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Design Parameters for DIII-D Steady-State Scenario Discharges

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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 $(\beta_N \geq 4)$. 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 $G = \beta_N \mathrm{H}/q_{95}^2$ [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. β_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 β_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 β_N was increased. At the maximum β_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 β_N (Fig. 1), with variation of f_{BS} with q_{core} comparable to the variation with

q_{95}. At $\beta_N \approx 2.8$, the trend is for f_{BS} to increase with q_{core} except at $q_{core} \approx 2$ 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}, β_N was relatively high (3.8) and at the highest q_{core}, β_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 β_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 β_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 ≈20 A cm^{-2} additional J_{NI} is required in the region 0.2<ρ<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

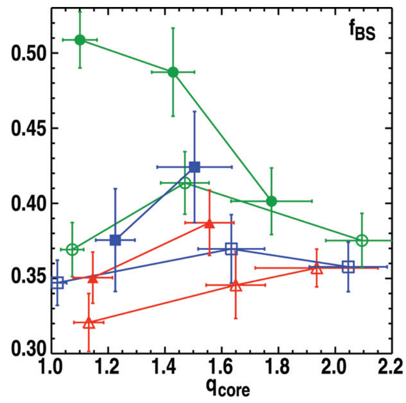

Fig. 1. Calculated bootstrap current fraction. β_N=2.8 (open), maximum beam power (closed), q_{95}: 4.5 (triangles), 5.6 (squares), 6.8 (circles). q_{core} is the average value of q in the region 0.0 < normalized radius ρ<0.3.

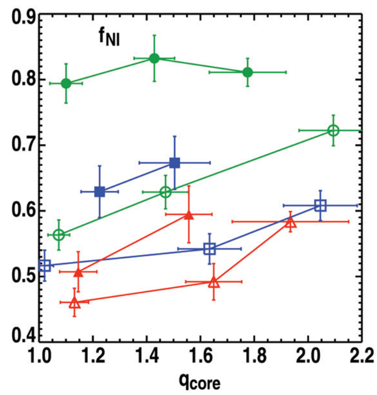

Fig. 2. Noninductive current fraction. Symbols are as in Fig. 1.

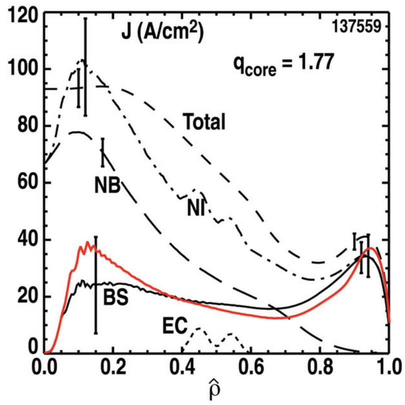

Fig. 3. Current density profiles in a discharge with the maximum neutral beam power, q_{95}=6.8, q_{core}=1.77. The total is from an equilibrium reconstruction, bootstrap (BS), electron-cyclotron (EC), neutral beam (NB) and total noninductive (NI) are calculated. The red curve is bootstrap at $\beta_N \approx 2.8$.

ECCD predicts q_{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_{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_{min}, the additional current density is located off axis. The primary path to increased f_{BS} with J_{BS} added off-axis is broadening of the pressure profile to allow stable operation at increased β_N. Broadening of the pressure profile increases n and T gradients off-axis, and thus J_{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 β_N=4 with total pressure peaking factor less than 2.6 [5].

At fixed β_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_{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 α-heating, the fraction of I_p driven by external current sources f_{CD} would be expected to increase with B_T as a result of the scaling of energy confinement with input power. Assuming H_{89P} confinement scaling, $P_{CD} \propto B_T^{1.9}$ at constant β_N and q_{95}, and for current drive efficiency of the form [4] $nI_{CD}/(P_{CD}T_e)$, then $f_{CD}=C_{CD}P_{CD}\ \beta_N\ q_{95}^2/(B_T f_G^2) \propto B_T^{0.9}$ (where f_G is the Greenwald density fraction and C_{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_{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 β_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_{NBCD} and f_{NI} also increased.

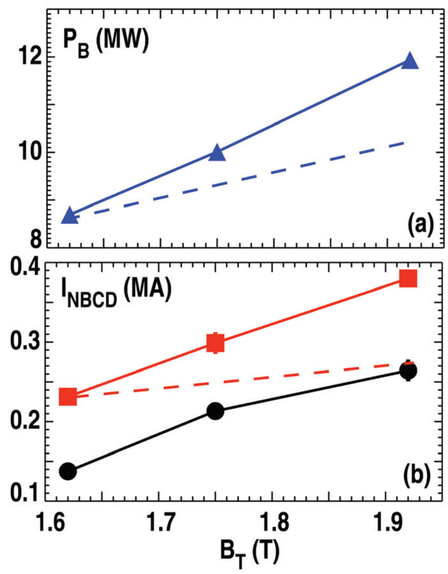

Fig. 4. As a function of the toroidal field strength (a) neutral beam power at constant β_N, (b) total neutral-beam-driven current. The dashed lines show the trend that would be expected from scaling which is linear in B_T. Anomalous fast ion diffusion: none (red), 1-2 m^2/s (black).

In DIII-D steady-state scenario experiments, the minimum achievable n is used in order to maximize f_{CD}. To minimize n, the plasma shape is chosen to optimize the use of the divertor cryopump capability [1]. Typically H_{98}=1.5 as long as n is above approximately 4.5×10^{19} m^{-3}, but as n decreases during the high β_N phase of a discharge as the wall particle source is depleted, a trend toward decreasing τ_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 $4.0\text{x}10^{19}$ m^{-3}, H_{98} typically is about 1.1.

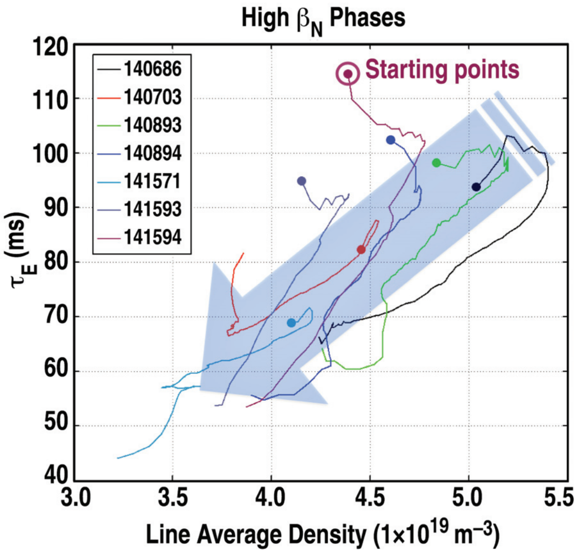

Fig. 5. For several discharges, in the approximately constant β_N>3 phase, energy confinement time as a function of density.

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} = $1.03\text{x}10^{-4}$ and f_{BS} scales with β_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}≈6.2, f_{NI}=1 at β_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}≈5, the f_{NI}=1 solution is at higher β_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}≈6.2 is at lower β_N=3.6 but higher H_{89}=2.2, and at q_{95}≈5 the solution moves to β_N=3.85, H_{89}=2.5. In all cases, MHD stability must be sufficient to reach the required β_N.

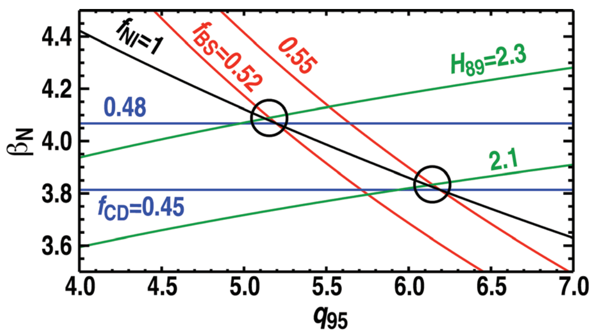

Fig. 6. Contours of self-consistent discharge parameters derived from f_{BS} and f_{CD} scalings and f_{NI}=f_{BS}+f_{CD} with B_T=1.75 T, q_{core}=2, n=$4.5\text{x}10^{19}$ m^{-3}, f_p=2.5, P_{CD}= 16 MW, and fast ion stored energy fraction = 0.25. The circles highlight f_{NI}=1 solutions at two values of q_{95}.

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[1] C.T. Holcomb *et al.*, 2009 Phys. Plasmas **16** 056116
[2] J.R. Ferron *et al.*, 2011 Nucl. Fusion **51** 063026
[3] J.R. Ferron *et al.*, 2011 "Balancing Current Drive and Heating in DIII-D High Noninductive Current Fraction Discharges," submitted to Nucl. Fusion (2011).
[4] C. Gormezano *et al.*, 2007 Nucl. Fusion **47** S285
[5] J.R. Ferron *et al.*, 2005 Phys. Plasmas **12** 056126