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The Limits of β Imposed by MHD Modes near the Plasma Edge in ASDEX Upgrade

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Abstract The MHD stability of advanced scenarios in ASDEX Upgrade with an internal transport barrier and a non-monotonic q-profile is studied. The NBI system of ASDEX Upgrade will be changed during the year. The current drive possibilities of the new system are investigated and the stability of the achievable q-profiles is studied.

1 Introduction

In the so called advanced scenarios, the aim is to reach steady state tokamak operation with the help of intrinsic bootstrap current.

As the maximum pressure gradient is, of course, off-axis, a high bootstrap current results in non-monotonic q-profiles since it is proportional to the pressure gradient. In order to reach high bootstrap current, the β-value of the plasma has to be sufficiently high.

The high β-values can create problems concerning the MHD stability of the plasma. It seems possible to suppress the ballooning modes and, thus, decrease turbulence and transport with a flat or reversed shear in the core. However, other (low-n) instabilities (e.g. double tearing and infernal modes) can become unstable under these conditions [1]. Consequently, the q-profile has to be optimized so that all core instabilities are stabilized. The ultimate β-limit is then given by the external kink modes.

2 Equilibria

In this study, we investigated two types of equilibria. The first set was created by optimizing the q-profile in order to achieve maximum stability against MHD-instabilities. This allowed us to find the theoretical limit for the device. No limits for the current distribution were imposed.

The second set was created keeping in mind the limitations of the device, especially its current drive capabilities. This was done using the ASTRA transport code [2] that takes into account the bootstrap current and the current drive from the NBI and ECRH systems.

The pressure profile used in this study avoids large local pressure gradients and it was assumed that the plasma is in H-mode, and, consequently, there is a pressure pedestal near the plasma edge. The pressure profile used is shown in Fig 1.

The reversed shear allows to suppress the ballooning modes in the core region giving access to the second stable region. However, other modes like double tearing modes and infernal modes, can become unstable with reversed shear profiles. If q can be kept between rational surfaces, in this case 1.5 and 2, and the region of high pressure gradient is far from the rational values, the core instabilities are avoided. After optimization with respect to the MHD stability, the relatively flat q-profile is extended as far from the core as possible and then crosses the $q = 2$ surface very steeply in order to avoid unstable modes on the rational surface. The optimal q-profile is shown by the blue line in Fig. 2.

In practice, the limitations of the current drive system impose additional boundary conditions to the theoretically optimized q-profile. Therefore, the current drive capabilities of ASDEX Upgrade after the modifications of the NBI system are taken into account in the q-profile calculations. After the modifications, the beams will be directed more tangentially, which helps to drive the current off-axis and in creating q-profiles that are not monotonic.

The effect of the new NBI system on the q-profile can be seen by comparing two identical ASTRA transport calculations of the current distribution that differ only in the NBI configuration (Fig. 3). With the new NBI system, it is possible to achieve negative shear in the core even without a large bootstrap current fraction. In the centre, q can be kept above 1.5, while in the old system it would drop below 1 where the plasma is prone to sawteething.

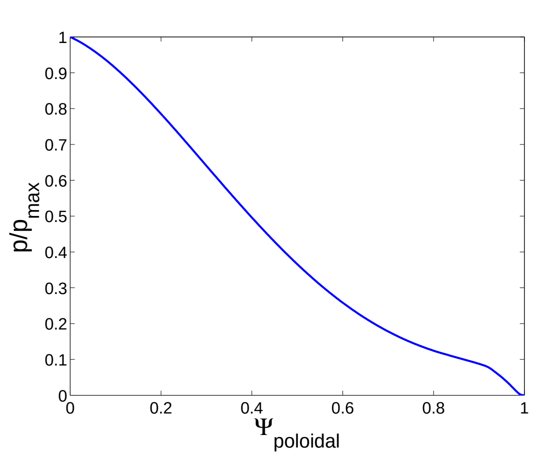

Figure 1: *The pressure profile used in the equilibrium calculations*

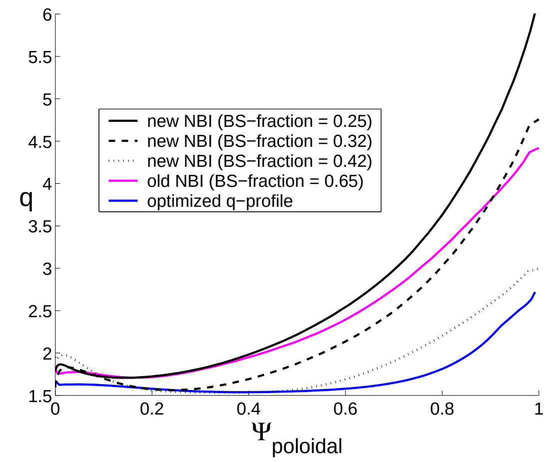

Figure 2: *The optimal q-profile and the q-profiles that can be achieved in reality in ASDEX Upgrade*

By further increasing the bootstrap current fraction, it is possible to get even closer to the optimal profile (Fig. 2). With high bootstrap current fractions, it is possible to reach negative shear profiles even with the old NBI configuration. With the new system, the low shear region can be extended far from the core region.

3 Stability

The stability of the equilibria was analyzed using the GATO [3] code for low toroidal mode number analysis, and the GARBO [4] code for high toroidal mode number analysis. The possibility of stabilizing the plasma with a conductive wall structure around the plasma was also considered.

Stability without a wall. The stability without a wall structure was studied by keeping the q-profile fixed and varying the plasma β. The q-profile varies in the range from 1.5 to 3, and the most unstable external kink modes were found for toroidal mode numbers 1 to 3. It was found that, without any stabilizing structures, the plasma becomes unstable at $\beta = 1.2\%$. The mode structure of the instability is shown in Fig. 4.

Wall stabilization. The role of a perfectly conducting wall is studied as a method to further improve β by stabilizing the external kink modes. Unfortunately, the walls of

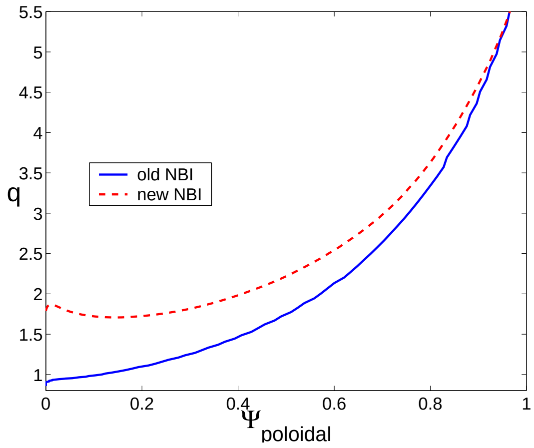

Figure 3: *The q-profiles achieved with the old and new NBI. The bootstrap current is 25 % of the total current for both cases*

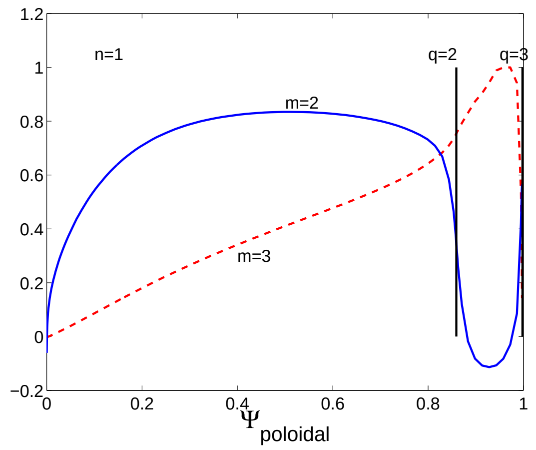

Figure 4: *Fourier decomposition of an n=1 kink mode*

ASDEX Upgrade are too far to have a remarkable stabilizing effect. Therefore, introducing additional wall structures are under discussion right now. Such a wall would have a 3-dimensional structure, of course, due to all the ports for heating and diagnostics. We will consider here only an axisymmetric wall, however, since even a two dimensional analysis

As a first approximation, the shape of the wall was assumed to be the same as the plasma boundary. The distance of the wall from the plasma edge was varied and the stabilizing effect is shown in Fig. 5. By placing a wall at 1.4 times the distance from the plasma centre to the edge, β can be increased to 5 % without instabilities. The walls of ASDEX Upgrade are too far to have this kind of stabilizing effect. Therefore, an additional wall would be very beneficial. Of course this wall would have 3-dimensional structure due to all the ports and require a separate analysis.

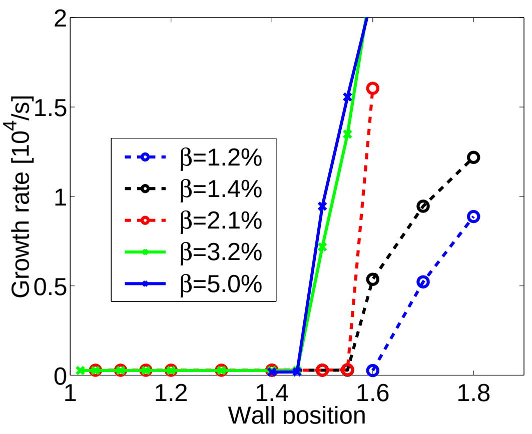

Figure 5: *Wall stabilization of an n=1 kink mode for the optimized q-profile*

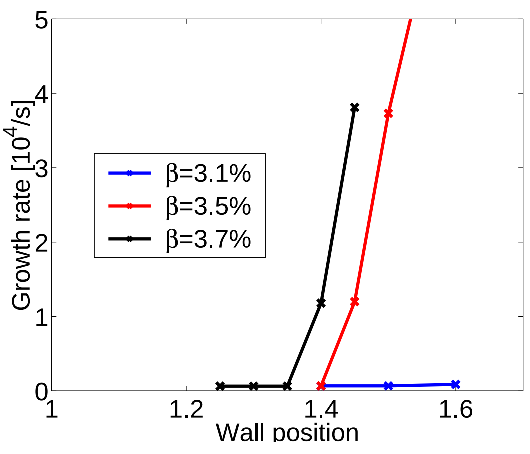

Figure 6: *Wall stabilization of an n=1 kink mode for the q-profile that can be achieved in ASDEX Upgrade with the new NBI system. The bootstrap current fraction is 35 %.*

The same analysis was done for the q-profile that can be achieved in ASDEX Upgrade (Fig. 6). The result of this analysis shows that the achievable q-profile is less susceptible for kink instabilities. However, when there is an instability, it is more difficult to stabilize it with a conductive wall. The reason for this is that the q-profile crosses the value 2 deeper in the core. The profile also increases more steeply in the edge region. The steep rise can stabilize the unstable modes without a wall. However, when the modes become unstable, the wall must be brought closer to the the plasma in order to stabilize them.

It has to be remembered that, since the bootstrap current is proportional to the pressure gradient, the achieved q-profile depends on the chosen pressure profile. If the region of steep pressure gradient is further away from the core, it would be possible to move the $q = 2$ surface closer to the edge, and then the conductive wall would have a stronger stabilizing effect.

Ballooning stability. All the above equilibria were also analyzed for high-n ballooning stability using the GARBO code. It was found that, as the β increases to $\approx 3.2\%$, the plasma becomes unstable in a very narrow (< 1 cm) region close to the plasma edge. However, this would not lead to a catastrophic instability, but would be part of the ELM phenomenon causing a small drop in the H-mode pedestal when the stability boundary is crossed, and then becoming stable again.

4 Conclusions

It was found that with the proposed modifications to the ASDEX Upgade NBI system, it is possible to achieve negative shear in the core, which is necessary for the internal transport barrier. The stability analysis of the negative shear equilibria showed that without a conductive wall around the plasma, kink modes would make the plasma unstable. However, with a conductive wall these modes can be stabilized and $\beta \approx 5\%$ can be achieved without instabilities for optimized the q-profile. When the limitations of the new NBI current drive system are taken into account, the maximum achievable β with a conductive wall at 1.4 times the plasma radius falls to 3.7 %.

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