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Analysis of the Structure of Tearing Modes in ASDEX Upgrade

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1. Introduction

The occurence of tearing modes and the associated magnetic islands limits the energy content of magnetically confined fusion plasmas and may set a severe constraint on the performance of a future fusion reactor [1]. Thus, detailed knowledge of tearing mode behaviour is required. The magnetic structure of a tearing mode is determined by the helical magnetic equilibrium and perturbation fluxes. The dynamic behaviour is governed by the perturbation flux and can be described by the nonlinear stability parameter Δ'. Ren [2] has developped a method to determine Δ' from ECE temperature data for use at TFTR. However, this method is not suited for the strongly asymmetric islands in ASDEX Upgrade due to its constraints. Here, a more precise model of the magnetic structure and the temperature profile of a magnetic island is needed to analyse the experimental observations and to determine Δ'. This work presents such a model and a typical example of an experimentally observed magnetic island.

2. Experimental Setup for the Observation of Magnetic Islands

In ASDEX Upgrade the plasma electron temperature profile is measured by Electron Cyclotron Emission spectroscopy (ECE) at different radial positions in one poloidal cross-section. Due to the toroidal rotation of the neutral beam heated plasma a magnetic island seems to rotate in the poloidal cross-section and causes a periodic variation in the temperature profiles. A contour plot of the ECE signals of several radial positions during one period gives an image of a magnetic island temperature profile.

Since the usual sample rate of 32 kHz of the diagnostic is not sufficient for mode frequencies of typically 20 kHz measurements have been made with higher sample rates at fifteen adjacent radial positions in the island region. For the fast measurements a system with sixteen Nicolet ADCs was used which allow data recording during a part of the shot time. The remaining ADC was used to record the signal of one Mirnov coil as reference for the island phase. A scan of the toroidal magnetic field (about 2% per second) was applied in some shots (with sample rates of 1MHz or 500kHz and measurement times of 1s or 2s). Thus, the radial position of the ECE channels was shifted by the same percentage (e.g. 6cm at a major radius of 2.0m) and the complete island could be observed at least in a part of the measurement time though the island position usualy varies slightly from shot to shot.

The data was converted into temperature signals according to the procedure applied to the regular ECE signals. Further smoothing of the radial profiles was needed for the calibration of the ECE channels is usually associated with some error. Since at the observed microwave frequencies the plasma behaves as black body radiator the ECE signal contains white noise and some kind of filtering of the mode frequency and its harmonics is necessary. Therefore, several magnetic islands were averaged to the temperature profile of one where the incoherent noise signal is attenuated. This averaging process was performed over a short period of time in which the island structure can be expected to be stable (e.g. 5ms, according to hundred islands at a mode frequency of 20kHz). For further evaluation a Fourier transform of the temperature profile of the averaged island was made and the radial profile of the Fourier components and their phase was analysed (an example will be given below).

3. Numerical Modelling of Magnetic Islands

A magnetic island is determined by the magnetic equilibrium flux and the perturbation flux. The formation of a magnetic island leads to an altered plasma temperature profile, i.e. to temperature flattening inside the island separatrix. Thus, the magnetic structure determines the Fourier components of the island temperature profile. Hence, by fitting the Fourier components of a theoretically predicted temperature profile to the experimental data the fluxes may be reconstructed and the nonlinear stability parameter Δ' can be assessed.

Modelling the island temperature profile requires the solution of the heat flux equation. For a simplified symmetric magnetic island Fitzpatrick [3] has presented an analytical model of the temperature profile. However, in order to reconstruct the magnetic structure of the strongly asymmetric islands in ASDEX Upgrade more realistic flux functions must be assumed which require a numerical treatment of the heat flux equation.

In the vicinity of the resonant surface in absence of any heat source or sink and using $\nabla_\perp^2 T = \nabla^2 T - \nabla_{||}^2 T$ the heat flux equation reduces to

$$\kappa_\perp \nabla^2 T + (\kappa_{||} - \kappa_\perp)\nabla_{||}^2 T = 0 \quad . \tag{1}$$

Here, $\nabla_\perp$ and $\nabla_{||}$ denote the derivative of the temperature T perpendicular or parallel to the magnetic field lines and $\kappa_\perp$ and $\kappa_{||}$ denote the (constant) thermal conductivities. The missing heat source has to be replaced by suited boundary conditions. The term

$$\nabla_{||}^2 = (\vec{b} \cdot \nabla)^2 \tag{2}$$

must be calculated assuming an expression for the magnetic field structure. If the temperature variations along lines with constant helical angle vanish the calculation can be performed on a poloidal cross-section of the tearing mode. A slab geometry is used with the radial coordinate r and the helical angle $\zeta = m\Theta$ where m is the poloidal mode number and Θ the poloidal angle. The magnetic field is conveniently written in terms of the helical flux $\chi(r,\zeta) = \chi_0(r) + \chi_1(r)\cos\zeta$ according to $\vec{B} = \nabla\chi \times \hat{e}_z$ where $\chi_0(r)$ and $\chi_1(r)$ denote the radial function of the equilibrium and perturbation flux. The equilibrium flux can be computed from a simple current profile $j(r) = j_0(1 - (r/a)^2)$ to be

$$\chi_0(r) = \frac{\mu_0 I_0}{8\pi a^4}(r^2 - r_{res}^2)^2 \tag{3}$$

where I_0 is the plasma current, r_{res} the minor radius of the resonant surface and a the minor plasma radius. For the radial form of the perturbation flux the ansatz

$$\chi_1(r) = \begin{cases} \frac{\mu_0 I_0 r_{res}^4}{8\pi a^4}\alpha \left(\frac{r}{r_{res}}\right)^m \left(1 - \beta\frac{r}{r_{res}}\right) & \text{for}\, r \leq r_{res} \\ \frac{\mu_0 I_0 r_{res}^4}{8\pi a^4} \frac{\alpha(1-\beta)-\gamma+\gamma r/r_{res}}{(r/r_{res})^{m+1}} & \text{for}\, r > r_{res} \end{cases} \tag{4}$$

is used where α, β and γ are the fit parameters. Both parts of the function connect at the resonant surface but with different derivatives. They were constructed to have the correct behaviour in the limits $r \to 0$ and $r \to \infty$.

The partial differential equation (1) is solved numerically (by the commercially available PDE solver FlexPDE) to give the island temperature profile of which a Fourier transform is made. The example presented in fig. 1 is similar to the experimentally observed island in the next section. Due to the asymmetry of the realistic fluxes the island geometry is asymmetric. According to theory [3] the temperature profile inside the island separatrix is nearly flat whereas the temperature is a flux surface function outside apart from the X-point region. The heat flux concentrates on a small region around the separatrix and heat is transferred over the island at the X-points where the temperature deviates from the flux surfaces. This takes place on a scale of the critical island width W_c that an magnetic island must have to be completely flattened (see [3]). As described by Fitzpatrick [3] the maxima of the first Fourier component give approximately the position of the island separatrix at the O-point whereas the minimum of the first Fourier component determines the position of the resonant surface. The minimum of the first Fourier component is associated with a π jump in phase that facilitates the detection. The modelled perturbation flux yields a value of $\Delta' = -3.7$ belonging to a neoclassical tearing mode.

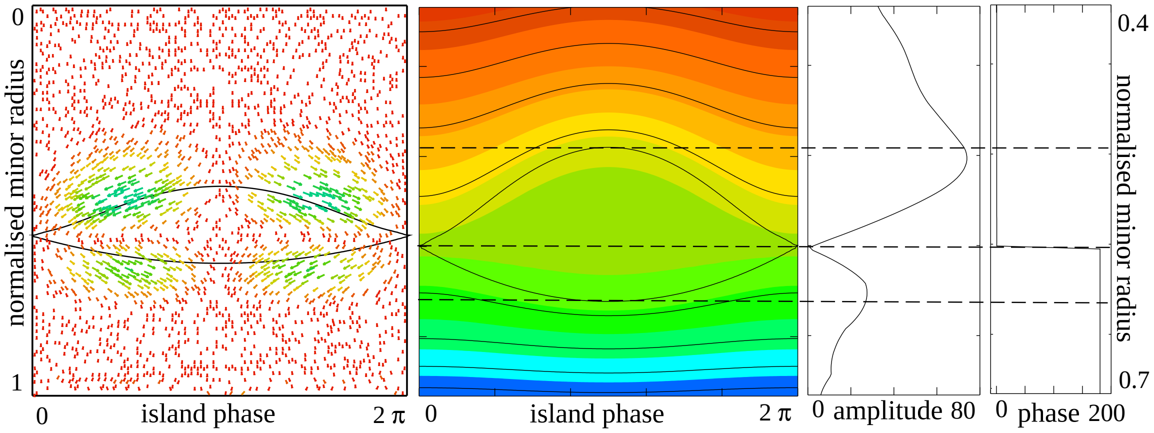

Figure 1: *Modelled heat flux around an asymmetric magnetic island (left), island temperature profile (center) with flux surfaces and radial profile of the first Fourier component (right). The heat flux plot was made with $\kappa_{||}/\kappa_{\perp}$ unrealistically low. Otherwise, the heat flux would concentrate on an extremely small region around the island separatrix.*

4. Experimental Observation of Magnetic Islands

Fig. 2 shows the temperature profile of an averaged (3,2) neoclassical magnetic island occuring at the β limit and the analysis of geometry by the first Fourier component. Consistent with theory the island is asymmetric, but the temperature profile inside the island is not completely flattened as expected from theory. Substructures of the temperature inside a magnetic island have also previously been reported [4]. In accordance with the numerical model the temperature seems to deviate from the flux surfaces near the X-point on a width of about 3cm. This may correspond to the critical island width W_c. From this the ratio of the parallel to perpendicular thermal conductivities can be computed to be in the order of 10^7 whereas a value of 10^{10} and hence $W_c \approx 0.8cm$ would be expected [5]. The physics causing this discrepancy is not yet clear but it implies that W_c may be relevant for neoclassical tearing mode dynamics. A toroidal magnetic field scan was made in this shot and the shift of the resonant surface with changing field has been determined (see fig. 2). With a given q-profile the resonant surface should move inward with rising toroidal field but the opposite is observed in this case. This may be explained by a changing current profile and thus q-profile.

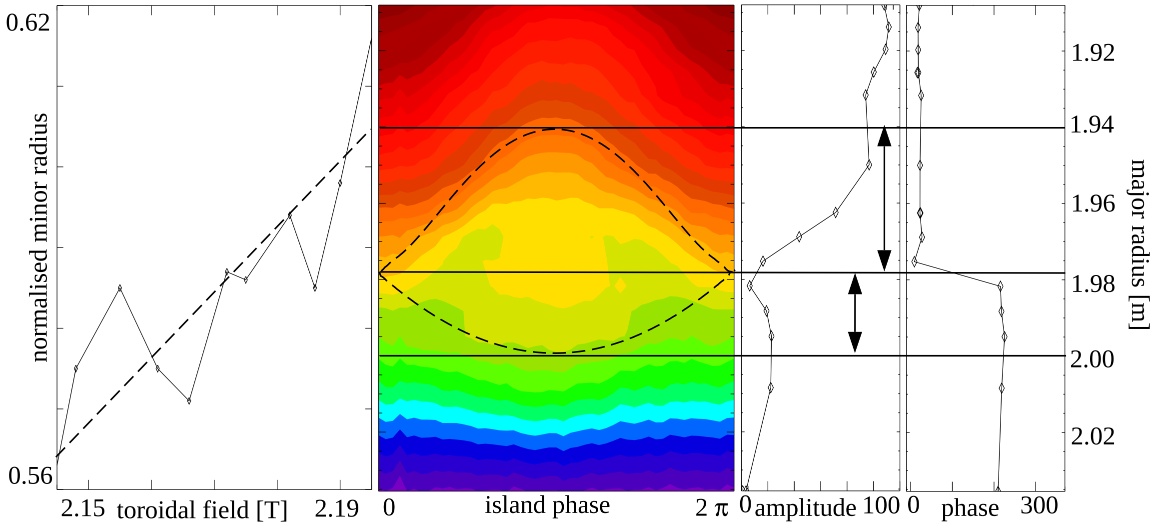

Figure 2: *Temperature profile (center) and determination of geometry of an averaged (3,2) neoclassical magnetic island in ASDEX Upgrade (# 11681, 3.3-3.305s). The separatrix (broken line, taken from the numerical model) can be inferred from the amplitude of the first Fourier component (right) and the location of the resonant surface from its phase. The further rise of the Fourier amplitude may be due to a coupled (2,2) mode. During a scan of the toroidal magnetic field the resonant surface unexpectedly moves outward with rising field (left) (the shift is less than 2cm).*

5. Conclusions

The electron temperature profile of a (3,2) magnetic island associated with a neoclassical tearing mode in ASDEX Upgrade has been experimentally observed with high spatial and temporal resolution by ECE. The geometry of the magnetic island can be analysed by its Fourier components. Modelling of the island temperature profile was performed by numerical solution of the heat flux equation taking into account realistic radial profiles of the magnetic fluxes. Comparing the theoretically predicted temperature Fourier components to the experimentally observed data the magnetic structure can be reconstructed. However, a reliable determination of Δ' could not yet be done. Future work will focus on establishing such a method.

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