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Multi-section Traveling Wave Antenna for heating of large machines as DEMO

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HIGHLIGHTS

- A Traveling Wave Antenna in a resonant ring is a suitable system for ICRH in DEMO.
- Multiple sections TWA allow to inject a large amount of auxiliary heating power.
- No complex matching-decoupling systems are needed.

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ABSTRACT

The main advantages of ICRH&CD are its ability to achieve power deposition in the center of the plasma column without any density limit along with direct heating of plasma ions. The challenge is then to couple large amount of power through the plasma boundary, where an evanescence layer has to be crossed, without exceeding the voltage standoff at the antenna. A solution presently considered is the reduction of the power density by means of antennas distributed all along the wall of the machine. In [1] we have shown that a suitable launcher can be constituted by sections of Traveling Wave Antenna (TWA) mounted in resonant ring systems. They are launching a traveling wave in one direction along the structure that leaks its energy to the plasma and is refueled periodically by generators. Each section is constituted by a series of equidistant mutually coupled grounded straps aligned in the poloidal direction which radiates its power to the plasma proportionally to the total strap number divided by their inter-strap distance. Due to the large number of radiating elements, the launched power spectrum is very selective. A detailed discussion on the multi-section antenna is made in view of its test on a mock-up. We study the influence, in ring shaped structures, of its geometrical parameters on its response along with the influence of the periodicity of sections and feedings. This extends the work done in [2]. The aim is to prepare for a proof-of-concept system to be tested in an operating tokamak machine.

1. Introduction

Ion Cyclotron Resonant Heating is a well-established technique to heat directly ions of the Deuterium Tritium mix in order to reach the high temperature needed for the fusion reaction to work. The capability to heat ions in the plasma core without density limits is a peculiarity of ICRH systems. The power coupled to the plasma edge is transferred to Fast Magnetosonic Waves that propagate across the magnetic surfaces up to the point where a particle–wave interaction takes place, transferring momentum to the ions increasing their temperature. With Ion Cyclotron Current Drive it is possible to help in sustaining the plasma discharge in long pulsed or steady state reactor. Currently, the way towards a fusion reactor implies big machine with large volumes of plasma. Those volumes require a large amount of auxiliary heating power to ignite and burn the fusion fuel. ICRH is one of the systems that can provide part of this auxiliary power. It is based on proven RF technology in terms of power generation and transmission with high wall-plug efficiency. Nowadays, the launching structure is designed to fit into the vacuum vessel ports and to provide a large power density to the plasma edge with some unwanted side effects like impurity production due to RF sheath rectification. Usually those systems are short series of poloidal current carrying conductors, called straps, fed independently. We believe that reducing the power density is one of the ingredients to cope with the impurity production. We have shown in [1] that: (i) increasing the number of straps is beneficial for

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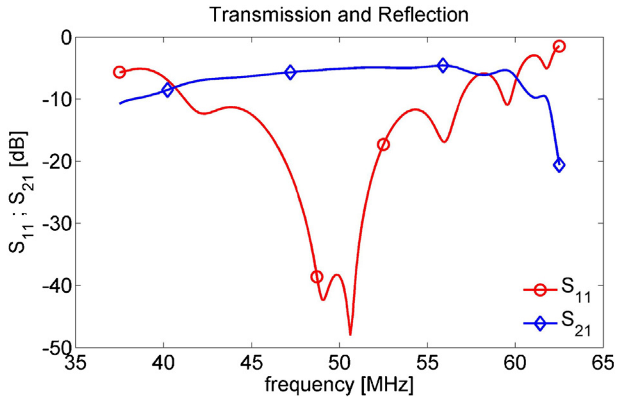

Fig. 1. Transmission (blue-◇) and reflection (red-○) coefficients of a TWA section highlighting the band-pass filter-like response.

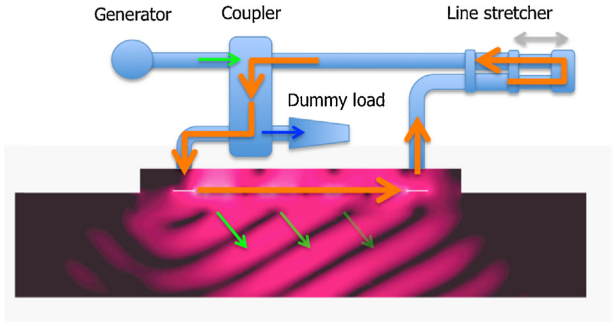

Fig. 2. A TWA resonant ring system with the main component labeled. The structure of the coupled field is visible in front of the antenna aperture. The arrows give an idea of the power flow in the system.

the coupling and absorption of the power due to the capability of obtaining sharper power spectra, (ii) a Traveling Wave structure is a suitable system to obtain those spectra reducing the power density and (iii) the system presents some good characteristic like an intrinsic load resilience to plasma load variation. A very similar system, firstly proposed in [3,4], is now under development for generation of helicon waves for off-axis Current Drive [5,6] while a comparison with a conventional system was done in [2]. A possible solution to inject the required amount of power needed by a DEMO reactor is presented by a series of TWA sections integrated in the reactor blanket. In this paper we analyze in more detail the effect and the implications of such series of antennas from the point of view of how to realize a suitable feeding for all sections and how this series of structure interacts with the plasma. A first section will describe briefly the TWA system in a resonant ring guiding the reader through the key points that explain the design choices of the multi-section TWA system that is then analyzed in subsequent paragraph.

2. Traveling Wave Antenna

2.1. Single section

The Traveling Wave Antenna section is equivalent to a RF or microwave band-pass filter. When power is fed at one of the two ends it will be transported to the other end of the structure, if the operating frequencies lie inside that passing band and if the end is terminated on the iterative impedance of the periodic structure Z_{it}. This system can be also described as a transmission line terminated on a matched load that corresponds to the characteristic impedance Z_0 of the line itself. An example is shown in Fig. 1 where the characteristics of the 2-port network describing the TWA section are represented, i.e. the transmission (S_{21}) and reflection (S_{11}) coefficients.

Two cases can be described: without plasma, and with plasma. In the first case, when there is no power coupled to the plasma and the ohmic losses are negligible, the transmission coefficient is almost identically 1, being $Z_0 = Z_{it}$. All the power at the input port is transported to the output port corresponding to a lossless transmission line. The electromagnetic (EM) field propagates along the TWA structure by means of a unidirectional (i.e. traveling) *slow* wave, where *slow* refers to the fact that its phase velocity $v_{ph} \ll c_0$. In the second case, when a magnetized inhomogeneous plasma permeates the space in front of the antenna aperture, part of the radially decaying EM field couples with the plasma. Then some of the power traveling on the (*slow wave*) structure of the antenna leaks into the plasma and it is transported inside the core via the excitation of Fast Magnetosonic Waves. If the antenna structure is long enough, all the power will be coupled to the plasma and nothing will reach the second port. While this seems good at a fist sight, describing in more detail the behavior of the structure drives to a different conclusion. The power transferred to the nth-strap is equal to the difference between the power at the (nth-1)-strap and the power leaked to the plasma. After each step, part of the power is transferred to the plasma resulting in a smaller current in the consecutive strap. After a certain amount of steps (straps) that depends on the coupling with the plasma, no more current is flowing on the straps and no more power is available. From this point on, all remaining straps are not useful anymore leading to a not optimal use of the available space allocated for the antenna. In the extreme case of no losses, an infinite number of straps are required or a suitable matched load is needed to absorb the power without reflections.

A sufficiently short section terminated on its Z_{it} is a suitable choice because it will lead to a more constant current density distribution while maximizing the number of current straps, with a beneficial effect on the coupling spectrum and at the same time decreasing the power density. The fact that the section is terminated on its own iterative impedance Z_{it} allows the extraction of the uncoupled power from the structure with no reflections at the ends. We have demonstrated in [1] that an efficient way to recirculate this uncoupled and extracted power is the use of the TWA section inside a resonant ring. The ring is composed by: a TWA and, outside the vacuum vessel, a power coupler, an RF power generator, a dummy load and an adjustable length transmission line (line stretcher) all with $Z_0 = Z_{it}$. This last component is used to fulfill the resonance condition $l_{RR} = n2\pi$: the electrical length of the resonant ring has to be an integer number of 2π. This kind of system is used in the test of high power RF and microwave components and can be found, for that exact purpose, also inside the fusion community i.e. the US ITER team [7]. An example of this system is shown in Fig. 2 with the computation of the field in an equivalent (dielectric) load in place of the magnetized plasma [8]. The circulating circuit connected to the TWA is considered ideal and modeled via S-matrices. The TWA in a resonant ring system shows good performances characterized by an operating band in which no power is reflected back to the generator or dumped in the dummy load when the system is tuned by means of the line stretcher. An example of the performances is reported in Figure 25 of [1].

The value of the Z_{it} ranges between 75 and 300 Ω. The use of a tap on the fed straps can bring this impedance down to a value of commercially available components, e.g. 50 Ω, for the recirculating circuit and feeding lines. In the computations done in this paper no impedance transformer (tap) was used; the value of the Z_{it} was taken to be equal to the one at the top of the strap. This is indeed the position where the maximum voltage is achieved. It is then clear that one of the design goals is to find a structure with the lowest possible value of that impedance in order to have the low-

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