FIRST RESULTS OF THE RENEWED URAGAN-2M TORSATRON

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The results of experimental investigation on the vacuum magnetic surfaces in the l=2 torsatron with an additional toroidal field Uragan-2M at wide varying operation parameters are presented. Also the first results on the wall conditioning in the Uragan-2M with the ECR and RF discharges in atmosphere of hydrogen in steady-state mode at low magnetic field, plasma production and heating with RF power are described.

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1. INTRODUCTION

"Uragan-2M" (U-2M) is a medium-size torsatron with the reduced helical ripples of the magnetic field, the moderate shear and the magnetic well (to $\delta V'/V' \approx -4.3\%$). For U-2M, the winding with $l = 2$ and $m = 4$ was chosen to provide a maximum possible access to the plasma column. In the case of low m values (below 5) an additional toroidal magnetic field is necessary to create closed magnetic surfaces [1]. The separate control of electric currents in the helical and toroidal coils provides the possibility of wide-ranging optimization of the magnetic configurations in U-2M. The magnetic configuration parameters, e.g. the average minor radius a of the last closed magnetic surface (LCMS), the angle of rotational transform and others, can be changed in regimes varying the operation parameter K_φ ($K_\varphi = B_{th}/B_0$, $B_0 = B_{th} + B_{tt}$, where B_{th} is the toroidal magnetic field produced by the helix, and B_{tt} is the additional toroidal magnetic field) and the average vertical magnetic field with the circular minor axis of the torus $\langle B_\perp\rangle/B_0$ controlling the shift Δ of the magnetic axis from the circular minor axis of the torus.

The machine has the major plasma radius R = 1.7 m, the average minor plasma radius $a \leq 0.22$ m and the toroidal magnetic field $B_0 \leq 2.4$ T. In the range of $0.29 \leq K_\varphi \leq 0.4$ the rotational transform can be changed from $\iota(a) \approx 0.4$ (in 2π units) up to $\iota(a) \approx 0.75$ ($0.3 \leq \iota(0) \leq 0.57$ at the magnetic axis) [2, 3].

U-2M was assembled for the first time in the early nineties [4]. After the long period of downtime U-2M was completely reassembled and put into operation at the end of 2006. In U-2M the reaction at supports was reinforced to restrain the helical windings and the vacuum pumping system was modernized. The U-2M torsatron is equipped with two compact RF frame antennas.

Here, the results of studies on the magnetic surfaces in the steady magnetic fields of $0.09 \leq B_0 \leq 0.1$ T in the above-mentioned range of K_φ and for different $\langle B_\perp\rangle/B_0$ values are presented. The results obtained are compared with the results of previous measurements carried out after the first assembling of U-2M. Also described are the results on the wall conditioning, plasma production and heating with the RF power.

2. EXPERIMENTAL RESULTS

2.1. INVESTIGATION OF THE VACUUM MAGNETIC SURFACE STRUCTURE

The measurements have been performed using the scanning luminescent rod method [4, 5] in a poloidal cross-section of the torus $\varphi = \pi$ where the magnetic surfaces are vertically elongated. The luminescence of the rod was recorded using either a Polaroid film or a CCD camera. Earlier, in [6] the measurements of the magnetic surface structure were performed in the poloidal cross-section of the torus $\varphi = 0$ where the magnetic surfaces are vertically elongated also. The measurement data and the calculation results obtained using the code of [7] for the two poloidal cross-sections of the torus are compared.

The diameter of the luminescent rod is 2 mm. The emission aperture of the small electron gun used in the experiments is 1.2 mm. In our case the mapping of magnetic surfaces has a feature that the layer of the magnetic surfaces to be measured is filled up with electrons. In the image of this layer one can see the separate electron beam turns (the first ten are the best visible). For the non-perturbed magnetic surfaces with a large average radius, the measured electron layer thickness does not exceed (3.5 – 4) mm (Fig.1a). As regards the quality, for the magnetic surfaces with a small average radius (3 – 6) cm (regime with K_φ = 0.34), recorded are 30 – 40 turns of the e-beam.

The magnetic configurations with the rotational transform $\iota > 1/3$ in the region near the magnetic axis and with $\iota < 1/2$ for outer surfaces are of practical interest. The configurations with closed magnetic surfaces without magnetic islands and with a sufficiently large cross-section ($a \approx 20.5$ cm) are measured for $K_\varphi = 0.31$ ($\langle B_\perp\rangle/B_0 \approx 1.14\%$ and $1.85\% \leq \langle B_\perp\rangle/B_0 \leq 2.6\%$, Fig.1b), $K_\varphi = 0.32$ ($1.88\% \leq \langle B_\perp\rangle/B_0 \leq 2.6\%$, Fig.1c), $K_\varphi = 0.33$ ($\langle B_\perp\rangle/B_0 \approx 1.92\%$) and $K_\varphi = 0.295$ ($\langle B_\perp\rangle/B_0 \approx 1.8\%$). Here the vertical magnetic field values are restricted mainly due to the existence of the island structure of the resonance i =1/3 with a cross size cross-section of (2–5) cm (such a resonance was observed previously in [6]).

The measurement results on the average radius a of LCMS and the magnetic axis shift Δ as a function of the

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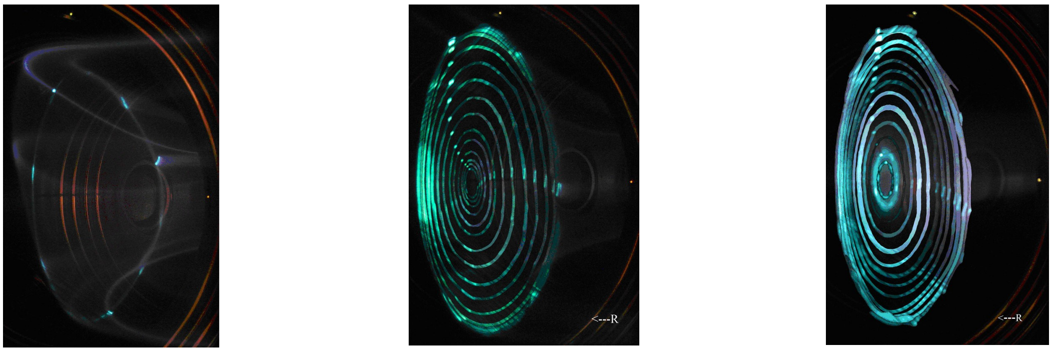
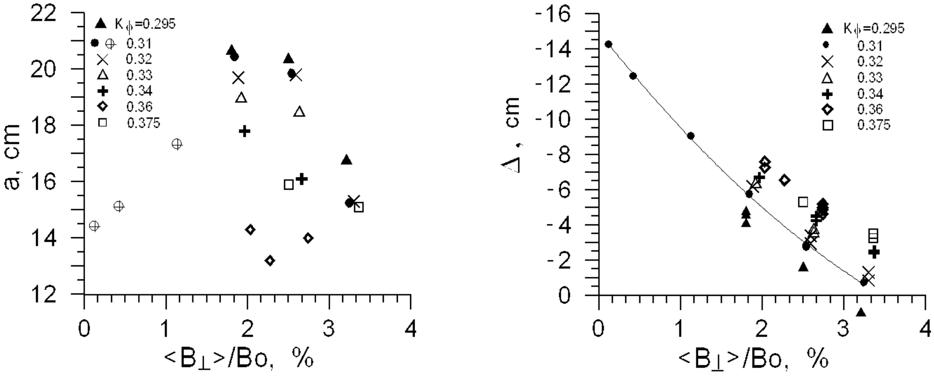
vertical magnetic field value are shown in Fig.2a and Fig.2b respectively (the symbol ⊕ indicates configurations, the volumes of which are limited by vacuum chamber because of the magnetic configuration shift by the vertical magnetic field). The radius a was measured with an accuracy of 1cm. The magnetic axis position is calculated as a midpoint of the smallest measured elliptical magnetic surface.



a b c

Fig.1. Magnetic surfaces for different regimes: a) $K_\varphi = 0.31$, $\langle B_\perp\rangle/B_0 \approx 0.43\%$, $\Delta \approx -12.4$ *cm; b)* $K_\varphi = 0.31$, $\langle B_\perp\rangle/B_0 \approx 2.55\%$, $\Delta \approx -2.8$ *cm; c)* $K_\varphi = 0.32$, $\langle B_\perp\rangle/B_0 \approx 2.59\%$, $\Delta \approx -3.4$ *cm*



a b

Fig.2. Last closed magnetic surface average radius a (a) and the magnetic axis shift Δ (b) versus the vertical magnetic field ($R_{axis} < R_o$)

2.2. WALL CONDITIONING

The wall conditioning in the Uragan-2M torsatron is carried out with ECR and RF discharges in the hydrogen atmosphere in the continuous mode at the low toroidal magnetic field B_T = (0.02 – 0.1) T. This process is accompanied by local heating of the vacuum vessel elements up to 100° C.

The RF-discharge wall conditioning is carried out both in the pulsed and continuous modes. In the pulsed operation both frame antennas are used. In the continuous mode the RF frequency is 4.7 MHz and the RF power launched is up to 1 kW. No special antenna is designed for this type of wall conditioning. The frame antenna is used as a wave launcher. It is fed by the RF power with a disconnected ground contact. In this way the electrostatic wave excitation is realized.

As the neutral hydrogen pressure $P_{H_2} = 4.8\times10^{-5}$ Torr the breakdown is observed for the magnetic field value at the stellarator axis B_0 = 0.016 T and higher. The plasma fills up the whole vessel volume. The maximum plasma density, determined from the probe measurements, is $n_e = 4\times10^9$ cm^{-3}. The electron temperature is surprisingly high, $T_e \approx 55$ eV. The plasma parameters vary slightly with the steady magnetic field change. As the magnetic field value B_0 = 0.077 T the neutral gas pressure variation in the range $P_{H_2} = (1.6\times10^{-5} - 1.6\times10^{-4})$ Torr exerts a stronger influence on the plasma parameters: the electron temperature gradually increases from $T_e \approx 40$ eV to $T_e \approx 55$ eV as the pressure rises. The plasma density has a maximum at $P_{H_2} = 4.8\times10^{-5}$ Torr and then decreases to $n_e = 1.6\times10^9$ cm^{-3} at the maximum gas pressure.

In the case of the discharge in hydrogen, the cleaning is associated with the chemical reactivity of the atomic hydrogen capable to create volatile substances. To produce the atoms efficiently, the value of electron temperature should be close to the hydrogen molecule dissociation threshold $T_e \sim \varepsilon_{d,H_2} = 4.4\,\text{eV}$ that is by order of magnitude less than in the RF discharge. The plasma density should be of one order higher. In future experiments it is planned to optimize the RF discharge and to approach the required parameters.

2.3. PLASMA PRODUCTION

Uragan-2M torsatron is equipped with two compact RF frame antennas. Antenna 1 has a broad $k_\parallel$ spectrum and is used for plasma production. Antenna 2 with the narrower $k_\parallel$ spectrum heats the plasma in the Alfven frequency range. Two generators with an RF power 0.5 MW and frequency in the range of 10 MHz are used.

The antenna with the broad $k_{\|}$ spectrum provides a reliable gas breakdown in the pressure range of $(3\times10^{-6} - 8\times10^{-5})$ Torr and produces the plasma with the density $n_e = (1–2)\times10^{12}$ cm^{-3}. Combined usage of two antennas with the RF power $P_{RF} \sim 100$ kW (after the preliminary short-time wall conditioning) results in the plasma density increase up to $n_e = 6\times10^{12}$ cm^{-3}. The evolution of the plasma density and the impurity optical lines intensity with two antennas is shown in Fig. 3. The increase of the carbon line intensity with time evidences that, to improve the plasma parameters, a careful wall conditioning should be carried out.

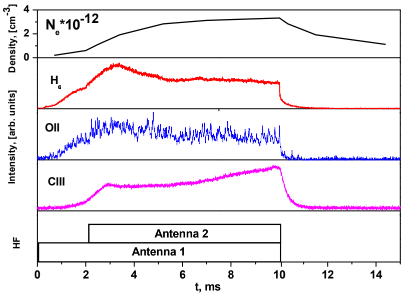


Fig.3. Time dependence of the plasma density and impurity lines intensity with switching on two antennas

3. CONCLUSIONS

Analysis of the vacuum magnetic surfaces was carried out in the wide range of K_φ ($K_\varphi = 0.295 – 0.4$) and with the normalized vertical magnetic field $\langle B_\perp\rangle/B_0$ values. The configurations with closed magnetic surfaces without magnetic islands having a sufficiently large cross-section ($a \approx 20.5$ cm) were measured for $K_\varphi = 0.31$ and $\langle B_\perp\rangle/B_0 \approx 1.14\%$, 1.85% and 2.55%. The measurements demonstrated a reasonable agreement with the numerical calculations.

Different methods of wall conditioning were applied to this machine with emphasis on both the pulsed and steady-state RF discharge conditioning.

Two compact RF antennas of a frame type with different $k_{\|}$ spectra were used for plasma production and heating. The plasma density obtained in the experiments is in the range of $n_e = (10^{12} – 10^{13})$ cm^{-3} (the RF power is $P_{RF} \sim 100$ kW).

REFERENCES

1. V.E. Bykov, et al. // *Fusion Technology.* 1990, v.17, p. 140-147.
2. O.S. Pavlichenko. Stellarators and other helical confinement systems // *Proc. of the IAEA Technical Committee Meeting. Germany, Garching, 10-14 May 1993* / IAEA, Vienna, 1993, p. 60-77.
3. O.S. Pavlichenko for the U-2M group // *Plasma Phys. Control. Fusion.* 1993, 35, B223-230.
4. H. Hailer, et al. // *14th EPS Conf. on Control. Fusion and Plasma Physics. Madrid, 1987.* v. 11 D, Part I, p. 423-426.
5. G.G. Lesnyakov, et al. // *Nuclear Fusion.* 1992, v. 32, N 12, p. 2157-2176.
6. G.G. Lesnyakov, et al. // *23rd EPS Conf. on Control. Fusion and Plasma Physics, Kiev, 24-28 June 1996*/ Contributed Papers, EPS, 1996, Part II, v. 20C, p. 547-550 (Rep. b025).
7. N.T. Besedin, G.G. Lesnyakov, I.M. Pankratov // *Problems of Atomic Science and Technology. Series “Thermonuclear Fusion”.* Moscow, 1991, N 1, p. 48-50 (in Russian).

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ПЕРВЫЕ РЕЗУЛЬТАТЫ МОДЕРНИЗИРОВАННОГО ТОРСАТРОНА УРАГАН-2М

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Представлены результаты экспериментального исследования вакуумных магнитных поверхностей в *l*=2 торсатроне с дополнительным магнитным полем Ураган-2М для широкого изменения операционных параметров. Также описаны первые результаты подготовки первой стенки в Урагане-2М при помощи ЭЦР и ВЧ разрядов в атмосфере водорода в стационарном режиме при низком магнитном поле, создания и нагрева плазмы ВЧ- мощностью.

ПЕРШІ РЕЗУЛЬТАТИ МОДЕРНІЗОВАНОГО ТОРСАТРОНУ УРАГАН-2М

А.А. Білецький, В.Л. Бережний, П.Я. Бурченко, В.В. Чечкін, В.Я. Чернишенко, Л.І. Григор’єва, С.П. Губарев, В.Г. Коновалов, А.Є. Кулага, Д.В. Курило, Г.Г. Лесняков, О.В. Лозін, С.М. Мазніченко, Ю.К. Миронов, В.Є. Моісеєнко, Ф.І. Ожерел’єв, Г.П. Опалева, В.К. Пашнєв, О.С. Павличенко, А.В. Прокопенко, В.С. Романов, Ю.Ф. Сергієв, А.І. Скибенко, А.Н. Шаповал, А.Ф. Штань, О.М. Швець, С.І. Солодовченко, Є.Л. Сороковий, В.С. Таран, І.К. Тарасов, В.І. Терешин, С.А. Цибенко, В.С. Войценя, Є.Д. Волков, М.І. Золототрубова

Представлено результати експериментального дослідження вакуумних магнітних поверхонь в *l=2* торсатроні з додатковим магнітним полем Ураган-2М для широкої зміни операційних параметрів. Також описані перші результати підготовки першої стінки в Урагані-2М за допомогою ЕЦР і ВЧ розрядів в атмосфері водню в стаціонарному режимі при низькому магнітному полі, створення і нагріву плазми ВЧ потужністю.