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Introduction

Significant improvements in both normalized and absolute performance have been obtained in the DIII–D and JET tokamaks by optimizing the current and pressure profiles. These discharges produced the highest neutron rates in single-null plasmas in both machines (1.4 1016/s for DIII–D, 5.6 1016/s for JET). In DIII–D, β_N $[\beta / (I/aB)]$ and H ($\tau_E/\tau_{ITER89P}$) have reached 4 simultaneously. In JET, confinement improves significantly (H up to 2.5 in L mode, up to 3 in H mode); however, MHD stability limits β to $\beta_N \leq 1.8$.

In both machines, a region of good confinement forms in the center of the discharges and moves radially outward with time at constant auxiliary power. The clearest signature of this region of good confinement is the large gradient in the ion temperature and rotation profiles. The steep gradient regions imply low transport; hence, the transition region to normal gradients is called a core transport barrier. The confinement improvement can also be seen in the electron density and, to a lesser extent, the electron temperature, but not necessarily over the same radial region. This behavior occurs while the edge parameters are typical of L mode and can persist in combination with the edge transport barrier characteristic of the H mode.

MHD Stability and Performance Limitations

The performance of both DIII–D and JET is limited by MHD stability; the maximum achieved β_N decreases with pressure peaking as seen in MHD stability calculations [1,2]. Figure 1 shows time histories of the β_N and pressure peaking for typical high performance discharges of both machines. As the transport barrier moves out with time, the pressure peaking lessens and the β_N rises. Without the reduction in pressure peaking, both machines find a disruptive limit in discharges with an L–mode edge [2,3]. The disruption on both machines typically is preceded by a rapidly growing $n = 1$ mode. In DIII–D, further optimization involves initiating an H–mode transition at the proper time to avoid the disruption [4]. The subsequent edge density rise lowers the pressure peaking and allows higher β_N. The performance is limited by a variety of instabilities [3], but most commonly the limiting mode is a global mode similar to the ‘‘X event’’ which limits VH–modes on DIII–D and hot-ion

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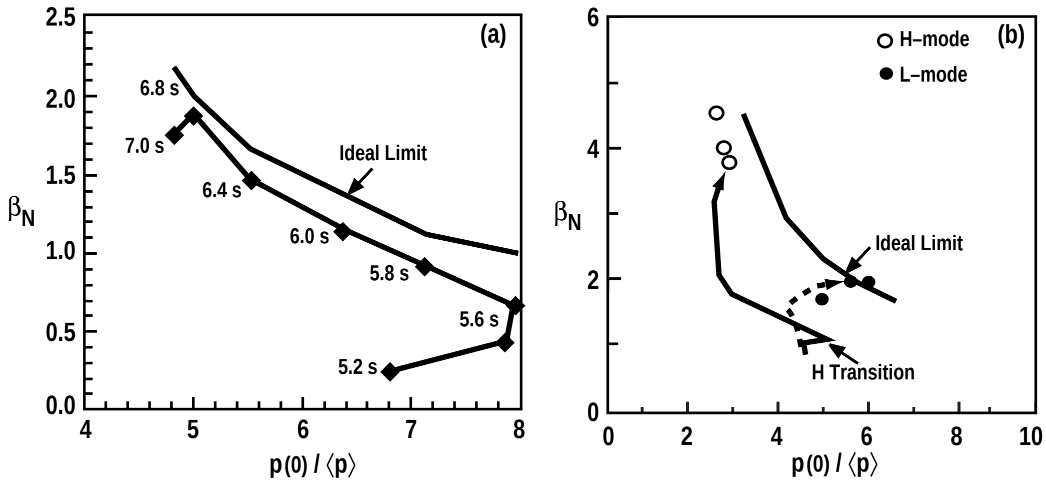

Fig. 1. Calculated β_N limit and measured β_N versus pressure peaking factor for (a) JET pulse 40847 and (b) DIII–D pulses 84736 (H mode) and 87009 (L mode). The DIII–D plot shows maximum performance times for other pulses.

modes on JET. However, $\beta_N > 4$ has been achieved. The optimization on JET has focused on real-time control of the auxiliary power to keep the plasma below the β limit with an L–mode edge. As the barrier expands, the pressure peaking drops and more power can be applied. The performance in JET with H–mode edge has not followed the favorable pattern in DIII–D. The fusion rate shows little or no improvement in JET following the H–mode transition. However, the majority of cases have an H–mode transition following an MHD event which strongly affects the rate of rise of the fusion rate. In both machines, the good core confinement reduces the loss power to the edge below the H–mode power threshold. In JET, a current ramp also raises the threshold. Thus, the discharges can stay in L mode despite a large input power. In JET, the MHD instability causes the barrier to be ‘‘leaky,’’ raising the power flow to the edge above the H–mode threshold.

The core barrier in JET has not been observed to move past the $q = 2$ surface, and the contraction of the barrier coincides with a ‘‘soft’’ MHD instability. It is possible that the lower power density in JET provides insufficient drive for the barrier to pass the low order rational surfaces, while the higher power density on DIII–D allows the barrier to move past these rational surfaces to merge with the edge barrier. Experiments in DIII–D to optimize discharges in the same manner as JET are underway. The halt of the barrier expansion in JET could also be a result of differences in current profile. The inferred q profiles are quite different on DIII–D and JET. Figure 2 shows the q profiles from EFIT magnetic equilibrium reconstructions for both machines. For JET, magnetic and kinetic data are inputs to EFIT, and the mapping of ECE from both sides of the magnetic axis to magnetic coordinates is used to determine the radial position of the magnetic axis. The axis position determines $q(0)$ in this analysis. The time of the appearance of $q = 1.5$ outside the barrier in the reconstructed q profiles is coincident with a burst of MHD which limits the fusion performance. The appearance of a low-order rational surface with little magnetic or rotation shear to limit the mode width could be the cause of the barrier contraction and the H mode. This q profile evolution could also explain the observation that the H–mode transition occurs at roughly the same time

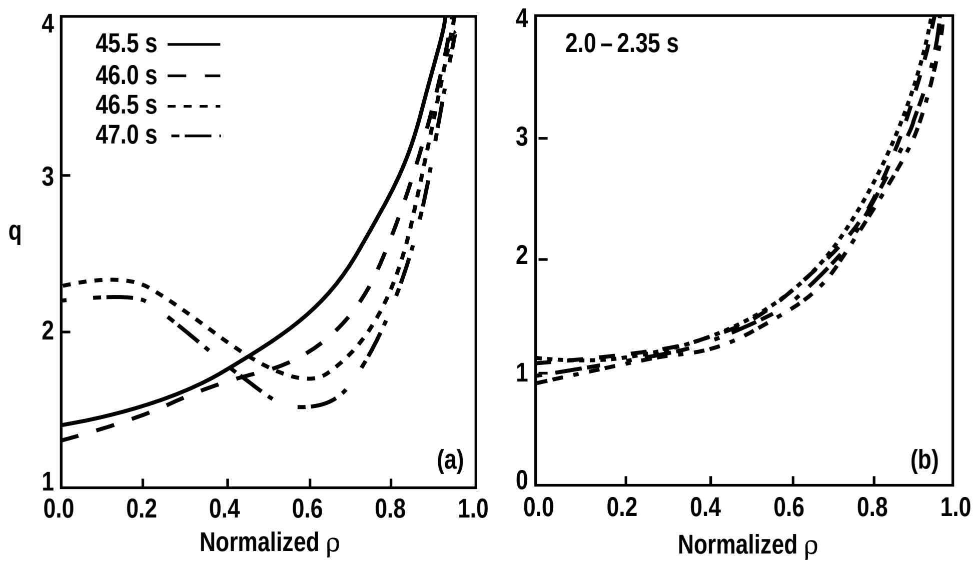

Fig. 2. Time evolution of q profiles for (a) JET pulse 40554 and (b) DIII–D pulse 88964.

independent of the discharge history. The timing of the appearance of $q = 1.5$ is controlled by the current ramp and electron temperature outside the barrier which are not closely correlated to the transport behavior inside the barrier. There are still significant questions about the q profiles shown on Fig. 2(a), especially whether the time evolution is consistent with the neoclassical Ohm's law. Calculations to check this are underway. For DIII–D, the magnetic, kinetic, and E_r-corrected MSE data are used in the EFIT reconstruction [5,6]. The profile is monotonic with $q(0) \simeq 1$ for the entire high performance phase. Bursting $m = 1/n = 1$ MHD activity is observed throughout, but there is no evidence of sawteeth. [Earlier reconstructions with magnetics only and reconstructions with uncorrected MSE data showed significantly higher $q(0)$ during the high performance phase.] The higher magnetic shear may lessen the effects of the barrier moving through such low-order rational surfaces.

Confinement

Both machines show reduction in the ion heat conduction to or below the neoclassical level inside the transport barrier. In the case of DIII–D plasmas with an H–mode edge, the good confinement region extends to the edge of the plasma and the time behavior is consistent with no conducted power in the ion channel. In JET plasmas with an L–mode edge, ion conduction is near neoclassical levels in the core and dominates the power balance outside the transport barrier [7]. The leading hypothesis to explain this behavior is that sheared $E \times B$ flows stabilize the long wavelength turbulence, leaving only neoclassical effects. Figure 3 shows a comparison of $\gamma_{E\times B}$, the measured $E \times B$ shear, with γ_{max} the maximum linear growth rate [8]. The DIII–D case shows that $E \times B$ shear exceeds γ_{max} at all radii at a time when the transport is consistent with no ion conduction across the entire plasma. The JET case, on the other hand, shows γ_{max} exceeds $\gamma_{E\times B}$ by a factor of 2 or more at a time when the good confinement region extends to $\rho = 0.5$. This result should be interpreted cautiously because the uncertainty in the q profile could significantly change γ_{max} and the $E \times B$ shear calculation assumes neoclassical poloidal rotation

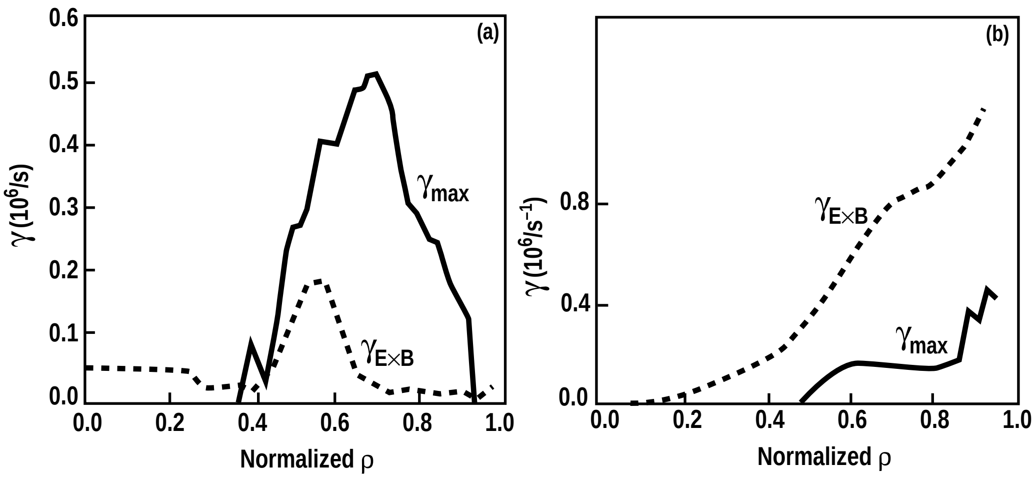

Fig. 3. Comparison of the $E \times B$ shearing rate with the maximum linear growth rate for (a) JET pulse 40554 and (b) DIII–D pulse 88964 at times near the peak performance.

in the absence of measurements. Neoclassical poloidal rotation does not model the DIII–D rotation measurements well [9]; therefore, the $E \times B$ shear may be significantly different. However, analysis of earlier times on the JET discharge show $\gamma_{max} > \gamma_{E \times B}$ by a factor of 5. Further quantitative work is necessary to draw conclusions about the consistency of the $E \times B$ stabilization hypothesis with JET data.

Conclusions

The basic phenomenology of discharges with core transport barriers is the same for DIII–D and JET. The limitations on performance in both cases are well described by MHD stability calculations. Since the discharge behavior of the two machines is so similar, it seems reasonable to apply a simple parameterization of fusion performance [10] which describes well the best performance discharges on DIII–D. The highest fusion performance shot on JET has $Q_{DD} = 3.1\ 10^{-3}$ at 3.2 MA. Scaling from the highest Q_{DD} DIII–D single-null discharge would predict $Q_{DD} = 4.2\ 10^{-3}$ for JET. Raising the plasma current to 4.0 MA would increase the projection to 6.6 10^{-3}. Realization of such performance would require significant effort to develop lower q plasmas with an H–mode edge. Because the performance is so closely tied to the current profile, this class of discharges also shows significant potential for steady state if current profile control can be demonstrated.

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