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CONF-920610--17

1992 INTERNATIONAL CONFERENCE ON PLASMA PHYSICS

29 June-3 July 1992
Innsbruck, Austria

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FG 05-88ER53265

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Abstract

Magnetic perturbations cause the region near the separatrix of a magnetic divertor to become stochastic. The last magnetic surface to provide magnetic confinement passes inside the X-point a distance that is proportional to the square root of the applied perturbation. Particles that diffuse across the last confining surface can follow open magnetic lines to the divertor plates. The strike points of these field lines on the divertor plates lie in helical discrete stripes. The properties of these stripes is important for determining if one can control the heat loads on divertor plates as well as assessing the effects of natural perturbations, such as MHD activity, on divertor designs.

Introduction

The prediction and preferably the control of the width of the scrapeoff layer of a divertor is a central issue in the design of ignition tokamaks such as ITER. Divertor simulations generally assume that the plasma is bounded by a sharp separatrix, which is correct only if the toroidal symmetry is perfect. Toroidal asymmetries in the magnetic field cause the last confining magnetic surface to lie inside the ideal separatrix and create a layer of open magnetic field lines that lies between the last confining magnetic surface and the ideal separatrix. The width of this layer, which we call stochastic layer, is approximately proportional to the square root of the toroidally asymmetric perturbation near the X-point.[1] It is important to know the effects of naturally occurring perturbations, such as toroidal ripple or MHD modes, on the design of divertors. The introduction of magnetic perturbations may allow an optimization of the width of the divertor scrapeoff layer and control of the heat deposition on the divertor plates.

In the simulations that assume a sharp separatrix, the width of the scrapeoff layer is determined by the assumed diffusion coefficient, which is usually of order 1 m^2/s. The field lines of scrapeoff layer strike the divertor plates in a stripe with a width that is simply determined by axisymmetric magnetics.

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If the magnetic perturbations are sufficiently large, the scrapeoff layer will be dominated by the stochastic layer. The field lines of the stochastic layer strike the divertor plate in a stripe that is in proportion much narrower (about a factor of 6) than is the divertor stripe filled by the field lines of an axisymmetric scrapeoff layer. The greater width of the scrapeoff layer in comparison to the divertor stripe has important implications for the design of divertors.

Methodology

The basic features of magnetic field line motion near a separatrix are generic and can be efficiently investigated using an area preserving map. Pomphrey and Reiman have made related calculations[2] using wires to model a divertor configuration instead of a map. The simplest divertor map has a single positive parameter k,

$$x_{n+1} = x_n - k\, y_n\, (1-y_n)$$
$$y_{n+1} = y_n + k\, x_{n+1},$$

an O-point at x=0, y=0, and an X-point at x=0, y=1. The map provides a good representation of the magnetic field lines of a single-null tokamak divertor. Toroidal asymmetries can be simulated using k or by additional terms.[3] Here, toroidal asymmetries will be simulated using k, but the results are not qualitatively changed by other representations. The smaller k, the closer the last confining magnetic surface passes to the X-point. For k=0.6, the closest approach is x=0, y=0.997, Fig. (1a,b); for k=0.9, the closest approach is x=0, y=0.854. Each iteration of the map corresponds to a toroidal angular advance ζ_0. Near the O-point the rotational transform of the field lines per iteration $1/q_1$ is

$$\sin(2\pi/q_1) = k\, (1-k^2/4)^{1/2}.$$

One obtains a transform of roughly unity near the axis if 10 iterations of the map constitute a single toroidal circuit, $\zeta_0=2\pi/10$.

The width of the stripe on the divertor plates is uniquely determined by the stripe formed by field lines as they cross the plane y=1, which passes through the X-point. The toroidal location ζ at which field lines cross x-ζ plane is determined using a continuous analogue to the discrete map. Letting $\phi=\zeta/\zeta_0$, $0\le\phi\le1$, the (area preserving) continuous analogue is

$$x(\phi) = x_n - k\, y_n\, (1-y_n)\, \phi$$
$$y(\phi) = y_n + k\, x(\phi)\, \phi.$$

The behavior of field line trajectories that cross the last confining surface at a random point can be assessed by adding a small area-expanding step to each iteration of the discrete map, $x_{new}=(1+R\delta)x_{old}$, with R a random number between 0 and 1 and δ the expansion coefficient. For k=0.6, we find that for $\delta<<10^{-13}$ the strike points form helical stripes that are independent of δ, Figs. (2a,b). For larger values of δ the strike points form a single stripe, Fig. (3-4), which has a width that scales as $\delta^{1/4}$.

Discussion of Results

Particles that diffuse across the last confining surface of a tokamak with a divertor can follow open magnetic field lines to the divertor plates. The strike points of these field lines on the divertor plates lie in discrete stripes. The region between the last confining magnetic surface and the separatrix of the ideal divertor is called the stochastic layer. The open magnetic field lines of the stochastic layer enter the region from one divertor plate and leave striking another divertor plate after an integer number of complete poloidal circuits N_p. The discrete stripes on the divertor plates correspond to the number of poloidal circuits made by open field lines. The area of the stripes scales as $1/N_p^2$. The open field lines that approach the last confining surface make many poloidal circuits before striking a divertor plate in a stripe that is much narrower than the stochastic layer (≈15%) but nonetheless of non-zero width. An open field line that makes many poloidal circuits in going from one divertor plate to another in essence densely fills the stochastic layer except for the regions in the stochastic layer that are occupied by magnetic islands.

The complicated filling of the stochastic region by the open field lines gives an associated complexity to the ambipolar electric potential that exists along any open magnetic field line that is embedded in a plasma. Although we have not calculated the particle transport from the EXB drifts associated with the ambipolar potential, we expect a diffusive effect that would smear the stripe structures.

Acknowledgement

This work was supported in part by US DoE grants DE-FG05-88ER53265 and DE-FG05-90ER54106.

References

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2. N. Pomphrey and A. Reiman, PPPL Rpt. 2801 (1992)

3. T. J. Martin and J. B. Taylor, Plasma Phys. Contr. Fus., 28, 321 (1984)

FIGURES

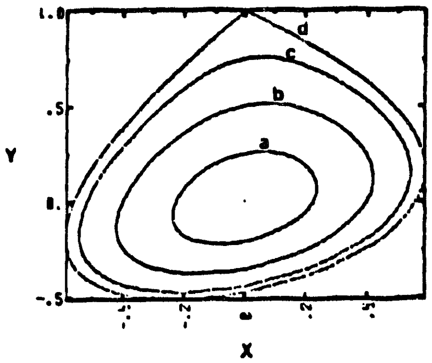

Fig. 1a Phase portrait for the simple single-null tokamak divertor map when map parameter k=0.6. Initial conditions are $x_0=0$, a:$y_0=.25$, b:$y_0=.5$, c:$y_0=.75$, d:$y_0=.997$.

Fig. 1b Reverse video of the phase portrait near X-point. Abscissa goes from -0.001 to 0.001, and ordinate goes from 0.997 to 1.

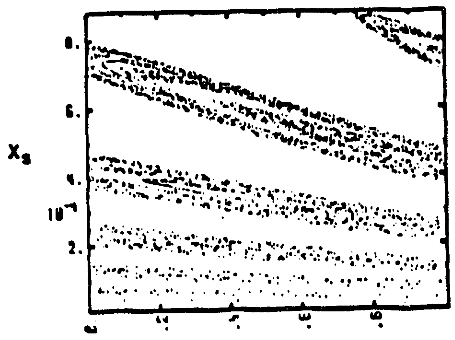

Fig. 2a Foot-print of the strike points on the divertor plate when the expansion coefficient $\delta=0$. Trajectories start in the stochastic scrapeoff layer at $x_0=0$ and $0.997<y_0<1$.

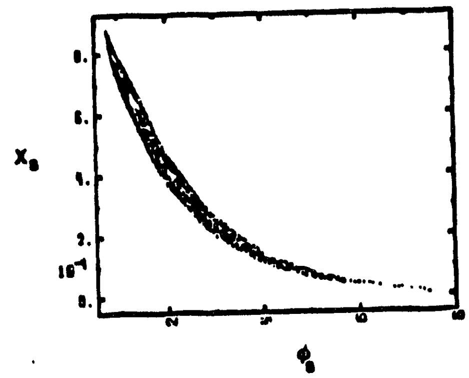

Fig. 2b When the foot-print for $\delta=o$ is unfolded in the ϕ direction, we get a sharply defined, narrow, helical stripe.

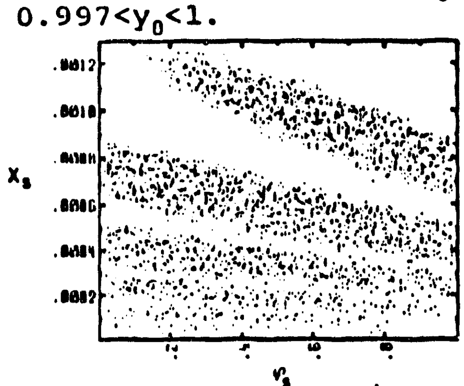

Fig. 3 Foot-print of the strike points when $\delta=10^{-13}$.

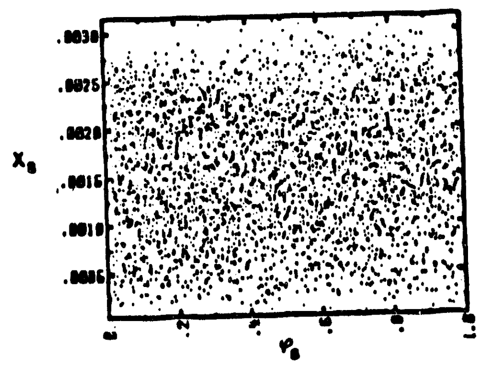

Fig. 4 Foot-print when $\delta=10^{-11}$. Now the foot-print is a continuum, whose width scales as $\delta^{1/4}$.

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