Stability of Super Dense Core Plasmas in LHD

J. H. Harris[1], R. Sanchez[1], D. J. Spong[1], N. Ohyabu[2] , K. Watanabe[2], J-A. Jimenez[1]

[1]*Fusion Energy Division, Oak Ridge National Laboratory, USA*

[2]*National institute of Fusion Science, Toki, Japan*

[3]*CIEMAT, Madrid, Spain*

Author affiliations should be centered 10-point italic type

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Recent experiments [1] 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 ~ 4.5×10^{20} m^{-3}, and improved confinement. We have examined ideal MHD stability of these SDC configurations the using the 3-D COBRA stability code [2]. These calculations 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 β ~3-4%. Of course, resistive versions of the modes are expected to appear at lower β. 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. Experiments like this in LHD and other stellarators such as the TJ-II heliac could also help elucidate the nature of ballooning modes in three-dimensional confinement systems.

Keywords: stellarator, heliotron, magnetohydrodynamic stability, ballooning modes, high-beta

1. Inroduction

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 > 5×10^{20} 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 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 > 1×10^{22} m^{-3} may make alternative reactor scenarios with low temperatures accessible.

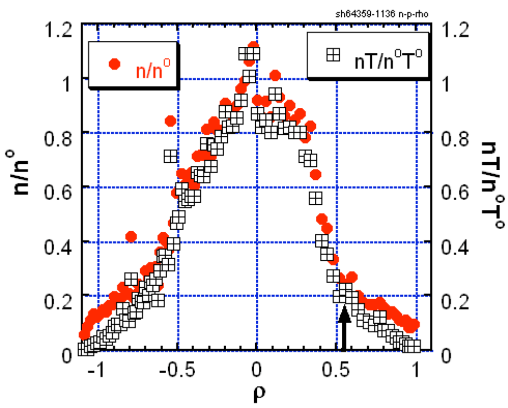

Fig. 1.Sample density and pressure profiles for an SDC plasma in LHD.

2. Stability calculations

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 $V' = \int dl/B$,

author's e-mail: harrisjh@ornl.gov

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 β ~3-4%. 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.

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.

Experience with tokamaks (TFTR) suggests that ballooning modes will be difficult to observe on external magnetic coils because of their short coherence length, so that internal diagnostics like local ECE emission will have to be used. So far, magnetic fluctuation measurements in high-beta LHD plasmas show only low mode number resistive interchanges that appear and then disappear as the plasma pressure is raised.

The non-monotonic rotational transform profile calculated for these equilibria is not surprising, but still merits experimental confirmation; the most convincing measurement would be a motional Stark broadening measurement of the poloidal magnetic field, a technique

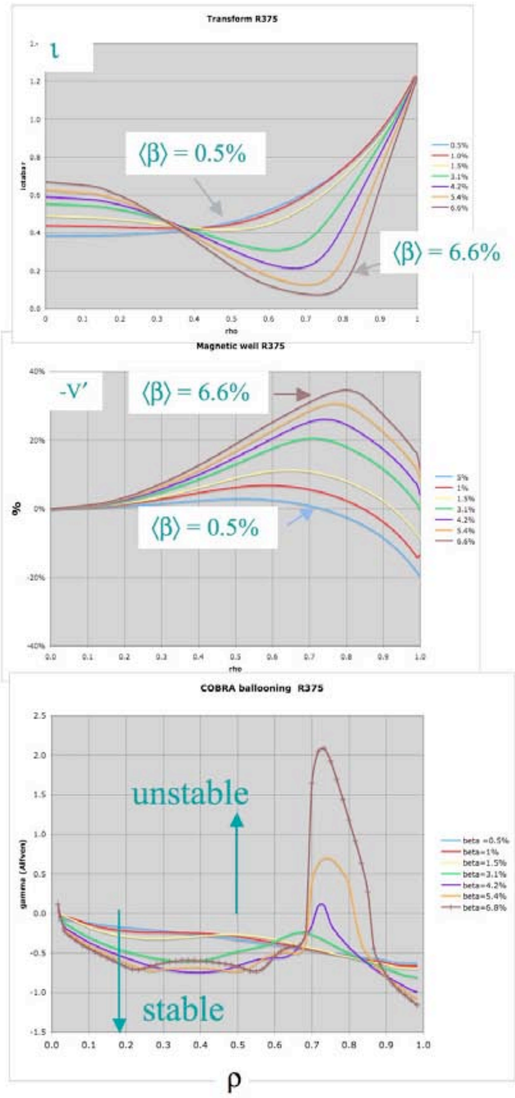

Fig. 2. Radial profiles of finite-beta rotational transform, specific volume, and ballooning growth rate for model sequence of LHD SDC equilibria.

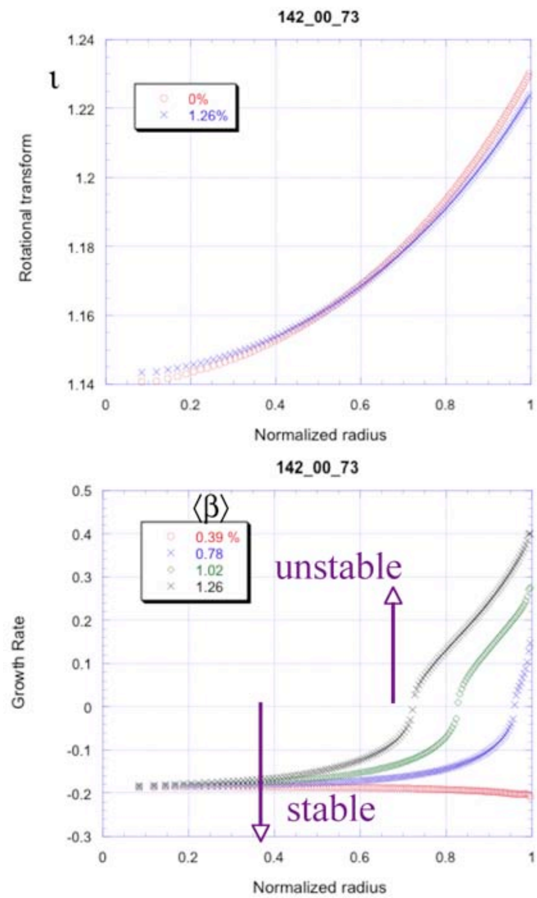

Fig. 3 Radial profiles of rotational transform and ballooning growth rate for TJ-II.

which is widely used in tokamaks, but needs to be imported to stellarators.

Similar computational studies have been carried out for the TJ-II heliac [4]. 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 neutral beam power (from injectors originally used at ORNL) expected to become available on TJ-II within the next year. Joint experiments by TJ-II and ORNL staff in 2007 have already succeeded in obtaining simultaneous operation of both injectors with a total injected power of just under 1 MW. These trials will continue when TJ-II re-commences operation in October, 2007.

3. Acknowledgements

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[1] H. Yamada, invited paper, this conference.
[2] N. Ohyabu et al, Phys. Rev. Lett. **97,** 055002 (2006).
[3] R. Sanchez et al, Comp. Phys. Comm **141**, 55 (2001).
[4] E Ascasíbar et alPlasma Phys. Control. Fusion **44,** B307 (2002).