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

V.G. Merezhkin

RRC Kurchatov Institute, Moscow 123182, Russia. vmerej@fusion.ru

1. Early data on energy confinement at T-10

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

$$
\tau_e \approx 1.2 \times 10^{-20} A_e^{0.4} \left( a/R \right)^{0.21} \bar{n}_e q_a^{7/6} R^{17/6} / B_t^{1/3} \quad [\text{s, cm, cm}^{-3}, \text{G}].
$$

(1)

The noticeable less $\tau_e$-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 $\sim 7 \times 10^{13}$ 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 $3 \times 10^{13}$ cm$^{-3}$. The calculated $P_{rad}$ value for oxygen impurity was in 2-2.5 times higher at this density, but at $7 \times 10^{13}$ cm$^{-3}$ its value have reached $\frac{1}{2}$ experimental $P_{rad}$ value. Nevertheless, the $\tau_e$ code data for “O” case was not far from experiment. Fig. 1a shows the experimental $\tau_e$ ($\bar{n}_e$) dependence in 200 kA regime [4] and two calculated ones: for $Z_{eff} = 1$ (solid line), and for real $Z_{eff} = 2.25$. Measured and calculated neutron rate $Y_n$ vs. $\bar{n}_e$ are shown in 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 $D^0$ 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=2.4-2.5 T, I=305-320 kA, q=2.4),
the energy confinement time increased after decreasing the average Zeff value and radiation
power near in 1.5 times. Fig. 2 shows the measured
τE values in wide range of electron density in 306
kA regime with Zeff = 1.3-1.5, as well as two τE
values found before in the high-density range in 320
kA regime at Zeff =2.1-2.3. It should be noted that,
a maximal τE value of 60 ms at \( \bar{n}_e \approx 7 \times 10^{13} \) cm\(^{-3}\) in Zeff
\( \approx 2.2 \) case is close to \( \tau_{E_{\text{max}}} \) value in 200 kA regime at
the same Zeff \( \geq 2 \), but at twice lower density (see fig. 1a). A constant τE value (~50 ms) at
different current and density was found in FTU SOC regimes, also [6].

The energy confinement time in a low-Zeff regime increases by 40 % at \( \bar{n}_e = 4 \times 10^{13} \)
\( \text{cm}^{-3} \), mainly due to decrease of loop-voltage and OH power. However, the P_{\text{rad}}/P_{\text{oh}} ratio still
reached a significant value \( \sim 0.35 \) at highest density. The P_{\text{rad}} value (150 kW at \( \bar{n}_e =5.9 \times 10^{13} \)
\( \text{cm}^{-3} \)), 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_{\text{rad}} at t/a \( \leq 1 \) should be less by \( \sim 20\% \), 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_{\text{rad,net}} value turns out to be systematic in the low-Zeff regime in a
wide range of the mean electron density (1±6) \( 10^{13} \text{cm}^{-3} \).

The experimental τE values in the low-Zeff regime
and two predictive τE \( (\bar{n}_e) \) 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 τE rise with density in P_{\text{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 τE 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 \( \sim 15 \text{ eV} \), the P_{\text{rad}} power continuously rises, which causes further decrease of
T_e(a). Such critical process evolves at \( \bar{n}_e > 7.7 \times 10^{13} \text{cm}^{-3} \) 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 \(4 \times 10^{14}\) cm\(^{-3}\). In this high-density discharge, the energy confinement time was \(\sim 90\) ms, while the saturated \(\tau_e\) 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 \(\tau_e\) meanings in the low-density discharges and in the typical high-density discharges with repetitive pellet injections agree well with Alcator type linear scaling \(\tau_e \sim \bar{n}_e^\alpha\).

The recent T-10 and FTU experiments show that the linear density scaling predicts the upper bound for \(\tau_e\) 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 \(\tau_e\) value in \(Z_{\text{eff}} \approx 2\) 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 \(Z_{\text{eff}}\) 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 \(\tau_e\) value and other parameters were counted through 150 ms after the ending of the density rise phase.

![Graph 1](image1.png)

![Graph 2](image2.png)

Fig. 4a shows the calculated \(\tau_e\) 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 \(\bar{n}_e^{\text{max}} > 2.5 \times 10^{13}\) cm\(^{-3}\) and \(Z_{\text{eff}} > 1.15\) due to decreasing the edge electron temperature down to a critical value \(\sim 15\) eV at \(P_{\text{rad}} \geq 0.6\) P\(_{\text{th}}\). So, the modeling have shown a satisfactory agreement with \(\tau_e\) data for 0.8 MA pellet regime at \(Z_{\text{eff}}\) not higher than 1.15. With increase of \(Z_{\text{eff}}\) 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 \( \tau_E \) 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 \( \tau_E \) data that are close to experimental ones for the pellet-fueled discharge in \( Z_{\text{eff}} = 2 \) case (fig. 4b). Fig. 4b shows that, under \( Z_{\text{eff}} \leq 1.2 \), the \( \tau_E \) could reach 150 ms in pellet-fueled discharge in this FTU regime.

The lowest value of \( Z_{\text{eff}} \leq 1.3 \) 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 \( \beta_p^{ \text{AT}} \approx 0.42 \) found for 11612 shot at \( \bar{n}_e = 1.9 \times 10^{14} \text{ cm}^{-3} \) is very close to experimental \( \beta_p \). At the same time, \( \beta_p^{ \text{AT}} \) and \( \tau_E^{ \text{AT}} \), found at \( Z_{\text{eff}} = 1.2 \) for 18598 shot at highest density (fig. 5) noticeable overestimate the real ones: by \( \sim 20 \% \) for \( \beta_p \) and by \( \sim 40 \% \) for \( \tau_{E} \). (The \( Y_n^{\text{AT}} \approx 3 \times 10^{13} \text{ s}^{-1} \) is by factor of 2 higher than in experiment, also.) One can assume, that a clear disagreement of calculated \( \beta_p \) 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, \( Z_{\text{eff}} \) value.

4. Summary

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