The Study of the RMF effect on the Performance of Field Reversed Configuration Thruster

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X. F. Sun¹, Y. H. Jia, T. P. Zhang, J. J. Chen
Science and Technology on Vacuum Technology and Physics Laboratory,
Lanzhou Institute of Physics, Lanzhou 730000 , China

Abstract: A Field Reversed Configuration (FRC) plasmoid will be formatted by applying a Rotation Magnetic Field (RMF). The azimuthal currents that driven with RMF will couple with the radial magnetic field produced from axial magnetic field gradient and then a Lorentz force($J_\theta \times B_r$) created and accelerates the plasmoid to a high velocity. This potential advantage services to space thruster can produce highly variable thrust and specific impulse at high efficiency. While the critical acceleration mechanism of this method is that the plasmoid electron current can be effectively driven. This study concerns to the effect of antisymmetric and symmetric RMF antenna on the ionization of the propellant. The RMF magnetic topology and the driven electron current from two different RMF antennas are compared, and which will be useful for the optimized designing of FRC thruster.

Nomenclature

\[ B_{\omega} = \text{Rotation Magnetic Field} \]
\[ I_{\text{RMF}} = \text{The driven current of RMF} \]
\[ J_\theta = \text{The driven current density of RMF} \]
\[ \Phi = \text{The magnetic flux} \]
\[ F = \text{Lorenz Force} \]
\[ \omega = \text{Frequency of RMF} \]
\[ B_r = \text{Radial direction magnetic field} \]
\[ r = \text{Plasma radius} \]
\[ n_e = \text{Plasma electron density} \]

I. Introduction

The first time for the Rotation Magnetic Field is used to the formation of the FRC plasma was in 1960s, and the early investigated devices in Australia were called “rotamak” which chiefly serves for the nuclear fusion.¹ But until late 1990s, many experimental facilities began to adapt RMF for the
formatting of FRC, such as the Star Thrust eXperiment (STX), Translation Confinement Sustainment (TCS), and TCSU. The RMF acts as two roles in fusion rotamak, one is the production of FRC plasma and the other is the sustainment i.e. fusion confinement. The two sets of antennas with two phases will generate a transverse magnetic field ($B_n$). The oscillation of the antenna current will make the $B_n$ rotates at the poloidal direction. Due to their light weight, the electrons will tie to the field lines of $B_n$ and an azimuthal current ($J_{φ}$) is driven, while the ions are fixe.

The matched condition for the current drive of RMF is that the frequency of $B_n$ should between the ion cyclotron frequency and electron cyclotron frequency. Besides, the electrons collisions frequency must be lower than the electron cyclotron frequency as the same time. Then, the RMF can penetrate into the plasma and drive a non-inductive current ($I_{RMF}$) rather than $Δφ$ powerfully. At present, most of the experiments of rotamaks have shown its significant advantages of RMF. It avoids the transient high voltage and large current for the ionization of the plasma. Even though the penetrated distance of RMF field is little, it can also achieve the steady state of FRC plasma. Moreover, the RMF peak density is much more than other FRCs. In general, the driven azimuthal current of RMF can reach to tens of thousands Ampere. If a radial direction magnetic field of $B_r$ is preexistence, the coupling of the current and magnetic field will produce a Lorenz Force ($F=I_{φ}B_r$) that lead to the acceleration of the FRC plasma. For that reason, the FRC concept has been employed to the space propulsion.

The Electrodeless Lorentz Force (ELF) thruster based on the current driven of RMF has been experimented to accelerate the plasmoid to a high velocity. Several kinds of ELF thrusters have been developed by MSNW business and Washington University. On all of them, the “even-parity” dipole RMF antennas system has been applied. The maximum azimuthal current can up to 20kA with the RF power of RMF. The RMF-based thruster has a wide range of power scalability, no magnetic detachment issues, and is essentially propellant independent. Therefore, it is thought to one of the most competitive of the high performance electric propulsion system for space.

In order to improve the energy confinement and enlarge the local induced azimuthal electric field, an innovation so called “Odd parity” antenna has been applied to the RMF system for FRC. The difference between the odd- and even-parity RMF antennas is that the axial variations of $B_n$. Their symmetric and antisymmetric current drive calculations cases are gained by Guo et al. The FRC current drive experiments has displayed that the FRC thermal confinement will improve evidently if the “Odd parity” antenna is used. Comparisons of ion heating by even- and odd-parity RMFs of FRC have been considered by Cohen et al. using numerical analysis, the results reveal that the ions are better heating in a wider range of odd-parity RMF frequencies. The Welch’s PIC simulated results indicate that the good RMF penetration and evolution with odd-parity antenna. The investigations of Melnik demonstrate that the odd-parity FRC will make the external magnetic field higher and fluctuations less. In a word, the odd-parity RMF antenna is more suitable for the production and confinement of FRC plasma.

Therefore, it is feasible to learn the effect of RMF antenna on the performance of FRC thruster. This paper is arranged into the following sections. The configuration of the antennas will give a brief review in Sec. II. The magnetic field topology will be examined in Sec. III. The simulation results of different RMF antennas are displayed in Sec. IV. Finally, the conclusions are discussed.

### II. Configuration of the Antennas

The schematic of the RMF antenna with even-parity and odd-parity configuration are shown in Fig. 1. Different from the geometric configuration of the current ELE thruster RMF antenna, the antennas are split into two parts so that they can be operated in two differentiated modes. The up and down two
parts of the antennas in Fig. 1 are labeled with blue and red color, respectively. For the even-parity configuration, the currents direction of the up and down antennas are the same. But for the odd-parity configuration, the antennas currents direction of the separated two parts are opposite. Therefore, the horizontal (perpendicular to z direction) magnetic field that created by the RMF antennas are the same as the even-parity case and opposite as the odd-parity case. The pink arrows in Fig. 1 indicate the directions of the induced magnetic field from RMF antennas.

![Fig. 1 Schematic of two different RMF antennas.](image)

**III. Magnetic Field Topologies of Two RMF antennas**

For simplicity, a 2D model is established to master the evolution of some parameters. And the numerical results are brought out in section A.

**A. Simulation of 2D RMF Current Driven**

![Fig. 2 The simulation results of a 2D RMF current driven with COMSOL software. (a) RMF rotation](image)
magnetic field; (b) Electron density; (c) Ion density; (d) Current density.

A 2D current driven COSMOL fluid model is developed to understand the primary physics process of RMF at first. The simulation results are drawn in Fig. 2. The 2D model consists of four parts. The inner ring is the discharging plasma region. The area between the inner and outer ring is set to the quartz glass. And the eight small rings represent the RMF antennas which carrying sinusoidal currents with phased 90° apart. The rest region is setup to the vacuum.

The total input power is 3.5kW, the RMF frequency is 250kHz, and the propellant is Argon. In Fig. 2 (a)-(d) are the numerical results of rotation magnetic field, electron density, ion numerical density, and the driven current, respectively. The maximum rotation magnetic field is 500Gs, the electron density is 3.76e+19m⁻³, the ion number density is 8.75e+20m⁻³, and the azimuthal current density is about 5e+3A/m².

The horizontal and the vertical coordinate axis in Fig. 2(a)-(d) represent the x direction and y direction, respectively. And the length units of them are all meter which have not labeled on the figures. Even the numerical results shown in Fig. 2 are a little crude (due to the numerical accuracy), it can provide some quantitative and qualitative references for the further study of the coupling of the RMF and plasma. At first, a significant dynamic rotation magnetic field (as shown in red contour lines) is formed in Fig. 2(a). Then the electron density and ion density will increase as the effect of RMF. The peak density distributions of electron and ion which are as the same shape with RMF are shown in Fig. 2(b) and 2(c). When the electrons are tied to RMF lines and move only along the magnetic field lines, an azimuthal electron current will be occurred and is showed in Fig. 2(d).

In order to examine the effect of the RMF frequency on the drive current, the driven electron current density and electron density with different RMF frequencies are plotted in Fig. 3. The range of the frequency is between 150kHz and 300kHz. It is evident that the current density and electron density are direct proportion to the RMF frequency which is agreement with most of the roughly estimated result \( J_\theta = n_e \omega_r \). Besides, there is a turning point on both of the two curves when the RMF frequency is 160kHz. This means that there is a critical optimum frequency for the plasma penetration, ionization, and the current driven of the RMF. That is to say the effect of RMF frequency on the performance of the FRC thruster should be seriously considered.

![Fig. 3 The driven electron current density with different RMF frequencies](image)

**B. Magnetic Field Topology of Even- and Odd-parity RMF Antenna**

Since the 2D model cannot be used to study the coupling of the plasma with different antenna configurations, a 3D COMSOL simulation model is developed. But, the complex and large amount of calculation for the 3D model make it difficult for us to learn the FRC plasma detailed. Thus, some
primary results are given in the following. The 3D model with calculation mesh generation and the cross section along z direction are shown in Fig. 4.

The axial (z) direction cross section magnetic field topologies of the even- and odd-parity RMF antenna are figured in Fig. 5. All parameters in simulations are set to the same as the 2D calculation situation. It is obvious that the intensity of the magnetic field in odd-parity is a little greater. The maximum value of the magnetic field in even-parity is 0.05T, while it is 0.06T in the odd-parity. Meanwhile, the distribution of the magnetic field is more uniform in odd-parity which would be more efficient in the confinement and current drive of the plasma.

IV. The Simulation Results of Different RMF Antenna

The axial direction cross section driven current density with the even- and odd-parity RMF antenna are displayed in Fig. 6. Except the geometry size, the input power, propellant and RMF frequency in the 3D numerical simulation are all set the same as the 2D calculation situation. Similar to the magnetic field topology, the driven azimuthal current density in odd-parity case is more availability than the even-
The driven azimuthal current density with different antenna configuration parity antenna. The larger current density in odd-parity RMF antenna shows it can significantly improve the performance of the FRC thruster according to the expression of Lorentz Force $F = J \times B_r$.

In Fig. 7, it shows the axial direction cross section electric field and electron temperature with the even- and odd-parity RMF antenna, respectively. From the simulation results, it is easy to see that both of the local electric field and the electron temperature in odd-parity antenna are larger than the even-parity antenna. These results are agreement with those in Ref. 10 and 12. And which can also indicate that the plasma ionization rate and energy confinement will be better. Therefore, the odd-parity antenna may be an effective way to improve the performance of the FRC thruster.

![Fig. 6](image1.png)

![Fig. 7](image2.png)

Fig. 6 The driven azimuthal current density with different antenna configuration

Fig. 7 The axial direction cross section electric field and electron temperature with the even- and odd-parity RMF antenna

V. Conclusions

The RMF effect on the performance of Field Reversed Configuration Thruster has been studied. It is found that there is a critical optimum frequency for the plasma penetration, ionization, and the current driven of the RMF in 2D model. The 3D simulation results show that the odd-parity RMF antenna is more efficient than the even-parity antenna in energy confinement, current drive, local electric field, and plasma equilibrium. Thus, the odd-parity may improve the performance of the FRC thruster greatly. Finally, as a result of the complexity and large amount of computations of the 3D model, only the primary results are given in this paper. But, the more simulation and experiment results will be presented later.

References


