Prospects for Suppression of Neoclassical Tearing Modes (NTMs) in FIRE by LHCD

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NTMs in Burning Plasma Experiments

- NTMs may limit the attainable β in FIRE ($\beta_N \approx 1.8$-2.0) and ITER-FEAT ($\beta_N \approx 1.7$).

- The m/n = 3/2 mode is most commonly observed, degrading confinement.

- NTMs are due to pressure flattening across a magnetic island, and require some “trigger” to produce a “seed” island.

- Stabilizing effects:

  - finite ratio of parallel to perpendicular thermal conduction, which prevents the pressure from flattening across the island (not important for FIRE/ITER parameters);

  - ion polarization current arising from the time-varying radial electric field due to the island’s rotation (theory still controversial, but predicts a ρ_i* scaling for the critical β_N);

  - possible dependence of seed island width on the Magnetic Reynolds Number.

Application to FIRE

- The adverse scaling with ρ_i* of the critical β_N for NTMs is a potential threat to the performance of all BP-scale tokamaks.

- FIRE and ITER-FEAT have roughly the same dimensionless plasma parameters:
  - ν_e* is slightly higher (factor $\approx$ 1.8) in FIRE;
  - ρ_i* is slightly higher (factor $\approx$ 1.6) in FIRE;
  - for reference performance, β_N is slightly higher in FIRE (1.8-2.0 versus 1.7).

- "Calculations" using the polarization drift model suggest that these differences cancel out: both FIRE and ITER-FEAT are predicted to be marginal to the 3/2 mode for their reference β_N-values.

- Some NTM control technique must be included in the design of a BP experiment:

  - ECCD for ITER-FEAT (Perkins, Harvey)

  - Another method for FIRE (e.g., LHCD ?) -- no gyrotrons at the EC frequency.

Suppression of NTMs by Modulated CD

- “Worst case” - ignore polarization drift.

- Island growth equation:

$$dw/dt \propto \Delta' + 6.4\,(\mu_0 L_q / B_\theta w)\,(j_{bs} - C\, j_{\sim cd})$$

where $j_{\sim cd}$ is the modulated driven current.

<u>Modulated RF Source:</u>

- Can suppress arbitrarily small islands, limited only by the detector threshold.

- Perkins & Harvey find $C \approx 0.65$ for a 50/50 on/off source - needs $j_{cd} > 1.6\, j_{bs}$.

<u>Continuous RF Source:</u>

- Works for ECCD because very narrow deposition produces "natural" modulation.

- Probably doesn't work for LHCD (but try ray-tracing/deposition calculations across island with flattened density/temperature).

- Still can have a favorable effect on Δ'.

LHCD Requirements for FIRE

- Bootstrap current density:
  - reference Q = 10 parameters / profiles;
  - q = 1.5 is at $r/a \approx 0.73$;
  - $I_{bs} \approx 1.0$ MA, broad j_{bs} profile over $r/a > 0.5$.
    - $j_{bs}(q = 1.5) \approx 50 (\beta_N/1.8)$ A/cm^2
- LH-driven current density:
  - from calculations with TSC (Kessel) for a near-reference FIRE case (density may need to be lowered near the edge).
  - 5.6 GHz, $N_{//} \approx 2.5$.
  - $j_{cd}(q = 1.5) \approx 100 (P_{LH}/10\text{ MW})$ A/cm^2

β_N	1.5	1.8 ref Q=10	2.0	2.5
P_{LH}(MW) 50/50 on/off	6.5	8	10	13

Effect of Unmodulated CD on Δ'

- Treating CD as a perturbation of the local current density gradient:

$$r\Delta'_{cd} \approx r\Delta'_{0} - (2\mu_0 L_q r / B_\theta)\,(dj_{cd}/dr)$$

with typically $r\Delta'_0 \approx -3$ for the 3/2 mode.

- A positive value of dj_{cd}/dr makes Δ' more negative and reduces the maximum size of the NTM-driven island.

- By adjusting LHCD deposition in FIRE to peak slightly further out, the value of dj_{cd}/dr at $q \approx 1.5$ can be made very large.

- For the reference case in FIRE ($\beta_N \approx 1.8$), we find that an unmodulated 10-MW LHCD system could reduce the maximum island width by about factor-of-four ($r\Delta'_{cd} \approx -12$):

$$w_{max}/a \text{ (no CD)} \approx 0.25$$

$$w_{max}/a \text{ (with CD)} \approx 0.06.$$

Conclusions

- To support high-field BP designs such as FIRE, there is a need for development of LHCD-based NTM control techniques.
- For this purpose, the LHCD system should be optimized for penetration to the q = 1.5 surface and should have the largest positive local value of dj_{cd}/dr.
- A 10-MW 5.6 GHz LHCD system for FIRE would seem capable of driving sufficient current at the q = 1.5 surface to suppress NTMs up to $\beta_N \approx 2.0$, provided it is given a feedback-modulation capability.
- Ray-tracing/deposition calculations are needed in a 3-D configuration with density and temperature flattened across magnetic islands to see whether any “natural” modulation occurs for LHCD.
- Even without modulation, LHCD should be able to reduce maximum NTM island widths substantially by modifyng Δ' .