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# Skeletal Structures in High-Current Electric Discharges: Observations, Hypotheses and Proof-of-Concept Studies

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The present topic arises from extending the plasma physics research to an interdisciplinary field. An attempt of the authors to interpret the results of their analyses of a wide scope of experimental data [1], accumulated in the Kurchatov Institute for various types of electric discharge (tokamaks, Z-pinch, plasma focus), revealed [2] the necessity to go beyond the frames of conventional high-temperature plasma physics. The respective extensions covered, in particular, the following fields:

(i) physics of dusty plasmas in which a new branch is found -- namely, plasmas with microdusty skeletal structures built up by a fractal condensed matter -- which radically differs from ordinary dusty plasmas which work with isolated dust microparticles of a multiple electric charge and possess the respective strong non-ideality of the plasma;

(ii) physics of nano-objects, first of all, carbon nanotubes (or similar nanostructures composed of other chemical elements and their combinations);

(iii) physics of electric breakdown which allows for the probable key role of the microdust;

(iv) physics of ultra-disperse (nano-)materials and its various applications.

The studies included the following stages:

- identification of the phenomenon of long-lived, non-chaotic filamentary structures in high-current electric discharges (the longevity, ~ 500 ns, of transverse-to-axis, long. ~ 1 cm, straight filaments in gaseous Z-pinch E-2 was shown in [2(b,c)]);
- formulation of hypotheses [2] which suggested the long-lived filaments (LLFs) in plasmas of high-current electric discharges to possess a microsolid skeleton which might be assembled during electric breakdown from wildly produced carbon nanotubes (or similar nanostructures of other chemical elements);
- verification of above hypotheses both in recent experiments or in analyzing available databases from former experiments (see below);
- analysis of anomalous properties of nanostructures, which have been assumed in hypotheses [2] about skeletal structures and received a support from the recent research in the field of nanophysics.

The proof-of-concept studies aimed on verification of hypothesis [2] gave, as a major result, the evidences for:

(i) tubularity of building blocks of skeletal LLFs, including millimeter-centimeter long LLFs in gaseous Z-pinch E-2 [3(a,d)], plasma focus LV-2 [3(a,d)], and small and moderate size tokamaks [3(b,d)]. The high-resolution visible-light images of plasma were taken by a fast-framing camera, an electronic optical converter (EOC), and a streak camera;

(ii) presence of tubular and cartwheel-like structures, in the range of diameters D ~ 100 μm - 10 cm, in the images of plasma taken by an EOC before appearance of the discharge electric current detected by the Rogovsky coil (~ 100 ns, in plasma focus LV-2, and ~300 μs, in tokamak T-6) and by laser shadowgraphy of an early, «dark» stage of discharge (10-20% of maximal current) in a vacuum spark [3(d)]; (see Figs. 1-4);

(iii) presence of tubular and cartwheel structures in various dust deposits in tokamak T-10, in the range D~10 nm -10 μm [4(a)], and the dendricity of various skeletons [4(b)], including tubular ones, that favours a streamer-like picture of assembling of skeletons.

Topological identity of above structures (especially, cartwheels), and the observed trend of assembling bigger tubules from smaller ones (i.e. self-similarity), allow us to draw a bridge between the microsolid skeletons in dust deposits and the centimeter-millimeter sized skeletal LLFs in plasmas of high-current electric discharges. In a broader frame, this supports the suggested necessity [2] to go beyond the frame of classical electrodynamics in describing the long-range, macroscopic correlations/bonds in a wide range of plasmas.

The concept of skeletons opens new opportunities for interpreting observed phenomena of nonlocal transport (cf. survey [5] for tokamaks). The presence of straight radially-directed filaments [3(a,b,d)] suggests the possibility of a direct, essentially non-diffusive transport of energy toward the plasma core (e.g., in the «wild cable» regime [3(c)]).

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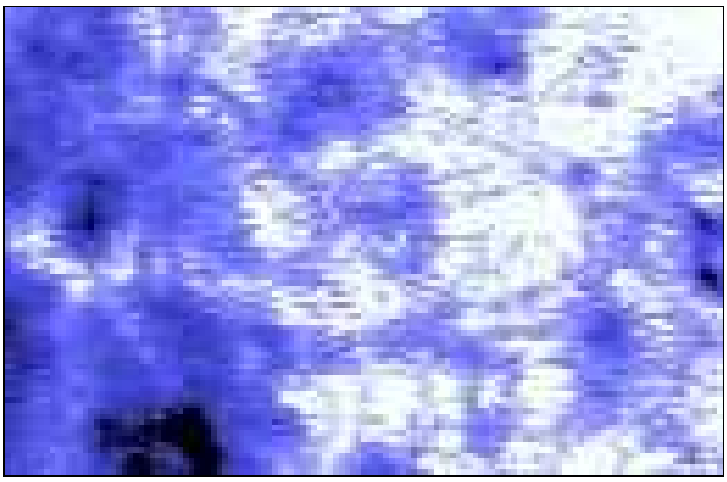

Figure 1. The elliptic image of a cartwheel-like structure (negative, image's width ~ 2.5 cm, toroidal direction - horizontal) seen in tokamak T-6 at t ~300 μs *before* appearance of the plasma electric current [6]. The image is taken by an electronic optical converter (EOC) in the framing regime (time exposure 15 μs).

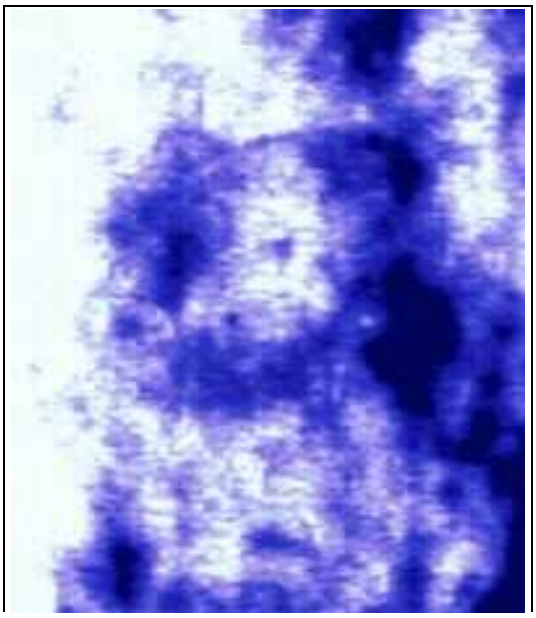

Figure 2. The elliptic image of a ring-shaped structure with a black central spot (all conditions are similar to those of Fig. 1) [6]. Image's width 2.5 cm. Large axis of the ellipse is 2.2. cm. There is also a tubular structure superimposed on the left part of the above ellipse (the lower edge of this tubule is of 6 mm diameter, and a black spot in the center of this edge is 2 mm thick).

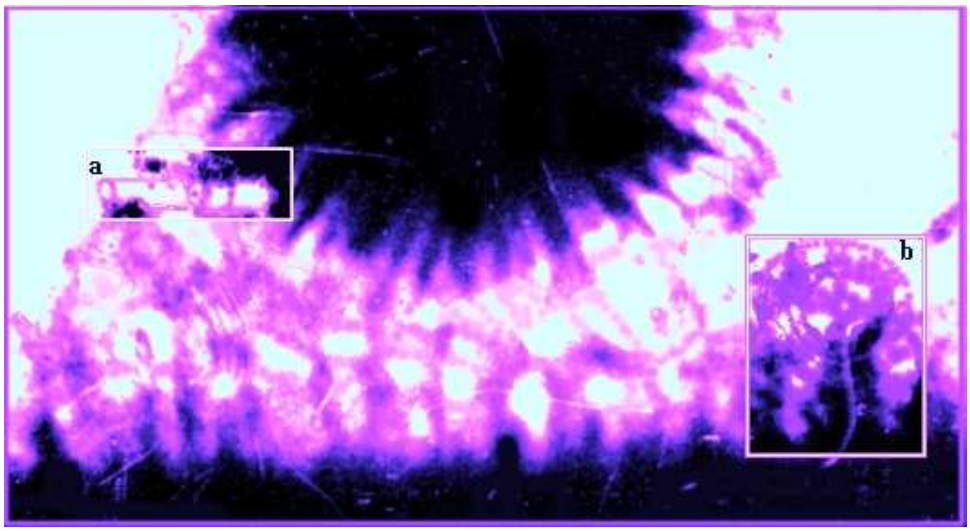


Figure 3. The tubular and cartwheel structures in a low-inductance vacuum spark (condenser capacitance 12 μF, voltage bias 10 kV, maximum current ~ 150 kA, period ~ 5 μs, flat cathode with central hole of diameter 3 mm is 2 mm from a round-shaped edge of a rod anode). The image (positive) is taken by a laser shadowgraphy (pulse duration 6 ns, λ=337 nm) using an electronic optical converter (EOC), at initial, «dark» stage when plasma's self emission is not yet detectable by the EOC (at this stage the electric current is lower than 20% of its maximum) [7]. The images in the windows 'a' and 'b' are processed with a higher level of contrasting. The cartwheels are seen in the window 'b' and, as an elliptic structure of a larger size, in the left hand side of the image.

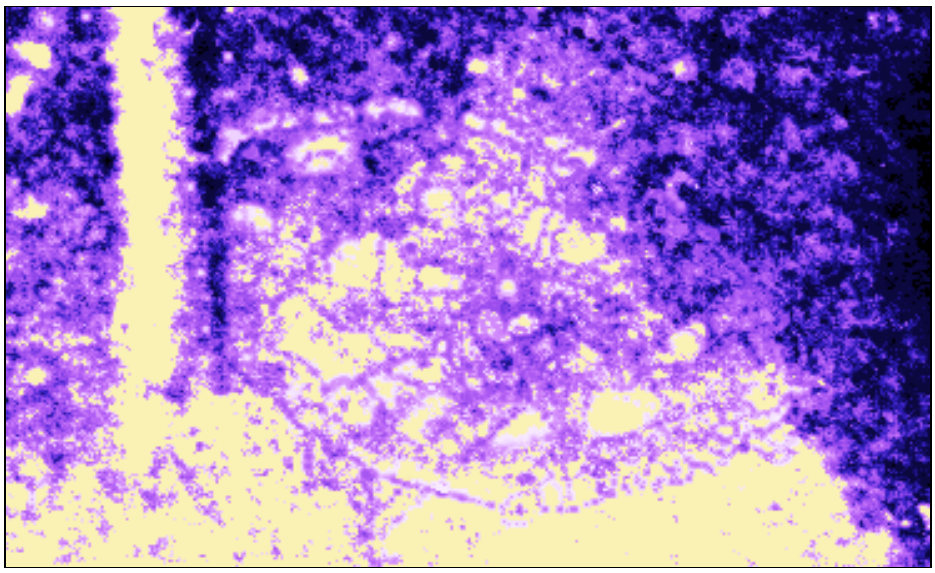

Figure 4. The tubular and cartwheel structures which are observed 100 ns *before* appearance of the electric current in the plasma focus facility [8] of the Filippov type (imaging with the help of an EOC; positive; time exposure 2 ns; image's width 4.6 cm). The structures are seen on the background of the annular vertical porcelain insulator whose left edge is seen at the left hand side of the image as a vertical white band (the mushroom-shaped anode is located upper than the image's top, and the bottom of the cathode chamber is near the image's bottom).