

Adaptation of the PRETOR Code to Stellarator Simulations. Application to Shots of the Flexible Helic TJ-II

Joan Fontanet ¹, Javier Dies ¹, Francisco Castejón ², Carlos Alejandre ²

1. Departament de Física i Enginyeria Nuclear. Escola Tècnica Superior d'Enginyeria Industrial de Barcelona. Universitat Politècnica de Catalunya. Barcelona (Spain)

2. Asociación EURATOM-CIEMAT para la Fusión. Madrid (Spain)

INTRODUCTION

Stellarator plasmas have a very complex geometry and so do the vacuum chambers of these devices. Transport properties depend on the local characteristics of these devices, but transport codes usually make some approximations, as averaging magnitudes in each magnetic surface. Therefore it is good to validate the results of a simulation using several codes. Thus the PRETOR code [1] has been adapted to devices without axial symmetry, like stellarators, in order to compare its simulation results with those obtained with other stellarator transport codes.

The 'Departament de Física i Enginyeria Nuclear' of the 'Universitat Politècnica de Catalunya' (UPC) has some experience in the development of the transport code PRETOR. This code has been validated with shots of DIII-D, JET and TFTR [2], and it has also been used in the simulation of the fast burn termination of ITER [3].

The 1.5D transport code PRETOR was initially developed in JET to simulate shots in big tokamaks and it has been validated in a wide range of JET operational conditions. The version of the code PRETOR V 2.2 was taken as a starting point and a great work concerning issues such as programming, modelling and simulating has been developed in order to achieve the PRETOR-STELLARATOR version.

The EURATOM-CIEMAT association has recently started the operation of the flexible heliac TJ-II and first experimental results are now available [4]. In order to simulate shots of TJ-II its magnetic configuration is introduced into the new version of PRETOR and the transport results are compared with those obtained with the code PROCTR, which is commonly used to simulate stellarator transport [5,6]

MAGNETIC EQUILIBRIUM AND GEOMETRY

In a tokamak it is possible to solve in a relatively easy way the Grad-Shafranov equation to determine the plasma equilibrium configuration, but for stellarators, due to the complex geometry of their coils, the resolution of the equilibrium must be done by means of powerful numerical codes. Thus the VMEC (Variational Moments Equilibrium Code) code [7] is used.

VMEC solves the magnetic equilibrium equations from a given initial plasma pressure profile and gives as a result the flux surface geometry. The cylindrical coordinates (R, Z, ϕ) of a point in a magnetic surface are defined in terms of flux coordinates (ρ, θ, ξ) according to the following expressions:

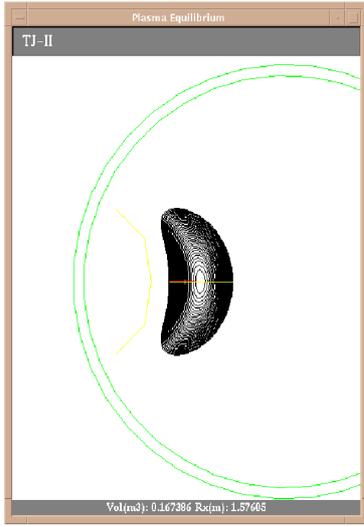


Figure 1. Representation of TJ-II magnetic surface in PRETOR

$$R(\rho, \theta, \xi) = \sum R_{m,n}(\rho) \cos(m\theta - n\xi)$$

$$Z(\rho, \theta, \xi) = \sum Z_{m,n}(\rho) \sin(m\theta - n\xi)$$

$$\phi(\rho, \theta, \xi) = \xi$$

For a stellarator as complex as the TJ-II and due to the distinctive shape of its magnetic surfaces, the number of Fourier nodes needed to describe the magnetic configuration are over one hundred.

The simulation code PRETOR works in only one spatial dimension, thus, in order to calculate the energy and particle flux the real 3D geometry of stellarators must be taken into account by the metric value averaged over the whole flux surface $\langle (\nabla\rho)^2 \rangle_\psi$

$$q_e = - \langle (\nabla\rho)^2 \rangle_\psi n_e \chi_e \frac{\partial T_e}{\partial \rho} + q_e^{na} + \frac{3}{2} T_e \Gamma_e$$

$$\Gamma_i = - \langle (\nabla\rho)^2 \rangle_\psi D_i \frac{\partial n_i}{\partial \rho} + \langle |\nabla\rho| \rangle n_i V_{p,i}$$

where q_e is the radial energy flux for electrons, n_e is the electron density, χ_e is the thermal conductivity, T_e is the electron temperature, q_e^{na} is the heat flux by helicoidal ripple and Γ_e is the radial electron flux. Γ_i is the ion flux, D_i is the diffusion coefficient, n_i is the ion density and $V_{p,i}$ is the pinch velocity of ions.

VMEC also gives the magnetic field of each surface according to the general expression

$$B(\rho, \theta, \phi) = B_0(\rho) [I + \sum b_{m,n} \cos(n\theta - m\phi)]$$

ENERGY AND PARTICLE TRANSPORT

In order to calculate the thermal conductivity, the particle diffusivity and the pinch velocity the Rebut-Lallia-Watkins model [1] was implemented in PRETOR. But this model has been obtained empirically in tokamaks. Thus the RLW model must be replaced by other phenomenological models such as the Alcator, Kaye-Goldston for the electron conductivity or the model of Hinton-Hazeltine for the ion conductivity. For the particle diffusivity the models of Alcator and pseudoclassical are proposed [5].

These proposed transport models depend on several free coefficients that can be chosen to reproduce the experimental data and to follow the real evolution of the shot. When no experimental data are available, the transport coefficients are chosen so that the obtained confinement time fit the value given by the different scaling laws as for instance LHD, Gyro-reduced Bohm, or Lackner-Gottardi.

LHD:	$\tau_E = 0.17 R^{0.75} a^2 B^{0.84} n_e^{0.69} P^{-0.58} A^{0.5}$
Gyro-reduced Bohm:	$\tau_E = 0.25 R^{0.6} a^{2.2} B^{0.8} n_e^{0.6} P^{-0.6} \kappa A^{0.5}$
Lackner-Gottardi:	$\tau_E = 0.172 R a^2 B^{0.8} n_e^{0.6} P^{-0.6} l^{0.4} A^{0.5}$

TJ-II SIMULATIONS

The flexible heliac TJ-II has recently started operation in the Asociación EURATOM-CIEMAT. Its first plasmas have been simulated using the PRETOR-STELLARATOR code to benchmark the results of the improvements that have been introduced in the code. A first simulation work has been based on the TJ-II shot #955, whose main parameters are showed in table 1.

<i>Parameter</i>	<i>Value</i>
ECRH heat power	250 kW
Central electron temperature	500 eV
Averaged small radius	12 cm
Averaged electron density	$0.5 \times 10^{19} \text{ m}^{-3}$
Radiated power	$\sim 200 \text{ kW}$

Table 1. Main parameters of TJ-II shot #955

The parameters needed to simulate this shot have been introduced in PRETOR together with the geometry of the configuration of this shot, previously determined by running the VMEC code. The experimental profile of temperature have been reproduced by choosing an empirical model with no density dependence with the density for the thermal conductivity

$$\chi_e = C_1 + C_2 e^{-(1-\rho)/0.05} \quad \text{with: } C_1 = 4.5 ; C_2 = 25$$

$$\chi_i = C_1 + C_2 e^{-(1-\rho)/0.05} \quad \text{with: } C_1 = 1.5 ; C_2 = 35$$

The same shot have been simulated with PROCTR code, a commonly used transport code in stellarators, and its results have been compared with those calculated with PRETOR. In figure 2 are plotted the simulated and experimental electron and ion temperature profiles as well as the conductivity profiles.

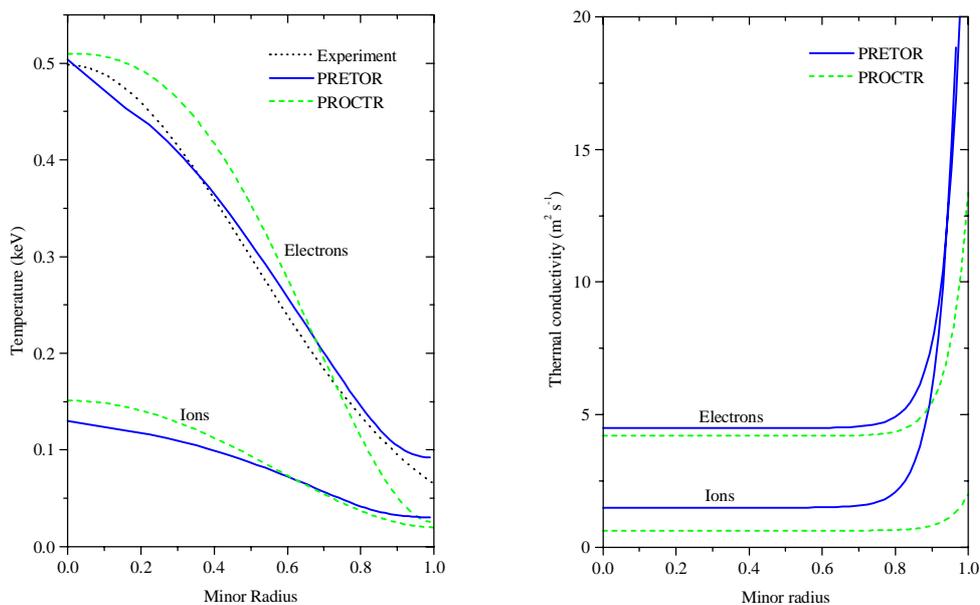


Figure 2. Temperature and conductivity profiles for TJ-II shot #955. Simulated results obtained using PRETOR and PROCTR and experimental data.

CONCLUSIONS

PRETOR code, which was initially developed for tokamak plasmas, has been adapted to stellarators ones and its results have been benchmarked with PROCTR stellarator code. The separation of the evaluation of any kind of physical magnitudes in several modules makes it possible to change some of these modules without changing the whole code.

As a result of this work it has been seen that in order to simulate stellarators, the magnetic equilibrium and geometry calculation, the transport models and the energy confinement time must be modified.

VMEC code has been used to evaluate the magnetic equilibrium and the geometry. VMEC gives the geometry of magnetic surface as a Fourier series that is easily adapted to PRETOR.

PRETOR solves the transport equations in one spatial dimension, thus, in the evaluation of heat and particle flux, the real 3D geometry of stellarators must be taken into account by the factor $\langle (\nabla\rho)^2 \rangle_\psi$

The temperature obtained with PRETOR reproduces the experimental profile when adequate parameters of transport models are chosen.

The same plasma conditions have been simulated with PROCTR, a commonly used transport code in stellarators. The results obtained are compatible with those calculated with PRETOR, taking into account the uncertainties that exist in experimental data, like radiation profiles, impurities densities, transport and effective Z.

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