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Analysis of the Dynamics of Tearing Modes in ASDEX Upgrade

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1. Introduction

A tearing mode is a resistive magnetohydrodynamic (MHD) instability characterised by a helical perturbation current on a resonant surface in a tokamak plasma. In a classical tearing mode the perturbation current is due to an unfavourable equilibrium current profile. The associated perturbation of the magnetic configuration leads to reconnection of the flux surfaces and hence to the formation of so-called magnetic islands. Due to the resulting dramatically reduced radial heat isolation the temperature and density profiles inside the islands are flattened. An important consequence is a loss of confined energy what can be observed by a drop in β occuring at mode onset. Another consequence is a reduction of helical bootstrap current which represents a destabilising perturbation current. In high β discharges reaching the β limit this loss of bootstrap current associated with a small seed island generated e.g. by a sawtooth crash may lead to further island growth although the seed island should be classically tearing stable. These so-called neoclassical tearing modes (NTM) limit the energy content of magnetically confined fusion plasmas at high β [1]. Thus, tearing modes deserve closer investigation of their magnetic structure [2] and dynamics. In this work the theoretically predicted island dynamics given by the generalised Rutherford equation is compared with experimental observations in ASDEX Upgrade. Thus, the free parameters of the Rutherford equation can be assessed.

2. Theoretical description of magnetic island dynamics

The growth of a neoclassical tearing mode can be described by the generalised Rutherford equation for the magnetic island width W [3, 4]:

$$\begin{aligned}\frac{\tau_{res}}{r_{res}}\frac{dW}{dt} &= r_{res}\Delta'(W)\\ &\quad + r_{res}\beta_p\left(a_{BS}\sqrt{\varepsilon}\frac{L_q}{L_p}\frac{W}{W^2+W_0^2} - a_{GGJ}\frac{r_{res}}{R_0^2}\frac{L_q^2}{L_p}\frac{1}{W} - a_{Pol}\left(\rho_p\frac{L_q}{L_p}\right)^2 g(\varepsilon)\frac{1}{W^3}\right)\\ &\quad - a_{ECCD}\frac{1}{2\sqrt{\pi}}\frac{r_{res}}{d}L_q\frac{I_{ECCD}}{I_P}\frac{1}{W}\quad .\end{aligned} \tag{1}$$

Here, $\tau_{res} = \mu_0 r_{res}^2/(1.22\eta)$ is the resistive time scale (η plasma conductivity), r_{res} the minor radius and $\varepsilon = r_{res}/R_0$ the inverse aspect ratio of the resonant surface. $L_q = q/q'$ and $L_p = p/p'$ denote shear and pressure decay length. The values of $\beta_p = 2\mu_0 p/B_p^2$ (B_p poloidal magnetic field) and the poloidal ion larmor radius $\rho_p = \sqrt{2m_iT}/(\sqrt{e}B_p)$ (T in eV) are also to be taken at the resonant surface. The nonlinear stability parameter $\Delta'(W)$ describes the stability of the equilibrium current profile against tearing mode instability [5]. The following destabilising bootstrap term includes the reduction of neoclassical drive by finite heat conductivity across the island through $W_0 = 5.1(\chi_\perp/\chi_\|)^{1/4}(r_{res}L_q q/(\varepsilon m))^{1/2}$ that will lead to an incomplete flattening of $T_e(r)$ within the island for small W [6]. The next two terms describe the stabilising effects of shaping and toroidicity (Glasser-Green-Johnson-effect) and of the polarisation currents induced by the motion of the island through the plasma [7, 8]. In the cases considered here the plasma collisionality is low and hence $g(\varepsilon) = \varepsilon^{3/2}$ is used whereas the polarisation term becomes much more important in 'collisional' plasmas where $g(\varepsilon) = 1$. The constants a_{BS}, a_{GGJ} and a_{Pol} are the free numerical parameters of the Rutherford equation whose values have to be determined in this work. The last term describes the stabilising effect of electron cyclotron current drive (ECCD). The deposition of microwave power in an area of width d (typically $d = 5cm$) causes a noninductively driven current I_{ECCD} (I_P is the plasma current). The coefficient can be approximated by $a_{ECCD} = 34d/W \cdot exp(-d/W)$ if $d/W \leq 0.5$ and $a_{ECCD} = 10.311$ if $d/W > 0.5$ [9].

As a necessary but not sufficient condition for $dW/dt > 0$ and hence instability of a neoclassical tearing mode β_p must exceed a critical value $\beta_{p,crit}$. In this case the generation of a seed island e.g. due to a sawtooth crash is sufficient for further growth of the mode if the seed island width exceeds a critical width $W_{seed,crit}$. The island grows until its width is equal the saturated island width W_{sat} which is in good approximation proportional to β_p. During the increase of magnetic island size β_p drops from its initial value due to the flattening of the pressure profile.

3. Fit of the Rutherford equation

The magnetic structure of an island can be visualised by its electron temperature profile measured by electron cyclotron emission (ECE) spectroscopy [2]. Further analysis can be performed with the Fourier transform of the temperature profile [2, 6] in order to assess r_{res} (taken as constant) and W for some timepoints. Together with the electron density (measured by interferometry, DCN deconvolution) $T_e(t)$ from ECE gives the plasma pressure and thus $\beta_p(r_{res}, t)$. The pressure profile gives L_p (taken as constant). From $T_e(t)$ also $\tau_R(t)$ can be derived using the neoclassical resistivity for small ε [10] and $Z_{eff}(t)$. For ρ_p an averaged value of $T_e(r_{res})$ is used. $L_q = 0.3$ m is taken from a q-profile using a modelled current density. A typical value for W_0 is 8mm (with $\chi_{\|}/\chi_{\perp} = 10^{10}$). For the function $\Delta'(W)$ a constant value $\Delta'_0 = -m/r_{res}$ is used (m is the poloidal mode number) [3].

The island width evolution $W(t)$ is reconstructed from its relative change measured by Mirnov coil signals (which measure any change of the poloidal magnetic field that also contains the perturbed field dB_1/dt of the rotating island) and the absolute values measured by ECE. The Mirnov signal according to the observed (3,2)-modes is separated by singular value decomposition. The signal is integrated and the envelope is taken in order to get the amplitude $\hat{B}_1(t) \sim W(t)^2$. ELM activity and sawteeth which show up in the Mirnov signal have to be removed. The seed island width can be assessed by the signal at mode onset.

The Rutherford equation has to be fitted to the experimentally measured island dynamics in order to obtain the values of the free parameters a_{BS}, a_{GGJ} and a_{Pol}. Since dW/dt cannot be taken from the measurements of $W(t)$ with sufficient accuracy due to signal noise the Rutherford equation has been numerically solved for varying sets of parameters a_{BS}, a_{GGJ} and a_{Pol} using the measured $\beta_p(t)$. The best fits have been determined by application of a least squares fit neglecting the island growth phase (where $W(t)$ cannot be measured with sufficient accuracy) and giving the same weight to the island decay phase as to the rest. Thus, a_{Pol} can be determined with more confidence since the polarisation term is most effective with small W. Fitting has been done for four different β limit discharges in ASDEX Upgrade (plasma current 800 kA, line averaged density $6 \cdot 10^{19} m^{-3}$, heating power 10 MW, toroidal magnetic field 2.05-2.17 T, $q_{95} \approx 4.5$). An example is shown in fig. 1. Fig. 2 shows the projection of the fifty best parameter sets (a_{BS}, a_{GGJ}, a_{Pol}) for those discharges to the a_{BS}-a_{GGJ} and the a_{BS}-a_{Pol} plane. All these parameter sets yield very similar solutions of the Rutherford equation. The linear dependence of a_{GGJ} on a_{BS} is due to the $1/W$ dependence of both bootstrap and Glasser-Green-Johnson effect when W is large and W_0 can be neglected. Thus, regarding the unevitable uncertainties of the different measurements entering into the plasma parameters of the Rutherford equation it is not reasonable to look for the very best fit and hence only a range of the parameters can be obtained.

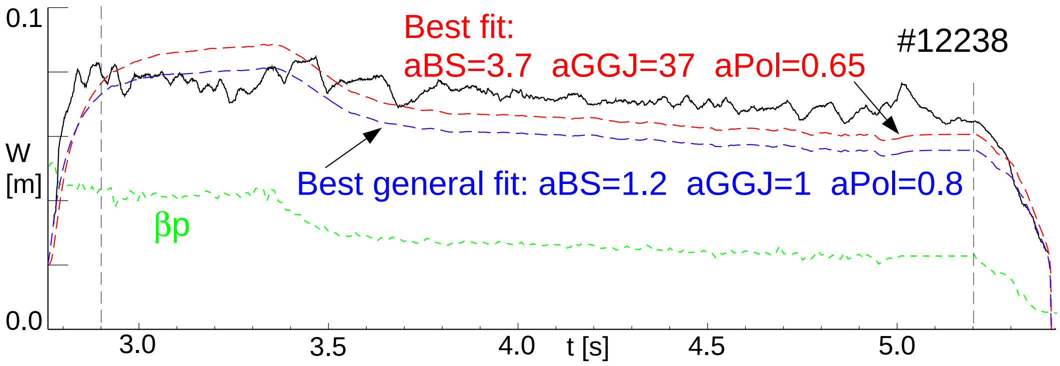

Figure 1: *Best fit of the Rutherford equation for discharge 12238 of ASDEX Upgrade. Also the best general parameter set for discharges 11657, 11671 and 12238 yields a good fit. For comparison $\beta_p(t)$ is shown (dotted).*

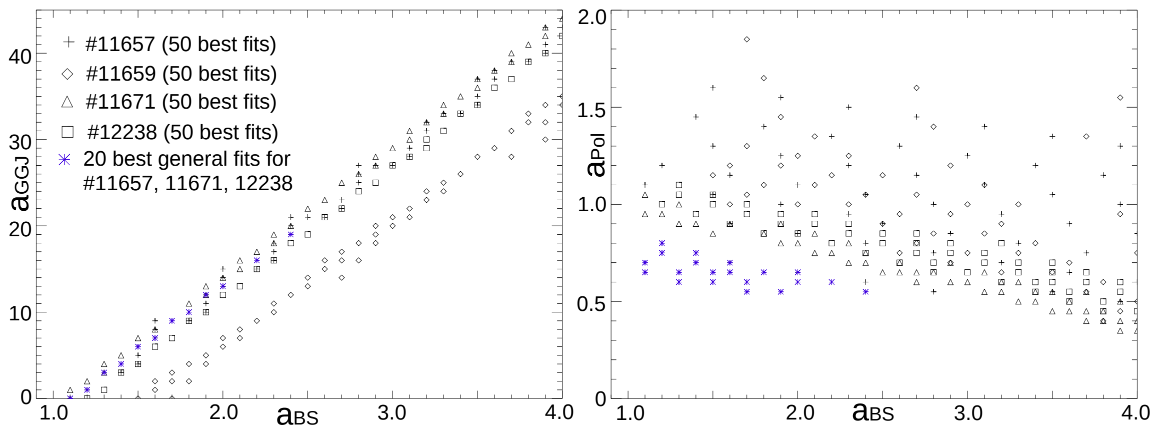

Figure 2: *Best fits of the free parameters of the Rutherford equation for discharges 11657, 11659, 11671 and 12238 of ASDEX Upgrade in projection to the a_{BS}-a_{GGJ} and a_{BS}-a_{Pol} plane. Also shown are the best general parameter sets for discharges 11657, 11671 and 12238.*

For the determination of the free parameters of the Rutherford equation a general parameter set for all discharges has to be found. This has been done by minimisation of the averaged fitting errors of the fits for three of the discharges. As result we get some best general parameter sets also yielding very similar results. For an example and comparison of the parameters see figs. 1 and 2. The best general parameter set also gives fair fits for the discharges 11657 and 11671 which however do not model the island decay.

Fig. 3 shows the stabilising effect of ECCD in the solution of eq.(1) for the same example as above. Using the experimentally measured $\beta_p(t)$ a value of $I_{ECCD}/I_P = 0.8\%$ is needed for modelling complete stabilisation. However, β_p increases with decreasing W in real stabilisation experiments requiring higher values of I_{ECCD}/I_P for complete stabilisation. Thus, a model of $\beta_p(W)$ should be implemented for consistent simulation of ECCD stabilisation. Complete ECCD stabilisation of NTMs has been experimentally performed in ASDEX Upgrade with $I_{ECCD}/I_P = 1-2\%$ as calculated by

TORAY [11].

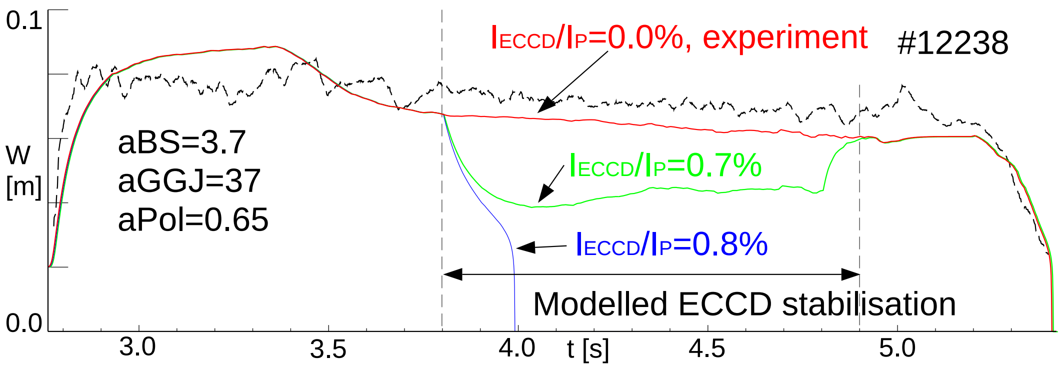

Figure 3: *Simulation of ECCD stabilisation by the numerical solution of the Rutherford equation with the best fitting parameters and the measured* $\beta_p(t)$ *for the discharge. Using* $I_{ECCD}/I_P = 0.7\%$ *the island size is reduced, using* $I_{ECCD}/I_P = 0.8\%$ *complete stabilisation is attained.*

4. Conclusions

The free parameters of the Rutherford equation have been assessed by fitting its solution to the experimentally observed island width evolution for four experiments in ASDEX Upgrade. Because of the inaccuracies of experimental measurements only ranges for the parameters can be determined. Also a range of general parameters can be found that gives fair fits for three of the experiments. The determination of the free parameters of the Rutherford equation is important for the computation of the required microwave power for ECCD stabilisation of neoclassical tearing modes in existing and planned fusion experiments. With the determined parameters the Rutherford equation can be used in order to simulate ECCD stabilisation.

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