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Study of Vacuum Vessel Boronization in Globus-M Tokamak.

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1. Introduction

The effective way to reduce the impurity contamination in tokamak plasmas is the coating of the first wall with boron-carbon films. In Globus-M experiment the boron-carbon film was deposited on the vacuum vessel inner surface in glow discharge (GD) in the mixture of helium and carboran $C_2B_{10}H_{12}$. This technique as well as some properties of produced B/C coatings are described in [1,2].

The essential advantages of this method are the low cost and the simplicity of implementation. The carboran is the non-toxic and non-explosive substance. It is a powder at the room temperature, which is intensively evaporated at the temperature higher than 40^0C.

Globus-M [3] is a low aspect ratio tokamak (plasma major radius R=0.36 m, minor radius a=0.36 m, toroidal magnetic field B_T 0.1-0.6 T, plasma current up to 0.36 MA) presently operating in Ohmic heating regime. The first experiments were performed in the vacuum vessel with stainless steel limiters. Later on the vessel inner cylinder and partly the poloidal limiters were protected with graphite tiles.

The first boronization of the vacuum vessel was performed at a low percentage of carboran. The carboran vapor pressure was less than 10% of He pressure in GD applied during 30 minutes. However, this procedure led to significant reduction of hydrogen recycling and 20% increase of plasma current at the same loop voltage waveform. Then the B/C films were deposited on the substrates from different materials in a high frequency glow discharge out of the Globus-M vacuum vessel and their properties were studied in details. The last boronization in Globus-M was carried out at the essentially lower helium to carboran vapor pressure ratio in the range 3/1-5/1. After the boronization the analysis of the spatial distribution and the structure of the deposited film has been undertaken. For this purpose silicon probes (plates of approximately 1 cm^2 area) were placed in 16 points on the vessel inner surface and the graphite limiters.

2. Experiment

The Globus-M vacuum vessel is an all-welded stainless steel construction of ~ 1 m^3 inner volume. The vessel plan view is shown in Fig.1. The contour of the vertical cross-

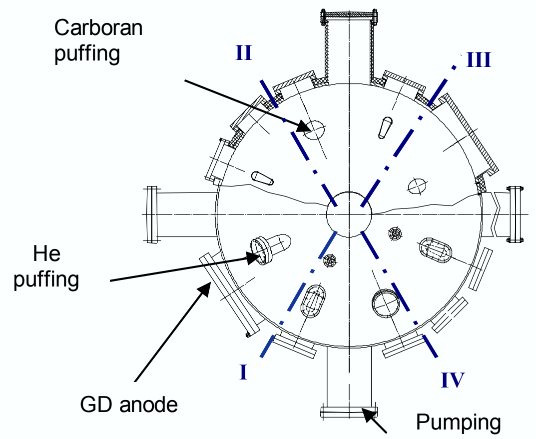

Fig.1. Vacuum vessel plan view showing position of He and carboran puffing and GD electrode. I, II ,III, IV – sections for silicon plates positioning.

section is shown in Fig.2. Figures 1 and 2 show also the position of silicon plates located in four sections along the torus.

The routine procedure of the vessel conditioning include the bake-out at the temperature up to 200^{0}C and the GD cleaning in hydrogen and noble gases. The GD voltage is applied between the single electrode (anode) and the earthed vessel. The electrode of 20 mm diameter is positioned in the tokamak midplane (see Fig.1). The parameters of the vessel and the GD characteristics are shown in Table 1. The helium pressure was provided by the piezoelectric valve. The carboran was evaporated by heating the ampoule containing the carborane powder. The steady state temperature of 45-48^{0}C was sufficient to sustain the required pressure.

Table 1. The vessel parameters and GD characteristics

Diameter of outer wall	1260 mm
Diameter of graphite limiter	252 mm
Vertical axis of torus	1.094 m
Vessel volume	1.05 m^3
Inner surface area	5.7 m^2
GD voltage	300 V
Current density	30 μA/cm^2
Gas pressure	2·10^{-1} Pa
He to carboran pressure ratio	3/1-5/1

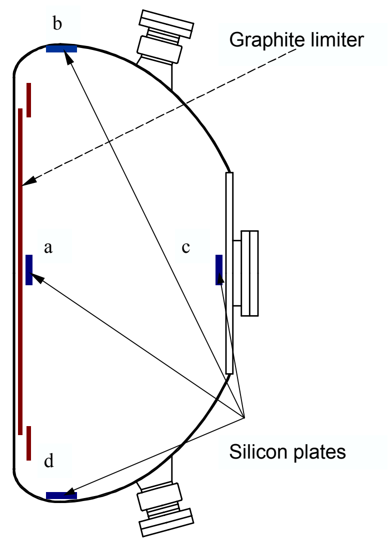

Fig.2. Vacuum vessel cross-section showing the position of silicon plates and graphite limiter

3. Results

First detailed study of carboran film properties was performed for the films deposited on the silicon, quartz and glass plates in 40 MHz He or Ar glow discharge in a small laboratory device [4] (the distance between electrodes was 35 mm). The basic results can be summarized as follows. The deposition rate decreased when the substrate temperature rised in the range of 20^0 – 100^{0}C. The films had the amorphous structure. The B/C ratio was determined from the nuclear reactions analysis (NRA) using 1 MeV nuclei of deuterium and appeared to be about

48%/52%. The content of hydrogen (result of infra red spectrum analysis) reached 40-50% at the room temperature and could be reduced by annealing at a higher temperature. The optical bandgap value is about 3.8 eV. The characteristic values of the specific resistance ~ 10^6 Ohm×cm at the room temperature and ~10^5 Ohm×cm at the temperature of 100^0C. The films are transparent in the visible range.

After the vessel boronization with a small fraction of carboran vapor pressure (less than 10% of He pressure) the following analysis of silicon plates revealed a formation of thin films with a typical thickness of 100Å. The film had an amorphous structure, but the content of boron did not exceed 4%. After 200 plasma shots with the plasma current of 150 kA accompanied by routine GD cleaning in helium during 70 hours the amorphous structure transformed to the diamond-like one. Remarkable, that the hydrogen in the film was practically absent.

More detailed analysis was undertaken after the boronization with the ratio of helium to carboran pressure in the range 3/1-5/1 during 1.5 hour. The boronization was followed by a short experimental series from 80 plasma shots with plasma current of 200 kA and 12 hours of glow discharge cleaning in helium.

Table 2. Film thickness on Si plates

Film thickness (μm)				
Position	a	b	c	d
I	–	1	0.5	0.4
II	0.03(RBS)	0.65	0.1(RBS)	0.3
III	–	0.3	0.3	0.3
IV	–	0.3	1.2	0.4

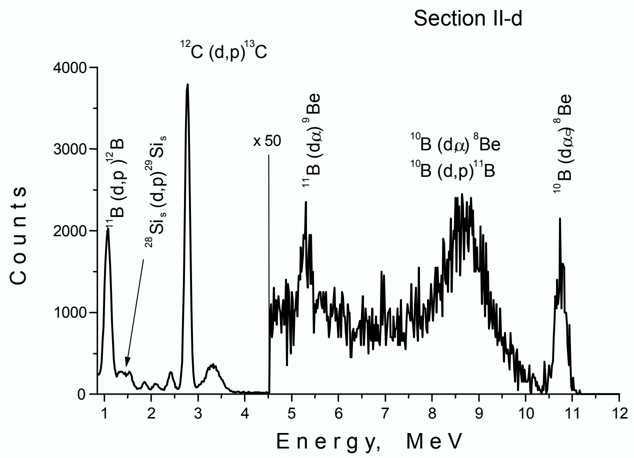

Fig.3. Energy spectrum of protons and α-particles originated in the reactions of 1 MeV deuteron beam with carbon and boron isotopes in the deposited film. Angle of observation 135^0 relatively the beam.

The distribution of the film thickness deposited on silicon plates in different points of the vessel is shown in Table2. The plates numbering is given according to Fig.1 and Fig.2. The thickness of films was measured by optical methods except the positions II-a and II-c. The film composition in the cross-section II (Fig.1) was studied by means of electrostatic accelerator using NRA and Rutherford backscattering analysis (RBS) [5,6].

Fig.3 shows the energy spectrum of protons and α-particles originated in the reactions of 1 MeV deuterons with nuclei of carbon and boron isotopes. The boron/carbon ratio in the deposited films was determined by integrating the peaks of $^{10}B(d,\alpha)^{8}Be$ and $^{12}C(d,p)^{13}C$ reactions. The film composition is given in Table 3. The content of iron was obtained from the RBS spectrum of the primary beam.

Table 3. Film composition

Substrate	Composition
II-a	$B_{0.32\pm0.02}C_{0.52}Fe_{0.16}$
II-b	$B_{0.01}C_{0.56\pm0.02}Fe_{0.43}$
II-c	$B_{0.27\pm0.02}C_{0.55}Fe_{0.18}$
II-d	$B_{0.43\pm0.02}C_{0.47}Fe_{0.10}$

4. Conclusion

The described procedure of Globus-M vessel boronization leads to a formation of the amorphous boron-carbon film with a typical B/C ratio of 3/4-3/5. The film thickness varies within a factor of 4 along the vessel surface. No obvious correlation between the film thickness and the position of the glow discharge electrode and the gas puffing ports was observed. The physical properties of the B-C coating deposited in DC glow discharge on the vessel surface are similar to properties of the films obtained in 40 MHz discharge. The appearance of iron in the film structure can be explained by a sputtering of the vessel material during boronization and the tokamak routine operation. Thinner films have a lower content of boron. The tokamak operation (plasma shots and routine GD cleaning) leads to a significant reduction of hydrogen content in the boron-carbon films.

The last boronization was preceded by the vessel bake-out after the opening to the atmosphere and GD cleaning in He during 120 hours. However, the boronization resulted in by 1.5 times increase of plasma current at the same loop voltage waveform and by a factor of 4 decrease of the radiation losses fraction.

Further work will include study of the film structure evolution in plasma experiments

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