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Designing a VH–mode core/L–mode edge discharge

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Abstract. An operating mode with a very high confinement core like the VH–mode but a very low power flow to the divertor plates and low edge particle confinement like an L–mode would be beneficial. For a large tokamak like the proposed ITER, the power density at the separatrix is not that far above the scaled H–mode power threshold so not much of the power can be radiated inside of the separatrix without causing a return to L–mode. The thicker scrape-off layer of an L–mode increases the radiating volume of the scrape-off layer and helps shield impurities from the core. This is especially important if the first wall is metallic. In this paper an H–mode transport model based on ***ExB*** velocity shear suppression of turbulence will be used to show that it is possible to have a strongly radiating mantle near the separatrix, which keeps the edge in L–mode, while having a VH–mode core with a broad region of suppressed turbulence. The existing results of enhanced L–mode confinement during impurity injection on a number of tokamaks will be surveyed. The operating conditions which will most likely result in the further improvement of the core confinement by control of the heating, fueling, and torque profiles will be identified.

Keywords. Tokamak, VH–mode, plasma confinement

1. Introduction

The design of tokamaks capable of sustained thermonuclear burn, such as ITER, has identified the need to spread out the heat load on the first wall. Most of the thermal power must be dissipated by radiation prior to reaching the divertor target plates. The method used to reduce the divertor heat load must be compatible with a high core confinement regime. It is well known that too much core radiation or gas puffing can cause a loss of the H–mode regime. However, the loss of the edge transport barrier characteristic of H–modes does not always cause a return to the standard L–mode confinement. The energy confinement in high power discharges with high impurity radiation fractions can be as good or better than during an H–mode. The first reported occurrence of enhanced confinement due to impurity injection was the Z–mode of ISX-B [1]. Another limiter tokamak TEXTOR has also seen improved confinement during impurity injection which they named the I–mode [2]. The diverted tokamak JFT–2M reported on the evolution of a core enhanced confinement mode, the IL–mode, after the radiative collapse of an H–mode [3]. The energy confinement of the IL–mode was sometimes even higher than during the preceding H–mode. There are many similarities between these modes. They all have very peaked density and temperature profiles, high radiated power fractions, were free of sawteeth even though the edge safety factor was about three, and had apparently hollow impurity density profiles. The energy confinement improvement factor (H–factor) over ITER-89P [4] L–mode scaling was about two in these tokamaks. Smaller H–factors of 1.5 to 1.8 have been seen on ASDEX [5] and DIII–D in high power neon induced divertor L–modes. The neon density profile in the

DIII–D discharges was measured with charge exchange recombination and found to be peaked like the electron density profile [6] however this discharge was sawtoothing.

The improved confinement in these discharges may be due to the same mechanism which improves the core transport in VH–mode: the suppression of turbulence by the shear in the ***ExB*** rotation. Calculations with a transport model including the ***ExB*** suppression effect [7] presented below show that if the heating profile is sufficiently centrally peaked, and if there is strong edge radiation, then there can be a mode of operation with a VH–mode core and an L–mode edge. This theoretical regime has similar properties to the observed enhanced confinement modes discussed above.

2. Simulation of a VH–mode core / L–mode edge discharge

The details of the theoretical model and its application to H–mode and VH–mode can be found in Ref. 7. For the present study all that is necessary is to know that the self-consistent electric field in the plasma is computed from the radial force balance equation for the primary ions

$$E_r = U_{i\varphi}B_\theta - U_{i\theta}B_\varphi + \frac{1}{Z_i e n_i}\frac{dP_i}{dr} \quad . \tag{1}$$

The time dependent equations for the energy, particle and toroidal momentum balance are solved in a flux-surface averaged geometry. The key feature of the equations is that the fluxes of energy, particles, and toroidal momentum are taken to have a turbulence induced component which is reduced by the factor

$$A(S_\perp) = \frac{1}{1 + S_\perp^2} \quad , \tag{2}$$

where $S_\perp$ is the toroidal generalization of the shear in the ***ExB*** velocity [8]

$$S_\perp \equiv \frac{RB_\theta}{B}\frac{\partial}{\partial r}\left(\frac{E_r}{RB_\theta}\right)\Big/ S_{crit} \quad . \tag{3}$$

Here S_{crit} is the critical value of the shear needed to suppress the turbulence. The ***ExB*** velocity shear reduction can cause a bifurcation into an improved transport mode. The location and width of the transport barrier is determined by the heating, fueling and momentum source profiles [7]. Usually the transport barrier will form at the separatrix first and will be limited to a narrow width as is typical of H–mode. At high power the transport barrier can grow into the core signaling the VH–mode phase. If the heating source is above the VH–mode level, but there is strong edge radiation, a mode with an L–mode edge and a VH–mode core can form as shown in figure 1. Notice that the transport suppression factor $A(S_\perp)$ in figure 1(d) is very small from r/a ~ 0.3 to 0.6. In this region only the background transport (representing neoclassical) is left. The gradients of all of the plasma profiles are much steeper in this interior transport barrier. The transport would be reduced at the edge if it were not that nearly all of the power is radiated away from r/a = 0.8 to 1.0 in this case. The poloidal rotation of the main ions and the second derivative of the ion pressure are neglected in calculating $S_\perp$ for this simulation.

The requirement for a transport barrier to form is basically that the local ***ExB*** shear exceed a threshold. If the heating source is concentrated in the center of the plasma a transport barrier will form in the center at a lower total heating power than if the source deposition is broader. The fraction of the core volume covered by the improved transport zone increases with increasing power so the global H-factor is predicted to increase with power. The effect of toroidal rotation is complex. Momentum injected in the direction of the plasma current tends to increase the ***ExB*** shear and increase the width of the improvement

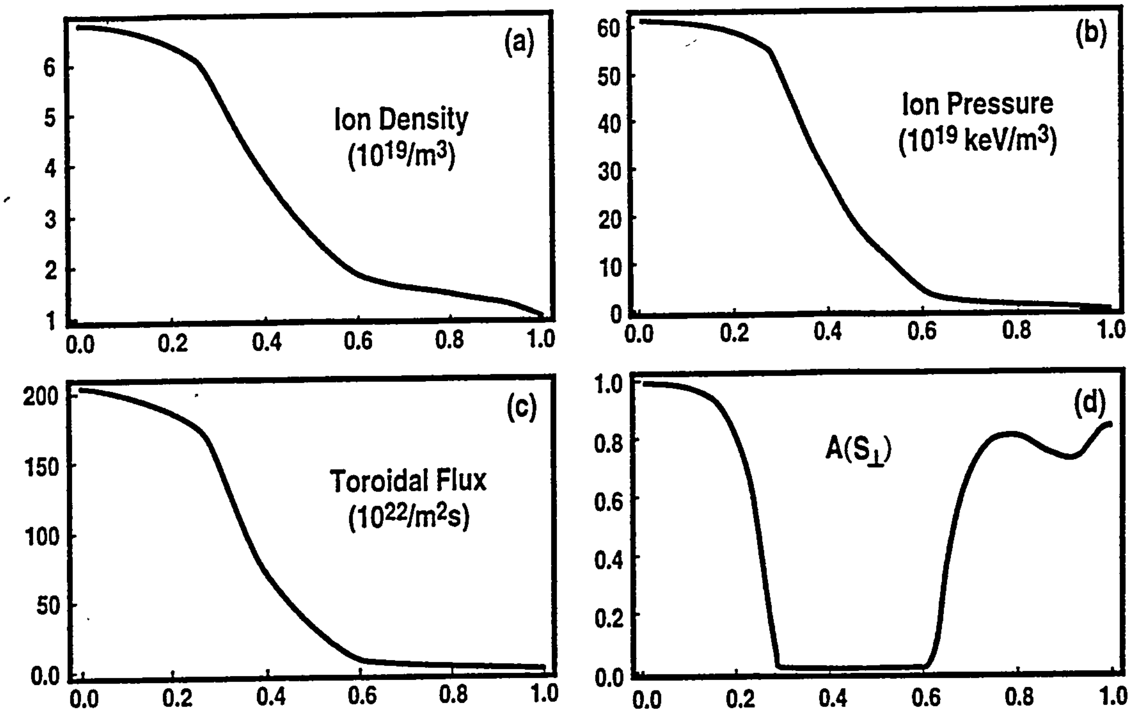

Figure 1. A simulated V H–mode core / L –mode edge discharge showing the radial profiles of (a) ion density, (b) ion pressure, (c) toroidal flux, and (d) the electric field shear suppression factor of Eq. (2).

zone. Momentum injected counter to the current tends to increase the total power required but can result in an interior transport barrier with the opposite sign for ***ExB*** shear than for co-injection. Balanced injection can still result in a core transport barrier due to the diamagnetic term in the ***ExB*** shear. This enhanced confinement mode scales well with the size of the plasma. Since the radiation zone for a given impurity species has a width determined by the temperature profile the width can be taken to be invariant. For a constant radiation zone width the fraction of the volume of the plasma inside of the radiation zone increases linearly with minor radius. The maximum H–factor achievable is when all of the core except the edge radiation zone is improved. Thus the maximum H–factor theoretically increases with minor radius. In order to be able to produce this regime the plasma has to be free of large MHD instabilities. The shape of the pressure profile in figure 1(b) is better matched to shape of the ideal ballooning mode stability threshold than is a typical H–mode, which has a high edge pressure gradient. The sawteeth have been observed to be converted to a continuous 1/1 mode which does less damage to the transport in the Z–mode plasmas [1]. Another way to suppress sawteeth would be to reverse the central shear with non-inductive current profile control. This may occur naturally due to the large bootstrap current expected from the strongly peaked pressure profile of figure 1(b).

Accessibility of this regime is another issue of concern. The VH–mode on DIII–D is typically terminated by a low mode number MHD instability [9]. After the initial VH–mode termination event the discharge settles into an ELMing H–mode. Neon injection into ELMing H–modes has been demonstrated (DIII–D, ASDEX–U) to be able to induce an H to L transition without disruption. At sufficiently high power the core transport barrier of the VH–mode should be re-established after the H/L transition of the edge layer. Another path would be to prevent the edge transport barrier from ever forming by injecting neon at the same time as the high power. Time dependent simulations with our transport code show that for strong central heating a transport barrier can form in the core first but is lost once the edge transport barrier forms, similar to the JT–60U high β_p discharges [10]. Suppressing the edge transport barrier with impurity radiation before it forms could result in a different final state than the H/L transition route.

The hollow impurity density profiles inferred for the Z–mode and other sawtooth-free modes is a very important property for this mode to be of practical value to a reactor. Since the turbulent transport in the center is suppressed, the neoclassical transport can be dominant for the ions. The ion temperature gradient can drive an outward impurity flux in the banana regime [11] which is a good candidate for explaining the observed hollow impurity profiles. The enhanced peaking of the fuel ion density due to this effect would help to increase the diamagnetic velocity contribution to the ***ExB*** shear.

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