26th EPS Conf. on Contr. Fusion and Plasma Physics, Maastricht, 14 - 18 June 1999 ECA Vol.23J (1999) 1705 - 1708

IDEAL MHD STABILITY CHARACTERISTICS OF ADVANCED OPERATING REGIMES IN SPHERICAL TORUS PLASMAS AND THE ROLE OF HIGH HARMONIC FAST WAVES

J. E. Menard, S. C. Jardin, S. M. Kaye, C. E. Kessel, J. Manickam, M. Ono, F. Paoletti[1], S. A. Sabbagh[1], T.-K. Mau[2]

Princeton Plasma Physics Laboratory, Princeton, NJ 08543-0451, USA
[1]*Columbia University, New York, NY, USA*
[2]*University of California - San Diego, La Jolla, CA, USA*

1. Introduction

The spherical torus (ST) configuration shows promise as a Volumetric Neutron Source (VNS) [1] and possibly as a net energy producing reactor [2, 3]. The ARIES reactor study group has recently completed a physics analysis of an ST-based power plant (ARIES-ST) [4], and this analysis highlights several important issues which would have to be addressed if the spherical torus is to be an efficient energy producing device. Magnetohydrodynamic (MHD) stability is a key factor in this analysis, and it is found that high normalized β and strong shaping are required to achieve the very high β necessary to compensate for resistive losses in the normally conducting toroidal field (TF) coil when the bootstrap fraction is near unity. Wall stabilization in combination with plasma rotation [5] and/or active feedback [6, 7] is essential for the ST reactor to be economical, as no-wall β limits are roughly half those of wall-stabilized cases. These stability studies also find that a broad pressure profile is optimal for stability when a conducting wall is present. At this time, it is unclear whether the heating and transport properties of burning ST plasmas are compatible with such profiles. Interestingly, however, high-harmonic fast waves (HHFW) have been proposed as a means of efficiently heating electrons in high β plasmas and will soon be tested at the multi-megawatt level (up to 6MW) in the National Spherical Torus Experiment (NSTX) [8]. At sufficiently high β, high-harmonic fast waves should damp far off-axis [9, 10], and the power deposition profile should be controllable by varying the inter-strap phasing of the NSTX 12-strap antenna. NSTX will also eventually have up to 5MW of neutral beam injection (NBI). Thus, by varying the mix of HHFW and NBI heating power, it may be possible to systematically control not only β, but also the pressure profile peaking factor (through the deposition profile) and hence MHD stability. Details of the ARIES-ST MHD stability studies are discussed in Section 2, the possible role of high-harmonic fast waves in influencing MHD stability in NSTX is discussed in Section 3, and Section 4 summarizes these results.

2. ARIES-ST MHD Stability Characteristics

Because of the inefficiency of present non-inductive current drive methods, achieving high bootstrap current fraction is critical to economical steady-state operation of a tokamak reactor. Troyon and bootstrap current scalings together imply that $\beta \propto \varepsilon^{1/2}(1+\kappa^2)(\beta_N)^2/f_{BS}$ so the most important parameters to optimize when $f_{BS} \approx 1$ are κ and β_N. Exhaustive optimizations of plasma

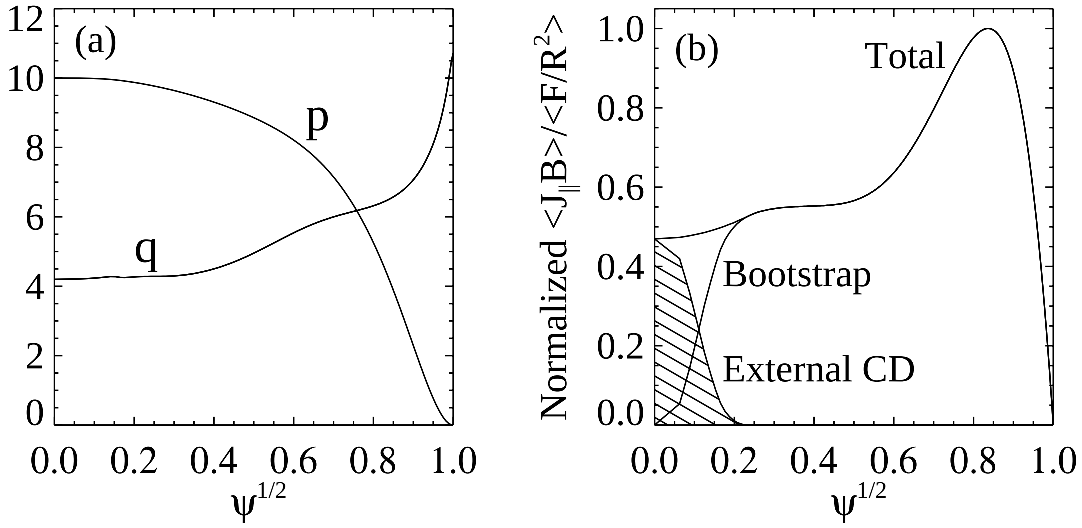

Figure 1. *Profiles of (a) safety factor q and normalized pressure p as a function of the square-root of the normalized poloidal flux and (b) surface-averaged parallel current density for the ARIES-ST reactor.*

shape, internal profiles, poloidal field (PF) coil configuration, and reactor size find that the following reactor configuration is optimal: A=1.6, κ=3.4, δ=0.65, β=50% (90% of marginal β), β_N=7.3, f_{BS}=0.95, R_0=3.2 meters, B_{t0}=2.08 Tesla, and I_p=28.5MA. Profiles of the safety factor, plasma pressure, and current density are shown in Figure 1. With regard to MHD stability, when a conducting wall is utilized to suppress external pressure-driven kink modes, a broad pressure profile optimizes stability because such a profile places the region of largest pressure gradient and largest plasma current density closest to the stabilizing influence of the wall. Under these conditions, ideal ballooning modes localized near the plasma edge limit the maximum β_N when p′ at the edge is zero. Because most of the pressure profile is in the second-stability regime, these modes are least stable near the transition back into first stability. This behavior is evident in the *s*-α [11] diagrams of Figure 2a which shows that ballooning modes become marginally stable in the vicinity of $\psi^{1/2}$=0.99. While ideal ballooning theory is a useful guide, its validity is questionable in this region where very strong E×B shear and other non-ideal effects are present [12].

Unlike ideal ballooning modes which exhibit a stability threshold reasonably well represented by a critical β_N, the wall stabilized kink modes treated here tend to be more strongly influenced by shaping parameters. The n=1 kink mode in particular is strongly influenced by the elongation and requires a stabilizing wall very close to the plasma surface for κ values only 20% larger than those used in the reactor design. Thus, even assuming that the n=0 vertical instability can be suppressed for the ARIES-ST configuration, n=1 kink modes would likely limit κ to values not much larger than already under consideration. Further, strong positive shear at the plasma edge achieved through high δ is required to keep the marginal wall-plasma separation distance reasonable. The kink marginal stability wall position as a function of toroidal mode number is plotted in Figure 2b, and it is evident that intermediate-n (n>3) modes are the modes

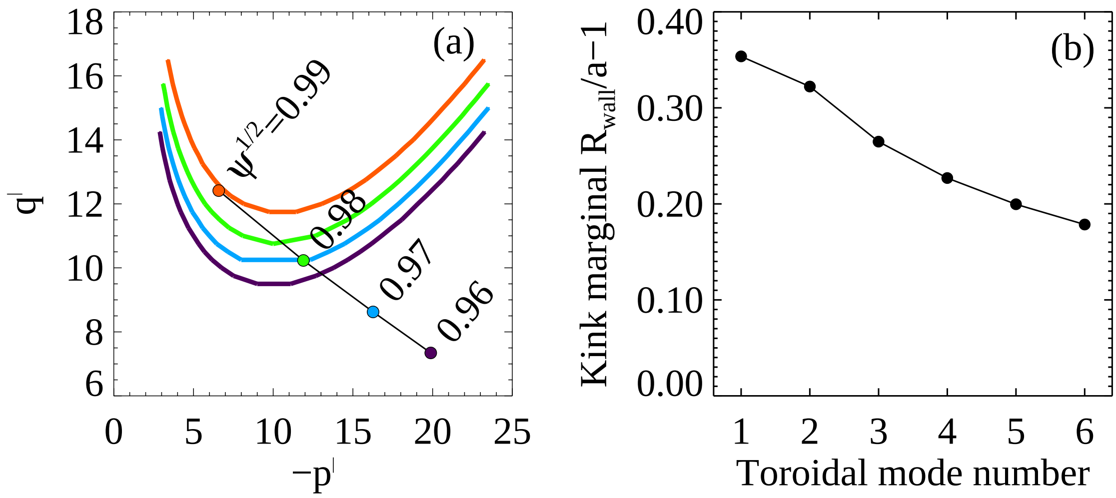

Figure 2. *(a) Ideal ballooning marginal stability (s-α) contours near plasma edge (b) kink marginal wall separation distance as a function of toroidal mode number for the ARIES-ST reactor equilibrium.*

most difficult to stabilize for these profiles. As discussed in Ref. 13, these intermediate-n modes appear to be predominantly driven by a combination of large edge-localized Pfirsch-Schluter and bootstrap currents. The importance of high δ is best understood by noting that the marginal wall position is found to decrease by roughly a factor of two for all mode numbers if δ is decreased from 0.65 to 0.35.

3. The Role of High-Harmonic Fast Waves in NSTX

As discussed in Section 2, a broad pressure profile (p(0)/⟨p⟩=1.4) as shown in Figure 1a is found to be optimal for kink stability. Thus, it is desirable to experimentally test the impact of pressure peaking factor on kink modes under similar conditions. One possible means of modifying the pressure profile is to influence the power deposition profile of auxiliary heating. The power deposition profile from NBI heating in NSTX will likely be peaked on-axis and difficult to change without changing target equilibrium parameters. High-harmonic fast waves on the other hand are predicted to damp far off-axis in high β NSTX plasmas, and both the input power and (to some extent) the deposition location can be controlled relatively easily. Thus, assuming the pressure profile is not too resilient to variations in the heating profile, HHFW injection in combination with NBI may allow real-time control of the plasma β and pressure peaking factor. In long-pulse discharges with large bootstrap current fraction, controlling both of these parameters simultaneously would also allow control of the bootstrap current profile and hence control of the entire equilibrium configuration.

Wall stabilization in combination with active feedback and plasma rotation is likely to be essential to realizing the full potential of the ST concept. NBI in NSTX will be uni-directional, so it is expected that NBI induced plasma rotation speeds will be quite fast in NSTX and should aid kink stabilization. However, for edge kink stabilization, what likely matters most is the rotation speed at the mode rational surfaces near the plasma edge. Since the NBI induced rotation may be weaker near the edge, it is not clear that central NBI alone will be sufficient to sustain the needed rotation rate [7]. HHFW may also play a role in this situation, as recent analysis shows [10] that at sufficiently high ion temperature, HHFW power can be absorbed by thermal ions at high cyclotron harmonic number. This interaction occurs predominantly with bulk ions, so while some ions will be lost, highly energetic ion tails may not be formed. Through this off-axis ion ejection it may be possible to locally enhance the radial electric field and generate toroidal (possibly sheared) $E \times B$ rotation at mode rational surfaces near the edge. While less proven than NBI heating at this point, the 6MW HHFW heating system presently being installed on NSTX may prove to be a very flexible tool for plasma profile control in addition to providing auxiliary heating and current drive.

4. Summary

The ARIES reactor study group has found an economically attractive ST-based reactor configuration with: A=1.6, κ=3.4, δ=0.65, β=50%, β_N=7.3, f_{BS}=0.95, R_0=3.2 meters, B_{t0}=2.08 Tesla, and I_P=28.5MA which yields a cost of electricity of approximately 80mils/kWh. MHD stability analysis finds that a broad pressure profile is optimal for wall-stabilizing the pressure driven kink modes typical of such configurations, and that wall stabilization is crucial to achieving the high β needed for an economical power plant. The 6MW high-harmonic fast wave system presently being installed on NSTX should allow real-time control of the plasma β, and in combination with NBI may permit experimental investigations of the effect of pressure profile peaking on MHD stability in the near-term. In the longer term, ejection of ions through resonant interaction with HHFW might be used to induce a controllable edge radial electric field with potentially interesting effects on edge MHD and confinement.

Acknowledgments

This work was supported by the United States Department of Energy under contract number DEAC02-76CHO3037.

References

[1] Y.-K. M. Peng, J. D. Galambos, and P. C. Shipe, Fus. Technol. **21**, 1729 (1992).
[2] Y.-K. M. Peng *et al.*, in *Plasma Physics and Controlled Nuclear Fusion Research 1994*, Vol. 2 of *Fifteenth conference proceedings* (IAEA, Vienna, Seville, Spain, 1994), p. 643.
[3] R. D. Stambaugh, V. S. Chan, R. L. Miller, and M. J. Schaffer, Fus. Technol. **33**, 1 (1998).
[4] S. C. Jardin *et al.*, Fus. Engin. and Design to be published (1999).
[5] D. J. Ward and A. Bondeson, Phys. Plasmas **2**, 1570 (1995).
[6] R. Fitzpatrick and T. H. Jensen, Phys. Plasmas **3**, 2641 (1996).
[7] A. M. Garofalo *et al.*, Phys. Plasmas **6**, 1893 (1999).
[8] J. Spitzer *et al.*, Fus. Technol. **30**, 1337 (1996).
[9] M. Ono, Phys. Plasmas **2**, 4075 (1995).
[10] J. Menard *et al.*, Phys. Plasmas **6**, 2002 (1999).
[11] J. M. Greene and M. S. Chance, Nucl. Fus. **21**, 453 (1981).
[12] B. N. Rogers, J. F. Drake, and A. Zeiler, Phys. Rev. Lett. **81**, 4396 (1998).
[13] J. E. Menard *et al.*, Nucl. Fus. **37**, 595 (1997).