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AS AN ALTERNATE CONFINEMENT CONCEPT

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**STATUS OF THE FIELD-REVERSED CONFIGURATION
AS AN ALTERNATE CONFINEMENT CONCEPT**

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ABSTRACT

The status and main issues of field-reversed configuration research are briefly reviewed. The unusual fusion reactor potential of these plasmas is also described, in particular for systems that would burn D-³He fuels. The field-reversed configuration is ideal for possible use of advanced fuels because it has a very high plasma beta and because its simple geometry includes a natural divertor that should allow efficient direct conversion.

INTRODUCTION

A field-reversed configuration (FRC) is an elongated compact toroid^{1,2} that ideally contains no toroidal field. Such plasmas are generally formed in a theta pinch when a bias magnetic field is applied in the reversed direction from the main field. A typical FRC produced by this field-reversed theta-pinch method is sketched in Figure 1. One observes that the FRC consists of two distinct regions: a closed-field-line torus inside the separatrix, and an open-field-line edge layer.

Figure 1 illustrates the significant advantages of an FRC over most toroidal magnetic confinement concepts, that give promise for development into an economical fusion reactor system:

- (a) Although the closed field lines form a torus, the FRC presents a simple cylindrical geometry. This allows a similar geometry for magnet coils, vacuum chamber, and blanket and, therefore, less engineering complexity than systems with complete toroidal symmetry.
- (b) The FRC plasma is readily translatable along a cylinder by means of a weak gradient in the external solenoidal field. This property allows more efficient magnetic compression heating and a physical separation of the high technology formation from the burn and quench chambers.

(c) Because the FRC has no or little toroidal field, it has very high plasma beta ($\langle \beta \rangle$ averaged over the separatrix volume in the range 0.5-1).

(d) The edge layer structure results in a natural divertor that deposits exhaust plasma conveniently at the ends of a cylindrical system and may allow direct conversion of the charged particle fusion power.

Clearly, the above reactor advantages are only potential, and the usefulness of the FRC as a possible fusion reactor will be determined by its stability and confinement properties, which are still insufficiently understood at the present time.

STATUS OF FRC RESEARCH

Although known for about three decades, field-reversed configurations have been intensively studied only in the last ten years. Remarkable progress has occurred in recent FRC experiments, resulting in plasmas with relatively good confinement and without gross instabilities.

Most FRCs are formed by the field-reversed theta-pinch method. This formation has been substantially improved in recent years, in particular with nontearing field-line-connection techniques. However, despite relatively good success at forming FRCs, the theta-pinch approach remains a dynamic process and it is generally felt that slow FRC formation techniques (on resistive rather than Alfvén timescales) should be developed. Such work has been initiated.³

FRC equilibrium is relatively well understood theoretically and experimentally. General analytical properties for elongated FRCs have been obtained from the MHD model that provide much insight and that have been found in good agreement with experimental data and with more detailed numerical calculations. In addition, magnetic compression and translation are two important ways of modifying FRC equilibria that have been successfully demonstrated.

The typical equilibrium parameters of present FRCs are listed in Table 1.

FRC gross stability remains most intriguing: the MHD model predicts many unstable modes, in particular the internal tilt, while present experiments appear free of instabilities during the entire FRC lifetime. Tearing instabilities seem to have disappeared with more careful formation techniques² and the destructive $n=2$ rotational mode has been controlled by application of weak multipole fields.⁴ The highly kinetic nature of present FRCs may explain in part the observed stability. These FRCs are characterized by values $s \leq 2$ (s is the ratio of torus minor radius to average ion gyroradius) for which kinetic theory⁵ predicts a grossly stable behavior. The same theory also predicts a gradual transition to observable instability (internal tilt mode) for $s > 3$. However, elongation, edge layer, profile effects, conducting boundaries, Hall effects and plasma rotation are stabilizing factors that may always play some role.

Some facts seem to emerge from the available confinement data base. The energy confinement of hot FRCs is somewhat anomalous in scaling, with a magnitude intermediate between Bohm and classical. Particle transport is the dominant energy loss mechanism and there is evidence from some cross-field anomalous electron heat transport as in tokamaks. The energy confinement of various FRC experiments is compared in Figure 2 to some tokamak results. The FRC internal magnetic flux decay times are generally comparable to the particle confinement times, preventing steady-state conditions up to now.

Several important FRC research issues have emerged for future investigation:

(a) Gross FRC stability is the most crucial issue. Plasma and fusion products confinement in FRC reactor systems will probably require substantially

higher values of s than in present experiments. Such less kinetic FRCs may not be grossly stable without additional stabilization mechanisms. High-energy particles, either injected into the plasma or naturally occurring (charged fusion products) may help to retain substantial kinetic effects and overall gross stability.

(b) The scaling of FRC confinement as s increases is also a key issue. Increasing s should result in increased confinement times and reduced pressures on the separatrix, thereby allowing a much clearer assessment of FRC confinement properties. The LSX (Large s Experiment) device has been designed⁶ to produce FRCs with $s \sim 8$ and to address stability and confinement issues. Studies of electron thermal conduction and of internal flux loss at higher T_e values than in present experiments will be initiated by magnetic compression in the FRX-C/LSM device.⁷

(c) The development of new FRC formation methods is an important issue that is just beginning to be addressed.³ Such work could lead to attractive FRC sources that use power from rotating machinery instead of the pulsed power and relatively high voltages that characterize present experiments.

REACTOR STUDIES

Pulsed Systems

Several pulsed FRC reactor studies have been made. Translating systems exploit most of the FRC reactor potential. Typically, an FRC is formed in a field-reversed theta-pinch with a D-T fuel mixture and heated to ignition by magnetic compression prior to injection into and translation through a slightly tapered linear burn chamber. The first such study was CTOR,⁸ for which Figure 3 illustrates schematically the separation of formation and burn functions. The FRC motion terminates in a quench chamber where expansion directly converts internal plasma energy to electrical energy. Recently, the FIREBIRD design⁹ included into the physics model some experimental

confinement scaling laws. Both studies suggest that attractive FRC reactors are possible for $s \sim 20-40$, with burn chamber lengths of 40-100 m and net electrical powers of 0.3-1 GW.

The techniques of FRC formation, heating, and translation incorporated in the above systems have been demonstrated experimentally. In addition, these studies appear consistent with present confinement scaling laws. However, gross stability at $s \sim 20-40$ is implicitly assumed, which is a major uncertainty. One should note that translation allows moderate ($2-4 \text{ MW/m}^2$) wall loading. If higher wall loading (by about an order of magnitude) is felt acceptable, stationary systems such as TRACT or LINUS are possible.¹⁰

Steady-State Systems

Although a detailed steady-state FRC reactor study has yet to be made, there has been a recent growing interest in that direction.¹¹⁻¹⁵ In addition to the attractiveness of a steady-state system, the main motivations are enhanced FRC stability and the possible use of advanced fuel cycles. The FRC plasma current would be sustained by neutral beam injection, in a manner similar to that conceived earlier^{16,17} for the closely-related Field-Reversed Mirror (FRM). Figure 4 illustrates the basic FRM concept. Gross plasma stability might be achieved with $s \leq 10$ and with a high energy tail in the ion population maintained by the beams.

In the 2XIIB device, the formation and sustainment of an FRM was attempted.¹⁸ Field reversal was probably not achieved, for reasons that remain unclear. However, subsequent studies suggest that plasma currents could be driven with neutral beams by introducing either an impurity ion species¹¹ (the Ohkawa effect) or by application of weak multipole fields.¹⁹ With either method, one could perhaps sustain an FRC or even attempt a slow FRC

formation and build-up. Such experiments have not yet been undertaken. Hirano demonstrated¹¹ that only a small amount of Ohkawa current is needed at the field null to induce and sustain the bootstrap (diamagnetic) current of a high beta FRC. However, as in earlier FRM studies,^{16,17} this implies low s values: the required seed current appears comparable¹³ to the plasma current for $s \geq 10$. This requirement may be lowered because most charged fusion products are confined for relatively large s values, and their preferential trapping in velocity space¹⁴ may produce a substantial current.

D-³He Steady-State Systems

The D-³He fuel cycle has long been recognized as one of the most attractive for generating clean fusion energy. Other deuterium-based advanced fuels such as Catalyzed-D and D-D-³He have similar confinement and temperature requirements for ignition, but do not reduce as much the 14 MeV neutron production.¹² The p-¹¹B fuel cycle also appears desirable for clean fusion energy, but requires temperatures around 500 keV for ignition, and radiation losses appear to prevent ignition at such temperatures.¹² However, until recently, the use of D-³He was not considered (except in generator-satellite systems) because of the lack of abundant natural ³He on earth. This situation has changed with the discovery of a large resource of ³He embedded in the moon surface that can be accessed by lunar mining.²⁰

The FRC is ideal for use of the D-³He fuel cycle.²¹ Its high plasma beta and power density allow substantial reactivity, little radiation losses, and most of the fusion power in the form of 14.7 MeV protons. These charged particles can be diverted in the FRC edge layer towards electrostatic direct converters, resulting in very high plant efficiencies. These attractive features are illustrated in Table 2, where the approximate parameters of a 1 GW FRC reactor are

compared for a pulsed D-T system such as CTOR⁸ and for a conceptual steady-state D-³He system.²¹ One observes that the 14 MeV neutron production with D-³He can be reduced by about a factor 100 compared to that of a D-T system. Another (possibly crucial) advantage of the D-³He system is that gross FRC stability may be achieved at $s \sim 10$ with the help of high energy neutral beams, large-orbit protons, and possibly larger plasma elongations. This may not be the case for the D-T pulsed system at $s \sim 30$, in spite of the alpha particles.

Table 2 also reveals some disadvantages in using a D-³He rather than a D-T fuel cycle. The desirable operating temperature is higher by about an order of magnitude. Hence, plasma heating appears a formidable and costly engineering task for the D-³He case. However, the alpha particles produced by D-T reactions may be of considerable help and many studies^{17,22-24} indicate the possibility of a gradual transition from D-T to D-³He during the start-up phase. This phase would also include FRC formation and heating to D-T ignition by magnetic compression, in a way similar to that of the pulsed D-T system. The increased complexity of the D-³He start-up would be largely compensated by its less frequent use, compared to a repetitively-pulsed D-T system.

The higher confinement parameter ($n\tau_E \sim 10^{21} \text{m}^{-3}$) required by the D-³He cycle is another disadvantage. The required values of $n\tau_E$ and τ_E are listed in Table 2. The required τ_E are to be compared with the values τ_{Ea} based on (Lower-Hybrid-Drift) anomalous transport and with the classical values τ_{Ec} . Present FRC confinement is approximated reasonably well by $\tau_{Ea} \sim \tau_N/2$, where τ_N is obtained from a steady-state particle transport model.²⁵ Table 2 indicates a modest (factor 3) discrepancy between τ_E and τ_{Ea} for the D-T case, but a rather large discrepancy (factor 100) for the D-³He case. The latter

comes mostly from the smaller s value (calculations²³ yield $\tau_E \sim \tau_{Ea}$ for $s \sim 40$).

Anomalous transport may be minimized with smooth FRC pressure profiles.²² Such profiles can be obtained in part²⁵ with lower $\langle \beta \rangle$ values. For such cases, the overall plant efficiency may not be decreased much if the increased synchrotron radiation can be used to heat the gas/alkali mixture of an MHD generator.²⁶ Curiously, anomalous transport may perhaps be suppressed even more efficiently if $\langle \beta \rangle$ can approach unity with sufficient plasma heating power.²⁷ Then, the FRC energy confinement is believed to become independent of internal local properties such as anomalous transport. Future research should clarify the physical basis of this very attractive feature. In any case, anomalous transport does not need to be completely suppressed since the values τ_{Ec} in Table 2 indicate that substantial anomalies can be tolerated.

CONCLUSIONS

Field-reversed configurations offer an unusual fusion reactor potential with a simple geometry, demonstrated translatability, very high plasma beta, and a natural divertor. In addition, present FRCs appear to have relatively good confinement and to be free of gross instabilities. Several FRC reactor studies have been made, for pulsed systems based on the above favorable properties. However, stability might be a limiting factor for such less kinetic FRCs. Recently, there has been a growing interest in FRC reactor systems similar to the closely-related Field-Reversed Mirror. High-energy particles, either beam-injected or naturally occurring, could provide steady-state operation and gross stability of relatively small FRC plasmas. Such systems may also exploit the ideal FRC attributes for advanced fuels, in particular for the D-³He fuel cycle. However, their development depends

on a successful compromise between stability and confinement requirements.

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Table 1. Typical parameters of present FRCs

n	(m^{-3})	$(1-5) \times 10^{21}$
B	(T)	0.5-1
T_e	(keV)	0.1-0.2
T_i	(keV)	0.1-1
r_s	(m)	0.05-0.2
$l_s/2r_s$		3-10

Table 2. Approximate parameters of a 1 GW FRC reactor

system	Pulsed ⁸	Steady-State ²⁰
fuel requirement	D-T T breeding	D- ³ He 50 kg/y ³ He
Plant efficiency	0.4-0.5	0.7-0.8
14 MeV neutrons(GW)	2	2×10^{-2}
r_s (m)	1	1
n (m^{-3})	3×10^{21}	10^{21}
T (keV)	10	100
B (T)	6	9
s	30	10
$\langle \beta \rangle$	0.7	0.9
$n\tau_E$ ($m^{-3}s$)	2×10^{20}	10^{21}
τ_E (s)	6×10^{-2}	1
τ_{Ea} (s)	2×10^{-2}	10^{-2}
τ_{Ec} (s)	30	10^3

REFERENCES

1. W.T. ARMSTRONG et al., "Field-Reversed Experiments (FRX) on Compact Toroids", *Phys. Fluids*, **24**, 2068 (1981).
2. M. TUSZEWSKI, "Field-Reversed Configurations without Toroidal Field", Review Article accepted for publication in *Nucl. Fusion* (1988).
3. Z.A. PIETRZYK et al., "Initial Results from the Coaxial Slow Source FRC Device", *Nucl. Fusion*, **27**, 1478 (1987).
4. S. OHI et al., "Quadrupole Stabilization of the $n=2$ Rotational Instability of a Field-Reversed Theta-Pinch Plasma", *Phys. Rev. Lett.*, **51**, 1042 (1983).
5. D.C. BARNES et al., "Kinetic Tilting Stability of Field-Reversed Configurations", *Phys. Fluids*, **29**, 2616 (1986).
6. A.L. HOFFMAN et al., "Design of a Large s FRC Experiment", *Proc. 8th US-Japan Workshop on Compact Toroids*, Osaka, Japan, November 21-22, 1986, p. 73.
7. D.J. REJ et al., "A 1-GW FRC Compression-Heating Experiment", *Proc. 8th Symp. on the Physics and Technology of Compact Toroids*, University of Maryland, June 4-5, 1987, p. 167.
8. R.L. HAGENSON and R.A. KRAKOWSKI, "A Compact Toroid Fusion Reactor Based on the Reversed Field θ -Pinch", *LA-8758-MS*, Los Alamos Scientific Laboratory (1981).
9. G.C. VLASES et al., "Design of a Translating Field-Reversed Configuration Reactor", *Fusion Technology*, **9**, 116 (1986).

10. R.A. KRAKOWSKI et al., "Reactor Systems Studies of Alternative Fusion Concepts", *Proc. 8th Int. Conf. Plasma Physics and Controlled Nuclear Fusion Research*, Brussels, Belgium, July 1-10, 1980, Vol. 2, p. 607, IAEA, Vienna (1981).
11. K. HIRANO, "A Steady-State Axisymmetric Toroidal System", *Nucl. Fusion*, **24**, 1159 (1984).
12. H. MOMOTA et al., "Advanced Fuels in a Field-Reversed Configuration", *Fusion Technology*, **11**, 436 (1987).
13. M. OKAMOTO, "A Steady State Solution To a Field-Reversed Configuration", *Nucl. Fusion*, **27**, 833 (1987).
14. H.L. BERK, H. MOMOTA, and T. TAJIMA, "Plasma Current Sustained by Fusion Charged Particles in a Field-Reversed Configuration", *Phys. Fluids*, **30**, 3548 (1987).
15. R.E. SIEMON, "Workshop on Steady State Compact Toroids for Fusion Systems", to be published in *Comments on Plasma Phys. Controlled Fusion*, **12**, (1989).
16. G.A. CARLSON et al., "Conceptual Design of the Field Reversed Mirror Reactor", UCRL-52467, Lawrence Livermore National Laboratory (1978).
17. J.G. GILLIGAN, G.H. MILEY, and D. DRIEMEYER, "Conceptual Design of a Compact Field Reversed Mirror Reactor--SAFFIRE", *Proc. 4th Topical Meeting on the Technology of Controlled Nuclear Fusion*, King of Prussia, Pennsylvania, October 14-17, 1980, Vol. 2, p. 840, EPRI (1981).
18. T.C. SIMONEN et al., "2XIIIB Plasma Confinement Experiments", *Proc. 7th Int. Conf.*

Plasma Physics and Controlled Nuclear Fusion Research, Innsbruck, Austria, August 23-30, 1978, Vol. 2, p. 389, IAEA, Vienna (1979).

19. J.H. HAMMER and H.L. BERK, "A Steady-State Beam Driven Field Reversed Mirror", *Nucl. Fusion*, **22**, 89 (1982).
20. L.J. WITTENBERG, J.F. SANTARIUS, and G.L. KULCINSKI, "Lunar Source of ^3He for Commercial Fusion Power", *Fusion Technology*, **10**, 167 (1986).
21. H. MOMOTA et al., "D- ^3He Fuels in a Field-Reversed Configuration", *IPPJ-855*, Nagoya University (1987).
22. G.H. MILEY, "Compact Tori for Alternate Fuel Fusion", *Nucl. Instrum. Methods*, **207**, 111 (1983).
23. V.A. BURTSEV, V.M. KOZHEVIN, and A.N. MAKHANKOV, "Reactor Aspects of the Compact Toroid Based Thermonuclear System", *Proc. 4th Meeting and Workshop on Fusion Reactor Design and Technology*, Yalta, USSR, May 26-June 6, 1986, Vol. 1, p. 413, IAEA, Vienna (1987).
24. M. OHNISHI et al., "Self-ignition of an Advanced Fuel FRC Reactor by Fusion Product Heating", *Fusion Technology*, **12**, 249 (1987).
25. M. TUSZIEWSKI and R.K. LINFORD, "Particle Transport in Field-Reversed Configurations", *Phys. Fluids*, **25**, 765 (1982).
26. R.B. CAMPBELL, M.A. HOFFMAN, and B.G. LOGAN, "Microwave Superheaters for Fusion", *Proc. 12th Symp. on Fusion Engineering*, Monterey, CA, October 12-16, 1987, Vol. 2, p. 909, IEEE (1987).

27. **K. HIRANO, "A Self-Consistent Modeling of a Quasi-Steady State Compact Torus Evolving to Ignition", *IPPJ-801*, Nagoya University (1986).**

Figure 1. The Field-Reversed Configuration (FRC)

Figure 2. Values of nT_i as functions of T_i for several FRC and tokamak experiments.

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Figure 3. CTOR: a pulsed FRC reactor study.

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Figure 4. The Field-Reversed Mirror (FRM).