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The stochastic edge region of W7-X

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Abstract

The topology of stochastic magnetic fields in the edge region of Wendelstein 7-X (W7-X) is investigated. The Kolmogorov lengths of flux tubes are computed and compared with the corresponding connection lengths to the plasma-facing components (divertor elements and first wall). It is shown that the mean Kolmogorov length decreases with increasing β, and that stochastic layers exist in the considered cases. The field line diffusion coefficient in dependency of the Kolmogorov length is estimated from the radial displacements of flux tubes and the corresponding heat diffusion coefficients are also given. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

A stochastic scrape-off layer (SOL) is expected to diminish plasma–wall interaction problems like power and particle exhaust, erosion and impurity control. While in some tokamak experiments, e.g. TEXT [1] and Tore Supra [2], additional coils are used to produce small magnetic field perturbations, the edge region of the so-called high-ι vacuum magnetic field of the optimized W7-X Helias stellarator is already stochastic [3,4]. In Ref. [5] a numerical method was developed to determine the Kolmogorov lengths of flux tubes in this geometrically complicated, three-dimensional edge region. There, it was shown that the mean Kolmogorov length decreases with increasing plasma beta and that stochastic layers exist. In this previous work the plasma-facing components, that is, the divertor, baffle and side plates and the first wall were not yet taken into account, and the magnitude of the field line diffusion coefficient was not estimated. These will be the subjects of this work.

Section 2 deals with the geometry of the divertor elements [6] and the topology of high-ι magnetic fields with volume-averaged β-values of $\langle\beta\rangle = 0\%$, 2% and 4%. In Section 3 the stochastic layers of these fields are determined, and in Section 4 the field line diffusion coefficient in dependency of the Kolmogorov length is estimated from the radial displacements of flux tubes and the corresponding heat diffusion coefficients are given. Finally, Section 5 contains a short summary.

2. Magnetic field topology and divertor geometry

The high-ι vacuum magnetic field of W7-X is characterized by 5/4 island remnants embedded in a stochastic region outside the last closed magnetic surface (LCMS) [3,4]. Mapping of the finite-β magnetic fields for $\langle\beta\rangle = 0\%$, 2% and 4%, shows reduction of the 5/4 island remnants with increasing β, that is, the stochasticity is increased in the edge region. In the considered cases the plasma magnetic field enlarges the islands in the edge region which leads to a stronger island overlap and, therefore, an increased stochasticity [5].

In Fig. 1 the upper halves of the Poincaré plots with the corresponding plasma-facing components are shown at the symmetric bean-shaped cross-section. The shapes and the widths of the island remnants, the forms and positions of the divertor elements and also the distances of islands and divertor elements to the LCMS vary poloidally and toroidally because of the three-dimensional geometry. Further, the distance of the LCMS to the divertor elements and to the island remnants increases with increasing β because of the decreasing plasma volume. While the island sizes decrease, the positions of

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the island O-points remain almost unchanged [3,4]. Therefore, the divertor will work for various finite-β equilibria.

As already described in Ref. [5], the rotational transform value at the LCMS decreases from $\iota = 1.21$ ($\langle\beta\rangle = 0\%$) to $\iota = 1.15$ ($\langle\beta\rangle = 4\%$), while $\iota = 1.25$ for the islands. That is, the edge region of the high-ι W7-X magnetic field is formed by a three-dimensional, stochastic field with shear that contains remnants of the 5/4 islands. The connection lengths of the edge field lines to the plasma-facing components are determined by the forms and positions of these components.

3. Stochastic layers

The Kolmogorov and connection lengths are determined numerically by field line tracing. A parallelized

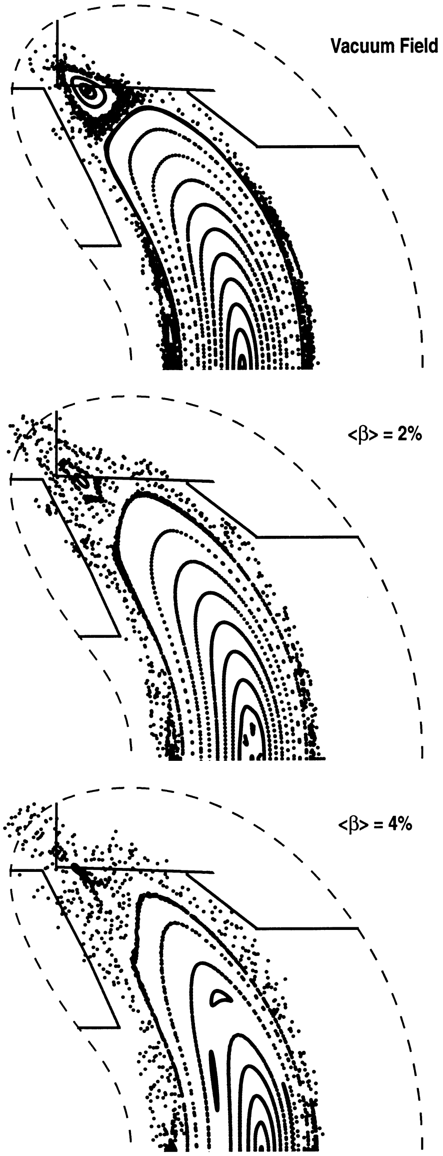

Fig. 1. Upper halves of the Poincaré plots at the bean-shaped cross-section of the high-ι magnetic field for $\langle\beta\rangle = 0$, 2, and 4%. The straight solid lines mark the divertor elements and the dashed line represents the first wall.

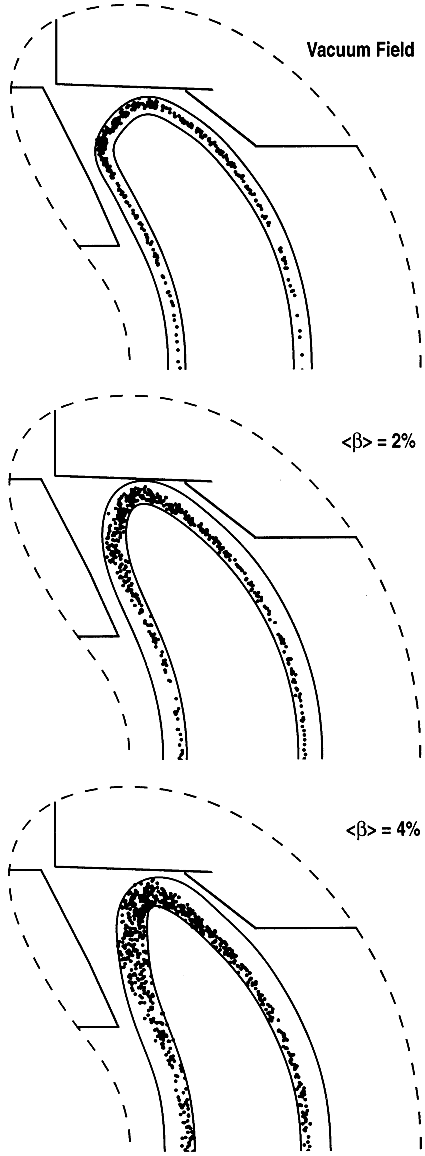

Fig. 2. Stochastic layer (dots) with divertor elements (straight solid lines) and first wall (dashed line). The constant distance between the two limiting surfaces amounts to 6 cm (vacuum field), 8 cm ($\langle\beta\rangle = 2\%$) and 10 cm ($\langle\beta\rangle = 4\%$).

version of the Gourdon code has been extended in order to determine the intersection points of the field lines with the plasma-facing components and to calculate the corresponding connection lengths.

For computing the Kolmogorov lengths, the numerical method described in Ref. [5] is used with some small alterations. Here, a region which lies inside the target plates and which contains the LCMS and the interesting edge region is defined by two limiting surfaces with constant spacing in between (distance: 6 cm for the vacuum case, 8 cm for $\langle\beta\rangle = 2\%$ and 10 cm for $\langle\beta\rangle = 4\%$) (compare Fig. 2). In the region defined in this way, bundles of 256 field lines are started on the circumferences of small circles ($r_0 = 0.0001$ m) and traced for 25 toroidal turns or until they leave the grid box on which the magnetic field is defined [7]. The initial circles are homogeneously distributed in the edge region of a cross-section. Three cross-sections with $\varphi = 0°$, 18° and 36° (φ = toroidal angle) are considered and per cross-section 3000 field line bundles are traced in both directions. During the field line tracing intersections of the field lines with the plasma-facing components and the corresponding connection lengths are determined. The mean value of the connection lengths of field lines forming a flux tube defines the connection length L_c of the flux tube.

Because of the exponential scattering of close field lines in a stochastic field, the circumference d of the area increases with

$$d(l) = d_0 \exp(l/L_K), \tag{1}$$

with d_0 being the circumference of the initial circle, l the length of the flux tube and L_K the Kolmogorov length, which measures the stochasticity. The function $\ln(d(l))$ is fitted (least squares fit) by a straight line with its slope given by the inverse of the Kolmogorov length.

Comparing the Kolmogorov lengths with the corresponding connection lengths, two transport regimes are distinguished [8–10], namely, the stochastic transport region with $L_c > L_K$, and the laminar transport region with $L_c \leqslant L_K$ where the parallel transport is the dominant feature. In Fig. 2 the resulting stochastic layers for $\langle\beta\rangle = 0\%$, 2% and 4% are plotted. In each case the stochastic layer covers the LCMS. Its width varies poloidally and toroidally (not shown in Fig. 2), and increases slightly with β. The constant distance between the limiting surfaces gives a measure of how thick the stochastic layer is. Its width varies between ≈0.5 and 10 cm depending on β and the toroidal and poloidal positions. The region between the stochastic layer and the target plates belongs to the laminar transport regime. The Kolmogorov length decreases from $L_K > 100$ m close to the LCMS to $L_K \approx 15$ m at the outer border of the stochastic layer. In order to investigate the influence of the stochasticity on the cross-field heat transport in the stochastic layer it is at the very least necessary to esti-

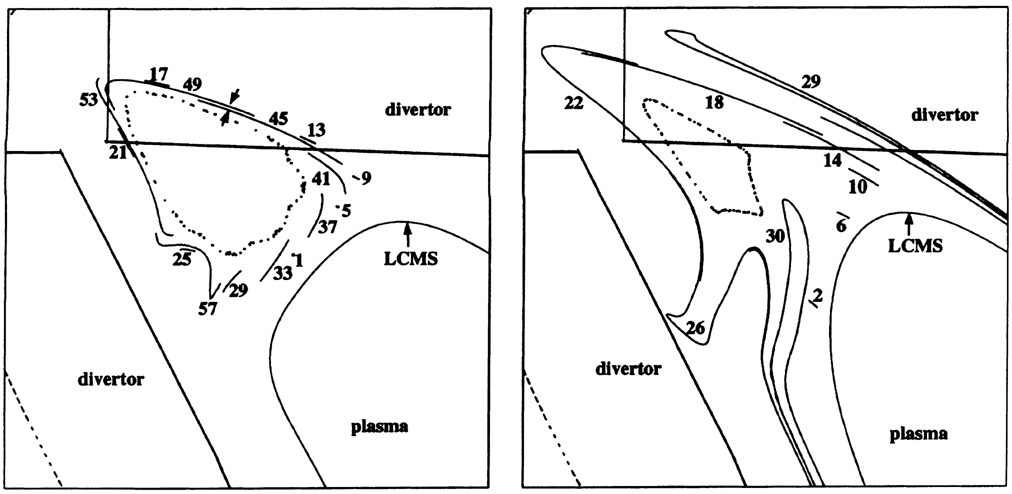

Fig. 3. Two types of flux tubes (initial radius $r_0 = 0.001$ m) are plotted at the top of the bean-shaped cross-section. Because of their increasing circumferences, the conservation of the magnetic flux and the scale of the plots (1 cm in the plot ≡ 0.068 m in real size), the region inside the flux tubes is not resolved so that they appear as thin lines. The toroidal positions of the cross-sections of the flux tubes are given by the period numbers (5 periods ≡ 1 toroidal turn ≈ 35 m). The plotted flux tubes reach the same poloidal region after four periods because of $\iota \approx 1.25$ close to the island remnants, which are marked by the dots. The left figure shows a flux tube of the vacuum case which is characterized by $L_K \approx 73$ m, $L_c \approx 82$ m, and $D_{FL} \approx 4 \times 10^{-7}$ m^2/m. For $\langle\beta\rangle = 2\%$ a flux tube is plotted in the right figure. It is characterized by $L_K \approx 26$ m, $L_c \approx 96$ m and $D_{FL} \approx 3.2 \times 10^{-6}$ m^2/m. In the left figure the two arrows give an example of how to measure the radical displacements Δr_i of a flux tube.

mate the field line diffusion coefficient D_{FL}. This will be done in the next section.

4. Field line diffusion

Because of the rather complex three-dimensional magnetic field structure it seems nearly impossible to compute the radial displacements of stochastic field lines without the framework of a numerical code. The radial distance between two closed magnetic flux surfaces already varies approximately by a factor 10 depending on the poloidal and toroidal positions (Fig. 1). Additionally, relatively large island remnants are embedded in the edge region, and stochastic field lines encircle as well the LCMS as the island remnants. Nevertheless, tracing a single flux tube and plotting it for various toroidal lengths at any toroidal cross-section shows the radial displacement of the flux tube to itself. In Fig. 3 two examples are given. There the toroidal length of the flux tube is characterized by the period number (5 periods $\equiv$ 1 toroidal turn $\approx$ 35 m). Thus, the radial displacement can be directly determined at many points and the field line diffusion coefficient can be estimated by

$$D_{FL} = \frac{1}{N}\sum_{i=1}^{N}\frac{(\Delta r_i)^2}{2\Delta l_i}, \qquad (2)$$

with Δr_i the radial displacement and Δl_i the toroidal distance between the two flux bundle locations. The quantities are measured at N positions with $N \approx 10$–20.

Of course the field line diffusion coefficient obtained by this method can only be considered as a rough estimate, but nevertheless it gives an order of magnitude. Analysing flux bundles with different Kolmogorov lengths, the results summarized in Fig. 4 have been obtained. There, D_{FL} is plotted as a function of the Kolmogorov length L_K. It increases with decreasing L_K. The corresponding heat diffusion coefficient is estimated by $\chi_{erg} = D_{FL} v^e_{th}$ [8–10] with v^e_{th} the electron thermal velocity. For W7-X a velocity of $v^e_{th} = 3.5 \times 10^6$ m/s and an anomalous cross-field heat transport coefficient of $\chi^e_\perp = 5$ m^2/s have been considered (edge electron temperature $T_e = 70$ eV, edge density $n = 0.2 \times 10^{20}$ m^{-3}, $\chi^e_\perp n = 10^{20}$ m^{-1} s^{-1}, [11]). The stochasticity only influences the

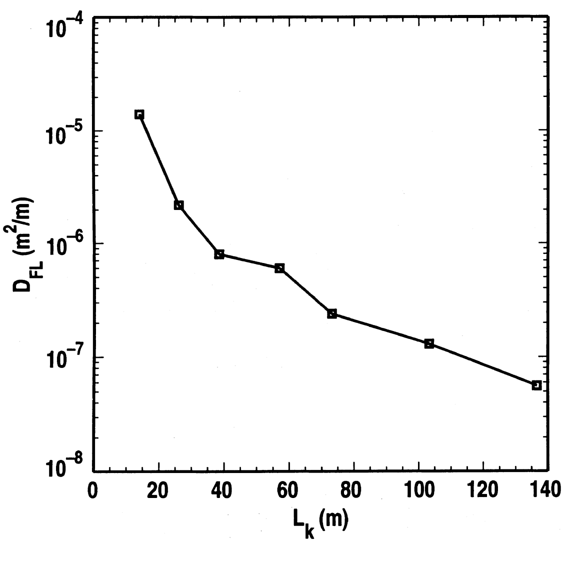

Fig. 4. The field line diffusion coefficient D_{FL} is plotted in dependency of the Kolmogorov length L_K.

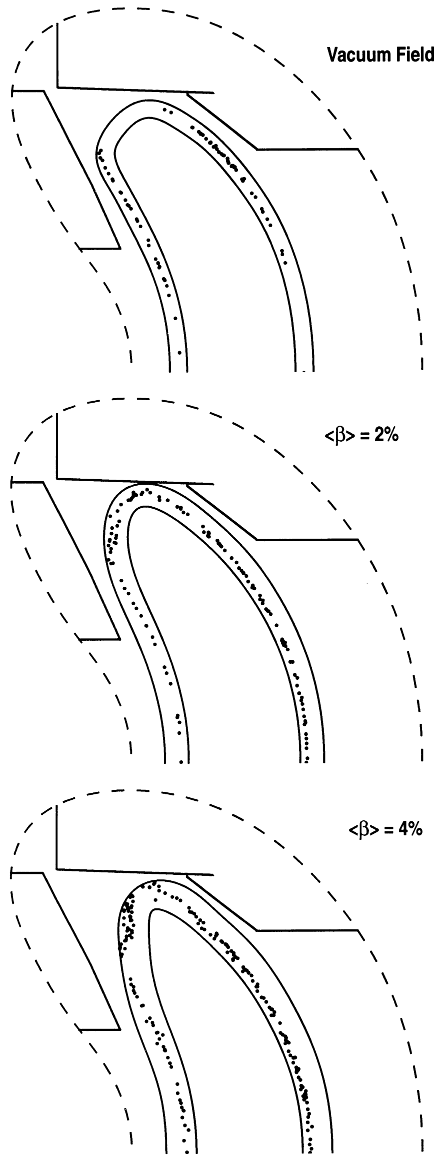

Fig. 5. Part of the stochastic layer with $L_K \leqslant 35$ m (dots). For details see Fig. 2.

cross-field heat transport if $\chi_{erg} \geqslant \chi_{\perp}^{e}$. Therefore, for these parameters only field lines with $L_K \leqslant 35$ m ($D_{FL} > 1 \times 10^{-6}$ m^2/m, $\chi_{erg} > 3.5$ m^2/s) will contribute to an enhanced cross-field transport. As shown in Fig. 5 the outermost part of the stochastic layer fulfills this condition. There the flux tubes with $L_K \leqslant 35$ m are plotted. In this thin layer the stochasticity may be large enough, so that a small influence of the stochasticity on the cross-field heat transport may be expected for the considered magnetic field configurations, at least for higher β-values.

For the future, the influence of the electron distribution function, in particular of the fast electrons ($E \approx 4kT_e$, [11]) together with the influence of the stochasticity needs to be assessed in detail. Further, the influence of the stochasticity on the cross-field heat transport is expected to increase in larger fusion devices. For example, scaling W7-X (major radius $R_0 = 5.5$ m) to the size of the Helias reactor ($R_0 = 22$ m) [12] would increase D_{FL} by a factor 4, and the higher edge temperature ($T_e = 0.18$ keV, [11]) would also increase χ_{erg}.

5. Summary

The stochasticity of magnetic fields in the edge region of W7-X has been quantified. It has been shown that the mean Kolmogorov length decreases with increasing β, and that stochastic layers ($L_K < L_c$) exist in the considered cases taking the forms and positions of the divertor elements into account. Further, an estimate of the field line diffusion coefficient and the corresponding heat diffusion coefficient have been given.

References

[1] N. Ohyabu et al., Nucl. Fusion 25 (1985) 1684.
[2] A. Samain et al., J. Nucl. Matter 128&129 (1984) 395.
[3] E. Strumberger, Laboratory Report IPP 2/339, Garching, 1997.
[4] E. Strumberger, Proc. 24th EPS Conf. on Contr. Fusion and Plasma Physics, Berchtesgaden, EPS, vol. 21A, Part IV, 1997, p. 1677.
[5] E. Strumberger, Contr. Plasma Phys. 38 (1998) 106.
[6] H. Greuner et al., in: Proc. 18th SOFT, Karlsruhe, vol. 1, 1994, p. 323.
[7] E. Strumberger, Nucl. Fusion 37 (1997) 19.
[8] F. Nguyen et al., Nucl. Fusion 37 (1997) 743.
[9] F. Nguyen, Transport dans un plasma de fusion en présence d'un champ magnétique chaotique, Thesis No. 92/PA07/7293, doctorat de l'Université Paris VII (1992).
[10] A. Grosman et al., Contr. Plasma Phys. 38 (1998) 82.
[11] J. Nührenberg et al., Contr. Plasma Phys. 32 (1992) 204.
[12] C.D. Beidler et al., in: Proc. 24th EPS Conf. on Contr. Fusion and Plasma Physics, Berchtesgaden, EPS, vol. 21A, Part IV, 1997, p. 1681.