J. Plasma Fusion Res. SERIES, Vol. 5 (2002) 210–214

Internal Magnetic Probe Measurement in Heating Experiment of FRC Plasma by Low-Frequency Magnetic Pulse

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(Received: 11 December 2001 / Accepted: 8 May 2002)

Abstract

Internal magnetic probes are used for direct measurements of time-varying magnetic fields in a heating experiment of a field reversed configuration (FRC) plasma by a low-frequency magnetic pulse. The low-frequency magnetic pulse is applied by an antenna which consists of two single-turn coils. The frequency of the applied magnetic field is lower than the ion cyclotron frequency at the separatrix. A large amplitude oscillation is detected by an magnetic probe which is oriented with the axis in the azimuthal direction and located near the separatrix. Since the observed oscillation is transient, the magnetic probe signal is analyzed by the wavelet transform. The phase velocity of the oscillation in the direction parallel to the equilibrium magnetic field is measured using the wavelet cross-spectrum function and it approximately agrees with the Alfvén velocity. The experimental results suggest that the shear Alfvén wave is excited.

Keywords:

FRC, plasma, magnetic probe, wavelet transform, Alfvén wave

1. Introduction

The development of auxiliary heating methods has long been one of the most important issues of the field reversed configuration (FRC) studies [1]. Recently, we reported that the application of the low-frequency magnetic pulse was effective for the heating of a FRC plasma [2]. The obvious increases of both pressure balance temperature (sum of the electron and ion temperatures, $T_{total} = T_e + T_i$) and ion temperature (T_i) obtained by the measurement of the Doppler broadening of the spectral line of OV were observed during the application of the magnetic pulse. The increment of T_{total} was almost equal to that of T_i ($\Delta T_{total} \simeq \Delta T_i \simeq 20$ eV), suggesting that the energy of the magnetic pulse was absorbed mainly by ions. Although the heating mechanism has been indistinct so far, excitation of a sort of plasma wave was verified by inserting magnetic probes into the plasma. In this paper, we report the properties of the excited wave using the results of the internal magnetic probe measurements. Since the observed wave signals are transient, we analyze the magnetic probe signals by the wavelet transform.

2. Experimental Apparatus

The experiment is carried out in the confinement region of the FIX device [3]. In FIX, the FRC plasma is produced by the theta pinch discharge after the introduction of deuterium gas in the formation region and then is translated to the confinement region. The confinement region consists of quasi-DC magnetic field coils and a metal vacuum chamber, as shown in Fig. 1.

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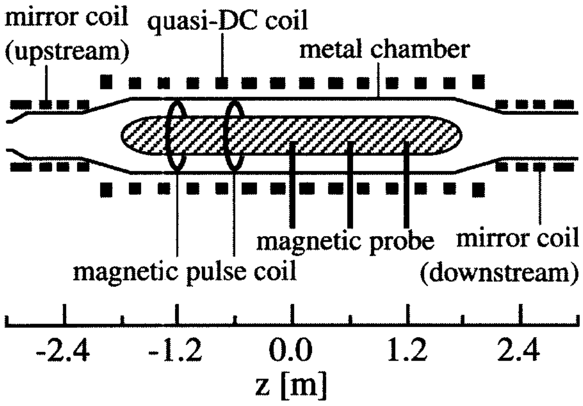

Fig. 1 Schematic drawing of the confinement region of the FIX device. The hatched region represents the translated FRC plasma.

The radius and the length of the straight section of the metal chamber are 0.4 m and 3.4 m, respectively. The strength of the quasi-DC magnetic field is $B_z \simeq 0.04$ T. The separatrix radius and the length of the plasma are $r_s \simeq 0.20$ m and $l_s \simeq 3.6$ m. The lifetime of the plasma is about 350 μsec. The electron density and the pressure balance temperature are $\bar{n}_e = 3 \sim 4 \times 10^{19}$ m^{-3} and $T_{total} = T_e + T_i = 100 \sim 140$ eV, respectively.

Two single-turn coils are placed coaxially with the device axis at $z = -1.2$ and -0.6 m, as shown in Fig. 1. The radius of each coil is 0.33 m. Each coil is sealed by a Pyrex tube to prevent the serious interaction with the plasma. A serial couple of 3.3 μF capacitors is connected to each coil as a power supply. The LC configuration provides a damped sinusoidal current of 60 μsec duration. The typical waveform of the coil current measured by a Rogowski coil is shown in Fig. 2. The two coil currents are supplied with π radians out-of-phase. The frequency of the applied magnetic pulse is about 80 kHz and is lower than the ion cyclotron frequency near the separatrix ($\omega_{ci}/2\pi \simeq 400$ kHz).

In order to measure the time-varying magnetic fields near the separatrix of the FRC plasma during the application of the magnetic pulse, small magnetic probes are inserted into the plasma. Three magnetic probe arrays are located at $z = 0.0$, 0.6 and 1.2 m, as shown in Fig. 1. Each array has magnetic probes oriented with the axis in the azimuthal direction (b_θ probe) in addition to magnetic probes oriented in the radial direction (b_r probe). The intensity of these probe signals is calibrated to each other. When we measure the z component of the magnetic field (b_z), the magnetic probe arrays are rotated through 90° and the b_θ probes are oriented in the

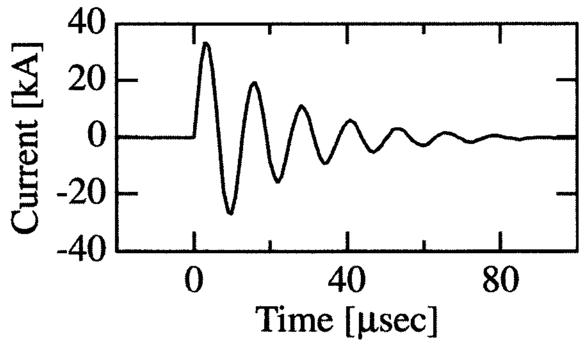

Fig. 2 The typical waveform of the coil current. The magnetic pulse is started at $t = 0$ μsec.

axial direction.

3. Spectral and Cross-Spectral Analysis using Wavelet Transform

A time-frequency analysis of magnetic probe signals is performed by the wavelet transform [4] using the following simple analyzing wavelet

$$\Psi_a(t) = \frac{1}{\sqrt{a}} \exp\left(-\frac{(t/a)^2}{2\sigma} + \mathrm{i}\,\frac{2\pi t}{a}\right) \qquad (1)$$

where "a" is the wavelet scale which corresponds to the inverse of the frequency. The wavelet transform of a function $f(t)$ is given by

$$W_f(a,\tau) = \int f(t)\,\Psi_a(t-\tau)\,\mathrm{d}t \qquad (2)$$

which is a function of both scale "a" and time "τ". Choosing the σ parameter in eq. (1), we can balance the time and frequency resolutions as appropriate for a certain signal. We usually choose $\sigma = 1.0$.

The delayed wavelet cross-spectrum function [5] is given by

$$C_{fg}(a,\Delta\tau) = \int W_f^*(a,\tau)\,W_g(a,\tau+\Delta\tau)\,\mathrm{d}\tau \qquad (3)$$

where $f(t)$ and $g(t)$ are two signals obtained at two separated observation points. The $\Delta\tau$ value maximizing the $C_{fg}(a, \Delta\tau)$ function gives the travel time of the component with frequency $F = 1/a$ from one observation point to the other separated point [6].

4. Experimental Results and Discussion

The low-frequency magnetic pulse is applied to a quasi-steady state of a translated FRC plasma. Figures 3(a)–3(d) show the time evolution of signals of the internal magnetic probes located at $z = 0.60$ m. During the application of the magnetic pulse, a coherent oscillation is observed on the b_θ probe [Fig. 3(a)]. On

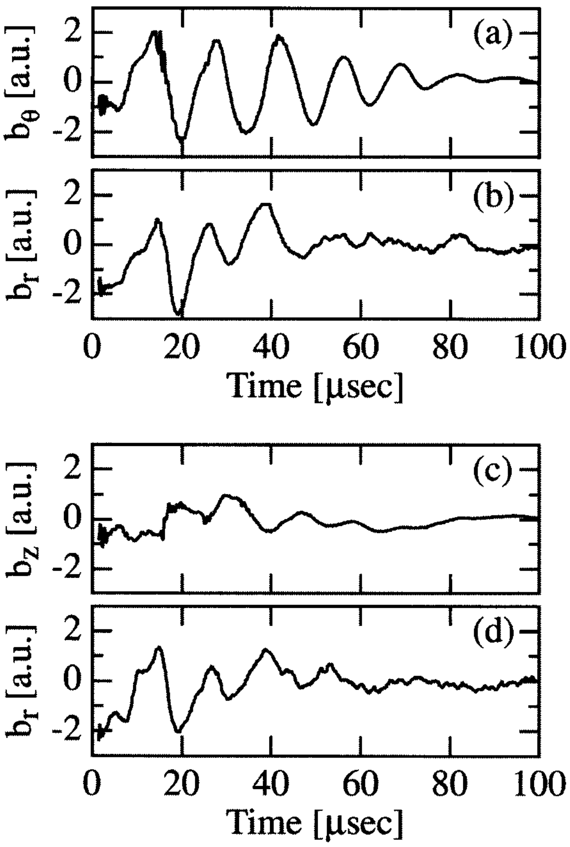

FIG. 3. The internal magnetic probe signals at $z = 0.6$ m. They are oriented with their axes in (a) the azimuthal direction (b_θ probe) and (b) the radial direction (b_r probe) of the FIX device. The b_θ and b_r probes are installed at the radial positions of $r = 0.20$ and $r = 0.21$ m, respectively. In figures (c) and (d), the magnetic probe arrays are rotated through 90° and the b_θ probe is oriented in (c) the axial direction (b_z) of the FIX device. The magnetic pulse is started at $t = 0$ μsec.

the contrary, the oscillation on the b_r probe is less coherent and its amplitude is smaller than that on the b_θ probe, as shown in Fig. 3(b). Next, the b_θ probe is oriented with the axis in the z direction in order to measure the b_z component. In this case no such coherent oscillation can be seen on the b_z component, as shown in Fig. 3(c). On the other hand, the waveform of the b_r probe signal [Fig. 3(d)] is almost the same as that in Fig. 3(b). In the case without the magnetic pulse, no such oscillation is observed on all internal magnetic probe signals, showing that the observed magnetic oscillation is excited by the magnetic pulse.

Although the magnetic field produced by the pulse coil has no component in the azimuthal direction, results of the measurement show that the excited magnetic oscillation has a strong component in the azimuthal direction. In addition, the distance between the magnetic probes and the magnetic pulse coils is so far that no signal is detected by the magnetic probes when the magnetic pulse is applied in the vacuum field. These results suggest that a sort of plasma wave is excited and propagated.

Since the coherent oscillation can not be observed on the b_z component and the observed oscillation on the b_r probe is less coherent, we mainly analyze the b_θ probe signals for observing the wave characteristics. The wavelet transform coefficients $|W_f(a, \tau)|$ of the signals of the coil current and the three b_θ probes at $z = 0.0$ m, 0.6 m and 1.2 m are shown in Figs. 4(a)–4(d). The results of the wavelet transform evidently show that the wave observed on the b_θ probes [Figs. 4(b)–4(d)] is excited later than the start of the magnetic pulse [Fig. 4(a)]. The frequency of the excited wave is found to be about 80 kHz and it is the same as that of the applied magnetic pulse. Figures 4(b)–4(d) show that the amplitude of the excited wave on the b_θ probes decreases as the distance from the magnetic pulse coils increases. The attenuation length of the excited wave in the z direction is estimated to be $z \simeq 0.65$ m. Furthermore, Figs. 4(b)–4(d) also show that another low frequency oscillation ($F \leq 50$ kHz) is coexisting with the excited wave. At $z = 1.2$ m, the amplitude of the another low frequency oscillation is larger than that of the excited wave. This another oscillation is also observed on the b_r and b_z components and is detected even in the case without the magnetic pulse. Therefore, this oscillation is not excited by the magnetic pulse but is naturally existing in the FRC plasma.

The delay of the oscillation phase is clearly seen among the raw signals of the three b_θ probes at $z = 0.0$, 0.6 and 1.2 m, suggesting that the excited wave is propagated in the z direction. In order to measure the propagation velocity of the excited wave, the delayed wavelet cross-spectrum function $|C_{fg}(a, \Delta\tau)|$ is calculated. As an example, the result of the calculation of the $|C_{fg}(a, \Delta\tau)|$ from two b_θ probes at $z = 0.0$ and 0.6 m is shown in Fig. 5. In this case, we choose $\sigma = 0.1$ in Eq. (1) for the improvement of the time resolution. The peak of the $|C_{fg}(a, \Delta\tau)|$ is clearly shifted from the $\Delta\tau = 0$ point and can be seen at $\Delta\tau \simeq 4$ μsec. Therefore, the phase velocity of the propagation in the z direction is estimated to be $V_{phase} = \Delta z/\Delta\tau \simeq 1.5 \times 10^5$ m/sec, which is approximately agrees with the Alfvén velocity, V_A.

These results suggest that the excited wave is the

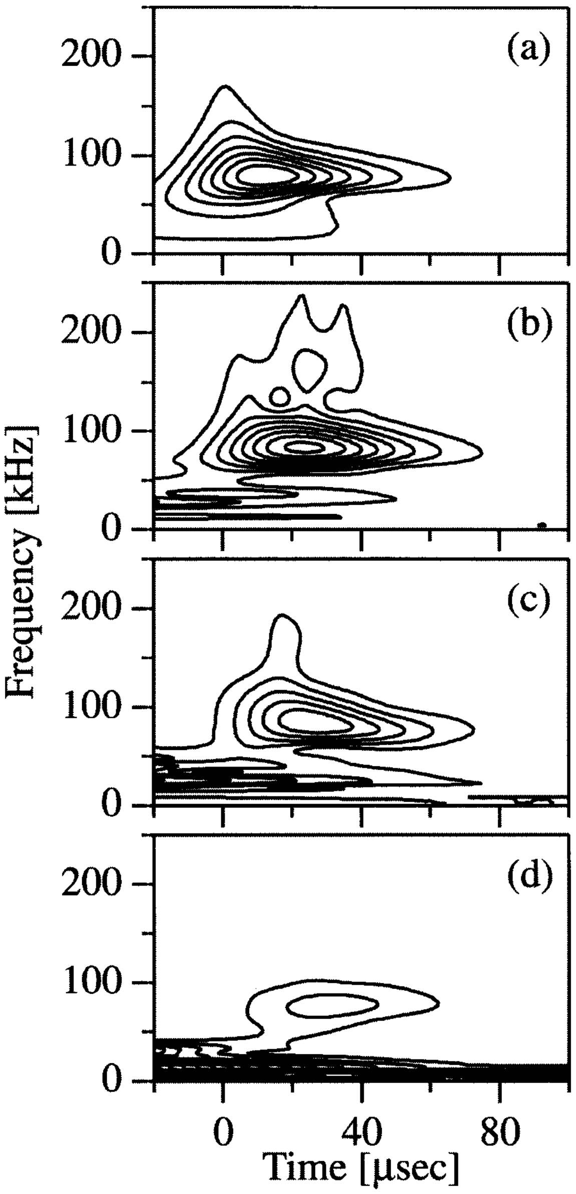

FIG. 4. The wavelet transform coefficients of the signals of (a) the coil current and three b_θ probes at (b) z = 0.0 m, (c) 0.6 m and (d) 1.2 m. The radial location of these b_θ probes is r = 0.24 m. In the figures (c) and (d), the contour scale is enhanced twice that in the figure (b). The magnetic pulse is started at t = 0 μsec.

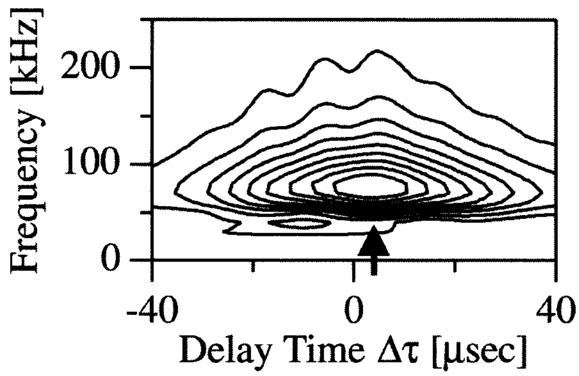

FIG. 5. The delayed wavelet cross-spectrum function for two b_θ probe signals at z = 0.0 and 0.6 m. The radial location of the b_θ probes is r = 0.24 m. The peak of the spectrum is shown by an arrow.

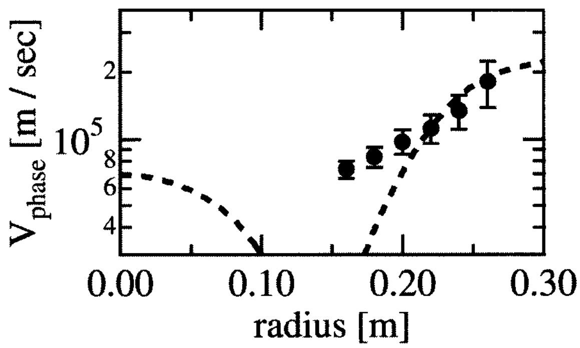

FIG. 6. Radial profile of the phase velocity of the excited wave in the z direction. The dashed line is the theoretical phase velocity of the shear Alfvén wave for the experimental condition.

shear Alfvén wave, since the shear Alfvén wave is transverse magnetic (strong b_θ and weak b_z) at low wave frequencies and its phase velocity in the direction parallel to the equilibrium magnetic field is equal to V_A [7]. The excitation of the shear Alfvén wave may be due to the mode conversion of the compressional wave which is excited directly by the z component of the applied magnetic pulse to the shear Alfvén wave at the Alfvén resonance layer where both wave types locally have the same wavelength in a direction parallel to the equilibrium magnetic field [7-10].

The excited wave is observed in the relatively wide region around the separatrix. The radial profile of the measured phase velocity is shown in Fig. 6. The phase velocity outside the separatrix ($r_s \simeq 0.20$ m) is found to be larger than that inside the separatrix, as shown in Fig. 6. Outside the separatrix, the experimentally obtained phase velocity approximately agrees with the theoretical phase velocity of the shear Alfvén wave in low β plasmas ($V_{phase} = V_A\,[1 - (\omega/\omega_{ci})^2]^{1/2}$) [7]. Although the local β value outside the separatrix is nearly zero, it rapidly varies along the radial direction in the FRC plasma and it exceeds even unity inside the separatrix. It may be the reason of the deviation of the experimental data from the theoretical value inside the separatrix. One of other possible reasons of the deviation is the difference between the topology of the magnetic field lines inside the separatrix and that outside the separatrix which separates the regions of open and closed magnetic field lines. However, the attenuation length of the excited wave inside the separatrix and that outside the separatrix are almost the same ($z \simeq 0.65$ m) and are much less than the length of the plasma (3.6 m), suggesting that the difference of the topology of the magnetic field lines does not have a primary role in the the deviation of the experimental data from the theoretical value.

For the identification of the ion heating mechanism, further detailed measurements of the wave properties and the temporal evolution of the radial profile of electron and ion temperatures are required. However, the fact that the phase velocity of the excited wave is on the same order as the ion thermal velocity ($V_{\rm phase} \simeq V_{\rm thi}$) in the large region of the plasma is worth being mentioned here.

5. Summary

Internal magnetic probes are used for direct measurements of time-varying magnetic fields in the heating experiment of the FRC plasma by applying the low-frequency magnetic pulse. The large amplitude oscillation is detected by the b_θ magnetic probes. Since the observed oscillation is transient, we analyze the magnetic probe signals by the wavelet transform. The frequency of the oscillation is found to be the same as that of the applied magnetic pulse. The phase velocity of the oscillation in the z direction is measured by calculating the delayed wavelet cross-spectrum function and it approximately agrees with the Alfvén velocity. These results suggest that the shear Alfvén wave is excited.

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