GA–A25070

OPERATIONAL ENHANCEMENTS IN DIII–D QUIESCENT H–MODE PLASMAS

by

T.A. CASPER, K.H. BURRELL, E.J. DOYLE, P. GOHIL,
C.J. LASNIER, A.W. LEONARD, T.H. OSBORNE, P.B. SNYDER,
D.M. THOMAS, and W.P. WEST

JUNE 2005

GENERAL ATOMICS

DISCLAIMER

GA–A25070

OPERATIONAL ENHANCEMENTS IN DIII–D QUIESCENT H–MODE PLASMAS

by
T.A. CASPER,* K.H. BURRELL, E.J. DOYLE,† P. GOHIL,
C.J. LASNIER,* A.W. LEONARD, T.H. OSBORNE, P.B. SNYDER,
D.M. THOMAS, and W.P. WEST

This is a preprint of a paper to be presented at the 32nd EPS Conf. on Plasma Physics, June 27 through July 1, 2005, Terragona, Spain, and to be published in the *Proceedings.*

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

Work supported by
the U.S. Department of Energy
under W-7405-ENG-48, DE-FC02-04ER54698,
and DE-FG03-01ER54615

GENERAL ATOMICS PROJECT 30200
JUNE 2005

GENERAL ATOMICS

Operational Enhancements in DIII-D Quiescent H-Mode Plasmas

T.A. Casper[1], K.H. Burrell[2], E.J. Doyle[3], P. Gohil[2], C.J. Lasnier[1], A.W. Leonard[2],
T.H. Osborne[2], P.B. Snyder[2], D.M. Thomas[2], and W.P. West[2]

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

In recent DIII-D experiments, we concentrated on extending the operating range and improving the overall performance of quiescent H-mode (QH) plasmas. The QH-mode offers an attractive, high-performance operating mode for burning plasmas due to the absence of pulsed edge-localized-mode-driven losses to the divertor (ELMs). Using counter neutral-beam injection (NBI), we achieve steady plasma conditions with the presence of an edge harmonic oscillation (EHO) replacing the ELMs and providing control of the edge pedestal density. These conditions have been maintained for greater than 4 s (~30 energy confinement times, τ_E, and two current relaxation times, τ_R [1]), and often limited only by the duration of auxiliary heating. We discuss results of these recent experiments where we use triangularity ramping to increase the density, neutral beam power ramps to increase the stored energy, injection of rf power at the electron cyclotron (EC) frequency to control density profile peaking in the core, and control of startup conditions to completely eliminate the transient ELMing phase.

1. Higher Density Regime

To date, we require particle control using divertor cryo-pumping along with neutral-beam injection opposite plasma current (counter-NBI) to achieve QH-mode operation in DIII-D. We are able to achieve QH-mode conditions over a fairly wide range of operating conditions [2] including pedestal stored energy and collisionality consistent with ITER operational needs. We observe this operation to be extremely robust. We maintain QH edge conditions where the pedestal region remains ELM-free with particle exhaust due to the presence of an EHO. We have found that edge stability is consistent with a model based on peeling-ballooning-mode theory [3]. This theory predicts that the region of stability will expand with stronger shaping. We increase the triangularity within a discharge by pulling the lower x-point down as shown by the EFIT contours in Fig. 1. This results in an increase in the operating range for both the core and pedestal densities while maintaining stability to ELMs. In this high-density operation, the coherent EHO transforms to more broadband, turbulent-like fluctuations but the QH characteristics remain. This transition to high-density operation is achieved at the expense of core performance in that ion temperature (T_i) and rotation (Ω_i) decrease in the core (shot 118821 in Fig. 2). This results in a net loss in stored energy and β_N remains relatively constant in time even though the density rises.

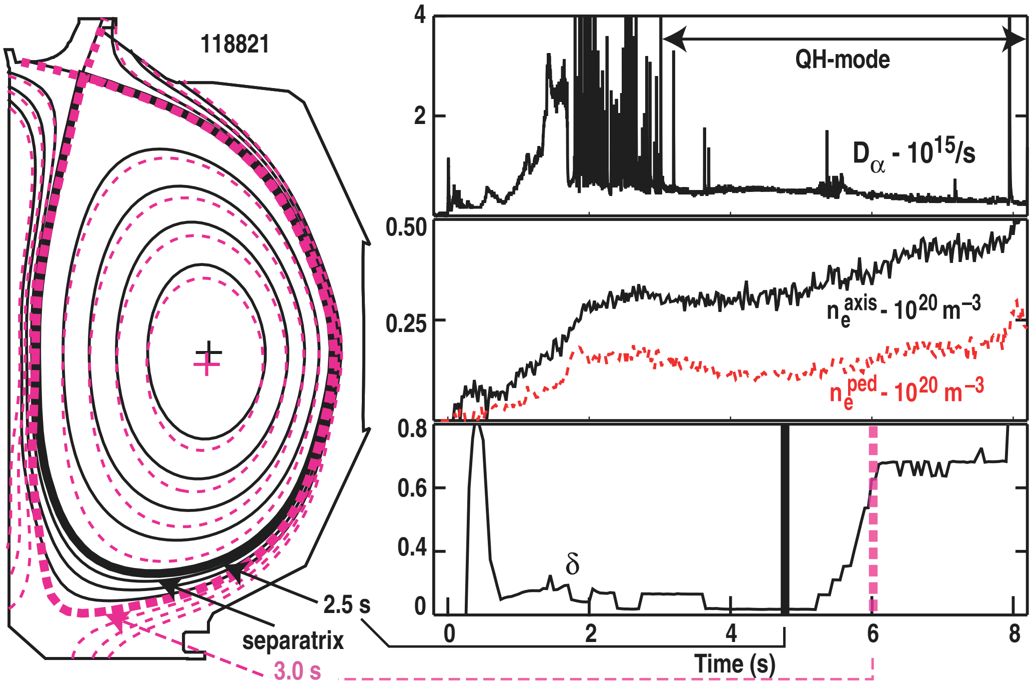

Fig. 1. Shape change from 2.5 s < t < 3 s (EFIT) increases triangularity, δ, to achieve an increase in density while maintaining the QH-mode.

2. Improved Stored Energy Using Control of Density Profile

We are able to recover this loss in core parameters using a combination of EC power injection and intense NBI heating along with the triangularity ramping to achieve the higher density operation. Typically, QH-mode discharges exhibit a propensity for forming a core transport barrier in addition to the edge barrier that results in quiescent double barrier (QDB) conditions. With the enhanced core confinement due to formation of the transport barrier, additional NBI injection and its fueling in the core can result in pressure profile peaking and β limitations. We have previously observed [4] that EC power injection into the core region provides the ability to control this density profile peaking. Using this combination of EC injection for density profile control and NBI power ramp to increase the stored energy, we achieve $\beta_N \sim 3$ as is shown in Fig 2. This combination of EC and

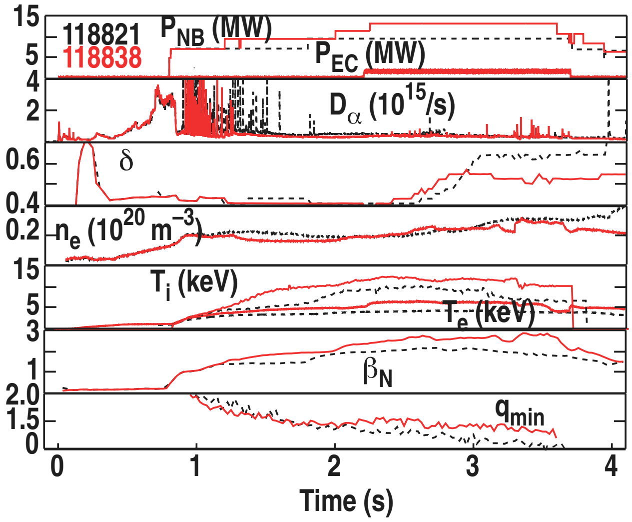

Fig 2. In shot 118838, we ramped the NBI power while using EC power to control the density rise (due to transport barrier with added NBI) to obtain $\beta_N \sim 3$ while maintaining $q_{min} \sim 1.5$ in QH-mode. Shot 118821 is a constant power, high-density QH reference discharge.

NBI also modifies the core current profile evolution [4]. We achieve long durations, 2 s for 118838 shown, where the on-axis value of q remains stationary and near 1.5. Establishing this stationary q profile is consistent with a model based on fluctuations and a hyper-resistive current-diffusion [5,6] term in Ohm's law. By controlling the EC and NBI power, we can manipulate both the density profile peaking and the current profile to alter the value of q_{min} in these weakly negative shear discharges.

These QH-mode plasmas remain markedly resilient to changes in auxiliary heating power where up to 3 MW of EC power plus 15 MW of NBI have been injected without loss of the desirable, ELM-free pedestal conditions. We find that, once a threshold in injected power is reached, the edge pedestal conditions remain constant while the core conditions can rise dramatically with the formation of a core transport barrier as indicated by the ion temperature profiles shown in Fig. 3. This saturation in edge conditions, while not currently fully understood, results in the resilience of QH discharges to changes in the injected power.

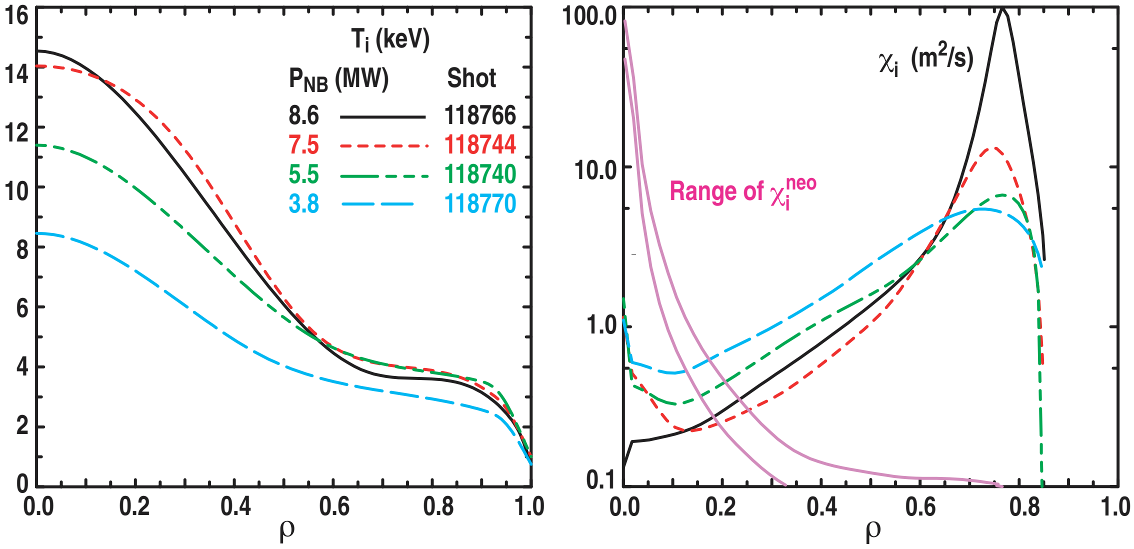

Fig 3. Pedestal T_i remains constant with increased NBI power. Core T_i rises with reduced χ_i and a stronger internal barrier (QDB).

3. ELM-free Startup

Utilizing both the advantages of shaping and particle control, we have demonstrated an additional advantage to the QH-mode of operation, plasma startup and totally ELM-free discharge evolution. As shown in Fig. 4, by carefully controlling the startup conditions; plasma shape, fueling and heating, we are now able to access the QH regime directly, without first encountering an extended period of ELMs. This would provide distinct advantages for a QH-mode operating scenario for ITER and fusion reactors.

4. Summary

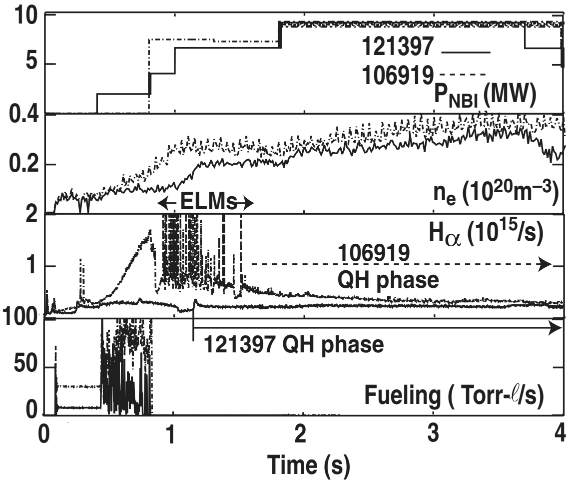

Fig. 4 Using particle and heating control, shot 121397 enters QH phase without ELMing period as compared with an earlier shot 106919

In recent DIII-D experiments, we have expanded the regime of QH-mode operation over a fairly broad range of q_{95}, plasma current and toroidal field [2]. As discussed here, using strong shaping we have increased the density range to include operation over $0.1<n_E^{ped}(10^{20}\text{m}^{-3})<0.65$. While operation at the higher density resulted in lower core stored energy, using a combination of EC-density control with increased NB power injected, we have more than recovered this loss in stored energy and achieved a peak $\beta_N = 2.85$. In addition, we have improved control of plasma startup and obtained totally ELM-free discharges.

This work was supported by the U.S. Department of Energy under W-7405-ENG-48, DE-FC02-04ER54698, and DE-FG03-01ER54615.

References

[1] D.R. Mikkelsen, Phys. Fluids B **1**, 333 (1989).
[2] K.H. Burrell, *et al.,* Phys. Plasmas **12**, 05121 (2005).
[3] P.B. Snyder, *et al.*, 31st EPS Conf. on Plasma Phys., London, Vol. 28G (2004 ECA) P-2.156.
[4] T.A. Casper, *et al.*, 30th EPS Conf. on Control. Fusion and Plasma Phys., St. Petersburg, Vol. 27A (2003 ECA) P3-207.
[5] T.A. Casper, *et al.*, Bull. Am. Phys. Soc. **49**, 265 2004.
[6] A.H. Boozer, J. Plasma Phys. **35**, 133 (1986).