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Field Ergodization by External Coils on the COMPASS Tokamak

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Abstract. We investigated the magnetic field resulting from a set of "saddle coils" on the COMPASS tokamak, which is now being transferred from UKAEA Culham to IPP Prague. The purpose of the saddle coils is to create resonant magnetic perturbations (RMPs), either to simulate effects of RMPs that inevitably occur because of error fields or to exploit the impact of RMPs on the plasma, for example their ability to control the edge localized modes (ELMs). We have thus focused on examining the perturbation Fourier spectra and their resonances with the unperturbed safety factor profile. Those resonances result in creation of magnetic islands on the resonant magnetic surfaces and possibly of an ergodic region which leads to an increase in radial transport. Knowledge of the Fourier spectrum enables us to estimate the sizes and positions of the islands and location of the ergodic region. The computed perturbation field is also used to obtain Poincaré plots of intersections of field lines with a poloidal plane, which give a more precise image of the ergodic region. We present results of calculations for a selected configuration of saddle coils which gives a good edge ergodization, and discuss its possible impact on Type-I ELMs.

Introduction

Resonant magnetic perturbations (RMPs) are nonaxisymmetric perturbations of the tokamak equilibrium magnetic field. Their application to tokamak plasmas grew in importance in past years mainly because of their proven ability as a technique to suppress the Type-I Edge Localized Mode (ELM) instability, as demonstrated on the DIII-D tokamak [*Evans et al.*, 2005]. Generation of controlled RMPs by external coils is also an important technique for other areas of tokamak research. Examples of application are: simulation of the effect of RMPs that occur naturally because of various error fields, or investigation of neoclassical tearing modes (NTMs) [*Buttery et al.*, 2001].

The COMPASS (COMPact ASSembly) tokamak [*Pánek et al.*, 2006] is equipped with a flexible set of saddle coils for RMP generation, and is thus suitable for research of RMP effects. An especially interesting area of possible research is the suppression of the Type-I ELMs. ELMs are periodic instabilities localized at the plasma edge which lead to sudden release of the stored energy and particles from the tokamak plasma. They present a way to control plasma density and impurity content, but their bursty nature leads to increased wall and divertor power load. This would be a problem especially in a tokamak of the size of ITER, as the consequence would be an unacceptably rapid erosion of the divertor material. It is thus desirable to suppress ELMs or mitigate their negative impact by making them smaller and more frequent. It has been first observed on the DIII-D tokamak that applying RMPs created by a set of external coils can completely suppress ELMs or lead to ELMs of increased frequency and decreased amplitude. The mechanism is apparently connected to the observed decrease of density (and consequently pressure) gradients in the pedestal region near the separatrix. In those experiments RMPs lead to increased radial transport of particles, apparently by causing ergodization of magnetic field lines in the edge pedestal region, but details of the mechanism are not well understood [*Nardon et al.*, 2007].

Given the importance of the ELM suppression effect and its incomplete understanding, we would like to study it on COMPASS at IPP Prague, using the existing set of saddle coils. We assume that the new neutral beam injection (NBI) heating system [*Urban et al.*, 2006], which was not available during COMPASS operation at UKAEA Culham, will enable us to obtain Type-I ELMs suitable for such an experiment. To facilitate experiments with RMPs, we have performed calculations of the magnetic field generated by the COMPASS saddle coils.

First, an overview of the RMP theory is presented, starting with recalling some facts about the tokamak equilibrium and magnetic islands that appear when the equilibrium is perturbed. We summarize important properties of the perturbation field that must be taken into account when examining a system of RMP coils, and discuss the phenomenon of field line ergodization.

In the subsequent section, the saddle coils of COMPASS are described, together with the configuration we chose to examine. Methods and results of our examination of this configuration are then presented. Finally, we give our conclusion and ideas for future work.

Theory of RMPs

Magnetic islands

In the plasma equilibrium, the following relation holds as a manifestation of force balance between pressure and electromagnetic force:

$$\nabla p = \vec{j} \times \vec{B} \tag{1}$$

As a result of (1), the field lines stay on surfaces of constant pressure. In a toroidally symmetric equilibrium, a concentric set of nested surfaces around the magnetic axis is formed. To label them, we may use the flux of the poloidal component of the magnetic field inside a surface. The flux function is by definition constant on every such surface. The surfaces are also called "flux surfaces", or "magnetic surfaces". The poloidal flux, normalized so that it is 0 at the magnetic axis in the center of the chamber and 1 at the separatrix (plasma border), is a convenient way to express radial position and is noted ψ.

The field lines have the form of helices around the magnetic axis due to the tokamak toroidal and poloidal fields. The pitch of this helix is however not constant, because of the varying strength of both poloidal and toroidal fields. The average pitch of the helix is given by the parameter q – the safety factor. In some cases it is convenient to introduce an intrinsic poloidal "angle" coordinate θ^*, such that the field line looks like a straight line in the plane of (ϕ, θ^*) coordinates, where ϕ is the toroidal angle. In those coordinates, the equation for a field line is $\theta^* = \phi/q$. Together with ϕ, the functions ψ and θ^* define a complete coordinate system, with (ψ, θ^*) being coordinates in a poloidal plane. The transformation between usual Cartesian coordinates (R, Z) and the intrinsic coordinates (ψ, θ^*) depends on the particular equilibrium and provides information about the equilibrium – namely, the shape of flux surfaces and field lines.

If the toroidally symmetric equilibrium is perturbed by an additional toroidally asymmetric field, structures called "magnetic islands" appear. The perturbation has the biggest impact if it stays constant along a field line, so the deviation caused by the perturbation amplifies by resonance. For analysing this resonance, the intrinsic coordinate θ^* is useful. A perfectly resonant perturbating function has the form $\cos(m\theta^* + n\phi)$ and it is resonant with field lines on a surface where $q = -m/n$, resulting in the creation of a chain of magnetic islands. A general perturbation may be decomposed in a sum of functions proportional to $\cos(m\theta^* + n\phi)$ with varying m and n, which is effectively a Fourier decomposition in angles θ^*, ϕ. The coefficients B_{mn} of the Fourier decomposition of a perturbation $\delta B = \sum_{m,n} B_{mn} \cos(m\theta^* + n\phi)$ determine the width of island chains that the perturbation creates. Namely, the half-width of island is given by the formula [*Bécoulet et al.*, 2006]:

$$\delta_{mn} = \sqrt{\frac{4qR_M}{k_\theta S_h} b^r_{mn}}, \tag{2}$$

where $k_\theta = \frac{m}{r}$, $S_h = \frac{r}{q}\frac{dq}{dr}$ is the magnetic shear, b^r_{mn} is the (m, n) Fourier component of the radial part of the perturbation field normalized to B_M (field on the magnetic axis), and R_M is the major radius.

Basic facts about the perturbation field

The amplitude of the perturbation field Fourier components is a function of the radial position, expressed by the dimensionless flux variable ψ. If the perturbation is created by external coils, it will be generally strongest near the coils at the edge and diminish towards center. The shape of the radial dependency is different for every Fourier component and is determined by the number m. It can be approximated by the function r^{m-1}, where r is the radial distance from the magnetic axis [*Fitzpatrick et al.*, 1994]. It should be noted that m in this result is the mode number in the Fourier decomposition with respect to the geometric poloidal angle θ, not the intrinsic angle θ^* that is used elsewhere in the present work. Angles θ and θ^* are not completely identical, they differ especially near the separatrix.

The dependency on r leads to the necessity of employing perturbations with a high m number, so that they have a significant effect near the separatrix, avoiding large islands in the center where they might cause undesirable tearing modes. For resonance at a given value of q, this also means maximizing the n (toroidal mode number) of the perturbation.

Ergodization

If the island chains on different magnetic surfaces are sufficiently wide in the radial direction to overlap, they create a stochastic (also called ergodic) layer where magnetic surfaces are destroyed. Field lines then wander chaotically through the whole layer, making it possible to reach the vicinity of any point from any other point by following a field line. The transport in the ergodic layer is then significantly enhanced. There is a simple criterion for appearance of an ergodic region: the Chirikov criterion. It states that two neighboring island chains separated by a distance $\Delta_{m,m+1}$ must be wide enough so as to overlap, i.e.

$$\sigma_{chir} \equiv \frac{\delta_{mn} + \delta_{m+1,n}}{\Delta_{m,m+1}} > 1 \qquad (3)$$

where δ_{mn} is the half-width of an island, given by (2).

COMPASS saddle coil system

The saddle coils of COMPASS are composed of several dozens of poloidal and toroidal segments. The segments can be connected independently by two linkboards, resulting in a large number of possible configurations. For our investigation we chose a configuration as shown in Fig. 1. This configuration tries to maximize the perturbation field on the low field side and to obtain the greatest possible n, which in the case of COMPASS is only $n = 2$ due to the symmetry of coils.

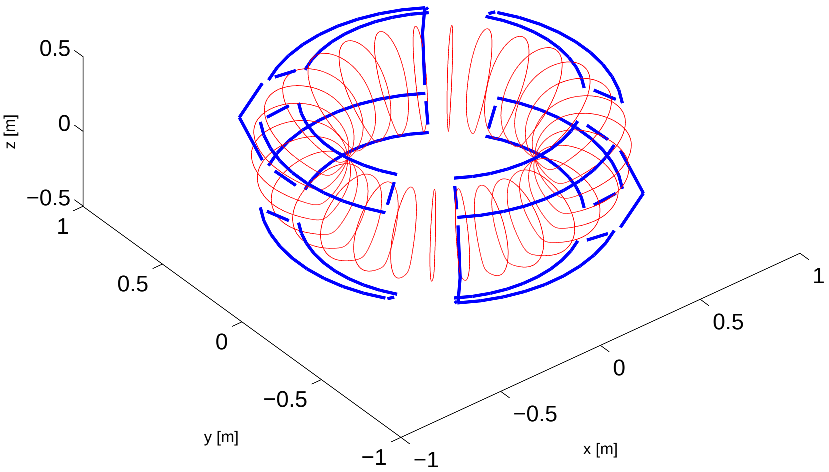

Figure 1. Schema of coils used in the studied configuration, with the outline of the plasma volume (thin lines).

Methods and results

Our aim is to obtain positions and sizes of the islands resulting from the RMPs. From the positions and sizes, we can estimate the ergodization by applying the Chirikov criterion (3). The criterion can be verified by tracing field lines of the known perturbation field and plotting their intersection with a poloidal plane – a surface-of-section Poincaré plot – which visualizes the islands and ergodic regions.

A similar task has been already performed for the DIII-D, JET and MAST tokamaks and for several design options of the RMP coils for ITER [*Bécoulet et al.*, 2006]. We therefore use the codes developed at CEA Cadarache for those cases, with modifications necessary to accommodate the significantly more complex saddle coil system of COMPASS.

Our calculations are performed in several steps. First, we describe the positions of individual coils and choose a specific configuration by specifying the currents in individual coils. Using the Biot-Savart law, we calculate the vector $\vec{A}$ on a cylindrical coordinate mesh in the area of interest. We perform Fourier decomposition of $\vec{A}$ in the toroidal angle coordinate ϕ and continue with the main Fourier component, which is $n = 2$ for COMPASS due to coil symmetry. We have thus eliminated one variable and the rest of the calculations can be performed in only two dimensions. From the $n = 2$ component of $\vec{A}$ we compute the corresponding component of magnetic field $\vec{B}$.

To proceed with the required computations of magnetic islands, we need to know the projection of the perturbation field onto the direction perpendicular to flux surfaces, and its contravariant component in this direction. To compute it, a knowledge of the equilibrium flux surfaces of $\psi = \text{const.}$ is necessary. We start with the the MHD code ACCOME [*Tani et al.*, 1992] , which has been already used to predict the equilibrium for COMPASS operation in IPP Prague [*Bilykova et al.*, 2006]. We chose an equilibrium for a case with NBI heating [*Urban et al.*, 2006], resulting in reverse shear, as the heating is applied off-axis. The resulting radial profiles of plasma variables and separatrix position are used as input to the MHD equilibrium code HELENA [*Huysmans et al.*, 1991], which recomputes the equilibrium and outputs the mesh of intrinsic coordinate system (θ^*, ψ) and its metric. The resulting mesh is shown in Fig. 2.

We project the perturbation field vector onto the resulting mesh, thus obtaining the necessary contravariant radial component. Using the metric, we can also compute the magnitude of this component in physical (Tesla) units. Fig. 3 shows the dependency of this field (normalized to the total field) on the position in the poloidal plane.

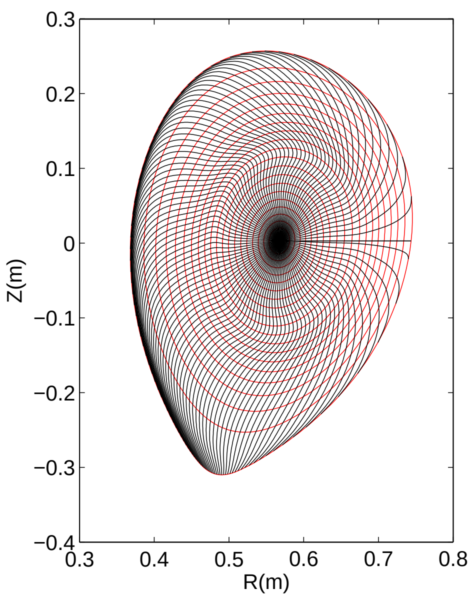

Figure 2. The coordinate mesh of (θ^*, ψ) intrinsic coordinates, computed by HELENA from the equilibrium predicted by ACCOME for a shot with NBI heating.

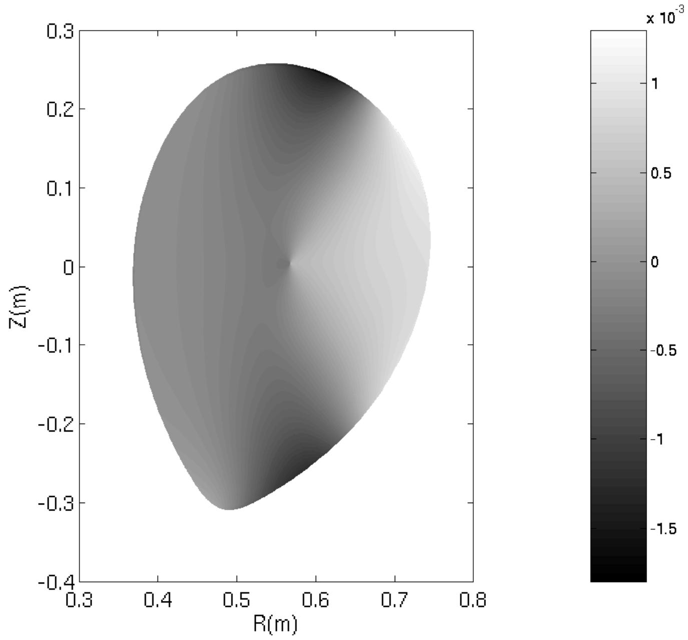

Figure 3. Magnitude of the radial component of the main $n = 2$ Fourier harmonics of the perturbation field as a function of position in the poloidal plane. The field magnitude is normalized to the total field.

The radial component is finally subjected to Fourier decomposition in the intrinsic poloidal angle θ^*. The dependency on θ^* is again obtained using the (θ^*, ψ) mesh from HELENA. What results is the

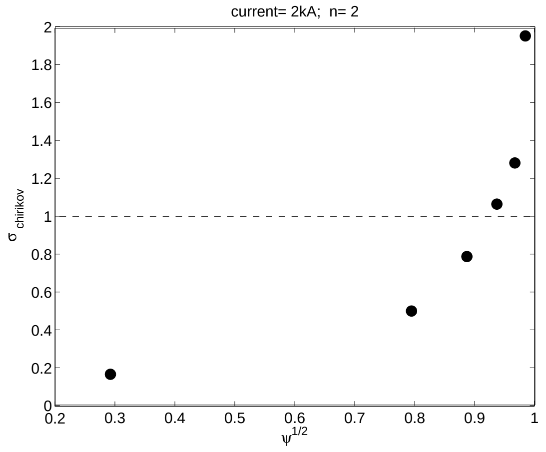

Figure 4. Dependence of the Chirikov parameter $\sigma_{\mathrm{Ch}ir}$ on the dimensionless radial coordinate $\sqrt{\psi}$ for the coil current of 2 kA.

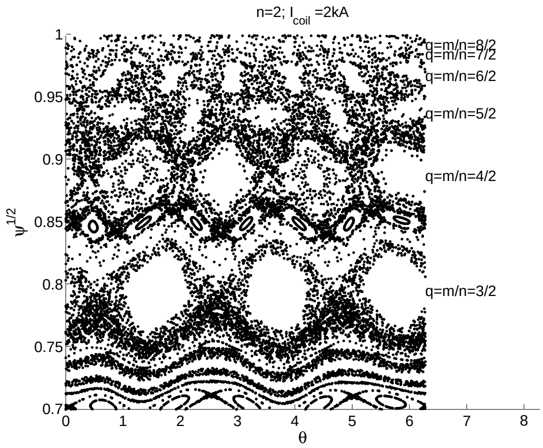

Figure 5. Poincaré plot of intersection of field lines with the poloidal plane, for the coil current of 2 kA.

dominant $n = 2$ component of the (m, n) spectrum of the contravariant radial component of $\vec{B}$. This is sufficient for examination of resonance with the q profile, using the criterion for resonance $q = m/n$. We use the spectrum below to compute island sizes, the Chirikov parameter and estimate ergodization. Positions of the magnetic islands can be obtained from the resonance criterion, because islands are located at the resonant values of q.

All the previous calculations were done with a saddle coil current of 1 kA. The field components for another current are obtained through multiplication by an appropriate factor. For estimating the resulting ergodization, we chose a current of 2 kA, which is a realistic value for COMPASS saddle coils. Fig. 4 shows the radial dependence of Chirikov parameter $\sigma_{\mathrm{Ch}ir}$ obtained from the island distances and sizes computed from the $B_{mn}(\psi)$ components. We can see that $\sigma_{\mathrm{Ch}ir}$ is greater than 1 in the region of $\sqrt{\psi} > 0.95$, whose ergodization is believed to be crucial for an effect on ELMs. Finally, we integrate the field line equations, using the previously obtained values of perturbation field. We begin with starting positions distributed on a rectangular mesh in the poloidal plane, and from each of these initial conditions we follow the field line for 400 turns around the major axis and plot the intersections with the poloidal plane. Fig. 5 shows the result. We may observe that the ergodic region is larger than predicted by the Chirikov criterion, it extends from a value of $\sqrt{\psi}$ less than 0.85.

Conclusion

We have developed a procedure to obtain the perturbation field spectra, sizes and positions of the resulting islands, estimate of field line ergodization and Poincaré plots for a selected configuration of the COMPASS saddle coils and a known equilibrium. We have seen that the studied configuration of saddle coils produces good ergodization of the pedestal region in the ACCOME-predicted equilibrium. Considering the experience from DIII-D, we may expect an effect on Type-I ELMs, if we succeed in obtaining them on the re-installed Compass. Knowledge of islands and ergodization is also a prerequisite for any other exploitation of saddle coils.

Future research will be concentrated on the investigation of the observed discrepancy between ergodization estimate based on Chirikov criterion and Poincaré plots. The Chirikov criterion is expected to underestimate ergodization because it takes into account only the primary resonances and not the higher order resonances. The observed discrepancy is however probably larger than would be expected.

A possible improvement to the process outlined above would be to integrate the computation of intrinsic coordinate mesh into the ACCOME code, which would eliminate the need for recomputation of the equilibrium using HELENA code.

Finally, a limitation of our calculations is that they are done by superposing the vacuum field of saddle coils with the equilibrium field, disregarding a possible plasma response to the perturbation field. The impact of a plasma response to the perturbation field is currently the subject of ongoing research in CEA Cadarache and it should be represented in our codes, once it is better theoretically understood.

The plasma response is expected to be caused mainly by eddy currents caused by the interaction of the perturbation field with the toroidal rotation. Better knowledge of the toroidal rotation in COMPASS will be thus needed to estimate the plasma response.

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