Wall Stabilization in High Beta Spherical Torus Plasmas


1Department of Applied Physics, Columbia University, New York, NY, USA
2Plasma Physics Laboratory, Princeton University, Princeton, NJ, USA
3Los Alamos National Laboratory, Los Alamos, NM, USA
4Institute for Electromagnetic Field Theory, Chalmers U., Goteborg, Sweden
5Oak Ridge National Laboratory, Oak Ridge, TN, USA
6University of Wisconsin, Madison, WI, USA
7General Atomics, San Diego, CA, USA
8Johns Hopkins University, Baltimore, MD, USA
9Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China

9th Workshop on MHD Stability Control
November 21 – 23, 2004
Princeton, NJ
Wall stabilization physics understanding is key to sustained plasma operation at maximum $\beta$.

- High $\beta_t = 39\%$, $\beta_N = 6.8$ reached

\[ \frac{\beta_N}{\beta_i} = 12 \quad 10 \quad 8 \quad 6 \]

- Global MHD modes can lead to rotation damping, $\beta$ collapse

- Operation with $\frac{\beta_N}{\beta_N^{\text{no-wall}}} > 1.3$ at highest $\beta_N$ for pulse $> \tau_{\text{wall}}$

- Physics of sustained stabilization is applicable to ITER
Latest experiments address basic Resistive Wall Mode physics

• Motivation
  - NSTX RWM first observed / published in 2001
  - Use new diagnostic and control capabilities to examine outstanding, basic RWM physics questions

• Outline
  - RWM dynamics and toroidal mode spectrum
  - Critical rotation frequency, $\Omega_{\text{crit}}$
  - Toroidal rotation damping physics
  - Resonant field amplification (RFA)
Theory provides framework for wall stabilization study

- **Theories**
  - Ideal MHD stability – DCON (Glasser)
  - Drift kinetic theory (Bondeson – Chu)
  - RWM dynamics (Fitzpatrick – Aydemir)

\[
\begin{align*}
\left(\hat{\gamma} - i\hat{\Omega}_\phi\right)^2 + \nu_* (\hat{\gamma} - i\hat{\Omega}_\phi) + \left(1-s\right)(1-md) \left[S_* \hat{\gamma} + (1+md)\right] &= \left(1 - \left(md\right)^2\right) \\
\text{plasma inertia} &\quad \text{dissipation} &\quad \text{mode strength} &\quad \text{wall response} &\quad \text{wall/edge coupling}
\end{align*}
\]

\[
S_* \sim 1/\tau_{wall}
\]

Unstable RWM dynamics follow theory

- Unstable n=1-3 RWM observed
  - ideal no-wall unstable at high $\beta_N$
  - n > 1 theoretically less stable at low A

- F-A theory / experiment show
  - mode rotation can occur during growth
  - growth rate, rotation frequency $\sim 1/\tau_{wall}$
    - $\ll$ edge $\Omega_\phi > 1$ kHz
  - RWM phase velocity follows plasma flow
  - n=1 phase velocity not constant due to error field

- Low frequency tearing modes absent

**Graphs:**
- Growth w/o mode rotation
- Mode rotation during growth

**Key Points:**
- $\beta_N$
- $|\delta B_p|(n=1)$
- $|\delta B_p|(n=2)$
- $|\delta B_p|(n=3)$
- $\phi_{B_p}(n=1)$
- $B_z(G)$ (f<40 kHz, odd-n)

**Time Axes:**
- t(s)
Camera shows scale/asymmetry of theoretical RWM

RWM with $\Delta B_p = 92$ G

Theoretical $\Delta B_\psi (x10)$ with $n=1-3$ (DCON)

- Visible light emission is toroidally asymmetric during RWM
- DCON theory computation displays mode
  - uses experimental equilibrium reconstruction
  - includes $n = 1 – 3$ mode spectrum
  - uses relative amplitude / phase of $n$ spectrum measured by RWM sensors
Soft X-ray emission shows toroidal asymmetry during RWM

USXR separated by 90 degrees

- Experiment / theory show RWM not edge localized
- Supported by measured $\Delta T_e$

114024, $t=0.273s$
$\beta_N = 5$

DCON $n = 1$ mode decomposition

$\psi_n = 0.13$
$\psi_n = 0.24$
$\psi_n = 0.4$
Experimental $\Omega_{\text{crit}}$ follows Bondeson-Chu theory

- **Experimental $\Omega_{\text{crit}}$**
  - stabilized profiles: $\beta > \beta_{N \text{ no-wall}}$ (DCON)
  - profiles not stabilized cannot maintain $\beta > \beta_{N \text{ no-wall}}$
  - regions separated by $\omega_{\phi}/\omega_A = 1/(4q^2)$

- **Drift Kinetic Theory**
  - Trapped particle effects significantly weaken stabilizing ion Landau damping
  - Toroidal inertia enhancement more important

- **Alfven wave dissipation yields** $\Omega_{\text{crit}} = \omega_A/(4q^2)$
\[ \Omega_{\text{crit}} \] follows F-A theory with neoclassical viscosity

- **Experimental \( \Omega_{\text{crit}} \)**
  - Stabilized points: \( \beta > \beta_N^{\text{no-wall}} \) (DCON)
  - Points not stabilized cannot maintain \( \beta > \beta_N^{\text{no-wall}} \)
  - Regions separated by \( \omega_{\phi}/\omega_A = 1/(4q^2) \)

- **F-A Theory**
  - Standard F-A theory has \( \Omega_{\text{crit}} \sim 1/q \)
  - Neoclassical viscosity includes toroidal inertia enhancement (K. Shaing, PoP 2004)
  - Yields \( \Omega_{\text{crit}} \sim 1/q^2 \)
MARS-F kinetic damping model computes $\Omega_{\text{crit}} \sim 1/q^2$

- Points are MARS-F predictions, not experimental data
- Theory (Bondeson&Chu, PoP96) predicts $\omega_{\text{rot}}^{\text{cr}} \propto 1/q^2$
- Rotational stabilization of RWM seems in favor of low-aspect-ratio (high-$q$)
- Difference between JET and DIII-D in equilibria profiles and plasma-wall shapes also change critical rotation
Plasma rotation damping described by NTV theory

**Neoclassical toroidal viscosity (NTV)**
\[ \delta B^2 \tau_i^{0.5} \]

- Rapid, global damping observed during RWM
  - Edge rotation ~ 2kHz maintained
  - Low frequency tearing modes absent

**Toroidal rotation profile evolution**

- \( \frac{\Omega_{\phi}}{2\pi} (\text{kHz}) \)
- \( R (\text{m}) \)
- \( t(s) \): 0.226, 0.236, 0.256

**Initial damping evolution**
- \( T_{\text{NTV}} \)
- \( -\rho R^2 (d\Omega_{\phi}/dt) \)
- \( t = 0.276 \text{s} \)
- \( T_{\text{measured}} \)
- \( T_{\text{theory}} \)

**Graphs**

- \( \Omega_{\phi} / 2\pi \) vs. \( R \)
- \( T_d (\text{N m}^2) \) vs. \( R \)
Rotation Damping Evolution Depends on Mode Type

- Core rotation damping with 1/1
  - leads to “rigid rotor” plasma core
  - damping rate $\sim 1/\tau_E$
- Momentum transfer across rational surface near $R = 1.3m$
- Rapid, global rotation damping by RWM
  - damping rate $\sim 1/\tau_{wall}$
- Edge rotation maintained
NTV Torque Contributes to Measured Core Rotation Damping During Large 1/1 Mode

- NTV torque applied to plasma core
- Rotating mode Doppler shifted relative to q=1 surface
- Resonant EM torque applied on 2/1 island
- Fluid viscosity included

\[
T_{\text{damping}} = -\rho R^2 \left( \frac{\partial \Omega}{\partial t} \right)
\]
Resonant Field Amplification increases at high $\beta_N$

- Plasma response to applied field from initial RWM stabilization coil pair
  - AC and pulsed $n = 1$ field
- RFA increase consistent with DIII-D
- Stable RWM damping rate of 300s$^{-1}$ measured

Completed coils will be used to suppress RFA, stabilize RWM, sustain high $\beta$
Evidence for resonance with AC error field observed

- Theory / experiment show AC frequency match may be responsible for mode trigger
- Mode rotates counter to plasma rotation
- $n=1$ phase velocity not constant due to error field
- Estimate of $\omega_{AC}/2\pi \sim 350$ Hz consistent with PF coil ripple
- Initial results – quantitative comparison continues

F-A modified resonance

$$\left( S_* v_* / (1 + md) + 1 \right) \hat{\omega}_{AC}^2 + \left( s(1 - md) + \Omega_{\phi}^2 \right) = 0$$

“static error field” response

New condition

$$\hat{\omega}_{AC}^2 - v_* (1 + md) / 2S_* = 0$$
RWM stabilization system being installed for 2005 run

- RWM sensor array used in 2004 experiments
- 6 $B_r$ coils now installed on NSTX
  - Pre-programmed capability in 2005 for RFA suppression / MHD spectroscopy experiments
- 3-channel switching power amplifier (SPA) on-site
- Real-time mode detection and control algorithm development in 2005 for feedback experiments
Passive stabilization research at low aspect ratio illuminates key physics for general high $\beta$ operation

- Plasma $\beta_t = 39\%$, $\beta_N = 6.8$, $\beta_N/l_i = 11$ reached; $\beta_N/\beta_N^{no\text{-}wall} > 1.3$
- Unstable $n = 1$-$3$ RWMs measured ($n > 1$ prominent at low $A$)
- Critical rotation frequency $\sim \omega_A/q^2$ strongly influenced by toroidal inertia enhancement (prominent at low $A$)
- Measured rapid, global plasma rotation damping associated with neoclassical toroidal viscosity
- Resonant field amplification of stable RWM increases with increasing $\beta_N$ (similar to higher $A$)
- Evidence for AC error field resonance observed

Completed RWM active stabilization coil to be used for research in 2005