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In recent DIII-D experiments [1-3], we have systematically studied the physics that affects the choice of parameters for a discharge where the goal is 100% noninductively driven current ($f_{NI}=1$) at high plasma pressure ($\beta_N \approx 4$). The choice of parameters will be a compromise that results in sufficiently high values of the bootstrap current fraction $f_{BS}$, the efficiency of the externally driven current, and the fusion gain parameter $G = \beta_N H / q_{95}^2$ [4]. The available adjustable parameters are the $q$ profile, the toroidal field $B_T$, and the plasma density $n$. The tokamak geometry and the discharge shape are constrained by the existing DIII-D design. $\beta_N$ will be close to the stability limit, which must be high enough to give access to the required $f_{BS}$ and $G$. The input power is that required for external current drive at $f_{NI}=1$ and it must match the power required to maintain the pressure against transport losses [4].

To assess the effect of the $q$ profile [2], the self-consistent response of the temperature ($T$) and density profiles was measured in two sets of discharges with $q_{min}$ and $q_{95}$ varied independently ($q_{95}$ is the value of $q$ near the discharge boundary and $q_{min}$ is the minimum value), one set at $\beta_N \approx 2.8$ and one set with the maximum available neutral beam power injected ($\beta_N \approx 3.5$ in most cases). The focus was on weak shear discharges without large, local pressure gradients that would reduce the stable $\beta_N$. The effects on stability and transport of more detailed features of the $q$ profile such as the profile of the magnetic shear and the radial location where $q=q_{min}$, also important for the choice of steady-state scenario parameters, will be considered in future work. Changes in the measured $n$ and $T$ profiles resulted in a systematic broadening of the pressure profile as either $q_{min}$ or $\beta_N$ was increased. At the maximum $\beta_N$, the peaking factor for the thermal pressure $f_p$ is roughly independent of $q_{min}$ and $q_{95}$.

The calculated $f_{BS}$ for the experimental data is maximum at the largest value of $q_{95}$ and the largest values of $\beta_N$ (Fig. 1), with variation of $f_{BS}$ with $q_{core}$ comparable to the variation with...
$q_{95}$. At $\beta_N=2.8$, the trend is for $f_{BS}$ to increase with $q_{core}$ except at $q_{core}=2$ where the relatively high $q_{core}$ is offset by reduced $T$ and $n$ gradients. At the maximum beam power, $f_{BS}$ increases with $q_{core}$ at the lowest $q_{95}$ values, but at $q_{95}=6.8$ the scaling is the opposite because at the lowest $q_{core}$, $\beta_N$ was relatively high (3.8) and at the highest $q_{core}$, $\beta_N$ was relatively low (3.1). The neutral beam current drive fraction [2] was highest in the relatively low $n$ discharges at the highest $q_{core}$, so that the calculated $f_{NI}$, in most cases, also increases with both $q_{core}$ and $q_{95}$ (Fig. 2).

At the highest values of $\beta_N$ the reduced $f_p$ results in $J_{BS}$ profiles which are relatively uniform in the region inside the H-mode pedestal (Fig. 3). This $J_{BS}$ profile shape is not a good match to the peaked profile of current density $J$ in weak shear discharges. In addition, $J_{BS}$ is only a small fraction of $J$ in the inner portion of the discharge. Therefore, to achieve $f_{NI}=1$, the profile of the externally driven noninductive current that results in a match between the total noninductive current density $J_{NI}$ and $J$ will need to be peaked on axis.

The scan of the $q$ profile indicates that $f_{NI}=1$ with $f_{BS}>0.5$ is presently best achieved in DIII-D at $q_{95}>6$. The preferable $q_{min}$ value is relatively high (e.g. $>2$) to minimize the external current drive requirement near the axis by reducing $J$ and increasing $J_{BS}$ in that region, but $\beta_N$ must be increased above the value observed at the highest $q_{core}$ value in this experiment. An excess of externally-driven current density near the axis which reduces $q_{min}$, as in the case in Fig. 3, must be avoided. This is possible through injection of a substantial fraction of the neutral beam power off-axis, consistent with the case in Fig. 3 where $\approx 20$ A cm$^{-2}$ additional $J_{NI}$ is required in the region $0.2<\rho<0.7$ at $q_{95}>6$ in order to reach $f_{NI}=1$. The capability to inject 5 MW off-axis has been made available for 2011 DIII-D experiments.

Modeling of a discharge with 5 MW on-axis beam injection, 5 MW off-axis injection, and 3.5 MW off-axis
ECCD predicts $q_{\text{min}}=2$ with a fully penetrated electric field.

In order to satisfy the requirements on the figure of merit $G$ in the steady-state scenario of ITER or in a reactor, $q_{95}=5$ is thought to be necessary. The small value of $f_{\text{BS}}=0.4$ observed in this experiment at $q_{95}=5$, though, is not sufficient for practical steady-state operation. As $q_{95}$ is reduced with fixed $q_{\text{min}}$, the additional current density is located off axis. The primary path to increased $f_{\text{BS}}$ with $J_{\text{BS}}$ added off-axis is broadening of the pressure profile to allow stable operation at increased $\beta_N$. Broadening of the pressure profile increases $n$ and $T$ gradients off-axis, and thus $J_{\text{BS}}$ there, and results in higher stability limits. For MHD stability, the peaking factor for the fast ion pressure must be comparable to $f_p$ so that the total pressure peaking factor is low. This will be facilitated by off-axis neutral beam injection in DIII-D. Previous estimates have found ideal-wall stability at $\beta_N=4$ with total pressure peaking factor less than 2.6 [5].

At fixed $\beta_N$ and $q_{95}$, the toroidal field strength ($B_T$) is the parameter to adjust to obtain a balance between the required current drive ($P_{\text{CD}}$) and heating powers when all external power sources provide both heating and current drive [3]. In cases like DIII-D where there is no $\alpha$-heating, the fraction of $I_p$ driven by external current sources $f_{\text{CD}}$ would be expected to increase with $B_T$ as a result of the scaling of energy confinement with input power. Assuming $H_{\text{99p}}$ confinement scaling, $P_{\text{CD}} \propto B_T^{1.9}$ at constant $\beta_N$ and $q_{95}$, and for current drive efficiency of the form [4] $n I_{\text{CD}}/(P_{\text{CD}} T_e)$, then $f_{\text{CD}}=C_{\text{CD}} P_{\text{CD}} \beta_N q_{95}^2/(B_T f_G^2) \propto B_T^{0.9}$ (where $f_G$ is the Greenwald density fraction and $C_{\text{CD}}$ is a constant). If $n$ is maintained at a low level through pumping of divertor exhaust so that $f_G$ decreases as $B_T$ is increased, the driven current increases faster than linearly with $P_{\text{CD}}$ because of increases in $T_e$.

This type of scaling was demonstrated in DIII-D in a series of neutral-beam-heated discharges [3] with $q_{95}=6.2$ and $\beta_N=3.4$ (Fig. 4). A factor 1.2 change in $B_T$ required a factor 1.4 increase in the neutral beam power, resulting in a factor 1.6-1.8 increase in the total neutral beam driven current. Because $B_T/I_p$ was held constant during the scan, $f_{\text{NBCD}}$ and $f_{\text{NI}}$ also increased.

In DIII-D steady-state scenario experiments, the minimum achievable $n$ is used in order to maximize $f_{\text{CD}}$. To minimize $n$, the plasma shape is chosen to optimize the use of the divertor cryopump capability [1]. Typically $H_{\text{98}}=1.5$ as long as $n$ is above approximately $4.5 \times 10^{19} \text{ m}^{-3}$, but as $n$ decreases during the high $\beta_N$ phase of a discharge as the wall particle source is...
depleted, a trend toward decreasing $\tau_E$ is observed (Fig. 5). This places constraints on the ability to reduce $n$ in order to maximize the total externally driven current. No reproducible quantitative relation between $n$ and $H_{98}$ has been found as yet, but for $n$ near 4.0$x10^{19}$ m$^{-3}$, $H_{98}$ typically is about 1.1.

A set of self-consistent parameters for $f_{NI}=1$ operation in DIII-D can be determined by combining the observed scalings of $f_{BS}$ and $f_{CD}$. A fit to the data from the $q$ profile scaling experiment yields $C_{CD} = 1.03x10^{-4}$ and $f_{BS}$ scales with $\beta_N$, $q_{core}$, $q_{95}$ and $f_p$ as shown in [2]. In the example in Fig. 6, the circles highlight $f_{NI}=1$ solutions at two values of $q_{95}$.

At $q_{95} \approx 6.2$, $f_{NI}=1$ at $\beta_N=3.8$ (similar to the discharge discussed in [1]). For the heating and current drive powers to be balanced, the required confinement enhancement factor $H_{89}$, 2.1 in this case, must match the value in the discharge. At $q_{95} \approx 5$, the $f_{NI}=1$ solution is at higher $\beta_N=4.1$, requiring a larger $H_{89}=2.3$. To adjust the power balance, $B_T$ can be changed. For instance, for the parameters of Fig. 6 but at higher $B_T = 2.0$ T, the $f_{NI}=1$ solution at $q_{95} \approx 6.2$ is at lower $\beta_N=3.6$ but higher $H_{89}=2.2$, and at $q_{95} \approx 5$ the solution moves to $\beta_N=3.85$, $H_{89}=2.5$. In all cases, MHD stability must be sufficient to reach the required $\beta_N$.

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