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FRC Translation Experiment into the Neutral Gas Background in the FIX Device

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Abstract

Translating an FRC plasma through a neutral gas background is equivalent to the injection of a warm neutral beam end-on into the FRC. Controlling a translated FRC density and rethermalization of the kinetic energy of that are expected by gas puffing without complex NBI device. We carried out FRC translation experiment into the neutral gas background based on this point of view. In the FIX device, the FRC produced in the quartz formation region is translated into the metal confinement region. The translated FRC is reflected by the downstream mirror field. The FRC reaches equilibrium state after one or two bounces. Typical translation velocity of FIX-FRC is about 1.5×10^5 m/sec, which is equivalent to a 200 eV incident neutral D beam. The neutral gas (D_2) pressures of ~10^{-2} Pa averaged inside the confinement region can be introduced using a piezo electric valve which is installed on the end of FIX-device. An FRC is translated into neutral gas background whose averaged density is about 1~3×10^{-2} Pa. The mean free path $\lambda_{\mathrm{ionize}}$ (~0.1 m) of D_2 is shorter than FRC separatrix length l_s under the parameters of FIX-FRC plasma. As the result of this experiment, the radii of the FRC increase 10~20 % of those of normal FRC after the 1st reflection. An increasing in the particle number inside the separatrix is observed after the translation into the neutral gas background. The total energy inside the FRC after translation is also observed to increase a little.

Keywords:

compact torus, FRC, translation, rethermalization, refueling

1. Introduction

A field-reversed configuration (FRC) [1] plasma has only poloidal magnetic field and is confined in a basically simple solenoidal magnetic field. The structure of the FRC is quite simple, like a vortex, and therefore it has a magnetic null inside its separatrix. These properties make the average plasma beta, the plasma pressure normalized by the solenoidal magnetic field pressure $\langle\beta\rangle = 1 - (r_s/r_w)^2/2$ extremely high, up to 0.9. Owing to this high beta feature, possibility of achieving a neutron-lean reactor using advanced fuels D-^{3}He was considered [2]. Another significant feature of the FRC is that the plasma can be translated from the quartz source region to the metal confinement region along the guide field.

Translating a FRC plasma into the background neutral gas is equivalent to the injection of a warm neutral (molecular) beam end-on into the FRC. The FRC produced in the FIX (FRC Injection eXperiment) can be translated with the velocity of about 1 ~ 2×10^5 m/sec. In this case pre-filled background D_2 gas is equivalent to a 150~300 eV neutral D_2 beam injection. The density of translated FRC is expected to be controlled without significant energy loss by simple gas puffing.

Translation of FRCs have successfully demon-

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strated in several facilities since the early 1980s [3,4]. In most of these experiments, plasma temperature increases rapidly during the translation. This phenomenon is called rethermalization. In 1995, Himura et al. suspects that a shock wave is the mechanism for the rethermalization [5]. The increase of the plasma energy by the rethermalization is however less than the kinetic energy loss with inelastic reflection at the downstream mirror region. The kinetic energy of translated FRC may be rethermalized with the warm neutral beam effect.

2. Experimental Setup

A schematic drawing of FIX device is shown in fig. 1. The FRC is produced in the quartz formation region using the negative bias theta pinch method and then translated into the metal confinement chamber, where it is confined, by a gradient in the solenoidal guiding field.

A 1 m long and 0.31 m inner diameter theta pinch coil contains a 0.27 m inner diameter quartz discharge tube. The FRC plasma is formed in this quartz discharge tube. The fuel gas D_2 is introduced by two gas puff systems. Typical parameters of the FRC in formation region are an electron density ne of 5×10^{21} m^{-3}, a pressure balance temperature T_{tot} of 300~400 eV and x_s (= r_s/r_w, where r_s is the separatrix radius and r_w is the wall radius) of 0.35. Independently driven mirror coils are installed at both ends of the main coil. The FRC is ejected from the formation region into the confinement region by unbalanced operation of these mirror coils. The axial velocity of translation is about 1 ~ 2 $\times$ 10^5 m/sec.

The confinement region is made of 6 mm thick stainless steel and has a straight section with a length of 3.4 m and a radius of 0.4 m. Both end of the straight section are tapered to a 0.5 m inner diameter, and have strong magnetic mirror fields there. Typical strength of the magnetic field is 0.04 T in the confinement region, 0.13 T in the upstream mirror region and 0.15 T in the downstream mirror region. Typical parameters of the FRC in confinement region are n_e of 3×10^{19} m^{-3} and T_{tot} of 100~200 eV. The FRC radii are estimated from data of 35 chs magnetic pickup loops installed inside the metal confinement chamber. The CO_2 laser interferometer is installed near the mid-plane of straight section to measure the line integrated density of the FRC. The plasma temperature T_{tot} is calculated from the radial pressure balance equation. Two ionization probes are used for estimating the neutral gas diffusion in the confinement chamber. These ionization probes are installed on the FIX machine axis for the gas diffusion measurement. The time response of the ionization probe is shorter than several tens of micro seconds. They are pulled out of the chamber when the FRC plasma is produced. A piezo electric valve is set on the end of the downstream mirror section and introduces the background neutral gas into the confinement chamber.

The typical results of the background gas diffusion measurement is shown in Fig. 2. Figure 2(a) shows the time evolution of neutral gas density measured with the C1 ionization probe. Figure 2(b) shows that with the C5 ionization probe. Time sequence of the FRC production is shown in Fig. 2(c). The formation of a FRC plasma is not affected very much, however, a small amount of the background neutral gas come into the formation region when the FRC is produced. The warm neutral D_2 beam injection equivalent to the energy of 240 eV and the fueling the particle number of 2.6×10^{18} are expected under the condition of an FRC translation velocity v_z~1.5×10^5 m/sec and the deuterium background pressure ~2×10^{-2} Pa.

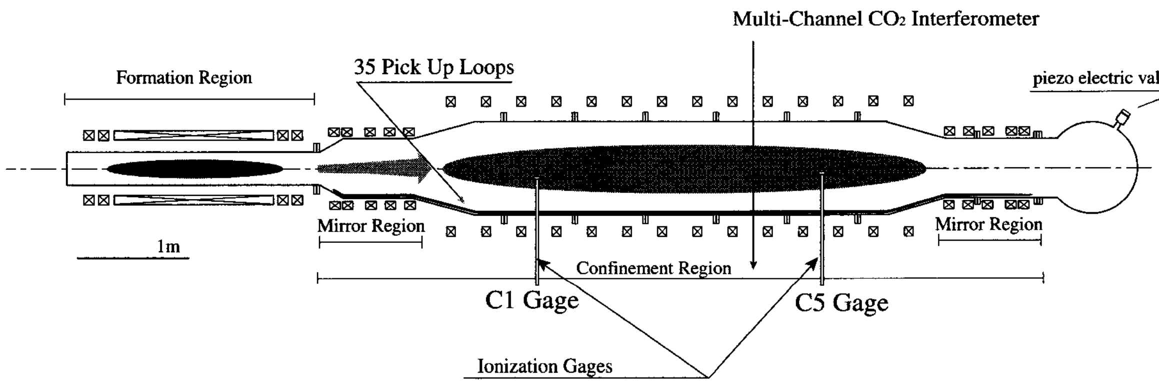

Fig. 1 Schematic drawing of FIX device and diagnostics.

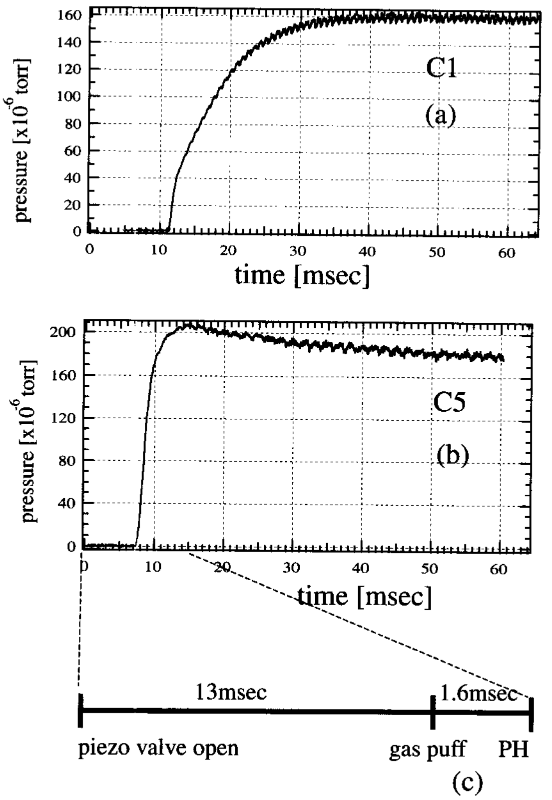

Fig. 2 (a) Time evolution of neutral gas pressure at C1. (b) Time evolution of neutral gas pressure at C5. (c) Time sequence of neutral gas injection experiment. Time origine is the time of piezo valve opening in each graph.

3. Experimental Results

The experimental results of normal FRC translation are shown in Figs. 3(a) and 3(c). Figures 3(b) and 3(d) show the results of the FRC translation into the D_2 neutral background gas. Figures 3(a) and 3(b) show the typical time history of the separatrix shapes of the FRC at the time of 20 μsec, 30 μsec, 49 μsec, 61 μsec and 70 μsec from PH (Pre heat). Figures 3(c) and 3(d) show the time history of the FRC gravity center and its axial position. Both of these are calculated from averaging the 10 shots. The velocity of translation into the neutral gas is observed to be faster than that of normal plasma shot. The velocity after the first reflection (2nd pass) of the background gas shot become slower than that of normal plasma shot. The rethermalizations are observed on the reflection process on both shots. In the back ground gas shot case radial - plasma expansion after the first reflection is observed obviously.

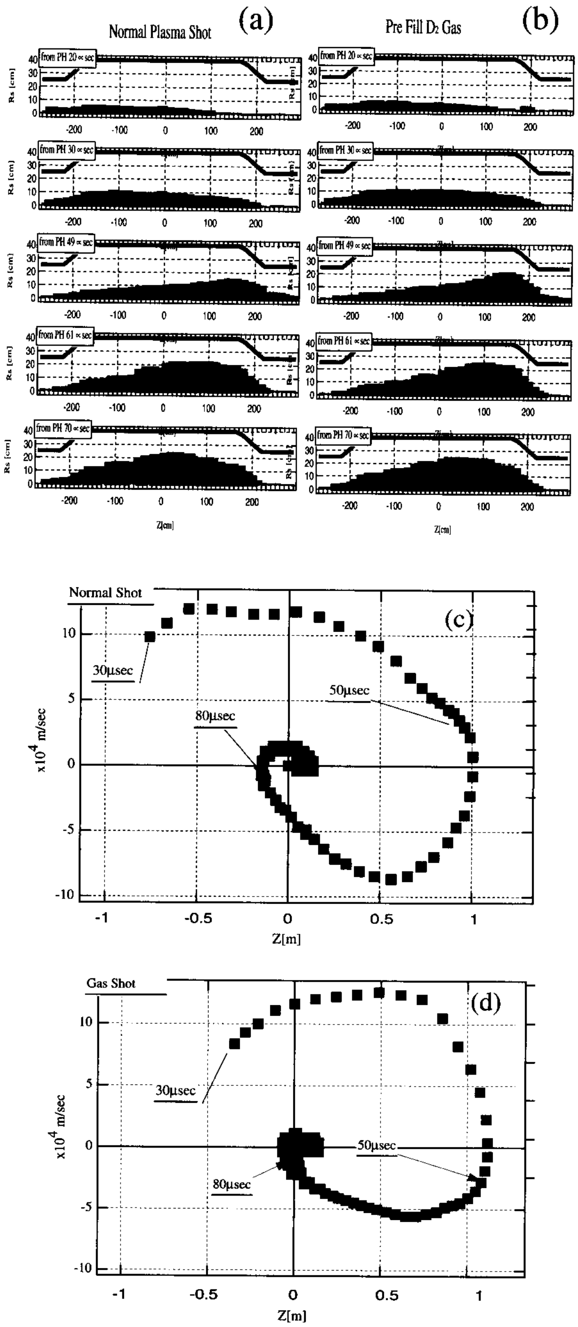

Fig. 3 (a) Time history of the separatrix shape of the normal FRC translation. (b) Time history of the separatrix shape of the FRC translated into the neutral D_2. Both (a) and (b) graphs include the data of time from 20 μsec, 30 μsec, 49 μsec, 61 μsec and 70 μsec. (c) Time history of the FRC center of gravity under the normal translation. (d) Time history of the FRC center of gravity into the background neutral D_2. Both (c) and (d) graphs are averaged of 10 shots. In both (c) and (d) graphs vertical axis show the axial velocity, horizontal axis show the position on Z axis.

The comparisons of plasma parameters between normal shots and background gas shots are shown in Fig. 4. Each trace shows the time evolution averaged about 10 shots. The time evolutions of FRC volumes are shown in Fig. 4(a), those of the total temperature are shown in Fig. 4(b), those of the particle number inside the FRC are shown in Fig. 4(c) and those of the total energy inside the FRC are shown in Fig. 4(d). Solid lines show the data of the background gas shots and dashed lines shows the normal shots in Fig. 4. About 6 $\times$ 10^{18} of D_2 particles are expected to penetrate translated FRC under the condition of pre fill D_2 pressure ~ 3 $\times$ 10^{-2} Pa and the translated FRC radius ~ 0.1 m. The increase of the particle number at the first pass is consistent to that. After the first reflection particle number increase to ~125 % of that of normal shot. More neutrals are considered to be captured by fatter FRC which grow radially on their 1st pass. The mean free path of deuterium ionization (λ_i) is about 0.08 m under the typical FIX-FRC parameter. The translated FRC length of about 3.5 m is long enough when compared with the λ_i. Supposing that all of the warm neutral beam energy changes the energy inside the FRC, the increase of energy after 1st pass is expected to be ~200 J. The increase of the plasma energy is observed to be about half of it or less. The mean free path of hot ions on the charge exchange is about 0.06 m. Hot ions escape from FRC by charge exchange are calculated to be negligible small. An ion mean free path is about 0.5 ~1 m. It is not negligible for FRC scale. Thus the escaping hot ions may be the cause of the energy loss of 1st pass. Figure 5 shows the translation velocity and the total energy of the FRC. In this case rethermalization efficiencies are calculated to be 60 % (normal plasma shot) and to be 55 % (into gas background). The energy of FRC on 1st pass is increased because the particle number and the translation velocity increase. Thus the total energy after the first reflection also increases. So the rethermalization efficiency is considered to increase when the FRC is translated into the neutral gas.

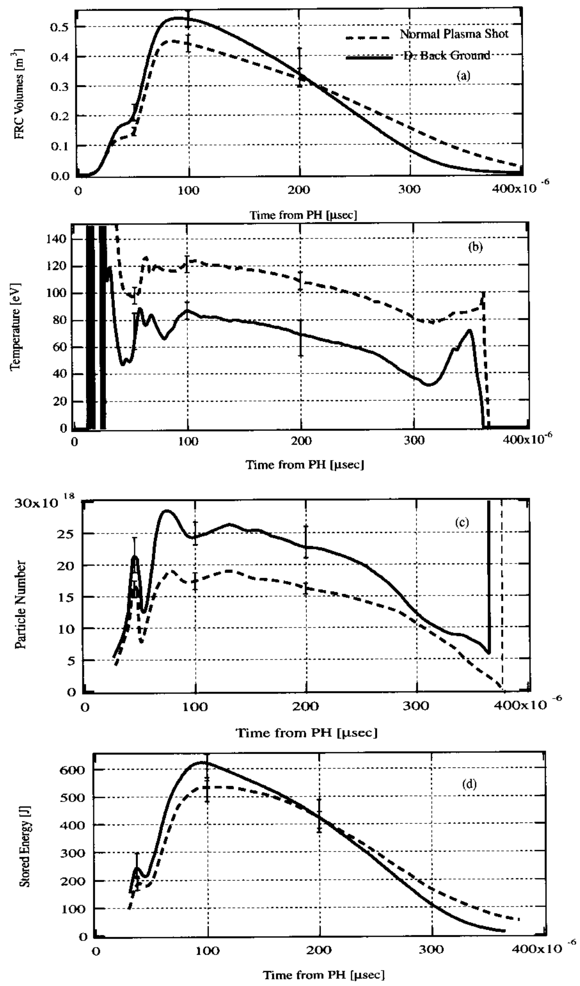

Fig. 4 Time evolutions of plasma parameters. (a) FRC volumes. (b) Total temperature $T = T_i + T_e$. (c) Particles inside the separatrix. (d) Energy inside the FRC. Solid lines show the data for translation into the deuterium background. Dashed lines show the data of normal plasma operation.

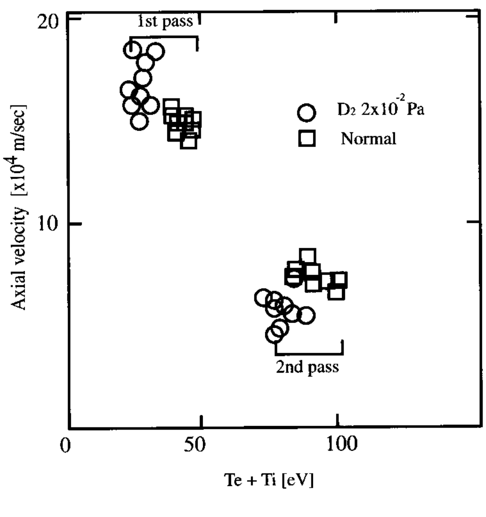

Fig. 5 Axial FRC velocity. Circles show the data of normal plasma shot. Rectangles show the data of translation into the neutral deuterium.

4. Summary

An FRC translation experiment into the dense neutral gas has been carried out. The FRC is translated with gathering almost all the neutral particles along its path. The FRC radius grows fat and its volume increases to be 120 %. The first pass velocity into the background gas is faster than that of normal shot. The rethermalization efficiency under the back ground gas condition is almost equal to that of normal shot. Thus the total energy inside the FRC tends to be increase. This translation technique may be applicable for refueling without energy loss. The particle confinement time however is to be shorter because of dense neutral particle.

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