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[1]Lawrence Livermore National Laboratory, Livermore, California
[2]Oak Ridge Institute of Science and Education, Oak Ridge, Tennessee
[3]University of California-Los Angeles, Los Angeles, California

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In a tokamak discharge with 100% noninductively driven current (f_{NI} = 1) and a large fraction of self-generated bootstrap current (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. 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 β_N discharges through a scan of q_{min} and q_{95} at two values of β_N. As expected, both f_{BS} and f_{NI} increased with q_{95}. The temperature and density profiles were found to broaden as either q_{min} or β_N is increased (Fig. 1). A consequence is that f_{BS} does not continue to increase at the highest values of q_{min} (Fig. 2). The density and temperature profile shape changes as β_N is increased modify the bootstrap current density (J_{BS}) profile from peaked 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) (Fig. 3). 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_{min}≈1.35-1.65, q_{95}≈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 current set of external current drive sources. This experiment will also aid in establishing the physics basis for f_{NI} = 1 discharges for the ITER steady-state mission and for a DEMO reactor.

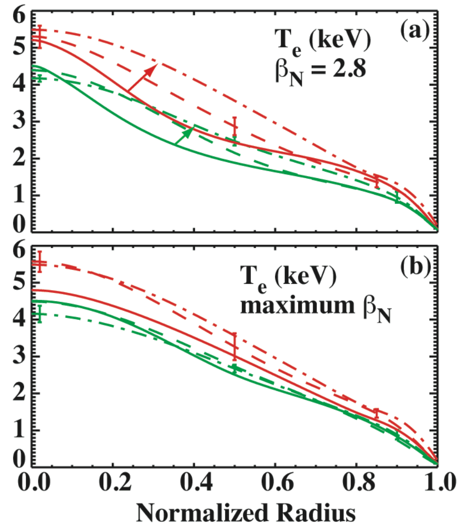

Fig. 1. Radial profiles of electron temperature at different values of q_{95}: 4.5 (red), 6.8 (green) and q_{min}: 1 (solid), 1.5 (dashed), 2 (dot-dash). (a) β_N = 2.8, (b) maximum β_N.

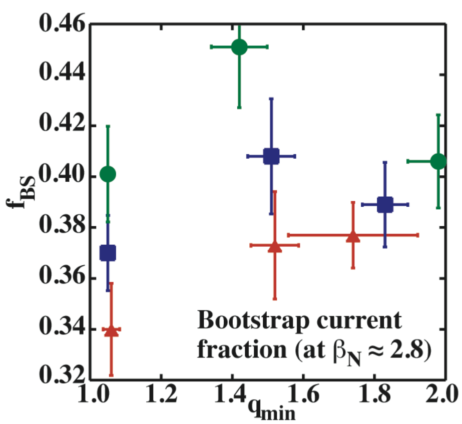

Fig. 2. Bootstrap current fraction at β_N = 2.8 as a function of q_{95}, 4.5 (red triangles), 5.6 (blue squares), 6.8 (green circles), and q_{min}.

Because of the close coupling between the plasma profiles in a f_{NI} = 1 discharge, the optimum q profile is difficult to model, thus motivating an experimental study. The bootstrap current density is proportional to q and the temperature and density gradients, but the q profile is strongly dependent on J_{BS} when f_{BS} is large. The gradients depend on the transport coefficients, which depend on q as well as the magnetic shear. The pressure limit also depends on the q profile and the gradients.

For this experiment, discharges were produced with nine different q profiles, q_{min}≈1, 1.5, and 2 and q_{95}≈4.5, 5.6 and 6.8. The plasma current was changed at constant toroidal field in order to vary q_{95}. The density and temperature profiles were measured both at β_N=2.8 and at the maximum achievable β_N, 3.1-3.8 depending on the q profile, which is within 10%-20% of the calculated stability limit. The noninductive current density profiles were computed from models, obtaining f_{NI} between 0.45 and 0.9.

In the lower β_N=2.8 set of discharges, there is significant broadening of the temperature profiles as q_{min} increases [e.g. T_e profiles in Fig. 1(a)]. In the maximum β_N discharges, though, the temperature profiles are all broad and are relatively independent of q_{min} [Fig. 1(b)]. In all cases, T_e and T_i increase across the entire profile as q_{95} decreases, as would be expected at higher

I_p. The pumping of the particle exhaust in the divertor region results in relatively low pedestal density and peaked density profiles. The density gradient peaks near ρ=0.2 in the low β_N case, but the profiles broaden with the increase in β_N.

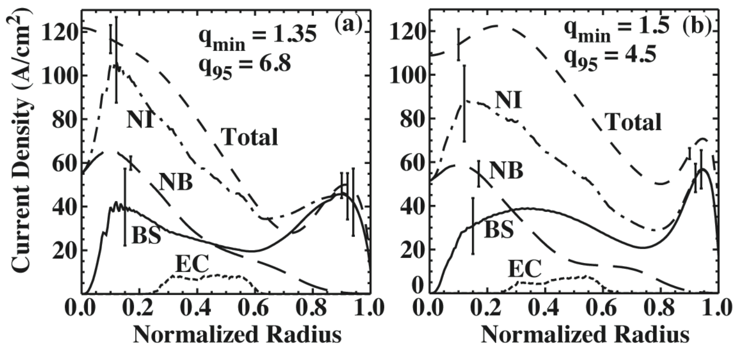

Fig. 3. Radial profiles of the current density components. (a) q_{min} = 1.35, q_{95} = 6.8, β_N = 3.6, (b) q_{min} = 1.5, q_{95} = 4.5, β_N = 3.45. The total current density is from an experimental equilibrium reconstruction, the noninductive current density components are calculated from models [bootstrap current (solid), neutral beam driven (long-dash), electron cyclotron driven (dot-dot-dot), total noninductive (dot-dash)].

The J_{BS} profile at β_N=2.8 is peaked in the region inside the H-mode pedestal, primarily as a result of the peaked density gradient. At the maximum β_N, though, the broader density and temperature profiles result in J_{BS} that is reduced near the axis and increased at mid-radius, producing the relatively flat J_{BS} profile inside the H-mode pedestal. There is no systematic dependence on q of the maximum J_{BS} in the H-mode pedestal region as larger temperature gradients at lower q_{95} are compensated by the q scaling of J_{BS}. However, at the highest β_N there is a systematic increase with q_{95} in the width of the J_{BS} peak in the pedestal region.

The commonly used model $f_{BS} \propto q_{95}\, \beta_N$ only roughly agrees with these experimental results because it does not include changes in the n and T profiles or a dependence on q_{min}. In this experiment, as expected f_{BS}/β_N increases with q_{95} and increases with q_{min} in the range 1-1.5, but it decreases as q_{min} is increased from ≈1.5 to 2 and, for a given q profile, as β_N is increased.

This study showed that the optimum q profile for f_{NI}=1 operation with the external current drive sources presently available at DIII-D is q_{min}≈1.35-1.65, q_{95}≈6.8 where the shapes of the J_{NI} and total J profiles are most similar [Fig. 3(a)]. In the discharges studied for this experiment, f_{NI}≈0.85 in this case. The required external current drive near the axis is provided by the neutral beams and additional current drive to match the J_{NI} and J profiles can be provided by off-axis ECCD. The fraction of neutral beam driven current can be comparable to f_{BS}, particularly in discharges at the highest q_{min} which have the lowest ne and highest T_e. At q_{min}=1 the difficulty is a significant mismatch in the region ρ<0.2 where $J >> J_{BS} + J_{NBCD}$. At lower q_{95} [Fig. 3(b)] where f_{NI}<0.7, substantial additional external current drive located off-axis would be required to achieve f_{NI}=1. This additional current drive can be provided by the off-axis beam injection planned for DIII-D in 2011. The off-axis beams can also enable the study of discharges with q_{min}>2.

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