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*University of California-Los Angeles, Los Angeles, California.

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# CONFINEMENT AND PEDESTAL CHARACTERISTICS IN H-MODE WITH ECH HEATING

R. PRATER, J.S. deGRASSIE, P. GOHIL, T.H. OSBORNE
*General Atomics, PO Box 85608, San Diego, California 92186-5608, USA*

E.J. DOYLE, L. ZENG
*University of California-Los Angeles, PO Box 957099, Los Angeles, California 90095, USA*

Access to the H-mode regime of improved confinement and good global confinement when the plasma heating is dominantly of the electrons is critical to the success of ITER, since the proposed heating schemes for ITER, including heating by fusion products, deposit most of their heat in the electron fluid. Most of the world database for the L-H transition and for confinement is derived from discharges with high power positive-ion neutral beam injection (NBI), which primarily heats the ions. Issues for dominant electron heating include the H-mode power threshold and effect on rotation, density profile, global confinement, pedestal height, and edge localized mode characteristics. Experiments have been performed on DIII-D using electron cyclotron heating (ECH) to simulate heating in ITER. These experiments suggest that the H-mode transition power for ECH is significantly lower than that for NBI in deuterium plasmas but about the same for helium plasmas. The global confinement with ECH relative to the H98(y,2) scaling is around 75% under the conditions of these discharges. The pedestal with pure ECH has a higher electron temperature and lower density than for NBI, and the width of the pedestal region is nearly identical.

## 1. Introduction

The physics of all plasma heating technologies projected for ITER is similar to that of electron cyclotron heating (ECH). MeV neutral beam injection (NBI), ECH, ion cyclotron wave minority heating, lower hybrid current drive, and heating by fusion products all deposit most of their power thermally in the electron fluid. In addition, these heating approaches introduce little or no toroidal angular momentum and little NBI or no fueling. However, most of the world database for confinement and performance in tokamaks [1] was developed using positive-ion neutral beam injection, which on the contrary introduces substantial angular momentum resulting in strong rotation and rotational shear. In order to project to ITER it is necessary to consider tokamak performance in present devices with primarily electron heating. ECH is an excellent approach to developing these projections because it closely simulates the heating in ITER, although the ECH heating profile may be different than the alpha heating profile in ITER.

## 2. Experimental Considerations

It is widely recognized that confinement at H-mode levels is needed by ITER to achieve its performance goals [1]. This means that the heating power must be sufficient to trigger the transition to the H-mode of improved confinement and that the confinement in the H-mode must be sufficient relative to the H-mode scaling. Recent experiments on DIII-D using a combination of co- and counter-injection of neutral beams have shown strong sensitivity of the H-mode threshold auxiliary heating power to the plasma density, the beam torque, the ion species, and the plasma shape [2]. Hence, comparing performance for ECH dominated plasmas must be done under similar conditions of density and low rotation.

## 3. Experiments

Experiments in deuterium plasmas show that the H-mode threshold ECH power is smaller than for NBI by about a factor 2. Figure 1 shows measurements from two deuterium DIII-D discharges. On the left side is a discharge in which the ECH power is increased in steps, first by modulating the power and then by stepping it up, and on the right side is a similar discharge with ramped NBI power instead of ECH power. For ECH, the H-mode transition (where the D emission drops and the density starts to increase) takes place at a heating power of 1.2 MW, while for the NBI case the transition does not take place until just after a step from 2 MW to 2.8 MW. In this discharge the co- and counter-injection NBI is approximately balanced, so that little net rotation is created. In past studies, low torque NBI has provided lowered threshold power for the H-mode compared to full co-injection [2].

The ECH for Fig. 1 is aimed to deposit power near $\rho$=0.7, with no current drive. (Here, $\rho$ is the square root of the normalized toroidal flux.) This deposition location is in the region where ECH might be used for control of neoclassical tearing modes. One view of the H-mode transition is that it depends on the power transported from the core to the plasma boundary, so the power deposition profile is immaterial (provided, as in this discharge, that plasma radiation is not a significant loss mechanism). However, it is also possible that the peripheral nature of this ECH heating profile is beneficial to the H-mode transition.

Confinement in these two discharges is better with neutral beam heating than ECH heating. For NBI the H-mode confinement factor $H_{98(y,2)}$ [1] is 1.05 in the steady condition after the transition, while for ECH it is 0.76. It is likely that part of the difference in confinement is due to the far off-axis heating of the ECH case, but it is also likely that heating electrons is subject to greater transport losses in the electron channel. Typically in DIII-D discharges like those shown in Fig. 1, the electron-ion energy coupling is weak in the core of the plasma, so stronger transport processes in the electron fluid are not ameliorated by the lower ion transport rates.

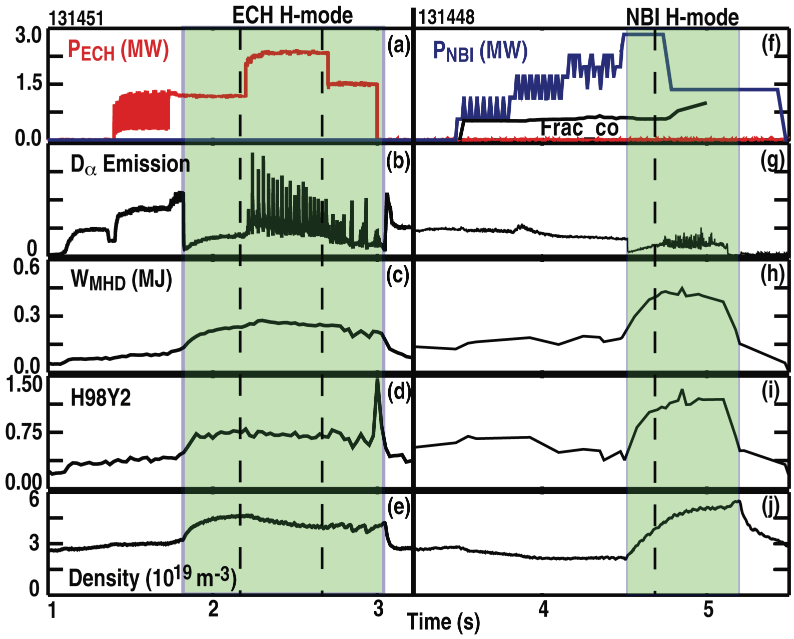


Fig. 1. Two DIII-D discharges in deuterium with toroidal field 2.0 T and plasma current 1.0 MA. The configuration is lower single null. The discharge on the left (a-e) has ECH power deposited near $\rho = 0.7$ and on the right (f-j) NBI power. The NBI power is provided by co- and counter-current sources, so that the net fraction of co-injected power is about 0.5 as shown in (f). (a,f) Incident power, (b,g) $D_{\alpha}$ emission (au), (c,h) plasma stored energy, (d,i) confinement factor H98(y,2), and (e,j) line-integrated electron density.

After the step up in ECH power at 2.4 s in Fig. 1, the H-factor decreases further to 0.7, and little increase in stored energy is seen, while in the NBI case the H-factor increases to 1.18 after the NBI power is stepped down to 1.45 MW. In addition to changes in transport, a factor affecting the global confinement is the edge localized modes (ELMs), which become very large in the ECH case but remain small and frequent in the NBI case. ELMs cause increased transport from the core, particularly for the Type I ELMs of the ECH case. Also, in the ECH case the density decreases when the ECH power is stepped up, due at least partly to the ELMs but also this may be due to density pumpout effects sometimes observed when electron heating is applied or increased. Another factor is that when the NBI power is stepped down the balance between co- and counter-injection is lost and net torque by the NBI causes plasma rotation to increase. Plasma rotation is known to be beneficial to confinement [6], and hardly any loss in stored energy is seen when the NBI power decreases. An additional factor in both cases is that the total heating power is not much greater than the transition power.

The nature of the pedestal in NBI and ECH H-modes is an important factor for ITER because the plasma performance depends to a large extent on the height of the transport barrier that forms at the plasma boundary in H-mode discharges [7]. In Fig. 2 the boundary profiles are shown for the two discharges (ECH and NBI) of Fig. 1. Figure 2 shows that for ECH only, the density at the top of the pedestal is 20% higher for NBI than for ECH, while the electron temperature is 40% higher in the ECH case. The pressure profile at the edge is therefore higher in the ECH case, assuming that $T_i = T_e$ in the ECH case, since the measurement of $T_i$ requires beams which are absent in the ECH discharge. $T_i$ may in fact be significantly smaller than $T_e$ in the pedestal of ECH discharges, so the difference in pedestal pressure is probably larger than that shown in Fig. 2(f).

An important issue for ITER is access to the H-mode in the non-DT phase when heating by the fusion products is not significant so the power will be limited to the available auxiliary heating. Operation in the H-mode during the hydrogen or helium phase is important for such concerns as assessing the strategy for suppressing ELMs and addressing the coupling of the ICRF heating system with an H-mode edge. Because of this relevance, experiments on the H-mode threshold power in helium have been performed. Figure 3 shows that the threshold power in helium is higher than for deuterium by a factor around 1.5. The point for ECH+NBI, which uses the maximum ECH power available plus sufficient balanced NBI power to achieve the transition, is consistent with the NBI-only data points. This is in contradiction to the results from deuterium in which the transition was at much lower in power for ECH. It is noteworthy that both helium and deuterium exhibit the same torque dependence: low or negative torque implies lower threshold power than positive torque.

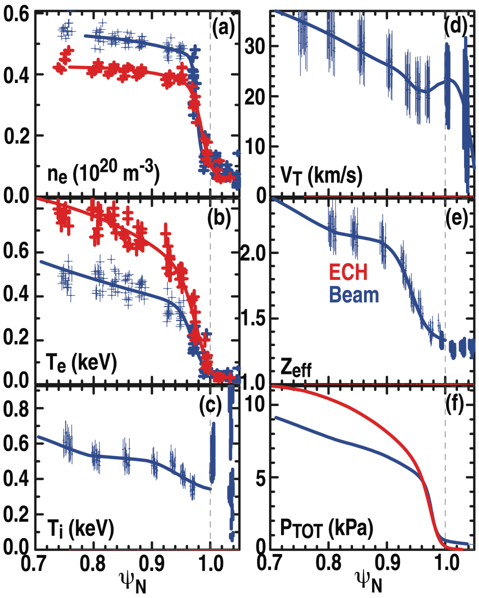


Fig. 2. Measurement of (a) electron density, (b) electron temperature, (c) ion temperature, (d) toroidal rotation velocity, (e) effective ion charge $Z_{eff}$, and (f) total pressure, as a function of normalized poloidal flux. The profile measurements are made over the last 20% of the period between ELMs. The last closed flux surface is identified by the vertical dashed line.

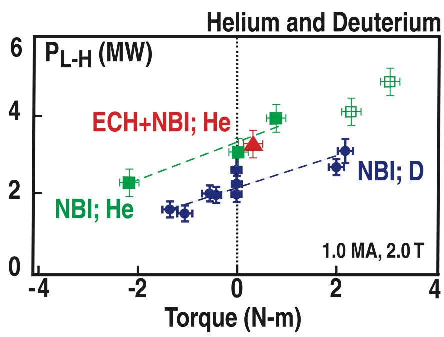


Fig. 3. Threshold power for helium working gas (square points) and deuterium (round points). Most points are for NBI, but the triangle point is for helium with mostly ECH plus a small amount of nearly balanced NBI. The hollow square points are lower limits on the threshold power for helium, as these discharges did not achieve the H-mode.

## 4. Discussion and Conclusions

Unqualified conclusions are not possible now because the database of ECH discharges is too small. Nevertheless, some tentative conclusions may be drawn.

First, the threshold power appears to be significantly lower for ECH than for NBI in deuterium, although the threshold powers are quite similar in helium. Second, confinement as characterized by the value of H98(y,2) for ECH H-mode discharges is smaller than that of NBI H-mode discharges by around 25% in the few shots available with similar parameters. The pedestal widths are nearly the same for ECH and NBI, but as expected for ECH the $T_e$ pedestal height is larger but the density is lower. Distinct differences are seen in the ELM behavior, with ECH more likely to have regular large Type I ELMs.

**Acknowledgments**

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