FEATURES OF FORMATION, CONFINEMENT AND STABILITY OF THE FIELD REVERSED CONFIGURATION

Sergei V. Ryzhkov

Bauman Moscow State Technical University

2nd Baumanskaya Street, 5, Moscow, 105005 Phone: (095) 263-65-70

E-mail: ryzhkov@power.bmstu.ru

The field reversed configuration (FRC) is an innovative confinement system that offers a unique fusion reactor potential because of its compact and simple geometry, transport properties, and high plasma beta. Brief review of the simple compact system with natural advantages and reactor potential is given. Theoretical and experimental results in a FRC plasma study are discussed. Last results in compact toroids research are presented which advance the understanding of the formation and stability properties of the field reversed configuration. Confinement properties of oblate (*Elongation*<1) and prolate (*E*>2) FRCs (elliptic shape and racetrack) are discussed. Numerical study is overviewed.

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INTRODUCTION

Field reversed configuration (FRC) is a system with open and closed magnetic field lines separated by separatrix that confines fuel ions and fusion products. The axial field inside the reactor is reversed (as compared to the externally applied magnetic field) by azimuthal plasma current. This open system has toroidal confinement, but the magnetic field has poloidal component only. The FRC is being investigated as an alternative to the tokamak, as a means of fueling a tokamak and as a propulsion/power source for deep space missions. Previous work [1-4] indicates that a FRC would be a very attractive fusion power plant.

Notable experimental results include: improved confinement and sustainment are carried out; rotating magnetic field for current drive is applied; hotter, denser and longer lived plasma is achieved and important measurements are made. Impressive results in FRC research plus good accessibility and low cost encourage to say about the system of interest for an advanced fuel fusion reactor as a future practical fusion power plant. But fusion plasma parameters in FRC still no achieved. So, in order to achieve them it is necessary to solve following problems: decreasing of transport in plasma and increasing of lifetime of magnetic configuration.

FORMATION

Theta-pinch formation of FRCs has been used successfully in early experiments. Viable FRC startup and sustainment methods - RMF current drive and merging spheromaks - are being examined recently.

It has been proposed that the externally applied rotating magnetic field (RMF) will keep the reversed configuration in steady state [5,6]. Recently, several experiments have shown [e.g. 7] that RMF technique can be applied to FRCs, both as a formation and a sustainment mechanism. In addition, the application of RMF, specifically to FRC, has been studied theoretically [8,9] and numerically [10,11].

Parameter often used to characterize an RMF equilibrium is ζ. This parameter represents the ratio of the equilibrium line current density, to the maximum possible synchronous line current density (corresponding to all the electrons co-rotating with the RMF). Normally ζ is found to be in the range $0.3<\zeta<0.7$. If $\zeta\rightarrow 1$ the equilibrium will be lost, because at that point the RMF starts to slow the electrons down. However a $\zeta=1$ plasma with full penetration could be stably sustained if end mirrors were used to continue the FRC length.

RMF current drive for startup and sustainment has been recently tested on the Star Thrust Experiment (STX) and Translation, Confinement, and Sustainment (TCS) experiments (University of Washington). Significant progress has been made in detaching the separatrix completely from the wall by the flux conserver equipped outside of the quartz chamber. It is shown that the quasi-steady equilibria may be achieved by RMF. Future research will extend these results towards realizing hotter, denser and longer lived FRC by increasing the magnetic flux by the RMF. Partial penetration (a little beyond the field null) is observed in the present experiments. Inward radial flow is predicted and measured. The role of inward flows will be studied in near future.

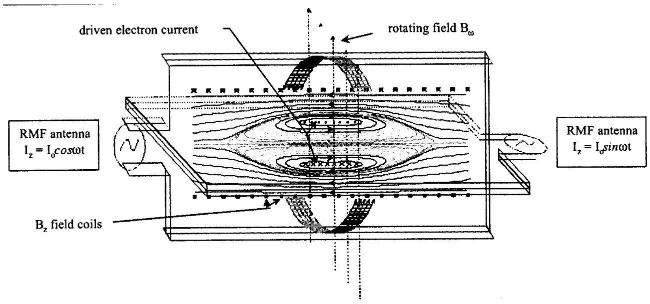

Fig. 1. RMF antenna surrounding an FRC plasma

Recent experiments have scaled up rotating magnetic field current drive in a fully ionized FRC plasma. This not only demonstrates one solution to the FRC current drive problem, but unexpectedly, RMF also quites internal magnetic fluctuations and greatly increases energy and particle confinement times. Improved confinement is also observed by using end mirror coils and neutral beam injection at Osaka University on the FIX (FRC Injection eXperiment) facility [12].

CONFINEMENT

See Ref. [13] for details of the remaining particle and power balance equations. The electron power balance is solved to obtained a self-consistent electron temperature. The power losses are due to charged particle transport, neutrons, synchrotron radiation and bremsstrahlung have been estimated.

It is shown that anomalous transport in plasma consisting of large orbit non-adiabatic ions and adiabatic electrons can be avoided. Moreover, new model of radial transfer is just beginning to be investigated [14]. A new model of anomalous transport is developed especially for FRC. The main features of this model are taking into account complex field of drift waves propagating in plasma and analysis of motion of the particles interacting with field fluctuations.

Recent theoretical and experimental advances suggest that stable, low-transport-rate FRCs may indeed exist. Numerical studies show stabilization of tilt and shift modes in oblate FRCs by a close fitting conducting shell. However, oblate FRCs with no nearby wall are not simultaneously stable to both tilt and shift. Furthermore, hybrid simulations reveal near stabilization of the tilt by a combination of spontaneously generated weak toroidal magnetic fluxes and associated strong poloidal ion flows in the absence of a nearby conducting boundary. Axisymmetric resistive MHD simulations of spheromak merging [15] have been performed and simulations using the MHD field data was used to track particle orbits [16].

Recent 3D hybrid code (kinetic ions and fluid electrons) calculations show a stabilization of the tilt in an FRC correlated with self generation of oppositely directed toroidal flux ropes. Simulations [17] have shown that there is a reduction in the tilt mode growth rate in the kinetic regime, but no absolute stabilization has been found for s <1. Also two-dimensional evolution of the reconnection has been studied.

Experimental studies in recent years have addressed various FRC-related topics at Tokyo University, the TS-3 and 4 devices [18], in the TRAP [19] experiment, in the Cornell Field Reversed Ion Ring Experiment, FIREX, on FRX-L (Field Reversed eXperiment, Liner) at Los Alamos National Laboratory in Magnetized Target Fusion [20] implosion experiments, and the Swarthmore Spheromak Experiment (SSX-FRC) [21].

Typical FRC parameters achieved in experiments are summarized in Table 1.

Table 1

Separatrix radius, r_s	0.03 - 0.40 m
Separatrix length, l_s	0.2 - 1 m
Electron density, n_e	0.005 - 5 x10^{21} m^{-3}
Ion temperature, T_i	0.03 - 3 keV
Electron temperature, T_e	0.03 - 0.5 keV
External B-field, B_e	0.05 - 2 T
Average beta, $<\beta>$	75 - 95 %
Energy confinement time, τ_E	0.05 - 0.5 ms

STABILITY

The parameter most often used to characterize FRC stability is s, the average number of gyroradii radially between the 0-point (null field point) and the separatrix. Power plants will require $s > 20$ and perhaps even higher, while experiments have operated only with $s \leq 8$.

More recently, an empirical criterion, the so-called S^*/E stability scaling has been useful for making some projections to delineate FRC stability regimes, where $E \equiv L_s/r_s$ is the plasma elongation, and S^* is defined by $S^* \equiv r_s \omega_{pi} /c$, where $L_s \equiv$ separatrix length, c ≡ speed of light and $\omega_{pi} \equiv$ ion plasma frequency. S^* is based on the maximum density, and the average density inside the separatrix is a large fraction (i.e. $< \beta > \approx 0.9$) of the maximum. The S^* parameter is preferable to use as a radial size index from two points of view: 1) it is based on the natural length scale of two-fluid analysis, c/ω_{pi}, which is comparable to the ion gyroradius for $\beta \approx 1$; and 2) it less unambiguous since density is routinely measured and relatively easily measured. The size parameter s is more difficult to calculate, because the ion temperature must usually be inferred.

The S^*/E scaling is based on the assumption that the magnetohydrodynamic (MHD) growth rate varies as$\approx E^{-1}$. This scaling combined with a "reactive" effect from Hall effects or FLR (which is independent of E) gives the condition $S^*/E \equiv const$ for marginal stability. Recent works that certain pressure profiles allow the favorable “1/E” scaling to persist for large elongation.

The stability of very elongated field-reversed configurations is solved [22] by an expansion in the small parameter (inverse elongation).

Since the FRC is unstable to several low-n MHD modes, two-fluid or kinetic effect has been considered to explain the FRC lifetime longer than the MHD time scale [23]. 2D flowing equilibria with the magnetic and flow structure is presented. The proposed theory of the “most probable state of turbulence” is based on the two-fluid model. The formalism of equilibrium and stability analyses of a flowing two-fluid plasma is developed to investigate the effect of the flow on the high beta plasmas and some new stationary energy states [24] are found but the question which state is preferred is still without answer.

Narrow ion rings have proved to be unstable to rapid azimuthal breakup and thermalization, at least in the conditions found so far in FIREX. An isotropic distribution of energetic particles would be more stable. This might be achieved by an altered injection strtucture.

The FRC stability observed in the experiments can not be explained within linear theory. Global stability remains the leading issue affecting the future of FRC research. A standart ideal MHD analysis of tilting suggests that internal current profile and separatrix shape have a strong influence on tilting stability, of course, in this theory ballooning modes are still unstable with fast growth rates. The stabilization mechanism is likely to be a lengthening of the separatrix and the non-linear wave-particle interaction.

So, a combination of kinetic and nonlinear effects may explain the transport observed experimentally.

Also power balance issues, such as effective resistivity, opening field lines and enhancement of the losses concerning RMF must be considered.

CONCLUSIONS

The development of a theory of relaxed/ natural minimum-energy FRC states (two-fluid plasma physics), improved confinement (examination of confinement properties using neutral beam injection), startup by merging two spheromacs to form an FRC and efficient current drive by rotating magnetic fields are the most recent highlights.

Encouraging recent physics progress by the small worldwide FRC research community has enhanced the prospects for successful FRC development. Highlights include indications that natural minimum-energy FRC states exist [24], stable operation at moderate *s*, startup by merging two spheromacs to form an FRC [25], efficient current drive by rotating magnetic fields, and attractive D-^{3}He FRC power plant design.

In other words, the main achievements are developing of FRC stability theory; concept of RMF; and experiments increasing of lifetime of FRC. Besides, a big interest presents experiments with electric field inside plasma (possible confinement improvement) [26].

Experiments on several facilities had demonstrated a FRC can be formed inside a θ–pinch, RMF coil or by spheromaks merging and then translated along a connecting guide field into a region with a steady magnetic field.

The FRC reactor is cylindrical, which would simplify much of the maintenance involved. The open field lines guide charged particles toward the ends for possible direct conversion as well as effectively removing the energetic fusion products ions and impurities from the system. Details of fusion core engineering, including a high performance cylindrical blanket and shield concept, are discussed in Ref. 27.

Favorable results from theory and experiments have raised hopes for development into a practical fusion system. The present level of research on FRC's has left many issues unresolved, support for theoretical analyses and modeling of experimental data is needed. So, FRC research should be continued and expanded. FRC community is strong through collaborations and sharing of ideas, problems and solutions.

Brief review of the simple compact system with natural advantages and reactor potential is given. Theoretical and experimental results over the last decade are discussed. Conceptual designs and power plant parameters are presented. Favorable results from theory and experiments have raised hopes for development a FRC into a practical fusion system.

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