The Present State of Investigations on Stellarators in Kharkov*)

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At present, two stellarator type fusion devices, Uragan-2 M and Uragan-3 M, are in operation in Kharkov. At the Uragan-3 M machine, investigations of the low-density low-collisional plasma are continued. L-H-mode-like transition is studied with particular attention to the mechanisms of its formation and impact on divertor flow behaviour. For a higher density plasma, a scenario of the RF Alfvén resonance heating in high $k_{\|}$ regime is realized both with continuous and pulsed gas injection. On Uragan-2 M the studies of RF wall conditioning are in progress. A new wall conditioning scheme which uses the high frequency slow wave is implemented.

Keywords: torsatron, wall conditioning, RF heating, plasma confinement, L-H transition, divertor plasma flow

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1. Parameters of Devices

1.1 Uragan-2 M

Uragan-2 M device is an $l = 2/m = 4$ stellarator-type fusion device with $R = 1.7$ m, $\bar{a} \leq 0.24$ m, $\iota/2\pi \leq 0.45$. Owing to additional toroidal magnetic field coils the helical ripples are reduced. The magnetic configuration has a moderate shear, and the magnetic well is up to $\delta V'/V' \approx -4.3$ %. Presently the maximum toroidal magnetic field is 0.5 T. The possibility to vary the toroidal and vertical magnetic fields provides a certain experimental flexibility for this device.

For plasma production and heating, RF methods are used with different designs of antennas. At present three RF antennas are installed in U-2 M. A small frame antenna (SA) is designed specially for the wall conditioning procedures. Owing to its smallness, this antenna could be inserted and removed through a small vacuum port. It can be fed both at low (~ 8 MHz) and high (~ 140 MHz) frequencies with the power up to 1.5 kW. A larger size frame antenna (FA) is intended for operation with low (~ 10^{12} cm^{-3}) density plasma. Recently the new four-strap RF antenna (FSA) has been installed and put into operation without and with controlled gas (H_2) puff. According to the calculations [1], this antenna will give a possibility to operate at plasma density higher than 10^{13} cm^{-3}. To produce the plasma, the FA is pulsed before the FSA antenna pulse.

Two identical RF generators having $P_{RF} \sim 500$ kW peak power are used to drive FA and FSA. The power delivered to the antennas in experiments is lower ($P_{RF} \sim 200$ kW) and is restricted by arcing at the feed-throughs.

A system of magnetic diagnostic was developed for U-2 M. It can provide measurements of the quasi-stationary and variable harmonics of the plasma currents (longitudinal and Pfirsch-Schlüter currents), detect the island structure of magnetic surfaces near $\iota/2\pi = 0.5$, and register MHD fluctuations with poloidal and toroidal mode numbers $m = 0$, $m = 1$, $m = 2$ and $n = 0$, $n = 1$, $n = 2$, $n = 4$, correspondingly.

Other diagnostics are: interferometry along several chords, single-channel radiometry along the central chord, the optical spectrometry, bolometry, probe diagnostics, etc.

Besides, the whole set of the HIBP (Heavy Ion Beam Probing) system using Tl^+ or Cs^+ primary ions with the energy ≤ 200 keV is now under commissioning for measurements of the radial distribution of plasma parameters.

1.2 Uragan-3 M

A distinctive feature of the torsatron U-3 M ($l = 3$, $m = 9$, $R = 1$ m, $\bar{a} \approx 0.12$ m, $\iota(\bar{a}) \approx 0.3$, $B_{max} = 1.3$ T) is that the helical and vertical magnetic field coils are placed into a large (5 m in diameter) vacuum tank. The U-3 M magnetic configuration has a natural helical divertor. The divertor plasma flows end at the helical coil casings far away from the plasma column (see Fig. 1).

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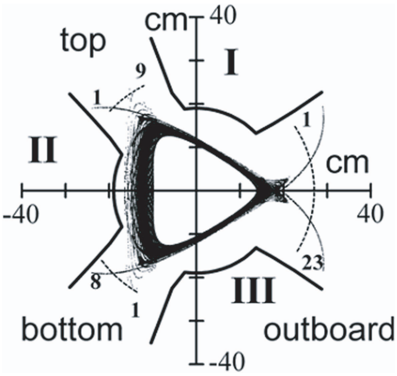

Fig. 1 Helical coils I, II, III and Langmuir probe arrays 1-23, 1-8, 1-9 in symmetric poloidal cross-section of U-3 M. Poloidal projection of magnetic field lines at plasma edge is also shown.

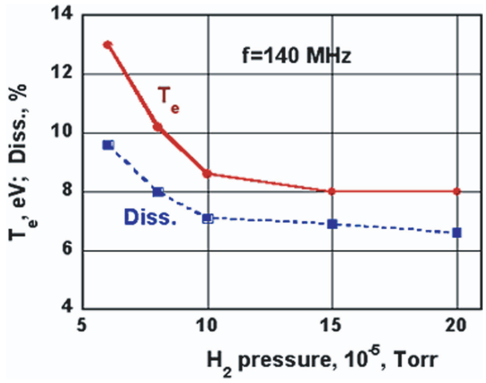

Fig. 2 Electron temperature and degree of dissociation of H_2 molecules evaluated using spectroscopy data as function of neutral gas pressure in RF discharge at f = 140 MHz.

2. Experimental Results

2.1 Uragan-2 M

At present, the U-2 M team focuses the major efforts on research of wall conditioning, in particular, aiming to provide the vacuum conditions necessary for operation at high RF power. A series of experiments on the RF vacuum chamber wall conditioning has been carried out for developing a conditioning scenario. A discharge driven by the slow wave at frequencies $\omega \gg \omega_{ci}$ is studied.

The function of the discharge wall conditioning is to remove adsorbed atoms or molecules from the wall with subsequent pumping out [2]. The adsorbed particles can be removed by the ion or atom impact causing the momentum transfer or chemical interaction. For conditioning plasma which is confined magnetically, as would be in superconducting stellarators, the flux of ions to the wall is not uniformly distributed. Therefore, the wall conditioning with chemically active neutral atoms is advantageous. Neutral atoms are produced efficiently in a partially ionized neutral gas. Such a scenario for wall conditioning is realized for the hydrogen discharges where the cleaning agents are the H atoms resulting from the dissociation of H_2 molecules. They have energies about 2.5 eV. If the electron temperature in the discharge is less than the ionization threshold, 4-10 eV, the dissociation rate is higher than the ionization, and one electron produces a number of neutral atoms during its lifetime.

The experiments show a good performance of the SA at low and high frequencies. With this antenna operating at frequency ~ 140 MHz, the stationary discharge is obtained with high degree of hydrogen dissociation (Fig. 2), what is suitable for cleaning the chamber wall from organic contaminants.

2.2 Uragan-3 M

A detailed study of the divertor plasma flows (DPF) characteristics when the plasma is produced and heated by RF fields at $\omega \lesssim \omega_{ci}$ is one of the key problems to investigate here: DPF spatial distributions, ion and electron energy in DPFs, flow fluctuations, changes with L-H mode transition, etc.

A strong vertical asymmetry (VA) of DPFs has been observed earlier in U-3 M [3], with larger DPF outflowing to the ion ∇B drift side ("ion side"). A conclusion was then made and confirmed by the numerical modeling [3] and the direct ion energy measurements [4] that the asymmetry results from the direct (non-diffusive) ion loss. However, the role of electrons in the DPF asymmetry had never been clarified experimentally. Now, as a result of processing of I-V characteristics of the divertor probe arrays (see Fig. 1), it is shown that the hotter electrons outflowing to the divertor on the electron ∇B drift side ("electron side") make a much larger contribution to the VA of DPFs than the ions on the ion side. Moreover, in contrast to the fast ion loss on the ion side, the large DPF and the electron temperature in it on the electron side are substantially reduced with the H-like mode transition. This is one more (in addition to given in [5]) evidence that the improved confinement in the H-like mode in U-3 M is associated with reduction of particle and energy loss mainly through the electron channel.

When studying the spectral characteristics of the density (ion saturation current) fluctuations in the DPFs, lower-frequency oscillations (5-30 kHz) are observed in the flow on the ion side, while the higher-frequency ones (30-60 kHz) appear on the electron side. This is also a characteristic of the DPF vertical asymmetry, suggesting an idea that the DPF fluctuations are somehow associated with fast ion and electron loss. The clarification of the nature of this link needs further studies.

Extensive comparative studies of the plasma characteristics before and after transition to the better confinement of low-collisional plasma ($\bar{n}_e \sim 10^{12}\,\mathrm{cm}^{-3}$) are additional issues being investigated in U-3 M. Those are measurements of plasma characteristics, estimation of the energy confinement time, and studies of edge turbulence and anomalous transport.

It has been shown before [6] that the L-H-mode-like transition in U-3 M is triggered by the fast ion (FI) loss. The FI loss results in the edge E_r bifurcation to a more negative value with an E_r shear increase. The stronger shear of E_r and, accordingly, of the poloidal rotation velocity $E \times B$, results in suppression of the edge turbulence and turbulence-induced transport. The correlation between the level of turbulent transport (an edge effect) and the rate of mean electron density $\bar{n}_e$ decay (a core plasma characteristic) is distinctly seen in Fig. 3. In particular, the H-like mode transition is displayed in a strong suppression of the edge turbulent transport and suspension of density decay.

Recently the energy sweeping technique of charge exchange atoms with time resolution 1-3 ms and spatial resolution ~ 3 cm is implemented at U-3 M. It is shown that the technique can be applied for analyzing the ion energy distribution in the low- collisional plasma, produced by the frame antenna. Thus, there appears the possibility to measure the ion energy distribution during different phases of discharge, including L-H transition. The ion energy distribution was found to be close to the Maxwellian distribution only in the ion energy range 0.4-2.5 keV that corresponds to the ion temperature near the center of plasma confinement volume T_i ~ 300-400 eV. An irregular scatter of points above 4.0 keV does not allow making any definite conclusion about character of energy distribution for ions with such energies. The data for T_i used below belong to values found for 0.4-2.5 keV energy range.

Using the set of magnetic sensors (Rogowski loop, diamagnetic coils), soft x-ray data, and charge exchange data, the energy confinement time is estimated for the low-collisional plasma in Uragan-3 M. Averaged along the cross section plasma parameters before transition are: $\bar{n}_e \approx 1.1 \times 10^{12}\,\mathrm{cm}^{-3}$, $\bar{T}_e \approx \bar{T}_i \approx 190\,\mathrm{eV}$, $\tau_E \approx 2.7\,\mathrm{ms}$; and after transition: $\bar{n}_e \approx 1 \times 10^{12}\,\mathrm{cm}^{-3}$, $\bar{T}_e \approx 470\,\mathrm{eV}$, $\bar{T}_i \approx 275\,\mathrm{eV}$, $\tau_E \approx 5.0\,\mathrm{ms}$. For such plasma parameters the stellarator scalings give the following energy confinement times: $\tau_E^{\mathrm{ISS95}} \approx 1.9\,\mathrm{ms}$ and $\tau_E^{\mathrm{LHD}} \approx 3.4\,\mathrm{ms}$. The transition to the improved confinement mode occurs when the power density for every plasma particle is near $W/(Vn_e) \approx 0.37 \times 10^{-19}$ MW/particle. This value is rather close to the values obtained earlier in experiments on other stellarators (CHS [7], L-2 [8]).

The strategy of usage of the Alfvén resonance heating with compact strap antenna (CSA) [1] is a result of balance of the technological restriction to have a compact antenna which occupies one device port and necessity to suppress the excitation of low $k_{\parallel}$ Alfvén resonances that reside at the plasma periphery and cause plasma edge heating. The experiments with the CSA antenna were attempted earlier [9, 10]. They showed plasma density increase from $\bar{n}_e \approx (0.5\text{-}2) \times 10^{12}\,\mathrm{cm}^{-3}$ provided by a preceding pulse of the FA to $\bar{n}_e \approx (0.5\text{-}1.5) \times 10^{13}\,\mathrm{cm}^{-3}$. In that time U-3 M was not equipped with diagnostics for measuring electron temperature. Since the expected heating in Alfvén resonance conditions is the electron heating, the result of those experiments remains incomplete. Second experiment also

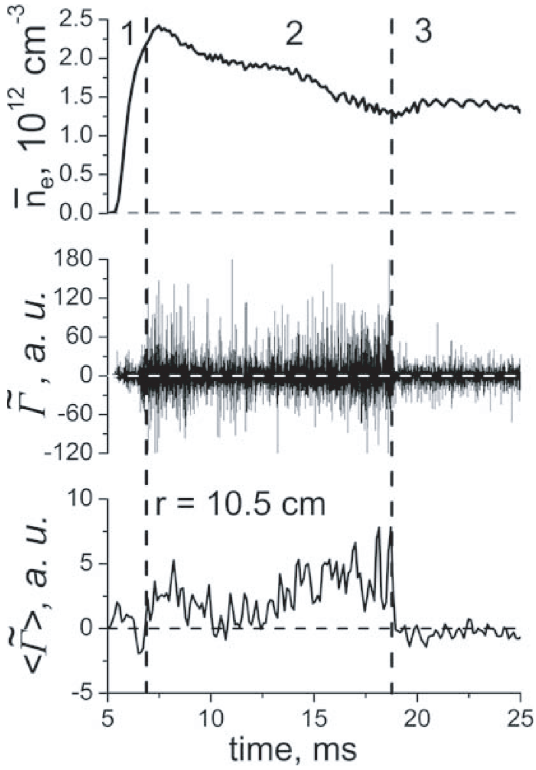

Fig. 3 Time evolution of line-averaged electron density, $\bar{n}_e$, edge radial turbulent flux, $\tilde{A}$, and its average (by 1 ms intervals), $\langle\tilde{A}\rangle$. Phases of discharge with H-like mode state (1, 3) and L-like state (2) are separated by vertical dashed lines.

suffered from high radiation losses resulted in low plasma temperature what is indicated by the light emission from low charged states of light impurities. In current series of experiments, the electron cyclotron emission (ECE) diagnostics is employed.

The CSA has been put into operation and several regimes of pulsed discharges with $\bar{n}_e \approx (0.5\text{-}2.0) \times 10^{13}\,\mathrm{cm}^{-3}$ were investigated [11]. At $\bar{n}_e \approx 0.5 \times 10^{13}\,\mathrm{cm}^{-3}$ the ECE measurement showed that the central electron temperature reached 300-700 eV.

This is less than at the stage of FA operation, but, owing to higher plasma density, the plasma energy content becomes higher. The ion temperature is significantly lower than the electron one, $\leq 100\,\mathrm{eV}$, as measured by Doppler broadening of CV line (227.1 nm). The ions are heated through the Coulomb collisions with the electrons and possibly by RF field via the cyclotron mechanism. The plasma characteristics do strongly depend on the gas feeding procedure, i.e., on the gas pressure if the hydrogen is supplied continuously or on the amount of gas puffed just before discharge or during the discharge. A couple of examples is shown in Fig. 4 and Fig. 5.

In the case without gas puffing, the growth with time of intensity of soft x-rays radiation is in a high correlation with the rise of CV line intensity and the rise of plasma density. This is an indirect indication that there is no sig-

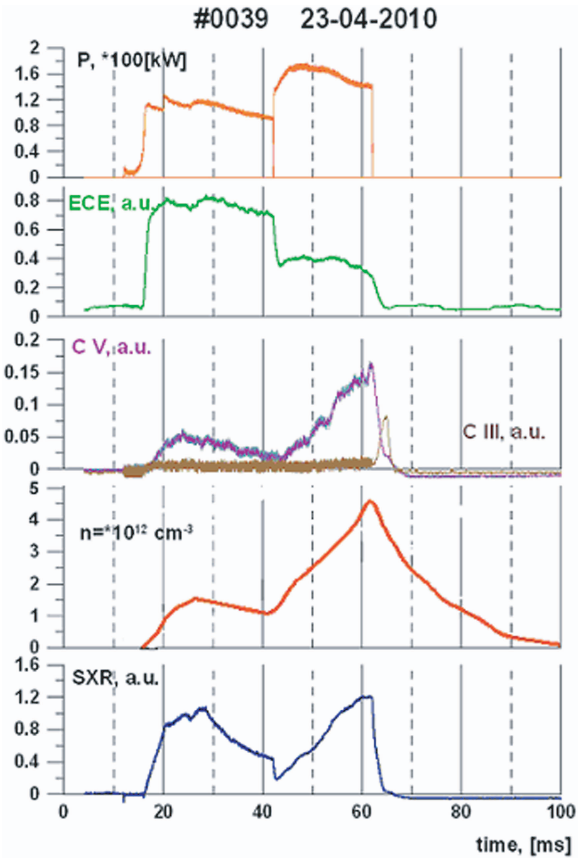

Fig. 4 Evolution of RF power, ECE radiation and electron temperature, CV and CIII lines emission, plasma density and SXR intensity in a shot with continuous gas flow. Neutral gas pressure is 9.3×10^{-6} Torr.

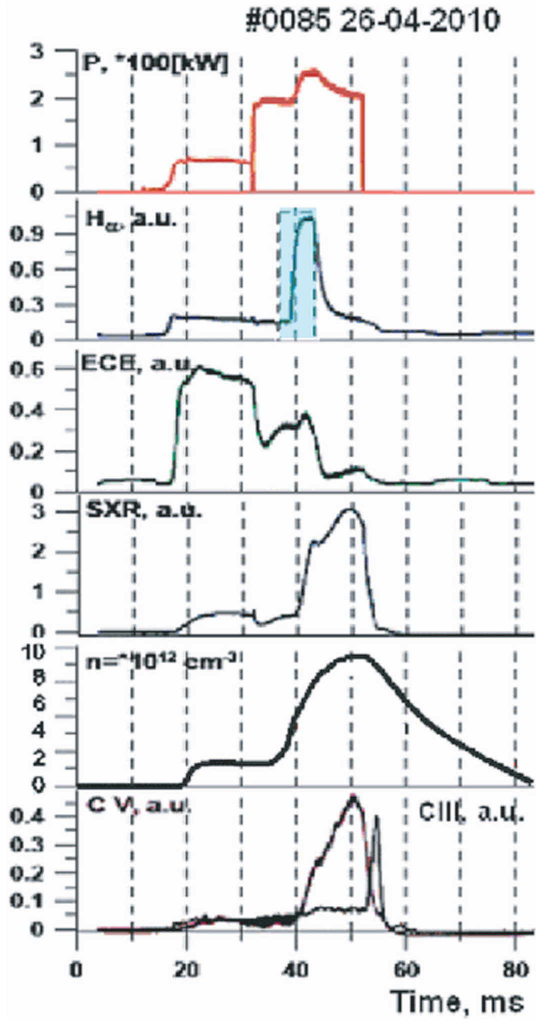

Fig. 5 Evolution of RF power, H_α hydrogen line intensity, ECE signal, soft x-ray intensity, plasma density and CV and CIII lines emission in a shot with a strong gas puff (colored in blue). Neutral gas pressure is 9.3×10^{-6} Torr.

nificant increase with time of the concentration of C^{4+} ions in plasma. When hydrogen gas is puffed during the CSA antenna pulse (Fig. 5), the CV line and SXR intensities do not grow in agreement with each other. This difference indicates that the carbon influx is reduced by the H_2 puff. The peak of the radiance of CIII line (229.6 nm) is due to recombination of C^{3+} ions after RF pulse termination.

3. Summary

- A high frequency continuous discharge driven by a portable antenna provides noticeable dissociation of the molecular hydrogen and, therefore, seems prospective for wall conditioning.
- A four-strap RF antenna was installed into the vacuum chamber of U-2 M and started to operate in combination with the frame antenna which is used for plasma production.
- The estimated energy confinement time for low collisional plasma in U-3 M was found to be close to the value predicted by LHD scaling.
- An obvious correlation has been revealed between the rate of mean plasma density decay during the RF pulse and the level of edge radial turbulent flux. In particular, this level undergoes a noticeable drop with the H-mode-like transition, thus showing up the nature of confinement improvement.
- In that regime of U-3 M operation the higher temperature electrons outflowing to the divertor on the electron side make a considerably larger contribution to the DPF VA than the FIs on the ion side. In contrast to the FIs, the DPF with these electrons is highly sensitive to the H-mode-like transition and strongly reduced with transition.
- The experiments in U-3 M demonstrate high $k_{\|}$ Alfvén resonance heating scenario with compact CSA antenna. Initial plasma density $\bar{n}_e \approx 10^{12}\,\mathrm{cm}^{-3}$ is increased several times during the CSA antenna pulse and is strongly controlled by the gas puff. Electron heating is dominant, but some ion heating is also observed. The plasma with higher energy content as compare to results of experiments with the frame antenna was obtained.

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