



Design and RF test of a prototype traveling wave antenna for helicon current drive in KSTAR

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ABSTRACT

Non-inductive current drive by fast wave at very high ion cyclotron harmonics, known as 'helicons' has the potential for high off-axis current drive efficiency compared with the other known non-inductive current drive techniques. However, non-inductive current drive by helicon wave has not been validated experimentally. To validate its anticipated performance experimentally, an antenna design is one of the most important issues. A Traveling wave antenna has particularly valuable features for launching the fast wave such as load resiliency, narrow $n_{||}$ spectrum, and simple RF circuits without additional-external matching systems. Low power level helicon wave coupling experiments has been conducted successfully using a mock-up TWA in KSTAR. In the next step, in order to investigate a high power performance, a new prototype TWA based on the mock-up TWA has been designed, fabricated and measured for a medium power (100–300 kW) RF system. The prototype TWA having a Faraday shield was made of copper and consists of 10 current straps with 5 inch coaxial feeding lines as input and output ports. The detailed design parameters and electromagnetic characteristics of prototype TWA are discussed.

1. Introduction

An important goal of the KSTAR tokamak is to develop advanced scenarios ($\beta_N > 3$) with non-inductive current drive for steady-state operation [1]. Several predictions show that non-inductive current drive by absorption of fast waves at very high ion cyclotron harmonics, known as helicons has the potential for high current drive efficiency compared to other known non-inductive current drive methods [2–4]. However, non-inductive current drive by helicon wave has not been validated experimentally. Therefore, the basis of physics and engineering issue of helicon current drive has been investigated in KSTAR tokamak. The primary challenge is to design an antenna that can couple an RF wave to the plasma while maintain the good impedance matching during abrupt changes of plasma characteristics such as L/H-mode transitions, and edge localized mode activity. The antenna should also impose the desired value of parallel refractive index ($n_{||}$), and the electric field polarization at the launcher must be controlled so as to excite primarily the fast wave. The traveling wave antenna (TWA) is an attractive option because of its insensitivity to the variation of loading resistance without additional-external matching circuit and it already showed good performances in the other tokamak experiments [5–7].

The first step of the helicon current drive experiment was to construct a low power (mW) mock-up comblane-type TWA, to install it into

the KSTAR tokamak, and to measure the coupling and impedance matching properties in an L/H-mode plasma, in order to resolve an engineering and physics issue for high power helicon current drive. The coupling measurement was performed using a two port vector network analyzer (VNA: Agilent E5071C), which was connected to the input and output ports of mock-up TWA installed in KSTAR vacuum vessel. Various experiments have been conducted on a variety of plasma conditions to measure the variation of impedance matching, coupling, and change of dominant $n_{||}$ [8]. To distinguish the slow and fast wave couplings, the magnetic pitch angle was scanned during a discharge for both L/H-mode plasmas. The experimental and analytical results show that the fast wave was dominant in fairly high coupling, and load resiliency can be obtained by using the TWA concept [8].

In the next step, the most important aspects that remained to be addressed, both theoretically and experimentally, have to do with the wave propagation and absorption, stray heating channels such as scrape-off layer heating, and the non-linear aspects of wave such as parametric decay instability, in addition to the current driving capability [9,10]. In order to investigate these issues in helicon current drive, a medium power, 100–300 kW, RF system has been developed. The detailed configuration and characteristics of RF system including RF source, transmission line layout, and RF vacuum window will be published elsewhere.

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In this paper, we focused on the design and analysis of prototype TWA for high power helicon current drive, and discuss its detailed electromagnetic characteristics including the scattering parameters and $n_{||}$ spectrum based on the simulation and measurements. All electromagnetic simulations in this work has been done with commercial software package, CST MWS [11].

2. Design and simulation results of TWA

2.1. Basic properties of TWA

A TWA is a class of antenna that uses a traveling wave on a guiding structure with continuous or periodic radiating structure. A simple example is a slotted waveguide antenna, where the waveguide is perturbed with periodic slots in the structure at a certain position. The reasonable design goal of TWA is to have most of the power in the waveguide radiated from the structure when the wave propagates through the entire structure while maintaining good impedance matching. If the length of TWA is infinitely long, it radiates all RF wave, but in the most of realistic TWA, a matched load will be connected at the end of antenna in order to absorb the remainder of the incident power.

The TWA can be represented by a simplified equivalent circuit model as shown in Fig. 1, which consists of infinite radiating structure elements in the longitudinal direction. Where R represents the sum of Ohmic loss and resistive loading, M is the mutual reactance between neighboring radiating structure elements. The incident power is transmitted to the adjacent radiating structure elements by mutual reactance, and the rest of power is radiated. If the number of radiating structure elements are infinite, then all the incident energy is radiated while the incident power is transferred to the next radiating element in sequence. If the resistive term is much smaller than the mutual reactance, then the input impedance of TWA can be approximately expressed as an Eq. (1) [12].

$$Z_{in} = \omega M \left[1 - \frac{1}{8} \left(\frac{R}{\omega M} \right)^2 + \dots \right] \quad (1)$$

Eq. (1) means that input impedance of the TWA is nearly independent of the resistive loading, and this is the fundamental principle that makes the TWA is load resilient.

Among the various TWA types, a combline antenna was chosen for testing helicon current drive experiment in KSTAR. A combline antenna consists of several poloidal current straps placed in toroidal direction with only two external connections, the input and output port, and it was equivalent to an RF band pass filter if the radiation was neglected [13]. The current straps are inductively coupled and generate a slow wave structure along the toroidal direction inside the antenna box. This is a very valuable feature which can launch the desired $n_{||}$ spectrum.

2.2. Mock-up TWA

The mock-up TWA for 500 MHz was designed based on the combline filter design theory. The mock-up TWA was made of stainless steel and consists of 7 current straps with N-type input and output connectors as shown in Fig. 2. The dimensions of the mock-up TWA were 600 mm, 200 mm, and 50 mm in the toroidal, poloidal, and radial directions, respectively. The spacing (D) between current straps was 68 mm. The dimensions of the current straps are 20 mm, 130 mm, and 10 mm in the

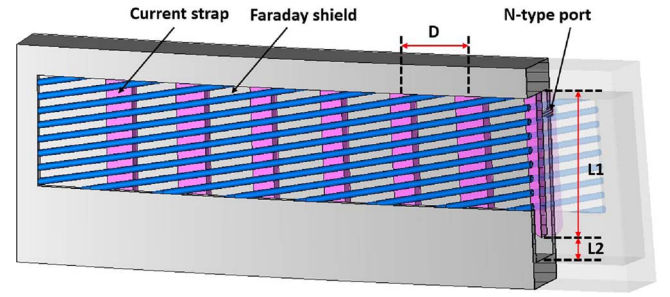


Fig. 2. 3D model of mock-up TWA.

toroidal, poloidal, and radial direction respectively. The electrical length of current strap ($L1$) and gap between end of current strap and ground box ($L2$) represent the inductance and capacitance, respectively, which were important design parameters in combline antenna design.

The feeding structure of the antenna can be simplified to a monopole antenna with capacitance by $L2$, where the resonant frequency is determined by the combination of $L1$ and $L2$. The impedance bandwidth of combline antenna is mainly determined by $L1$, and the optimum electrical length(θ) of $L1$ is approximately 53° to achieve the maximum impedance bandwidth [14,15].

$$BW = K \frac{\theta \tan(\theta)}{\tan(\theta) + \theta(1 + \tan^2(\theta))} \quad (2)$$

Eq. (2) shows the impedance bandwidth dependence on the electrical length of current strap, where K was a constant that depends on the current strap geometry. In order to obtain the maximum impedance bandwidth, the required capacitance was also increased, which causes an increase in the electric field strength at the end of current straps. To reduce electric field strength, the shape of the end of current straps was designed as a round shape as shown in Fig. 2. Although mock-up TWA was intended for low power test, electric field strength has been considered for the high power prototype TWA. By considering both the impedance bandwidth and electric field strength, the electrical length of current straps was determined to be approximately 78° . The Faraday shield was used to launch the fast wave, and it was tilted by 10° considering alignment with the fixed magnetic field for targeted discharge in KSTAR [16].

The power spectrum was calculated from the electric field along a line parallel to the Faraday shield above 10 mm as shown in Fig. 3. The peak $n_{||}$ of mock-up TWA was 3 at 500 MHz, which was considered to be the optimal value for helicon current drive in KSTAR [17].

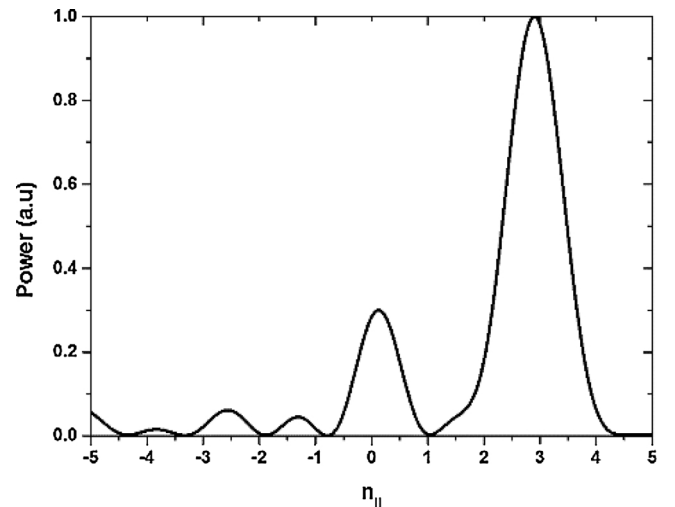


Fig. 3. Calculated power spectrum of the mock-up TWA at 500 MHz.

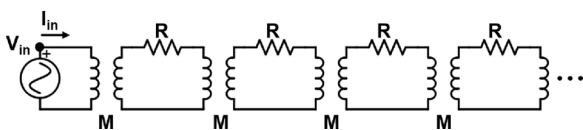


Fig. 1. Simplified equivalent circuit model of semi-infinite TWA.

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