JET-P(95)06

MHD Stability of Advanced Tokamak Scenarios

H A Holties[1], G T A Huysmans, J P Goedbloed[1],
W O K Kerner, V V Parail, F X Söldner.

JET Joint Undertaking, Abingdon, Oxfordshire, OX14 3EA, UK.
[1] FOM Instituut voor Plasmafysica Rijnhuizen, Nieuwegein, The Netherlands.

Preprint of a paper to be submitted for publication in
Nuclear Fusion

March 1995

ABSTRACT

We have performed a numerical parameter study in order to find MHD stable operating regimes for advanced tokamak experiments. In this study we have concentrated on internal modes. Ballooning stability and stability with respect to infernal modes are considered. Our calculations confirm that pressure gradients are the main driving force for infernal modes. It is possible to stabilise infernal modes by elimination of pressure gradients in the region of small shear. We show that an increase of the difference between q on axis and the minimal value of q leads to destabilisation of infernal modes. Higher shear around the minimum q surface stabilises these modes. Resistivity does not lead to a significant more unstable situation. In the region of positive shear pressure gradients are limited by the destabilisation of ballooning modes. The results of the study have been used to construct an equilibrium that is stable up to $\beta_p = 2.39$, $\beta_N = 3.58$.

1. INTRODUCTION

In the 1994 experimental campaign at JET, part of the experiments are devoted to creating plasmas with inverted q profiles commonly encountered in steady state plasmas with a high bootstrap fraction. Current drive and heating mechanisms are used to control the shape of equilibrium profiles, in order to maintain a stable plasma at all times [1]. In this paper the MHD stability study of such scenarios is presented. Because of the general nature of the study the results will also be valid for experiments other than the JET experiment.

In this section we will give an overview of MHD stability considerations for equilibria with inverted q profiles. Section 2 will present aspects of the infernal mode, a dangerous instability that only exists in plasmas with a low shear region. In section 3 we describe the model used to study the stability for a class of equilibria with inverted q profiles. Section 4 presents the results of this study, and the conclusions can be found in section 5.

In tokamak fusion research there are two paths being followed which should lead to a working fusion reactor. One path, the one taken by ITER EDA [2], extrapolates experimental results from existing tokamaks. This leads to large machines that have large plasma currents and a pulsed operation. Other approaches, commonly referred to as advanced tokamak scenarios, try to find ways to operate the fusion tokamak in steady state [3,4,5]. The advanced tokamak experiments must have their current driven non inductively. From an economic point of view it is advantageous to have a large fraction of the current driven by the bootstrap effect. The bootstrap current is proportional to the pressure gradient:

$$J_{BS} \propto -\sqrt{\varepsilon}\,\frac{\partial p / \partial r}{B_p}, \qquad (1)$$

where p is the pressure, r a radial coordinate, ε the local inverse aspect ratio r/R, and B_p the poloidal magnetic field. It is clear from this equation, that in order to have a large bootstrap current large values of the poloidal beta are required. Since the pressure gradient has a maximum somewhere off axis it can also be seen that the current profiles of advanced tokamak scenarios will in general be non-monotonic. The non-monotonic current profiles give rise to inverted safety factor profiles which have a minimum that is situated just outside the position of maximum current. The safety factor q is defined by:

$$q = \frac{1}{2\pi} \oint \frac{B_\phi}{R B_p} dl, \tag{2}$$

where B_ϕ is the toroidal magnetic field and R is the major radius. The integral is taken over a single poloidal loop around the flux surface. The shear is given by:

$$s \approx \frac{\Psi}{q} \frac{dq}{d\Psi}, \tag{3}$$

where Ψ is the poloidal flux. In the region of small shear around a minimum in the q profile the so-called infernal mode can become unstable. The infernal mode is a pressure driven internal MHD-instability with low to intermediate toroidal and poloidal mode numbers (n,m) that is excited in a region of low shear. Several authors [6,7] have already shown that this infernal mode is easily destabilised and could very well be responsible for limiting the maximum attainable plasma beta. However, little is known about the exact dependence of the infernal mode on plasma profiles and therefore this mode will be studied in more detail. The MHD stability of the advanced tokamak scenarios requires control of the plasma profiles. To find how the control of these profiles influences the stability is the main objective of this paper.

Apart from the infernal mode there are several types of MHD instabilities that one can expect in the scenarios that we are considering. At first there is the ballooning stability. Ballooning instabilities are high n pressure driven modes. It is known that negative shear, as well as large positive shear, has a stabilising effect on the ballooning mode, so that we can expect that the plasma region inside the minimum in the q profile will be able to sustain large pressure gradients before the ballooning mode is destabilised. However, just outside the minimum there is a region of small positive shear which will be the region where ballooning instabilities will limit the pressure gradient the most.

The internal kink mode will not be dangerous because in the equilibria that are studied here the minimal value of the safety factor is well above 1. The external kink, on the other hand, could have influence on the stability boundaries. This is a low-n mode which is mainly driven by a finite edge current density. The stability of this mode has been studied extensively and much is known about its stability. For example, shaping of the plasma can stabilise the external kink and also large shear at the plasma edge has a stabilising effect. Here, we have used an up-down symmetric D-shaped plasma. This may not be the best shape when external kinks are considered. Plasmas with X-points for example are known to be more stable against kink modes [8]. However, our first interest is the infernal mode and because this is an internal mode the shape of the plasma will probably not have a big influence on its stability and we have used a simpler shape to make the calculations not unnecessarily time consuming.

Tearing modes are also potential candidates for instability. These are low (n,m) resistive MHD instabilities that are driven by a current density gradient. The driving force of the tearing mode is concentrated in a small layer around a resonant surface and there is a stabilising force that is proportional to m^2 [9], so for the tearing instability to exist there has to be a flux surface in the plasma with a sufficiently low value of the safety factor. At the relatively high safety factor values ($q \approx 2.5$ or higher) we will look at we have not encountered tearing modes for realistic values of the resistivity.

2. THE INFERNAL MODE

The infernal mode is first mentioned in an article by Manickam et al [10] where it is shown that in regions of low shear the standard ballooning theory breaks down and it is not necessarily true anymore that the most unstable ballooning type mode is a high-n mode. Instead, if one plots the growth rate as a function of nq at low nq an oscillatory behaviour can be seen and unstable bands in nq are formed. If for a given value of the safety factor q an integer value of n coincides with such a window there exists an unstable low n mode that is called the infernal mode. In this article only monotonic q profiles were considered.

In 1993 an article was published by Ozeki et al [6] in which non-monotonic profiles were taken into consideration. Here it was shown that for the internal low-n MHD stability, and in particular for the infernal mode, a hollow current profile, as compared with parabolic and flat profiles, gives rise to the most unstable equilibrium. Moreover, they showed that for such profiles the infernal mode is the first to be destabilised at high β_p over a large range in parameter space. They also showed that using a more peaked pressure profile could stabilise the infernal instability by moving the maximum pressure gradient out of the region of small shear.

The article of Ozeki et al was motivated by the observation of a β_p collapse in JT-60 experiments with a large bootstrap fraction [11]. Also from JET there is evidence that the infernal mode is responsible for a collapse of the plasma temperature in some pellet fuelled discharges. Here it has been observed [12] that when the safety factor on axis reaches a value of 1.5 the central temperature profile flattens abruptly and a residual m=3 structure is present afterwards. Charlton et al [13] analysed these discharges. They found that for a reconstructed equilibrium the q profile was flat in the centre and the n=2, m=3 infernal mode was unstable for values of q_0 just below 1.5. The calculated growth rate of this instability was in good agreement with the experimentally observed one. From a non-linear time evolution of this mode they also found that its effect on the plasma parameters was to flatten the central pressure profile, just as was observed in the experiment.

From all this we can conclude that, although the infernal mode has become of interest only recently, it is a dangerous mode that could very well be one of grave importance to the newly developed advanced tokamak scenarios. We will present an extensive study of the infernal mode stability for plasmas with negative shear in the framework of linear resistive MHD.

3. MODEL

For the study of the MHD stability of advanced tokamak scenarios three numerical codes have been used. For the construction of MHD equilibria using a pressure gradient profile and a current profile as input the HBT [14,15] code was used. For this purpose it was extended so as to be able to use an averaged toroidal current density profile as input for the equilibrium construction. The ballooning stability of these equilibria was also calculated with this code. For the low-n MHD stability the resistive MHD code CASTOR [16,17] was used. The MHD equilibrium code HELENA [18] was used as an interface between these two stability codes by calculating the geometric quantities needed by CASTOR using output from HBT.

We have used a JET relevant geometry consisting of a D-shaped plasma with an inverse aspect ratio of 0.34. The constructed equilibria all have a total toroidal plasma current of 2.1 MA but in the parameter studies we will vary the safety factor on axis and the q profile and plasma current will change accordingly. Low values are taken for the current because it must be driven non-inductively. In the stability calculations we have used an ideally conducting wall at the plasma boundary. The equilibrium profiles are parametrised to be able to control important features like the position of the maximum pressure gradient and of the maximum current density. The input profiles are:

$$\begin{aligned}\langle J_\phi \rangle &= 1 + A_J\Psi + B_J\Psi^2 + C_J\Psi^3 \\ &\quad + D_J\left(\Psi - \Psi^2\right)^\gamma \exp\left(-\left((\Psi - \Psi_0)/\delta\right)^2\right)\end{aligned} \tag{4}$$

$$\frac{dP}{d\Psi} = 1 + A_p\Psi + B_p\Psi^2 + C_p\Psi^3 + D_p\Psi^4 + E_p\Psi^5. \tag{5}$$

Here $\langle J_\phi \rangle$ is the flux surface averaged toroidal current density normalised to 1 at the magnetic axis, P is the plasma pressure, its gradient is also normalised to 1 at the axis, and Ψ is the normalised flux going from 0 at the axis to 1 at the plasma boundary.

The expression for the toroidal current density consists of two parts. The first part is a truncated series expansion in Ψ which models the bulk background plasma current. The second part gives locally a bump in the profile of which the position, width, and height can be controlled by respectively Ψ_0,δ, and D_J. The function in front of the exponent guarantees that this term will not contribute to the current density on axis and at the edge. γ is a parameter that controls how fast it will go to zero at those positions. The bump gives us control over the position, width, and depth of the local minimum in the q profile and models a locally driven current coming either from bootstrap effects (which we did not take into account self-consistently) or from an external mechanism like lower hybrid current drive. The pressure gradient profile consists only of a series expansion in Ψ. These parametrisations leave us enough freedom to study a wide range of profile effects on the stability.

4. RESULTS

In this section we will look at the dependence of the infernal instability on several parameters. First, we will look at the stability of a reference equilibrium which was chosen to resemble typical equilibria produced by the transport code JETTO [19] in the modelling phase of the profile control experiments at JET. After this we will look at the effects of changes in the pressure and the current profile.

4.1 The Reference Equilibrium

In fig.1 the equilibrium profiles for the reference equilibrium are shown. Here Ψ is the normalised flux. The pressure gradient is largest halfway between the magnetic axis and the plasma edge, not far from the region of small negative shear. The q profile is everywhere well above 2 and the edge safety factor is high. This is caused by the low plasma currents that will be used in the profile control experiments.

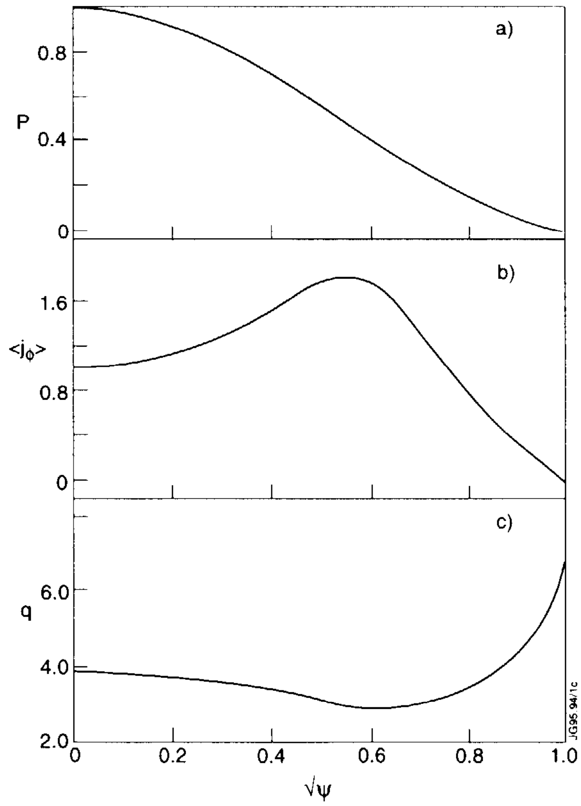

Fig.1 The pressure, current density, and safety factor profiles of the reference equilibrium. Here Ψ is the normalised flux.

In fig.2 it is shown how the growth rate of the infernal mode behaves for different values of the toroidal mode number n as a function of the minimum q value. The growth rate is normalised to the inverse of τ_A, $\tau_A = R_m/V_A$, R_m is the major radius of the magnetic axis, and V_A is the Alfvén speed on the magnetic axis. In this scan all profiles and β_p are kept fixed, while the total current is varied. The q profile scales approximately with the inverse of the total current. The q_{min} value corresponding to a total current of 2.1MA is 2.926. The poloidal beta is 1. As has been noted in [6], q_{min} is a very important parameter for the stability of the infernal mode. The infernal mode is most unstable for values of q_{min} just below a rational value so that there are two resonant surfaces in the plasma and the infernal mode is mainly localised between these two surfaces. As could have been expected from the analysis by Manickam et al [10] the growth rate is more a function of n times q than of the safety factor alone so that for higher values of n the range of unstable q values is smaller, but successive unstable regions are closer together. One can easily see that the largest stable window in q_{min} is therefore just above an integer value. This is confirmed by the results in fig.2. If we take n=1, 2, and 3 into account there are stable windows between q_{min} = 3.1 and 3.2, and between q_{min}=3.55 and 3.6. For a stable window to exist at all the growth rate of the infernal mode must be a decreasing function of nq so that high toroidal mode numbers ($n \geq 4$) do not contribute to the unstable region. Here it is also important to notice that the mode structure becomes more and more localised for high-n so that in these cases the infernal mode probably has a less deteriorating effect on the plasma. Notice further that there is a hump in the growth rate when a rational q surface leaves the plasma, thereby eliminating two rational surfaces.

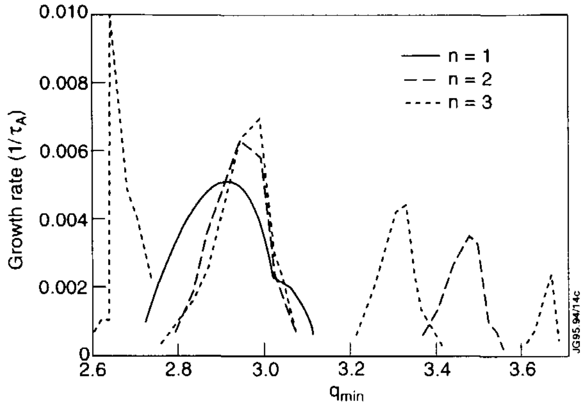

Fig.2 Growth rate of the infernal mode as a function of the value of q_{min} for the reference equilibrium; β_p= 1. Curves are shown for n=1,2,3.

Next, we have looked at how changing the poloidal beta influences the stability (see fig.3). Since the infernal mode is a pressure driven mode it is obvious that increasing the plasma pressure will have a destabilising effect on its stability. An important consequence of this is of course that for higher β_p the stable window will get smaller and can even disappear

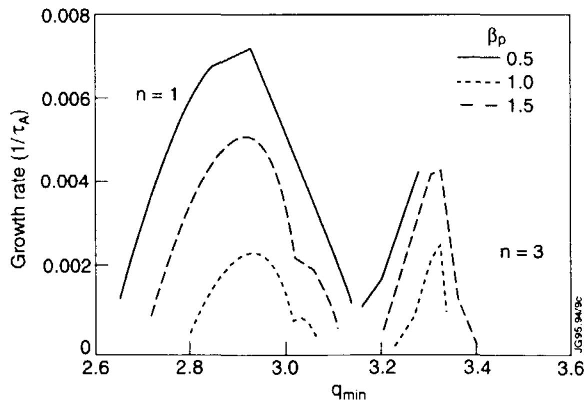

Fig.3 Growth rate of the infernal mode for β_p=0.5, 1.0, 1.5. Curves are shown for n = 1, 3.

altogether, as happens for this equilibrium at β_p=1.5. On the other hand, at low β_p the infernal mode can be stabilised. This fact can be utilised in the start-up phase of an experiment to fix the profiles at low β and start heating while keeping the profiles (in particular the q profile) constant. In this way dangerous parameter regimes for the infernal instability can be avoided.

In fig.4 we can see the effect which resistivity has on the infernal mode. Here η is the resistivity normalised with respect to $\mu_0 V_A R_m$, where μ_0 is the magnetic permeability, V_A is the Alfvén speed on the magnetic axis, and R_m is the major radius on the magnetic axis. Finite values of the resistivity destabilise the infernal mode for parameter ranges where the ideal case is stable. However for realistic values of the resistivity (in JET this would mean $\eta \approx 10^{-8}$-10^{-9}) there is no significant effect on the stability boundary. For values of q_{min} where the ideal infernal mode is stable the growth rate of the resistive infernal mode scales as $\eta^{0.5}$.

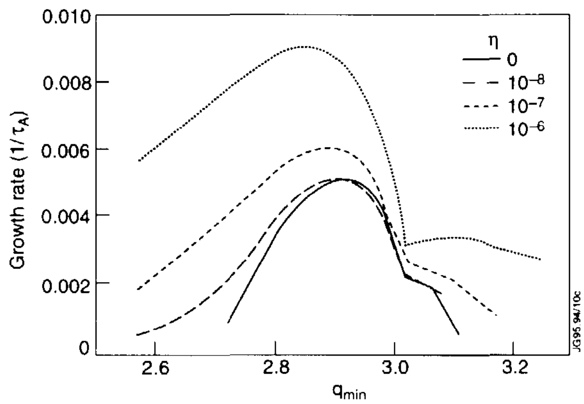

Fig.4 Influence of resistivity on the growth rate of the infernal mode.

4.2 Pressure Profile Effects

In fig.5 three equilibrium pressure profiles are shown. The current density profile is identical to the one in fig.1. Profile A belongs to the reference equilibrium and it has a dP/dΨ that is peaked near the axis. Profile B represents an equilibrium in which dP/dΨ has the same magnitude all over the plasma, except at the edge where it drops off rapidly. Profile C represents a more flat pressure profile with a gradient that is peaked near the edge. In the figure the pressure is normalised such that for profile A the pressure on axis is equal to one.

In Table I the maximum stable plasma beta with respect to ballooning stability is shown for these profiles. These calculations were done keeping the pressure and current

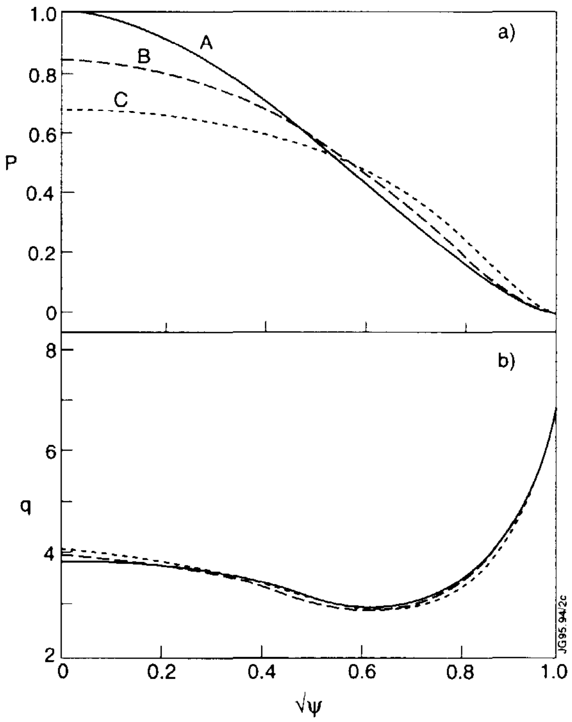

Fig.5 Pressure and safety factor profiles used to study the dependence of the infernal stability on the overall pressure profile. The current density profile is kept fixed.

Table.1: Plasma betas for which the three equilibria of fig.5 are marginally stable to ballooning modes. Also shown are the flux coordinates at which ballooning modes are first destabilised.

Profile	β_N	β_p	Ψ
A	2.63	1.76	0.57
B	2.23	1.49	0.59
C	1.84	1.23	0.72

profiles constant, while varying their relative amplitude such that the total current remained constant and only the plasma beta changed. β_N is the normalised beta defined by

$$\beta_N = \langle\beta\rangle / \frac{I_p}{aB}. \tag{6}$$

$\langle\beta\rangle$ is the volume averaged plasma beta, I_p is the total plasma current, a is the minor radius of the plasma, and B is the vacuum magnetic field on axis. Comparing the results we see that the maximum beta is smaller when the pressure gradient is shifted to the outer region of the plasma. In the central region of the plasma we have a negative shear, and here the plasma enters a second region of stability. As long as a the large pressure gradient is localised inside the minimum in q, high values of plasma pressure, and thus of the plasma beta, can be reached. In the table the value of $\Psi$where the ballooning mode is first destabilised is shown. When the largest pressure gradient is inside the minimum in q (profiles A and B) ballooning modes are first destabilised in the region of small positive shear. But when the maximum pressure gradient is on the outside the instabilities follow this gradient and occur first more on the outside.

The infernal mode stability behaves in an entirely different way. In fig.6 stability curves are plotted for the three equilibria at a normalised plasma beta of approximately $1.5\left(\beta_p \approx 1\right)$. Here we see that the shift of the maximum pressure gradient to the outside has a stabilising effect. The range in q_{min} over which the infernal mode is unstable is smaller for this case. We can conclude that, unlike ballooning modes, the infernal mode is destabilised by a pressure gradient in the region of small shear, even when this gradient

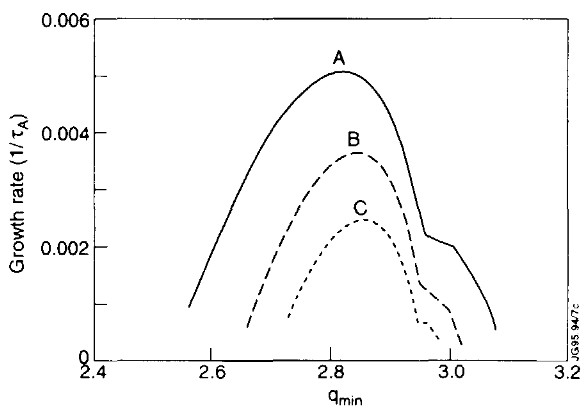

Fig.6 Growth rate of the infernal mode for the three equilibria shown in fig.5.

is maximal in a region of negative shear. The shear on the outside of the minimum in q is higher than on the inside and this has a stabilising effect on the infernal mode when the maximum pressure gradient is located there.

As Ozeki et al have shown, moving the pressure gradient to the inside is also stabilising for infernal modes. The pressure profile of an optimal equilibrium will be a trade-off between ballooning and infernal stability considerations, and the fact that for pressure profiles peaked in the centre the plasma averaged beta is inherently lower than for a configuration with a broad pressure profile.

The effect of the pressure gradient in the low shear region becomes more clear when we flatten the pressure profile locally. In fig.7 equilibrium A corresponds to the reference equilibrium. In equilibrium B the pressure gradients are small but finite in the low shear region. Only at the position of minimum q the gradient vanishes altogether. In equilibrium C the pressure gradient has been removed completely around q_{min}. The growth rates of the infernal mode are shown in fig.8. For equilibrium B infernal modes have smaller growth rates due to the suppressed pressure gradients, the effect is largest when q_{min} is almost three. Equilibrium C is stable against infernal modes as long as there are resonant surfaces for the dominant harmonic (in this case the m=3 harmonic) in the plasma. Infernal modes are different in character when there are no resonant surfaces for the dominant harmonic. The mode couples more strongly to higher poloidal mode numbers and therefore the stability threshold also

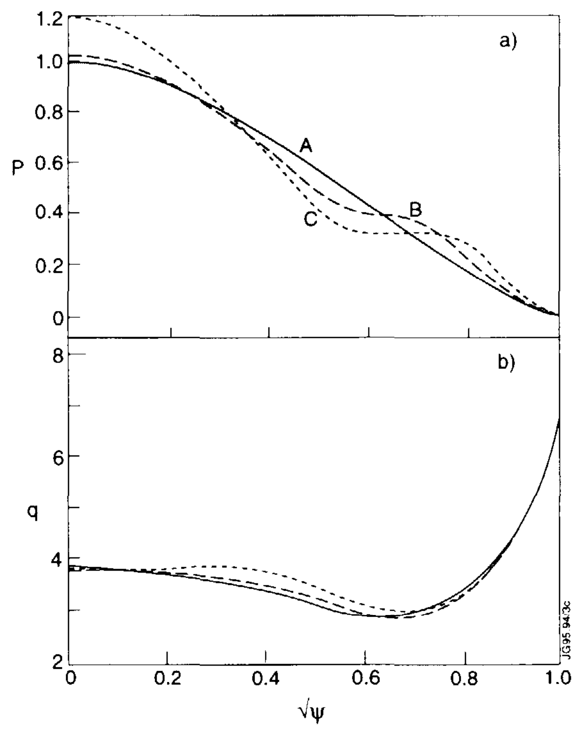

Fig.7 Pressure and safety factor profiles used to study the dependence of the infernal stability on the local pressure gradient. The current density profile is kept fixed.

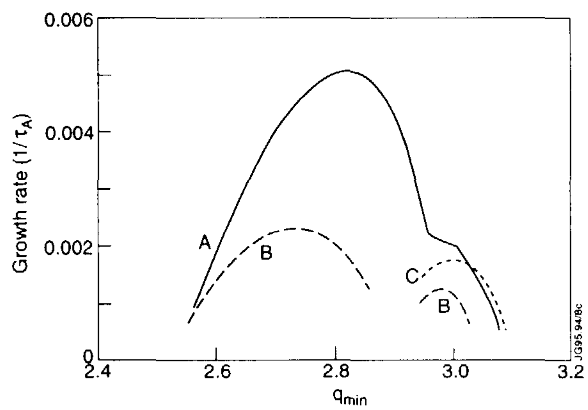

Fig.8 Growth rate of the infernal mode for the three equilibria shown in fig.7.

depends on the plasma parameters at the corresponding resonant surface(s). This mode is more difficult to stabilise, as can be seen in fig.8.

The dependence on the pressure gradient in the low shear region indicates that infernal modes might have a self healing character. The infernal modes encountered in this study are similar to interchange modes (see fig.13). This means that neighbouring flux surfaces are interchanged by the mode and the plasma profiles have the tendency to be flattened. The infernal mode could thus remove its own driving force and be stabilised without doing too much damage to the global plasma parameters.

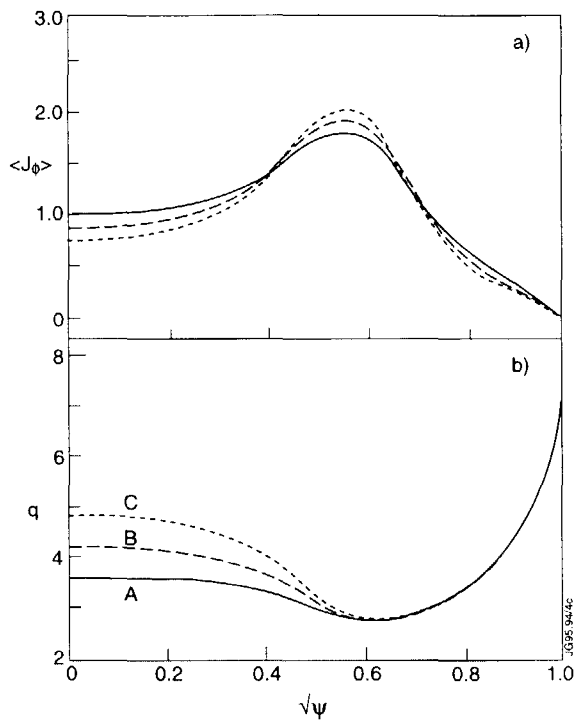

Fig.9 Current density and safety factor profiles used to study the dependence of the infernal stability on a variation of q in the plasma centre.

4.3 Increasing the Local Current Density.

Here we will look at the influence of an increase of the localised bump in the current density relative to the background current density by increasing the parameter D_j in equation 4. The three current profiles that are considered here are shown in fig.9. In the figure the current profile is normalised such that for profile A the current density on axis is equal to one. The q profiles are also shown and one can see that, for a given total plasma current, an increased bump in the current profile only effects the q profile on the inside of the minimum. The value of the safety factor on a given flux surface mainly depends on the total current that flows within this surface. When we increase the localised bump with respect to the background current this means that the current density near the axis diminishes, and this causes an increase in the central q value.

In fig.10 the resulting stability curves for the n=1 infernal stability are shown. The effect of increasing the localised bump in the current is to deepen the well in the q profile.

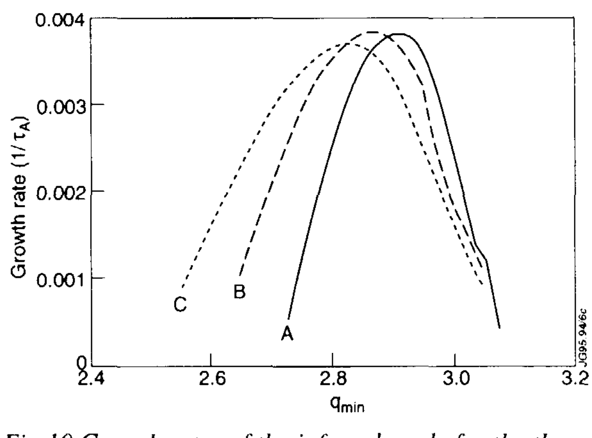

Fig.10 Growth rates of the infernal mode for the three equilibria shown in fig.9.

This means that when we make a scan over q_{min}there is a wider range over which there are two resonant surfaces in the plasma between which the infernal mode can be destabilised, and thus decreasing a stable window in q. It seems that the higher (negative) shear on the inside of the minimum does not have a strong stabilising effect for this case. The ballooning stability does not show any significant changes for the profiles considered here.

4.4 A Broader Local Current Density.

In this section we will look at the effect of a broader localised current density. We have changed the width of the bump in $\langle J_\phi \rangle$ while keeping the total amount of current in this bump constant. In fig.11 the equilibrium profiles are shown. Since the background current density is not influenced by the profile changes we are looking at here, and since for the equilibrium reconstruction the total plasma current is kept constant, q on axis and q at the boundary do not depend on these changes. The effect is to vary the depth of the well in the q profile, but in contrast to the previous section this variation is more local and also varies the width of the well, and thereby the shear on the inside and on the outside of the minimum in the safety factor.

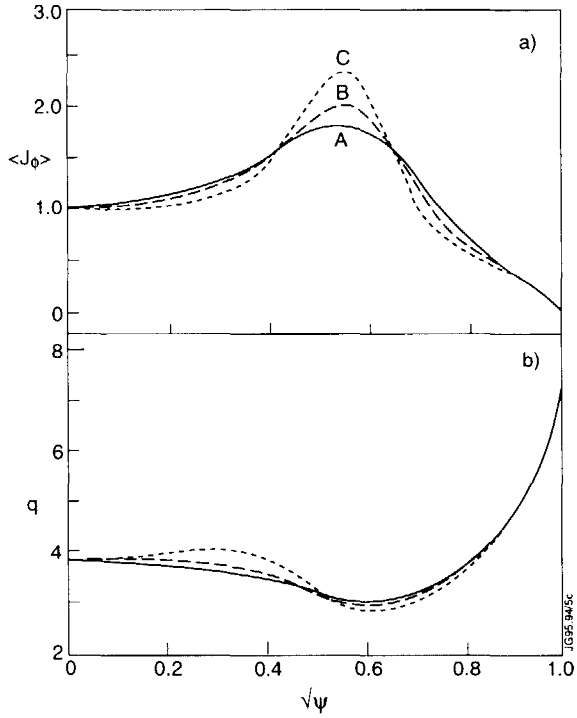

Fig.11 Current density and safety factor profiles used to study the dependence of the infernal stability on the width of the low shear region.

Table II: Plasma betas for which the three equilibria of fig.11 are marginally stable to ballooning modes. Also shown are the flux coordinates at which ballooning modes are first destabilised.

Profile	β_N	β_p	Ψ
A	2.63	1.76	0.57
B	2.58	1.72	0.54
C	2.40	1.60	0.51

Table II shows how the ballooning stability behaves for these profiles. Surprisingly enough the ballooning stability diminishes for cases with more shear. But when we look at the position where the ballooning mode is destabilised first we see that this position moves to the inside. For a given pressure profile, ballooning modes are destabilised at some critical small positive value of the shear. In the equilibria we are studying here, the pressure gradient is large in the inner region of the plasma. Therefore the ballooning modes are easier destabilised when the critical shear shifts in that direction.

When we look at the stability curves for the profiles A, B, and C (fig.12) we see that a broader localised current results in a smaller unstable range of q values, and in larger growth rates. The first effect is related to the one discussed in the previous section. But the second is caused by the smaller shear at the rational surface when the minimum in q is more shallow. Another effect we can see in fig.13, where we show vector plots of the most unstable infernal modes for cases A and C. For case C the unstable mode extends over a much smaller volume of the plasma. This means that for such a profile the effect of the instability on the plasma is only local and could therefore be less dangerous for the overall confinement.

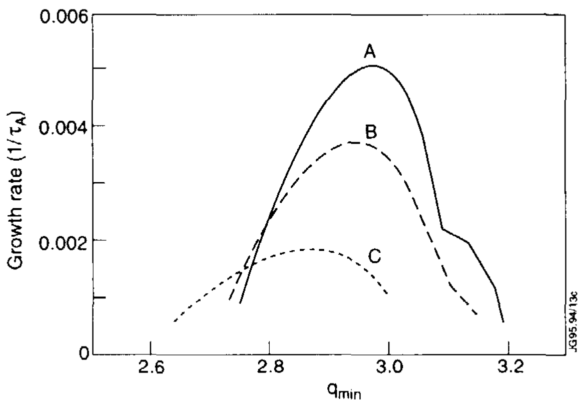

Fig.12 Growth rates of the infernal mode for the three equilibria shown in fig.11.

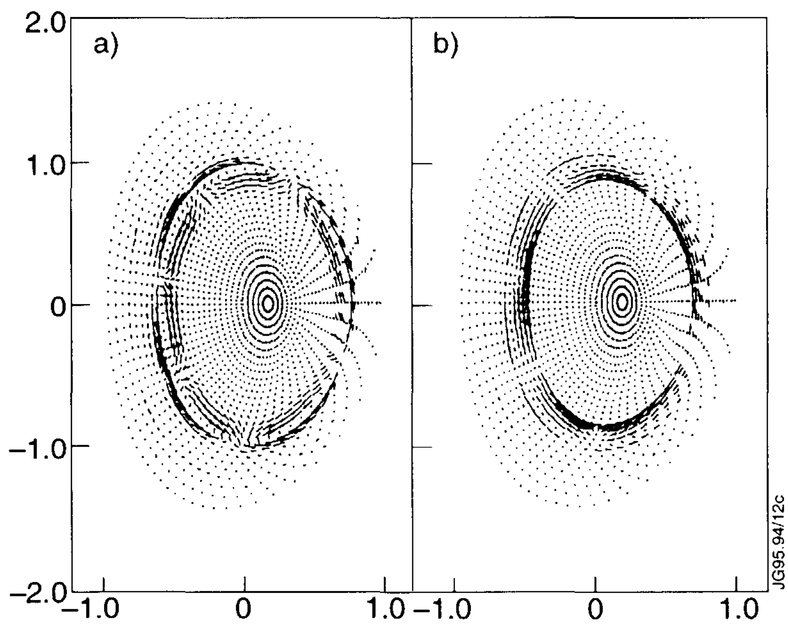

Fig.13 Vector plots of the infernal mode with the largest growth rate corresponding to case A (left) and case C (right) of fig.11. The infernal mode on the left extends over a larger plasma volume.

4.5 An Optimised Equilibrium

To get an idea what an optimal profile would look like we show here the stability results for an equilibrium that has been optimised with respect to ballooning and internal modes.

The resulting profiles are shown in fig.14. The current density has been chosen such that there is a large region of negative shear in the plasma, while the pressure profile has been customised such that the ballooning modes are marginally stable in the region of positive shear, and pressure gradients are small in the region of small shear.

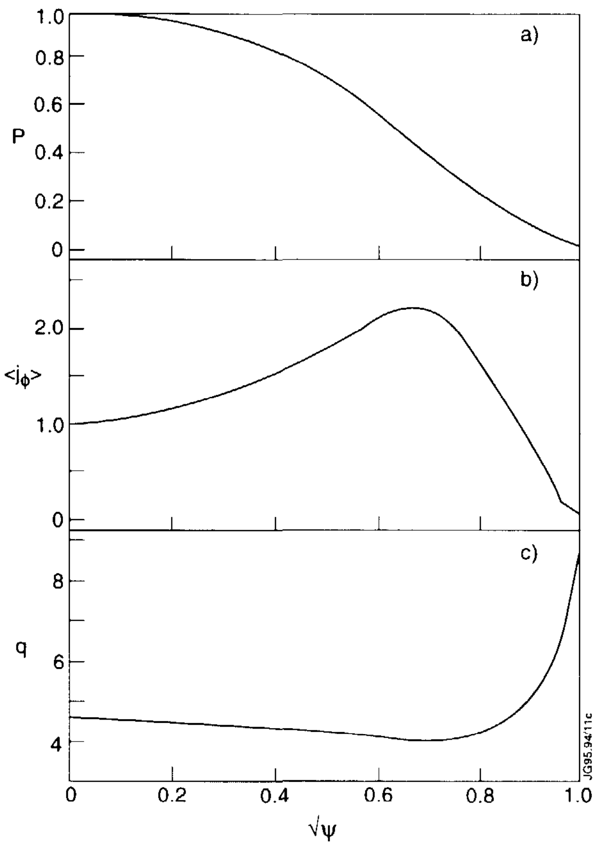

Fig.14 Pressure, current density and safety factor profile of an equilibrium optimised with respect to internal instabilities.

This equilibrium is stable against ideal internal modes up to β_p=2.39 and β_N=3.58. The growth rate of resistive modes is very small, even for large values of the resistivity (growth rate $\leq 10^{-3}/\tau_A$ for $\eta=10^{-6}$). Because of the low pressure gradient in the region of small shear the infernal mode is stable, even when the minimal q is just below 4. The results show that it is possible to reach considerable values for the plasma beta, especially when there is sufficient control of the plasma profiles.

5. CONCLUSIONS

We have found that a number of plasma parameters are important for the stability.

At first, the infernal mode, because it is pressure driven, is destabilised by a large pressure gradient in the region of small shear. Moving the maximum pressure gradient to the region of large shear near the plasma boundary has a stabilising effect although this can have an undesirable effect on the ballooning stability of the plasma.

A deeper minimum in the q profile leads to a larger range of unstable q_{min} values. Making the sides steeper has, through the larger shear, as effect that the growth rate of the infernal mode gets smaller. And having a very localised minimum in the q profile forces the infernal instability to be localised also. It could turn out (and this should be investigated) that, following the results of reference [13], the infernal mode flattens the pressure profile locally, thereby removing its driving force. In that case, a localised instability might not lead to deterioration of the plasma parameters and this could be acceptable.

A high β stable equilibrium will be characterised by negative shear in the plasma centre, the q profile reaching a shallow minimum near the edge that extends over a small part of the plasma and q growing fast at the edge. The pressure gradient will be limited by stability considerations. It can be large in the core but will have to fall before the q profile reaches its minimum. In the region of positive shear it will be limited by ballooning stability considerations. It seems unlikely that such plasmas can be obtained without external current drive mechanisms.

Control of the positions of small shear and of high pressure gradients is needed to guarantee MHD stability. In the start-up phase of an advanced tokamak experiment, low beta plasmas could be used to prepare a current profile (and thereby a desirable q profile), and when this profile is reached, to try to freeze it in with external current drive mechanisms while heating the plasma to obtain high beta values.

ACKNOWLEDGEMENT

This work was performed as part of the research programme of the association agreement of Euratom and the 'Stichting voor Fundamenteel Onderzoek der Materie' (FOM) with financial support from the 'Nederlandse Organisatie voor Wetenschappelijk Onderzoek' (NWO) and Euratom. It was partly funded under JET study contract no. JT3/13761.

REFERENCES

[1] F.X. Söldner et al, Contr. Fusion and Plasma Physics, (Proc. 21st Eur. Conf. Montpellier) (1994) to be published.

[2] ITER Joint Central Team, Plasma Phys. Contr. Fus. **35** (1993) B23.

[3] M. Kikuchi, Plasma Phys. Contr. Fus.**35** (1993) B39.

[4] R.J. Goldston et al, Contr. Fusion and Plasma Physics, (Proc. 20th Eur. Conf. Lisbon) **17C**, Part I (1994) 319.

[5] R.J. Goldston et al, Contr. Fusion and Plasma Physics, (Proc. 21st Eur. Conf. Montpellier) (1994) to be published.

[6] T. Ozeki, M. Azumi, S. Tokuda, S. Ishida, Nucl. Fusion **33** (1993) 1025.

[7] J. Manickam, in Workshop on Stabilization of the internal kink and other MHD issues, June 23-25, 1993, San Diego.

[8] T. Ozeki, M. Azumi, H. Ninomiya, S. Tokuda, T. Tsunematsu, S. Seki, Nucl. Fusion **28** (1988) 1859.

[9] J. Wesson, Tokamaks, Clarendon press (1987).

[10] J. Manickam, N. Pomphrey, A.M.M. Todd, Nucl. Fusion **27** (1987) 1461.

[11] S. Ishida, Y. Koide, T. Ozeki, M. Kikuchi, S. Tsuji, H. Shirai, O. Naito, M. Azumi, Phys. Rev. Lett. **68** (1992) 1531.

[12] JET Team, in Plasma Physics and Controlled Nuclear Fusion Research 1988 (Proc. 12th Int. Conf. Nice, 1988), **1**, IAEA, Vienna (1989) 215.

[13] L.A. Charlton, L.R. Baylor, A.W. Edwards, G.W. Hammett, W.A. Houlberg, P. Kupschus, V.E. Lynch, S.L. Milora, J. O'Rourke, G.L. Schmidt, Nucl. Fusion **31** (1991) 1835.

[14] J.P. Goedbloed, Comp. Phys. Commun. **24** (1981) 311.

[15] J.P. Goedbloed, G.M.D. Hogewey, R. Kleibergen, J. Rem, R.M.O. Galvão, P.H. Sakanaka, Plasma Physics and Controlled Nuclear Fusion Research 1984 (Proc. 10th Int. Conf. London, 1984), **2**, IAEA, Vienna (1985) 165.

[16] W. Kerner, S. Poedts, J.P. Goedbloed, G.T.A. Huysmans, B. Keegan, E. Schwarz, Contr. Fusion and Plasma Physics (Proc. 18th Eur. Conf. Berlin), **4** (1991) 89.

[17] G.T.A. Huysmans, J.P. Goedbloed, W. Kerner, Phys. Fluids B **5** (1993) 1545.

[18] G.T.A. Huysmans, J.P. Goedbloed, W. Kerner, Proc. CP90 Conf. on Comp. Phys. Proc., World Scientific Publ. Co. (1991) 371.

[19] G. Cenacchi, A. Taroni, 8th Eur. Conf. on Comp. Phys. Eibsee (1986).