Additional Heating Experiments of FRC Plasma

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Abstract : Additional heating experiments of neutral beam (NB) injection and application of low frequency wave on a plasma with extremely high averaged beta value of about 90% – a field reversed configuration (FRC) plasma – are carried out on the FRC Injection experiment (FIX) apparatus. These experiments are made possible by translating the FRC plasma produced in a formation region of a theta pinch to a confinement region in order to secure better accessibility to heating facilities and to control plasma density. By appropriate choice of injection geometry and the mirror ratio of the confinement region, the NB with the energy of 14keV and the current of 23A is enabled to be injected into the FRC in the solenoidal confining field of only 0.04-0.05T. Confinement is improved by this experiment. Ion heating is observed by the application of low frequency (80kHz ; about 1/4 of the ion gyro frequency) compressional wave. A shear wave, probably mode converted from the compressional wave, is detected to propagate axially.

1. Introduction

A plasma with field reversed configuration (FRC) [1] is confined in basically solenoidal magnetic field. It consists only of poloidal field and the magnetic field strength is zero on its magnetic axis. Therefore, the beta value, or the plasma pressure normalized by the solenoidal magnetic field pressure ($B_w^2/2\mu_0$) is 100% on the magnetic axis ($r = R$). Even the beta value $\langle\beta\rangle$ averaged inside the separatrix ($r = r_s$) is as large as about 90%. Due to such high beta nature, advanced fuel of D-^{3}He is considered to be burned in the AETEMIS [2] – FRC based conceptual reactor design – with confining magnetic field of 5.4T. This is smaller than that of the D-T fuelled ITER. In the latter, magnetic field near the magnetic axis is 5.7T and it is stronger (12.5T) at the toroidal field coils [3].

In the ARTEMIS, the FRC is assumed to be produced in the formation region of a theta pinch and to be translated into a confinement region. It will, then, be brought into burning state by neutral beam injection (NBI) and magnetic compression heating. While, in experiments, NBI heating has not been done so far because of poor accessibility of the FRC to the NBI facility and high plasma density. The neutral beam does not penetrate deep in the theta-pinch-produced FRC, the density of which is normally higher than 1×10^{21}m^{-3}. In our FRC Injection Experiment (FIX) apparatus, the FRC with the density of 5×10^{21}m^{-3} is produced in a formation region of the theta pinch. This FRC is ejected or translated into a large bore confinement region to realize the plasma density which is appropriate for the NBI [4,5], and in addition, to improve accessibility of the FRC to heating facilities. To this FRC, NBI experiments were carried out [6]. As the rise time of the beam current (~ 1ms) and the duration of the NB pulse (~5ms) is longer than the FRC configuration life time of 0.5ms, NB injection into the confinement region is started in advance before the FRC is translated (Section 2).

The Alfven wave is known to be capable of heating the plasma with nonuniform density and magnetic field [7]. It was also employed in a heating experiment of a high beta ($\langle\beta\rangle$ ~ 50%) theta-pinch plasma [8]. To seek the applicability of the wave heating on FRC plasmas with even higher beta value, a fast rising (faster than longitudinal Alfven transit time) magnetic pulse was applied and increase of the stored energy was observed [9]. Ion heating and propagation of shear wave was observed in later experiments [10](Section 3).

2. Neutral Beam Injection Experiment

In Fig.1, a schematic drawing of the FIX apparatus is shown together with the NB injector and the RF antenna. The main compression coil of the theta pinch in the formation region has the length of 1.2m and the diameter of 0.31m. Two independently driven mirror coils are equipped at both ends of the main compression coil and the FRC is translated by their unbalanced operation. The confinement region is made of 6mm thick stainless steel and it has the length of 3.4m and the radius of 0.4m. As its penetration time of the magnetic field is 2.4ms, therefore, it works nearly as a flux conserver during the lifetime of the FRC of 0.5ms. Typical strength of the confining solenoidal magnetic field, density, the pressure-balance temperature T_{tot} and the separatrix radius r_s are 0.04-0.05T, 5×10^{19}m^{-3}, 100-150eV and 20cm, respectively, in the confinement region.

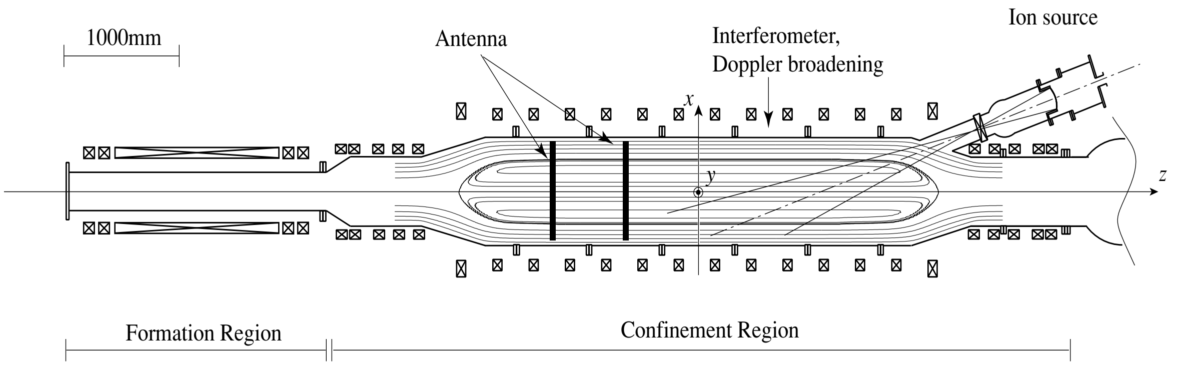

Fig. 1. Schematic drawing of the FRC Injection Experiment (FIX) Apparatus. A neutral beam injector and a pair of antennas for wave heating are also shown.

The problem associated with the ionization of the beam is solved by the translation, or the plasma density to ionize most of the neutral particles in the beam to be ionized inside the separatrix was realized. There, still, is another problem that the gyro radius of the ionized beam may not sufficiently be smaller than the size of the plasma. Even ionized beam (proton) with perpendicular energy as low as 5keV has the gyro radius of 20cm, which is almost equal to the separatrix radius. Ions are extracted from a bucket type ion source and are accelerated by 218mm diameter multi-apertured (each aperture has the diameter of 4.5 – 5.0mm) electrodes and then they are neutralized. The beam is focused down to about 10mm FWHM at 0.8m from the electrodes. As the neutral beam current extractable from the source is more than proportional to the beam energy, higher energy is desired to extract larger current. In order to endow the NB higher energy and smaller gyro radius, the beam was injected to the FRC not perpendicularly to the magnetic field but with the angle of 19 ^{B}. Thus the maximum beam current of 23kA was obtained with the beam energy of 14keV. Perpendicular and parallel (relative to the solenoidal magnetic field) component of the beam energy on the axis of the NB injector is 1.5keV and 12.5keV, respectively, and the ion gyro radius is about 10cm for B_w of 0.04T. In order to realize higher trapping efficiency of the NB, the axis of the NB injector has the impact parameter of 10cm from the axis of the confinement region. From a calculation in which the effect of ionization and particle orbit are included, 60% of the incident NB is trapped in the confinement region even when the mirror ratio is 4.

In Fig. 2, the change with time of the plasma energy in the confinement region is shown when the mirror ratio was 8. Before 100 μs, the energy increased because the FRC was fed into the confinement region. After 10μs, FRC is seen to decay gradually. The decay is slower when the NB was injected (solid line) than the case when the NB was not injected (dashed line). It must be mentioned that the confinement degradation took place when the mirror ratio was increased. But the confinement was more than recovered with the NBI

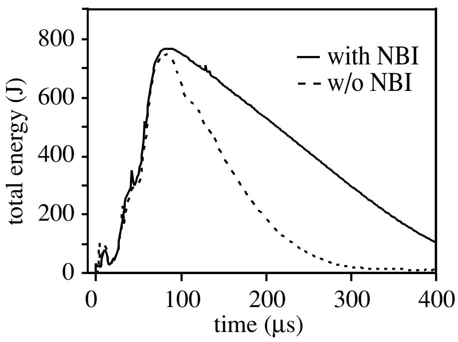

Fig. 2. Time evolution of the stored energy with (solid line) and without (dashed line) the NBI.

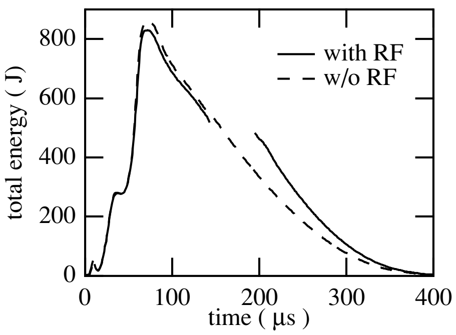

Fig. 3. Time evolution of the stored energy with (solid line) and without (dashed line) the wave heating.

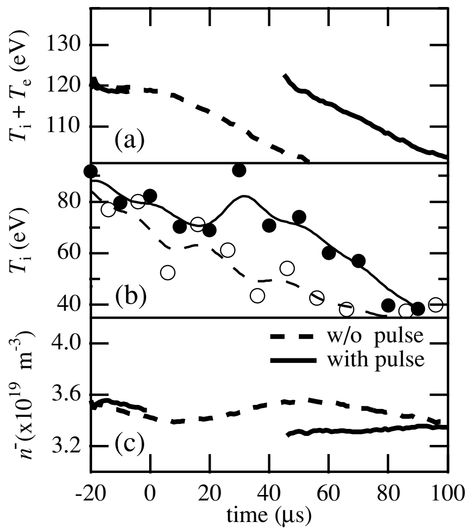

Fig. 4. Time evolution of (a) pressure balance temperature, (b) ion temperature measured by the OV Doppler broadening and (c) average density with (solid line and solid circle) and without (dashed line and open circle) the wave heating.

3. Wave Heating Experiment

Low frequency oscillating magnetic field was applied to the FRC by a pair of one turn coils. Each coil had the radius of 0.33m and was sheathed in a pyrex tube to prevent arching. They were arranged at 0.6m and 1.2m, respectively, from the axial mid plane co-axially to the axis of the confinement region, in such a way as to surround the plasma. Maximum electric current of 33kA was fed to each coil through a capacitor discharge and 80kHz oscillation with e-folding damping time of 25μs was obtained. The wave was applied to the FRC at 150μs when the transient phenomena associated with the translation disappeared and the FRC started to decay quietly.

In Fig. 3 change with time of the total energy stored inside the separatrix is compared between the case when the wave was applied (solid line) and the case when the wave was not applied (dashed line). From 150 to 190 μs, when the wave was applied, the stored energy is not shown because the plasma volume could not be measured by the disturbances from the wave to the diamagnetic probe array. Apparent increase of the stored energy is recognized with the wave. The total stored energy inside the separatrix of the FRC is written as $E_{tot} = (5/2)\langle\beta\rangle V\, B_w^2 / (2\mu_0)$, with good approximation, where V is the volume inside the separatrix, the result is due to increase of r_s and B_w. As the magnetic flux is conserved in the confinement region, B_w increases with r_s.

In Fig. 4 (c), average density is seen to have decreased by the wave. This fact signifies that the increase of the stored energy is not caused by the supply of particles but by the heating, as is seen in Fig. 4 (a). In Fig. 4 (b), ion temperature measured by OV (278.10nm) Doppler broadening is plotted with (solid circle and solid line) and without (open circle and dashed line) the wave. As the equipartition time between 0^{4+} and D^+ is shorter than $10\,\mu s$, they should have the same temperature. The fact that the increase of T_{tot} is ascribed to the increase of T_i signifies that, not electrons, but ions were heated by the wave.

Magnetic field fluctuation was detected by small magnetic probes inserted in the plasma near the separatrix at the mid-plane and 0.6m downstream of it. When the oscillating current fed to a pair of loop antenna was phased by π, magnetic field fluctuation which has the same frequency as the applied current was observed to propagate axially. Though the applied magnetic field was a compressional mode and it did not have azimuthal (θ) component, detected fluctuation had θ component. The amplitude of this component was larger than other components by a factor of about 2.

4. Discussions

In Fig.2 of the NBI experiment, at 150 μs for example, the stored energy and energy loss rate were 390J and 5.0MW, respectively, when the NB was not injected. They improved to 640J and 2.3MW with the NBI. While, the power supplied from the NB is only 0.3MW, which is 1/8 of the improved loss rate of 2.3MW, even if all the NB power is assumed to be trapped in the confinement region. Increase of the stored energy of 250J at 150 μs can not be explained either. Because, whether the increase is due to the trapping of the NB energy itself or due to heating of the FRC, maximum possible value of the energy from the beam is only 48J during 150 μs. From these facts, the experimental result should be interpreted that the improvement of confinement was brought about by the NBI. Further studies are required to clarify the reason.

In the wave heating experiments, a shear wave was observed to propagate axially. This observation is suggestive of the process to have taken place that a compressional wave with a frequency lower than the ion cyclotron frequency propagated across the field and then at the Alfven resonance layer, it was converted to the shear Alfven wave, which damped and heated the plasma. Actually, the propagation velocity v_{ph} of the fluctuation in the axial direction is almost equal to the theoretical prediction of the shear Alfven wave. The dependence of v_{ph} on the magnetic field strength, or the difference of v_{ph} at different radial position has also the same tendency as theories [11-13].

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