Wall Stabilized Operation and Active Feedback Physics Design in NSTX

S. A. Sabbagh¹, J. Bialek¹, R. E. Bell², A. H. Glasser³, B. LeBlanc², J.E. Menard², F. Paoletti¹, M. Bell², T. Biewer², R. Fitzpatrick⁴, E. Fredrickson², A. M. Garofalo¹, D.A. Gates², S. M. Kaye², L. L. Lao⁵, R. Maingi⁶, D. Mueller², G. A. Navratil¹, M. Ono², Y.-K. M. Peng⁶, D. Stutman⁷, W. Zhu¹, and the NSTX Research Team

¹Department of Applied Physics and Applied Mathematics, Columbia University, New York, NY, USA
²Plasma Physics Laboratory, Princeton University, Princeton, NJ, USA
³Los Alamos National Laboratory, Los Alamos, NM, USA
⁴University of Texas at Austin, Austin, TX, USA
⁵General Atomics, San Diego, CA, USA
⁶Oak Ridge National Laboratory, Oak Ridge, TN, USA
⁷Johns Hopkins University, Baltimore, MD, USA

Workshop on Active Control of MHD Stability: Extension of Performance

Columbia University - November 18th, 2002
NSTX is operating at sufficiently high beta to study passive wall stabilization

- **Motivation**
  - Conducting walls can stabilize global modes in a rotating plasma
  - Resistive wall mode (RWM) can heavily damp rotation
  - Examine sustained stabilization by active feedback (needed for reactors)

- **Outline**
  - Operation in wall-stabilized, high beta regime
  - Resistive wall mode and rotation damping
  - Physical mechanisms for higher $\beta_N$ and longer pulse
  - Active feedback stabilization system physics design
NSTX is equipped to study passive stabilization

**Machine**
- Aspect ratio $\geq 1.27$
- Elongation $\leq 2.5$
- Triangularity $\leq 0.8$
- Plasma Current $\leq 1.5$ MA
- Toroidal Field $\leq 0.6$ T
- NBI $\leq 7$ MW

**Analysis**
- EFIT – equilibrium reconstruction
- DCON – ideal MHD stability
  (control room analysis)
- VALEN – RWM growth rate
Plasma operation now in wall-stabilized space

- Normalized beta, $\beta_N = 6.5$, with $\beta_N/l_i = 9.5$; $\beta_N$ up to 35% over $\beta_{N\text{ no-wall}}$
- Toroidal beta has reached 35% ($\beta_t = 2\mu_0\langle p \rangle / B_0^2$)
Maximum $\beta_N$ strongly depends on pressure peaking

- $F_p = p(0) / \langle p \rangle$
- $P$ profile from EFIT using $P_e$, diamagnetic loop, magnetics
- Time-dependent calculations required to evaluate stability limits and mode structure
Theoretical RWM growth rate depends on $\beta_N$

- Growth rate depends on mode structure and $\nabla p$ drive
  - Mode structure depends on equilibrium parameters
- Quantitative agreement between theory and experiment
  - Growth rates, passively stabilized $\beta_N$ range agree well
  - Based on DCON input from plasma 106165

Passive stabilization

With-wall limit ($\beta_N$ wall)

No-wall limit ($\beta_N$ no-wall)

$F_p \sim 2.2$

$\Delta \beta_N \sim 2$
Operational improvements yield higher, sustained $\beta_N$

- n=1 error field reduced by an order of magnitude in 2002
- H-mode pressure profile broadening raises $\beta_N$ limit
- $q_{\text{min}} > 1$ maintained (EFIT $q_{\text{min}}$ without MSE)

![Graph showing improvements over time]

- 2001 (High error field)
- 2002 (Reduced error field)

- $\beta_N$
- $F_p$
- $q_{\text{min}}$
- $\Delta B_r$

- n = 1 no-wall unstable (DCON)
- n = 1 unstable (with-wall)
- n = 1 unstable (no-wall)

- 3.5 $\tau_{\text{wall}}$ (VALEN)
- Locked mode detector
- H-mode

- RWM

- t(s)
N=1 error field greatly reduced by EF coil correction

- **n=1 amplitude reduced by factor of 12**
- **n=2 amplitude increased slightly**
  - Still only 2 Gauss at plasma edge
- **n=3 is largest predicted amplitude**
  - 4 Gauss at plasma boundary
  - Localized effect from coil feeds
- **RED** = magnetic measurements before correction
- **BLUE** = using measured coil radius, before correction
- **GREEN** = using measured coil radius, after correction

Calculations assume \( I_{PFS} = 10 \text{kA} \)

J. Menard
At high $\beta_N \sim 5$, external modes are well-coupled to passive stabilizing plates, independent of gap. Confirmed by ideal MHD stability calculations. Higher error field (2001 data) may have also lowered $\beta$ limit for smaller outer gap.
Rotation damping rate larger when $\beta_N > \beta_{N \text{ no-wall}}$

- Rotation damping rate is $\sim 6$ times larger when $\beta_N > \beta_{N \text{ no-wall}}$
Two stages of rotation damping during RWM

• Initial stage: Global, non-resonant rotation damping

• Final stage: Local rotation damping at resonant surfaces appears as rotation slows

• Analogous to rotation dynamics in induced error field experiments
Rotation damping during RWM is rapid and global.

- Damping from rotating modes alone is localized and diffusive.
\( T_\text{e} \) perturbation measured during RWM

- No low frequency (< 80 kHz) rotating modes observed during measured \( \delta T_\text{e} \)
- \( \delta T_\text{e} \) displacement precedes n=2 rotating mode
Rotation damping strongest where mode amplitude largest

- Field ripple damping by neoclassical parallel viscosity $\sim \delta B r^2 T_i^{0.5}$ possible candidate for observed damping profile
Core rotation damping decreases with increasing $q$

- Largest rotation damping ($dF_\phi/dt = -600$ kHz/s) at $B_t < 0.4$T, $q_{\text{min}} < 2$
  - Factor of 8 times larger than damping from $n=2$ island
- When $q_{\text{min}} \sim 2$, rotation damping rate is reduced and $F_\phi$ is maintained longer
- Consistent with theory linking rotation damping to low order rational surfaces

EFIT $q_{\text{min}}$ without MSE

<table>
<thead>
<tr>
<th>$B_t$</th>
<th>$q_{\text{min}}$</th>
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<tbody>
<tr>
<td>0.34T</td>
<td>1.4</td>
</tr>
<tr>
<td>0.39T</td>
<td>1.7</td>
</tr>
<tr>
<td>0.44T</td>
<td>1.9, 2.1</td>
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$I_p = 0.8$ MA
High $\beta_N$ plasmas with $q_{\text{min}} > 2$ have longer pulse length

- Typically (15 ms < $\tau_{\text{wall}}$ < 25 ms), $\tau_{\text{wall0}} \equiv 20$ ms
- (1.8 < $F_p$ < 2.3); $n=1$ mode typically computed stable for $\beta_N < 4.5$

W. Zhu
Plasma stabilized above no-wall $\beta_N$ limit for 18 $\tau_{\text{wall}}$

- Plasma approaches with-wall $\beta_N$ limit
  - $F_\phi(0)$ increases as $\beta_N >> \beta_N$ no-wall
- Passive stabilizer loses effectiveness at maximum $\beta_N$
  - Neutrons collapse with $\beta_N$ - suggests internal mode
  - Larger $\nabla p$ drive, mode shape change
- TRANSP indicates higher $F_p$
  - Computed $\beta_N$ limits conservative
Neutron collapses at highest $\beta_N$ suggest internal mode

- Neutron production primarily from plasma core
- No clear locked mode signal during collapses
Mode intensifies in divertor region at highest $\beta_N$

VALEN / DCON computed $n = 1$ external mode currents

$\beta_N = 5.1$  $\rightarrow$  $\beta_N = 7.1$

• Increased $\nabla p$ drive more significant in producing higher growth rate
Ideal no-wall $\beta_N$ limit exceeded and maintained

- Ideal no-wall limit violated for 400 ms
- $t_{\text{pulse}} \sim 8 \tau_E$
- Computed $\tau_{\text{wall}}$ for $n = 1$ mode decreases by factor of 100
- Average of computed $\tau_{\text{wall}}$ gives pulse length $> 20 \tau_{\text{wall}}$

VALEN $n=1$ RWM growth times

<table>
<thead>
<tr>
<th>t (s)</th>
<th>$\delta W$ (arb)</th>
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$I_p = 0.8 \text{ MA}$
$P_b = 4.2 \text{ MW}$

$108730$

$\beta_N > \text{no-wall } \beta_N$ limit
Active stabilization might sustain 94% of with-wall $\beta$ limit

- System with ex-vessel control coils reaches 72% of $\beta_{N \text{wall}}$

In-vessel control coils

VALEN model of NSTX (cutaway view)

Growth rate (s$^{-1}$)

- Passive
- Active gain (V/G)

With-wall limit ($\beta_{N \text{wall}}$)

$\beta_N$

$10^{-1}$ $10^{0}$ $10^{1}$ $10^{2}$ $10^{3}$ $10^{4}$ $10^{5}$

$5.0$ $5.5$ $6.0$ $6.5$ $7.0$ $7.5$

VALEN: J. Bialek
Control coils among plates reach only 50% of $\beta_{N \text{ wall}}$

VALEN model of NSTX (cutaway view)

Modeled active feedback coils

Growth rate ($s^{-1}$)

Active gain (V/G)

Passive

With-wall limit ($\beta_{N \text{ wall}}$)

VALEN: J. Bialek
Access to $\beta_N = 8$ conceptual design target exists

- Pressure peaking factor close to existing EFIT experimental reconstructed value
- Need to maintain elevated $q$ as $I_p$ is increased to sustain plasma

F. Paoletti
Research on passive stabilization and high $\beta_N$ rotation damping physics has begun

- Passive stabilization above ideal no-wall $\beta_N$ limit by up to 35%
  - Improvement in plasmas with highest $\beta_N$ up to 6.5; $\beta_N/l_i = 9.5$
- The $\beta_N$ limit increases with decreasing pressure profile peaking
- Stability limit insensitive to plasma proximity to passive plates in high $\beta_N$ plasmas with reduced error field
- Global $T_e$ perturbation measured during RWM
- Rotation damping at $\beta_N > \beta_{N\text{ no-wall}}$ has two stages
  - Global, non-resonant damping
  - Local, resonant field damping during final stage
- Rotation damping rate substantially decreases as q increases
- Passive stabilizers may become ineffective at highest $\beta_N$ due to increased $\nabla p$ drive and altered mode structure
- Active feedback design shows sustained $\beta_N/\beta_{N\text{ wall}} = 94\%$ possible