A TRAVELLING WAVE ARRAY SYSTEM AS SOLUTION FOR THE ICRF HEATING OF DEMO

R. RAGONA*, A. MESSIAEN, J. ONGENA, D. VAN EESTER, M. VAN SCHOOR
Laboratory for Plasma Physics, LPP-ERM/KMS
Brussels, Belgium
Email: Riccardo.Ragona@rma.ac.be

J-M. BERNARD, J. HILLAIRET
CEA, IRFM Cadarache
Saint Paul-lez-Durance, France

J-M. NOTERDAEME*
Max-Plank-Institute fur Plasmaphysik
Garching-bei-Munchen, Germany

M.Q. TRAN
Swiss Plasma Center, EPFL
Lausanne, Switzerland

*Ghent University, Applied Physics Department
Ghent, Belgium

Abstract

Travelling Wave Array (TWA) antennas distributed along the periphery of the tokamak are presently considered as Ion Cyclotron Resonance Frequencies (ICRF) heating solution for the DEMO reactor. Compared to the conventional ICRF antenna systems currently in use or designed for future machines like ITER, the TWA consists of antenna sections integrated in the breeding blanket scattered around the machine, each one fed through a variable coupler in a resonant ring configuration. Previous modelling of an antenna system for DEMO with 16 quadruple TWA sections of 8 straps shows that a power capability exceeding 50MW can be obtained in the frequency band of interest using the reference low coupling plasma profile of ITER. The described system optimizes the coupling to the plasma by providing a large number of radiating elements, which results in enhanced antenna directivity hereby decreasing the antenna power density. This results in a maximum strap voltage amplitude of only 15kV and maximum inter-strap voltage amplitude of 18kV. The generators remain matched for all loading conditions: the system is totally load resilient. Following the recommendation of the WP/C/Review Panel, a TWA ICRH system consisting in fewer sections concentrated in front of the equatorial ports is analysed in this paper and compared to the previous design. Reducing the number of sections increases the power density and its associated voltages. To couple 50MW on the ITER density profile, voltages up to 30kV are now required. Some aspects like the coupling between sections and its repercussion on the feeding network are briefly discussed. To assess the feasibility of the TWA fed by a resonant ring as ICRH system for a DEMO reactor, a test on an existing medium-size tokamak is under study.

1. INTRODUCTION

To heat the core of a large fusion machine Ion Cyclotron Resonant Heating (ICRH) is a logical first choice as it enables coupling auxiliary heating power directly to the ions. In addition, ICRH does not suffer from a cut-off frequency and is thus an ideal method to heat plasmas at very high density, as projected for DEMO. A drawback of ICRH, however, is the difficulty of coupling large amounts of power through the plasma boundary without exceeding the voltage standoff of the antenna(s) located along the wall. This is because most of the RF wave (k_r, k_p) spectrum (z along the toroidal direction, y along the poloidal one) excited by the antenna, located at the wall, is evanescent up to a cut-off plasma density. The latter is an increasing function of |k_r| and |k_p|. For a given plasma profile and ion mix, the antenna coupling can be increased by tailoring the spectrum through the phasing an array of toroidal straps such that to concentrate the excitation near low values of |k_r| and |k_p|. However, the value of |k_r| cannot be too low: it must exceed the vacuum propagation coefficient k_0, to avoid the excitation of so-called coaxial modes, and it must lead to good central power deposition for the chosen heating scheme. The coaxial modes are waves propagating between the wall and the plasma boundary, leading to edge power deposition. For this reason they should be avoided. The peaking of the k_r spectrum around k_r=0 is obtained by straps of sufficient length and with approximately constant current in the poloidal direction. High fields are required for the high power to tunnel through this evanescence layer, for the foreseen reactor parameters. A final request for the ICRH system is to be load resilient in order to continue to deliver the power in presence of fast changes of antenna loading due to ELM’s.

R. RAGONA et al.
Two options are considered for the ICRH system of DEMO:

— An in-port plug-in antenna as the one in its final development for ITER;
— A Traveling Wave Array antenna (TWA).

A large power density and its associated large voltages and currents characterize the first option. It is an adaptation to DEMO of the ICRF in-port system of ITER with its feeding network [1,2]. The ITER system has been optimized in the following way: it is constituted of 8 effective long straps with nearly constant current amplitude. Three short straps fed in parallel by means of a 4-port junction constitute the effective long strap. The frequency response of the 4-port junction is adapted to cover the ITER frequency band (40-555MHz) by a well-positioned service stub [3]. The triplet array is arranged in 4 poloidal columns of triplet pairs. Each poloidal triplet pair is fed by its own power source through a 3dB hybrid to insure load resilience and through matching-decoupling network. Pre-matching stubs are adjusted to decrease the antinode voltage from the output of the plug-in up to the decouplers and the main matching system. The decouplers are used to counteract the power transfer between triplets due to mutual coupling. They are also used to feedback control the antinode voltage amplitude in the lines at the input of the 4 port junctions. Double stub tuners are used as main matching circuits. Vertical Septa are placed between the 4 triplet pairs to decrease mutual coupling and avoid too large constraints to the decoupler network. Special care is taken to have an appropriate RF grounding of the plug-in to the vessel. The toroidal phasing control of the 4 poloidal triplet pairs is obtained by the phasing of the generators. The poloidal phasing in quadrature of each triplet pair is due to the hybrids. The voltage antinode amplitude at the plug-in input of the decoupler-matching network is used to control the antenna current amplitude. An automatic system for the adjustment of the complete matching-decoupling network has been developed and tested at LPP on an ITER mock-up in presence of variable dummy load [4]. It uses 23 simultaneously motorized feedback loops.

To reduce the antenna power density and the associated high voltage in low coupling conditions, TWA antennas distributed around the periphery of the tokamak are presently considered for the DEMO reactor [5]. A TWA section consists of an array of parallel grounded straps, each terminated by a self-integrated tuning reactance. Due to the inter-strap mutual coupling, the TWA array constitutes a passive travelling wave structure interacting with the plasma in front of it. The absence of vertical septa between the straps can substantially increase the coupling of the TWA to the plasma. Those septa are inserted on purpose in the classical ICRH antennas to reduce the inter-strap mutual coupling and the resulting matching problems. The TWA network acts as a band-pass filter between its input and output strap connections, i.e. it can sustain the propagation of a traveling wave in a frequency band determined by its geometry. When operated inside its band, it is equivalent to a lossy transmission line section loaded by the coupling to the plasma and the ohmic losses. The inter-strap phase difference can be adjusted by the choice of the frequency inside its frequency band. If the TWA section is fed in resonant ring configuration, the non-radiated part is recirculated of its input power. This TWA antenna system has the advantage to combine many interesting properties [6-9]:

(a) It optimizes coupling to the plasma. The TWA array coupling scales as the ratio \(n_{\text{eff}}/S_{\text{z}}\) of the total number of straps \(n_{\text{eff}}\) to their inter-distance \(S_{\text{z}}\). The coupling of \(m_{\text{eff}}\) sections of TWA arrays scales as \(m_{\text{eff}}n_{\text{eff}}/S_{\text{z}}\). Furthermore, the radiated power capability per strap, for a given strap voltage, is also larger (e.g. factor 2 for \(k_{\phi}=3\text{m}^{-1}\)) than for a conventional antenna, as e.g. in the ITER design, due to the removal of the vertical septa between the straps.

(b) The generators remain matched for all loading conditions and therefore the system is totally load resilient.

(c) The radiated power \(k_{\phi}\) spectrum is very selective and can be tuned to concentrate the power in that part of the spectrum that allows a sufficiently large tunnelling through the evanescent zone and at the same time good absorption in the core plasma.

(d) At ring resonance, an almost 100% power absorption by the plasma and associated negligible absorption in the loads of the hybrid couplers can be obtained for a broad range of loading resistances and frequencies. The voltage on the elements of the TWA adjusts itself such that all the power provided by the generators is delivered to the plasma and ohmic losses.

(e) The Voltage Standing Wave Ratio (VSWR) remains close to 1 (i.e. there is a negligible amount of power reflected back from the antenna) in all parts of the feeding circuit, in contrast to standard antennas. For the TWA system this aspect ensures a lower line voltage for a given coupled power and leads therefore to a smaller transmission line size or improved reliability.
Previous modelling of an antenna system for DEMO of 16 quadruple TWA sections of 8 straps shows that a power capability exceeding 500MW can be obtained in the frequency band 46-54 MHz for a maximum strap voltage amplitude of only 15kV and a maximum inter-strap voltage amplitude of 18kV using the reference low coupling plasma profile of ITER (hereafter “ITER-2010-low” [10]). Presently the TWA system presented in [6,8] has been successfully tested on a scaled mock-up loaded by a salty water dummy load. To assess its feasibility for a DEMO reactor, a test on an existing tokamak is needed. Indeed, the TWA concept has been only partially tested for fast wave current drive at high harmonic cyclotron frequencies (200MHz) [11] and a convincing test for standard IC minority heating scenarios is still missing. Another experimental verification of some properties of the combline TWA at very high cyclotron harmonic frequency (500MHz) has been reported in [12].

To follow the recommendation of the Review Panel of the WPHCD of PPPT, in this paper the case of an ICRH system made of TWA sections grouped in 4 sectors of the machine is analysed. Each sector is made of 3 or 4 TWA sections. The total power is fixed at 50MW and the required voltage on each strap is computed when the arrays are loaded by the ITER-2010-low profile. A first section describes briefly the target scenario defining the driving frequency for the array’s design. A second section introduces the new configuration and presents the preliminary results for the RF coupling performances. A third section briefly discusses the proof of principle on an MST machine (like WEST). Discussion and conclusions are drawn in the last section.

2. SCENARIO

The target heating scenario for the computation made in this paper is minority heating of $^3$He and second harmonic heating of T ($\omega = \Omega_{3He} = 2\Omega_T$); the key concentrations are $X[^3He]=3\%$, $X[D]=X[T]$. Fig. 1 shows the power absorption fraction, computed with TOMCAT [13], for the different components of the plasma in the activated phase, i.e. in presence of fusion born alpha particles, 10% in total, of which 1% fast. The parameters used are: a major radius of 9m, a minor radius of 3m, a central density of $10^{20}m^{-3}$, a central ion and electron temperature of 28keV and a toroidal number of 50 (that corresponds to a $k_z \approx 4m^{-1}$). The figure shows the presence of a suitable window starting at 40MHz, where the $^3$He and T cyclotron resonance layers enter in the confined plasma from the low magnetic field side (LFS), and ending at 68MHz where the layers exit on the high magnetic field side (HFS). Fusion born alpha particles have a wide Doppler shift and absorb power well away from their cyclotron layer. Fortunately they are not playing a role in the abovementioned band, while they play a key role in the frequency ranges just below and just above the preferred one. Electrons are absorbing a considerable fraction of the power; this is a drawback of the big machine size and is a consequence of the fact that – unlike cyclotron heating – electron Landau damping and transit time magnetic pumping are not localised but only require the thermal velocity of the electrons and the wave phase velocity to be of similar size. An optimal frequency range for heating is then in the band 50MHz to 55MHz, which will be used in what follows. A complete analysis of the possible scenario with all the details will be published soon [14].

![FIG. 1. Power absorption fraction vs frequency for the activated case.](image)
3. TRAVELLING WAVE ARRAY SYSTEM

The design power for the DEMO ICRH system is set to 50MW. It is assumed here to be launched from 4 equatorial ports of the machine. The aim is to evaluate the performance of a TWA system using only the equatorial port for the feeding. Installation and remote handling aspects are not discussed here. The system proposed consists of 12 or 16 TWA sections displaced poloidally in groups of 3 or 4 for each equatorial port, as shown in Fig. 2. The figure depicts an elevation cut in the middle of one port of the vessel for the triplet case (Fig. 2a) and quartet case (Fig. 2c). The cross-section of the central blanket module (blue) shows the poloidal location of the TWA sections. An overall view showing the three external blanket modules, one vacuum vessel sector and the three TWA sections embedded in the blanket modules is presented in Fig. 2b.

Each section is made by an array of 8 straps of the T-type, i.e. grounded centrally by a post. The two ends of each strap are terminated by an integrated capacitor. The dimensions of each array are: strap width of 20cm, strap height of 54cm, strap inter-distance of 30cm, box depth of 21cm and total box length of 2.80m. The aperture of a section measures 1.54m². The power requirement per group/port is 12.5MW. For the triplet, the power per section amounts to 4.17MW with a power density of 2.7MW/m² while for the case of the 4 arrays the power per section is 3.13MW with a power density of 2.03MW/m². The plasma last close magnetic surface (LCMS) is at slightly different distances from the antennas (Fig. 2). For the analysis, the mean value of 23cm is assumed. The RF performances of the two cases are investigated by means of the recently upgraded ANTITER-II code [15]. In absence of an official DEMO plasma density profile that covers also the scrape off layer (SOL), the chosen profile in front of the antenna is the ITER-2010-low. It should be noted that this profile represents a low coupling scenario. The amount of power that can be coupled depends heavily on the density profile; mainly on the antenna/cut-off density distance and on the slope of the profile around that location. Thus the results presented here are valid only for the particular profile used. A different profile could increase the coupled power even by an order of magnitude [16]. The driving frequency is set to 50MHz, as discussed in the previous section. The geometry of the two cases is shown in Fig. 3. The triplet has an inter-distance between the sections of 60cm, larger than the 22cm of the 4 sections case, allowing a better isolation of the feeding networks. The
The maximum poloidal extent is limited by the height of the vessel port. The feeding of each section is made by a resonant ring. The feeding lines, 2 for each section, are routed through the equatorial port. Even using large diameter coaxial transmission lines (30 cm) most of the space of the port is left free and could be used by other systems/diagnostics. The three sections show a fairly good isolation between them. On the contrary, the 4 sections are more coupled together due to their reduced inter-distance. Further analyses are required to characterise the complete feeding network for these two cases. The results reported here correspond to the performances of the antenna only, excluding the effect on the generators.

The voltages required to obtain the power of 4.17MW/section, for the triplet case, and of 3.13MW/section, for the 4 section case, are shown in Fig. 4 along with the inter-strap phasing. The voltage values are higher (factor 2) w.r.t to the previously presented antenna design because the number of sections is drastically reduced. The former design uses 32 sections while the one presented here uses 12 or 16 sections. The injected, radiated and recirculated powers for a single sector are tabulated in Table 1. The maximum voltage in each array is tabulated for convenience (cf Fig. 4). Ohmic losses in the antenna structure and in the feeding lines are not considered here so the radiated power corresponds to the power delivered by the generator. The recirculated power is added to the generator power by means of the resonant ring and injected to the array. The normalised power spectra for the two cases analysed in this paper are presented in Fig. 5. This corresponds to the case where all the arrays are fed in the same direction and with the same phasing. The large directivity in the toroidal direction is due to the large number of straps in each section while the directivity in the poloidal direction results from the interaction of the poloidal sets. Different phasing could be easily investigated.
TABLE 1. POWER CIRCULATION AND MAX VOLTAGE PER SECTOR

<table>
<thead>
<tr>
<th>Section</th>
<th>Power: (MW)</th>
<th>-Injected</th>
<th>-Radiated (Generator)</th>
<th>-Recirculated</th>
<th>Max. Voltage (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>5.56</td>
<td>3.81</td>
<td>4.20</td>
<td>1.36</td>
<td>28.6</td>
</tr>
<tr>
<td>#2</td>
<td>5.76</td>
<td>4.17</td>
<td>4.14</td>
<td>1.62</td>
<td>28.3</td>
</tr>
<tr>
<td>#3</td>
<td>5.78</td>
<td>4.51</td>
<td>4.16</td>
<td>1.62</td>
<td>30.0</td>
</tr>
<tr>
<td>#4</td>
<td>-</td>
<td>4.13</td>
<td>3.18</td>
<td>0.95</td>
<td>24.8</td>
</tr>
</tbody>
</table>

FIG. 5. Normalised (left) poloidal and (right) toroidal power spectra.

4. PROOF OF PRINCIPLE ON MST

A proof of principle of the TWA concept for ICRH on a medium size tokamak (MST) is a needed step in order to be accepted in the conceptual design of DEMO. The TWA concept was presented in the early '90 [7,17] and tested only for FWCD at high frequency [11,12]. More recently, the travelling wave antenna concept has found new interests for application in the helicon current drive frequency domain [18,19] and in lower hybrid frequency range [20]. Despite that, a test for ICRH in a metal wall machine, in steady state operation, has never been done before. Those two conditions are fundamental for a reactor. For this reason, a test on WEST is presently under consideration [21]. It uses the equivalent of a single section of the DEMO proposed system, independently of the configuration (32 or 12/16 sections). WEST is the ideal machine for this task; it is a metal wall machine, is designed for steady state operation, is already equipped with a powerful ICRH system, has dedicated diagnostics and the WEST team has a long experience in ICRH physics, engineering and technology. A test on WEST will allow validating experimentally the performances expected from a TWA in reactor relevant conditions. Moreover, the design and exploitation of such system will allow extrapolating RAMI (reliability, availability, maintainability, inspectability) parameters that are key factors during the design of a fusion reactor like DEMO. A preliminary RAMI analysis is presented in [21] but more complete analysis will be published elsewhere. Fig. 6 presents and artist’s view of the TWA system for WEST. The location inside the machine will allow comparing the TWA with the classical antenna design already installed. Another proposal consists in a set of TWA antennas to be installed in the T-15MD device in construction at the National Research Centre Kurchatov Institute in Moscow [22].
5. DISCUSSION AND OUTLOOK

A system made of 32 T-sections was presented previously with a power capability, when loaded by the ITER 2010 low coupling profile, exceeding 50MW at a maximum strap voltage of 15kV and at a power density of less than 1MW/m². Following the recommendation of the WPHCD Review Panel, a new TWA system that fits into the space of few (here considered 4) equatorial ports is analysed and presented here. This constraint reduces the number of elements from 32 to 12-16 thus increasing the power density and the associated strap voltages. A total power of 50MW with a 4 sector system results in a power per section of 12.5MW. Two cases are considered: 3 and 4 vertically displaced sections. TWA sections could not be placed too close together poloidally without incurring in coupling of the feeding networks that results in the use of decoupling-matching networks, like for the classical designs. To couple 4.17MW, each section of a triplet requires voltages in the order of 30kV which is decreased to about 25kV for the four sections with a unit power of 3.13MW. Further optimisations are possible by changing the geometry of the arrays, e.g. increasing the number of strap and varying their dimensions. It is very important for the reader to keep in mind the high sensitivity of any ICRH system to the plasma density profile. For this reason, the results presented here have to be considered as a worst case scenario. Substantial improvements, i.e. lower voltage for the same amount of coupled power, could be achieved by using a different profile.

Each section, that is an independent antenna box which measure approximately 2-2.5m, could be potentially deployed in the machine from the equatorial port. It could be mechanically connected only to the central blanket module remaining electrically isolated from the neighbouring (blanket) modules. In the equatorial plane, the toroidal extension of a blanket module is of about 1.5-1.8m. Due to the small lateral emboss (only a fraction of the antenna box total length), the box should not suffer from mechanical problem in case of disruption forces. A dedicated analysis to assess the magnitude of those forces is required before proceeding with the RF design validation. Connections to the RF power feeding lines and cooling pipes could be performed from the equatorial port by a dedicated remote handling procedure. Each TWA section is made of the same material as the first wall of the machine so no particular issues are expected for what concern material reliability and activation.

To overcome the increased power density and voltage resulting from the configuration presented in this paper, a different layout for the arrays could be foreseen. Array sections could be placed on top and at bottom of each equatorial port in order not to interfere with any other system that require ports (e.g. EC, NB, diagnostics) thus increasing the number of sections back to 32 (one for each machine sector, i.e. 16 in the DEMO version here considered). Sections will be then slightly more vertically (poloidally) displaced from the equatorial plane. An assessment of the power deposition profiles in the core plasma is in progress. Analogously, 32 sections could be arranged in the equatorial plane in the space between two ports, ideally directly integrated in the blanket. On this particular aspect, a research activity has been started. Having a large number of sections has the advantage of reducing not only the power density but also the required size for the feeding lines. This means a reduced impact on the breeding blanket where those lines have to be routed. In an extreme but still reasonable case, TWA sections of the size of a single blanket module could be designed to be operated at very low power. A fast estimate could be made considering that each sector of the machine is made by 3 blanket modules, for a total of
48 giving a power per module of 1.04MW. Considering two arrays of 1.5m x 0.55m results in a power density of 0.63MW/m². It can be shown that the voltages required by this compact array are in the range of 15kV, when loaded by the ITER-2010-low profile.

In conclusion, TWA arrays are a good option for an ICRH system in DEMO. They allow maximising the power coupling while reducing the high voltages (and relative EM fields) at the antenna aperture, thus reducing the deleterious interaction with the SOL. Different layouts are possible to accommodate the reactor requirements in terms of power capability, integration in the blanket and RAMI scoring. A test on a MST (WEST in particular) is the needed step to assess the TWA design not only in terms of RF properties, but also for the other key factors above mentioned, especially in a RAMI context.

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