Studies in DIII-D of High Beta Discharge Scenarios Appropriate for Steady-State Tokamak Operation With Burning Plasmas

by
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Multiple steady-state scenarios are under study at DIII-D with different current profiles and $\beta_N$ operating ranges

Common goals:
• $f_{NI} = 1$ (steady-state)
• high $\beta_T$ (fusion power density)

In this talk:
• Optimization of elevated $q_{min}$ discharges \textbf{(Holcomb,ClI1.3)}
  – Motivation for increased $q_{min} \approx 1.5$-2: $J_{BS} \propto 1/B_\theta$
• Discharges with increased $l_i \approx 1.1$-1.4
  – Motivation: the increased $\beta$ limit without wall stabilization and better confinement at higher $l_i$
• Comparison of ideal stability and current density profiles

Other DIII-D steady-state scenarios not discussed here:
• Very broad current profile, $q_{min} > 2$ \textbf{(Garofalo PoP 2006)}
• Hybrid with on-axis current drive \textbf{(Petty, IAEA 2008)}
Confinement and Achievable $\beta_N$ are Optimized at Intermediate Values of the Shape Squareness

• Observed change in maximum achieved $\beta_N$ is in agreement with ideal MHD modeling of low-n kink (Holcomb, CI1.3)

• In the reduced confinement at higher squareness:
  - ELMs are smaller, less regular
  - Core rotation is lower
  - Density fluctuation level is higher
Unbalanced Double-null Minimizes $n_e$ for Efficient Current Drive with Little Impact on Confinement

- Small bias away from ion $B_x \nabla B$ direction results in lower density than a balanced shape or a bias toward $B_x \nabla B$

- These dRsep changes do not affect confinement

Petrie PO3.8
ECCD with a relatively broad deposition profile enhances stability to the 2/1 tearing mode at high beta

- n = 1 mode avoided in discharge with ECCD (blue)
- n = 1 appears after ECCD is turned off (red)
- Alignment of broadly deposited ECCD with q = 2 surface not necessary for improved 2/1 stability
- See Turco TP6.3
Duration of $f_{NI}$ near 1 extended through operation at increased $\beta_N$ without termination by a 2/1 NTM

- $\beta_N = 3.5-3.7$
- Surface voltage $\approx 0$, indicating $f_{NI} \sim 1$, for $\approx 0.7\tau_R$
- Calculated $f_{NI} \approx 1$ and $f_{BS} \approx 0.65$
- Present limitations:
  - Available neutral beam energy limits duration
  - Neutral beam and ECCD power limit $I_{NI}$

**Graph**: Time evolution of $\beta_N$, $f_{NI}$, $f_{BS}$, and surface voltage. The goal is to achieve $0$ V and $f_{NI} = 1$.
High initial $I_i$ obtained using long ohmic phase to allow current to penetrate to the axis

- After H-mode transition, $I_i$ decreases
  - Broad $J_{BS}$ profile
  - $J_{BS}$ peak in the H-mode pedestal
- All co-injection $P_{beam}$ used to maximize $\beta_N$
- $q_{min} \approx 1$
\( \beta_N \) remains above 4 for 1 s as the current profile evolves

- Initially \( \beta_N \approx 4.5 \) is below \( 4l_i \), the control room estimate for the ideal \( n = 1 \) no-wall stability limit
- Confinement well above standard H-mode value
  - Decreases as \( l_i \) drops
- Current profile not yet stationary
  - Future step in scenario development
MHD spectroscopy indicates a reduction in $n = 1$ kink mode stability at $\beta_{N}/l_i \approx 4$

- Indicator is change in slope of response (red points)
- Consistent with the ideal MHD no-wall kink stability limit near $4l_i$
With $f_{NI}$ at or Above 1, the $l_i > 1$ Scenario is a Candidate for Steady-state Operation

- Measured surface voltage $< 0$
- Agrees with transport code modeling
- Calculated $f_{NI} \approx 1.2$
- Calculated $f_{BS} \approx 0.9$
Stabilization by coupling to an ideal wall is required to obtain high $\beta_N$ with elevated $q_{\text{min}}$ but not at high $l_i$.

- $\beta_N$ is at the ideal-wall limit.
- Rotation or feedback is required to stabilize resistive wall modes.

Calculated ideal $n = \infty$ and $n = 1$ stability limits:

- $\beta_N$ is near or below no-wall limit ($\approx 3.8l_i$).
- $\beta_N = 5$ should be possible at $l_i > 1.4$ without rotation or hardware to stabilize resistive wall modes.
Profiles of $J_{\text{IND}}$ differentiate the near stationary elevated $q_{\text{min}}$ scenario and the still transient high $l_i$ discharge.

To convert to steady-state:
- Replace peaked $J_{\text{IND}}$ with efficient on-axis CD
- Reduce H-mode pedestal $J_{BS}$

Good alignment between $J_{NI}$ and $J_{\text{TOTAL}}$
- Small residual $J_{\text{IND}}$
Progress has been made on two different approaches to a steady-state scenario with high fusion gain

- **Elevated q_{min} scenario** has been optimized toward long duration operation with high $\beta_N$ and $f_{NI} = 1$
  - Details of the discharge shape can have a significant effect on performance
  - Duration with surface voltage $\approx 0$ extended at higher $\beta_N$ without termination by a 2/1 tearing mode

- **In the high $l_i$ scenario**, $\beta_N > 4.5$ obtained simultaneously with $f_{NI} > 1$ and $f_{BS} > 0.8$
  - Peak $\beta_N$ is less than the ideal no-wall $n = 1$ stability limit
  - Indicates the possibility of steady-state operation with $q_{min} \approx 1$ without wall stabilization