Excitation and Propagation of Low Frequency Waves in a FRC plasma

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Abstract. Low frequency ($f = 1/5 - 1/3 f_{ci}$, f_{ci}; ion gyro frequency in the external field B_w) waves are excited with an antenna which is compatible with a reactor in a plasma with field reversed configuration (FRC). Near and outside the separatrix r_s of the FRC plasma, though the applied wave is mainly compressional mode, azimuthal and radial compornents are observed in the magnetic field disturbance of the excited wave, which propagate with the dispersion relation consistent with the shear Alfven wave. These disturbances penetrate deep into the FRC plasma across the surface where the wave frequency exceeds local ion gyro frequency and propagate along magnetic lines of force with sound velocity, which behaviour is consistent with the shear Alfiven wave with finite temperature correction. Axial magnetic disturbance propagates axaially and radially from the antenna across the plasma column.

1. Introduction

In low beta Tokamak plasmas, there are various wave modes which are available for plasma heating. On the othre hand, in high beta plasmas like a theta pinch and a FRC[1], only waves with $f > f_{pe}$ (f; wave frequency, f_{pe}; electron plasma frequency) or $f < f_{ci}$ (f_{ci}; ion gyro frequency) are available for heating. This is because f_{pe} is by far larger than f_{ce} (f_{ce}; electron gyro frequency) even at low density, peripheral region of high beta plasmas. Here, the plasma temperature is low and therefore, cold plasma approximation should be valid in discussing wave propagation.

In the theta pinch plasma, heating was observed by the application of low frequency magnetic perturbation generated by external windings[2]. Heating was mainly ascribed to the existence of the Alfven resonance condition. In the FRC plasma, compressional magnetic field disturbance was applied by a pair of loop antenna, previously, which were arranged coaxially with the plasma in such a way as to surround the plasma. By this experiment[3,4], ion heating was observed. It was also observed that magnetic field perturbation with θ component, which did not exist in the applied wave, propagated axially. This sesult seems to imply that the compressional wave propagated across the magnetic field and is mode converted to the shear Alfven wave, which propagated along the magnetic field[5].

Here we report the excitation of low frequency waves by a small antenna which is compatible with a reactor; an antenna which is smaller than the previons one. It is also reported how the waves penetrate deep in the FRC plasma.

2. Experimental Set Up

In our FRC Injection Experiment (FIX) apparatus, the FRC plasma is produced in a formation region of 0.31m-diameter, 1.6m - long theta pinch apparatus, which plasma is ejected axially into a confinement region of 0.8m-diameter, 3.4m-long metal chamber. Schematics of the FIX apparatus is shown in Fig.1 together with small RF antenna and magnetic probes. Magnetic field at the formation region is about 0.8T and that of the confinement region is about 0.04T. The ejected plasma travels down the confinement region and is reflected by a mirror field installed at the downstream end of this region. The reflected plasma, then, travels up the confinement region and is reflected by a mirror field at the upstseam end of this region. The plasma loses some portion of its translational kinetic energy when it is reflected and the dynamics associated with the ejection disappears eventually[5]. At this moment, the separatrix radius r_s of the FRC plasma is about 16cm. And the plasma starts to decay gradually; r_s and the pressure balance temperature T decreases with time. By this process of translation, averaged density n and T of the FRC plasma of about $5\times10^{21}/m^3$ and 300eV, respectively, at the formation region changes to $5\times10^{19}/m^3$ and 100eV, respectively, at the confinement region.

Two kinds of FRC wave heating experiments were conducted; one with a large antenna and the other, with a small antenna. The large antenna consists of a pair of one turn loops with the diameter of 0.66m. They were arranged at 1.2m and 0.6m ($z=-1.2m$ and $z=0.6m$; the origin of the z-axis is at the center of the confinement region) respectively, from the axial midplane co-axially to the axis of the confinement region in such a way as to surround the plasma. The small antenna is a rectangular-shaped ($70\times250mm$) one-turn loop which was located at the $z=-0.6m$ cross sectional plane axially, and radially, 0.25m from the axis of the apparatus and is displaced from the separatrix of the plasma by 0.05m when $r_s=0.20m$ and the plasma is correctly centered. Each of these antennas are energized by a capacitor bank and ringing magnetic field which decays with the e-folding time of about $50\mu s$ is obtained. Frequency of the ringing can be changed from 50 to 100kHz and most data are taken at around 100kHz. As the large antenna is surrounding the plasma, it will excite magnetic fluctation in the plasma more efficiently than the small antenna. On the other hand, for future reactor, in which the magnetic field will be stronger and therefore the wave frequency should be higher and the size of the plasma should be larger, latter antenna is superior than the former one. In both cases the main component of the wave magnetic field radiated from the antenna is B_z.

Induced magnetic disturbance in the plasma was measured by arrays of small magnetic probes arranged in radial (r-array) and axial (z-array) directions. Three components B_r, B_θ, B_z of the magnetic field disturbance are measured at each probe location.

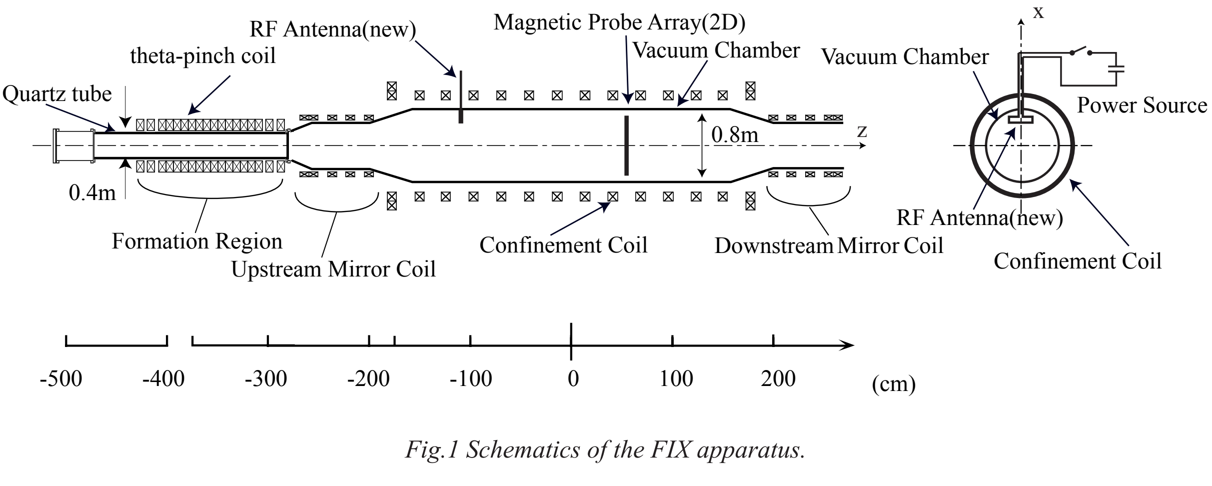

Fig.1 Schematics of the FIX apparatus.

3. Experiments

In Fig.2, typical temporal behaviour of the separatrix radius at $z=-0.6m$ cross sectional plane of the confinement region is shown. At $100\mu s$, translated FRC plasma passes this plane (1-st pass) and at $170\mu s$ the plasma reflected back from the downstream mirror field passes (2-nd pass) here again. After $220\mu s$, the plasma is seen to decay quietly. The oscillation from 260-300μs is the noise due to the RF wave picked up by a diamagnetic probe, from which signal, r_s was obtained. At the first pass, near the center of the confinement region, reversed field is measured by magnetic probes inserted deep into the plasma. When the plasma is decaying quietly, reversed field is not measured so far, probably because the center of the plasma is shifted radially off the probe position. But even in this case, measured magnetic field near the center of the apparatus is smaller than 20% of the confinement field. Ion gyro frequency for this magnetic field is less than the frequency of the applied RF wave.

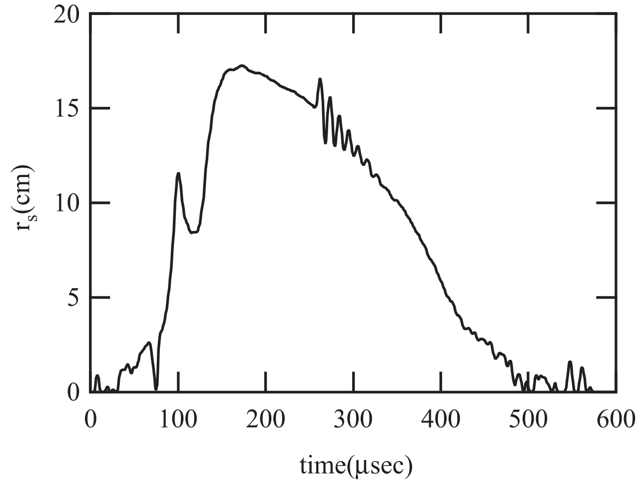

Fig.2 Temporal behaviour of the separatrix radius at z= -0.6m of the confinement region.

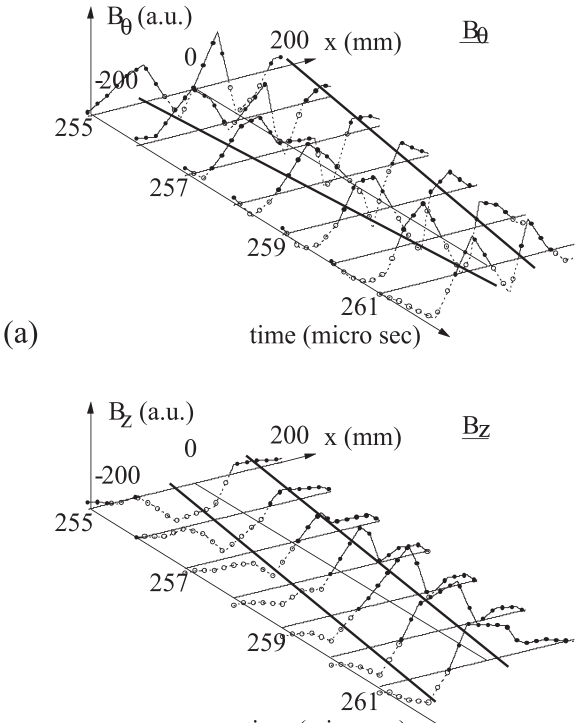

Fig.3 Propagatiom characteristics of (a) the B_q disturbance and (b) the B_z disturbance measured at the cross sectional plane (z=0.6m).

It is already reported that in the case of the large antenna, induced magnetic pertrbation has θ component even though applied wave does not have the θ component. It is also the case when the small antenna is used. In Fig.3 (a) propagation characteristics of the B_θ disturbance excited by the small antenna measured by the r-array of magnetic probes in a cross sectional plane $z=0.6m$ is shown. In this figure, B_θ amplitude is plotted at each instance of time (the antenna is energized at $t=238\mu s$, in this case. The axial phase velocity v_z of the B_θ disturbance is seen to be a function of the radius r and the phase is seen to be delayed inside the plasma, which signifies that v_z is smaller when r is smaller. Though the wave applied by the small antenna is not azimuthally symmetric but applied at a certain azimuthal position ($\theta = 0$), excited B_θ pertubation is seen to propagate azimuthally symmetrically. Disturbance of B_r exhibits the same tendeny as the B_θ disturbance. In Fig.3(b), similar plot for B_z disturbnce is shown. It is seen to propagate in z direction and, different from B_θ disturibance, across the plasma column, away from the antenna. In Fig.4, spatial dependence of the phase velocity of the B_θ perturbation is shown. Circles are the data for the case of the small antenna and squares are the data for the case of the large antenna. Open circles are obtained by calculation in which the wave is assumed to emanate from the axial cross sectional plane where the antenna exists and propagates to a plane where r-array of the magnetic probes are located. Solid circles are obtained from the data collected by z-array of magnetic probes. In this case, axial phase velocity is calculated from the phase difference of each probe without any assumption on wave propagation. In this figure, local Alfven velocity and sound velocity are also shown by a dashed line and a dash and dotted line, respectively.

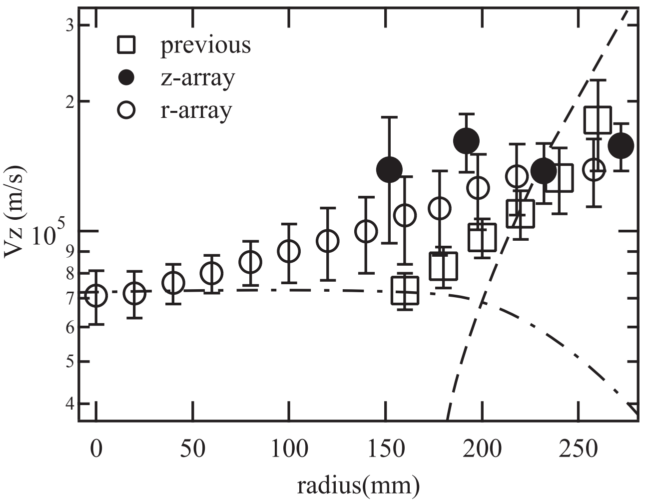

Fig.4 Spatial dependence of the phase velocity of the B_q disturbance.

4. Discussions and Conclusions

In the induced magnetic field disturbance, θ component was observed, even though the applied RF field did not have or had only small portion of the θ component. Near and outside the separatrix this B_θ disturbance is seen to propagate axially with the Alfven velocity calculated from the local plasma density and the magnetic field, suggesting the wave is shear Alfven wave mode converted from the compressional wave. Deep inside the separatrix, the strength of the confining magnetic field decreases, and eventually, local ion gyro frequency becomes smaller than the frequency of the induced B_θ disturbance. By the cold plasma approximation, shear Alfven wave is not accessible to such region. But in the experiment, B_θ disturbance is seen to penetrate in this region and propagates axially with the sound velocity, approximately. The reason will be explained by the finite temperature correction to the MHD equation[6]; shear Alfven wave penetrates in this region and further, the axial phase velocity approaches the sound velocity. In the case of the B_z disturbance, it is seen to propagate axially and also across the magnetic field away from the antenna with the sound velocity. This result may signify that B_z disturbance is ascribed to the compressional wave. This assertion does not exclude the possibility that the wave responsible for the B_θ disturbance may have B_z component due to finite temperature, gradient in density with maximum scale length of 3-4 ion gyro radius at the separatrix[7] and the Hall effect and so on.

In the case of the small antenna, the energy supplied to the antenna was about 1/4 of the previous experiment with large antenna, and the heating effect was not remarkable. With small antenna, comparable heating effect to the large antenna will be obtained by increasing electrical power to the antenna or by increasing the number of antennas. It will also be possible to obtain higher temperature by using continuous wave source.

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