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Acceleration of electrons during the second fast vortex electric field ramp up in the FT-2 tokamak plasma

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Acceleration of electrons by the vortex electric field, E, arising in the plasma periphery during the fast, (1-2) ms, loop voltage, U_l, ramp up till (10-15) V, in the quasistationary ohmic heating stage 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, [1]. 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 usually 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. At the same time the SXR, HXR intensity, $I_{SXR,HXR}$, and the energy spectrum, $I_{HXR}(W_\gamma)$, in range (0.4-10) MeV were registered. 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 using expressions: $(\gamma^2 - 1)^{0.5} = 6\times10^4 \cdot\hat{E}\cdot\Delta t$, $W_e^m = m_0c^2\cdot(\gamma - 1)$, to estimate the effective vortex electric field accelerating freely runaway electrons during this time, $\hat{E}$. The fast U_l increase producing the significant E growth in the plasma periphery is provided by switching on an additional power source to the first winding of the FT-2 tokamak transformer. Parameters of the tokamak, discharge, and plasma in the OH quasistationary stage are the following: a = 8 cm; R_0 = 55 cm; B_T = 22 kG, $\Delta B_T/B_T$ = (2–8)% at r > 4 cm; the working gas is hydrogen, which is preionized by the reverse vortex electric field; I_p = 22 kA; U_l = 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 locally trapped electrons. In our experiments SE and CE were appropriatly registersd with a heterodyne radiometer and direct amplification receiver, $I_{SHR,\,HXR}$ – with a photoelectric detector. Data about evolution of the HXR energy spectrum during a discharge were obtained by spectrometr, [1]. The MHD-activity level was measured with a magnetic probe. The Thomson scattering diagnostics and microwave interferometry provided data about T_e, N_e radial profiles and $N_e(t)$. Usual technics was used to register B_T, I_p, U_l.

The basic experimental results and estimates are presented in Fig.1 - 5. Oscillograms, Fig.1 and 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, appropriatly with, α_{se}=12 dB, and without, α_{se}=0 dB, the additional attenuation in the SE transmitting waveguide, show the following. The second fast U_l ramp up during the OH quasistationary stage, at 15 ms of the discharge, under both, low and high, densities initiates the I_p growth from 22 kA to 30 kA with rate $\approx$ 4 MA/s, accompanying not only by the 50% U_l decrease and 20% N_{e0} increase but also by arise of the short, 3 ms, MHD-activity and HXR flashes. After 3 ms it is observed the fast outward-inward plasma displacement, Δr = 3 mm, and then the slower 5 mm outward one. At the same time the longer, 10-15 ms, SE, SXR flashes and, with a some delay, the second HXR one of the such duration appear. At low and high densities P_{se}, I_{SHR} icrease firstly but begin to diminish in arising the second HXR flash. The P_{mw} flashes in the ranges f_p - $2f_p$ are not observed in this time at any plasma density. I_p reaches up to 30 kA and becomes more or less constant during 3 ms till the second HXR flash appearance. Then it goes down slowly as P_{se}, $I_{SXR, HXR}$, N_{e0} and U_l increases up to the initial level. In the regimes studied any relaxations of discharge and plasma parameters, MW and SXR, HXR emissions, U_l, N_{e0} are not observed. Practically there is no influence of the second U_l ramp up on the W_e^m growth rate.

Fig.3 and 4 show time dependences of I_{HXR} with quanta of different energy obtained from data on the HXR energy spectrum during the plasma OH at low and high densities, (1), and – OH under the second fast U_l ramp up, (2). It is seen that in OH inspite of plasma density the more intensive but lesser hard HXR arises firstly and then, with the 5-10 ms delay,- the lesser intensive but more hard one. The HXR flashes of the same duration appropriating the second HXR one registered with a photoelectric detector, Fig.1; 2, appear 6-8 ms later of the U_l ramp up. The first short HXR flashes are not detected because of the unsufficient spectrometer time resolution. At the low plasma density the HXR flash amplitude is lesser than at the high one. The flash amplitudes diminish together with the quant energy growth. The flashes of the quant energy larger than 2.25±0.5 MeV at the low density and 3.75±0.5 MeV at the high one are not observed.

Fig.5 exhibits the time dependences of the effective vortex electric field Ê obtained for different densities in accordance with the procedure mentioned above. One can see that 1 ms after the U_l ramp up at the high density Ê reaches up to 0.1 V/cm and goes down during 10 ms quickly, of the 3ms decay time, in the beginning, and then – essentially slower, of the 18 ms decay time, up to the initial level 0.0.1 V/cm. At the low density Ê seems to be some lesser in value but it changes in time as well as at the high one.

It was shown, [3], that run away electrons appear during the discharge in the plasma region with -7 cm < r_b < +7 cm. At high density they are freely accelerated by the vortex electric field if the plasma MHD-activity is small and at 15 ms come to the limiter due to the slow drift orbit displacement with the maximum energy up to 2 MeV. At low density electrons accelerated up to the threshold energy, 0.5 MeV, excite the "fan" instability in the centeral plasma region with – 4 cm < r_ω < +4 cm. Due to enhanced diffusion the such electrons go out from this region quickly to the plasma periphery where they are additionally accelerated and come slowly to the limiter with energy 1.5 MeV essentially larger than the twiced threshold one. Behavior of $P_{se, ce}$, $I_{SHR, HXR}$ during the discharge witnesses about it, Fig.1; 2.

Analysis of the data presented in Fig.1-5 and estimation results shows that the second fast U_l ramp up initiates the significant, 10-fold, E growth at the edge diminishing during the E field penetration into the plasma. In this time I_p increases and resonance magnetic surfaces are displaced to the limiter where excitation of the MHD-modes of m = 6; 5; 4 becomes possible. But the short flash of the MHD-activity appropriating the m = 6 mode excitation arises only. During the flash and some outward plasma displacement more than early quantity of electrons come to the limiter and chamber walls. Accelerated electrons of energy larger than 300 KeV produce the first HXR flash. As the flow of charged particles from the plasma becomes unambipolar the radial electric field arises near the limiter. The fast E penetration through the plasma region with dimensions equal to the arised magnetic island width, 0.1a = 1cm. After the MHD-flash the E penetration becomes slow. The penetration depth estimated on data about on I_p, U_l appropriating the beginning and end of the second HXR-flash seems to be small, Δr = 1 cm. The SE, SHR and second HXR flashes, absence of the CE one witness about the runaways quantity and energy increase due to the E growth in this plasma region and their free acceleration up to 2 MeV at low and - 4 MeV at high densities. The life time of this group of electrons estimated on the SE, SXR and second HXR flash duration or on the P_{se}, $I_{SHR, HXR}$ decay time is of 10 ms, on the relative delay the SE и HXR flashes – 5 ms. Duration of the I_p, U_l restoration up to initial level and SE, SXR, second HXR flashes as well as the I_p и P_{se}, I_{SHR}, I_{HXR} decay times are near-by in value. Appearance of fast electrons moving in the plasma periphery roughly with the light velocity, $v_r \approx c$, not only helps to the I_p increase but the m = 5; 4 modes damping also, as appropriating MHD-activity flashes are not observed in this period.

Estimations show that for appearance of the such electron group when the I_p addition equal to 8 кA is maximum it is necessary to create in the plasma periphery, r > 6 cм, where $N_e = 1\times 10^{12}$ cm^{-3}, T_e = 20 eV, Z_{ef} = 3, the electric field, E ≥ 0.03 V/cm, providing the runaway birth rate $S \geq 4\cdot10^{-2}$ and relative density $N_r/N \geq 2\cdot10^{-4}$ of accelerated electrons with the life time 5 мс. Taking into account that the "fan" instability is not observed in this period it is possible to determine the maximum value of E = 0.08 V/cm from the instability excitation condition, [2]. Thus: 0.03 V/cm < E < 0.08 V/cm. This is in accordance with estimations of the effective electric field accelerating electrons in the plasma periphery: 0.02 V/cm < Ê < 0.07 V/cm at the low plasma density and 0.03 V/cm < Ê < 0.1 V/cm at the high one, Fig.5. Dimensions of the region, r ≥ 6 cm, where quantity of accelerated electrons increases are evaluated on data: ΔI_p = 8 кA, $N_r = 2\cdot10^{8}$ cm^{-3}, $v_r \approx c$.

Accordance of the experimental data and estimation results allows to consider that the growth and sustainment of I_p after the second fast U_l ramp up are basically produced by appearance of the relatively longliving group of accelerated electrons in the plasma periphery. The such electrons form the ring current-carrying beam which apparently changes the poloidal magnetic field structure and damps appropriate MHD-modes. The data obtained let to suppose also that two factors else may influence on the L-H transition and improved plasma confinement observed in the FT-2 tokamak under the second fast U_l ramp up, [4]. Firstly, the additional radial electric field arising in the plasma near the limiter due to fast losses of accelerated electrons during the short MHD-flash helps to the such transition into H-regime with the peripheral improved plasma confinement. Then, the ring current-carrying beam arised not only damps peripheral resonance MHD-modes but may provide appearance of the region with the reversed magnetic shear and improved volume plasma confinement.

REFERENCES

1. Esipov L.A., Its E.R., Kiptily V.G., et al. The combined diagnostic technique for studying accelerated electrons in the FT-2 tokamak. Plasma Phys. Rep., 1998, Vol.24, No.3, pp.228-232
2. Parail V.V. and Pogutse O.P., Voprosy teorii plazmy (Reviews of Plasma Physics), Leontovich M.A., Kadomtsev B.B., Eds, Moskow: Energoatomizdat, 1982, no.11, p.5
3. V.N.Budnikov, L.A.Esipov, E.R.Its et al. Behavior of accelerated electrons during and after the fast vortex electric field ramp up in the FT-2 tokamak plasma. Contributions to the 26th EPS Conf. on Contr. Fus. and Plasma Phys., 14-18 June 1999 in Maastriht, organized by the Plasma. Phys. Division of the EPS. P4.097. http://epsppd.epfl.ch/#p4.htm
4. V.N.Budnikov, V.V.Bulanun, L.A.Esipov, et al. "Nonlocal" transport in current ramp-up experiments in the FT-2 tokamak. Plasma Phys. Rep., 1999, Vol.25, No.12, pp.969-975

Fig. 1

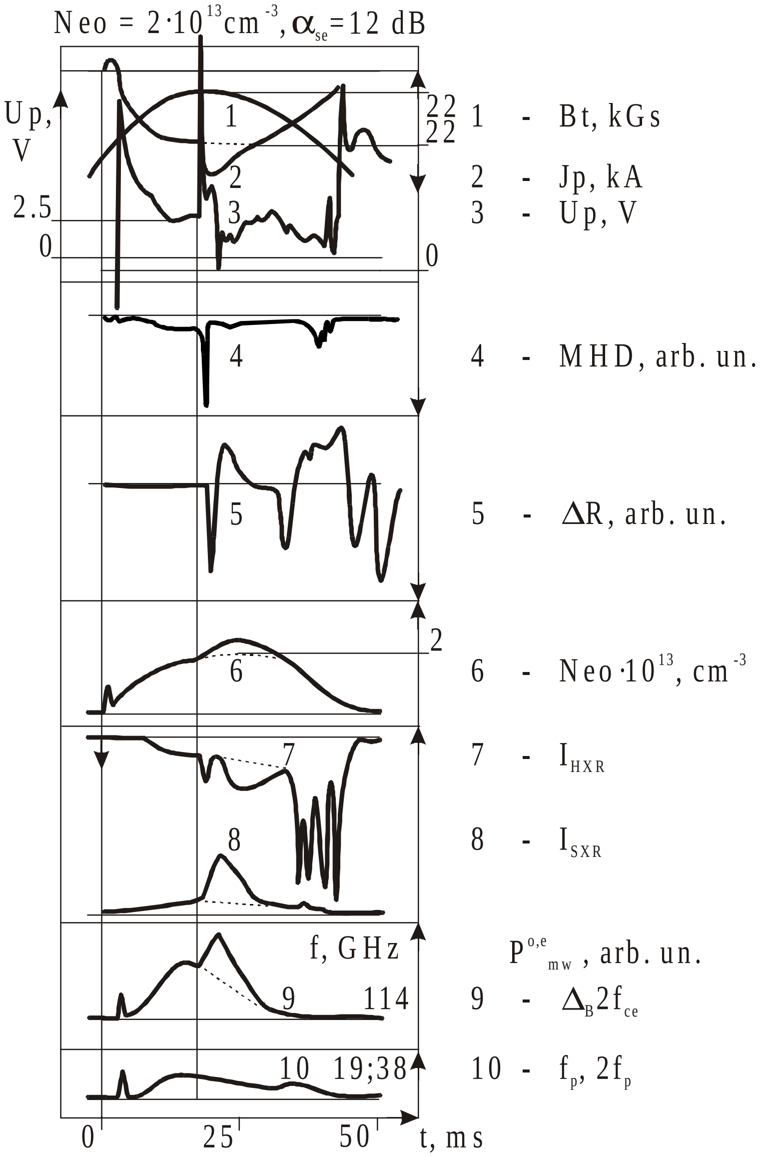
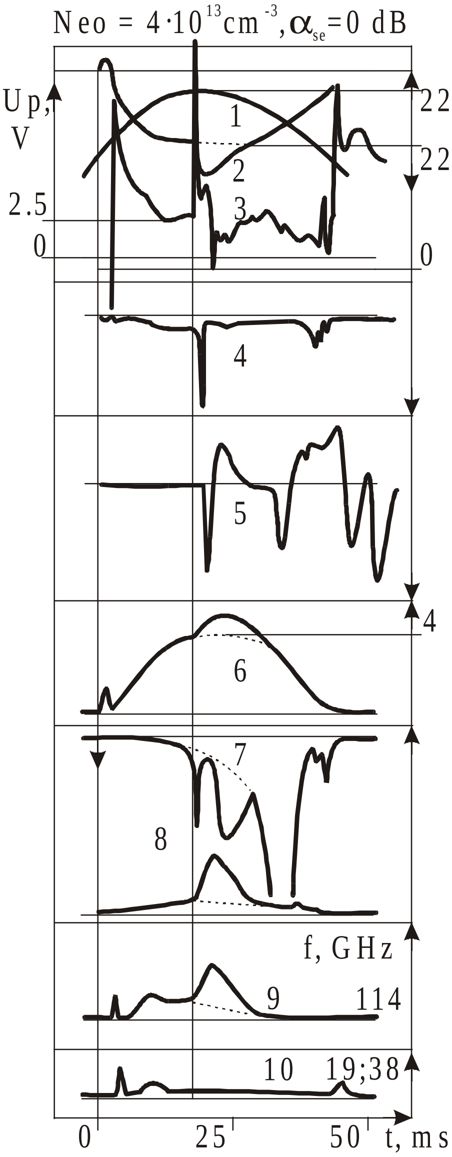


Fig. 2



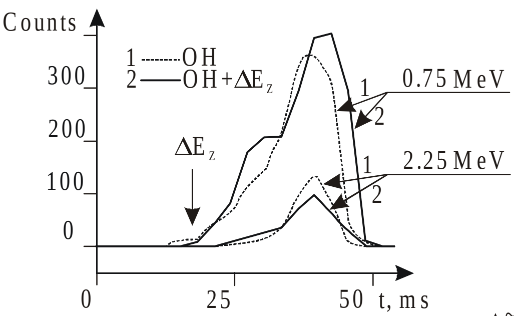
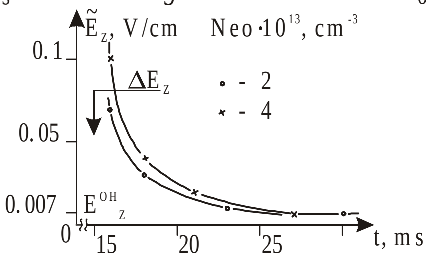


Fig. 3

Fig. 5



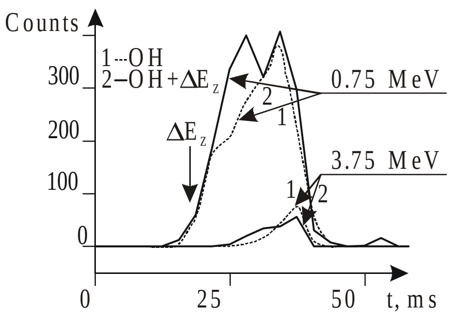


Fig. 4