Energy confinement time study at the FT-2 tokamak.

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The tokamak anomalous transport enigma which is in the focus of the fusion community for already more than fifty years is one of the last remaining puzzles of the high temperature plasma physics. Nowadays investigations of the turbulent transport are performed at tokamaks of very different size and utilize both diagnostics possessing unique performance and massively parallelized gyrokinetic computations. A small research FT-2 tokamak is equipped with a set of microwave turbulence diagnostics including the radial correlation Doppler reflectometry and the correlation enhanced microwave backscattering in the UH resonance possessing unique, sub-millimeter, spatial resolution and ability to measure the turbulence radial wavenumber spectra [1, 2]. It also diagnose the plasma rotation and its oscillations related to GAMs with high temporal and spatial precision [3]. The gyrokinetic model of the FT-2 tokamak turbulent transport phenomena has been created in the framework of the ELMFIRE global full-f code and successfully benchmarked against the experimental data [4, 5, 6]. However, in spite of the very detailed insight in the multi-scale turbulence nonlinear dynamics in selected discharges, general transport properties of the FT-2 discharge, in particular, scaling of the energy confinement have not been studied yet. The present paper fills in this gap.

Experimental/modeling approach

The FT-2 tokamak (a=0.08m, R=0.55m, 19kA $< I_{pl} <$34 kA, 2T $< B_T <$ 2.5T, q_{95}~3-6) experimental database is elaborated in a wide density and plasma current range to determine the energy confinement scaling. Only the Ohmic discharges performed in three different working gases (hydrogen (H), deuterium (D) and helium (He)) were analyzed. The energy confinement time scaling is found in a wide range of available plasma parameters using the ASTRA code transport modeling based on the experimental data. Electron temperature profiles were measured with laser Thomson scattering diagnostics, which was also used in combination with microwave interferometry to determine the electron density profile. Ion temperature profile in the central zone was measured with NPA diagnostics. These measurements were expanded to the plasma edge using the impurity spectroscopy. Radiation losses were measured by bolometric diagnostics. The effective charge was used as a fitting parameter allowing to reach the coincidence of measured and calculated loop voltages $U_{p\,exp} =$

$U_{p\,calc}$, in the assumption of neoclassical plasma conductivity [7]. Flat radial profile of Z_{eff} was supposed in the modeling.

Scaling results

All available in the data base FT-2 steady state ohmic discharges were taken into account to plot the τ_E scaling. As the FT-2 experimental database covers a long period of measurements at different experimental setups, wide set of plasma parameters and tokamak camera conditions a special approach to systematize these data is needed. Selection of plasma discharges was performed according to the plasma current I_p and toroidal field B_T values. Namely, the FT-2 discharges at $B_T \sim 2\text{-}2.2\text{T}$ were chosen and two plasma current ranges were considered: low current case (LCC, $I_p\sim$19-22 kA, $q_{95}\sim$4-6) and high current case (HCC, $I_p\sim$29-34 kA, $q_{95}\sim$3-4).

The experimental values of energy confinement time determined as $\tau_E = W / (P_{OH}-dW/dt)$, where W stands for the plasma thermal energy content and P_{OH} is the ohmic heating power, is
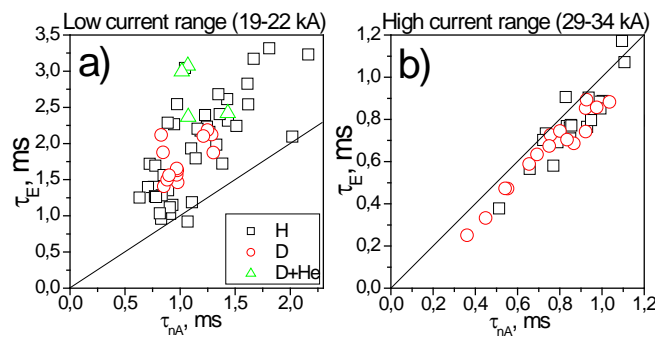

Figure 1: Energy confinement time dependence on neo-Alcator scaling prediction for a) low current and b) high current cases. Black line stands for the neo-Alcator scaling. Hydrogen is black, deuterium is red, deuterium with small portion of helium is green.

shown in Fig.1a against the neo-Alcator scaling prediction $\tau_{nA} = 0.007{\cdot}aR^2{<}n_e{>}q_{95}$ for different densities in the LCC. Due to the tokamak operational limits for the LCC the line averaged density is limited here by $<n_e> \sim 3{\cdot}10^{19}\text{m}^{-3}$. As one can see in Fig.1a the spreading of points is high the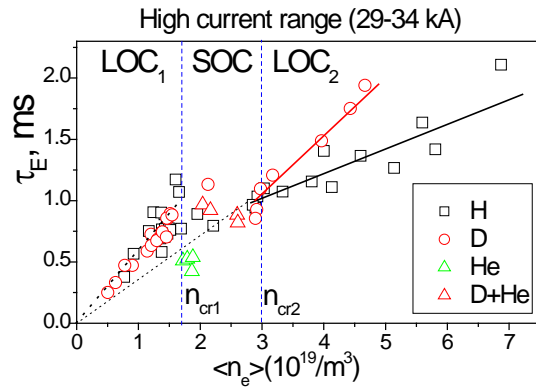re, nevertheless they could be fitted by a linear dependence indicating substantially better confinement than the neo-Alcator scaling prediction (shown by solid line). No visible isotope effect on global energy confinement is observed here in agreement to [6, 8], where both in experimentally and in global gyrokinetic studies no isotope effect was observed in the dominant, electron energy channel however clear isotope difference in particle and ion energy channel was demonstrated.

On contrary, in the HCC a quite good coincidence with the neo-Alcator scaling τ_{nA} was found at low densities up to $n_e < n_{cr1}\sim 1.7{\cdot}10^{19}\text{m}^{-3}$ (Fig.1b and Fig.2). Unlike the LCC here we have much smaller spreading of experimental points. No isotope effect is seen in Fig.1b that can be accounted for a minor role of ions in the energy balance at low densities and by expected dominance of TE mode in the drift-wave turbulence at small plasma density [9].

Figure 2: The energy confinement time dependence on density. Dotted lines at n_{cr1} and n_{cr2} mark transition between different confinement tendencies. Black and red solid lines show linear approximation for H and D plasmas at high densities. H - black, D – red circles, He - green, D with He– red triangles.

At higher plasma density $n_e > n_{cr1}$ the $\tau_E(n_e)$ linear dependence saturates, as it is demonstrated in Fig.2 where energy confinement times obtained in HCR in three gases in the full range of available from FT-2 database densities are presented. There are quite few helium plasma experiments so systematic research of that gas is not possible. The only conclusion concerning He is that elaborated helium discharges has twice lower confinement time than H and D plasmas. Small portion of helium on periphery of deuterium plasma (red triangles) does not affect distinctly the energy confinement, so further we will not consider that case separately from standard deuterium discharges.

The linear dependence $\tau_E(n_e)$ seen in Fig.2 at smaller density $n_e < n_{cr1}$ is well known to the community as a linear ohmic confinement (LOC) regime. The growth of confinement time is saturated in the density range between n_{cr1} and $n_{cr2} \sim 3 \cdot 10^{19} m^{-3}$ and then continue increasing with density, but at a smaller rate. Effective charge is found to be a quite essential parameter

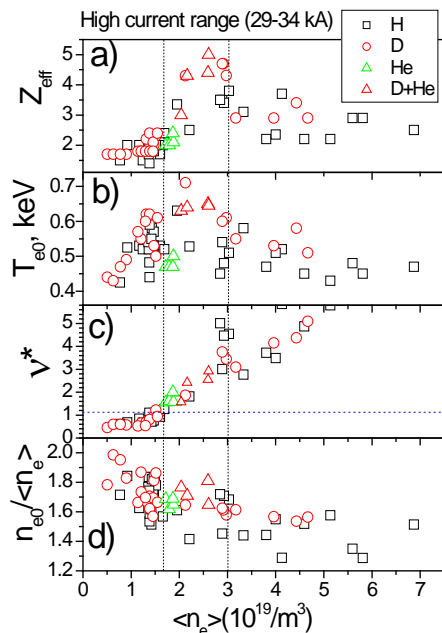Figure 3: a) effective charge b) central electron temperature c) effective collisionality d) electron density peaking parameter

here. The $Z_{eff}(n_e)$ dependence plotted in (Fig.3a) shows anomalous growth of the effective charge at densities $n_{cr1} < n_e < n_{cr2}$, just corresponding to the $\tau_E(n_e)$ saturation stage. The central electron temperature growth observed at smaller density $n_e < n_{cr1}$, is terminated at the saturation stage, where the temperature is maximal (Fig.3b). As it is seen in see Fig.3d, the density peaking parameter $n_e(0)/\langle n_e \rangle$ demonstrates monotonous decrease with density that corresponds to a slow widening of n_e profile. It should be stressed that the effective collisionality introduced as $v^* = 0.018 \cdot n_e qRZ_{eff}/T_e^2 \varepsilon^{3/2}$ and calculated using chord averaged values of n_e and T_e is passing the unit value at $n \sim n_{cr1}$ (Fig.3c). Another important effect observed in Fig.2 at densities higher than $n_{cr2} \sim 3 \cdot 10^{19} m^{-3}$ is the obvious isotopic separation of confinement: in D plasma τ_E rises twice as fast as in the H one.

Discussion

Transition from linear τ_E growth (LOC regime) described by neo-Alcator scaling to some kind of saturated stage observed at FT-2 in HCC is similar to transition from LOC to saturated ohmic confinement (SOC) regime, observed at many tokamaks [10]. Empirical estimation of the LOC to SOC transition density performed in [11] had resulted in the expression $n_{crit} \sim 0.65 \cdot A^{0.5} \cdot B_T / (Rq)$. For the FT-2 tokamak parameters it gives a value of density in the range of $n_e \sim (7\text{-}10) \cdot 10^{19} \mathrm{m}^{-3}$, which is much higher than the actual value n_{cr1} where this effect is observed at FT-2. On the other hand the analysis of the LOC to SOC transition performed in [4] had shown that it is controlled by the v^* value. In the FT-2 HCC the LOC to SOC critical density corresponds to the transition criteria $v^* \sim 1$.

The secondary increase of τ_E at high densities is especially well pronounced in D plasmas. The isotope difference could be attributed to larger energy transfer to the ion channel in H plasma and to decrease of the ion confinement time with growing power in the L-mode [12].

Conclusions

Summarizing the obtained results we would like to note that the energy confinement time dependence on density determined for the small research FT-2 tokamak shows transition from the neo-Alcator scaling observed at low densities $n_e < 1.7 \cdot 10^{19} \mathrm{m}^{-3}$ to the saturated stage at density close to the critical value predicted for (LOC) to (SOC) transition by the $v^* \sim 1$ criteria. Anomalously high values of effective charge are determined for saturated stage of $\tau_E(n_e)$ dependence. For the first time the effect of secondary linear growth of τ_E at higher densities $n_e > 3 \cdot 10^{19} \mathrm{m}^{-3}$, which does not follow the neo-Alcator scaling and shows no saturation within tokamak operational limits is observed. It is more pronounced in the D plasma and could be related to the energy confinement isotope effect which is found just for this high density range.

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