High-\(\beta\) steady-state scenarios in DIII-D with on-axis current drive

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Abstract. Experiments in the DIII-D tokamak have demonstrated potential new paths to fusion steady state based on peaked current profiles with \(q_{\text{min}}\approx 1\) that have high ideal stability limits, excellent confinement and benefit from efficient on-axis current drive. In the hybrid scenario, steady-state conditions (\(V_{\text{surf}}=0\)) using central ECCD and NBCD are achieved in 1.0 MA discharges with a beta value (\(\beta_N=3.6\)) that is 80\%-90\% of the ideal \(n=1\) with-wall limit. Interestingly, the hybrid mechanism that anomalously broadens the current profile to maintain \(q_{\text{min}}\approx 1\) and prevents sawteeth continues to function despite the intense central current drive. In the “high \(\ell_i\)” scenario, the combination of broad pressure profile and a peaked current profile tailored to maximize \(\ell_i\) allows \(\beta_N\approx 4.8\) and \(H_{98y_2}\approx 1.8\) to be achieved transiently in a discharge that is overdriven (\(V_{\text{surf}}<0\)). The achieved \(\beta_N\) is near the no-wall limit with the ideal-wall limit higher at \(\beta_N\approx 5.6\).

I. Introduction

This paper discusses two high-\(\beta\) scenarios in DIII-D with on-axis current drive that are consistent with the Q=5 steady-state mission in ITER. While both cases have \(q_{\text{min}}\approx 1\), the hybrid scenario relies on the self-organized current profile produced by that regime, whereas the high \(\ell_i\) scenario takes a more active approach to create an optimized current profile. Hybrid plasmas have the advantage of robustness and insensitivity to the current drive profile; the high \(\ell_i\) scenario is more complex but has higher stability limits and higher confinement, as well as a less critical need for a high pedestal.

II. Steady-State Hybrid Scenario

In DIII-D, experiments show that the beneficial characteristics of the hybrid scenario are maintained when central co-current drive is applied to increase the non-inductive fraction to \(\approx 100\%\) [1]. The advantages of the hybrid regime over the \(q_{\text{min}}\approx 2\) Advanced Tokamak (AT) regime are (1) good alignment between the current drive and plasma current profile is not necessary as poloidal magnetic flux pumping self-organizes the current density profile in hybrids with an \(m/n=3/2\) tearing mode [2], and (2) the current drive in hybrids can be located near the plasma center where the current drive efficiency is highest. The high current drive efficiency can fully compensate for a lower bootstrap current fraction in the \(q_{\text{min}}\approx 1\) regime compared to the \(q_{\text{min}}\approx 2\) AT regime.

The natural attributes of the hybrid scenario make it a robust regime for high-\(\beta\), steady-state plasmas, as shown in Fig. 1 where the surface loop voltage \(V_{\text{surf}}=0\), thermal confinement factor \(H_{98y_2}\approx 1.56\) and normalized beta \(\beta_N=3.64\) (toroidal beta \(\beta_t=3.1\%) are sustained for the maximum duration of the beam pulse without exciting the deleterious \(m/n=2/1\) tearing mode. Half of the plasma current is driven non-inductively near the plasma center by electron cyclotron current drive (ECCD) and neutral beam current drive (NBCD), with the other half
generated by the bootstrap current. The non-inductive currents calculated by TRANSP are overlaid with the measured plasma current in Fig. 1a. While this demonstrates that $V_{\text{surf}}=0$ is consistent with the calculated non-inductive currents, Fig. 2a shows that the reconstructed current profile is not consistent with the sum of the driven current profiles. The current profile anomaly is displayed in Fig. 2b, where the calculated non-inductive current density is subtracted from the total current density determined by equilibrium reconstruction. Inside of the $q=3/2$ surface, the current profile is strongly overdriven and the current relaxation time is sufficiently short that $q_{\text{min}}$ should drop below 1 by the end of the discharge. The fact that $q_{\text{min}}$ remains above unity and sawteeth are absent shows that the hybrid scenario maintains an anomalously broad current profile even in the presence of strong central current drive.

The beta value obtained in steady-state hybrids is 80%-90% of the ideal $n=1$ with-wall limit. The theoretical stability limits are calculated by the DCON code using EFIT reconstructions constrained by the experimental pressure profile, MSE polarimetry and a neoclassical calculation of the pedestal bootstrap current density. These experiments utilized both on-axis and off-axis beam deposition (two of the six co-beams can inject off-axis) to affect the stability limit by varying the pressure profile peakedness ($f_p = P_\phi < P>$). Figure 3 shows that in hybrids with complete current drive, $\beta_N=3.64$ (i.e., $\beta_N=4.9\ell_i$) is reached and maintained for the duration of high power NBI. This value exceeds the no-wall $n=1$ stability limit (average DCON value $\beta_N=4\ell_i$) and is close to the ideal-wall $n=1$ limit. Using off-axis beam power reduces $f_p$ from ~3.4 to ~3.1, mainly by changing the fast ion pressure profile, with the
largest systematic differences between on/off-axis injection occurring for $\beta_N>3.3$. On average the DCON calculated ideal-wall limit is $\approx10\%$ higher for hybrid plasmas with off-axis beam injection, but experimentally little difference is seen in the maximum beta ($\beta_N=4.0$ for 0.8 s) with or without off-axis beam power. Future plans have DIII-D increasing the number of off-axis beams from two to four, and the number of co-beams from six to eight, which may allow the theoretical advantages of a broader pressure profile to be more easily realized.

III. High $\ell_i$ Scenario

By taking a more active approach in tailoring the peaked current profile to maximize $\ell_i$, the ideal stability limit and confinement can be increased beyond the more passive approach described in the previous section. These performance improvements arise largely as a result of higher poloidal field in the discharge core and larger magnetic shear in the outer half of the plasma. The benefits of this “high $\ell_i$” scenario are seen in Fig. 4, where $\beta_N=4.8$ and $H_{98(\nu,2)}=1.8$ are achieved transiently at $\ell_i=1.3$ [3]. To form the high $\ell_i$ target, the discharge begins with a long ohmic phase so that the electron temperature is low and the current density profile becomes peaked in the core with $q_{min}=1$. Next, ECCD at $\rho=0.4$ is added to increase the electron temperature and “freeze in” the peaked current profile, after which high power beam heating is applied to transition the plasma into ELMy H-mode and ramp up $\beta_N$. As described later, the ohmic current profile slowly becomes less peaked in time during the H-mode phase, resulting in the decreasing confinement time (and thus decreasing $\beta_N$ at fixed heating power) seen in Fig. 4 as $\ell_i$ evolves to a lower value.

Plasmas with high $\ell_i$ and $\beta_N=4\text{-}5$ are predicted to be stable to low-n ideal MHD instabilities even without the effect of a conducting wall. As seen in Fig. 5, the peak $\beta_N$ for the discharge shown in Fig. 4 is near the no-wall $n=1$ limit calculated by DCON, with the ideal-wall $n=1$ limit higher at $\beta_N=5\text{-}6$. The ideal infinite-n ballooning mode stability limit calculated using the BALOO code is slightly below that of the ideal-wall $n=1$ mode. Consistent with these stability calculations, a global, pressure-limiting instability has not yet been clearly observed in the experiment. Instead, in cases where stability determines the limit to performance (such as when $\beta_N$ is raised above 5), the observed mode is most commonly a $m/n=2/1$ resistive tearing mode.

Broadening of the pressure profile with increasing $\beta_N$ plays an important role in enabling stable access to high plasma pressure along with the elevated values of $\ell_i$. The broad pressure profiles obtained in these high $\ell_i$ plasmas, $f_p=2.5$, strongly increases the ideal-wall stability limit [4]. Interestingly, a low H-mode pedestal height, which can result from pedestal physics and/or the application of 3D magnetic fields, is not necessarily detrimental to this steady-state scenario as it works to raise $\ell_i$ and thus the ideal-wall limit. As a result, the high $\ell_i$ scenario is a promising option for the ITER Q=5 steady-state mission that can perform well in plasmas with a low pedestal height.

The elevated $\ell_i$ in present experiments is largely a result of the inductively-driven current profile. Figure 6 displays the individual current density components (bootstrap, NBCD, ECCD and ohmic),
as well as the total current density, calculated by the ONETWO transport code for the discharge in Fig. 4 at 3.35 s; for reference, the total current density profile from a well-constrained equilibrium reconstruction is also plotted. The plasma current is actually overdriven with a bootstrap current fraction of ≈80% and $V_{\text{surf}} < 0$. The negative surface loop voltage penetrates relatively quickly through the outer half of the plasma, with the negative inductively-driven current density outside $\rho = 0.5$ offsetting some of the bootstrap current, helping to maintain an elevated value of $\ell_i$. The negative loop voltage penetrates slowly towards the axis during the high $\beta_N$ phase, decreasing the ohmic current in the plasma center and causing $\ell_i$ to drop over time. With a long enough pulse duration, this discharge would eventually evolve to a relatively low $\ell_i$ case because of the high pedestal bootstrap current.

To make the high $\ell_i$ scenario not only fully non-inductive but also stationary, the portion of the evolving ohmic current driven by the positive loop voltage in the core needs to be replaced with on-axis ECCD and NBCD (and higher plasma current is needed to eliminate the negative loop voltage). The maximum value of $\ell_i$ that can be obtained by tailoring the profile of the externally-driven current density will decrease with increasing bootstrap current in the outer half of the plasma. Therefore, the “optimized high $\ell_i$” equilibrium has about 50% bootstrap current and 50% external current drive near the axis. Transport code modeling of the steady-state current profile using TGLF [5] to self-consistently predict the temperature profiles examined the accessible current density and pressure profiles to maximize the stationary value of $\beta_N$ consistent with the calculated stability limits. The result of this modeling study is a stationary 1.1 MA plasma with $\ell_i = 1.07$, $\beta_n = 4$ and $H_{98(y,z)} = 1.1$ using a combination of central ECCD (9 MW), mixed on/off-axis NBCD (20 MW total) and 50% bootstrap current. The ideal n=1 stability limit for this case is $\beta_N = 4.1$ without a conducting wall and $\beta_N = 4.8$ with a wall. This simulated high $\ell_i$ case is consistent with the planned upgrades to the DIII-D heating systems.

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