon NTs and larger rigid-body structures built up from possibly minimal number of individual NTs. We present the pictures where fortunately the image of a separate tubular structure is found, which is only slightly superimposed over other formations, including similar tubules. The originals were obtained with the help of the transmission electronic microscope TEM JEM-100CX (for magnification $M = 10\,000$, its space resolution is $\delta = 5$ nm) and scanning electronic microscope SEM JSM-35CF (for $M = 20\,000$, $\delta = 120$–$150$ nm). The original images are processed with the MDC method (the latter may increase space resolution by the order of magnitude). However, in the cases most favorable for identification of the structuring under search, identification of tubularity in rough approximation practically doesn't need the MDC processing. In such a case, the MDC processing resolves the fine structure of the tubule.

The figures show typical examples of microtubules found out in small dust particles taken in three different ways from the tokamak T-10: namely, (i) dust particles deposited at a glass filter used while dust deposit was pumped out from the crimps in the tokamak vacuum chamber (Fig. 1), (ii) dust particles extracted from the oil used in the tokamak vacuum pumping system (Figs. 2 and 3), and (iii) thin films deposited at the internal surface of the tokamak vacuum chamber (Figs. 4 and 5).

First of all, the results suggest the probable presence of multiwall NTs in the typical dust particles.

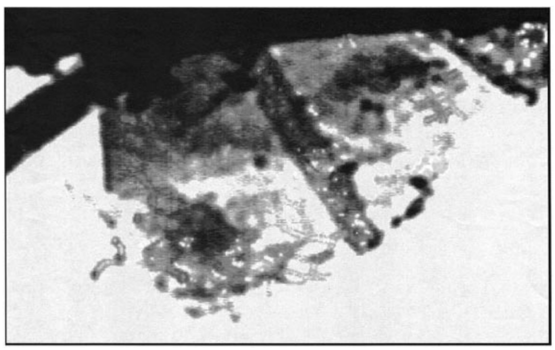

Fig. 1. The transmission electronic microscope (TEM) image of the dust deposit at a glass filter fiber (seen as a black region on the top of the figure). The dust was pumped out from the crimps in the T-10 tokamak chamber. Magnification of the original image is 9000. The original image was processed with the MDC method. Figure height 560 nm. A large rod is 370 nm long and of 55 nm diameter (the non-uniformity of the rod is caused probably by the slight inhomogeneity of its tubular sheath). The rod is linked to a network of substantially thinner tubules. Diameter of the tubule which enters the large rod from the left, not far from the lower edge of the rod, is $\sim 7$ nm. The separate tubules of similar diameter are seen to the left from the above network.

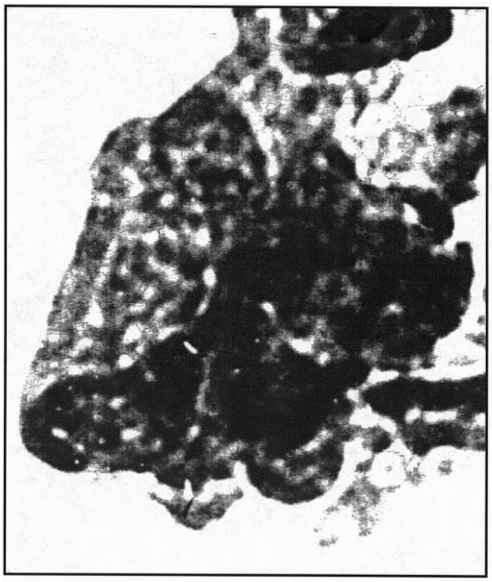

Fig. 2. The TEM image of the microtubule which is a small fragment of a dust particle of $\sim 1.2\,\mu m$ diameter, extracted from the oil used in the vacuum pumping system of tokamak T-10. The original image of magnification 34 000 was processed with the MDC method. Figure height 270 nm. The tubule, whose edge with the distinct central rod is seen in the lower left part of the figure, is of $\sim 70$ nm diameter and $\sim 140$ nm long. Diameter of the slightly inhomogeneous cylinder, which is seen on the left side of the tubule and is a constituent part of the tubule, is $\sim 10$ nm. The radial bonds between side-on cylinder and central rod are of $\sim 10$ nm diameter.

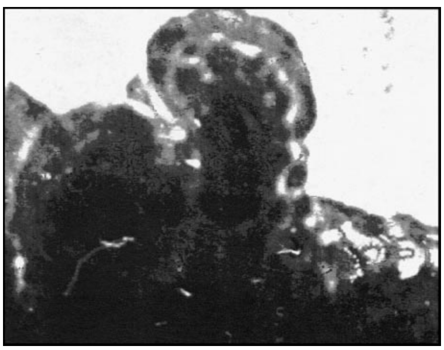

Fig. 3. The TEM image of the microstructure of a cartwheel type (all conditions are similar to those of Fig. 2). The cartwheel is seen on the top of the figure as a wheel declined with respect to figure's plane and connected with radial bonds to a thick vertical formation. The latter formation is a sort of the axle-tree for the above wheel. Figure height 200 nm. Diameter of the cartwheel is $\sim 100$ nm while diameter of radial bonds in this cartwheel varies in the range 5–10 nm.

Fig. 4. The scanning electronic microscope (SEM) image of a number of tubules found in the surface layer of the fracture of $\sim 15\,\mu m$ thick film deposited at the internal surface of the T-10 tokamak chamber. Figure height $3\,\mu m$. Magnification of the original image is 2000. Diameter of tubules lies in the range 0.4–$0.6\,\mu m$. Diameter of the spots on the axis of these tubules is $\sim 0.1\,\mu m$.

This conclusion is based on (a) the coincidence of the diameter of the observed cylindrical blocks with that of the typical multiwall NT (the latter diameter varies in the range from few nanometers to few tens of nanometers [14]) and (b) resolvable tubularity of such structures. The tubularity (i.e. concentration of the matter in the wall of a cylindrical axisymmetric structure) of the thinnest resolved tubules, of several nanometer diameter, may be seen in Fig. 1 (see a network of 5–10 nm diameter filaments which are connected with the larger cylindrical rod, and espe-

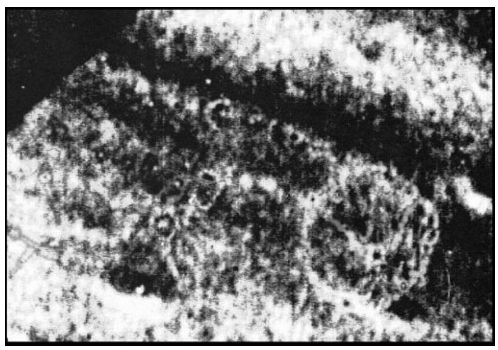

Fig. 5. The SEM image of the tubule seen in the surface layer of the film deposited at the internal surface of the T-10 tokamak chamber. Figure height $15\,\mu m$. Magnification of the original image is 2000. Diameters of the tubule and its central spot are $\sim 5\,\mu m$ and $\sim 1\,\mu m$, respectively.

cially separate tubules located to the left from the above network).

Second, there are evidences for the presence of larger tubular structures assembled from cylindrical blocks (presumably, multiwall NTs). An example of such a tubule may be seen in Fig. 2. The tubule of $\sim 70$ nm diameter has in its edge cross-section the distinct radial bonds connecting the ring-shaped structure with an inner rod located roughly on the axis of this tubule. Note that diameters ($\sim 10$ nm) of cylindrical blocks in the ring-shaped structure and of the inner rod are typical for the multiwall NTs.

Third, there are evidences for the presence of a distinguishable structuring that might be helpful for verifying the concept [1–3] of generations of self-similar tubules in a very broad range of length scales. Here, the most important pattern is the above-mentioned structure in the edge cross-section of the tubule in Fig. 2. It is worth to call this structure a *cartwheel*. Another example of the cartwheel is shown in Fig. 3.

Regarding the structuring of the cartwheel type, one may consider our data as an indication on the non-exotic nature of the ring-shaped tubules. Diameters of the rings and ring-shaped tubules may vary in the range from several tenths to few hundreds of nanometers and from several nanometers to few tens of nanometers, respectively. The ring-shaped carbon NTs have been for the first time observed only few years ago [15], and the geometrical completeness of such tori (e.g., their apparent coincidence with a coiled, not self-closed NT) is disputed in the literature. The observations of the cartwheel structure assembled from typical NTs, to our knowledge, were not reported in the literature. Therefore, regardless of the fine structure of the self-closure of a ring-shaped structure, the present evidences enable us to suggest wide abundance of the cartwheel-type structuring in the above-mentioned range of length scales.

Fourth, the films of micrometer scale thickness, which at first glance look as a relatively homogeneous medium, appear to contain tubular formations embedded in the surface layer of a continuous medium (these tubules seem to be assembled from smaller tubules but in our case the resolution of fine structure of the 'embedded' tubules is not sufficient). Typical examples of such tubules are shown in Figs. 4 and 5.

## 3. Macrotubules in tokamak plasmas

Major evidences for the rigid-body tubular LLFs of macroscopic size found in plasmas of tokamaks TM-2, T-4, T-6 and T-10 are given in [4;6]. The typical LLF is a straight cylindrical formation varying in length from few centimeters up to the diameter of the plasma column. Mostly, the tubular LLFs are found at the periphery of the plasma column, however, similar structures in the central hot plasma are found as well. Such an LLF of few centimeters diameter resembles a cable: it has a distinct inner cylinder of few millimeters diameter and an axisymmetric tubular sheath, with a distinct boundary and, often, intricate coaxial structuring.

The main stress in [4;6] is made on the identification of straight LLFs directed nearly radially (i.e. in tokamaks, across a strong magnetic field) as this suggests the possibility of a direct (non-diffusive, non-local) energy transport toward plasma core. The apparent rigidity of wild cables suggests the necessity to introduce a separate, 'network' component which penetrates the conventional, 'fluid' component.

Here, we present a couple of typical examples of tubules with the cartwheel in the edge cross-section

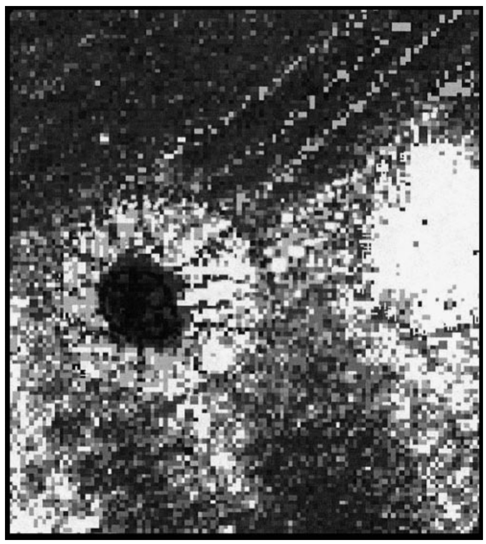

Fig. 6. Tubule with the cartwheel at the periphery of tokamak TM-2. Image is taken in the visible light with the help of a strick camera (for details of imaging see [16]). Positive, height 6.4 cm. Diameters of the entire tubular structure, inner dark circle, and darker spot inside it, are $\sim 2.5$ cm, 1 cm, and 3 mm, respectively.

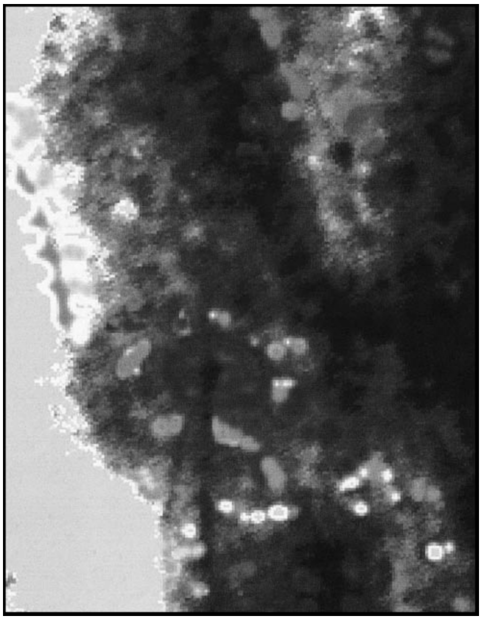

Fig. 7. Cartwheel structure in tokamak TM-2 plasma. Figure height 5 cm. Diameters of larger and smaller ring-shaped structures on a common axle are $\sim 2.2$ cm and $\sim 1$ cm, respectively. Diameter of the axle at the cartwheel's plane is $\sim 2$ mm.

of the tubule. Figs. 5 and 6 show the MDC-processed visible-light image from small tokamak TM-2 (tokamak major radius 40 cm, minor radius 8 cm, toroidal magnetic field 2 T, total electric current $\sim 25$ kA, electron temperature $T_e(0) \sim 0.6$ keV and density $n_e(0) \sim 2 \times 10^{13}$ cm$^{-3}$). It is clear that the visible light data from this, 'cold' tokamak plasma are most favorable for identification of the structuring under search.

## 4. Conclusions

The data presented suggest that (i) tokamak dust in its various forms is rich with nanoscale tubular structures; (ii) the above structures may assemble similar tubular structures of diameter up to micrometer scale length; (iii) thin films of micrometer scale thickness sometimes contain tubular structures embedded in the surface layer of a relatively homogeneous medium; (iv) the presence of distinguishable structures (namely, tubules with the cartwheel in the edge cross-section) found in tokamak dust and tokamak plasma (i.e. at very different length scales), is compatible with the hypothesis [1–3] about microsolid skeletons, assembled from carbon nanotubes (or similar nanostructures), of the observed long-living filaments in plasmas. (See Fig. 7.)

## Acknowledgements

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