# Achieving and Sustaining Steady-State Advanced Tokamak Conditions on DIII–D*

M.R. Wade,[1] M. Murakami,[1] D.P. Brennen,[2] T.A. Casper,[3] J.R. Ferron,[4] A.M. Garofalo,[5] C.M. Greenfield,[4] A.W. Hyatt,[4] R. Jayakumar,[3] J.E. Kinsey,[6] R.J. La Haye,[4] L.L. Lao,[4] E.A. Lazarus,[1] J. Lohr,[4] T.C. Luce,[4] C.C. Petty,[4] P.A. Politzer,[4] R. Prater,[4] E.J. Strait,[4] A.D. Turnbull,[4] J.G. Watkins,[7] and W.P. West[4]

[1]Oak Ridge National Laboratory, Oak Ridge, Tennessee, 37831 USA
email: wade@fusion.gat.com
[2]Oak Ridge Institute for Science Education, Oak Ridge, Tennessee 37831 USA
[3]Lawrence Livermore National Laboratory, Livermore, California 94551 USA
[4]General Atomics, P.O. Box 85608, San Diego, California, 92186-5608 USA
[5]Columbia University, New York
[6]Lehigh University, Bethlehem, Pennsylvania 18015 USA
[7]Sandia National Laboratories, P.O. Box 5800, Albuquerque, New Mexico 87185

Recent experiments on the DIII-D tokamak have demonstrated the feasibility of sustaining advanced tokamak conditions that combine high fusion power density ($\beta$ > 4%), high bootstrap current fraction ($f_{BS}$ ~ 65%), and high non-inductive current fractions ($f_{NI}$ ~85%) for several energy confinement times. The duration of such conditions is limited only by resistive relaxation of the current density profile. Modeling studies indicate that the application of off-axis will be able to maintain a favorable current density profile for several seconds. Full integration of the key elements identified by the modeling studies as necessary to prevent the current relaxation and achieve steady-state conditions (density control at high $\beta$, efficient off-axis ECCD) is yet to be achieved, but separate studies of these elements have shown each to be feasible. These experiments have taken advantage of recent improvements in both the stability and confinement quality of tokamak plasmas. These advances are essential in achieving steady-state conditions since achieving fully non-inductive operation economically is predicated on obtaining a high bootstrap current fraction ($f_{BS} \propto q\, \beta_N$), which favors high $\beta_N$ operation with elevated q values (typically, $q_{min}$ > 1.5, $q_{95}$ > 4). In order to maintain an adequate fusion power density ($\beta \propto \beta_N/q$) and fusion gain ($\beta\, \tau_E \propto \beta_N\, H_{89}/q^2$) at these higher q values, operation well above the generally accepted long pulse limits on both stability ($\beta_N$ = 3) and confinement ($H_{89}$ = 2) is required. Further constraints arise from the need to drive current non-inductively to supplement the bootstrap current. This externally driven current typically scales as $I_{CD} \propto T_e\, P_{CD}/n_e$; hence, lower density is favorable in maximizing the externally driven current.

Figure 1 shows the temporal evolution of a representative shot of this class of discharges. During the high power phase, $\beta_N$ ~ 4.1, $H_{89}$ ~ 3.0, with $q_{min}$ > 1.5 is sustained for ~ 600 ms

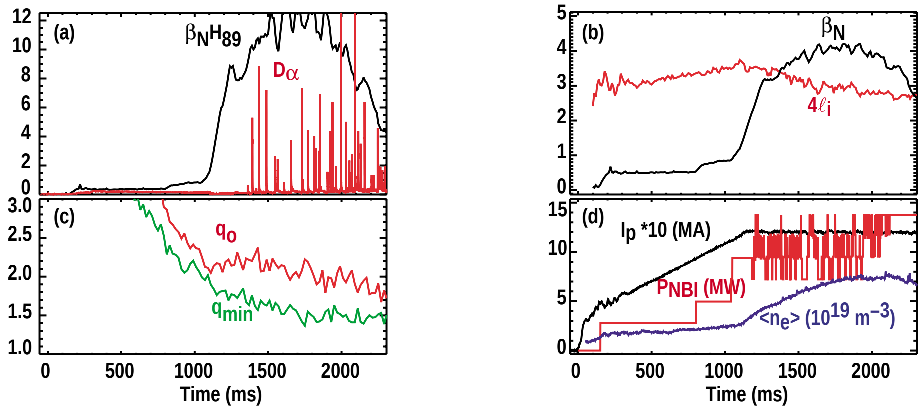


Fig. 1. Plasma parameters versus time for an ELMing H-mode discharge (106795) with $\beta_N H_{89}$ > 10 for 5 $\tau_E$ (a) $\beta_N\, H_{89}$ (upper trace) and divertor $D_\alpha$ (a.u.); (b) $\beta_N$ and $4\ell_i$; (c) $q_0$ (upper trace), $q_{min}$ (lower trace); (d) 10x plasma current (MA), neutral beam injected power (MW) and line-averaged density ($10^{19}$ $m^{-3}$).

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or approximately 5 $\tau_E$. In terms of absolute plasma parameters, these plasmas simultaneously achieve fusion power density $\beta$ = 4.2%, fusion gain $\beta\tau$ = 0.66 %-s, $\beta_p \sim 2$, bootstrap current fraction $f_{BS}$ = 65%, and non-inductive current fraction $f_{NI}$ = 85%. This level of performance is comparable to that achieved in the 1999 experimental campaign but was achieved in a plasma shape conducive to active divertor exhaust ($\kappa$ = 1.85, $\delta$ = 0.65, $q_{95}$ = 4.1) as opposed to the optimized shape used in 1999 ($\kappa$ = 2.0, $\delta$ = 0.9, $q_{95}$ = 5.6). These results took advantage of improved knowledge of the effect of resonant error fields on the plasma rotation when $\beta$ increases past the empirical ideal no-wall limit ($\beta_N \sim 4\ \ell_i$). In the best cases, this has allowed operation with $\beta_N \sim 6\ \ell_i$.

The termination of the high performance conditions is due to the onset of an m=2/n=1 neoclassical tearing mode (NTM) when $q_{min}$ approaches 1.5. Statistical analysis of the onset of these NTMs indicate that most occur with $1.5 < q_{min} < 1.7$ and $\beta_N >\sim 4\ \ell_i$. This is qualitatively consistent with a theoretical model that these tearing modes are classically destabilized by the rapid growth of $\Delta'$ as an ideal stability limit boundary is approached. Note that in this case the approach to this stability boundary is dominated by the current profile evolution since $\beta$ is essentially constant. If the proposed destabilization mechanism is correct, maintaining the favorable current density profile from early in the high performance phase should reduce the susceptibility to these NTMs.

Self-consistent, time-dependent transport simulations using ONETWO/CalTrans combined with an ECCD ray-tracing code (TORAY) indicate that this favorable current profile can be maintained for several seconds using 3.5 MW of ECCD distributed broadly off-axis ($\Delta_{FWHM}$=0.27 centered at $\rho_{EC}$=0.38). The ECCD efficiencies computed by TORAY have been benchmarked against both experiment and a full 3-D collisional Fokker-Planck code. The transport coefficients are based on those obtained in the experiment with an additional degradation in confinement introduced in a manner such that the transport coefficients scale as would be expected by the ITER H98-ELYy2 scaling expression ($\chi \sim P^{+0.69}$). These simulations indicate that through radial distribution of the ECCD the q profile can be maintained slightly inverted with $q_{min}$ > 1.5 for 10 , which is about twice the current redistribution time. Studies of the sensitivity of these results to the prescribed transport coefficients have shown that the favorable q profile can be maintained even with $\chi_e$ and $\chi_i$ increased by a factor of 2 for $\rho \leq 0.8$ over the base case.

A major uncertainty in the modeling is the degree to which the density can be controlled during the high performance phase since this has serious consequences on the achievalbe ECCD efficiency. Experiments in 2001 demonstrated that an approximate 40% reduction in line-averaged density can be obtained by activating the upper divertor cryopumps and using a slightly unbalanced DND configuration. However, NTMs tend to occur at slightly lower $\beta_N$ in cases with good density control. This, coupled with the fact that lower density tends to lead to higher $T_i/T_e$ in these beam-heated discharges, has resulted in only a modest improvement in the ECCD current drive capability. Experiments seeking to use ECCD in these discharges to control the current density profile evolution have therefore been unsuccessful to date in delaying the NTM onset.

In conclusion, experiments on DIII–D have demonstrated the feasibility of achieving advanced tokamak conditions that sustain high fusion power density ($\beta$ > 4%) and a high bootstrap current fraction ($f_{BS} \sim 65\%$) for several energy confinement times. The termination of these conditions is due to the resistive evolution of the current profile, leading to the onset of NTMs as $q_{min}$ approaches 1.5. Having demonstrated the feasibility of the major elements required for efficient off-axis ECCD (namely, sustained high $\beta$, density control, and efficient ECCD) separately, the DIII–D program is now focussed on the self-consistent integration of these elements into a steady-state, high fusion gain plasma solution. Studies in 2002 will focus on achieving high $\beta$ conditions with higher $T_e$ and higher $q_{min}$, in hopes of both improving the ECCD current drive capability and minimizing the susceptibility to NTMs.