Plans for TM torque scaling studies

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Goal: investigate the scaling of the Maxwell torque and the locking threshold from DIII-D to ITER

1. Motivation

2. Roadmap

3. Free Boundary Solver Development
Small islands are often born rotating with the plasma.

NTV and Maxwell torques slow the island rotation.

Islands may lock if torques are strong enough.

Disruptions often occur after locking.
Start-up is an example where error-fields are a concern for ITER.

- Error-fields exert a Maxwell torque that slows mode rotation
  - Locking occurs if error fields exceed a critical magnitude

- As designed ITER’s error-field correction system will be able to reduce error-fields to
  \[ \frac{\delta b}{B} \approx 5 \times 10^{-5} \]

- Extrapolation from current experiments predicts a threshold for mode locking during start-up between:
  \[ 1.3 \times 10^{-5} \lesssim \left( \frac{\delta b}{B} \right)_{\text{crit}} \lesssim 2.7 \times 10^{-4} \]

- Fitzpatrick’s nonlinear analytic theory predicts a locking threshold:\(^1\)
  \[ \left( \frac{\delta b}{B} \right)_{\text{crit}} \approx 5 \times 10^{-5} \]

- Here we plan of using simulations to study the scaling of Maxwell torques and locking thresholds in realistic equilibria

\(^1\)R Fitzpatrick, PPCF 2012
Roadmap for Maxwell torque scaling and locking studies

- Identify equilibria for study
  - Want a tearing mode unstable case: $\Delta' > 0$
  - No pedestal to avoid ELM’s
  - Generating model equilibrium is easier than finding a good reconstruction

- Use heuristic neoclassical viscosity to rapidly explore the parameter space.
  - The long term goal is to use continuum kinetic closures
  - Kinetic closures are computationally expensive

- Run initial simulations without flow or error fields
  - Not interested in the formation of the islands, so use tricks to speed up computation
  - Add flows and RMPs after islands saturate
Step 1: Generate tearing unstable equilibria with ITER like shaping.

- Use experimental coil currents from DIII-D with ITER shaping
  - Also interested in using ITER’s coil
- Adjust equilibrium $F$ and $P$ profiles to create tearing unstable cases
  - Target a 2/1 or 3/2 mode
  - Use resistive DCON to quickly assess the stability
- Requires incorporating the free boundary solver into fg_nimeq
- Scale unstable equilibrium to JET and ITER length scales.
  - Fix $\epsilon$ and $\beta_N$
  - Scale $R$, $F(\psi)$, $P(\psi)$, $I_c$, etc consistently
Step 2: Revive the heuristic neoclassical viscosity to rapidly explore the parameter space\textsuperscript{2}.

- The heuristic closure has the form:
  \[
  \nabla \cdot \Pi_\alpha = n m_\alpha \mu_\alpha \left\langle B^2 \right\rangle \frac{\vec{V}_\alpha \cdot \vec{e}_\Theta}{(\vec{B} \cdot \vec{e}_\Theta)^2} \vec{e}_\Theta
  \]

- The dampening frequency, \( \mu_\alpha \), can be used to control the island size.
  - Normalize island widths across cases (DIII-D, JET, and ITER)
  - Study small, medium, and large saturated islands

- The heuristic closures mimics the dominant neoclassical effects
  - Only exerts a force in the poloidal direction
  - Poloidal flow dampening
  - Polarization current
  - Bootstrap current

\textsuperscript{2}T. A. Gianakon, S. E. Kruger, and C. C. Hegna, POP 2002
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Simultaneously solve for \( \Lambda = \frac{\psi}{R^2} \) and \( K = \frac{\mu_0 J_\phi}{R} \):

\[
\nabla \cdot R^2 \nabla \Lambda = -FF' - \mu_0 R^2 P'
\]

\[
R^2 K = -FF' - \mu_0 R^2 P'
\]

The boundary flux \( \Lambda_b = \frac{\psi_b}{R^2} \) is solved simultaneously with the interior flux:

\[
\Lambda_b = -\frac{1}{4\pi R_b} \left[ \sum_{quad} M_{bq} K_q + \sum_{coils} M_{bc} I_c \right]
\]

The response matrices \( M \) are computed at initialization.

This method eliminates the need for nested iterations that are traditionally used during free boundary solves.
Vertical instability prevents the free boundary solver from converging.

The free boundary solver is tested using a DIII-D reconstruction.

Free boundary calculations use reconstructed F and P profiles and the experimental PF coil currents.

Free boundary plot shows $RB_\phi$ after the 10th iteration.

NIMUW uses up-down symmetry to stabilize vertical motion.
A proportional-integral-derivative (PID) controller provides position control.

Independent vertical and radial feedback systems use a generalization of the algorithm described in Jardin’s textbook\(^3\):

\[
\delta I^n_c = \alpha_1 \Delta \psi^n + \alpha_2 \left( \Delta \psi^n - \Delta \psi^{n-1} \right) + \alpha_3 \sum \Delta \psi^i
\]

\[
\Delta \psi \equiv \psi (R_1, Z_1) - \psi (R_2, Z_2)
\]

- Feedback system is unstable when only the proportional term is used.
- The derivative term provides dampening.
  - Critical for stabilizing the algorithm
- The integral term has been implemented but needs testing.
- Feedback parameters, \(\alpha_n\), are normalized by the coils response function.

\(^3\)S. Jardin, Computational Methods in Plasma Physics, 2010
The free-boundary solver converges with feedback.

The free-boundary solver reproduces the original reconstructed equilibrium.

Two vertically aligned equilibrium coils are also used for both radial and vertical position control.

Feedback current is 3% of the total current in the two feedback coils.
Model equilibria are generated by prescribing $F$ and $P$ profiles.

Reconstructed EQ Pressure

Model EQ Pressure

- Model pressure profile: $P = P_0 \left(1 - \hat{\psi}\right)^2 + P_{\text{open}}$
- Free-boundary solver also outputs EFIT eqdsk file.
  - Use resistive DCON to assess stability
Conclusions/Future Work

- Beginning Maxwell torque scaling and mode locking studies
  - Locked modes are a concern for ITER

- \texttt{fg\_nimeq} has been modified to generate free boundary equilibria
  - PID controller provides position control
  - Shape control may be needed in future

- Plan on using free-boundary solver to generate model equilibria for study
  - Start with experimental coil currents with ITER shaping
  - Modify $F$ and $P$ profiles to generate tearing unstable cases
• Solid lines: reconstructed pressure profile
• Dashed line: modified pressure profile