Structure and chemical composition of magnetic dust formed in Globus-M tokamak

A.N. Novokhatsky[1)], A.E. Gorodetsky[2)], V.K. Gusev[1)], A.P. Zakharov[2)], R.Kh. Zalavutdinov[2)]

[1)] A.F.Ioffe Physico-Technical Institute, Russian Academy of Sciences, St. Petersburg, Russia
[2)] A.N.Frumkin Institute of Physical Chemistry and Electrochemistry, Russian Academy of Sciences, Moscow, Russia

Globus-M is the first Russian spherical tokamak that has been constructed in A.F.Ioffe Physico-Technical Institute. The tokamak has a low aspect ratio (major radius is 0.36 m, minor radius is 0.24 m, toroidal magnetic field is 0.4 T) and high specific power deposition [1]. Usually the Globus-M first wall is protected by graphite tiles (about 90% of its inner vessel area facing to plasma). About 7000 shots (total duration ~700 s) were performed in the first wall configurations at which only 65 % of an internal surface of vacuum vessel have been protected by graphite during the period from March, 2006 till July, 2009 (see Fig. 1). The graphite shielding has been removed from an outer cylindrical part of the vacuum vessel for reduction of RF power losses in the ICR heating experiments. Despite the presence of two graphite toroidal and eight tungsten poloidal limiters, theouter cylindrical part of the vacuum vessel was remained unprotected to powerful plasma fluxes. The power launched into the Globus-M plasma during each discharge was usually 0.5-1 MW. Main part of the power was deposited onto graphite divertor tiles each with the wetted area of 0.01-0.02 m^2. High specific auxiliary heating power made plasma-wall interaction rather intensive which resulted in material erosion and redeposition. To minimize chemical sputtering and improve a thermal shock resistance the graphite during manufacturing process was doped mainly by Ti and additionally by Si or B. The tokamak

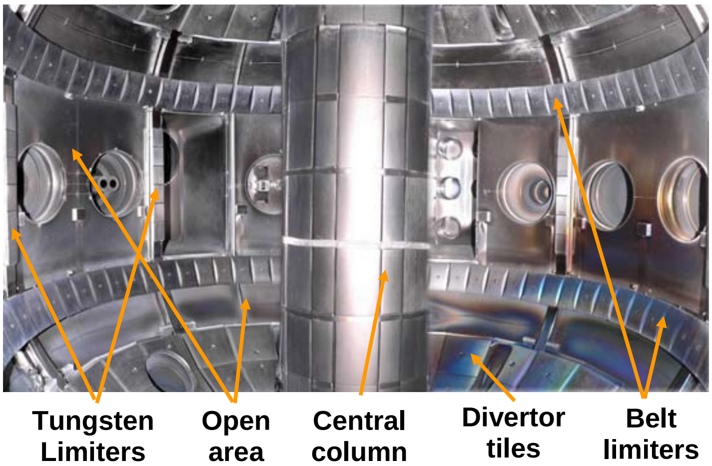


Fig. 1. Plasma facing components in Globus-M tokamak. Open area – polishing stainless steel 12X18H10T. Other surfaces are covered by RGTi tiles and tungsten.

inner surface has been boronized 7-8 times per year. The results concerning formation of mixed layers in the plasma were presented in [2-4].

Plasma-wall interaction in Globus-M was accompanied by dust formation as well as in other tokamaks [5]. After campaign 2006-2009, dust for analysis was collected from the surfaces exposed to direct plasma impact as well as from the shadowed zones (Fig. 2). The dust consisting of easily scattered, difficultly collected carbon and loose small metal particles ranging in size from tens of nanometers to millimeters, basically brilliant black color. The most part of magnetic large particles (hundred μm) had metal shine and temper colors from pale yellow to dark blue.

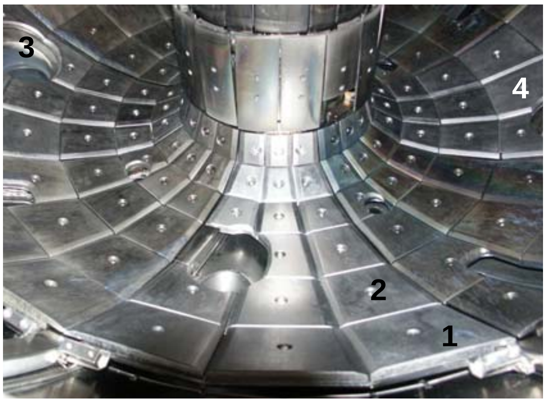
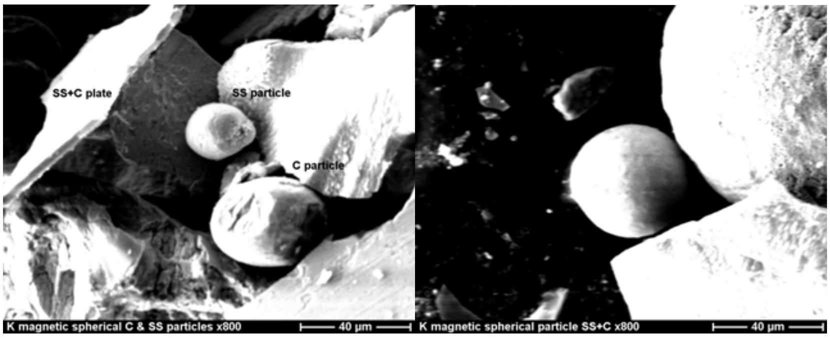


Fig. 2. Lower part of Globus-M divertor plates. Figures show the dust collected places: surfaces exposed to direct plasma (1 and 2) and shadowed zone (3 and 4).

Morphology and chemical composition of the magnetic dust were studied using electron probe microanalyzer Camebax (Cameca, France) by methods of scanning electron microscopy (SEM) and electron probe microanalysis (EPMA). EPMA (electron beam ~1 μm, depth of analysis ~3 μm for carbon matrix and ~1 μm for metal) allowed to determine of dust chemical composition. Structure of the dust was investigated by means of X-ray diffraction (XRD). The XRD analysis was fulfilled using diffractometer DRON-3 (Russia) with a copper tube (λ_{Cu} = 0.154 nm) and with a graphite monochromator. The registration of diffracting beams was carried out in the range of angles 2θ from 10 to 90º with step 0.05º and exposition time in each point 1.5 s (depth of analysis ~10 μm for carbon matrix and ~5 μm for metal). The magnetic particles were collected by a permanent magnet and then they were transferred on a conducting polymer tape



a) b)

Fig. 3. SEM micrographs of lamellar a) and spherical b) magnetic particles. Some spherical particles are covered with carbon.

It has been observed earlier [6] that about 10% of dust was magnetic. The magnetic fraction of the dust mainly consisted of lamellar and spherical particles with sizes of 3-1000 μm (Fig. 3). All spherical particles contained iron and other components of stainless steel and evidently derived from plasma interaction with vacuum vessel surface uncoated by graphite tiles. The spheres were coated with carbon, boron, and oxygen. One of possible mechanisms of magnetic spherical particle formation may be melting of stainless steel due to its interaction with plasma and consecutive boundary-layer separation from metal covered by carbon and/or boron film. Another possible reason of light element presence is collisions of a hot magnetic metallic particle having sufficiently high kinetic energy with the vacuum vessel surface covered by carbon, boron or boron oxides. During deceleration the particle was covered by chemical elements of wall coating.

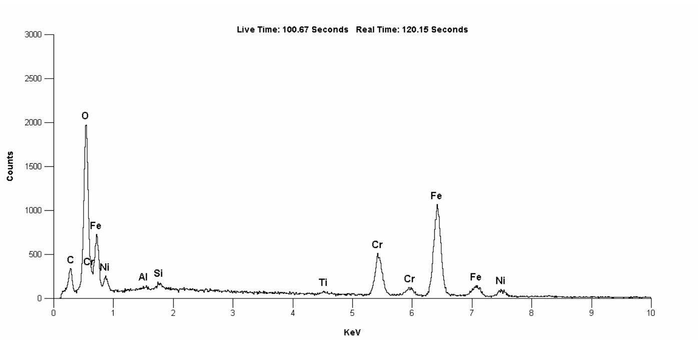


Fig. 4. EDS spectrum of metallic lamellar particles. There is a high oxygen peak caused by thick oxide film (thickness ~1 μm).

EDS spectrum of metallic lamellar particles collected from Globus-M is shown in Fig. 4. The lamellar particles with a size of 10–1000 μm and thickness of 2–4 μm were similar to “metallic ice”. The lamellar particles contained mainly stainless steel components (Fe, Cr, Ni, Ti) and oxygen (Fig. 4). As followed from a calculation of chemical composition of the plates, oxides Fe_2O_3 and Cr_2O_3 were present. Fig. 5 shows XRD spectrum of the plates where the main stainless steel diffraction peak (111) with inclusions of ferrite (110) were present. However, the intensity of the ferrite peak (110) was comparable with the intensity of austenite peak (111). This result testifies that in exfoliating particles of the steel the ferrite amount was larger than in the initial steel.

Metallic large particles with sizes of 10–1000 μm were formed as a result of hydrogen embrittlement of the stainless steel under interaction with hydrogen isotopes. The steel was heavily oxidized. There were a lot of traces from microarcs that resulted in steel melting. The most part of the plates consisted of terraces with microarc traces (Fig. 6). The terraces were connected with consecutive cohesive separation of the plates from a massive matrix. The plates and terraces were formed due to hydrogen, carbon and oxygen accumulation in surface layers and development of mechanical stresses and corresponding strains. A boundary between the strained and unstrained steel was located at depth of a few μm. During the arcing the plates were separated. There is a high oxygen peak caused by thick oxide film (thickness ~1 μm).

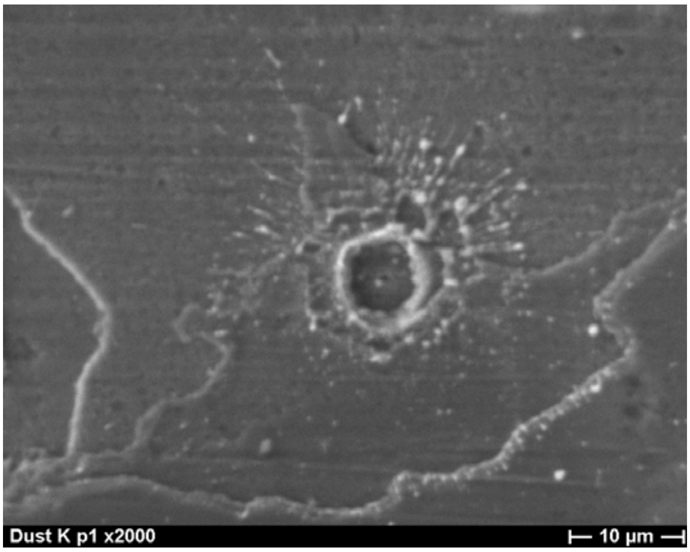


Fig. 6. Traces from microarcs that resulted in steel melting.

Magnetic large metal particles could arise during the interaction of plasma with in-vessel stainless steel elements of construction (the corbels fixing an internal limiter, edges of substrates of divertor plates, unprotected parts of frames). Indisputable source of metal particles were unipolar arcs, traces from which were observed elsewhere.

Conclusions. The analysis of magnetic dust and large particles has allowed concluding that places of possible contact of plasma with stainless steel in tokamak should be completely protected by the first wall armor. For minimization of dust formation in tokamak it is necessary to carry out boronization procedure with care, without blowing a considerable quantities of carborane into the vacuum vessel.

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