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HERCULES (Helical Rotating Cusp Fields Experiments)

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Abstract

High β plasma is widely believed to make a nuclear fusion reactor cost effective. The helical rotating cusp field configuration is proposed in this paper. In this configuration the main fields for a plasma confinement will be mirror fields and also rotating cusp fields with the axis of prior mirror fields. If the rotating fields create the plasma rotation, it may be anticipated that the current is due to the centrifugal force drift in the plasma. This current will be estimated at 100 kA/m^2 in typical case. To analyze these fields effect, MHD code of one fluids model is developed. Firstly this code has been tested and successfully passed the shear Alfvén wave propagation. Next this code is adapted to the non-rotating cusp and mirror field configurations. The calculation results of the cusp and mirror fields show that the min-B configuration works well for confinement of the plasma within a certain time limit. An analysis of the rotating field effects will be the next problem to solve in the very near future.

Keywords:

min-B configuration, mirror, helical cusp, rotation, FRC, spheromak

1. Introduction

High performance plasma is necessary to make the nuclear fusion reactor with cost effective. It is widely believed that Spherical Torus (ST) has the potential to achieve cost performance reactor [1-4]. However, ST needs center stack, in which there are many toroidal coils and ohmic coils. The center stack radius must be small size due to the low aspect ratio. Thus it might be questionable with respect to the current load for ohmic heating and strong toroidal field in spite of small cross-sectional area of the center stack. Also, it might be problem with respect to the heat load of the center stack from high temperature plasma. If it is possible to make plasma stable without the center stack, a reactor design will be easier. The possibilities of the current drive are the rotational magnetic fields using Rotomak [5], and neutral beam injection (Ohkawa current)[6], coaxial helicity injection [7], and high harmonic fast wave [8].

On the other hand, as already known, cusp fields with mirror fields have natural min-B configuration. This device has no center stack. Therefore, if the rotating cusp fields would generate the current due to the centrifugal drift ($\boldsymbol{F}\times\boldsymbol{B}/B^2$), this current might confine the plasma. This current is represented by $\sum_i n_i m_i R\omega^2/B$ in simplest case, where n_i, m_i, R, ω and B are the ion density and mass, the radius of plasma, the angular frequency, and the magnetic field, respectively. The $\boldsymbol{j}\times\boldsymbol{B}$ term is balanced to the centrifugal force in this case. The current density of 100 kA/m^2 is estimated by $n_i = 10^{20}$ m^{-3}, $R = 2$ m, $f = 30$ kHz, $m_i = 1.6\times10^{-27}$ kg, and $B = 0.1$ T. Therefore, it is very important to inquire whether the plasma will rotate or not by rotating fields. In this paper, the modified min-B configuration as Hercules (Helical Rotating Cusp Fields Experiments) is presented. The above-mentioned configuration has the desirable properties to make a cost effective nuclear fusion device. Also, the superconducting coil with low AC hysteresis is developing now, and it is hoped to afford to use the superconducting coils with these

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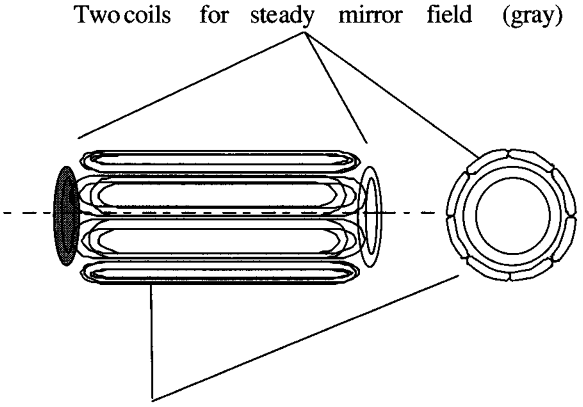


Fig. 1 (a)

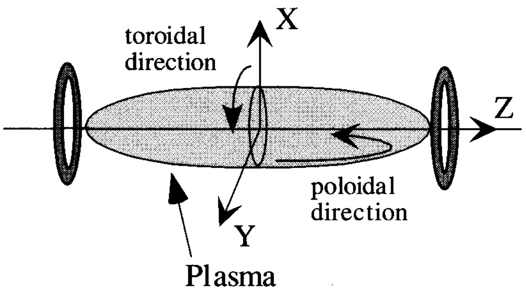


Fig. 1 (b)

frequency level in the near future. The schematic of this magnetic configuration is shown in Fig.1. The magnetic fields by plasma current would reconnect the end of mirror fields, and Spheromak or FRC plasma would be anticipated in the center region of the mirror fields. This steady state low temperature plasma is the suitable target for additional heating, such as NBI (neutral beam injection). NBI will make high temperature plasma in the core region, also it generate the plasma current. In the periphery, the low temperature plasma sustained by the rotating fields would protect the wall (low temperature plasma insulation). The fuel will be fed to one side of mirror end, and, the other end will be attached to a nozzle of high temperature plasma jet. Thus, the direct electric conversion will be applicable. To analyze these magnetic configurations and the rotation field effects, at least 3-dimensional MHD code of one fluid model is necessary. Therefore, firstly 2-dimensional program is developed, and 3-dimensional program will be developed soon.

The preliminary results of this 2-dimensional code are presented in this paper.

2. Governing Equations

One fluid model for plasma is used here. The governing equations are follows.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0$$

$$\rho \frac{\partial \boldsymbol{v}}{\partial t} + \rho \boldsymbol{v} \cdot \nabla \boldsymbol{v} = -\nabla p + \boldsymbol{j} \times \boldsymbol{B} + \mu \left(\nabla^2 \boldsymbol{v} + \frac{1}{3} \nabla (\nabla \cdot \boldsymbol{v}) \right)$$

$$\frac{\partial p}{\partial t} = -\nabla \cdot (p\boldsymbol{v}) + (\gamma - 1)[-p\nabla \cdot \boldsymbol{v} + \eta \boldsymbol{j} \cdot \boldsymbol{j} - \nabla \cdot \boldsymbol{q} + \Phi]$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = -\nabla \times \boldsymbol{E}, \quad \mu_0 \boldsymbol{j} = \nabla \times \boldsymbol{B}, \quad \boldsymbol{E} = -\boldsymbol{v} \times \boldsymbol{B} + \eta \cdot \boldsymbol{j},$$

$$\boldsymbol{q} = -\kappa \nabla_{//} \left(\frac{p}{\rho} \right), \quad \Phi = 2\mu \left(\boldsymbol{e}_{ij} \boldsymbol{e}_{ij} - \frac{1}{3} (\nabla \cdot \boldsymbol{v})^2 \right),$$

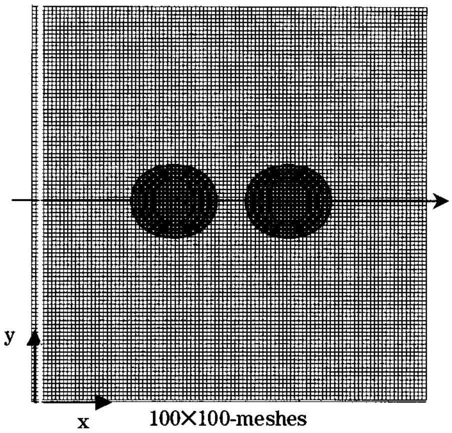
$$\boldsymbol{e}_{ij} = \frac{1}{2} \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right)$$

Here ρ, p, $\boldsymbol{v}$ are the plasma density, pressure, and velocity, respectively. $\boldsymbol{B}$, $\boldsymbol{E}$, $\boldsymbol{j}$ are magnetic field, electric field, and current density, respectively. Also, γ is the ratio of specific heats, μ is the coefficient of kinematic viscosity, η is resistivity, and κ is thermal conductivity. For simplicity these plasma properties are set to be constant at the first code test.

To solve these equations, we used CIP (the Constrained Interpolation Profile) method [9,10] for plasma fluid; and SAM (a Simple Algorithm for MHD) is developed to guarantee div$B$ = 0 at any time steps.

3. Calculation Results and Discussion

The 2-dimension MHD code was tested under the conditions of shear Alfvén wave. The initial conditions are as follows. A uniform magnetic field is in the (x,y) plane; $B_x = 1$, $B_y = 0$, $B_z = 0$, and the mesh system is 100×100. In this coordinate system, the fluid displacement of the Alfvén wave is along z-direction. Therefore, the plasma velocity is put 10^{-3} along z-direction within the circle of 8 meshes in the center. For severe test condition, the inverse of the magnetic Reynolds number is set to be 0. Thus, the magnetic reconnection should not occur by plasma current. Figure 2 shows the results of the shear Alfvén wave propagation in this calculational area. The region that has z-direction positive velocity is split into two parts in Fig. 2(a), and a magnetic field of z-direction B_z in one region is positive, and B_z in the other is negative in Fig. 2(b). To testify the accuracy of incompressiveness, the sum of the z-direction flow rate is checked. It always keeps the initial value. Also, it is confirmed that the peak position of the z-direction velocity moves with Alfvén speed along the magnetic field line (in this case



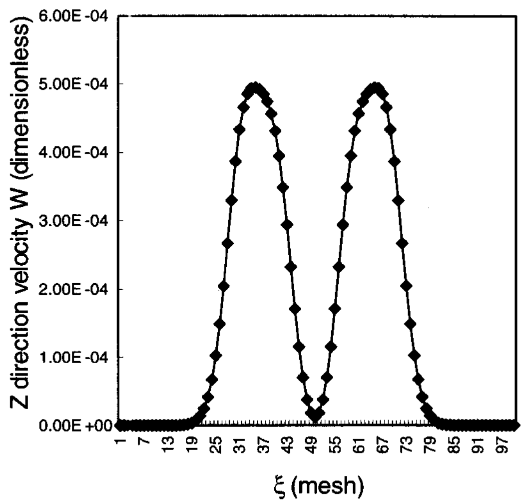


Fig. 2 (a)

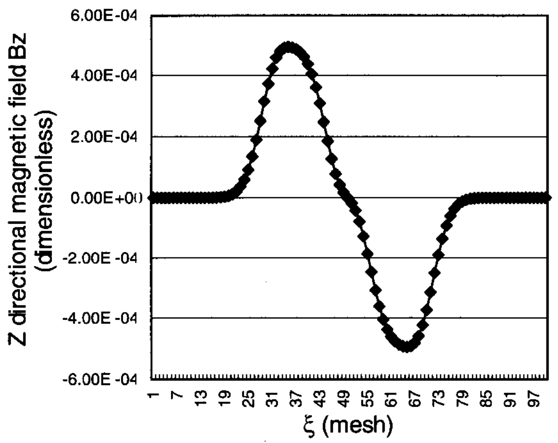


Fig. 2 (b)

along x-direction). Therefore, the propagation wave is really shear Alfvén wave. Unfortunately, the waveform of x and y-direction velocity did change and the plasma density and pressure changed slightly to the initial value (10^{-4}), however these error did not grow at any time. These errors are caused by limited cell size, thus this is not essential problem. It is concluded that the program has been working successful in this case.

Next this MHD code is adapted to analyze the cusp and mirror field configuration. For simplicity the cusp is not moving, and 2-dimension space is used, i.e. the calculation plane is the cross-section at the center of a mirror magnetic field shown in Fig.1, and the calculational area is 100×100-meshes. The cusp coils (quadrupole) are put out of this plane; the pole stands at normal angle to this plane. Figure 3 shows the typical absolute value of the magnetic field and the initial plasma density along x-axis. The profile of this plasma is parabola type and its radius is 30-meshes. Only plasma is set in the central region of this magnetic field without current. Therefore there is no $\boldsymbol{j}\times\boldsymbol{B}$ force in the plasma at the initial condition. Because of non-equilibrium, plasma moves due to the pressure gradient. When plasma moves outside, the cross-field velocity creates $\boldsymbol{E}$, and next step new $\boldsymbol{B}$ by $-\nabla\times\boldsymbol{E}$ will create $\boldsymbol{j}$ in the plasma. This $\boldsymbol{j}\times\boldsymbol{B}$ force will act to stop plasma

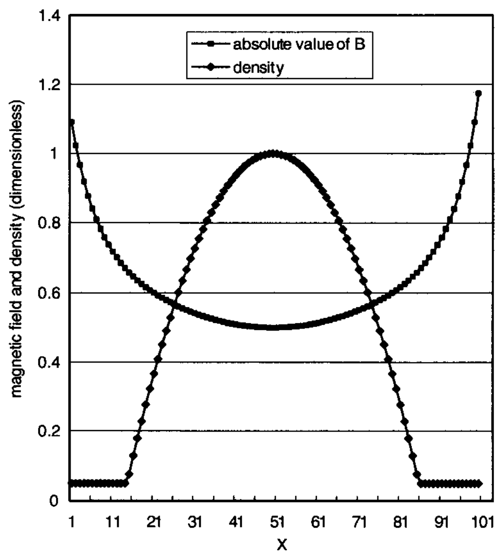


Fig. 3

Table 1

Rp	0	0.5	1	2	3	4	5	10	20
mass loss rate	0.0214	0.022	0.0216	0.0193	0.0121	0.0114	0.0102	0.0023	7E-06

moving. The mass loss rate is defined by the weight loss calculated by the out flux at the initial plasma radius with respect to the initial plasma weight per unit time. The dimensionless time is defined by the one mesh proceeding time by sound speed. The mass loss rate is studied in various magnetic fields. Table 1 shows that the mass loss rate vs. the ratio of the magnetic pressure and the plasma pressure R_p (the inverse of β value). When β value is larger than 1, the mass loss rate is huge and almost constant. However, the mass loss rate decreased rapidly with the magnetic field increase; namely β value decrease. Although it is needless to say that these results depend on the initial plasma properties and profiles. However, in general we confirmed that min-B configuration works quite well to confine plasma within a certain time limit using our 2-dimension MHD code.

4. Conclusion

The min-B configurations of Hercules are proposed here. Also 2-dimensional MHD code is developed to analyze the magnetic configurations. At present, only 2-dimensional problem for the quadrupole and mirror fields was treated here, however, it is confirmed that the min-B configuration has the potential to achieve the cost effective plasma confinement device. Up to now 3-dimensional and rotating fields are not treated here. These are very important issues that need to be solved soon.

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