Translation of Field-Reversed Configuration into a Confinement Region Filled with Neutral Gas

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The effects of the background particles on the translation process have been investigated by NUCTE-III and the newly upgraded NUCTE-III/T devices. In NUCTE-III experiments, field-reversed configuration (FRC) plasmas are translated into weakly ionized plasma with translation velocity of 100km/s. The decay time of the particle inventory and the poloidal flux were prolonged in the experiments. The relative motion between translated FRC and background particles can be assumed to be equivalent to axially injected warm neutral beam. In this point of view, particle simulation under the experimental conditions has also been performed to investigate the effects of the injected particles. The equivalent beam injection with higher injection energy can supply not only the particle inventory but also the kinetic energy into the target FRC plasma. To clarify the second effects of the above, the experimental device has been upgraded. This realizes higher injection velocity up to 150km/s and controllable background gas density. The confinement properties with NUCTE-III/T experiments have been observed to be similar to the initial experiments on NUCTE-III.

Keywords: field-reversed configuration, translation, neutral beam injection, fueling, high beta

1. Introduction

Future reactor systems may draw upon translation technique whereby a field-reversed configuration (FRC) is realized by separating a complex high voltage theta-pinch region and a static confinement one which has better accessibility for additional heating methods *e.g.* NBI heating facility [1]. There have been several reports that the confinement properties of FRC were improved by translation. In the FRX-C/T, the translation experiments with a static gas fill gave evidence for the improvement of particle confinement or refueling of the particle inventory inside a separatrix [2]. Recently, an improved confinement mode was found in TCS experiments with super Alfvenic translation velocity [3]. This translation process forms self-organized toroidal flow and toridal magnetic field have been observed, and a magnetic structure with a high safety factor and a magnetic shear at an edge region of FRC [4]. In NUCTE-III translation experiments, FRC plasmas have been translated into weakly ionized plasma with neutral particles. Enhancements of confinement properties have been observed, such as prolonged particle and poloidal flux confinement time and delayed onset time of n = 2 rotational instability [5]. In this study, the effects of the background plasma and neutral particles in an improved confinement were investigated with the NUCTE-III and the newly upgraded NUCTE-III/T, featuring a quasi-static confinement region. Several initial experimental results are presented in this paper.

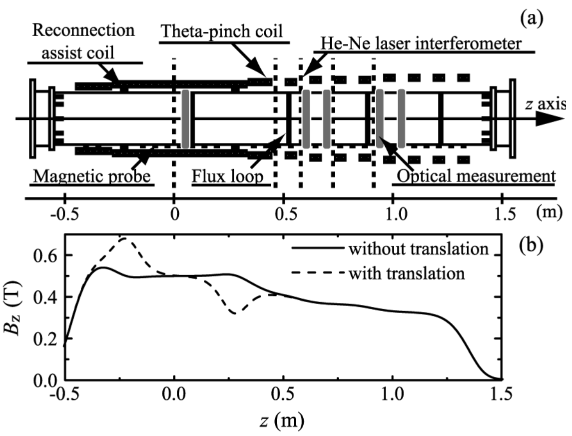

Fig.1 Schematic view of experimental device NUCTE-III for translation experiment (a) and the axial profile of the guide field (b).

2. Experiments on NUCTE-III

A negative-biased theta-pinch device called NUCTE-III was modified for the translation experiment as shown in Fig. 1 (a). The theta-pinch coil measured 1.7 m, and its radius r_c tapered with the axial position [6]. The external guide field is 0.4 - 0.6 T, as shown in Fig. (b) , at a peak of discharge, and its rise time and decay time were 4 μs and 120 μs, respectively. A transparent quartz discharge tube with a length of 2 m and radius of 0.235 m is

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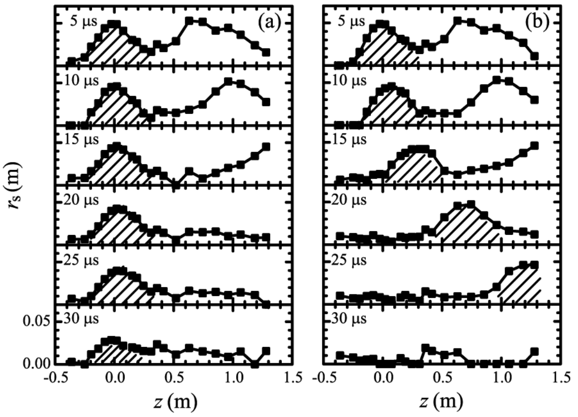

Fig.2 Time evolutions of the axial separtrix radius profile without the translation (a) and with the translation (b). Hatched regions indicate the observed FRCs in the cases with and without translation.

evacuated to 1.0 x 10^{-6} mTorr and filled with 10 mTorr of deuterium gas. The preheating plasma was formed by the ringing z-discharge method.

The FRC plasma is initially produced throughout the vacuum chamber, shown in Fig. 2 (a) and (b). By turning on the reconnection assist coil at 5 μs, the plasma was rapidly split into two parts at z = 0.30 m. The plasma in upstream chamber was reliesed at 15 μs due to the gradient of the guide field, and completely ejected before t = 20 μs. For the translation, the confinement field modified by the assist coils as shown by a dashed line in Fig. 1 (b). Then the remaining FRC plasma in the upstream chamber was translated smoothly into the downstream chamber. The plasma started to translate at 15 μs then it is passing through z = 0.5 m at t = 20 μs and finally arriving in downstream chamber at t = 25 μs, with an average translation velocity of approximately 90 km/s. Without the assist coil, the FRC plasma would remain in the upstream chamber by the confinement field indicated by a solid line in Fig. 1 (b) and collapsed by 30 μs with a growth of n = 2 rotational instability.

Figure 3 shows the time evolution of typical plasma parameters: total particle inventory (N_T), poloidal flux (ϕ_p), total temperature (T_T), plasma energy (E_p), and kinetic energy (K_p). The markers denoting the translation are represented as the average of several discharges. Up to the start of translation, each parameter corresponds to those without translation within the range of experimental error and reproducibility. With the progress of translation, differences in time evolutions appear. The total inventory of the FRC plasma increased while the loss rate of the poloidal flux decreased. On the other hand, the loss rate of the total temperature increased while the internal plasma energy remained unchanged. The ion temperature estimated by the ion Doppler spectroscopy method was about 120 eV, half of the total temperature. The ion temperature slightly decreased with increasing translation

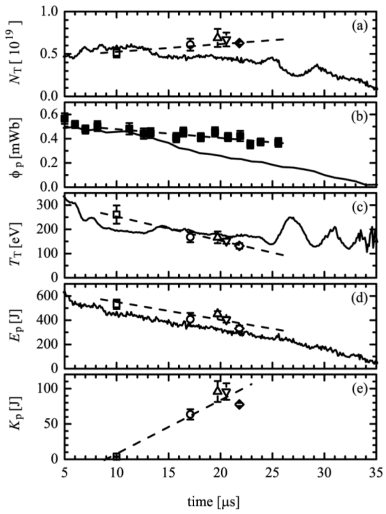

Fig.3 Time evolutions of the plasma parameters. (a) total inventory, (b) poloidal flux, (c) total temperature, (d) stored energy, (e) kinetic energy.

velocity. The temperature was almost the same as without translation. In this experiment, there was a small quantity of neutral particles (deuterium atoms), electrons, and deuterium ions compared to the bulk FRC plasma in the translation region. The background particle density was estimated by the absolutely calibrated D_α and D_β line intensity profiles and the electron density profile [6]. The estimated average neutral atom and electron densities over the translation region were 2-3×10^{20}m^{-3} and 1-4×10^{20}m^{-3}, respectively.

The observed improvement in the confinement related to the neutral particles, electrons, and ions injected into the FRC plasma. Translating an FRC plasma through a neutral gas and plasma background is equivalent to the injection of a neutral beam end-on into the FRC. The reaction processes considered in this paper concern

Table I Energy Deposition Ratio

Energy Deposition Ratio	Deuterium		Helium	
Injection Velocity (Translation Velocity)	100 km/s [%]	150 km/s [%]	100 km/s [%]	150 km/s [%]
Inside Separatorix	93.6	81.1	90.6	53.2
Outside Separatrix	3.3	17.6	7.6	41.2
Electron	2.84	5.71	3.82	7.27
Ion	94.1	93.0	94.4	87.1

Table II Deposition Energy

	Deuterium		Helium	
Injection Velocity Translation Velocity	100 km/s [eV]	150 km/s [eV]	100 km/s [eV]	150 km/s [eV]
Injection energy	104	235	208	469
Inside Separatrix	97.6	190	189	250
Outside Separatrix	3.5	41.3	15.9	193

charge exchange and electron collisional ionization with the maximum injection velocity and the equivalent kinetic energy at about 100 km/s and 100 eV, respectively [6]. The calculated characteristic length of charge exchange and an electron collisional ionization are 0.9 mm and 1.2 mm, respectively. Because the lengths are much shorter than the separatrix length and radius, the injected neutral particle will be ionized near the separatrix surface of FRC plasma and captured by the FRC plasma. The captured particle inventory was estimated by the equation $N_{\mathrm{injection}} = \pi r_s^2 l_{\mathrm{transn}} n_D$, where n_D, r_s, and l_{trans} were the neutral atom density, the separatrix radius, and the distance of the translation, respectively. Approximately 1-4 × 10^{18} of particles were injected. This value was comparable to the increase in the total inventory of FRC plasma, as shown in Fig. 3. The beam energy deposited into the FRC plasma was also estimated. Because of our experimental condition, most of the beam energy was deposited by the plasma ion [7]. The estimated energy of the particle injection was about 40 J and the increase of plasma energy would be very small. The total inventory of plasma and the plasma energy estimated from the loss rate of no-translation FRC plasma were about 3.7 × 10^{18} and 340 J, respectively. The differences of these values from the obtained experimental values $N_T \sim 6 \times 10^{18}$ and $E_p \sim 400$ J were about 2.3 × 10^{18} and 60 J, respectively. These values were nearly equal to the estimated injection values. In our experiment, the equivalent temperature of the translation velocity was comparable to the plasma temperature. Therefore, the heating effect was small in our experimental conditions. In the experiments with higher translation velocity, the heating effect of this equivalent NBI would be clarified.

Detailed two-dimensional calculations of the equivalent neutral beam injection in our experimental conditions were performed using a particle simulation code [8]. The results were summarized in Table I and II. At a translation velocity of 100 km/s, 90% of the injected neutral beam was deposited just inside the separatrix. Moreover, 90% of the beam energy was deposited into the plasma ions. With increasing translation velocity, the energy which was deposited inside the separatrix decreased. However, the ratio of injected energy deposited into the electrons increased. The deposition rate was strongly dependent on the number of background neutral particles due to recharge exchange reactions. Also, the simulation results in Table II indicates that the heavier particle was more effective for heating. In this way, NUCTE-III device was upgraded to clarify the energy recovery process through injected background particles.

3. Experiments on NUCTE-III/T

The NUCTE device was upgraded based on the above-mentioned experiment and simulation results as shown in Fig.4. The confinement region consists of a quartz tube with a length of 1.4 m and a diameter of 0.4 m for the center part and two tapered stainless-steel chambers with a length of 0.8 m on both ends. The confinement coil consists of equally spaced eight coil elements with an equivalent coil radius of 0.3 m and a width of 0.1m and each mirror coil consists of four coil elements. The skin time of the metal chamber and the coil bobbin were approximately 5 ms. The calculated profile of a guide magnetic field is shown in Fig. 4 (b). The mirror ratios of the upstream and the downstream were 3 and 4, respectively. The typical magnetic field strength at the center of the confinement coil was 63 mT.

The configuration of a theta pinch coil was tapered , as shown in Fig. 4 (a) and the gradient of the confinement field was about 0.12 T/m. The working gas of deuterium wassupplied into a discharge tube by a fast gas puff valve. The equivalent gas pressure in the confinement region was about 10 mTorr of gas fill. Typical strength of bias field was about 32 mT and the pre-heating plasma was formed by ringing B_z field method. Axial motion of translated FRC plasma was monitored by the excluded flux method (-3.5 m < z < 0.5 m) and electron density measurement with a 3.39 μm He-Ne laser interferometer at a formation region (z = -0.4 m) and triple probes at upstream (z = -1.7m) and down stream (z = -3.4m) mirror regions. The effect of the background particle of D_2 was investigated by the comparison of plasma behaviors which were produced under the different pre-filled gas pressure. The pre-filled

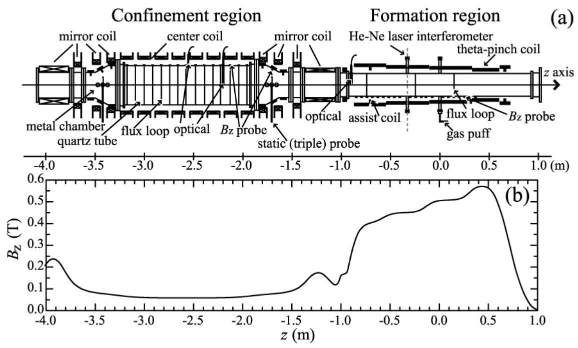

Fig.4 Schematic of NUCTE III/T (a) and the magnetic field profile (b)

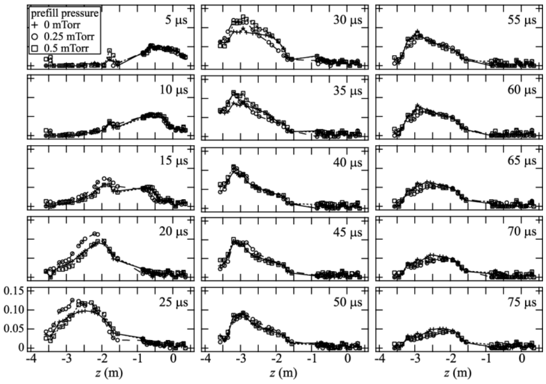

Fig. 5 Typical time evolution of an axial separtrix profile.

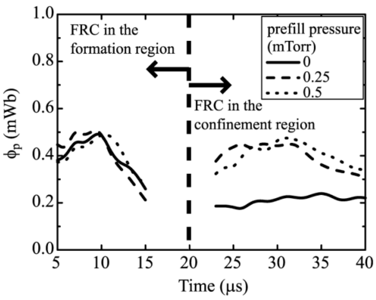

Fig.6 Time evolution of the poloidal flux of the translated FRC plasma..

gas pressure (0.25 and 0.5 mTorr) was much lower than the puffed working gas of 10 mTorr. The source plasma parameters of a separtrix radius, length, separatrix volume, total temperature, ion temperature and electron density were 0.05 m, 0.6 m, 0.005 m^3, 0.6 mWb 220 eV, 120 eV and 3×10^{21} m^{-3}, respectively, and it is same with the previous experiments on NUCTE-III.

Figure 5 shows the time evolution of the axial separatrix profiles. The symbols of plus, open, and closed circles indicate the cases of translation without pre-fill and pre-fill with 0.25 and 0.5 mTorr, respectively. All of FRC plasmas were translated with the same velocity of less than 100 km/s in this initial series of experiments. The velocity was nearly equal to or less than the thermal velocity of the initial formed FRC plasma.

Without a pre-fill pressure, the FRC plasma radius was expanded at the first pass and becomes about 0.1 m. Other measured parameters of separatrix volume, electron density, and total temperature at the first pass were about 0.04 m^3, 3×10^{20} m^{-3} and 40 eV, respectively. These plasma parameters were equivalent with those estimated by the adiabatic expansion model [9]. The first reflection at the downstream mirror did not change any of these plasma parameters. After the bouncing process between mirrors, the FRC gradually decayed and then terminated by n = 2 rotational instability at about 100 μs.

The effect of the pre-fill gas at fast pass was investigated experimentally. The difference on the time evolution of plasma radius was indicated in Fig. 5. With the increase of pre-fill gas, plasma radius at the first pass was increased from 0.1 to 0.13 m. The poloidal flux, which was estimated by a rigid rotor profile model, also increased from 0.2 mWb to 0.4 mWb as shown in Fig.6. The estimated loss rate of poloidal flux was decreased from 15 Wb/s to 3 Wb/s during first pass. Figure 7 shows the total inventory at z = -0.4 m, -1.75 m (upstream taper metal chamber), -3.3 m (downstream taper chamber) during the first pass. The total inventory was estimated by the time evolution of the plasma volume and the electron density. The inventory at the upstream chamber was about 1.5×10^{19} in three cases with different background pressure, however at the downstream region, it increased from 1.0 to 1.2×10^{19} dependent on pre-fill pressure. The estimated average loss rate then decreased from 4×10^{23} to 2×10^{23} s^{-1}. The injected particle inventory was 1-3×10^{18} by the above-mentioned estimation. This value is consistent with the experimental result.

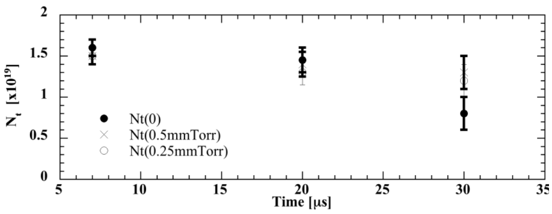

Fig.7 Time evolution of total particle inventory.

4. Summary

The effects of the background particles on the translation region were investigated by NUCTE-III and NUCTE-III/T device. In NUCTE-III experiments, an FRC plasma was translated into weakly ionized plasma. The prolonged decay time of the particle inventory and the poloidal flux were observed. In NUCTE-III/T experiments, similar experiments results were also observed. Particle simulation was also performed to investigate the effects of the injected particles, and it indicates the equivalent beam injection by background particles supplied the FRC plasma with not only the particle inventory but also the kinetic energy. In the near future, to clarify the energy recovery process due to the possible heating effect of an equivalent NBI, the dependence on the kind of background gas and parameters of translating FRC plasma, as well as the translation velocity, will be investigated on NUCTE-III/T.

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