J. Plasma Fusion Res. SERIES, Vol. 3 (2000) 63–66

First-Step Experiments of Neutral Beam Injection into an FRC Plasma

ASAI Tomohiko*, YONEDA Tomohiro, KODERA Fuji, OKUBO Mamoru, OKADA Shigefumi and GOTO Seiichi
Plasma Physics Laboratory, Graduate School of Engineering, Osaka University, 2-1 Yamada-oka, Suita, Osaka 565-0871, JAPAN

(Received: 18 January 2000 / Accepted: 12 May 2000)

Abstract

We describe a novel neutral beam (NB) injection system for extremely high beta Field-Reversed Configuration (FRC) plasmas, and show the initial results of preliminary experiments performed on the FRC Injection Experiment (FIX) device. An oblique injector with a set of three concave electrodes for beam extraction is used to focus the beam enabling it to pass through a narrow port. The beam target is a large bore FRC plasma contained in a mirror field with a mirror ratio of 2–9. The results make it clear that the beam improves the plasma performance, increasing the configuration lifetime by more than 200% compared with no NB injection under the same conditions.

Keywords:

FRC, high-beta, neutral beam injection, confinement

1. Introduction

A Field-Reversed Configuration (FRC) plasma [1] has attracted attention as a $\beta = 1$ fusion reactor core because of its high beta nature and engineering simplicity. Unfortunately, present FRCs are operated only in a pulsed fashion. For the steady state operation of FRCs, it is necessary to sustain this confinement structure. Neutral beams may be used to drive current, and to modify the internal structure and bulk parameters of the plasma, as is the case for tokamaks.

In the conceptual reactor "ARTEMIS" [2], neutral beam (NB) injectors are installed perpendicular to the geometric axis, for the purpose of driving toroidal current. In the FIX (FRC Injection Experiment) device [3], high-energy beam ions injected perpendicularly would merely pass through the core plasma region and strike the chamber wall because of its low confinement magnetic field. However, beam particles injected obliquely to the geometric axis can move between the magnetic mirrors even in the low confinement field. We have installed an NB injector at an angle of 19° to the geometric axis of the FIX. The ratio of the vertical velocity components to the parallel one of the beam ions is chosen to be outside the loss cone of the mirror field at a mirror ratio of $R_M \sim 10$ in the vacuum case. Thus, we can use a high power NB source with several hundred kW of power.

In this paper, we will describe the outline of the NB injection system, and show the initial result of experiments performed on the FIX device. The experimental result is discussed and compared with the calculations of injected beam particle orbits.

2. Experimental Apparatus

Experiments were performed on the FIX device. The FIX device, shown in Fig. 1, consists of a formation region and a confinement region. The FRC is produced by the field reversed theta pinch (FRTP) method with deuterium puffing system. The FRC plasma is

Corresponding author's e-mail: tomohiko@ppl.eng.osaka-u.ac.jp

instantaneously injected along a magnetic guide field into the confinement chamber, which is made of stainless steel and serves as a flux conserver. After some bouncing motions between the mirrors, the injected plasma reforms to a quasi-steady equilibrium state. The applied typical confinement magnetic field is 0.04 T. The mirror coils are spaced 3.4 m apart; the mirror field strength is 0.08–0.40 T, there so the mirror ratio can be chosen to be 2–10. Typical plasma parameters in the confinement region are; electron density $n_e \sim 2.0 \times 10^{19}$ m^{-3}, total plasma temperature $T_{tot} \sim 150$ eV, separatrix radius $r_s \sim 0.2$ m, and separatrix volume $V \sim 0.4$ m^3. The plasma diagnostics consist of diamagnetic probes and noninvasive optical systems. An array of 35 magnetic probes is located just inside the flux conserver wall to measure the axial magnetic field Bw. An excluded flux analysis, made with these probes, is used to determine the separatrix shape $r_s(z)$ of the FRC. A multichord CO_2 laser interferometer (10.6 μm) is installed parallel to the y-axis at $z = 0.6$ m.

The bucket-type ion source is employed in the NB injection system. The electrodes, made of oxygen free copper, have 218 mm of effective diameter with 1628 apertures of either a 4 or 4.5 mm diameter. They are concave with a curvature radius of 800 mm. The configuration of neutral beams is focused at 800 mm on the beam axis as shown in Fig. 2. The power supplies for the beam sources are capacitor banks that are switched with Insulated-Gate Bipolar Transistor (IGBT) units. Using this system, neutral hydrogen beams with 320 kW of power (14 keV, 23 A) and a 10 ms pulse width are produced. The DC level outputs for these power supplies are listed in Table 1. Shown in Fig. 3 are the degree of neutralizations and the current density profile of the neutral beam measured at 600 mm on beam axis for a beam energy of 5 kV. The injected neutral beam has a 77% degree of neutralization and a 5.3 mm radius at the focal point.

In our experiment, we mounted the neutral beam injector as shown in Fig. 1. The injector is installed at an angle of 19° to the geometric axis so that the injected beam particles do not strike the chamber wall and are outside the loss cone of the mirror field in the case of $R_M \sim 10$ for the vacuum case.

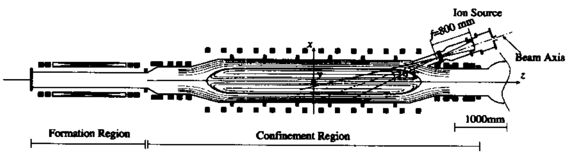

Fig. 1 Schematic diagram of the FRC confinement chamber with NB injection system.

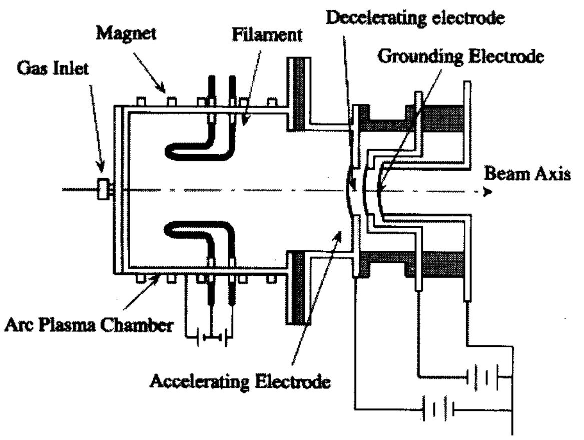

Fig. 2 Schematic view of the ion source; it consists of an arc plasma chamber and three electrodes. The electrodes have an effective diameter of 218 mm and a radius of curvature of 0.8 m.

Table 1 DC level output of power supplies.

	Voltage	Maximum Current	Pulse Width
Accelerating Power	15kV	40A	10ms
Decelerating Power	-3kV	4A	20ms
Arc Power	300V	500A	40ms
Filament Power	12V	1000A	10s

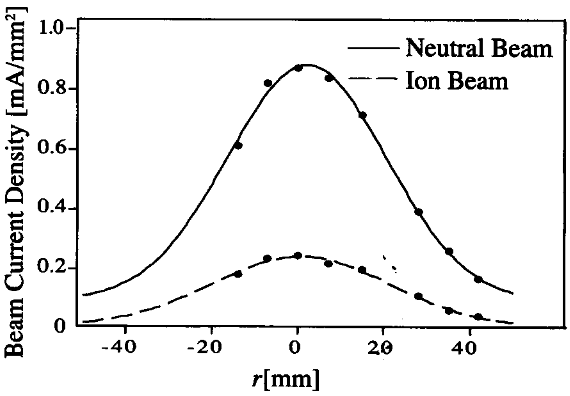

Fig. 3 Radial distribution of the beam current density at z = 600 mm in case of 5 kV of accelerating voltage and 3.0 A of current.

3. Calculation of Beam Orbit

To consider the experimental phenomena, it is necessary to understand the behavior of the injected high-energy beam in detail. Then we calculated the trajectories of ionized beam particles using the method described later, with equilibrium configurations that have the parameter of the FIX-FRC.

The equation of motion: $m d\boldsymbol{v}/dt = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$ is solved by the numerical method to obtain the trajectories of the charged particles. Here m, q, $\boldsymbol{v}$, $\boldsymbol{E}$ and $\boldsymbol{B}$ are the mass, the electric charge, the velocity of the particle, the electric field and the magnetic field, respectively. In this calculation, because quasi-neutral condition is assumed, the electric field $\boldsymbol{E}$ is neglected. Since the FRC consists only of an axially symmetric poloidal magnetic field and has no toroidal field, $\boldsymbol{B}$ is calculated from the poloidal flux function ψ in cylindrical coordinates (r, θ, z) as follows.

$$\boldsymbol{B} = \begin{pmatrix} B_r \\ B_\theta \\ B_z \end{pmatrix} = \begin{pmatrix} -\frac{1}{r}\frac{\partial \psi}{\partial z} \\ 0 \\ -\frac{1}{r}\frac{\partial \psi}{\partial r} \end{pmatrix}. \qquad (1)$$

Here the magnetic flux function ψ is obtained from a 2-D equilibrium calculation. The relation between the normalized, dimensionless parameters and the original parameters is given by

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \frac{1}{r_w}\begin{pmatrix} x \\ y \\ z \end{pmatrix}, \quad \begin{pmatrix} V_x \\ V_y \\ V_z \end{pmatrix} = \frac{2\pi m}{q r_w B_w}\begin{pmatrix} v_x \\ v_y \\ v_z \end{pmatrix}, \quad \Psi = \frac{\psi}{\psi_w}$$

$$\text{and} \quad \tau = \frac{q B_w}{2\pi m} t. \qquad (2)$$

Here r_w, B_w and ψ_w are the wall radius, the magnetic field and the flux function at the chamber wall, respectively. If the initial conditions of position ($X(0)$, $Y(0)$, $Z(0)$) and velocity ($V_X(0)$, $V_Y(0)$, $V_Z(0)$) for the ionization point are given, the particle trajectory can be obtained by using the *Runge-Kutta* method. Adaptive step size control [4] is used to obtain results of the intended precision. As additional constraints, the canonical angular momentum ($p_\theta = \partial L/\partial\dot{\theta} = mr^2\dot{\theta} + q\Psi/c$) and Hamiltonian H of the particle are conserved. Here, H is represented as:

$$H = \frac{1}{2m}\left(m^2\dot{r}^2 + m^2\dot{z}^2\right) + \frac{(p_\theta - q\Psi)^2}{2mr^2}. \qquad (3)$$

The value of the flux function $\psi(r, z)$ at the particle's location is obtained from a 2-D numerical FRC equilibrium in the strong mirror field [5], which reflects the experimentally observed FRCs confined in the FIX device.

The beam particles ionized inside the separatrix are trapped by a comparatively low external mirror ratio where the particles can quickly escape because they are in the loss cone at the case of $R_M = 4$ of simple straight mirror field. Typical calculated ion trajectory is shown in Fig. 4.

4. Experimental Results

Preliminary experiments using the NB system have been performed. Figure 5 shows the difference in the time evolution of volume between FRCs with and without NB injection, in the case of mirror ratio of 8. Each curve corresponds to an average of over 14 shots, which obtained by alternate FRC shots with and without NB injection. In the beam injection experiment here, the initiation of the beam pulse so early prior to the FRC formation time (some 1 ms before an FRC is formed) results in the output of the pulse becoming the designated and stable DC-level. The formation process

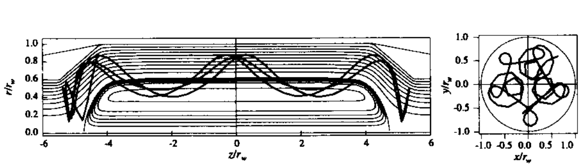

Fig. 4 Typical trajectory of an injected beam ion in the confinement chamber simulated numericaly forthe case of $E_b = 10$ keV, $R_M = 4.0$.

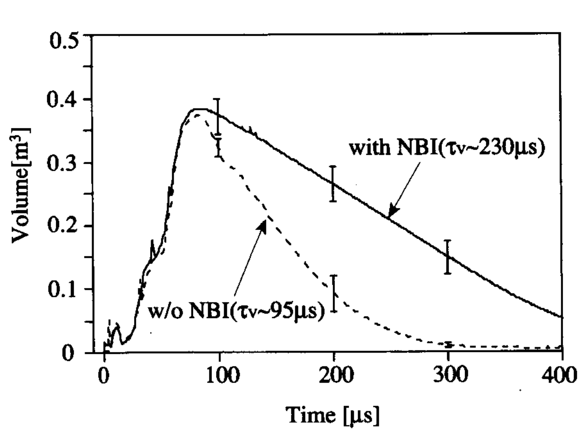

Fig. 5 Time evolution of separatrix volume in the case of mirror ratio R_M~8. The characteristic decay time τ_V of the volume increase from 95 μs to 230 μs with NB injection.

itself is not influenced by this beam operation. Just after translation at about 80 μs ($t = 0$ refers to the preheating capacitor bank discharge time), the FRCs in the two cases have almost the same volume and separatrix radius. They, however, decay at drastically different rates. Here, we define the confinement lifetime as the e-folding time τ_V of the volume decrease just after translation. We find that the configuration lifetime increases by about 240% with an injection power of 320 kW (14 keV, 23 A) compared to the case with no NB injection.

5. Summary

The first experiment of NB injection into FRC plasmas is performed on the FIX device. The NB injector is driven at nearly maximum power; 320 kW (14 kV, 23 A). In this case, we find that the configuration lifetime increases by about 240% as compared with the case of no NB injection. The result demonstrates the successful application of NB injection into the FIX experiment, and marks one of the first key step in research into the steady state operation of FRCs.

Trajectories of beam ions are also evaluated numerically. Injected fast beam ions are trapped by comparatively low mirror fields ($R_M \cong 4$). The trapped ions bounce between the magnetic mirrors while also gyrating and circulating about the geometric axis. These "spiraling-ions" may prove useful in modifying the internal structure and bulk parameters of the FRC.

In the future, we will explore the possibilities of using NB injection to drive seed currents, to heat the electrons, and to modify the confinement structure.

Acknowledgment

The authors are grateful for the assistance of the members of the FIX group. The first author would like to acknowledge Dr. A. Martin for helpful suggestions and discussions. We thank Mr. Y. Suzuki for his support on the numerical work.

References

[1] M. Tuszewski, Nucl. Fusion **28**, 2033 (1988).
[2] H. Momota *et al.*, Fusion Technol. **21**, 2307 (1992).
[3] A. Shiokawa *et al.*, Phys. Fluids **5**, 534 (1993).
[4] W.T. Vetterling *et al.*, *NUMERICAL RECIPES Example Book [C]* (Cambridge University Press, 1992).
[5] Y. Suzuki *et al.*, submitted to Phys. Plasmas.