INFLUENCE OF MOVABLE B_4C-LIMITER ON CHARACTERISTICS OF RF DISCHARGE PLASMA IN THE URAGAN-2M TORSATRON

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A variant of the B_4C movable biased pumped limiter for the Uragan-2M torsatron is described. Some results of experiments with the limiter moved from the vacuum chamber wall to the central region of the plasma column in the work mode of Uragan-2M operation are reported. The effect of limiter-plasma interaction on parameters of the RF plasma discharges is discussed.

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INTRODUCTION

A movable biased pumped B_4C limiter has been designed, manufactured and installed in the Uragan-2M torsatron (U-2M) recently [1]. The main goal was to suppress plasma-wall interaction and in that way to reduce the amount of heavy impurities in the plasma. Also, the limiter could be used in studies of erosion of the head plate material and its transport, the possibility of partial solid target boronization of vacuum chamber walls, in electrode biasing experiments, etc. At the initial stage of experiments on U-2M hot-pressed boron carbide was used as the material for the limiter head, since it was previously studied in detail and tested in limiter experiments on the Uragan-3M torsatron [2-4]. The limiter was tested in RF/UHF discharge cleaning modes [5, 6] on U-2M. But in first experiments no effect was observed of the limiter head position (up to 10 cm from the wall) on signals from Langmuir probes located in poloidal torus cross-sections different from where the limiter was placed, even when the limiter crossed the last closed magnetic surface. This meant that introducing the limiter into the region of plasma confinement did not lead to a cutoff of the plasma column.

In this work a new variant of the B_4C limiter was created and tested in the operating RF discharge mode in U-2M. New results concerning the limiter influence on the RF plasma parameters are obtained and discussed.

1. DESCRIPTION OF THE NEW LIMITER. EXPERIMENTAL CONDITIONS

The new limiter (Fig. 1,a) includes two $90 \times 90 \times 8$ mm head plates manufactured by hot pressing of boron carbide powder in vacuum. The limiter plate material has the following characteristics: the density is 2.45…2.47 g/cm^3 (B 78.2 %, C 21.5 %), the heat conductivity is ~30 W/m, the electrical resistivity is ~10^{-2} Ω m and melting temperature is 2350°C. The limiter head plates are placed on an insulator. This allows to measure signals from the limiter plates (current, potential) and to apply a negative or positive bias (pulsed or stationary). The limiter in situ in the U-2M vacuum chamber is shown in Fig. 1,b. For comparison the previous version of U-2M limiter is presented in Fig. 2. The general schematic presentation of the U-2M torsatron is given in Fig. 3, showing the vacuum chamber wall, toroidal magnetic field coils 1-16 and location of the RF antennae, limiter and diagnostics around the torus. The Poincare plots of the magnetic force lines in the poloidal cross-section of the U-2M torus where the limiter was inserted (between the coils 10 and 11, see Fig. 2) are shown in Fig. 4 [7, 8].

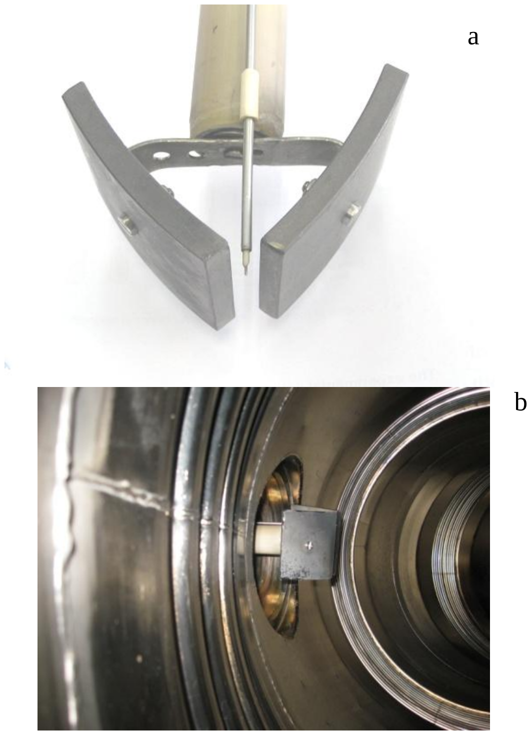

Fig. 1. a – the head part of the present B_4C-limiter; b – the limiter in situ in the vacuum chamber of the U-2M torsatron

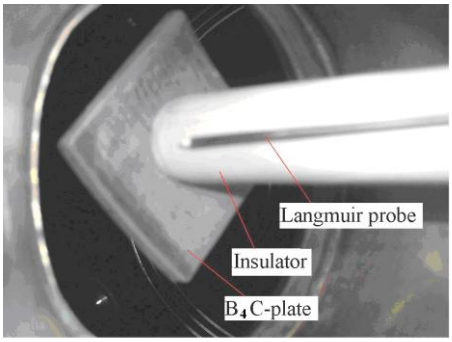

Fig. 2. Head part of the previous version of the movable B_4C-limiter in the branch pipe of the port #1 of the U-2M torsatron [1]

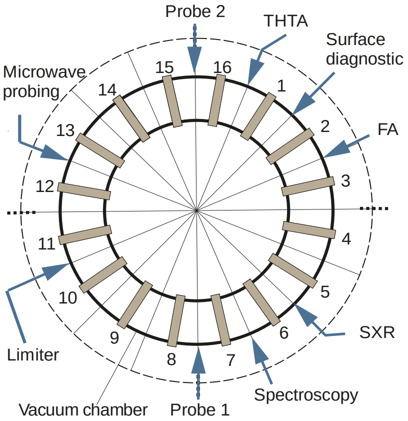

Fig. 3. Disposition of the limiter, RF antennae (three-half-turn antenna, THAT and frame antenna, FA) and diagnostics around the U-2M torus relative to the toroidal field coils 1-16

To reveal the limiter effect on plasma characteristics, two electric (Langmuir) probes were placed in different positions. One of the probes (see probe 1 in Fig. 2) was installed between the coils 7 and 8 in 2 cm from the wall. The location of this probe with respect to the closed magnetic surfaces (insertion in Fig. 5,a) was similar to the position of the central part of the limiter, in the sense that the probe was located near the major axis of the "ellipse" of the last closed magnetic surface. Another probe (see probe 2 in Fig. 2) was located on the opposite side of the torus between the coils 15 and 16 at the 13 cm distance from the wall on the minor axis of the "ellipse" (insertion in Fig. 5,b). The plate-driving assembly provides location of the limiter at the distance 34…14 cm from the minor (circular) axis of the torus, instead of 34…24 cm in the "old" version. Microwave probing of the plasma was carried out with 140 GHz injected along the small axis of the "ellipse". Microwave probing of the plasma was carried out with 140 GHz injected along the small axis of the "ellipse" between the coils 12 and 13. The receiving antenna was placed on the opposite (internal) side between the coils 12 and 13. Microwave probing of the plasma was carried out with 140 GHz injected along the small axis of the "ellipse" between the coils 12 and 13. The receiving antenna was placed on the opposite (internal) side between the coils 12 and 13.

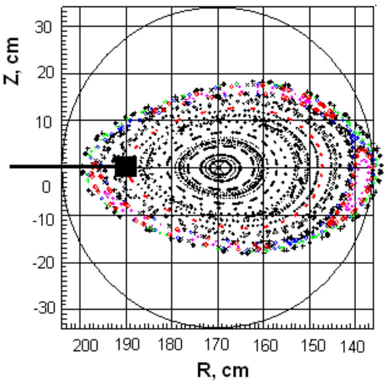

Fig. 4. Calculated Poincare plots of magnetic force lines in the poloidal cross-section of the U-2M torus [7, 8] where the limiter was inserted (between the coils 10 and 11, see Fig. 3)

The experiments were carried out in the operating modes of the pulsed plasma discharge with typical for the U-2M device parameters [9]. In the $m = 2 / l = 4$ Uragan-2M torsatron with additional toroidal field coils hydrogen plasma is produced and heated by RF fields in the Alfven range of frequencies ($\omega \lesssim \omega_{ci}$). The RF power from two oscillators was applied to two antennae, namely, the frame antenna (see FA in Fig. 2, 4.8 MHz, 50 kW) and the three-half-turn antenna (THTA, 5 MHz, 120 kW) with the toroidal magnetic field 0.36 T. The fuelling gas (hydrogen) was admitted into the vacuum chamber continuously, with the initial pressure varied from $6\cdot10^{-6}$ to $2\cdot10^{-5}$ Torr. The plasma pulse duration was 5…25 ms, with one pulse every 2 min. The three-half-turn antenna was used for Alfven heating of plasma with the line-averaged density $\bar{n}_e \sim (3…5)\cdot10^{12}$ cm^{-3} and the electron temperature up to ~100 eV. For effective operation of this antenna a target plasma with $\bar{n}_{eo} \sim 10^{12}$ cm^{-3} was produced with the frame antenna. In the standard heating mode, to prevent the effect of light impurities caused by the frame antenna, the three half-turn antenna was energized in 1 ms after the frame antenna switch off.

2. EXPERIMENTAL RESULTS

During experiments the limiter was moved from the position where its B_4C head plates were flush with the 34 cm diameter vacuum chamber wall to the distance of 17 cm from the wall, corresponding to the minor radius $r \approx 17$ cm. In each point of the limiter position plasma discharges with identical parameters were ignited and electric probe, spectroscopic, soft X-ray [10] and light emission measurements together with density $\bar{n}_e$ control [11] were performed.

The electric probe data reveal an apparent dependence (decrease) of the ion saturation current I_s on the limiter position when it moves to the minor axis (see Fig. 5). The stronger effect is observed for the probe # 1 (see Fig. 5,a) which is located in the cross-section similar to those with the limiter head plates. The signal decrease from the probe # 2 located in the cross-section different from those of the limiter (see Fig. 5,b) means that the head plate configuration of the present limiter results in a plasma column cutoff when inputting the limiter through the plasma boundary.

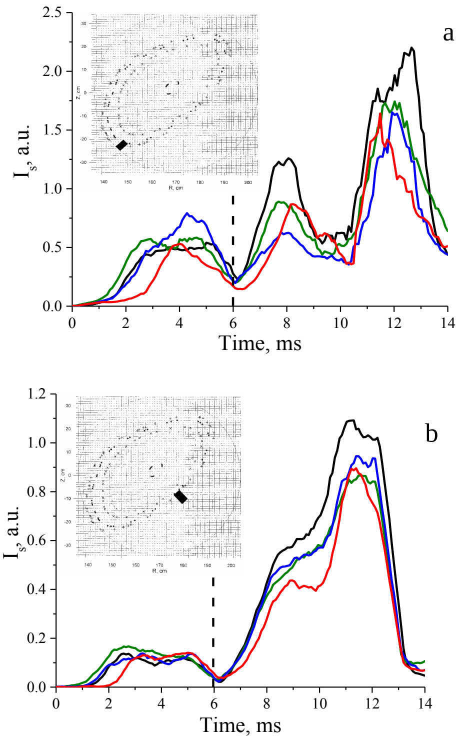

Fig. 5. Time evolution of the ion saturation current I_s to the probe 1 (a) and probe 2 (b) depending on the limiter position. The probe positions are indicated in the insertions as. The position of the limiter head plate (in cm from the chamber wall) is 0 cm (black), 5 cm (green), 10 cm (blue), 15 cm (red). The vertical dashed line indicates the moment of three-half-turn antenna switch on

Spectroscopic signals for different limiter positions are shown in Fig. 6. A comparatively slight effect of the limiter plate repositioning on the H_α intensity is observed, while the OII and CIII intensities essentially decrease and OV increases with the limiter put at the distance of 15 cm from the wall.

Soft X-ray signals appreciably increases at the same time (Figs. 7, 8). This one can explain by sputtered boron carbide input in plasma, similar as it observed for O and C impurity in ref. [10]. But the absence of the noticeable change of plasma density (Fig. 9) and decrease of ratio of signals from thin and thick foils allows assume the possible plasma electron temperature increase. The additional experiments, including spectroscopic measurements of boron inputting in plasma during the discharge and electron temperature measurement with another method, may shed light in this question.

Schematic drawing of experiment with the 20-channels visible light camera and time evolution of the light emission without and with the limiter are presented in Figs. 10,a,b respectively. As it is clear from Fig. 10,b, the emissivity of visible light is substantially higher at the plasma periphery without limiter. In the central area the difference in emission is opposite. Thus, in discharges with limiter light emission from the central region is higher.

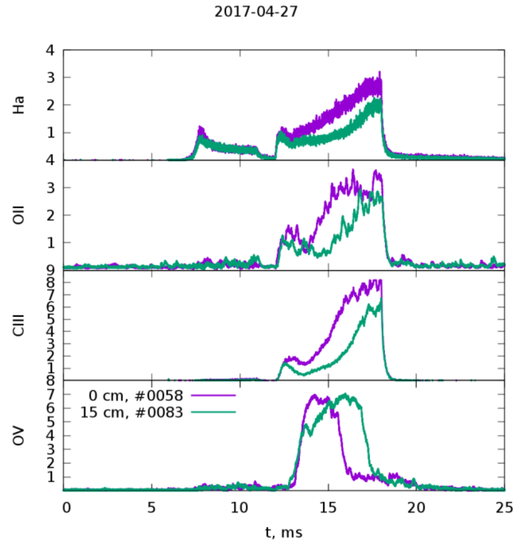

Fig. 6. Time evolution of spectroscopic signals H_α, OII, CIII, OV during the RF discharge depending on the limiter position 0 cm from the wall (violet) and 15 cm (green)

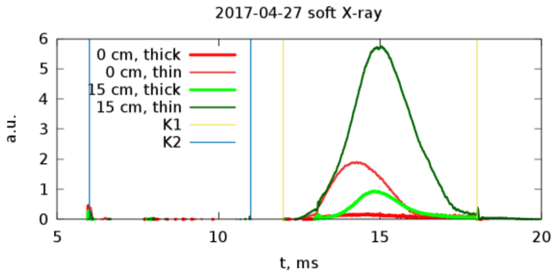

Fig. 7. Time evolution of X-ray signals for different limiter position for thick and thin Al foils

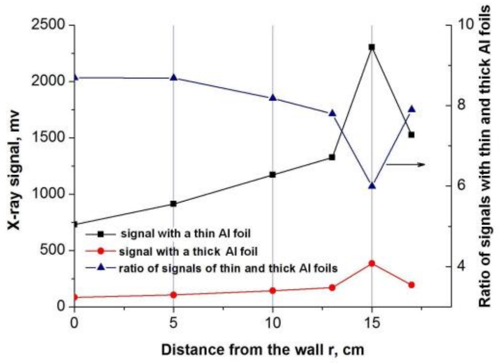

Fig. 8. Soft X-ray signals for thick (red) and thin (black) Al foils versus limiter position

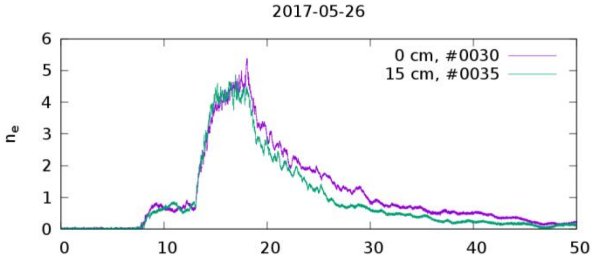

Fig. 9. Time evolution of the line-average electron density. Limiter position relative to the wall: 0 cm (violet), 15 cm (green)

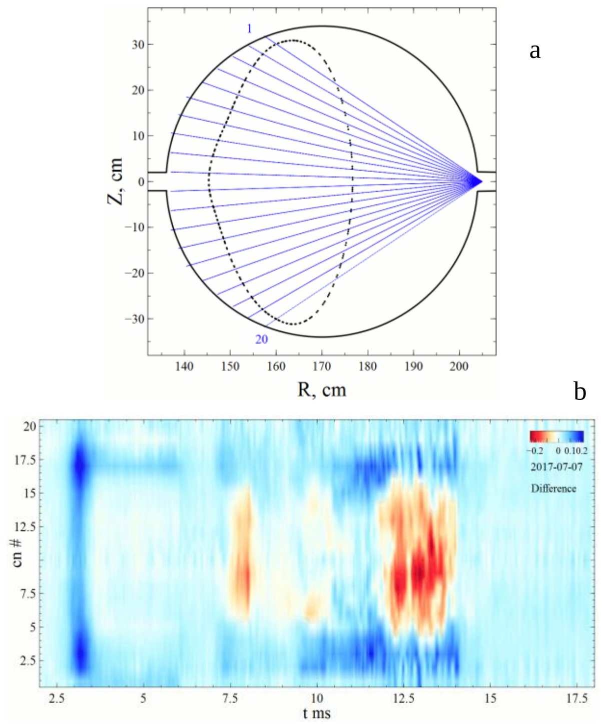

Fig. 10. Lines of sight of 20-channels visible light camera (a) and difference between visible light emission of discharge without limiter (blue) and with limiter position at 15 cm (red) (b)

After U-2M work campaign the limiter was demounted, to analyze changes of its surface. Strong macro damage is seen of one of the plates (right one in Fig. 11,a). The cracking in the nearest surface bulk of boron carbide as the result of local abrupt overheating could be the reason for such damage. Some spalls of the plate material were founded on the vacuum chamber bottom. Most likely, such macro damages were formed when limiter was placed at the nearest distance from the center 17 cm.

Another B_4C plate of the limiter head part (left one in the see Fig. 11,a) has no visible macro damages. Note that the similar spall effect has been observed when using the B_4C limiter for solid target boronization in the U-3M torsatron [4]. But in that case the negative pulsed voltage of about 200 V was applied to the limiter to provide arcs forming which caused macro damages mainly in the form of craters (Fig. 11,c).

Some words about possibility of using the B_4C-limiter to provide partial so called “solid target boronization” of the vacuum chamber wall. To form one molecular layer on the whole surface of the U-2M vacuum chamber wall, about 2.5×10^{20} boron particles are required. In view of this fact, the erosion of boron carbide plates during prolonged discharge cleaning procedure and, especially, the erosion during limiter experiments in work regime, a few hundreds of boron monolayer could be formed on the significant part of the wall during work campaign. Really, the weight loss of the plates after a few work campaigns of the U-2M device, presented in the Table shows the average magnitude ≈380 mg per campaign, i.e. about $2\cdot10^{22}$ particles. Note, that we have excluded the last results marked by $^{*)}$ because of macro damages of the right plate.

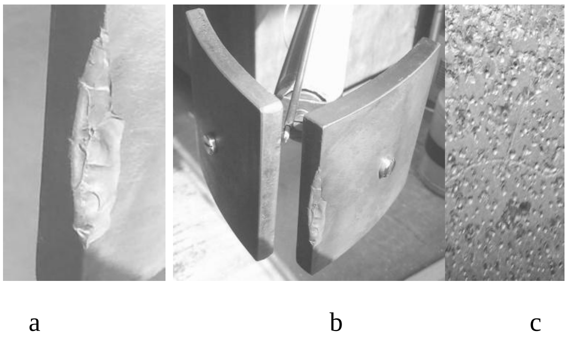

Fig. 11. Head plates of the limiter after exposure to work plasma pulsed discharges in the U-2M torsatron (a) and surface morphology of B_4C damages (b, c)

B_4C plates weight loss after U-2M work campains

Weight loss, mg				Average magnitude
Time year	Left plate	Right plate	Sum	–
2011-2012	123	248	371	–
2012-2013	116	378	494	–
2013-2014	124.8	153.7	278.5	≈ 380 mg/ campaign
2016-2017	118	545*	663*)	–

SUMMARY AND CONCLUSIONS

A new variant of the movable B_4C-limiter has been designed, manufactured and installed in the Uragan-2M torsatron. The influence of the limiter position relative to the minor axis was investigated in the regime of plasma heating in pulsed RF discharge.

Langmuir probes data have shown the essential dependence (decrease) of ion current during the limiter motion to the center. Most strong effect is observed for the probe located 2 cm from the wall in the poloidal cross-section similar to those with limiter head plates. The fact of signal decrease from the probe 2 located in the plasma column cross-section different from those of the limiter, means that the present limiter head plate configuration leads to the plasma column cutoff during limiter motion through the plasma boundary to the minor axis.

Spectroscopic measurements have shown no essential influence of limiter plate repositioning in the plasma on the H_α line intensity. The CIII line intensity essentially decreases and OV line increases under limiter installation at the distance of 15 cm from the wall. Soft X-ray signals appreciably increase at the same time. This can be explained by input of sputtered boron carbide into plasma. But the absence of the noticeable change in the plasma density suggests possible electron temperature increase. Additional experiments, including spectroscopic measurements of boron release into the plasma during the discharge, could shed some light on the question.

A strong macro damage of one of the plates (Fig. 11,b) was observed after limiter exposure to plasma. The cracking in the nearest surface bulk of boron carbide as the result of local abrupt overheating could be the reason for such damage. Most likely, such a macro damage was formed when the limiter was placed at the nearest distance from the plasma coloumn axis 17 cm. The second B_4C plate on another side of the limiter head part has no visible macro damages. It is expected that due to erosion of boron carbide plates the procedure of so called "solid target boronization" on the significant part of the U-2M torsatron vacuum chamber could be possible with the using of B_4C-limiter.

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ВЛИЯНИЕ ПОДВИЖНОГО B_4C-ЛИМИТЕРА НА ХАРАКТЕРИСТИКИ ПЛАЗМЫ ВЧ-РАЗРЯДОВ В ТОРСАТРОНЕ УРАГАН-2М

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Представлена усовершенствованная модель подвижного B_4C-лимитера торсатрона Ураган-2М. Изложены и обсуждаются предварительные результаты, полученные в экспериментах по взаимодействию плазмы импульсных ВЧ-разрядов с лимитером при его движении к центральной области плазменного шнура.

ВПЛИВ РУХОМОГО B_4C-ЛІМІТЕРА НА ХАРАКТЕРИСТИКИ ПЛАЗМИ ВЧ-РОЗРЯДІВ У ТОРСАТРОНІ УРАГАН-2М

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Представлена удосконалена модель рухомого B_4C-лімітера торсатрону Ураган-2М. Викладені і обговорюються попередні результати, отримані в експериментах із взаємодії плазми імпульсних ВЧ-розрядів з лімітером при його русі до центральної області плазмового шнура.