Evolution of energy losses and of microturbulence at modulated ECRH of L-2M stellarator plasmas

G.M. Batanov, V.D. Borzosekov, S.E. Grebenshchikov, N.K. Kharchev, A.A. Kharchevsky, Yu.V. Kholnov, L.V. Kolik, E.M. Konchekov, A.A. Letunov, A.E. Petrov, N.N. Skvortsova V.D. Stepakhin, D.G. Vasilkov

A.M. Prokhorov General Physics Institute RAS, Moscow, Russia

This work continues series of experiments on modulated electron-cyclotron resonance heating (ECRH) of plasma at the L-2M stellarator [1]. A distinctive feature of the L-2M modulated ECRH is 100% level of the modulation so that plasma confinement in the magnetic trap represents a sequence of alternating phases of ECRH and of phases without any plasma heating. Some characteristic time intervals should be pointed out in each single ECRH phase from the start of the ECRH pulse (Fig. 1(a)): **I** – a stage of low energy losses which begins with the ECRH pulse start; **II** – a stage of steep increase of energy losses; **III** – a stage of transition to a quasi stationary state; **IV** – a relaxation stage at which any heating is absent.

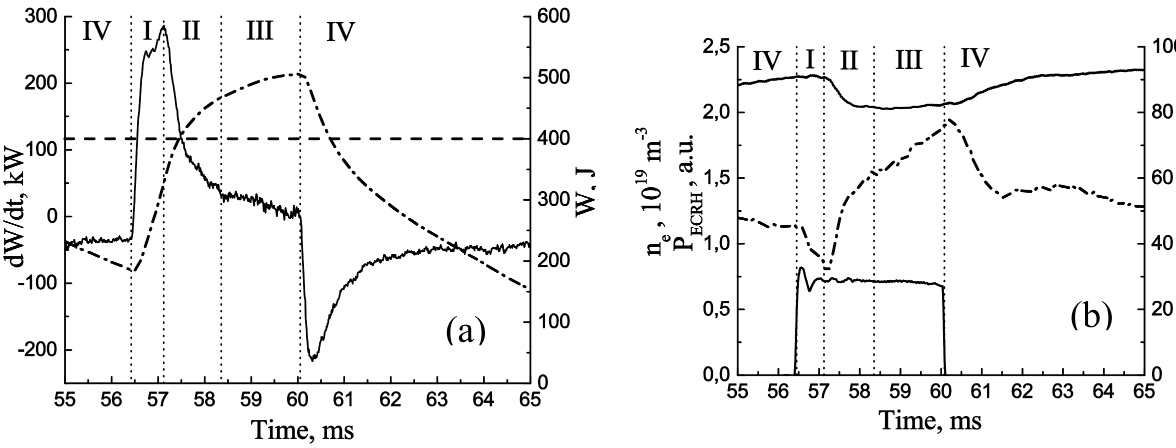

Fig. 1. Typical stages of modulated ECRH. Vertical dotted lines represent temporal boundaries of the stages. (a) Plasma energy derivative d*W*/d*t* (solid line) and plasma energy *W* (dash-dotted line). (b) Average electron density n_e (top solid line) along the central chord of the microwave interferometer, radiative losses P_{rad} (dash-dotted line) and ECRH pulse P_{ECRH} (bottom solid line).

On-axis modulated ECRH experiments were carried out at the L-2M stellarator (R = 100 cm, a = 11.5 cm, B_0 = 1.34 T) at average electron density $n_e = 2 \cdot 10^{19}$ m^{-3} and X2 (extraordinary wave, second harmonic of electron gyrofrequency f_{ECRH} = 75 GHz) ECRH power P_{ECRH} = 400 kW.

Plasma density fluctuations were studied by passive registration of collective scattering of gyrotron radiation used for ECRH. Following diagnostics and techniques were used: small-angle scattering on long-wavelength fluctuations (k = 1 cm^{-1}) from all length of the central chord [2]; backscattering on short-wavelength density fluctuations (k = 30 cm^{-1}) from half-length of the central chord [3]; Bragg scattering at $\pi/2$ angle on short-wavelength fluctuations (k = 20 cm^{-1}) from ECRH region [4]. Long-wavelength density fluctuations (k = 4 cm^{-1}) at the plasma edge were measured with Doppler reflectometry (f_{RF} = 37.5 GHz) [5].

The plasma energy derivative dW/dt represents power of total losses P_{los}, including radiative losses power P_{rad}, within time intervals between ECRH pulses (stage **IV**):

$$P_{los} = - \mathrm{d}W/\mathrm{d}t \qquad (1)$$

It should be noted that $P_{rad} \equiv$ - dW/dt 5-6 ms after ECRH switch-off and while the average density n_e remains constant (Fig. 1(b)) it allows one to determine numerically radiative losses power P_{rad} at any time.

The plasma column is formed during the first ECRH pulse and then average density remains almost constant during whole pulse train of modulated ECRH and even 10 ms after the last pulse. It implies that in the second and subsequent ECRH pulses the plasma energy derivative dW/dt is power going on energy increase of charged particles. Thus

$$\mathrm{d}W/\mathrm{d}t = P_{ECRH} - P_{n.a.} - P_{rad} - P_{2los} \qquad (2)$$

where P_{ECRH} — is nominal power of a microwave beam used for ECRH, $P_{n.a.}$ — is power of the microwave radiation that is not absorbed in the gyro-resonance region and that is leaking from the vacuum chamber through diagnostic ports (Fig. 2), P_{2los} — is power of energy losses associated with neoclassical and anomalous transport.

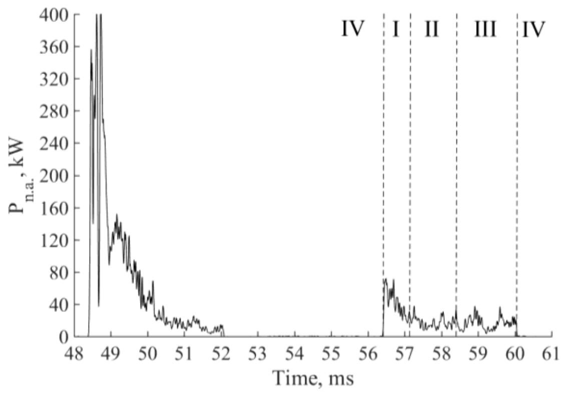

Fig. 2. Evolution of a non-absorbed microwave radiation level during modulated ECRH. The first pulse and the second pulse are shown.

Unabsorbed microwave power in the plasma $P_{n.a.}$ can be estimated numerically assuming that largest spike of the signal (Fig. 2) at the start of the first ECRH pulse, before plasma breakdown is achieved, is proportional to nominal heating power P_{ECRH} = 400 kW. Now it is possible to estimate power of neoclassical and anomalous energy losses P_{2los}, for example at the stage **I** estimation with expression (2) yields P_{2los} = 60 kW. It seems interesting to compare power of neoclassical and anomalous energy losses P_{2los} at the stage **II** with losses at the stage **IV** when plasma energy values W are equal (Fig. 1(a)). Such comparison for the discharge 21375 yields following result: energy value W = 400 J is achieved (Fig. 1(a)) at the stage **II** (1 ms after the second ECRH pulse start) and it is also achieved at the stage **IV** (0.7 ms after the second ECRH pulse end) while neoclassical and anomalous energy losses according to the expressions (1, 2) are P_{2los}(II) = 225 kW and

P_{2los}(IV) = 75 kW for these moments of time respectively. This implies three times lower energy losses at the plasma relaxation stage (stage **IV**) than during major length of the ECRH phase (stages **II**, **III**).

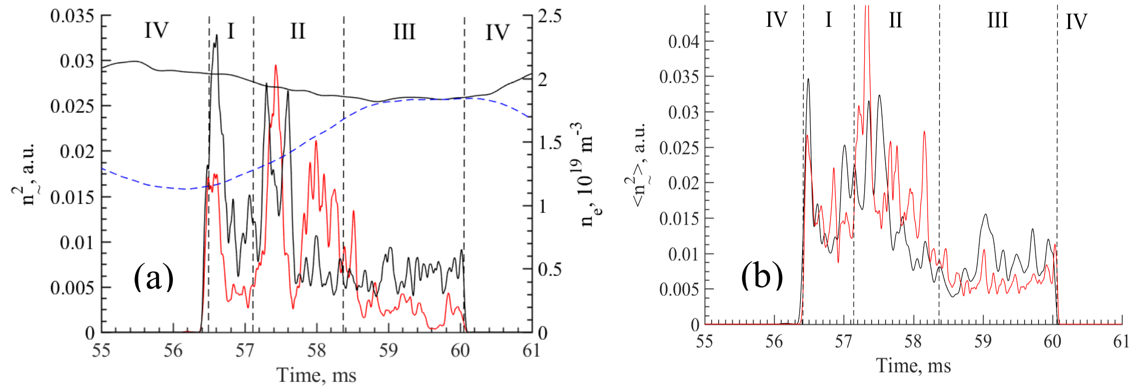

Fig. 3. Evolution of density fluctuations intensity. (a) Short wavelength density fluctuations intensity $n_{\sim}^{2}$ in the ECRH region (scattering to the upper half-plane of the torus — black line, to the lower half-plane — red line) and average plasma density n_e along the central chord (top black line) and along the edge chord (dashed blue line) of the laser interferometer. (b) Averaged along the central chord intensity $\langle n_{\sim}^{2}\rangle$ of short wavelength density fluctuations (black line) and long wavelength density fluctuations (red line).

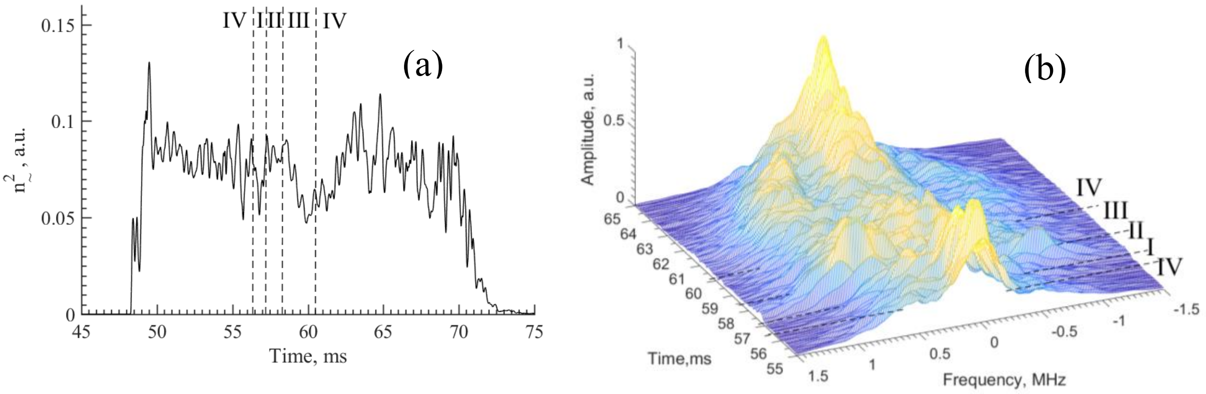

Fig. 4. Doppler reflectometry results. (a) Long wavelength density fluctuations intensity $n_{\sim}^{2}$ at the plasma edge. (b) Evolution of Doppler reflectometry spectra.

Measurements of short-wavelength density fluctuations in the ECRH region clearly indicate a high level of fluctuations with a burst-like behavior during whole length of stages **II** and **III** (Fig. 3(a)). This high level of the fluctuations drastically decreases at the beginning of the stage **III** and the decrease almost coincides in time with stabilization of a density pump-out process routinely observed at central ECRH [6] in stellarators. The stabilization implies stopping of density decrease in the heating region and stopping of density increase at the plasma edge (Fig. 3(a)) when a quasi-stationary hollow density profile is finally formed.

Results of long-wavelength density fluctuations measurements at the plasma edge do not demonstrate any significant change of fluctuations intensity during all stages of modulated

ECRH (Fig. 4(a)). The results of chord averaged measurements of both short-wavelength and long-wavelength density fluctuations (Fig. 3(b)) are very similar to the results of short-wavelength fluctuations measurements in the ECRH region (Fig. 3(a)). Thus, it is logical to assume that intensity of density fluctuations is substantially higher in the ECRH region than at the plasma edge during stages **I** and **II**.

The last noteworthy feature observed in the experiments is the considerable change of the Doppler reflectometry spectra (Fig. 4(b)) during the stages of modulated ECRH. The spectrum that is just a relatively narrow peak near zero frequency at the stage **I** start becomes significantly widened at the stage **II** start. In addition to the central peak a peak shifted by 0.75 MHz arises. This shift indicates appearance of an unstable drift mode that propagates in the poloidal direction coinciding with an electron diamagnetic drift direction. Despite ECRH switch-off at the stage **IV** start, the spectrum remains significantly widened for 2–3 ms. Then it again becomes a narrow peak near zero frequency.

Let us briefly summarize results. Four easy distinguishing stages of energy losses evolution during modulated ECRH were found: a short stage (0.5–0.7 ms) of low losses just after ECRH switch-on, a stage of rapidly increasing losses (1–1.5 ms), a quasi-stationary stage (2 ms) with almost constant high losses and a stage of low losses between ECRH pulses. Decrease of electron density in the plasma ECRH region and increase of density at the plasma edge are observed during the first three stages. Between the ECRH pulses reverse process of density evolution is observed. During a whole time interval when ECRH is active a high level of short-wavelength density fluctuations is registered in the plasma central region, in addition, at the first two stages high-amplitude bursts of intensity are observed. Widening of spectra that happens with a delay relatively to ECRH switch-on is typical for long-wavelength density fluctuations at the edge as well as narrowing of the spectra with a delay after ECRH switch-off.

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