*35th EPS Conference on Plasma Phys. Hersonissos, 9 - 13 June 2008 ECA Vol.**32D**, P-2.008 (2008)*

Robustness of second order magnetic barriers at noble irrationals in the ASDEX UG tokamak

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In magnetic confinement schemes for fusion plasmas such as tokamaks, stellarators and reversed field pinches, magnetic islands are formed when the resistive MHD perturbations resonate with the pitch of a magnetic surface. Resonance occurs when $q(\psi_{mn})=m/n$. q is the safety factor of the magnetic surface labeled by magnetic coordinate $\psi=\psi_{mn}$. m and n are poloidal and toroidal mode numbers of the magnetic perturbation, respectively. When the neighboring islands grow and overlap, magnetic field lines in the overlap region become chaotic. Generally, the enhanced plasma transport resulting from chaotic field lines has a deleterious effect on plasma confinement [1–2]. On the other hand, magnetic perturbations from external coils are also used to induce chaos and suppress undesirable modes, such as the use of I-coils in the DIII-D to suppress type I edge localized modes (ELMs) [3-4]. Controlling the enhanced plasma transport from stochastic field lines is an important issue in fusion science. In this paper, we use a flux-preserving map, called ψ-θ map [5] with the Ciraolo, Vittot and Chandre method of building invariant manifolds inside chaos in Hamiltonian systems [6-8]. In the Ciraolo, Vittot and Chandre method [6-8], a second order perturbation, $\varepsilon^2 f$, is added to the perturbed Hamiltonian. The second order perturbation is localized in phase space and has a finite base. It creates a good magnetic surface inside the region of chaotic magnetic field lines and reduces the plasma transport. We call this method the $\varepsilon^2 f$ method. The value and beauty of this method of building magnetic barriers in tokamaks is that the magnetic perturbation that has to be added to the equilibrium Hamiltonian to create an invariant KAM torus inside chaos is at least an order of magnitude smaller than the magnetic perturbation that causes chaos. Further this additional term consists of a finite, limited number of Fourier modes. So this method is highly economic.

In this work, we investigate the resilience of second order magnetic barriers in the Axially Symmetric Divertor Experiment Upgrade (ASDEX UG) tokamak. We use the term 'resilience' to describe the response of the barrier to increasing the strength of the magnetic perturbation. The unperturbed generating function for magnetic field lines in the ASDEX UG is based on the standard safety factor profile, $q(\psi)=0.8+4\psi$. ψ is the toroidal magnetic flux. This expression for q correctly describes the experimental position of the MHD modes in the ASDEX UG. For magnetic perturbation, we chose two tearing modes with mode numbers

$(m,n)=\{(3,2),(4,3)\}$, $\chi_1(\theta,\varphi)=\delta[\cos(3\theta-2\varphi)+\cos(4\theta-3\varphi)]$. The (3,2) mode is resonant at ψ_{32} = 0.175, and the (4,3) mode is resonant at $\psi_{43} = 0.1\overline{3}$. This magnetic perturbation destroys the magnetic surfaces at and in the neighborhood of the resonant magnetic surfaces ψ_{32} and ψ_{43} when $\delta=2.1\times10^{-4}$, and forms magnetic islands. Phase portrait of the magnetic field line trajectories and its close-up for $\delta=2.1\times10^{-4}$ are shown in figures 1(a) and (b).

To create a magnetic barrier inside region of chaotic magnetic field lines in ASDEX UG, we add the second order control term, $\chi_C=A_2[B_1\cos(3\theta-2\varphi)+B_2\cos(4\theta-3\varphi)]$, $A_2=-0.5\delta^2[(d/d\psi)(1/q(\psi_b)]$, $B_1=3/(3\omega_b-2)$, $B_2=4/(4\omega_b-3)$, $\omega_b=\iota(\psi_b)$ in the poloidal flux. ψ_b denotes the location of the magnetic barrier. In a recent study [9], we chose ψ_b=0.15. This ψ_b corresponds to the safety factor q_{mediant}=7/5, the mediant q of resonant surfaces $(m,n)=\{(3,2),(4,3)$. The result is shown in figure 2. Once the barrier is created by adding the second order control term to the Hamiltonian, we first investigated the resilience of the barrier, i.e., what happens to the barrier as the amplitude of the magnetic perturbation δ is increased. Does the invariant torus (i.e. the barrier) break down or continue to exist? How large does the amplitude δ have to be for the barrier to break?. We found that on increasing the amplitude of magnetic perturbation δ to 2.18208×10^{-4}, the magnetic barrier breaks up into magnetic islands. See figures 3(a) and 3(b). Secondly, we build the magnetic barrier on the surface that has noble irrational q, with the q_{mediant} as its convergent, i.e., $q_{\text{noble}}=[1;2,2,1,1,1,\ldots]$. On double precision computers, we found that the 38[th] convergent of the q_{noble} gives, with $|q_{n+1}-q_n|=0$, q_{noble}=1.41982127170454. The subscript n denotes the n[th] convergent. The corresponding noble magnetic surface is ψ_{noble}=0.154955317926135. This surface is very close to the surface ψ_{mediant}=0.15. We found that the barrier at ψ_{noble} continues to exist up until $\delta=2.65\times10^{-4}$, and breaks up when $\delta=2.7\times10^{-4}$. See Figs. 4(a) and 4(b). This means that the barrier at the noble surface ψ_{noble} is more resilient compared with the barrier at corresponding mediant surface ψ_{mediant}.

In our future work, we plan to add higher order magnetic perturbations as control terms to study the resilience of the barrier at noble irrational surfaces. We plan to calculate the diffusion coefficient for magnetic field lines with and without the magnetic barrier, and estimate the effect of the barrier on the diffusion of field lines. The value and beauty of this method of building magnetic barriers in tokamaks is that the magnetic perturbation that have to be added to the equilibrium poloidal flux as control terms to create the magnetic barrier are at least an order of magnitude smaller than the magnetic perturbation, and that the control perturbations have a finite, limited basis in phase space. This method is highly. The limitations of the work we reported include the lack of effects of turbulence, collisions and self-consistent plasma response. This work is supported by US Department of Energy grants DE-FG02-01ER54624 and DE-FG02-04ER54793.

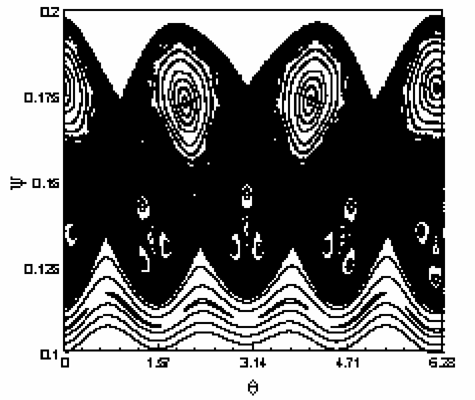

Figure 1a: Trajectories of magnetic field lines in ASDEX UG when $\delta=2.1\times10^{-4}$.

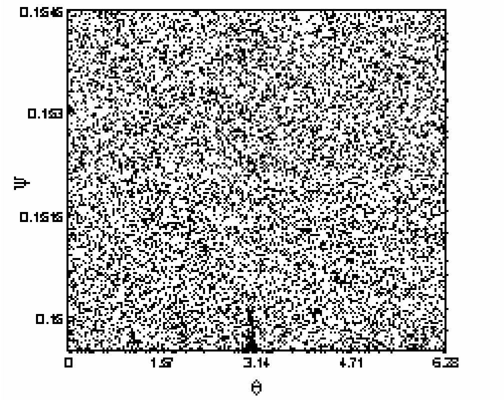

Figure 1b: Close-up view of figure 1a.

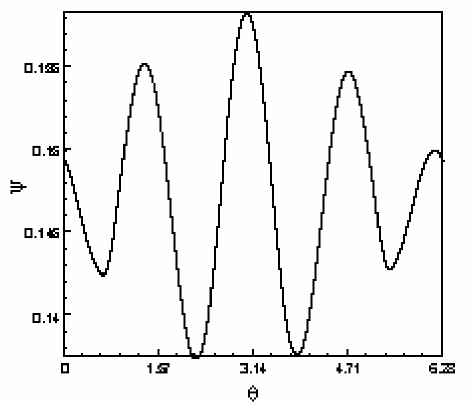

Figure 2: The magnetic barrier created by adding χ_C to poloidal flux, at ψ_{mediant} $q_{mediant}$=7/5, when $\delta=2.1\times10^{-4}$.

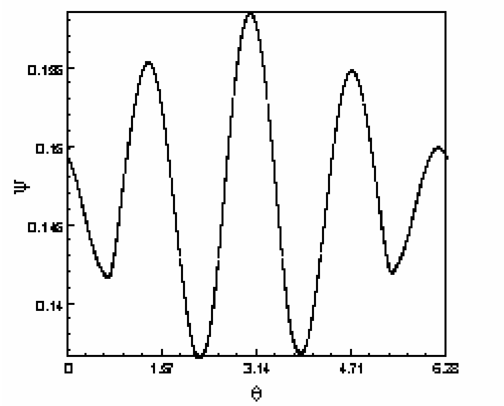

Figure 3a: The magnetic barrier created in figure 2 breaks up into magnetic islands as δ is increased to δ to 2.18208×10^{-4}.

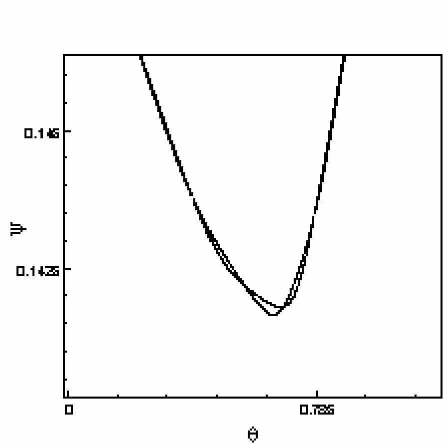

Figure 3b. A close-up view of figure 3a.

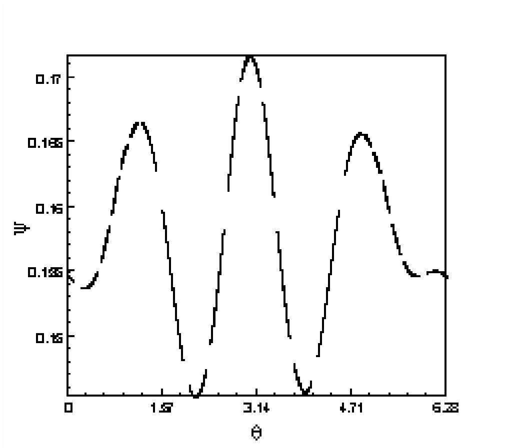

Figure 4a: The magnetic barrier created by adding χ_C to poloidal flux, χ_C at ψ_b corresponding to q_{noble} =[1;2,2,1,1,…] breaks up into magnetic islands when $\delta=2.7\times10^{-4}$.

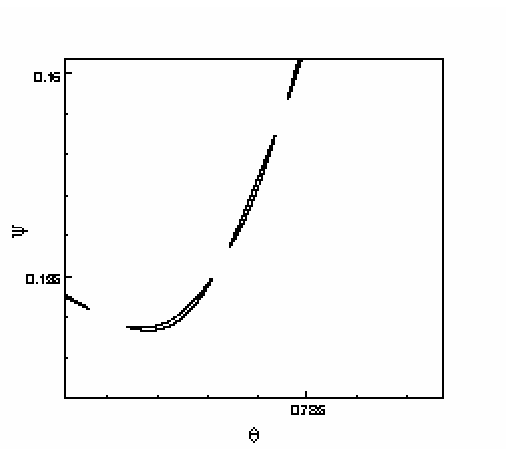

Figure 4b: A close-up view of figure

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