Investigating Steady-State Operating Scenarios on DIII-D Using Flexible Current Drive Actuators

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I. Introduction

Fully noninductive operation ($f_{NI}=I_{NI}/I_P=1$) is planned for many next-step tokamaks, including ITER, FNSF-AT [1], and DEMO. A possible scenario for achieving high fusion gain, high bootstrap current fraction ($f_{BS}=I_{BS}/I_P$) operation is to use an elevated minimum safety factor (q_{min}) and high normalized β_{tor} (β_N), since $f_{BS}\propto\beta_{pol}\propto q\beta_N$ and fusion power $\propto\beta_N^2$. On DIII-D, neutral beam injection (NBI) and electron cyclotron (EC) waves are used for heating and current drive. NBI is the primary tool for attaining high β_N on DIII-D but high power on-axis NB current drive (NBCD) tends to drive peaked current density profiles and low q_{min}. Therefore one of the four beamlines was upgraded to provide a flexible injection angle between 0° and 16.5° to horizontal (Fig. 1). When the magnetic field pitch is aligned with the beam injected at 16.5°, significant off-axis current drive was predicted and confirmed to exist [2]. This current density is distributed widely about the plasma half-radius.

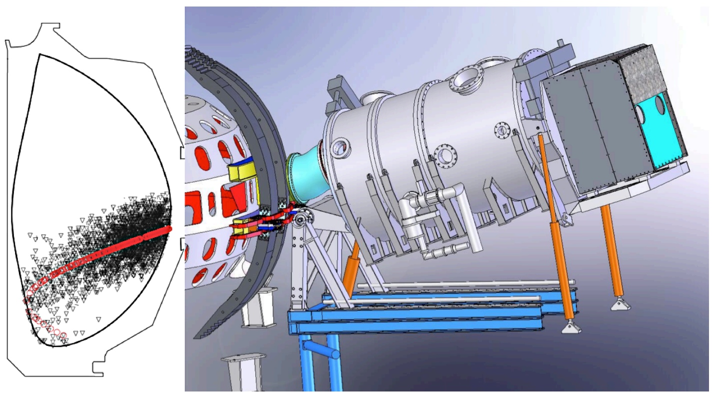

Figure 1. 5 MW of off-axis neutral beam injection 16.5° to horizontal on DIII-D.

Compared to on-axis heating, off-axis heating reduces the on-axis pressure and current density, effectively broadening both profiles which is known to increase the β_N limit due to ideal-wall kink modes [3]. Off-axis NBI was used in steady state experiments that had two goals. The first was to demonstrate $q_{min} > 2$ and $\beta_N > 4$ plasmas with broad current and pressure profiles – conditions expected in a steady state DEMO. Broad profiles are expected to have high β_N limits due to increased wall stabilization, and good confinement due to a large volume of weak or negative magnetic shear [4]. The second goal was to extend high performance elevated q_{min} operation to multiple current profile relaxation time scales (τ_R) to confirm passive stability of tearing modes and provide a demonstration of conditions that could be useful for ITER and FNSF.

II. Exploration of Access to $q_{min} > 2$, High β_N Operation

Broader current and pressure profiles have been achieved using off-axis NBI compared to on-axis NBI. Previous experiments using only on-axis NBI and ~2.25 MW of off-axis electron cyclotron current drive (ECCD) showed that it is difficult to sustain q_{min} above 2 at $\beta_N \approx 2.7$, $B_T = 2.1$ T, and $q_{95} = 6.7$. These conditions were reproduced with the following changes: (1) up to 4 MW off-axis NBI, (2) an additional ~1 MW of EC power, and (3) reversed toroidal field polarity to maximize off-axis NBCD. Figure 2 compares key equilibrium quantities obtained with and without off-axis NBI. The plasma heated by off-axis NBI was sustained with $q_{min} \approx 2.4$ and $\rho_{qmin} \approx 0.3$ at $\beta_N \approx 2.7$ for as long as NBI energy was available. The pressure profile peaking factor was reduced from ~3.5 down to ~2.5. The pressure profile broadening is due chiefly to a less peaked fast ion pressure profile and increased electron heating at mid-radius by the off-axis NBI and ECCD, and to a lesser extent by reduced divertor pumping.

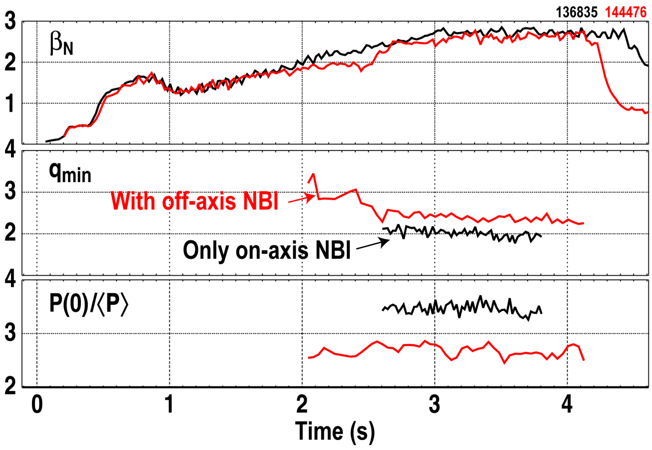

Fig. 2. Using off-axis NBI improves access to and sustainment of broad current and pressure profiles with $q_{min} > 2$.

Plasmas produced with the highest values of q_{min} (2–3) typically had a thermal energy confinement time (computed using the measured thermal profiles) that matched or exceeded the ITER98y2 thermal confinement scaling prediction [5]. However the same plasmas had a ~18% lower global energy confinement scale factor H_{89P} (thermal+fast ion, [6]) than plasmas with q_{min} between 1 and 1.5. This suggests enhanced fast ion loss at higher q_{min} and qualitative evidence for this is seen by increased Alfvén eigenmode activity with increasing q_{min}. While the $q_{min} > 2$ plasmas have calculated ideal-wall $n = 1$ β_N limits in excess of 4, with the available heating power the maximum β_N achieved with $q_{min} > 2$ was ~3.3. On-going work is focusing on new fast ion and turbulence measurements for a more detailed understanding of the relatively poor fast ion confinement in these plasmas to determine if the dominant transport mechanisms can be mitigated.

III. Extension of High Performance, Quasi-Stationary Operation to $2\tau_R$

Off-axis NBI has proved beneficial for achieving discharges with modest q_{min} (1.3–1.8) to optimize profiles for stability and sustain them for a suitable duration. Such plasmas have been shown [7] on DIII-D to be promising candidates for long pulse or fully noninductive

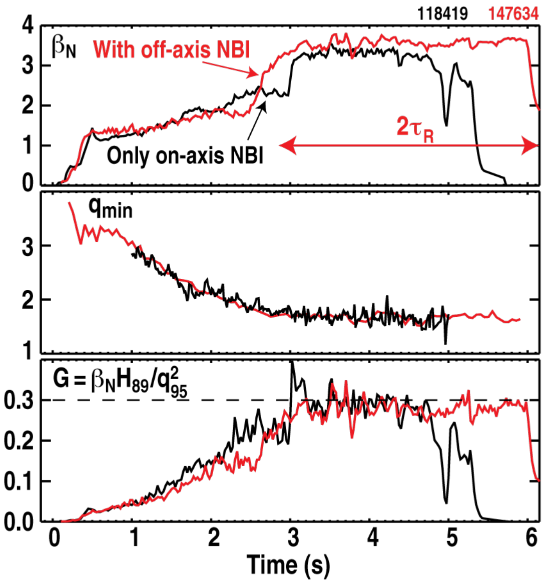

Fig. 3. High performance quasi-stationary plasma duration extended by using off-axis current drive.

operation on an ITER-sized machine with projected fusion gain $Q \approx 5$. The $m/n=2/1$ tearing mode is the most common instability that can terminate good performance, and this is sensitive to the current profile and the proximity to the ideal-wall $n=1$ kink mode β_N limit [8]. The demonstrations of nearly or fully noninductive operation on DIII-D have been limited to durations less than 1 τ_R and β_N close to predicted ideal MHD limits [9]. When operating close to stability limits one must evaluate the evolution of the current profile to a stationary state over several τ_R to demonstrate access to and robustness of the target equilibrium. Better still is to adjust the plasma parameters to raise the stability limit far above the required operating pressure.

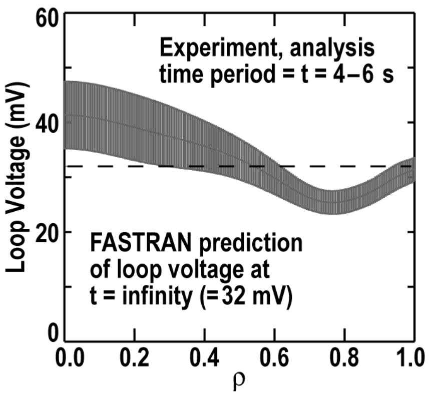

Fig. 4. At the end of the high β_N phase the loop voltage is approaching the fully relaxed value predicted by FASTRAN [12].

Using off-axis NBI, quasi-stationary plasmas have been produced without tearing modes for $2\tau_R$ with $q_{min} =$ 1.4, β_N =3.5, 50% bootstrap current, 70–75% noninductive current, and an equivalent fusion gain that projects to $Q \approx 5$ in an ITER-sized device. The duration is limited by the NBI energy. This surpasses earlier results in similar plasmas lacking off-axis NBI and with less ECCD power that were stationary for 1 τ_R (Fig. 3, black traces). The loop voltage profile is nonzero but relatively uniform by the end of the high β_N phase (Fig. 4), and q_{min} does not evolve to 1 in experiment or simulation [10] (Fig. 5). Ideal stability analysis using the DCON code [11] predicts the no-wall $n=1$ kink mode β_N limit is in the range of 3–3.4, while the ideal-wall $n=1$ β_N limit is 4–5. (Fig. 6). Compared to similar plasmas without off-axis NBI, the pressure profile is less

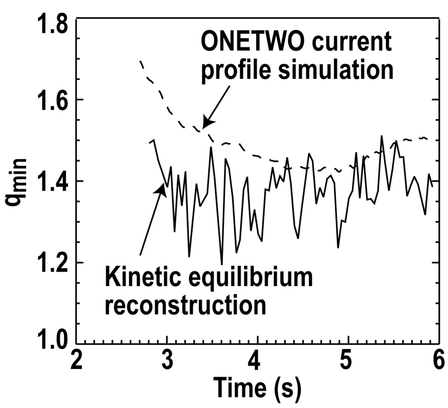

Fig. 5. With a nearly relaxed loop voltage and ~70% noninductive fraction q_{min} stays near 1.4.

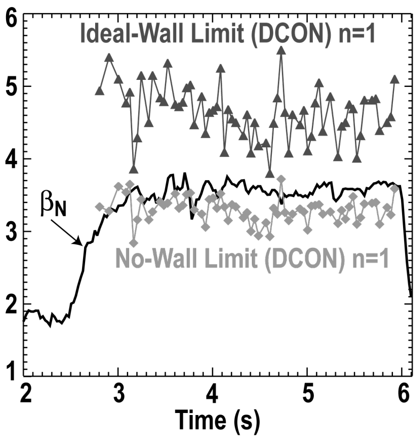

Fig. 6. Calculated ideal $n=1$ kink β_N limits.

peaked, and this contributes to the high calculated β_N limits. Replacing the remaining inductive current density in these plasmas will require more current drive power and operation close to the predicted ideal wall β_N limit for higher bootstrap fraction.

IV. Summary

On DIII-D, progress has been made in elevated q_{min} steady state scenario development by using off-axis NBI. Current and pressure profile broadening enables access to higher ideal MHD β_N limits. Plasmas with $q_{min} > 2$ so far have lower normalized energy confinement H_{89P} than similar plasmas with lower q_{min}. Plasmas with $q_{min} \approx 1.4$ have been taken to nearly stationary conditions for 2 τ_R at $\beta_N = 3.5$.

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