Reconstruction of the particle pinch in the transient process after ECRH switching on in the T-10 tokamak

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1. Introduction

The experiments with ECRH in the T-10 tokamak have shown the existence of anomalously fast changes of the heat transport in the transient processes after ECRH switching on/off [1]. From the analysis of the experiments it follows that the most likely explanation of this effect is arising of the additional particle flux from the ECR heating zone to the periphery, so-called "density pump-out" effect, experimentally observed in many tokamaks [2, 3] and stellarators [4, 5] in different regimes.

Note that study of the particle transport and evolution of the density profile with ECRH is important for ITER in which the main heat contribution by α-particles will be in the centre of plasma. Moreover investigation of these processes will allow to receive the important information needed for the construction of tokamak fueling systems.

In this work the inverse problem is formulated to analyze the transient process after ECRH switching on and to reconstruct the transport coefficients. We have analyzed a wide database of T-10 shots with different plasma parameters and ECRH powers and determined the particle diffusivity and pinch velocity in the transient process. The new experimental results of the investigation of "density pump-out" effect carried out in T-10 tokamak are also presented in this work.

2. Inverse problem

To describe the transient process after ECRH switching on let us write the equation for stationary density $n^S(r,t)$ with unknown stationary transport coefficients D_n^S and v_p^S and the equation for density in the transient process after ECRH switching on $n(r,t)$ with unknown diffusivity D_n and pinch velocity v_p. Density n, diffusivity D_n and pinch velocity v_p can be written as follows:

$$n(r,t)=n^S(r)+\tilde{n}(r,t),\ D_n(r,t)=D_n^S(r)+\tilde{D}_n(r,t),\ v_p(r,t)=v_p^S(r)+\tilde{v}_p(r,t).$$

$$\tilde{D}_n(r,t)=\begin{cases}0, t<t_S\\ \tilde{D}_n(r,t), t\ge t_S\end{cases},\quad \tilde{v}_p(r,t)=\begin{cases}0, t<t_S\\ \tilde{v}_p(r,t), t\ge t_S\end{cases} \qquad (1)$$

We assume here that the transport coefficients can be changed in a time interval that is essentially less than the energy confinement time in T-10 tokamak.

Subtracting the former equation from the latter and taking into account (1) we obtain the equation for density variation in the transient process:

$$\frac{\partial \tilde{n}}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\left(D_n^S + \tilde{D}_n\right)\frac{\partial \tilde{n}}{\partial r}\right) - \frac{1}{r}\frac{\partial}{\partial r}\left(r\left(v_p^S + \tilde{v}_p\right)\tilde{n}\right) + \Delta P + \Delta P_D + \Delta P_V,$$
$$\frac{\partial \tilde{n}}{\partial r}\left(r = 0, t\right) = 0,\ \tilde{n}\left(r = 1, t\right) = 0. \qquad (2)$$

Where, $\Delta P = P - P^S$ is change of the particle source in the transient process, $\Delta P_D = \frac{1}{r}\frac{\partial}{\partial r}\left(r\tilde{D}_n \frac{\partial n^S}{\partial r}\right)$, $\Delta P_V = -\frac{1}{r}\frac{\partial}{\partial r}\left(r\tilde{v}_p n^S\right)$.

To reconstruct the transport coefficients from the experimental measurements of density the inverse problem is formulated. Let us assign a discrepancy functional (normalized difference between the experimentally measured $n^{\exp}(r,t)$ and calculated values $\tilde{n}(r,t)$ of density):

$$J = \frac{1}{2}\frac{\sum_{k=1}^{M}\sum_{i=1}^{N}\gamma_i\left[\tilde{n}(r_i,t_k) - n^{\exp}(r_i,t_k)\right]^2}{\sum_{k=1}^{M}\sum_{i=1}^{N}\gamma_i\left[n^{\exp}(r_i,t_k)\right]^2} \qquad (3)$$

It is necessary to find stationary transport coefficients D_n^S, v_p^S and their variations $\tilde{D}_n$, $\tilde{v}_p$ so that the solution of the equation (1) provides minimum of the discrepancy functional (3).

The inverse problem in general form is too difficult to solve due to noisy experimental data; in addition to that its input data are the solutions of the Abel problem.

To simplify the inverse problem two suppositions are made:

1) We assume that the particle source does not change in the transient process, that is $\Delta P = P - P^S = 0$. This assumption holds true in the central part of the plasma in time intervals $\Delta t = 20 - 30ms$ after ECRH switching on for sufficiently high densities.

2) We assume that only one transport coefficient is changed in the transient process: either particle diffusivity ($\tilde{D}_n \neq 0$, $\tilde{v}_p = 0$) or pinch velocity ($\tilde{D}_n = 0$, $\tilde{v}_p \neq 0$).

Solution of the inverse problem is based on a parameterization of unknown functions and minimization of the discrepancy functional (3).

3. Analysis of the experimental data

The experiments analyzed in this work were carried out in the T-10 tokamak with different values of central ECRH power P_{ECRH}, average density <n> and total plasma current I_p ($\langle n_e \rangle = 1.7 \cdot 10^{19} - 3.1 \cdot 10^{19}$ cm^{-3}, I_p=180-220 kA, P_{ECRH}=0.5-1 MW). The density measurements were carried out using microwave and laser interferometers (15 chords). To reconstruct local values of density from the chord-averaged data the Abel problem was solved.

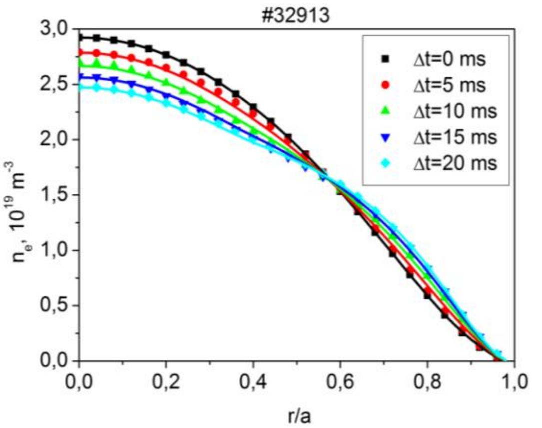

Fig.1. The comparison between the experimental (symbols) and calculated (lines) values of the density.

The comparison between the experimental and calculated values of the electron density is presented in Fig.1. It illustrates the accuracy of the inverse problem solution. Fig.2 shows the jump of the pinch velocity after ECRH switching on while the particle diffusivity does not change. One can see that after ECRH switching on the total inward particle pinch decreases

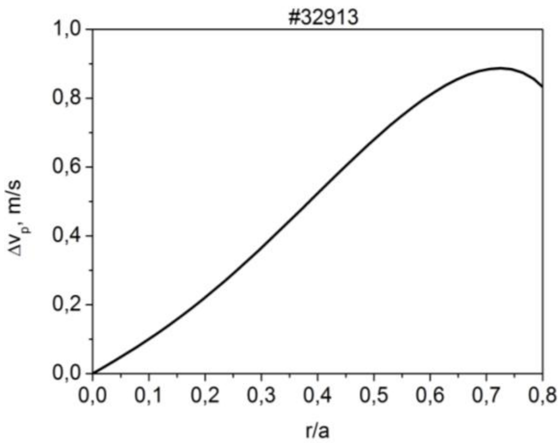

Fig. 2. The jump of the pinch velocity after ECRH switching on.

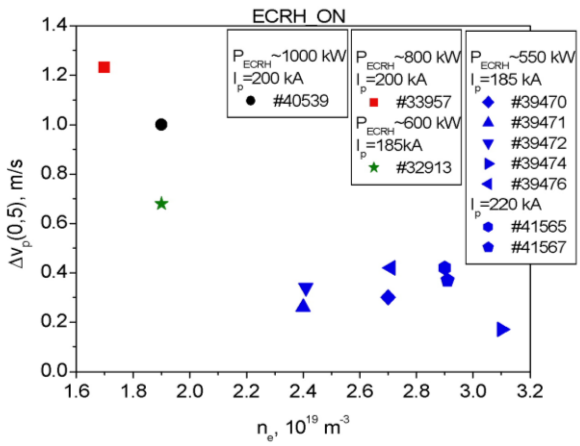

Fig. 3. The variations of the pinch velocity depending on the average density and ECRH power. All values correspond to the radius r=0,5.

in the absolute value. Fig.3 shows the variations of the particle pinch in the transient process for the group of shots with different average densities and ECRH powers. Analysis of the obtained results shows that the change of the particle pinch grows with the increase of the ECRH power.

4. New experimental results

Fig.4 – Fig.5 present the new experimental results of the "density pump-out" effect study carried out in the T-10 tokamak. Experiments were performed with fixed central ECRH power P_{ECRH}=1.2 MW and total current I_P=250 kA. Average density was varied from $\langle n_e \rangle = 2x10^{19}$ m^{-3} to $\langle n_e \rangle = 4{,}7x10^{19}$ m^{-3} for different shots. Fig. 4 gives the time evolution of

the central chord density for shots with different average densities. One can see that the central chord density decreases after ECRH switching on and the density reduction depends

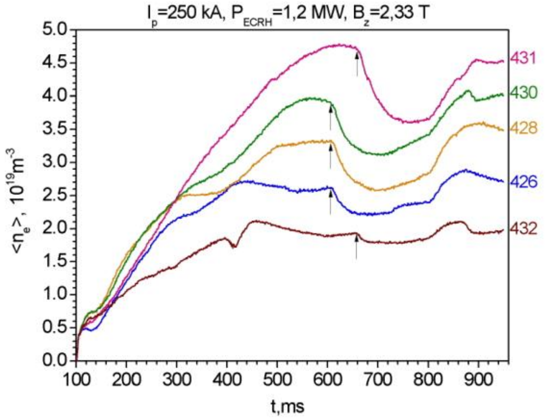

Fig.4. The time evolution of the central chord density for shots with different average density. Arrows refer to the instants of ECRH switching on.

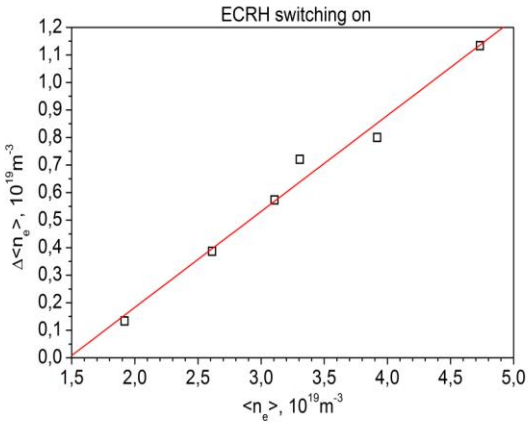

Fig.5. The dependence of the maximal change of the central chord density on the average density.

on the average density. Fig.5 shows the maximal change of the central chord density as a function of the average density. The experiments show that the particle flux from the ECR heating zone to the periphery increases with the growth of the average density.

5. Conclusions

The inverse problem for reconstruction of the particle diffusivity and the pinch velocity in the transient process after ECRH switching on have been formulated. For group of T-10 shots we have determined variations of the transport coefficients in the transient process. The analysis of the obtained data shows that the changes of the diffusivity and the pinch velocity in the transient process depend on the ECRH power. The results of the new experiments carried out in the T-10 tokamak show that “density pump-out” effect increases with the growth of the average density. Note these experimental results differ from the experiments carried out in ASDEX Upgrade [6].

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