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Fitting of the Modified Rutherford Equation: a comparison bewteen ASDEX Upgrade and JT-60 results

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The Modified Rutherford Equation and NTM stabilization experiments with ECCD

The Modified Rutherford Equation (MRE) is used to model and compare with the experimental observations the temporal behavior of a magnetic island width W associated to the Neoclassical Tearing Mode (NTM) instability in tokamak plasmas. The MRE has the form [1],[2]:

$$\frac{\tau_s}{r_s}\frac{dW}{dt} = r_s\Delta' + c_{\mathrm{sat}}(r_s\Delta'_{\mathrm{GGJ}} + r_s\Delta'_{\mathrm{bs}}) + c_{\mathrm{stab}} r_s \Delta'_{\mathrm{ECCD}} \tag{1}$$

where the free coefficients c_{sat} and c_{stab} are machine independent parameters which account for toroidicity corrections and incomplete physics at saturation ($dW/dt = 0$) and at stabilization ($dW/dt < 0$), respectively. As the MRE is derived in cylindrical geometry with large aspect-ratio assumption [3], it is very important to test it against experimental data and in particular to compare the fitting results from different machines to check the consistency of the model over a large database and its predictive capabilities for ECRH power requirements in ITER. In this work, the MRE is tested against experimental data from ASDEX Upgrade and JT-60 to get a common set of c_{sat} and c_{stab} in the case of $m/n = 3/2$ NTMs in H-mode plasmas.

Experimental database: ASDEX Upgrade and JT-60 experiments on NTM stabilization with ECCD

The database selected from JT-60 and ASDEX Upgrade consists of 14 discharges in which a $(3,2)$ NTM has been completely or partially stabilized by using the Electron Cyclotron Current Drive (ECCD). The analyzed experiments have been performed in H-mode scenario, $\beta_N \sim 2$ and $q_{95} \sim 4.5$ at ASDEX Upgrade [4] and $\beta_N \sim 1.5$ and $q_{95} \sim 3.8$ at JT-60 [5]. As fig. 1 shows, NTM stabilization experiments are performed in a very similar way both at ASDEX and at JT-60: the NTM is triggered by an increase of NBI power and once the mode has reached a saturated phase, ECCD is injected for $2-3$ seconds after which the island usually shrinks to zero and the β rises again. At ASDEX Upgrade the ECRH system used to inject ECCD consists of 4 gyrotrons which deliver up to 1.5 MW at $B_T \sim 2.2$T. At JT-60 the 4 gyrotrons deliver up to 3 MW at $B_T \sim 3.7$ T. The main difference between the two machines lies in the different schemes

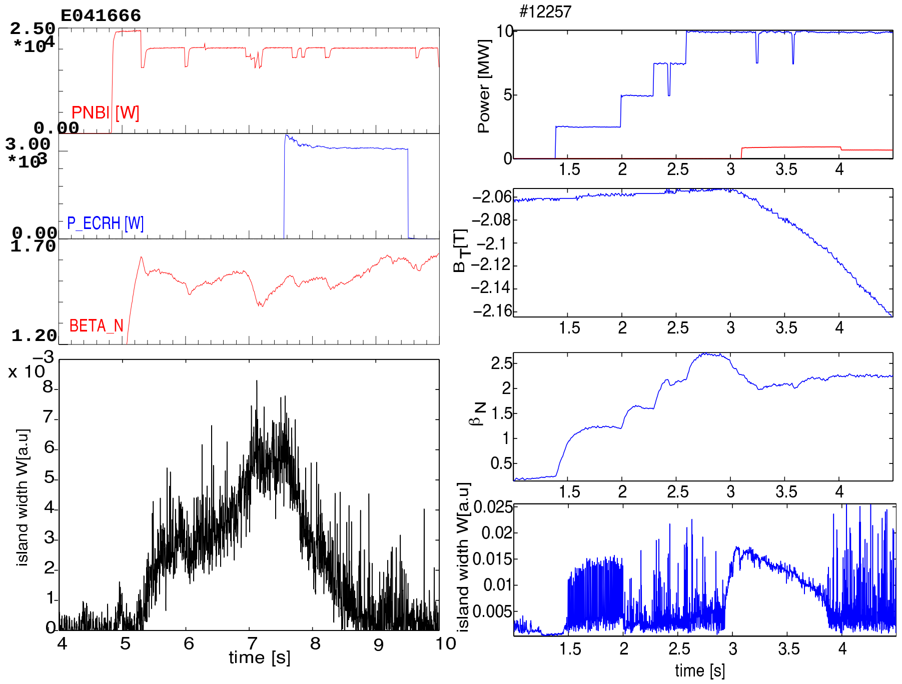

Figure 1: NTM stabilization experiments: JT-60 (left) vs. ASDEX Upgrade(right) scheme

adopted to hit the resonance surface of the NTM. At ASDEX Upgrade a slow linear scan of the toroidal magnetic field B_T (10% variation) is performed to hit the O-point of the magnetic island whereas at JT-60 the ECCD injection localization is optimized by slightly changing the ECCD beam position in the plasma between discharges. This has important implications in the alignment between ECCD and the magnetic island. In fact, for ASDEX Upgrade the radial alignment is linearly changing in time (at the speed rate of the linear B_T scan) whereas for JT-60 the alignment is considered to be almost constant in time. The misalignment at JT-60 is assumed to be ~ 2 cm as estimated from the localization of the effective increase of the temperature δT_e during ECCD injection [5].

Determination of c_{sat}

The fitting coefficient c_{sat} is evaluated by measuring all the necessary plasma parameters at saturation time t_{sat} when $dW/dt = 0$ and $\Delta'_{\mathrm{ECCD}} = 0$ and therefore $c_{\mathrm{sat}} = \frac{\Delta'}{\Delta'_{\mathrm{bs}} + \Delta'_{\mathrm{GGJ}}}$. One of the main challenges for applying the MRE for the study of the NTMs is that a set of about 20 parameters and delicate quantities such as the saturated island size W_{sat}, the bootstrap current density j_{bs}, q profile and the various gradient lengths $L_n = n/n'$, $L_T = T/T'$, $L_q = q/q'$, the ECCD current density j_{ECCD} and the ECCD deposition width d, etc. need to be calculated. In this work, the same tools and same definitions have been consistently used to calculate these quantities for both machines. Fig. 2 shows that the result for the fitting of c_{sat} for ASDEX Upgrade (# < 40000) and JT-60 (# > 40000) are in good agreement. The indicative error bars in

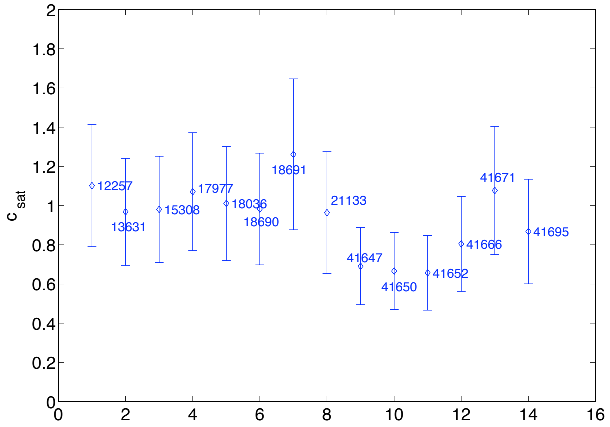

Figure 2: Values of c_{sat} for the complete database from ASDEX Upgrade and JT-60.

fig. 2 are obtained by using a gaussian error analysis tool which randomizes the experimental quantities present in the MRE within their standard deviation. Sensitivity studies showed that the three most determining quantities for the evaluation of c_{sat} are W_{sat}, j_{bs} and L_q. The error bar on c_{sat} was calculated by randomizing for 10000 times these three quantities over their standard deviation, which was assumed to be 15%, 15% and 10% respectively.

Determination of c_{stab} and integration of the MRE

Once c_{sat} is calculated, the ECCD term in the MRE is "switched on" and the plasma parameters are measured at the time t_{ECCD} when the mode is observed to be experimentally stabilized. The MRE is then integrated [6] as $W(t) = \int \frac{dW}{dt} dt$ and c_{stab} is determined by matching the simulated evolution *W(t)* with the experimental one $W(t) \sim \sqrt{\dot{B_\theta}}$ as shown in fig. 3. Fig.3 also shows the results for the determination of c_{stab}. The evaluation of c_{stab} is very delicate since the efficiency of the ECCD injection depends on the relative width of the ECCD beam (W/d) and the radial misalignment ΔR between the center of the island and the ECCD beam. For modelling the stabilization, the initial misalignment ΔR_0 is an important parameter and therefore when matching the simulated $W(t)$ with the experimental one it is not possible to clearly discriminate between the effect of c_{stab} and ΔR. In principle this would be possible if the ECRH power would be the minimum required one. The analyzed experiments, though, did not aim at this study, which is anyway planned for the future. Various aspects determine the large uncertainty on c_{stab}; as far as the modeling of the Δ_{ECCD} term in Eq. 1 is concerned, the contribution of the $(0,0)$ component of the ECCD injected current (change in Δ') should be also taken into account [7] together with a more realistic asymmetric shape of the magnetic island W [8]. The experimentally uncertainty

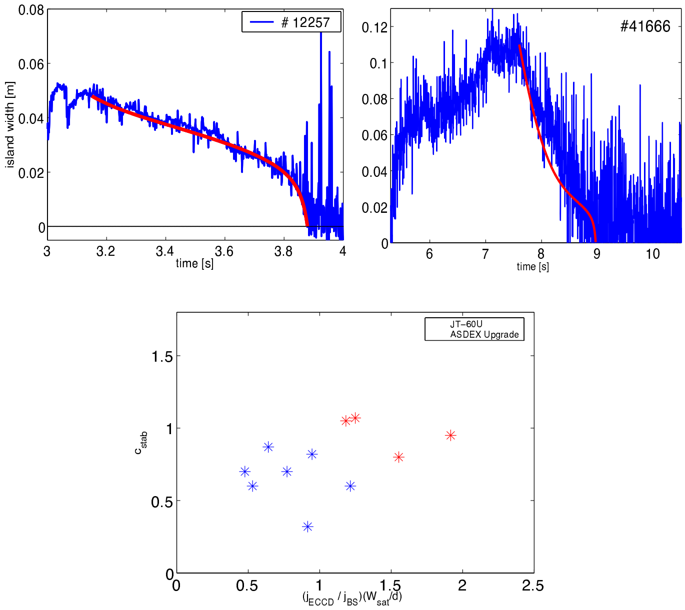

Figure 3: Example of integration of the MRE for #12257 (ASDEX Upgrade) and #41666 (JT-60) and values of c_{stab} for the database evaluated by integrating the MRE and by matching it to the experimental time evolution of the mode.

on the estimate of the radial misalignment ΔR should be reduced.

Conclusion

In this work the two coefficients c_{sat} and c_{stab} in Eq. 1 are calculated using experimental data both from ASDEX Upgrade and JT-60. Both c_{sat} and c_{stab} are close to unity for both machines. A study on the uncertainty of c_{sat} is carried out. The uncertainties of W_{sat}, j_{bs} and L_q most affects the error bar on c_{sat}. For calculating c_{stab} the MRE is integrated and the simulated $W(t)$ is compared with the experimental one. The simulation and the experiment are in good agreement as long as the misalignment ΔR is changed linearly in time for ASDEX Upgrade experiments and is assumed constant for JT-60 experiments. To get more robust results, however, experiments for the ECRH power threshold for complete NTM stabilization are planned and sensitivity studies on c_{stab} are already ongoing.

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