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# Role of stochasticity in the W7-X edge transport

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**Abstract**

The energy transport in the edge of W7-X for topologies with coexisting regular flux surfaces, closed islands and stochastic regions is simulated with the 3D Monte Carlo plasma edge transport code EMC3-EIRENE using realistic geometries for wall, divertor targets and baffles. The radial plasma temperature profiles are obtained for a large range of anomalous cross-field heat diffusion coefficient. It is observed that the widths of both the radial temperature profiles and the deposition patterns on the divertor target elements shrink steadily with reducing the cross-field conductivity and no residual diffusion from field-line stochasticity appears in the limit of small diffusion coefficient. The energy transport seems to behave in a manner that the stochastic zone close to the main separatrix would consist of regular magnetic surfaces. The analysis clearly indicates that the stochastic energy transport to the targets in typical W7-X configurations remains marginal compared to the dominant collisional processes.

## Introduction

In the past few years, the stochasticity of edge magnetic configurations has found various new applications ranging from the concept of ergodic divertor to the control of transient edge phenomena like ELMs [1, 2]. Resonant radial magnetic edge perturbations cause a destruction of smooth magnetic surfaces leading to a “braided” magnetic field structure. This structure diffuses radially showing a characteristic exponential streching of its flux-tube elements. Although the magnetic field mapping is flux preserving and strictly reversible, the stochastic effects resulting in a continuous radial diffusive process are expected to be finite, resulting in a diffusion, from one magnetically connected region to the other, of the physical quantities (energy or particle densities). In the edge region of the stellarator W7-X, the plasma transport to the targets is expected to be due to a combined effect of an intrinsic transport process across the magnetic field and a transport along the stochastic magnetic field lines that diffuses radially. Previous transport studies, based purely on the magnetic properties of the W7-X configurations, provide an estimate about the degree of stochasticity of the edge region and predict a significant effect of stochasticity on the radial heat transport. In the present work the energy transport in W7-X is studied using a simple 3D fluid model implemented in stochastic edge configurations for a range of cross-field heat diffusivity $\chi_\perp$. The results are analyzed with respect to the effects of stochasticity associated with three major magnetic configurations.

**Topology of the boundary layer in W7-X and stochastic transport**

In Poincaré plot projections, the W7-X edge region exhibits typical patterns following roughly the basic structure of the main edge resonance (islands remnants) (Fig. 1). The three W7-X magnetic configurations analyzed here are: (I) the standard configuration, $\iota$ = 5/5, with finite plasma $\beta$ = 4%, (II) the standard configuration with finite control coil current (largest island size) and (III) a configuration with higher rotational transform. The stochasticity is strongest close to the separatrix (X-points) and drops towards the island centers (O-points). If the stochasticity is not too strong, closed magnetic surfaces are found even radially outside of the main island chain (case I). In the standard configuration with enlarged islands, case II, and in the “high iota” configuration, case III, the radial magnetic perturbations responsible for the stochasticity are stronger than in case I and the stochastic region fills the whole boundary volume around the closed island regions. For the high-iota configuration, case III, the Kolmogorov lengths were estimated in Ref. [3] for various plasma $\beta$ values by tracing the initial circumference $d_0$ of a small flux tube along the field lines up to a toroidal extension $l$ and characterizing its exponential growth by $d(l) = d_0 \exp(l/L_\mathrm{K})$. The value of $L_\mathrm{K}$ was found to decrease from $L_\mathrm{K} > 100$ m close to the LCMS (last close magnetic flus surface) to $L_\mathrm{K}$ 15 m at the outer border of the stochastic layer, which is defined by $L_c > L_\mathrm{K}$ and was found to extend about 6 cm in thickness. The region between the stochastic layer and the targets is the laminar zone, defined by $L_c \leq L_\mathrm{K}$. The statistical average representing field line diffusion, $D_\mathrm{FL} = \langle (\Delta r_i)^2 / 2\Delta l_i \rangle$, was also estimated, where $\Delta r_i$ is the radial displacement and $\Delta l_i$ the corresponding toroidal distance between the two flux bundle locations associated with a common value of the Kolmogorov length LK. For W7-X the value of DFL was thus found to increase with decreasing $L_\mathrm{K}$ [3]. A simple collisionless model was used in [3] for estimating the values of the stochastic diffusion, $\chi_\mathrm{st}$, which would compete with an assumed value of $\chi_\perp$=3 $\mathrm{m}^2\ \mathrm{s}^{-1}$ for the intrinsic anomalous diffusion coefficient. Assuming the temperature and density, 70 eV and $10^{19}\ \mathrm{m}^{-3}$ respectively and adopting a simple expression suitable for collisionless conditions [4], $\chi_\mathrm{st} = \langle x_\perp^2(\lambda) \rangle / 2\tau = D_\mathrm{FL} v_{th}$, $\lambda = v_{th}\tau$ being the collisional mean free path, a required value for field line diffusivity $D_\mathrm{FL} = \chi_\perp / 3.5 \times 10^6 \approx 10^{-6}\ \mathrm{m}^2$/m was estimated. This, in turn, corresponds to $L_\mathrm{K} \approx 35$ m. It was therefore concluded that the stochastic transport may

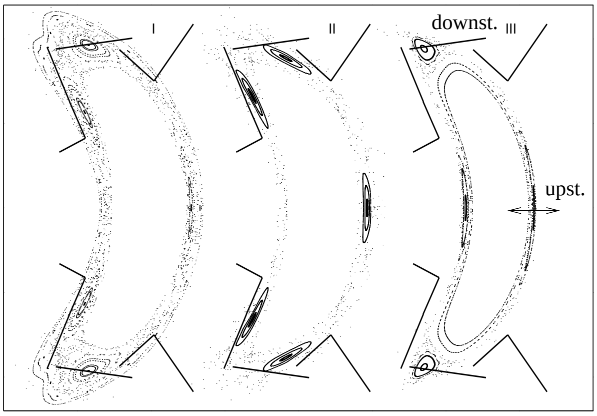


Figure 1: The edge magnetic configurations for W7-X.

indeed be significant in a narrow sub-domain of the W7-X stochastic layer, for which $L_{\mathrm{K}} \leq 35$ m [3].

## Energy transport in W7-X edge

In order to investigate the role of the stochastic transport for realistic plasma conditions, we use the EMC3 code [5], which simulates the plasma edge transport in full 3D geometry for both the configuration and the plasma-facing structures (divertor targets, baffles and wall). Stochastic effects are inherently included in the correct tracing of the all field lines. For the purpose of this paper we restrict the study to the diffusive heat transport in the relevant region outside the LCMS.

$$\nabla_{\|}.\left(-\kappa_s \nabla_{\|} T_s\right) + \nabla_{\perp}.\left(-\chi_{\perp s} n \nabla_{\perp} T_s\right) \;\; = \;\; 0. \qquad (1)$$

Here $\kappa_s$ and $\chi_{\perp s}$ represent the classical thermal conductivity and the anomalous cross field diffusivity associated with the species $s$, respectively, other terms and symbols in the above equations have their usual meanings. Apart from the magnetic configuration considered for the estimates in [3] (case III in Fig. 1), the present analysis includes two additional configurations, namely, the standard magnetic configuration ($\iota$ = 5/5) with finite plasma $\beta$ = 4% and that with a finite control coil current $I_{cc}$ = 25 kA. The fluid model was implemented using a total input power $P$ = 10 MW and a background plasma density $n = 1 \times 10^{19}$ m$^{-3}$, yielding steady-state temperature distributions in the 3D edge configurations. The radial profiles of the electron temperature $T_e$, plotted in Fig. 2 for all cases, show the temperature variation along upstream and downstream segments marked in Fig. 1 and effects of change in the cross-field heat diffusion

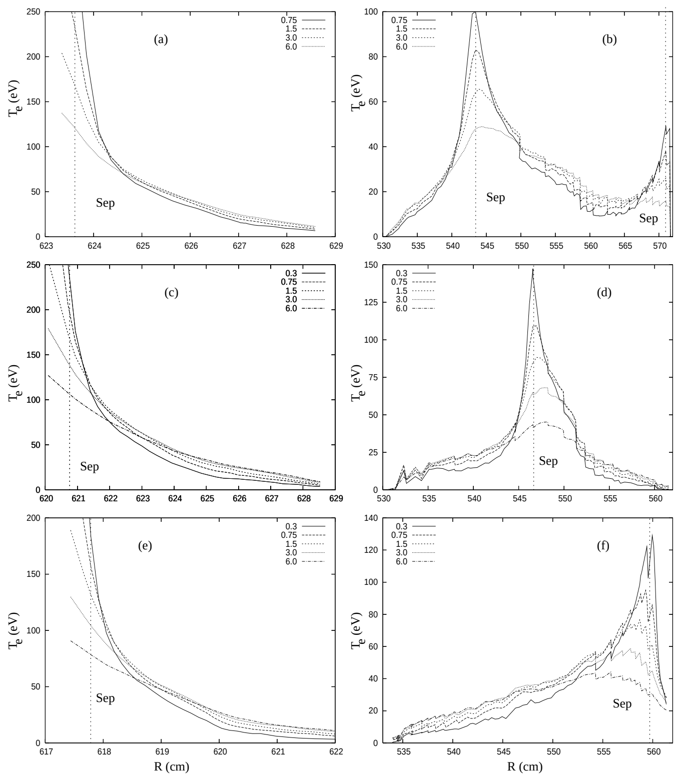


Figure 2: Radial profiles for upstream (left) and downstream (right) temperatures for cases I (top), II (middle) and III (bottom), plotted for various $\chi_\perp$

coefficient $\chi_\perp = \chi_{\perp e,i}$ which is varied from 6 $m^2$ $s^{-1}$ to 0.3 $m^2$ $s^{-1}$. The width of temperature profiles clearly show a gradual shrinking throughout the $\chi_\perp$ scan with no saturation due to a residual stochastic transport, indicating that the transport remains mostly laminar. The above observation can only be explained in the framework of a collisional model like that developed by Rechester and Rosenbluth [4], where the field line diffusion is coupled to the intrinsic transport leading to an effective stochasticity-driven transport. As discussed in [4], the condition $L_d < L_c$ is an essential requirement for the stochastic transport to be effective in the collisional cases, here $L_d$ is a parallel decorrelation length over which particles diffuse from the original flux tube to neighboring uncorrelated ones. From the present simulations $L_d$ is indeed found to be larger than required to allow any effective stochastic transport for the given connection length distributions.

**Summary and conclusions**

A 3D study of the plasma energy transport in the W7-X edge region was performed with the Monte Carlo transport code EMC3. The electron temperature profiles were simulated for different values of the intrinsic anomalous cross-field diffusivity $\chi_\perp$ for a fixed plasma background density and input power. Smaller values of the cross-field diffusion coefficient decrease the width of the radial temperature profiles while no significant effects of a residual stochastic transport were recovered in the temperature profiles even in the limit of very small cross-field diffusion coefficients. The absence of a residual stochastic transport, even in regions with $L_K < L_c$ agrees with classical collisional estimates of stochastic diffusion including intrinsic parallel and cross-field heat transport effects and can be ascribed to the insufficient stochastic decorrelation over the relatively short connection lengths.

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