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BOOTSTRAP CURRENT AND MHD STABILITY IN A 4-PERIOD HELIAS REACTOR CONFIGURATION

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The bootstrap current (BC) that results from the difference in frictional and viscous forces between trapped and circulating ions and electrons in magnetic confinement systems can impact the equilibrium and magnetohydrodynamic (MHD) stability properties of stellarator systems. We investigate the equilibrium and ideal MHD stability of a 4-field period Helias reactor configuration with aspect ratio 8.4 and plasma volume $1500m^3$ [1] using the three dimensional (3D) free boundary version of the VMEC code [2] and the 3D TERPSICHORE code [3] with a converged selfconsistent bootstrap current in the collisionless $1/\nu$ regime [4]. We also examine equilibria with analytic toroidal current profiles that model the behaviour of the BC that is in part or totally suppressed by counter electron cyclotron current drive (ECCD).

Converged profiles for the BC are obtained up to volume averaged $<\beta>\simeq 4.6\%$. Under free boundary conditions, the BC causes a slight outward shift and elongation of the plasma column. The pressure profile is prescribed as $p(s) = p(0)[1 - s - 0.1(1 - s^{10})]/0.9$, where $0 \le s \le 1$ is the radial variable roughly proportional to the volume enclosed. Thus, the pressure profile is nearly parabolic but with a vanishing gradient at the edge of the plasma to avoid current profile discontinuities at the plasma-vacuum interface (PVI) generated by finite BC. With this profile, the BC is hollow and peaks just outside midvolume between $s = 0.5$ and $s = 0.6$. The BC peak shifts weakly inwards with increasing $<\beta>$ as shown in Fig. 1. The BC increases the rotational transform ι at the edge from 0.96 in vacuum to almost unity without surpassing this value at relatively modest values of $<\beta>$. At $<\beta>\simeq 2.5\%$, the ι-profile is flat and close to unity in the outer 20% of the plasma volume and this extends to the outer 40% when $<\beta>\simeq 4.5\%$. The ι-profiles for the vacuum state and at finite β due to the action of the BC are displayed in Fig. 2. The toroidal component of the BC reaches $-300kA$ at $<\beta>\simeq 4.5\%$. This behaviour can have adverse implications for ideal MHD stability. Not only is the Mercier criterion destabilised, but global external modes are also predicted. Furthermore, if we artificially suppress the BC, the configuration remains unstable, but the eigenvalue is an order of magnitude smaller as shown in Fig. 3. The internal plasma potential energy δW_P can be separated into three terms, namely $\delta W_P = \delta W_{C^2} + \delta W_D + \delta W_J$ [5]. The stabilising component is δW_{C^2}, while δW_D denotes the ballooning/interchange instability driving mechanism and δW_J denotes the parallel current density $\boldsymbol{j}\cdot\boldsymbol{B}/B^2$ driving mechanism associated with global kink modes. The global mode structure that is destabilised at $<\beta>\simeq 4.5\%$ is dominantly driven by $\boldsymbol{j}\cdot\boldsymbol{B}/B^2$ as $|\delta W_J| >> |\delta W_D|$. We have found that the flux surface averaged contribution of $\boldsymbol{j}\cdot\boldsymbol{B}/B^2$ to δW_J is weak indicating that the direct contribution of the BC to the kink destabilising mechanism is small. However, the BC alters the Pfirsch-Schlüter current significantly and this provides the main driving energy for the global mode observed. The radial profiles of δW_{C^2}, δW_D, δW_P and δW_J are displayed for the full selfconsistent BC case at $<\beta>\simeq 4.5\%$ in Fig. 4. The main point that can be extracted from these results is the probable requirement of some external means for rotational transform control like ECCD in a Helias reactor.

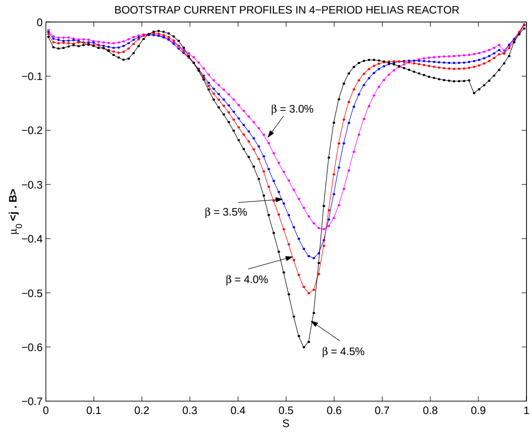

Fig. 1. The converged selfconsistent bootstrap current profiles in the collisionless $1/\nu$ regime in a 4-period Helias reactor at $<\beta>\simeq 3\%$, 3.5%, 4% and 4.5%.

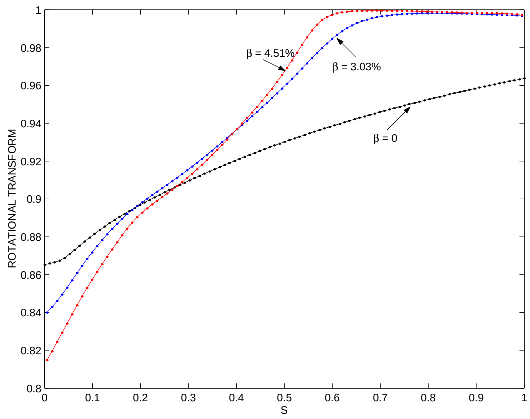

Fig. 2. The rotational transform ι-profiles in vacuum, at $<\beta>\simeq 3\%$ and at $<\beta>\simeq 4.5\%$ obtained with converged selfconsistent bootstrap currents in the collisionless $1/\nu$ regime in a 4-period Helias reactor.

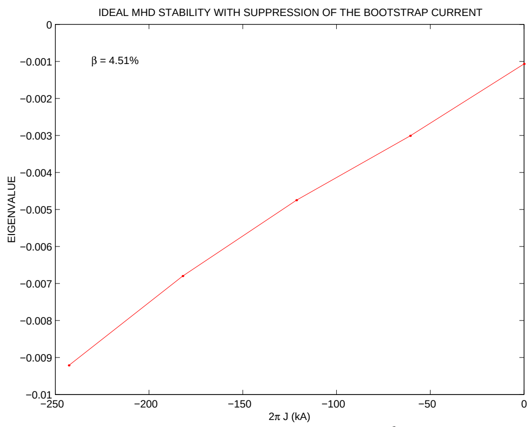

Fig. 3. The unstable eigenvalue of a global external kink mode dominated by the $m/n = 1/1$ component as function of the toroidal current as the magnitude of the BC is artificially suppressed while keeping its profile fixed.

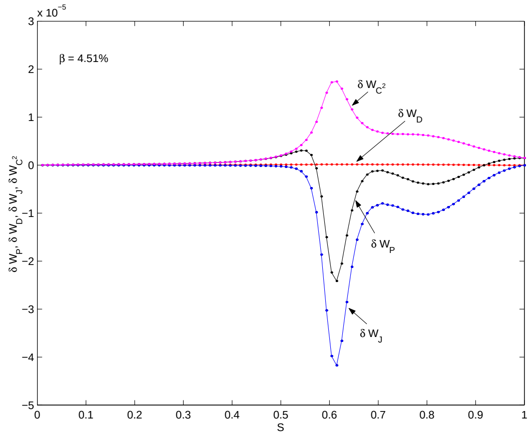

Fig. 4. The radial profiles of energy principle components δW_{C^2}, δW_D, δW_P and δW_J for the full $(-303kA)$ selfconsistent BC case at $<\beta>\simeq 4.5\%$ in a 4-period Helias reactor.

To model the combined effects of the BC with counter ECCD, we consider an analytic polynomial input toroidal current profile of the form

$$2\pi J'(s) = \frac{2310}{(1-22\alpha)} s^2(s^4-\alpha)(1-s)^4 2\pi J(1) \qquad (1)$$

where $2\pi J(s)$ corresponds to the toroidal plasma current enclosed within s and prime $(')$ denotes the derivative with respect to s. We vary both the total toroidal current $2\pi J(1)$ and α simultaneously to obtain a sequence of equilibria for which the ECCD balances the BC. Typically, $2\pi J(1) = -285, -150, -45. - 15, +15, +45kA$ for $\alpha = 0.0023, 0.0227, 0.0386, 0.0432.0.0477, 0.0523$, respectively. Note that the ECCD contribution to the current profile is not chosen to cancel the BC everywhere, but peaks at 1/4 to 1/3 of the plasma volume which can be seen in Fig. 5. This precludes parasitic edge heating. The ι-profiles corresponding to the different currents are displayed in Fig. 6. At $<\beta>\simeq 4.5\%$, the ι-profile near the edge remains close to unity for weak counter ECCD ($2\pi J(1) = -285kA$). When the ECCD globally compensates the BC, the edge-ι drops below 0.95 and for the case of overcompensation ($2\pi J(1) = +45kA$) the edge-$\iota \simeq 0.93$.

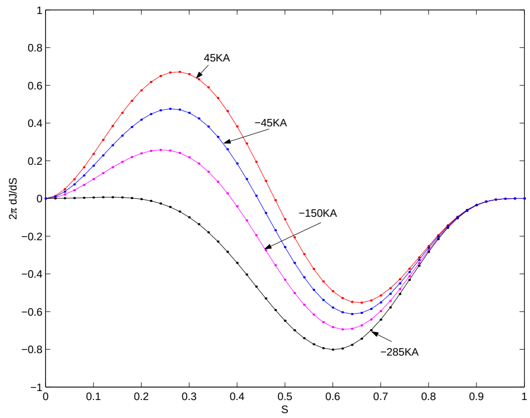

Fig. 5. Analytic toroidal current profiles that model the combination of BC and counter ECCD.

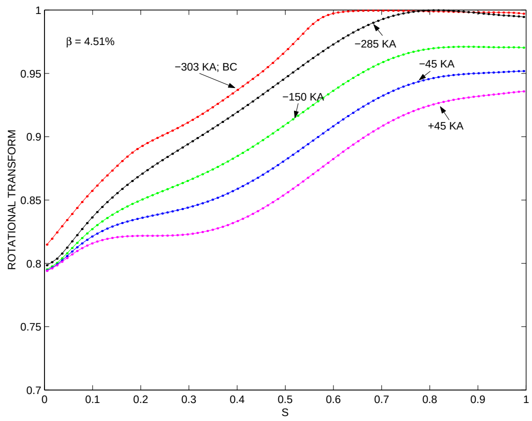

Fig. 6. The ι-profiles corresponding to the toroidal current and current profiles of Fig. 5 at $<\beta>\simeq 4.5\%$. For reference, the profile of the selfconsistent BC ($-303kA$) case is also shown.

The global external kink mode dominated by the $m/n = 1/1$ component is stabilised by the counter ECCD and the corresponding reduction in the edge rotational transform such that marginal stability conditions are achieved when the total current $2\pi J(1) \sim +40kA$. The unstable eigenvalue as a function of the toroidal current is shown in Fig. 7. The perturbed energy associated with $\boldsymbol{j}\cdot\boldsymbol{B}/B^2$ that drives the global kink mode decreases in magnitude (in absolute terms) with increasing counter ECCD (Fig. 8).

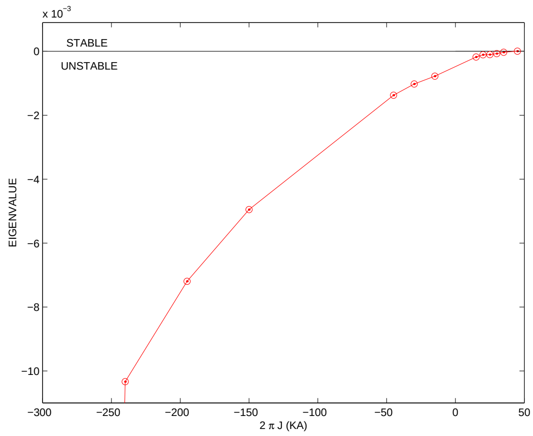

Fig. 7. The unstable global ideal MHD eigenvalue as a function of the toroidal current in a 4-period Helias reactor at $<\beta>\simeq 4.5\%$ for a model current profile that combine the vbootstrap current with counter ECCD.

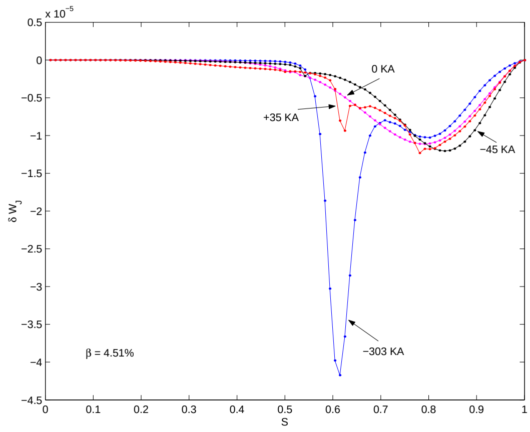

Fig. 8. The contribution of the parallel current drive δW_J to the perturbed energy at $<\beta>\simeq 4.5\%$ for model current profiles of $-45kA$ and $+35kA$, for the selfconsistent BC case ($-303kA$) and for vanishing current.

Wall stabilisation of the global kink modes has been investigated with a closely fitting conducting shell in which the average wall radius can approach the plasma within 1% (Fig. 9). For the equilibrium with selfconsistent BC at $<\beta>\simeq 4.5\%$, the unstable eigenvalue can be reduced by a factor of three with the closely fitting shell without achieving stability. For the model toroidal current profile of BC partially compensated by ECCD with $2\pi J(1) = -150kA$, a wall to plasma diameter ratio of about 1.09 is required to achieve marginality, as shown in Fig. 10.

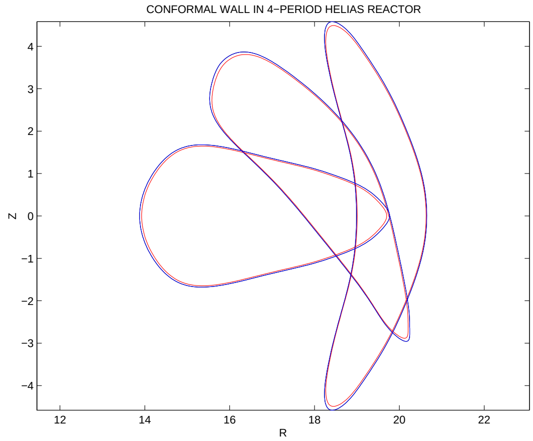

Fig. 9. The plasma-vacuum interface of a free boundary 4-period Helias reactor equilibrium at $< \beta > \simeq 4.5\%$ (in red) and a nearly conformal model conducting shell (in blue).

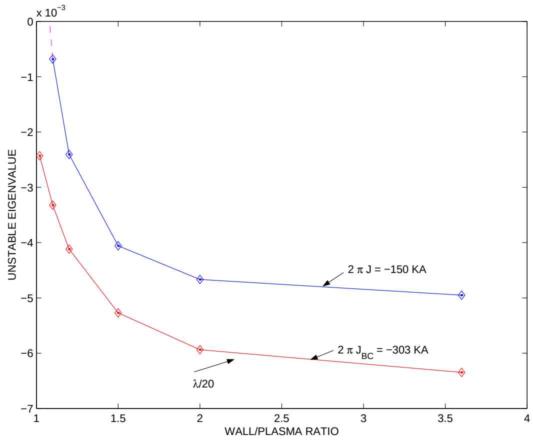

Fig. 10. The unstable eigenvalue λ of a global external kink mode in 4-period Helias reactor equilibria at $< \beta > \simeq 4.5\%$ with a selfconsistent bootstrap current $(-303kA)$ and with a model toroidal current of $-150kA$.

In summary, converged selfconsistent bootstrap current profiles computed in the collisionless $1/\nu$ regime in a 4-period Helias reactor cause a slight outward shift and elongation of the plasma column as $< \beta >$ is raised from 0 to 4.5%. The most significant impact of the BC is on the rotational transform profiles which becomes flat and approaches unity in the outer 20% of the plasma volume at $< \beta > \simeq 2.5\%$ and extends to the outer 40% at $< \beta > \simeq 4.5\%$. This destabilises the Mercier criterion and global external $m/n = 1/1$ kink modes and underscores the relevance of rotational transform profile control. Thus, a sequence of equilibria with a polynomial toroidal current profile that models the combination of BC and ECCD demonstrates that with mild ECCD overcompensation (toroidal current varied from $-300kA$ to $45kA$), the edge rotational transform is decreased from unity to about 0.93 at $< \beta > \simeq 4.5\%$ to stabilise the external kink mode. The analysis of the various contributions to the energy principle reveals that 1) the parallel current density dominates the $m/n = 1/1$ energy perturbation, 2) the direct effects of the BC and the ballooning/interchange perturbed energy are weak and 3) the BC alteration of the Pfirsch-Schlüter current constitutes the dominant driving mechanism. A closely fitting shell decreases the growth rate of the external mode by a factor of 3 for the selfconsistent BC case at $< \beta > \simeq 4.5\%$. For the model $-150kA$ toroidal current case that combines BC and counter ECCD, a wall to plasma ratio ~ 1.09 suffices to stabilise the mode.

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