Dependence of Bootstrap Current, Stability, and Transport on the Safety Factor Profile in DIII-D Steady-State Scenario Discharges

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This Work Tests the Dependence of the Bootstrap Current on Choice of Target Safety Factor (q) Profile

Important for Achieving Steady-State Development Goals

1. Fully noninductive operation with a high bootstrap current fraction $f_{BS} \equiv I_{BS}/I_P \propto \beta_P \propto q\beta_N$

2. Avoid local noninductive “overdrive” $J_{NI} > J_{TOTAL}$ (incompatible with steady-state)

3. Achieve sufficient fusion gain $G \sim \beta_N H_{89}/q_{95}^2$ (G=0.3 for ITER $Q=5$ operation)

- Conventional approach has been to try to maximize $f_{BS}$ by targeting high $q_{min}$ and $\beta_N$ with $q_{95}$ set by a trade-off with $G$
There is a Recursive Relationship Between Target q-Profile and $J_{BS}$ at high $f_{BS}$

- Limits our ability to predict $J_{BS}$
- Experiment designed to vary q and measure resulting profiles

Bootstrap Current Density

$q$-profile

Shear

Energy and Particle Transport

Density & Temperature Profiles

$J_B \propto \nabla p/B_p$
Experiment Produced Nine Different q-Profiles With \( q_{\text{min}} \approx 1.1, 1.5, 2 \) and \( q_{95} \approx 4.5, 5.6, 6.8 \)

- \( q_{95} \) adjusted by \( I_p \) at fixed \( B_T \)
- First scan at fixed \( \beta_N = 2.8 \) and second scan pushed \( \beta_N \) to maximum limited by stability or confinement
- Measured \( q \), density and temperature profiles
- Calculated Bootstrap Current Density using '99 Sauter formula in ONETWO transport code

\[
\frac{\langle J_{BS} \cdot B \rangle}{B_{T0}} = - \frac{F}{B_{T0}} \left[ \frac{T_e}{d\psi} \left( L_{31} \right) + \frac{n_e}{d\psi} \left( (L_{31} + L_{32}) \right) + \frac{T_i}{d\psi} \left( L_{31} \right) + \frac{n_i}{d\psi} \left( (L_{31} + \alpha L_{34}) \right) \right]
\]

- Compared all quantities averaged over few hundred to \(~1000\) ms for better statistics
q-Profile Variation at $\beta_N = 2.8$ Led to Systematic Differences in Measured Density and Temperature

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<tr>
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<td>$q_{\text{min}}$</td>
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<td>1.1</td>
<td></td>
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Variation with $q_{95}$:
- $n_e, T_e, T_i$ higher at low $q_{95}$ ($q_{\text{min}} \approx 2$ shown here)

Variation with $q_{\text{min}}$:
- $n_e$ higher and more peaked
- $T_e$ more peaked
- $T_i$ lower ($q_{95} \approx 4.5$ shown here)
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Variation with $q_{\text{min}}$:
- $n_e$ higher and more peaked
- $T_e$ more peaked
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These dependencies hold true in general in $\beta_N = 2.8$ data set (4 of 9 points in $q$-scan shown)
At $\beta_N = 2.8$, the Bootstrap Fraction Increased With $q_{95}$ in Agreement With $f_{BS} \propto q_{\beta_N}$ Scaling

- Bootstrap Fraction leveled off or dropped with $q_{\text{min}}$ above $\sim 1.5$
- This is contrary to expected $q_{\beta_N}$ scaling
Increased Stability at Lower $q_{\text{min}}$ Resulted in Highest Achieved $\beta_N$ and $f_{\text{BS}}$ Occurring at $q_{\text{min}} \approx 1.1$

Achieved $\beta_N$ (Closed Symbols) and $n=1$
Ideal-Wall Limit from DCON (Open Symbols)

Bootstrap Current Fraction at Maximum Achieved $\beta_N$

Lowest $q_{\text{min}}$, $q_{95} \approx 6.8$ discharge had ~10% higher $H_{89}$ than all others
Increasing $\beta_N$ Broadened $J_{BS}$ By Increasing $\nabla T_e$ and $\nabla T_i$ at Larger Radius

- This example, 2 shots: $q_{95}=5.6$, $q_{\min}\approx1.5$  
  $\beta_N \approx 2.8 \rightarrow 3.6$
- Similar broadening with $\beta_N$ for all $q$-profiles
- Broadening favorable for avoiding local noninductive current overdrive near $\rho\approx0.2$
- For some $q$ profiles, $dn_e/d\rho$ changed as well
Extrapolating to the $n=1$ Ideal Wall $\beta_N$ Limit
Suggests $f_{BS}$ Maximizes Near $q_{min} \approx 1.5$

- Measured $f_{BS}/\beta_N$ decreased going from low to high $\beta_N$ at “fixed” $q$-profile
- This reflects change in density and temperature profiles with $\beta_N$
- Used the difference between measured $f_{BS}/\beta_N$ at low and high $\beta_N$ to scale to $f_{BS}$ at the calculated ideal wall limit
Lower $f_{BS}$ at $q_{min} > 1.5$ Caused Mostly By Lower Density and Lower Temperature Gradients

- Profiles from 3 shots: $q_{95}=6.8$, $q_{min} \approx 2$ (dash)
  $q_{min} \approx 1.5$
  $q_{min} \approx 1.1$
- $\beta_N$ pushed to maximum
- In each row, first two quantities are leading scale factors of bootstrap terms in 3rd column
\( q_{\text{min}} > 1.5 \) Had Higher Measured Density Fluctuations and Calculated Growth Rates Than \( q_{\text{min}} \approx 1.1 \)

- FIR scattering spectrograms of \( \tilde{n} \) (\( k_{\theta} < 1 \text{ cm}^{-1} \))
- Linear TGLF runs show \( q_{\text{min}} \approx 1.1 \) was basically stable, \( q_{\text{min}} \approx 2 \) unstable to ITG type turbulence at mid-radius

\[ q_{\text{min}} \approx 1.1 \]
\[ q_{95} = 6.8 \]
\[ \beta_N = 2.8 \]
Summary and Conclusions

- In our scans of $q_{\text{min}}$ and $q_{95}$, the bootstrap current fraction increased with $q_{95}$ but did not continue to increase with $q_{\text{min}}$ above about 1.5 as expected by $f_{BS} \propto q_{\beta_N}$
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- New tools (off-axis NBI, more ECCD) may allow access to higher $\beta_N$ limits and higher bootstrap fractions