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Abstract The Ion cyclotron range of frequency (ICRF) is a versatile system and is capable of making contribution to different phases of the plasma during operation. Because of its low cost, high plug to power efficiency and, in a number of areas, proven technology, ICRF is currently one of the auxiliary heating systems well suited for a reactor and considered as one of the heating methods for DEMO. In a machine like DEMO where relatively large RF power needs to be coupled to the plasma, current ICRF system would need to couple large power over a limited surface, with elevated power densities, a condition not acceptable in DEMO. A novel design of an ICRF antenna that utilizes a low power density launching surface is introduced. The requirements for such structure in a DEMO environment and the engineering boundary conditions that are imposed by the machine on the structure are described. The most critical parameters required for integrating such a structure in DEMO are described.

1. Introduction

An ICRF heating can be utilized in different phases of the plasma, e.g. plasma start-up, current ramp-up, and direct or indirect ion heating. ICRF power can be used for various scenarios in a future DEMO machine; heating and current drive (H&CD). The ICRF system is an already established method in several fusion facilities, and will be used in ITER [4].

A typical ICRF antenna in its present configuration is shown in figure 1 and consists of few (or many, e.g. 4 x 6 for ITER antenna) poloidal current straps, integrated in a port of limited size in the vacuum vessel (VV) or within an antenna frame, inside the machine. Such configuration carries with it a number of drawbacks: (i) reduced coupling due to the evanescence of ICRF waves in the low density edge of plasma, (ii) possible high Z impurity release due to generation of larger sheath potentials (due to accelerated ions in the vicinity of the antenna as a result of those potentials, producing surface sputtering), and (iii) as a result of (i), high strap voltage and currents (with large radiated power density) needed to couple the power, with the possibility of voltage arcs or breakdown, making exploitation of ICRF system challenging for DEMO. Furthermore in DEMO, there is a strong incentive to reduce as much as possible the number of ports for the antennas (since openings reduce the tritium breeding ratio (TBR)) and thus a heating systems which will require the smallest impact on TBR will be favoured for the T self-sufficiency of DEMO. This again means at first sight a reduction of allocated ports using high power density systems. However an alternative is to integrate the heating system into the machine and in particular in the blanket. To realize this, a novel distributed antenna is currently under development [2a, b, c] and [8, 9, 10] constituted of poloidal strip lines (antenna straps) around the torus, covering toroidally 360° of the wall, as shown in figure 2. They will be integrated in a slot in the first wall (FW) of the vacuum vessel, as shown in figures 2. a,b. Such an antenna optimizes the coupling to the plasma because: (i) for a given inter-distance between the straps, the array coupling scales proportionally to the total strap number: this allows the coupling of large amount of power with affordable voltage and current constraints [8, 9], (ii) the absence of vertical septa between the straps leads to a significant increase of coupling with respect to a conventional antenna, where the septa are inserted to reduce mutual coupling effects and (iii) the radiated power spectrum can be very selective in the best $k_{//}$ for coupling and heating [8, 9]. Furthermore, such antenna potentially avoids, to a large extend, with its 360^0 symmetry, the occurrence of induced currents at non-intended location, which would lead to RF electrical fields, sheaths and additional impurity production.

DEMO, needs to be self-sufficient in Tritium, and this imposes stringent challenges on the new system designs not faced by its predecessors (e.g. ITER). The novel ICRF antenna will be integrated in the breeding blanket (BB) and will thus have to fulfil corresponding boundary conditions: not impair its functions of neutron shielding and tritium breeding, have the same power handling capabilities during operation as the blanket FW, be able to match the blanket modularity and be fully compatible with the remote handling (RH) procedure for the blanket.

The following sections highlight the basic configuration of the novel ICRF antenna as well as the major engineering constraints imposed on the concept by DEMO. The present status is highlighted and concluded with a future outlook.

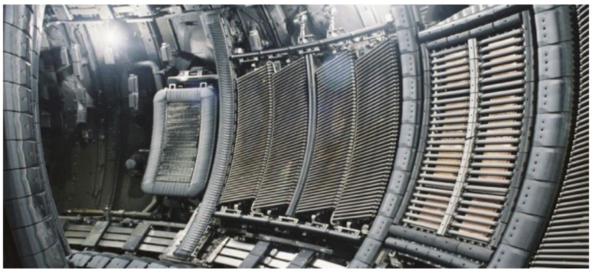


***Fig.**1. Example of present ICRF antenna configuration as seen on JET. On the right, the ILA, a high power density antenna, situated in a port of limited size toroidally and poloidally. In the middle, the A2 antenna, in a frame inside the vessel. On the right is a LH antenna, not discussed here (adapted from [11])*

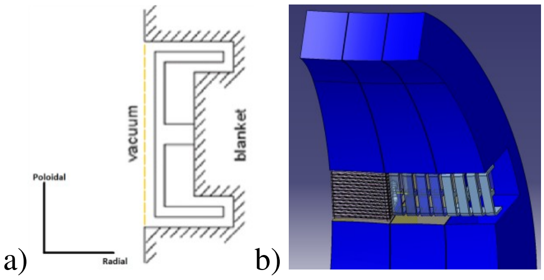


Fig.2. Middle and right: radial build of ICRF antenna in one blanket sector (dotted yellow line is the FS) and a view of one blanket sector with antenna inside (FS is shown in front of the left segment for illustration but covers all the structures)

2. Novel antenna configuration

The concept will consist of identical straps in a 360° toroidal array of limited poloidal extend. They are integrated in the blanket, covered by the FW, which will be slotted in the toroidal direction and acts as a Faraday shield (FS). Straps will be placed inside a recess as presented in Fig. 2.a. The dimensions of the recess and of straps are yet to be optimized, but typical presently assumed values are 100 cm in poloidal extend and 20 cm radially behind the FW. Inside the recess, there will be an array of ~20 cm wide (toroidal direction) straps separated by ~3-4 cm each. The thickness of the antenna strap will be ~2 cm. The antenna is thus not filling all the space in the slot. For neutronics calculations a composition of antenna 10% + vacuum 90% is considered to be a good first assumption (the antenna is then considered as a mix of different layers of materials the straps may be made from, and any coolant material that may be used inside) [3]. Figure 2a shows a radial build with a single strap integrated in the BB, and figure 2b. shows part of a distributed antenna in one outboard breeding blanket sector. The FS is the slotted FW located between the straps and plasma (shown covering the left blanket segment in figure 2b). The poloidal positon of the antenna will be between the vertical and equatorial ports. Its position will be influenced by a trade-off between physics functionality and engineering as well as integration constraints.

3. Antenna feeding

One feeding concept, discussed here, avoids the necessity to feed and match each strap separately. Feeding is periodically done on sections of the array, with each BB sector fed with a number of transmission lines (TLs) in resonant ring configuration (figure 3) [8, 9, 10]. This system has many advantages: (i) only the first and last straps of each array section are connected to an external line, (ii) the generators remain essentially matched for all loading conditions and is therefore mostly load resilient.

The actual feeding scheme, with the location of and number of feed lines to the straps to be fed per blanket sector is still under assessment. Possible approaches could be that for one blanket sector (i) two straps of the central outboard blanket segment (COBS), cf. figure 3.a, or (ii) the outermost straps in the left outboard blanket segment (LOBS) and right outboard blanket segment (ROBS) are fed as shown in figure 3.b. The number of straps in each BB sector must be chosen such as to avoid a too large strap current decay between the first and last strap of each section. The lines will have to be routed through each vertical port down to the blanket segments where the straps are located. Two lines could be interfaced with each active strap, though one line may suffice as well [5]. The materials of the feeding lines in the BB are likely the same as the BB structural material with a thin conducting layer (likely Cu). The material of the TL's can be chosen to take into account the high temperature and the neutron irradiation [12]. For the antenna, materials used for straps will have to be similar to the blanket FW and BB structural material itself [3], since this, among others, will then have the same effect as the FW itself, in terms of the reaction cross section with the plasma neutrons. Exact material composition will be decided based on integration and optimization studies. Electrical connections of the straps and how they are expected to interface with the TLs are respectively shown in figure 4. Vacuum feedthroughs (i.e. ceramic windows) will separate the pressurized lines segments from those inside the VV (which are evacuated). They can be installed behind dog-leg structures and neutron shields. Another problem is the insulating material in the coaxial transmission lines, which position the inner conductor inside the outer conductor. They are made from ceramics. The choice of material type for the electrically insulating component and its location along the TLs will be a trade-off between avoiding long lines under vacuum and loss of performance under the high neutron environment found in DEMO [12].

Except for the antenna, the components needed for the ICRF system in DEMO are already well-known from present day tokamaks with ICRF systems (e.g. power supplies, generators, TLs, etc.). The power sources, their auxiliaries and ex-vessel TL routing will be investigated at a later stage when the in-vessel components of the system are defined with more details. The novel antenna design will ultimately require a proof of principle in a relevant machine, to be investigated at a later stage.

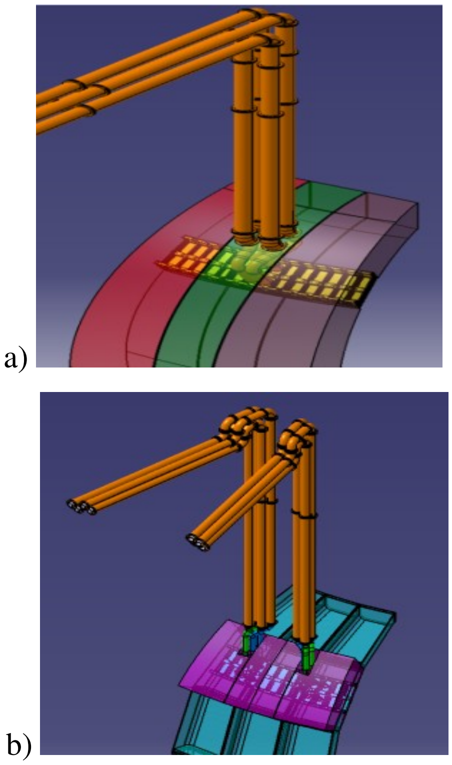
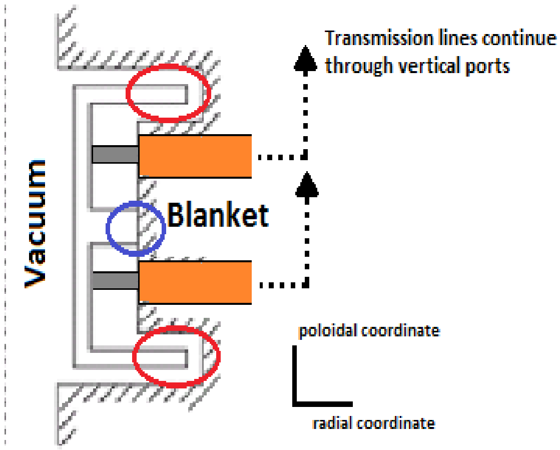


***Fig.** 3a COBS feeding and 3b. ROBS and LOBS feeding*



* Two (or one) lines feed/active strap

* Red circles: capacitor configuration (strap-blanket)

* Blue circle: short circuit contact

***Fig.4.** Radial build showing an active (i.e. fed with power directly via TLs) antenna strap, with associated components and electrical connections. Faraday screen not shown.*

4. Constraints imposed by DEMO

An ICRF antenna in the blanket is a tightly integrated component in DEMO. Strict constraints are imposed by the machine on the antenna. They will have to be taken into account in the design and integration process in DEMO. The following sections describe the most important constraints.

4.1 Breeding Blanket constraints

The hosting BB is one of the most critical technological components of DEMO. It has a vital role for tritium breeding but also acts as a shielding component, protecting the poloidal and toroidal field magnet coils from heat and neutron flux coming from the plasma side. with the antenna integrated in the blanket, the ICRF antenna must further guarantee to [2a]:

1) Maintain the BB functions of tritium breeding and neutron shielding.

2) Be as reliable as the BB itself

3) Minimize the complexity, e.g. by sharing the cooling with BB

4) Be compatible with RH procedure for BB modules

The following sections discuss the major boundary conditions imposed by the BB on the antenna.

4.1.1 Size constraints

The antenna straps are ultimately limited in size by the modules of BB itself. This is particularly pronounced in the poloidal direction, the direction of the major extension of the straps. The current baseline design of the antenna assumes the straps are 1 meter in length poloidally. The current BB segmentation of DEMO is depicted in figure 5. The antenna is foreseen to occupy a poloidal position above the equatorial and below the vertical ports at 40^0 poloidally [6] (taking the equatorial port plane as the 0^0 reference), and thus will likely lie inside OB3 in figure 5. The present dimensions of this BB unit are 2.01m (poloidally) by 1.39m (toroidally) [1], leaving ample space for the straps based on their current dimensions. Any future optimization of the straps dimensions, especially poloidally will have to take the dimensional limitations of the BB modules into account.

4.1.2 First wall loads

One requirement for the antenna that it should be as reliable as the BB itself. This means, among others, an ICRF structure that is capable of handling the intense heat and neutron loads in DEMO. Other loads exist, including i.e. heat coming from the BB units themselves during breeding reactions and the radiated ICRF power itself (low in comparison with plasma side loads [5]) or forces and EM loads from plasma movements and disruptions. The heat and neutron loads from the plasma are given the main focus here, since they are the primary loads the ICRF antenna is expected to handle.

Some quantitative figures as input for the antenna design already exist [1]. The ICRF antenna will be heavily bombarded by the energetic 14.1 MeV fusion neutrons and part of their energy will be deposited in the antenna structure in the form of volumetric heating. A volumetric neutron heating of 0.5MW/ m^2 , and an additional surface heat flux of 500 kW/ m^2 are adequately assumed for initial antenna design activities. Peak steady state wall heat flux depends on optical transparency of the FS, the straps shape and also plasma physics conditions such as fraction of radiated power, power-fall-off length, etc. Adequate cooling schemes have to deal with both the neutron and heat loads on the antenna.

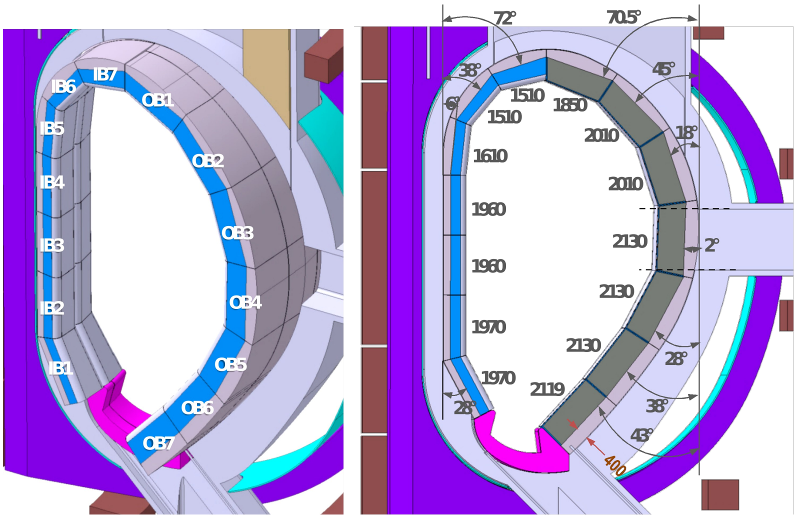


Fig. 5. One blanket sector of DEMO with 3 OB and 2 IB blanket BB segments for HCPB blanket concept with poloidal dimensions [1]

4.1.3 Cooling circuit

The previous section focused on the loads expected on the antenna structure coming from the plasma side which needs to be handled using suitable cooling. One of the requirements on the antenna one is that it should not increase the complexity of the machine. This points to the need of sharing the cooling circuit for antenna with that of the BB. Several blanket options are currently being assessed in the framework of EU DEMO activities: the helium cooled pebble bed (HCPB), helium cooled lithium lead (HCLL), water cooled lithium lead (WCLL) and the dual cooled lithium lead (DCLL). For the purpose of simplicity and to focus the scope of initial design and integration activities, emphasis is given here on one BB concept, the helium cooled pebble bed (HCPB), motivated by the cooling scheme it foresees for the FW. Indeed, since the HCPB concept has its FW cooled using horizontal cooling channels, transforming this into a FS by introducing slits parallel to the cooling channels, causes the smallest disturbance with respect to the initial cooling scheme. Solutions for integrating the cooling circuit with the straps remain to be defined. The important factor here will be the operating temperature window: since straps are foreseen to be made from the same materials as the FW itself, a temperature window between $300-500C^0$ defines the lower and upper operational limits. The following is a description of the cooling scheme for a HCPB BB concept, with the characteristics of coolant highlighted.

Table. 1. Helium coolant characteristics of a HCPB blanket concept

Inlet pressure, p_i	8 MPa
Pressure drop	0.08 MPa
Inlet temperature , T_i	300 ^{0}C
Outlet temperature , T_o	500 ^{0}C
Inlet density, ρ_i	6.65 kg/m^3
Inlet velocity, u_i	77 m/s

4.1.4 Tritium breeding ratio (TBR)

The loss of TBR was assessed for a reference antenna [6], including a number of parametric variations, using MCNP (Monte Carlo N-Particle code for neutron transport calculations). The loss of TBR for the antenna stays in all cases below about 0.006. To put this in perspective, the total surface area of $70\,m^2$ of the ICRF antenna straps produce loss of TBR of the same order than a port of $1.4\,m^2$ in size in the vacuum vessel, this is a factor of 50 less in area. This however did not yet take TLs feeding straps into account; a refined TBR calculation will be done after more proper definition of feeding lines becomes available. Cooling the straps in parallel will be preferred. Ongoing integration studies will concentrate on a design based on such a configuration for the cooling.

4.1.5 Structural integrity

The straps will be electrically and physically connected to the BB modules, through a middle connection (the central strap short circuit- see Fig.2a), which also acts as access for the cooling and as structural support. Active straps (i.e. ones which are fed with RF power) will additionally have connections with the TLs in addition to this central short circuit. The central short circuit will act as the inlet-outlet for the coolant circuit coming from the BB. It also needs to provide support for the straps. The structural integrity of the straps will have to be assessed and possibly optimized under all scenarios, steady state and transient (e.g. disruptions and vertical displacement events (VDE's)). It is of prime importance therefore to ensure an adequate design that takes the structural integrity of the straps in addition to their cooling needs into account. This is an ongoing activity.

4.2 Remote handling constraints

Among the requirements that a DEMO ICRF antenna must fulfil is to be fully compatible with RH procedures of its host, the BB units. Currently envisaged scheme for RH of BB modules is through the vertical ports [7], elaborated in figure 6a,b. The BB units are aligned poloidally in segments. In a given blanket sector, 3 OB and 2 IB BB segments are found. Each segment will be handled from the vertical port separately from the others. This means that there should no physical connection between the segments or between the straps which would prevent them from being handled separately by RH equipment.

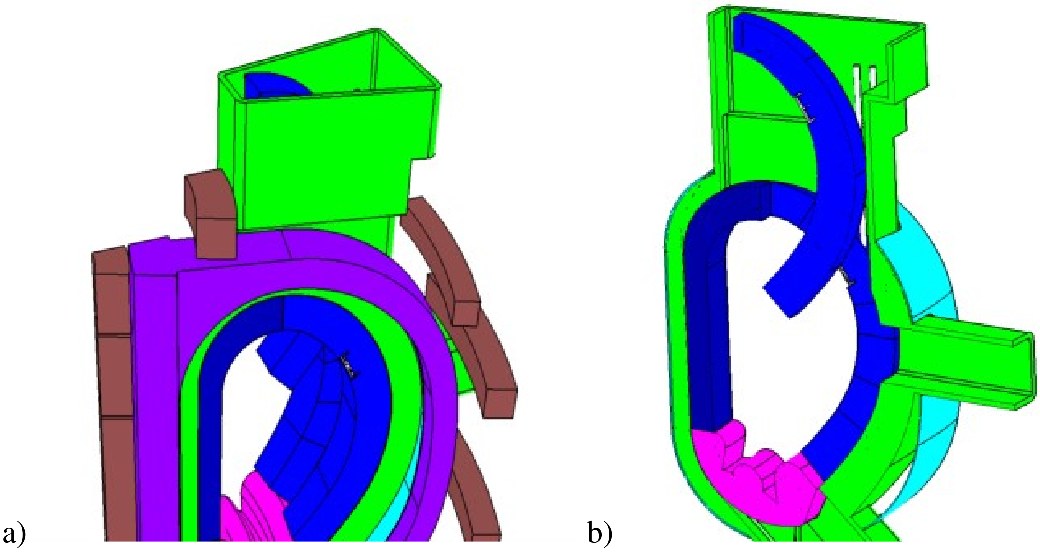


Fig.6. Remote handling of blanket segments is done through vertical ports. Each segment is handled separately from the others.

5. Summary and future outlook

This paper summarized the efforts and progress so far in the WPHCD for the ICRF in DEMO, with particular focus on a novel antenna concept that offers improved coupling while mitigating problems such as high power density surfaces. It emphasizes the engineering challenges and integration tasks which must pass to be considered for a future implementation in DEMO. The current status was highlighted, and necessary actions for further progress were explained. The ICRF system in DEMO is a tightly integrated structure that needs considerable design, integration and optimization efforts. Any such foreseen structure in DEMO must be compliant with the constraints imposed by DEMO, in particular by the hosting BB and its RH procedures. An adequate cooling scheme using the same circuit as that of BB must be integrated and the antenna must operate at the same level of safety and reliability as the BB FW itself. The effect of TBR and neutron shielding must be assessed in detail. Initial studies that included only the antenna straps were performed to calculate the TBR, with encouraging results. Further calculations are needed to take the feeding of antenna into account. Any ICRF antenna integrated in the VV must be compatible with the RH procedures of DEMO breeding blanket. And finally, a proof of principle on a relevant machine will be needed.

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