MHD stability of high-$\beta$ and long-pulse NSTX spherical torus plasmas

Presented by J.E. Menard, PPPL for the NSTX Research Team

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How does low aspect ratio change stability?

- Primarily through safety factor “q”
  
  $q$ is $\frac{\text{# toroidal transits}}{\text{# poloidal transits}}$ of a magnetic field-line on a magnetic surface
  
  - MHD instabilities try to satisfy $k \cdot B = 0$
    
    • Instability wave-vector $k = n\nabla\phi - m\nabla\theta$
    
    • Occurs on resonant rational $q = m/n$ surface
    
    • $n =$ toroidal mode number (integer)
    
    • $m =$ poloidal mode number (integer)
  
  - High $q$ and shear in $q$ profile stabilizing
    
    • Field-line bending energetically unfavorable

- Spherical torus ($A = R_0/a \leq 1.6$)
  
  $q_{\text{edge}} = 11$

- Tokamak ($A > 2.5$)
  
  $q_{\text{edge}} = 4$

- $q \propto (1+\kappa^2)\frac{aB_T}{I_P A}$
  
  - Higher $q$ for given $I_P / a B_T$ at low $A$
  
  - Increased shear in $q$ profile at low $A$
MHD stability improved at low A

- Efficient reactor needs high toroidal $\beta$
  $\beta = \text{kinetic pressure} / \text{magnetic pressure}$
  Generating toroidal field (TF) is costly

- Theory and experiment show
  - $\text{MAX}(\beta_T) \propto I_p / a B_T$
  - $\beta_N \equiv \beta_T(\%) a B_T / I_p(\text{MA}) \leq C \approx 3-6$

- $\beta_N$ increases at low $A$
  - $\beta_N$ up to 6 at low $A$
  - $\beta_N = 3-4$ in standard tokamak

- $I_p / a B_T \propto (1+\kappa^2) / A q$ \Rightarrow
  - Stable $I_p / a B_T$ increased at low $A$

Higher $\beta_N$ and $I_p / a B_T$ at low $A$ result in $\beta_T$ up to 35%
Highest $\beta_T$ discharges limited by $m/n=1/1$ modes

- $I_p=1\text{MA}, B_T=0.3\text{T}, P_{\text{NBI}}=5\text{MW}$
  - Both discharges terminate rapidly

- Before rapid termination….

  Sometimes, $\beta$ rises throughout discharge
  Most times, $\beta$ saturates, then drops

When $q(0)$ is near 1 and $\beta_T > 20\%$, 10-15kHz $n=1$ instability appears

$n=1$ mode larger in high $\beta$ shot (!)

How is drop in $\beta$ avoided?

Difference appears to be sustained rotation
Instability dynamics from non-linear simulations
(from Wonchull Park, M3D code, PPPL)

Simulation without rotation ⇒

B-field lines
Hot core
Cold island

With sufficient rotational flow and shear, reconnection can be interrupted
May explain long-lived 1/1 modes in high $\beta_T$ NSTX discharges
Steady-state ST also requires high $\beta_p$

- Self-driven current fraction \( \propto \beta_p \equiv 2\mu_0\langle p \rangle / B_P^2 \)
- \( \beta_T \propto \beta_N^2 / \beta_P \Rightarrow \) Need very high \( \beta_N \) for steady state

\[ 2A\beta_t/(1+\kappa^2) \% \]

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<th>$\beta_P$ / A</th>
<th>0.0</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
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<td>$q^* = 2$</td>
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NSTX $\beta_T = 40\%$ target
ST Reactor ($\kappa = 3.4$)
High $\beta_T$ and $\beta_N$
High $\beta_P$ and $\beta_N$
Want $q^* \approx 2.5$ at high $\beta_N > 8$
High $\beta_p$ discharges limited by “bursting” n=1

$\beta_p$

Rapid n=1 bursts cause $\beta$ drops
- $\beta$ can recover between bursts

Mode $B_\theta$
Gauss

Continuous modes degrade $\beta$?

$f_\phi(0)$
kHz

Each n=1 burst reduces rotation
- Also triggers continuous modes?

non-rotating n=1 $\delta B_R$

Non-rotating n=1 becomes unstable once rotation is low
- Causes final collapse of plasma $\beta$
High $\beta_p$ shots operate above no-wall limit

Theory and other experiments (DIII-D):
$\Rightarrow$ resistive wall and plasma rotation can stabilize “resistive wall mode”

NSTX high $\beta_p$ shots may be hitting with-wall limit
Stability increases at low A

- Low A $\Rightarrow$ high $I_p$ / a $B_T$ and $\beta_N$ $\Rightarrow$ high $\beta_T \leq 35\%$
  - High $\beta_T$ discharges limited by *long-lived* $n=1$ modes

- High $\beta_P$ and high $\beta_N$ needed for steady-state ST
  - High $\beta_P$ discharges limited by *bursting* $n=1$ modes

- Highest $\beta_P$ discharges are above stability limits w/o wall
  - Rotational stabilization of resistive wall mode