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Neutral-Beam Assisted Experiment of an FRC Plasma

S. Goto, F. Kodera, T. Asai, M. Okubo and S. Okada

Plasma Physics Laboratory, Graduate School of Engineering, Osaka University
Yamada-oka 2-1, Suita, Osaka 565-0871, Japan

Abstract

Two kinds of neutral beam injection experiments have been undertaken. First, the tangential-like injection prolongs the configuration lifetime of the FRC to be about 2 times. The dependence of the lifetime to the beam current is examined. Secondary, the axial beam injection to the FRC formation stage has attained the higher temperature and the lower density FRC production than the usual ones. The confinement scaling in this region is compared with that in the nominal range.

1. Introduction

Among the present magnetic configurations of the confinement, the Field-Reversed Configuration (FRC) gives the highest beta value up to about 100%, and has very compact feature that the slender and elliptic toroid is surrounded by the simple mirror field. The experimental lifetime τ_l is, however, considerably short since the loss power is big and hence the realistic techniques for the additional heating and the current drive have not been approved. Then, application of the rotating magnetic field is expected to make the current drive of the FRC [1]. Possibility of the wave heating has been also explored experimentally [2]. The high power neutral beam injection may be a useful candidate for the heating, as demonstrated here.

The required performance on the ion sources is quite crucial as for the present-day FRC plasma. The energetic ions move with very large Larmor radius and go around the separatrix surface because of the high beta nature. This requests the large current at low energy, and hence the power source must be reasonably developed. In this paper, the newly developed neutral beam injection system is briefly presented together with the experimental device. The two kinds of the first experiments in beam-assisted FRC plasma are demonstrated after that.

2. Experimental Device

A schematic diagram of our FRC device (FIX) is shown in Fig. 1. The major parts are categorized to be three regions: Formation and Confinement regions, and two types of ion sources. The FRC plasma for the confinement is kept in the simple mirror geometry with the long straight field of 0.04 T. The mirror ratio is chosen to be between 3 and 10. The typical plasma parameters here are the following; $n_e = (2 \sim 5)$ x

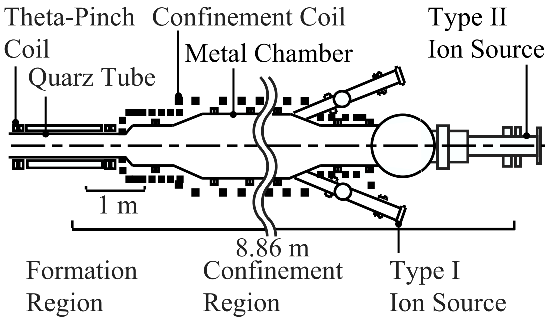

Fig. 1. FIX-FRC experimental device.

10^{19} m^{-3}, $T_e + T_i \sim 150$ eV, $r_s \sim 0.2$ m, $2l_s \sim 3$ m and $\tau_l = 0.3 \sim 0.5$ ms. This state of the FRC can be obtained by the decompression of the initial FRC in the formation region, through the translocation technique. The FRC formation is done in the usual theta-pinch system, where the main compression of the peak field ~ 1 T with the rising time ~ 3.4 μs can produce the FRC plasma of $n_e \sim 5 \times 10^{21}$ m^{-3}, $T_e + T_i \sim 400$ eV, $r_s \sim 0.05$ m and $2l_s \sim 1$ m under the filling gas pressure ~ 10 mTorr of D_2.

The type I ion source is mounted obliquely to the magnetic axis and two sources are installed. The details of the geometrical relation between the type I and the FRC is somewhat complex and shown elsewhere, but this situation effectively corresponds to the tangential injection against the toroidal current. The type II is located at the end of FIX device, and looking up the formation region directly. Both types are fundamentally the bucket type. The power supplier consists of the semiconductor IGBT regulator and the capacitor bank for the energy storage. The regulator can carve partly the stored charge and supply to the electrodes of the sources.

3. Experiments

3.1. Oblique injection experiment

The type I is used for this, which has a set of concave electrodes with its radius 0.8 m of curvature and 0.2 m caliber [3]. The extracted ions can be focused 0.8 away from the electrodes since the 80% neutralization of ions is attained near the electrode front. This enables for the beams to pass through a small aperture port. The working voltage is fixed at 14 kV in this experiment and the output current is changed from 8 A to 48 A.

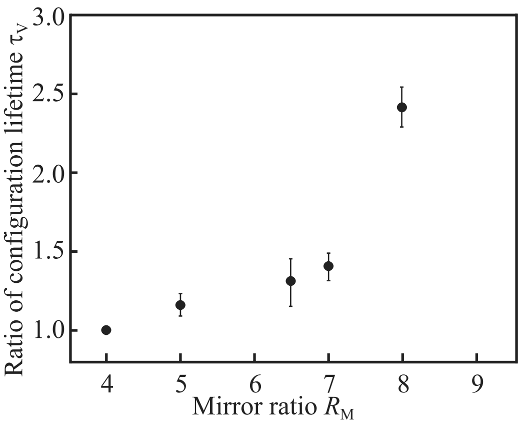

Fig. 2. Mirror ratio dependence of τ_V.

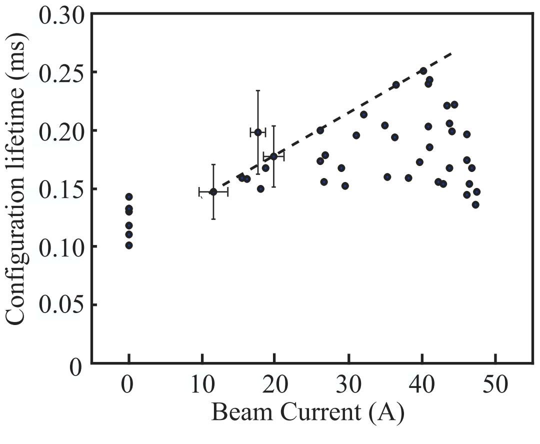

Fig. 3. Improvement of configuration lifetime τ_V.

The perpendicular and the parallel energy components of the central beamlet become 1.5 keV and 12.5 keV, respectively. Then, the Larmor radius effectively comes down to 0.1 m even for weak external field of 0.04 T. Almost of fast ions make spiral motions between two mirrors, and may slow down with the time constant of about 150 μs.

In order to clarify the beam-assisted effect to the configuration lifetime of the FRC, we have evaluated the time-dependent FRC volume. From the time-dependent value, the e-folding time τ_V can be estimated which we have designated as the measure of the effect. The indirect indication of the fast ion trapping inside the mirrors is given in Fig. 2. The ratio of τ_V to that at the mirror ratio $R_M = 4$ suggests that most of the fast ions may escape outside the mirror below $R_M = 7$. The beam-injection effect clearly appears above $R_M = 8$, where we have examined the improvement of τ_V by increasing the beam current as shown in Fig. 3. The data below the current 24 A were obtained by one source of type I. Beyond 24 A we additively used one more of type I. The best shot at each current above 24 A shows that τ_V still increases according to the beam current. However, the data points are very much scattered, and the worst one comes to the no-beam case. The reason on the scattered result has not been understood yet.

The mechanism on the confinement improvement is also undetermined, but two possibilities are considered. One is the reduction of the endloss flow by formation of electrostatic potential in front of the mirror throat [4], and this may relax the pressure gradient around the separatrix surface. The other is the heating of electrons by its momentum drag. It is quite difficult for the former to be diagnosed. The latter case may be judged through the electron temperature measurement by Thomson scattering which is now undertaken.

3.2. Axial injection experiment

The usual method to form the FRC relies on the theta-pinch action, which produces rather high density plasmas. The particle confinement scalings of FRC have been

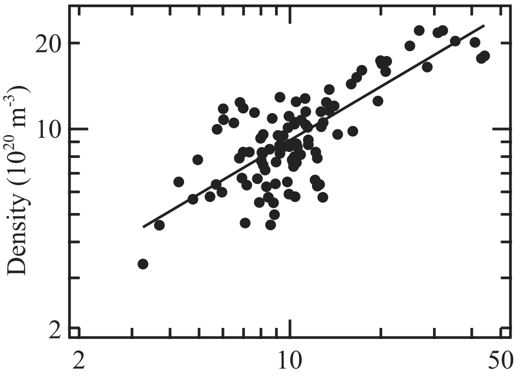

Fig. 4. Possible low density range of FRC plasma production.

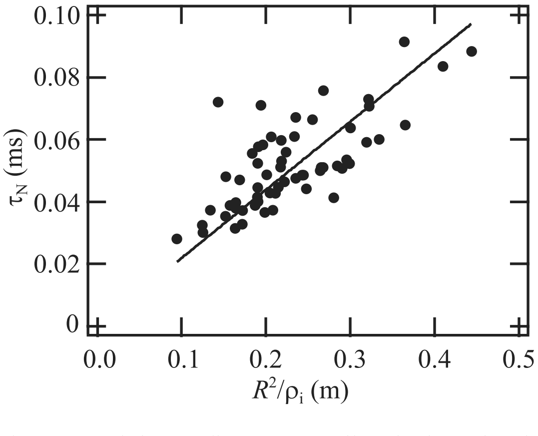

Fig. 5. Particle confinement scaling in low density region.

obtained in the rage of (1 ~ 10) x 10^{21} m^{-3}. Only one data in the lower density of (3 ~ 5) x 10^{19} m^{-3} in the FIX translation experiment indicates the difference from the nominal scaling by a better factor of 3 to 5. Here we have therefore expected the density range of the order of 1 x 10^{20} m^{-3}, although the formation technique stays the same but employs new pre-pre-ionization process. For this purpose, the ionization process between high energy hydrogen atom and gaseous molecule is found to be suitable for the free-electron production in the gas.

The neutral beam source of type II was used for the pre-pre-ionization process [5]. This source has fairly big parameters of 25 kV and 80 A at maximum for 10 ms duration, so that here the working condition is selected to be 23 kV and 19 A. This condition is evaluated to give the number of free electrons to be, for instance, 3 x 10^{17} m^{-3} for the filling pressure 130 mPa D_2 which corresponds to about 1% of the filling atoms. The usual theta-pinch action in FIX device has attained a successful formation of the lowest density FRC of $n_e \sim 3 \times 10^{20}$ m^{-3} and $T_e + T_i \sim 1$ keV.

The density-scan full data are plotted in Fig. 4. Note here that the formed FRC can be confined in the formation region instead of translation operation. The peak field B_p of the compression has been reduced to be about 0.5 T with the crowber circuit. The crowber timing has the small jitter and then the peak field is fluctuated to some extent. This may influence the scattering of the data in Fig. 4. When we plot the data as $n(T_e + T_i)$ versus B_p^2, the data points has a clear linear relation. So the value of T_i required for the estimation of the Larmor radius may be relatively reliable at fixed one data, where T_i/T_e is supposed to be 2 on the analysis. Thus the relation of the particle confinement time τ_N to the R^2/ρ_i is obtained as shown is Fig. 5, where R is the major radius of the FRC at the midplane and ρ_i is the ion Larmor radius against B_p. The result indicates that the coefficient of the fitted line is 2.8 larger than that in the nominal high density region. The reason of such a difference is not understood yet.

4. Summary

We have firstly done the neutral beam injection experiments on the high beta system of the FRC, with the aid of our own development of ion source technique. We have shown that the configuration lifetime prolongs remarkably and also the low density and high temperature production of the FRC plasma is feasible.

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