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Neoclassical Transport Studies in Stellarators Using PRETOR Code

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Abstract

Using PRETOR-Ste code a neoclassical transport study has been done for TJ-II, as well as for LHD device. In the first case, previous results that were obtained using Monte Carlo techniques are reproduced and some of the results obtained with PRETOR-Ste are closer to experimental data. The low collisionality regime is also studied in TJ-II showing the possibility of having the electron root for the electric field in the plasma center. In the case of LHD, results are in concordance with experimental data and with previous studies.

Keywords:

neoclassical transport, TJ-II, LHD, radial electric field, helical system, Monte Carlo technique

1. Introduction

The "Departament de Física i Enginyeria Nuclear" (DFEN) of "Universitat Politècnica de Catalunya" (UPC) collaborates with the "Laboratorio Nacional de Fusión" of Ciemat using remote participation tools. This collaboration includes the development of a new version of PRETOR code, called PRETOR-Ste code, with the aim of performing transport analysis in stellarators [1].

TJ-II is a four period stellarator (heliac type, $B(0) \leq$ 1.2T, R = 1.5m, $a \leq$ 0.23m). The plasmas are produced and heated with Electron Cyclotron Resonance Heating (ECRH) (2 gyrotrons, 300kW each, 53.2 GHz, 2nd harmonic, X-mode polarization) [2] and nowadays Neutral Beam Injection (NBI) heated plasmas are available. TJ-II plasmas heated by Electron Cyclotron (EC) waves are in the long mean free path regime, since the collisionality is extremely low. In this regime, the magnetic topology of the configuration is a key ingredient to explain the transport and it happens to be very complicated in TJ-II, being necessary to take into account about 150 terms in the Fourier description of magnetic field and magnetic surfaces. In this situation, previous studies done with DKES code, present a poor convergence, and the error bars obtained from the calculation are pretty wide, making doubtful any result. Monte Carlo code MOCA is able to overcome this difficulty and to estimate neoclassical transport in the plasma core, giving again doubtful results outside this area. [3]

The Large Helical Device (LHD) is a heliotron with ten periods and major radius R = 3.9m, magnetic field B = 3T and minor radius a = 0.6m. Previous studies were made with TOTAL[4] and PROCTR [5] code. Electric field calculated with PROCTR is larger than the experimental one in the plasma center [6] but it has a similar profile.

2. Neoclassical model of transport coefficients

The neoclassical transport losses in helical plasma configurations are divided into axisymmetric tokamak like part [7,8] and an asymmetric helical ripple part [9,10]. The effects of the electric field E_r^{neo} are included in the ripple transport simulation. This electric field is calculated using the ambipolar condition $\Gamma_e^{asym} = \sum_k Z_k \Gamma_k^{asym}$, where Γ_e^{asym} is the asymmetric part of the neoclassical electron flux, Γ_k^{asym} and Z_k are the asymmetric neoclassical ion flux and the ion charge for each species k respectively. The composition of the TJ-II plasmas in these shots is hydrogen and we have included 1% of carbon concentration as an impurity.

The expression for the radial asymmetric neoclassical flux associated with helical-ripple trapped particles Γ_j^{na} and heat flux Q_j^{na} of electrons ($j = e$) and ions ($j = i$) are given by [11]:

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$$\Gamma_j^{na} = -\varepsilon_t^2 \varepsilon_h^{1/2} v_{dj}^2 n_j \int_0^\infty x^{5/2} e^{-x}\, \tilde{v}_j \frac{A_j(x,E_r)}{\omega_j^2(x,E_r)} \mathrm{d}x$$

$$Q_j^{na} + \frac{5}{2}\Gamma_j^{na} T_j = -\varepsilon_t^2 \varepsilon_h^{1/2} v_{dj}^2 n_j T_j^2 \int_0^\infty x^{7/2} e^{-x}\, \tilde{v}_j \frac{A_j(x,E_r)}{\omega_j^2(x,E_r)} \mathrm{d}x$$

where $x = m_j v^2 / 2T_j$

$$A_j(x,E_r) = n_j'/n_j - Z_j e E_r / T_j + (x - 3/2)T_j'/T_j$$

$$\tilde{v}_j(x) = v_j^0 x^{-1.5} \varepsilon_h^{-1} \left\{ \left[(1 - 1/2x) erf(x^{1/2}) + \frac{e^{-x}}{(\pi x)^{1/2}} \right] + \overline{Z}_j \right\}$$

$$\omega_j^2(x,E_r) = 4.21\tilde{v}_j^2 + 1.5(\varepsilon_t/\varepsilon_h)^{1/2}(\omega_E + \omega_{Bj})^2 + (\varepsilon_t/\varepsilon_h)^{3/2} \left[\frac{\omega_{Bj}}{4} + 0.6\,|\omega_{Bj}|\, \tilde{v}_j (\varepsilon_t/\varepsilon_h)^{3/2} \right]$$

Here ε_t is the toroidal inverse aspect ratio, ε_h is the helical ripple modulation, n_j is the plasma density, T_j is the plasma temperature, v_{dj} is the thermal velocity, ω_E is the $\boldsymbol{E} \times \boldsymbol{B}$ drift, ω_B is the ∇B drift frequency. The prime denotes the derivative with respect the radial coordinate.

Since the estimation of TJ-II neoclassical transport is difficult and expensive in terms of computational time with Monte Carlo techniques, we take the previous models to perform the calculations along the present work.

3. TJ-II density and temperatures profiles and neoclassical calculations

In order to compare the model previously described with Monte Carlo results [3], PRETOR-Ste is used with experimental fixed density profiles [12], and temperature profiles are calculated to fit a standard parabolic shot. Two different cases will be used for the neoclassical estimations, corresponding to high and low densities, both with the same heating power (P_{ECRH} = 300 kW). In both cases an almost flat ion temperature profile is taken, which is similar to the obtained experimentally.

Two simulations are performed for low and higher density regimes. The density and temperature profiles used in both simulations are plotted in Fig. 1. In both cases there is only one root of the ambipolar equation, giving a high electric field at minor radius $r = a/4$ and a small one at $r = a/2$. The high electron fluxes are mainly due to high electron temperature gradients and in the case of ions, fluxes are due to electric field, because ion density and temperature are almost flat.

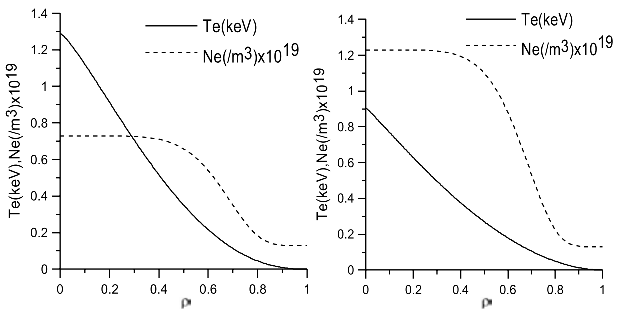

Fig. 1 Density and temperature profiles in the case of low density scenario (left) and high density scenario (right)

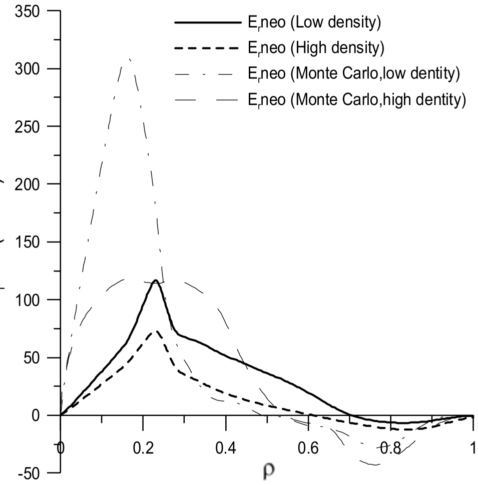

Fig. 2 Comparison of neoclassical electric field (E_r^{neo}) obtained in this paper with previous results using Monte Carlo techniques [3] in the case of low density and high density scenarios.

The ambipolar equation is solved for every point in the plasma and it is plotted in Fig. 2. There is a strong positive electric field at the center and a small negative one at the edge. This is a typical feature in stellarators with the same size as TJ-II and heated with ERCH [13,14], although in the TJ-II there is only one solution of the ambipolar equation, so the transition between positive and negative electric field should be soft according to this model.

Perpendicular electron and ion thermal diffusivities (corresponding to diagonal terms of the transport matrix) for low density case are shown in Fig. 3. Maximum values for electron conductivities are 2.0 m^2/s and 5.5 m^2/s, in the high and the low density cases respectively. Comparing these results with previous studies made with Monte Carlo techniques, smaller electric field and higher thermal diffusivities are obtained when the model described in this paper is applied, although in both cases there is only one solution of the ambipolar equation. The reason for this phenomenon is that in general, the TJ-II works in the low collisionality regime in the center, because of the typical low ion temperatures and densities. Nowadays NBI injector has been installed and will be operative soon, in this case a higher ion temperature is expected. In this scenario, a higher ion collisionality regime can be obtained by increasing ion temperature. Running this case with PRETOR-Ste, the electron and ion fluxes at $r = a/4$ are shown in Fig. 4, and at this point there are three roots of the ambipolar equation. The electric field suffers a sudden transition between positive to negative values at a point close to $r = a/2$, and TJ-II will have the same behavior as others stellarator devices.

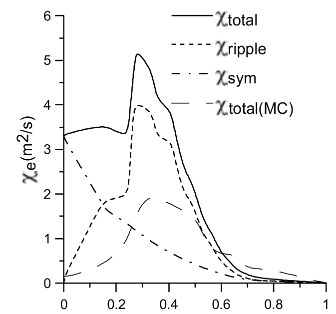

Fig. 3 Comparison of neoclassical thermal diffusivities obtained in this paper with previous results using Monte Carlo (MC) techniques [3] in the low density case for TJ-II.

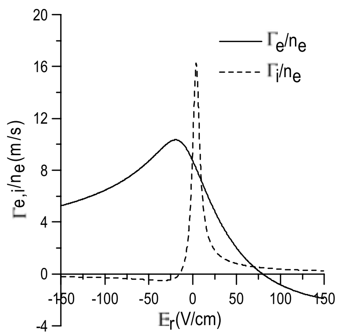

Fig. 4 Normalized electron and ion neoclassical fluxes in the low ion collisionality regime for $r = a/4$.

4. LHD density and temperatures profiles, neoclassical calculations and comparison with experimental data

The neoclassical diffusivities and electric field of the LHD shot #32940 [15] are analyzed and compared with experimental data obtained by the charge exchange spectroscopy (CXS). This shot is produced under the condition of major radius R_{ax} = 3.75m (the standard configuration), magnetic field strength of B ≈ 1.52 T, average minor radius of a = 0.51m and the species are Hydrogen and Helium.

The experimental electron density and temperatures profiles used are shown in Fig. 5, electric field in Fig. 6 and thermal electron diffusivities are plotted in Fig. 7.Neoclassical electric field (E_r^{neo}) has high positive values in the central region (${E_r^{neo}}_{max}$ ≈ 200 V/cm) and small positive values as far as normalized minor radius $\rho = 0.7$. From this point to $\rho = 1$ negative values are obtained. Real Electric field (E_r) measured with the CXS has a similar profile, although central calculated value is 2 times higher than experimental one and E_r is always positive, even in the region $\rho > 0.7$. One possible reason for these discrepancies is the existence of anomalous transport that is not automatically ambipolar and, therefore, the electric field cannot be obtained only from imposing the ambipolar condition to neoclassical fluxes. Some other reasons are that ion temperature profile and ion and impurity density profiles are not completely determinate by experimental data. On the other hand, neoclassical thermal diffusivity (χ_e^{neo})is smaller than the experimental one ($\chi_e^{\exp}$) by a factor of 2 in the region $0.2 < \rho \leq 0.7$, and probably higher in central region.

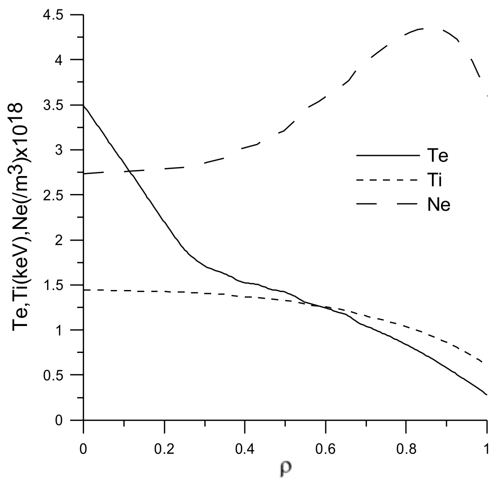

Fig. 5 #32940 shot density and temperature profiles used in LHD simulations

5. Conclusion

Neoclassical transport models for the radial electric field

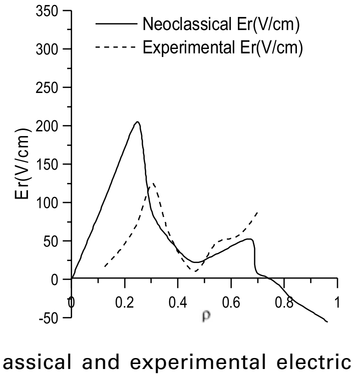

Fig. 6 Neoclassical and experimental electric field (E_r) for #32940 LHD shot

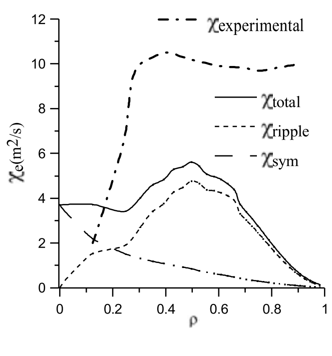

Fig. 7 Neoclassical and experimental electron thermal diffusivities for #32940 LHD shot

and diffusivites have been implemented in the PRETOR-Ste code which has been developed in the “Departament de Física i Enginyeria Nuclear”. The results for TJ-II standard shots show an electric field with a high positive value at the plasma center and a small negative value at the edge with only one solution of the ambipolar equation, but this situation may change in the future with NBI heating, because ion temperature will increase and three solutions will be possible. These results show that transport in the plasma center is probably neoclassical for ECRH heated plasmas, and outside, it is anomalous.

Previous studies of neoclassical transport for the same conditions were made with Monte Carlo techniques. Some of the conclusions of that paper were that probably the real electric field obtained was too large and thermal diffusivities were too low due to the approximations made for the calculations. Comparing the results of this paper with previous ones, smaller electric field and higher diffusivities are obtained in a wide region in the plasma core and according to that, the main conclusions of this paper seem to be correct, although in both cases, results close to the edge are doubtful due to low collisionality. In fact, the transport coefficient obtained from the analysis of experimental results rises strongly close to the edge [5], differently of what it is obtained in this work

A study of the LHD #32940 shot has been done with PRETOR-Ste. The E_r^{neo} obtained is larger than the experimentally measured in the plasma core but their profile are quite similar in the $0 < \rho \leq 0.7$ range. Calculated neoclassical diffusivity is smaller than the experimental one by a factor of 2 in the $0.2 < \rho \leq 0.7$ range. In the future, more LHD studies will be done in order to check the goodness of the code to simulate LHD shots.

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