Neoclassical Tearing Modes in Next-Step-Option Tokamaks

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FIRE Physics Workshop

May 1-3, 2000

Impact of NTMs on NSOs:

- NTMs are the most serious potential limitation on the attainable β in FIRE and ITER-FEAT.

- The m/n = 3/2 mode (considered here) is the most commonly observed mode and produces a deterioration in confinement above some β_{crit}.

- The m/n = 2/1 mode (not considered here) is less common, but generally leads to disruption.

Theory:

- NTMs are driven by the depletion of bootstrap current due to pressure flattening across a magnetic island, requiring some “trigger” to produce a “seed” island of sufficient width.

- There are two important stabilizing effects:

    - finite ratio of parallel to perpendicular thermal conduction, which prevents the pressure from completely flattening across the island;

    - the ion polarization current arising from the time-varying radial electric field seen by the plasma due to the island’s rotation.

Experimental Results (m/n = 3/2 mode):
(DIII-D, ASDEX-U, JET)

- The critical β_N for onset of NTMs is found to be proportional to ρ_i^*, in qualitative agreement with a model in which the polarization current is the dominant stabilizing effect.

- The critical β_N and the minimum seed island width increase with collisionality (DIII-D, ASDEX-U), again in qualitative agreement with the polarization-current stabilization model.

- The critical β_N at low collionality is higher in JET, suggesting that the maximum seed island width may itself be dependent on collisionality, e.g, via the Magnetic Reynolds number.

- Hysteresis is generally observed, consistent with the trigger seed island exceeding the minimum required, after which the island remains while β_N drops toward $\beta_{N,crit}$.

- Confinement degradation is consistent with a model in which the island width is thermally “shorted out”; however, there are instances where the density also drops, in which case confinement degradation is more severe.

Figure from La Haye, Buttery, Guenther, Huysmans, and Wilson showing critical values of β_N / ρ_i versus $\nu_{ii} / \varepsilon\omega_e$ from DIII-D, ASDEX-U and JET. The DIII-D and ASDEX-U data overlay almost exactly and show an increase in β_N / ρ_i with $\nu_{ii} / \varepsilon\omega_e$,whereas the data from JET show a generally flatter dependence and substantially higher values of β_N / ρ_i at low values of $\nu_{ii} / \varepsilon\omega_e$.

Figure and preprint from R. La Haye on request.

Application to NSOs:

- ITER-FEAT and FIRE have roughly the same dimensionless plasma parameters, except for collisionality, which is higher in FIRE.

- Also, assuming that reference temperatures are reached, ρ_i* is somewhat higher in FIRE.

- However, NTMs are potentially more serious in FIRE than in ITER-FEAT for two reasons:

  - reference Q = 10 performance requires a larger β_N-value ($\approx$ 2.5 versus $\approx$ 1.8);

  - stabilization by ECCD may be inapplicable because of the unavailability of gyrotrons at the required frequency.

- Thus the question arises: Is the higher collisionality (together with somewhat higher ρ_i*) in FIRE sufficient to provide significantly increased stability against NTMs?

Collisionality Effect on Polarization-Current Stabilization:

(all parameters evaluated at the q = 1.5 surface)

	$\nu_{ii}/\varepsilon\omega_e{}^*$
ITER-FEAT (reference Q = 10 case)	≈ 0.17
FIRE (reference Q = 10 case)	≈ 0.14
Regime of present experiments	0.02 - 0.15

- FIRE is <u>not</u> more collisional than ITER-FEAT in this regard, but <u>both</u> are moderately into the more favorable collisional regime.

Collisionality Effect on Finite-Parallel-Thermal-Conduction Stabilization:

(assuming empirical χ and a gyro-Bohm scaling between the two machines, which gives $\chi \approx$ 0.3 m^2/s at the $q = 1.5$ surface in both cases, and assuming $\chi_{//} \approx 0.5$ x Spitzer)

	$(\chi / \chi_{//})^{1/4}$	w_0/a
ITER-FEAT	$\approx 1.0 \times 10^{-3}$	0.4×10^{-2}
FIRE	$\approx 1.6 \times 10^{-3}$	0.7×10^{-2}

- The island width below which finite parallel thermal conduction is stabilizing is somewhat larger for FIRE than for ITER-FEAT, but in both cases the island width is very small, implying that this effect is likely to be unimportant.

Collisionality Effect on Bootstrap Current:

	ν_e* (at q = 1.5)
ITER-FEAT	≈ 0.024
FIRE	≈ 0.055

- Since the bootstrap current is reduced by collisionality like $1/[1 + (\nu_e^*)^{1/2}]$, there will be slight reductions in NTM drive relative to the lowest-collisionality neoclassical regime.

“Calculations”:

- Use parameters of Q = 10 reference ITER-FEAT and FIRE cases;
- Consider m/n = 3/2 mode only;
- Include only T_e contribution to bootstrap current (slightly enhanced to allow for n contributions);
- “Circularize” the shaped cross-section in order to apply theory;
- Use the “Wilson” polarization-current model with g = 0.12 (within the theoretical range g = $\varepsilon^{3/2}$ - 1.0, and chosen to match present data in the range $\nu_{ii}/\varepsilon\omega_e^* \approx 0.10 - 0.15$);
- “Relative” numbers (i.e., comparisons between ITER-FEAT and FIRE) should be taken more seriously than “absolute” numbers.

NSOs: Parameters of Reference Cases

	ITER-FEAT	FIRE
Fusion Power (MW)	410	220
Heating Power (MW)	40	22
Plasma Major Radius (m)	6.2	2.0
Plasma Minor Radius (m)	2.0	0.525
Plasma Current (MA)	15	6.44
Field at Plasma Center (T)	5.3	10.0
Elongation (κ_{95})	1.7	1.77
Average Triangularity (δ_{95})	0.35	0.4
Safety Factor (q_{95})	3.0	3.0
Volume Average Density (10^{20} m^{-3})	1.0	4.5
Density Profile, exponent α_n	0.1	0.5
Average Temperature $<T>_n$, (keV)	8.5	8.0
Temperature Profile, exponent α_T	1.0	1.0
Total β, including alphas (%)	2.5	3.0
Total β_N, including alphas	1.8	2.5
Collisionality, ν_e*, at q = 1.5 surface	0.024	0.055
Normalized Ion Larmor Radius, ρ_i*	0.0015	0.0029

Figures showing values of β_N and seed island width for which NTMs are unstable in ITER-FEAT and FIRE. The critical β_N values for these two machines are found to be about 1.0 and 2.0 respectively (relative magnitudes should be regarded as more credible than absolute values). The minimum seed island widths are found to be about 1% and 2%, respectively, of the mean minor radii.
Figures available from P. Rutherford on request.

Send email to: prutherford@pppl.gov

Figure from La Haye, Buttery, Guenther, Huysmans, and Wilson showing regimes of stability and instability at various β_N values on a ρ_i versus $\nu_{ii} / \varepsilon\omega_e$ plot. Figure shows "second" regimes of stability at very low ρ_i. This is obtained by postulating a dependence of the maximum seed island width on the magnetic Reynolds number, and using such a dependence to obtain a fit to the combined DIII-D, ASDEX-U and JET data. Existing experimental data just marginally enters this highly favorable predicted regime.

Figure and preprint available on request from R. La Haye. (lahaye@apollo.gat.com)

Summary:

- The critical β_N value for NTMs is higher in FIRE than in ITER-FEAT and only slightly below that required for reference performance.

- Approaches to avoiding/suppressing NTMs:

  - self-limitation of seed island widths in reactor-scale tokamaks (e.g.,due to higher Reynolds number - La Haye, et al.);

  - active control of seed island width (e.g., by operating in non-sawtoothing regimes - the present experimental approach);

  - active island current drive, ECCD/LHCD.

- Experiments are needed in different collisionality regimes (C-Mod?), as well as experiments that vary separately the seed island width and the collisionality;

- Experiments would be useful that separate the n and T_e bootstrap drive at q = 1.5;

- For FIRE, island feedback by LHCD could be studied - first proposed many years ago.