GA–A24347

QUIESCENT H–MODE, AN ELM-FREE HIGH-CONFINEMENT MODE ON DIII–D WITH POTENTIAL FOR STATIONARY STATE OPERATION

by
W.P. WEST, K.H. BURRELL, J.S. deGRASSIE, E.J. DOYLE, C.M. GREENFIELD, C.J. LASNIER, P.B. SNYDER, and L. ZENG

AUGUST 2003

DISCLAIMER

GA–A24347

QUIESCENT H–MODE, AN ELM-FREE HIGH-CONFINEMENT MODE ON DIII–D WITH POTENTIAL FOR STATIONARY STATE OPERATION

by
W.P. WEST, K.H. BURRELL, J.S. deGRASSIE, E.J. DOYLE,* C.M. GREENFIELD, C.J. LASNIER,† P.B. SNYDER, and L. ZENG*

This is a preprint of a paper to be presented at the 30th European Physical Society Conference on Controlled Fusion and Plasma Physics, St Petersburg, Russia, July 7–11, 2003 and to be published in the *Proceedings.*

*University of California, Los Angeles, California.
†Lawrence Livermore Natonal Laboratory, Livermore, California.

Work supported by
the U.S. Department of Energy
under Contract Nos. DE-AC03-99ER54463,
DE-FG03-01ER54615, and W-7405-ENG-48

GENERAL ATOMICS PROJECT 30033
AUGUST 2003

Quiescent H-mode, an ELM-Free High-Confinement Mode on DIII-D With Potential for Stationary State Operation

W.P. West[1], K.H. Burrell[1], J.S. deGrassie[1], E.J. Doyle[2], C.M. Greenfield[1], C.J. Lasnier[3], P.B. Snyder[1], and L. Zeng[2]

[1]*General Atomics, P.O. Box 85608, San Diego, California, 92186-5608, USA*
[2]*University of California, Los Angeles, California, USA*
[3]*Lawrence Livermore National Laboratory, Livermore, California, USA*

1. A Brief Introduction to Quiescent H-Mode

The quiescent H-mode (QH-mode) is an ELM-free and stationary state mode of operation [1] discovered on DIII-D. This mode achieves H-mode levels of confinement and pedestal pressure while maintaining constant density and radiated power. The elimination of edge localized modes (ELMs) and their large divertor loads while maintaining good confinement and good density control is of interest to next generation tokamaks. This paper reports on the correlations found between selected parameters in a QH-mode database developed from several hundred DIII-D counter injected discharges.

Time traces of key plasma parameters from a QH-mode discharge (#106919) are shown in Fig. 1. On DIII-D the negative going plasma current (a) indicates that the beam injection direction is counter to the plasma current direction, a common feature of all QH-modes. The D_α time behavior (c) shows that soon after high powered beam heating (b) is applied, the discharge makes a transition to ELMing H-mode, then the ELMs disappear, indicating the start of the QH period that lasts for the remainder of the high power beam heating (3.5 s). Previously published work [1-4] showing density and temperature profiles indicates that long-pulse, high-triangularity QH discharges develop an internal transport barrier in combination with the QH edge barrier. These discharges are known as quiescent, double-barrier discharges (QDB). The H-factor (d) and stored energy (c) rise then saturate at a constant level and the measured axial and minimum safety factors remain above 1.0 for the entire QH duration. During QDB operation the performance of the plasma can be very good, with $\beta_N{}^*H_{89L}$ product reaching 7 for >10 energy confinement times. These discharges show promise that a stationary state can be achieved.

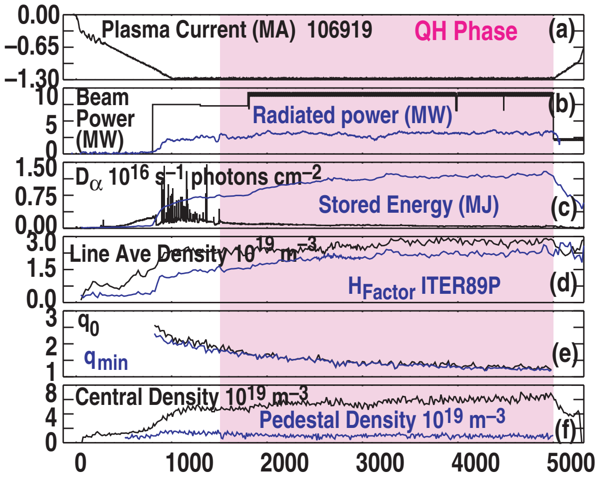

Fig. 1. Selected time traces of an example long-duration QH-mode discharge are shown.

In most cases the discharges are operated in a configuration that results in strong exhaust from divertor cryopumps, and the electron density at the top of the pedestal remains below 0.3 of the Greenwald density limit [5]. The QH-mode is usually accompanied by a saturated, coherent, multi-harmonic edge electromagnetic mode (EHO) [6] that is observed in magnetic probe data, and in density sensitive diagnostics, such as reflectometry and beam emission spectroscopy. The fundamental, typically found in the range of 5 to 10 kHz, has been identified as an n=1 toroidal mode. Harmonics are observed up to the n=7 toroidal mode [1,5]; usually one of the first three toroidal modes dominates the power spectrum.

2. DIII-D QH-Mode Database

While QH-modes are robustly obtained in counter injected discharges on DIII-D, the reasons behind the suppression of ELMs and the nature of the EHO are not understood. As a guide to future experimental and theoretical work, a QH database has been developed from the 1999-2002 DIII-D campaigns. Discharges taken during the counter injection experiments were searched for QH periods. For each QH period, the shot number, start and end times are stored. In addition numerous plasma parameters available from the standard DIII-D data set are averaged over the period and stored. Several criteria are used to identify a QH period. First, during a shot, time periods that are ELM free for more than 100 ms are chosen. To exclude L-mode and ohmic phases, the average H-factor (ITER89P) during the candidate period must be greater that 1.5. To exclude standard ELM free periods, the time rate of increase of the line-averaged density must not exceed 2.5×10^{19} m^{-3} s^{-1}. Only the five longest periods that pass the criteria in each shot are included. A total of 690 QH periods from 292 counter-injected discharges are in the database.

EHO properties are not a part of the standard DIII-D data set. To add information about the EHO during each QH period, spectral analysis of a magnetic fluctuation probe, located at the outboard midplane, is carried out on 10 ms subdivisions of the QH period. To qualify as an EHO, spectral power above background was required in at least two of the first three harmonic frequencies, ω, 2ω, and 3ω, where ω lies between 4 and 12 kHz. The averages of the fundamental frequency, ω, and spectral power (∝ to the square of the amplitude of the B signal) and the dominant mode number over the entire QH period are stored in the database.

Although the dataset contains a large number of discharges, the range of some control variables is limited and cross correlation between control variables may exist as a consequence of the DIII-D program emphasis, which has been focussed on high performance QDB discharges in strongly pumped upper single-null. High performance generally implies significant injected beam power (>7 MW), so data at low beam power are sparse. Our experience has shown that QH-mode is most readily achieved at low density; only infrequent attempts have been made to increase the density during QH operation. As a result, data at pedestal densities above 0.3 of the Greenwald density limit are sparse.

3. Counter Neutral Beam Injection and QH Mode

Neutral beams provide power, momentum, and fuel to the plasma, and in counter injection edge fast ions can be lost to the wall. Of the seven heating beams on DIII-D, four (known as left beams) are injected at an angle of 47 deg. to the central axis, i.e. more tangential. The other three (known as right beams) have a steeper angle of 63 deg, more perpendicular. From the database, we find that the observed duration of QH periods increases with total injected power in the range of 2 to 6 MW. The QH duration as a function of the balance between left and right beams is shown in Fig. 2. These data, and other data not shown, indicate that left beam power is important in achieving long duration QH modes on DIII-D. We note that the maximum achieved QH duration on DIII-D, ~4 s, is limited by hardware capabilities. A fast ion orbit code has been used to follow the banana orbits of ions born in the pedestal region of the plasma with the initial velocity determined by the heating beam energy and direction. In the edge region, most of the ions born from the left beams are lost to the outer wall in a single banana orbit, while ions from the right beams do not immediately reach the wall. These data inspired recent experiments comparing injection with only left or only right beams. In one set of discharges it is shown that at 7 MW of injected power with right beams only, QH mode is initiated but the initiation time is delayed by 1.4 s compared to an otherwise similar left beam only discharge. In another pair of discharges, shown in Fig. 3, the ELMs cease and QH mode begins at ~1500 ms, when only left beams are injected. In one case, shot 114915, the left beams remain on throughout the time shown, and the discharge remains in QH. In shot 114916 beam injection changes to right beams only at 1800 ms [Fig. 3(d)], and the discharge begins ELMing ~600 ms later [Fig. 3(b)]. From these two experiments, we can conclude that QH mode can be initiated and sustained for a significant time without the high fraction of prompt edge fast ion loss from left beam injection, but it is significantly more robust with left beam injection. Edge density, Fig 3(e), is also affected by the left/right injection. During right beam injection the edge density rises. When ELMs begins again at ~2800 ms, the edge density has risen to the same value it had at the initiation of QH-mode.

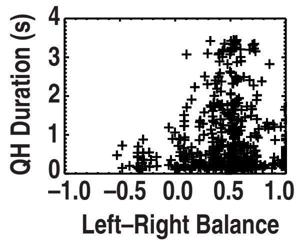

Fig. 2. The duration of QH-mode phases of counter-injected discharges is shown as a function of the left-right beam balance, (Pleft-Pright)/(Pleft+Pright).

4. Plasma Shaping and the EHO

Edge stability is known to improve with plasma shaping [7,8]. A measure of the extent of plasma shaping is the "shape factor," $S = I_p{*}q_{95}/(a{*}B_T)$, where I_p is the plasma current, q_{95} is the safety factor at the 95% flux surface, a is the minor radius, and B_T is the toroidal field [8]. Strong shaping (large S) from increased elongation and/or triangularity allows the plasma to carry more current at fixed q_{95}, a, and B_T. Fig. 4(a) shows the dependence of the QH duration and the EHO power on S. A histogram of the dominant mode vs. S is shown in Fig. 4(b). The fundamental mode dominates at high S. The response of the magnetic probes to plasma modes peaks at low frequency, perhaps explaining the power dependence in Fig. 4(a).

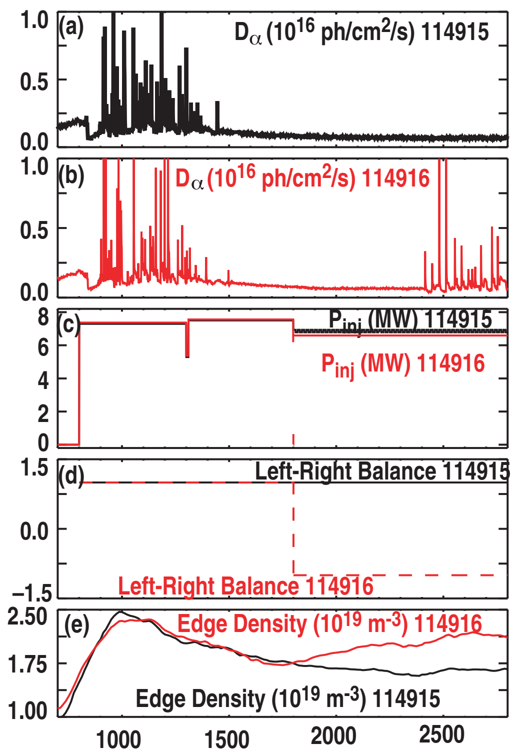

Fig. 3. Divertor D_α signals from (a) 114915, a left beam only discharge and (b) 114916, a discharge with a switch to right beams only at 1800 ms; (c) the injected power in both discharges; (d) the left-right balance, (Pleft-Pright)/(Pleft+ Pright), and (e) the edge density inn both discharges.

5. QH Duration and EHO Power

Of the several hundred examples of QH-mode on DIII-D, only one has been found which shows no evidence of an EHO, but the QH duration shows no correlation with EHO power (Fig. 5). Long-lived QH modes, limited in duration by hardware related events, are observed at very low EHO powers. On the other hand, examination of particular QH-mode discharges with large amplitude EHOs shows that sudden interruption by fast ELM-like events can occur several times during a long period with high beam power.

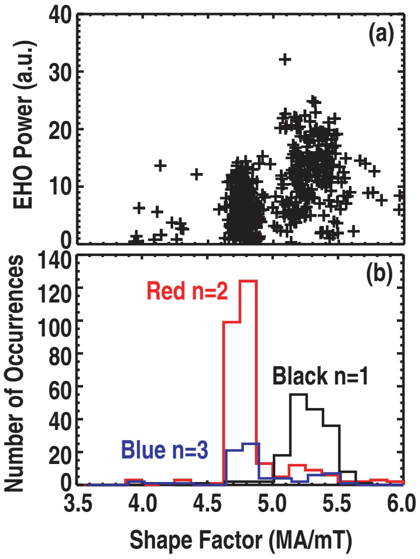

Fig. 4. The observed EHO power (a) and a histogram of the frequency of observation of the first three toroidal modes (b) vs. shape factor.

6. Summary and Discussion

Details of neutral beam injection play a role in the QH-mode. QH-mode duration tends to be longer using left (more tangential) beam injection. Very recent experiments indicate that QH-mode initiation is possible with only right beam injection. Left beam injection increases edge fast ion loss and momentum input. Beam induced particle fueling is likely to be different between left and right beams. Density increase during right beam operation is implicated in QH deterioraton. More experiments are needed to clarify why left beam injection seems preferable, but not necessary.

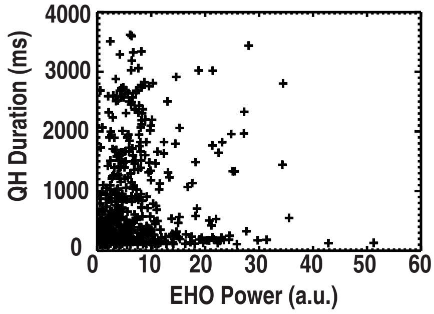

Fig. 5. The duration of QH-mode phases as a function of the relative power of the EHO is shown.

A coherent, saturated edge harmonic oscillation is observed in a vast majority of QH-mode phases. The nature of this mode is not well understood. Plasma shape is seen to play a role in the amplitude of the EHO, as measured by magnetic probes. Stronger shaping, which is known to play a role in ELM stability [7], leads to a dominance of the n=1 toroidal mode and higher EHO amplitude. Interestingly, while the presence of an EHO is strongly associated with the QH mode, its amplitude is not obviously related to the maximum observed QH duration. More experimental work is planned on the effect of shaping.

Expansion of the QH database will continue. Most important is to include edge plasma properties in both QH and non-QH phases of counter-injected discharges. Such database work will compliment work on the detailed measurement of edge profiles and subsequent analysis of edge stability using advance MHD models such as ELITE and GATO.

Work supported by U.S. Department of Energy under Contract Nos. DE-AC03-99ER54463, DE-FG03-01ER54615, and W-7405-ENG-48.

[1] K.H. Burrell, M.E. Austin, D.P. Brennan, *et al*., Phys. Plasmas **8**, 2153 (2001).
[2] C.M. Greenfield, K.H. Burrell, J.C. DeBoo, *et al*., Phys. Rev. Lett **86**, 4544 (2001).
[3] E.J. Doyle, *et al*., Plasma Phys. Control. Fusion **43**, A985 (2001).
[4] W.P. West, M.R. Wade, C.M. Greenfield, *et al*., Phys. Plasmas **9**, 1970 (2002).
[5] M. Greenwald, J.L. Terry, S.M. Wolfe, *et al*., Nucl. Fusion **28**, 2199 (1988).
[6] K.H. Burrell, M.E. Austin, D.P. Brennan, *et al*., *Plasma Phys. Control. Fusion* **44,** A253 (2002).
[7] J.R. Ferron, M.S. Chu, G.L. Jackson, *et al*., Phys. Plasmas **7**, 1976 (2000).
[8] E.A. Lazarus, *et al., Plasma Phys. Control. Nucl. Fusion Research* **1**, 609 (1994)