

Numerical Study of Heat Transfer in Partially Destroyed Magnetic Configurations.

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1. Introduction. A 3-dimensional plasma fluid transport problem for fusion edge plasmas is considered. Conventional numerical methods of fluid or gas dynamics are not applicable, if the coordinate line along one of the main transport directions exhibits ergodic behavior at least in some regions of the computation domain. In stellarator plasma edges, or in Tokamaks with radial field perturbations as foreseen for TEXTOR under dynamic ergodic divertor (DED) operation [1], such complications can arise. We have proposed a novel "Multi Coordinate System Approach" (MCSA) [2] within a framework of a Monte Carlo procedure. A 3-dimensional plasma fluid code is developed and bench-marked against 2D B2-code results (checking the correct treatment of curvilinear coordinate systems). In 3D application discussed here we utilize the possibility of microscopic resolution inherent to our Monte Carlo treatment of a fluid problem. We separate fluxes in the radial direction caused by 1) (anomalous) cross-field diffusion and 2) the magnetic field perturbation. This allows to assess the validity of theoretical predictions for transport in perturbed magnetic fields without idealization, i.e. based upon the real perturbation field without the commonly employed parametrisation in terms of field line diffusion and Kolmogorov length.

2. 3D edge transport model We base our model on the Braginskii set of equations. The classical transport coefficients η_0 and $\chi_{||\alpha}$ are used for the coordinate aligned with the magnetic field, and the transport perpendicular to magnetic field line described by anomalous expressions $D_{\perp}, \chi_{\perp\alpha}, \eta_{\perp}$:

Continuity equation ($n_i = n_e \equiv n$, $\mathbf{h} \equiv \mathbf{B}/|B|$):

$$\frac{\partial n}{\partial t} + \nabla \cdot (\mathbf{h}V_{||}n - \mathbf{V}_{\perp}n) = -\nu_n n + Q_n, \quad \text{with} \quad \mathbf{V}_{\perp} \equiv \frac{D_{\perp}}{n} (\nabla n - \mathbf{h} \mathbf{h} \cdot \nabla n) \quad (1)$$

Parallel momentum equation ("e"+"i", $\mathbf{V}_i = \mathbf{V}_e \equiv \mathbf{V}$; $p_{||} \equiv mn\mathbf{h} \cdot \mathbf{V}$):

$$\frac{\partial p_{||}}{\partial t} + \nabla \cdot ((\mathbf{V}_{\perp V} + \mathbf{h}V_{||V}) p_{||} - D_{\perp V} \nabla p_{||} - (D_{||V} - D_{\perp V}) \mathbf{h} \mathbf{h} \cdot \nabla p_{||}) = -\nu_V p_{||} + Q_V \quad (2)$$

$$\mathbf{V}_{\perp V} \equiv \left(1 - \frac{\eta_{\perp}}{mnD_{\perp}}\right) \mathbf{V}_{\perp}, \quad V_{||V} \equiv V_{||} + \frac{4\eta_0}{3mn^2} \mathbf{h} \cdot \nabla n, \quad D_{\perp V} \equiv \frac{\eta_{\perp}}{mn}, \quad D_{||V} \equiv \frac{4\eta_0}{3mn},$$

$$\begin{aligned}
 \nu_V &\equiv -\mathbf{V}_\perp \cdot \mathbf{N} + (\eta_0/mn) (\operatorname{div} \mathbf{h})^2 + (2/3mn) \mathbf{h} \cdot \nabla \eta_0 \operatorname{div} \mathbf{h}, \quad \mathbf{N} \equiv \mathbf{h} \cdot \nabla \mathbf{h}, \\
 Q_V &\equiv -\mathbf{h} \cdot \nabla p + \mathbf{h} \cdot \mathbf{F}_S + mn \mathbf{V}_\perp \cdot [\mathbf{V}_\perp \cdot \nabla] \mathbf{h} - \left(\frac{2}{3} \mathbf{h} \cdot \nabla + \operatorname{div} \mathbf{h} \right) \eta_0 \\
 &\quad \cdot (3\mathbf{V}_\perp \cdot \mathbf{N} + \operatorname{div} \mathbf{V}_\perp)
 \end{aligned}$$

\mathbf{F}_S is the momentum source density due to interaction with the neutral gas (friction). Energy equation for species $\alpha = e, i$:

$$\frac{\partial u_\alpha}{\partial t} + \nabla \cdot \left((\mathbf{V}_{\perp\alpha} + \mathbf{h}V_{\parallel\alpha}) u_\alpha - \kappa_{\perp\alpha} \nabla u_\alpha - (\kappa_{\parallel\alpha} - \kappa_{\perp\alpha}) \mathbf{h} \mathbf{h} \cdot \nabla u_\alpha \right) = -\nu_\alpha u_\alpha + Q_\alpha \quad (3)$$

$$\begin{aligned}
 \text{where } u_\alpha &\equiv \frac{3}{2} n T_\alpha, \quad \mathbf{V}_{\perp\alpha} \equiv \left(1 - \frac{\kappa_{\perp\alpha}}{D_\perp} \right) \mathbf{V}_\perp, \quad V_{\parallel\alpha} \equiv V_\parallel + \frac{1}{n} \kappa_{\parallel\alpha} \mathbf{h} \cdot \nabla n, \\
 \kappa_{\perp\alpha} &\equiv \frac{2\chi_{\perp\alpha}}{3n}, \quad \kappa_{\parallel\alpha} \equiv \frac{2\chi_{\parallel\alpha}}{3n}.
 \end{aligned}$$

We use our MCSA [2] with a set of (typically 20-40) local coordinate systems related with each other by the mapping procedure (loc.cit) derived from field line tracing. The source terms (all contributions, which have not been casted into the form of the divergence of a flux) in all equations are split into a positive part Q (treated explicitly as contribution to the initial distribution in our Monte Carlo procedure) and a negative part written as a product of a loss frequency ν and the transported quantity n, p and u , respectively, which is simulated in an implicit way during random walk generation.

3. Model validation We demonstrate the validity of this procedure by applying the code to strongly simplified plasma flow problems, without ergodicity, Shafranov shift and limiters, but with, most importantly, all effects included which result from the curvilinearity of the configuration. We have simplified the metrics of our test problem such that conventional 2D edge plasma fluid codes (B2 in our case) can provide solutions. Even without the assumption of the existence of flux surfaces explicitly used in the 3D code we are able, indeed, to fully recover the 2D temperature fields obtained with B2 (see Fig.1), for identical sets of input parameters (transport model and boundary conditions).

4.Radial fluxes in perturbed edge plasma regions. We have considered the problem of "fine resolution" of the structure of the heat transfer in partially destroyed magnetic configurations to separate the contributions from parallel and anomalous perpendicular diffusion in the radial transport. Model parameters have been chosen relevant for the edge plasma of TEXTOR during DED operation. One of the unique advantages of our approach is the possibility to distinguish (microscopically) the part resulting from the parallel transport from the true cross field transport. Configurations with different degree of magnetic field ergodization have been compared in terms of these contributions to radial energy fluxes. For simplicity we discuss here only the electron energy equation in cylindrical geometry, because the effects of "partial ergodicity" in the edge can expected

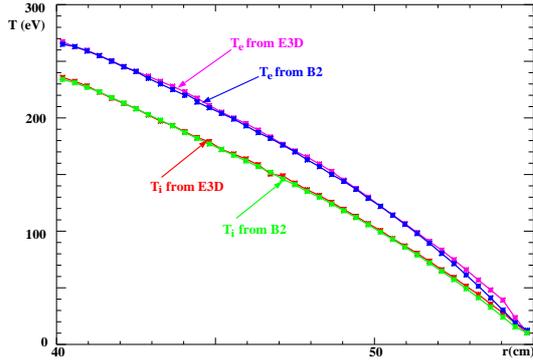


Fig.1 Temperature profiles from B2 and E3D

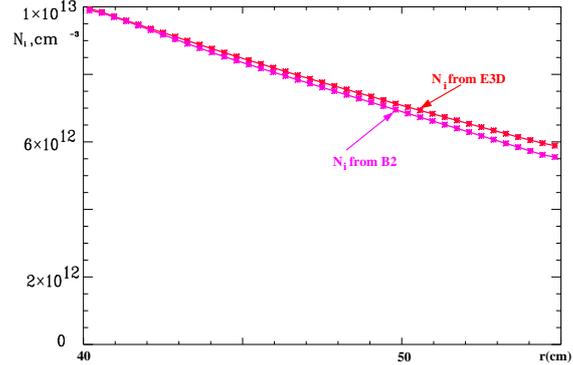


Fig.2 Density profiles from B2 and E3D

to be most important here. We consider the outer radial zone (SOL) between $r=40$ cm (interface to core) and $r=49$ cm (wall, $T_e = 0$ there), and impose a non-radiative heat flow of 250kW into the electron channel. Furthermore we keep the density fixed at the constant level of $1.10^{13} \text{ cm}^{-3}$ in order not to mix effects from particle and energy transport. We use an analytical model for the perturbation magnetic field [3], given in terms of the Fourier spectrum $b_{m,n}(r)$ of the perturbation, and corresponding to an intermediate size of the current in the DED perturbation coils. Distinct from conventional theoretical approaches, however, we then do not need to invoke the quasi-linear theory to find statistical magnetic field parameters: field diffusion, Kolmogorov length etc. (see, e.g., [4]) and to derive semi-phenomenological expression for the associated heat fluxes then [5]. Instead we solve the heat transport from on the perturbation field as it is, and as it competes with the assumed anomalous transport normal to the field lines (set to $\chi_{\perp e} = 3 \text{ m}^2/\text{s}$ here) in the self consistently derived temperature field. In that sense we are able to check, even quantitatively, the quasi-linear theory and the transport models derived from it, for each specific application. The typical Poincaré map on the section $\vartheta = \text{const}$ (note: not on $\phi = \text{const}$) for the field is presented on the Fig.3. It is easy to see that we are dealing here with an only partly ergodized case with still large remaining islands and relatively broad "laminar zone" (the region where the radially inclined field lines intersect the wall after only a small number of toroidal turns). Such magnetic configurations will be typical for TEXTOR under DED operation. The results for one such case are summarized in fig.4. One might expect that in the case when the effects of ergodicity of the magnetic field play a dominant role the parallel diffusion should give a main contribution to the radial transport. We consider here the intermediate range of perturbation amplitudes. Larger amplitudes would enhance the laminar zone, for which our Monte Carlo approach works, but certainly is over-sophisticated. Both radial fluxes are found to be of the same order of magnitude in the ergodic field region, between $r=43$ and $r=46$ cm. The radial flux due to the parallel diffusion strongly exceeds the perpendicular diffusion in the laminar zone, around $r=46$ to 50 cm. A reversal of the perpendicular anomalous flux can even be

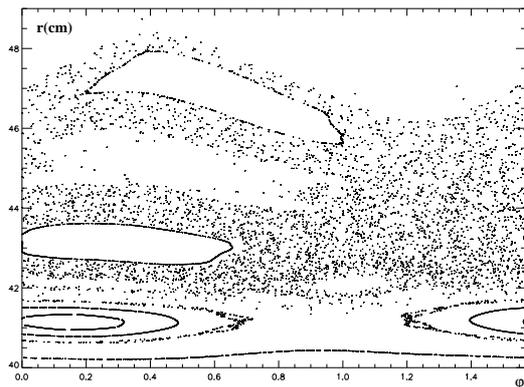
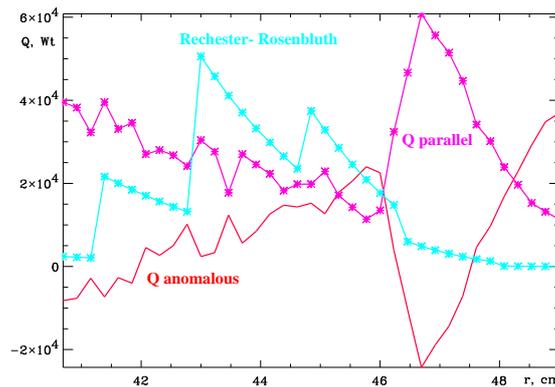
Fig.3 Poincaré map for $\theta = \text{const.}$ 

Fig.4 Structure of the radial heat flux

observed at the transition region between the laminar and ergodic zone. Such a behavior can be attributed to the complicated interlacing of the field lines in the region where the heat exchange between the field lines coming from the ergodic and laminar zone takes place. Such effects certainly would be missed out in any simpler (physically and/or geometrically reduced) model than the one described here. Still further out in the laminar zone the parallel contribution to radial transport starts to diminish again, because the self-consistently derived electron temperature has dropped (and hence χ_{\parallel}) to a few eV here (from the starting value of 150 eV at the inner boundary of our computational domain for this case).

Conclusions.

Our MCSA Monte Carlo method has proved its capability to solve 3 dimensional plasma edge flow problems even in the presence of ergodized field regions, in which no globally adequate mesh discretisation can be formulated. It furthermore provides a direct and quantitative check (on a case to case basis) of the validity of the various analytical and semi-analytical theories for plasma transport in ergodized magnetic fields. It has been shown that complicated cross field flow patterns (including reversal, locally, of the anomalous flow direction) can arise in particular due to the presence of connected domains (ergodic and laminar) with very different transport properties.

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