Beam-Assisted Low Density Formation of Field Reversed Configuration (FRC) Plasma

KODERA Fuji, ASAI Tomohiko, OKUBO Mamoru, OKADA Shigefumi and GOTO Seiichi

Plasma Physics Laboratory, Graduate School of Engineering,
Osaka University, Suita 565-0871, Japan

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Abstract

A new ionization process of the working gas through the neutral beam particles is utilized in order to assist in the formation of the field reversed configuration plasma. This method improves the lower density limit of the formed plasma. The beam-assisted formation method enables the density of the produced FRC plasma to be lowered from $2.7 \times 10^{21} \text{ m}^{-3}$ to $3.4 \times 10^{20} \text{ m}^{-3}$ and also allows higher temperatures up to $1,300 \text{ eV}$. The separatrix radius and the trapped flux do not depend on the density in the low density regime. The particle confinement time is longer than the empirical scaling by a factor of 2.8. In addition, the attainable minimum density becomes smaller, as the current of the neutral beam is increased. This suggests that more fast neutral atoms produce more electrons due to their collision against molecules of the working gas before pre-ionization. It is inferred that these electrons help the formation. Under a low density regime of less than $1.0 \times 10^{21} \text{ m}^{-3}$, the maximum produced electron number density by the neutral beam injection is estimated to be $2.9 \times 10^{17} \text{ m}^{-3}$ at a filling pressure $= 130 \text{ mPa}$ (the molecule number density $= 3.6 \times 10^{19} \text{ m}^{-3}$).

Keywords:
field reversed configuration, low density formation, neutral beam ionization, confinement scaling, rotational instability

1. Introduction

A Field Reversed Configuration (FRC) plasma [1] is an elongated high $\beta$ compact toroid without toroidal field, which is proposed as a candidate for a D-He fusion reactor core. The conceptual reactor design 'ARTEMIS' [2] has been proposed based on the FRC plasma. This design requests the plasma parameters of the electron density $n_e = 4 \times 10^{20} \text{ m}^{-3}$ and the ion and electron temperature $T_i = T_e = 1 \text{ keV}$ in the initial formation before the main heating with high power neutral beams. The plasma produced by the typical theta-pinch method usually has a density of around $5 \times 10^{21} \text{ m}^{-3}$ with fairly low temperatures. One possible method to reduce the density is to translate the formed FRC plasma into a large volume confinement region. This has been conducted in FIX experiments [3,4] and TCS experiments [5,6]. In these experiments some different confinement characteristics have been also found compared with those of the usual high density FRC plasmas. Then, the FRC characteristics in the wide density region must be important and should be explored, and especially the improvement of the formation method is required in order to study the low density FRC plasma.
Several formation experiments have been attempted in order to obtain low density theta-pinch and FRC plasmas. High voltage theta pinch experiments [7-9] were reported. Instead of a capacitor bank, a charged transmission line was used for energy storage in this method. For example, the density of the theta-pinch plasma was in the order of $10^{18} \text{ m}^{-3}$ and the temperature was up to 10 keV. In the NUCTE device [10] the low density FRC formation was also studied. In this experiment, the preionized plasma is compressed by a strong bias field in order to enhance the plasma flow from the formation region to the outside region, and the initial plasma is then diluted before the start of the compression field. The critical density of the produced FRC plasma is lowered from $1.1 \times 10^{22} \text{ m}^{-3}$ to $5.6 \times 10^{20} \text{ m}^{-3}$ and the temperature is increased from 350 eV to 810 eV. These two methods imply that efficient ionization in the initial state should be attained before the main compression for the FRC formation. Therefore, a sufficient amount of electrons in the pre-ionization stage is required in order to obtain an effective ionization level just before the main compression, when we attempt to develop a new technique of the low density FRC formation.

A technical problem associated with low density plasma production involves the lessening of the ionization rate in the low pressure range. In the typical theta-pinch method, ionization is governed mainly by electron impact. If the mean free path of the electron becomes longer than the scale of the chamber, the breakdown of the working gas is not sufficient to form the FRC plasma. Some additional means are expected to aid the ionization of the working gas. In general, these means include photo-ionization, microwave ionization and electron beam injection. In our FRC injection experimental device (FIX), we have tried to find a new ionization method using fast neutral particles with the aid of the conventional ion beam source already installed for FIX-FRC heating experiments [11]. Fast atoms of the neutral beam injected into the formation region collide with the working gas molecules and ionize them to some extent. We intend the ionized particles to assist the FRC formation at low filling pressures.

The explanation of the FIX device and its diagnostics are given in sec. 2. The experimental results regarding time histories of the plasma parameters are presented in sec. 3. Sec. 4 is devoted to discussion, and conclusion is given in sec. 5.

### 2. Experimental Apparatus

#### 2.1 System overview

A schematic diagram of the FIX device is shown in Fig. 1(a). This device has a formation region and a confinement region. The formation region shown in Fig. 1(b) consists of a 2,120 mm-long quartz tube with a 275 mm inner diameter and a 309 mm inner diameter theta-pinch coil. The theta-pinch coil is composed of 14 coils with 76 mm widths in each with its separation 8 mm. The position $z = 0$ indicates the center of the coil axis, and this area is called the midplane. A pair of driven mirror coils, named mirror left (ML) and mirror right (MR), is mounted 50 mm apart from each end of the theta-pinch coil. They have the same inner diameter as the theta-pinch coil.

The formed FRC plasma can be quickly translated to the confinement region through the proper control of the ML and the MR coils. In the right-hand side of Fig.
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In the plasma formation, the deuterium gas is introduced into the quartz tube by two puff systems mounted at \( z = \pm 250 \text{ mm} \). The puff system can regulate the amount of the filling gas with the aid of operation conditions, that is, the deuterium gas pressure inside the fast acting valve and the electrical voltage to drive the valve. In addition, the filling pressure under the plasma production phase is influenced by the delay time of the gas puff action.

The deuterium gas is partly ionized by a Pre-Ionizer (PI) shown in Fig. 1(b) in the usual FRC plasma formation. The PI coil is also illustrated in this figure. Radio frequency hexapole current pulse is fed to this coil. After pre-ionization, the plasma is preheated by a ringing current through the theta-pinch coil. The plasma may be fully ionized for a short time by the PreHeating (PH) in the standard operation. Low density formation is not successful because the working gas is not well-ionized before the PH operation. The idea in this work is to improve the ionization level during the PI action by the ionization process between the gas and fast neutrals. The neutral beam injection has been expected to assist the pre-ionization in the PI phase.

The FRC plasma is produced by the fast rising (3.5 \( \mu \text{s} \)) magnetic field \( B_e \). The peak value of \( B_e \) can be chosen to be from 0.40 T to 0.85 T. The power source is the main capacitor bank (50 kV, 84 kJ) charged to 40 kV. Usually, the discharge current is crowbarred at its peak, but in this experiment its timing is changed to the value shorter than the normal condition to produce weaker \( B_e \) keeping the same rising rate \( dB_e/dt \) unchanged. It is found that the weaker peak field is necessary to avoid a collapse of the compressed plasma during the pinch phase. The time evolution of the compression field is shown in Fig. 2. The dotted line shows that the crowbar switch is turned on at \( t = 3.1 \text{ \( \mu \text{s} \)} \) after the compression field starts, and the solid line indicates that it runs at \( t = 0.8 \text{ \( \mu \text{s} \)} \). A field reconnection to form the FRC plasma is forced by the ML (charged to 39 kV) and MR (charged to 37 kV).

The plasma diagnostics consist of a diamagnetic loop array and a He-Ne interferometer. Each loop has its own compensation probe. The separatrix radius \( r_s \) is derived from each loop signal and the axial \( r_A \) profile is estimated from 11 loop signals. The plasma radius in the midplane is represented at \( z = -34 \text{ mm} \). A line integrated density \( \int n_e \, dr \) is measured with a 3.39 \( \mu \text{m} \) He-Ne laser interferometer at the midplane.

The total temperature \( \langle T_i + T_e \rangle \) is obtained by the radial pressure balance of an FRC equilibrium. The temperature is estimated from the following equation;

\[
\kappa \langle T_i + T_e \rangle = \frac{B_e^2}{2\mu_0}/\langle n_e \rangle,
\]

where \( B_e \) is the magnetic flux density measured by the compensation probe at \( z = 58 \text{ \mu m} \), \( \mu_0 \) is the magnetic permeability in vacuum, \( \kappa \) is the Boltzmann constant and \( \langle n_e \rangle \) is the average electron density estimated from the line integrated density and the separatrix radius at the midplane.

### 2.2 Ion source

Our beam system employs the bucket type ion source [12-14]. The axis of the ion source coincides with the geometrical axis of the FIX device in order to aim at the formation region. The schematic diagram of the ion source is shown in Fig. 3, where the ion source has three electrodes to accelerate the beam particles. The electrode has a racetrack shape and the effective length, the minor width and the thickness of copper electrodes are 306 mm, 151 mm and 1.5 mm, respectively. The electrode has 1,757 small holes of 4 mm and 4.5 mm in diameter. The power supply of the ion source [15] consists of the filament, the arc, the acceleration and the deceleration units. Each maximum rating output is
Neutralization efficiency is estimated. The neutralization efficiency is 85% and the amount of the neutral beam injected into the formation region is 23% of the whole neutral beam because of the geometrical factor. The injection operation is shown in the following section.

3. Experimental Result

3.1 Low density formation

The filling pressure in the quartz tube governs the plasma density of the formed FRC. It is fairly difficult to measure the filling pressure in our case, because the working gas is filled into the vacuum vessel by means of the puff system. The decompressed plasma in the PH phase is utilized in order to indicate the equivalent filling pressure. When the plasma produced by the PH alternating current expands to reach the wall in the fast quarter period, it is assumed that the neutral gas is fully ionized and the particle diffusion can be neglected in the axial direction. We can then define the initial plasma density \( <n_{\text{io}} > \) as \( <n_{\text{io}}>/2 \), where \( r_i \) is the quartz tube radius.

We firstly show the case that the compression field is applied to preheated plasma of the density \( n_{\text{io}} \approx 1.5 \times 10^{20} \text{ m}^{-3} \) which corresponds to an equivalent filling pressure of 570 mPa. In this condition, the normal density plasma is produced. The typical time evolution of the line integrated density of the plasma is shown in Fig. 4(a), where the time is measured from the start of the PH field. The FRC plasma is formed and reaches a quiescent phase after a radial and axial compression motion. The characteristic parameters in the quiescent phase are obtained as an average value between \( t = 25.0 \mu s \) and \( t = 27.5 \mu s \). The density \( <n_{\text{i}} > \) is \( 1.9 \times 10^{21} \text{ m}^{-3} \) in this phase. The \( n = 2 \) rotational instability appears as a growing modulation, whose period is 6 - 8 \( \mu s \) at \( t \geq 40 \mu s \), and the FRC configuration disappears at \( t \approx 100 \mu s \). A density lower than \( 1.0 \times 10^{21} \text{ m}^{-3} \) might be formed by decreasing the filling pressure if sufficient pre-ionization can be achieved, but there exists a lower density limit in our normal experimental conditions. The density limit in this way without the neutral beam is about \( 1.3 \times 10^{21} \text{ m}^{-3} \).

In order to overcome the pre-ionization problem, a powerful neutral beam has been employed as the pre-ionizer. Examples of the low density formation are shown in Fig. 4(b), (c) and (d). The neutral beam is injected into the vacuum vessel from \( t = -3 \text{ ms} \) and the typical power measured in the ion source is 440 kW (23 kV, 19 A). The waveform of the line integrated density is shown in Fig. 4(b) at the reduced \( n_{\text{io}} = 4.4 \times 10^{19} \)
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Fig. 4 Typical waveforms in the FRC plasma experiments. The line integrated density of a normal density plasma (a), and low density plasmas (b) and (c), and the waveform (d) of \( r_s \) of the plasma in the same shot as (c).

3.2 Parameter range

The summarized density, temperature, separatrix radius and trapped flux plots of 105 shots are shown in the following four figures. The density in the quiescent phase is shown in Fig. 5 as a function of \( n_0/\langle n_D^2 \rangle \), where the different symbols represent the values of the compression field \( B_c \) in the same phase. The equivalent filling pressure is varied from 64 mPa to 830 mPa, and the plasma density covers the range from \( 3.4 \times 10^{20} \text{ m}^{-3} \) to \( 2.7 \times 10^{21} \text{ m}^{-3} \). The density exhibits an approximately linear dependence on the initial plasma density.

The total temperature is shown in Fig. 6 whose symbols have the same meanings as those of Fig. 5. The temperature ranges from 270 eV to 1,300 eV. The temperature has the tendency to be inversely proportional to the density. The highest temperature plasma does not coincide with the lowest density one, because the temperature is also dependent on the intensity of the compression field. Note that the compression field is smaller than the standard one in the equilibrium state in order to keep the large \( r_s \) plasma, while the mirror ratio is 2.0 - 2.5. These tendencies will be discussed in the later section.

The separatrix radius in the midplane is shown in Fig. 7. The data points of the plasma less than \( 1.0 \times 10^{21} \text{ m}^{-3} \) are selected to study the behavior of the low density plasma. The illustrated range is decided in order to notice the trend in the low density condition. The value of \( r_s \) is between 37 mm and 80 mm. The values of the density in the quiescent phase. The \( n = 2 \) mode starts at \( t = 28 \mu s \) and also grows. The period of oscillation is as long as that in the normal density plasma. But the instability decays and disappears from 60 \( \mu s \) to 90 \( \mu s \), and the configuration continues. The FRC deformation in this operation is suppressed without the multipole field which is usually used for the stabilization of the \( n = 2 \) rotational instability. The behavior of the plasma produced at \( n_D^2 = 3.0 \times 10^{19} \text{ m}^{-3} \) is shown in Fig. 4(c) and (d). The density is \( 4.2 \times 10^{20} \text{ m}^{-3} \) in the quiescent phase. The ripple-like oscillation of the waveform in Fig. 4(c) begins from \( t \approx 45 \mu s \) with this period shorter than in other cases. In this case, the instability does not grow and disappears at \( t \approx 70 \mu s \). It is found that this configuration is sustained after the extinction of the instability. The signal for \( r_s \) following the instability phase, as shown in Fig. 4(d), proves this fact. The waveform of \( r_s \) is not different from the normal density plasma, and it is found that a lifetime is not shorter than the plasma of the normal density.
Fig. 5 The plasma density in low density operation as a function of initial plasma density or molecule number density. The symbols represent the compression field in the quiescent phase. $\times$: $0.55 < B_r < 0.50$, $*: 0.50 < B_r < 0.55$, $\triangle$: $0.45 < B_r < 0.50$, $\Box$: $0.40 < B_r < 0.45$ and $\circ$: $B_r < 0.40$ T.

Fig. 6 Relationship between total temperature and density. The symbols represent the compression field in the quiescent phase. $\times$: $0.55 < B_r < 0.50$, $*: 0.50 < B_r < 0.55$, $\triangle$: $0.45 < B_r < 0.50$, $\Box$: $0.40 < B_r < 0.45$ and $\circ$: $B_r < 0.40$ T.

Initial Plasma Density ($10^{19}$ m$^{-3}$)
Molecule Number Density ($10^{19}$ m$^{-3}$)

Fig. 7 Separatrix radius versus plasma density. The symbols represent the compression field in the quiescent phase. $\times$: $0.55 < B_r < 0.50$, $*: 0.50 < B_r < 0.55$, $\triangle$: $0.45 < B_r < 0.50$, $\Box$: $0.40 < B_r < 0.45$ and $\circ$: $B_r < 0.40$ T.

Fig. 8 Trapped flux in low density operation. The symbols represent the compression field in the quiescent phase. $\times$: $0.55 < B_r < 0.50$, $*: 0.50 < B_r < 0.55$, $\triangle$: $0.45 < B_r < 0.50$, $\Box$: $0.40 < B_r < 0.45$ and $\circ$: $B_r < 0.40$ T.

One of the important features of the FRC formation is the maximization of the trapped flux contained within the configuration. The trapped flux $\Phi$ is estimated from the following equation by the rigid rotor model [16]:

$$\Phi \equiv \pi \frac{\alpha}{2} \frac{r^2}{2} B_r x_r^3,$$

where $\alpha = 7/8$, $r_w$ is the inner coil radius and $x_r = r/r_w$.

The obtained result is shown in Fig. 8. The points are scattered between 0.2 mWb and 1.5 mWb in the low density regime. This result may be due to the sensitivity of $x_r^3$ in the equation.
3.3 Particle confinement

As presented in Fig. 4(b), (c) and (d), the formed FRC plasma assisted by the neutral beam does not have the indication, in all the shots, that the configuration disappears due to $n = 2$ rotational instability even if the instability begins to grow. The particle confinement time $\tau_\text{p}$ is derived from the waveforms of the diamagnetic probe array and the interferometer during the whole time of the configuration life. The time $\tau_\text{p}$ can be obtained by an exponential fitting curve to the time evolution of the particle inventory. The raw traces of the particle number and the fitting curve are seen in Fig. 9. The maximum difference between the two waveforms is about 30% and the fitting dispersion is 18% for $\tau_\text{p} = 83 \mu s$. The confinement times of the low density plasmas are plotted versus $R^2/\rho_e$ in Fig. 10, where $R$ and $\rho_e$ are the radius of the magnetic field null ($r_b\sqrt{2}$) and the ion gyro radius in the external field, respectively. The solid straight line represents a line fit $\tau_\text{p} = 0.22 \times 10^{-3} R^2/\rho_e$ to the experimental data, where $T_i$ is taken to be two thirds of $\langle T_i + T_e \rangle$. It is mentioned that $\tau_\text{p}$ is larger than the empirical scaling [17] by a factor of 2.8.

4. Discussion

Our pre-pre-ionization method using the neutral beam produces low density plasma of the order of $10^{20}$ m$^{-3}$. In this method, the formed plasma may be influenced by the amount of the neutral particles injected into the formation region. We must discuss the relation of the injected particle number to this effect. The limit of the attained density depends on the beam equivalent current as shown in Fig. 11. The beam power and current are changed from 25 kW (5 kV, 5 A) to 440 kW (23 kV, 19 A) as the ion source output. The data points of the closed circles present the obtained density limit in the same power and current of each horizontal value, where the open circles express the observed density in the different discharge condition corresponding to the higher filling gas pressure than the
limiting case. As the current of the neutral beam is increased, the minimum density becomes smaller. The result of this experiment leads to the conclusion that the deuterium molecules are effectively ionized by the neutral beam injection and then the lower density plasma can be formed.

For the validity of the above conclusion we may estimate the number of electrons created by the binary collision between the fast hydrogen atom and the hydrogen molecule. The total cross-section of the electron production is $3 \times 10^{-16} \text{ cm}^2$ [18]. On the other hand, the fast hydrogen atom injected into the formation region is $3.7 \text{ A}$ which is $2.3 \times 10^{19} \text{ s}^{-1}$ for the case of $440 \text{ kW (23 kV, 19 A)}$ in the ion source. Here, we assume that for $1 \text{ ms}$ of the beam duration the produced electrons undergo no loss process such as recombination and diffusion. The mean free path of the fast neutral particle at $23 \text{ keV}$ is $0.93 \text{ m}$ at a typical filling pressure of the low density operation ($130 \text{ mPa, } n_{D_2} = 3.6 \times 10^{19} \text{ m}^{-3}$) and thus the maximum number of produced electrons are $n_e = 2.9 \times 10^{17} \text{ m}^{-3}$. In the case of the lowest density obtained at the equivalent filling pressure ($60 \text{ mPa (} n_{D_2} = 1.6 \times 10^{19} \text{ m}^{-3}$), the mean free path is $2.1 \text{ m}$ and the removed electrons are $1.5 \times 10^{17} \text{ m}^{-3}$. We suppose that the FRC plasma can be formed under this ionization condition. On the other hand, using the filling pressure $= 13 \text{ mPa (} n_{D_2} = 0.36 \times 10^{19} \text{ m}^{-3}$), the FRC plasma has not yet been attained. The mean free path is $9.3 \text{ m}$ and the electron number density is $0.40 \times 10^{17} \text{ m}^{-3}$ for this case. If the number of the fast particles reaches ten times as many as the present one, the electron number is sufficient to produce a lower density FRC.

The relation between the compression field and the formed plasma is discussed. The Barns' equation [19] on the FRC equilibrium is expressed by the following.

$$\langle \beta \rangle = \frac{n_e \kappa (T_e + T_0)}{B_0^2/2 \mu_0} = 1 - \frac{x_e^2}{2},$$

where $\langle \beta \rangle$ is the average beta value. The experimental value of $\langle \beta \rangle$ can be given by the value of $x_e$ in the quiescent phase. The mean value of $\langle \beta \rangle$ is $0.94$ and its dispersion is $0.017$ for all the data of $105$ shots. As a result, temperature is inversely proportional to density under the fixed compression field. In addition, the experimental relation of temperature to density shown in Fig. 6 may be understood to show the difference of the compression field. The relation between the energy of the formation plasma and the magnetic energy is presented in Fig. 12. Energy exhibits an approximately linear dependence on $B_0^2$. When the compression field is stronger, the plasma energy is increased.

5. Conclusion

The FRC plasma density can be lowered when the pre-ionization process is assisted at its formation phase by the neutral beam injection. The density limit is shifted from $2.7 \times 10^{21} \text{ m}^{-3}$ to $3.4 \times 10^{19} \text{ m}^{-3}$. As the density is lowered, the temperature changes from $270 \text{ eV}$ to $1,300 \text{ eV}$. The separatrix radius and the trapped flux do not depend on the density in the low density regime. The particle confinement time is larger than the empirical scaling by a factor of $2.8$. The behavior of the low density plasma is different from that of the normal density plasma. The $n = 2$ rotational instability does not grow up to the broken state of the FRC. The reason for this phenomenon has not so far been explained.

The dependence between the beam current and the low density limit is found. We suppose that the electrons are produced by the collision between the fast neutral atoms and the gas molecules, and this may aid in the plasma formation. As the result of the estimation, it may be possible to increase the number of produced electrons in the pre-ionization phase for more low density FRC formation.

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References


