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High performance low and high q discharges in DIII–D

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Abstract. The High performance H-mode regime on DIII-D has been extended to both low q and high q (high β_p) and low *q* operation. In high current operation, VH-mode discharges were obtained for the first time with I_P(MA)/B_T(T) > 1. These discharges had $q_{95} = 3.4$, $H = 2.9$, $\beta_N = 3$, and $\beta_T\tau_E$= 3%-sec. $\beta_T\tau_E$ was improved by approximately 50% over previous results. These discharges were obtained with neutral beam injection during the plasma current ramp up which maintained the axial *q* above 1. In low current operation, neutral beam heated discharges with 100% of the plasma current from non-inductive sources were obtained at high *q*, $q_{95} = 15$, with $\beta_N = 3.9$, $H = 3.1$, and $\beta_p = 4.9$. These discharges represent an extension of the high performance regime to $q_{95} > 7.2$, which was made possible by reduction in the locked mode low density limit, as the result of improvements in the magnetic field error correcting coils. These low current discharges do not exhibit some of the standard signatures of VH-mode, but appear to represent a new regime of improved H-mode confinement. Similar, non-VH-mode, high energy confinement discharges were obtained at low density and moderate *q* .

Keywords. H–mode, VH–mode, low *q*, high β_p

1. Introduction

Historically on DIII-D the VH–mode high energy confinement regime [1] has been limited to moderate values of *q* , $4.5 < q_{95} < 7.2$, in full size double null divertor discharges ($1.3 < I_P$(MA) < 2.0 at B_T (T) = 2.1, $\kappa = 2$). On DIII–D, VH–mode is characterized by a second transition during the ELM free phase of an H-mode discharge [2]. At the VH–mode transition, density fluctuation bursts, MTEs, disappear, the ***ExB*** velocity shear penetrates radially inward from the plasma edge, and the thermal diffusivity is reduced in a region near $r/a = 0.7$. We refer to the transition as the VH–mode *spin-up* because of the associated rapid increase in the toroidal velocity. Until the observations presented in this paper, ELM free H–mode discharges without spin-up had been limited to normalized thermal energy confinement, $\tau_N = \tau_E^{TH}/\tau_{JET/DIII\text{-}D} < 1.5$ ($H = \tau_E/\tau_{ITER89P} < 2.3$), where $\tau_{JET/DIII\text{-}D}$ is the thermal energy confinement scaling for ELM free H–mode derived from

JET and DIII–D data [3], while for VH–mode, $\tau_N > 2$ ($H > 3$). The time between the L to H–mode transition and the spin-up increases strongly with q [2].

2. Low *q* VH–mode

Since VH-mode has not been obtained in H–mode with ELMs [2], the reduction in the time between the L–H transition and the spin-up with decreasing q favors obtaining VH–mode at low q. However, previous attempts at obtaining high plasma current VH–mode failed to achieve high energy confinement, $\tau_N < 1.5$ [4]. This degradation in confinement at low q was associated with an $n = 1$ mode, observed on magnetic probes at the vacuum vessel wall, with a frequency consistent with the toroidal rotation frequency of the plasma center, and growth time of about 1 msec. Following a few milliseconds of growth of this mode a small ELM like spike was observed on the D_α emission. After this event the energy confinement did not continue to increase, and in most cases decayed rapidly. This evidence suggested a connection between the low q confinement degradation and q on axis reaching 1. By using high power, 5 MW, neutral beam injection during the plasma current ramp up, we were able to slow the current penetration and thus maintain q_0 above 1 for a longer period of time. During the early beam injection, the plasma shape was adjusted slightly towards an upper single null divertor, which directed the grad-B drift away from the x–point and thus maintained the discharge in L–mode. In the plasma current flattop the discharge was returned to a symmetric double null and an L to H–mode transition occurred within 200 ms. This produced a discharge with $q_0 = 1.2$ at the L to H–mode transition. This discharge, with $q_{95} = 3.4$, $I_P = 2$ MA, $B_T = 1.7$ T, showed typical VH–mode behavior, reaching $\tau_N = 2.1$, $H = 2.9$, $\beta_N = 3$, and $\beta_T\tau_E = 3\%$-sec, in an 850 ms ELM free period (figure 1). This value of performance parameter $\beta_T\tau_E$ was a significant improvement over the previous best result on DIII–D of 2%-sec.

3. High performance non-inductive discharges

Since the ELM free period becomes shorter while the time between the L to H–mode transition and the VH-mode spin-up becomes longer as the plasma current is reduced, it has been difficult to obtain VH-mode in discharges with $q_{95} > 7.2$ ($I_p < 1.3$ MA, at $B_T = 2.1$ T, $\kappa = 2$, double null) because the time to spin-up becomes longer than the ELM free period. However it is also found that the time to spin-up is reduced as the plasma density is reduced. Recent improvements in the static error field correction [5] have allowed operation at lower density without locked modes on DIII–D. Discharges with $I_P = 0.6$ MA, at $B_T = 2.1$ T, $q_{95} = 15$, and 790 ms ELM free periods at an electron density of 1×10^{19} m^{-3} before neutral beam injection were obtained with this technique. These discharges did not show the characteristic VH–mode spin-up but achieved similar energy confinement performance, $\tau_N = 2.2$, $H = 3.1$, at high $\beta_p = 4.9$, and $\beta_N = 3.9$. Transport calculations for this discharge indicate that the sum of the bootstrap and neutral beam driven current is greater than the net plasma current. Moreover, by using the motional Stark effect measurements of the vertical field as a function of time [6], the loop voltage is calculated to be negative over the entire plasma cross section consistent with a fully non-inductive plasma current density profile. The unexpected result of VH–mode quality energy confinement without spin-up may be a property of the low density operation as discussed in the next section of this paper.

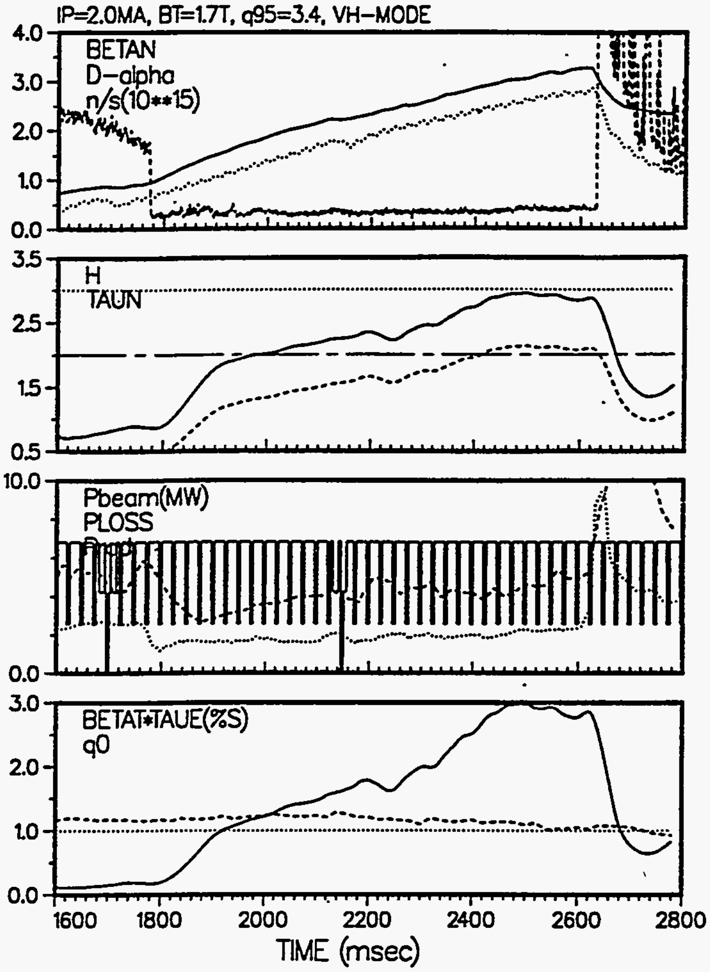

Figure 1. Time evolution of low q, $q_{95} = 3.4$, VH–mode discharge.

4. High performance low density discharges

In moderate q, $q_{95} = 5.5$, double null discharges at low density, the VH–mode spin-up no longer occurred, but the energy confinement time remained comparable to higher density VH–mode discharges. Figure 2 shows a comparison of the profiles for a higher density VH–mode discharge and a lower density high confinement ELM free H–mode at approximately 500 ms following the L to H–mode transition when both discharges have achieved $\tau_N = 2.1$. The good performance low density discharge has high central ion temperature with the ion temperature well separated from the electron temperature. The toroidal rotation profile of the low density discharges is typical of discharges without spin-up, with low ***ExB*** velocity shear in the region near $r/a = 0.7$. The low density discharge also has high effective thermal diffusivity $\chi_{EFF} = -q_e + q_i) / (n_e \nabla T_e + n_i \nabla T_i)$ in the region near $r/a = 0.7$ which is also typical of discharges which are not in VH–mode. There is some indication of reduced thermal diffusivity in the H–mode pedestal region in the low density discharge relative to the higher density VH–mode discharge, however convection is thought to play a role in this region as well. The low density and VH–mode discharges have comparable effective thermal diffusivities inside $r/a = 0.5$.

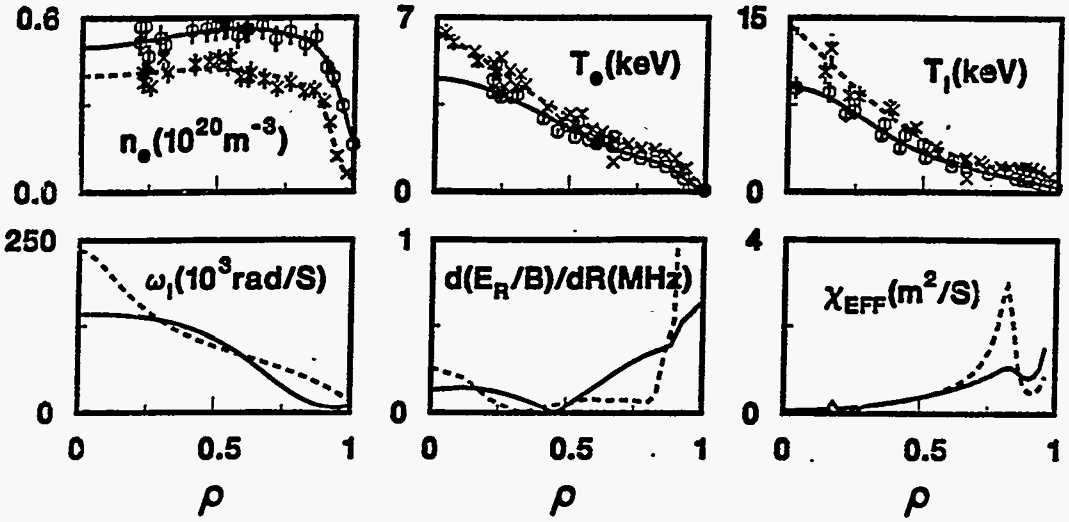

Figure 2. Profiles of high density VH–mode (solid) and low density high performance ELM free H–mode discharge (dash) at 500 ms following the L–H transition when both discharges have achieved $\tau_N = 2.1$.

5. Discssion and conclusions

The observation of VH mode in discharges with $q_{95} = 3.4$ demonstrates that very high energy confinement can be obtained at more reactor relevant high $I_P/B_T > 1$. The apparent importance of controlling the axial q value in obtaining good VH-mode at low q supports the importance of current profile control in advanced tokamak scenarios.

The observation of high performance discharges with non-inductive current density profiles demonstrates that these current profiles can be compatible with very high confinement regimes. The fact that these discharges are not VH–mode may be related to the low density at which they were obtained. These discharges are good targets for FWCD experiments due to their low total current, high temperature, and low density.

The origin of the confinement enhancement observed in the high performance non-VH–mode low density discharges remains unclear. There is some indication of reduced thermal diffusivity in the H–mode pedestal region but the good confinement might also result from the separation of the better confined ions from the electrons at lower density as in hot ion mode [7]. Before the improved error field correction, hot ion mode could only be achieved at low plasma current on DIII–D.

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