Braking of Tearing Mode Rotation by Resistive Walls in ITER

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Introduction

- ITER plasmas will be surrounded by relatively distant ($r_v/a \simeq 1.5$) vacuum vessel with time constant ($\tau_v \equiv \mu_0\, r_v\, \delta_v/\eta_v$) of $\tau_v = 376\,\mathrm{ms}$.
- Region between edge of plasma and vacuum vessel occupied by layer of blanket modules with time constant of $\tau_b = 23\,\mathrm{ms}$.
- Eddy currents excited in two walls brake rotation of tearing modes in plasma giving rise to dangerous locked modes.
- What is critical island width above which tearing mode rotation is suppressed in ITER due to interaction with two walls?

Main Features of Calculation

- Conventional “thin shell” approximation for walls is not used because skin-depth in wall material is less than wall thickness in both walls when tearing mode is rotating.
- Island width evolution equation takes impurities and neoclassical reduction in conductivity into account.
- Island frequency evolution equation involves solution of poloidal and toroidal plasma angular equations of motion.
- Both equations of motion include plasma inertia, viscosity, and electromagnetic braking torque.
- Poloidal angular equation of motion also includes neoclassical poloidal flow damping.
- Wesson-type plasma current density profile adopted.
- Tearing mode eigenfunctions are calculated from current density profile.

Vacuum Vessel

- ITER vacuum vessel fabricated from austenitic stainless steel, type 316(N)-IG. Such steel has electrical resistivity of $\eta_v = 7.4 \times 10^{-7}\,\Omega\,\mathrm{m}$.[1]
- 3D model (with port openings)[2] of vacuum vessel indicates that longest decay time of $n = 1$ eddy currents in vacuum vessel, in absence of plasma, is $\tau_v = 188\,\mathrm{ms}$.
- Theoretically, we expect $\tau_d = \tau_v/(2\,m)$.
- Assuming that slowest decaying mode is $m = 1$, we deduce that $\tau_v = 376\,\mathrm{ms}$.
- Effective thickness of vacuum vessel is $\delta_v = \tau_v\,\eta_v/\mu_0\,r_v = 7.4\,\mathrm{cm}$.

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[1] K. Ioki, et al., Fusion Eng. Design **83**, 787 (2008).

[2] G. Navratil, et al., 2nd Meeting of ITPA Topical Group on MHD, Distruptions, and Control (2002).

Blanket Modules

- Detailed 3D modeling of ITER blanket modules[3] shows that, as far as their interaction with non-rotating resistive wall modes is concerned, they act like simple wall in which ratio of electrical resistivity to wall thickness takes value $\eta_b/\delta_b = 1.33\times 10^{-4}\,\Omega$.
- Given that $r_b/a \simeq 1.2$, we deduce that $\tau_b = \mu_0\, r_b\, \delta_b/\eta_b = 23\,\mathrm{ms}$.
- Because blanket modules effectively fill space between their inner radius, $r_b = 1.2\,a$, and vacuum vessel, we deduce that effective thickness of blanket modules is $\delta_b = 0.25\,a$.
- Effective electrical resistivity of blanket modules is $\eta_b = 6.6\times 10^{-5}\,\Omega\,\mathrm{m}$.

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[3] F. Villone, et al., Nucl. Fusion **50**, 125001 (2010).

Calculation Parameters

- Toroidal magnetic field - $B_\varphi = 5.3\,\mathrm{T}$. Major radius - $R_0 = 5.3\,\mathrm{m}$. Minor radius - $a = 2.0\,\mathrm{m}$. Effective ion charge number - $Z_{\mathrm{eff}} = 1.7$. Momentum confinement time - $\tau_M = 3.7\,\mathrm{s}$.[4]
- Inner wall radius - $r_b = 1.2\,a$. Inner wall thickness - $\delta_b = 0.25\,a$. Inner wall time constant - $\tau_b = 23\,\mathrm{ms}$.
- Outer wall radius - $r_v = 1.5\,a$. Outer wall thickness - $\delta_v = 0.037\,a$. Outer wall time constant - $\tau_v = 376\,\mathrm{ms}$.
- Poloidal mode number - $m = 2$. Toroidal mode number - $n = 1$. Rational surface radius - $r_s = 0.87\,a$. Electron number density - $n_e = 9.8 \times 10^{19}\,\mathrm{m}^{-3}$. Electron temperature - $T_e = 5.6\,\mathrm{keV}$. Ion temperature - $T_i = 5.7\,\mathrm{keV}$. Natural frequency - $\omega_0 = 0.42\,\mathrm{kHz}$.[4]

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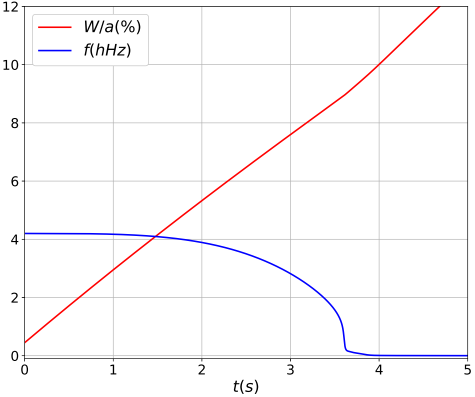
[4] L. Urso, PhD Thesis, 2009. R.J. LaHaye, et al. Nucl. Fusion **57**, 014004 (2017).

Calculation Results - I

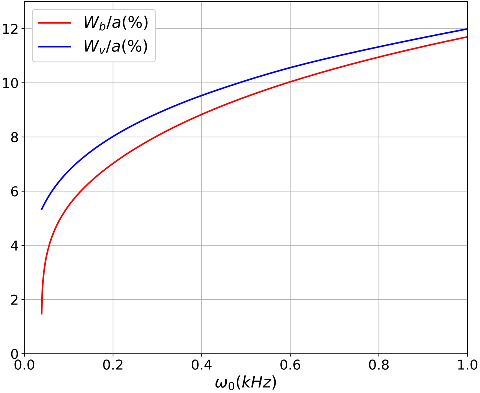


Slowing down curve of $m = 2/n = 1$ tearing mode interacting with two walls. W is island width, and f is mode rotation frequency.

Calculation Results - II

- Wall locking takes place in two stages. First, mode locks to blanket module layer, and is left rotating at about $15\,\mathrm{Hz}$. Second, mode locks to vacuum vessel, and is left rotating at less than $0.5\,\mathrm{Hz}$.
- Critical island width required to trigger wall locking in ITER is about 9% of plasma minor radius, which is similar to critical island widths observed in existing tokamaks.

Rotation Frequency Scan



W_b is critical island width to lock to inner wall. W_v is critical island width to lock to outer wall. ω_0 is mode rotation frequency in absence of walls.

Conclusion

- Even only assuming diamagnetic levels of rotation, critical island with above which wall locking occurs in ITER is likely to be similar to that observed in existing tokamaks.
- In other words, ITER is no more likely to be prone to wall locking than existing tokamaks.