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Electron Energy Balance Near the Density Limit in T-10 and FTU OH regimes

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1. Early data on energy confinement at T-10

The early τ_E meanings found in T-10 OH regimes [1] did not contradict with T-11 scaling:

$$\tau_E \approx 1.2\times10^{-20}\, A_i^{\,0.4} (a/R)^{0.21}\, \bar{n}_e q_a^{7/6} R^{17/6} / B_T^{1/3} \quad [\text{s, cm, cm}^{-3}, \text{G}]. \qquad (1)$$

The noticeable less τ_E-data (by 20-30 %) relative to predictive ones from scaling (1), and from T-11 electron coefficients [2], were found, first, when the mean electron density in T-10 was raised up to ~7 10^{13} cm^{-3} by secondary and slowly rise of density with programming gas-puff in 1s OH discharge. With this density rise scenario, the density limit in T-10 is increased near double at plasma current 200-320 kA. However, the secondary rise of density was not followed by reduction of Z_{eff}, and the radiation power rose, as $\bar{n}_e^2$, at high density.

It was unclear what type of light impurity, C or O, is main and we tried to distinguish them from the modeling radiation power using the coronal model [3] and 1-D time-depended transport code AT. The results have shown that the predictive P_{rad} value for "C" impurity is in one order of magnitude less than real ones at density of 3×10^{13} cm^{-3}. The calculated P_{rad} value for oxygen impurity was in 2-2.5 times higher at this density, but at 7×10^{13} cm^{-3} its value have reached ½ experimental P_{rad} value. Nevertheless, the τ_E code data for "O" case was not far from experiment. Fig. 1a shows the experimental τ_E ($\bar{n}_e$) dependence in 200 kA regime [4] and two calculated ones: for Z_{eff} = 1 (solid line), and for real Z_{eff} = 2-2.5. Measured and calculated neutron rate Y_n vs. $\bar{n}_e$ are shown in Fig. 1b.

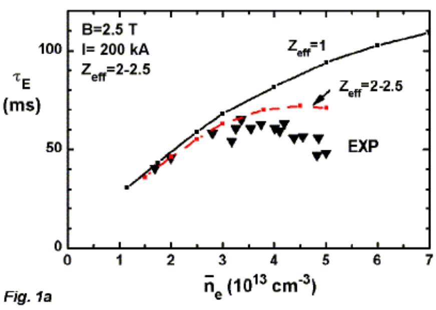

Fig. 1a

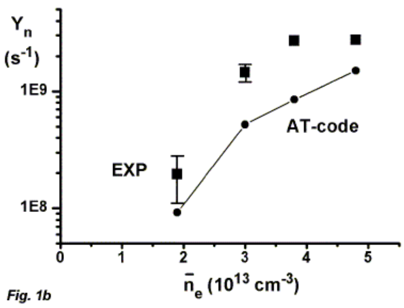

Fig. 1b

In 2003, the subroutine for calculation of P_{rad} was renewed in AT code. There was taken into account the additional recombination term to coronal model [3] for C-X process between the impurity ions and hydrogen atoms [5]. The local neutral density D° is known in AT-code from solutions of two tasks for the main plasma – the charge particles diffusion and penetration of cold neutrals. Besides the absolute neutrals density, the key parameter in calculation of the P_{rad} value was the average Z_{eff}, which was determined from the local continuum measurements and from the plasma conductivity in separate program Sigma+.

2. Low-q and low-Zeff OH regime on T-10

In 2004, in a standard low-q regime on T-10 (B_T=2.4-2.5 T, I_p=305-320 kA, $q_a \cong$2.4), the energy confinement time increased after decreasing the average Z_{eff} value and radiation power near in 1.5 times. Fig. 2 shows the measured τ_E values in wide range of electron density in 306 kA regime with Z_{eff} = 1.3-1.5, as well as two τ_E values found before in the high-density range in 320 kA regime at Z_{eff} =2.1-2.3. It should be noted that, a maximal τ_E value of 60 ms at $\bar{n}_e \approx 7\ 10^{13}$ cm^{-3} in Z_{eff} $\approx$ 2.2 case is close to τ_E^{max} value in 200 kA regime at the same Z_{eff} $\geq$ 2, but at twice lower density (see fig. 1a). A constant τ_E value (~50 ms) at different current and density was found in FTU SOC regimes, also [6].

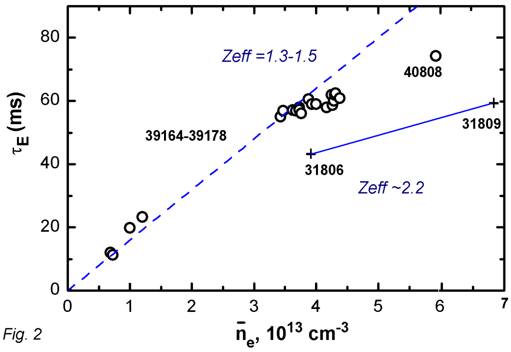

Fig. 2

The energy confinement time in a low-Z_{eff} regime increases by 40 % at $\bar{n}_e$ = 4×10^{13} cm^{-3}, mainly due to decrease of loop-voltage and OH power. However, the P_{rad}/P_{oh} ratio still reached a significant value ~ 0.35 at highest density. The P_{rad} value (150 kW at $\bar{n}_e$ =5.9 10^{13} cm^{-3}), which was measured by piroelectric bolometer, gives the sum of loss: from the impurity radiation - in the main plasma and in scrap of layer - and from fast C-X neutrals. So, we can wait, that a net P_{rad} at r/a $\leq$ 1 should be less by ~ 20%, at least. This value, of 120 kW, is higher than calculated ones for oxygen impurity, by factor of 1.4. This discrepancy between calculated and experimental $P_{rad.net}$ value turns out to be systematic in the low-Z_{eff} regime in a wide range of the mean electron density (1÷6) 10^{13} cm^{-3}.

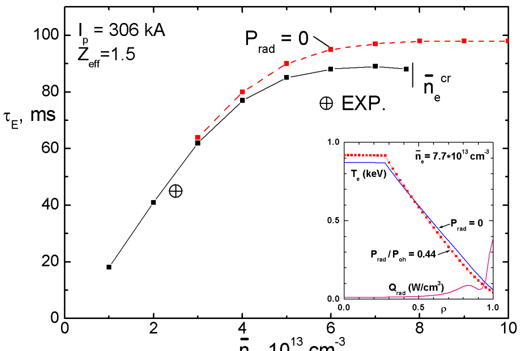

Fig. 3

The experimental τ_E values in the low-Z_{eff} regime and two predictive τ_E ($\bar{n}_e$) dependences are shown in fig. 3. The first calculated dependence (solid line) takes in to account the electron energy loss with impurity radiation, and the second one ignores it. The decrease of τ_E rise with density in P_{rad} = 0 case can be explained by increase of the loss with neoclassical ions heat conductivity at relatively low plasma current in T-10. The radiation loss rapidly rises with density, but its influence on τ_E is rather weak, due to its peripheral nature (see insertion in fig. 3). This loss reduces the electron temperature near the plasma edge. If T_e (a) is falls down to ~15 eV, the P_{rad} power continuously rises, which causes further decrease of T_e (a). Such critical process evolves at $\bar{n}_e$ > 7.7 10^{13} cm^{-3} in the regime shown on fig. 3.

3. Modeling of the FTU OH regimes

The possibility of the improving of the energy confinement in high-density OH regimes by repetitive pellet injections was successfully tested on FTU in 1997. Later on, the FTU experiments [7] have found a continuous rise of kinetic energy during 0.4 sec in OH discharge, when the mean electron density, increasing at each pellet injection, reached 4×10^{14} cm^{-3}. In this high-density discharge, the energy confinement time was ~ 90 ms, while the saturated τ_E value was 40-50 ms on FTU in all high-density gas-fueled discharges. The recent confinement studies for a set of 7.2 T discharges with different current on FTU [8] have shown that τ_E meanings in the low-density discharges and in the typical high-density discharges with repetitive pellet injections agree well with Alcator type linear scaling $\tau_E \sim \bar{n}_e$.

The recent T-10 and FTU experiments show that the linear density scaling predicts the upper bound for τ_E data in OH regimes, which can be close to real ones, if radiation loss and/or neoclassical ion heat conductivity contribute a small part in overall plasma energy loss. The first modeling data for 0.7 MA /6T Ohmic discharge on FTU have shown the saturation of τ_E value in Z_{eff} = 2 regime at mean density higher than 10^{14} cm^{-3}. A more definite modeling data, recently found four two regimes with different currents at constant B_T = 7.2 T described in [6, 8] and for 1.2 MA /8T regime on FTU [7], are discussed below. It was supposed at modeling, that Z_{eff} could be close to unity in a pellet-fueled discharge, while its value could be rather high, of 3-4, in a gas-fueled discharge. The density rise scenario was accepted continual in time (in both cases); the calculated τ_E value and other parameters were counted through 150 ms after the ending of the density rise phase.

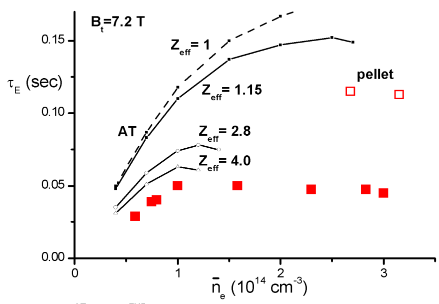

Fig. 4a. τ_E^{AT} and τ_E^{EXP} density dependences in 0.8 MA FTU regime.

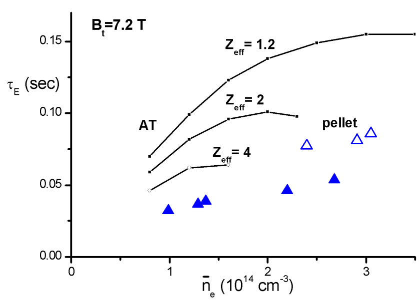

Fig. 4b. τ_E^{AT} and τ_E^{EXP} density dependences in 1.1 MA FTU regime.

Fig. 4a shows the calculated τ_E density dependences for FTU 0.8 MA/7.2 T regime, which are obtained from modeling the separate OH discharges, as in T-10 case. At modeling this regime, it was impossible to run the discharge scenario at $\bar{n}_e^{max} > 2.5\ 10^{13}$ cm^{-3} and Z_{eff} > 1.15 due to decreasing the edge electron temperature down to a critical value ~ 15 eV at $P_{rad} \geq 0.6\ P_{oh}$. So, the modeling have shown a satisfactory agreement with τ_E data for 0.8 MA pellet regime at Z_{eff} not higher than 1.15. With increase of Z_{eff} up to 4, it was possible to find a satisfied agreement with experiment at lowest density and in the initial phase of SOC regime, where the calculated τ_E data overestimate the real ones by 20-30%, only. In contrast with 0.8 MA regime, the modeling of 1.1 MA regime give the calculated τ_E data that are close to experimental ones for the pellet-fueled discharge in $Z_{eff} = 2$ case (fig. 4b). Fig. 4b shows that, under $Z_{eff} \leq 1.2$, the τ_E could reach 150 ms in pellet-fueled discharge in this FTU regime.

The lowest value of $Z_{eff} \leq 1.3$ was really obtained in pellet-fueled plasmas in 0.7 MA regime in 11612 shot and in 8T/1.2 MA regime in 18598 shot. The $\beta_p^{AT} \approx 0.42$ found for 11612 shot at $\bar{n}_e = 1.9\ 10^{14}$ cm^{-3} is very close to experimental β_p. At the same time, β_p^{AT} and τ_E^{AT}, found at $Z_{eff} = 1.2$ for 18598 shot at highest density (fig. 5) noticeable overestimate the real ones: by ~ 20 % for β_p and by ~ 40 % for τ_E. (The Y_n^{AT}~ 3 10^{13} s^{-1} is by factor of 2 higher than in experiment, also.) One can assume, that a clear disagreement of calculated β_p and Y_n value with experimental data in this shot is due to a significant radiative part in the electron energy loss connected with heavy impurity in plasma, which does not increase, noticeably, Z_{eff} value.

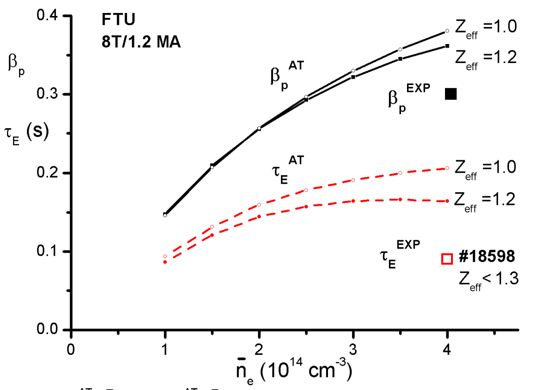

Fig. 5. β_p^{AT} ($\bar{n}_e$) and τ_E^{AT} ($\bar{n}_e$) dependencies for high-field regime on FTU and real β_p and τ_E meanings in 18598 pellet-fueled discharge

4. Summary

Including the radiation loss from the light impurity in AT code increase the accuracy of predictive τ_E value at T-11 electron transport coefficients [2] and $\chi_i = \chi_i^{neo}$. For T-10, the calculated τ_E = 85-88 ms overestimate the experimental τ_E^{max} value by 12-15 %, only. For FTU, the calculated τ_E data overestimate by ~ 30% the experimental ones at low density, in the initial phase of SOC regimes and in the typical high-density regimes with repetitive pellet injection.

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