MHD STABILITY ISSUES IN A BURNING PLASMA

by

E.J. STRAIT

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PRESENT UNDERSTANDING OF MHD STABILITY LIMITS IS SUFFICIENT TO DESIGN A BURNING PLASMA EXPERIMENT

- Ideal MHD stability limits are well understood and predictable
  - Upper limit to plasma stability
  - Credible foundation for design of next-step devices

- Non-ideal effects introduce greater uncertainty
  - Resistivity, finite Larmor radius, energetic ions, …

- Resistive instabilities are less predictable but may be avoidable
  - Neoclassical tearing modes can be avoided transiently by profile modification
  - Recent experiments have suppressed NTMs with localized current drive

- Steady operation very near stability limits has been demonstrated

- Burning plasma experiments go beyond present experience with MHD stability, and present new scientific challenges
FULL STABILIZATION OF NTM OBTAINED WITH MODEST ECH POWER

- Resonance moved 2 cm outward
- No ECCD
- Full Stabilization

- After reaching the seed size, the stabilization is rapid because the mode growth rate is negative
- $\beta_N$ increases during stabilized phase
- Even in presence of large sawteeth the mode doesn’t grow

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1.1 MW ECH
STEADY STATE HIGH PERFORMANCE DISCHARGES CAN BE ACHIEVED USING UNDERSTANDING OF STABILITY LIMITS AND DISCHARGE CONTROL

- \( \beta \) controlled to remain \(~20\%\) below predicted RWM limit
  - \( \beta \) also kept \(5\%\) below experimental 2/1 NTM \( \beta \) limit
- Discharge continued in steady state until beam termination
- No sawteeth
  - \( q_0 \geq 1 \)
MSE shows $J(r)$ profile has reached resistive equilibrium with $q_0 \sim 1.05$
WHAT DISTINGUISHES A BURNING PLASMA FROM EXISTING EXPERIMENTS?

- **Self-heating**
  - Less external control over profiles (p, j, Ω)

- **Energetic particle effects**
  - Large isotropic population of fast ions

- **New ranges of dimensionless parameters**
  - \( \rho_i^* = \rho_i/a \sim T^{1/2}/aB \)
  - \( S = \tau_A/\tau_R \sim aBT^{3/2}/n^{1/2}Z_{eff} \)
  - \( \nu^* = \nu_i/\epsilon\omega_{bi} \sim nqRZ_{eff}/\epsilon^{3/2}T^2 \)

<table>
<thead>
<tr>
<th>DIII-D</th>
<th>C-MOD</th>
<th>JT-60U</th>
<th>JET</th>
<th>FIRE</th>
<th>IGNITOR</th>
<th>ARIES-RS</th>
<th>ITER-FEAT</th>
<th>ITER-FDR</th>
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<td>aB (m-T)</td>
<td>1.3</td>
<td>1.7</td>
<td>3.5</td>
<td>4.3</td>
<td>5.3</td>
<td>6.1</td>
<td>10</td>
<td>11</td>
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</tbody>
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EXISTING EXPERIMENTS ARE SUFFICIENT TO INVESTIGATE MANY ISSUES OF MHD STABILITY

- Ideal MHD stability limits
  - Profile dependence
  - Shape dependence
  - Aspect ratio dependence

- Feedback stabilization of RWM

- ECCD stabilization of NTM

- Edge-driven instabilities
  - Identification of instability
  - Dependence on bootstrap current

- Stability with non-inductively driven current profiles
BURNING PLASMA-SIZE EXPERIMENTS (WITHOUT ALPHA HEATING) ARE REQUIRED TO INVESTIGATE SCALING OF MHD STABILITY PHYSICS

- **NTM beta limit scaling**
  - Threshold island size decreases with decreasing $\rho_i^*$
  - Seed island size decreases with increasing $S$

- **Edge-driven instabilities**
  - Edge gradients determine stability limit
  - Pedestal width determines coupling to core
  - Scaling of edge parameters is not well understood

- **Resistive wall mode stability**
  - Rotation frequency required for stabilization may increase with $S$ ($\Omega \tau_A \sim 0.05$)

- **Runaway avalanche during disruption**
  - Number of e-foldings increases with plasma current
  - Runaway electron current multiplication
    - $\geq 10^2$ at $I_p = 2$ MA
    - $\geq 10^6$ at $I_p = 5$ MA
NTM THRESHOLD SCALES LINEARLY WITH NORMALIZED ION LARMOR RADIUS

- But scaling of $\beta_N/\rho_{i*}$ with collisionality is not consistent between machines
  - Possible additional dependence on $\rho_{i*}$ or $S$
- $\beta_N \propto \rho_{i*} f(\nu)$ is consistent with polarization/inertial model of Wilson et al.

Best fit $f(\nu)$ is different for each device

Sawtooth-induced 3/2 NTM, ELMing H–mode
SAWTOOTH INDUCED SEED ISLANDS SCALE INVERSELY WITH MAGNETIC REYNOLD'S NUMBER

- Seed islands estimated from m/n = 3/2 Mirnov level upon excitation

\[
\frac{\tilde{w}_s}{r} \approx \left( \frac{16rR}{3sB_T} \right)^{1/2} |\tilde{B}_r| \quad \text{with} \quad |\tilde{B}_r| \approx \frac{1}{2} \left( \frac{b}{r} \right)^4 |\tilde{B}_\theta|_{\text{wall}}
\]

- Best fit has \( \frac{w_{\text{seed}}}{r} \propto S^{-0.46 \pm 0.05} \), correl \( r = -0.74 \) consistent with dynamical coupling model of Hegna et al.
EDGES STABILITY AND ELM CHARACTER DEPEND CRITICALLY ON COLLISIONALITY

- With increasing edge density or $\nu^* \propto n/T^2$.
  - Calculated $j_{\text{BOOT}}$ decreases $\Rightarrow$ edge magnetic shear increases, $\nu = S_0 - 2 \left( \frac{\langle j_{\text{EDGE}} \rangle}{j_{\text{TOR}}^2} \right)$, $\Rightarrow$ SS access lost
  - ELM modes increase in n.
  - Pressure gradient is reduced from calculated limit for n=5 edge localized ideal kink/ballooning (GATO) to ideal nigh n ballooning mode limit (BALOO).
ELM SIZE CORRELATES WITH RADIAL WIDTH OF PREDICTED UNSTABLE INTERMEDIATE n KINK MODE

- Highly localized instability computed from GATO
  ⇒ Type I ELM has little effect
  \( \delta T_e \sim 300 \text{ eV} \)
- Predicted instability computed from GATO code penetrates into core
  ⇒ High performance is lost
  \( \delta T_e \sim 400 \text{ eV} \)

**Discharge #92001**
- H Mode
- \( n = 5 \)
- \( m = 6 \)
- \( m = 7 \)

**Discharge #87099**
- NCS H Mode
- \( n = 5 \)
- \( m = 11 \)
- \( m = 12 \)
- \( m = 13 \)
- \( m = 14 \)
- \( m = 15 \)
A BURNING PLASMA (STRONG ALPHA HEATING) IS NEEDED TO INVESTIGATE KEY ISSUES OF MHD STABILITY

- Energetic particle interactions with MHD modes (sawteeth, fishbones, TAE, ballooning modes, etc.)
  - Stabilization or destabilization of MHD modes by alphas
  - Enhanced transport of alphas by MHD modes

- Self-heating ($P_\alpha \gg P_{\text{external}} \Rightarrow Q \geq 10$)
  - Stability limits with pressure profiles determined by alpha heating
  - Plasma rotation with little or no external momentum input (RWM stability, mode locking, error field sensitivity)

$$\Omega \sim \omega^* \sim T/a^2B$$

- Steady-state operation ($\tau > \tau_{\text{CR}} \sim a^2T^{3/2}/Z_{\text{eff}}$)
  - Stability limits with self-consistent current density and pressure profiles
STABILITY LIMIT DEPENDS STRONGLY ON THE FORM OF THE PRESSURE PROFILE

- DIII-D high $p_0/\langle p \rangle \sim 6.0$ (L–mode): $\beta_N \leq 2.5$
  - Limited by fast $n = 1$ disruption

- TFTR high $p_0/\langle p \rangle \sim 6.0$ (ERS–mode): $\beta_N \leq 2$
  - Limited by fast $n = 1$ disruption

- DIII-D low $p_0/\langle p \rangle \sim 2.5$ (H–mode): $\beta_N \leq 4$
  - No disruption limited by ELM-like activity from finite edge pressure gradients

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![Graph showing stability limits for different modes with pressure profiles and beta values.](image-url)
ROTATION DECELERATES ABOVE THE NO-WALL $\beta$ LIMIT
(EVEN WITH LARGE TORQUE)

Two competing models are being investigated

- Gimblett and Hastie torque balance model with marginally unstable RWM predicts qualitative behavior
- New data is consistent with resonant amplification of static error fields by marginally stable RWM
CONCLUSIONS

- Some issues of MHD stability require burning-plasma parameters to investigate
  - NTM beta limit scaling
  - Edge-driven instabilities
  - Resistive wall stabilization
  - Disruption scaling (runaway avalanche)

- Some key issues of MHD stability can only be addressed with strong alpha heating
  - Energetic alpha interactions with MHD modes
  - Stability with profiles determined by self-heating ($t >> \tau_E$)
  - Stability with self-heating and relaxed current density profile ($t >> \tau_{CR}$)

- Many of the issues requiring a burning plasma are not purely MHD stability issues but issues of integration (transport, profile control, burn control, etc.)
INTEGRATION OF SEPARATE ELEMENTS MAY BE THE MOST IMPORTANT MISSION FOR A BURNING PLASMA EXPERIMENT

- Strong coupling of transport, heating, and stability leads to a more “self-organized” plasma than in a short-pulse, externally heated tokamak.

  - Pressure profile → Fusion rate → Alpha heat deposition → Thermal transport → Pressure profile
  - Pressure profile → Bootstrap current profile → Thermal transport → Pressure profile

- MHD instabilities can intervene in these loops:

  - Pressure, current density, and fast ion profiles → Instabilities → Modification of profiles

- Investigation of such a complex, non-linear system represents a scientific challenge, and may yield some surprises.

RECOMMENDATION: A “next step” burning plasma experiment is needed as the only way to address this challenge.