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Low power density ion cyclotron arrays for fusion reactors

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HIGHLIGHTS

- A low power density, high directivity, FW heating and current drive launching structure is proposed for use in a commercial fusion reactor.
- The structure, integrated in the reactor blanket first wall, is modular, unobtrusive and imposes no specific constraints to the blanket functions.
- It may significantly reduce the undesirable effects of FW evanescence in the plasma scrape off layer such as increased thermal wall loading, localized hot spots, impurity production, and enhanced $E \times \mathbf{B_0}$ particles convection.

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ABSTRACT

Ion Cyclotron Radio Frequency (ICRF) Heating and Current Drive (H&CD) is a well established technique of auxiliary heating in present tokamaks, as it features high on-axis heating and current drive efficiencies associated with proven and low cost technology. An important limiting factor to the use of ICRF as candidate heating method in a commercial reactor is linked to the evanescence of the fast wave in vacuum and in most of the SOL layer, imposing proximity of the launching structure to the plasma boundary and causing high RF standing and DC rectified voltages at the plasma periphery, possible voltage breakdowns and enhanced local wall loading. Further to previous work (Bosia et al., Ion Cyclotron and Lower Hybrid Arrays applicable to Current Drive in Fusion Reactors, in: AIP Proc. of 20th Topical Conf on RF Power in plasmas No. 1580, 2013, 215) developing new concepts for Ion Cyclotron and Lower Hybrid Heating & Current Drive arrays, based on the use of periodic structures, a practical example for an in-blanket IC array for DEMO1 is presented in this study.

1. Introduction

The launching structures used to heat and/or to drive current in thermonuclear plasmas in the Ion Cyclotron (IC) range of frequency are usually arrays of few, short ($l_s \ll \lambda$) sections of poloidal strip lines ("current straps"), connected at one end to ground potential and fed at the other end by a radio frequency (RF) power source via a coax line ("feeder"), and through an impedance matching network.

The IC fast wave is evanescent in vacuum and in most of the scrape-off layer. Most of the radiated power is reflected back to the launching structure, generating high RF Electric (E-) fields at the plasma/array boundary, even at moderate power density. In some systems, the input power is divided among two (or more) straps with in-parallel connections to reduce the power density and lower the E-field. This method is impractical for poloidal/toroidal high multiplicity arrays required to apply large amounts of RF power to reactor grade tokamaks, as it requires the use of one or more main ports to house the power division network [2]. Therefore, as all other auxiliary heating candidates, the dimension of the port(s) sets a lower limit to the RF radiated power density (in ITER ≈ 10 MW/m^2, with E-fields limited by design below 2 MV/m if parallel to $\mathbf{B_0}$ and 3 MV/m if perpendicular).

At this power density level, IC in-vessel components operate quite close to the voltage breakdown limit and RF arcs are frequent. Active arc detection (usually performed by monitoring some effect of an abrupt variation of the reflection coefficient at some point of the transmission system) and forced arc extinction (by temporary total suppression of the input power) are a must to prevent severe damages to the launching structures. In addition, the process of RF sheaths formation, due to a non linear rectification of the RF potential $V = \int E \,\|\, dl$ at the ends of $\mathbf{B_0}$ magnetic flux tubes, generates an E-field DC component (sheath) in the peripheral plasma, accelerating ions towards the first wall and producing undesirable effects such as an increased thermal wall loading, localized hot spots, impurity production, and enhanced $E \times \mathbf{B_0}$ particles convection.

These drawbacks appear to be an important limiting factor to the use of ICRF as candidate heating method in a commercial reactor.

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In this paper the new concept of a *ring array launcher* integrated in the reactor blanket [1] and using a periodic structure of coupled elements for RF power division is applied to DEMO1 geometry. In the paper, a comb-line structure is analyzed as an example, although other types of periodic structures could be suitable and/or more convenient. The simple and modular structure of the periodic structure allows an easy integration in significantly wider, unused surfaces of the blanket first wall, and therefore an operation at a RF E-field low enough to make the overall effects of the wave evanescence negligible.

The purpose of this paper is to present a concept to be developed in a more detailed design. As such, it is intentionally restricted to the analysis of a periodic structure of poloidal elements supporting the propagation of a toroidal slow wave with phase velocity $v_{\mathrm{ph.z}}$ and (low, but not negligible) radiation losses, defined by a constant and toroidally uniform resistance per unit length R, with an EM field polarization suitable to couple to a radially propagating magnetosonic fast wave. DEMO1 [15] reactor blanket geometry is assumed for applicative examples, essentially related to power and power density figures. The paper does not try to solve all integration and operation problems, which would require a much more important design effort and information on the reactor itself.

It is shown that, in principle, this array could deliver enough RF power for both heating and current drive of the whole plasma in steady state operation at very low plasma density, and thus to be a possible candidate for replacing the tokamak Ohmic heating system.

2. In-blanket ion cyclotron array in DEMO geometry

An acceptable design for an in-blanket IC array imposes a number of essential constraints. The array should:

1. not impair any blanket function, in particular not reduce the blanket neutron shielding and Tritium breeding;
2. use the same materials as the first wall and withstand the same mechanical, thermal and nuclear loads;
3. be modular and fully match the blanket modularity;
4. share the cooling system with the blanket modules;
5. assure the same level of safety of operation in normal and abnormal conditions;
6. not increase the complexity of the blanket module Remote Handling maintenance.

A quoted section of DEMO1 is drawn in Fig. 1(a).

One of the 18 sectors of the reactor is shown in Fig. 1(b). The sectors are further segmented in three toroidal modules, (to be removed, in one piece, from the reactor core, through the top ports by remote handling, for maintenance, repairs and Tritium recovery) and 20 poloidal sub modules, as shown. The poloidal position of the array sub module is arbitrarily positioned as shown in Fig. 1(c) above a main radial port. It has mechanical links only with its own blanket module and is removed from the vessel with the blanket module with an unmodified standard RH procedure (Requirement 6). Other poloidal positions are obviously possible, such as at the top, minimizing the power transfer to fusion α particles and possibly enhancing by a factor 2 the ICCD efficiency [3], or on a high field side position, avoiding the cut off layer at the ion–ion resonance.

Table 1
Dimensions of array elements.

Array element total length	1.0 m
Array element width	0.2 m
Array element thickness	0.06 m
Array element spacing	0.03 m
Back plate gap	0.05 m

Among other options, some of which are sketched in Fig. 2, the array discussed here is a balanced comb-line structure of many elements [4,5], four of which are sketched in Fig. 2. The array elements are short poloidal sections of electro-magnetically (EM) coupled strip lines, inserted in a poloidal recess of the blanket first wall, short circuited in the middle to the back wall and terminated at the two ends (a and b in Fig. 2(a)) by vacuum shunt capacitors, dimensioned to suitable values. Poloidal coupling between top and bottom halves is disregarded, because it is small and not important for our present discussion. Indicative dimensions are listed in Table 1. The array elements are therefore “whole metal” (Requirement 2). They could be tilted to be orthogonal to the $\mathbf{B_0}$ lines in order to improve coupling to the fast wave and to minimize sheath potentials as shown in Fig. 3(a). The common back plate of the strip lines is recessed 0.10 m from the plane of the elements. Including components thicknesses, the total geometrical depth of the IC array is less than 0.20 m. The geometry of the comb line, as well as the definitions of dimensions, voltages and currents used in the paper is shown in Fig. 1(a).

ICCD arrays used or proposed so far (JET, ITER....) consist of only few (2–4) elements and the progressive phase advance is imposed by externally phased currents (usually at 90°) [2]. The inter elements EM coupling is disturbing, as it causes an uncontrolled, plasma dependent, reactive RF power circulation, reducing plasma coupling and array directivity. Poloidal conductive septa are often used to minimize coupling, in order to maintain the proper current phasing and an acceptable impedance match at all array inputs. Therefore, the radiating elements are usually inserted in a box like

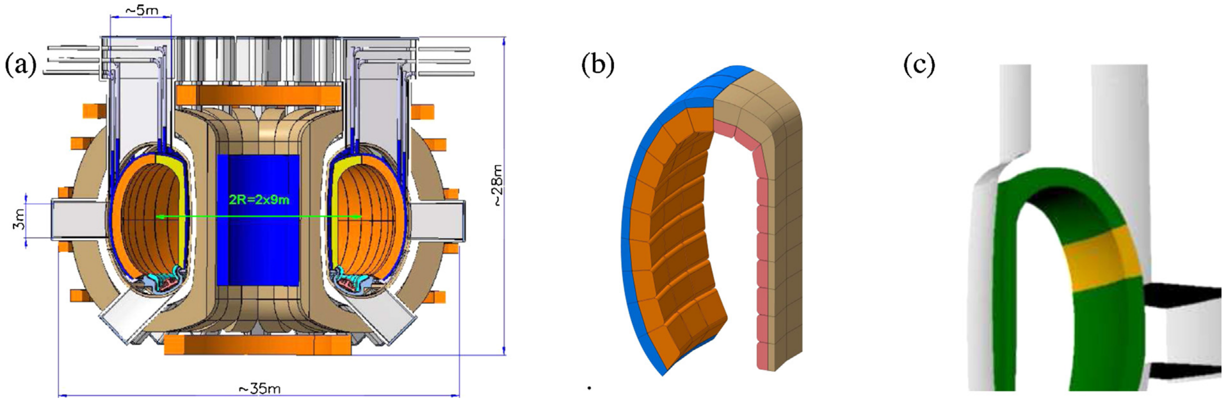

Fig. 1. (a) 2D sketch of DEMO1. (b) One sector of DEMO1 blanket showing toroidal and poloidal modularity. (c) Poloidal position of the ring array discussed in the example of this paper.