Features of the pulsed mode of the ECR plasma heating at the L-2M stellarator

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Using a train of microwave millisecond pulses for electron cyclotron resonance heating (ECRH) it is possible to study relaxation processes in current-free plasmas. For the axial ECRH experiments at the L-2M stellarator (R = 100 cm, a = 11.5 cm, B = 1.28–1.35 T), the second harmonic (f = 75 GHz) of the extraordinary wave is used routinely for plasma heating [1]. In the presented experiments, we utilized sequences of 2.6 ms microwave pulses (3–4 pulses in the sequence) at two heating powers (P_{ECRH} = 0.2 MW, P_{ECRH} = 0.36 MW) and various pauses (1.4–2.4 ms) between microwave pulses. Plasma breakdown and following heating at pulsed mode of ECRH is achieved during the first microwave pulse while following pulses heat high-temperature current-free plasma.

At both ECRH powers used in the experiments (fig.1) the average plasma density only slightly increases (10-12%) towards the microwave pulse train end. At P_{ECRH} = 0.36 MW the central electron temperature T_e measured via the electron-cyclotron emission (ECE) diagnostic (74 GHz channel) decreases down to 0.33 keV during pauses between the microwave pulses. During the 2nd and subsequent pulses central electron temperature T_e reaches its quasi steady-state value and this value is lower in each subsequent pulse. The plasma energy W measured via diamagnetic diagnostic also reaches its quasi steady-state value during the 2nd and subsequent pulses while during pauses between the pulses it decreases by 1/3. Radiative losses P_{rad} measured with bolometer increase in average during the whole pulse train such that at the last pulse $P_{rad} = 0.2 \cdot P_{ECRH}$.

Another prominent feature of pulsed mode ECRH is fast (0.4–0.5 ms) increase of heat losses that arises with a 0.5–1 ms delay relatively to ECRH pulse start. This feature could be clearly seen from the time dependence of the diamagnetic diagnostic signal dW/dt where the signal sharply decreases 0.5–1 ms after the ECRH pulse start. Just before (0.2–0.4 ms) the dW/dt sharp decrease one can observe the decrease of radiative losses P_{rad}. Sharp increase of the floating potential measured with a Langmuir probe at the plasma edge arises 0.2–0.3 ms after the sharp decrease of the diamagnetic signal dW/dt and well coincides in time with the radiative losses increase and with the increase of Hα spectral line intensity.

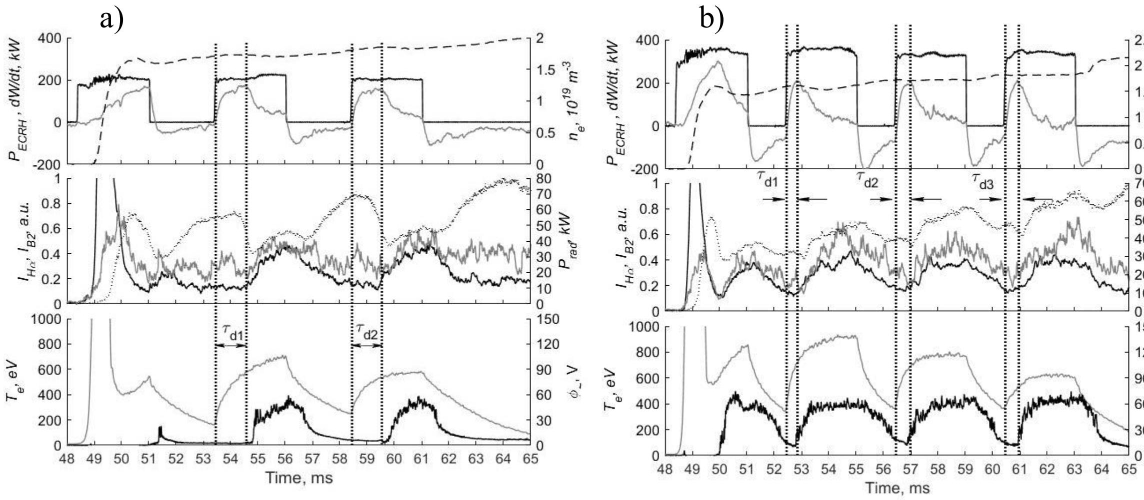

Fig.1. Time dependences of plasma parameters at pulsed mode ECRH for a) P_{ECRH} = 0.2 MW and b) P_{ECRH} = 0.36 MW. Top-down: (top) ECRH power P_{ECRH}(solid black line), diamagnetic diagnostic signal dW/dt (solid gray line), average electron density n_{e} (dashed black line); (middle) Hα spectral line intensity (solid black line), B2 spectral line intensity (solid gray line), radiative losses P_{rad} (dotted black line); (botom) floating potential of Langmuir probe $\varphi_{\sim}$ (solid black line), central electron temperature T_{e} measured with ECE diagnostic (solid gray line). Vertical dotted lines indicate moments of ECRH pulse start and of heat losses appearance where τ_{d} stands for delay time.

The delay between the ECRH pulse start and the sharp decrease of the diamagnetic signal becomes longer in each subsequent pulse of the pulse train. Varying heating power while using same microwave pulse train configuration (pulse duration, pause duration) we found that this delay becomes shorter at higher ECRH powers. Though true nature of the heat losses “jump” is still unclear to us some suggestions could be made: substantial broadening of the ECRH deposition profile; finite time of heat propagation from the ECRH absorption region to the plasma periphery; formation of heat damping region in the edge plasma due to sputtering of a wall coating during the first microwave pulse, thus in subsequent microwave pulses this cold region will absorb some energy before actual heat losses to the vessel wall will appear.

Mentioned above pulse-to-pulse decrease of the central electron temperature value that was achieved during ECRH pulse is also accompanied by flattening of the electron temperature profile (fig.2). The electron temperature growth rate after the ECRH pulse start as well as the fall rate after the ECRH pulse end also decreases in each subsequent pulse. All mentioned temperature effects correlate with a pulse-to-pulse increase of average radiative losses that in turn is a result of impurity accumulation in the core plasma. Pulse-to-pulse increase of soft X-ray intensity (fig.3) while average density is constant and electron temperature decreases allows us to make a conclusion that effective charge Z_{eff} increases and consequently that impurity accumulation takes place during pulsed mode ECRH.

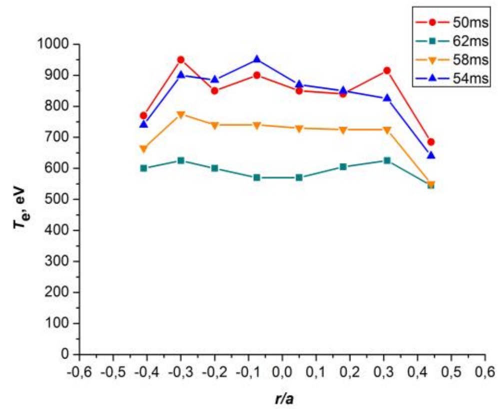

Fig.2. Electron temperature profiles in the core region at different moments of time for pulsed mode ECRH at P_{ECRH} = 0.36 MW.

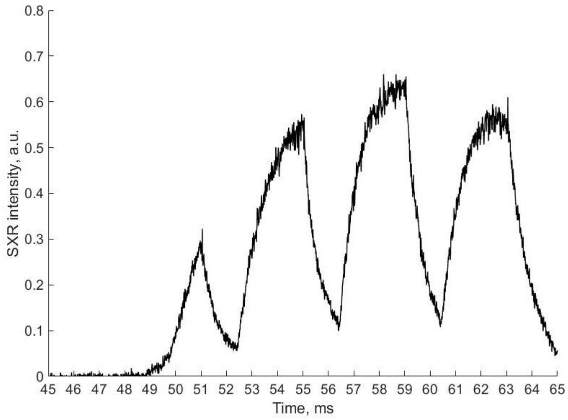

Fig.3. Time dependences of soft X-ray intensity from the core region for pulsed mode ECRH at P_{ECRH} = 0.36 MW.

It is also interesting to study evolution of micro turbulence at pulsed mode ECRH. Density fluctuations of various scales were measured in the experiments. Long-wavelength (k = 2 cm^{-1}) density fluctuations were monitored via Doppler reflectometry (ordinary wave, 37 GHz) at the plasma periphery. The level of density fluctuations $<n_{\sim}^{2}>$ (fig.4) remains more or less constant both during the ECRH pulses and during the pause between the pulses. The same level of fluctuations is kept even during 6 ms after the end of the ECRH pulse train. More interesting is evolution of the spectrum (fig.5). One can found that before the 3rd microwave pulse a peak around zero frequency is dominant. Just after the 2nd microwave pulse an additional peak arises at -0.6 MHz frequency and after the 3rd microwave pulse this peak becomes dominant till the microwave pulse train end while the zero frequency peak decreases. Appearance of Doppler shifted peak indicates appearance of plasma poloidal rotation in the edge region and change of the edge confinement conditions.

At the L-2M stellarator there is a set of density fluctuations diagnostics [2] based on detection of collective scattering of the microwave radiation used for ECRH. As the ECRH radiation is probing radiation for these diagnostics the data on density fluctuations is available only during a microwave pulse at pulsed mode ECRH but not during pauses between pulses. The data on time evolution of the short-wavelength (k = 22 cm^{-1}) density fluctuations level in the core region, including the ECRH absorption region, was obtained via one of the ECRH scattering diagnostics. This diagnostic measure microwave radiation scattered at $\pi/2$ angle. It was found that the level of the short-wavelength density fluctuations increases from pulse to pulse at pulsed mode ECRH and it also increases within the pulse itself (fig.4). The fact that the fluctuations level at the start of each subsequent pulse is lower than it was at the end of previous pulse suggests that during pauses between microwave pulses the level of the short-wavelength density fluctuations in the ECRH absorption region vicinity decreases. Pulsations of the fluctuations level on the scale of 0.2–0.3 ms also can be seen. Such pulsations of both short-wavelength and long-wavelength density fluctuations level are possibly arise due to large scale density fluctuations.

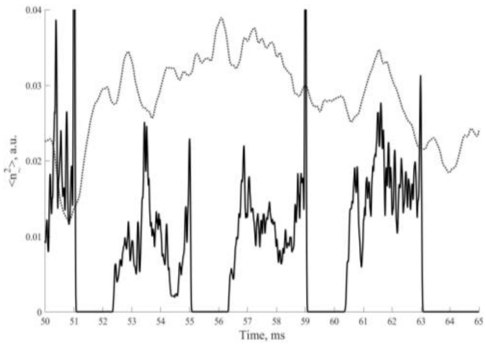

Fig.4. Time evolution of density fluctuations level $\langle n_{\sim}^2 \rangle$: black line – short-wavelength fluctuations in the core region; gray line – long-wavelength fluctuations at the edge

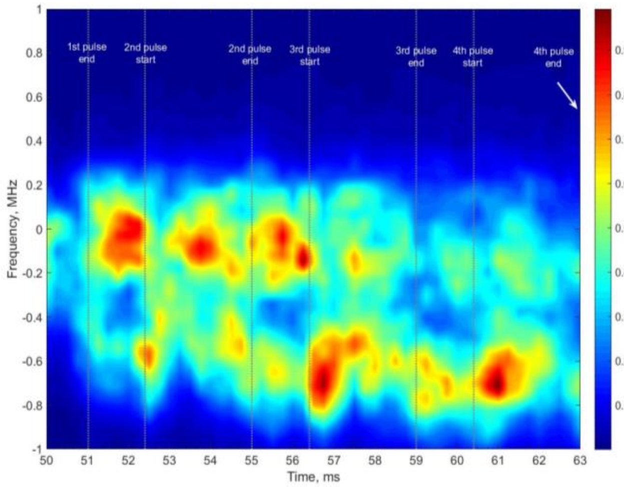

Fig.5. 3-D (time, frequency, amplitude in color) spectrum of Doppler reflectometer signal for pulsed mode ECRH at P_{ECRH} = 0.36 MW. Vertical dotted gray lines indicate moments of ECRH pulses start/end.

Let us summarize most interesting features of pulsed mode ECRH at the L-2M stellarator: 1) increase of the short-wavelength density fluctuations level while the long-wavelength density fluctuations level remains almost constant during whole microwave pulse train; 2) sharp increase of heat losses that happens with a delay relatively to the ECRH pulse start, that becomes shorter at higher ECRH powers and longer in each subsequent pulse during the ECRH pulse train; 3) decrease of the central electron temperature and flattening of the electron temperature profile along with decrease of plasma heating/cooling rate during microwave pulse train.

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