Journal of Fusion Energy, Vol. 26, Nos. 1/2, June 2007 (© 2006)
DOI: 10.1007/s10894-006-9043-4

Recent Advances in the SPIRIT (Self-organized Plasma with Induction, Reconnection, and Injection Techniques) Concept

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Since its inception at the 1997 Innovative Confinement Concept meeting, the Self-organized Plasma with Induction, Reconnection, and Injection Techniques (SPIRIT) concept has been continuously advanced both theoretically and experimentally. The main features of this concept are: (1) formation of large-flux Field Reversed Configuration (FRC) plasmas by merging two spheromaks with opposite helicities; (2) flexibility to assess FRC stability by varying the plasma shape and kinetic parameter, by using passive stabilizers, and by injecting energetic ions; (3) sustainment of the FRC for a time significantly longer than the energy confinement time using an ohmic transformer and/or neutral beam injection. Experiments carried out in TS-3/4 and SSX and more recently in Magnetic Reconnection Experiment (MRX) have further verified the effectiveness of this formation scheme for large-flux FRCs. An improved understanding of FRC stability over plasma shape and kinetic parameter has been obtained in MRX. New numerical simulations showed that FRC plasmas can be globally stabilized by injecting energetic ions. Many of these aspects of the SPIRIT concept can be further studied in the current MRX device.

KEY WORDS: Magnetic confinement; field reversed configuration; neutral beam injection.

INTRODUCTION

Field-reversed configurations (FRCs) have significant advantages for a cost-effective, high-performance, high-power-density reactor concept [1]. Among other magnetic confinement concepts, FRC configurations offer a highest possible beta, which is crucial in achieving a cost-effective reactor. As a compact toroid, its simply-connected geometry and natural divertor allow for direct conversion of fusion energy to electric energy. There exist, however, significant scientific challenges for FRC configurations becoming a realistic fusion reactor candidate [2], in the following four critical areas: (1) development of reactor-relevant formation schemes for large-flux FRC; (2) stabilization of global scale magnetohydrodynamic (MHD) instabilities of large S^* (ratio between separatrix radius to ion skin depth) FRCs; (3) development of sustainment schemes over a time much longer than any transport times such that physics of sustainment decouples from confinement; and (4) sufficient improvement in confinement properties for favorable energetic balance.

In response to the demands in all these four areas, a new concept called Self-organized Plasma with Induction, Reconnection, and Injection Techniques (SPIRIT) has been proposed at the 1997 Innovative Confinement Concept meeting [3,4]. The

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main features of this concept are: (1) formation of FRC plasmas with large flux (50 mWb) by merging two spheromaks with opposite helicities, where the sphromaks are formed by the flux core induction scheme; (2) flexibility to assess the stability characteristics of FRC plasmas by varying plasma shape and kinetic parameter S^*, by using passive stabilizers, and by injecting energetic ions; (3) sustainment of the FRC for a time significantly longer (1–10 ms) than the energy confinement time using a center stack ohmic-heating (OH) transformer and/or neutral beam injection. Since then, significant progress has been made both theoretically and experimentally. This paper is intended to briefly summarize these advances and to provide near-future prospects on the possible experiments on Magnetic Reconnection Experiment (MRX) [5] to further advance in these areas.

FRC FORMATION BY SPHEROMAK MERGING

The traditional formation scheme of FRCs based on the theta-pinch mothod [2] suffers from difficulties in applicability to reactor-relevant devices due to the required high-voltage, pulsed operation. Alternate methods are being pursued to form large-flux FRCs in a more controlled manner. One method is based on the Rotating Magnetic Field (RMF) [6,7], which has been successfully applied for slow formation of FRCs with limited flux. Another method is based on the merging of counter-helicity spheromaks [8,9]. In TS-3, the annihilation of oppositely-directed toroidal field during merging is converted to an increase in ion temperature of up to 200 eV with a poloidal flux of up to a few mWb in a relatively small facility [9]. Recently, this technique was also successfully applied to form FRC plasmas in the SSX device [10]. More recently in MRX (see Figure 1), this method has been further verified for its effectiveness of the formation scheme for large-flux FRCs, as shown in Figure 2. It should be noted that the presence of a passive stabilizer is important to form FRCs in a repeatable and relatively stable fashion [11]. FRC plasmas with poloidal flux up to 10 mW have been obtained using only one flux-core at each end of the device in MRX. In the SPIRIT concept, double flux-core at each end of the device is proposed to achieve larger flux of formed FRC plasmas.

GLOBAL STABILITY OF FRC PLASMAS

One of the most important scientific issues in FRC research is to understand and control the stability of low-n (toroidal mode number) MHD modes. Significant progress in the theoretical understanding of FRC stability properties has been achieved in the past few years. According to an empirical scaling relation [12] based on experimental data for prolate FRCs, stability with respect to global MHD modes is achieved for $S^*/E <$ 3–4, where E is the separatrix elongation. The stabilizing effects including finite ion Larmor radius effects (ion FLR effects), the effects of the Hall term, and the effects of sheared ion flow have been considered on the $n = 1$ tilt mode in prolate FRC configurations [13–23]. These studies have resulted in significant advances in the basic understanding of FRC stability properties:

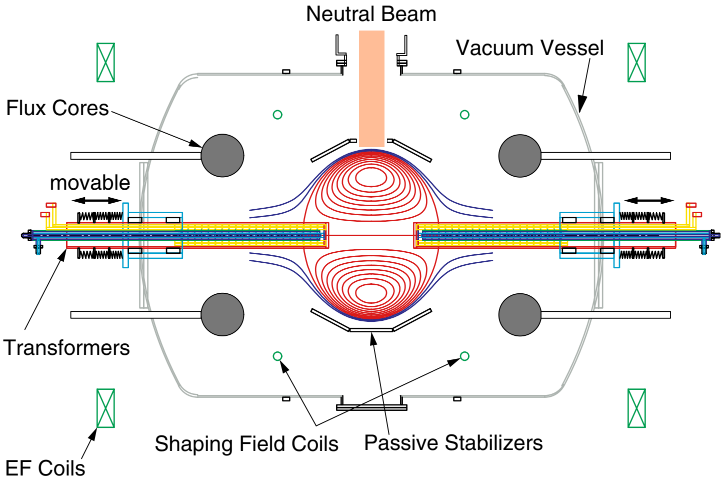

Fig. 1. Schematics of the MRX device, including a pair of current drive transformers, passive stabilizers, and neutral beam injection.

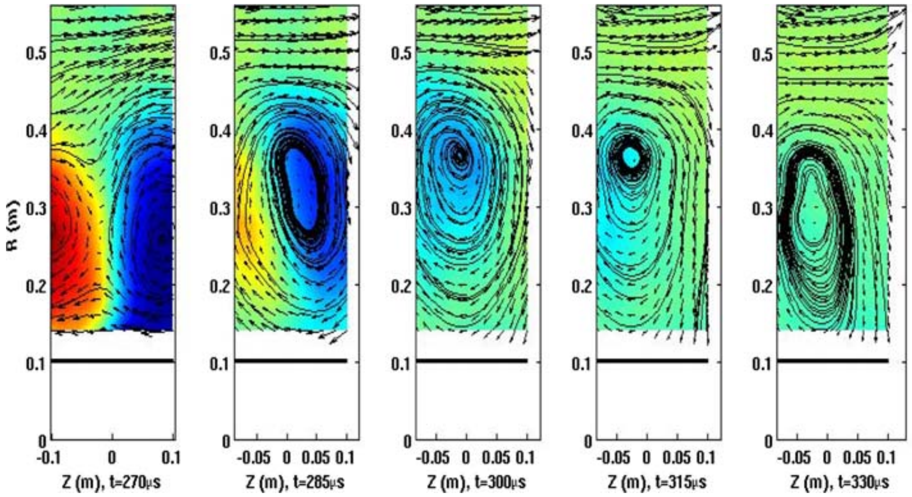

Fig. 2. Formation of large-flux He FRC by counter-helicity merging of spheromaks in MRX [11].

the role of ion FLR effects in affecting FRC stability properties has been clarified, modern relaxation theory and the properties of two-fluid flowing equilibria have been studied; effects due to resonant particles and the Hall term, and the nonlinear saturation of the $n = 1$ tilt instability has been discovered in low-S^* configurations. Figure 3 shows theoretically calculated growth rates versus E/S^* over wide ranges of parameters [20], consistent with the experimental observations [12].

The global stability properties of oblate (small elongation, $E < 1$) FRC configurations have been investigated numerically using both 3D MHD and hybrid simulations [16] in direct relation to the SPIRIT concept. It is found that the $n = 1$ tilt mode becomes an external mode when $E < 1$, and that this mode can be effectively stabilized by a close-fitting conducting shell, even in the small-Larmor-radius (MHD) regime. Interchange mode stability properties are strongly profile dependent, and all $n \geq 1$ interchange modes can be stabilized for a class of pressure profiles with a separatrix beta larger than 0.035. Our simulation results [16] show that all $n = 1$ modes can be stabilized in the MHD regime, but additional means of stabilizing the $n > 1$ co-interchange (kink) modes are required.

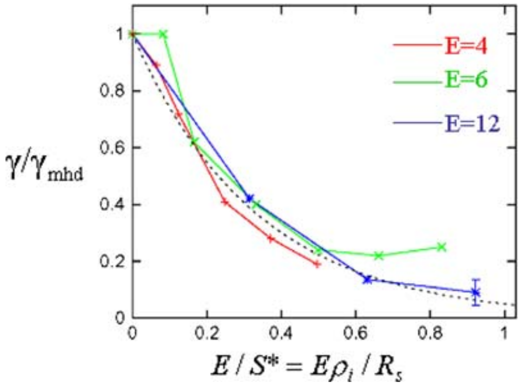

Fig. 3. Growth rates of the $n = 1$ tilt instability for three elliptical FRC equilibria with $E = 4$, 6, and 12 [20].

Injection of energetic beam ions may provide an additional stabilizing mechanism, provided that the beam ions carry a significant fraction of the total plasma current. In addition, the injection of energetic beam ions is expected to contribute to plasma heating and sustainment of the FRC configuration. A more recent numerical study of the effects of energetic beam ions on global modes in the FRC has been performed using the HYM code [24]. Linearized simulations have shown that the resonances can contribute significantly to stabilization or destabilization of the low-n kink modes depending on the beam parameters and the mode polarization. More importantly, nonlinear hybrid simulations have demonstrated that the beam-driven instabilities are not dangerous, because they saturate nonlinearly at low amplitudes by changes in the beam ion distribution function [24]. Table 1 summarizes stability properties for different stabilizing methods. It should be note that by combining conducting shell and beam ions, oblate FRC plasmas can be made completely stable against all MHD modes, as exampled by nonlinear simulations shown in Figure 4.

Table 1. Effects of Different Stabilizing Mechanisms on FRC Stability Properties

Stabilizing mechanism	Prolate FRC ($E > 1$)	Oblate FRC ($E \sim 1$)
Toroidal rotation and nonlinear effects	Unstable (the $n = 1$ tilt and higher-n MHD modes) except for long kinetic configurations with $S^* < 20$ and $E \geq 5$, with multipole field added	Unstable (the $n = 1$ tilt and higher-n MHD modes)
Conducting shell	Unstable (No effect on stability)	Unstable (Axially polarized $n > 1$ kink modes)
NBI	Unstable (the $n = 1$ tilt mode)	Unstable (Some of the $n \geq 1$ modes are stabilized depending on the mode polarization and the NBI parameters.)
NBI plus conducting shell	Unstable (the $n = 1$ tilt mode)	*Stable* (with respect to all global modes)

Guided by these extensive theoretical results, a series of experiments studying the dependence of FRC stability on the plasma shape and passive stabilization have been carried out using a conducting center column, a pair of shaping coils (see Figure 1), and an extensive set of magnetic probe arrays [11]. It is found that the passive stabilizer is not only crucial for formation of FRC by counter-helicity merging of spheromaks, but also to suppress $n = 1$ tilt and shift modes. The plasma shape is controlled largely by the shaping coils, allowing for the plasma elongation varying from a moderate oblate shape of $E = 0.6$ to an extremely oblate shape of $E = 0.35$. The plasmas stability and lifetime is significantly improved when the elongation is extremely small. The kinetic parameters S^*/E of these plasmas are relatively large, and thus, the FRC plasmas are more MHD-like. These FRCs contain a significant amount of poloidal flux (5–10 mW), which is crucial for the neutral beam injection (NBI) experiments proposed in MRX.

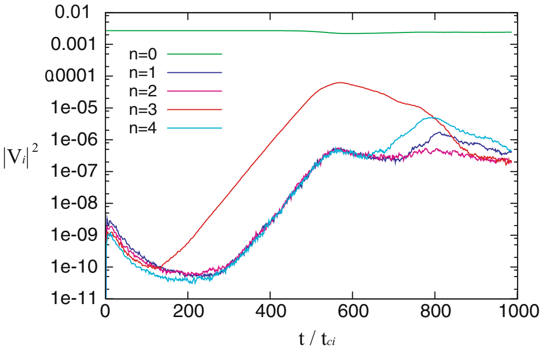

Fig. 4. Time evolution of the $n = 0$–4 components of the ion kinetic energy from 3D nonlinear hybrid simulations including the effects of a conducting shell and beam stabilization. The $n = 3$ mode is the linearly unstable mode, which saturates nonlinearly at $t = 550t_{ci}$ (apparent growth of other modes at $t = 200$–500 is due to weak numerical coupling to the $n = 3$ mode). The Alfven time is $t_A = 20t_{ci}$. [24].

CONCLUSIONS: FURTHER DEVELOPMENT OF THE SPIRIT CONCEPT IN MRX

An important method to sustain FRC plasmas against decay is by injecting energetic beam ions [25,3,4,26]. This is in contrast to the RMF method [27,28] which may be limited to current drive at the plasma edge when S^* is large. A key element of the SPIRIT concept is to incorporate neutral beams injected directly into the center region of the FRC plasmas. In order to confine such energetic ions in the center region, FRCs with large poloidal flux are required. For example, 20–30 keV hydrogen ions require flux on order of 15–20 mW [26], which is currently only possible in FRCs formed by spheromak merging. The maximum flux achieved in MRX is only a factor of 2–3 away from this value [11], which should be easily attainable with only minor upgrades. Another complementary way to sustain and/or amplify the FRC flux is to use an ohmic transformer, as demonstrated in TS-3 [29]. Currently, a prototype transformer with 50 mW in a single swing is being built for this purpose. With long-lived, stable FRC plasmas possessing large poloidal flux, the MRX facility provides an unique opportunity to further develop the SPIRIT concept using injection of a neutral beam with low energy ($<$ 40 keV) and large current ($>$ 50 A). Successful tests on stability improvement and FRC sustainment by these techniques would place the FRC concept in a much better position as a fusion reactor candidate.

REFERENCES

1. M. Tuszewski, *Nucl. Fusion*, **28**, 2033 (1988).
2. L. C. Steinhauer, *et al*., *Fusion Tech*., **30**, 116 (1996).
3. M. Yamada, H. Ji, and P. Heitzenroeder, *Proc. ICC "Innovative Approaches to Fusion Energy,"* Pleasanton, Calif. Oct. (1997).
4. H. Ji, and M. Yamada, *J. Plasma Fusion Res. Series*, **2**, 195–197 (1999).
5. M. Yamada, H. Ji, T. A. Carter, S. C. Hsu, R. M. Kulsrud, N. L. Bretz, F. C. Jobes, Y. Ono, M. Katsurai, T. -H. Watanabe, T. Sato, and T. Hayashi, *in* Fusion Energy 1996. *Proc. 16th Int. Conf., Montreal, Canada, 1996*. Paper IAEA-CN-64/CP-19.
6. I. E. Jones, and W. N. Hugrass, *J. Plasma Phys*., **26**, 441 (1981).
7. H. Y. Guo, A. L. Hoffman, R. D. Brooks, A. M. Peter, Z. A. Pietrzyk, S. J. Tobin, and G. R. Votroubek, *Phys. Plasmas*, **9**, 185 (2002).
8. M. Yamada, Y. Ono, A. Hayakawa, M. Katsurai, and F. W. Perkins, *Phys. Rev. Lett*., **65**, 721 (1990).
9. Y. Ono, M. Yamada, T. Akao, T. Tajima, and R. Matsumoto, *Phys. Rev. Lett*., **76**, 3328 (1996).
10. C. D. Cothran, A. Falk, A. Fefferman, M. Landreman, M. R. Brown, and M. J. Shaffer, *Phys. Plasmas*, **10**, 1748 (2003).
11. S. P. Gerhardt, E. Belova, M. Inomoto, M. Yamada, H. Ji, and Y. Ren, "Improved Stability of Oblate Field-Reversed Configurations through Passive Stabilization and Plasma Shaping," to be submitted to Phys. Rev. Lett. (2006).
12. M. Tuszewski, D. C. Barnes, R. E. Chrien, J. W. Cobb, D. J. Rej, R. E. Siemon, D. P. Taggart, and B. L. Wright, *Phys. Rev. Lett*., **66**, 711 (1991).
13. H. Ji, M. Yamada, R. Kulsrud, and H. Himura, *Phys. Plasmas*, **5**, 3685 (1998).
14. A. Ishida, H. Momota, and L. C. Steinhauer, *Phys. Fluids* **31**, 3024 (1988); N. Iwasawa, A. Ishida, and L. C. Steinhauer, *Phys. Plasmas* **8**, 1240 (2001).
15. E. V. Belova, S. C. Jardin, H. Ji, M. Yamada, and R. Kulsrud, *Phys. Plasmas*, **7**, 4996 (2000).
16. E. V. Belova, S. C. Jardin, H. Ji, M. Yamada, and R. Kulsrud, *Phys. Plasmas*, **8**, 1267 (2001).
17. D. C. Barnes, *Phys. Plasmas* **8**, 4856 (2001); *Phys. Plasmas* **9**, 560 (2002).
18. H. Yamada, T. Katano, A. Ishida, and L. C. Steinhauer, *Phys. Plasmas*, **10**, 1168 (2003).
19. H. Ohtani, R. Horiuchi, and T. Sato, *Phys. Plasmas*, **10**, 145 (2003).
20. E. V. Belova, R. C. Davidson, H. Ji, and M. Yamada, *Phys. Plasmas*, **10**, 2361 (2003).
21. E. V. Belova, R. C. Davidson, H. Ji, and M. Yamada, *Phys. Plasma*, **11**, 2523 (2004).
22. L. C. Steinhauer, and A. Ishida, *Phys. Rev. Lett*., **79**, 3423 (1997).
23. L. C. Steinhauer, H. Yamada, and A. Ishida, *Phys. Plasmas*, **8**, 4053 (2001).
24. E. V. Belova, R. Davidson, H. Ji, and M. Yamada, "Advances in the Numerical Modeling of Field-Reversed Configurations", to appear in Phys. Plasmas. (2006).
25. J. H. Hammer, and H. L. Berk, *Nucl. Fusion*, **22**, 89 (1982).
26. M. Yamada, H. Ji, S. Gerhardt, E. Belova, R. Davidson, and D. Mikkelsen, "SPIRIT: A Research Program for Oblate Field Reversed Configuration Formation, Stability and Sustainment Studies", to be submitted (2006).
27. A. L. Hoffman, *Phys. Plasmas*, **5**, 979 (1998).
28. S. A. Cohen, and R. D. Milroy, *Phys. Plasmas*, **7**, 2539 (2000).
29. Y. Ono, A. Morita, T. Itagaki, and M. Katsurai, *in* Plasma Physics and Controlled Nuclear Fusion Research 1992. *Proc. 14th Int. Conf., Würzburg, Germany, 1992, Vol. 2*. (International Atomic Energy Agency, Vienna, 1993), p. 619.