Role of plasma-wall interaction in the transient processes in the currentless plasma of the L-2M stellarator after switching-on of auxiliary ECR heating

G.M. Batanov, M.S. M.S. Berezhetskii, V.D. Borzosekov, S.E. Grebenshchikov, I.A. Grishina, N.K. Kharchev, A.A. Kharchevskii, Yu.V. Khol'nov, L.V. Kolik, E.M. Konchekov, N.F. Larionova, A.A. Letunov, V.P. Logvinenko, D.V. Malakhov, A.I. Meshcheryakov, A.E. Petrov, K.A. Sarksyan, S.V. Shchepetov, N.N. Skvortsova, V.D. Stepakhin, I.Yu. Vafin, D.G. Vasilkov

A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, Moscow

Switching-on of high-power auxiliary heating, additional gas puffing, or pellet injection can trigger transient processes in the plasmas of toroidal magnetic confinement devices. During these processes, plasma undergoes a transition from one stationary state to another. A similar situation is typical of spontaneous formation of transport barriers [1−7].

An increase in the electron-cyclotron resonance heating (ECRH) power at the L-2M stellarator to 0.6–0.8 MW resulted in a substantial increase in the heat load on the inner surface of the vacuum vessel. Estimates show that the heat load in a narrow region near the corner of the magnetic separatrix exceeds 0.5 MW/m^2. Such high heat loads motivate investigation of the plasma-wall interaction in the transient processes after switching-on of auxiliary ECRH.

The experiments were carried out under central ECRH at the second harmonic of the electron cyclotron frequency (75 GHz) with two toroidally spaced gyrotrons (with a microwave power of 0.2–0.25 MW each). The vacuum vessel was preheated at 200 °C and boronized in a glow discharge in a helium-carborane mixture [8]. The sector limiter did not affect the plasma flow toward the wall. Boronization of the vacuum vessel provided adsorption of the diffusive plasma flux from the plasma column. Pulsed puffing of hydrogen was regulated to avoid a considerable decrease in the plasma density, which is routinely observed at L-2M during ECRH with only one gyrotron and is attributed to plasma adsorption by the vessel wall. The pulse duration of the first gyrotron was 12 ms (from 48 to 60 ms relative to the beginning of the magnetic field pulse). The second gyrotron was switched on 4−8 ms after the first one (at 52 or 56 ms).

The L-2M diagnostics allow one to measure the central-chord-averaged electron density, the electron temperature from the second-harmonic electron-cyclotron emission

(76- and 74-GHz channels) and from the soft X-ray (SXR) intensity (foil technique), radiative losses with a bolometer, the H_α and C_{III} spectral line intensities, MHD activity, electric potential fluctuations near the separatrix, density fluctuations and poloidal rotation with a Doppler reflectometer, and density fluctuations through scattering of the heating gyrotron radiation.

Switching-on of the first gyrotron leads to gas breakdown and the subsequent growth of the density, which lasts for 1 ms and during which the density reaches its maximum value of (2–2.4) × 10^{19} m^{-3}. Then, due to adsorption at the boronized wall, the density gradually decreases throughout the ECRH pulse. In discharges with only one gyrotron, additional gas puffing was used to compensate for this decrease and maintain the average density at a constant level of (1.6–1.8) × 10^{19} m^{-3} after it had reached its maximum value at 50 ms (Fig. 1). In such discharges, the electron temperature reaches a steady-state value at 54 ms. In discharges with two gyrotrons, the second gyrotron was switched on 4–8 ms after first one, when the electron temperature reached 2/3 of the above-mentioned steady-state value. It is seen from Fig. 1 that switching-on of the second gyrotron at 52 ms leads to an increase in the growth rate of the electron temperature, while the plasma density remains constant. It is natural to expect the doubling of the heat load on the wall while the electron temperature is growing after the second gyrotron is switched on. This should results in gas desorption from the wall and pulsed gas outflow into the near-wall region. This is confirmed by a fast four- to sixfold increase in radiative losses, which starts about 1 ms after the second gyrotron is switched on (Fig. 1). The intensities of the H_α and C_{III} spectral lines also increase with the same 1-ms time delay.

The density begins to increase with a substantially longer time delay (≈2 ms) than radiative losses and the H_α/C_{III} intensities (Fig. 1). The decrease in the electron temperature in the plasma center also starts with a time delay of 2 ms. Apparently, this is due to the continuous gas outflow from the wall and the finite propagation time of the plasma formed at the periphery from the wall toward the center. This is confirmed by an increase in the growth rate of the SXR intensity from the central region, which also starts with a 2-ms time delay (Fig. 1).

Gas outflow from the wall should primarily affect the parameters of the edge plasma. The change in these parameters is clearly observed in the spectra of the Doppler reflectometer (Fig.2). An appreciable narrowing of the spectra and a decrease in the Doppler shift are observed with the same 2-ms time delay as the increase in the density and the decrease in the temperature. These observations, as well as a decrease in the plasma potential and potential fluctuations measured by a Langmuir probe located at the last closed flux surface, indicate a decrease in the peripheral temperature (Fig.3). On the other hand, gas outflow enhances MHD activity (Fig.3) and density fluctuations (Fig.4), both short-wavelength (k = 30 cm^{-1}) and long-wavelength (k = 1 cm^{-1}). Apparently, turbulence is enhanced in the plasma core (r/a = 0.4–0.7), because backscattering and small-angle scattering data demonstrate a burst of density fluctuations at 54 ms (Fig.4). The energy of density fluctuations with k = 20 cm^{-1}, which is measured in local central regions, remains constant (Fig.4). This allow us to assume that the plasma flow propagating from the near-wall region weakly affects (if any) the density gradients and, accordingly, the growth rates of drift instability near the cyclotron resonance when the flow reaches the plasma center.

The release of adsorbed atoms and molecules from the boronized wall is only possible through cathode sputtering or unipolar arcing. The flux of neutral atoms emitted from the wall is ionized in the edge plasma (r/a = 0.8–0.9), where the electron temperature is 0.1–0.2 keV and the local plasma density is higher than the average density due to the hollow density profile. An increase in the density in this region generates an inward plasma flux, which is accompanied by a poloidal inhomogeneity of the density. A change in the radial and poloidal density gradients leads to a change in the growth rates of drift instabilities and, accordingly, in the level of turbulent density fluctuations. A similar effect was observed in TJ-II experiments with ECRH and nitrogen injection [2].

In the experiments with auxiliary ECRH, two scenarios of the further development of the above processes are possible: (1) a new steady state is established; (2) the density continues to increase up to the critical value at which the cut-off for X-wave propagation is achieved and the plasma, being no longer heated, gradually degrades.

Thus, after auxiliary ECRH is switched on, the total microwave power density in the L-2M stellarator reaches 1.6–2.0·MW/m^3 and the average heat load onto the boronized wall reaches 0.4 MW/m^3. In this case, the following effects are observed: radiative losses and the plasma density increase, the electron temperature decreases, the electric field and plasma poloidal rotation at the periphery are suppressed, and turbulence in the plasma core is enhanced. Thus, the primary process governing the subsequent changes in the plasma parameters (including turbulence) is an increase in the heat load onto the vacuum vessel wall, followed by an enhanced gas outflow from the wall.

The authors are grateful to the RFBR for support of density fluctuations measurements (project 14-02-00589) and SXR intensity measurements (project 15-02-

09192). This work was also supported by the RAS program I.11P "Fundamental problems of plasma confinement and heating in magnetic confinement devices" and by state contract N01200953485 "Study of high-temperature plasma confinement in stellarators."

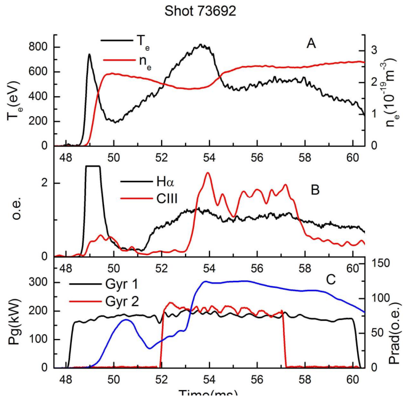

Fig.1. Time dependences: A) average electron density n_e and central electron temperature T_e; B) H_α and C_{III} spectral line intensities; C) radiative losses (blue line) and gyrotrons power.

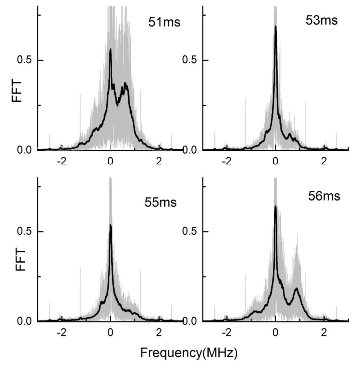

Fig.2. Doppler reflectometer spectra (frequency $f = 37.5$ GHz) at 51,53,55, and 56 ms.

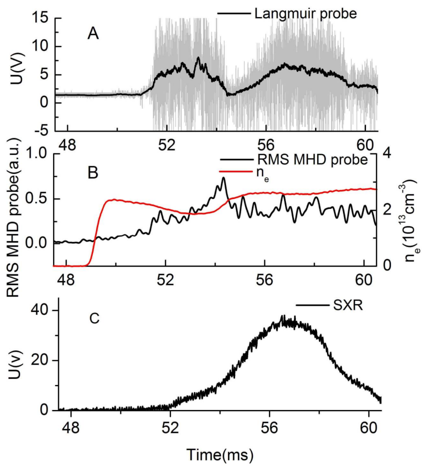

Fig.3. Time dependences: A) floating potential measured by Langmuir probe; B) magnetic field fluctuations measured by magnetic probe (signal is averaged over 100μs), red line - average density; C) SXR intensity measured along central chord;

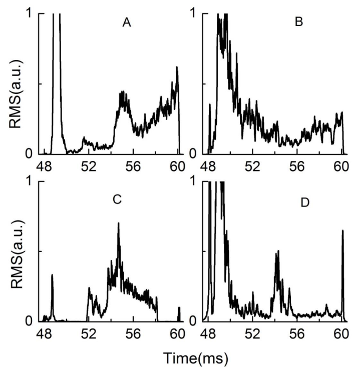

Fig.4. Squared density fluctuations obtained by measuring ECRH X-wave scattering (signals are averaged over 100 μs): A) scattering of high frequency (>1MHz) component from ECRH absorption center (k = 20 cm^{-1}); B) scattering from 2 cm outward from ECRH center (k = 20 cm^{-1}); C) small-angle scattering from full central chord (k = 1 cm^{-1}); D) backscattering from ½ of central chord (k = 30 cm^{-1}).

[1] V.F. Andreev, Yu.N. Dnestrovskij, M.V. Ossipenko et al. Plasma Phys. Control. Fusion, 2004, V.46, P.319.

[2] B.P. van Milligen, E. de la Luna, F.L. Tabares et al. Nucl. Fusion, 2002, V.42, P.787.

[3] N.L. Vasin, V.A. Vershkov and V.A. Zhuravlev.Sov. J. Plasma Phys.,1984,V.10, P.525.

[4] L. Spitzer et al. Stellarator reactor concept.Oakridge National Laboratory Report, 1954.

[6] S. Gunter, R. Wolf, F. Leuterer et al. Phys. Rev. Lett., 2000, V.84, P.3097.

[7] A. Fujisawa, Plasma Phys. Control. Fusion, 2003, V.45, P. R1-R88.

[8] A.I. Meshcheryakov, D.K. Akulina, G.M. Batanov et al. Plas. Phys. Reps., 2005, V.31, P.452.