6-th Symposium «Current Trends in International Fusion Research: A Review», Washington, D.C., USA, March 2005

EVIDENCES FOR AND THE MODELS OF SELF-SIMILAR SKELETAL STRUCTURES IN FUSION DEVICES, SEVERE WEATHER PHENOMENA AND SPACE

A.B. Kukushkin, V.A. Rantsev-Kartinov

Russian Research Centre "Kurchatov Institute"

CONTENTS

A review is given of

1. Evidences for self-similar structures of a skeletal form (namely, tubules and cartwheels, and their simplest combinations), called Universal Skeletal Structures (USS), observed in the range 10^{-5} cm - 10^{23} cm [1] in

- **electric discharges in various fusion devices,**
- **severe weather phenomena,**
- **space**

2. Models for interpreting the phenomenon of skeletal structures

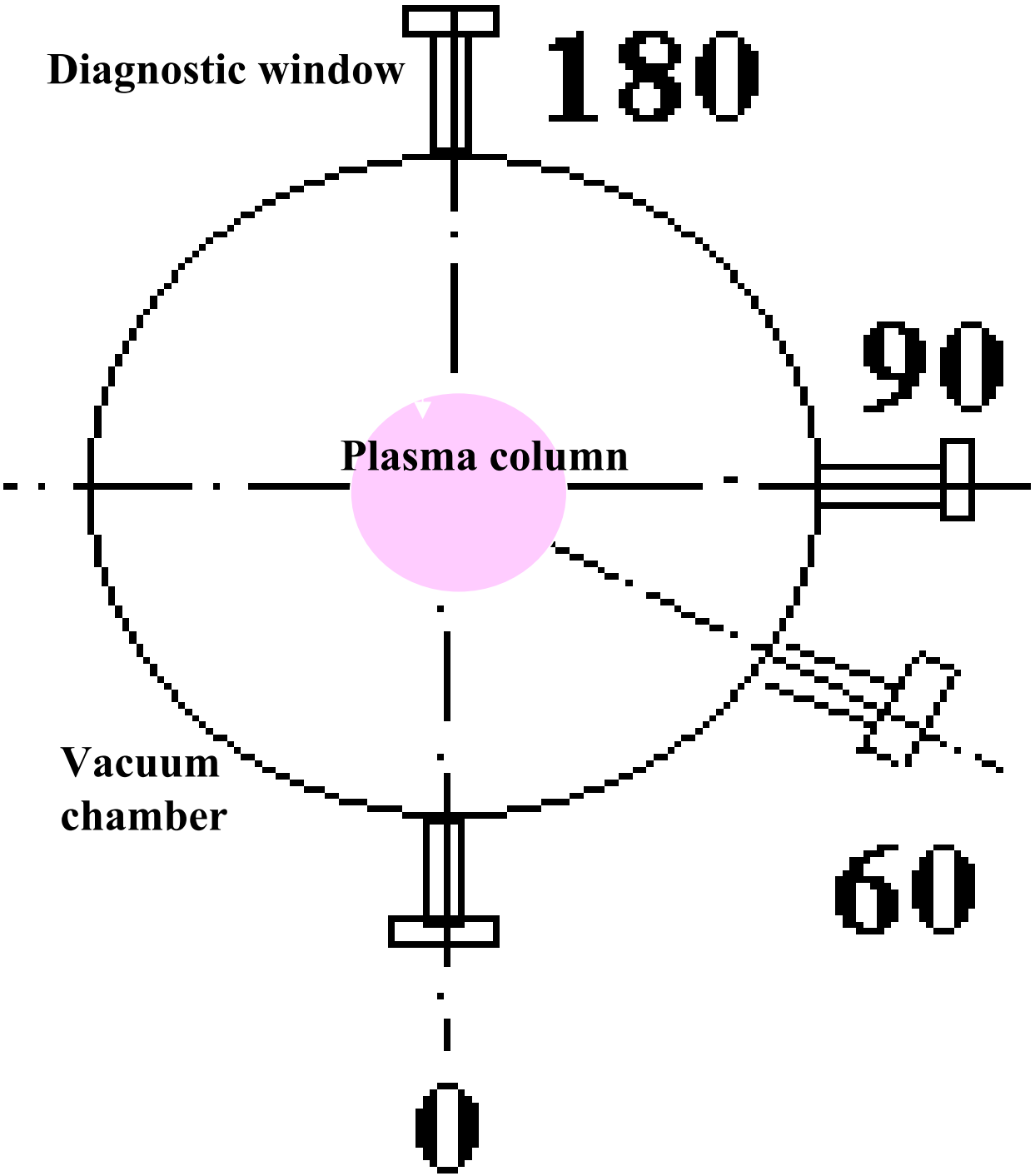
3. Probable applications -- both inside and outside the fusion science -- of a fractal condensed matter (FCM) which might be responsible for the USS phenomenon

[1] A.B. Kukushkin, V.A. Rantsev-Kartinov, Phys. Lett. A 306, 175-183 (2002).

CONTENTS-1

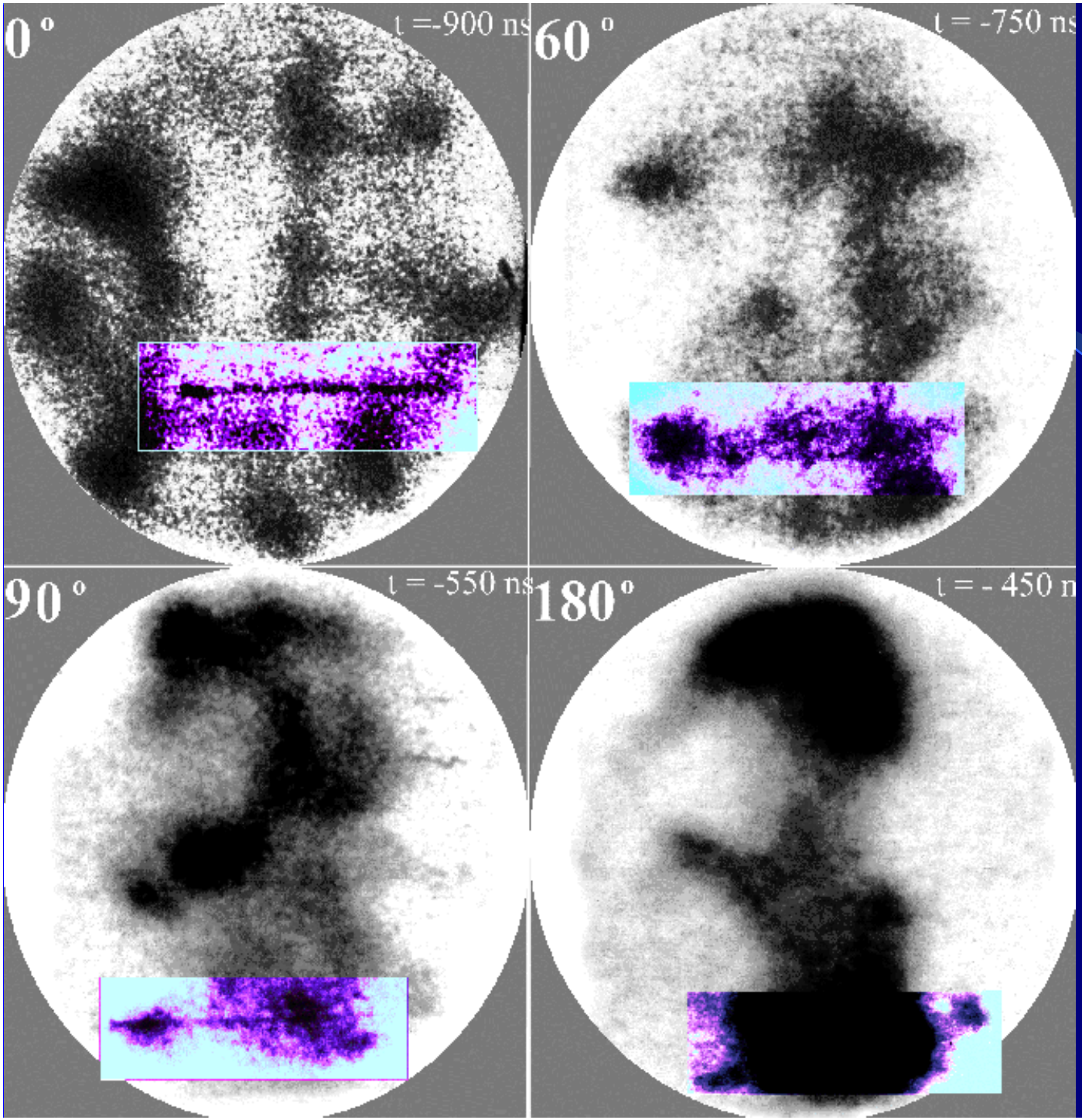
1. Evidences for self-similar structures of a skeletal form (namely, tubules and cartwheels, and their simplest combinations), called Universal Skeletal Structures (USS), observed in the range 10^{-5} cm - 10^{23} cm in

- high-current electric discharges in various fusion devices (tokamaks, including the dust deposits in tokamaks; Z-pinches, plasma foci; laser-produced plasmas),
- severe weather phenomena (tornado, hailstones, lightning-born long-lived luminous objects),
- space (supernova remnants and some galaxies of similar form, “colliding galaxies”, etc.);



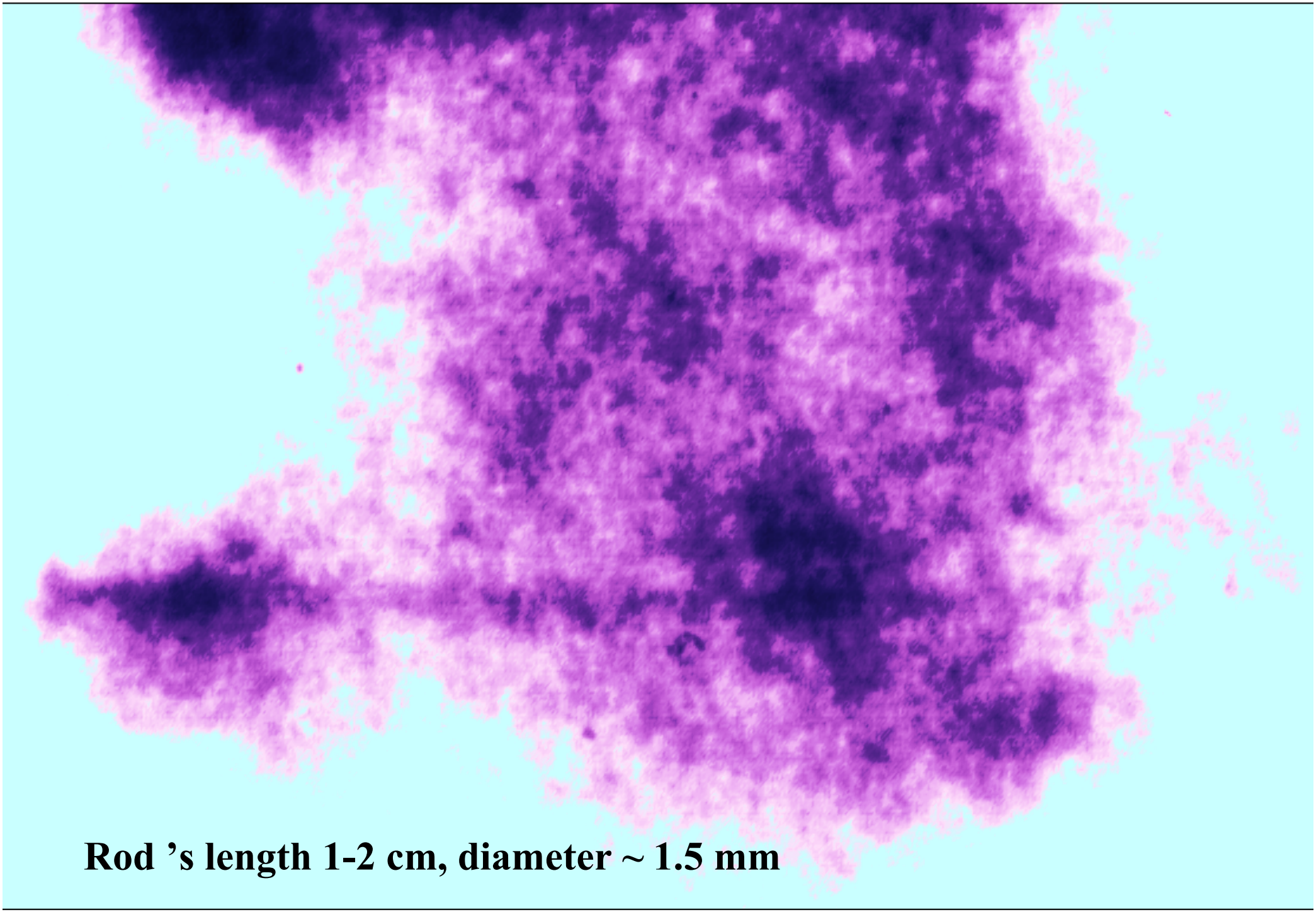
Z-pinch facility

Top view



Longevity of a straight filament in a Z-pinch.

The images of a Z-pinch taken in visible-light. The circle is produced by the geometry of the optics collecting the light. The images are taken at different time moments and different observation angles θ in the plane orthogonal to Z-pinch axis (Z-pinch axis is directed vertically; time t is counted from the major singularity of electric current derivative; circle's diameter ≈ **3 cm**; time exposure 60 ns; initial pressure of deuterium gas 1.2 torr). The windows -- of enhanced (a,b,c) and diminished (d) contrasting -- show the evolution of a rigid-body formation of a spoke-like form.



Rod ’s length 1-2 cm, diameter ~ 1.5 mm

The hypothesis of 1998 suggested the long-lived filaments (LLFs) to possess

a microsolid skeleton

which might be assembled during electric breakdown,

i.e. , prior to appearance of major plasma,

from wildly produced carbon nanotubes (or similar nanostructures of other chemical elements).

The proof-of-concept studies have shown the presence of tubular and cartwheel-like structures in the range 10^{-5} cm - 10^{23} cm [1] in

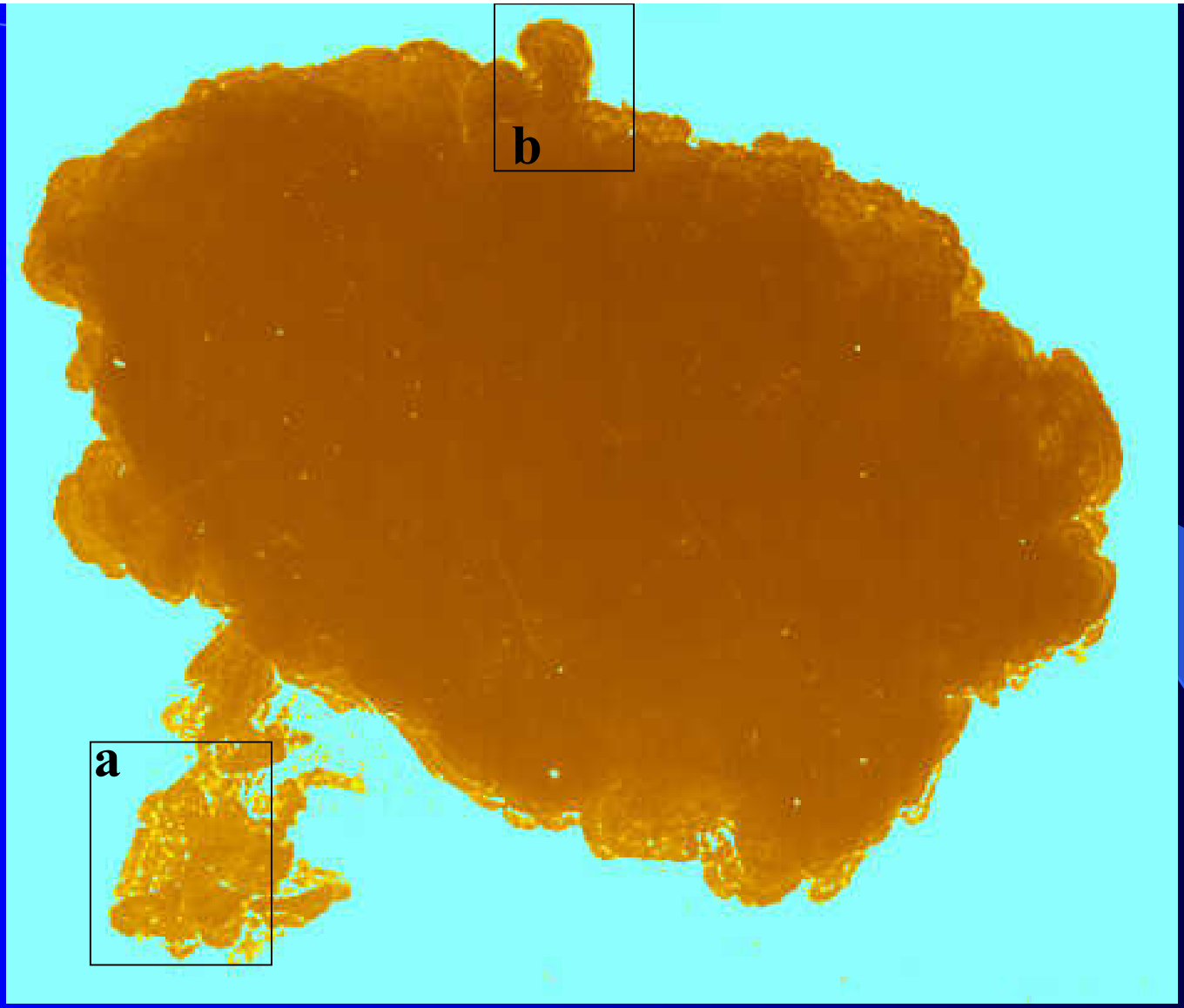
- **electric discharges in various fusion devices,**
- **severe weather phenomena,**
- **space**

Here we present a short gallery of the high-resolution images illustrating the above similarity through the entire above-mentioned range of length scales.

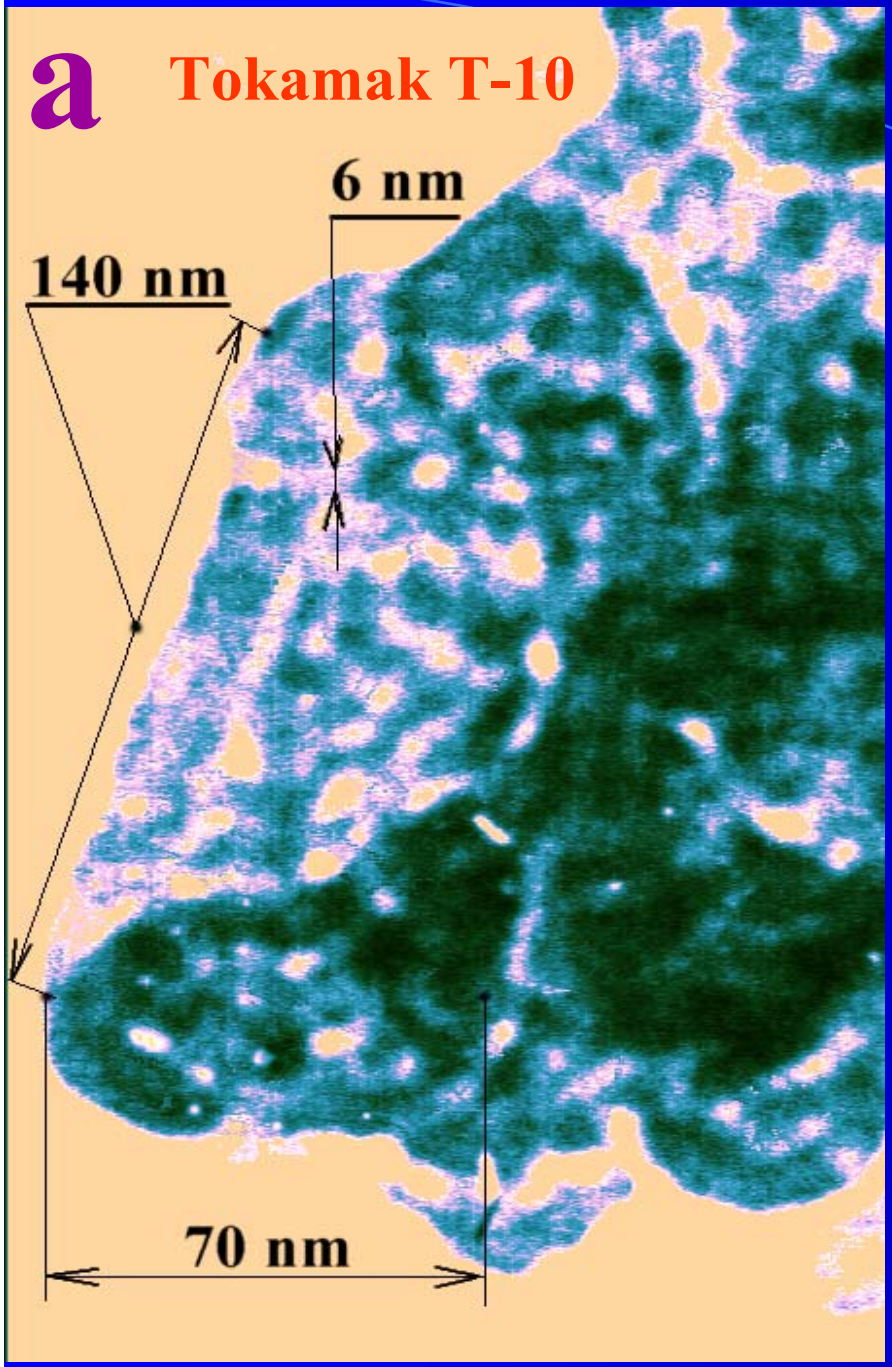
Phenomenon of universal skeletal structures (USS) in laboratory high-current electric discharges, severe weather phenomena, and space

Size (cm)	10^{-6}-10^{-3}	~10^{-2}-10	~1-10	10^{3}-10^{5}	~10^{11}-10^{23}
Univ. Skelet. Struct. (USS)	Dust deposits in toka-mak	Electric discharge in tokamaks, Z-pinches, plasma foci, vacuum spark, laser plume	Hail-stones	Tor-nado	Solar coronal mass ejection; supernova remnants; some galaxies
Data source	TEM, SEM images +	Optical and x-ray imaging* of plasma (electronic optical converters, streak camera, Kerr cells)	Photo	Photo, video	Space telescopes (optical, x-ray)

(+) Transmission/scanning electron microscopy.
(*) Including the images taken at *electric breakdown* stage of discharge in tokamak, plasma focus and vacuum spark

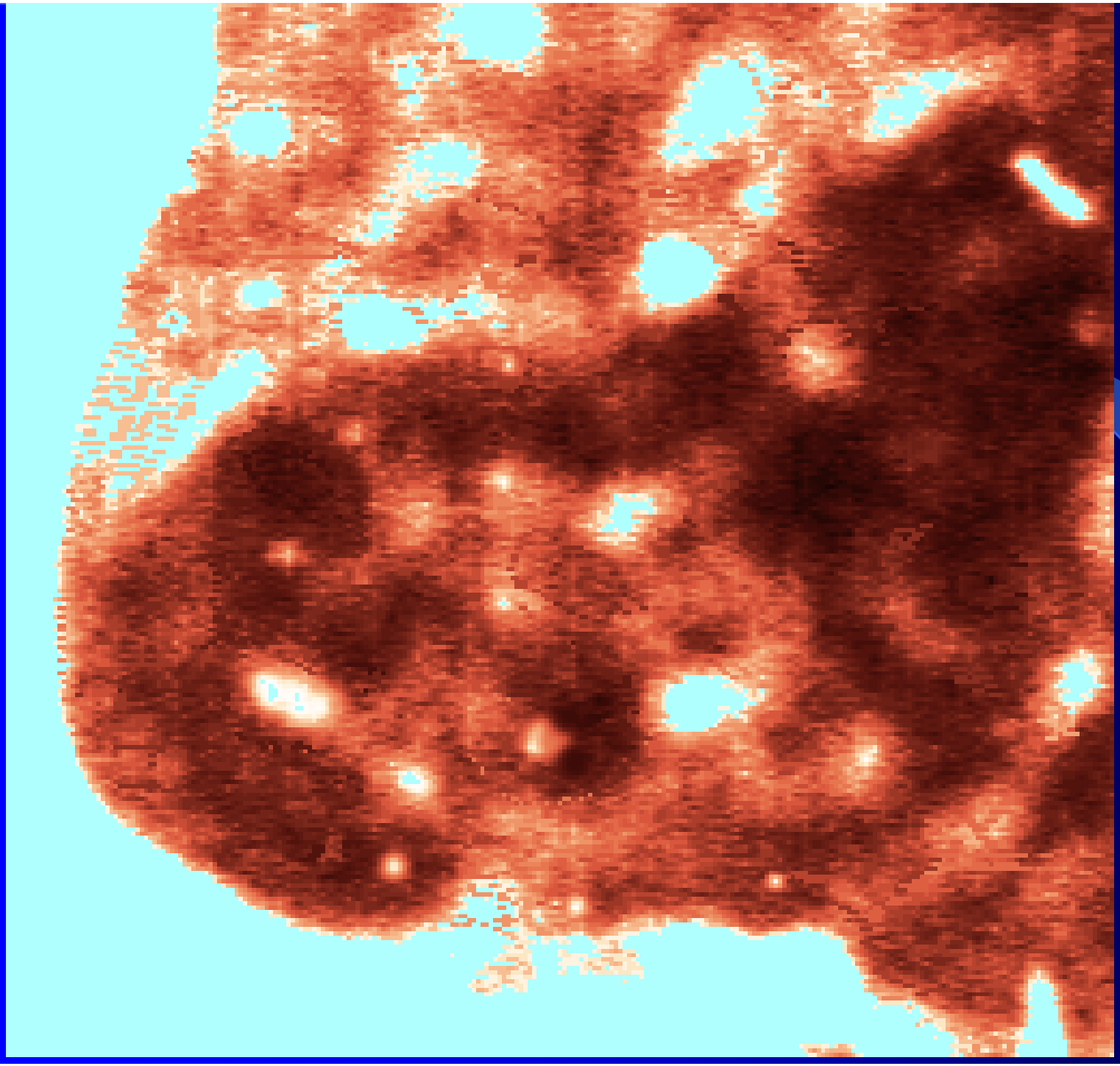


The TEM image (magnification 34,000) of a dust particle, of ~1.2 micrometer diameter, extracted from the oil used in the vacuum pumping system of tokamak T-10.

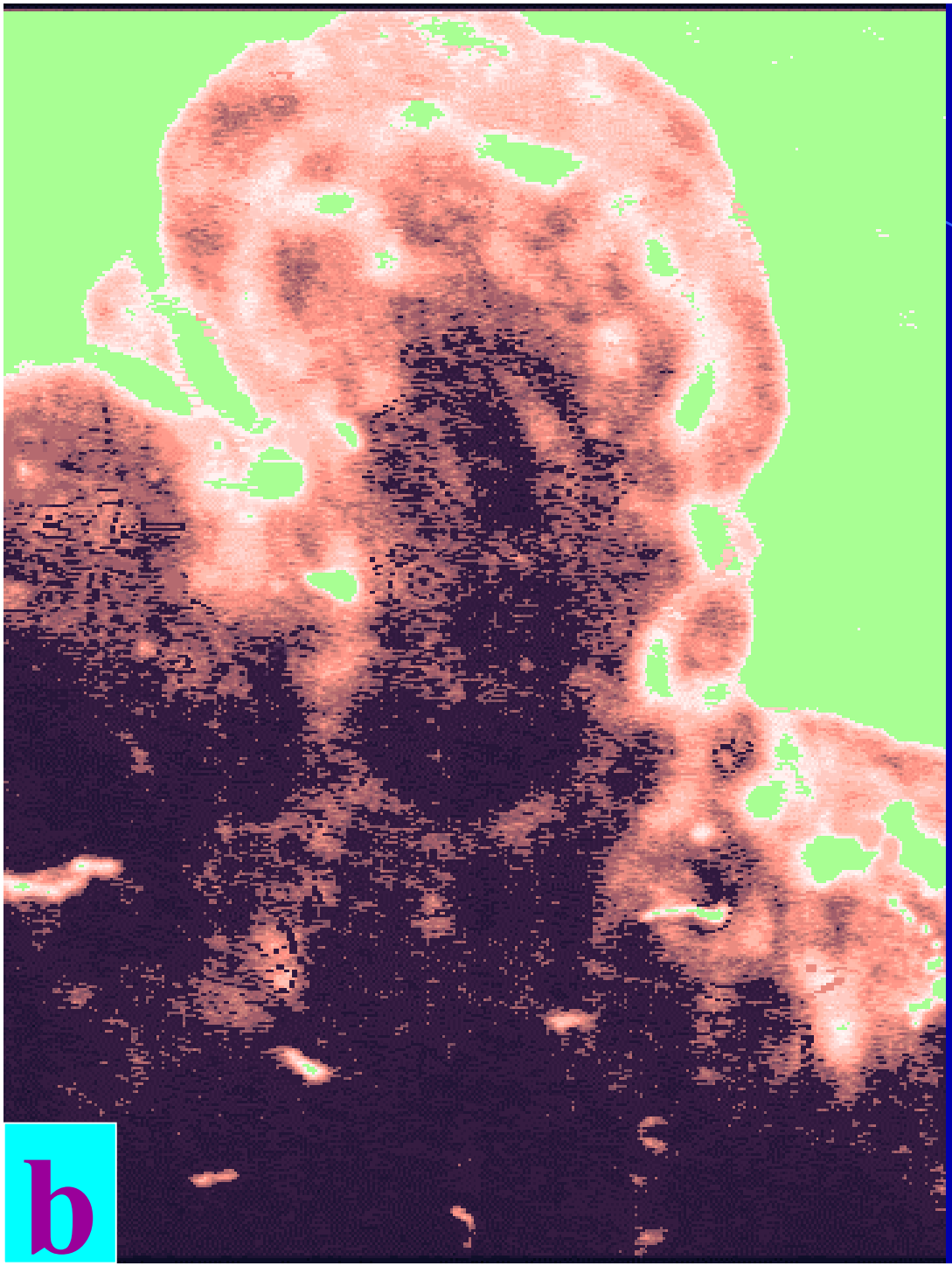


The TEM image (magnification 34,000) of a small fragment of the **dust particle**, of ~1.2 micrometer diameter, extracted from the oil used in the vacuum pumping system of **tokamak T-10**. Image's **height 270 nm.** The tubule whose edge with the distinct central rod is seen in the lower left part of the figure, is of **~70 nm** diameter and **~140 nm** long.

The central internal rod plays the role of a trunk because the radial links exist not only in the edge cross-section of the cartwheel but also between the trunk and the side-on tubules in the intermediate cross-sections. Thus, the tubular building block seems to be such a particular product of a general dendritic mechanism, which gives the *optimal* building block for the buildup of skeletal objects of macroscopic size (note that just tubular blocks were suggested [1] to be responsible for the self-similarity of macroscopic skeletons).

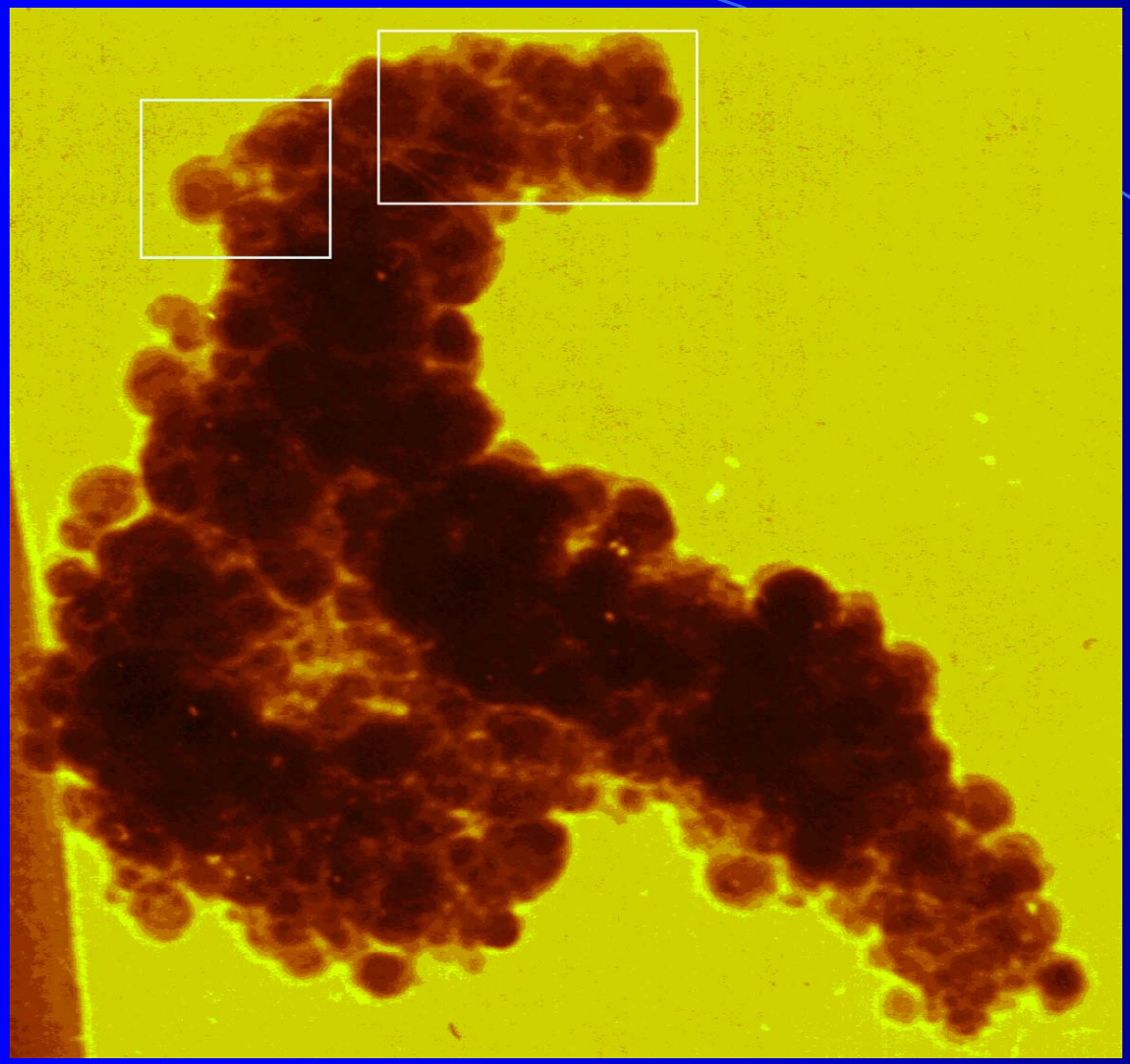


The lower edge of a tubular structure seen in the previous figure

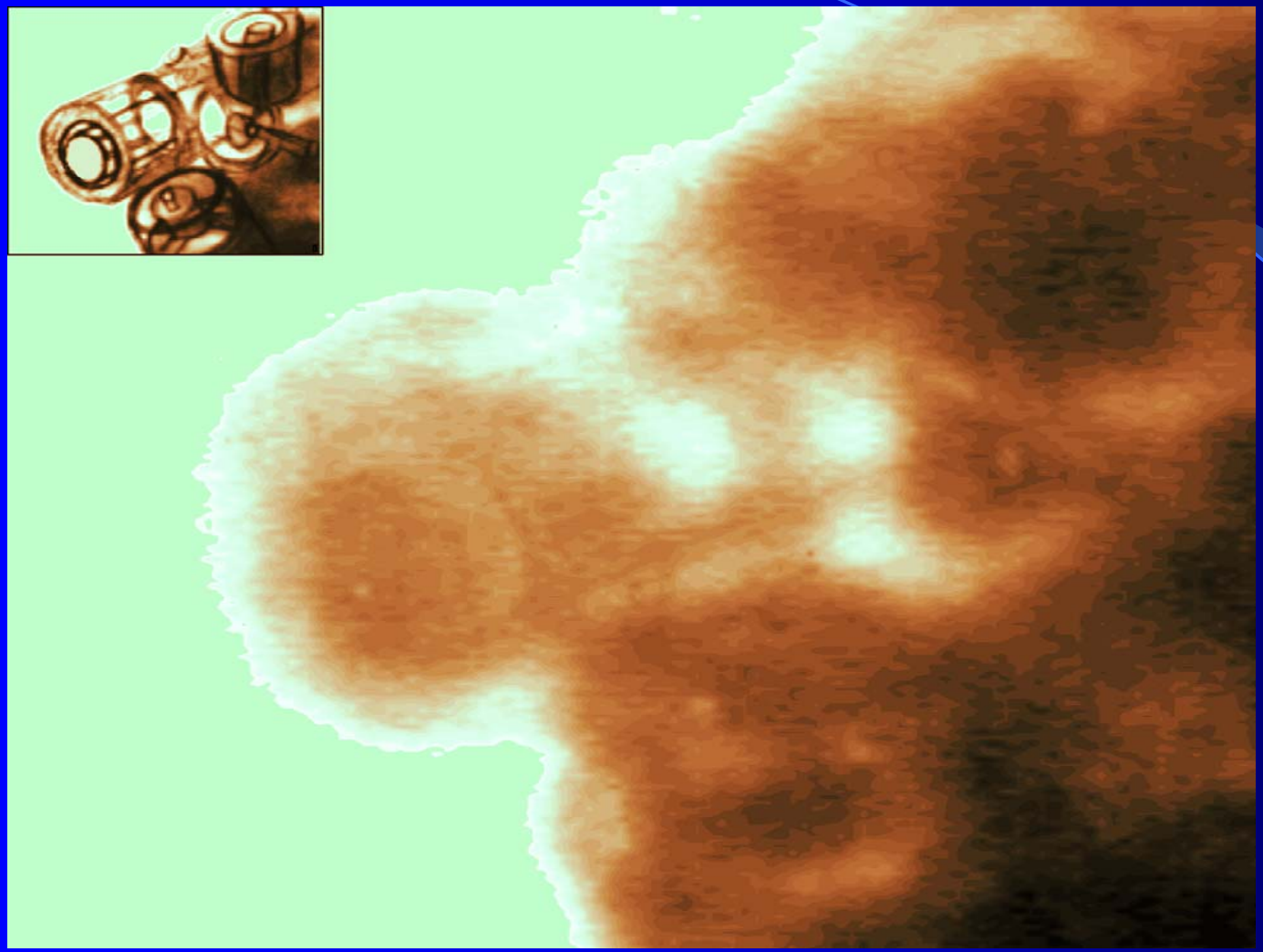


Tokamak T-10

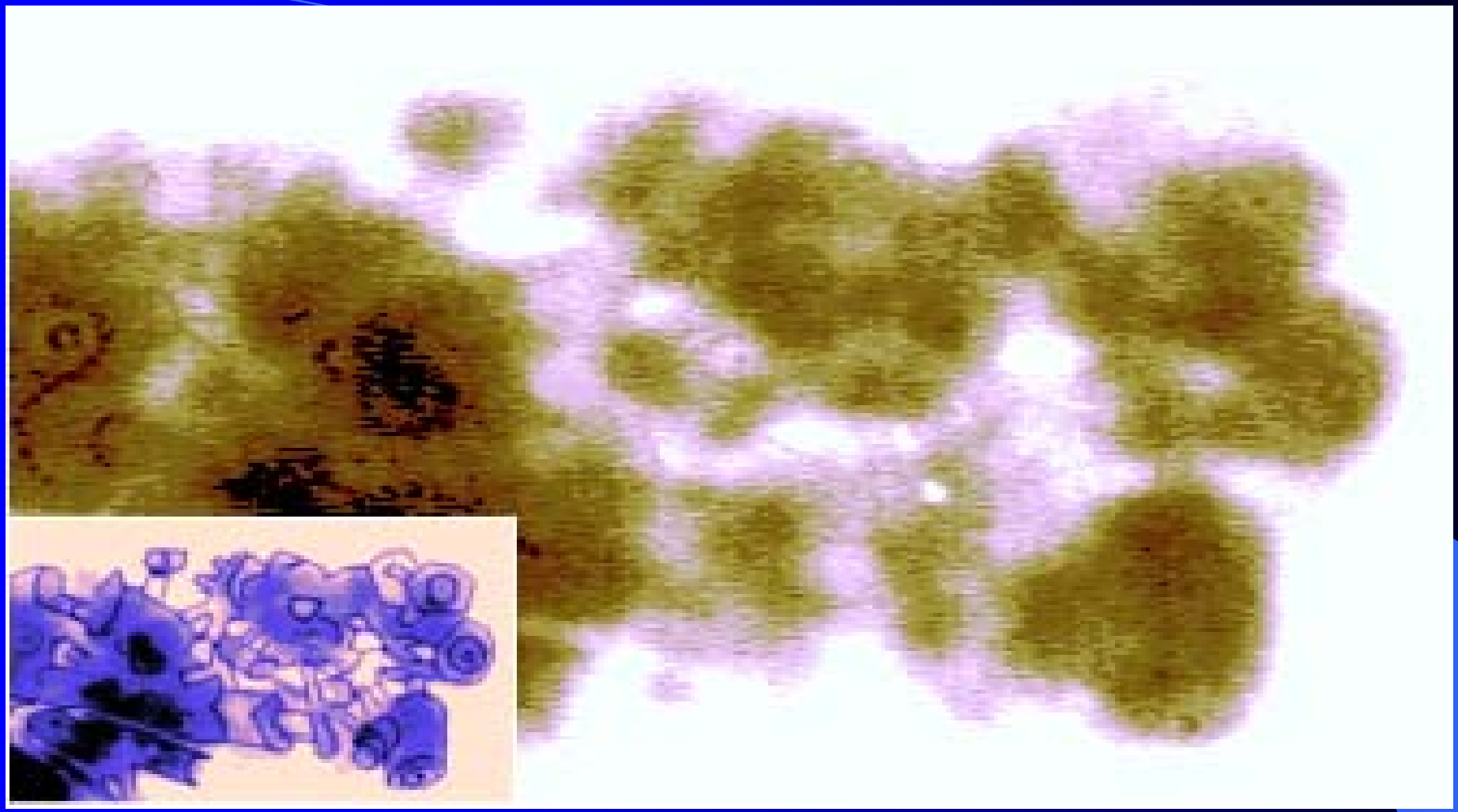
Another fragment of the same dust particle. The cartwheel (namely, a coaxial two-ring structure, D ~ 100 nm) is declined with respect to image's plane and located on a thick rod (which probably "works" as an axle of the cartwheel).



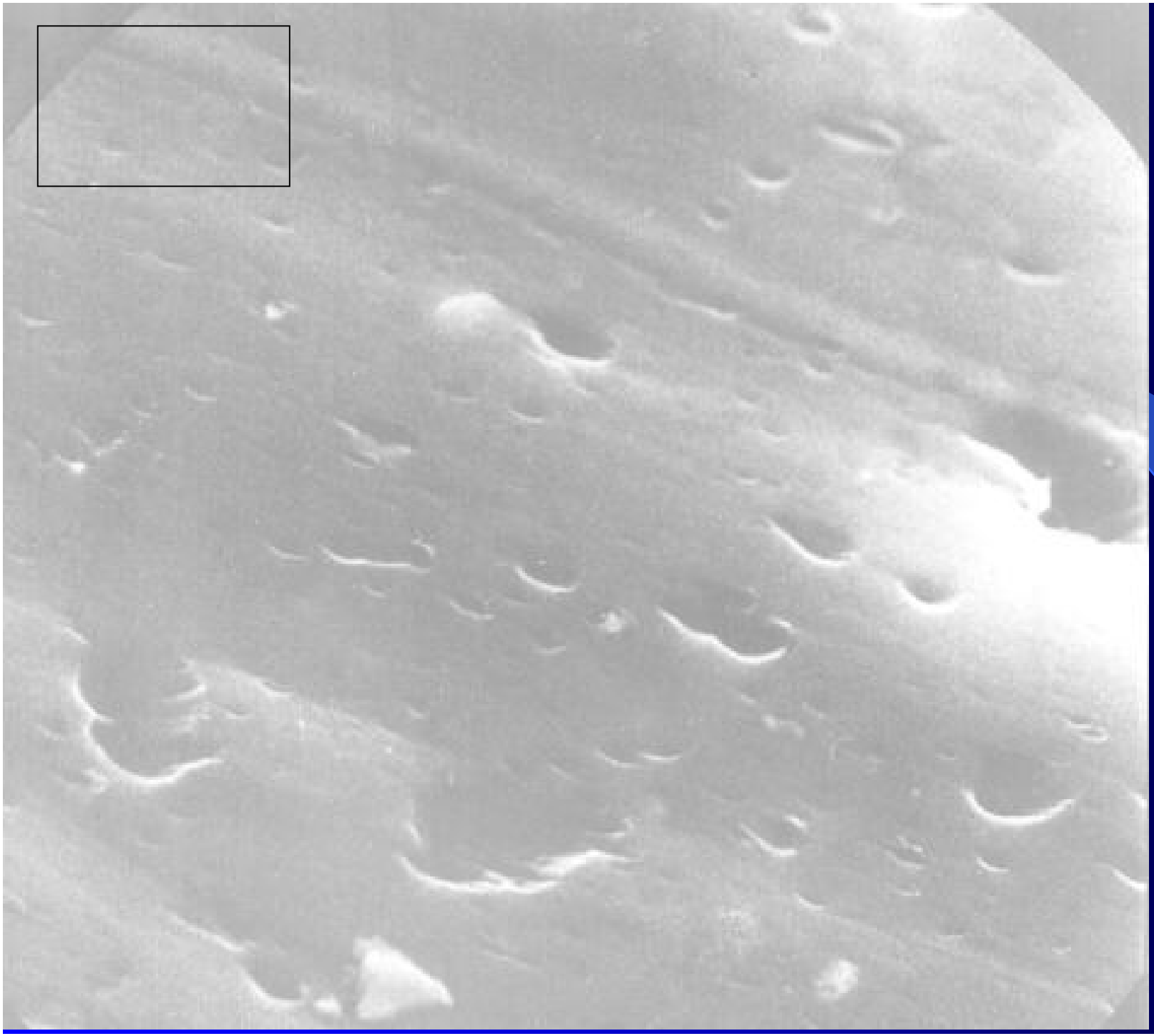
The TEM image (magnification 26,000) of an agglomerate of visually separate dust particles redeposited at a glass fiber of the filter during vacuum suction of the dust from the crimp in the tokamak T-10 vacuum chamber (the fiber is partly seen as a black band on the left hand side of the image). Figure width **590 nm**. The magnified images of the windows are given below.



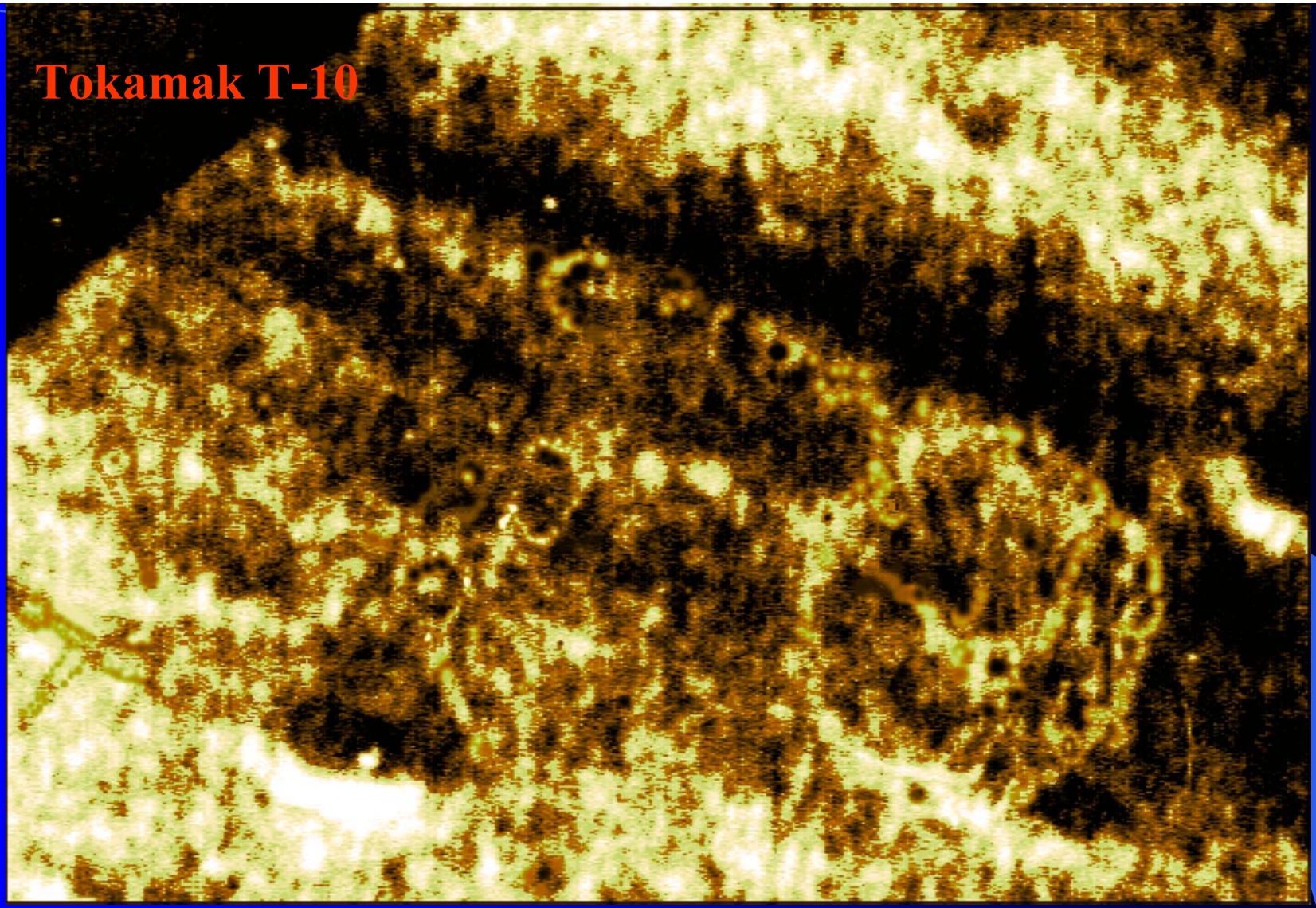
The left upper edge of the agglomerate from the previous figure. The visually separate, quasi-spherical particle appears to be a projection of the edge of a tubular structure (d ~ 30 nm) which is a part of the skeletal structure of the agglomerate. Figure width ~120 nm. A schematic drawing shown in the frame in the left upper corner is obtained with the help of a mosaic MDC method (see Sec.2 in [2(b)]).



The right upper edge of the above agglomerate. It shows a bunch of dendritic structures (presumably, cartwheels on their own axle-trees). Figure width is ~180 nm. A schematic drawing shown in the left lower corner is obtained similarly to that in the previous figure.



The SEM image (magnification 2,000) of the surface layer of the film deposited at the internal surface of the T-10 tokamak chamber. Figure height ~ 90 μm. The magnified image of the window is shown below.



The scanning electron microscope (SEM) image (magnification 2,000) of the surface layer of the **film** deposited at the internal surface of the **tokamak T-10** chamber. Figure height is ~15 μm. Diameter of the tubular structure, whose edge is seen in the right lower part, is **~5 μm**.

30th EPS Conference on Contr. Fusion and Plasma Phys., St. Petersburg, 7-11 July 2003
ECA Vol. 27A, P-2.75

First Results of Tokamak T-10 Investigation of Scanning Tunneling Microscope *in situ*

L.N. Khimchenko[1], M.I.Guseva[1], A.L.Suvorov[2], B.A.Loginov[2], O.N.Makeev[2]

[1]Nuclear Fusion Institute, RRC "Kurchatov Institute", Moscow, Russia

[2]Institute for Theoretical and Experimental Physics, Moscow, Russia

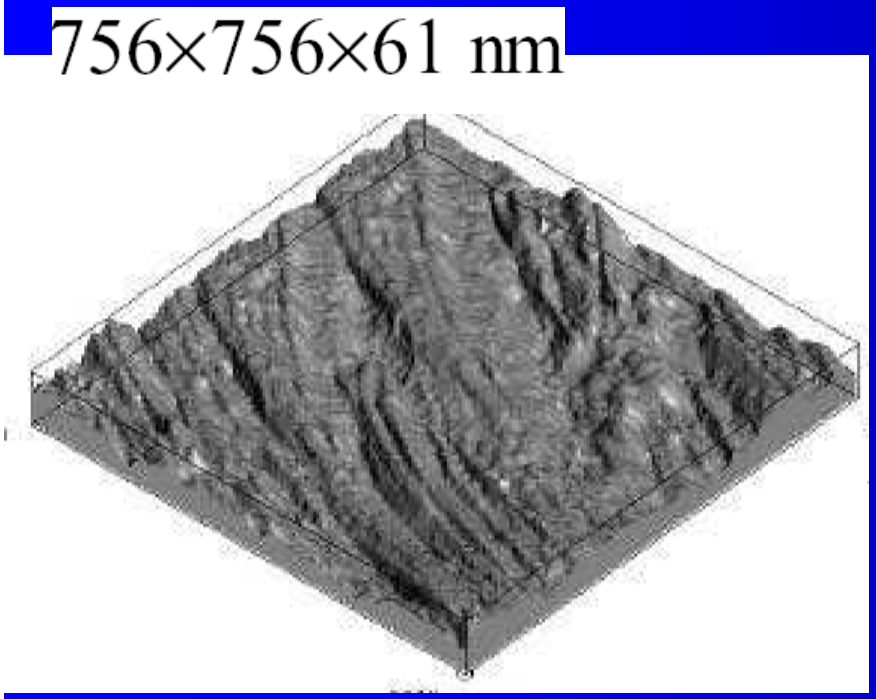
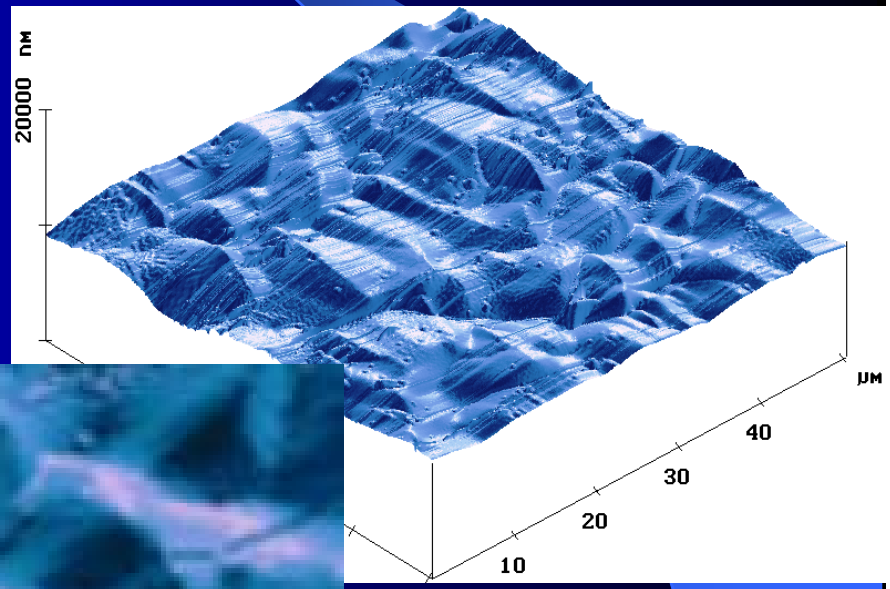


Fig.6. T-10 films, scanning by miniature STM inside the tokamak



D ~ 7 microns

D ~ 7 microns

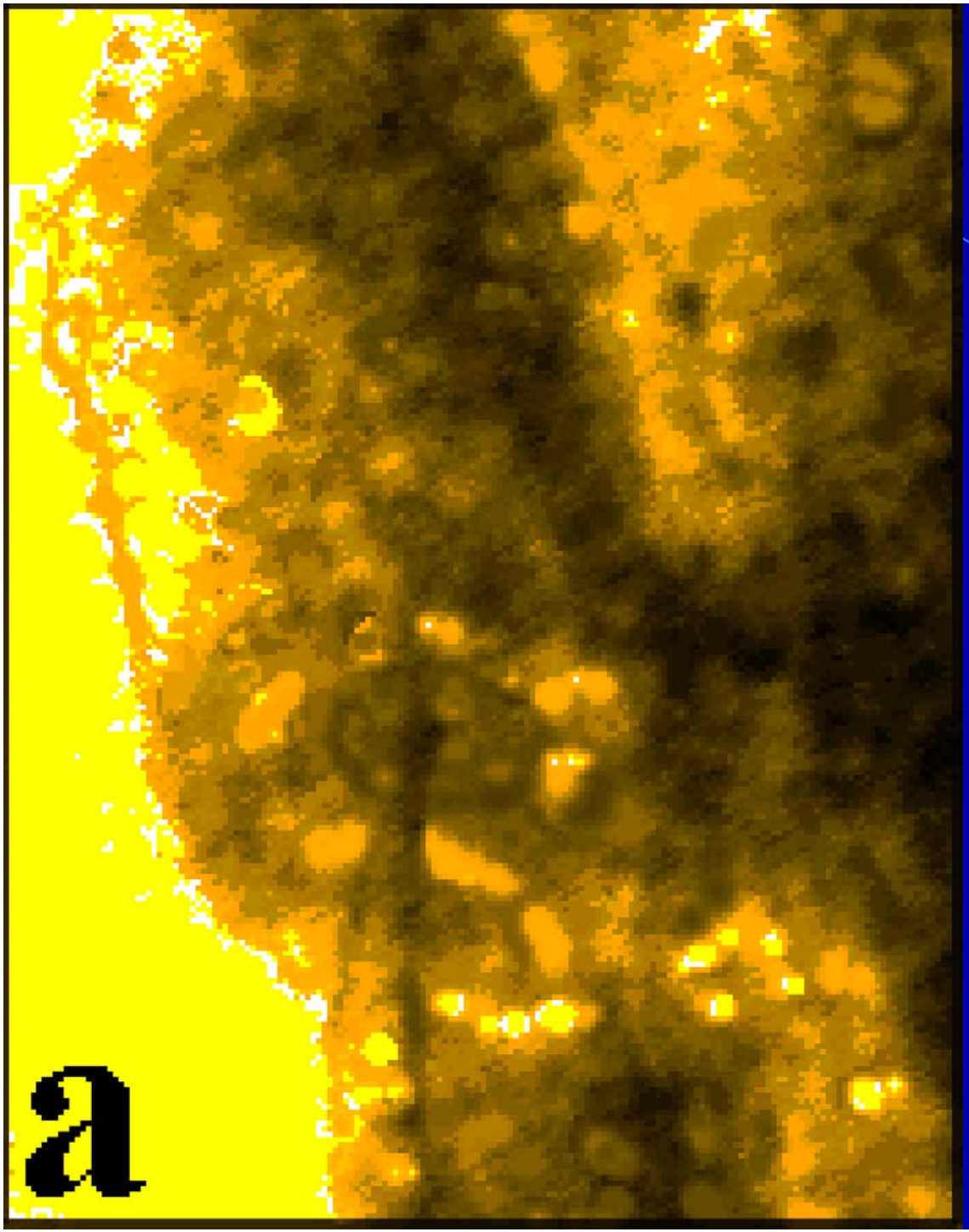
Spectroscopic studies of homogeneous thin carbon erosion films on mirrors and flakes with high deuterium content formed in tokamak T-10.

N.Yu. Svechnikov, et.al. The 23rd Symp. on Fusion Technology, Venice, 2004 (to be published in Fus. Engin. Device)

V.G. Stankevich, B.N. Kolbasov, N.Yu. Svechnikov, et al. **Thermal and Spectroscopical Characterizations of Tokamak T-10 Smooth Deuterated Carbon Erosion Films.** Int. Conf. on Materials for Advanced Technologies, Singapore, 7-12.12.2003. Publisher: Materials Research Society Singapore, Institute of Mat. Res. and Engin., paper 1-8-13P.

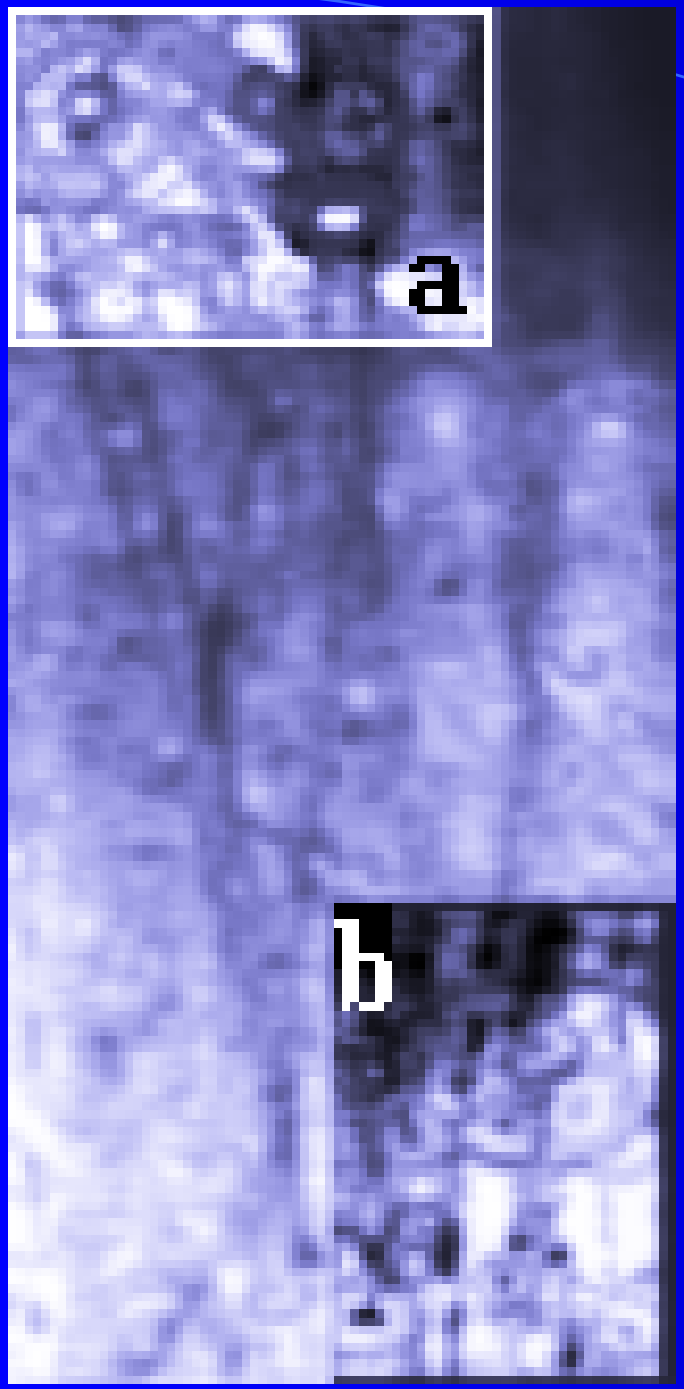
Redeposited hydrocarbon films on plasma facing elements in tokamaks accumulate hydrogen isotopes. Hydrocarbon thin films on metal mirrors and thick flakes with a high deuterium content, redeposited under D-plasma discharges inside the T-10 tokamak vacuum chamber, have been studied by means of Fourier-transform infrared (FT-IR) reflection, electron paramagnetic resonance (EPR), and photoluminescence spectroscopy.

The films from T-10 differ from conventional, gas deposition-formed films by the presence of vibration modes of CD_2, CD_3 (carbon-deuterium) and CH_{1-3}, adjoined to sp^3 bonds in graphene: there is a strong fraction of "free" graphene sheets.



Tokamak TM-2

The «cartwheel» structure in tokamak TM-2 plasma (minor radius 8 cm, toroidal direction is horizontal). Diameters of larger and smaller ring-shaped structures on a common axle are ~2.2 cm and ~1 cm, respectively. Image (positive) is taken in visible light by a streak camera with time resolution < 1 μs (original picture is taken by Vinogradova N.D., Razumova K.A. Int. Conf. Plasma Phys., Culham, U.K., 1965).

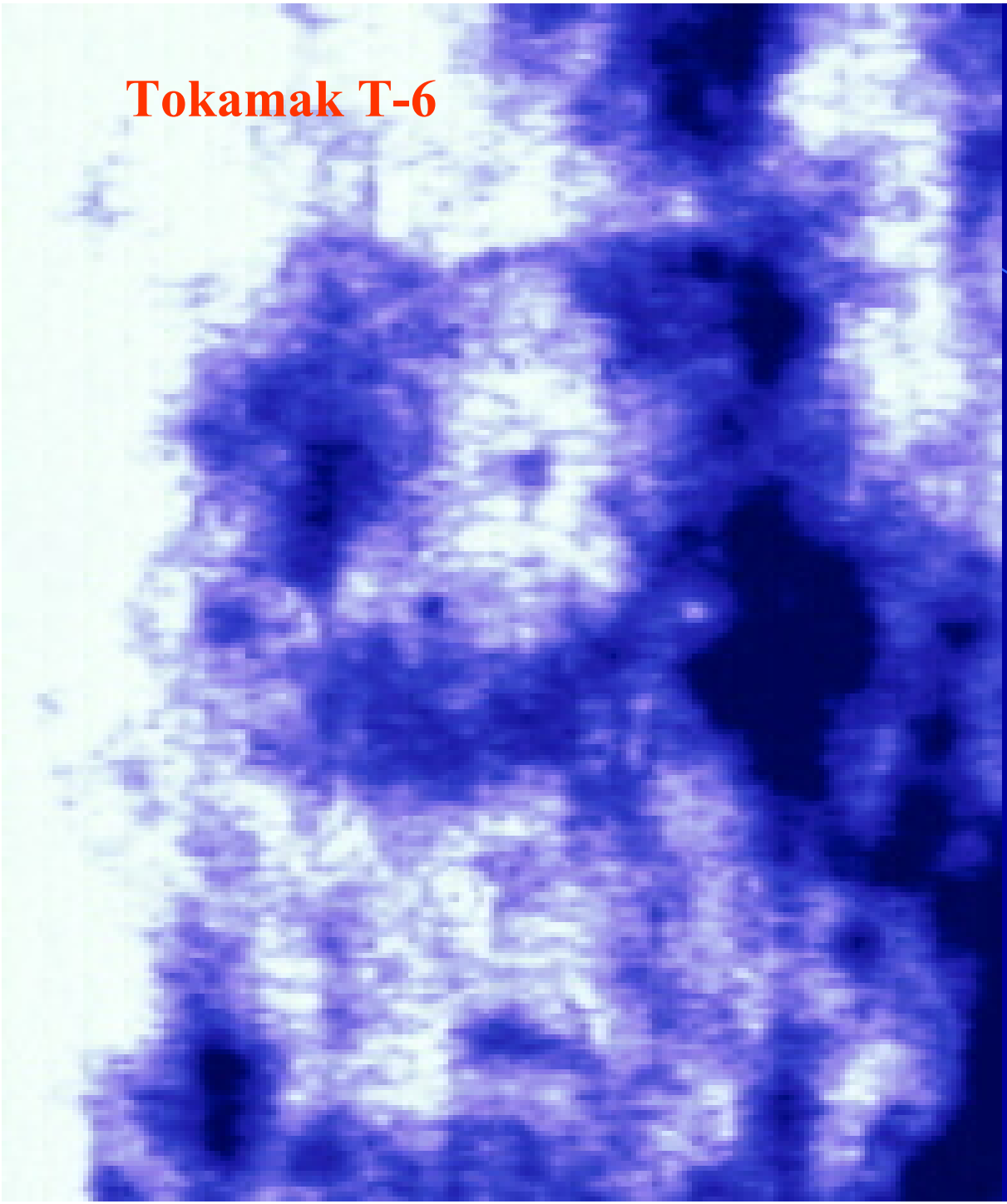


Tokamak T-10

Tubular long filaments and cartwheel structures are seen in the visible light in the far periphery of **tokamak T-10** (minor radius a = 33 cm) when illuminated by the carbon pellet emission (the pellet's track is outside the image).

Negative, image's **height is ~8.5 cm**.

Diameter of the long thick filament is **~ 3-4 mm**. The windows "a" and "b" and the residual part of the image have different levels of contrasting to show the continuity of structuring and the fine structure of the cartwheels (see, e.g., a cartwheel in the left upper corner of window 'a'). The cartwheel in the window 'b' is located in the edge cross-section of a vertically aligned tubular structure.

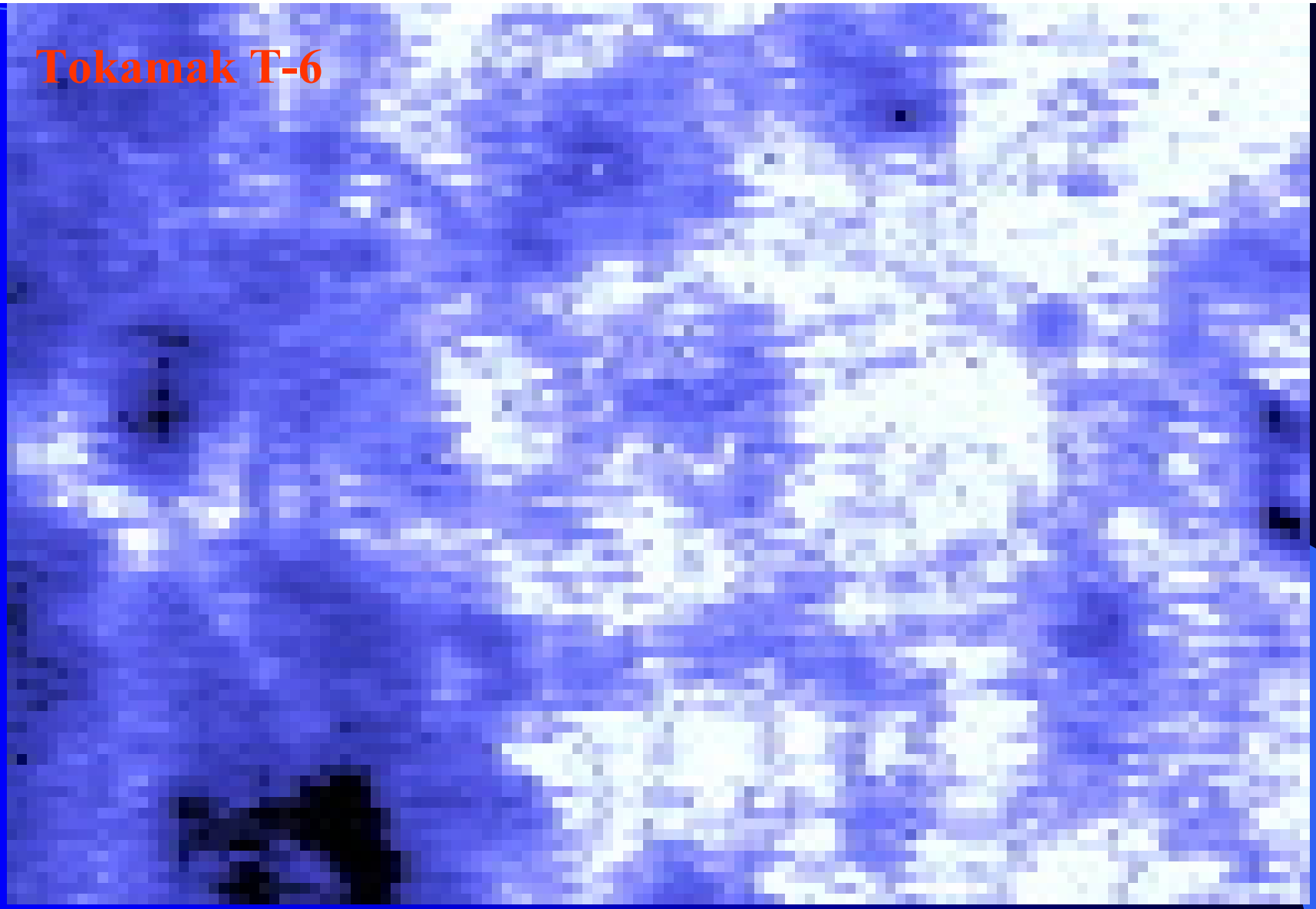


The image (negative, width 2.5 cm) is taken by an electronic optical converter in the framing regime (time exposure 15 μs) in tokamak T-6 (minor radius a= 20 cm, toroidal direction - horizontal) at t ~300 μs *before* appearance of the plasma electric current.

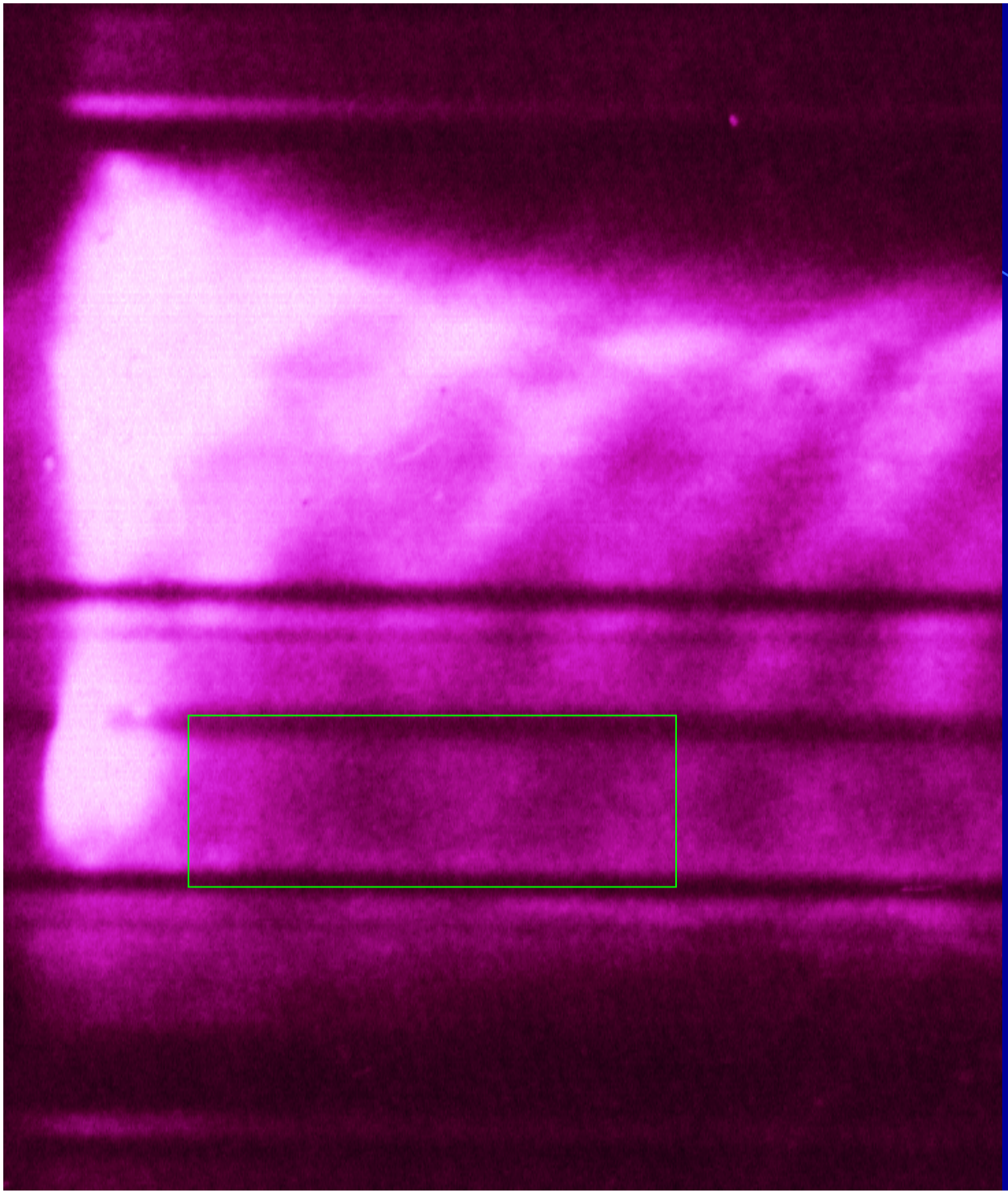
The elliptic image of a ring-shaped structure with a black central spot. Large axis of the ellipse is 2.2. cm.

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).

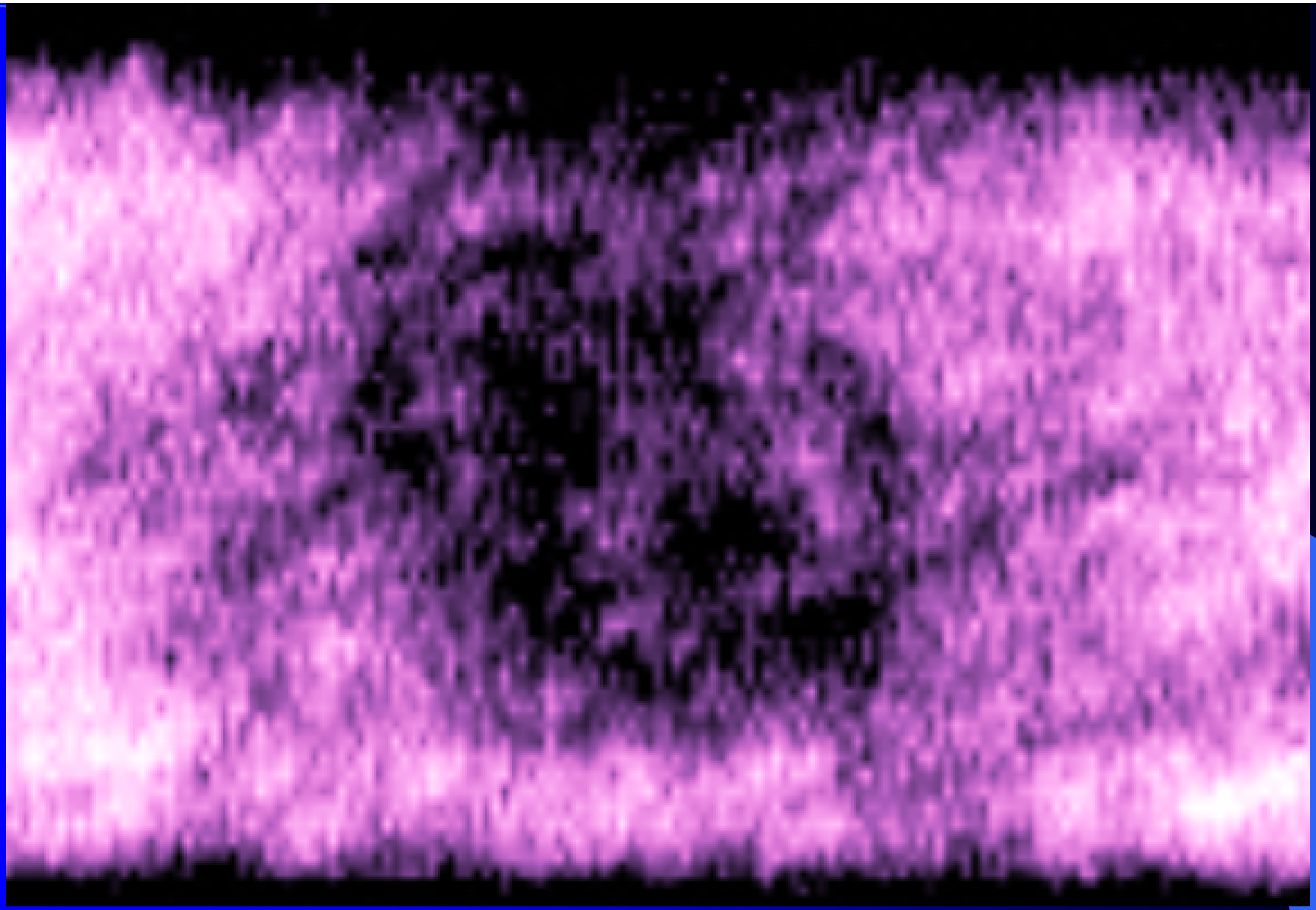
(Original data by V.A. Krupin)



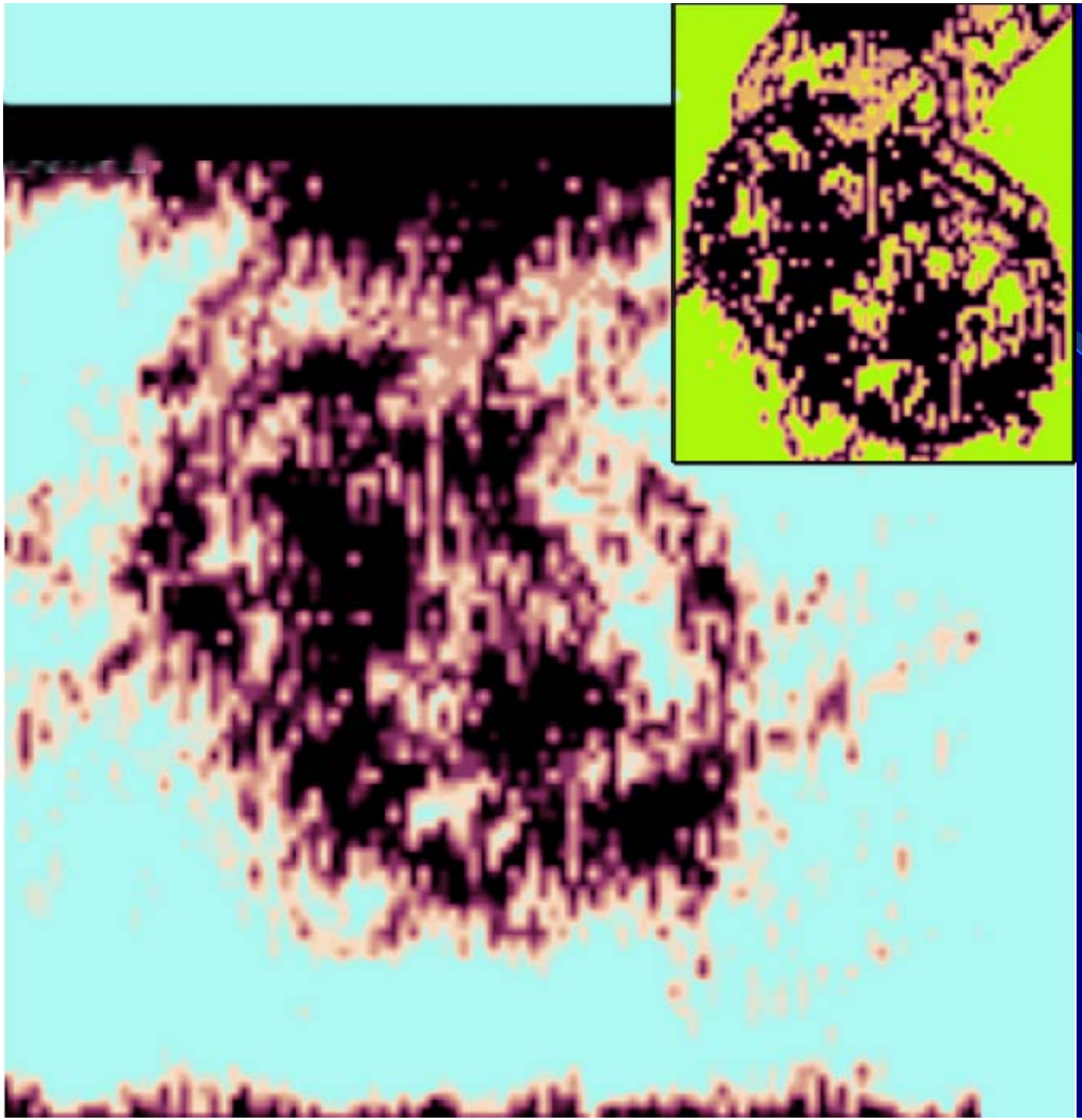
The elliptic image of a cartwheel-like structure (image's width ~ 2.5 cm, toroidal direction - horizontal) seen in tokamak T-6 (minor radius a= 20 cm) at t ~300 μs *before* appearance of the plasma electric current. The image is taken by an electronic optical converter (EOC) in the framing regime (time exposure 15 μs). (V.A. Krupin)



Tokamak T-6
Streak camera imaging
of
toroidally rotating plasma column

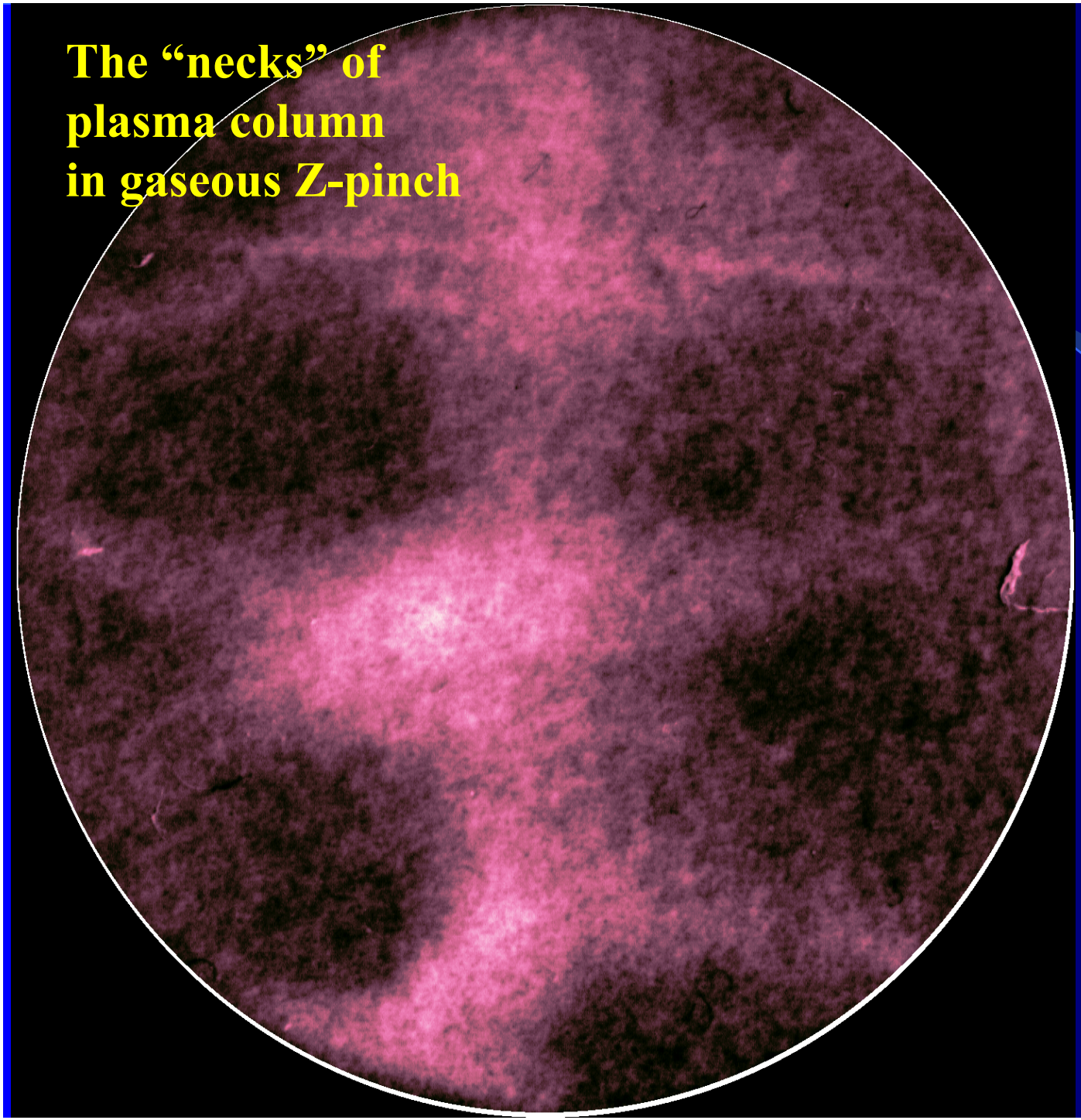


The fragment of previous image

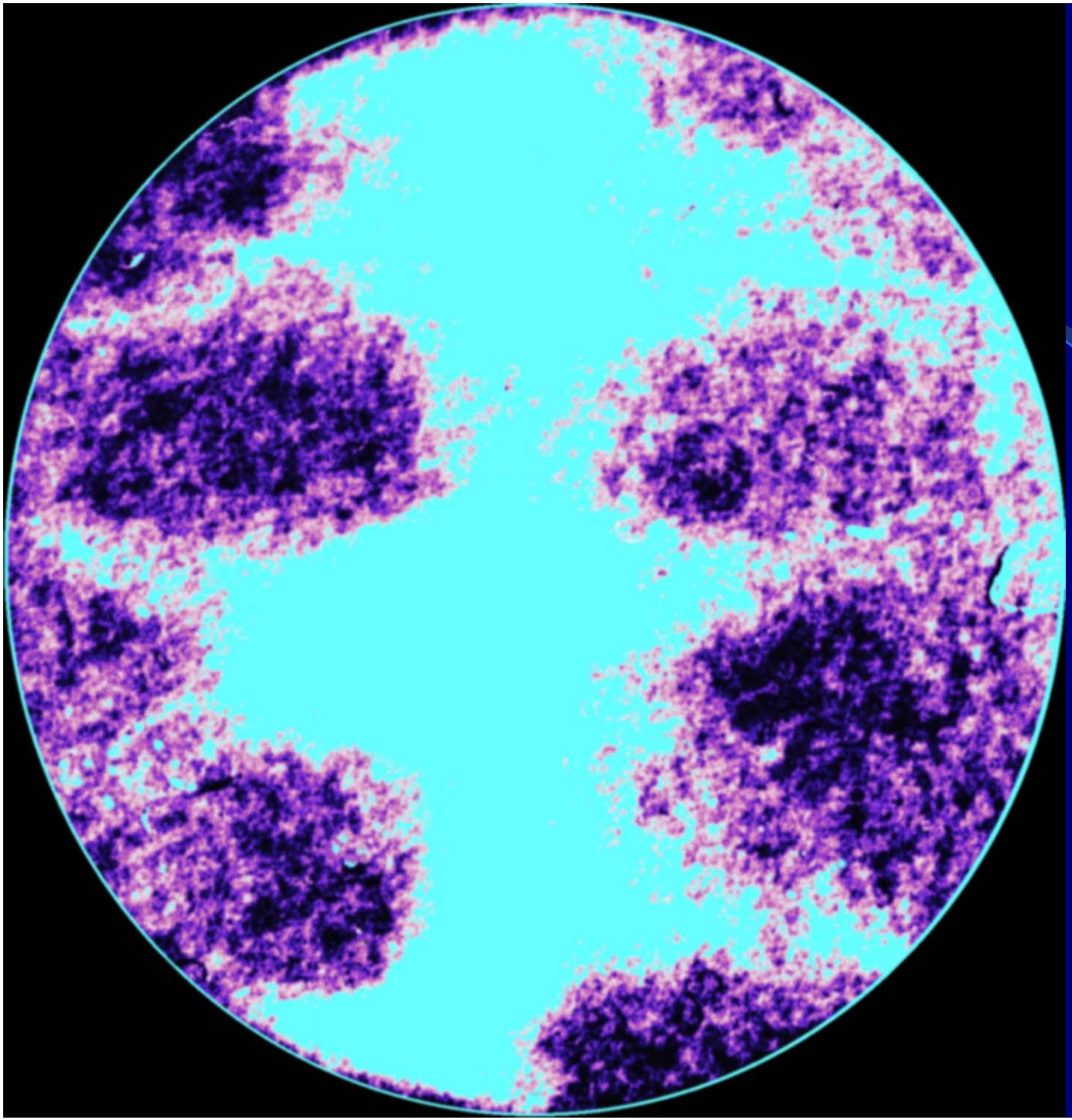


The above image is processed with multilevel dynamcial contrasting method

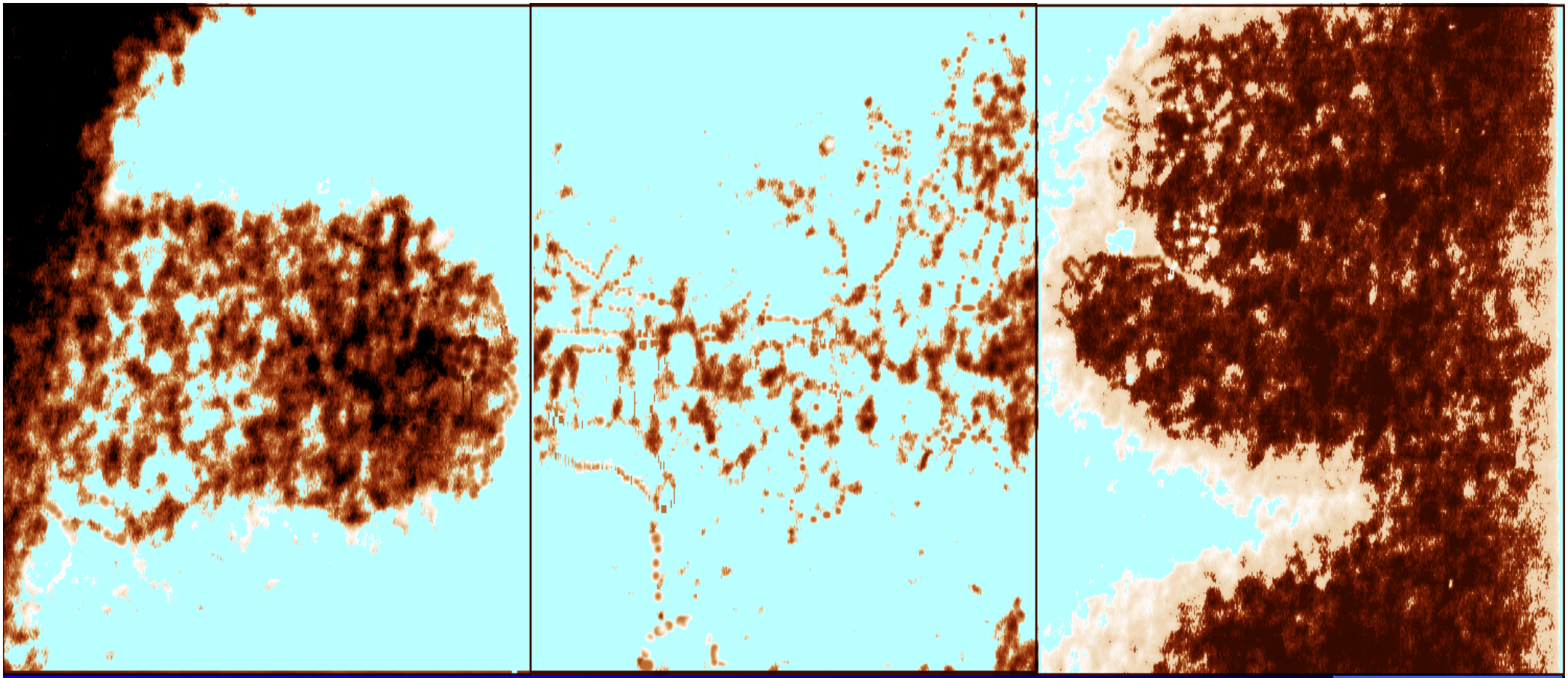
Insert: reconstruction of the structure of a filamentary formation



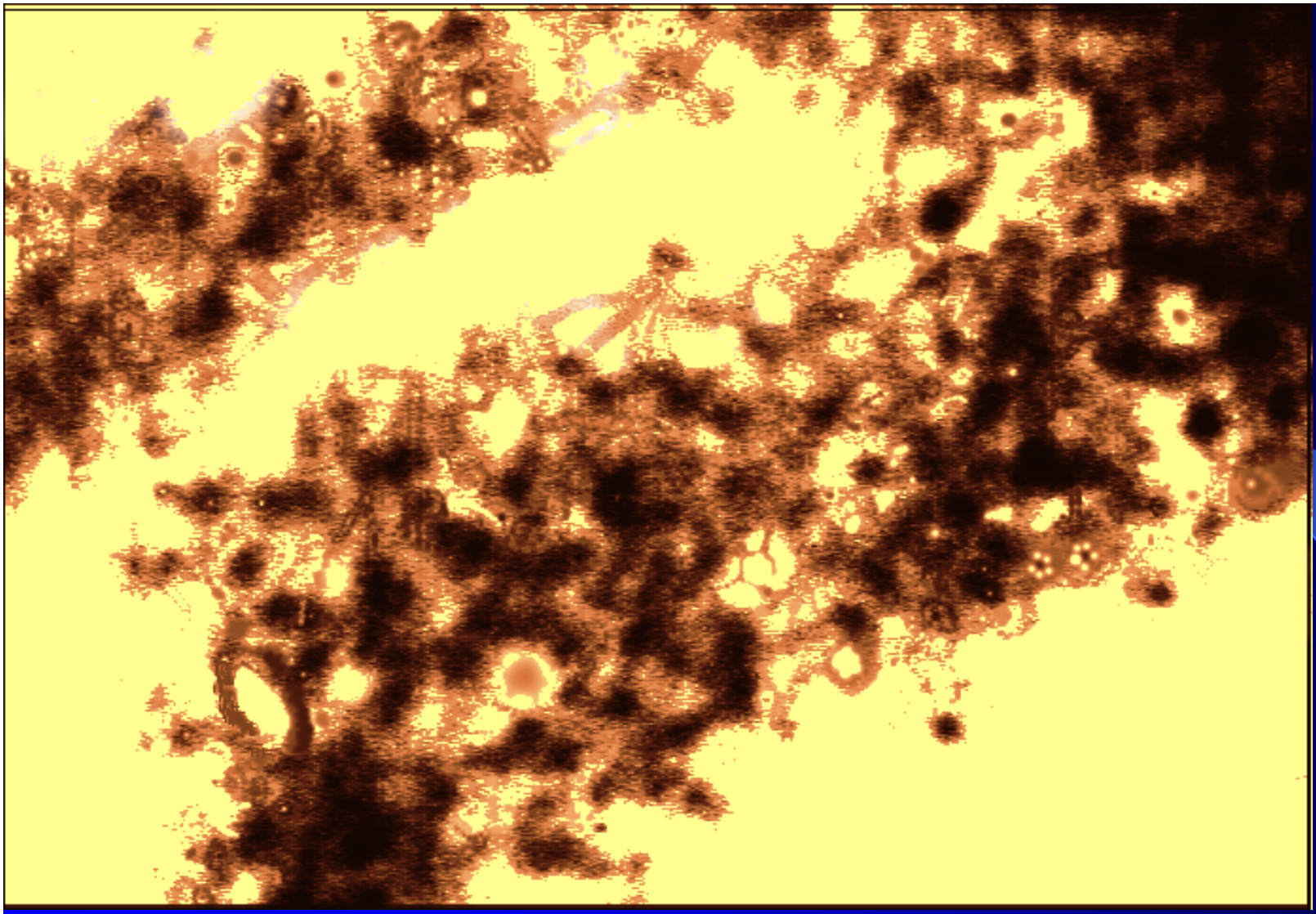
Visible light picture (positive) of a layer, 7.5 cm wide and 5 cm thick, located near the axis of a gaseous Z-pinch in the neck region at time t=+50 ns after major singularity of electric current (the layer is «extracted» by the optics collecting the light). The chamber is 60 cm long and 20 cm in diameter, major axis is directed vertically, maximal current ~ 360 kA, working gas deuterium, time exposure 10 ns



The original image is processed with the method of multilevel dynamical contrasting



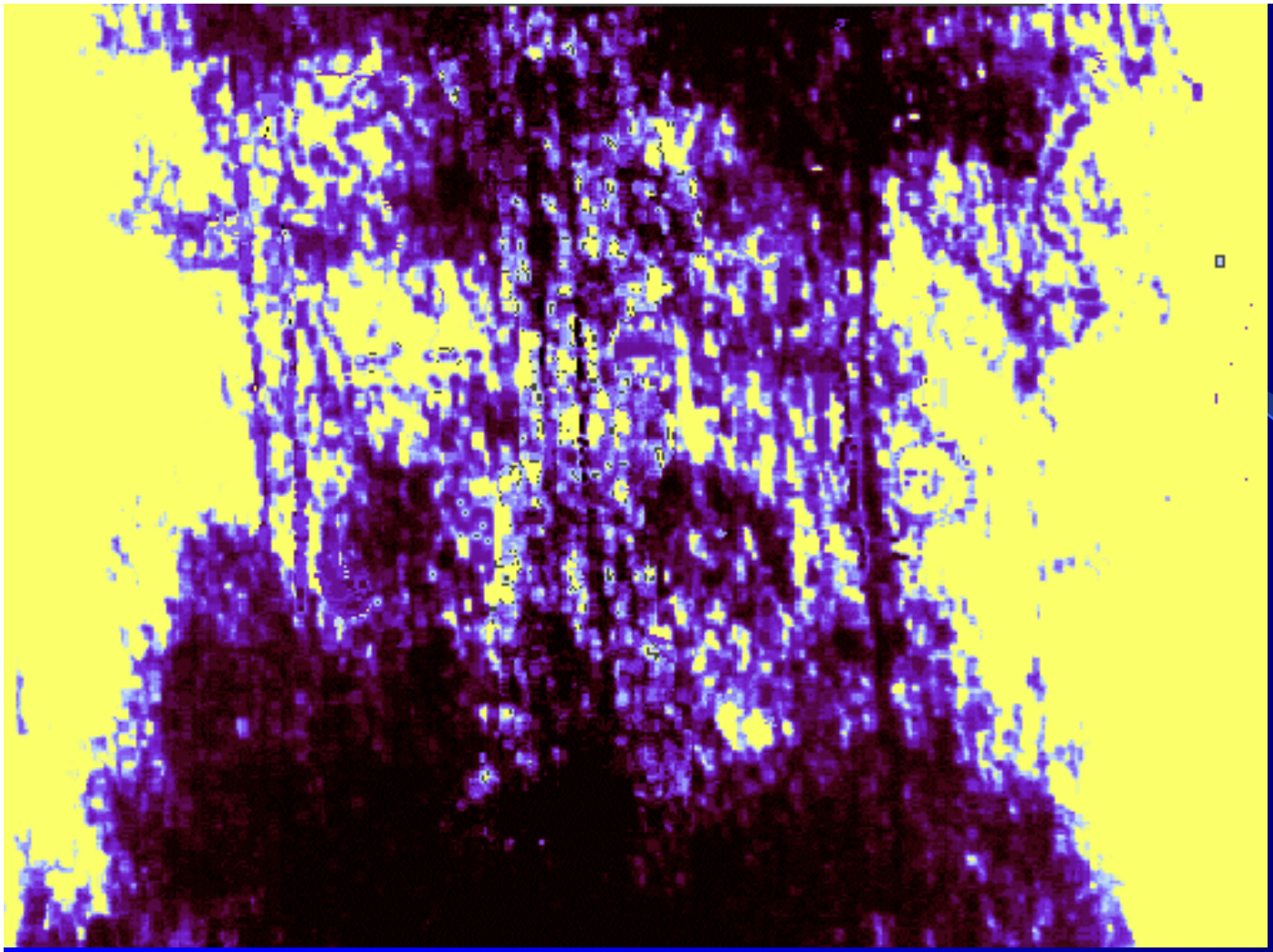
The original image is processed with the method of multilevel dynamical contrasting with different maps of contrasting in central and peripheral windows to show the continuity of the structuring in the regions of substantially different luminosity. Dendritic tubular filaments (of a diminished luminosity, with respect to strong background) in the central section are of diameter d = 0.7 - 1.5 mm, while thick fractal formations («dark filaments») in the neck, in the left and right windows, are of d ~1.2 and 0.5 cm, respectively.



Z-pinch

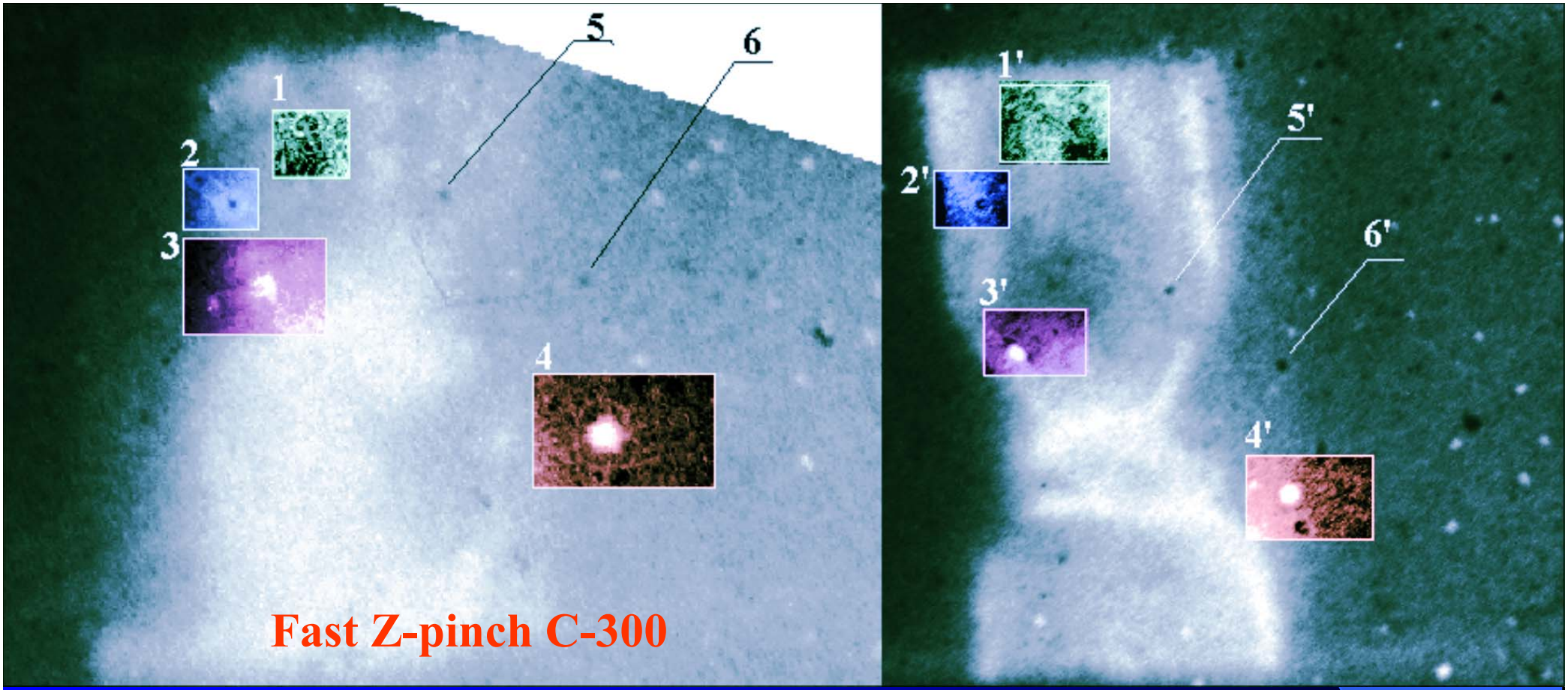
Image width 3.5 cm (positive)

Typical radially directed filamentary formation in the Z-pinch. Here, the axis of the Z-pinch is located at the left edge of the image, time t =+300 ns. Diameter of a ring at the left edge of a dark fractal filament is ~3 mm, and the thinnest resolvable tubules are few hundreds of microns in diameter.

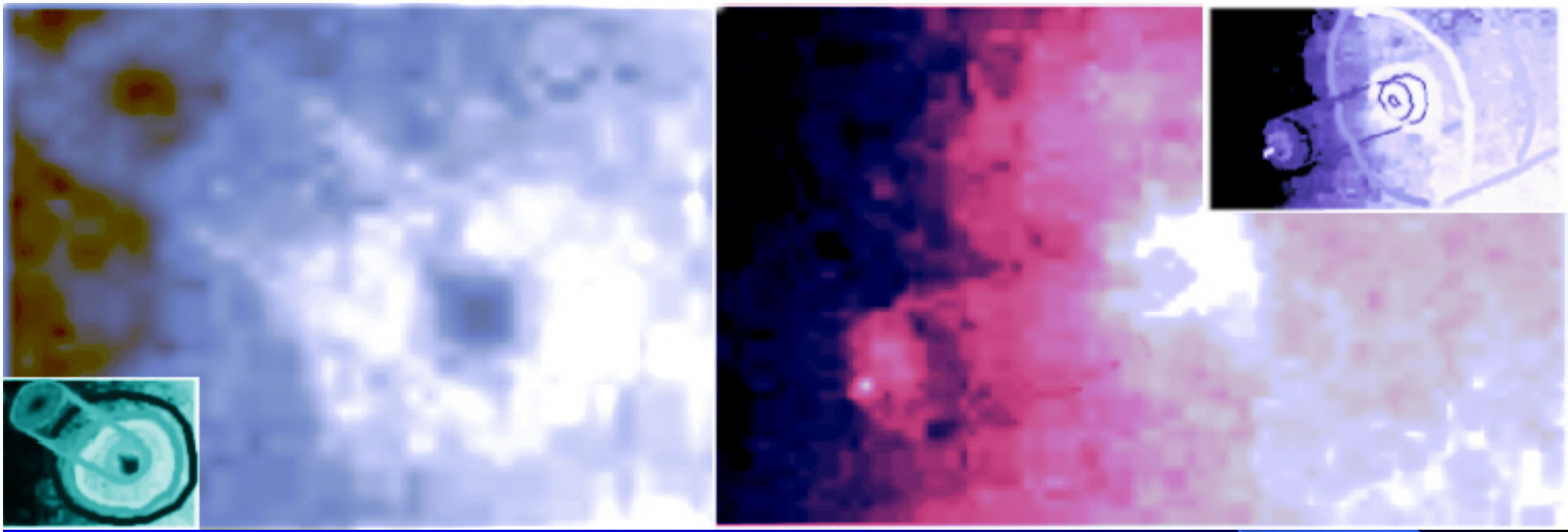


The picture illustrates the presence of a network built up by the tubular rigid-body filaments which are hidden in the ambient plasma at the implosion and stagnation stages of the discharge but appear to be stripped by the magnetic field when it pushes the plasma out of the Z-pinch's neck (it is such event that leads to a singularity of the total electric current through the Z-pinch).

The «stripped» neck of a **Z-pinch** (chamber L~60 cm, D~20 cm, I_{max} ~ 360 kA, working gas deuterium, Z-pinch axis is directed vertically). Negative, t = 0 ns, time exposure 2 ns; image's height 1.65 cm. Vertical tubules **d ~0.3 mm**, horizontal tubules **d ~ 0.1-0.2 mm**, coaxial tubule **d ~1 mm**.



Two successive images (positives) taken with the help of an electronic optical converter in soft x-rays with interframe time ~ 15 ns. Both images are analyzed with respect to probable existence of objects which conserve their structure during the interframe (note that the relative layout of such objects may differ due to internal restructuring or global rotation of the entire structure). Such structures are found in the windows 1-4 where the original image is processed with the MDC method [1]. Also, typical recognizable dark spots are marked (see labels 5 and 6). All the windows 1-4 (and respectively 1'-4') exhibit the presence of the same, conservative and quite distinctive structuring that indicates on the longevity of these structures.

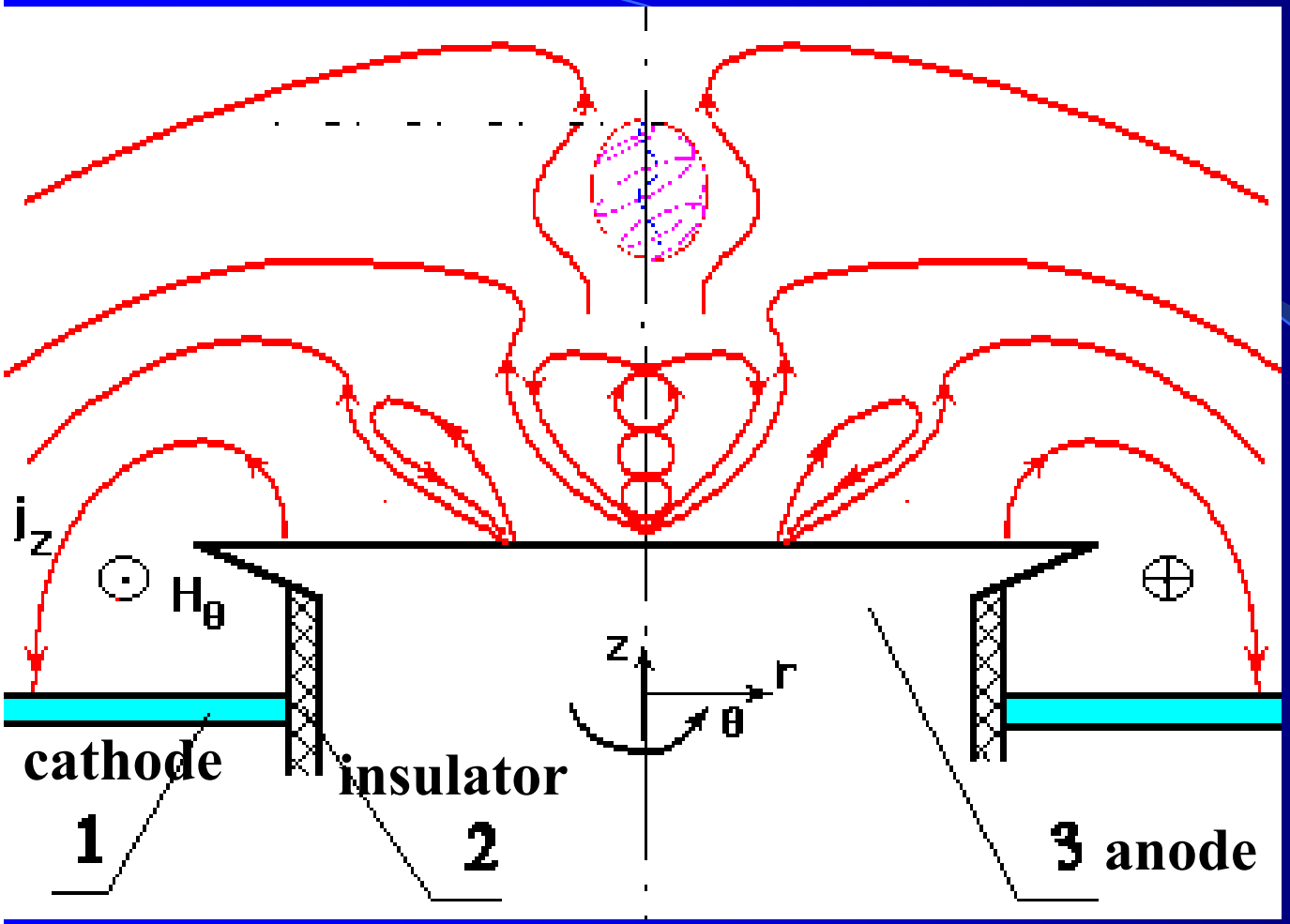


Fast Z-pinch C-300

The magnified fragments of preceding figure (windows 2, 3). The width of the images are ~1 mm, 1.75 mm, respectively. The windows show tubular structures of various diameter and declination.

For each image, we give a schematic drawing of the structuring, which is obtained with the help of the method of a mosaic Multilevel Dynamic Contrasting.

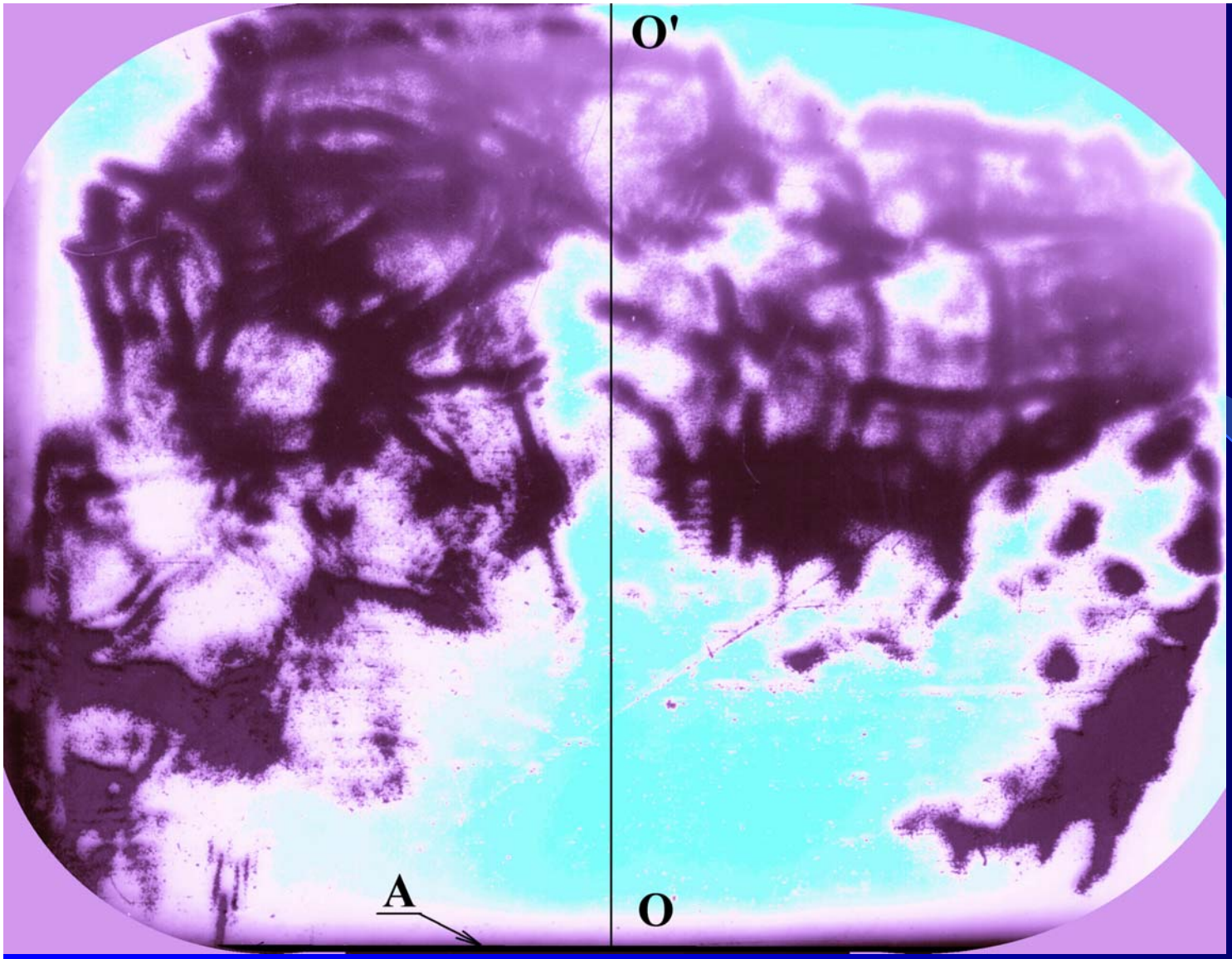
Filippov type plasma focus facility



Mushroom-shaped anode, 11 cm diameter, located inside a coaxial metallic chamber, which acts as the cathode.

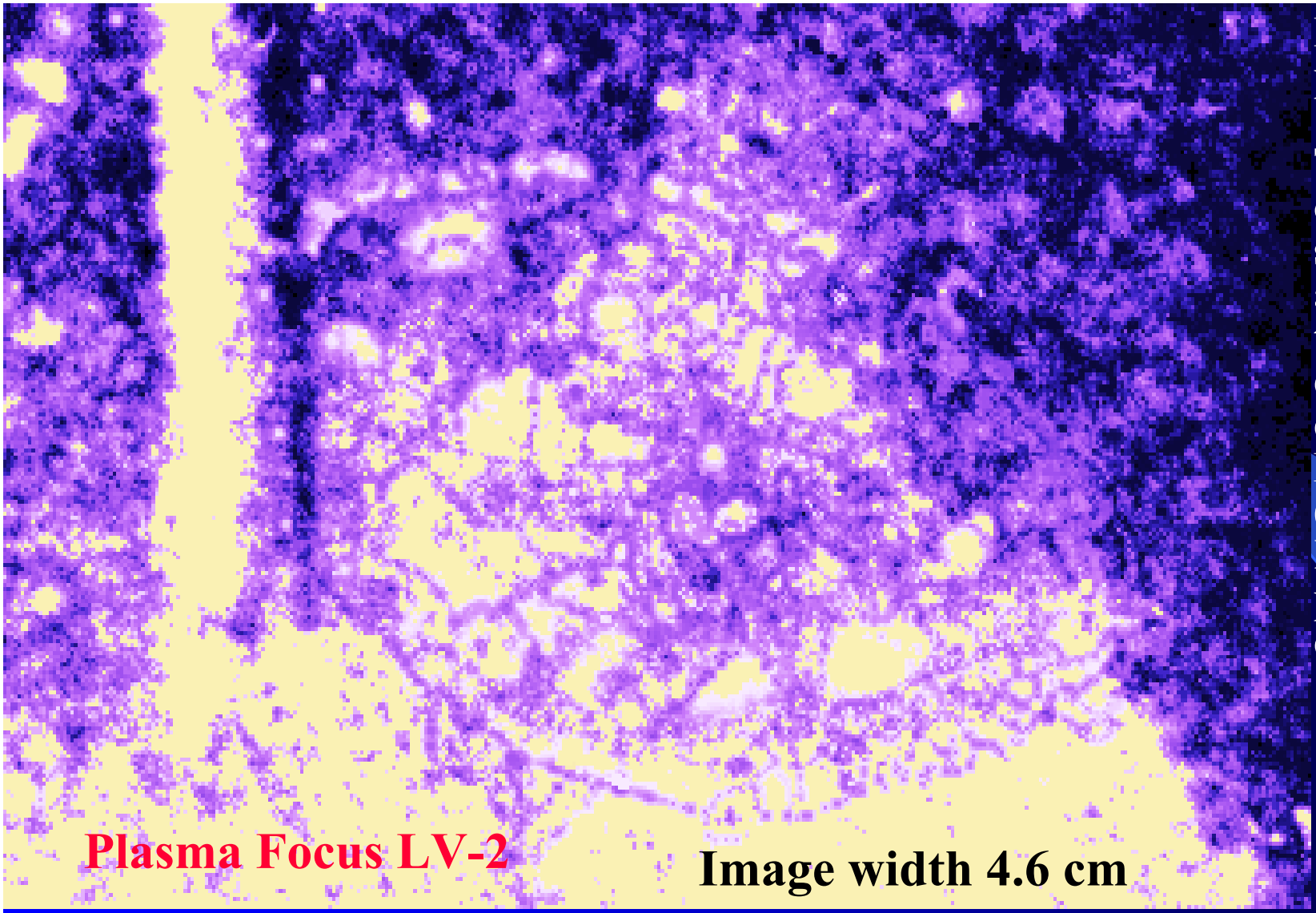
Capacitance, 180 μF;
Initial inductance, 55 nG;
Initial voltage, 16-24 kV, varying with energy of 20-50 kJ, respectively;
Maximum current, 600 kA.

Motion picture of the magnetic field front (and electric current sheath) in plasma focus discharge which may producing a filamentary spheromak-like magnetic configuration (Fus. Technol. 1997)
(1, cathode; 2, insulator; 3, anode).



The anode is at the bottom of the diagnostic window (4 cm diam.), the plasma focus major axis coincides with the vertical axis of the window

The shadowgrams taken with the help of a ruby laser (0.01-J laser pulse energy; 15-ns duration; pulse direction perpendicular to the system axis).
Deuterium gaseous discharge of initial pressure 163 Torr.
Time t= +174 ns (zero corresponds to major (first) singularity of electric current derivative).



Filippov type plasma focus

The tubular and cartwheel structures which are observed at a time 100 ns before detection of electric current Rogowski coil (imaging with the help of an EOC; positive; time exposure 2 ns).

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 image's top, and the bottom of the cathode chamber is near the image's bottom). Original data by M.M. Orlov, A.R. Terentiev, V.A. Khrabrov.

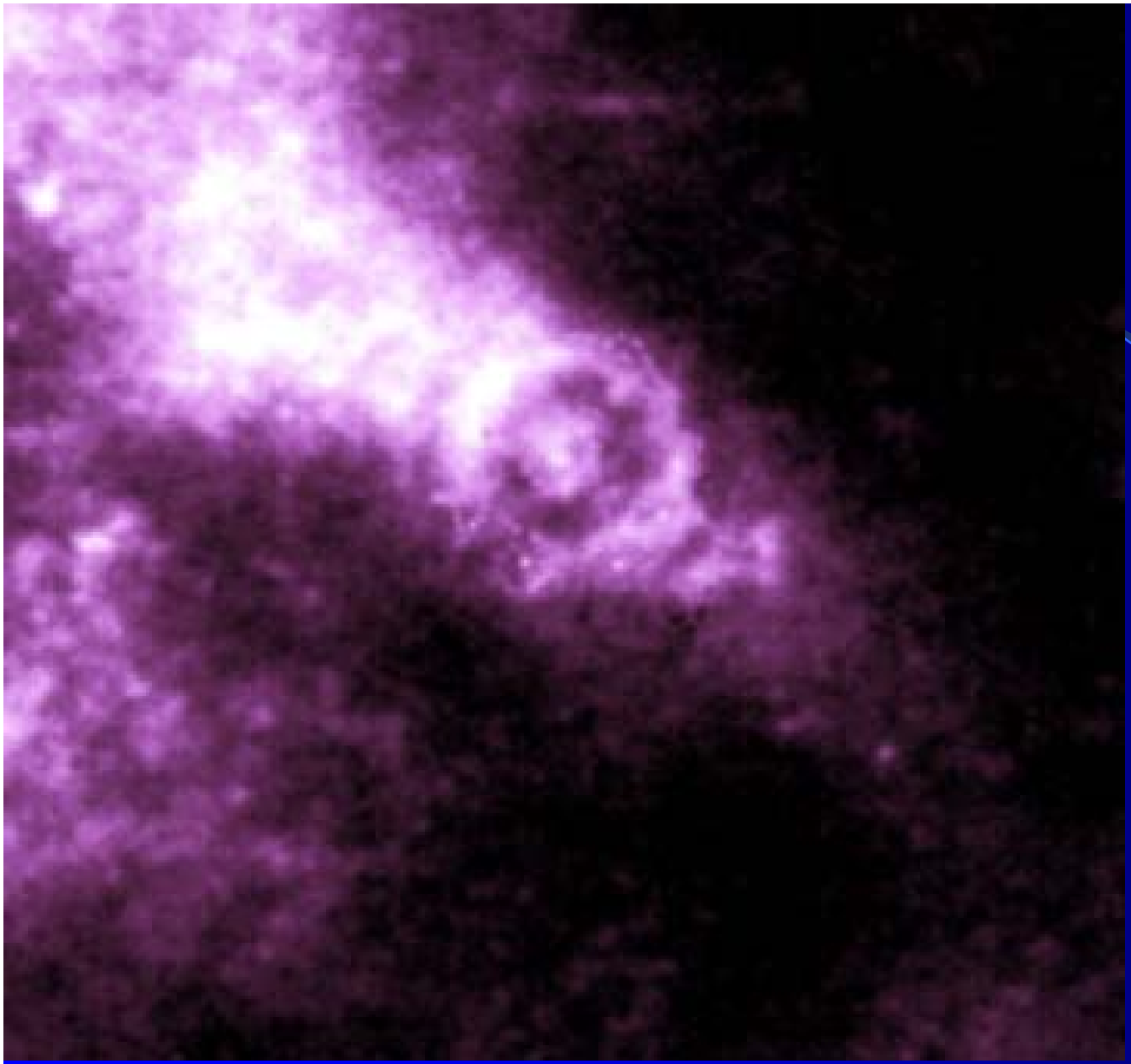
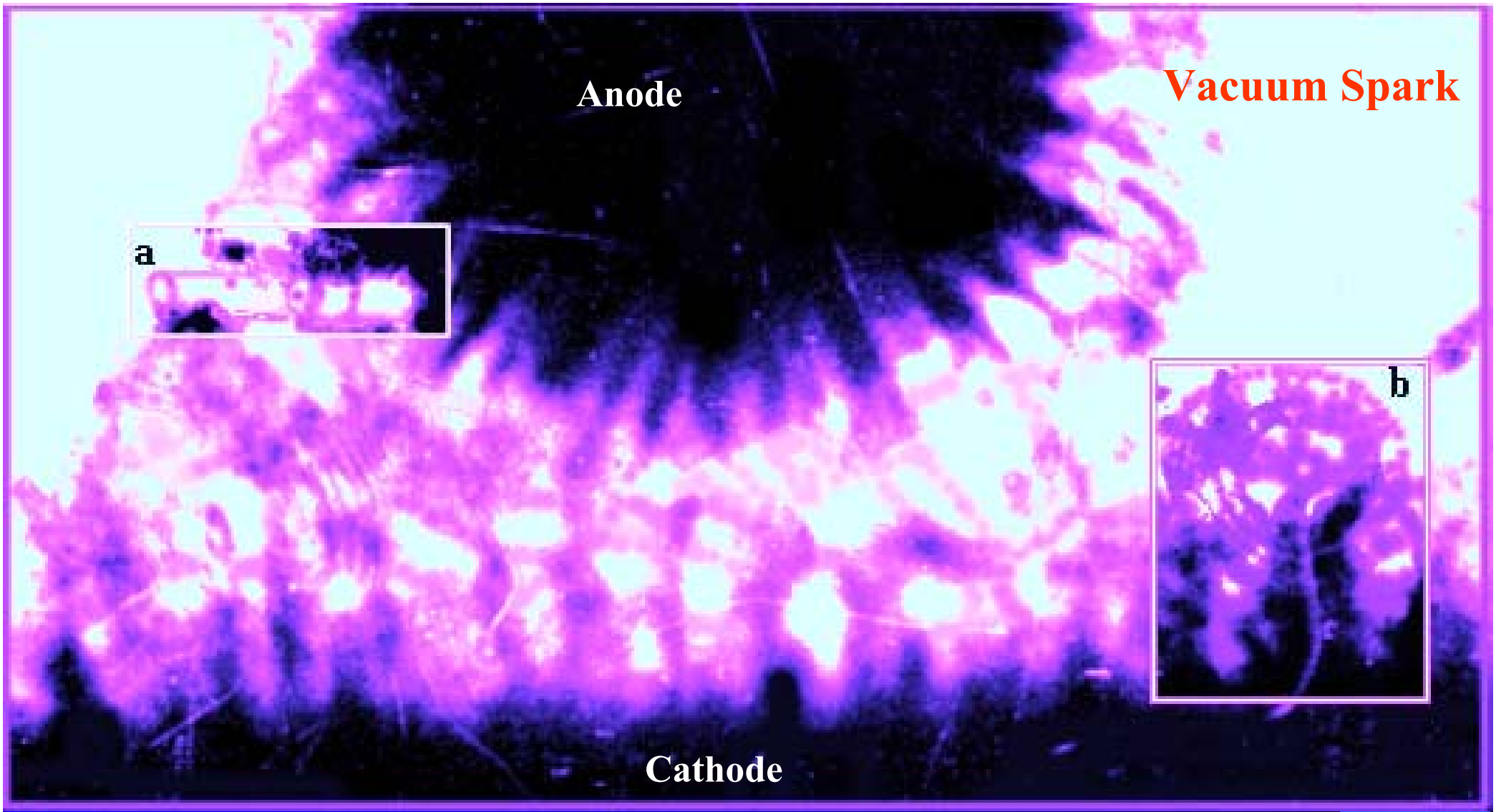


Image width 2.5 mm

Typical tubular formation (of diameter ~ 0.5 mm) directed nearly perpendicular to the curvilinear filamentary current sheath at the implosion phase of the discharge in the plasma focus facility of the Filippov type.

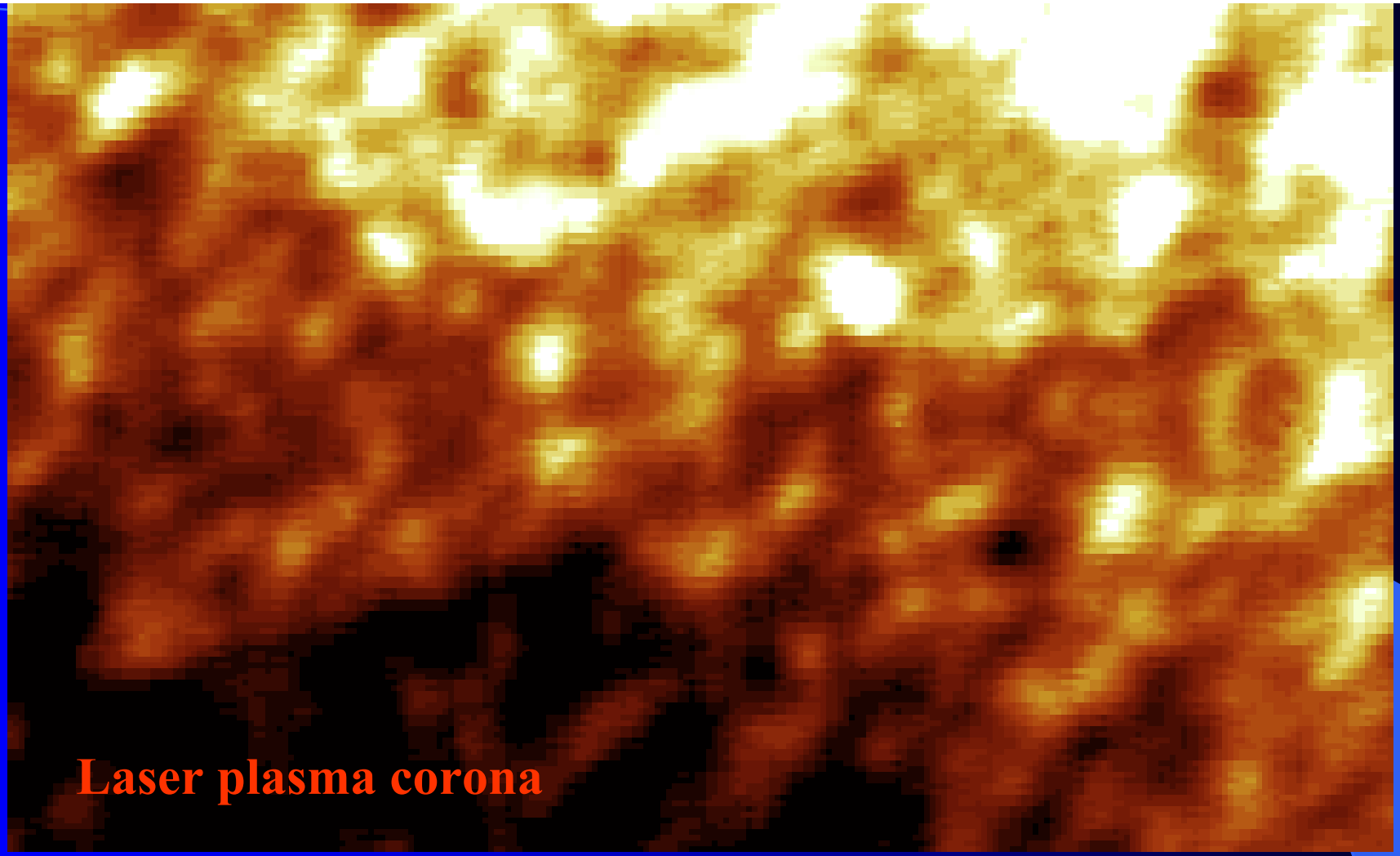
The picture is a shadowgram (positive) taken from the facility's top (laser pulse of 2 ns duration passes up through a hole in the mushroom anode, i.e. the picture shows radial projection of the tubular formation).



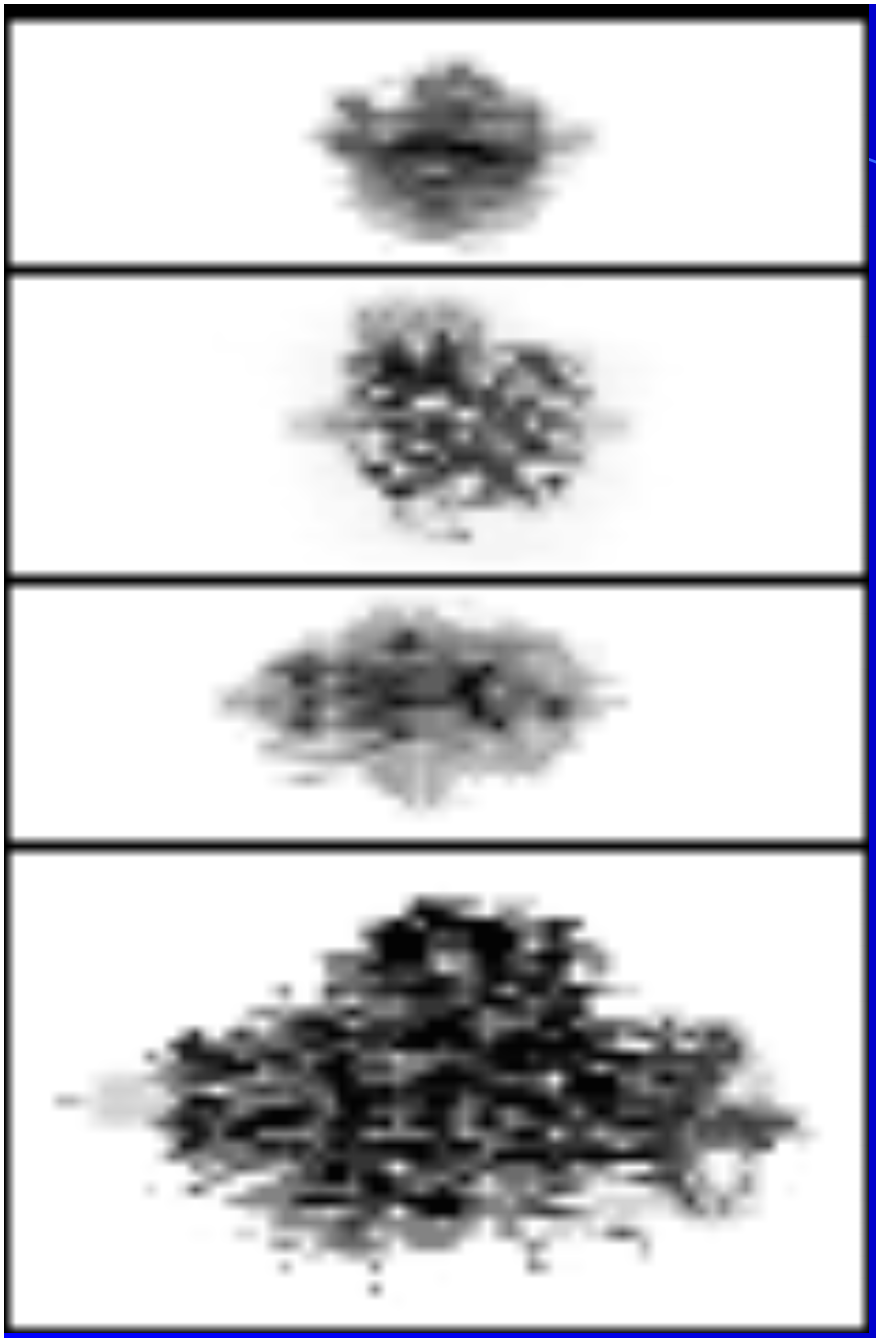
The tubular and cartwheel structures in a low-inductance vacuum spark (condenser 12 μF, 10 kV, Imax ~ 150 kA, period ~ 5 μs). Flat cathode with central hole of diameter 3 mm is 2 mm from a round-shaped edge of a rod anode. Laser shadowgraphy (pulse duration 6 ns, λ=337 nm) using an electronic optical converter (EOC), at initial, «dark» stage when plasma's self emission is not yet detectable by the EOC (at this stage, electric current < 20% of Imax). Higher level of contrasting in windows 'a' and 'b'. Original data by A.S. Savjolov et. al. (MEPhI).

The filtered X-ray pinhole image (negative) of the typical plasma corona produced by the Nd laser pulse (= 1.06 μm, 2.5 ns duration, power density 5 10^{13} W/cm^2) incident on the lavsan foil with aluminum dots. The original is taken from the database of experiments [*]. The target was located approximately on the bottom of the image, the beam was directed downward. Image height ~ 5 mm. The magnified image in the frame is shown in the next slide.

[*] L.A. Bolshov, V.V. Gavrilov, N.G. Kovalsky, *et. al.*, Sov. Phys. JETP 65, 1160 (1987).



A fragment of the image of the previous figure marked with a frame. Image's width ~750 μm. One may see the image of a walking-stick whose end knob (of diameter ~ 80 μm) is seen on the right-hand side on the figure. This stick is oriented horizontally and declined with respect to figure's plane. One more handle-like structure of smaller diameter is seen on the stick behind the end knob. There is one more structure, though less distinct one, which is located on the stick, behind the latter structure - it looks like a cartwheel-like structure for which the stick serves as an axle-tree.



The X-ray pinhole images (negatives) of the brightest part of a plasma produced by the Nd laser pulse (= 1.054 μm, 2.5 ns duration, power density 5 10^{13} W/cm^2) in the inner part of the «agar-agar» ($C_{14}H_{18}O_7$) film target of thickness 0.5 mm and mass density 2 mg/cm^3. The originals are taken from the database of experiments
[A.E. Bugrov *et. al.* Zh. Eks. Teor. Fiz. (JETP), **111,** 903 (1997)].
The upper edge of the target was located approximately on the top of each image, the beam was directed downward. The images are taken through aluminum filters. Four time-integrated images correspond to different thickness of these filters, in the range 5 μm to 20 μm, with the thinnest one for the bottom image. Image's width is 720 μm. Spatial resolution is 20 μm. A straight filament directed orthogonal to laser pulse direction is seen on all the images whereas the elliptical images of the circular filaments centered around the above-mentioned filament are distinct mostly for the thinnest filter (see right-hand side of the bottom image).