Stability of Super Dense Core Plasmas in LHD

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Magnetohydrodynamic ballooning modes have long been thought to set the upper limit of normalized pressure $\beta = 2\mu_0 p/B^2$ in stellarator plasmas. As yet, however, their existence has not been confirmed experimentally, even in parameter ranges where they were expected, such as recent experiments in the Large Helical Device (LHD) in which values of β of nearly 5% were obtained [1]. It is therefore of great interest to look for specific experimental conditions in which the excitation and observation of ballooning modes might be possible.

Experiments [2] using pellet injection into reduced-recycling discharges in the Large Helical Device have yielded Super Dense Core (SDC) plasmas with very peaked density profiles, high central density $> 5 \times 10^{20}\ \text{m}^{-3}$, improved confinement, and values of β in the range of 1-2%. Figure 1 shows sample profiles of density and pressure for one these plasmas taken from Reference 1. These plasmas have good

Fig. 1. Sample density and pressure from from an SDC plasma in LHD.

confinement, and exhibit an internal diffusion barrier, whose mechanism is under study [3]. Since the maximum density in stellarators is limited only by input power, operation at very high densities $> 1 \times 10^{22}\ \text{m}^{-3}$ may make alternative reactor scenarios with low temperatures accessible.
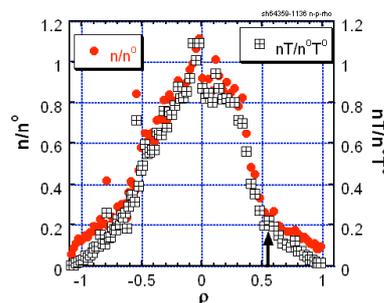
We have examined the ideal MHD ballooning stability of these LHD SDC configurations the using the 3-D COBRA stability code [3], with a model pressure profile that approximates that seen in the experiment. Figure 2 shows the radio profiles (against normalized minor radius) of rotational transform ($\iota = 1/q$, where q is the safety factor) and specific volume $V' = \int dl/B$,

where the integral is along field lines, and $V'' < 0$ corresponds to a magnetic well. The equilibria show very strong outward Shafranov shifts, a non monotonic ι profile in which the core region has tokamak-like shear ($\iota' < 0$) and a pronounced magnetic well, and surrounded by an edge or "mantle" region with stellarator-like shear ($\iota' > 0$) and a magnetic well.

COBRA calculations of ballooning growth rates (plotted in inverse Alfven times in Fig 2 show that the core region inside the zero-shear radius has direct access to second stability, i.e., the stability margin increases with β. Outside the zero-shear radius, the plasma becomes unstable to ballooning modes at average $\beta \sim 3\text{-}4\%$. Studies of the eigenfunctions show that the modes are localized in the region of bad curvature in each field period. Radially, the inner edge of the region of ballooning instability is inside the magnetic well, a further indication of the mode's ballooning (as opposed to interchange) character. Of course, resistive analogues of the modes are expected to appear at the lower β values accessed in the experiments so far.

Fig. 2. Radial profiles of finite-beta rotational transform, specific volume, and ballooning growth rate for model sequence of LHD SDC equilibria.

These MHD effects may play a role in improving core confinement, and may also provide a useful mechanism to constrain the plasma pressure in the outer plasma region and thus help maintain the favourable SDC state. Ongoing studies on LHD of radially resolved transport are expected to shed some light on this in the future.
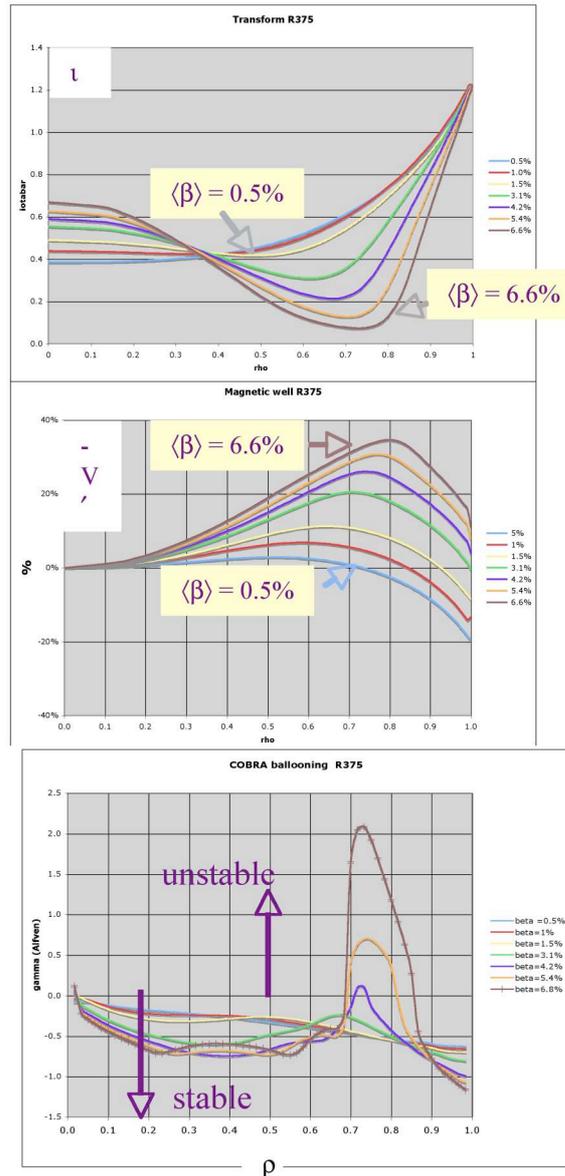
Similar studies have been carried out for the TJ-II heliac. Figure 3 shows profiles of rotational transform and ballooning growth rate for a broad pressure profile $p = p_0(1-\rho^2)$ and several different values of β. Ballooning modes appear in the outer region for modest values of volume-averaged $\beta < 1\%$, which should become accessible with the 1-2 MW of NBI expected to become available on TJ-II within the next year.
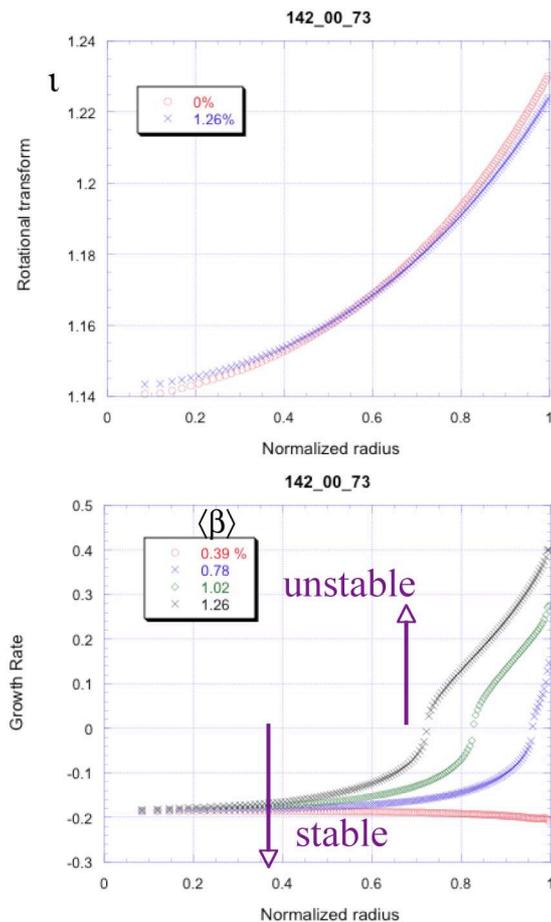
Fig. 3 Radial profiles of rotational transform and ballooning growth rate for TJ-II.

References

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