Effects of Toroidal Currents upon Magnetic Configurations and Stability in WENDELSTEIN 7-AS

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Abstract. The proposal of new concepts for current carrying hybrid stellarators has raised the issue if current driven instabilities, in particular major disruptions, may be suppressed or mitigated by the externally provided poloidal magnetic field. In W7-AS the internal toroidal currents such as bootstrap and Okhawa currents are cancelled by opposite currents driven inductively or by electron cyclotron current drive (ECCD). In this way the edge rotational transform is controlled, and net current-free stable plasmas are maintained. On the other hand, the current drive systems provide a flexible tool to investigate current driven instabilities as well as various issues concerning the effect of magnetic shear on confinement and MHD mode behaviour. The stability studies in the presence of significant toroidal currents have been made in the accessible range of the external rotational transform ι_{ext} = 0.30...0.56 involving the low order rational surfaces ι = 1/2, 3/2, 3/4 and 1. In addition the rational surfaces ι = 1/3 and 1/4 could be accessed by reverse current drive. Target plasmas heated by electron cyclotron resonance heating (ECRH), neutral beam injection (NBI) or both were investigated in order to assess to which extent the stability depends on particular current density profiles. Disruption-like events, preceded by tearing mode activity, have been observed in a wide range of the external rotational transform. The mode structures have been analyzed by X-ray tomography, electron cyclotron emission (ECE) diagnostics and magnetic measurements. The experimental data are roughly consistent with stability calculations on the basis of a cylindrical Δ'-analysis. In contrast to the tokamak case the plasma equilibrium is maintained even after a thermal collapse enabling a recovery of plasma energy and inductive current. The improved positional stability can result in the formation of very large magnetic islands. Severe disruption-like effects may be controlled by excluding relevant rational surfaces, in particular ι = 1/2, from the outer plasma region.

1. Introduction

The elimination of current driven instabilities such as kink and tearing modes as well as internal and major disruptions by net current-free operation represents an inherent advantage of stellarator devices. The W7-AS stellarator is mainly operated in this mode achieved by generating and heating plasmas with electron cyclotron resonance heating (ECRH) and/or neutral beam injection (NBI) rather than with ohmic heating (OH). The existing OH transformer is usually utilized to drive small inductive currents up to several kA in order to cancel the bootstrap current as well as currents generated by the heating systems. Beyond this, ohmic current drive provides a tool to investigate various issues concerning the modification of equilibrium flux surfaces by toroidal currents and the effect of magnetic shear on confinement and on the MHD mode spectrum and mode stability. The assessment of potential detrimental effects due to MHD instabilities associated with significant toroidal currents in W7-AS is the main scope of this paper. The issue has been raised recently in connection with design studies for compact quasi-axisymmetric stellarator configurations, which can be considered to be hybrids between drift-optimized stellarators and advanced tokamaks [1]. In such systems the relatively large bootstrap current is intended to provide an essential contribution to the total rotational transform.

Former experiments in the ohmically heated W7-A stellarator [2] have shown that m = 2 tearing modes and hence major disruptions could be stabilized with modest external helical fields providing a rotational transform $\iota_{ext} \geq 0.15$ and accordingly a fraction $\iota_{ext}/\iota(a) \geq 0.3$, where ι_{ext} is the external rotational transform and $\iota(a)$ the total rotational transform at the plasma edge. This effect has been attributed to the improved positional stability and the shift of the relevant rational surface away from the steep current gradient region.

The current drive experiments were resumed in W7-AS in order to extend the existing disruption database by incorporating results of the advanced stellarator line. In particular, the lower aspect ratio in W7-AS compared with W7-A is considered to influence the stability of current driven modes. Also, the accessible range of the external rotational transform $(0.30 \leq \iota_{ext} \leq 0.565)$ and the plasma parameters are different in W7–AS.

2. Modification of the Equilibrium by Toroidal Currents

The achievement of plasma equilibria in currentless stellarators requires the cancellation of the line integral of the poloidal magnetic field component along a closed contour encircling the minor axis on each magnetic surface. This condition, which is a consequence of $\nabla \times \mathbf{B} = \mathbf{j} \equiv 0$ (Ampère´s law), can only be fulfilled by using non-axisymmetric configurations. Toroidal currents in such systems will affect the plasma equilibrium in two

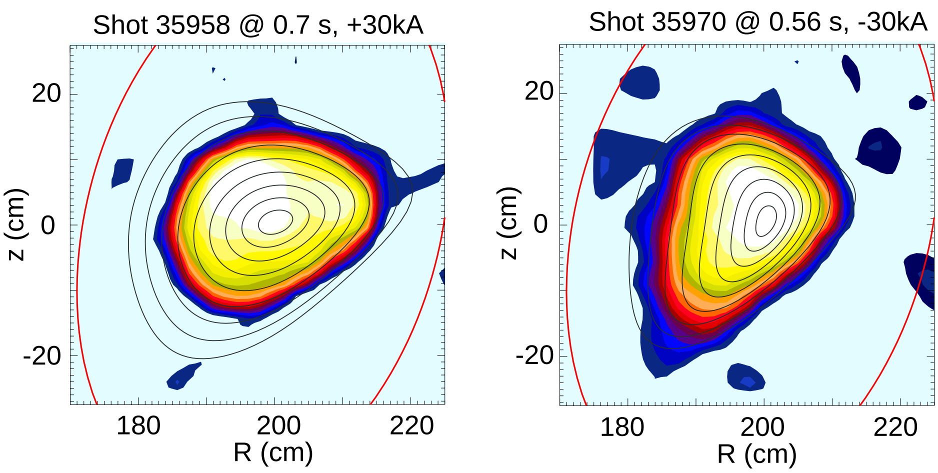

FIG. 1 Modification of flux surfaces due to inductive currents of ±30 kA (ECRH plasma at B = 2.5 T and $\iota_{tot}(a) \approx 0.4$). Emissivity contours from X-ray tomography are compared with NEMEC equilibrium calculations (black contour lines). In the case where the current increases the rotational transform (left), the axis shift is mitigated by high central ι ($\iota(0) \approx 1$) despite the peaked pressure profile. In the reversed current case (right) the pressure profile is broad due to an extended central region with very low ι ($\iota(0) \approx 0.1$) causing a noticeable outward shift relative to the shift at the edge.

ways: first, the toroidal current implies a hoop force in the direction of the major radius; and second, the change of the total rotational transform $\iota \approx \iota_{ext} + \iota_p \equiv 1/q$ leads to a change of the Shafranov shift, which scales approximately with $(1/\iota)^2$. Here, ι_{ext} and ι_p denote the transform provided by the stellarator field and by the toroidal current, respectively, and q is the safety factor. In W7-AS a constant external vertical field can be applied for horizontal position control, but it is not required even in the case of high plasma β. The effects of toroidal currents on the configuration become particularly obvious by comparing cases where the current is driven in opposite directions. An example is given in *FIG. 1*, where X-ray emission contours are compared with equilibrium surfaces calculated with the free boundary code NEMEC [3]. In addition to the changes of the flux surface geometry by toroidal currents the associated changes of the ι–profile can make a significant impact on plasma transport and MHD stability. In particular, the mutual dependence between confinement properties and the bootstrap current under the influence of rational surfaces and magnetic shear has been investigated [4]. Concerning the MHD stability, studies of the dependence of the Alfvén spectrum on magnetic shear have been made [5]. The investigation of current driven instabilities is described in the following.

3. Experiments

In W7-AS a variety of different current density and rotational transform profiles have been realized in order to assess the operational limits imposed by current driven instabilities [6]. The diagnostics of these instabilities, on the other hand, provides a tool to derive information on the current profiles, which has in particular been exploited in the case of ECCD experiments. In experiments with inductive currents we have created different low order rational surfaces varying the ratio $\iota_{ext}/\iota(a)$. The most important effects are disruption-like events associated with the rational surface $\iota = 1/2$. An example is shown in *FIG. 2*, where

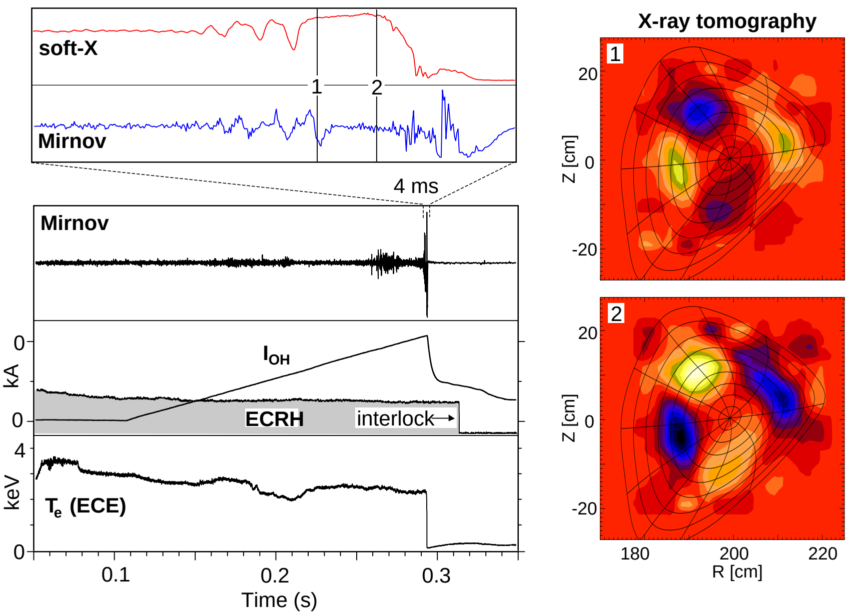

FIG. 2 Current ramp during a quasi-stationary ECRH discharge (W7-AS #47623) leads to a disruption-like event preceded by a growing rotating and locking m = 2 tearing mode. Right: Mode structure from X-ray tomography. The equilibrium X-ray profile has been removed by Fourier filtering of the raw data.

m = 2 tearing modes grow to high amplitudes within ~ 1 ms followed by a short period of mode locking leading to a very fast decay of the temperature profile (~ 0.1 ms). The current decays on a timescale of ≤ 5 ms down to a lower level, indicating that a remaining cold plasma is still confined.

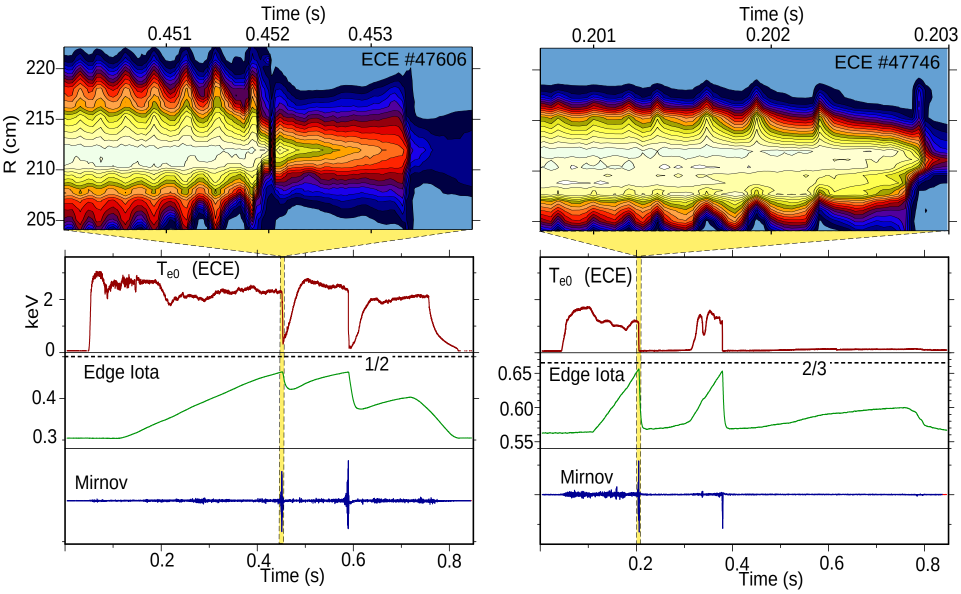

FIG. 3 Repetitive disruption-like events at ɨ = 1/2 (left) and ɨ = 2/3 (right) preceded by growing rotating and locking (m,n) = (2,1) and (3,2) modes, respectively. The ECE temperature contours (top) show the presence of modes with even and odd poloidal mode numbers before the thermal collapse. The equilibrium is maintained by the fixed external field. The increase of the edge rotational transform (middle) is due to the OH current ramp.

Similar events could be observed at ɨ = 2/3 in a few cases as illustrated in *FIG. 3*, where repetitive disruptive phenomena originating at ɨ = 1/2 and ɨ = 2/3 are compared. The signature of the precursor activity due to the (m,n) = (3,2) tearing mode is very similar to the (2,1) case as regards the mode growth during phases of mode rotation and locking. In the two ECRH discharges shown in the figure the increase of the current was limited by these effects. Typically, values of $\tilde{B}/B_0(r=a) \geq 0.1\%$ are reached for the magnetic perturbation at the plasma edge before the collapse. In other cases, in particular in the presence of rational surfaces other than ɨ = 1/2, only partial or almost no collapses were observed.

Frequently almost no rotating m = 2 modes were found in discharges where NBI heating was used. The growth rate of the modes is comparable with the rotational frequency of typically a few kHz in this case. The modes get almost immediately locked, and as a consequence of the external fields, by which the plasma position is almost kept fixed, the m = 2 islands reach a substantial size extending from the edge to a position of r/a ≈ 0.3...0.4. This leads ultimately to a fast crash indicating a direct contact of the large m = 2 islands with the limiters or the break-up of the magnetic surfaces. The last conjecture is substantiated by the measured energy and pitch-angle distribution of the energetic ions observed during the crash by the fast ion loss detector [7]. The measured energy and pitch-angle distribution of the lost ions reflects the slowing down distribution of the injected beam ions, and this cannot be explained by increased loss cone effects but rather by a field structure connecting the plasma interior with the limiter. An example of these features is shown in *FIG. 4*, which refers to a discharge,

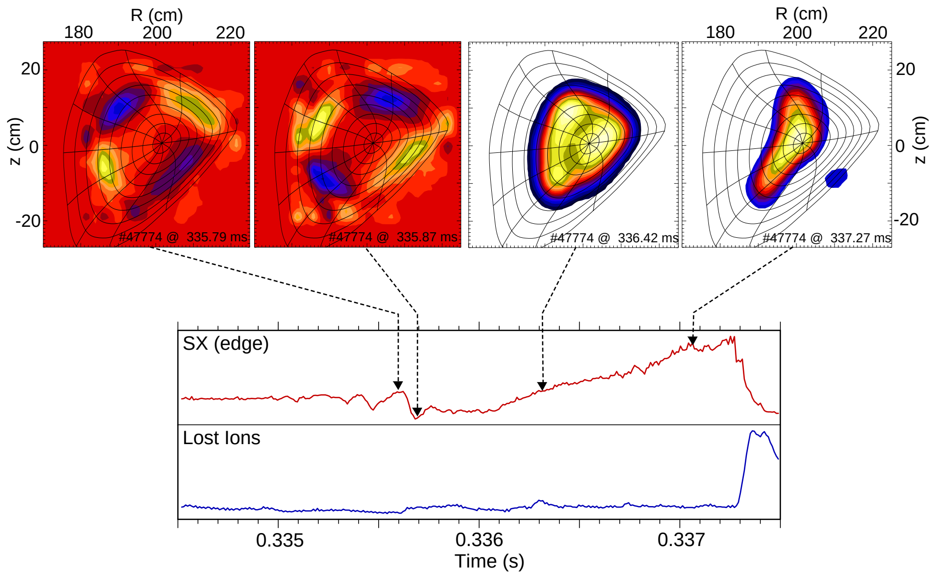

FIG. 4 Soft disruption during combined ECRH and NBI heating. The left two X-ray tomograms at the top showing solely the perturbed emissivity reveal m = 2 modes in the rotating phase. During the locked period a large m = 2 perturbation with a possible m = 3 contribution in the interior part develops, as can be recognized in the two reconstructions including the equilibrium emissivity (top right). During the temperature collapse losses of fast ions from NBI are observed (bottom).

where a partial collapse takes place during the current ramp within a phase of combined ECRH and NBI heating.

Additionally, experiments with non-inductive current drive were conducted in order to particularly investigate the effect of the bootstrap current on the MHD stability. This was accomplished by using combined heating with 0.5 MW of ECRH and 1 MW of NBI (co-injection), resulting in a maximum plasma current of ≈ 20 kA ($\cong \iota_p \approx 0.1$) that could be achieved without using the OH transformer.

The major part is attributed to the bootstrap current, and there is also a significant contribution of a beam driven Okhawa current. Although the dependence of these currents on the plasma parameters may represent a feedback mechanism causing current saturation effects in the case of increased losses, the current could be driven beyond critical values associated with the major resonances $\iota = 1/2$ and $\iota = 2/3$. The current ramp was only transiently affected by MHD effects at rational surfaces.

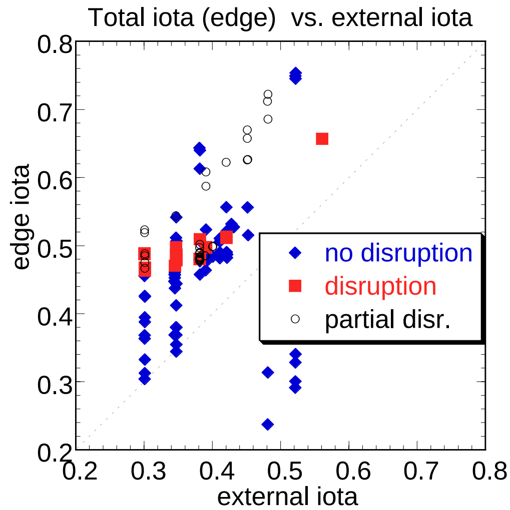

FIG. 5 Database of 137 shots (ECRH, NBI and ECRH+NBI) classified according to the absence of disruptive events, and the occurrence of large (almost complete) or small (partial) disruption-like effects, respectively. The operational diagram shows the total edge transform achieved as function of the external transform.

A summary of the present current drive experiments is given in the operational diagram shown in *FIG. 5*. The database of 137 shots covers different heating scenarios (ECRH, NBI and ECRH+NBI). The shots are represented by the boundary values of the rotational transform achieved for different values of the external transform. The experiments with reversed current drive, which were performed in order to access the rational surfaces ι = 1/3, 1/4 and 1/5 with significant currents (≥ 10 kA), are below the dotted line representing the currentless case. The shots are classified according to the absence of disruption-like events, and the occurrence of large or small disruptive effects, respectively. The strongest effects are connected with the formation of the ι = 1/2 surface in the outer plasma region in the presence of currents exceeding ≈ 10 kA.

4. Stability Calculations

Similarly as in the former examination of W7-A current profiles [2] a stability analysis on the basis of a Δ′- calculation was performed for a few typical W7-AS cases. The contribution of the bootstrap current to the total current density was roughly estimated on the basis of an axisymmetric model [4,8]. The iota-profiles were evaluated in the approximation of equilibria calculated without taking the toroidal current selfconsistently into account (i.e. flux geometry effects as shown in *FIG. 1* are neglected). Then the contribution of the toroidal current to the rotational transform was added. The Δ′–code solves the tearing mode equation for the perturbed helical flux function Ψ in cylindrical tokamak geometry [9], and therefore, the analysis may be considered to yield an estimate of the lower stability limit, since stabilizing effects due to toroidal geometry effects and pressure induced curvature effects are neglected. The tearing mode stability index Δ′, with Δ′ > 0 in the unstable case, denotes the discontinuity of Ψ′/Ψ across the resonant surface and is sensitive to the local current density gradient. The external helical field does not directly enter into the stability calculation but only through the iota-profile. The size of the magnetic islands associated with the tearing mode, and hence the

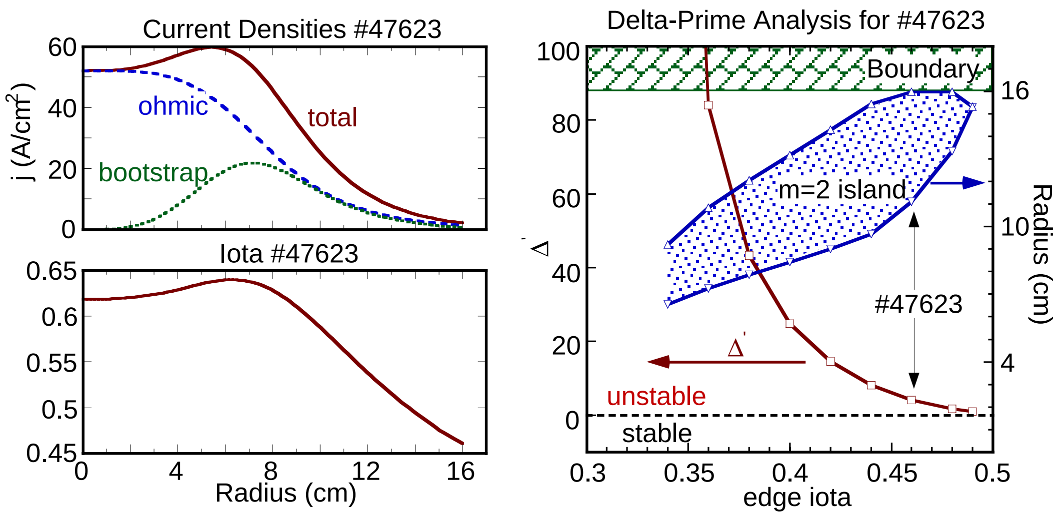

FIG. 6 Inductive current drive during 0.4 MW ECRH heating at 2.5 T and ι_{ext} = 0.35. Left: calculated current density and iota profiles just prior to the disruptive event shown in FIG. 2. The bootstrap current is estimated to contribute about 6.5 kA to the total current of 19.5 kA at this time. The (m,n) = (2,1) tearing mode is expected to be unstable as predicted by a Δ´ analysis (right). The results are given as a function of the edge rotational transform, which was varied in the calculations while maintaining the current profile of #47623. In the upper part the boundaries of the predicted islands are indicated (right scale).

strength of the magnetic field perturbations, can be assessed by using the nonlinear dependence of Δ' on the island width w, where $\Delta'(w)$ is taken across the island and the saturated island size is inferred from the condition $\Delta'(w) = 0$. The numerical results obtained in W7-A, which were in good agreement with the experimental data, could be reproduced in a benchmark test with the present version of the code.

In contrast to the results concerning ohmically heated plasmas in W7-A the calculations for W7-AS current profiles predict unstable modes in a wide parameter range even for cases with the highest values of ι_{ext}. An example of a Δ'- analysis is given in *FIG. 6* referring to the case shown in *FIG. 2* (#47623), where an almost complete thermal collapse occurred. The calculation predicts unstable (m,n) = (2,1) tearing modes in conjunction with a width of the respective island of $w \approx 5$ cm extending up to the limiter. This in agreement with an island width of 4 – 6 cm estimated from the tomographic mode reconstructions. The predicted values for $\tilde{B}/B_0(r=a)$ are generally significantly smaller than the experimental values. The figure contains a numerical scan of the external rotational transform showing that the current profile of #47623 is expected to be unstable almost in the entire range, where $\iota = 1/2$ is present in the plasma. The case where a disruption was observed coincides with the prediction of islands extending to the limiter. The nonlinear evolution of the magnetic islands has been assessed in this case by using the classical resistive MHD Rutherford equation $\tau_{\mathrm{res}}/r_{\mathrm{s}} \cdot \mathrm{d}w/\mathrm{d}t = r_{\mathrm{s}} \cdot \Delta'(w)$ [10], where $\tau_{\mathrm{res}} = \mu_0 r_{\mathrm{s}}^2/(1.22\eta)$ is the resistive time at the radius of the rational surface r_{s} and η is the neoclassical resistivity. Using the initial value $\Delta'(0) = 4.7$ the Rutherford equation yields $\mathrm{d}w/\mathrm{d}t = 28\,\mathrm{cm/ms}$ in the linear phase of the island growth which is consistent with the experimental value of $\mathrm{d}w/\mathrm{d}t = 17 - 25\,\mathrm{cm/ms}$ as derived from the growing oscillations appearing in an X-ray signal.

The most relevant cause for the different stability behaviour in W7-AS as compared with W7–A is the increased contribution of the bootstrap current in W7–AS, which leads to broader current densities and steeper gradients at the rational surfaces near the edge. Furthermore, additional heating (ECRH, NBI) in W7-AS leads to current profiles differing from those obtained in W7-A. The typical current profiles as shown in *FIG. 6* are characterized by noticeable gradients extending throughout the plasma from the hot plasma region to the edge. Therefore, a proper radial shift of the relevant resonant surfaces by means of superimposing an external helical field does not provide an effective way of stabilization, unless the resonance is expelled from the plasma.

The lack of tearing mode activity in most of the reversed OH-current experiments may be connected with the bootstrap current as well, since in this case the bootstrap current compensates the inductive current in the outer region. Hence, the width of the total current profiles along with the gradients in the outer region are reduced. In principle, the absence of current driven modes in reversed shear scenarios could be consistent with neoclassical tearing modes [11], which are expected to be stabilized in reversed shear configurations. The role of neoclassical modes particularly with regard to stellarators, where pre-existing islands have to be considered in consequence of the 3–d equilibrium configuration, is discussed in [12]. However, the experimental results are also consistent with the classical Δ'- analysis in the reversed shear case, which predicts stability against tearing modes. On the other hand the Δ'-

code predicts stability in some cases of normal shear, where tearing modes of higher mode number m (> 2) are observed. But the accuracy of the Δ'-calculations may suffer from uncertainities of the current and iota-profiles, and so far no distinct difference of growth times (generally < 1 ms) could be found, which are expected to be noticeably larger for neoclassical modes.

5. Conclusions

Current driven instabilities do not play a role in net current-free stellarator operation. Bootstrap currents, which lead to changes of the magnetic configuration and provide a source for driving instabilities, can almost be eliminated or maximized, respectively, by a proper design of the stellarator field. The studies presented in this paper are considered to support the assessment of current driven instabilities in stellarators with significant toroidal currents. The major conclusion from this work is that tearing modes causing a subsequent thermal collapse may not generally be avoided by a sufficiently high external helical field. Also, changes of the equilibrium configuration induced by currents may affect the confinement and MHD stability by the formation of rational surfaces and the modification of shear. However, in contrast to the tokamak case, where a current quench implies the progressive displacement of the current channel along with the disappearance of the confining poloidal field, the plasma equilibrium is maintained in a current carrying stellarator. Thus the effect of disruptive instabilities is significantly mitigated in hybrid stellarators, and the current may eventually be raised beyond critical values. The weaker resilience against current driven instabilities in W7–AS compared to W7–A is likely to be attributed to different current profiles resulting from a larger contribution of the bootstrap current and the power deposition of the additional heating systems. Therefore, any influence of configuration parameters such as the aspect ratio on the stability could not be verified. Most probably, deleterious effects can be avoided if $\iota = 1/2$ is kept outside the current gradient region.

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