Long-Pulse High-Performance Discharges in the DIII–D Tokamak*

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T.C. Luce,[1] M.R. Wade,[2] P.A. Politzer,[1] S.L. Allen,[3] M.E. Austin,[4] B. Bray,[1] K.H. Burrell,[1] T.A. Casper,[3] M.S. Chu,[1] J.R. Ferron,[1] A.M. Garofalo,[5] P. Gohil,[1] I. Gorelov,[6] C.M. Greenfield,[1] W.W. Heidbrink,[7] C. Hsieh,[1] A.W. Hyatt,[1] R. Jayakumar,[3] R.J. La Haye,[1] L.L. Lao,[1] C.J. Lasnier,[3] E.A. Lazarus,[2] A.W. Leonard,[1] Y.R. Lin-Liu,[1] J. Lohr,[1] M.A. Mahdavi,[1] M.A. Makowski,[3] M. Murakami,[2] T.W. Petrie,[1] C.C. Petty,[1] R. Prater,[1] R.I. Pinsker,[1] B.W. Rice,[3] E.J. Strait,[1] J.G. Watkins,[8] W.P. West,[1] N.S. Wolf,[3] K.-L. Wong[6]

[1]General Atomics, P.O. Box 85608, San Diego, California 92186-5608
[2]Oak Ridge National Laboratory, Oak Ridge, Tennessee.
[3]Lawrence Livermore National Laboratory, Livermore, California
[4]University of Texas at Austin, Austin, Texas.
[5]Columbia University, New York, New York.
[6]Princeton Plasma Physics Laboratory, Princeton, New Jersey.
[7]University of California, Irvine, California.
[8]Sandia National Laboratories, Albuquerque, New Mexico.

Significant progress in obtaining high performance discharges for many global energy confinement times in the DIII–D tokamak has been realized since the previous IAEA meeting (Fig. 1). In relation to the previous data, the normalized performance has increased ~40% for durations of ~15 τ_E. (The normalized performance is measured by the product β_N H_{89} indicating the proximity to the conventional β limits and energy confinement quality, respectively). The duration at constant normalized performance of 9 has increased approximately a factor of three. This high performance was achieved at global parameters chosen to optimize the potential for maintaining fully non-inductive current sustainment at high performance, which is a key program goal for the DIII–D facility in the next two years.

The best long-pulse discharge has β_N H_{89} ~ 9 for 2.1 s as shown in Fig. 2. The discharge has neutral beam injection (NBI) in the current ramp to obtain high minimum q (q_{min}) which leads to both higher stability limits and higher bootstrap fraction. The plasma is held in L–mode to build the core pressure, then a shape change is made to trigger an H–mode transition. This recipe is consistent with ideal MHD calculations showing an inverse correlation of the global β limit with pressure peaking factor. The β in these discharges is

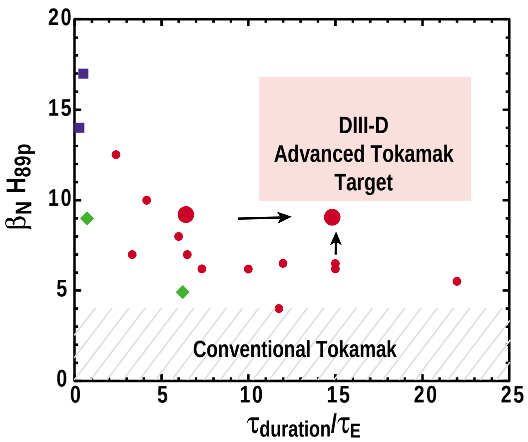

Fig. 1. Significant improvement in long-pulse advanced tokamak performance has been achieved. Smaller points are database from last IAEA; the larger points are the upper envelope of a database of ~200 discharges from 1999.

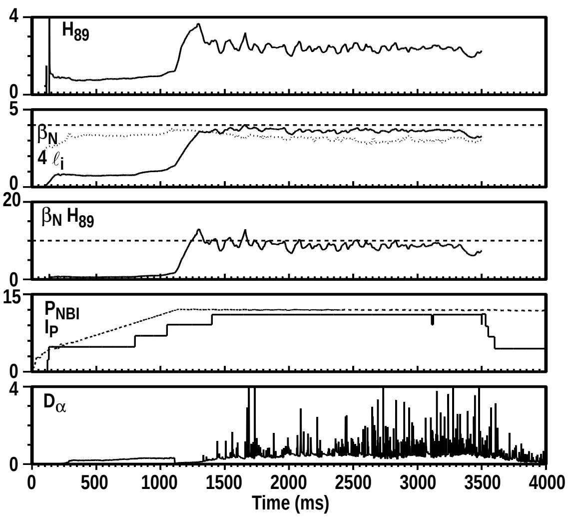

Fig. 2. β_N H_{89} ~ 9 sustained for ~15 τ_E, 1 τ_R. The quantity τ_R is the current profile relaxation time at constant current.

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close to 5%. After a short ELM-free period, the discharge makes a transition to an ELMing edge without loss of stored energy. Following the H–mode transition, the density rises to the "natural" H–mode density in DIII–D; in this case, it is about 60% of the Greenwald density. This paper will focus on three key aspects of this class of discharges — the transition at high performance to an ELMing H mode, limitations to increasing β in the steady high-performance phase, and impact of the current profile evolution.

Examination of the β evolution during the ELM-free period finds the β rise stops prior to the first ELM. The β does not drop, rather, it transitions to a different evolution which is constant in time or slowly rising. This transition is correlated with the onset of bursting high frequency (100–200 kHz) magnetic fluctuations with toroidal mode numbers n = 5–9. The frequency and mode number characteristics, along with the correlation of the instability onset with beam timing, indicates that these modes are Alfvénic and driven by the fast-ion population from NBI. Experiments during this campaign will investigate eliminating the instability by reducing the NBI voltage and reproducing the β evolution by real-time feedback control.

The main limitation to increasing β during the ELMing period has been identified as a resistive wall mode (RWM), in contrast to previous high performance discharges which seemed to be limited by a neoclassical tearing mode. The distinguishing characteristic of the recent discharges limited by RWM appears to be a q profile with stronger shear at the edge. Other parameters such as rotational shear may also play a role. The limiting mode has been identified as a RWM by its characteristics observed on an array of saddle coils located outside the vacuum vessel (growth rate and real frequency consistent with the vessel time constant) and by the fact that the modes appear as β rises above the ideal MHD limit in the absence of a wall. This calculated limit in many discharges is well correlated with 4 ℓ_i which is shown in Fig. 2. The oscillations in β_N are due to a growing RWM which reduces β, which in turn reduces the mode drive and thereby its amplitude. In many cases the high performance phase is terminated by a RWM causing a nearly complete thermal quench and a partial current quench; however, major disruptions are infrequent and the plasma normally recovers to a standard sawtoothing ELMing H mode. Experiments this year will focus on avoidance of the RWM by real-time β control and raising the no-wall limit. Substantial increases in β will require implementation of an active stabilization system. Preliminary experiments with a prototype system were carried out successfully in the last campaign.

The majority of discharges in the database exhibit high performance for several energy confinement times, then encounter a stability limit. Since the kinetic profiles are stationary, the onset of instability implies the current profile evolution to an unstable state is responsible. This indicates that sustainment of the current profile noninductively is a key requirement for extending the duration of the high performance. Measurement of the internal loop voltage profile in discharges similar to that shown in Fig. 2 indicate that ~75% of the plasma current is supplied noninductively. The remaining Ohmic current is localized near the half radius. Calculations indicate about 50% of the plasma current can be attributed to bootstrap current. The edge current density measured in equilibrium reconstructions is consistent with these bootstrap current calculations. Sustainment of the current noninductively will employ two new tools recently installed in DIII–D. A four-gyrotron system for electron cyclotron current drive (ECCD) is now being commissioned. A flexible steering system will allow control of the location of the ECCD between shots. A second cryopump recently installed in the upper divertor will help control the density to obtain lower-density, higher-temperature discharges needed for maximizing noninductive current drive. Experiments directed toward fully non-inductive sustainment of discharges like that shown in Fig. 2 will begin this year, with the goal of demonstrating β_N $H_{89} \geq 10$ fully noninductively for a duration limited only by the heating system hardware.