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VH-MODE DISCHARGES IN THE DIII-D TOKAMAK*

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Introduction. A regime of very high confinement (VH-mode) has been observed in divertor discharges in DIII-D.[1] The VH-mode, first seen following the initial boronization of the DIII-D vessel[2] in 1991, exhibits total energy confinement a factor of 2.5 to 3.5 greater than that predicted by the ITER89-P L-mode scaling relation.[3] Also, confinement of thermal energy alone is greater than 1.6 times that of the JET/DIII-D H-mode scaling[4] and in many cases has exceeded twice that amount.

VH-mode is observed during a long (≤0.8 sec) ELM-free phase of the discharges. At the beginning of the ELM-free period, the plasma appears to be in H-mode, with confinement near that predicted by the JET/DIII-D scaling. In the usual H-mode, confinement is observed to decrease or remain constant over time. In the present discharges, confinement has been observed to remain nearly constant for up to hundreds of milliseconds, after which the behavior sharply deviates from H-mode as the confinement begins to increase over time (Fig. 1). This increase in confinement continues until the occurrence of a beta-related ($\beta > 2.8\,I/aB$) global MHD event, which rapidly decreases the plasma stored energy with a temperature reduction across the entire profile. Magnetic measurements indicate that at least in some cases, this event includes both an internal $n = 1$ mode and a more localized $high - n$ mode near the edge. After this event, the plasma relaxes into an ELMing H-mode phase.

As a consequence of the boronization, the plasmas in these discharges are unusually clean, with very low radiated power ($P_{rad}/P_{aux} \leq 0.25$). In previous H-mode discharges, the radiated power increased during the ELM-free phase, sometimes reaching levels comparable with the input power if the ELM-free period was long enough. Also, Z_{eff} is constant or decreasing over the length of the discharge, with a central value of ≈1. It is noted that most of the energy in these discharges is thermal energy, with ≤10% contained in fast ions.

We have obtained VH-mode over a wide range of conditions on several different occasions. In all cases, boronization of the vessel was required. Most of the VH-mode discharges to date have been double-null divertor configurations, although we have also been able to achieve VH-mode in a single-null configuration with high triangularity (shape similar to double-null, but biased toward the lower null). VH-mode has been obtained at plasma currents of 1 to 2 MA, with toroidal fields of 1.6 to 2.1 T and moderate to high (4–16 MW) neutral beam power. Low ohmic target density ($\approx 3\times10^{19}\,m^{-3}$ with $I_P = 1.6$ MA) is found to be essential. Discharges with higher target densities result in the early onset of ELMs, which limit the time available for the development of VH-mode. Although the data set is insufficient to determine how confinement scales with plasma current, it is consistent with a linear scaling.

Internal Features of VH-mode. The high confinement of the VH-mode is seen to coincide with the broadening of the steep temperature-gradient region of both the ions and electrons in the outer portion of the plasma. The radial electric field shear region seen in H-mode broadens, corresponding to a decrease in turbulence. The current profile also shows a unique feature: modeling indicates that a region of high current density develops near the plasma edge, which is caused by a large bootstrap current. This is believed to be associated with the access of the outer portion of the plasma volume to the second regime of ballooning stability.

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The transition from the L–mode to H–mode in these discharges looks quite similar to that seen previously.[5–8] Within 100 μs of the transition, density fluctuations decrease inside the separatrix ($\rho > 0.9$); as shown by reflectometer and FIR scattering measurements; within 1 msec of the transition, a shear in the electric field develops in this region (both time scales above represent the temporal resolution of the measurement). Over the next few tens of milliseconds, the FIR scattering shows a decrease of about a factor of 2 in the amplitude of the density fluctuations in the bulk of the plasma around $\rho = 0.8$, similar to that seen previously.[7]

When the VH–mode develops out of the H–mode in the present discharges, the electric field shear region is seen to broaden and move deeper into the plasma (Fig. 2). Although the data are incomplete, indications are that the density fluctuations in the region $0.7 < \rho < 0.9$ decrease further by a factor of about 2.

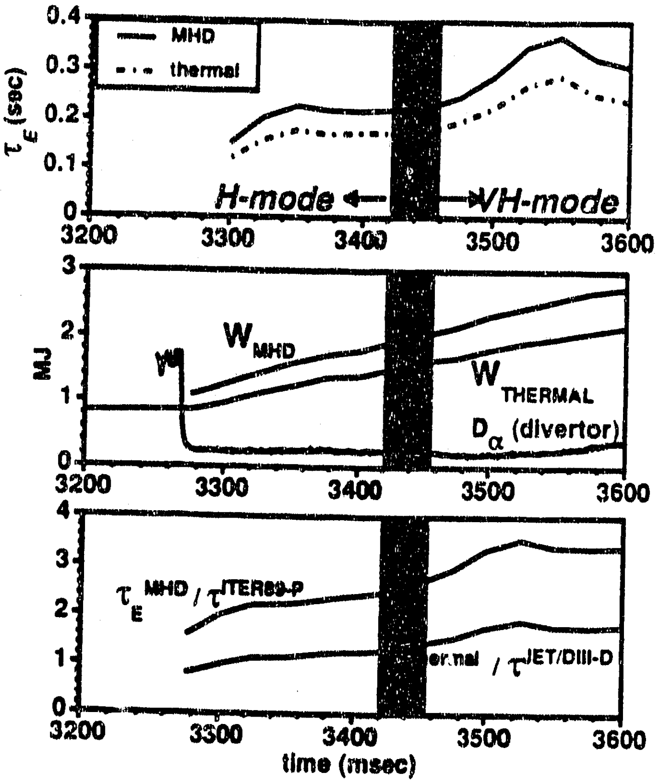

FIG. 1. Time traces of a double-null divertor discharge which evolves from H– to VH–mode. Shaded region denotes transition from H– to VH–mode. Shot 72220, I_p = 1.6 MA, B_T = 2.1 T, P_{NBI} = 12.5 MW.

Examination of ion (from CER) and electron (from Thomson scattering) temperature profiles during the ELM-free phase (Fig. 3) shows that the steep gradient regions seen near the edge in H–mode continue to extend deeper into the plasma during the transition to VH–mode. Whether this effect is strongest for the ions or electrons varies somewhat from shot-to-shot. The density profiles (Fig. 3) develop in a way that is roughly consistent with "normal" H–mode, with the usual increase of density over time.

Time-dependent transport analysis using the ONETWO[9] code shows that the single-fluid diffusivity χ_{eff} during the early (H–mode) phase of the ELM-free period is approximately the values previously obtained for H–mode discharges with similar parameters. At the time of the sudden increase in confinement, however, χ_{eff} decreases sharply, by as much as a factor of 2 to 4 (Fig. 3), most notably in the region $0.5 \leq \rho < 0.9$ with little change in convection or other power balance terms. Note that the region of largest decrease in χ_{eff} corresponds to the region of increased electric field shear. Accordingly, one possible explanation for the VH–mode confinement improvement is electric field shear stabilization of turbulence. The VH–mode bulk confinement improvement would then be a further extension of the bulk confinement improvement seen in H–mode.[8,10]

Bootstrap Current and Implications. As previously mentioned, after boronization, we find that DIII–D discharges have low radiated power, low neutral density and low recycling. These conditions lead to rather low $n_e(a)$ and high $T_e(a)$, and therefore low collisionality ($v^* \approx 0.6$ at $\rho = 0.9$). This combined with the high pressure gradient seen in H–mode make the conditions ideal for production of a large bootstrap current near the edge.

Modeling with the ONETWO code reproduces this high edge bootstrap current (Fig. 4). The resulting current profile shape is consistent with the results of modeling the equilibrium with the EFITD[11] code. Although it is possible to generate an equilibrium from the magnetics data which does not contain the bump in the current profile, the best fit (lowest χ^2) is obtained when this feature is included.

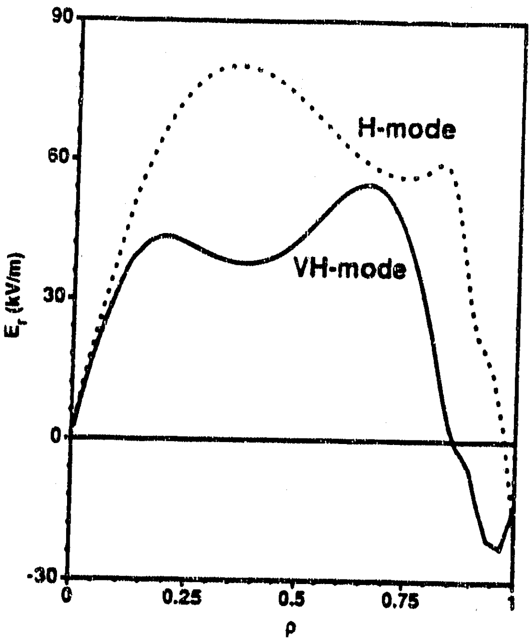

FIG. 2. The radial electric field shear region is both broadened and pushed deeper into the plasma during VH–mode. Shot 73290, I_p = 1.6 MA, B_T = 2.1 T, P_{NBI} = 10.6 MW.

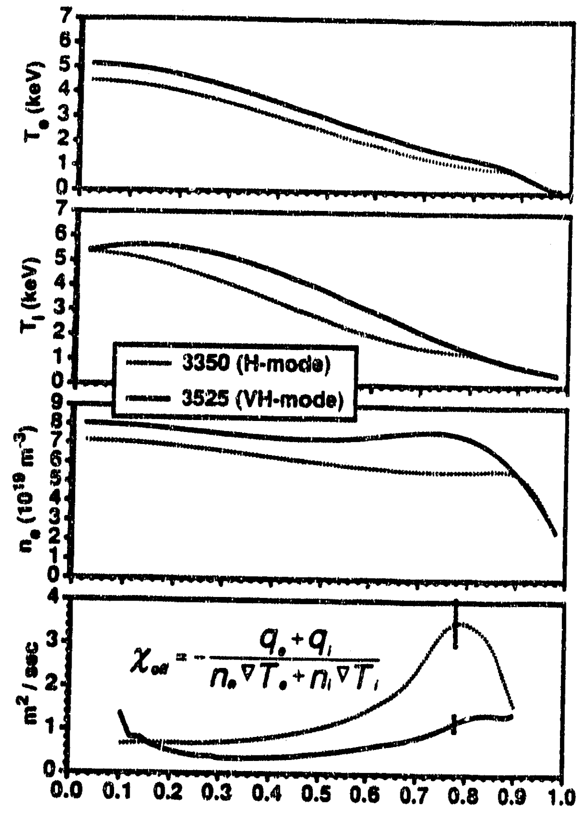

FIG. 3. The profiles of the VH–mode contain steep gradient regions which are extended further inward than those in H–mode. Transport analysis shows that this corresponds to a decrease in the single-fluid diffusivity, most notably in the outer half of the plasma. Shot 72220, I_p = 1.6 MA, B_T = 2.1 T, P_{NBI} = 12.5 MW.

This large edge current produces low shear, which in this high triangularity plasma configuration, is associated with possible access to the second regime of stability to ballooning modes.[12] In the VH–mode discharges studied, it appears that access to second stability may be correlated with the improvement in confinement.

In Fig. 4, we see that the confinement begins to improve after the bootstrap current has begun to increase. The MBC code[13] predicts that when the bootstrap current at $\rho = 0.85$ reaches 50 A/cm^2, 30% of the plasma volume will have entered the second stable regime to ideal ballooning modes. Note that this calculation requires the edge current density to be known with greater accuracy than is available, so this result is qualitative. However, for any reasonable value of edge current density, the MBC code prediction is similar. With the assumption of zero current density at the plasma edge, the (first) marginal stability pressure gradient is below the measured pressure gradient.

Conclusions. We have observed a regime of very high confinement (VH–mode) in the boronized DIII–D tokamak, during which the confinement has been observed to exceed 3.5 times that of the ITER89-P L–mode scaling relation. In this ELM-free phase, confinement is seen to increase with time, and is terminated by a global MHD event which is associated with high β. Low radiated power, Z_{eff}, and a low fast-ion fraction are also characteristics of the VH–mode.

In the VH–mode, we observe that the steep gradient regions of the temperature profiles are extended inwards more deeply than previously seen in H–mode. This high-gradient region is also seen to correspond to an extended radial electric field shear layer, and a decrease in density fluctuations of perhaps a factor of two below H–mode. Transport calculations in this region show a sharp decrease in the single-fluid heat diffusivity.

Another remarkable feature of these plasmas is the existence of a region near the plasma boundary with high bootstrap current, which modeling predicts to correspond with a significant fraction of the plasma volume accessing the second regime of ballooning stability.

Although a causal relationship has not been established between these characteristics, it is believed that both the electric field shear stabilization of turbulence and the second stability access play important parts in the observed confinement improvement. Further experimentation and analysis is expected to shed some light on these issues.

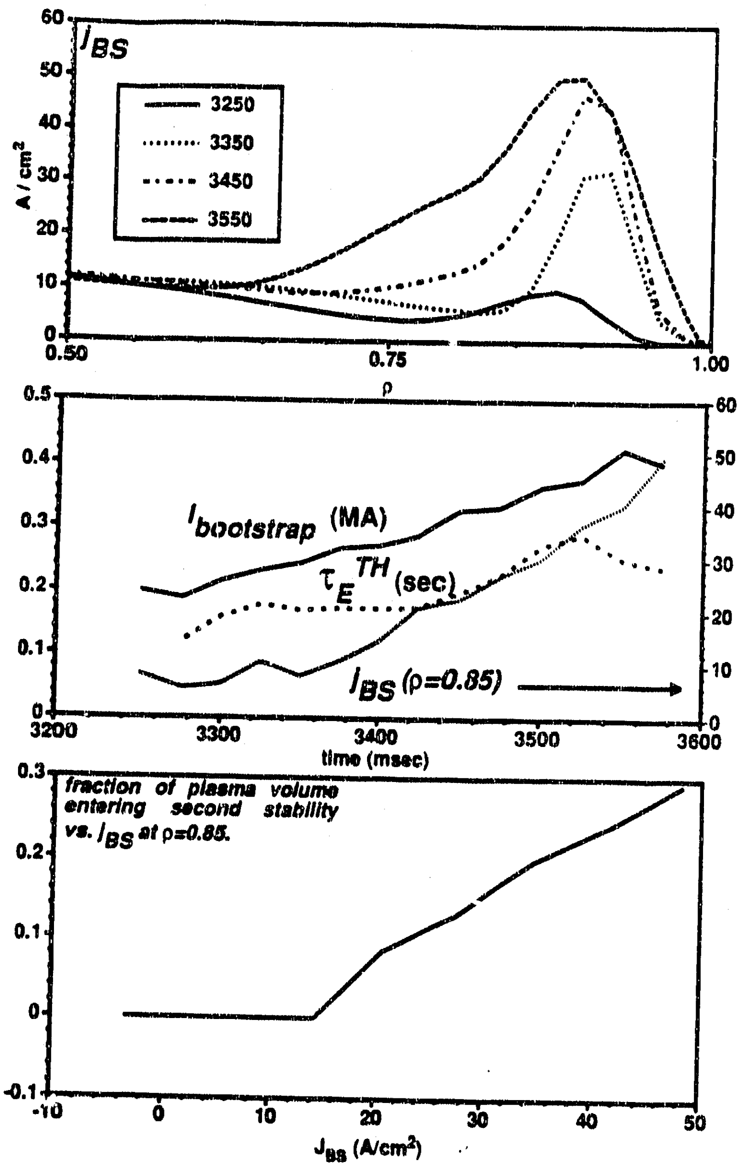

FIG. 4. As the plasma evolves from H– to VH–mode, the calculated bootstrap current increases near the edge. Modeling using the MBC code predicts that a large portion of the plasma volume is entering the second stability regime. Shot 72220, $I_p = 1.6$ MA, $B_T = 2.1$ T, $P_{NBI} = 12.5$ MW.

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