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Physics of Resonant Magnetic Perturbations in Toroidal Plasmas
トロイダルプラズマにおける共鳴磁場摂動の物理

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Recent experiments on a variety of tokamaks and stellarators/heliotrons have demonstrated that 3D, resonant magnetic perturbation (RMP), fields can be beneficial for controlling the properties of high temperature plasmas. These results are of significant scientific interest for understanding the basic physics that defines the confinement and stability properties of toroidal plasmas. In tokamaks, applied RMPs have been used to suppress edge MHD instabilities while maintaining H-mode transport barriers. In stellarators/heliotrons intrinsic RMPs produce islands and an edge stochastic layers that are associated with improved confinement. Here, we discuss common features of RMP physics found in the DIII-D tokamak and the LHD heliotron.

1. Introduction

An interesting aspect of Resonant Magnetic Perturbations (RMP) in tokamaks is that the RMP fields act primarily on particle confinement with minor effects on energy confinement [1]. This is inconsistent with a straightforward application of quasi-linear transport theory, which predicts that heat flux along open field lines should be dominant. This suggests that either the global magnetic topology induced by the RMP fields in a tokamak H-mode pedestal is different from that observed with RMP fields in Ohmic plasmas [2] or that other physics effects are competing with parallel heat conduction along open stochastic field lines in plasmas with edge transport barriers. In stellarators/heliotrons, stochastic boundaries have been associated with the formation of edge transport barriers that have properties similar to H-modes in tokamaks [3].

Here, we discuss comparisons of edge stochastic layers in tokamaks and stellarators/heliotrons with the goal of developing a common physics basis for better understanding the general properties of the confinement and stability in these two devices.

2. Magnetic Topology Measurements

In low β tokamaks, with relatively small plasma flows, vacuum calculations of the magnetic topology match experimentally observed magnetic islands very well [2]. On the other hand in H-modes, with high edge temperatures, imaging magnetic islands with visible spectral lines is not possible so we must rely on new techniques for measuring the properties of the magnetic topology. Several new techniques developed in the LHD heliotron are now in use on the DIII-D tokamak. These include soft x-ray imaging [4,5], heat pulse propagation studies [6] and 3D equilibrium reconstructions [7]. These are needed to better understand the plasma response to RMP fields and changes in the field topology that affect the plasma performance.

3. Topological Effects on Plasma Performance

A working assumption is that the structure of the edge magnetic topology plays an essential role in the plasma performance. For example, when RMP fields from perturbation coils are applied to DIII-D tokamak H-modes the toroidal and poloidal rotation is strongly altered while the radial electric field (E_r) across the pedestal plasma at the edge goes from being entirely negative (radially inward) to mostly positive (radially outward) as shown in Fig. 1.

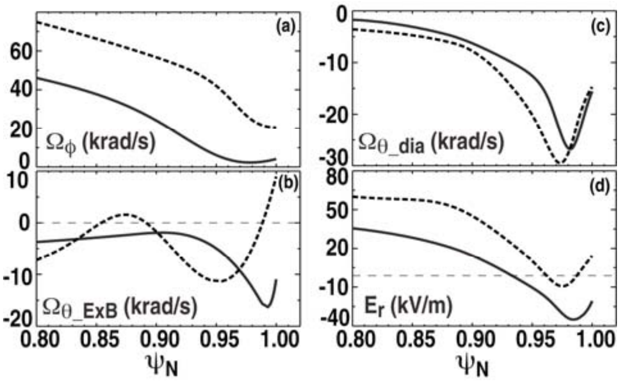

Fig.1. Change in the (a) toroidal (Ω_ϕ), (b) poloidal ExB (Ω_{θ_ExB}), (c) poloidal diamagnetic (Ω_{θ_dia}) rotation and (d) radial electric field (E_r) with (dashed) and without (solid) the RMP in DIII-D shot 123306.

These data are consistent with an increase in the plasma potential due to a loss of thermal electrons from the pedestal region along open magnetic field lines that connect to divertor target plates. Numerical studies have shown that vacuum RMP fields create magnetic structures known as homoclinic tangles in the separatrix of a diverted tokamak plasma [8]. The lobes of these tangles can intersect the divertor target plates allowing field lines from inside the separatrix to escape and hit divertor surfaces. Experimental data has verified the existence of homoclinic tangles due to RMP fields [8,9].

Similar effects are seen in the poloidal flow (v_{pol}) profile of the LHD heliotron near the edge of the plasma where the vacuum magnetic field is intrinsically stochastic due to the finite geometry of the helical coils. As shown in Fig. 2, charge exchange spectroscopy (CXS) measurements of v_{pol} going from the good flux surface region through the edge stochastic region show a sharp reversal of the flow starting at the edge of the stochastic field region. Here, positive E_r field measurements indicate open field lines but do not directly indicate a stochastic field. It is not clear whether the magnetic field is stochastic as predicted by vacuum calculation or healed by the plasma.

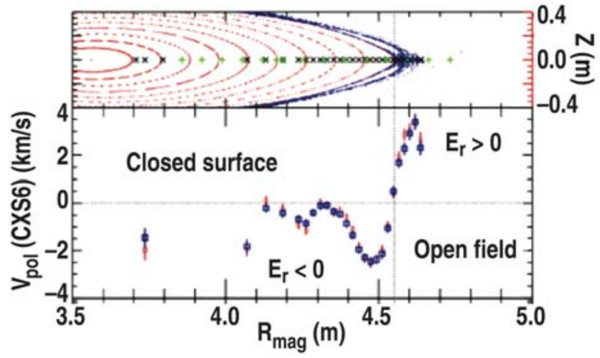

Fig. 2. (a) Closed flux surfaces bounded by a stochastic magnetic field region on the horizontal midplane where CXS measurements are made (x's and +'s), (b) v_{pol} profile from CXS measurements showing a sharp reversal from negative flows in the closed surface region to positive in the open field region.

Note that there is a strong similarity between v_{pol} in LHD and Ω_{θ_ExB} in DIII-D [dashed curve, Fig. 1(b)]. In LHD the radial position where v_{pol} changes from negative to positive is thought to indicate the location of the last closed flux surface. Outside this point the field is open and E_r is positive (radially outward). Inside this position E_r is negative (radially inward). Applying this observation to the DIII-D data suggests that the last closed flux surface in DIII-D could be significantly closer to the separatrix than indicated by vacuum field calculations, which may be a consequence of the plasma response to the RMP field in DIII-D. On the other hand, there is typically a significant change in the toroidal rotation of the DIII-D plasma when the RMP field is applied and this has an impact on E_r through radial force balance.

Comparisons of the magnetic structure in DIII-D and LHD, based on heat pulse propagation studies [6], soft x-ray imaging [4,5] and HINT2 3D equilibrium reconstructions [7], are expected to provide key information on the extent of the stochastic region and the existence of islands versus good flux surfaces. HINT2 results for LHD indicate that the width of the stochastic region increases with β and edge localized mode suppression in DIII-D with RMP fields is known to improve with increasing normalized β. These results imply that there should be a clear dependence on E_r and plasma flows with increasing β in each machine.

4. Summary and Conclusions

Developing a better understanding of the plasma response to externally applied RMP fields in high confinement tokamaks and stellarators/heliotrons is important for improving the performance of the next generation of toroidal magnetic devices. A key element needed for progressing along this development path is the ability to diagnose the global magnetic topology of the plasma edge. Methods such as heat pulse propagation studies, that have been used in the LHD to distinguish between good flux surfaces, magnetic islands and stochastic layers, have recently been applied in DIII-D and the result are being used to determine whether variations in the thickness of the edge stochastic layer with increasing β or RMP field amplitude are correlated with changes in the radial electric field, plasma flows and turbulence.

Acknowledgments

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