Optimization of the Safety Factor Profile for High Noninductive Current Fraction Discharges in DIII-D

by
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With
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Introduction
In a Steady-State Tokamak the q Profile is Closely Coupled to Both Transport Coefficients and Noninductive Current Sources

- **Bootstrap**: depends on n, T profiles, local q

\[
\langle J_{BSB} \rangle = -\frac{F q}{B T_0 \rho} \left[ T_e \frac{\partial n_e}{\partial \rho} L_{31} + n_e \frac{\partial T_e}{\partial \rho} (L_{31} + L_{32}) + T_i \frac{\partial n_i}{\partial \rho} L_{31} + n_i \frac{\partial T_i}{\partial \rho} (L_{31} + \alpha L_{34}) \right]
\]

- **Transport**: depends on the q profile and determines the n, T profiles
- **Steady-state**: at high $f_{BS}$, the q profile is largely determined by the $J_{BS}$ profile
- **Stability limit**:
  - Limits on pressure depend on the q profile
  - Reducing n, T gradients increases the $\beta_N$ limit
- **Presently this complex interdependence is difficult to understand using only models**
n, T Profiles were Measured vs q Profile at $\beta_N = 2.8$ and at the Maximum $P_{beam}$, then $J_{BS}$, $f_{BS}$, $J_{NI}$, $f_{NI}$ were Calculated.

- $q_{min} \approx 1, 1.5, 2$, $q_{95} \approx 4.5, 5.6, 6.8$
- Measured and calculated profiles averaged during phase of approximately constant $\beta_N$
- Maximum $\beta_N$ close to the calculated ideal-wall $n = 1$ stability limit.

![Graph showing safety factor (q) vs normalized radius with $\beta_N = 2.8$.](image)

![Graph showing $\beta_N$ vs $q_{95}$ for different values of $q_{95}$.](image)
Temperature and Density Profiles
$T_e$ and $T_i$ Profiles Broaden as $q_{\text{min}}$ is Increased ($\beta_N = 2.8$)

- $T_e$, $T_i$ increase as $q_{95}$ is decreased
- $dT_e/d\rho$, $dT_i/d\rho$ increase in the H-mode pedestal as $q_{95}$ decreases
At the Maximum Achieved $\beta_N$, the Temperature Profiles are Nearly Independent of $q_{\text{min}}$

- Profiles at $q_{\text{min}} \approx 1$ and $\approx 1.5$ are significantly broader at higher $\beta_N$
- Temperature dependence on $q_{95}$ is still present
Pumping of the Particle Exhaust in the Divertor Results in Low Pedestal Density and Peaked Density Profiles

- At $\beta_N = 2.8$:
  - Density gradient locally peaked near $\rho = 0.2$
  - Density gradient largest at $q_{min} = 1$

- At the maximum $\beta_N$, profile is broader and pedestal density is higher
The Scaling of the Thermal Pressure Peaking Factor Summarizes the Changes in the $n, T$ Profiles with $q_{\text{min}}$ and $\beta_N$

- At $\beta_N = 2.8$ pressure is less peaked at higher values of $q_{\text{core}}$
- Pressure peaking is significantly reduced at the maximum $\beta_N$
  - Little dependence on the $q$ profile as all $n, T$ profiles are relatively broad

$$f_p = \frac{n_e(0)T_e(0) + n_i(0)T_i(0)}{\langle n_eT_e + n_iT_i \rangle}$$
Calculated Bootstrap Current
At $\beta_N = 2.8$, $J_{BS}$ is Peaked Near $\rho = 0.1$

At Maximum $\beta_N$, the $J_{BS}$ Profile is Significantly Broadened

- $q_{\text{min}} = 1$: peaked $n_e \rightarrow \max J_{BS}$
- H-mode pedestal: no systematic variation of $J_{BS}$ with $q_{\text{min}}$ or $q_{95}$
  - $\partial / \partial \rho$ larger at lower $q_{95}$ but $J_{BS} \propto q$
- Both temperature and density profiles broader at max $\beta_N$
- H-mode pedestal: $J_{BS}$ profile width increases with $q_{95}$

![Computed bootstrap current density (A/cm²)]

$\beta_N = 2.8$

![Computed bootstrap current density (A/cm²)]

maximum $\beta_N$

$\frac{q_{\text{min}}}{q_{95}} = \frac{2}{4.5} = \frac{5.6}{6.8}$
The Dependence of $f_{BS}$ on $q_{core}$ is Comparable to the Dependence on $q_{95}$

- $f_{BS}$ is maximum at the largest values of $q_{95}$ and $\beta_N$.
- Reduced $f_{BS}$ at highest $q_{core}$: $n$, $T$ profile broadening and low achieved $\beta_N$.

$N_{open} = 2.8$

$N_{closed} = \text{max } \beta_N$
The Commonly Used Scaling $f_{BS} \propto \beta_p \propto \beta_N q_{95}$ is not the Best Description of the Results

- Offset at $q_{95} = 0$: $q_{core}$ important
- Max $\beta_N$ points below $\beta_N = 2.8$ data: reflects $n$, $T$ profile changes

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Scaling Function $f(q_{\text{core}}, q_{95}, f_p)$ Reflects the Observed Dependence of $f_{\text{BS}}/\beta_N$ on $q$, $n$, $T$ Profiles

- **Test case illustrates $J_{\text{BS}} \propto$ (local $q$ value)**
  - Differs from experiment $J_{\text{BS}}$ profiles
- **Plasma divides into two regions:**
  - Inner half: $J_{\text{BS}} \propto q_{\text{core}}$
  - Outer half: $J_{\text{BS}} \propto q_{95}$

Two regions $\rightarrow$ scaling function with separate $q_{\text{core}}$ and $q_{95}$ terms
- Opposite scaling of $\nabla n, \nabla T$ with $f_p$ in the inner and outer regions
  - Opposite signs for $\alpha_{\text{core}}$ and $\alpha_{95}$

Bootstrap current computed using constant $n$, $T$ profiles $(\text{A/cm}^2)$

\[
\frac{f_{\text{BS}}}{\beta_N \text{thermal}} = A q_{\text{core}} f^\alpha_{\text{core}} + B q_{95} f^\alpha_{95}
\]

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Total Noninductively Driven Current
The Calculated $f_{\text{Ni}}$ Increases with Both $q_{\text{core}}$ and $q_{95}$

- Result of combined changes in $f_{\text{BS}}$ and $f_{\text{NBCD}}$
- One exception: $q_{\text{core}} = 1.8$, $q_{95} = 6.8$ where max $\beta_N$ is low

$f_{\text{NBCD}}$ increases with $q_{\text{core}}$
- Higher $T_e$, lower $n_e$

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\( q_{95} = 6.8 \) Discharges are the Closest to \( f_{NI} = 1 \), \( J_{NI} \) and J Profile Shapes are Best Matched at \( q_{core} \geq 1.4 \)

- **\( J_{BS} \) profiles at max \( \beta_N \) are roughly uniform while J profile is peaked**
  - Externally driven current (\( J_{CD} \)) required at \( \rho < 0.8 \)
  - \( J_{NBCD} \) profile aligns well with J inside \( \rho < 0.8 \)
- **Required \( J_{CD} \) near the axis is very large for \( q_{core} \approx 1 \)**
- **At the highest \( q_{core} \), possibility of \( J_{NI} \) overdrive near the axis**
To Achieve $f_{NI} = 1$ at $q_{95} \approx 5$, Significantly Increased $J_{NI}$ Located Off Axis is Required

$q_{95} \approx 5$ required for sufficient fusion gain in a reactor or for ITER steady-state mission.

In this example:

- $f_{BS} \approx 0.39$, $f_{NI} \approx 0.6$

For $f_{NI} = 1$ in this example (compared to $q_{95} = 6.8$):
- Factor 2 additional $J_{NI}$ is required
- >factor 3 additional total noninductive current is required
Paths to Higher $f_{BS}$ at Fixed $q_{95}$ are Increased $\beta_N$, Increased $q_{core}$ or Increased Gradients

- **Increase $\beta_N$ limit by broadening P profile**
  - $n$, $T$ profiles broaden as $\beta_N$ is increased
  - $\beta_N$ limits may be higher than calculated
  - Off-axis beam injection to broaden fast ion pressure profile
    - $f_p$ total (here $\approx 3.3$) closer to $f_p$ thermal (here $\approx 2.6$)
  - Broader P moves gradients and $J_{BS}$ off-axis

- **$q_{\text{min}}$ controllable with external CD**
  - Choose high $q_{\text{min}}$ to increase $J_{BS}$, reduce external CD requirement
  - Compatible with off-axis beam injection

- **Increasing gradients (larger $f_p$) reduces $\beta_N$ limit**
  - Focus on reduced $n_e$, increased $T_e$ to increase CD and $J_{BS}$
Other DIII-D Discharges Have Demonstrated Higher $f_{BS}$ with Decreased $n_e^{ped}$ and Increased $T_e$

- Illustrated by comparison to a discharge from a 2008 AT-style discharge with $f_{BS} = 0.7$, same $q$ profile, $\beta_N = 3.1$
- Average $n_e$ lower, but still with substantial core density gradient
- Higher $T_e$ maintains $P_e$, $J_{BS}$
- Reduced $n_e$, increased $T_e$ increases $J_{CD}$
- Possible fast ion diffusion can reduce $J_{NBCD}$
  - Curve in red assumes 1 m$^2$/s
At $\beta_N = 2.8$, $T_e$, $T_i$ profiles broaden with increased $q_{\text{min}}$

Increasing $\beta_N$ broadens all profiles

At high $\beta_N$, core $J_{BS} < J$ with ~uniform profile
- No systematic dependence on the $q$ profile

Peaked profile of $J_{CD}$ needed so that $J_{NI}$ matches $J$

$q_{95} > 6$ is the best choice for $f_{NI} = 1$ with the present DIII-D external current drive sources
- Planned off-axis NBCD, ECCD are good matches to the current drive requirements

Path to $f_{NI} = 1$ at $q_{\text{min}} \approx 5$ is increased $\beta_N$ and $T_e$,
reduced $n_e$, relatively high $q_{\text{min}}$