Behavior of accelereted electrons during and after the fast vortex electric field ramp up in the FT-2 tokamak plasma

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Behavior of electrons accelerated by the vortex electric field, E, arising in the plasma periphery during the fast, (1-2) ms, loop voltage, U_p, ramp up till (10-15) V, in the initial and quasistationary OH stages was studied in the FT-2 tokamak at various densities, N_{e0}= (2-4)$\times 10^{13}$ cm $^{-3}$. For this purpose the combined, MW+ HXR, diagnostics was used. It is based on simultaneous measurements of the synchrotron emission power, P_{se}, of accelerated electrons in the electron cyclotron frequency range f_{ce} - $2f_{ce}$ and the collective emission one, P_{ce}, which appears due to the nonlinear conversion of the intense plasma waves excited by an electron beam into electromagnetic ones, in the electron plasma frequency range f_p - $2f_p$ together with the HXR intensity, I_{hxr}, and the energy spectrum, $I_{hxr}(W_\gamma)$, in range (0.4-10) MeV,[1]. These data can witness about appearance of the accelerated electron beam, their maximum energy, $W_e^m \approx W_\gamma^m$, excitation of magnetized Langmuir waves by the beam on the anomalous Doppler effect under the "fan" instability development, [2]. On delay of the HXR beginning relatively the SE one, Δt, it is possible to estimate using expressions: $(\gamma^2 - 1)^{0.5}$ = $6\times 10^4\, \hat{E}\, \Delta t$; $W_e^m = m_0c^2 (\gamma - 1)$, the effective vortex electric field accelerating freely runaway electrons during this time, $\hat{E}$. The parameters of the FT-2 tokamak, discharge, and plasma in the quasistationary stage 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 vortex electric field; I_p = 22 kA; U_p = 2.5 V; $q_a \geq 5$; N_{e0} = (2-4)$\times 10^{13}$ cm $^{-3}$; T_{e0} = 600–400 eV; T_{i0} = 100 eV; and $Z_{eff} \approx$ 2–3. The tokamak has some peculiarities: small MHD-activity, significant local B_T mirrors providing fast losses of trapped electrons, the N_{e0} increase independence on the gas puffing rate up to 8 ms of the discharge.

The basic experimental results and estimates are presented in Fig.1-4. Oscillograms, Fig.1,2, obtained in regimes of low, $N_{e0} = 2\times 10^{13}$ cm $^{-3}$, and high, $N_{e0} = 4\times 10^{13}$ cm $^{-3}$, plasma densities, with, α_{se}=12 dB, and without, α_{se}=0 dB, the additional attenuation in the SE transmitting waveguide show the following.

Microwave emission appears in the $2f_{ce}$, f_{ce} magnetic broadening ranges and at electron plasma freqencies $2f_p$, f_p, (6-8), at 4 ms after the first U_p ramp up, when $N_{e0} = 1\times 10^{13}$ cm $^{-3}$, $T_{e0} \approx$ 120 eV, $Z_{eff} \approx 1$, and behaves later in a similar way. P_{mw} increases smoothly together with N_{e0}, grows slower after the HXR appearing at 8 ms, becoming the highest possible one, (20-30) - fold larger than the thermal level at low density or of the thermal level at high one, and then diminishes together with the N_{e0} decay and I_{hxr} increase to the discharge end. At the same time: $P_{mw}(f_p) \approx P_{mw}(2f_p) >> P_{se}$.

The second fast Up ramp up during the quasistationary discharge stage at both, low and high, densities initiates the I_p growth from 22 kA to 30 kA with rate $\approx$ 4 MA/s, accompanying by the 50% U_p decrease and 20% N_{e0} increase. The short and, after 3 ms, longer HXR flashes arise. In frequence ranges (6,7) at low density and (6) at high one P_{se} icreases firstly but began to diminish in arising the second HXR flash. P_{mw} in the ranges (8) and, only at the high density, (7) does not change. I_p is more or less constant during 3 ms till the second HXR flash. Then it goes down slowly as P_{mw}, N_{e0} and U_p increases up to the initial level. In the regimes studied any relaxations of discharge and plasma parameters, MW and HXR emissions, U_p, N_{e0}, P_{mw}, I_{hxr} were not observed.

In Fig.3 time dependencies of $W_e^m \approx W_\gamma^m$ are presented together with the twiced threshold energy of accelerated electrons, $2W_{||}^*$, necessary for the "fan" instability development at low density. It is seen that after the first U_p ramp up W_e^m increases linearly during the discharge but with the different rate equal 0.13 MeV/s at low and 0.21 MeV/s at high density being larger than $W_{||}^*$. Practically there is no influence of the second U_p ramp up on the W_e^m growth rate.

Analysis of the estimates fulfilled according to [2] for our case shows the following. After the first U_p ramp up conditions fruitful for acceleration of electrons are created in the initial plasma formation and OH stage. These conditions are essentially damaged in the quasistationary OH one due to the N_{e0}, Z_{eff} increase and the U_p decrease. The fast low density beam with anisotropic energy of freely accelereted long living electrons, $W_e \approx W_{||} \geq W_\perp = W_c = (1+Z_{eff}/2)N_eR_0/U_p$, $W_c \approx (5\text{-}50)$ keV, arising in the initial plasma formation stage exists during the OH one in the region -7 cm $\leq r \leq 7$ cm. At low density, $N_{e0} \leq 2\times10^{13}$ cm^{-3}, relatively high $T_{e0} \geq 100$ eV, Fig.4, electrons of energy $W_{||} > W_{||}^* \approx 9(f_{ce}/f_p)^3 W_c$, $W_{||}^* \approx$ (200-900) keV, initiate the "fan" instability in the centeral plasma region, -4 cm $\leq r \leq 4$ cm, in which the plasma wave absorption is small and the condition: $E_c/4E + [(Z_{eff}+1)E_c/E]^{0.5} = F_i < \mathrm{Ln}\Lambda$, where $E_c = 0.04N_e/T_e$, $\mathrm{Ln}\Lambda$ - the Dreicer electric field and Coulomb logarithm, is fulfilled. In this region the slowed down dense beam component with short living electrons of isotropic energy, $W_{||} \approx W_\perp \approx W_{||}^*$, appears. Nonlinear transformation of excited plasma waves and essential increase of $W_\perp$ in comparison with W_c provides the simultaneous $P_{se,ce}$ growth. At high density, $N_{e0} \geq 2\times10^{13}$ cm^{-3}, there are no conditions for development of the "fan" instability because of the low accelerated electron density and the high plasma wave absorption. In this case runaway electrons are freely accelerated again. Therefore P_{se} decreases up to the thermal level, P_{ce} is absent, and W_e^m grows.

Experimental data on behavior of $P_{se,ce}$, I_{hxr}, $W_e^m \approx W_\gamma^m$ presented above support the such model as a whole but witness also about some its peculiarities typical for the FT-2 tokamak. They manifest themselves in the following way. Indeed development of the "fan" instability occurs at larger densities, $N_{e0} \leq 3\times10^{13}$ cm^{-3}, too. In this time the typical for it relaxations of U_p, N_{e0}, $P_{se,ce}$, I_{hxr} were not observed. The abnormally high P_{ce} was measured. Data about additional acceleration of slowed down electrons, $W_e^m \geq 2W_{||}^*$, were obtained. In the quasistationary OH stage at densities, $N_{e0} > 3\times10^{13}$ cm^{-3}, the synchrotron emission of the thermal level and the very intensive microwave emission in the frequency range fp - 2fp having the nontransformation nature were registered as well as essential increase of the W_e^m growth rate.

These facts can be explained taking into account the FT-2 tokamak specifity: the high B_T frilliance initiating fast losses of locally trapped electrons, with $W_\perp > W_\perp^* \approx 5$ keV and $W_{||} > 0.3$ keV at $\Delta B_T/B_T \approx 2\%$, r = 4 cm; inhomogeneous $N_{eo}(r)$ profile; low MHD activity.

At low densities, $N_{e0} \leq 3\times10^{13}$ cm^{-3}, the B_T ripples help to support the W_e anisotropy and to diminish the time, τ_a^*, necessary to accelerate electrons up to $W_{||}^*$. Besides in the electron distribution function the region with $df/dW_{||} \geq 0$ may appear. Therefore the

Cherenkov excitation of plasma waves becomes possible too. Due to the energy accumulation during multiple full internal reflections of plasma waves in the inhomogeneous plasma relaxation time, τ_ω, and P_{ce} can increase. In this case absence of the relaxations usually observed under development of the "fan" instability may be connected with overlapping the instability flashes when $\tau_\omega > \tau_a^*$.

In the plasma periphery, where absorption of plasma waves excited becomes essential, Fig 4, free acceleration of runaway electrons takes place. Due to anomaleous diffusion electrons of the slowed down beam component reach quickly this region. Here they are additionally accelerated from the threshold energy up to ≈ 3 MeV and go to the limiter together with electrons of the fast beam component because of the slow drift orbit displacement occuring under the low MHD activity level. Therefore: $W_e^m > 2W_{||}^*$ and the life time of such electrons becomes longer than the diffision one.

At high density, $N_{e0} > 3\times10^{13}$ cm $^{-3}$, decrease of P_{se} up to the thermal level and essential growth of W_e^m up to ≈8 MeV witness that the "fan" instability finishes and the free acceleration regime begins. In the such situation the intensive microwave emission observed in the frequency range f_p-$2f_p$ whose power weakly depends on N_{e0} may be a usual thermal bremsstralung or cyclotron emission, synchrotron one amplified up to a saturation level by the relativistic beam moving in the rippled B_T field.

The second fast U_p ramp up produces significant increase of E in the plasma periphery. Estimates of $\hat{E}$ were made on experimental data about the relative delay of the SE and HXR flashes and W_e^m. It is shown that 1ms later of the U_p ramp up $\hat{E}$ is of ≈ 0.1 V/cm independently on N_{e0}. Then it diminishes exponentially during 10 ms up to the initial level, E_{oh} = 0.007 V/cm. Appearance of the SE, HXR flashes and absence of the CE one at low density allow to conclude that E penetrates only in the plasma region where free acceleration of runaway electrons occurs. The increased E promotes to the birth rate growth and acceleration of the runaway electrons as well as additional acceleration of fast electrons coming here from the centeral plasma region up to energies which values are not larger than previous ones, W_e^m, before the U_p ramp up. Therefore effects experimentally observed under the second U_p ramp up at different N_{e0} are similar. They are apparently initated by the increase of the density and energy of the fast beam component. Accelerated electrons appearing in the plasma periphery under the such conditions can be as current currying ones and produce the observed I_p growth.

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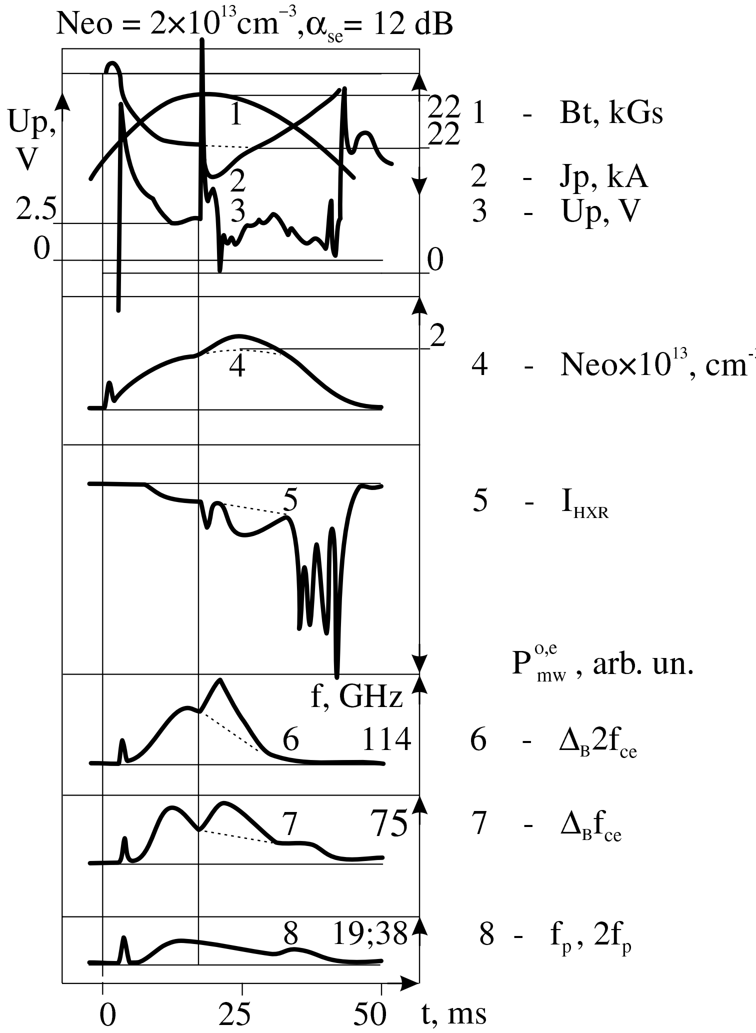

Fig. 1

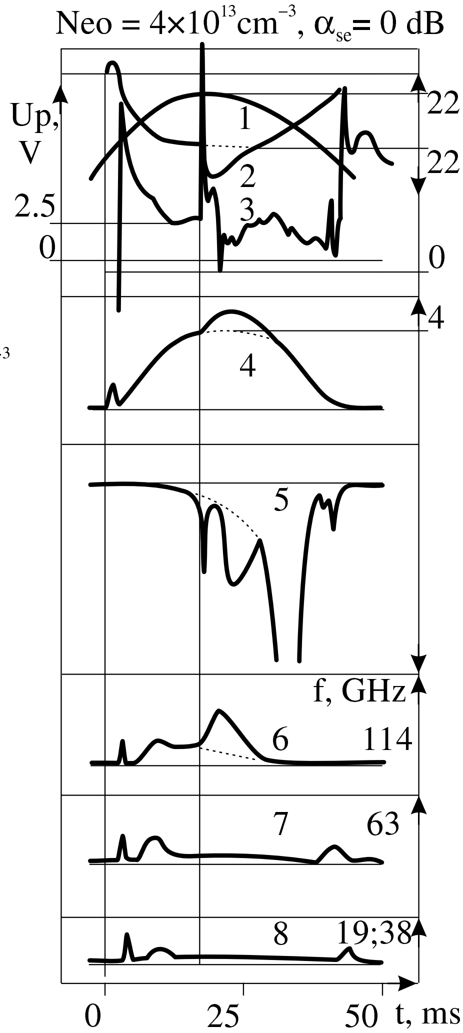

Fig. 2

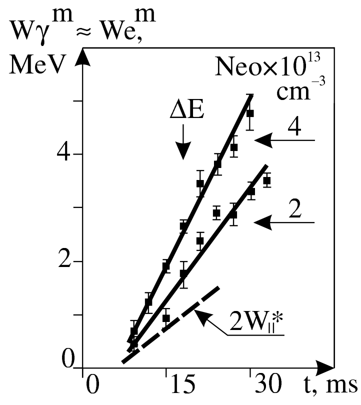

Fig. 3

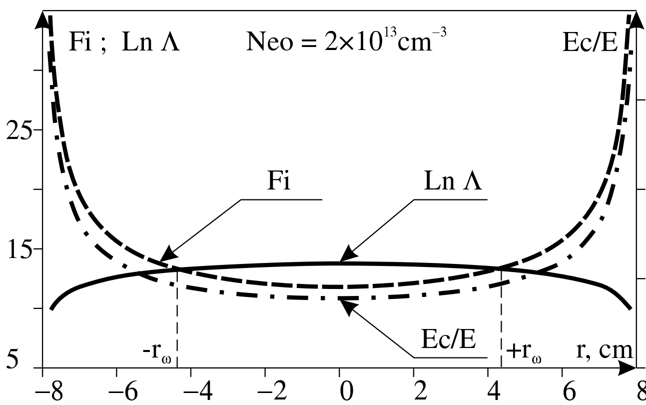

Fig. 4