STELLARATOR RESEARCH AT IPP KIPT: STATUS AND PROSPECTS

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Features of the recent Uragan-2M campaign are reviewed together with some theoretical advances. They include experiments with B_4C limiter, studies of various 1…20 kHz oscillations, development of a new in-situ diagnostics for wall conditions, i.e. the thermal desorption probe, the improved numerical model of RF plasma production in stellarators in the ion cyclotron and electron-cyclotron frequency ranges, a new positive-definite form of time-harmonic Maxwell's equations and plasma start-up studies.

PACS: 52.35.Hr

INTRODUCTION

For the recent Uragan-2M campaign, a new variant of the movable B_4C-limiter has been designed, manufactured and installed. The influence of the limiter position relative to the minor axis was investigated on plasma parameters in the regime of plasma heating in pulsed RF discharge. The CIII line intensity essentially decreases and OV line increases under limiter positioning at the distance of 15 cm from the wall. The soft X-ray signals appreciably increase at the same time. This can be explained by input of sputtered boron carbide into plasma or increase of plasma temperature.

An appearance of various 1…20 kHz oscillations was observed in Uragan-2M. Two multichannel pinhole cameras were recently installed in U-2M for monitoring the oscillations of visible light emission from two positions in the same plasma cross-section. New electronics was designed and manufactured for measuring the plasma density, electron temperature and plasma potential profiles with high time resolution in cold, low density RF conditioning discharges via triple Langmuir probe technique.

The thermal desorption method has been developed for diagnosing impurity level on Uragan-2M vacuum chamber surfaces in situ. Using this method the investigations of outgassing rate were carried out and estimation of the number of molecules layers was done in the Uragan-2M torsatron after wall conditioning by RF plasma discharge in different regimes combined with pumping. With this method the influence of plasma treatment on hydrogen retention and release from 12X18H10T stainless steel (SS) was examined under different kinds of plasma conditions. The contributions of RF pulsed discharges during wall cleaning and RF pulsed plasma heating regime to hydrogen release were evaluated in Uragan-2M.

A numerical model of RF plasma production in stellarators in the ion cyclotron and electron-cyclotron frequency ranges is developed. This model is aimed for numerical analysis of the plasma discharge for the vacuum chamber wall conditioning. New features of the model presented are account of molecular ions, H_2+ and H_3+, in the particle balance equations. The radio-frequency module of the code is modified accordingly. A new module that calculates second harmonic electron cyclotron heating in case of weak wave damping is created and incorporated into the code.

A newly developed positive-definite form of time-harmonic Maxwell's equations will be useful for numerical models.

Three-Half-Turn (THT) antennas that have 3 straps oriented perpendicular to the magnetic field lines are used for plasma heating in Uragan-3M and Uragan-2M. It is found in experiments that THT antennas are capable of creating dense plasma at slightly decreased compared to regular regime magnetic fields, but with long idle time. Such feature is investigated at both experimental devices.

The prospects of stellarator research at IPP KIPT are strongly determined by integration of the studies to the Eurofusion Consortium activity within S1 work package.

B_4C–LIMITER USAGE IN RF PLASMA DISCHARGES

A new variant of the B_4C-limiter was created and tested in the operating RF discharge mode in U-2M. The main goal was to suppress plasma-wall interaction and in that way to reduce the amount of 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. The new limiter (Fig. 1) includes two 90 mm × 90 mm × 8 mm head plates manufactured by hot pressing of boron carbide powder in vacuum. The

ISSN 1562-6016. ВАНТ. 2019. №1(119)

plate-driving assembly provides location of the limiter at the distance 34…14 cm from the minor (circular) axis of the torus The Poincare plots of the magnetic force lines in the poloidal cross-section of the U-2M torus where the limiter was placed [1, 2] are shown in Fig. 2.

Fig. 1. The head part of the B_4C*-limiter*

The influence of the limiter position relative to the minor axis was investigated in the regime of plasma heating in pulsed RF discharges [3].

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 2cm 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.

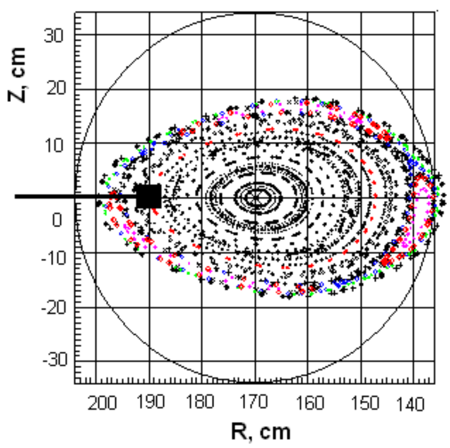

Fig. 2. Calculated Poincare plots of magnetic force lines in the poloidal cross-section of the U-2M torus [1,2] where the limiter was inserted

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 measured by two identical SXR sensors with different foils appreciably increase at the same time (Fig. 3). This can be explained as plasma electron temperature increase. But additional experiments, including another method of plasma temperature measurement and spectroscopic measurements of boron release into the plasma during the discharge, could shed some light on the question.

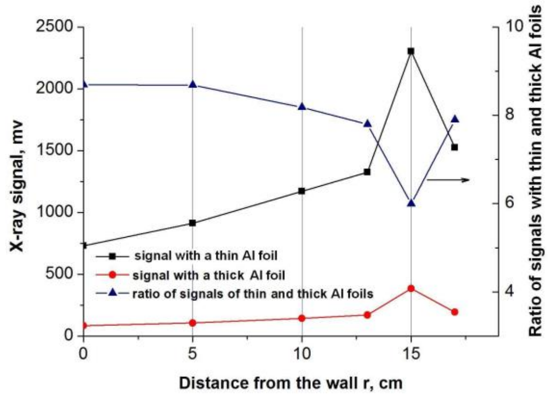

Fig. 3. Soft X-ray signals for thick (red) and thin (black) Al foils versus limiter position

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. To form one molecular layer on the whole surface of the U-2M vacuum chamber wall, about $2.5\cdot10^{20}$ boron particles are required. The weight loss of the plates after a few work campaigns of the U-2M device shows the average magnitude ≈380 mg per campaign, i.e. about $2\cdot10^{22}$ particles. We plan to install two more B_4C-limiters in other cross-sections to increase the quantity of sputtered boron. Switch on negative bias on the limiter plates and using arc regime can essentially increase of boron carbide erosion [4], too.

LOW FREQUENCY OSCILLATIONS

Previously observed [5] MHD oscillations were studied in low magnetic field B_0=0.01 T ($\omega >> \omega_{ci}$) radio frequency discharges [6] of the Uragan-2M (U-2M) stellarator. Coherent oscillations are observed by bolometers, triple Langmuir probe microwave interferometer (140 GHz) and magnetic pick-up coils in different toroidal cross-sections of U-2M. The Langmuir probe (LP) is used for measurement of complete profiles up to plasma center in cold, low density RF discharges under consideration. New electronics was designed and manufactured for T_e, n, V_p measurements with high time resolution via triple Langmuir probe (TP) technique [6]. A comparison of the TP measurements and conventional single pin scanned LP measurements shows good agreement (Fig. 4).

Two multichannel pinhole cameras were recently installed [6, 7] in U-2M for monitoring the oscillations of visible light emission from two positions in the same plasma cross-section. These coherent fluctuations are observed in set of diagnostics, as it is shown in Fig. 5.

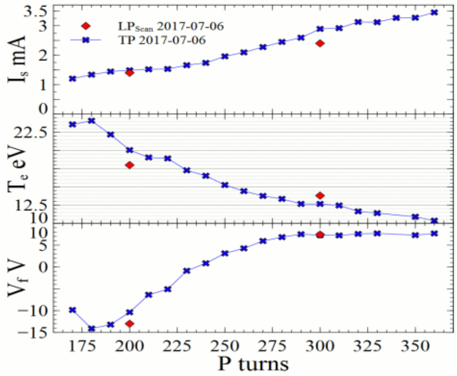

Fig. 4. TP (blue crosses) and conventional single pin scanned LP (red squares) data of ion saturation current, electron temperature and floating potential

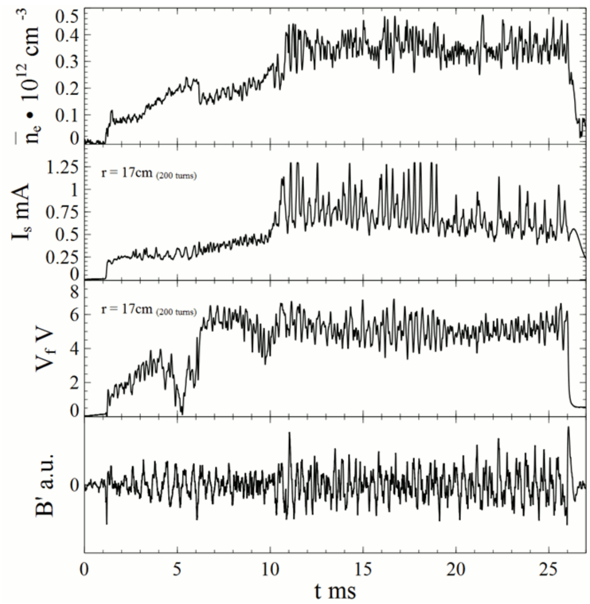

Fig. 5. Signals of interferometer, probe ion saturation current and floating potential, magnetic pick-up coil

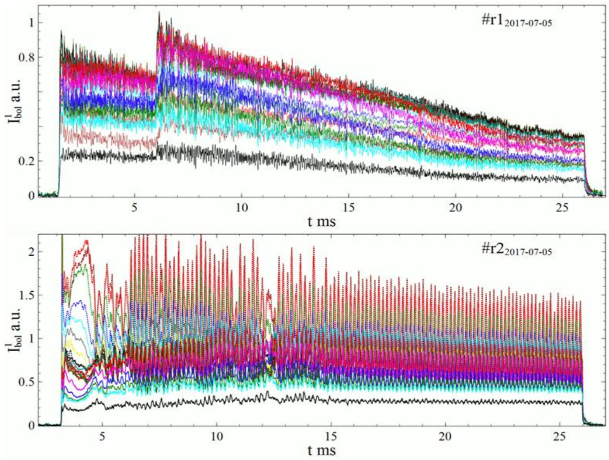

Fig. 6. Signals from 20-channals bolometer in two magnetic configurations

Variation of the magnetic configuration of U-2M substantially modifies the features of the oscillations in the plasma of such low magnetic field discharges (Fig. 6).

Significant dependence of the fluctuations amplitude is clearly observed in this figure. In addition to significant variation of the fluctuations amplitude, the modification of the oscillating modes types and frequency ranges were also observed. Different shapes of the plasma profiles are observed in different configurations according to the TP measurements.

Due to variation of magnetic configuration rotating $m = 2$ mode is transformed into the Sawtooth-like oscillations. Clear phase inversion of the Sawtooth-like oscillations is observed both in 12-channal and 20-channal bolometers (as it is seen from Fig. 7).

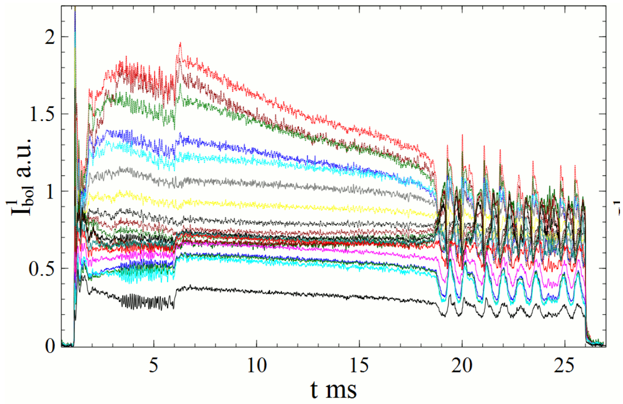

Fig. 7. Signals from 20-channels bolometer

Thus, variation of the magnetic configuration of U-2M substantially modifies fluctuations amplitude, oscillating modes type and frequency. Rotated *m=2* mode is transformed into the Sawtooth-like oscillations in different magnetic configurations. Strong dependence on the magnetic configuration indicates that observed in U-2M phenomena can have similar nature as in stellarator high temperature plasmas.

WALL CONDITIONS DIAGNOSTICS IN SITU USING STAINLESS STEEL THERMAL DESORPTION PROBE

The method and device has been developed and used for operative estimation of impurity level, outgassing rate and number of impurity gases molecular layers, on the surface of the Uragan-2M (U-2M) vacuum chamber walls [8, 9]. It is based on the thermal desorption of gases into a vacuum vessel from the surface of a special stainless steel probe during its heating up to temperature of 300ºC. Using this method the investigations were carried out of the wall conditions, outgassing rate and estimation of the number of molecules layers, in the Uragan-2M torsatron *in situ* after discharge cleaning in different regimes and pumping [10]. It had been indicated that the VHF and RF discharge cleaning in low magnetic fields of 0.01…0.02 T is more effective than the regimes without magnetic field. After preliminary short time VHF/RF discharge cleaning and long time pumping the number of impurity molecules layers was decreased from 40 up to less than one layer (Fig. 8). The analysis of the obtained data allows saying that such method could be used to monitor the quality of wall conditioning processes during preparing to plasma experiments.

The proposed method was also tested in the high temperature regime 400…700ºC to measure hydrogen outgassing from the SS probe [10] after hydrogen plasma treatment. It was observed the essential (one order of magnitude) increase of hydrogen outgassing at 500°C from stainless steel after two hours exposure by RF plasma discharge in working regime in Uragan-2M stellarator (point 2 in Fig. 9).

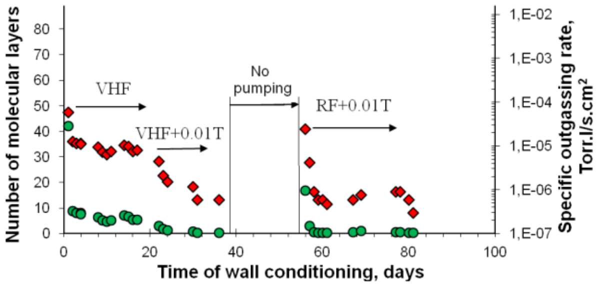

Fig. 8. Uragan-2M wall conditions: green points correspond to number of molecular layers on the surface of SS probe; red rhombs correspond to SS probe outgassing rate at 300ºC after VHF or RF discharge cleaning and pumping

It means that hydrogen concentration in the SS probe also increased. Then a few high heating pulses (5 V, 10 s, brown points in Fig. 9) were applied to the probe to remove hydrogen from the probe bulk. Time interval between pulses was two minutes.

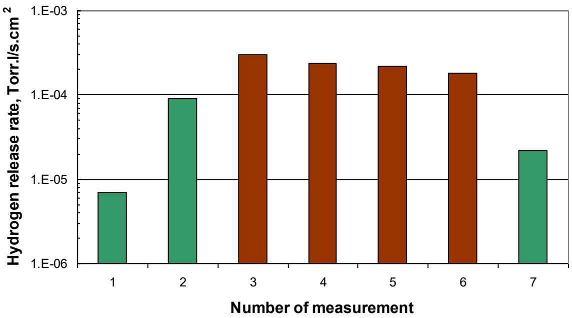

Fig. 9. Hydrogen release from the SS probe: green color – sample temperature under the measurement was 500ºC, brown color – sample temperature under the measurement was 600…700ºC

From pulse to pulse the SS probe temperature increased from 600°C (first pulse) to 700°C (fourth pulse). Then, after the probe cooling down to the room temperature, the measurement of hydrogen release rate at the temperature of 500°C was carried out (see point seven in Fig. 9). It is seen that after four high heating pulses hydrogen gas release (hydrogen outgassing rate) decreased in about four times.

So, using proposed method one can effectively monitor not only the surface conditions but hydrogen retention with the vacuum chamber wall material, too. Note, that not only hydrogen particles in different states impact on the U-2M wall surface. It may be nitrogen, oxygen, carbon, etc. Study of recycling process for those is also important. In general case this is of a great interest not only for fusion device but for different plasma installations, e.g., plasma accelerators, devices for vacuum-plasma or magnetron deposition, glow discharge plasma facilities etc.

In the nearest future we are going to developed wall conditions diagnostics of Uragan-2M by setting additionally of three stainless steel thermal desorption probes to provide measuring outgassing rate in different cross-sections. It will give a more complete picture of the state of the vacuum chamber wall surface of the U-2M after RF discharge cleaning.

SELF-CONSISTENT MODEL FOR RF PLASMA PRODUCTION IN MOLECULAR HYDROGEN

A new self-consistent model of RF plasma production in stellarators in the ion cyclotron and electron-cyclotron frequency ranges is presented.

New model will be used for simulation of plasma start-up and for numerical analysis of the plasma discharge for the vacuum chamber wall conditioning [11] in stellarator type machines.

As a prototype for the whole code, the models for atomic gas [12] and for molecular hydrogen [13] are used, which are developed by the research group earlier.

The developed earlier model for atomic hydrogen can describe the final stage of plasma production. In the model for molecular hydrogen, only electron-hydrogen molecular collisions are accounted for. The particle balance is determined by ionization of the hydrogen molecule. This model is suitable for low plasma densities.

There is a need for a model which incorporated all the collision processes and is valid at all stages of plasma production. Note here that the lower dimensionality 0D model for all sorts of hydrogen and helium is described in [14].

A newly developed model [15] as well as the previous models includes the system of the particle and energy balance equations for the electrons and the boundary problem for the Maxwell's equations. A new feature is account of molecular ions, H_2^+ and H_3^+, in the particle balance equations, and the radio-frequency module of the code is modified accordingly.

On the base of this numerical model, a one-dimensional numerical code is developed. The code uses the neoclassical diffusion, turbulent transport, and elementary atomic and molecular collision processes. In the balance of neutral gas, the hydrogen retention and recombination at the wall surface are taken into account.

In this code, input power to electrons and ions is calculated by the RF module. The RF power is calculated by solving the boundary problem for Maxwell's equations.

In addition to the RF module, the numerical code is supplemented with a module for EC heating. A new module that calculates second harmonic electron cyclotron heating in case of weak wave damping is created and incorporated into the code. The code can work using either RF module or EC.

The ECRH module takes into account that power deposition is proportional to the plasma density and electron Larmor radius square. Besides, it is proportional to the width of the ion cyclotron zone which is narrow when the electron temperature is low. The width, in turn, is proportional to the square root of the temperature. The power deposition formula reads:

$$p_{ECRH} = p_0 f_{ECRH}(r)(n_e / n_0)(T_e / T_0)^{3/2},$$

where p_{ECRH} is the power deposition density, f_{ECRH} is the power deposition shaping function which depends on electron cyclotron zone position and the ECRH ray focusing, n_e is the plasma density, T_e is the electron temperature and the quantities indexed with zero are normalizing constants.

POSITIVE-DEFINITE FORM OF TIME-HARMONIC MAXWELL'S EQUATIONS

Time-harmonic Maxwell's equations are a subject for numerical treatment for analysis of the wave propagation in non-uniform plasma. In their original form, they contain sign-indefinite operators. This limits application of iterative procedures for their numerical solving.

In this paper the following form of the Maxwell's equations is proposed for further numerical solving.

$$\nabla\times\nabla\times\mathbf{E} - ik_0(\hat{\varepsilon}^* + 1)\cdot\nabla\times\mathbf{H} + k_0^2\hat{\varepsilon}^*\cdot\hat{\varepsilon}\cdot\mathbf{E} = -\frac{4\pi i k_0}{c}\hat{\varepsilon}^*\cdot\mathbf{j}_{ext}$$

$$\nabla\times\nabla\times\mathbf{H} + ik_0\nabla\times(\hat{\varepsilon} + 1)\cdot\mathbf{E} + k_0^2\mathbf{H} = \frac{4\pi}{c}\nabla\times\mathbf{j}_{ext}.$$

Here **E** and **H** are the electric and magnetic field vectors, $k_0=\omega/c$, $\hat{\varepsilon}$ is the dielectric tensor, $(\hat{\varepsilon}^*)_{i,k} = (\hat{\varepsilon})^*_{k,i}$, $\mathbf{j}_{ext}$ is the driving (external) current. This system of equations contains positive-definite operator in the left-hand side. This feature, in principle, could be preserved after the discretization that results in a linear algebraic system of equations with positively-definite matrix.

It is necessary to note that the above system is degenerate. This feature is inherited from the original Maxwell's equations. Thus, a straightforward discretization may cause appearance of spurious solutions. A special technique derived in Ref. 16 could be applied for discretization to avoid this unwanted effect.

The above system of equations, being of higher order, needs more boundary conditions than the original one. For this purpose, the components of the original system could be used since they are differential equations of the first order.

THREE-HALF-TURN ANTENNA PLASMA START-UP EXPERIMENTS

Three-Half-Turn (THT) antenna has 3 straps oriented perpendicular to the magnetic field lines. This antenna is fed through the central strap [17]. THT antennas are used for plasma heating in Uragan-3M and Uragan-2M. The research task was to study independent RF plasma creation with THT antenna in both devices. THT antennas are capable of creating dense plasma at decreased compared to regular regime magnetic fields, but with long idle time what is dangerous for antenna insulators because of high voltage at the antenna elements. Experimental conditions were changed through variation of magnetic field, pressure and RF generator parameters in order to find optimal regime of operation. The optimum magnetic field was 0.62…0.68 T at Uragan-3M and 0.37…0.4 T at U-2M while standard field was 0.7…0.72 and 0.4…0.42 T accordingly.

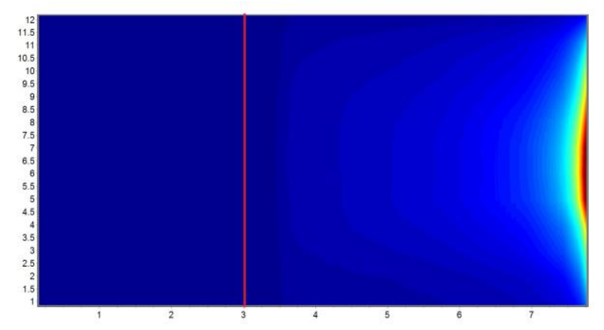

Fig. 10. 12-channel H_α filterscope signal. Magnetic field B_0=3700 G, P_{H_2}=7.2·10^{-6} Torr. RF pulse beginning is shown by red vertical line

The experiments on ICRF discharge initiation were performed at variable RF power (P=50…100 kW, anode voltage at generator, U_{k1}=5…7 kV), confining magnetic field B_0=0.4 T, to produce RF plasma in hydrogen at a continuous gas puff with pressure range p_{H_2}≈7.5·10^{-6}…1.5·10^{-4} Torr. The density n_e increased continuously from units 10^{9} cm^{-3}, passes (2…3)·10^{12} cm^{-3} in the T_e maximum and achieves a "quasistationary" level of ~7·10^{11}cm^{-3}. A 5 ms long delay from the beginning of RF pulse and discharge development is seen in Fig. 10.

SUMMARY AND FUTURE PLANS

Features of the recent Uragan-2M campaign are reviewed together with some theoretical advances. They 1…20 kHz oscillations, development of a new in-situ diagnostics for wall conditions, the thermal desorption probe, the improved numerical model of RF plasma production in stellarators in the ion cyclotron and electron-cyclotron frequency ranges, a new positive-definite form of time-harmonic Maxwell's equations and plasma start-up studies.

The future plans ensue of the general aim to achieve close integration to the EUROfusion consortium. Thus, the studies for wall conditioning, RF plasma start-up, high-beta plasma and plasma oscillations will have priorities.

ACKNOWLEDGEMENTS

The work is supported in part by the National Academy of Sciences of Ukraine, grants П-3-22, Х-4-3 and ЦВ-5-20.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement № 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

REFERENCES

1. G.G. Lesnyakov et al. // *Contributed Papers of 23rd EPS Conf. on Contr. Fusion and Plasma Phys*. 1996, v. 20 C, part. II (b025), p. 547-550.
2. G.G. Lesnyakov, A.N. Shapoval, O.S. Pavlichenko // *Problem of Atomic Science and Technology*. *Series "Plasma Physics" (18*). 2012, № 6 (82), p. 34-37.
3. A.V. Lozin et al. // *Plasma Physics Reports*. 2013, v. 39, № 8, p. 624-631.
4. G.P. Glazunov et al. // *J. of Nuclear Materials.* 1997, v. 241-243, p. 1052-1054.
5. M.B. Dreval et al. // *Problems of Atomic Science and Technology*. *Series "Plasma Physics".* 2016, № 6(22), p. 15.
6. M.B. Dreval et al. // *Problems of Atomic Science and Technology*. *Series "Plasma Physics".* 2018, № 6(118), p. 42.
7. M.B. Dreval et al. // *Fusion Engineering and Design*. 2018, v. 129, p. 345.
8. G.P. Glazunov et al. // *Problems of Atomic Science and Technology*. *Series "Plasma Physics".* 2012, № 6 (82), iss. 18, p. 117-119.
9. G.P. Glazunov et al. // *Fusion Engineering and Design*. 2018, v. 137, p. 196-201.
10. M.N. Bondarenko et al. // *Problems of Atomic Science and Technology*. *Series "Plasma Physics*". 2018, № 6, p. 71-73.
11. A.I. Lysojvan, et al. // *Nuclear Fusion.* 1992, № 32,p. 1361.
12. V.E. Moiseenko et al. // *Plasma Physics Reports.* 2013, № 39, p. 873.
13. Yu.S. Kulyk et al. // *Problems of Atomic Science and Technology. Series "Plasma Physics" (20).* 2016, № 6 (106), p. 56-59.
14. T Wauters et al. // *Plasma Phys. Control. Fusion.* 2011, № 53.
15. Yu.S. Kulyk et al. // *Problems of Atomic Science and Technology, Series Plasma Physics.* 2018, № 6 (118), p. 46-49.
16. V.E. Moiseenko, O. Agren // *J. Plasma Phys*. 2006, № 72**,** p. 1133.
17. A.V. Lozin et al. // *Problems of Atomic Science and Technology. Series "Plasma Physics".* 2013, № 1, p. 27-29.

Article received 15.01.2019

ИССЛЕДОВАНИЯ СТЕЛЛАРАТОРОВ В ИФП ХФТИ: СОСТОЯНИЕ И ПЕРСПЕКТИВЫ

В. Е. Моисеенко, Г.П. Глазунов, А.В. Лозин, А.Л. Конотопский, Д.И. Барон, А.А. Белецкий, М.Н. Бондаренко, В.В. Чечкин, Н.Б. Древаль, Л.И. Григорьева, М.М. Козуля, С.М. Мазниченко, Ю.К. Миронов, Р.О. Павличенко, В.С. Романов, А.Н. Шаповал, В.Б. Коровин, В.Г. Коновалов, Н.В. Заманов, Е.В. Турянская, Ю.С. Кулик, T. Wauters, A.I. Lyssoivan, O. Ågren, И.Е. Гаркуша и команда Урагана-2М

Рассмотрены особенности недавней кампании Ураган-2М и некоторые теоретические результаты. Они включают в себя эксперименты с B_4C-лимитером, исследования различных колебаний с частотой 1…20 кГц, разработку новой in-situ диагностики состояния стенок (термодесорбционный зонд), улучшенную численную модель ВЧ-создания плазмы в стеллараторах в ионном циклотроном и электронном циклотронном диапазонах частот, новую положительно определенную форму уравнений Максвелла для одной частоты и исследования по высокочастотному созданию плазмы.

ДОСЛІДЖЕННЯ СТЕЛАРАТОРІВ В ІФП ХФТІ: СТАН І ПЕРСПЕКТИВИ

В. Є. Моісеєнко, Г.П. Глазунов, О.В. Лозін, О.Л. Конотопський, Д.І. Барон, О.О. Білецький, М.Н. Бондаренко, В.В. Чечкін, М.Б. Древаль, Л.І. Григор'єва, М.М. Козуля, С.М. Мазніченко, Ю.К. Миронов, Р.О. Павліченко, В.С. Романов, А.Н. Шаповал, В.Б. Коровін, В.Г. Коновалов, Н.В. Заманов, О.В. Турянська, Ю.С. Кулик, T. Wauters, A.I. Lyssoivan, O. Ågren, І.Є. Гаркуша та команда Урагану-2М

Розглянуто особливості недавньої кампанії Ураган-2М і деякі теоретичні результати. Вони включають у себе експерименти з B_4C-лімітером, дослідження різних коливань з частотою 1…20 кГц, розробку нової in-situ діагностики стану стінок (термодесорбційний зонд), поліпшену чисельну модель ВЧ-створення плазми в стелараторах в іонному циклотронному і електронному циклотронному діапазонах частот, нову позитивно визначену форму рівнянь Максвелла для однієї частоти та дослідження з високочастотного створення плазми.