BEHAVIOR OF ACCELERATED ELECTRONS IN OH PLASMA DURING LOWER HYBRID CURRENT DRIVE AND ION HEATING IN THE FT-2 TOKAMAK

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In experiments on the lower-hybrid (LH) plasma pumping in the FT-2 tokamak, the current drive in the low-density plasma ($N_{eo} = 3 \times 10^{13}$ cm^{-3}) and the ion heating in plasma with higher density ($N_{eo} > 3 \times 10^{13}$ cm^{-3}) were observed [1]. Therefore, it is of importance to obtain information about the effect of high frequency (HF) pumping on the behavior of accelerated electrons, which are usually present in the ohmically heated plasma, and the influence of these electrons on the efficiency of the current drive, plasma confinement and heating. For this purpose, the FT-2 tokamak is equipped with a diagnostic facility for studying accelerated electrons. This diagnostic facility allows simultaneous measurements of the microwave synchrotron emission (SE) in the frequency range f_{ce} - $2f_{ce}$ and the collective emission (CE) in the frequency range f_p - $2f_p$, which appears due to the nonlinear conversion of the intense plasma waves excited by an electron beam into electromagnetic waves. Simultaneously, the intensity and the energy spectrum of HXR is measured [2]. Below, we present and discuss some results obtained in the FT-2 tokamak experiments by the such combined diagnostics.

The parameters of the FT-2 tokamak, the discharge, and the plasma in the quasisteady stage of the ohmic heating (OH) are the following: a = 8 cm; R_0 = 55 cm; B_T = 22 kG; $\Delta B_T/B_T$ = (2-8)%; r > 4 cm; the working gas is hydrogen, which is preionized by the reverse eddy electric field; I_p = 22 kA; U_p = 2.5 V; $q_a > 5$; $N_{eo} = (2\text{-}4) \times 10^{13}$ cm^{-3}; T_{eo} = 600-400 eV; T_{io} = 100 eV; and Z_{eff} = 2-3. For the HF plasma pumping in the LH frequency range, we use the pulse oscillator (920 GHz frequency, 100 kW power, and 5 ms duration) connected to the double-waveguide grill antenna. The antenna is positioned on the side of a lower magnetic field and provides the slowing-down of the pumping wave up to n = 2-4 (here: n = c/ v_{ph}, c -the speed of light, v_{ph} - the phase velocity of the pumping- wave). The specific features of the FT-2 discharge there are the low MHD activity and relatively large amplitude of B_T ripples. The ripples are responsible for the fast loss of the locally trapped electrons with the transverse kinetic energy exceeding the threshold value. In particular, for $\Delta B_T/B_T$ = 2% and r = 4 cm, this threshold energy is equal to 5 keV. In addition, the gas-puffing rate, which determines the value of N_{eo} in the relatively short quasisteady stage of the discharge, begins to affect the increase in the plasma density only 8 ms after the beginning of the discharge. Together with the combined diagnostics of accelerated electrons described above, we use the conventional methods providing information about I_p, U_p, B_T, MHD activity, $N_e(r)$, and intensities of hard and soft X-ray emission (I_{HXR} and I_{SXR}, respectively) during the discharge. The central electron temperature T_{eo} is estimated from the results of measurements of the soft X-ray energy spectrum obtained by using absorbing filters.

Figure 1 presents typical time dependences of the magnetic field (1), the discharge current (2), the loop voltage (3), the electron density (4) the intensity of scattered (5) and collimated (5') HXR; and the MW emission power in the frequency ranges $>2f_{ce}^{max}$ (6), $\Delta_B 2f_{ce}$ (7), $2f_{ce}^{min}$ - f_{ce}^{max} (8), $\Delta_B 2f_{ce}$ (9), $2f_p$ (10), and f_p (11). The time dependences are obtained for $N_{eo} = 3 \times 10^{13}$ cm^{-3} in the OH regimes with and without HF pumping; the additional MW-channel attenuation is 3 dB. It is seen from Fig. 1 that, in the OH regime, MW emission appears simultaneously in all the frequency ranges (curves 6-11), 4 ms after the beginning of the discharge, when $N_e = 1 \times 10^{13}$ cm^{-3}, T_{eo} = 120 eV, and Z_{eff} = 1. Then, the emission powers in all the frequency ranges vary in a similar way. At the 10th ms (i.e., 6 ms later), when HXR appears, P_{MW} attains its maximum and, then, decreases smoothly toward the end of the discharge, whereas N_{eo} and I_{HXR} continue to increase. In this case, P_{MW} (f_p,2f_p) >> P_{MW} (f_{ce} - 2f_{ce}) = (2-3)P_T (where P_T is the power of the thermal MW emission of electrons), and no relaxations of the plasma parameters, MW emission and HXR are observed. During the HF pumping, U_p at first decreases by 30%, then increases to the initial value as N_{eo} increases. When $N_{eo} > N_{cr} = 3 \times 10^{13}$ cm^{-3}, the current drive terminates. The appearance of fast ions and suprathermal electrons (with 8kT_e energy) is accompanied by the heating of ions and electrons and the fast two-fold increase in P_{MW} after the pumping is switched on and some slower decrease after the end of the pumping. With 6 ms delay, the 10ms flash of HXR occurs, during which I_{HXR} increases by 60%. No relaxations are observed. The difference between curves 5 and 5' obtained with the flux detector and the spectrometer affects insignificantly the estimate of both the delay and the duration of the HXR flash.

Experiments show [3] that, for $N_{eo} = 2 \times 10^{13}$ cm^{-3}, during the OH, the synchrotron emission P_{SE} increases by an order of magnitude, whereas the collective emission power, which is much higher ($P_{CE} >> P_{SE}$), remains almost constant. The HF pumping causes the decrease in U_p by 30%; this is an evidence that the current drive occurs. The powers P_{SE} and P_{CE} rapidly increase by (20-30)% after the pumping is switched on and rapidly decreases after the end of the pumping. With 8 ms delay, the 15 ms flash of HXR occurs, during which I_{HXR} increases by (80-100)%. For $N_{eo} = 4 \times 10^{13}$ cm^{-3}, during the OH, P_{SE} tends to the thermal level, whereas P_{MW} the frequency ranges f_p – 2f_p, remains unchanged. During the HF pumping, U_p, and P_{MW} remain almost unchanged in all frequency ranges. An appreciable growth of N_{eo} is observed also during the LH ion heating. Immediately after the switching on of the pumping, the 8 ms flash of HXR occurs, during which I_{HXR} increases by 100%.

Figure 2 presents the typical energy spectrum of HXR; plots 1 and 2 corresponds to linear and logarithmic ordinate scales, respectively. An average quantum energy can be determined from the slope of the straight line (Fig. 2, plot 2) constructed by the method of least squares. The maximum quantum energy corresponds to the intersection of this line with the abscissa. This energy is close to the maximum energy of accelerated electrons arriving at the wall and the limiter of the discharge chamber, W_e^{max}.The W_e^{max} time dependences for 5 different values of N_{eo} = (2; 3; 4) $\times 10^{13}$ cm^{-3} are shown in Fig. 3. It is seen that, for N_{eo} = 2×10^{13} cm^{-3} grows linearly during OH, and the HF pumping does not change significantly its growth rate, dW_e^{max}/dt = 0.1. For higher density, $N_{eo} = 3 \times 10^{13}$ cm^{-3}, (2), in the OH regime till 20 ms, the energy growth rate is of 0.2, by a factor of 2.0 greater than in the previous case, and further, the growth rate increases up to 0.4. However, the HF pumping decreases it by 50%. For $N_{eo} = 4 \times 10^{13}$ cm^{-3}, (3), in the OH regime dW_e^{max}/dt becomes equal to 0.3. But HF pumping diminishes it up to 0.1. Such are the basic experimental results.

Taking into account specific features of the FT-2 tokamak, the analysis of the experimental data shows the following. During the OH, the behavior of SE, CE, and HXR, as well as the dW_e^{max} is typical of plasma with a beam of accelerated electrons. For N_{eo} = (2- 4) $\times 10^{13}$ cm^{-3}, the beam, which appears already in the initial stage of the discharge, exists during the whole discharge. For $N_{eo} < 3 \times 10^{13}$ cm^{-3}, the beam continuously drives the fan instability [4] due to considerable B_T ripples and nonunformity of $N_e(r)$. In this case, a slowed-down dense beam component with isotropic velocity distribution and small electron life time is the main source of SE observed in the frequency range f_{ce} - $2f_{ce}$. Simultaneously, the nonthermal MW emission is observed in the frequency range f_p - $2f_p$ this is, mainly, the collective emission usually arising from the nonlinear conversion of intense plasma waves, which are excited by the beam, into electromagnetic waves. HXR is mainly due to the slowed-down electrons, which arrive at the chamber wall with the energy close to the doubled threshold for driving the fan instability. A growth in W_e^{max} (Fig. 3) seems to be due to an increase in the threshold energy with an increase in N_{eo}. A considerable increase in the W_e^{max} growth rate, which, for $N_{eo} = 3 \times 10^{13}$ cm^{-3} begins 20 ms after the beginning of the discharge, is an evidence that the driving of the fan instability is stopped to this instant, and HXR is now due to freely accelerated electrons, which arrive at the limiter with a higher energy than before. In denser plasma, $N_{eo} > 3 \times 10^{13}$ cm^{-3}, the beam of accelerated electrons with the maximum energy up to 10 MeV appears. This beam is the source of SE with a continuous (due to overlapping of harmonics) frequency spectrum; the power of SE is less than in the previous case. The intense MW emission, which is observed in the f_p - $2f_p$ frequency range and whose power weakly depends on N_{eo}, does not result from the mode conversion. This MW emission may be a usual thermal electron bremsstrahlung emission, which is amplified up to a saturation level by the relativistic beam moving in the rippled magnetic field B_T.

In experiments on the LH current drive and ion heating in the FT-2 tokamak, the regime of the HF pumping of the plasma was realized in the presence of a beam of accelerated electrons. The position and sizes of the region, in which the pumping wave is absorbed by the beam, can be estimated by the delay of the beginning and the end of the HXR flash with respect to the beginning of the HF pumping. For $N_{eo} = 2 \times 10^{13}$ cm^{-3}, the absorption region with the width l = 4 cm is located at the distance r = 4 cm from the center of the plasma column; for $N_{eo} = 3 \times 10^{13}$ cm^{-3} we obtain l = 3 cm and r = 5 cm; and for $N_{eo} = 4 \times 10^{13}$ cm^{-3} we obtain l = 2 cm and r = 7 cm. The absorption of the pumping-wave by accelerated electrons increases the efficiency of both the current drive and the intensity of plasma oscillations, which results in an increase in the loss of slowed-down electrons. This is confirmed by the fact that, for $N_{eo} = 2 \times 10^{13}$ cm^{-3}, P_{SE} and P_{CE} rapidly increase after the pumping is switched-on and rapidly decrease after the end of the pumping, as well as that the growth rate of the electron energy remains constant. For the higher plasma density $N_{eo} = 3 \times 10^{13}$ cm^{-3}, when the current drive terminates and the ion heating begins, the region of the absorption of the pumping wave by accelerated electrons shifts to the plasma periphery. In this case, the relative increase in P_{SE} is greater than in the previous case, whereas P_{CE} remains the same. The time of the decay of P_{SE} and P_{CE} after the end of the pumping increases, whereas the growth rate of the electron energy decreases. This can be due to an increase in the intensity of plasma oscillations during the pumping, which results in an increase in the loss of accelerated electrons, although not so much as in the previous case. For the plasma density $N_{eo} = 4 \times 10^{13}$ cm^{-3} and higher, P_{SE} and P_{MW} in the frequency range f_p - $2f_p$ remain almost unchanged during the pumping. However, the efficiency of the LH ion heating can decrease due to a partial absorption of the pumping wave by accelerated electrons near the limiter.

Thus, our experiments show that the beam of accelerated electrons can continuously drive the fan instability in the OH plasma with $N_{eo} < 4 \times 10^{13}$ cm^{-3} due to large nonuniformity of $N_e(r)$ and ripples of B_T existent in the FT-2 tokamak. The influence of the beam on the efficiency of the LH current drive and ion heating is demonstrated also. The intense nonthermal MW emission in the frequency range f_p - $2f_p$ is observed; the emission power depends weakly on N_e. This emission seems to be the thermal electron bremsstrahlung one, which is amplified up to a saturation level by a relativistic beam moving in the rippled magnetic field B_T.

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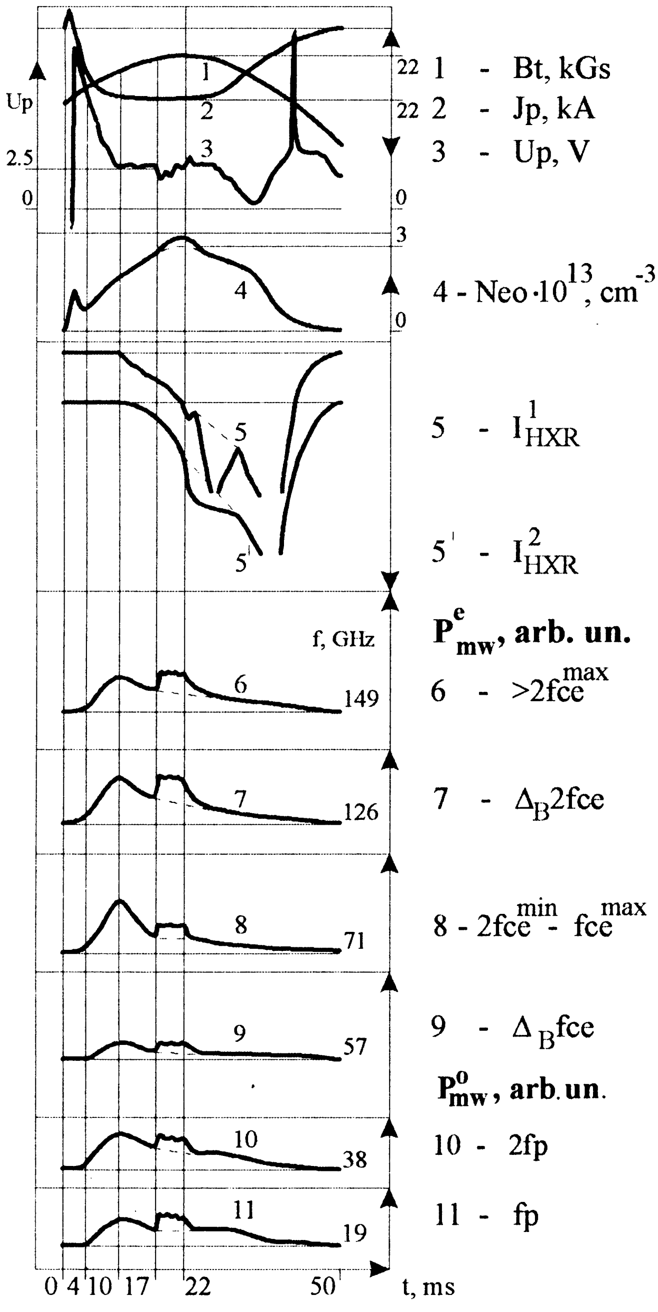

Fig. 1

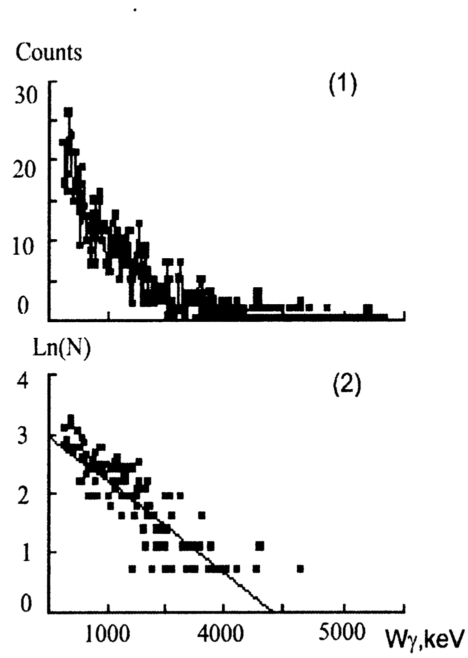

Fig. 2

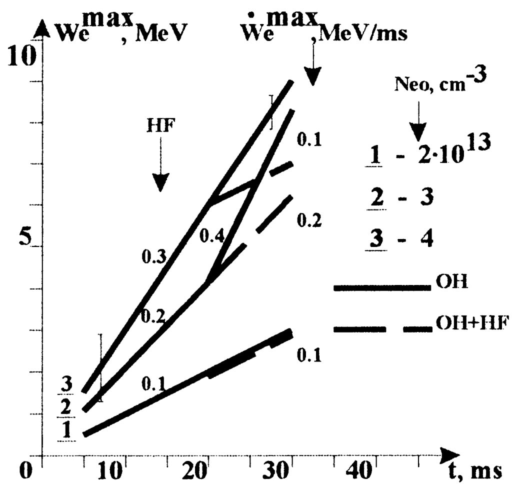

Fig. 3