Beta Limits in H-Modes and VH-Modes in JET

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Abstract. In Hot-ion H- and VH-modes, the highest achieved beta was about 10% below the Troyon value in the best case of discharge 26087. The operational space of the high beta discharges obtained before March 1992 has been explored as function of the parameters $H_{ITER89P}$, β_n, q_{95}, I_p . Also, a limiting envelope on the fusion reactivity as a function of the average plasma pressure and beta has been observed with $R_{DD} \propto \beta_{\varphi}{}^2.B_{\varphi}{}^4$. MHD stability analysis shows that the JET VH modes at the edge are in the 2-nd region for ballooning mode stability. The dependence of ballooning stability and the n=1 external kink on the edge current density is analysed.

Confinement and Beta value. The quality of the confinement as measured by the H-multiplier of the measured diamagnetic energy confinement time against the ITER-89P scaling has been correlated to the normalised toroidal beta $\beta_n=\beta_\varphi/(I_p(MA)/a(m)B_\varphi(T))$. It should be noted that the β values are typically 10% lower for the discharges analysed by TRANSP (based on the kinetic plasma pressure) than those used in this paper, which are obtained by equilibrium code calculations based on magnetic measurements. The ratio of H/q [Perkins], shown in fig. 1, is not very sensitive on the beta value, demonstrating that there is no gradual

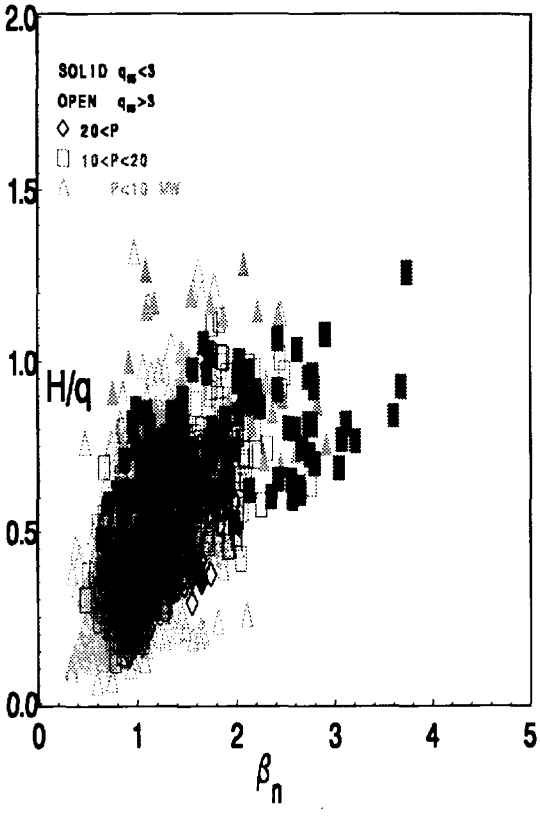

Fig. 1 H/q versus β_n for :P<10, 10<P<20, and P> 20 MW.

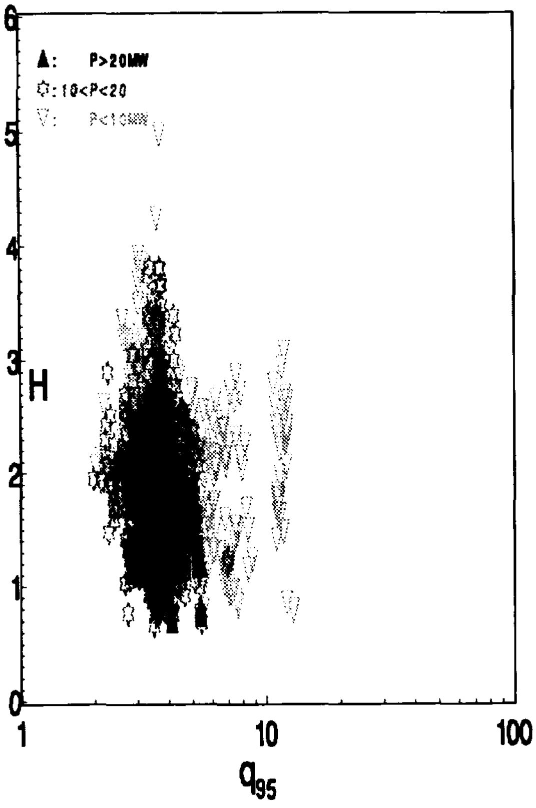

Fig. 2 The H-mode multiplier versus q_{95} on logarithmic scales for P.

deterioration of the confinement with beta. The ratio does not dependent on q_{95} or on the heating scheme applied (NBI, ICRH or combined heating).

Confinement and edge safety value q. At low values of q_{95} the confinement multiplier H however is deteriorating rapidly (fig.2) with H/q remaining roughly constant, similar to what has been observed by DIII-D [Lazarus]. The best values of H of ≈ 4.5 have been obtained at $q_{95} \approx 4$, at low $q_{95} > 2$ the H-multiplier found is again close to 2 and at high q the best values are again close to 2. There appears also a power dependence: the highest H values have been obtained at powers less than 10 MW. At power levels up to 20 MW very similar values have been reached, however with powers between 20 and 30 MW the best H-multiplier values are $\approx$ 2.2. The vast majority (75%) of these discharges are however limiter plasmas with only a small number of shots in an X-point configuration.

Fusion performance relation to beta values. The best fusion performance as measured by the DD-reaction rate has been obtained in high pressure or high beta discharges. This can been seen in fig. 3, which shows the square root of the DD-reaction rate R_{DD} ($2*R_n$, the DD neutron rate) as a function of the average measured plasma pressure from the equilibrium code calculations. The best performance can be described by the scaling:

$R_{DD}(10^{16}s^{-1}) \approx (1/60).\beta_\varphi^2.B_\varphi^4$. In the ion temperature range at JET the thermal DD-fusion rate is roughly proportional to $n_i^2T_i^2$ and the (temperature dependent) beam-thermal reactivity is comparable to the thermal fusion rate.

Performance Limitation. The duration of the good confinement period of a discharge in JET has been measured with the diamagnetic loops and can be expressed by a quantity $\Delta t(80\%)$, which is the time span the plasma energy is over 80% of its peak value. Fig. 4 gives $\Delta t(80\%)$

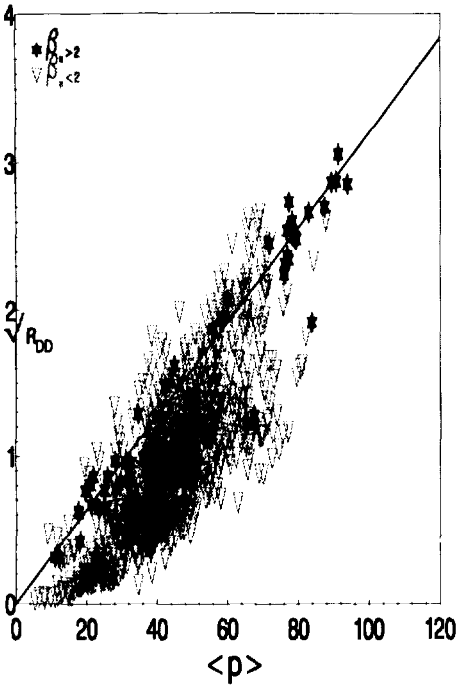

Fig. 3 $\sqrt{R_{DD}}$ $(10^{16}s^{-1})$ versus <p> for D plasmas with ICRH and D- NBI for $\beta_n >$ 1.

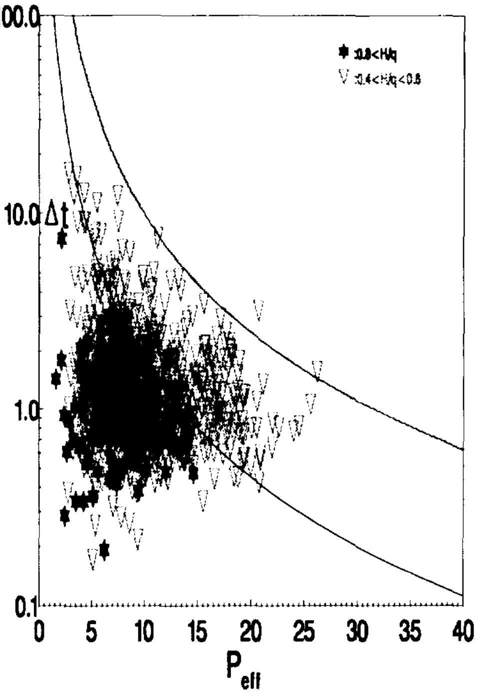

Fig. 4 $\Delta t(80\%)$ versus P_{eff}. The top curve corresponds to target plates T of 2500 °C . The lower curve, an upper bound for high confinement shots, corresponds to a T of 1100 °C.

as a function of $P_{eff}=P_{in}-dW/dt$. The limiting curve is given by $\Delta t(s) = 1000/P(MW)^2$, corresponding to a temperature of the target tile area of around ≈2500 °C [Wesson], [Jäckel]. It can be seen from the figure that the high performance discharges with $H(ITER89P)/q_{95}>0.8$ have much reduced performance duration. The reduction of the period of good confinement is related to the X-event, which in a very short time increases the effective power loss from the plasma to the target plates [Jaeckel].

MHD Stability of VH mode discharges. No global MHD stability limit (for ballooning and external kink modes) is reached in VH mode discharges. The β obtained in the VH modes, where β_N~2.6, is well below the theoretical global limit set by ballooning modes (at β_N~3.5). Local instabilities near the edge of the plasma driven by the large pressure gradient and the associated bootstrap current could however end the VH mode confinement. In this section we discuss the stability of ballooning modes, the second stability region and the stability of the external n=1 kink mode. The internal kink is discussed by [Alper].

For three different JET plasma shapes the access to second stability is calculated as a function of the edge current density; the shapes are that of the JET high performance discharge 26087

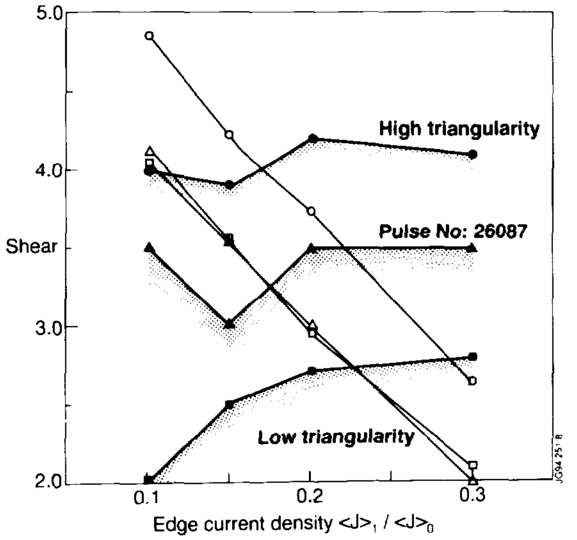

Fig. 5 The bold curves show the maximum shear below which the plasma is in the 2nd stability region (at ψ=0.95). The thin lines with the corresponding markers show the shear of the equilibria as a function of the edge current density (normalised to the central current density).

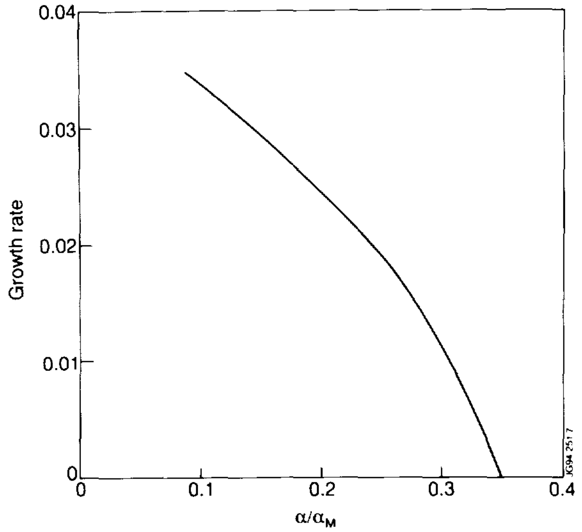

Fig. 6 The growth rate of the external kink as a function of the edge pressure gradient The pressure gradient is normalised to the pressure gradient α_M which is marginally stable to ballooning modes (at the first stability limit with zero edge current density).

δ=0.33), and for two other single X-point plasma configurations one with a small (δ=0.13) and one with a large triangularity (δ=0.42). The relevant plasma parameters match the values of the JET high performance discharge 26087. Fig.5 shows the result for the three cases. The relative edge current density $<J>_1/<J>_0$ needed to get into second stability is about 0.17 for the old JET shape (nearly up/down symmetric) and high triangularity case. For the low triangularity in the new JET configuration a slightly higher relative edge current of 0.23 is required.
The stability of the external n=1 kink mode for these equilibria is calculated using the CASTOR code [Kerner]. The stability of the external n=1 kink mode is found to depend strongly on the edge pressure gradient. The growth rate of the n=1 kink mode as a function of the edge pressure gradient is shown in fig.6. The n=1 kink mode is stable for pressure gradients larger than 0.35 of the ballooning limit, the experimental value of α/α_M is typically around 1. Thus, the region of second stability can be reached without the n=1 kink mode becoming unstable but it does need the stabilising effect of the edge pressure gradient. This stabilising effect is due to the favourable average curvature in toroidal geometry.

Conclusions. High confinement regimes have been obtained at a variety of q values at various β_n. Confinement enhancement over ITER89-P seems to degrade with decreasing q while H/q remains roughly constant, an optimum is obtained at q values around 3.5 with an H factor of $\approx$ 4.5. The fusion performance is roughly proportional to the plasma average pressure squared. This relationship favours for a given beta limit high toroidal field operation to getting high fusion performance. The good performance duration in the best cases, for moderate H/q values, seems to be set by simple tile heating to temperatures around 2500 °C, in the high performance this limitation is provoked earlier by the vast power load of the X-events. The MHD stability study of the high performance VH-modes has shown that the combination of high enough pressure gradient and current density at the plasma edge allows this region to become in the 2-nd stable ballooning region and be stable to the n=1 external kink.

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