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ABSTRACT.

In the framework of the study of the feasibility of an ECRH system for JET, the aim of this work is to verify that the foreseen 10 MW–170 GHz Electron Cyclotron (EC) input wave power would be sufficient for Neoclassical Tearing Modes control, crucial issue for operation at high b and to determine how much the required power might be further reduced in the case of the microwave source modulation. The stabilization of low order (m,n) modes is discussed using a Generalized Rutherford equation and JET ELMy H-mode scenarios are considered in a wide range of operational magnetic field.

1. INTRODUCTION

A study has been conducted to evaluate the feasibility of installing an ECRH system on the JET tokamak [1]. In this framework, the stabilization of Neoclassical Tearing Modes (NTMs) by Electron Cyclotron Heating (ECH) and Current Drive (ECCD), a crucial issue for operation at high b, is investigated in different plasma configurations.

The basis for the stabilization of low order (m,n) NTMs is discussed in terms of a Generalized Rutherfor Equation (GRE) dynamic model [2] coupled to the mode rotation frequency evolution [3], the control criterion being to reduce the mode amplitude to its stable marginal width by balancing the ECH and ECCD terms with all the other ones in the GRE.

The stability of the main (2,1) and (3,2) modes, often rotating at very high frequency in JET (10-20kHz), is investigated in JET ELMy H-modes scenarios in a wide range of operating toroidal magnetic field between 2.5 and 3.4T. The aim is to verify that the foreseen 10MW–170GHz EC input wave power, injected at the 2nd harmonic from the low field side, would be sufficient for NTM control in all the considered plasma configurations and to determine how much the required power might be further reduced in the case of the microwave source modulation.

2. MODE EVOLUTION EQUATIONS AND STABILIZATION CRITERION

The island Width (W) evolution of NTMs at the rational surface $q = m/n$ located at the minor radius rs is well described by a model based on GRE including stabilizing (–) and destabilizing (+) terms in the form:

$$dW/dt \propto -\Delta'_0 + \Delta'_{bs} - \Delta'_{GGJ} \pm \Delta'_{pol} - \Delta'_h - \Delta'_{cd} - \Re e(\Delta'_w) \qquad (1)$$

with the usual stability parameter Δ'_0 and the terms due to the Bootstrap current $\Delta'_{bs} \propto \beta_p \varepsilon^{1/2} L_q / L_p W/(W^2 + W^2_d)$, to the curvature $\Delta'_{GGJ} \propto \beta_p \varepsilon^{1/2} L_q/L_p W/(W^2 + W^2_d)$, to the ion polarization current $\Delta'_{pol} \propto \beta_p \varepsilon^{3/2} L^2_q/L^2_p \omega(w-w_T)/W^3$, to the ECH $\Delta'_h \propto P_{EC} L_q \eta_h[W,\delta_h]/n_e T_e$ and ECCD $\Delta'_{cd} \propto {}_{PEC} L_q I_{cd} \eta_{cd}[W/\delta_{cd}, W^2/\delta^2_{cd}]$ and to the eddy currents in the resistive wall $\Re e(\Delta' w) \propto 2m\,\omega^2$. The typical quantities in these terms are the local poloidal beta β_p, the local inverse aspect ratio ε, the local safety factor q and pressure p gradient lengths $L_{q,p}$, the mode frequency ω, the natural plasma frequency ω_T, the EC injected power P_{EC}, the EC driven current I_{cd}, the full e^{-1} power current density widths δ_h,δ_{cd}, the helical function $\eta_{h,cd}(W/\delta_{h,cd})$ related to how much the heating and the driven current are efficient in the island, the small width W_d due to the finite perpendicular transport reducing the bootstrap drive for the incomplete flattening of the pressure. The mode rotation frequency evolution is given through the balance of the electromagnetic, viscous and inertial torques as:

$$d\omega/dt = [-n\,(T_{em} + T_{visc}) - T_{in}] / I \qquad (2)$$

with the torque due to the eddy currents $T_{em} \propto \omega W^4$, $T_{visc} \propto (\omega-\omega_T)/W$, $T_{in} \propto (\omega-\omega_T)\, dW/dt$ and the moment of inertia of the plasma $I \propto W$.

The NTMs can evolve from an initial seed island to their saturated sizes when the local β_p is larger than a minimum marginal critical value $\beta_{p,cr}$ corresponding to the marginal island width below which the NTMs are unconditionally stable. The stabilization criterion is to reduce the mode at its marginal width W_{mar} by balancing Δ'_h and Δ'_{cd} with all the other terms in GRE. The Δ'_{pol} term, stabilizing if rotating in the direction of the ion drift, shifts the W_{mar} at larger values with respect to those calculated without this term and its stabilizing effect is much stronger if ω increases. In JET Neutral Beam Injection (NBI) heated plasmas the modes are often rotating with frequency up to 10kHz for (2,1) and 20kHz for (3,2), the natural frequency ω_T being comparable with ω, because in this case it includes both the ion diamagnetic frequency (1–2kHz) and the plasma rotation one. Therefore, for scenarios with NBI we choose ω/ω_T=1.2 with Δ'_{pol} not negligible compared to the other terms in GRE. The needed power should decrease for $\delta_h,\delta_{cd} < W_{mar}$ and for large W_d (~4cm in JET).

3. (2,1)-(3,2) MODE STABILITY BY P_{EC} CW INJECTION IN H-MODE SCENARIO

The stability of (2,1)-(3,2) NTMs is investigated for the H-mode scenario of the JET Pulse No: 73344 at 21.02s (2.65T/2.5MA/3.9KeV/8.8$10^{19}$ m^{-3}) for PEC continuously injected from the low field side from 2 different launching points above (Upper Mirror-UM) and below (Lower Mirror-LM) the midplane, located at $z = \pm 0.345$m. The main plasma parameters used in GRE are in Table 1:

The EC power needed for stabilization of these modes is calculated by using the ECH/ECCD profiles provided by the GRAY beam tracing code [4] with different toroidal and poloidal injection angles. The launching geometry is in agreement with the launcher conceptual design [5]. The results for various values of I_{cd} and δ_{cd} are plotted in Figure 1 (q = 2) and Figure 2 (q = 3/2), showing the role of all the terms in GRE. I_{cd} and δ_{cd} are ranged between 1.74-3.33kA/MW and 0.04-0.12m at q = 2 and between 2.6-7.2kA/MW and 0.035-0.1m at q=3/2.

EC power less than 6MW seems sufficient to stabilize the (2,1) mode at its marginal width for toroidal angles < 20° corresponding to the lower driven current density widths ~0.04m. It is to be noted that in this scenario $\Delta'_h << \Delta'_{cd}$. The mode (3,2) can be controlled using P_{EC}<3 MW, because the local EC peak current density is higher than in the previous case. The δ_{cd} is also smaller ~0.03-0.35m. A general trend of EC power needed for stabilization vs driven current Icd is given in Figure 3 for both the modes considering 2 fixed widths δ_{cd} = 0.05-0.1m: (2,1) is stabilized with P_{EC}

< 8MW for $I_{cd} > 2.5$kA/MW and (3,2) with $P_{EC} < 5$MW for $I_{cd} > 4$kA/MW. The stabilizing role of the ion polarization term Δ'_{pol} is shown. Less power is required as the dcd decreases and Icd increases.

In this reference scenario P_{EC} >10MW is required for $I_{cd} < 1.5$kA/MW (q = 2) and I_{cd} <2kA/MW (q = 3/2) for both the chosen widths dcd.

4. NTM STABILITY BY P_{EC} CW INJECTION IN REF. SCENARIO AT VARIOUS B

The stability for (2,1) and (3,2) modes is calculated for various magnetic fields between 2.5T<B<3.2T, rescaling the plasma current, the electron density and temperature by a factor $\alpha = B/B_{ref}$ keeping constant q_{95} and β. In Figure 4 P_{EC} is plotted against the magnetic field B, calculated for the optimum value of the injection toroidal angle in general different for each value of B. The values of power needed for stabilization using I_{cd} and δ_{cd} from the beam tracing are compared with those obtained with the same driven current for $\delta_{cd} = 0.05-0.1$m.

$P_{EC} < 6$MW are foreseen to stabilize the (3,2) mode at any magnetic field, while more than 8MW are required to control (2,1) at B > 2.8T for a driven current channel width $\delta_{cd} = 0.1$m. At high magnetic fields the (2,1) control becomes marginal because of the poor current drive efficiency. All the traces plotted in Figure 4 correspond to the data from the lower mirror both for q = 2 and q = 3/2.

5. (2,1) STABILITY BY PEC MODULATED INJECTION IN REF. H-MODE SCENARIO

The aim of the modulation is to minimize the ECCD power needed for NTM stabilization [6,7] by a gyrotron 50% duty cycle. Since for $W<<\delta_{cd}$ the helical efficiency hcd depends on W^2/δ_{cd}^2 without modulation and on W/δ_{cd} with modulation, Δ'_{cd} is more efficient in the second case and less P_{EC} is required for stabilization. For a current diffusion time much larger than the island rotation period the phasing of the ECCD peak with the centre of the mode is advantageous and therefore modulation could be useful, as in JET where the time modulation is small (30μs–100μs) respect to the current diffusion time (~100ms). Benefits come for $W/\delta_{cd}<0.5$. As in the previous cases we have $0.4<W/\delta_{cd}<1$, we can conclude that in JET the EC power modulation is not strongly competitive with CW injection, which is sufficient to stabilize the NTMs with less than 10MW. In Figure 5 is shown an example of stabilization by unmodulated (ECCD phasing between $-\pi$ and π) and modulated (ECCD phasing between $-\pi/2$ and p/2) EC power injection for the JET Pulse No: 76082 at 10.5s, 20MW NBI heating and (2,1) frequency of 12kHz.

CONCLUSIONS

The stabilization of rotating NTMs in JET, by application of localized EC power, is discussed in term of a generalized Rutherford equation coupled to the mode rotation frequency evolution. Detailed analysis of the power needed for stabilization of (2,1) and (3,2) modes has been performed for JET ELMy H-mode scenario in a wide range of operating magnetic field. $P_{EC} \leq 6$MW can control (3,2) mode in all the cases, while $P_{EC} \leq 8$MW stabilizes (2,1) except for B > 2.8T and $\delta_{cd} \geq 0.1$m . Modulation can be required only for $W/\delta_{cd} < 0.5$ to stabilize the (2,1) mode using less power than that one needed in CW injection.

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q	ψ	ε	r_s [m]	L_q [m]	L_p [m]	β_p	$n_e[10^{19}\,m^{-3}]$	T_e[keV]
2/1	0.68	0.3	0.91	0.4	0.28	0.38	6.9	1.6
3/2	0.49	0.25	0.77	0.55	0.35	0.60	7.6	2.4

Table 1: Main parameters used in GRE for (2,1)-(3,2) modes

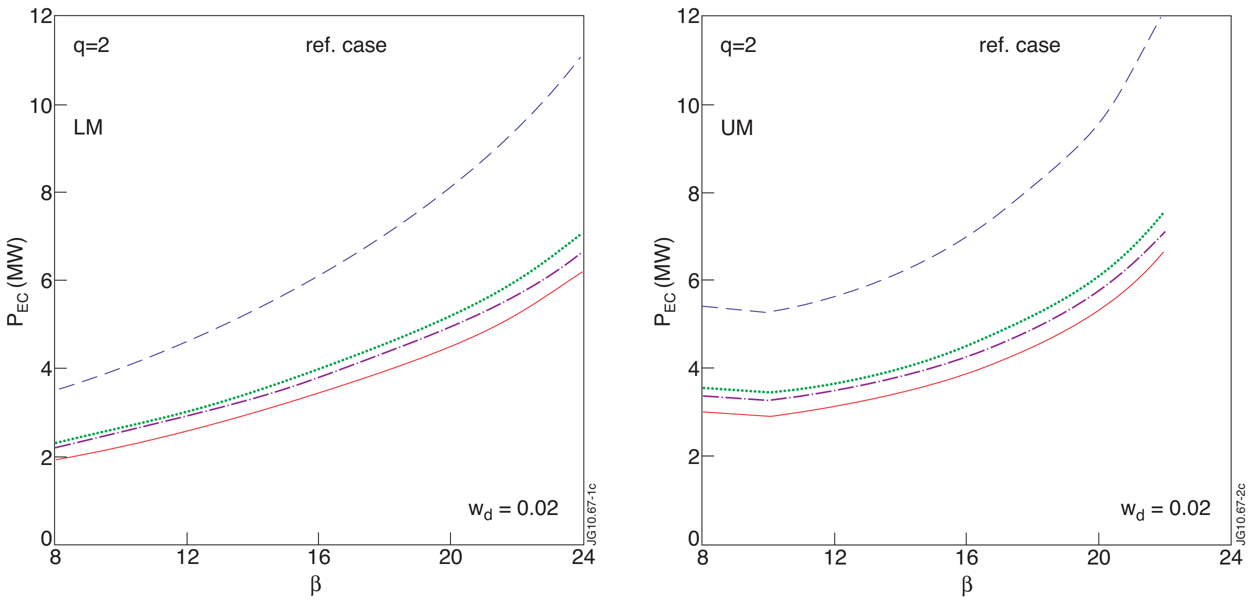

Figure 1: P_{EC} needed to stabilize the (2,1) mode, using the beam tracing results for I_{cd} and δ_{cd}, for both lower (left) and upper (right) mirrors. The roles of different terms in GRE are shown: $\Delta'_0 + \Delta'_{bs}$ (dashed line), $\Delta'_0 + \Delta'_{bs} + \Delta'_{GGJ}$ (dotted line), $\Delta'_0 + \Delta'_{bs} + \Delta'_{GGJ} + \Delta'_w$ (dash-dotted line) and $\Delta'_0 + \Delta'_{bs} + \Delta'_{GGJ} + \Delta'_w + \Delta'_{pol}$ (solidl line).

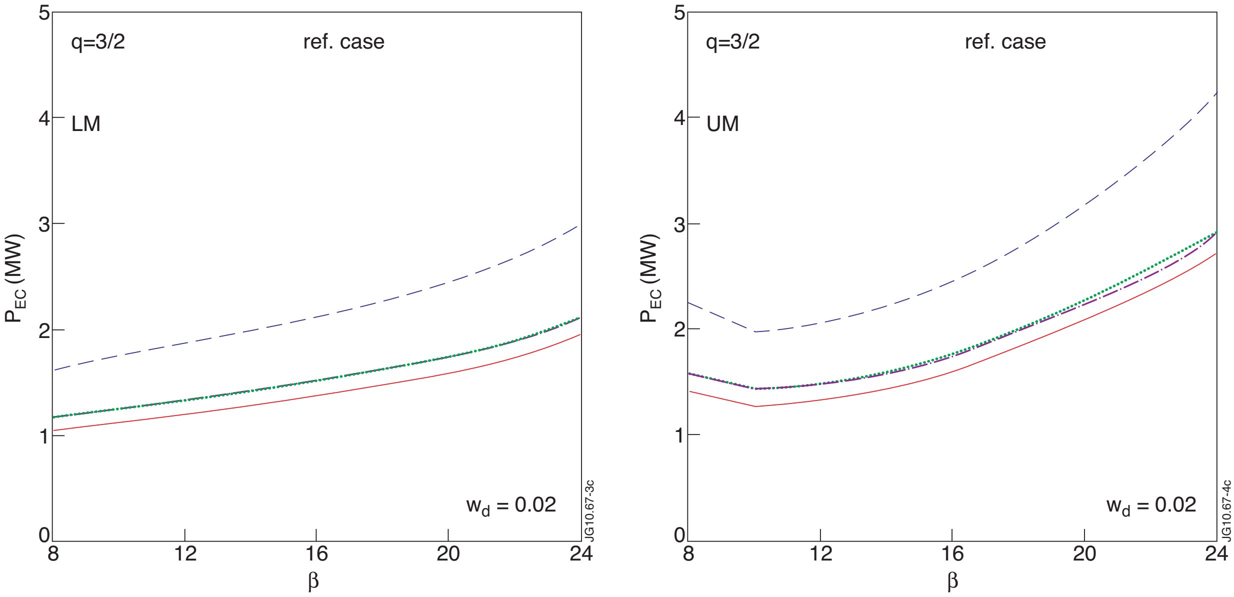

Figure 2: Same as in Figure 1 for the (3,2) mode. The effect of the resistive wall (dash-dotted line) is negligible at the location q=3/2.

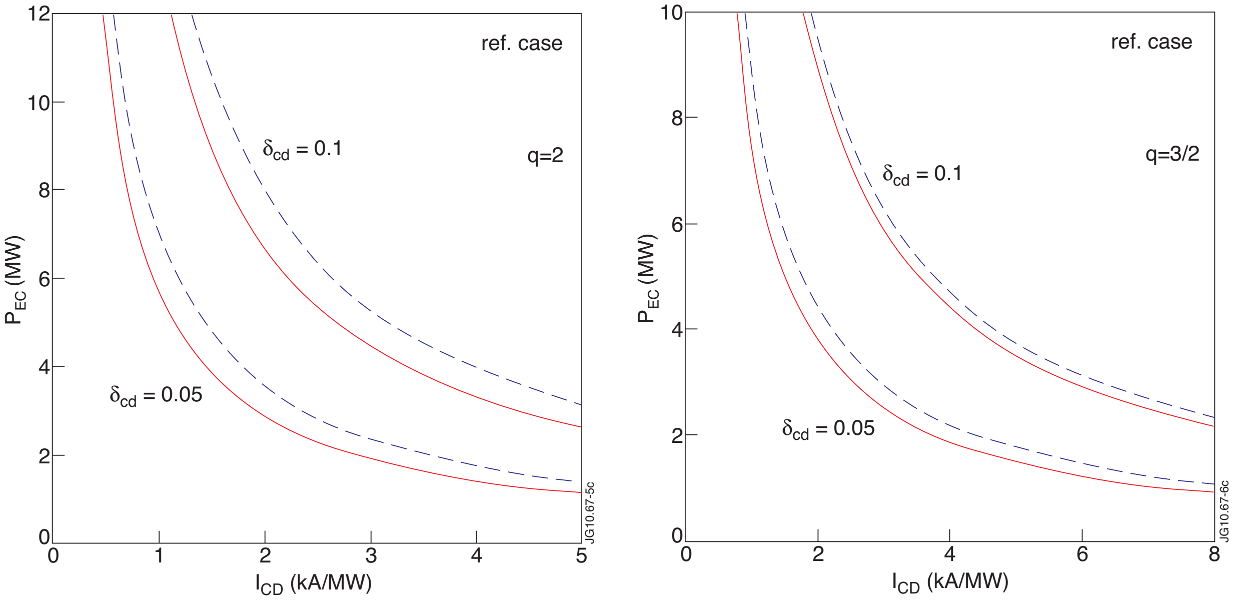

Figure 3: P_{EC} versus I_{cd} for 2 values of δ_{cd} =0.05−0.1m for (2,1) on the left and (3,2) on the right. The dashed lines refer to combination of terms in GRE without Δ'_{pol}, the solid traces with it.

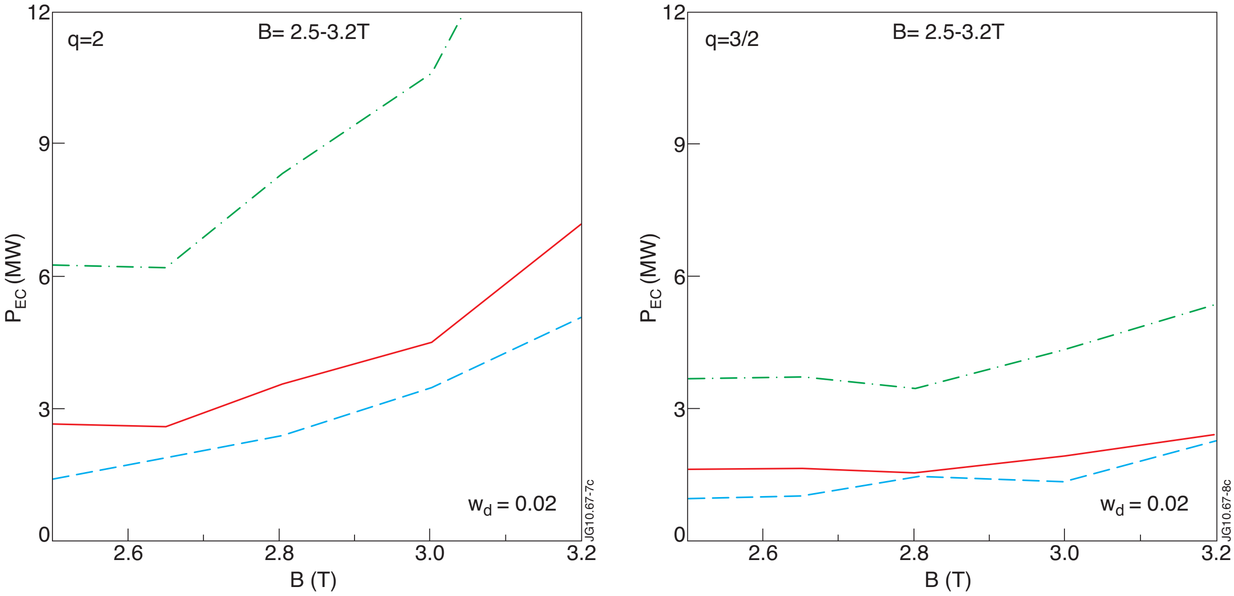

Figure 4: P_{EC} versus B using δ_{cd} = 0.05-0.1m for (2,1) on the left and (3,2) on the right. The dashed lines are from beam tracing, the solid and the dash-dotted lines for δ_{cd} = 0.05m and = 0.1m respectively.

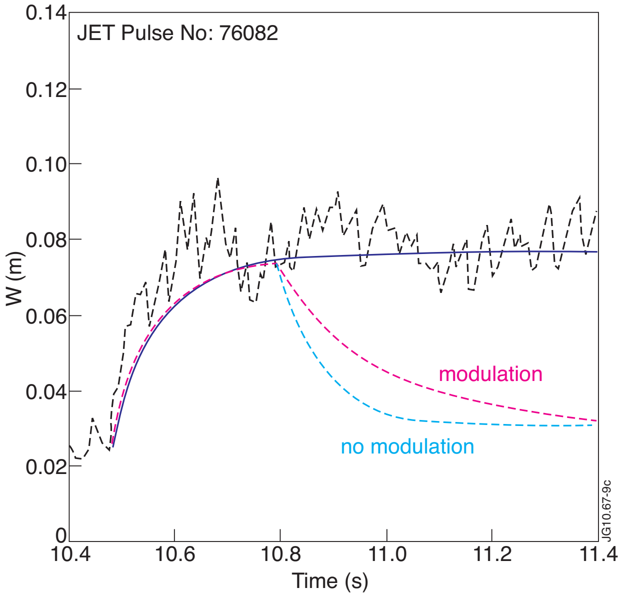

Figure 5: (2,1) amplitude evolution stabilized at its w_{mar} ~ 0.032m by unmodulated and modulated EC power injecting 1.5MW and 0.7MW respectively for W/δ_{cd}~.029. Experimental line is dotted.