New control methods for stabilization and equilibrium of a field-reversed configuration

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Abstract
Control methods for a field-reversed configuration (FRC) have been proposed and investigated on the NUCTE series theta-pinch based FRC devices. The FRC has been investigated as a candidate for a highly efficient fusion reactor core with several unique advantages such as simply-connected magnetic geometry, all the equilibrium current maintained by classical diamagnetism, open field region as a natural diverter and high mobility along the geometrical axis. However, these attributes of FRCs make it difficult to apply additional control methods such as inductive current drive. Therefore, several new control methods have been proposed and developed on NUCTE. In the translation process, “equivalent neutral beam injection” has been applied. The neutral particles injected into the FRC with relative velocity could fuel and heat the FRC plasma. Improvement of the particle and poloidal flux confinements and delay of onset of $n = 2$ rotational instability were observed in the translation process. Also coaxial helicity injection has been applied into the elongated theta-pinch FRC. Injected modest amount of helicity stabilize rotational mode deformation.

1. Introduction
Various control technique of a field-reversed configuration (FRC) stability and confinement have been experimentally investigated on the flexible $\theta$-pinch-based FRC facility, NUCTE [1]. On the translation process of FRC, translation velocity is effectively used to control the FRC dynamics and regeneration of kinetic energy into thermal energy. Use of a magnetized coaxial plasma gun (MCPG) has also been proposed as an effective method of control for FRCs. Indeed, these initial results demonstrate the effectiveness of control methods of FRC.

Pursuit of the FRC as fusion reactor core is motivated by highly favorable technological features: very high $\beta$, a natural divertor, linear device geometry, and axial mobility allowing separation of start-up and confinement functions. However, significant questions remain about the physics of FRCs, principally the global stability, the lack of effective control methods, and a fusion-relevant current drive.

The highest temperature and density FRCs, formed by $\theta$-pinches and generally translated into quasi-steady state magnetic field, have lifetimes limited to a few hundred microseconds, and scalability to larger sizes with long confinement and global stability has not been established. The proposed techniques emerge as control methods with multiple effects: suppression of instability, current sustainment, confinement improvement etc. In this work, passive control techniques of FRC through the translation process have been attempted.

The most dangerous global instability in a FRC is the rotational instability, which is the centrifugally-driven interchange mode with toroidal mode number $n = 2$. By this instability, the poloidal cross section deforms elliptically and then plasma contacts the discharge tube wall, limiting the configuration lifetime $\tau_{\text{FRC}}$ to about one particle loss time $\tau_N$. Externally-applied static multipole fields can suppress this instability [2]. However, it has been found that the toroidal asymmetry of the multipole field has a negative effect on the confinement [3].

FIG. 1. Schematic view of NUCTE-III with a magnetized coaxial plasma gun.
Regarding rotational instability, the TCS facility had yielded promising results [4]. These included suppression of the rotational mode as well as self-organization i.e. conversion of toroidal to poloidal flux. Interpretive modeling of these observations also showed that the core of the FRC was a two-fluid minimum energy state [5], another marker of self-organization. This raised a new intriguing possibility that the modest toroidal field in the self-organized states may be the key to suppressing the rotational instability [6]. In the NUCTE-III experiments, toroidal flux is actively injected into the FRC through the magnetized plasmoid formed by a MCPG. After a merging and relaxation process, FRC reaches the static equilibrium phase with a finite amount of magnetic helicity. The global stability of this FRC which toroidal flux is injected, is investigated experimentally.

2. Experimental setup

2.1. Theta-pinich based FRC device

A series of experiments has been performed with the theta-pinich based FRC device, NUCTE-III [1]. A schematic diagram of the device is shown in Fig. 1. The central part of the theta pinch coil is 0.9 m in length and 0.34 m in inner diameter. Passive mirror coils of axial length 0.3 m and 0.32 m inner diameter are mounted at each end. These coils provide an on-axis vacuum mirror ratio of 1.13. A transparent synthetic silica tube, 2 m in length and 0.256 m in diameter, is employed as a discharge chamber. In the standard operation condition, the amount of filled gas is 10 mTorr. In this series of tests, preionization plasma is formed by the theta-discharge method. Typical plasma parameters are listed in Table 1.

2.2. Set-up for translation experiments

The arrangement of the device for translation experiments are shown in Fig. 2 and 3. A FRC plasma is formed by the field-reversed theta-pinich (FRTP) method and translated along the gradient of the guide field. Figure 2 is the device arrangement for the translation experiment. The reconnection assist coil quickly forms the gradient of external magnetic field and pushes the FRC into the adjacent confinement section. A metal shell is mounted directly on a surface of this section.

Figure 3 is the schematic diagram of NUCTE-III/T. The tapered theta-pinich coil of 1.3m in length. A working gas of deuterium is puffed into the middle of the transparent quartz discharge tube by a fast gas-puff valve. The equivalent gas pressure is approximately 10 mTorr for the static gas-fill method.

The confinement section consists of a quartz discharge tube of 1.4 m in length and 0.4 m in diameter, as a center

<table>
<thead>
<tr>
<th>TABLE I. Typical plasma parameters during standard operation</th>
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<tr>
<td>Filling pressure [mTorr]</td>
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<tr>
<td>Bias field [T]</td>
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<tr>
<td>Separatrix radius [m]</td>
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<tr>
<td>Separatrix length [m]</td>
</tr>
<tr>
<td>Electron density (\times 10^{21} \text{ m}^{-3})</td>
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<tr>
<td>Total temperature [eV]</td>
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<td>Number of ion gyro radii ((\bar{\chi}))</td>
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FIG.2. Setup for translation in theta-pinich facility.

FIG.3. Experimental setup for the FRC translation experiments (NUCTE-III/T).
confinement region, and two tapered stainless-steel shells with an averaged skin time of 1.5 ms. The confinement coil consists of eight equally spaced coil elements, 0.3 m in radius and 0.1 m in width.

2.3. Magnetized Coaxial Plasma Gun
Magnetized plasmoid injection has been employed to inject magnetic helicity actively into the FRC [7]. Figure 1 shows the typical setup of NUCTE-III for coaxial helicity injection (CHI). Since the MCPG is mounted on-axis and generates a significant helicity, it provides an FRC-relevant version of CHI that has been quite successfully applied in both spheromaks and spherical tokamaks [8]. The electrodes of MCPG are extended to the end of the theta-pin coil and work as an accelerator. By the application of 22.5 kA of gun current with a pulse width of 15 μs between the inner and outer electrodes and driven by a 20 kV-15 μF capacitor, magnetized plasmoids are produced and rapidly accelerated.

Plasmoids with a velocity of about 40 km/s are injected into the vacuum vessel filled with a bias field of 0.032 T. A main reversed confinement field with a strength of 0.44 T, a 3 μs rise time and a 120 μs decay time are applied when the bias field strength rises to its maximum value.

3. FRC control through the translation process
3.1. Passive control of translation speed
As a simple and effective method to control stability and dynamics of translated FRC, the translation chamber is partially wrapped by metallic ring. Then the induced current on the shell provide radial force suppressing shift motion and axial force decelerating translation velocity. A metallic chamber on the confinement chamber may have same effect on the plasma but the ring technique has more flexibility, i.e. its dimensions can easily be changed. In the preliminary experiments, the trapping process of the translated FRC could be controlled by the metallic ring.

3.2. Equivalent NBI effect
When the FRC is translated into the confinement chamber filled with neutral gas, the background neutral particles are injected into FRC with the relative velocity. We called this the “equivalent NBI (E-NBI)” effect and investigated the efficiency with various neutral gases. Figure 3 shows the experimental setup for E-NBI experiments. Neutral gas is puffed into the confinement section from the end of the chamber by a fast solenoid valve. Then the FRC is injected into the confinement chamber filled with the neutral gas. The relative kinetic energy of neutrals are approximately 100eV (D₂), 200eV (He) and 2 keV (Ar), respectively, for translation speed of 100km.

Typical effects on the time evolution of plasma volume and total (pressure balance) temperature are show in Fig.4. The peak volume and its e-folding time have been increased with D₂ ad He E-NBI compared with standard operation i.e. translation into a vacuum. Also the temperature has been increased in the case of D₂ and He. In the case with Ar, we cannot find any improvement. That might be because of high injection energy and radiation loss of Ar E-NBI. Also in the case with D₂ and He, delayed the onset of instability.

4. Magnetic helicity injection
The resulting toroidal field produces a dramatic effect on

FIG.4. Time evolution of plasma volume and Total temperature with various background gas.
the rotational instability. Figure 5 (a) shows evidence for this on the bremsstrahlung emission $I_b \propto n_e^2/\sqrt{T_e}$. Without CHI, oscillation of $I_b$ rapidly sets in at about 25 μs, reflecting a rotating elliptical deformation of the FRC cross-section. When CHI is applied, the onset is delayed until 45 - 50 μs. It might be delayed indefinitely by a more sustained or intermittent MCPG operation. MCPG injection also reduces the toroidal rotation frequency $\Omega_i$ from 4.2 to 2.6 [$10^5$ rad/s]. Also, the e-folding time of flux $\tau_\phi$ for the initial value in the equilibrium (20μs) is extended from 57 to 67 μs (Fig.5 (b)). These improvements have been made despite the quite modest flux content of the plasmoid: ~ 0.05 mWb of poloidal and 0.01 mWb of toroidal flux, compared with the 0.4 mWb of poloidal flux in the pre-formed 0-pinch FRC.

5. Summary

In the translation process, a metallic ring and E-NBI have been demonstrated as simple and effective control methods for FRCs. The E-NBI technique depends strongly on the species of neutral gas. The neutral species, density and injection timing need to be optimized for better results.

The observed changes in the Bremsstrahlung and poloidal flux suggest that MCPG injection can actively control the rotational instability. Improved confinement has also been shown. This indicates an advantage of the MCPG in that it improves both confinement and stability. The conventional technique does not slow the toroidal rotation. Therefore, MCPG injection introduces its own stabilization mechanism i.e. a modest toroidal flux [4].

The MCPG also offers a number of other control channels. (1) Current drive, as in CHI on spherical tokamaks. (2) Plasma electrode: sustained plasmoid injection offers a control of the radial electric field. (3) Refueling; plasmoid injection increases the plasma inventory. NUCTE is an ideal platform for investigating the MCPG as a multi-faceted control method applicable in a broad range of parameters: density range of $1 \times 10^{20}$ to $5 \times 10^{21}$ m$^{-3}$ and total temperature from 50 to 500 eV.

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