Characteristics of a Novel Lower Hybrid Wave Antenna for the TST-2 Spherical Tokamak

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Abstract. A new type of traveling wave antenna which excites the lower hybrid wave directly was developed. This antenna is similar to the inductively-coupled combline antenna in that only the first element of the antenna array is excited externally, and subsequent elements are excited passively by mutual coupling between adjacent elements. The main difference is that whereas the inductively-coupled combline antenna makes use of mutual inductance, the presently proposed antenna makes use of mutual capacitance. The radiating elements are located at the voltage maximum, and the electric field induced in the plasma is in the toroidal direction rather than the poloidal direction, matching the polarization of the lower hybrid wave. Optimization studies were carried out to obtain a band-pass characteristic centered around 200 MHz, and a unidirectional wavenumber spectrum with the parallel index of refraction corresponding to approximately 5. Plasma current ramp-up to 2 kA has been achieved on the TST-2 spherical tokamak with 12 kW of RF power at 200 MHz during the initial experimental period using this antenna. Further optimization studies are being performed.

Keywords: Lower Hybrid Wave, Spherical Tokamak, Plasma Current Start-up, TST-2
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INTRODUCTION

In order to realize a compact fusion reactor based on the spherical tokamak (ST) concept, plasma operation without the use of the central solenoid must be demonstrated [1]. In particular plasma current ramp-up from zero to a level required for fusion burn is the most crucial issue. Plasma initiation and plasma current ramp-up in ST by waves in the lower-hybrid (LH) frequency range were demonstrated on the TST-2 spherical tokamak [2] at the University of Tokyo using an inductively-coupled combline antenna [3]. The formation of a low current (~ 1 kA) ST configuration and further current ramp-up to > 10 kA was achieved. X-ray observations were consistent with acceleration of electrons by a uni-directional RF wave. The inductively-coupled combline antenna used in Ref. [3] excites vertical electric fields which match the polarization of the fast wave. There is evidence that the LH wave is excited either linearly or nonlinearly. It is expected that the effectiveness of current drive would improve if the LH wave could be excited directly by the antenna rather than relying on such indirect processes.

A new type of traveling-wave LH wave antenna [4] has been developed for TST-2. This antenna is called the electrostatically-coupled combline (ECC) antenna in this paper. It consists of thirteen capacitively coupled elements with the electric field polarized in the toroidal direction. It therefore should couple predominantly to the LH wave directly. The input RF power is fed to only one of the outermost elements (the “input element”). Each of the intermediate elements is excited by mutual capacitance from an upstream neighboring element, and the power that is not radiated to the plasma as the LH wave exits from the last element of the array (the “output element”). The array behaves like a band-pass filter, and the phase shift between elements is determined by choosing the operating frequency within the pass-band. The feeders must attach to the outermost elements at appropriate points to achieve the input impedance of 50 Ω. This antenna is now installed in TST-2, and initial experiments using this antenna are being performed.

In this paper, the design of the ECC antenna is described, and the measurement results of its electrical characteristics and the results of initial plasma current ramp-up experiments are reported.

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DESIGN OF THE ECC ANTENNA

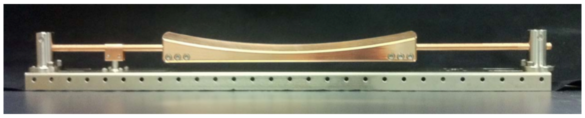

FIGURE 1. End element of the TST-2 ECC antenna.

A novel traveling wave antenna for launching LH waves was designed for use on TST-2. It consists of 13 identical modules. Each module consists of the radiating element (made of copper plated stainless steel) straddling the voltage maximum and two copper inductive rods at both ends. This assembly is suspended above the ground plane by means of brackets. The shape of the radiating element (house-shaped cross section) was chosen to reduce the stationary spatial harmonic field. The inductive rods are covered by stainless steel shields to reduce mutual inductive coupling and to inhibit possible excitation of the fast wave. The most upstream and downstream elements are special, in that they have only one neighboring element, so the inductance must be adjusted to obtain good band-pass characteristics. The RF power is fed to the most upstream element. Intermediate elements are excited by mutual capacitance between adjacent radiating elements, and the remaining power that is not radiated to the plasma exits from the most downstream element. The length of the radiating element is 280 mm and the gap between the bottom of the radiating element to the ground plane is 9.4 mm. The radiating element has a poloidal curvature that matches with the nominal shape of the plasma, and its height is 35.9 mm at the midplane. The total height (radial extent) of the antenna from the rear of the ground plane to the top of the radiating element is 64.9 mm at the midplane. The total length of the antenna, including the inductive rods, is 569 mm. A photograph of a single module (end element with a feeder) is shown in Fig. 1. (The circular cross section brackets that hold the inductive rods shown in this photograph have been replaced by narrower rectangular cross section brackets to increase the inductance during the optimization process.) The feeder is attached where the input impedance is 50 Ω.

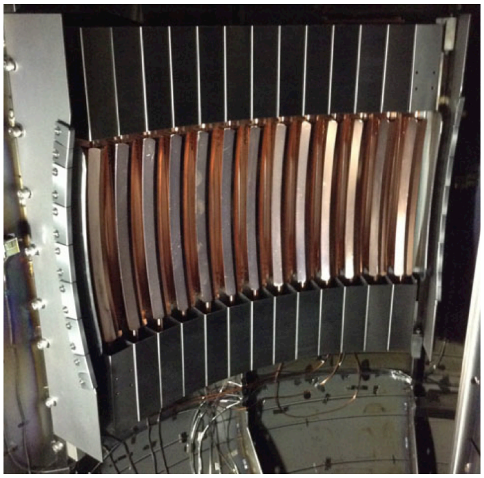

FIGURE 2. ECC antenna installed in TST-2.

Figure 2 shows the ECC antenna installed in the TST-2 vacuum vessel. No Faraday shield is provided, which makes the antenna structure very simple. The neighboring elements are spaced 4.2° apart in the toroidal direction. The front surface of the radiating element is exposed to the plasma (no Faraday shield), and is located at a major radius of 621 mm. The plasma facing surface of the antenna protection limiters on both sides of the antenna are located at a major radius of 607 mm. The limiter tiles are made of molybdenum. There are additional plates on both sides of the antenna (but inside the limiters) to adjust the capacitance of the end elements. The coupling between neighboring elements is predominantly capacitive, causing a backward wave (wave with the phase velocity opposite to the group velocity) to propagate through the antenna. The wavelength of the LH wave parallel to the magnetic field line is 300 mm for the desired $n_{||}$ (parallel index of refraction) of 5. With six elements per parallel wavelength or 60° phasing between adjacent antenna elements, the parallel wavelength would be 273 mm. At this phasing, the static ripple field 25 mm in front of the antenna is calculated to be 0.075for the ratio of the spatial harmonic field to the fundamental field.

ELECTRICAL CHARACTERISTSCS

The ECC antenna behaves like a band-pass filter. With the RF power delivered to the input element, the reflected power from the input element and the transmitted power from the output element were measured. In Fig. 3, the frequency dependences of the voltage reflection coefficient and voltage transmission coefficient (a) for the ECC antenna alone with a matched load (50 Ω) on the output port (top), (b) with feeder line and vacuum feedthrough on the input port and a matched load on the output port (middle), and (c) with feeder line and vacuum feedthrough on the input port and a matched load after feeder line and vacuum feedthrough on the output port (bottom) are shown. The photographs on the left side show the rear view of the ECC antenna for each case. A fairly flat pass band around 200 MHz observed for case (a) indicates that there is primarily a traveling wave propagating through the antenna. In this case, the phase shift between adjacent elements was 60°, as designed. The phase shift is reduced by up to 20% by placing sheets of resistive film in front of the antenna to simulate radiation into the plasma. In case (b) the reflection coefficient is increased by the mismatch introduced by the feeder line and the vacuum feedthrough. In case (c) a standing wave is produced by the mismatch introduced at both ends of the antenna. This is not desirable for current drive since the waves are launched in both directions in such a case. However, in the presence of a plasma, wave launching is found to be so efficient that no power reaches the output port of the antenna. For such a case, no standing wave is formed in the antenna and a uni-directional wave can be launched, although the wavenumber spectrum will deteriorate.

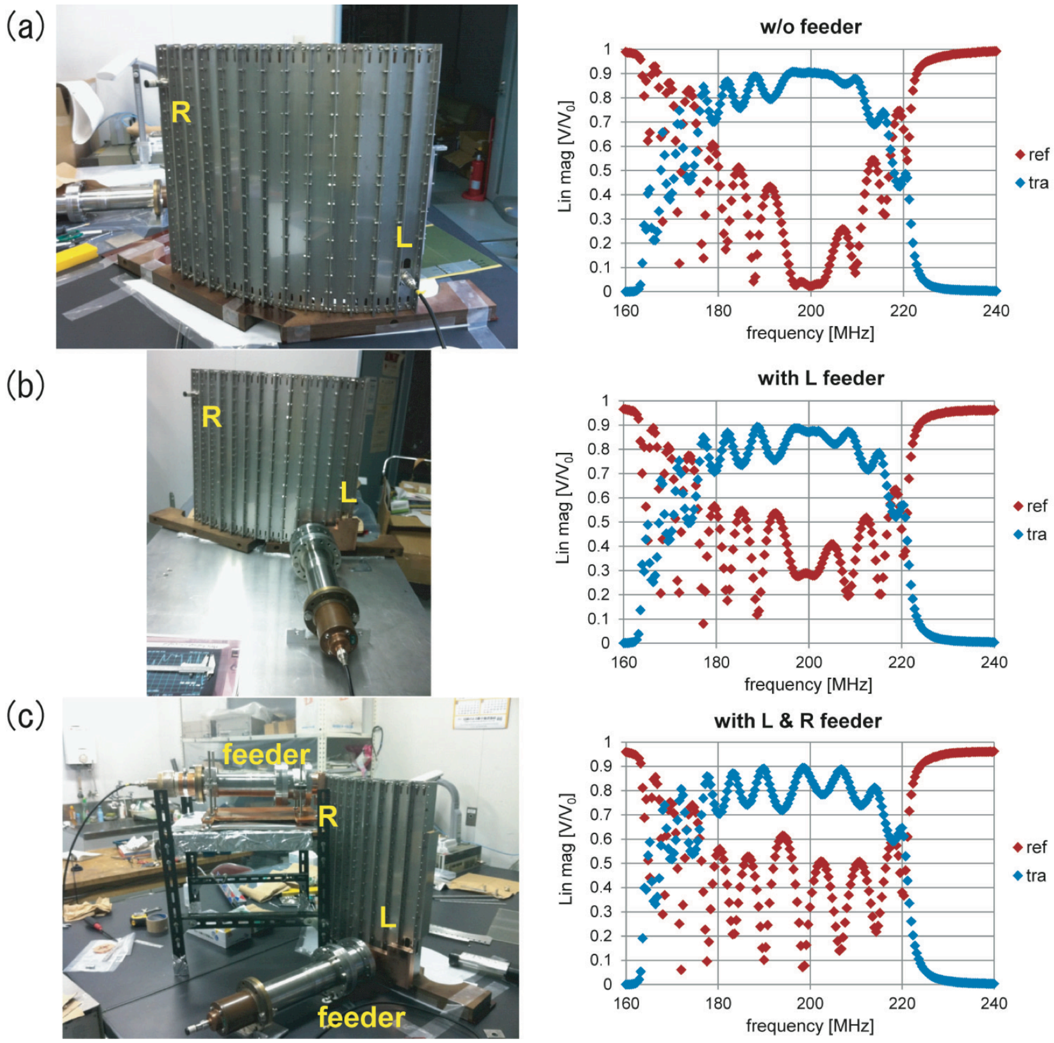

FIGURE 3. Frequency dependence of the voltage reflection coefficient and voltage transmission coefficient for (a) the ECC antenna alone (top), (b) with feeder line and vacuum feedthrough only on the input port (middle), and (c) with feeder line and vacuum feedthrough on both input and output ports (bottom).

INITIAL CURRENT RAMP-UP RESULTS

Preliminary results have been obtained during the initial experimental period using the ECC antenna. With preionization by 2.45 GHz microwave power, plasma current has been increased up to 2 kA with 12 kW of RF power at 200 MHz at a line-averaged density of 5×10^{17} m^{-3}. It is noted that both the reflected power from the input port and the transmitted power to the output port are both very low, indicating that most of the incident power was coupled to the plasma, exciting the LH wave. Power handling improves when the plasma density is lower, and up to 50 kW of RF power has been injected into the plasma successfully. Further optimization studies are presently being conducted.

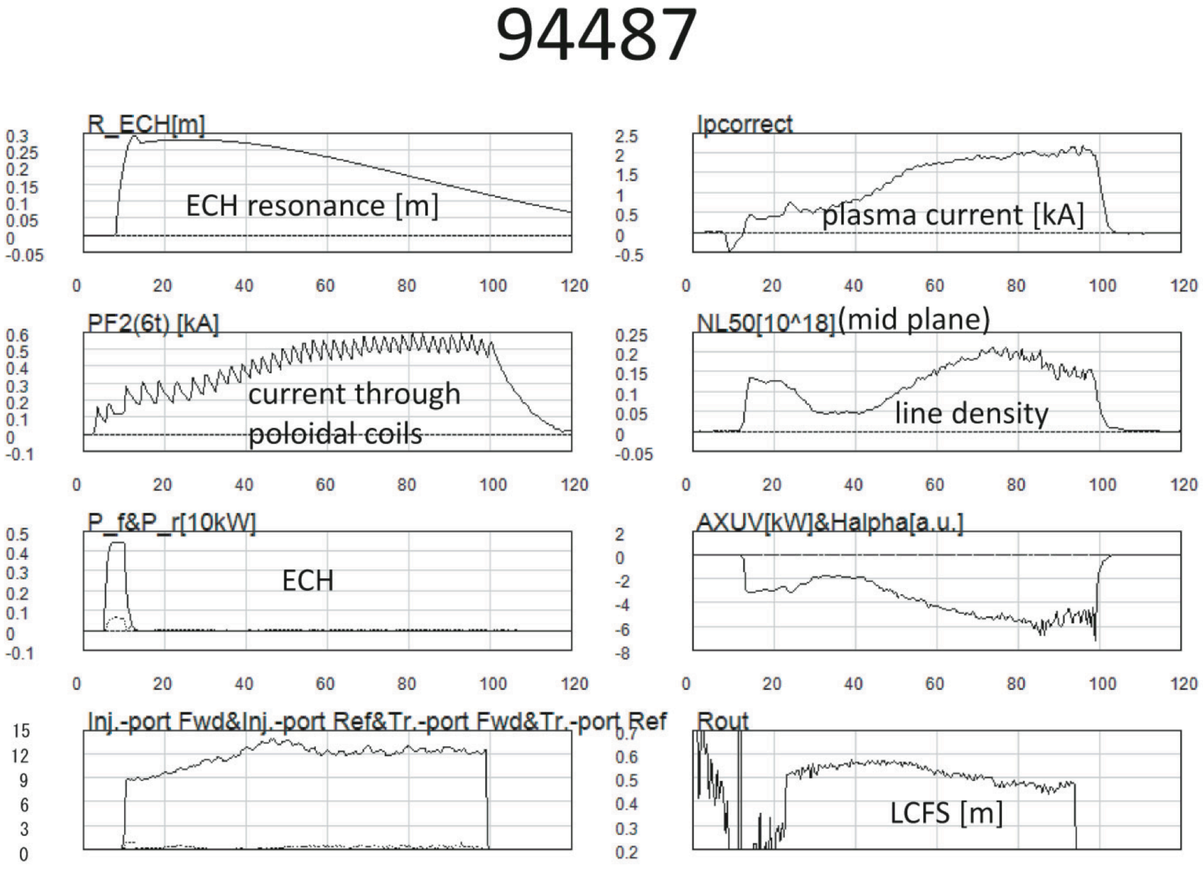

FIGURE 4. After preionization by 2.45 GHz microwave power, the plasma current was ramped up to 2 kA by the LH wave at 200 MHz excited by the ECC antenna.

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