PARTICLE TRANSPORT SIMULATIONS BASED ON SELF-CONSISTENCY OF PRESSURE PROFILES IN TOKAMAKS

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Simulation of particle and heat transport was performed with the ASTRA code. The equations for the electron temperature and density, ion temperature and current diffusion were solved. For the heat transport we used the canonical profiles model. Three T-10 pulses with toroidal magnetic field 2.5 T, plasma current 250…255 kA, initial average density 1.3, 2.4 and $3.2 \cdot 10^{19}$ m^{-3} respectively, on-axis 900 kW ECRH and D_2 puffing were considered. The model proved to describe rather fast penetration of the density disturbance from the edge to the core during 15…20 ms after gas puffing. The simulation of the density profiles agrees with experiment in Ohmic and ECRH phases, and during the gas puffing, describing the particle pump-out after ECRH switch-on. The neutral influx at the plasma edge increases after ECRH switch-on in agreement with D_α measurements. Both the effective diffusion coefficient and pinch velocity decrease slightly when the plasma density is increased. A set of two Ohmic and three NBI MAST pulses were considered for comparison.

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1. INTRODUCTION

The plasma density profile plays an important role in the plasma performance and that is why is being intensively investigated in most current tokamaks. In particular, the fusion power increases with plasma density peaking, as does the bootstrap current fraction. On the other hand, the density peaking may have negative effects for MHD stability and central impurity accumulation.

Recently, significant experimental results in the field of particle transport have been obtained. Evidence of an anomalous pinch has been demonstrated in the non-inductive current drive experiments with zero loop voltage in TCV [1] and Tore Supra [2]. According to current knowledge, the particle flux Γ_n can be presented in the form

$$\Gamma_n = V_w n - D[\nabla n + (C_q \nabla q / q - C_T \nabla T_e / T_e) n], \qquad (1)$$

where the first term is the neoclassical Ware pinch, n and T_e are the electron density and temperature, C_q, and C_T are constants to be determined from experiment. The terms in the round brackets present the anomalous pinch. The turbulent thermodiffusion generates a pinch velocity, inwards or outwards, proportional to $\nabla T_e/T_e$. On the other hand, the turbulent equipartition due to the curvature of the magnetic field lines drives an inward pinch proportional to $\nabla q/q$, called curvature pinch.

2. CANONICAL PROFILE PARTICLE TRANSPORT MODEL

Recent analysis of the plasma pressure profiles from various tokamaks confirmed the conservation of relative pressure profiles in the gradient zone under the variation of plasma density and deposited power [3]. Usually these profiles are close to the canonical ones, introduced by B. Coppi, B. Kadomtsev and others in 1980s. The conservation of pressure profiles means that the density and temperature profiles are consistently correlated under different external actions on the plasma. A simple transport model for the plasma density based on the self-consistency of the pressure profiles is proposed and validated for a number of T-10 and MAST pulses. The model naturally develops the canonical profiles model, used for simulations of the heat transport:

$$\begin{aligned} \Gamma_n &= nV_w - D_0 \nabla n - D_n (\nabla n - n \nabla n_c / n_c) - \\ &- D_p (\nabla p - p \nabla p_c / p_c) - D_{st} H(r_s - r) \nabla n \end{aligned}, \qquad (2)$$

where $p=nT_e$ is the electron pressure. The second term in (2) is linked with background diffusion, the next two - with canonical profiles, and the last term describes the sawtooth mixing in the central zone (r_s is the radius of the surface $q=1$, $H(z)$ is the Heaviside function). For the T-10 tokamak with circular cross-section and large aspect ratio, the Kadomtsev’s canonical profiles of density and pressure n_c and p_c were used. In the case of the spherical tokamak MAST the canonical profiles derived in [3] were used. The diffusion coefficients D_0, D_n and D_p were assumed to be proportional to the heat diffusivity coefficient used in the canonical profile model for the heat transport.

Simulations of particles and heat transport were performed with the ASTRA code. The equations for electron temperature and density, ion temperature and current diffusion were solved.

In order to compare the model (2) with the general form of the particle flux (1) it may be presented in another form. To do this we express p and p_c through n, T_e and n_c, T_{ec} respectively, separate terms with n, n_c and T_e, T_{ec} and use the approximate expression: $\nabla n_c/n_c \approx 1/3 \nabla p_c/p_c =$ $= -2/3 \nabla q_c/q_c$, valid for circular cylindrical plasmas. Thus we obtain

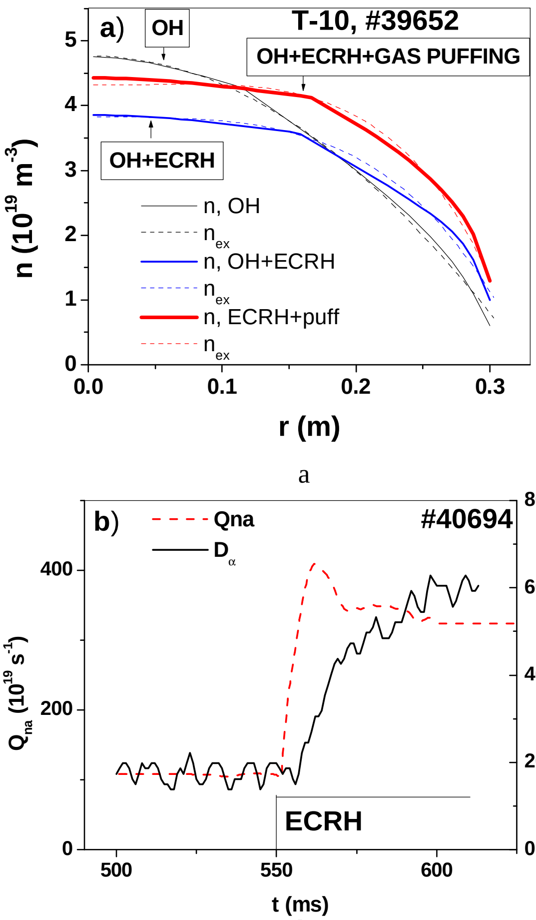
$$\begin{aligned} \Gamma_n &= -(D_n + D_p)[(\nabla n / n + 2/3 \nabla q_c / q_c) - \\ &- D_p / (D_p + D_n)(\nabla T_e / T_e - \nabla T_{ec} / T_{ec}]n + V_w n \end{aligned}. \qquad (3)$$

The first term in square brackets is quite similar to corresponding expression in (1), especially taking into account the value $C_q \approx 0.8$, obtained in [2] for the gradient zone, but the terms responsible for thermodiffusion are rather different. This term in (3) contains the difference of two large values, which may be positive or negative. Obviously, it is impossible to describe such a behaviour of the flux using a single factor C_T. The different signs of C_T in the central and gradient zones, observed by the authors of [2] are in agreement with this statement.

3. RESULTS OF MODELLING

3.1 T-10

Three T-10 pulses with the toroidal magnetic field 2.5 T, plasma current 250-255 kA, initial average density 1.3, 2.4 and $3.2 \cdot 10^{19}$ m^{-3} respectively, on-axis 900 kW ECRH and D_2 puffing were considered. The model proved to describe a rather fast penetration of the density disturbance from the edge to the core during 15-20 ms after the gas puffing start. The simulations of the density profiles agree with experiments in Ohmic and ECRH phases, and during the gas puffing, describing the particle pump-out after ECRH switch-on (Fig.1a). The subroutine adjusting the density of incoming cold neutrals in order to provide a required average electron density was used. The neutral influx at the plasma edge, determined in such a way, was increased after ECRH switch-on in agreement with D_α measurements (Fig. 1b). The effective diffusion coefficient and the pinch velocity decreased slightly when the plasma density was increased.



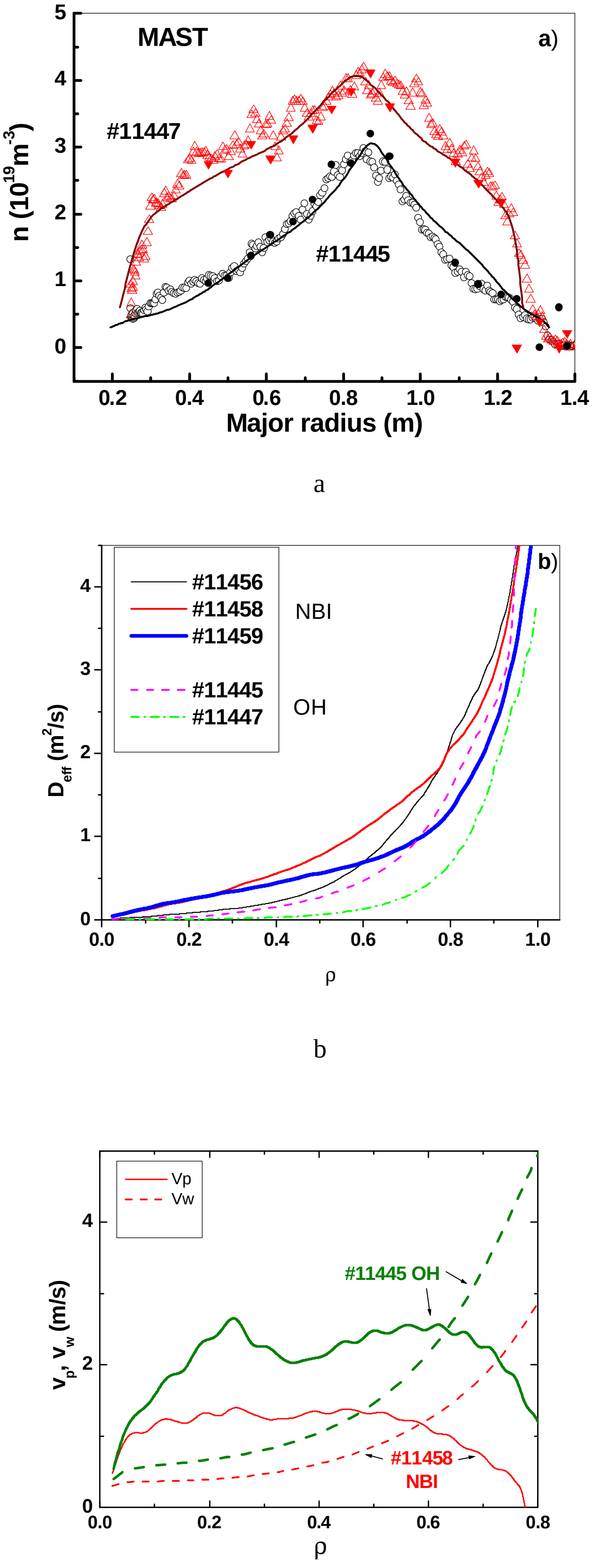
a

b

Fig. 1. a) Density profile, experiment (dashed) and simulation (solid);
b) Neutral influx at the plasma edge and D_α signal

3.2 MAST

A set of two Ohmic and three NBI MAST pulses were considered for comparison with the same proportionality coefficients between D_0, D_n, D_p and the heat diffusivity. The calculations proved to describe adequately the temperature and density profiles in these pulses, as presented in Fig. 2a.



a

b

c

Fig. 2. a) The comparison of experimental and calculated density profiles for two MAST shots;
b) Profiles of effective diffusion coefficient for Ohmic and NBI shots;
c) The profiles of anomalous and neoclassical Ware pinch velocities

Figure 2b shows the effective diffusion coefficients for Ohmic and NBI shots. We see that in the high-density Ohmic shot (#11447) the diffusion is minimal over the all plasma cross-section, while for another Ohmic shot (#11445) the diffusion is small only in the core. Note that for the NBI shot #11456 the beam was switched off at $t = 290$ ms just before the density measurements at $t = 300$ ms. Therefore in calculations at the time instant $t = 300$ ms we have no beam particle source. As a result, the value of D_{eff} in the region $0 < \rho < 0.7$ becomes much lower in comparison with its previous level and with the level of D_{eff} in other NBI shots at $t = 300$ ms.

Figure 2c shows the profiles of anomalous and Ware pinch velocities for Ohmic and NBI shots. It can be seen that for low-density shots, when the electron temperature is high, the anomalous pinch velocity in the gradient zone is much higher (in a factor of 3-4) than the neoclassical pinch velocity.

4. CONCLUSIONS

1. A simple model for particle transport in tokamaks based on self-consistency of pressure profiles is proposed. The model reasonably describes three T-10 pulses in ohmic, ECRH and gas puffing stages and five MAST pulses, with ohmic and NBI heating, thus proving to be promising for further investigations.
2. The anomalous pinch velocity in the gradient zone is 3-4 times higher than the neoclassical one both in T-10 and MAST pulses under consideration.
3. Results of T-10 pulses modeling are in qualitative agreement with the increase of neutral influx at the plasma edge manifested in D_α increase. Absolute measurements of neutral influx at the plasma edge are needed for proper model calibration.

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МОДЕЛИРОВАНИЕ ПЕРЕНОСА ЧАСТИЦ В ТОКАМАКАХ НА ОСНОВЕ КАНОНИЧЕСКИХ ПРОФИЛЕЙ ДАВЛЕНИЯ

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Моделирование переноса тепла и частиц проводилось с помощью кода ASTRA. Решались уравнения для электронной температуры и плотности, и диффузии тока. В качестве модели переноса тепла использовалась модель канонических профилей. Были рассмотрены три импульса Т-10 с тороидальным магнитным полем 2.5 Тл, полным током 250…255 кА и начальной средней плотностью соответственно 1.3, 2.4 и $3.2\cdot10^{19}$ м$^{-3}$. Во всех трех импульсах осуществлялся напуск D_2 на фоне центрального ЭЦР нагрева мощностью 900 кВт. Показано, что модель описывает наблюдающееся в эксперименте быстрое (за 15…20 мс) проникновение возмущения плотности с периферии шнура в центр при газонапуске. Полученные в результате моделирования профили плотности удовлетворительно согласуются с экспериментальными, как в омическом режиме, так и при ЭЦР нагреве и в процессе газонапуска, в частности, описывается вынос частиц из области ЭЦР нагрева. Поток нейтралов на границе плазмы возрастает при включении ЭЦР нагрева, что согласуется с измерениями D_α. Эффективный коэффициент диффузии и скорость пинчевания несколько уменьшаются с ростом плотности плазмы. Для сравнения рассмотрены два импульса в омическом режиме и три импульса с дополнительным нагревом нейтральным пучком с установки MAST.

МОДЕЛЮВАННЯ ПЕРЕНОСУ ЧАСТОК У ТОКАМАКАХ НА ОСНОВІ КАНОНІЧНИХ ПРОФІЛІВ ТИСКУ

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Моделювання переносу тепла і часток проводилося за допомогою коду ASTRA. Вирішувалися рівняння для електронної температури і густини, і дифузії струму. В якості моделі переносу тепла використовувалася модель канонічних профілів. Були розглянуті три імпульси Т-10 з тороідальним магнітним полем 2.5 Тл, повним струмом 250…255 кА і початковою середньою густиною відповідно 1.3, 2.4 і $3.2\cdot10^{19}$ м$^{-3}$. В усіх трьох імпульсах здійснювався напуск D_2 на фоні центрального ЕЦР нагрівання потужністю 900 кВт. Показано, що модель описує швидке (за 15…20 мс) проникнення збурювання густини, яке спостерігається в експерименті, з периферії шнура в центр при газовому напуску. Отримані в результаті моделювання профілі густини задовільно погодяться з експериментальними, як в омічному режимі, так і при ЕЦР нагріванні й у процесі газового напуску, зокрема, описується винос часток з області ЕЦР нагрівання. Потік нейтралів на границі плазми зростає при включенні ЕЦР нагрівання, що погодиться з вимірами D_α. Ефективний коефіцієнт дифузії і швидкість пінчування трохи зменшуються з ростом густини плазми. Для порівняння розглянуті два імпульси в омічному режимі і три імпульси з додатковим нагріванням нейтральним пучком з установки MAST.