Formation studies of field-reversed configurations on the HFRC-F device

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Abstract

Collisional-merging is a way to form high-performance field-reversed configuration (FRC) plasma. To improve the properties of merged plasma, one feasible way is to optimize the formation process. An experimental device named HFRC-F has been constructed in Huazhong University of Science and Technology, which is used to investigate the field reversed theta-pinch (FRTP) formation process of FRCs. Initial HFRC-F experiments obtain typical parameters with plasma density of 4×10^{20} m^{-3} and lifetime of 75 μs with B_{bias} = -0.015 T, B_{PI} = 0.015 T and B_{main} = 0.035 T. The results also show that, 1) the larger the main magnetic field, the higher the density. 2) the V_{PI} should be appropriate to obtain a larger frozen magnetic flux.

1. Introduction

A field-reversed configuration (FRC) is a compact toroid (CT) that has a predominant poloidal magnetic field but no or little toroidal field [1]. It has a simple axisymmetric structure. The averaged beta is near unity [2]. FRCs can also be translated [3], merged [4] and compressed [5] to optimize its properties. To improve the properties of the final plasma, one feasible way is to optimize the formation process. In order to investigate the field reversed theta-pinch (FRTP) formation process of FRCs, an experimental device named HFRC-F has been constructed in Huazhong University of Science and Technology.

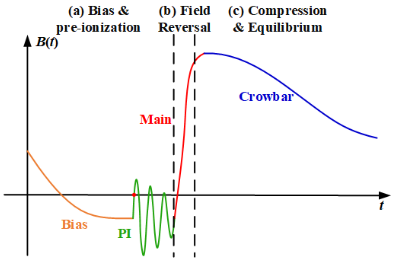

Figure 1. Typical magnetic field waveform of theta-pinch coils during formation process.

Field reversed theta-pinch (FRTP), which is investigated in this work, is a common way to form high-performance FRCs [6]. The typical magnetic field waveform is shown in figure 1. This process can be approximately divided into 3 stages: (a) bias and pre-ionization [7], (b) field-reversal, and (c) compression and equilibrium [8]. Several parameters in this process can be tuned to optimize the properties of the formed FRC. This paper focuses on the formation process, aiming at studying the influence on the plasma properties.

This paper is organized as follows. The experimental device is introduced in section 2. The experimental results are presented in section 3. Lastly, a summary is provided in section 4.

2. Experimental device

Figure 2 shows the diagram of the HFRC-F device, which can be roughly divided into five regions: the east-west end chamber, the east-west transition section and the quartz tube area. A total of 3 windows are opened on both sides and above the midplane of the quartz tube for the diagnostic system.

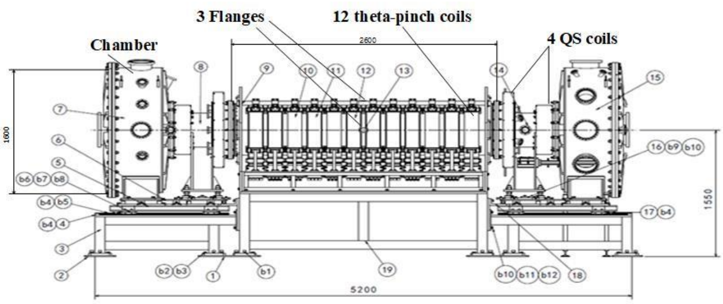

Figure 2. Diagram of the HFRC-F device.

The coil system consists of 12 theta-pinch coils and 4 quasi-steady state coils. The design parameters can achieve a bias magnetic field of -0.16 T, the PI magnetic field oscillation frequency of 150 kHz, and the main field to rise to 0.5 T within 5 μs. The quasi-steady state coils can be divided into 2 groups according to the radius (600 mm, 400 mm). A magnetic field of 1.0 T at the axis of the transition section can be obtained under rated conditions.

The diagnostic system consists of a carbon dioxide interferometer [9], an array of internal magnetic probes, several point magnetic probes and single loops [10]. The internal magnetic probe is arranged in the window above the quartz tube. The carbon dioxide interferometer is arranged in the midplane horizontal window of the quartz tube. The point magnetic probe and single loop are installed on the outer side of the quartz tube between each two theta-pinch coils.

3. Experimental results

At present, test of the HFRC-F device and the diagnostic system, as well as the quasi-steady state power supply and some theta-pinch power supplies have been completed. The maximum operating parameters are $V_{bias} = 10$ kV, $V_{PI} = 20$ kV, and $V_{main} = 24$ kV.

3.1 Typical Result

Under the discharge conditions of $V_{\mathrm{bias}} = 5$ kV, $V_{\mathrm{PI}} = 12$ kV, $V_{\mathrm{main}} = 12$ kV, the following typical results are obtained. When the outer gas is ionized, the formed plasma inhibits the penetration of the high-frequency magnetic field to a certain extent, and the remaining bias magnetic field is coupled with the subsequent ionized plasma to form an initial frozen magnetic flux. The results of the internal probe show that in the main and crowbar stage, the FRC plasma has a process of inward contraction, rebound, and finally inward contraction. It can also be seen from the results of the internal probe that the lifetime of the FRC is about 75 μs. The density results show that the main ionization occurs after the main field is triggered, at which time a rapid density climb can be observed. A subsequent compression process in the crowbar stage further increases the density.

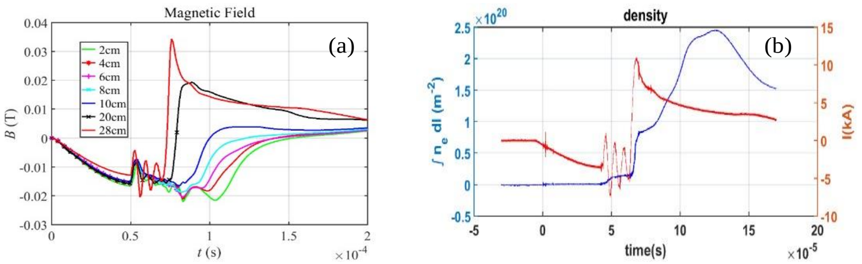

Figure 3. Typical result of formation process: (a) axial magnetic field, (b) string integral of density.

3.2 The effect of V_{PI} on pre-ionization

The response of the plasma under different PI voltage conditions was studied, and the results of the internal probe were obtained as shown in the figures 4. The results show that the magnitude of the PI voltage affects the timing of ionization. When the bias magnetic field is introduced, different ionization moments will lead to different superimposed magnetic fields during ionization, which will make the initial frozen magnetic flux different. Appropriate voltage coordination can increase the initial frozen magnetic flux.

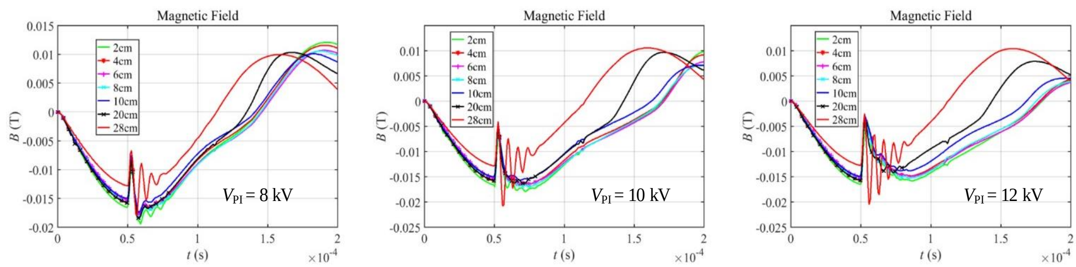

Figure 4. Axial magnetic field under different voltage of PI.

3.3 The effect of V_{PI} and V_{Main} on density

The typical results above show that the density evolution during FRC formation can be divided into three stages. This subsection mainly studies the effects of different PI voltages and different main voltages on the plasma density. The results show that under the same main voltage condition, changing the magnitude of the PI voltage only affects the plasma density in the pre-ionization stage. The final plasma density is affected by the main voltage, the higher the main voltage, the higher the density. For example, the density is almost 4 times as the voltage rise from 9 kV to 15 kV.

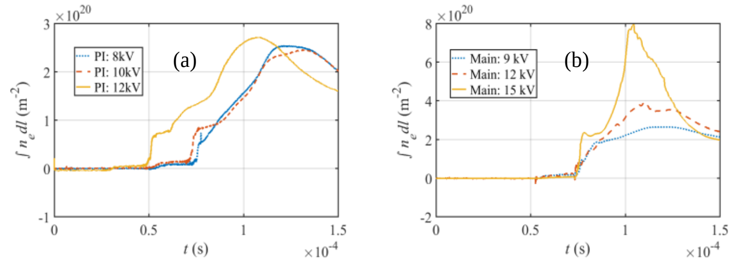

Figure 5. Compare of density: (a) different voltage of PI, (b) different voltage of Main.

4. Summary

A device named HFRC-F has been designed to study the formation process of the FRC plasma and improve its parameters. The device contains 12 theta-pinch coils and 4 quasi-steady state coils. The design parameters can reach the maximum bias magnetic field of -0.16 T, the PI frequency of 150 kHz, the main rises to 0.5 T within 5 μs, and the quasi-steady state field of 1.0 T. The device is equipped with internal magnetic probes, point magnetic probes, single loops, and a carbon dioxide interferometer to measure the evolution and distribution of plasma parameters. The experimental study shows that the appropriate PI voltage can increase the initial frozen magnetic flux, thereby prolonging the plasma life. The higher the main voltage, the higher the density of formed plasma.

Acknowledgements

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Referance

[1] Tuszewski M. 1988 Field reversed configurations *Nucl. Fusion* 28 2033
[2] Steinhauer L.C. 2011 Review of field-reversed configurations *Phys. Plasmas* 18 070501
[3] Sekiguchi J. Asai T. and Takahashi T. 2018 Super-Alfvenic translation of a field-reversed configuration into a large-bore *Rev. Sci. Instrum.* 89 013506
[4] Asai T. et al 2019 Collisional merging formation of a field-reversed configuration in the FAT-CM device *Nucl. Fusion* 59 056024
[5] Spencer R.L. et al 1983 Adiabatic compression of elongated field - reversed configurations *Phys. Fluids* 26 1564
[6] Milroy R.D. 1982 Numerical studies of a field - reversed theta - pinch plasma *Phys. Fluids* 25 775
[7] Armstrong W.T. et al 1981 ϑ - pinch ionization for field - reversed configuration formation *Appl. Phys. Lett.* 38 680
[8] Srinivasan R., Avinash K. and Kaw P.K. 2001 High β compact toroidal equilibria *Phys. Plasmas* 8 4483
[9] Yang C, Gao L, Chen Z, et al 2021 Design of a dispersion interferometer on a field-reversed configuration device *Rev. Sci. Instrum.* 92(2): 023508
[10] Chen Z, Ye H, Zhao Y, et al 2021 Development of a single capacitor-voltage-divider flux-loop for field-reversed theta-pinch plasmas *Rev. Sci. Instrum.* 92(10): 103504