H-MODE INVESTIGATIONS IN DIII-D

M. Shimada[a], K.H. Burrell, S. Ejima, D.P. Schissel, S. Allen[b], N.H. Brooks, G. Bramson, R.W. Callis, T.N. Carlstrom, A.P. Colleraine, D. Content[c], J.C. DeBoo, H. Fukumoto[d], P. Gohil, R.J. Groebner, D.N. Hill[b], R.-M. Hong, N. Hosogane[a], C.L. Hsieh, G.L. Jackson, G.L. Jahns, R. James[b], G. Janeschitz[e], A.G. Kellman, J. Kim, S. Kinoshita[d], L.L. Lao, P. Lee, J.M. Lohr, P. Lomas[f], J.L. Luxon, M.A. Mahdavi, C.P. Moeller, H. Nakamura[a], N. Ohyabu, T.H. Osborne, D. Overskei, M. Mayberry, S. Perkins[b], M. Perry[c], P.I. Petersen, T.W. Petrie, J.C. Phillips, W. Pickles[b], R. Prater, M. Rensink[b], J.T. Scoville, R.P. Seraydarian, T. Simonen[b], B.W. Sleaford, R.T. Snider, B. Stallard[b], R.D. Stambaugh, R.D. Stav, H.E. St.John, R. Stockdale, E.J. Strait, T. Taylor, J.F. Tooker, Y. Uesugi[a], R. Wood[b] and S. Yamaguchi[g]

(GA Technologies Inc., P.O. Box 85608, San Diego, Calif. 92138 USA)

[a]Japan Atomic Energy Research Institute; [b]Lawrence Livermore National Laboratory; [c]John J. Hopkins University; [d]Hitachi, Ltd.; [e]Max Planck Institut für Plasmaphysik, Garching, Fed. Rep. of Germany; [f]JET Joint Undertaking. [g]Mitsubishi Electric Corp.

INTRODUCTION

DIII-D is a large tokamak (major radius $R = 1.67m$, minor radius $a = 0.67m$), capable of producing vertically elongated limiter and divertor plasmas with high plasma current at modest toroidal field ($B_T = 2.2T$ on axis). To date, maximum plasma currents achieved are 3.0 MA in limiter plasmas (elongation in excess of 2.0), 2.0 MA in divertor plasmas (elongation 1.9). The DIII-D divertor is a reactor-compatible open divertor design, with no separate divertor chamber and no coils in vacuum. The divertor plates are two toroidal bands of carbon tiles on the bottom of the vacuum vessel. Deuterium plasmas are heated by hydrogen neutral beams (75 keV, coinjection only) and electron cyclotron heating /1/. Power levels to date are 6 MW (beam) and 1.0 MW (ECH).

PHENOMENOLOGY OF H-MODE DISCHARGES

Neutral beam heated divertor discharges in DIII-D /2/ have shown a clear transition to the H-mode (Fig. 1) which occurs after a 50-100 ms long L-mode phase. At this point, D_α radiation drops precipitously, density increases and energy confinement time improves significantly. Edge Localized Modes (ELM) limit total energy content in some discharges. During ELM-free phases, continuous rise in density and central electron and ion temperatures for periods up to 0.3 sec were observed, limited only by beam pulse length.

H-MODE THRESHOLD

The H-mode transition has a threshold in density and beam power (Fig. 2). At I_p =1 MA B_T = 2.1T, density threshold must exceed 2×10^{19} m^{-3} and power threshold is about 2.8 MW. Below the density threshold, the discharges are not sawtoothing, whereas all the shots above the density threshold have sawteeth before the beam. Therefore, the presence of sawteeth before the beam injection might be one of the prerequisites of L-H transition. In the discharges documented in Ref. 2, the ion ∇B drift was toward the divertor x-point. Discharges with inverted B_T shown in Fig. 2 are L-mode, although they have density and input power well above the threshold values with the normal B_T direction. This agrees qualitatively with ASDEX experimental results /3/ and the theoretical prediction by Hinton /4/. These discharges do have sawteeth before the beam injection, and the levels of D_α emission from the inside separatrix hit point were lower by a factor of 2 - 5 with reversed B_T, whereas levels of D_α from outside hit point did not change by reversing B_T.

EDGE LOCALIZED MODES

Repetitive bursts during the H-mode expel energy and particles from the main plasma. There are giant bursts like those indicated in Fig. 1 and also much smaller, more frequent mini-bursts. The giant bursts are observed in D_α/H_α signals, SX emission, VUV line intensities, diamagnetic loop signals and line average density. Diamagnetic loop signals and infrared camera measurements of the divertor plate indicate that 10-20% of plasma energy is lost to the divertor during the ELM burst. Many minibursts appear in discharges with low beam power. Radiation from impurity ions saturates quickly for discharges with mini-bursts. During the burst-free phase, continuous increase in impurity radiation was observed. For H-mode discharges with mini-bursts, precursor fluctuations were observed in the magnetic probe signals located on the large major radius side of the torus. The toroidal mode number was identified as $n \approx 6$, and the mode was rotating toroidally in the direction opposite to the plasma current. The infrared camera measurements /7/ indicate that the heat pulse hits the outside separatrix 0.5–0.6 msec earlier than the inside separatrix, which suggests that the burst originates from the large major radius side.

PARTICLE RECYCLING

Particle recycling flux measured by D_α photodiode array is plotted in Fig. 3 versus line average density of the main plasma for ohmic, L and H cases. In H-mode cases, values away from the bursts are plotted. This figure shows that the particle recycling flux increases non-linearly with an increase of density for ohmic and L-mode cases, and only small increase during H-mode. L-mode recycling levels are enhanced over ohmic values by a factor of two, and H-mode recycling levels are reduced by a factor of 5-10 from L-mode levels. Particle recycling flux at the divertor is a weak function of input power and toroidal field. Wall recycling flux is lower by a factor of ≈ 30 than divertor recycling flux, and the ratio does not vary strongly with ohmic, L and H cases.

ENERGY CONFINEMENT SCALING /5/

As discussed previously, the confinement characteristics of H-mode discharges are strongly influenced by the presence of ELM's. The interval between ELM's (50 msec to 300 msec for giant ELM's and 10 msec for mini-ELM's) is so short that the discharge tends not to reach steady state before the next ELM. Furthermore, the beam pulse length available for this study (0.3 – 0.4 sec) was not long enough for ELM-free H-mode discharges to reach steady state. Therefore, for the ELM-free transport study, the dW/dt corrections were important. The confinement times with and without the dW/dt correction are shown in Fig. 4, plotted against total input power. For the discharges with input power marginally above the threshold, the discharges are dominated by many mini-ELM's so that the dW/dt correction is small. Energy confinement in H-mode discharges show a factor of three improvement over Kaye-Goldston L-mode confinement scaling /6/ (with dW/dt correction: without dW/dt correction, improvement is factor of two). Up to 6 MW of neutral beam power available, the H-mode discharges show no apparent deterioration of energy confinement. In Fig. 5, energy confinement time is shown as a function of line average density of the main plasma. Again, τ_E values with and without the dW/dt corrections are shown. Neither of these values show a strong change for the density range investigated. H-mode τ_E also shows little variation with B_T (Fig. 6). τ_E scaling with plasma current is being investigated. With high power long pulse beam sources (14 MW, 3 sec), confinement studies of ELM-free transport without a large influence from ELM's, as well as effects of radiation loss will be possible in the near future.

ACKNOWLEDGEMENT

This work was supported by the U.S. Department of Energy Contract DE-AC03-84ER51044.

REFERENCES

/1/ R. Prater, *et al.* this conference.
/2/ J. Luxon, *et al.*, Proc. of 11^{th} Intl. Conf. on Plasma Phys. and Cont. Nucl. Fusion Res., Kyoto, Japan, 13-20 November 1986, IAEA-CN-47/A-III-3.
/3/ F. Wagner, *et al.*, *Nucl. Fusion*, **25** (1985) 1490.
/4/ F. Hinton, *Nucl. Fusion*, **25** (1985) 1457.

/5/ K. H. Burrell, *et al.*, to be published in *Phys. Rev. Lett.*
/6/ S. M. Kaye, *et al.*, *Nucl. Fusion*, 25, 65 (1985).
/7/ D. N. Hill, *et al.*, to be published in *Nucl. Fusion*.

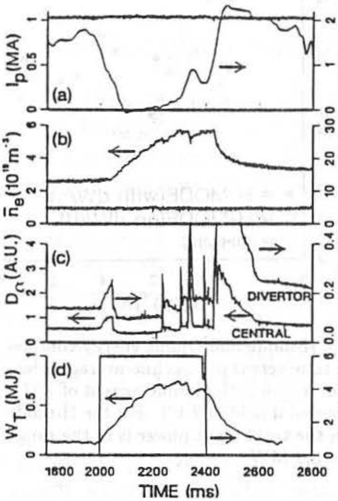

Fig. 1. (a) I_p and loop voltage at the plasma surface, (b) line-averaged density and deuterium gas injection rate, (c) D_α radiation along a horizontal chord through the plasma midplane and along a chord viewing the divertor region, (d) neutral beam power and plasma stored energy.

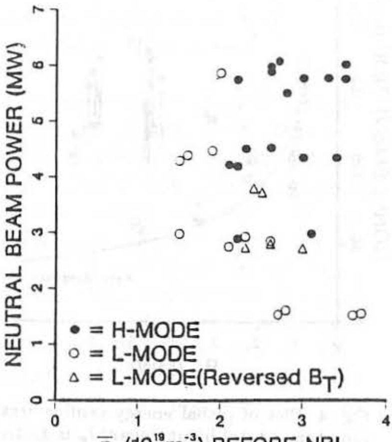

Fig. 2. Plot showing the region of parameter space where the H-mode exists. The density plotted is the plasma line-averaged density just before the neutral beams are turned on. Most of the cases are for the ion ∇B drift towards the divertor X-point. Those marked reversed B_T have the opposite polarity of the toroidal field, which means that the ion ∇B drift is away from the divertor X-point. Plasma current for all cases shown is 1 MA; the magnitude of the toroidal field is 2.1 T.

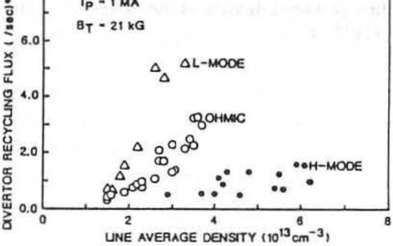

Fig. 3. Plot of particle recycling flux at the divertor versus line-average density of the main plasma. Particle recycling flux was measured by D_α photodiode array looking at the divertor region.

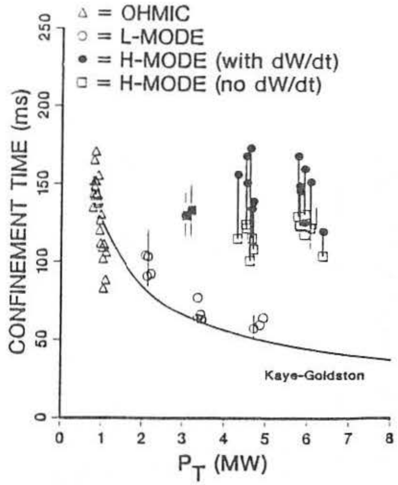

Fig. 4. Plot of global energy confinement time versus total input power, I_p is 1 MA and B_T is 2.1 T; Also shown for comparison with the L-mode data is the prediction of the Kaye-Goldston scaling law /6/.

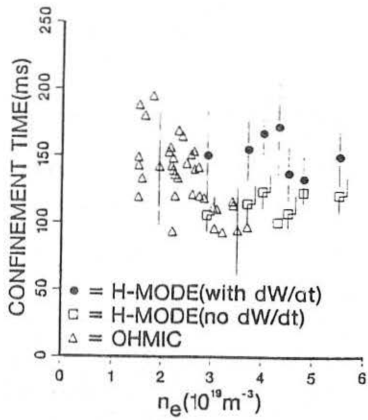

Fig. 5. H-mode and Ohmic energy confinement time versus plasma line-averaged density for a case with plasma current of 1 MA and toroidal field of 2.1 T. For the H-mode cases, the total input power is in the range 4.5 to 5.0 MW.

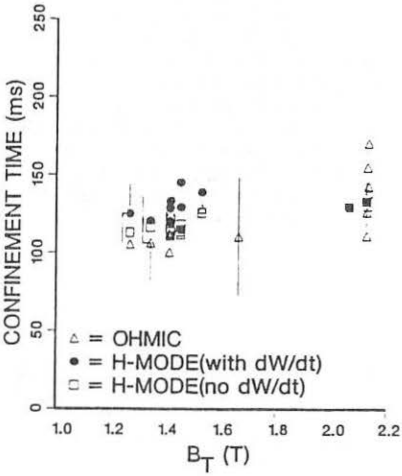

Fig. 6. H-mode and Ohmic energy confinement time versus toroidal field for a case with plasma current of 1 MA. For the H-mode data, the total input power is in the range 3.0 to 3.3 MW. The Ohmic data have line averaged density in the range 2.6 – 3.0 $\times 10^{19}$ m^{-3}.