Stability Modeling of DIII-D Discharges with Transport Barriers

L.L. Lao, J.R. Ferron, Y.R. Linliu, M. Murakami, \(^1\)
E.J. Strait, T.S. Taylor, and A.D. Turnbull

*General Atomics, San Diego, CA, U.S.A.*
\(^1\) *Oak Ridge National Laboratory, Oak Ridge, TN, U.S.A.*

41st Annual APS Division of Plasma Physics Meeting
Seattle, Washington
November 15 - 19, 1999
Stability Modeling of DIII-D Discharges with Transport Barriers

L.L. LAO, J.R. FERRON, Y.R. LIN-LIU, E.J. STRAIT, A.D. TURNBULL, T.S. TAYLOR, General Atomics, M. MURAKAMI, Oak Ridge National Laboratory — The stability of DIII–D discharges with transport barriers is systematically studied by modeling the pressure profiles using a hyperbolic tangent representation with various radii, widths, and amplitudes. The $q$ profiles are modeled using a spline representation with varying $q(0)$, $q_{\text{min}}$, and $\rho_{q_{\text{min}}}$. The equilibria are computed using the EFIT and the TOQ codes based on the parameters from a strongly shaped high triangularity DIII–D long pulse high performance discharge. Stability against the ideal low $n = 1$ and 2 modes is evaluated using the GATO code with a conducting wall at $1.5a$. The results show that the stability improves with increasing transport barrier width and radius but varies weakly with $q(0)$. When the transport barriers are L–mode like and have narrow widths in the plasma core, the stability is limited by the $n = 1$ mode. When they are H–mode like and have large widths extending toward the edge, the stability is limited by the $n = 2$ mode.

Work supported by U.S. DOE Contracts DE-AC03-99ER54463 and DE-AC05-96OR22464.
MOTIVATION

- Strong local pressure gradients are often observed in discharges with internal transport barrier (ITB) which can lead to instability at low beta
- Previous stability modeling studies have been mostly discussed in terms of $P(0)/<P>$
- Goals
  - Explore stable path to configurations with both ITB and high normalized beta $\beta_N$
  - Check sensitivity of stability limit to variations in $q$ and ITB profiles
OUTLINE / KEY RESULTS

- Stability limit improves with transport barrier width and radius
- Wall stabilization is crucial for ITB with large radius
- Stability limit varies weakly with q(0)
- $n = 2$ modes are more unstable in ITB with large radius and width
APPROACHES

- Ideal stability with a conducting wall
- Simulated equilibria with model q and pressure profiles based on spline and hyperbolic tangent representations
- Simulated equilibria with q and pressure profiles from self-consistent transport simulations
PREVIOUS STABILITY STUDY IS DISCUSSED MOSTLY IN TERMS OF $P(0)/\langle P \rangle$

- $P(\psi) = P_0 \ (1 - \psi)^m$, $q_{95} = 5.1$, $\rho_{q_{\text{min}}} = 0.65$, $q_{\text{min}} = 2.1$ and 1.5
- Vary pressure profile peakedness by varying $m$

![Graph showing $\beta_N$ vs. $\langle P^2 \rangle^{1/2}/\langle P \rangle$ with $q_0 = 3.9$ and $q_0 = 2.5$.](image)

Turnbull et al Nuc Fusion 38 (1998) 1467
HYPERBOLIC TANGENT PROVIDES GOOD PARAMETRIZATION FOR PRESSURE PROFILES WITH TRANSPORT BARRIER

- 3 parameters amplitude, radius, and width

\[
\begin{align*}
Y &= A \times \tanh \left( \frac{XSYM - X}{HWID} \right) + B \\
Y &= Y + SLOPE \times (XKNEE - X), \ X < XKNEE
\end{align*}
\]

PEDESTAL = A + B
OFFSET = B - A
WIDTH = 2 * HWID
ANALYSIS METHODS

- **Equilibrium**
  - ToQ, EFIT
  - Up-down symmetric DND based on long pulse high performance shot 95983
  - Pressure profiles modeled using hyperbolic tangent representation with various radii, widths, and amplitudes
  - q profiles modeled using spline representation with various q(0), q_{min}, and \( \rho_{q_{min}} \)
  - Fixed q_{95} \sim 5.1
  - Single transport barrier

- **Stability**
  - Low \( n \) modes evaluated using GATO with a conducting wall at 1.5a
  - High \( n \) ballooning evaluated using BALOO
SCANS

- ITB radius $\rho_{\text{ITB}}$
  - Fixed shape
  - Fixed $q(0)$, $q_{\text{min}}$, $q_{95}$, $\rho_{\text{qmin}} - \rho_{\text{ITB}}$
  - Hyperbolic tangent pressure with fixed half width $W_{\text{ITB}}$

- ITB half width $W_{\text{ITB}}$
  - Fixed shape
  - Fixed $q(0)$, $q_{\text{min}}$, $q_{95}$, $\rho_{\text{qmin}} - \rho_{\text{ITB}}$
  - Fixed $\rho_{\text{ITB}}$

- $\rho_{\text{qmin}} - \rho_{\text{ITB}}$
  - Fixed shape
  - Fixed $q(0)$, $q_{\text{min}}$, $q_{95}$
  - Hyperbolic tangent pressure with fixed half width $W_{\text{ITB}}$, $\rho_{\text{ITB}}$

- $q(0)$, $q_{\text{min}}$
PLASMA SHAPE IS BASED ON A DIII-D LONG PULSE HIGH PERFORMANCE DISCHARGE

- Up-down symmetric with a conducting wall at 1.5a
- q profiles are modeled using spline representations
LARGEST PRESSURE GRADIENT IS REDUCED AS TRANSPORT BARRIER WIDTH IS INCREASED AT CONSTANT $\beta$

- $P(\psi) = P_0/2 \{ 1 - TANH[ (\psi - \psi_{ITB})/ W_{ITB} ] \} - P_0/2 \{ 1 - TANH[ (1 - \psi_{ITB})/ W_{ITB} ] \}$
STABILITY LIMIT IMPROVES WITH INTERNAL TRANSPORT BARRIER WIDTH

- fixed shape DND, \( q_{95} = 5.1, q(0) = 3.2, q_{\text{min}} = 2.2 \)
- ideal \( n = 1 \) with wall at 1.5a, \( \psi_{\text{qmin}}^{0.5} - \psi_{\text{ITB}}^{0.5} = 0.05 \)
- stability improves due to geometric effect, closer to wall, and stronger shear
THE n = 1 UNSTABLE MODE HAS A GLOBAL RADIAL STRUCTURE

- $\beta_N = 4.3$, $W_{ITB} = 0.24$, $\psi_{ITB} = 0.36$, $q(0) = 3.2$, $q_{\text{min}} = 2.2$, $q_{95} = 5.1$, $\psi_{q\text{min}} = 0.42$

- Computed using GATO with a conducting wall at 1.5a
THE $n = 1$ UNSTABLE MODE HAS AN INFERNAL MODE STRUCTURE

- $\beta_N = 4.3$, $W_{\text{ITB}} = 0.24$, $\psi_{\text{ITB}} = 0.36$, $q(0) = 3.2$, $q_{\text{min}} = 2.2$, $q_{95} = 5.1$, $\psi_{q_{\text{min}}} = 0.423$
- Computed using GATO with a conducting wall at 1.5a

Normalized Poloidal Flux

- Large $m = 1, 2$ components although no $q = 1$ and $2$ surfaces
STABILITY LIMIT IMPROVES WITH INTERNAL TRANSPORT BARRIER RADIUS

- fixed shape DND, $q_{95} = 5.1$, $q(0) = 3.2$, $q_{\text{min}} = 2.2$
- ideal $n = 1$ with wall at 1.5a, $\psi_{\text{qmin}}^{0.5} - \psi_{\text{ITB}}^{0.5} = 0.05$
- stability improves mainly due to geometric effects
STABILITY LIMIT IMPROVES WITH INTERNAL TRANSPORT BARRIER RADIUS

- fixed shape DND, \( q_{95} = 5.1, q(0) = 3.2, q_{\text{min}} = 2.2 \)
- ideal \( n = 1 \) with wall at 1.5\( a \), \( \psi_{\text{qmin}}^{0.5} - \psi_{\text{ITB}}^{0.5} = 0.05 \)
- stability improves due to geometric effect, closer to wall, and stronger shear

![Graph showing stability limit improvements with internal transport barrier radius](image-url)
PREVIOUS STABILITY STUDY SHOWS THAT WALL STABILIZATION IS CRUCIAL

Turnbull et al Nuc Fusion 38 (1998) 1467

With a close wall $\beta_N$ is substantially increased

$\lambda_c = 1.5$

$\frac{p_0}{\langle p \rangle} = 2.4$

$\frac{p_0}{\langle p \rangle} = 4.8$

$\frac{R_{wall}}{R_{plasma}}$

$\frac{p_0}{\langle p \rangle} = 2.4$

$\frac{p_0}{\langle p \rangle} = 4.8$

$\frac{p_0}{\langle p \rangle} = 4.8$
WALL STABILIZATION IS CRUCIAL FOR STABILITY

- $\beta_N = 5.2$, $W_{\text{ITB}} = 0.06$, $\psi_{\text{ITB}} = 0.36$, $q(0) = 3.2$, $q_{\text{min}} = 2.2$, $q_{95} = 5.1$
- Computed using GATO with a conducting wall at 1.5a

![Graphs showing normalized poloidal flux and radial displacement with and without a wall at 1.5a]
STABILITY LIMIT VARIES WEAKLY WITH $q(0)$

- fixed shape DND, $q_{95} = 5.1$, $q_{\text{min}} = 2.2$
- hyperbolic tangent pressure representation
- ideal $n = 1$, wall at 1.5a

![Diagram showing stability limit variation with $q(0)$]
\( n = 2 \) MODES ARE MORE UNSTABLE IN ITB WITH LARGE WIDTH

- fixed shape DND, \( q_{95} = 5.1 \), \( q(0) = 3.2 \), \( q_{\text{min}} = 2.2 \)
- ideal \( n = 2 \), wall at 1.5a
- wall stabilization is less effective against \( n = 2 \) modes
SUMMARY

- Hyperbolic tangent function provides an useful representation to systematic study the effects of Internal transport barrier (ITB) width and radius on MHD stability
- Stability limit improves with transport barrier width and radius
- Wall stabilization is crucial for ITB with large radius
- Stability limit varies weakly with q(0)
- n=2 modes are more unstable in ITB with large radius and width
- Future work
  - More sophisticated pressure models, hyperbolic tangent + linear
  - Higher n modes, edge stability
  - Shaping, squareness, outboard bump