Multiple domain scheme for heat transport analysis in plasmas with magnetic islands: a first study.

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1. Introduction

In magnetically confined plasma experiments aiming to nuclear fusion, the existence of rational surfaces leads to the formation of so-called magnetic islands observed in magnetic configurations like tokamak, stellarator and reversed field pinch (RFP). The formation of islands modifies magnetic topology by breaking the nested magnetic surfaces, forming their own, individual axis as well as a separatrix contained inside certain flux surfaces around which the stochastic layer develops [1,2]. As a consequence, the presence of magnetic islands strongly modifies particle and heat transport, which affect the plasma confinement. Therefore, the transport under magnetic configuration with multi-axes needs to be studied further.

Transport research benefits of the availability of several well-developed 1.5D transport codes, which have been widely used in single axis magnetic configuration for decades while it is beyond their capability to treat situations with the presence of magnetic islands. Indeed in plasma configurations with multi-axes a monotonic radial coordinate is undefinable in the whole plasma volume, which, together with the correct metrics (the spatial derivative of the volume and the first element of the metric tensor, denoted as V' and G_1 in this paper, respectively), are essential to solve the transport equations. Facing this issue, a new approach capable of studying transport under multi-axis configuration is presented.

In this paper we show a preliminary study of the energy transport in RFX-mod [3], solving the equation $\frac{3}{2}n_e\frac{\partial T_e}{\partial t}+\frac{1}{V'}\frac{\partial \Gamma_e}{\partial \rho}=S_e$ under both single and multiple magnetic axes configurations, where $\Gamma_e=-V'G_1 n_e \chi\frac{\partial T_e}{\partial \rho}$ is the energy flux, n_e, T_e are the local plasma density and temperature, S_e is the energy source and χ is the thermal diffusivity. To this end, a new scheme with multi-axes (dubbed Multi Domain Scheme - MDS), together with a new tool, named DAx_transp3, is presented. DAx_transp3 is a Fortran routine capable of studying transport in both single axis scheme and MDS. It works as a proxy for ASTRA [4], giving the opportunity of testing the feasibility of the multi-axes domain in a controlled environment. DAx_transp3 routine has been successfully benchmarked with ASTRA in single axis regime based on the experimental data obtained on RFX-mod, and the results are shown in Section 2. Detailed information of DAx_transp3 routine and its preliminary results on multi-axes regime are also presented in Section 3.

2. Single domain: benchmark with ASTRA

Two electron temperature profiles, measured by Thomson scattering (TS) in shot #30068 at t=0.09s and t=0.11s, are shown in Figure 1, as a function of the minor radius r. The hot region is shifted around 10cm far from the geometrical center. These thermal structures are small in

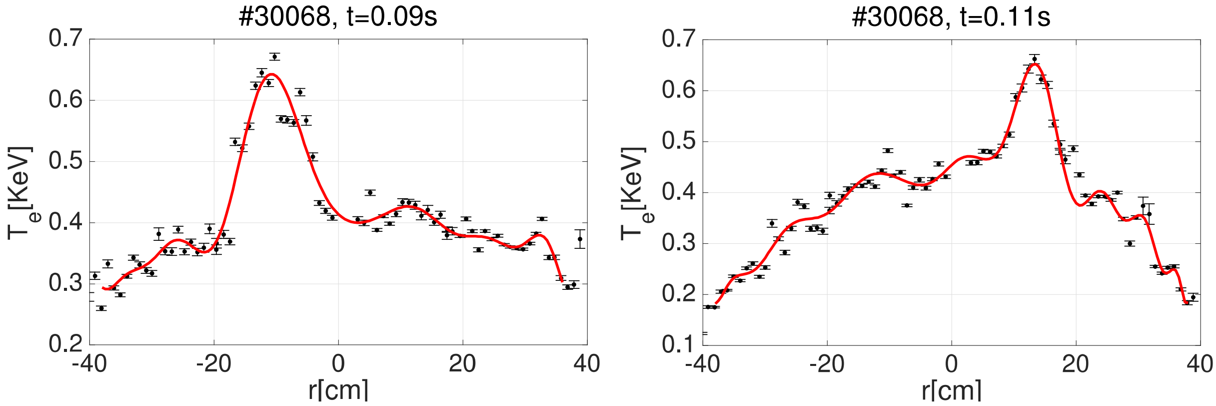

Figure 1. Two TS data from RFX experiment with shot number 30086 at different time. r is the minor radius.

the sense that they exist only on one side of the geometric center, and we dub these states as SHAx$_i$ state, in order to distinguish them from Single Helical Axis (SHAx) state [5,6], in which the dimension of the thermal structure is big enough to cross the geometric center of the vacuum chamber. It is important to notice that in both SHAx$_i$ and SHAx states only one magnetic helical axis is present, which means a global monotonic flux coordinate can be found. Figure 2 top shows the same T_e profiles, plotted as a function of the flux coordinate $\rho = \sqrt{V_\rho/(2\pi^2 R)}$, where V_ρ is the helical volume enclosed by each flux surface labeled by ρ and $R = 2m$ is the major radius of RFX. From the center towards the edge, a temperature gradient, which is related to electron internal transport barrier (eITB) [6], could be identified between the hot core and outer region, corresponding to the marked region in Figure 2.

The benchmark work was performed between DAx_transp3 routine and ASTRA, based on a database of about 20 shots with no separatrix. SHEq code [7] is capable of calculating the magnetic equilibrium as well as the flux surface average of the kinetic quantities. In particular, here it is used to provide ρ, $T_e(\rho), V'$ and G_1. Afterwards, these quantities, together with a selection of χ profiles, are provided as input information to both codes to find the best temperature profile matching between numerical results and experimental data. For DAx_transp3, the selection of best χ is done by hand while for ASTRA, it is done

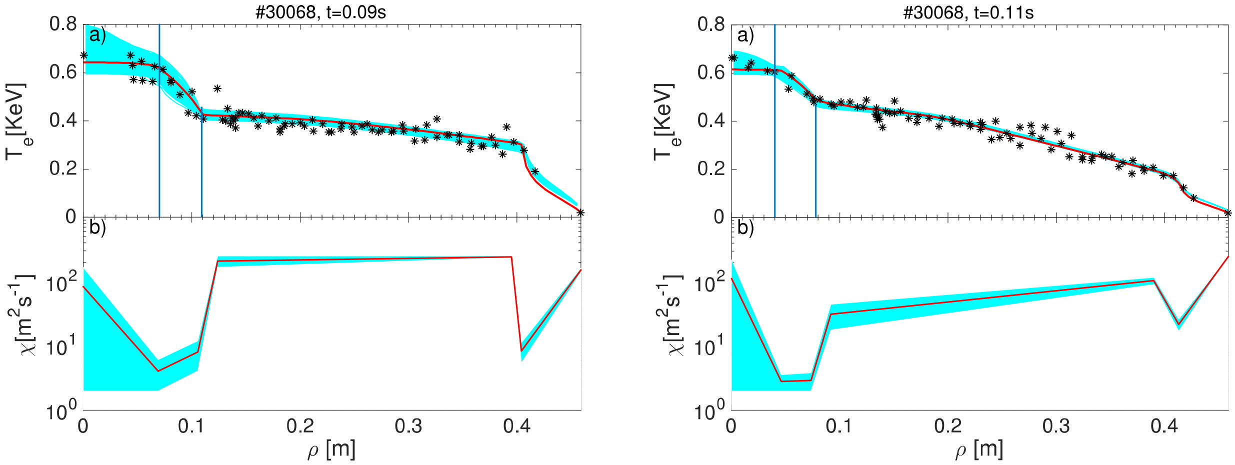

Figure 2. Benchmark result corresponding to the two cases shown in Figure 1. Upper panels (a) report the experimental T$_e$ (asterisks), the numerical profile computed with the DAx_transp3 routine (red line) and the CI's computed by ASTRA (blue shadow area). The lower panels (b) show the corresponding energy diffusivities (red line for the values used in the DAx_transp3 routine, blue area for ASTRA ones).

automatically using Genetic Algorithm [8], which generates a serials of "best choice", also named confidence interval (CI's). The benchmarking results are shown in Figure 2. In the upper two pictures, the black asterisks are the experimental electron temperature data while the red lines are the numerically computed T_e profile from DAx_transp3. The blue shadow area in Figure 2 shows the CI's of χ (bottom plots) and of the corresponding T_e profile computed by ASTRA. In these two cases, numerical results of both T_e and χ profiles from DAx_transp3 routine are in good agreement with ones from ASTRA, which indicates the benchmarking between DAx_transp3 routine and ASTRA is successful. Moreover the CI's of the resulting numerical $\mathrm{T_e}$ profiles are within the error of TS data, showing that the χ profiles correctly describes the energy transport level in the two cases.

3. Multiple Domain Scheme

Figure 3 shows a cross section of a so-called Double Axes (DAx)[7] magnetic configuration, in which there is a magnetic island with its own axis. The contour of the magnetic surfaces is plotted with the island separatrix represented by the red line. Region I is formed by nearly circular surfaces in the plasma core enclosed by the separatrix and nested around the main magnetic axis. The bean-shaped magnetic surfaces nested around the island O-point form region II. The surfaces outside the separatrix form region III. These regions are the three domains of MDS, in each of which a monotonic coordinate can be found and the kinetic quantities can be described as flux functions (i.e. they are constant over the flux surfaces).

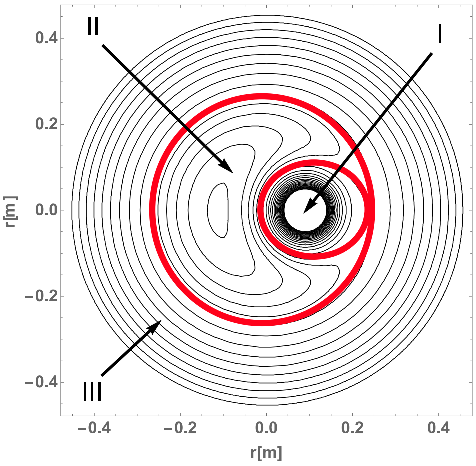

Figure 3. Poloidal cross-section of a DAx with the three domains of the MDS.

The three domains are coupled via common boundary conditions on fluxes and plasma quantities on the mutual interfaces. Under this regards a particular effort has been devoted to designing the coupling through the separatrix, which models the fluxes in the separatrix region located at the island boundary.

To this end, at each time-step, the DAx_transp3 routine solves the energy transport equation for a given diffusivity profile χ. The boundary conditions for zone I and II are: $\mathrm{dT_e/d\rho=0}$ at $\rho=0$ (i.e. on the core and island axes), $\mathrm{T_e}=T_{sep}$ at the edge (interface with the separatrix). The temperature profile in zone III is computed solving the same equation with different boundary condition: at the separatrix interface the temperature is fixed at T_{sep} whereas the edge temperature (interface with the plasma wall) is given by the experimental value T_a. After each time step the fluxes leaving (or entering, depending on the $\nabla\mathrm{T_e}$ sign) the three zones and entering the stochastic layer are computed, being respectively Γ_{I}, Γ_{II} and Γ_{III}. Then the evolution of the separatrix temperature is estimated with an explicit scheme: $\frac{\partial \mathrm{T_{sep}}}{\partial \mathrm{t}} = \frac{2}{3n_e}\frac{(\Gamma_{\mathrm{I}}+\Gamma_{\mathrm{II}}+\Gamma_{\mathrm{III}})}{\mathrm{V_{sep}}}$, being $\mathrm{V_{sep}}$ the volume of the stochastic layer surrounding the separatrix. $\mathrm{V_{sep}}$ has been chosen as the volume of the last cell of the island numerical grid (zone II). The simulation ends when convergence has been obtained in the three zones and the fluxes in the stochastic layer are mutually compensated, keeping constant the $\mathrm{T_{sep}}$.

Figure 4 reports an example of DAx case studied with the DAx_transp3 routine: the mapping of the experimental T_e in the three zones are reported with asterisks (upper panels) and with the continuous line for the numerical T_e profile. The lower ones show the corresponding diffusivity. The zone I and III have higher transport than the barrier region that exhibits a transport level comparable with the SHAx$_i$ eITB, in this example.

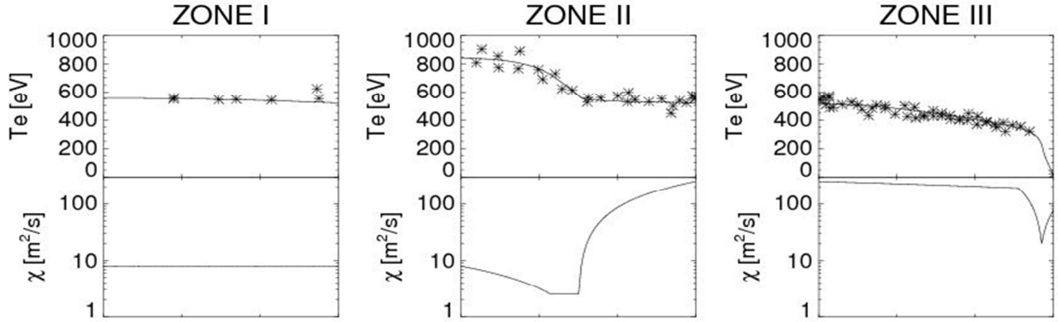

Figure 4. Experimental T_e in the three regions for shot 37386 at 60ms (asterisks) mapped over the local ρ. The continuous line represents the numerical temperature profile. The lower panels show the corresponding diffusivity profiles.

4. Conclusion and future work

The development of a new scheme to study transport in a magnetic configuration with islands is ongoing. A new tool, DAx_transp3 routine, has been developed and successfully benchmarked with ASTRA in QSH state without separatrix. The same tool has been tested on a DAx case, as shown. The next step is to build a larger database of QSH with separatrix, analyzing the influence of the presence of islands on plasma transport. Moreover, it is important to mention that besides the scheme presented in this paper, at least another scheme is under study: in the TJ-II stellarator [9] we are approaching the problem merging together zone I and III, finding a convenient flux coordinate and solving the transport equation by means of ASTRA. At the separatrix position an external routine has to be called in order to solve the transport in the zone II (island) and provide to the transport code the additional local energy source (or sink) to be included in the transport calculation.

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