Progress Toward High Performance Steady State Operation in DIII-D* EX-C

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Demonstration of steady-state operation with $Q \geq 5$ has been identified as a high level goal for ITER. This goal recognizes the benefits of steady-state operation both for elimination of cyclic fatigue and increased duty cycle in future fusion power plants. Advanced Tokamak (AT) research [1-4] on DIII–D works toward development of a scientific basis for scenarios capable of meeting this objective. Steady-state operation requires that all of the plasma current be driven by noninductive means, e.g. by sources other than the transformer. Our approach is to maximize fusion power and bootstrap current (f_{BS} = 55%-75%) by operating with high normalized beta $\beta_N \geq 3.5$ and elevated safety factor $q_{min} > 1.5$, and provide the remaining current using neutral beam (NBCD), electron cyclotron (ECCD) and fast wave (FWCD) current drive. Recent efforts focus on two different scenarios. In discharges with an elevated q profile and internal transport barrier (ITB), $\beta_N \approx 4 \approx 6l_i$ has been maintained for up to 2 s. Fully noninductive plasmas, with weak negative central magnetic shear, have obtained fusion performance $G = \beta_N H_{89}/q_{95}^2 = 0.3$, equivalent to that needed for the $Q = 5$ ITER steady-state scenario. Recent experiments have expanded the operating space for this scenario and identified several of the important parameters. Results from both sets of experiments, taken together with integrated modeling, motivate new hardware now being added to DIII-D to facilitate fully noninductive operation with still higher performance.

The first scenario [1] (Fig. 1), starts with an elevated q profile ($q_{min} > 2$) and has an ITB, two features not usually associated with high β. Access is facilitated by a broad current profile, which couples well to the vessel and internal and external coils used to actively control both error fields and the resistive wall mode (RWM). This allows operation well in excess of the no-wall limit to the n=1 kink mode, calculated at $\beta_N \approx 4l_i$. Calculations indicate the ideal wall limit may be as high as $\beta_N \approx 11l_i$, so that performance in present experiments is not limited by ideal-mode stability and higher β may still be obtained. Calculated stability limits are rather insensitive to pressure profile peaking, allowing coexistence of the high β with an ITB.

With high β_N and elevated q profiles, this scenario should have favorable prospects for fully noninductive operation. However, we have so far only sustained $\beta_N \approx 4$ with a continual toroidal magnetic field ramp. It is believed that this is related to the current profile broadening that has been identified as an essential feature. Also, as the current profile evolves through the high β phase, benign n=3 and n=2 neoclassical tearing modes (NTM) appear and disappear as q_{min} falls. The high β phase finally terminates with the onset of an n=1 NTM that appears when q_{min} decreases below 1.5. It is anticipated that under fully noninductive conditions, the NTM will be avoided simply by halting this evolution.

Efforts in a second scenario [2-3] emphasize optimization toward fully noninductive operation. These plasmas have $1.5 < q_{min} < 2.0$ with weakly reversed shear, $q_0 - q_{min} \leq 0.5$, and

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can be maintained for several τ_E with $\beta_N \leq 3.5$ and all current driven by bootstrap, NBCD and ECCD. They have also been maintained in stationary conditions with 5%-10% of the current driven inductively, limited only by the 2 s ($\sim 1 \times \tau_{CR}$) duration of present ECCD systems.

Recent studies focus on the behavior of this scenario as operational parameters are varied. Experiments over a range of densities have shown an advantage for low-density operation, primarily through its impact on the effectiveness of external current profile control tools. The noninductive current fraction f_{NI} is observed to increase with both safety factor q_{95} and β_N (Fig. 2). We need to simultaneously optimize f_{NI} and fusion performance, which varies with the parameter G, which decreases with q_{95}^2. Taken together, these observations suggest continued development should proceed with moderate q_{95} and a continued effort to increase β_N.

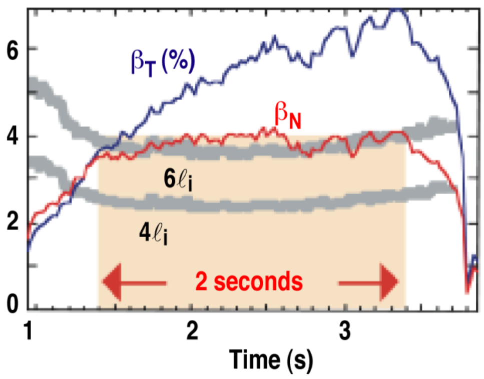

Fig. 1. $\beta_N \approx 4$ is maintained for 2 s in a discharge with an internal transport barrier and an elevated q profile. These discharges operate well above the no-wall stability limit which appears at $\beta_N \approx 4l_i$.

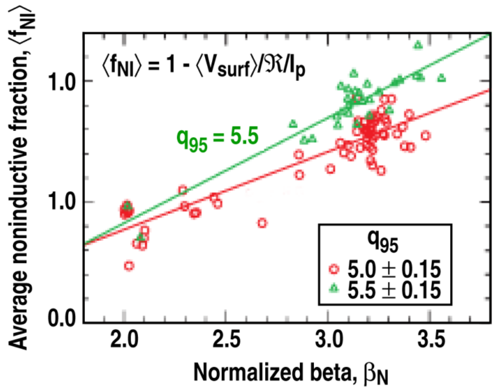

Fig. 2. The noninductive current fraction is maximized at both high q_{95} and high β_N in H-mode discharges with weakly negative central shear and $\beta_N > 2$ and $H_{89} > 2$ maintained for at least 0.7 s.

Active control is needed to reach and maintain the necessary conditions. We work toward the needed level of control both through continued development of a plasma control system, using model based controllers and real-time analysis. As α heating becomes dominant in a burning plasma, our best opportunity for external control will be through the current profile. A major effort is underway to implement active current profile control using ECCD, FWCD and NBCD. Although the ideal wall limit has been only slightly above the no-wall limit in present experiments in the weak shear scenario, the high β ITB results may point the way toward further current profile optimization to take advantage of active RWM control.

New hardware currently being installed is expected to greatly expand DIII-D capabilities for AT research [4]. Additional long-pulse gyrotrons will both increase the available ECCD power and remove the 2 s pulse length limitation. This will allow current drive further from the magnetic axis, expected to facilitate both higher β limits and improved capabilities for active current profile control. A new lower divertor cryopump will allow density-controlled operation in both single- and double-null configurations. Based on calculations and previous experiments [4], we anticipate this will allow operation at significantly higher β, increasing bootstrap current, external current drive efficiency and fusion performance.

The development of steady-state high performance discharges on DIII-D is supported by a major effort in integrated modeling. Simulations using theory-based models are used to design experiments and to interpret their results. These results are used to further refine the models, resulting in a continually improving predictive ability. Predictions based on these results, along with the anticipated hardware improvements, indicates great promise for further progress in AT scenario development. The same models, applied to day-1 capabilities of ITER, predicts favorable prospects for steady-state scenarios with $Q \approx 5$.

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