Cross-machine NTM physics studies and implications for ITER

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FOM-Rijnhuizen, Ass. EURATOM-FOM.
see annex 1, Pamela et al., Nuc Fus 43 (2003) 1540.
Are NTMs a problem for ITER?

- NTM physics is expected to scale with $\rho^*$
  - often observed in local $\beta$ onset scalings
  $\rightarrow$ low threshold in ITER?

\[ [M. Maraschek et al., EPS03] \]
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- NTM physics is expected to scale with $\rho^*$
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  - low threshold in ITER?

- But analyses in global $\beta_N$ suggests another possibility
  - which is it?

- Key aspect in resolving the onset is the seeding process...

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Which modes are a concern?

- **2/1 NTMs** terminate performance & unacceptable in ITER

- **3/2 NTMs** significant effect
  - typically 15-20% on confinement
  - trace Tritium experiments show consistent with ~50% fall in inward pinch in vicinity of island

- **Higher m/n NTMs** also impact fusion performance at low $q_{95}$
  - JET: 3.7MA, 2.9T, $q_{95}=2.7$
    - up to 13% effect on confinement
    - up to 30% effect on neutrons
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  - JET: 3.7MA, 2.9T, $q_{95}$=2.7:
    - up to 13% effect on confinement
    - up to 30% effect on neutrons
  - AUG: 4/3 NTMs at $q_{95}$=3.7:
    - up to 20% effect on stored energy

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Content

• NTM $\rho^*$ scalings:
  - Onset criteria for NTMs
  - How do the scalings do?

• Role of the seed: the Sawtooth
  - Influence on thresholds
  - Sawtooth control
  - Advances in sawtooth prediction

• The seeding process
  - Sawtooth coupling mechanisms
  - Other trigger mechanisms and effects

• Implications for ITER
NTM onset criteria

• NTMs driven by hole in bootstrap
  – but onset criteria depend on small island stabilisation effects
  – require a seed island to reach positive growth
  – these introduce a $\rho^*$ dependence in the metastable threshold

• Onset $\beta$ highly sensitive to seed size
  – scaling of seeding process may be the critical thing
  – uncertainties both in seed needed and seed obtained

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How do the $\rho^*$ scalings do?

Pretty good in terms of underlying NTM physics and metastable threshold...

- power ramp-down experiments measure $\beta$ at which 3/2 NTM self-stabilises

- ITER baseline operation point deeply into metastable region
  - small triggers can excite mode
  - mode removal requires driving island down to small sizes
How do the $\rho^*$ scalings do?

• But they are not predictive of NTM onset $\beta$ and time on JET...

- $\beta$ stays close to NTM onset scaling prediction once H-mode reached

♦ for both local and global parameter fits
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- similarly on AUG:

  - proximity to scaling is a necessary-but-not-sufficient condition for NTMs

- there must be an extra control parameter...

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What is the hidden control parameter?

• Employ neural network to look for pattern in data...
  - automatic optimisation from choice of 27 input parameters
  - train to predict onset time

• Network successful
  - predicts decreasing time to NTM as onset approached
    ♦ unlike $\rho^*$ scaling!
  - best network uses just $\beta_N$, $\rho^*$ and sawtooth period
    ♦ period even more significant than $\rho^*$
Role of the sawtooth

- Sawtooth period plays key role in NTM onset $\beta$
- Long sawteeth can lead to many low $\beta$ modes (blue)
- Sawtooth control can offer substantial mitigation (red)
  - here achieved by:
    - ICRH phasing to avoid core pinch
    - establishing sawtooothing heated L-mode to avoid peaked profiles
  - avoids all modes, even with much more heating power

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Sawtooth control in ITER

ITER has two possible strategies:

- early $\alpha$ production to stabilise sawteeth
  - extend further with modified start up and current drive
  - but still limited and not steady state
- current drive destabilisation
  - is this possible for fast particle stabilised (ideal) sawteeth?...

Destabilisation of fast particle stabilised sawteeth now achieved:

- core ICRH stabilises sawteeth
- ICCD destabilises as inversion radius is approached

Further progress with ECCD on AUG → see Maraschek talk today

[*Porcelli et al, NF44, 362]
Sawtooth prediction is key

- Good progress in the theory...
  
  eg: Rotation dependence on JET...

Experiment:

- kinetic effects stabilise sawteeth at high rotation
- important in reconciling data from present devices
Sawteeth with NNBI

- JT60U also finds fast particles from energetic negative ion beams stabilising...
  - 350keV NNBI gives sawteeth of 300ms
  - cf PNBI: 130ms

[Kramer et al, NF40, 1383]
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- Explained by Graves:
  - finite ion orbit effects change free energy
  - depends on deposition location...

- Possible mechanisms for sawtooth control in ITER?

[Graves et al, PRL92, 185003]
How is initial seed made?

- Sawteeth often trigger 3/2 NTMs before the crash...
  - Magnetic coupling?
    - NTM often too slow for toroidal coupling to n=2
    - 3 wave seeding possible:
      - bicoherence analysis shows phase lock between driving (11+43) and 32 fields
      - but frequencies are not always consistent...
  - Ion polarisation effects?
    - MHD can change island rotation*
    - potential to lower/reverse ion polarisation effects enabling seeding
    - avoids need for frequency locking

Forced reconnection at crash

- At low $\beta$, long sawteeth trigger NTMs directly at the crash
  - excite multiple NTMs & 2/1 much more likely → concern for ITER
  - codes such as NFTC and NIMROD now able to 3D model such processes in detail...

- Example: forced reconnection inducing a 3/2 in DIII-D
  - NIMROD simulation now includes rotation shear:
    - island is still destabilised by forced reconnection
    - but as island grows its structure becomes distorted by rotation

- Shows viability of mechanism for NTM seeding

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**Fishbone triggers - at higher $\beta_N$?**

- Fishbones also trigger NTMs
  - 3/2 NTM thresholds on AUG generally higher than for sawtooth
Fishbone triggers - at higher $\beta_N$?

- Fishbones also trigger NTMs
  - $3/2$ NTM thresholds on AUG generally higher than for sawtooth
  - although on JET these do not extend to low $\beta$
    - unlike cases with fast particle stabilised sawteeth

- Fishbones recently observed to also trigger $2/1$ NTMs:
  - at $\beta_N=2.5$ on JET
Ideal triggers at high $\beta_N$...

- At high $\beta_N$ often see weak/no seeding...
  - modes often near ideal limit
  - a particular issue for hybrid scenario and 2/1 NTMs

- Modelling of DIII-D case shows poles in classical tearing stability:

- Separate studies show 2/1 NTM threshold lowered by error fields
  - possibly an ion polarisation effect...
Conclusions for ITER on NTMs

• ITER deeply metastable to NTMs, but tractable?
  – benign scalings for some NTM onset mechanisms
  – control of seeds possible for others

• Baseline scenario - *key issues are fast particles & sawtooth*
  – further triggers at higher $\beta_N$ may remain at high $\beta_N$

• Hybrid scenario - *main concern is 2/1 NTM* (3/2 fairly benign)
  – does 2/1 onset threshold fall with $\rho^*$? - mitigate with high $q_{min}$?

• However, caution required for ITER...
  – adverse NTM physics scalings and high fast particle populations
  – need to confirm scalings of high $\beta_N$ modes, especially 2/1 NTMs
  – need to integrate control techniques into scenarios to develop ready to use tools (not lengthy research programmes) for ITER

Nevertheless, we now see the principal physics ingredients assembled, a new generation of codes identifying the effects, and good progress in control and predictive capability.

→ Ongoing work is important to provide solutions for ITER
Transient transport events can seed NTMs

- Ion polarisation effects depend on island rotation - \( \alpha_{\text{pol}} \sim \omega(\omega - \omega_{*i}) \)

Rotation from balance of ion and electron dissipation:

- naturally leads to small islands via ion polarisation effects
- higher e-dissipation raises \( w_0 \sim (D_e)^{0.5} \)

Does not require frequency matching between MHD modes and the island

May explain error field effects

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- Sawtooth period plays key role in NTM onset $\beta$
Preemptive current drive on DIII-D

- Use real time MSE tracking to put ECCD on NTM resonant surface, raising NTM thresholds
- Island evolutions show scale length of small island term, $w_d$, does not change much with $\rho^*$

- Mode removal in ITER will require driving islands down to similar size to those required in present devices
Use of correct local parameters

• Studies on AUG show that NTMs track correctly calculated bootstrap parameter, better than $\beta_p$

$\beta_p, \beta_p/L_p$ and $\beta_p/L_p^{corr}$ at $q=1.5$ surf.

$\frac{L_p^{corr}}{L_p^{corr}} = \frac{1}{3} \frac{1}{L_T} + \frac{2}{3} \frac{1}{L_n}$

W of (3/2)-NTM from FFT

2/1 NTM

W from FFT
How do the $\rho^*$ scalings do?

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- JET NTM onsets align well with natural discharge evolution
  - (clue: ICRH phasings)
\( \rho^* \) scalings sometimes work for NTM onset

- AUG discharges sometimes approach scalings from below and get NTM when the scaling is reached
**Formalism - origin of $\rho^*$ scaling**

- Evolution of island size $w$ governed by modified Rutherford:

$$\tau_r \frac{dw}{dt} = r(\Delta' - \alpha w) + r \beta_p \left\{ a_{bs} \left[ \frac{0.65 w}{w^2 + w_d^2} + \frac{0.35 w}{w^2 + 28 w_b^2} \right] - \frac{a_{GGJ}}{\sqrt{w^2 + 0.2 w_d^2}} - \frac{a_{pol}}{w^4 + w_b^4} \right\}$$

- Example: ion polarisation term, $a_{pol} \propto f(\Omega) g(v, \varepsilon) \rho_i \theta^2$

$$\Rightarrow \beta_{p-onset} \propto -r_s \Delta' \cdot \rho_i^* \cdot \frac{w_{seed} / \sqrt{a_{pol}}}{1 - (\sqrt{a_{pol} / w_{seed}})^2} \cdot g$$

- seed get $>$ seed need
- uncertainties in both

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ITER possible figure?

- Possibly how it looks...

\[ q_0 \]

\[ \beta_N \]

Poles in delta-prime \( \rightarrow \) 32/21

ELMs? \( \rightarrow \) 21?

Fishbone \( \rightarrow \) 32/21

3wave/Hegna \( \rightarrow \) 32

Sawtooth: forced reconnection \( \rightarrow \) 21/32/43
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• Network successful
  - predicts decreasing time to NTM as onset approached
  ♦ unlike $\rho^*$ scaling!
  - best network parameters:

<table>
<thead>
<tr>
<th>Parameters:</th>
<th>Residual $\dagger$</th>
<th>Errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_N$  $\tau_{\text{sawtooth}}$ $\rho_{i\phi}$</td>
<td>34.3</td>
<td>17%</td>
</tr>
<tr>
<td>$\beta_N$  $\tau_{\text{sawtooth}}$</td>
<td>34.4</td>
<td>20%</td>
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<tr>
<td>$\beta_N$  $\rho_{i\phi}$</td>
<td>35.7</td>
<td>26%</td>
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<tr>
<td>$\beta_N^*$</td>
<td>35.9</td>
<td>31%</td>
</tr>
<tr>
<td>$\rho_{i\phi}^*$</td>
<td>37.5</td>
<td>29%</td>
</tr>
</tbody>
</table>

$\dagger \Sigma (\text{predicted} - \text{actual time to NTM})^2$

- Sawtooth period more useful than $\rho_{i\phi}^*$!
Future work

• Continue good progress on sawtooth models
• Demonstrate sawtooth control with strong FP populations at high beta
• Explore NTM triggering mechanisms and ways to control them
• Find beta limit in hybrid scenario and how it scales
• Resolve NTM small island physics and its scaling - particularly for 2/1 modes