RESEARCHES ON PLASMA PHYSICS AND CONTROLLED FUSION IN IPP NSC KIPT

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Recent results of experimental and theoretical investigations, carried out in the Institute of Plasma Physics of the NSC KIPT, are presented in the report. The main problems of discussion are as follows: plasma confinement and heating in stellarators and electromagnetic traps; powerful quasi-steady-state plasma accelerators (QSPA); experiments relevant for ITER; fusion plasma theory; methods of high temperature plasma diagnostics; plasma technology. The main prospects of the IPP investigations are discussed also.

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1. INTRODUCTION

Investigations on plasma physics and controlled fusion were initiated in Kharkov Institute of Physics and Technology (KIPT) by academicians I.V. Kurchatov and K.D. Sinelnikov in 1956. The Institute of Plasma Physics, as a part of the National Science Center "KIPT", was established in 1994.

The main directions of recent researches of IPP are as follows. Fusion investigations (theory and experiments) are dealing with magnetic confinement of plasma in stellarators and electromagnetic traps, development of methods of plasma production and heating, mainly radio frequency (RF) methods, development of diagnostic methods of high temperature plasma, development and using the powerful pulsed and quasi-steady-state plasma accelerators. Some experiments are carried out in support of problems of fusion reactor ITER, in particular, analysis of the first wall and divertor plate materials behavior under high heat loads typical for ITER transient events, study of the properties of the first in-vessel mirrors of the diagnostic systems under their irradiations with particles and electromagnetic fluxes. Plasma technology methods, developed in IPP, are devoted to surface modification with pulsed plasma streams, coatings deposition with using different types of plasma sources, ozone generators and their applications. Different aspects of the fundamental problems of plasma physics are studied also.

The IPP is equipped by medium size torsatrons Uragan-3M and Uragan-2M (to be put in operation at the end of this year), electromagnetic trap Jupiter-2M, powerful quasi-steady-state plasma accelerator QSPA Kh-50, and a number of small size plasma devices. The main results obtained in IPP are presented here.

2. MAGNETIC CONFINEMENT INVESTIGATIONS

2.1. RESULTS OF EXPERIMENTS IN TORSATRON URAGAN-3M

The Uragan-3M (U-3M) magnetic system is located in the large vacuum chamber to insure spatial divertor operation [1]. It includes the helical windings ($l = 3$, $m=9$, $R = 1$ m) and four vertical magnetic field coils (see Fig.1). The toroidal magnetic field was varied in the range of $0.45 \le B_0 \le 1.3$ T. Plasma radius ≤ 12.5 cm, plasma density $1 \times 10^{12} \le n_e \le 9 \times 10^{12}$ cm^{-3}. The plasma production and heating was realized by RF fields in the multi-mode Alfven resonance regime ($\omega \lesssim \omega_{ci}$) with fixed input power $P_{RF} \le 200$ kW.

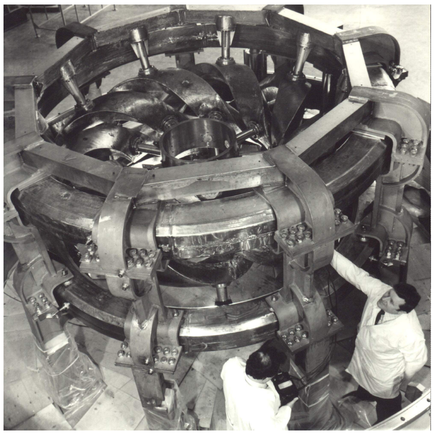

Fig. 1. Magnetic system of the torsatron Uragan-3M

Studies of effects associated with internal and edge transport barriers (ITB and ETB) formation were continued. It has been shown recently that a discharge regime spontaneously arises which is characterized by an increase of density, temperature, confinement time. According to estimates, the energy confinement time underwent an (1.2-1.3)-times increase. This regime was attributed to ITB formation in the region of island chain with stochastic magnetic field lines [2]. Later on, it was observed that in the process of ITB formation a layer with a strong shear of radial electric field E_r arose near the plasma boundary. In this layer turbulent low-frequency fluctuations of density and electric field were effectively suppressed. Accordingly, the anomalous transport associated with the turbulence was also reduced, that is, an ETB was also formed [3].

In particular, it has been observed (method of the microwave correlation reflectometry) that oscillations of the reflected microwave signal arise at the discharge phase preceding the ITB formation. These oscillations correspond to a ~1 cm radial shift of the reflecting layer with the frequency of ~400 Hz and to corresponding oscillations of the plasma poloidal rotation velocity. These oscillations are damped with the ITB regime setting in. Such oscillations-relaxations may be result from a position of the reflecting layer in the region of stochastic field lines (so-called "oscillating islands" observed recently in the LHD heliotron).

It follows from observations of time evolution of the poloidal rotation velocity that ITB formation is accompanied by occurrence of a sharp velocity shear. With this, the ITB appears more stable in layers with the relative radius ρ~(0.1…0.3) (counted from the magnetic axis), that is, in the region of the island structure, where its length can attain ~ 10 ms. In more distant layers (ρ ~0.4…0.7) the relaxations lasts longer and the stable regime sets in later and lasts for a shorter time (1…4 ms).

As recent research has shown, the formation of the ETB due to the hard bifurcation of the radial electric field E_r toward a more negative value is always preceded by a substantial rise of fast ion (>500 eV) content in the confinement volume and by an outflow of such ions to the divertor region on the ion toroidal ∇B drift side. It has been observed that the intensity of fast ion accumulation in the confinement volume and the rise of their loss are of a resonance character depending on the plasma density and magnetic field strength. On this basis, a conclusion is drawn that the fast ion generation is caused by an RF mechanisms, the most possible one being the local Alfven resonance in an essentially non-uniform plasma. Due to such a resonance, in a plasma layer where the relation $\omega = k_{\|} V_A$ is fulfilled (ω - generator frequency, $k_{\|}$ - parallel wave number defined by RF current distribution in the antenna, V_A - Alfven velocity) a strong increase of the RF field and of energy of ions interacting with this field, consequently, takes place. With this, the condition of the resonance wave excitation by the antenna in a bounded plasma is fulfilled for the plasma column, thus providing the observed dependence of the fast ion generation and loss on the plasma density and magnetic field.

An important aspect of the effect of fast ion generation in U-3M is its influence on ETB formation. The experimentally observed fact that the ETB formation is always synchronized with an increase of fast ion loss may indicate that the E_r bifurcation toward a more negative value and occurrence of a transient layer between the $E_r>0$ and $E_r<0$ regions at the plasma boundary where the anomalous transport is suppressed are driven by the orbit loss of locally trapped ions [4].

2.2. TORSATRON URAGAN-2M

Uragan-2M (U-2M) is the flexible torsatron with small helical ripples and considerably high parameters (R_0 = 170 cm, a_{pl} = 22 cm, $B_0 \leq 2.4$ T, l = 2, m = 4) (Fig. 2). The U-2M magnetic system consists of toroidal field (16 coils), helical field, vertical field and correction (trim) field coil system which provide realization of different magnetic configurations [5, 6].

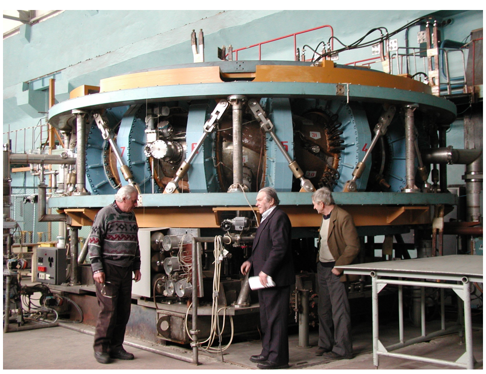

Fig. 2. The common view of the torsatron Uragan-2M

The first assembling of this device was done at the earlier ninetieth. Recently the U-2M device is under fully revision and reconstruction and should be put in operation at the end of 2006. The RF system for plasma production and heating with loop type antennae is manufactured, tested and installed in U-2M. The Alfven waves and fast magnetosonic waves will be used in these experiments for plasma production and heating.

2.3. ELECTROMAGNETIC TRAP JUPITER-2M

The magnetic system of the multislit electromagnetic trap (EMT) Jupiter-2M [7] (Fig. 3) is the consequence of magnetic coils with opposite currents in each near by coils. Seven annular magnetic slits and axial mirrors are closed by high voltage electric potentials. The electrons are confined in EMT by magnetic field and external electric field, while ions are trapped in potential well of the space charge of electrons. Magnetic field in annular slits is 8 kG. Axial mirror magnetic field – 17 kG. The plasma parameters: $n_e \lesssim 10^{12}$ cm^{-3}, T_e – 15 eV, T_i – 60 eV, confinement time – 2 ms, plasma volume – 50 l.

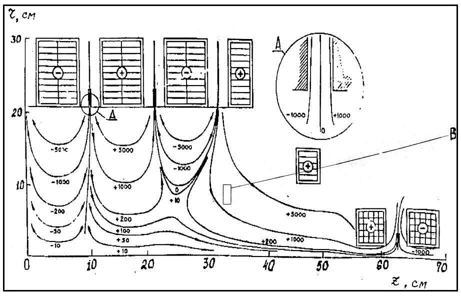

Fig. 3. Distributions of magnetic fields and electric potentials in EMT Jupiter-2M

The transport of electrons and its dependence on gas pressure, plasma fluxes through the annular and axial magnetic slits, potential distributions and the potential barrier values in the annular slits were investigated. Direct measurements have confirmed small losses of ions through the axial holes as compare to losses through the annular slits. It was shown that for plasma accumulation and heating in EMT with electron injection the coefficient of collisionless energy transfer to ions is ≤ 0.15.

The theory and numerical codes of plasma accumulation, heating and confinement in multislit EMT was developed (under the assumption of classical diffusion). The calculated plasma parameters in Jupiter-2M are in good agreement with the measured ones.

2.4. RF PLASMA PRODUCTION AND HEATING

The main method of high density plasma production and heating in toroidal systems of IPP ("Omega", "U-1", "U-3" and "U-3M" is high frequency one. The plasma production was carried out in regimes of resonance excitation of Alfven waves (or ICR) and fast magnetosonic waves in the frequency range $\omega \lesssim \omega_{ci}$. Under this the amplitudes of electric and magnetic RF-fields were risen and waves transformation had took place. Besides linear mechanisms of RF energy absorption the non linear (turbulent) processes took place also. As it was shown in experiments in U-3M torsatron [8], the main mechanism of ion heating under the RF plasma heating is parametric excitation of the ion Bernstein modes. Two main stages of plasma production can be marked out: 1) before wave stage – RF-break down with neutral gas ionization by electrons (and ions) in longitudinal electric field of antennas; 2) the wave stage, appeared under the achieving the definite level of plasma density, – eigen modes generation due to the wide (by $k_{||}$) spectrum of RF-power irradiated by antennae (with such method the plasma density of $7x10^{13}$ cm^{-3} and ion temperature up to 1 keV was obtained in “U-2”) [9].

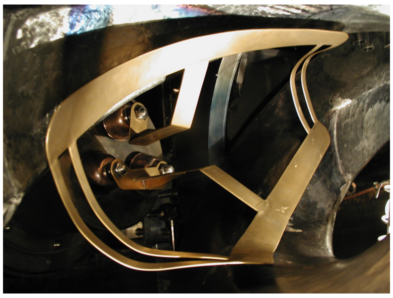

Fig. 4. HF antenna for torsatron Uragan-2M

The short parallel wavelength Alfven resonance heating in “U-2M” will be investigated. The portable multi-loop antennae to be used in this experiment were developed (Fig.4). The portable antennae will be developed which also could be used for fast wave heating. The minority and second harmonic heating will be also investigated.

2.5. PLASMA DIAGNOSTICS

Different methods of high temperature plasma diagnostics, in particular microwave correlation reflectometry [10], heavy ion beam probing (HIBP) [11] and so on, were developed. The first method is based on measurements of the shift of cross-correlation functions of two fluctuating microwave signals reflected from plasma layer sections which have the same density but differ by their poloidal and radial positions. This method was utilized in Uragan-3M experiments for measurements of the plasma poloidal rotation velocity and its fluctuations (with the frequency ~ 400 Hz).

The HIBP diagnostic, based on the analysis of the secondary particles of high energy probing particles, provides the plasma potential, plasma density and their fluctuations measurements with spatial resolution of an order several cm and temporal resolution < 0.01 ms. Many types of HIBP equipment was designed and manufactured by IPP and installed in different tokamaks and stellarators of the world: TM-4, T-10 (Kurchatov Inst., Moscow), Tuman-3M (Ioffe Institute, St. Petersburg), TJ-I, TJ-II (CIEMAT, Madrid), Wega (IPP, Greifswald). This diagnostic is in preparation for torsatron Uragan-2M.

2.6. PLASMA THEORY

2.6.1. *Modeling the neoclassical transport, equilibrium plasma currents and MHD stability ($1/\nu$ -regime) in the plasma of stellarators.* The computations of the neoclassical transport in the $1/\nu$ -regime of plasmas of conventional and advanced stellarators using the NEO numerical code [12] were performed at IPP together with the colleagues at the Graz Technical University (Austria) on the base of the code [13] computing the gradient of the magnetic surface function. The NEO code allows one to compute the neoclassical transport coefficients for the magnetic fields given in conventional coordinates not related to magnetic surfaces (Cartesian or cylindrical coordinates) as well as in magnetic coordinates where the “radial” coordinates serves as a mark of the magnetic surface. It enables one to determine transport coefficients for realistic configurations when the magnetic surfaces exist and one can employ the notion of local transport coefficients.

The computations were performed for conventional stellarators (torsatrons), the torsatron with the longitudinal magnetic field Uragan-2M (Kharkov), the devices TJ-II (Madrid, Spain), Yamator (Kharkov), CHS (Nagoya, Japan), as well as for advanced stellarators for which the magnetic configuration is determined through minimizing transport, bootstrap current, increasing plasma pressure etc, e.g., due to quasi-symmetry approximately valid inside the work volume and leading to the decrease of particle drift and transport coefficients. A deciding contribution into the development of the theory in this direction was made by J. Nuhrenberg, V.D. Shafranov and their colleagues.

On the ground of a broad international cooperation the theoreticians of IPP participated in calculations for the following projects of advanced stellarators: CHS-qu (Nagoya, Japan) and NCSX (Princeton, USA) (decreasing transport by one-two orders of magnitude compared with a conventional stellarator), quasi-helical HSX stellarator (Oak-Ridge, USA) (decreasing transport by three-four orders of magnitude in the central region and by two orders of magnitude at the edge), Wendelstein-7X device (Garching-Greifswald, Germany), whose configuration is chosen to decrease bootstrap current and to optimize transport (10 times decrease). In the projects of isodynamic stellarators where the loss of alpha-particles is optimized, the transport is decreased by several times though not so strong as in quasi-helical and quasi-symmetrical stellarators and in W-7X. For the LHD heliotron (NIFS, Toki, Japan) the NEO-based calculations clarified the conditions of relevance to earlier calculations on the ground of other numerical codes.

The calculations of transport coefficients in the $1/\nu$ -regime, i.e., in the region where the expected reactor-stellarator would operate, confirmed the expected values of transport coefficients obtained using magnetic coordinates, and permitted to determine their exact values for realistic characteristics of magnetic configurations of advanced stellarators.

2.6.2. *Modeling the nonlinear electron cyclotron heating and current drive in tokamaks and stellarators.* The nonlinear regime of electromagnetic wave absorption and current drive under conditions of electron cyclotron resonance is realized in toroidal traps (tokamaks and stellarators) for broad packets of electromagnetic field of the pumping wave, when a resonant electron moving along the magnetic line of force has time to be trapped by the wave field before leaving the resonance region. On the ground of the improved Monte-Carlo technique developed at KIPT a nonlinear theory of plasma heating and current drive in tokamaks and stellarators with the help of the electron cyclotron resonance was worked out. The nonlinear regime of absorption is shown to differ from one usually applied in calculations of the quasi-linear regime of electron heating at the second harmonic of the cyclotron frequency with the extra-ordinary wave propagating almost across the magnetic field [14]. The absorption and driven current decrease near rational magnetic surfaces in a tokamak. This feature may be used to sustain plasma stability with respect to neoclassical tearing modes including those in ITER [15].

2.6.3. *RF plasma creation and heating in Uragan-2M torsatron.* Plasma production in Uragan-2M with the waves of frequency below the ion cyclotron one with the inclusion of the local Alfven resonance excited by a crankshaft antenna was performed [16].

2.6.4. *Control and removal of impurities out of stellarator plasma.* An active technique for removing alpha-particles (products of fusion reaction) out of the reactor-stellarator plasma using stochastic heating of alpha-particles slowed-down to the energy order of 100 keV with lower-hybrid waves is proposed. Under the conditions chosen the lower-hybrid heating has no influence on the confinement of alpha-particles with the energy of 500 keV and more and of bulk plasma particles with the thermal energy order of 10 keV [17].

2.6.5. *ICR heating in open ended traps.* A scheme of a neutron source based on a gas-dynamic trap (GDL, Budker Nuclear Physics Institute, Russia) is proposed for which sloshing ions are produced by the cyclotron resonance at the fundamental or second harmonic of ions in the deuterium-tritium mixture with the energy consumption lower than one for other schemes of neutron sources. This scheme was also studied in [18, 19] for a straight-field line mirror.

2.6.6. *Influence of external low frequency helical perturbation in tokamak edge plasma.* The effect of plasma response on penetration of DED (Dynamic Ergodic Divertor) helical perturbation of magnetic filed was studied analytically and numerically in cylindrical and toroidal geometry [20, 21]. For parameters of the TEXTOR-DED (Germany) and HYBTOK-II (Japan) tokamaks the structure of the helical perturbation in plasma, plasma flows in the helical magnetic field, perturbation of the plasma current profile and the profile of ponderomotive force were studied. The calculated profiles are in a good qualitative agreement with the experimental data measured in plasma of CSTN-IV and HYBTOK-II tokamaks. It was revealed that the toroidal effects result in decreasing the magnetic field perturbation amplitude in the resonant zone. For the tokamaks HYBTOK-II and TEXTOR-DED the existence of plasma vortexes was shown and their structure was studied.

2.6.7. *Ion cyclotron parametric instability effect on isotope separation through selective ICR heating.* The PIC modeling of the excitation of short-wavelength ion cyclotron oscillations in plasma containing a mixture of ions of different isotopes in the electric field with the frequency close to the cyclotron frequency of an isotope to be separated has shown that turbulent heating of both resonant and nonresonant ions in the electric field of parametrically unstable oscillations occurs with the equal rate by an order of value and it can lower substantially the efficiency of this method of isotope separation [22].

2.6.8. *Oscillation and instability of plasma in crossed electrical and magnetic fields.* In crossed fields under ionization of atoms and molecules via electron impact in the strong electric field the energy of the ion generated is determined by the value of the electric potential at the point where the ionization took place. Ions are accelerated almost along the radius and their distribution over the energy of transverse motion has the shape of a Fermi-Dirac distribution. In such plasma nonlocal potential oscillations are possible whose frequencies are close to multiple modified ion cyclotron frequencies determined with the account of ion rotation in crossed fields. In the region where the oscillation frequencies intersect, the oscillations are unstable [23].

3. QUASI-STEADY-STATE PLASMA ACCELERATOR

The quasi-steady-state plasma accelerator QSPA Kh-50 [24], shown in Fig. 5, consists of two stages. The first one is used for plasma production. The main, second stage, is a coaxial system of shaped semitransparent active electrodes with magnetically screened elements, supplied from independent power sources. Average anode diameter is 50 cm, its length – 80 cm. The total energy of the capacitor banks supplying the main discharge and other QSPA active elements achieved 4 MJ.

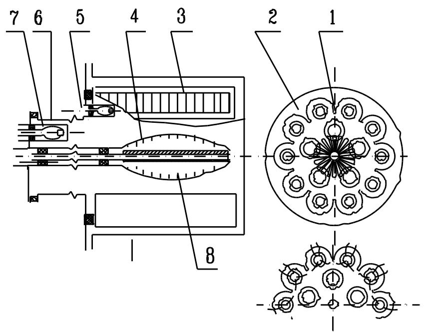

Fig. 5. The block diagram of the QSPA Kh-50 device. 1-anode transformer (T_A) ; 2-T_A collector; 3-T_A pies; 4: cathode transformer rods; 5: anode ionization chamber; 6: drift channel; 7: input ionization chambers; 8: needle-type emitters

The main parameters of hydrogen plasma streams (produced under main discharge capacitor voltage up to 15 kV and discharge current ~ 750 kA) were as follows: average density of $4x10^{16}$ cm^{-3}, plasma power density up to 250 GW/m^2, ion energy up to 0.9 keV and duration of plasma pulse – 0.1…0.25 ms. Plasma stream maximal pressure in near axis region achieved $(1.6…1.8)x10^6$ Pa. Total plasma energy achieved 0.5 MJ.

Plasma streams, generated by QSPA Kh-50, have been injected into magnetic system of 1.6 m in length and 0.44 m in inner diameter with magnetic field up to 0.72 T [25]. The diameter of magnetized plasma stream was (10…12) cm. Its total energy exceeded 160 kJ.

4. REACTOR APPLICATIONS

4.1. SIMULATION OF ITER TRANSIENT HEAT LOADS TO THE DIVERTER SURFACES

Energy range of ITER disruptions and ELMs is far above of that in recent tokamaks. Therefore, at present for experimental study of plasma-target interaction under the high heat loads the powerful plasma accelerators are applied. Quasi-steady-state plasma accelerators, with essentially longer duration of plasma stream as compare to pulsed plasma guns, are more attractive for simulation of ITER off-normal events. Besides, the obtained experimental results are used for validation of the predictive numerical models.

Targets of different materials (including tungsten and graphite) were exposed to plasma with various numbers of pulses (≤ 450): duration ~250 μs, ion energy ≤ 0.6 keV, the heat load ≤ 25 MJ/m^2 (relevant to ITER disruptions). To investigate the erosion mechanisms in conditions of ITER Type I ELMs, the samples were also exposed to the repetitive heat fluxes of 0.5 to 2.5 MJ/m^2 [26].

The shielding layer formation close to the irradiated target (with plasma density at least one order of value higher than one of incident plasma) was observed. The thickness of shielding layer grows with increasing the magnetic field. It, being equal (1…2) cm for sample irradiation with no magnetic field, exceeds 5 cm for B_{z0} = 0.72 T. Vapor shield formation and its influence on plasma energy transfer to the surface became clearly seen when the surface heat load achieves 1.1 MJ/m^2 (the evaporation threshold of tungsten). The fraction of plasma energy, which is absorbed by the target surface, is rapidly decreased with achieving the evaporation onset for exposed targets. The evaporated target material with higher atomic weight is more pressed to the target surface and the shield thickness is decreased. In particular, evaporated tungsten is concentrated in rather thin plasma layer of < 0.5 cm close to the surface.

The X-ray analysis of exposed tungsten surface showed essential decrease of the crystal lattice spacing. This result is explained by influence of compressive stress, appeared in consolidated surface layer, and accompanied by plastic deformation of material. The macro-stresses result in formation of cracks on the tungsten surface. Two types of cracks were registered: macro-cracks and micro-cracks between grains.

Simultaneously with macroscopic motion of the surface melt layer brittle fracture due to tungsten cracking is also important process accompanying the tungsten damage under the irradiation by powerful plasma streams. At the same time measurements of the mass defect showed that the evaporation process is not too much influence the tungsten erosion (< 0.04 mg/pulse). This is because the most metal droplets, formed under plasma irradiation, are remained at the sample surface.

Under the irradiation of graphite samples with powerful plasma streams (~ 24 MJ/m^2) the erosion crater was formed on its surface. The erosion velocity was ~ 2 μ m/pulse or < 1 $\mu m/(kJ/cm^2)$ when irradiating with no magnetic field. In the case of magnetized plasma the erosion coefficient was decreased and amounted ~ 1 μ m/pulse or (0.3…0.4) $\mu m/(kJ/cm^2)$. These experimental data are well agreed with results of numerical simulation, carried out for experimental conditions, typical for ITER disruptions, taking into account formation of shield layer.

It was shown that the neighborhood of graphite and tungsten essentially intensifies the process of tungsten erosion. Due to the formation on the tungsten surface of carbides WC and W_2C with melt point (~ 2800 ºC) less than one for tungsten, the threshold of permissible energy loads to the tungsten surface is decreased [27].

In the case of ELMs simulations the corrugations and dent structures, which arisen after initial 200 pulses with heat loads of 0.75 MJ/m^2, become dominant on the surface. Afterwards, relative stabilization of the surface pattern is observed. Measurements of mass loss are well correlate with results of microscopy observations. They demonstrate increase of mass loss rate with increasing the number of pulses up to 320, and then mass loss rate is falling down practically to its initial range.

Evaporation threshold of tungsten in conditions of our experiments is on the level of 1.1 MJ/m^2. Under the target exposure with such heat load the boiling is observed on the exposed surface. With increasing the number of pulses it becomes predominantly volumetric.

Increase of the mass losses by one order of value is obtained in conditions of the target heat load increase from 0.75 to 1.1 MJ/m^2. Thus, the boiling essentially adds to the mass losses, possibly due to intensification of evaporation and initiation of tungsten splashing [28].

4.2. FIRST MIRRORS OF ITER DIAGNOSTIC SYSTEMS

For last years the quite broad international program on solving the problem of first mirrors needed for many diagnostics in ITER is provided [29]. In the joint experiment with Tore Supra group in Cadarache the very important result was found out. Namely, when mirror surface is subjected to impact of plasma containing carbon as impurity (what is realized practically in every modern fusion device), the rate of mirror degradation depends on the properties of mirror material to form carbides. As an example, the rate of erosion of SS mirror (the carbide-forming material) was by factor 5 below the sputter erosion rate of Cu and Mo mirrors in comparison to the data known from published results on measuring sputtering yields. This result was supported by joint experiments with Basel University (Swiss tokamak TCV) and IPP experiments. Degradation of reflectance of SS mirror in glow discharge plasma D_2+3.5%CH_4, analyzed in IPP, is due to appearance of a quite thick C film; the Cu mirror, exposed in similar conditions, remained clean but degraded due to roughness appearance, mainly because of sputtering by carbon ions [30].

The method (based on comparison of the images of a bright object with sharp edges (like a ribbon of an incandescent lamp) obtained with “ideal” and with test mirrors) was developed for an in-situ control of the reason of degradation of the first mirror quality in large fusion devices. The method distinguishes between degradation of optical characteristics due to erosion by charge exchange atom flux and due to deposition of contaminants, and can be principally applied for providing similar control in ITER [31].

4.3. TWO-LAYER DIFFUSION SYSTEMS FOR HYDROGEN ISOTOPE RECYCLING CONTROL

In collaboration with Argonne National Laboratory and Sandia National Laboratory the technology of production of the W-Pd two-layer membranes with high erosion resistance and high hydrogen permeability have been created [32]. The obtained results allowed to start the creation of the working model of plasma facing diffusion system for hydrogen isotope recycling control.

The kinetics of hydrogen behavior in the Zr-Pd bimetallic diffusion systems was studied [33]. It was shown the principal possibility to provide the effective hydrogen removal from hydride-forming metals (Zr and Zr + 1 %Nb) in such two-layer systems. It is important for fusion reactor as gives possibility, using these data, to develop the methods to prevent hydrogen isotopes, especially, tritium accumulation in constructional materials. Besides, such systems can be used for testing material behavior under high hydrogen flows.

5. PLASMA TECHNOLOGIES

5.1. MODIFICATION OF MATERIAL SURFACES UNDER THEIR IRRADIATION WITH PLASMA STREAMS

The main processes are tempering (hardening) under fast heating with subsequent cooling the surface and nitration (when operating with nitrogen plasma).

Under the irradiation of structural steels and alloys by pulsed nitrogen plasma streams with energy density (10...15) J/cm^2 the increase of microhardness (in the depth of up to 30 μm) by (2…4) times was obtained. Simultaneously, the essential increase of surface wear resistance of structural steels was measured both for non quenched (by (10…15) times) and preliminary quenched (by 6…8 times). Improvement of corrosion properties of structural steels (and also permanent magnets) surfaces was obtained also [34].

The exposed metal surface (for instance, for 40H) is characterised by higher broadening of diffractional X-ray reflections. This can be interpreted as amorphisation of a surface layer. The period of γ-Fe crystal lattice for 12HN3A samples was measured. For plasma treated samples it was equal a=3,6256 A, i.e. considerably exceeded one of non treated samples (a=3,5264 A).

5.2. COATINGS DEPOSITION

Different types of plasma sources, like arc discharge, high frequency discharge, ECR discharge and combination of arc- and HF-discharges were used for development of coating deposition methods [35].

On the base of arc plasma source with magnetic separator the effective method of deposition of multi-layer composite coatings of the type TiN, (TiCr)N, (TiAl)N, (TiZr)N, TiC-TiCN-TiN, etc. was developed. The high quality films were obtained when combination of surface treatments (vibro-abrasive one, different gas discharges, etc.) was preceded to coating deposition.

Using the HF discharges led to essential decrease of the substrate temperature, and, therefore, provided coatings deposition to the metals and dielectrics (including inner surfaces of goods) with high adhesion.

The method of composite coatings deposition ($(TiAl_{0.2})N$, $Cr+(TiAl_{0.2})N$, $(TiCr_{0.2})N$, $Cr+(TiCr_{0.2})N$) to the cutting plates was developed. The wear resistance increase by 7 times was obtained for coatings with preliminary deposited Cr-layer. The durability of mills, coated with TiCN, was increased by (20…30) times.

5.3. GLOW DISCHARGES UNDER ATMOSPHERIC PRESSURE

Compact high-performance ozonators, based on the high frequency barrier discharge, were developed [36]. Ozone reactor with the flat electrodes coated by glass enamel had a value of the output concentration of ozone of an order of 30 mg/liter (air flow 0.5 l/min). Ozone concentration in water was of an order of 6 mg/liter.

Plasma sterilizer with ultrasonic cavitation was developed. A method of sterilization of instruments is based on operation in ozone-aqueous medium at low temperature (~ 25 °C). For additional cleaning of the tool surface the ultrasonic cavitations was applied. The results of the inactivation of spores Basillus cereus have shown effectiveness of this method of sterilization.

6. PROSPECTS OF FUTURE INVESTIGATIONS

Stellarator program: Studying the influence of magnetic configuration and power deposition profile on formation of ITB and ETB in the Uragan-3M torsatron.

Investigation of mechanisms of anomalous transport suppression in the RF discharge plasma of the stellarator U-3M at the vicinity of rational magnetic surfaces.

Implementation of the torsatron Uragan-2M with lower ripples of the helical magnetic field.

Experimental studies of maintenance and heating of dense plasmas ($(5…10)\cdot10^{13}$ cm^{-3}) in Uragan-2M device with using RF methods.

Study of particle and heat transport in RF-discharge plasma in stellarator system with reduced helical ripple.

Theoretical investigations and numerical simulations of excitation, propagation and absorption of RF waves in a high density toroidal plasma for development of optimal antennae for new stellarator systems.

Electromagnetic trap: Modernization of the EMT Jupter-2M with an aim of increasing the relative volume of displaced magnetic field with respect to the plasma volume to provide increasing the plasma parameters.

ITER relevant experiments: Studies of plasma-surface interaction under high heat loads with QSPA Kh-50 and PPA devices: plasma dynamics and surface effects

Further investigations of the first mirrors properties degradation under their exposure to irradiation of particles with broad energy spectrum. The main accent will be done on using the amorphous materials or materials coated with thick fine-grained films.

Investigations W-Pd two-layer membranes with high erosion resistance and high hydrogen permeability. Study of kinetics of hydrogen behavior in the Zr-Pd bimetallic diffusion systems and efficiency of hydrogen removal from hydride-forming metals.

Plasma technology: Development and investigations of compact EUV plasma source based on Magneto-plasma Compressor operating with heavy noble gasses.

Application of pulsed plasma streams for surface modification. Development of novel plasma methods for coating deposition (combination of coating deposition with pulsed plasma irradiation).

Development and investigation of arc-, glow-, HF- and ECR plasma sources for surface cleaning and sterilization under atmosphere pressure and in vacuum.

Development of plasma technologies for deposition of refractory coatings (tungsten and so on) on the base of metal dispersion in HF and ECR plasma sources.

Developments of methods of nanostructured films of different materials deposition.

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ИССЛЕДОВАНИЯ ПО ФИЗИКЕ ПЛАЗМЫ И УПРАВЛЯЕМОМУ ТЕРМОЯДЕРНОМУ СИНТЕЗУ В ИФП ННЦ ХФТИ

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Представлены результаты следующих экспериментальных и теоретических исследований, проводимых в настоящее время в Институте физики плазмы ННЦ ХФТИ: удержание и нагрев плазмы в стеллараторах и электромагнитных ловушках; мощные квазистационарные плазменные ускорители (КСПУ) для т/я и технологического применения; эксперименты, связанные с программой ИТЭР; теория термоядерной плазмы; разработка методов диагностики высокотемпературной плазмы; плазменные технологии. Обсуждаются также основные направления последующих исследований в ИФП.

ДОСЛІДЖЕННЯ З ФІЗИКИ ПЛАЗМИ ТА КЕРОВАНОГО ТЕРМОЯДЕРНОГО СИНТЕЗУ В ІФП ННЦ ХФТІ

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Представлено результати наступних експериментальних і теоретичних досліджень, що проводяться в Інституті фізики плазми ННЦ ХФТІ: утримання та нагрів плазми у стелараторах та електромагнітних пастках; потужні квазістаціонарні прискорювачі плазми (КСПП) для т/я та технологічних застосувань; експерименти з програми ІТЕР; теорія термоядерної плазми; розробка методів діагностики високотемпературної плазми; плазмові технології. Обговорюються також основні напрямки майбутніх досліджень в ІФП.