Analysis and modelling of MHD instabilities in DIII-D plasmas for the ITER mission

by
F. Turco

with
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Making progress by integrating modelling and experiment
  - MHD spectroscopy to measure the approach to a limit
  - The MARS-K model for plasma response calculations
  - The PEST3 model to evaluate $\Delta'$ trends

The ITER Baseline Scenario: moderate $\beta_N$, zero torque

The path to high $\beta_N$ and steady-state conditions
  - Modeling the no-wall limit crossing with non-ideal effects

The steady-state scenarios: high $\beta_N$, high torque

Low torque at high $\beta_N$

Discussion and conclusions
DIII-D studies demonstration plasmas relevant to these scenarios:

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Measure the approach to instability: MHD spectroscopy

MHD spectroscopy*:
A rotating kink-resonant n=1 field is applied with a set of “internal coils” (I-coils), at $f=10\ Hz$ or $f=20\ Hz$ \(\leftrightarrow\) rotation frequency of the RWM

→ The plasma response amplitude increases close to a stability boundary
→ The phase shows a “jump”

Used to probe the proximity to a stability limit

Expand the analysis and modeling space to the “stable” side of the modes

* Fasoli PRL1995
* Reimerdes PRL 2004
RWMs: slowly growing, slowly rotating kinks

- The ideal kink instability, with a realistic (non-ideal) wall model, is described by the RWM branch of the dispersion relation
  \[ \rightarrow \text{slow growth rate of the order of } \tau_{\text{wall}} \sim 2.5 \text{ ms in DIII-D} \]

- The RWM is influenced by
  - pressure and current profile gradients (ideal MHD)
  - resonances between the plasma rotation and the thermal particles drift frequencies
  - non-resonant contributions from fast-particles (NBI ions in DIII-D)

In DIII-D, RWMs
- Cause \textit{rotation and } \beta_N \textit{ collapses in the high-}q_{\text{min}}, \textit{high-}\beta_N \textit{ SS plasmas}
Drift kinetic effects are needed to describe the experimental observations

- RWMs do not usually appear in fast-rotating, low $q_{\text{min}}$ plasmas → kinetic damping of the RWM [Hu et al, PRL2004]

\[
\gamma \tau_w = -\frac{\delta W_{NW}}{\delta W_{WW}} \quad \text{Ideal MHD RWM dispersion relation}
\]

\[
\gamma \tau_w = -\frac{\delta W_{NW} + \delta W_K}{\delta W_{WW} + \delta W_K}
\]

\[
\delta W_K \sim \sum_{l=-\infty}^{\infty} \frac{(\omega - \omega_E) \frac{\partial f}{\partial \epsilon} - \frac{n}{eZ} \frac{\partial f}{\partial \psi}}{\omega - \langle \omega_p \rangle - \omega_b + i \nu_{\text{eff}} - \omega_E}
\]

- Kinetic dependences may extrapolate unfavourably for low external torque and lower fraction of fast beam-generated ions (ITER)
  → need to validate models for rotation and thermal/fast particles
MARS-K model is being validated to predict the stability in unexplored regimes.

Eigenvalue code, modified to solve for the response to an inhomogeneous forcing function \( \leftarrow \text{External field from the I-coils} \)

**The model includes**
- resistive DIII-D wall geometry
- rotation, \( T_e, T_i, n_e \) from experiment
- fast-NBI ions with a Maxwellian slowing down distribution function
- radially constant collisionality (for ions and electrons)

**[IBS] MHD stability below the no-wall limit, at zero torque**

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[IBS] Stable solution found at moderate to high torque

DIII-D IBS demonstration discharges match
- plasma shape (LSN)
- $q_{95} = 3.1$
- $Q = 10 \leftrightarrow \beta_N = 1.8, H_{98} = 1$ at $q_{95} = 3$

DIII-D can match the predicted torque $\rightarrow 0-0.7$ Nm

Solution non reproducible (50% of cases are unstable)
Narrow operating point found at $\geq 1$ Nm
Operation at 0 Nm remains elusive

Operating on a marginal point
$\rightarrow$ sensitive to small perturbations

Ideal no-wall limit $\beta_{NW} \sim 2.8-3.1$
Ideal with-wall limit $\beta_{WW} \sim 3.2-3.5$
IBS constant $\beta_N \sim 1.8-2.2$

Non-ideal effects $\rightarrow$ current profile, rotation, collisionality, resistivity?
[IBS] MHD spectroscopy shows that the plasmas are approaching a stability limit.

- Response amplitude increase
- Non-ideal effects $\leftrightarrow$ Lower limits
- Phase jump at $\sim 12-15$ krad/s
  $\rightarrow$ Typical of no-wall limit crossing

$\beta_N \sim 1.8-1.9$

$\beta_N \sim 1.9-2.1$
The plasma response trends indicate that non-ideal effects are present.

- At "moderate" rotation, the trends are consistent with the ideal model.
The plasma response trends indicate that non-ideal effects are present.

- At "moderate" rotation, the trends are consistent with the ideal model.
- At higher rotation, the response is off trend → kinetic damping?
The plasma response trends indicate that non-ideal effects are present.

- At “moderate” rotation, the trends are consistent with the ideal model.

- At higher rotation the response is off trend → kinetic damping?

- At very low rotation, with ECH, higher response → collisionality? resistivity?

Ideal MHD likely not sufficient to explain the trends.
[IBS] MARS-K reproduces only the higher rotation cases

- **Collisionality** is important to reproduce the higher rotation range correctly
- MARS does not capture the large increase at very low rotation
- The phase is overestimated by ~15-20°
The path to high $\beta_N$ is a good platform to validate models

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Higher $\beta_N$, Higher $q_{95}$
Pressure ($\beta_N$) scan to cross the no-wall $\beta_N$ limit

Increase the pressure with co-Ip NBI power
→ fixed $q_{95}$, $l_i$
→ Measure the plasma response

![Graph showing pressure ($\beta_N$) scan to cross the no-wall $\beta_N$ limit.](image-url)
\( \beta_N \) scan: It's crucial to assess the validity of the modeling results

- Rotation has an impact on the response amplitude
- The rotation is not constant across the \( \beta_N \) values

→ Sensitivity study: assess impact of rotation on the results
$\beta_N$ scan: MHD-only model does not reproduce approach to the no-wall $\beta_N$ limit

- Previous modelling* showed the MHD model without rotation has a pole at the no-wall limit

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*Lanctot, PoP2010
\( \beta_N \) scan: Drift kinetic model reproduces approach to the no-wall \( \beta_N \) limit correctly

- Previous modelling* showed the MHD model without rotation has a pole at the no-wall limit
- The pole is eliminated with the full kinetic model (thermal + fast ions)

\[
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- Previous modelling* showed the MHD model without rotation has a pole at the no-wall limit
- The pole is eliminated with the full kinetic model (thermal + fast ions)
- Without fast-ion damping the pole reappears \( \rightarrow \) 45\% higher than expt
- The phase shift is still overestimated above the no-wall limit

ITER: very small fast-ion \( \beta \) from NBI
\( \rightarrow \) will the plasmas be (45\%) more unstable?
\( \rightarrow \) Will the fast \( \alpha \)-particles be enough to stabilize them?

*Lanctot, PoP2010
\( \beta_N \) scan: Precession and bounce drift frequencies are the main factors.

- The full model is necessary to reproduce the experiment.
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Higher $\beta_N$ Higher Torque
MHD stability is the main challenge for high-\(\beta_N\) scenarios

- High rotation, \(\beta_N \leq 3.6\) can be made passively stable
- 2/1 tearing modes arise on \(\beta_N > 3.6\) flattop
- They degrade the confinement significantly → loss of 20-50% \(\beta_N\)

![Graph showing \(\beta_N\) and \(I_p\) over time with n=1 amplitude (G) measurements.](image_url)
Tearing limits are strongly correlated with the ideal with-wall limit

- The tearing index $\Delta'$ increases sharply at the ideal wall limit

Modelling of the approach to the ideal limit:
The tearing index $\Delta'$ increases sharply at the ideal wall limit. High $\beta_N$ operation is equivalent to operate with very large, very sensitive $\Delta'$. One solution is to increase the ideal limit:
- broaden J and p
- change the plasma shape

Modelling of the approach to the ideal limit:

Turnbull, PRL 1995
Turnbull, NF 1998
OFF-axis NBI used to broaden the pressure and current profiles

- The with-wall $\beta_N$ limits of the OFF-axis cases are $\sim 10\%$ higher.
Shape modifications can yield $\beta_{\text{limit}} \approx 6$

- The with-wall $\beta_N$ limits of the OFF-axis cases are $\approx 10\%$ higher
- Combined changes of outer gap and squareness: $\beta_{\text{lim}} 4.5 \rightarrow 6$
The PEST3 model captures the approach to tearing instability.

Time series of $\Delta'$ calculated* for experimental equilibria

Higher $\beta_N > 4$ cases $\rightarrow$ $\Delta'$ shows increasing trend towards the $2/1$ mode.
For stable plasmas, $\Delta'$ decreases

- The stable cases can have high $\Delta'$ values
- But show a stable or decreasing trend on the flattop

\[ \beta_N \sim 3.3-3.6 \]
[Rotation scan] All the high-$\beta_N$ plasmas have high NBI torque

What happens at low rotation, high $\beta_N$?

- Experiment $\rightarrow$ decrease the rotation at fixed $\beta_N$, $q_{95}$
- Model $\rightarrow$ capture the rotation effects?

- fixed equilibrium and $n_e$, $T_e$, $n_i$, $P_{\text{NBI}}$, etc, from a DIII-D plasma
- a self-similar rotation profile series
Rotation effects above the no-wall $\beta_N$ limit

- Broad peak in the response at 20-25 krad/s (~1% of the Alfvén velocity)
- Below the no-wall limit (IBS) the trend is increasing
• With thermal and fast ions, trend and amplitude are well matched.

• ...but the phase is underestimated by ~25%.

• If the fast-ions damping is neglected, the results diverge (more) from the measurements.

• Fast-ions destabilizing at high-$\beta_N$? consistent with $\beta_N$ scan results...

[Rotation scan] MARS-K reproduces the response amplitude with fast-ions.

MHD spectroscopy

Response AMP (G/kA)
Response PHI (°)

MARS-K w/o fast ions
MARS-K w/ fast ions

Rotation at $\rho$~0.6 (krad/s)
Summary and conclusions

Modelling the approach to instability: how are we doing?

- **ITER Baseline Scenario:**
  - Good match at moderate rotation ✓
  - MARS-K does not reproduce the high response at zero torque ❌

- **No-wall limit crossing:**
  - MARS-K reproduces very well the response amplitude ✓
  - The phase is overestimated at high $\beta_N$ ❌

- **Steady-state scenarios:**
  - PEST3 captures the approach to instability ✓
  - No rotation dependence! Needed to extrapolate❓

- **The rotation dependence at high $\beta_N$:**
  - MARS-K captures the amplitude trends ✓
  - The phase trends are not reproduced as well❓
What physics can be added and may be relevant?

- **Collisionality** → New MARS-Q: energy dependent collisionality operator
- **Finite ion orbits?**
- **The present version of MARS-K assumes a Maxwellian fast-ion distribution** (experimental profile in $\rho$, but no $v_{\parallel}$, $v_{\perp}$ dependence)
  → Neutral beam ions in DIII-D are strongly anisotropic
- **Large response at zero torque** remains a puzzle...

![Experimental beam-ion distribution (NUBEAM)](image)
EXTRAS
Current-driven mode: The mode structure is similar to that of the pressure-driven mode

- The mode eigenfunction is a combination of the main harmonics \( m=2,3,4,5 \)
- The structure of the mode extends radially inward \( \rightarrow \) not only at the edge
- Comparable to the pressure-driven mode

Previously developed RWM feedback techniques and the low \( q \) optimizations can be applied to both current-driven and pressure-driven, high \( \beta_N \) modes
MISK results for rotation scan
[IBS] MARS-K reproduces only the higher rotation cases

- Collisionality is important to reproduce the higher rotation range correctly
- MARS does not capture the large increase at very low rotation
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[IBS] MARS-K reproduces only the higher rotation cases.
The Hybrid Regime Addresses the Steady-State Challenges With An Alternative Approach

What is a hybrid? → Long duration, high confinement H-mode
→ More stable to 2/1 tearing modes

Ideal MHD with-wall limits are $\beta_{\text{limit}} \geq 4.5$

High $q_{\text{min}}$ present limits $\beta_{\text{lim}} \approx 3.5-4.5$ → predicted $\beta_{\text{lim}} \approx 5$

Current density

- Final J independent from sources
- $q$ relaxes to “hybrid” state – $q_{\text{min}} \geq 1$
- All external current driven in the plasma centre
- No alignment issues
- Most efficient CD

• Ideal MHD with-wall limits are $\beta_{\text{limit}} \geq 4.5$
The Highest $\beta_N$ Cases Are Limited By MHD

- At $\beta_N \leq 3.6 \rightarrow$ 2/1 tearing modes are avoidable
- At $\beta_N \geq 4 \rightarrow$ fishbone-like bursts, then 2/1 tearing modes $\rightarrow$ non-recoverable

Isolated bursts:

- $\tau \sim 1$ ms, $f \sim 25$-50 kHz
- $\tau \sim 50$ ms, $f \sim 10$-15 kHz

The activity does not decrease with density $\rightarrow$ not fishbones?

May be due to the large fraction of fast particles

The Highest $\beta_N$ Cases Are Limited By MHD
Hybrid plasmas reach fully NI conditions and $\beta_N=3.6$ for $\sim 2\, \tau_R$.

- Stable to the 2/1 TM at $\beta_N \sim 3.6$
- Loop voltage $\sim 0$ for $\sim 2\, \tau_R$
- Limited by NBI pulse duration
The Scenario Is Sustained At High Injected Torque – Lower Torque Degrades Confinement

- 1 neutral beam line added in counter-$I_p$ direction (~4 MW)
- Same $\beta_N$, stored energy obtained

Confinement decreases by ~20% for 35% lower $T$

$P_{\text{NBI}} = 11 \rightarrow 15$ MW (35% increase)

$T_{\text{NBI}} = 8.8 \rightarrow 5.6$ Nm (35% decrease)

$H_{98y2} = 1.72 \rightarrow 1.4$ (20% decrease)
With Present Confinement And \( n_e \), The DN Hybrid Is Consistent With an FNSF 6.7 MA Scenario

**INPUTS:**
- \( R=2.49 \) m, \( B_t=6 \) T
- \( q_{95}=6.2 \), \( \varepsilon=3.5 \)
- \( \beta_N=3.66 \), \( n_{\text{lin.av}}=4 \)

Impose \( I_p=6.7 \) MA
Fix \( \nu^* \)

**SCALED SCENARIO:**
With \( n/n_G=0.42 \)
Drive 3.35 MA with ECH+NBI
Need \( P_{\text{CD}}=75 \) MW

\( P \) to sustain \( \beta_N=172 \) MW
With Present Confinement And $n_e$, The SN Hybrid Is Consistent With an ITER 9 MA Scenario

**INPUTS:**

- $R = 6.2$ m, $B_t = 5.3$ T
- $q_{95} = 6.2$, $\varepsilon = 3.1$
- $\beta_N = 3$, $n_{\text{lin.av}} = 3.2$

**Impose** $I_p = 9$ MA

**Fix** $\nu^*$

**SCALED SCENARIO:**

- With $n/n_G = 1.17$
- Drive 4.5 MA with ECH+NBI
- Need $P_{\text{CD}} = 191$ MW
- $P$ to sustain $\beta_N \rightarrow 175$ MW

$Q = 7.1$
With present confinement and lower $n_e$, the SN hybrid is consistent with an ITER 9 MA, $Q=4.4$ scenario.

**Inputs:**
- $R=6.2$ m, $B_t=5.3$ T
- $q_{95}=6.2$, $\varepsilon=3.1$
- $\beta_N=3$, $n_{lin.av}=3.2$

Impose $I_p = 9$ MA
Scale $f_{GW}$

**Scaled Scenario:**
- With $n/n_G = 0.9$
- Drive 4.5 MA with ECH+NBI
- Need $P_{CD} = 112$ MW
- $P$ to sustain $\beta_N \rightarrow 233$ MW

$Q = 4.4$