Study of the transport coefficient dependence on the heating power in self-organized plasma in the T-10 tokamak

N.V. Kasyanova[1,2], K.A. Razumova[1], A.A. Borschegovskij[1], M.M. Dremin[1], N.A. Kirneva[1,3], S.V. Krylov[1], T.B. Myalton[1], G.E. Notkin[1], Yu.D. Pavlov[1], D.V. Ryzhakov[1], D.V. Sarychev[1], D.S. Sergeev[1], N.A. Solovev[1], M.V. Chukanov[1]

[1] *National Research Center "Kurchatov Institute", Moscow, Russia*

[2] *Moscow Institute of Physics and Technology, Dolgoprudny, Russia*

[3] *National Research Nuclear University MEPhI, Moscow, Russia*

1. Introduction

Effect of the energy confinement enhancement during impurity gas puffing in the T-10 tokamak is studied. The experiments with neon puffing described in [1] demonstrated that the radiation cooling of the plasma periphery resulted in the energy confinement increase of 40% whereas the density changed within 10%. It follows that confinement depends on the radiation power rather than plasma concentration. The purpose of the work is to determine the dependence of the transport coefficient on the radial thermal flux in the experiments with radiation cooling of the plasma periphery.

2. Dependence of the energy confinement on the radiation losses

Experiments were carried out in the T-10 tokamak (major radius R = 1.5 m, minor radius a = 0.3 m) with Ne and He puffing in various regimes with ohmic heating (OH) and on- and off-axis ECR heating (I_{pl}=230 kA, B_z= 1.9 - 2.3 T, n_e=1.5 - 4x10^{19} m^{-3}, P_{ECRH}=0.45 - 1.3 MW). Impurity gas puffing was performed either by the fast impulse valve (time duration is 2 ms) or by the valve with variable time duration (for tens of milliseconds).

Figure 1 demonstrates the dependence of the energy confinement on the radiation power in OH regimes with constant plasma current I_{pl}=230 kA and two different toroidal magnetic fields (B_z= 1.9 T and B_z= 2.3 T). It is seen that the energy confinement time increases with the radiation power growth and reaches the saturation level. Figure 2 shows the results obtained in ECR heated plasma with low radiation losses (I_{pl}=235 kA, B_z= 2.4 T, P_{EC} = 850 kW). In shot #70558 increase of the stored energy after ECRH switching on at t=500 ms is not observed. Increase of the radiation power on the plasma periphery due to Ne puffing (from P_{rad}=70 kW to P_{rad}=220 kW) results in W_{dia} growth (shots #70559, #70564).

Figure 3 shows the temporal behaviour of the stored energy W_{dia} in experiments with on-axis ECRH and impurity gas puffing (I_{pl}=230 kA, B_z= 2.3 T, P_{EC} = 450 kW). Strong deuterium puffing started after ECRH switching on (t=600 ms) has resulted in growth of the radiation losses due to intrinsic impurities (C and O). Additionally Ne was puffing during different amounts of time (Δt=10-20 ms). In the shot #71892 He was puffing through the fast valve (t=650 ms) and then Ne was added (t=800). Figure 4 demonstrates the dependence of the stored energy W_{dia} on the power of the radiation losses for the shots ##71887-71890 with Ne puffing. It is seen that W_{dia} increases with the growth of the radiation losses up to saturation level W_{sat} ~ 28 kJ. Comparing these results to the shot #71892 shows that He puffing also leads to rapid W_{dia} growth up to the same saturation level. Additional Ne puffing at t=800 ms does not change W_{dia}. So, one can conclude that the saturation level of W_{dia} does not depend on the kind of impurities although they radiate at the different radii and their atomic weights are markedly different.

3. Analysis of the experimental data

In this work, the explanation of the observed effect from a plasma self-organization position is offered. This approach assumes that the plasma pressure profile is self-consistent. Relaxation of the pressure profile distorted by external impact is described by the energy balance equation obtained in [2]:

$$\frac{\partial p}{\partial t} = \nabla\left[\kappa p \nabla \ln(p / p_c)\right] + q_{in} \qquad (1)$$

here p is the plasma pressure; $k_0 = \frac{\nabla p_c}{p_c}$ is the normalized derivative of the self-consistent pressure profile p_c; transport coefficient κ has the dimensionality of diffusivity.

The total heat flux $\Gamma = -\kappa(\nabla p - k_0 p)$ determined by the heating power q_{in} deposited into the plasma can be represented as follows: $\Gamma = \Gamma_0 + \Gamma_1$. Here Γ_0 corresponds to the self-consistent pressure profile and Γ_1 is associated with the profile distortion. Possible reason for the energy confinement enhancement is a reduction of the transport coefficient while the radial thermal flux decreases, as it has been shown in [3]. So the transport coefficient κ in equation (1) can be written as follows: $\kappa = \theta(\chi_0+\chi_1)$. The first term χ_0 corresponds to the undistorted self-consistent pressure profile, the second term $\chi_1(\Gamma_1)$ depends on the radial heat flux Γ_1 disturbing the pressure profile. During impurity gas puffing the radiation losses in the plasma periphery increase resulting in decrease of the radial heat flux Γ_1, hence the transport coefficient κ in the plasma edge reduces until it reaches the minimum value $\theta\chi_0$. As a result the stored energy of plasma increases and reaches the saturation level. The dependence of W_{sat} on plasma parameters is defined by the coefficient $\theta \sim p_0\beta_0/q_L$.

Figure 5 shows the value χ_0 obtained from the energy saturation level for different ECRH and OH regimes. It is seen that χ_0 does not depend on the heating power. From the increasing dependences of the stored energy on the radiation power for OH and ECRH regimes it was obtained that $\chi_1 \sim (\Gamma_1/\Gamma)^{\alpha}$ with $\alpha > 1$, as shown in figure 6. So, transport coefficient in equation (1) can be written as $\kappa = \frac{p_0^2 IR}{B_0^3 a^2}\left(\chi_0 + c\left(\frac{\Gamma_1}{\Gamma}\right)^{\alpha}\right)$ where p_0 is a pressure at the plasma centre, I is a plasma current, B_0 is a toroidal magnetic field, a and R are minor and major radii respectively. Figure 7 demonstrates the transport coefficient κ calculated for the shots #70558, #70559 and #70564 (see fig. 2) on the steady state at t= 670 ms. Here χ_0=0.9 m^3s/kg, c=0.39 m^3s/kg, α=2. It is seen that growth of the radiation losses due to neon puffing results in decrease of the transport coefficient on the plasma periphery (from 5.8 m/s^2 to 3.8 m/s^2) and increase of the stored energy.

4. Conclusions

1) It was shown that in both OH and ECRH regimes the stored energy first increased with growth of the radiation losses in the plasma edge due to the impurity gas puffing and then it reached a saturation level W_{sat}. 2) It is found that the energy saturation level depends only on the heating power and does not depend on the kind of impurity. 3) Functional dependence of the transport coefficient κ on the radial heat flux Γ_1 disturbing the pressure profile is obtained.

References

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[3] K.A. Razumova et al. Plasma Phys. Rep., 2016, vol. 42, 809

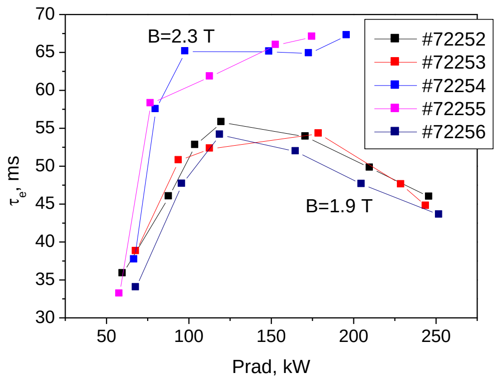

Figure 1. Dependence of the energy confinement time τ_e on the radiation power P_{rad} in OH regimes with Ne puffing.

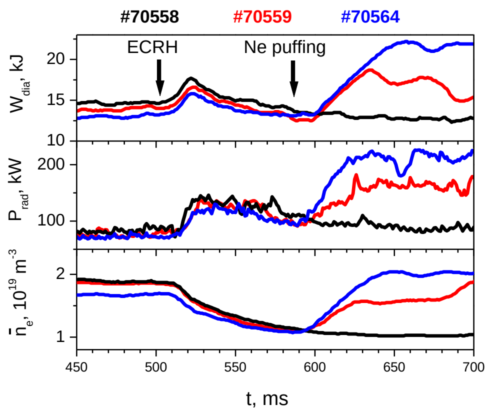

Figure 2. Time evolution of the stored energy W_{dia} (a), radiation power P_{rad} (b) and average density n_e (c) in ECRH regimes with (#70559, #70564) and without (#70558) Ne puffing.

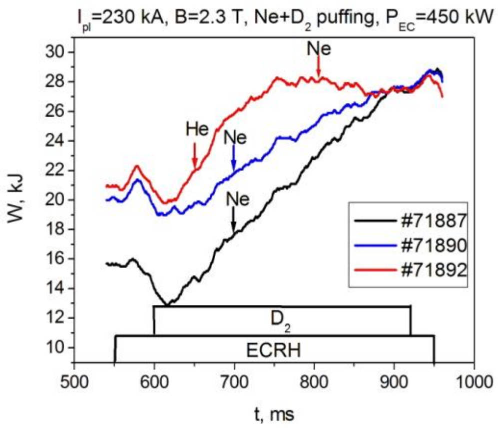

Figure 3. Time evolution of the stored energy W_{dia} in ECRH regimes with radiation cooling of the plasma periphery due to different impurities.

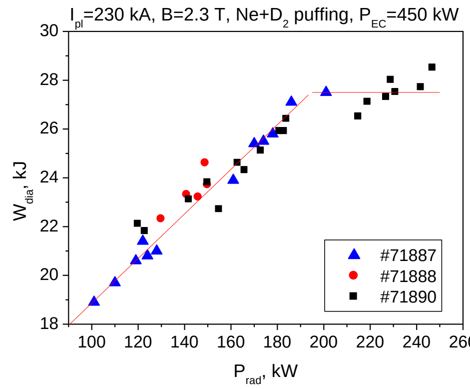

Figure 4. Dependence of the stored energy W_{dia} on the radiation power P_{rad} in ECRH regimes with Ne puffing.

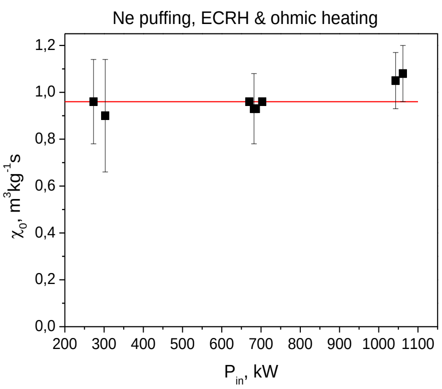

Figure 5. Coefficient χ_0 calculated in OH and ECRH regimes with different heating power P_{in}.

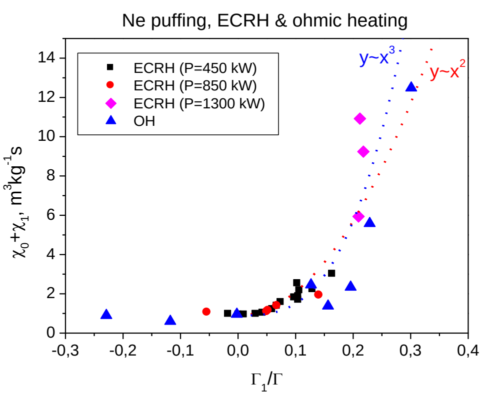

Figure 6. Dependence of the coefficient $\chi = \chi_0 + \chi_1$ on the disturbing heat flux Γ_1 normalized on the total heat flux Γ.

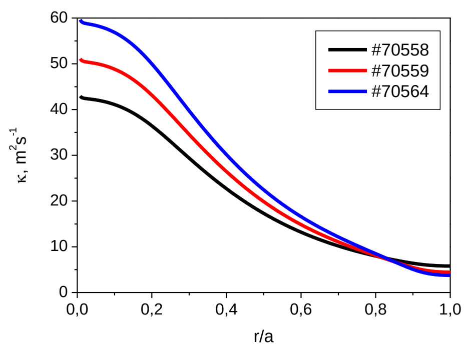

Figure 7. Radial dependences of the transport coefficient κ calculated for ECRH discharges without Ne puffing (#70558) and at steady state after Ne puffing (#70558, #70564).