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

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Abstract. In order to assess the optimum $q$ profile for discharges in DIII-D with 100% of the current driven noninductively ($f_{NI} = 1$), the self-consistent response of the plasma profiles to changes in the $q$ profile was studied in high $f_{NI}$, high normalized toroidal ($N$) discharges through a scan of $q_{\text{min}}$ and $q_{95}$ at two values of $\beta_N$. As expected, both the bootstrap current fraction, $f_{BS}$, and $f_{NI}$ increased with $q_{95}$. The temperature and density profiles were found to broaden as either $q_{\text{min}}$ or $\beta_N$ is increased. A consequence is that $f_{BS}$ does not continue to increase at the highest values of $q_{\text{min}}$. A scaling function that depends on $q_{\text{min}}$, $q_{95}$, and the peaking factor for the thermal pressure was found to represent well the $f_{BS}/N$ inferred from the experimental profiles. The changes in the shapes of the density and temperature profiles as $N$ is increased modify the bootstrap current density ($J_{BS}$) profile from peaked close to the axis to relatively flat in the region between the axis and the H-mode pedestal. Therefore, significant externally driven current density in the region inside the H-mode pedestal is required in addition to $J_{BS}$ in order to match the profiles of the noninductive current density ($J_{NI}$) to the desired total current density ($J$).

In this experiment, the additional current density was provided mostly by neutral beam current drive. The profiles of $J_{NI}$ and $J_{BS}$ were most similar at $q_{\text{min}} = 1.35-1.65$, $q_{95} = 6.8$, where $f_{BS}$ is also maximum, establishing this $q$ profile as the optimal choice for $f_{NI} = 1$ operation in DIII-D with the existing set of external current drive sources.

1. Introduction

In a tokamak discharge with 100% noninductively driven current ($f_{NI} = 1$) and a large fraction of self-generated bootstrap current [1] ($f_{BS}$), the safety factor ($q$) profile plays a key role as a result of the close coupling to both the transport coefficients and the sources of noninductive current density [2]. The bootstrap current density ($J_{BS}$) is proportional to the local values of $q$ and the temperature and density gradients, but the $q$ profile is strongly dependent on $J_{BS}$ when $f_{BS}$ is large. In a steady-state tokamak, $f_{BS}$ will be as large as possible in order to minimize the required external current drive power [3]. The temperature and density gradients depend on the transport coefficients, which also depend on $q$ as well as the magnetic shear. The stability limits to increasing pressure depend on the $q$ profile and the gradients. Finally, the amount of current that can be driven by external sources depends on the temperature and density profiles [3]. The complexity of these interactions and of the underlying processes limits the present ability to predict the self-consistent density, temperature, and $q$ profiles using models.

In order to assess the optimum $q$ profile for $f_{NI} = 1$ discharges in DIII-D, the self-consistent response of the plasma profiles to changes in the $q$ profile was studied in high $f_{NI}$, high normalized toroidal $\beta$ ($\beta_N$) discharges. In a systematic scan of the minimum value of $q$ ($1 < q_{\text{min}} < 2$) and $q$ at 95% of the normalized flux (4.5 < $q_{95}$ < 6.8), the temperature and density profiles were measured and the inferred profiles of the noninductively driven current densities (bootstrap, neutral beam driven $J_{NBCD}$, electron cyclotron driven $J_{ECCD}$) and the noninductive current fractions were computed from models. Measurements were made at both $\beta_N \approx 2.8$ and at the $\beta_N$ achieved with the maximum available neutral beam heating power, $\beta_N = 3.1$ to 3.8.
As expected, both $f_{BS}$ and $f_{NI}$ increased with $q_{95}$. However, the temperature and density profiles were found to broaden as either $q_{\text{min}}$ or $\beta_N$ is increased. Because of these profile changes and the role of $q_{\text{min}}$ in determining the total bootstrap driven current, the relation [3]

$$f_{BS} \propto e^{0.5} \beta_p \propto q_{95} \beta_N$$

(1)

is not the best description of the results in these experiments. An alternative scaling function is presented here that depends on $q_{\text{min}}$ and a measure of the pressure profile peaking in addition to $q_{95}$ and $\beta_N$. As $\beta_N$ was increased, the changes in the shapes of the density and temperature profiles were found to modify the $J_{BS}$ profile from peaked close to the axis to relatively flat in the region between the axis and the H-mode pedestal. A peaked noninductive current density ($J_{NI}$) profile is required, however, to match the total current density ($J$). Therefore, significant externally driven current density in the region inside the H-mode pedestal is required in addition to $J_{BS}$ to match the profiles of $J_{NI}$ and the desired total $J$.

These profiles were most similar at $q_{\text{min}} \approx 1.35-1.65$, $q_{95} \approx 6.8$, where $f_{BS}$ is also maximum, establishing this $q$ profile as the optimum choice for $f_{NI} = 1$ operation in DIII-D with the existing set of external current drive sources.

2. Description of the Experiment

The discharges for this experiment were created using the approach previously found to be optimum for high noninductive current fraction experiments in DIII-D [4]. Neutral beams at total power up to 13.5 MW from 5 beam sources that inject in the direction of the plasma current were the primary external power source, with additional heating from gyrotron power (up to 3.2 MW) applied as electron cyclotron current drive deposited in the region $0.25 < \hat{\rho} < 0.6$. ($\hat{\rho} = \rho/\rho_b$ is the normalized plasma radius, where $\rho$ is the square root of the normalized toroidal magnetic flux and $\rho_b$ is its value at the discharge boundary.) The $q$ profile was varied by changing the values of $q_{95}$ and $q_{\text{min}}$. The preprogrammed timing of the H-mode transition and the time evolution of $N$ were varied during the discharge formation in order to change the value of $q_{\text{min}}$ during the plasma current flattop. Data are displayed here as a function of $q_{\text{core}}$, the average value of $q$ in the region $0.0 < \hat{\rho} < 0.3$. The total plasma current was varied at constant toroidal field in order to change the value of $q_{95}$, a reactor-relevant optimization method since fusion gain $Q$ increases strongly with $B$.

Two separate sets of discharges were studied. In the first set, $\beta_N$ was held approximately constant at 2.7–2.8 through feedback control of the neutral beam power (with 8–10 MW required). In the second set of discharges, the neutral beam input power was increased to the maximum available (13.5 MW) resulting in $\beta_N \approx 3.5$. Two exceptions, the highest and lowest $q_{\text{min}}$ discharges at $q_{95} = 6.8$, achieved lower, 3.1, or higher 3.8, values of $\beta_N$ respectively. The maximum $\beta_N$ in the experiment was above the calculated ideal no-wall $n=1$ stability limit and within 5%–25% of the stability limit calculated with a perfectly conducting wall. The data presented in the figures in this report are the average of measurements obtained during the approximately constant $\beta_N$ phase of each discharge and the error bars show the standard deviation. Reconstructed equilibria together with the measured temperature and density profiles were used in the ONETWO [5] code to compute from models $J_{BS}$ [6,7], $J_{NBCD}$ (using NUBEAM [8]) and $J_{ECCD}$ (using TORAY-GA [9]).

The theoretical dependence of $J_{BS}$ on the temperature, density, and $q$ profiles is well illustrated by the form of the model [6,7]. $J_{BS}$ is directly proportional to the local value of $q$ and the total bootstrap current density is the sum of four terms, each proportional to the gradient of $n_e$, $n_i$, $T_e$, or $T_i$, the electron and ion densities and electron and ion temperatures, respectively.
\[ \langle J_{BS} B \rangle = -\frac{F q}{B_{T0} \rho} \left[ T_e \frac{\partial n_e}{\partial \rho} L_{31} + n_e \frac{\partial T_e}{\partial \rho} (L_{31} + L_{32}) + T_i \frac{\partial n_i}{\partial \rho} L_{31} + n_i \frac{\partial T_i}{\partial \rho} (L_{31} + \alpha L_{34}) \right]. \tag{2} \]

Here, \( q = B_{T0} \rho \frac{\partial \rho}{\partial \psi} \) was used in Eq. (5) of Ref. [6], \( \psi \) is the poloidal magnetic flux, \( F(\rho) = RB_t, \) \( B_{T0} \) is \( B_T \) at a reference major radius \( R_0, \) normally the center of the vacuum vessel, \( L_{31}, L_{32}, L_{34}, \) and \( \alpha \) are functions of the trapped particle fraction and the collisionality defined in Ref. [6], and \( \langle \cdot \rangle \) indicates flux surface average. Note that because the trapped particle fraction is zero on the axis in the approximation used here, \( J_{BS} \) always drops rapidly to zero between \( \hat{\rho} \approx 0.1 \) and the axis.

3. Density and Temperature Profiles

The electron and ion temperatures increase across the entire profile as \( q_{95} \) decreases at constant \( q_{\text{min}} \) [Figs. 1 and 2]. This is consistent with the increase in stored energy necessary to maintain a constant value of \( \beta_N \) as \( I_p \) is increased at constant \( B_T \) and with the increase in \( T_e \) with \( I_p. \)

At constant \( \beta_N \approx 2.8, \) the electron and ion temperature profiles broaden as \( q_{\text{min}} \) increases. This change is most clearly shown by the electron temperature profiles [Fig. 1(a)] where, at fixed \( q_{95}, \) the values at the axis and at the top of the H-mode pedestal are nearly independent of \( q_{\text{min}} \) while the values at mid-radius increase significantly as \( q_{\text{min}} \) increases. In the H-mode pedestal region (0.8<\( \hat{\rho} < 1.0 \)), \( |T_e/\partial \rho| \) and \( |\partial T_i/\partial \rho| \) increase as \( q_{95} \) decreases, reflecting...
an increased pedestal height, while there is no systematic trend with $q_{\text{min}}$.

With the maximum beam power, the temperature profiles are significantly broader in the $q_{\text{min}} \approx 1$ and $q_{\text{min}} \approx 1.5$ cases (Fig. 2). As a result, the temperature profiles are nearly independent of $q_{\text{min}}$. The exception is the case at $q_{\text{min}} \approx 1$, $q_{95} = 4.5$ where the temperature increases with beam power were small.

The pumping of the particle exhaust in the divertor region results in relatively low pedestal density, peaked density profiles, and little systematic dependence on the $q$ profile. At $\beta_N \approx 2.8$ [Fig. 3(a)], in the region nearest the axis ($0 < \rho < 0.5$), $n_e$ is highest at the lowest values of $q_{95}$ at a given $q_{\text{min}}$, but there is no consistent dependence on $q_{\text{min}}$. The lowest values of $n_e$ in the pedestal are at the highest value of $q_{\text{min}}$, but there is otherwise no systematic dependence on the $q$ profile. When $\beta_N$ is increased to the maximum possible with the available neutral beam power, the electron density increases, most noticeably at the H-mode pedestal, and the profiles broaden [Fig. 3(b)].

The key feature in the scaling of the density and temperature profiles with the $q$ profile is the broadening of profiles as a result of either increases in $q_{\text{core}}$ or $\beta_N$. This is reflected in the scaling of the peaking factor for the thermal pressure

$$f_p = \left[ n_e(0)T_e(0) + n_i(0)T_i(0) \right] / \left[ n_eT_e + n_iT_i \right]$$

as shown in Fig. 4. At $\beta_N \approx 2.8$, the pressure is systematically less peaked at higher values of $q_{\text{core}}$ and the pressure peaking is significantly reduced at the maximum achieved $\beta_N$. There is little dependence of the pressure peaking on $q_{\text{core}}$ in the high $\beta_N$ cases as all of the profiles are relatively broad.

4. Bootstrap Current Density

At $\beta_N \approx 2.8$, the calculated bootstrap current density is peaked near $\rho = 0.1$ [Fig. 5(a)]. The maximum $J_{BS}$ is in the discharges at $q_{\text{min}} \approx 1$ where the peak values of $|\delta n_e/\delta \rho|$ are the largest (Fig. 3), but at mid-radius ($\rho = 0.5–0.7$) these discharges have a small density gradient.

FIG. 3. Electron density for the discharges (a) at $\beta_N=2.8$ and (b) with the maximum available neutral beam power. The line types and colors are as described for Fig. 1.

FIG. 4. The peaking factor for the thermal pressure, as defined in Eq. (3), for all of the $\beta_N \approx 2.8$ (open symbols) and maximum neutral beam power (closed symbols) discharges. The dashed lines highlight the trends. The symbol types and colors indicate the value of $q_{95}$: 4.5 (red triangles), 5.6 (blue squares), 6.8 (green circles).
and thus the smallest $J_{BS}$. In most of the region $0<\hat{\rho}<0.7$, at a given $q_{\text{min}}$, $J_{BS}$ is highest at the lowest value of $q_{95}$. In the H-mode pedestal region there is no systematic variation of $J_{BS}$ with $q_{\text{min}}$ or $q_{95}$. In this region the larger temperature gradients at lower $q_{95}$ are compensated by the $q$ scaling of $J_{BS}$.

At the $\beta_N$ produced with the maximum available neutral beam power, the $J_{BS}$ profile is significantly broader than at $\beta_N=2.8$ [Fig. 5(b)]. The peak values near $\hat{\rho}=0.1–0.2$ are reduced by up to a factor of 2.5, and the bootstrap current density is increased at mid-radius. These changes are the result of broadening of both the temperature and density profiles. In the region of the H-mode pedestal, unlike in the $\beta_N=2.8$ cases, there is a systematic increase of the width of the $J_{BS}$ peak in the pedestal region with increasing $q_{95}$ that results primarily from an increase in the width of the electron and ion density gradient profiles.

5. Scaling of $f_{BS}$

The calculated bootstrap current fraction for the experimental data is maximum at the largest value of $q_{95}$ and the largest values of $\beta_N$ (solid green circles, Fig. 6) in agreement with Eq. (1). A feature not included in Eq. (1), though, is that the variation of $f_{BS}$ with $q_{\text{core}}$ is comparable to the variation with $q_{95}$. At $\beta_N=2.8$, the trend is for $f_{BS}$ to increase with $q_{\text{core}}$ with the exception of two of the data points with $q_{\text{core}}=2$, where the relatively high $q_{\text{core}}$ value is offset by broader temperature and density profiles and reduced gradients. At the maximum neutral beam power, the scaling of $f_{BS}$ with $q_{\text{core}}$ is similar to the scaling of $\beta_N$. For $q_{95} = 4.5$ and 5.6, $f_{BS}$ increases from $q_{\text{core}}=1$ to 1.5. At $q_{95}=6.8$, though, $f_{BS}$ decreases as $q_{\text{core}}$ increases as a result of the relatively low $\beta_N$ achieved at the highest $q_{\text{core}}$ and the relatively high $\beta_N$ achieved at the lowest $q_{\text{core}}$.

Values of $f_{BS}/\beta_{Nth}$ (Fig. 7) differ in two key ways from the proportionality to $q_{95}$ predicted by Eq. (1). ($\beta_{Nth}$ is computed from the thermal component of the pressure.) First, although the $f_{BS}/\beta_{Nth}$ values scale roughly linearly with $q_{95}$, the data extrapolate to an offset value at $q_{95}=0$. This reflects the importance of including $q_{\text{core}}$ in the scaling. Second, the data from the maximum beam power discharges lie systematically below the data from the $\beta_N=2.8$ discharges. This reflects the broadening of the density and temperature profiles when $\beta_N$ increases. The following improved scaling relation (Fig. 8) eliminates both of the
discrepancies with Eq. (1) by including both \(q_{\text{core}}\) and \(q_{95}\) and by including the thermal pressure peaking factor [Eq. (3)] to account for changes in the shape of the temperature and density profiles.

\[
f_{\text{BS}}/f_{\text{Nth}} = A q_{\text{core}} f_p^{\alpha_{\text{core}}} + B q_{95} f_p^{\alpha_{95}} \tag{4}
\]

In this function, the total bootstrap current is separated into a component in the innermost portion of the discharge that scales with \(q_{\text{core}}\) and a component in the outermost portion that scales with \(q_{95}\). There are separate exponents with opposite signs on the thermal pressure peaking factor for the two terms (\(\alpha_{\text{core}}=3.0, \alpha_{95}=-0.94\)) because, as \(f_p\) varies, the gradients in the innermost and outermost portions of the discharge change in opposite directions and at different rates.

6. Total Noninductively Driven Current

In almost all cases, the calculated \(f_{\text{NI}}\) increases with both \(q_{\text{core}}\) and \(q_{95}\) (Fig. 9) as a result of the combined changes in \(f_{\text{BS}}\) (Fig. 6) and \(f_{\text{NBCD}}\). Electron cyclotron current drive provided only 2%–4% of the total current because of the relatively high electron density.
$f_{\text{NBCD}}$ increases with $q_{\text{core}}$, a result of higher $T_e$ and reduced $n_e$, and increases with $q_{95}$. The sole exception to the increase in $f_{\text{NI}}$ with $q_{\text{core}}$ is the maximum neutral beam power discharge at $q_{\text{core}} \approx 1.77$, $q_{95} = 6.8$ where $f_{\text{NI}}$ is similar to the value in lower $q_{\text{core}}$ discharges as a result of relatively low $\beta_N$ and therefore relatively low $f_{\text{BS}}$.

Comparison of the calculated $J_{\text{NI}}$ to $J$ identifies the $q$ profiles that can best be maintained with noninductively driven current and thus are best suited to steady-state operation. The optimum $q$ profile is one with a high fraction of bootstrap driven current and a good match between the shape of the residual current density profile ($J - J_{\text{BS}}$) and the known methods to efficiently drive current by external means.

The highest bootstrap current fraction was found at the highest $\beta_N$, the highest $q_{95} = 6.8$ and $q_{\text{core}} \leq 1.5$. However, in the highest $\beta_N$ discharges, in the region between the axis and the H-mode pedestal the $J_{\text{BS}}$ profiles are relatively uniform. In contrast, the profiles of $J$ peak near the axis (Fig. 10). Current driven by neutral beams injected at the discharge midplane provided most of the externally driven current needed to match $J - J_{\text{BS}}$ because the $J_{\text{NBCD}}$ profile is peaked near the axis and rather broad. The match between $J_{\text{NI}}$ and $J$ in the region $\rho < 0.2$ varies strongly with $q_{\text{core}}$. At $q_{\text{core}} \approx 1.1$ [Fig. 10(a)] the residual current density is very large in this region because $J$ is large and because relatively high $n_e$ resulted in a relatively low peak value of $J_{\text{NBCD}}$. At $q_{\text{core}} \approx 1.77$ [Fig. 10(c)], $J_{\text{NI}}$ exceeds $J$ near the axis because the neutral beam driven current is the largest at this $q$ profile and $J$ is reduced at higher $q_{\text{core}}$. Noninductive current overdrive near the axis ($J_{\text{NI}} > J$) will reduce $q_{\text{core}}$ in steady state.

7. Summary

Systematic changes in the shapes of the density and temperature profiles were found as $q_{\text{min}}$ and $q_{95}$ were varied over the range of interest for tokamak operation with 100% of the current driven noninductively. There were also systematic changes as $\beta_N$ was varied. The primary change was a broadening of the profiles as either $q_{\text{core}}$ or $\beta_N$ was increased. The broadening of the density and temperature profiles reduces the gradients and, as a result, $J_{\text{BS}}$. Thus the $J_{\text{BS}}$ profiles are peaked near $\rho \approx 0.1$ at $\beta_N \approx 2.8$, but are much more uniform in the region inside the H-mode pedestal at the highest values of $\beta_N$. In addition, the highest values of $f_{\text{BS}}$ are at the mid-range value of $q_{\text{core}}$. Equation (1) is not a good predictor of $f_{\text{BS}}$ over the range of parameters of the discharges in this experiment. A scaling function of the form in Eq. (4) provides a much more complete description.

The relatively uniform $J_{\text{BS}}$ profiles in the region inside the H-mode pedestal in the highest $\beta_N$ discharges are not a good match to the peaked profile of $J$ in the weak shear discharges produced for this experiment. In addition, $J_{\text{BS}}$ is only a small fraction of $J$ in the innermost portion of the discharge (e.g. $\rho < 0.5$). Therefore, externally driven noninductive current must be provided with a peaked profile so that $J_{\text{NI}}$ is sufficiently peaked.
Of the discharges produced for this experiment, the three with $q_{95}=6.8$ are reasonable candidates for reproducible $f_{NI}=1$ operation in DIII-D with the present, or soon to be available, external current drive capability. Two of the three discharges had $f_{BS}<0.5$ and all three had $f_{NI}<0.8$. In the two discharges with $q_{core} \geq 1.43$, in order to increase $f_{NI}$ to 1, additional external current drive of $\approx 20$ A cm$^{-2}$ is required in the region $0.2<\hat{\rho}<0.7$. This additional current drive could be provided by the DIII-D ECCD system or by the planned off-axis neutral beam injection [10]. In the discharge with $q_{core}=1.1$, the total additional externally driven current that is needed is the same as in the two higher $q_{core}$ discharges, but the required current density is 2 to 3 times higher and it must be located near the axis. As ECCD is more efficient on axis than off axis, this required noninductive current could also be provided by the DIII-D ECCD system [11].

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References


FIG. 10. Radial profiles of current density in discharges with maximum available neutral beam power, $q_{95}=6.8$ and different values of $q_{core}$: (a) 1.1, (b) 1.43, (c) 1.77. The total current density (dashed line) is taken from the equilibrium reconstruction, the bootstrap current density (solid line), neutral beam driven current density (long dashed line) and electron cyclotron driven current density (dotted line) are calculated from models. The total noninductive current density (dash-dot line) is $J_{NBCD} + J_{ECCD} + J_{BS}$. 