Analysis of 2/1 neoclassical tearing mode mitigation techniques in MAST-U using the JOREK non-linear MHD code

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Introduction

The Mega Ampere Spherical Tokamak Upgrade (MAST-U) is performance limited in H-mode by Neoclassical Tearing Modes (NTMs). Control of NTMs is important for future reactor design. Active stabilisation methods such as electron cyclotron current drive are not possible in MAST-U due to being overdense. Electron Bernstein Wave current drive will be operational in the next MAST-U campaign, but its efficacy as an NTM stabilisation scheme is yet to be demonstrated. In lieu of active stabilisation methods, we explore the effect of moving the $q = m/n = 2/1$ rational surface radially to modify local shaping and classical drive, and determine its impact on $m/n = 2/1$ NTM stability using a combination of JOREK, theory and experiment.

JOREK setup

We simulate MAST-U shot 50553, which has a 2/1 NTM with a saturation width of 8cm as measured at the outboard midplane. The simulated plasma is limited with boundary located at $\psi_N = 0.95$. Profiles and boundary geometry are taken from the Motional Stark Effect constrained EFIT equilibrium and passed into JOREK. The $q = 2$ surface is moved radially by scanning on-axis $B_t = 0.48, 0.53, 0.58\,\mathrm{T}$ in JOREK (Fig. 1).

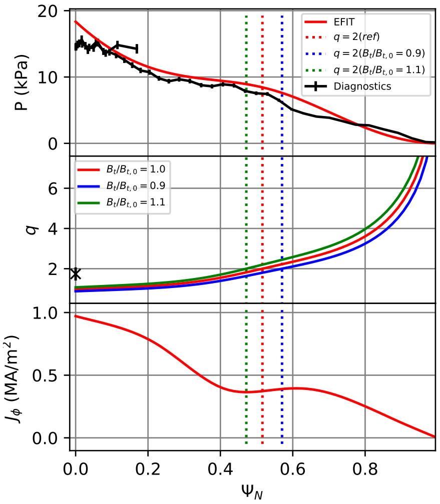

Figure 1: MSE constrained EFIT profiles from #50553.

We use JOREK's reduced MHD model, which eliminates fast magnetosonic waves [1]. A consequence of this is improved numerical stability and computational speedup in comparison to the full MHD version. However, the reduced MHD ansatz tends to make the simulation artificially stable to core ideal modes [2] and resistive modes which are pressure stabilised, such as NTMs [3]. The JOREK simulations here comprise 171 radial and 121 poloidal flux-aligned grid elements. Toroidal harmonics $n \leq 5$ are simulated. We take on-axis resistivity $\eta = 7.7 \times 10^{-8}\,\Omega\mathrm{m}$ as determined by the Spitzer-Harm formula with $T^{-3/2}$ dependence, where T is plasma temperature. Viscosity

$\nu = 2.7 \times 10^{-6}\,\mathrm{kg/m/s}$, which is estimated from semi-empirical work [4] and similarly follows $T^{-3/2}$ dependence. The thermal diffusion anisotropy is set to $\kappa_\perp/\kappa_\parallel \sim 10^{-8}$, which falls within the empirically [5] and semi-empirically [6] estimated ranges for experimental tokamaks. $\kappa_\parallel \sim 0.2\,\mathrm{kg/m/s}$ is estimated from the Spitzer-Harm formula for thermal diffusion and $\kappa_\perp$ is inferred from the above values for $\kappa_\parallel$ and anisotropy ($\kappa_\perp = \kappa_\parallel(\kappa_\perp/\kappa_\parallel) \sim 0.2 \times 10^{-8}\,\mathrm{kg/m/s}$). The simulations are seeded with islands of width $w_{\mathrm{seed}} \sim 1.7\,\mathrm{cm}$. Parallel and diamagnetic flows are not considered.

Results

Behaviour of the 2/1 magnetic island width normalised to minor radius a is shown in Fig. 2 for the three different toroidal field cases. The 2/1 magnetic island is clearly destabilised further with a greater saturation width if the $q = 2$ surface is moved radially inwards (increased B_t case) and vice versa.

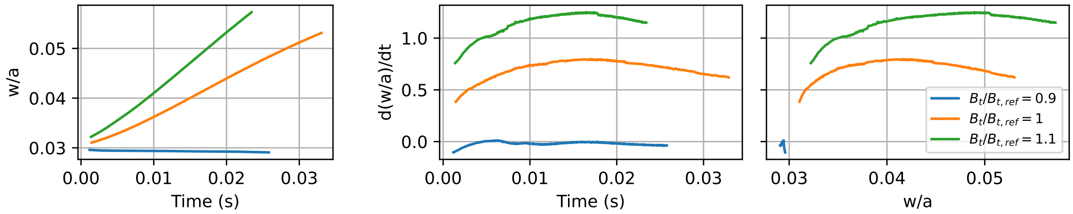

Figure 2: $w(t)$ (left), $d/(w/a)/dt$ as a function of time (centre) and of normalised island width (right).

We compare our results against the Modified Rutherford Equation (MRE), which theoretically models $w(t)$ in experimental discharges. Ignoring polarisation terms, this is [7, 8, 9]

$$\begin{aligned}\frac{dw}{dt} &= 1.22\frac{\eta}{\mu_0}\left[\Delta'_{\mathrm{CL}}(w) + \Delta'_{\mathrm{GGJ}}(w) + \Delta'_{\mathrm{BS}}(w)\right] \\ &= 1.22\frac{\eta}{\mu_0}\left[\Delta'_{\mathrm{CL}}(w) + \frac{D_R}{\sqrt{w^2 + 0.65w_d^2}} + a_1\frac{\mu_0 R_0^3 q_s^2}{F^2 q'_s} j_{bs}\frac{w}{w^2 + w_d^2}\right],\end{aligned} \tag{1}$$

where $\Delta'_{\mathrm{CL}}(w)$ is the classical stability contribution evaluated at $r_s \pm w/2$, r_s is the radius of the rational surface [7], $\Delta'_{\mathrm{GGJ}}(w)$ is the Glasser Greene Johnson term, D_R is the resistive interchange parameter (extracted from CHEASE [10]), which is typically stabilising and depends on plasma geometry, shaping (inverse aspect ratio ε, triangularity δ, elongation κ etc), and local pressure gradient, $\Delta'_{\mathrm{BS}}(w)$ is the contribution due to presence of toroidal bootstrap current j_{bs} (extracted from CHEASE), which is typically destabilising, a_1 is a geometric constant that we set to $\sim O(1)$ based on calibration against island width data from MAST-U shot 50553, and $w_d \propto (\kappa_\perp/\kappa_\parallel)^{1/4} \sim 2.5\,\mathrm{cm}$ is the characteristic diffusion width.

Reduced MHD can be artificially stable to tearing modes due to modifying D_R [3]. The modification for this equilibrium is s.t. $D_R \rightarrow 1.21D_R$. We now overlay the dw/dt phase plot from JOREK (Fig. 2, right) onto the relevant MRE for each case. These are shown in Fig. 3.

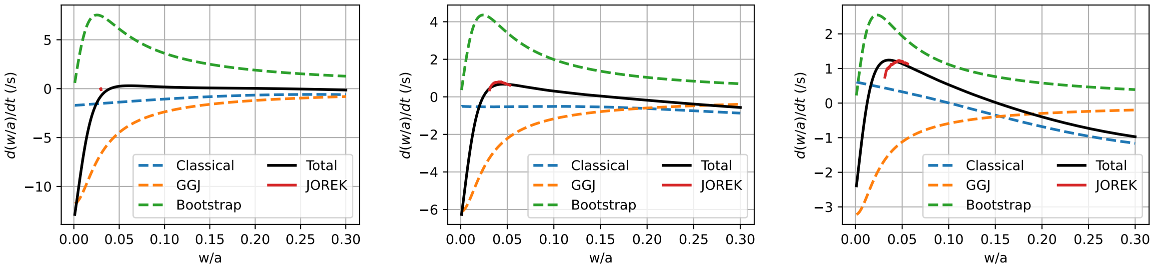

Figure 3: Comparison of $d(w/a)/dt$ between JOREK and the MRE, $B_t = 0.48, 0.53, 0.58\,\mathrm{T}$ (left to right).

The MRE reasonably estimates the peak dw/dt in the $B_t = 0.53, 0.58\,\mathrm{T}$ cases, though at smaller island widths than shown in JOREK. The MRE predicts larger saturation widths than is shown in the low and reference B_t cases. The predicted saturation width is sensitive to the behaviour of Δ'_{CL} at finite island width, which was originally derived in a cylindrical plasma and thus may not be fully accurate in the geometry considered here. In the low field case (left), the MRE predicts a slower growing island with a larger seeding width in comparison to the reference case due to enhanced GGJ and classical stability. In JOREK, the mode appears saturated at $w/a \sim 0.03$ despite the MRE predicting a fully stable mode. In this simulation, a resistive $1/1$ mode is present due to $q_0 < 1$. The $1/1$ mode may couple to the 2/1 mode and prevent it from fully stabilising [11]. In the high field case (right), we see reduced bootstrap drive, but also a reduced GGJ effect and stronger positive classical drive. This leads to a less stable island, in agreement with JOREK.

We now compare MAST-U shots 49107 and 49338 which contain 2/1 NTMs. 49338 is a repeat of the reference shot 49107 with a larger $q = 2$ surface radius due to increased on-axis current density. The last closed flux surface (LCFS) ε and δ are consistent. However, the LCFS κ is 10% larger in 49107 and squareness is greater. Several traces for both shots are shown in Fig. 4, left. The rational surface in 49338 is clearly pushed radially outwards by approximately 10% over the shot. At the $q = 2$ surface, we observe a corresponding 10% increase in ε and 40% increase in δ compared to 49107. Fig. 4, bottom left, shows that D_R is enhanced by $\sim 23\%$ over the reference case despite weaker LCFS shaping and a lower overall D_R profile. Fig. 4 top right and centre evaluate the MRE purely using the experimental inputs. Total $r_s\Delta' \sim 0$, which indicates the MRE-predicted saturation width is consistent with experiment. The individual MRE contributions show the GGJ term in shot 49338 is enhanced by $\sim 50\%$ compared to 49107 over the duration of the two shots, while the bootstrap and classical terms remain unaffected. This leads to a $(25 \pm 20)\%$ reduction in saturated width.

Discussion and conclusions

JOREK simulations show partial stabilisation of the 2/1 NTM if the rational surface is moved radially outwards via a change to the on-axis toroidal field. This is due to enhancements to GGJ

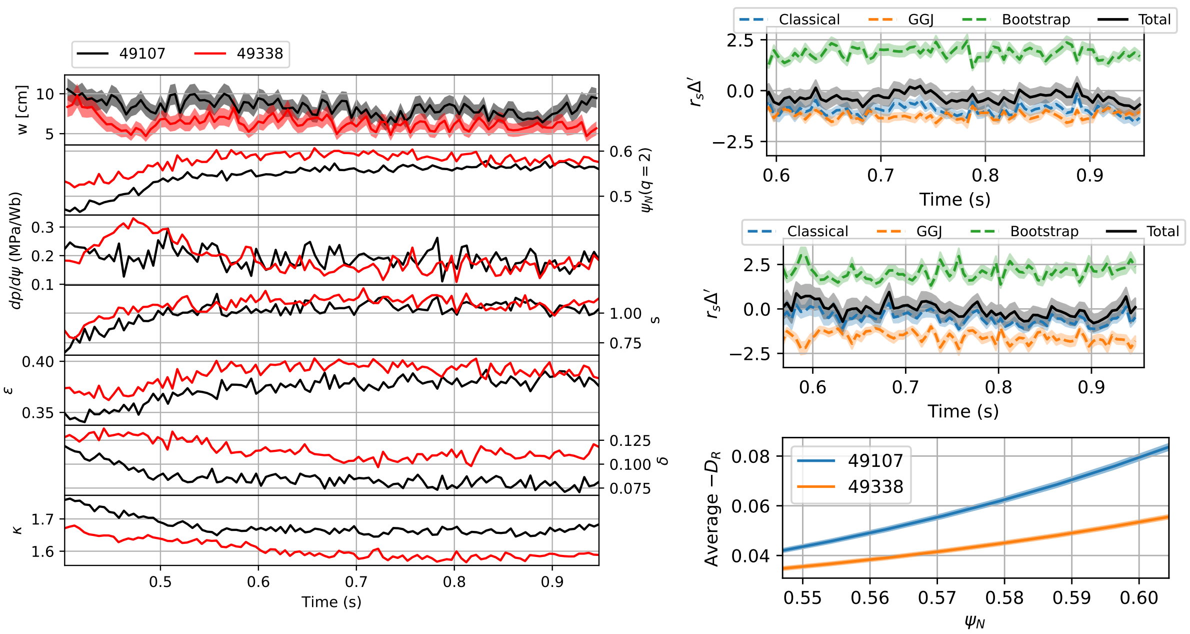

Figure 4: Left: Comparison of several traces evaluated at the $q = 2$ surface for MAST-U shots 49107, 49338. Right: MRE evaluated using experimental inputs (including measured island width from top left plot) for shots 49107 (top) and 49338 (centre). Bottom right: Resistive interchange profiles near respective q=2 surfaces averaged over $0.6\,\mathrm{s} \leq t \leq 0.9\,\mathrm{s}$.

and classical stabilisation as predicted by the MRE. The GGJ effect is enhanced due to stronger local shaping as a result of moving the q=2 surface closer to the plasma edge. This may be of particular importance for plasmas which suffer from low shaping in the core due to limited shaping penetration [12].

The simulations and theoretical results are in qualitative agreement with experimental cases where the rational surface was moved radially outwards via changes to the current density profile. A $(25 \pm 20)\%$ reduction in the saturated island width was observed. Future work will identify experimental shots where the $q = 2$ surface was moved via changes to B_t. This will shine a light on the feasibility of ramping B_t as an actuator for 2/1 mode stability.

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