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Progress on an Ion Cyclotron Range of Frequency System for DEMO

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An Ion Cyclotron Range of Frequency (ICRF) system can provide power for a number of tasks, experimentally verified on present machines: heating and current drive, first wall conditioning, plasma startup, removing central impurities, controlling sawteeth and current ramp down assist. The system has a high plug-to-power efficiency and most of the components external to the machine are sturdy, with industrial steady state capability.
Traditional ICRF antenna systems are often characterized by a high operating voltage and high power density. Low power density and low voltage however provides a bonus in terms of reliability. Therefore, travelling wave type antennas have been proposed [1]. They can be integrated in the blanket and use only a limited number of feeders. The effect on the tritium breeding ratio of such an antenna incorporated in the blanket, including the feeders, is small. The $k_{//}$ spectrum is peaked and the dominant $k_{//}$ value can be made optimized for coupling and bulk absorption, while avoiding the generation of coaxial modes in the edge. The coupling can be further enhanced with gas puffing near the antenna. Assuming the ITER-2010-low density profile, 50 MW can be coupled with a voltage on the antenna components of about 15 kV.

Keywords: ICRF, DEMO, travelling wave antenna, tritium breeding ratio

1. Introduction

The power density of a number present ICRF antenna is given in Table 1. Note that some of them were achieved in L-mode (TS, ILA), or in limiter configuration (JET). Using the power density assumed for ITER in the worst case (3.3 MW/m^2), about 15 m^2 would be needed to couple 50 MW in DEMO. This would lead to a typical reduction in the Tritium Breeding Ratio of 3.8 %. There is thus a definite need for antenna types that are not localized in ports. Travelling wave array (TWA) type antennas combine low power density and load resilience with a reduced number of feeders. They can be designed as part of the blanket, thereby avoiding the use of ports.

Table 1. Power density of a number of ICRF antennas

Experiment	number antenna	antenna surface [m^2]	Power [MW]	Power density [MW/m^2]
AUG	4	0.8	7.2	2.25
TS	3		13.2	15
JET	4	3.6	22	~1.5
JET ILA	1			6.2
ITER	1	~3	10	~3.3

2. TWA concept

2.1 Principle

A Traveling wave antenna [1,2] is an array of mutually coupled resonant straps connected in parallel, and where the power is fed at the first and last strap of the array. This becomes an array of resonators where the current on each of the intermediate straps is induced by mutual coupling (mostly inductive for the ion cyclotron frequency range). The current is decaying along the strap array due to power being coupled to the plasma. A circuit of such an array is shown in Fig.1 where a resistor is added in series to each strap to simulate the radiation resistance. This resistor is not used for the computation of the impedance matrix describing the array using ANTITER-II with a realistic plasm density profile in front of the antenna [3,4].

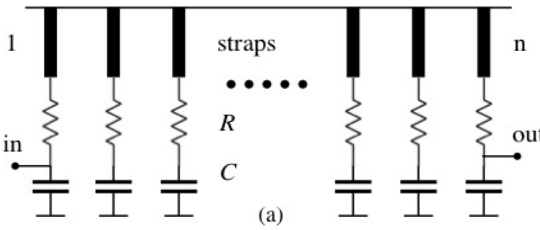

Fig. 1. Finite array of straps. Simplified model.

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2.2 Feeding schemes

Different feedings schemes are possible for the TWA.

2.2.1. Full ring with distributed feeding

In this case, input feeding lines are connected to a continuous array. The concept is shown in figure 2, and resulting spectra in figure 3.

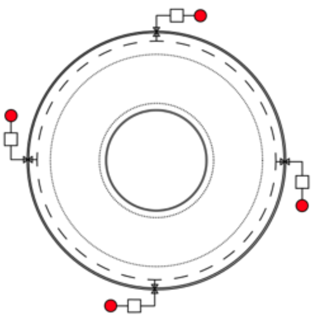

Fig. 2. Example of a ring with 28 straps and distributed feeding at 4 locations.

The concept has the advantage of the largest symmetry and of the smallest number of feeders. It however only works if the symmetry is fully maintained, with all straps and all generators working. This could lead to a reduction of the reliability of the overall system.

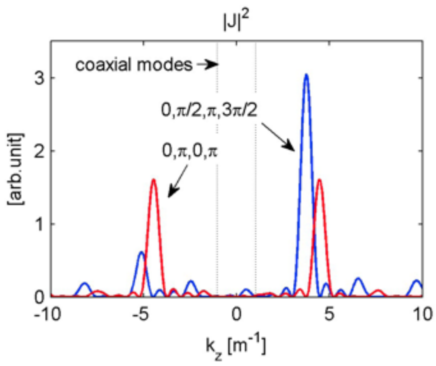

Fig. 3. Spectra for two phase differences between generators.

The system is not load resilient. A variation of the plasma loading on the antenna, or a failure of one generator, will lead to a change in the input impedance of the neighboring generators causing an important power imbalance. The result is that both neighboring generators are mismatched and receive a large amount of reflected power leading to the activation of the safety protection and a tripping the RF generators.

2.2.2. Ring with external resonant feeders

An alternative option is to use a number of independent TWA sections, as shown in Fig.4 (with four TWA sections). The resulting spectrum is shown in Fig. 5. The sections do not have to be contiguous and can be located in any poloidal position, e.g. on the top or bottom of the ports to avoid obstructing other systems. This allows a greater flexibility than a contiguous ring.

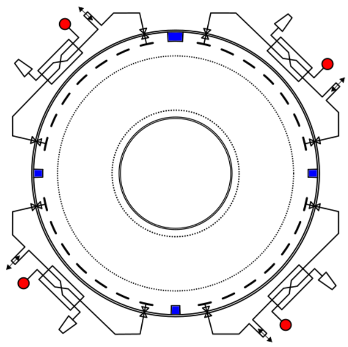

Fig. 4. Example of 4 TWA sections fed by 4 independent resonant rings.

The failure of one TWA section will not lead to a failure of the whole IC system but rather to a small reduction of the radiated power. Moreover, each TWA section should be designed with a safety margin with respect to its power and voltage capability. A majority of the components of the antenna system are located in areas where maintenance does not pose a problem (i.e. outside the cryostat, see Fig.6).

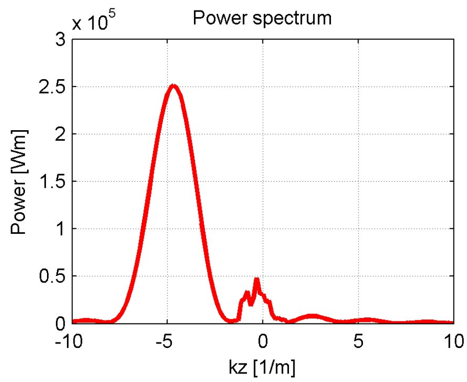

Fig. 5. Indicative spectrum for one of the sections in figure 4.

2.3. Resonant ring feeding scheme

The main advantage of using. separate TWA sections (as in 2.2.2) with a resonant ring feeding is that it allows to recirculate the RF power leaving the TWA array [3]. In this way, if one neglects ohmic losses in the antenna system, all the generator power can be deposited to the plasma. The antenna system [2, 3] then consists of: one TWA array, two line stretchers and two hybrids (See Fig. 6). The TWA is the only component inside the vacuum vessel. This increases the RAMI score considerably. All the transmission lines are matched so they can be safely operated without overvoltage and overcurrent, typical in unmatched lines. Ohmic losses are thus minimized.

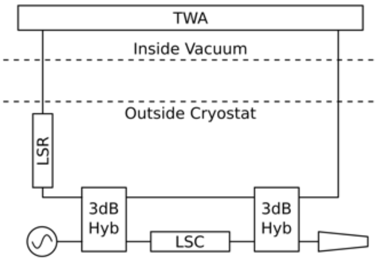

Fig. 6. Traveling wave array antenna fed by a resonant ring.

2.4. Application to DEMO

A system made of 16 contiguous TWA sectors is proposed, as schematically shown in the artist's view of Fig.7. Each sector is made of two superposed TWA arrays, each containing 8 straps. A detailed view of one TWA array is given in Fig.8.

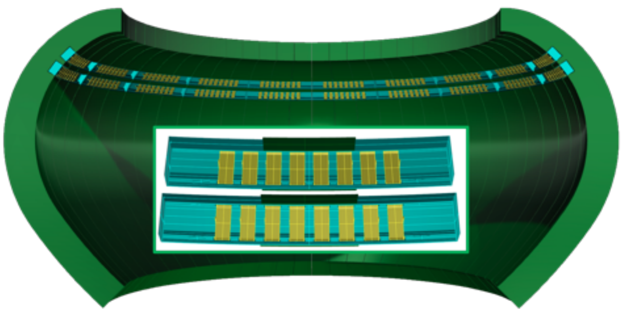

Fig. 7. Artist's view of the 16 sectors double 8 strap T array embedded in the blanket and proposed as a possible ICRF system for DEMO. Half of the machine is shown while in the inset a detailed view of the two TWA sections is presented.

A summary of the performance of the system is given in Table 2 where the coupled power, the maximum voltage on the straps and the power density per section are listed for different edge density plasma profiles. In the absence of a DEMO reference density profile, we have used the ITER-2010-low density profile (see Fig.9), which represents a "low coupling" profile. For this reason, the profile is moved forward and backward w.r.t. its reference position in order to show the different performances that depend heavily on the antenna-cutoff distance, and thus on the details of the profile.

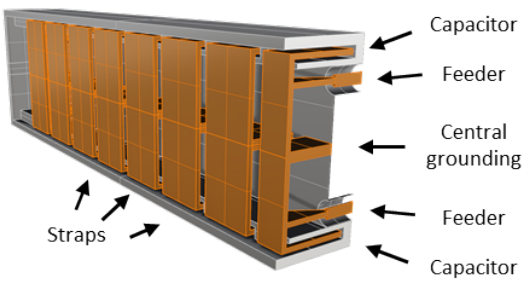

Fig. 8. One T-type TWA array section consisting of 8 (double) straps. Only the first and last strap are connected to feeders (top and bottom).

The requested power for DEMO (50 MW) could be obtained with a maximum voltage of 15 kV on the antenna structures at a power density of less than 1 MW/m^2. As expected, the profile plays a fundamental role in the calculation of the deposited power to the plasma. When displaced by -4 cm the power coupled exceeds 70 MW and decreases to 40 MW when displaced by +4 cm.

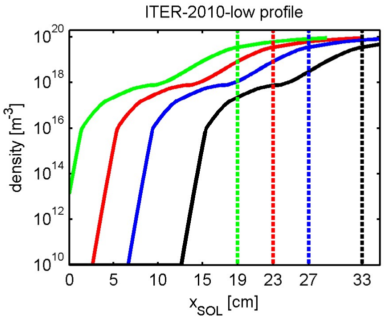

Fig. 9. Different plasma profiles used in the computation. The reference one (red) is the ITER 2010-low profile characterized by a distance between the antenna aperture and last closed magnetic surface of 23 cm. The other profiles are shifted by -4 cm (green), +4 cm (blue) and +10 cm (black).

3. Integration in the blanket

3.1. Blanket

Integrating the TWA antenna system in the most recent design for the Helium Cooled Pebble Bed (HCPB) blanket (consisting of radial breeding pins [5]) shows that using the He from the blanket as coolant, the maximum temperatures in the TWA antenna structure are well below 550^0C, which is the maximum allowed for EUROFER. The helium outlet temperature and pressure drop in the antenna cooling circuit are consistent with the BoP requirements of the blanket. Furthermore, cooling of the feeders inside the blanket and upper port area using He from the blanket. combined with radiative cooling of the feeders substantially simplifies the cooling concept and is compatible with remote handling of the blanket segments (See section 3.3). Figures 10a-d show the integration scenario proposed of an antenna in the blanket.

Table 2. Performance of the 16 double T arrays for different displacements in the edge density profile. The reference profile corresponds to distance from an antenna to the last closed magnetic surface of 23 cm (see figure 9).

Profile	Power (MW)	Voltage (kV)	Power density (MW/m^2)
-4 cm	72.2	15	1.16
Ref	59.5	15	0.930
+4 cm	40.6	15	0.635
+10 cm	27.4	15	0.428

3.2. Calculation of the Tritium Breeding Ratio

We used the most up to date Helium Cooled Pebble Bed (HCPB) blanket design [5] as a reference blanket for the analysis. To assess the TBR reduction we used a simplified blanket model with the interior blanket structure completely homogenized. The reference TBR without antenna and feeders is 1.2. With antenna and feeders, the TBR decreases to 1.18. The TBR reduction due to the presence of antenna and feeders in DEMO, assuming 360° coverage, is thus ~2% [6]. This small effect can be qualitatively understood. The antenna inserted at the front of the blanket leads to a reduction of the breeder volume (but the TB that is lost is an equivalent depth at the back of the blanket where the TB is already low anyway) and the TB loss is partly compensated by an increased tritium production in the less shielded breeder zone behind the antenna. The effect of the feeders is small because of their small numbers. The results are consistent with previous calculations where only the effect of the antenna was assessed [7].

3.3. Impact on remote handling

Electrical RF continuity is needed in the back plane of the antenna for the continuity of the RF currents. A continuous back plane leads to concerns in terms of grounding and forces due to induced currents. In addition, it raises questions on how to satisfy the requirements (i) for separate blanket segments (which are handled individually through the top ports of the machine) and (ii) a continuous back plane covering several segments. The continuity of the RF currents between separate breeding blanket segments could be realized using capacitive elements, but this solution still needs to be investigated.

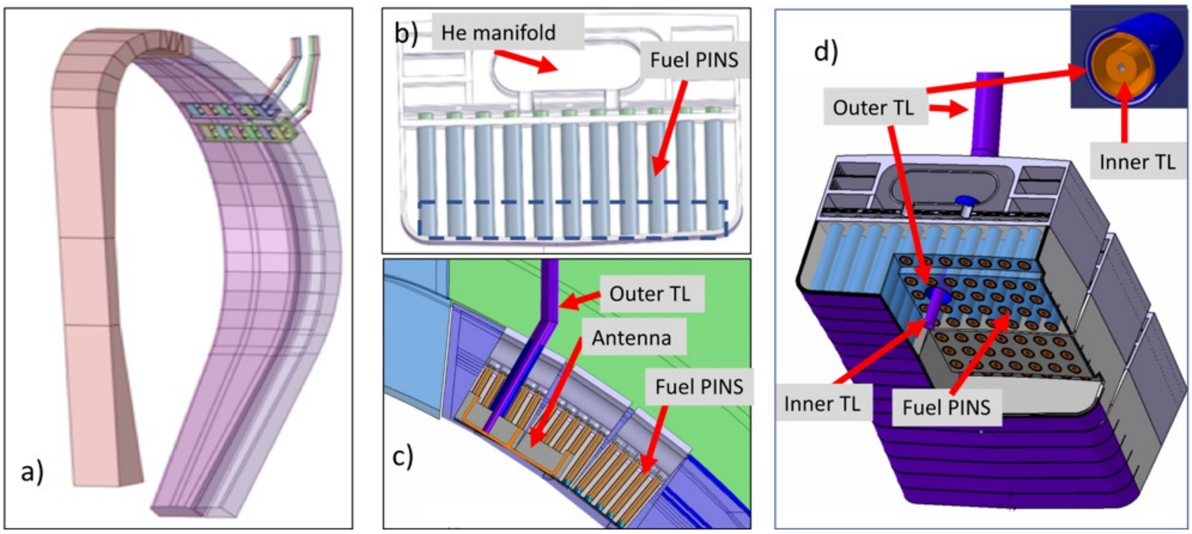

Fig. 10. a) one sector of DEMO (1/32 = 11.25°) with two antenna arrays (depth 339 mm and 1100 mm poloidal extend) and 4 transmission lines of 100 mm diameter each, as used for the MCNP calculations; b) radial cut through a breeding blanket, showing the fuel pins and the He cooling manifold, at the front is shown in dashed line the location of the antenna; c) poloidal cut through a breeding blanket segment, showing the fuel pins, and one T- type antenna array with a single TL feeder; d) 3-D detailed view of a blanket segment with the fuel pins and the He cooling manifold. It also shows how a TL essentially replaces one fuel pin (antenna not shown).

Because of remote handling, routing the transmission lines through the upper ports would be preferable and is possible both for a TWA antenna located in the upper part of the first wall of DEMO (see figures 10a-d) or near the equatorial plane (which maybe preferred if the emphasis is on heating) On the outside the TL could be connected using flanges, such that there is no need for rewelding and cutting.

4. Summary and concluding remarks

A TWA with an external resonant feeding scheme is a good candidate for an ICRF system on DEMO. A test on a medium size tokamak is however needed to provide a proof of the concept and is being envisaged [8].

Further alternative concepts, such as an ITER-like, in-port antenna are being considered in parallel They could have the advantage of a reduced need for integration, but would need to operate at higher power densities and voltages.

Acknowledgments

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