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Physics Issues of a Proposed Program, SPIRIT

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Abstract

Physics issues of the proposed program, SPIRIT (Self-organized Plasmas with Induction, Reconnection, and Induction Techniques) are discussed. The main purpose of this program is to explore the physics of global stability and sustainment of compact toroids, including FRC (field reversed configuration) as well as low-aspect-ratio RFP (reversed field pinch), spheromak and spherical torus.

Keywords:

compact toroid, MHD stability, dynamo effect

1. Introduction

Compact toroidal plasma configurations, such as FRC's, spheromaks, spherical toruses, and RFP's have been extensively studied in search of a cost-effective, high-performance, high-power-density reactor core. Since such configurations have characteristically high beta plasmas, they hold promise for opening the road to an advanced fuel reactor, provided confinement is sufficiently favorable. Among these compact toroidal configurations, the FRC is a particularly attractive candidate for a compact fusion reactor core. It has the highest beta (near unity) conceptually attainable in equilibrium. If questions regarding formation, stability, sustainment, and confinement are successfully resolved, then FRC's may offer a high-power-density and easily maintainable alternative approach to fusion power production.

The SPIRIT (Self-organized Plasmas with Induction, Reconnection, and Induction Techniques) [1] device, shown in Fig. 1, has been proposed to explore the physics of these compact toroids. The uniqueness and significance of the SPIRIT device are: (1) the novel inductive formation scheme by merging co- and counter-helicity spheromaks; (2) wide-range

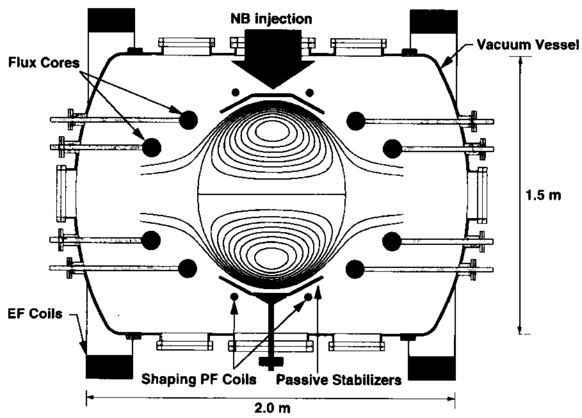

Fig. 1 Schematic view of SPIRIT device. Two pairs of flux cores are installed to form two spheromaks before they are forced to merge into an FRC (counter-helicity merging) or a larger spheromak (co-helicity merging). When a center stack with toroidal field coils is installed, finite toroidal field can be introduced at the edge of plasma to form an RFP or ST plasma during co-helicity merging.

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accessibility of the global stability and confinement characteristics of FRCs; (3) utilization of ohmic transformer and/or neutral beam injection to sustain CT plasmas for a significantly longer time than the energy confinement time; (4) great flexibility to address effects of aspect ratio on the RFP configuration.

The compact toroid plasmas in SPIRIT will be formed by merging two spheromaks. Each spheromak will be generated by induction using a pair of flux cores [2] at each end of the vessel by properly programming currents inside the flux cores. Then these two spheromaks, which carry identical toroidal currents with the same or the opposite toroidal field, are forced to merge along a common axis by controlled external coil currents. FRC can be formed by merging of counter helicity spheromaks [3] while a larger spheromak (or RFP and ST) can be formed as a result of co-helicity merging.

2. Global Stability of FRC Plasmas

The most striking feature of an FRC is the absence of a toroidal field. The internal plasma current flows toroidally, essentially perpendicular to the local field, which is in the poloidal direction. The resulting Lorentz force balances with pressure gradient in the radial direction, confining a plasma with a nearly unity beta. However, such a configuration will subject to tilt and shift instabilities.

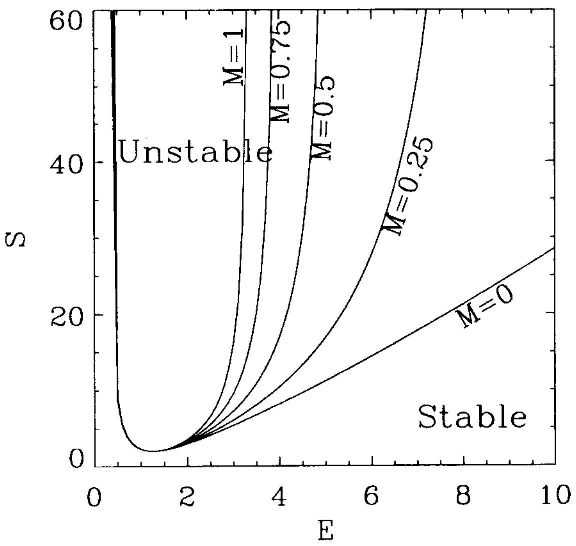

Fig. 2 Stability diagram in s and elongation for tilt mode of FRC plasmas. Stabilizing effects from ion diamagnetic drift, ion gyro-viscosity, and additional $\boldsymbol{E} \times \boldsymbol{B}$ rotation (represented by Mach number M) are taken into account.

An initial study [4] on the global FRC stability has been performed using a rigid body model in the parameter space of s (ratio of separatrix radius to average ion gyro-radius) and plasma elongation E (ratio of separatrix length to separatrix diameter). Tilt stability is predicted, independent of s, for FRC's with low E (oblate), while the tilt stability of FRC's with large E (prolate) depends on s/E. It is found that plasma rotation due to ion diamagnetic drift (a two-fluid effect) and collisionless ion gyro-viscosity can stabilize the tilt mode when $s/E < 2.8$ (see Fig. 2). Increasing stability with decreasing s is due to strong two-fluid and ion kinetic effects while a larger E further enhances stability by increasing tilting inertia. A small additional rotation (*e.g.* a Mach number of 0.2) can improve tilt stability significantly at large E.

Existence of a small number of energetic ions can also improve tilt stability by lowering effective s by a factor of $\sqrt{1 + \alpha(s^4/s_h^4 - 1)}$, where α is the fraction of energetic ion density and s_h is the parameter s for the energetic ions. For example, if the energetic ions have a 50 time higher energy than background ions, then $s^2/s_h^2 = 50$, the s can be lowered by a factor of 5 with $\alpha = 1\%$.

It is also found that radial shift is unstable when $E < 1$ while axial shift is unstable when $E > 1$. However, unlike tilt stability, gyro-viscosity has little effect on shift stability. Both tilt and shift stability is required for FRC plasmas to be experimentally studied in detail.

3. Sustainment of FRC plasmas

Another important goal of FRC research in the SPIRIT is the sustainment of FRC plasmas over a much longer time (1–10 ms) than the energy confinement time by an OH transformer and/or an neutral beam injection (NBI). The OH transformer in the SPIRIT with single-swing will have a flux of 0.1 Vsec, with a maximum one-turn loop voltage of 200 V.

According to a zero-D analysis, an NBI with 2–5 MW with help of an additional particle source may sustain the FRC plasma in a quasi steady-state fashion, satisfying requirement for balances of energy, particle, and magnetic flux. An intriguing feature of FRC sustainment via a heat source at the magnetic axis is possible activation of a cross-field thermoelectric force arising from electron temperature gradient to counter act against resistive diffusion [5]. In addition to this 2D effect, the 3D dynamo effect may also help to sustain the FRC configuration through conversion of kinetic energy from the beam to magnetic energy.

4. Low Aspect Ratio RFP

A growing consensus in the RFP community is that suppression of magnetic fluctuations and stochasticity will lead to significant improvement in confinement. Recent inductive poloidal current drive experiments in MST RFP have proven [6] that a modification of edge current profile can reduce magnetic fluctuation amplitudes and improve the confinement. A complementary approach to suppress the stochasticity-induced transport is to reduce the number of unstable modes and increase the distance between neighboring resonant surfaces at the lower limit of aspect ratio. In RFP with an aspect ratio of 6 (such as in ZT-40M), the number of unstable modes is around 10 and their locations are very close to each other, as shown in Fig. 3(a). With an aspect ratio of 3, such as in MST, the number of unstable modes is reduced to 6 with relatively larger distances between them (Fig. 3(b)). When the aspect ratio approaches unity, it is expected that the number of unstable modes decreases to 2 and the distance between their rational surfaces increase significantly, as illustrated in Fig. 3(c) where aspect ratio is 1.25. This physical intuition has been supported by preliminary results of nonlinear resistive MHD simulations in which the aspect ratio can be varied in a cylindrical geometry [7]. More recent studies using full 3D toroidal MHD codes are underway to explore possible advantages of a low aspect ratio RFP. The unique formation method employed in SPIRIT by merging can generate RFP's with lowest possible aspect ratio of 1.05, since only a small TF coil is needed in the center stack. With the OH transformer in the center stack, an aspect ratio of 1.3 can be obtained with a sustained discharge.

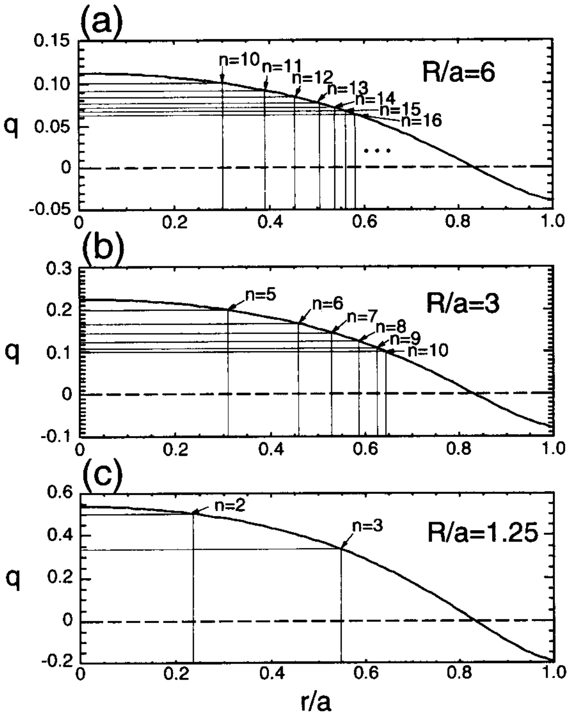

Fig. 3 Illustration of aspect ratio dependence of q profile and unstable modes in RFP.

5. Conclusions

With its novel inductive formation scheme, unique FRC sustainment methods, and great flexibility, the SPIRIT experiment will provide fundamental physics of global stability and sustainment of CT plasmas, especially FRC and low-aspect-ratio RFP plasmas. A successful demonstration of favorable properties of stability, sustainment, and confinement will open a new path towards high-power-density and easily maintainable fusion reactor concepts.

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