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

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

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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 Travelling 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.

Keywords: ICRF, DEMO, Traveling Wave Antenna, Heating, Current Drive.

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 works. 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 take 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 transport 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 strap is beneficial for 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 present some good characteristic like an intrinsic load resilience to plasma load variation. A very similar system, firstly proposed in [3], is now under development for generation of helicons waves for off-axis current drive [4,5]. 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

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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 figure 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.

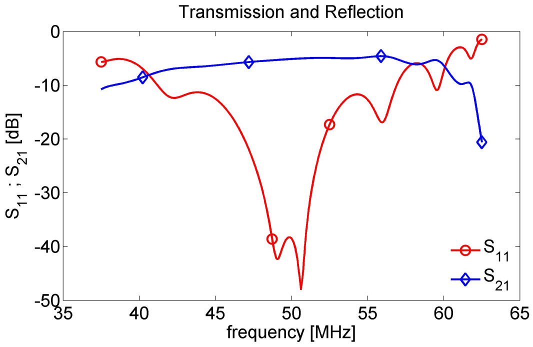

Fig. 1. Transmission (blue-◊) and reflection (red-O) coefficients of a TWA section highlighting the band-pass filter-like response.

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 $Z_0 = Z_{\mathrm{it}}$. 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 $v_{\mathrm{ph}} \ll c_0$. 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 $Z_0 = Z_{\mathrm{it}}$. This last component is used to fulfill the resonance condition $l_{\mathrm{RR}} = n2\pi$: 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 [6]. An example of this system is shown in figure 2 with the computation of the field in an equivalent (dielectric) load in place of the magnetized plasma [7]. 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].

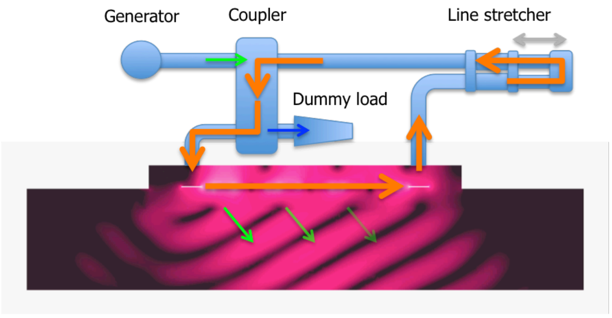

Fig. 2. A TWA resonant ring system with the main component labeled. The structure of the coupled field is visible in front of the antenna aperture. The arrows give an idea of the power flow in the system.

It is worth to be noted that the antenna structure has very low reflection at the input port inside the frequency pass-band and so a very low VSWR is achieved. More important is the fact that the generator is always matched to its load and so is always working at its maximum efficiency. The connection lines from the TWA to the hybrid coupler are matched lines so no problem related to overvoltages or excessive currents due to reflections are expected. This is a common problem of traditional designs where a matching circuit is needed to match the impedance of the antenna to the one of the line and usually also the generator. If the matching unit is not close to the antenna, the connecting unmatched line presents the above-mentioned problem. In a TWA section, the power leaked (or coupled) to the plasma, when ohmic losses are neglected, is equal to the difference between the power that enters the structure via the input port and the power that leaves the structure via the output port as shown in figure 22 of [1]. The generator connected to the hybrid coupler is providing this amount of power.

It is clear that is unlikely to provide all the required power for a DEMO machine, e.g. in the order of 100MW, via one single feeding structure so multiple refueling points are needed. A good way to obtain this subdivision is to use multiple TWA sections each with its own resonant circuit.

2.2 Multi-sections

A series of multiple TWA sections could be allocated inside the blanket of a reactor requiring a small amount of access ports, namely two to four per antenna sections. Those accesses are the transmission lines used to deliver and recirculate the power of the resonant rings. In a present proposal for the European DEMO, the routing of the transmission lines passes through the upper port of the vacuum vessel [8]. The advantages compared to a big equatorial port or line of sight holes in the blanket are evident, especially for neutronics issues. This series of sections could be evenly distributed inside the blanket allowing a large surface, although small compare to the internal blanket one, for the coupling of power but with negligible impact on the Tritium Breeding Ratio [9]. The sections could be contiguous creating a full continuous 360° structure avoiding the left and right terminations of each section. This solution could potentially reduce the impurity production following the interpretation of the experimental results obtained on ASDEX-U [10]. Another possible configuration is to align each module parallel to the total magnetic field B to reduce the contribution of the antenna parallel (w.r.t. B) Electric field component leading to sheath rectification potential as shown by the experimental result obtained on Alcator C-mod [11].

With an evenly distributed series of sections, each in its own recessed box, good isolation between sections is achieved. No major effects were found when a good absorption scheme is applied, by means of bulk losses in the dielectric mimicking the absorption mechanism in real magnetized plasmas, resulting in no substantial reflections from the plasma interface at the other side of the plasma column. Each section could be operated independently in phase and frequency resulting in a very flexible system. If operated at the same frequency, the total power coupled to the plasma is the sum of the power coupled in each section P, namely N*P where N is the number of sections. This result was verified with the coupling code ANTITERII. The isolation between sections was verified by means of a commercial full wave code (CST MWS) computing the S-matrix of a system of different sections and evaluating the cross talk between the adjacent ports. A first example is shown in figure 3 where a system of three sections was considered (see also figure 4 showing the section's arrangement). Like the previous case of a single TWA, each section is terminated on its iterative impedance Z_{it}. In the case of more then one section, this impedance is obtained in a similar way as the one of a single section but now taking into account that the system is a 6-port network instead of a 2-port one. Some care needs to be taken when assembling the impedance matrix for the linear system $[V] = [Z][I]$.

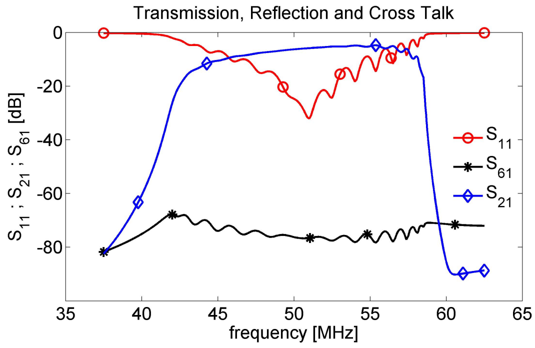

Fig. 3. Transmission (blue-◊) and reflection (red-O) coefficients for a TWA section and cross-talk (black-*) coefficient with respect to a neighbouring section with well isolated sections.

The 6x6 S-Matrix representing the three antennas is computed and representative components are displayed in the picture. The black-* curve is the S_{61} component concerning the amount of power received by the port #6, belonging to the third section, and port #1in the first section. This is the term that quantifies the amount of cross talk between the two sections. The blue-◊ curve it the S_{21} component, namely the transmission coefficient of one section. The isolation effect is clearly visible. A visualization of the field reveals the same result as shown in figure 4 where the isolines of the B- field are displayed when one of the three section is passive while the other two are operated in symmetric mode. A computation of the surface current density on the wall around the antenna aperture reveals a small amount of current on the side of the antenna box with respect to the current on the straps. This first result points towards the potentially low impurities release of the structure as follows from the interpretation of the results found with the ASDEX-U new antennas [10]. If the sections are made contiguous forming an all-around structure with one unique antenna recess, the same analysis as above gives a somewhat different result.

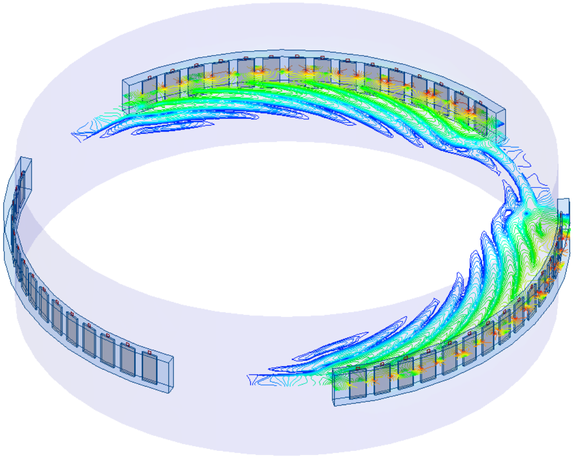

Fig. 4. |B| field isolines of a three sections structure. The isolation between sections is clearly visible in agreement with the results shown in figure 3. The shaded surface is the first wall of the blanket.

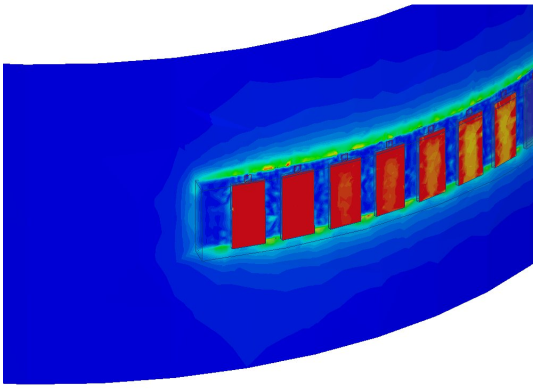

Fig. 5. Magnitude of the current density on the structure around the antenna aperture, that represents the first wall of the machine, and on the straps. The picture is a detailed view of one section of the structure in figure 4. The structure is fed on the left side (feeding line not shown).

In figure 6 the same coefficients of figure 3 are plotted for the new configuration. The S_{61} coefficient (black-* curve) is now far more important. A non-negligible part of the power injected in port #1 is going directly in port #6. In this case, no septa are provided to isolate the two ports and the effect of this coupling between the structures has to be taken into account. The behavior of the structure still remains equivalent to a lossy line as shown in figure by the reflection coefficient (red-O curve). Not surprisingly the transmission coefficient (blue-◊ curve) is lower than the one of isolated structure mainly due to the continuous configuration allowing the power to travel on toroidally continuous structure inserted in the blanket module. While the use of septa, like in the standard design, decreases this coupling it is useful to remind that this system is substantially different because of the use of a resonant ring as a feeding configuration. All those effects have to be studied and verified by means of numerical simulations and test bed measurements before the design of a realistic structure.

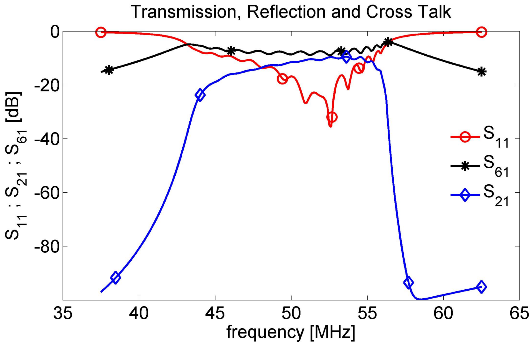

Fig. 6. Transmission (blue-◊) and reflection (red-O) coefficients for a TWA section and cross-talk (black-*) coefficient with respect to a neighbouring section with a continuous all-around structure.

3. Conclusions and discussion

We have shown that a set of evenly distributed Traveling Wave Antennas fed with resonant rings is a good candidate as a low power density ICRH&CD system for fusion devices especially when a low coupling condition is expected, as in a Fusion Reactor. The main advantages of this system are i) the possibility of a large coupling increase due to the use of TWA sections, ii) intrinsic load resilience due to the resonant ring configuration with iii) no complex matching-decoupling circuit, like in traditional design, and with only a line stretcher for tuning the system to the resonant condition; iv) a highly selective *k* spectrum is obtained due to the large number of straps that are phased in the optimal way due to the property of the TWA section. The possible large number of sections will lead to a large amount of input power coupled to the plasma on a large surface resulting in a low power density, that we believe being an essential ingredient for reducing impurity production. With multiple sections appropriately fed allowed inside the blanket, no big ports are needed with beneficial effects on the design of the machine. When moved from individual sections (suitably isolated) to a continuous 360° structure the effect of neigbouring fed strap became very important. A more deep analysis of this effect will be part of a next coming paper. The analysis of single TWA sections and contiguous sections will benefit also from the measurements on new low power test beds that are under construction in our laboratory.

Acknowledgments

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