Modelling of shear effects on thermal and particle transport in advanced tokamak scenarios

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Abstract. Evolution of thermal and particle internal transport barriers (ITBs) is studied by modelling the time-dependent energy and particle balance in DIII-D plasmas with reversed magnetic shear configurations and in JET discharges with monotonic or slightly reversed q-profiles and large ExB rotation shear. Simulations are performed with semi-empirical models for anomalous diffusion and particle pinch. Stabilizing effects of magnetic and ExB rotation shears are included in anomalous particle and heat diffusivity. Shear effects on particle and thermal transport are compared.

Improved particle and energy confinement with the formation of an internal transport barrier (ITB) has been produced in DIII-D plasmas during current ramp-up accompanied with neutral beam injection (NBI) [1]. These plasmas are characterized by strong reversed magnetic shear and large ExB rotation shear which provide the reduction of anomalous fluxes. The formation of ITB's in the optimized shear (OS) JET scenario starts with strong NBI heating in a target plasma with a flat or slightly reversed q-profile pre-formed during current ramp-up with ion cyclotron resonance heating (ICRH) [2]. Our paper presents the modelling of particle and thermal transport for these scenarios.

1. Heat and particle transport coefficients

The evolution of the electron density, $n_e(t,r)$, ion temperature, $T_i(t,r)$, and electron temperature, $T_e(t,r)$, has been simulated using standard energy and particle balance equations. The particle source includes a core fueling due to NBI and wall source produced by the ionization of recycling wall neutrals. Additional and ohmic heating, energy exchange between electron and ion species and energy losses due to the ionization of wall neutrals are taken into account in the energy balance of the corresponding plasma species. The transport coefficients are based on the L-mode large-scale Bohm-like model [3] completed with magnetic and ExB rotation shear dependences which reduce the anomalous transport to neoclassical values for electron density and ion energy and to a combination of gyroBohm-like and neoclassical transport for the electron energy:

$$\chi_i = \chi_{Bohm,i} F_{shear,Ti} + \chi_{neo,i} \qquad (1)$$

$$\chi_e = \chi_{Bohm,e}F_{shear,Te} + \chi_{gyroBohm} + \chi_{neo,e} \qquad (2)$$

$$D = D_{Bohm}F_{shear,n} + \chi_{neo,i}*\chi_{neo,e}/(\chi_{neo,i} + \chi_{neo,e}) \qquad (3)$$

Here χ_j is the thermal diffusivity of corresponding species (j=e,i), $\chi_{Bohm,j}$ is the Bohm-like thermal diffusivity ($\chi_{Bohm,e}=3.3\times10^{-4}(cT_e/eB_t)(a\nabla p/p)q^2$, $\chi_{Bohm,i}=2\chi_{Bohm,e}$, all notations from [3]), $\chi_{gyroBohm}$ is the gyroBohm-like transport coefficient, $\chi_{gyroBohm}=0.035(cT_e/eB_t)(\rho_*/a)(a\nabla p/p)$, $\chi_{neo,j}$ is the neoclassical thermal diffusivity and D is the L-mode particle diffusion coefficient, $D=0.15\chi_e$. The function $F_{shear,j}$ describes the shear stabilization of large-scale Bohm-like transport due to low/negative magnetic shear, s_m, and/or large ExB rotation shear that is roughly estimated with the measured toroidal rotation velocity of the carbon impurity, V_{tor}:

$$F_{shear,n} = 1/(1 + \exp\{[0.05|1 - |\nabla V_{tor}|/\gamma_n| - s_mq]/0.1q\}) \qquad (4)$$

$$F_{shear,Te} = 1/(1 + \exp\{[0.05|1 - |\nabla V_{tor}|/\gamma_{Te}| - s_m]/0.05\}) \qquad (5)$$

The shear correction for the thermal ion flux is given in Ref. 4. Two functions, γ_{Te} and γ_n, characterize thresholds for an ITB formation on the electron temperature and density profiles:

$$\gamma_{Te}=10^{24}(T_e/T_i)^{3/2}V_{Ti}^3/(c^2n_ia^3kR); \quad \gamma_n=0.14k^{-6}(c/a)(\omega_{pe}/\omega_{ce})^4 \qquad (6)$$

Here V_{Ti} is the thermal ion velocity, n_i is the ion density, k is the elongation, R is the major radius, ω_{ce} is the electron gyrofrequency and ω_{pe} is the electron plasma frequency. These threshold functions have been adjusted to describe the experimental evolution of the density and temperature in DIII-D and JET.

A particle pinch term includes the anomalous pinch velocity as proposed in Ref. 5 and the neoclassical (Ware) pinch:

$$V = 0.015(\omega_{ce}/\omega_{pe})^2D_{Bohm,n}F_{shear,n}\nabla q + c\varepsilon^{1/2}E_{pl}/B_{pol} \qquad (7)$$

Here ε is the inverse aspect ratio, E_{pl} is the plasma toroidal electric field, B_{pol} is the poloidal magnetic field. The transport coefficients given in Eqs. (1)-(7) are used to model the temperature and density evolution in the DIII-D and JET scenarios. The shear stabilization effects on thermal ion transport have been analyzed in Ref. 4. Here we complete our previous study with the simulations of particle and thermal electron transport. The simulations discussed below have been performed using the 1.5D transport code ASTRA [6].

2. Electron particle transport

Modelling of the density evolution in JET OS scenarios has been performed using experimental temperature and current density profile (Figs. 1, 2). The Bohm-like model for the diffusion coefficient ($F_{shear,n}=1$) provides a good agreement with the experimental density profile in L-mode target JET plasma, but it underestimates the density when strong central NBI fueling is applied. The ExB shear-dependent model allows to reproduce the formation and extension of particle ITB's (Figs. 1, 2). Our results are weakly sensitive to a possible underestimation of the wall source (Fig. 3). In these simulations the prescribed wall source distribution has been multiplied by a constant coefficient and the values of the density in the center and at mid-radius obtained with an increased particle source are shown. The weak sensitivity of density profiles to the value of the wall source can be explained by a strong non-

linear density-dependent diffusion and pinch. The modelling of a DIII-D discharge is shown in Fig. 4.
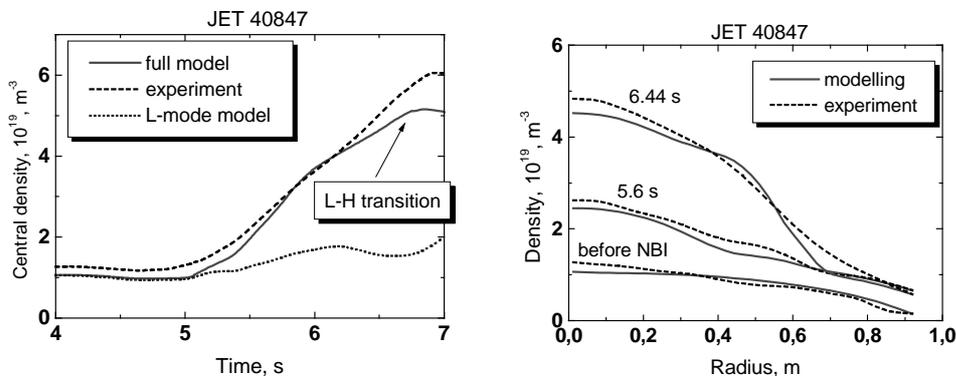

Fig. 1. Modelling of the density evolution in a JET OS discharge with an L-mode edge terminated with an ELM-free H-mode (shot 40847) : central density (left) and density profiles (right).
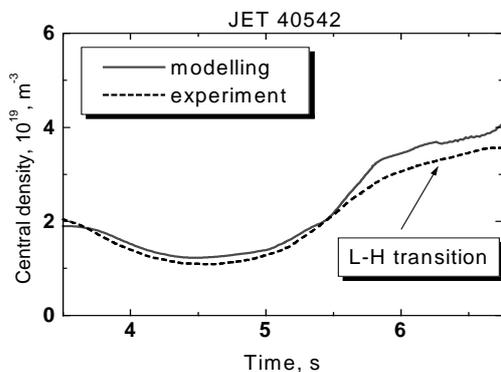

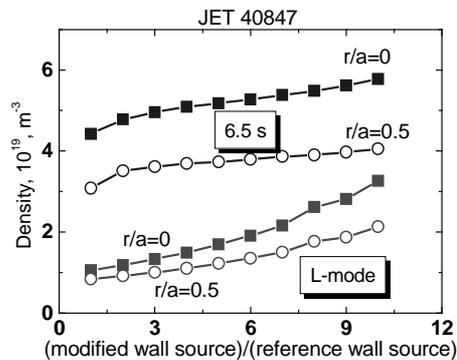*Fig. 2. Central density evolution in a JET OS discharge (shot 40542).*

Fig. 3. Sensitivity of the density modelling to a variation of the wall particle source (shot 40847).
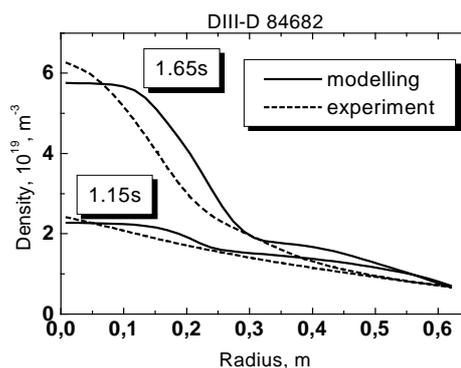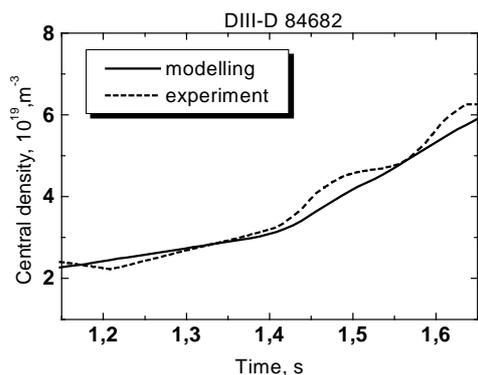

Fig. 4. Modelling of the density evolution in a reversed shear plasma in DIII-D (shot 84682).

3. Thermal electron transport

Thermal electron transport has been simulated using the experimental values of $n_e(t,r)$, $T_i(t,r)$ and current density profiles (Fig. 5). The electron temperature in plasma core has

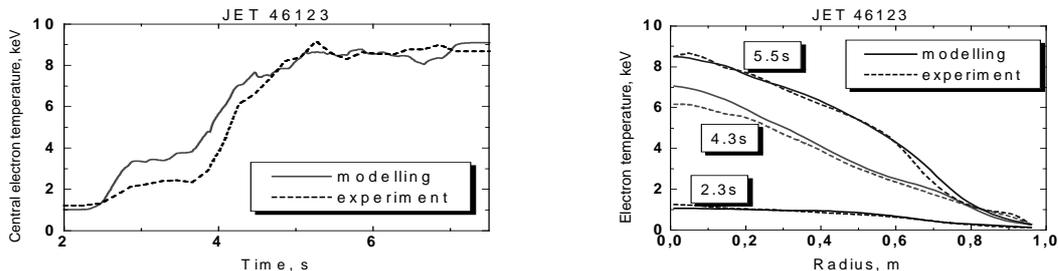been reproduced assuming full stabilization of large-scale Bohm-like transport.

Fig. 5. Electron temperature evolution in a JET OS plasma (shot 46123).
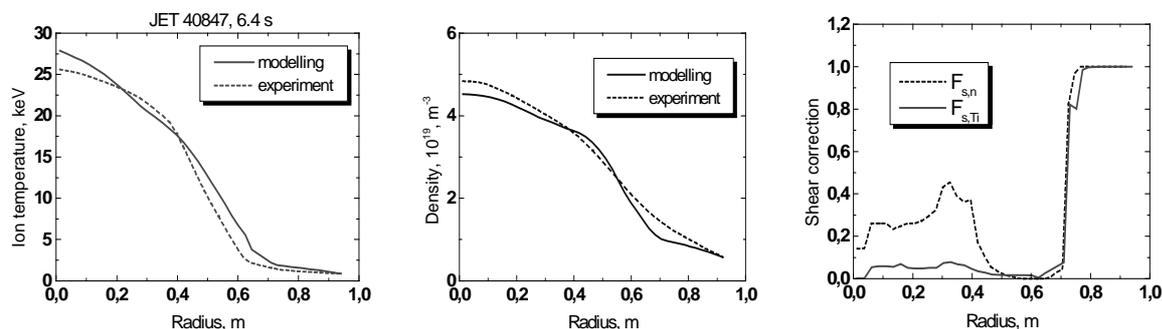Experimental Te-profiles are taken from ECE measurements.

Fig. 6. Comparison of thermal ion and particle transport in a JET OS plasma (shot 40847): particle and thermal ion shear corrections (right) providing the fit of temperature (left) and density (central) profiles.

4. Summary

Empirical shear-dependent transport coefficients for the anomalous particle and energy fluxes are presented and applied to advanced scenarios in DIII-D and JET to describe the ITB formation and evolution. Combined stabilizing effects of magnetic and ExB rotation shear suppress the anomalous large-scale particle and ion energy transport in the RS region in DIII-D discharges reducing particle and thermal ion diffusion to neoclassical levels. Both anomalous particle and thermal ion fluxes reduce strongly at the ITB location in JET OS plasmas whereas they are affected differently by the ExB rotation shear inside an ITB (Fig. 6). Stabilization of thermal transport is stronger than stabilization of particle transport in plasma region inside the ITB location in JET OS scenarios. We presented preliminary results on the modelling of thermal electron transport in JET discharges based on the full suppression of the Bohm-like transport. The χ_e-value inside an ITB is described with the remaining gyroBohm and neoclassical terms. However, further development of the gyroBohm term is required for understanding the thermal electron transport inside an ITB in other tokamaks as well as possible shear stabilisation of the gyroBohm-like term with a large Te-gradients [7].

References: [1] Rice B.W., et al., Nucl. Fus., **36** (1996), 1271; [2] Sips A.C.C., et al., Pl. Phys. Contr. Fus., **40** (1998), 647; [3] Erba M., et al., Pl. Phys. Contr. Fus., **39** (1997), 261; [4] Voitsekhovitch I., et al., 17th IAEA Conf., 1998, Yokohama; [5] Voitsekhovitch I., et al., 2nd Eur. Workshop "Role of Electric Field in Plasma Confinement and Exhaust", June 19-20, 1999, Maastricht; [6] Pereverzev G. V., et al., Nucl. Fus., **32** (1992), 1023; [7] Litaudon X., et al., this proceedings