

Analysis of β -limits in tokamak reactor scenarios

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Introduction: In the framework of the European Power Plant Conceptual Studies (PPCS) environmental, safety and economic aspects of a future power plant, called DEMO, are studied. Still many issues, such as geometrical size, pulsed or steady state operation need to be addressed. In these proceedings we present results of 'DEMO Physics Studies' concerning the analysis of β -limits in tokamaks. A high β -limit is a necessary condition for a working tokamak reactor. However, instabilities associated with ideal internal and external modes limit the plasma beta. Therefore, stability-optimized plasma profiles have to be found. Attractive steady-state scenarios should also be characterized by a high bootstrap contribution to the plasma current. And, the stability-optimized plasma profiles have to be consistent with possible heating and current drive scenarios in order to be relevant for tokamak reactor scenarios. We present stability studies of basic plasma and conducting wall configurations for tokamak reactor scenarios, which have been performed with the equilibrium VMEC/NEMEC code [1] and the linear stability CASTOR_FLOW code [2]. Ideal MHD stability limits are determined for pulsed and steady state scenarios with ad-hoc postulated pressure and q -profiles. Furthermore, the stabilization of $n \geq 1$ ideal modes by infinitely-conducting walls is studied using a set of walls in a parameterized distance from the plasma surface. These investigations will form a basis for later resistive-wall studies. Advanced tokamak scenarios with reversed q -profiles which are ideal stable may be unstable because of resistive coupled tearing modes. Therefore, the stability of these equilibria is also investigated with respect to resistive modes. Furthermore, the bootstrap contribution to the plasma current is computed for all considered plasma configurations. In order to arrive at stable plasma scenarios with optimized transport properties, the stability limit of a transport optimized equilibrium derived by the ASTRA code [3] is also analyzed.

Equilibria with monotonic q -profile. Although steady state advanced scenarios with reversed q -profile are the preferred operation mode for a reactor, pulsed scenarios with conventional monotonic q -profile are admitted as a fall-back option. The ideal MHD stability of low- n modes and the bootstrap currents of equilibria with monotonic q -profile are studied using various pressure profiles. The geometrical and physical parameters are: major radius $R_0 = 8.14$ m, minor radius $a_0 = 2.80$ m, aspect ratio $A = 2.91$, elongation $E = 1.71$, triangularity $\Delta = 0.35$, toroidal vacuum magnetic field $B_0(R_0) = 5.70$ T, total plasma current $I_p = 21.95$ MA, beta normalized $\beta_N = 3.59$, safety factor at the magnetic axis $q_a = 1.36$, safety factor at the plasma boundary $q_b = 4.07$. The pressure, total current and bootstrap current profiles are shown in Figs 1 and 2. The pressure profile A is a peaked ASDEX Upgrade-type profile with

pedestal, while the profiles B, C and D are similar to the ones given in Ref. [4,5]. As Fig. 2 illustrates, a peaked pressure profile (profile A) causes the bootstrap current to peak near the plasma centre, whereas a broad pressure profile (profile D) causes the bootstrap current to peak near the plasma edge. Due to the pedestal and the steep pressure gradient at the plasma edge of pressure profile A, the corresponding bootstrap current rises again at the plasma edge. In Fig. 3 the growth rates are plotted as function of the toroidal mode number n . For case A the growth rate increases with rising n . This is due to the steep pressure gradient at the plasma boundary. No unstable solutions could be found for $n \geq 3$ for cases B and C. For case D the growth rate is almost constant up to $n=6$ and then decreases. No unstable modes could be found for $n \geq 7$.

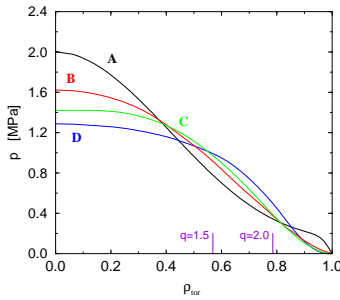


Fig. 1: Various pressure profiles named A, B, C, D.

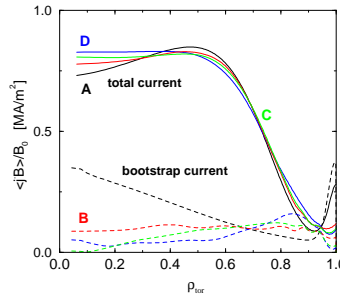


Fig. 2: Total currents and bootstrap currents.

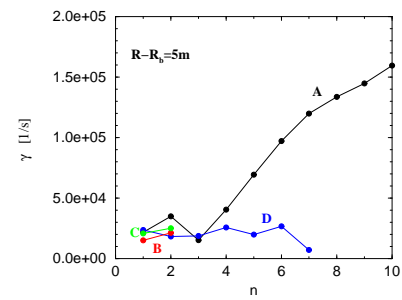


Fig. 3: Growth rates as function of n .

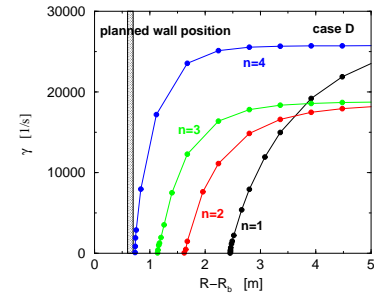
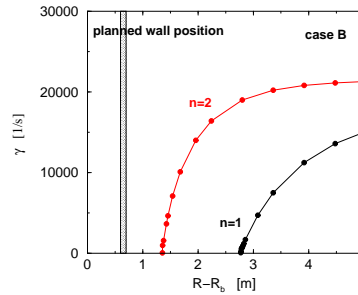
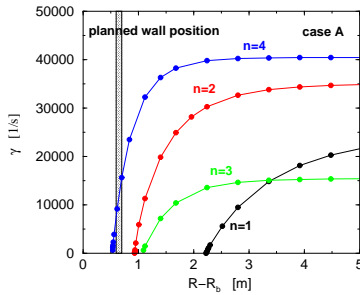


Fig. 4: Growth rates as function of the distance of the ideal wall ($R - R_b$, with R_b being the outermost radial coordinate of the plasma boundary) for cases A, B, D and $n=1-4$. The grey shaded area marks possible positions of an external wall in a distance between 60 and 70 cm.

In Fig. 4. the growth rates of cases A, B and D and toroidal mode numbers $n=1-4$ are plotted as function of the wall distance (case C is similar to case B). While modes with $n \leq 3$ are stabilized within this distance, the $n=4$ mode of case A stabilizes only for smaller wall distances. Furthermore, it is expected from these results that modes with $n > 5$ can only be stabilized by an ideal wall located very closely to the plasma boundary. The high- n modes of case A are localized at the plasma edge. These modes are so-called edge localized modes (ELMs). In contrast to case A, the high- n modes of case D are mainly localized inside the plasma. While the considered $\beta_N = 3.59$ is already the limit for cases A and D, cases B and C would allow slightly higher values if no higher n -modes appear.

Transport consistent scenario. This equilibrium was derived by 1.5 transport modeling taking into account tokamak heating and current drive systems, as well as bootstrap current. The geometrical and physical parameters of this equilibrium are: $R_0 = 8.10$ m, $a_0 = 2.80$ m, $A = 2.89$, $E = 1.71$, $\Delta = 0.42$, $B_0 = 5.68$ T, $I_p = 20.08$ MA, $\beta_N = 1.55$.

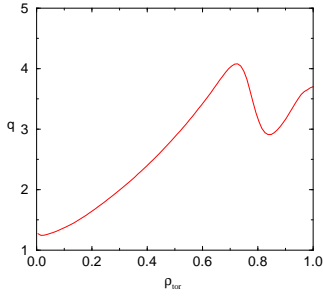


Fig. 5: Reversed q -profile.

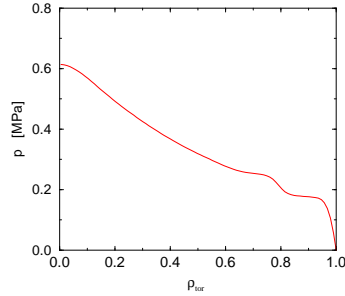


Fig. 6: Pressure profile.

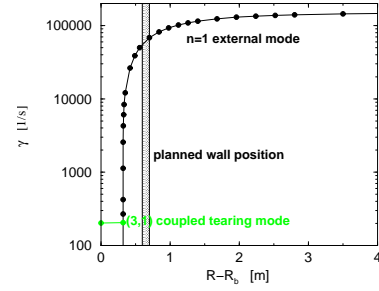


Fig. 7: Growth rate.

Already the $n=1$ mode can not be stabilized by an external wall within a reasonable distance (Fig. 7), because of the steep pressure gradient at the plasma edge (Fig. 6). Furthermore, when the ideal mode becomes stabilized a resistive coupled tearing mode appears. Due to the shape of the q -profile (Fig. 5) the major poloidal harmonic of the resistive mode is $m=3$. This mode can not be stabilized by an external wall, but also appears in case of an ideal wall located at the plasma boundary. Not shown here is the bootstrap current. Its shape fits very well the profile of the total current, but its magnitude is too small.

Stability and bootstrap current optimized scenario. Here we use optimized profiles of safety factor (Fig. 9), pressure and density (Fig. 8) developed for the advanced tokamak power plant ARIES AT by C.E. Kessel et al. [5].

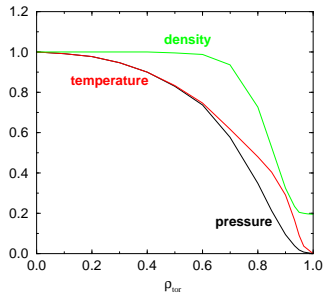


Fig. 8: p, T, n -profiles.

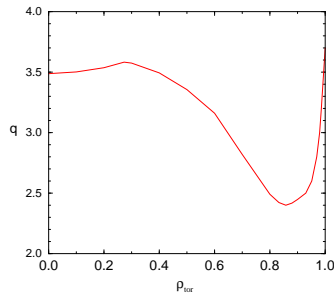


Fig. 9: q -profile.

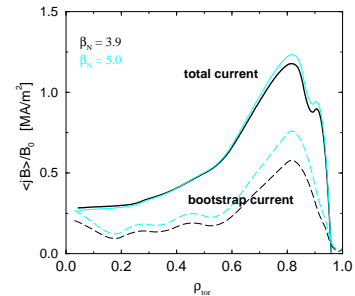


Fig. 10: Current profiles.

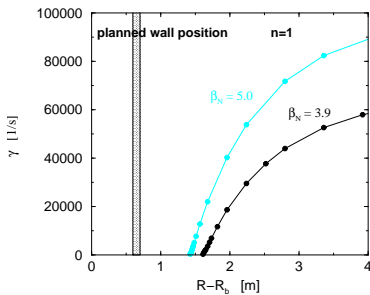


Fig. 11: Growth rates as function of the wall distance.

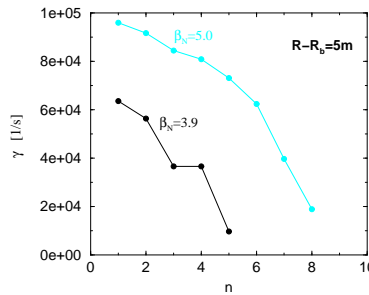


Fig. 12: Growth rates as function of n .

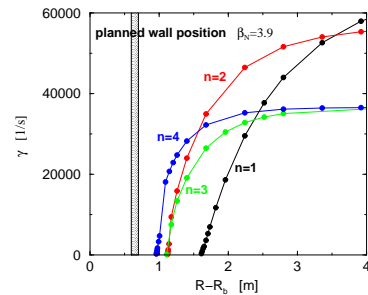


Fig. 13: Growth rates as function of the wall distance.

Using these profiles, equilibria for two β_N -values are investigated. The geometrical and physical plasma parameters are: $R_0 = 8.10$ m, $a_0 = 2.80$ m, $A = 2.89$, $E = 1.70$, $\Delta = 0.48$, $B_0 = 5.64$, $I_p = 24$ -25 MA, $\beta_N = 3.9$ -5.0. The bootstrap current profiles align very well with the total current profiles (Fig. 10). In case of $\beta_N = 5.0$ the bootstrap current fraction exceeds 50%. The growth rates as function of the ideal wall distance and the toroidal mode number are plotted for two β_N -values in Figs 11 and 12. As expected, the growth rates increase with

increasing plasma beta, whereas the stabilizing distance of the wall is reduced. For $n=1-4$ the growth rates as function of the wall distance are shown for $\beta_N=3.9$ in Fig. 13. Both, the growth rate and the stabilizing wall distance decrease with rising n .

Conclusions. Within the framework of linear MHD theory it is possible to design high- β tokamak equilibria with appropriate profile and magnitude of the bootstrap current, and desirable stability properties. The discussed optimized equilibrium is at least stable up to $\beta_N=5$, and the bootstrap current fraction exceeds 50%. The shape of the bootstrap current is well aligned with the total current profile. Nevertheless, none of the investigated equilibria is stable without external wall. This result underlines the need of stabilization structures, that is, resistive wall plus feedback system, in order to reach stable high- β plasma equilibria. The studies of various types of equilibria further show that also modes with $n>2$ may play an important role. Usually, the stabilizing distance of the external wall decreases with increasing toroidal mode number. Some of the equilibria become more and more unstable with increasing toroidal mode number. This is due to their steep pressure gradient at the plasma boundary. The transport consistent equilibrium demonstrates that if an equilibrium turns out to be ideal stable, its stability behaviour with respect to resistive modes should also be investigated in detail. In linear ideal MHD theory only equilibria with rational surfaces outside the plasma boundary ($m/n > q_b$) can be unstable with respect to external kink modes. That is, an equilibrium limited by a separatrix ($q \rightarrow \infty$) would be stable with respect to these modes. For the presented ideal MHD stability studies we used hypothetical plasma configurations with finite q -value at the plasma boundary, namely $q_b = 3.8 - 4.2$, and plasma shapes (no separatrix) with elongation $E = 1.70 - 1.96$ and triangularity $\Delta = 0.35 - 0.57$. But, whether a plasma is stable with respect to an external kink mode, or whether this mode can be stabilized by an external wall located in a technically feasible distance, depends sensitively on the choice of these parameters. Stability computations for the same core plasma, but slightly different plasma boundaries yield different results. Therefore, more realistic computations should be performed. As a first step, free-boundary equilibria should be calculated in order to obtain profound information on the overall equilibrium. Further, in contrast to the assumptions of the used ideal MHD model, there is a smooth transition from an almost ideal core plasma to the surrounding non-conducting vacuum. In the boundary region of a real plasma the resistivity increases continuously due to the decreasing temperature. And, the external wall is also resistive. For future computations we therefore suggest to take these resistivities into account and to perform the stability studies for plasma boundaries sufficiently close to the separatrix.

References

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