PROGRESS TOWARDS SUSTAINMENT OF ADVANCED TOKAMAK MODES IN DIII-D*

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Advanced Tokamak (AT) operating modes have been successful in improving the fusion performance of many existing tokamaks, as evidenced by the record D-D fusion reactivity achieved in DIII–D[1], JET [2], and JT-60U [3]. Through optimization of the plasma shape and radial profiles, AT modes lead to improved confinement, β, and bootstrap fraction relative to standard (ITER-like) ELMing H–mode. Improvements are observed in many different AT regimes such as VH–mode, negative central shear (NCS) with an internal transport barrier (ITB), high β_p, and high ℓ_i. To date, however, the duration of peak performance in all of these modes is limited to about 1–2 energy confinement times (τ_E), generally as a consequence of evolving pressure profiles and eventual MHD instability. Before AT modes can be seriously considered as an operating mode for a future fusion reactor, present experiments must sustain AT performance in a controlled manner for longer pulse lengths. In this paper, we review results of recent experiments on DIII–D directed towards this goal.

The normalized quantity $\beta_N H$ serves as a useful figure-of-merit for performance, where $\beta_N \equiv \beta/(I/aB)$ and H is the enhancement in thermal energy confinement time relative to the ITER98 ELMy H–mode scaling. Plotted in Fig. 1, for a variety of DIII–D ELM-free and ELMy H–mode discharges, is the length of time each discharge exceeds a given value of $\beta_N H$. While ELM-free edge conditions lead to the best overall AT performance with $\beta_N H \sim$ 8–11, the duration is limited by edge instabilities and the accumulation of impurities near the edge. Recent DIII–D experiments have focused on the formation and evolution of ITBs in plasmas with L–mode or ELMing H–mode edge conditions, which likely are more compatible with long-pulse sustainment.

In NCS discharges with an L–mode edge and an ITB, pulse length is typically limited to a few hundred ms by internal n=1 MHD modes driven by excessive pressure peaking in the core. High pressure peaking also leads to a large but poorly aligned bootstrap current, causing rapid evolution of q_{min}. Reducing and controlling the pressure peaking is essential for extending the pulse length in this regime. By reducing the shear reversal (smaller $q_0 - q_{min}$), raising the edge q, and lowering the neutral beam power and hence central fueling, L–mode edge discharges with an ITB have been sustained for more than 2 s (>5 τ_E). In these cases q_{min} reached a near-stationary value (>1), with the duration limited only by the neutral beam

*Work supported by the U.S. Department of Energy under Contract Nos. W-7405-ENG-48, DE-AC03-89ER51114, DE-AC02-76CH03073, DE-AC05-96OR22464 and Grant No. DE-FG02-89ER53297.

pulse length. However, the radius of the ITB remains narrow in these discharges and fast ions represent a large fraction of the total stored energy.

Modeling indicates that for L–mode edge NCS discharges to be a viable AT mode, the radius of the ITB and the radius of q_{min} ($\rho_{q_{min}}$) must be increased to a normalized radius of $\rho > 0.6$. DIII–D data is suggestive that the ITB can expand with $\rho_{q_{min}}$, but not conclusive because the variation of $\rho_{q_{min}}$ is limited. Furthermore, discharges with an ITB and monotonic q have been observed. To better understand the dependence of transport on the q-profile shape versus other stabilizing mechanisms such as E×B shear, we have developed new inductive startup techniques to produce larger $\rho_{q_{min}}$. Using H–mode transitions early in the current ramp to help raise the electron temperature in the region $0.5 < \rho < 1.0$ and slow current diffusion, profiles with $\rho_{q_{min}} = 0.7$ and $\ell_i \sim 0.6$ have been obtained. Experiments to produce an ITB in this configuration are in progress.

An ELMing H–mode edge is also compatible with long-pulse operation. The naturally broad H–mode pressure profiles lead to higher β and better bootstrap alignment than in L–mode. The best long-pulse performance has been achieved in low-density non-sawtoothing ELMing H–mode where $\beta_N H \sim 4.5$ was sustained for ~1 s (shot 89756 in Fig. 1). The q profile was monotonic in this case. Using new startup techniques, NCS q profiles have now been sustained for up to 2 s in ELMing H–mode (Type I ELMs), however, no significant ITB was observed and confinement times remain typical of standard ELMing H–modes with monotonic q. The combined effects of higher density, reduced T_i/T_e, reduced E×B shear, and perturbations due to ELMs are believed to contribute to the lack of improved transport in the core. In order to reduce the effect of ELMs, we have explored shape variations, in particular increasing the squareness shape parameter, which reduces 2nd stable access at the edge for ballooning modes and lowers the first stability limit on p'. Small high-frequency ELMs and a lower edge pedestal were observed in this shape, consistent with expectations from ballooning stability calculations. Under these conditions ITBs were produced with NCS q profiles. Experiments in low squareness shapes, which should exhibit similar edge stability properties, are underway.

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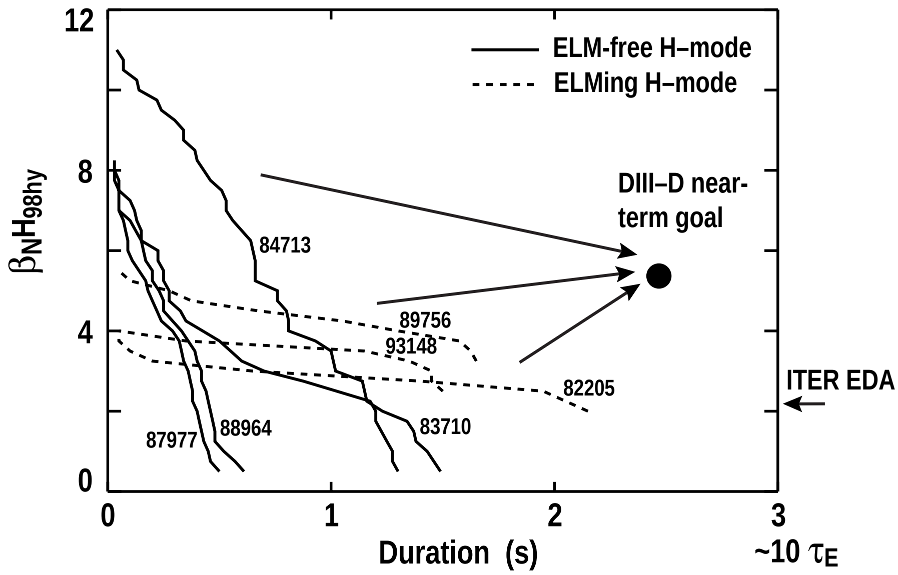

Fig. 1. The duration of time that DIII-D AT discharges exceed a given $\beta_N H$ value.