Development of a Fishbone Travelling Wave Antenna for LHD*

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A travelling wave antenna in the ion cyclotron range of frequencies (ICRF) is being developed for LHD, motivated by the need to provide a capability for rotational transform profile control by noninductively driven current. Stability calculations suggest that it is possible to increase the beta limit and obtain access to the second stability regime by controlling the rotational transform profile [1,2]. Current drive by the ICRF fast wave (magnetosonic wave) can be used for such a purpose.

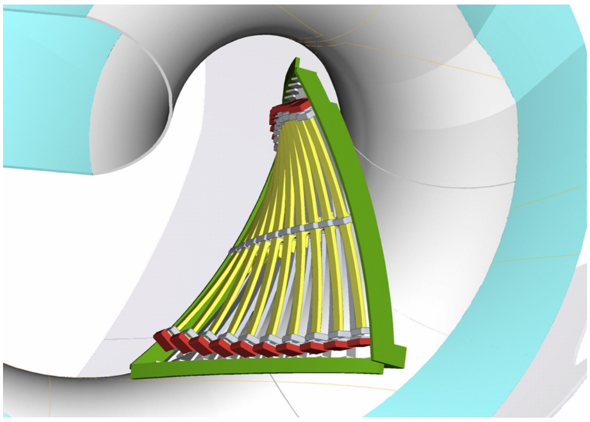

Fig. 1. *A drawing of the fishbone antenna inside the LHD vacuum vessel. The Faraday shield elements and the side protection tiles are removed for ease of viewing.*

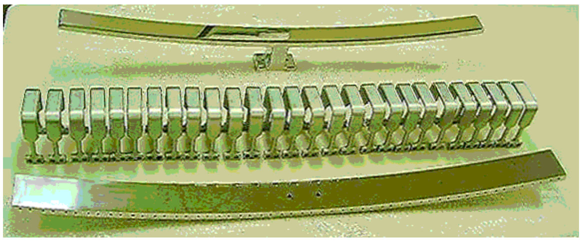

Fig. 2. *The T-bar current strap, the Faraday shield elements, and the backplate.*

A simple combline antenna [3] has been used successfully on JFT-2M [4]. The antenna being built for LHD is equivalent to two combline antennas stacked vertically, but has only one input and one output. Such a design enables high power operation even with limited port space. This antenna will be placed on the large major radius side of the torus where the plasma is elongated in the vertical direction (Fig. 1). The antenna is divided into 10 nearly identical modules, each consisting of a stainless steel half-wavelength resonant structure approximately 1 meter long, grounded at the midplane (T-bar current strap), a water-cooled stainless steel backplate, and a U-shaped molybdenum Faraday shield, shown in Fig. 2. These modules are placed side by side in the toroidal direction, following the helical shape of the plasma surface (Fig. 1). The whole assembly is surrounded by carbon protection tiles arranged in a "picture frame" configuration to reduce the plasma density at the Faraday shield. The spacing between adjacent straps (center to center) is 0.11 m, which corresponds to a wavenumber of 14 m^{-1} when the phase difference between adjacent current straps is 90°. The frequency of operation is chosen to be in the neighborhood of 75 MHz, with a bandwidth of about 20 MHz. Electron Landau damping of the fast wave will be used to heat electrons and to drive current in the plasma. In addition, second harmonic heating of hydrogen ions is also possible at a magnetic field of around 2.5 T. A schematic configuration of the fishbone antenna and an equivalent circuit are shown in Figs. 3 and 4, respectively. Here L, C, R are the self inductance, capacitance, and resistance (including the radiation resistance) of the top or the bottom half of the antenna, L_c is the inductance of the support leg of the T-bar current strap. The mutual inductance between neighboring current straps are different for even and odd modes, and are denoted M_{ee} and M_{oo}. The even mode is defined as the mode with current in the same direction in the top half and the bottom half of the current strap, whereas the odd mode has current in opposite directions in the top and bottom halves. It is assumed that there is no coupling from the even mode to the odd mode, and only the nearest neighbor coupling is considered. The resonant frequencies are given by

$$\omega_{\text{even}} = \frac{1}{\sqrt{CL}}$$

for the even mode (which has no net current in the support leg) and

$$\omega_{\text{odd}} = \frac{1}{\sqrt{C(L + 2L_c)}}$$

for the odd mode (which has twice the current in the support leg).

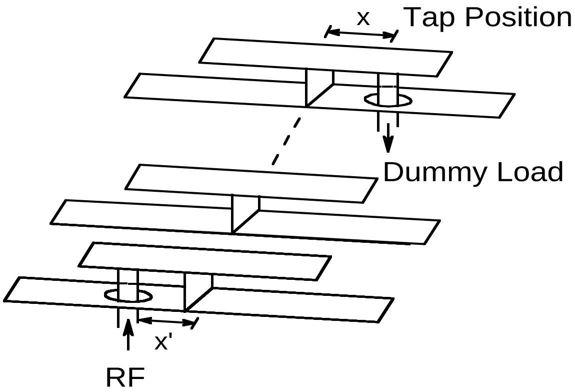

Fig. 3. A schematic of the fishbone antenna configuration.

Several mockup antennas were built to optimize the electrical properties of the antenna. The effects of geometry (strap length, strap to Faraday shield distance, Faraday shield geometry, strap to backplate distance, and strap spacing) on the pass-band characteristics were examined. The radiation resistance due to power radiated into the plasma was simulated by placing a resistive film in front of the antenna. The RF magnetic field in front of the Faraday shield was measured using a single-turn loop probe, approximately 1 cm in diameter. As expected, the phase varied monotonically in a step-wise fashion for a simple combline antenna, confirming that a traveling wave was excited. In the simple combline configuration, it is possible to select the phase shift between adjacent current straps arbitrarily in the range from 0 to π by choosing an appropriate frequency within the passband of the antenna. This gives a great flexibility in selecting the wavenumber of the excited wave. In

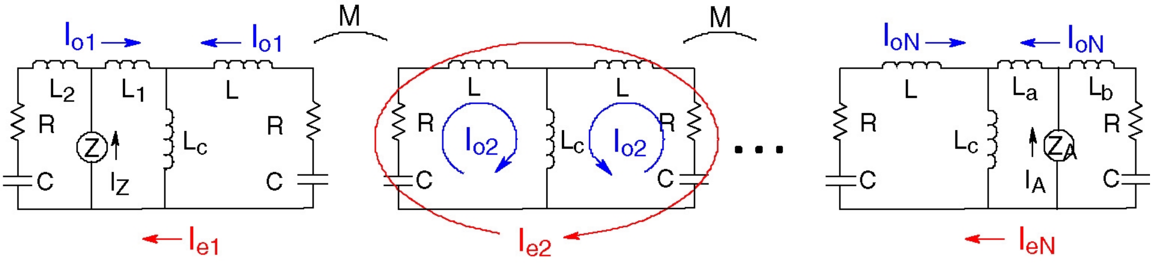

Fig. 4. An equivalent circuit diagram of the fishbone antenna.

the fishbone configuration, this flexibility is compromised because of the presence of even and odd modes as discussed in the next paragraph.

A 2 × 2 array was built to test the fishbone configuration. Two types of coupled resonances (symmetric and antisymmetric current modes), corresponding to the top-to-bottom pair (even and odd mode) and the side-to-side pair (0 and π mode), were observed. The even mode is the desired mode because it realizes the lowest poloidal mode number. Controlled excitation of the even mode is a major issue in the development of the fishbone antenna. The four resonances are shown in Fig. 5(a). The resonant frequencies for the 0 and π modes are given by

$$\omega_{\text{even}} = \frac{1}{\sqrt{C(L \pm M_{\text{ee}})}}$$

for the even mode and

$$\omega_{\text{odd}} = \frac{1}{\sqrt{C(L + 2L_{\text{c}} \pm M_{\text{oo}})}}$$

for the odd mode [5]. Relative magnitudes of inductances can be determined from these resonances as follows: $L_c/L = 0.13$, $M_{ee}/L = 0.27$, $M_{oo}/L = 0.12$. If the capacitance is assumed to be $C = 50$ pF, the self inductance is $L = 100$ nH. The data shown in Fig. 5(b) indicates that it is possible to separate the even and odd modes in frequency by installing a loop which links the top and bottom halves of the current strap. This has the effect of reducing L and M for the even mode but not affecting them much for the odd mode. This would make it easier to excite only the even mode, and is an option in case it proves difficult to not excite the odd mode.

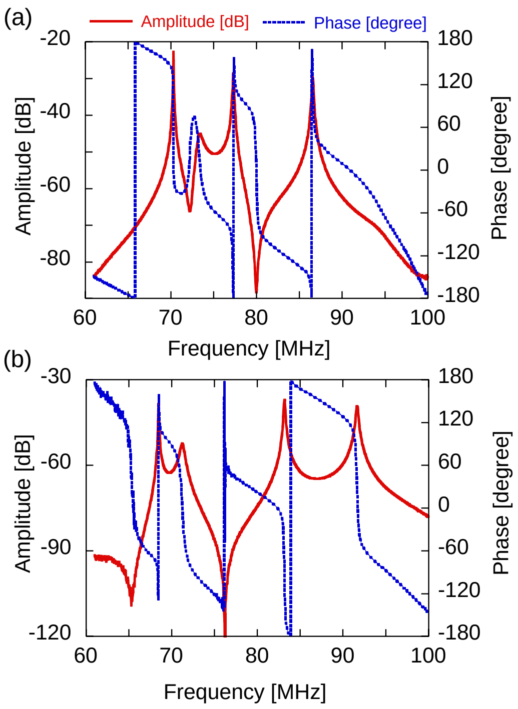

Fig. 5. Resonances of the four modes of the 2 x 2 array, (a) without the coupling loop 70.36MHz (odd-0), 73.13MHz (odd-π), 77.38MHz (even-0), 86.62MHz (even-π), and (b) with the coupling loop 68.72MHz (odd-0), 71.53MHz (odd-π), 83.23MHz (even-0), 91.93MHz (even-π).

A 4-module LHD prototype antenna was assembled. Since the first and the last elements have only one neighboring element, they are different from other elements. Therefore, adjustments must be made to ensure a clean bandpass characteristic. Extender elements were added to either the end elements or the middle elements to adjust the length of the straps (and therefore their inductance and capacitance). Matching from the feeder to the antenna was improved (the reflection within the passband decreased from –5 dB to –15 dB) by adopting a direct feeding method instead of the originally proposed loop coupling method. The top row and the bottom row can be excited either in phase or out of phase (or their linear combination). Coupling loops linking the top row and the bottom row (added to the first and last elements) have enabled approximately in-phase excitation of the top and bottom rows. A clean bandpass characteristic of the antenna with a 10 dB bandwidth of over 10 MHz centered around 74 MHz was obtained by adjusting the feeder position. Additional measurements using a 10-element mockup antenna (same dimensions as the LHD elements, but arranged on a flat plane) indicated that the coupling loop is not necessary provided the operating frequency is selected high enough to suppress excitation of the odd mode.

The LHD fishbone antenna has been assembled (Fig. 6) and final testing is being performed. Measurements of the excited fields suggest that because of the helical twist of the assembly, there is finite coupling between the even mode and the odd mode between adjacent current straps. Presently the carbon protection tiles (corresponding to the wooden parts in Fig. 6) are being designed to intersect the field lines of the LHD plasma. In addition, final adjustment of the antenna feeder position will be made before installation of the antenna in LHD.

Fig. 6. The LHD "fishbone" antenna assembled for final testing.

A test with plasma load was performed on the TST-2 spherical tokamak at the University of Tokyo using a 6-strap combline antenna with a passband (defined as the frequency range where the transmission is greater than –10dB) of 22–28 MHz. A low-power (1 kW level) high-harmonic fast wave (HHFW) was excited. At 25 MHz (approximately $8\Omega_H$) the excited toroidal wavenumber is 13 m^{-1} at R = 0.57 m, which corresponds to a toroidal refractive index of 25 and a toroidal mode number of 7.4. The loading resistance was so high that RF currents induced in the second strap became much smaller than that in the first strap. It is necessary to reduce the radiation resistance low enough to allow excitation of a travelling wave with high directivity. This was accomplished by reducing the density at the antenna by inserting a movable limiter beyond the antenna radius. In LHD, the antenna will be installed sufficiently far away from the plasma. This is an advantage compared to conventional loop antennas. We note that this type of antenna is equally applicable to next generation tokamaks such as ITER, as a simple high power in-port travelling wave antenna.

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