Study of the coupling of distributed ICRH antenna and of its optimization for heating of large machines as DEMO.

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Abstract. Traveling Wave Antennas (TWA) sections constituted by toroidal arrays of inductively coupled straps are considered for the ICRF heating of DEMO. They are mounted in resonant ring(s) configuration to obtain the appropriate feeding, matching and load resilience conditions [1]. On top of the minimization of the distance plasma-wave cutoff their coupling conditions can be optimized by (i) the increase of the total strap number, (ii) the choice of a radiated power spectrum centered on an as low as possible $|k_{//}|$ allowing still single pass absorption and avoiding coaxial modes excitation, (iii) the largest possible effective strap length l_{str} with uniform current amplitude. It is shown that a significant power capability increase with respect to the ITER antenna can be obtained for the same radiating surface and plasma profile mainly due to the absence of vertical septa between the straps.

Introduction

For the central heating of a fusion machine ICRH is a first choice method being able to couple RF power to the ions without density limit. The drawback of this method is the antenna coupling to the fast magnetosonic wave because the radiated wave components with $k_{//}\equiv k_z>k_0$ are evanescent from the antenna to the cutoff electron density $N_{CO}(f, k_z, k_y, B,$ ion mix) in the plasma profile. The coordinates are defined in Fig. 1a. The coupling of a large amount of power through the plasma boundary without exceeding the voltage standoff limit at the antenna(s) can therefore be difficult. To overcome this problem it is considered for DEMO to maximize the wave coupling to the plasma by the installation of antennas distributed all along the periphery of the wall inserted in the blanket modules. In reference [1] we have shown that such an antenna can be constituted by sections of Travelling Wave Antenna (TWA), mounted and fed in resonant ring circuit(s). Each section is constituted by a series of equidistant grounded straps aligned in the poloidal direction and acting as a slow wave structure due to their mutual coupling (see Fig. 1a). Figure 1b shows an example with a number m_{sec}=3 of TWA sections each fed by its own resonant ring circuit. The number m_{sec} can be increased until all sections are contiguous to minimize the antenna power density.

Coupling properties of toroidal antenna arrays and their optimalization.

The active power radiated by the antenna array is obtained from the Poynting's theorem applied at the output of the antenna box (see Fig. 1a) by $P_{rad}\propto\iint|E_y|^2\, G_{surf}\, dk_z dk_y$ where $G_{surf}(k_z,k_y)$ is the surface conductance ($\mathrm{Re}(H_z/E_y)$) of the external medium (i.e. plasma profile) at the antenna front and $|E_y|^2$ is the excitation function roughly proportional to the square of the strap current density amplitude $|J_{nstr}(k_z, k_y)|^2$. The proposed antenna concept acts on $|E_y|^2$ to maximize P_{rad} for a given G_{surf}. A toroidal array of n_{str} straps with same current amplitude $|I_{str}|$ but a phase difference $\Delta\phi$ between 2 consecutive straps and a strap inter-distance S_z has a radiated power k_z spectrum constituted of peaks centered on the values $k_{zmax,p}= \Delta\phi/S_z+p(2\pi/S_z)$ for $p=-\infty,...-1, 0, +1,...+\infty$ and k_y=0. The radiated power

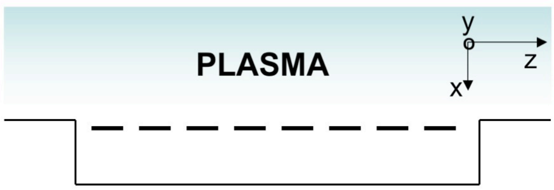

Fig. 1a. Cross-section of an n_{str} = 8 straps antenna array recessed in the wall.

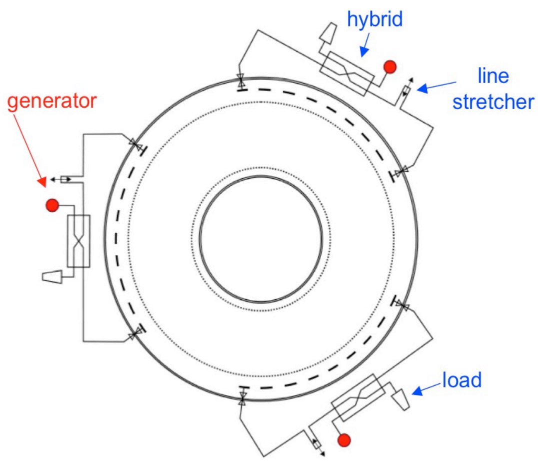

Fig. 1b. Equatorial cut of a machine with m_{sec} = 3 TWA sections, each fed in resonant ring configuration.

scales as $P_{rad} \propto \int |J_{nstr}(k_z)|^2\, dk_z \propto n_{str}/S_z$ for each value of p for a given G_{surf}. The surface conductance $G_{surf}(k_z,k_y)$ is a decreasing function of $|k_z|$ and $|k_y|$ due to the increase of distance antenna-N_{CO}. It depends also on the slope of the electron density profile $N(x)$ for $N>N_{CO}$ [2] and it shows the effect of coaxial modes excitation for $k_z^2+k_y^2 \le k_0^2$ [3]. The P_{rad} contribution to these modes leads to deleterious edge power deposition. Only the terms p=0 and ±1 have a significant contribution to the $k_{zmax,p}$ peaks due to the rapid decrease of $G_{surf}(k_z,k_y)$ when $|k_z|$ increases. Fig. 2 shows the outer part in front of the antenna of two reference density profiles considered as extreme cases for ITER [4] (labeled “2010 Low” and “2010 High” respectively). The large difference of the distances antenna-N_{CO} for different values of k_z and of the density slopes for $N>N_{CO}$ is striking. The relation $R_{rad}=2P_{rad}/(\sum_{nstr}\int|I_n(y)|^2dy)$ defines the distributed radiation resistance R_{rad} that is used to quantify the coupling. $|I_n(y)|$ is the current amplitude flowing in the nth strap and the summation is on all the straps of the section. Figure 3 gives the k_z spectrum for different $k_{zmax,0}=\Delta\phi/S_z$ values selected by the choice of the inter-strap phasing $\Delta\phi$. The figure shows the rapid decrease of $R_{rad}(k_z)$ when $k_{zmax,0}$ increases, the coaxial modes contribution if $|k_{zmax,0}|$

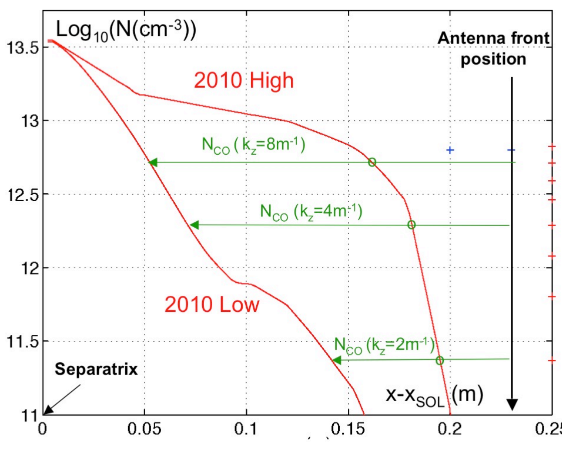

Fig. 2. Extreme reference plasma profiles considered for the ITER antenna design. The position of cutoff density for k_z = 2, 4 and 8m^{-1} are given for D-T plasma, f = 53 MHz, B_{sep} = 3.9 T.

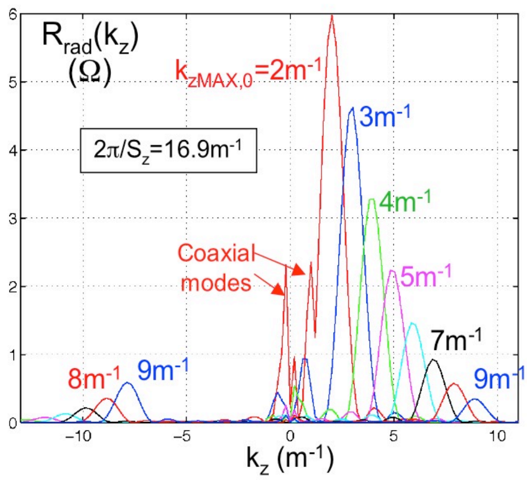

Fig. 3. Distributed antenna radiation resistance spectra for $k_{zMAX,0}$ values adjusted by the inter-strap phasing (TWA section of 12 straps with same parameters as for Fig. 2).

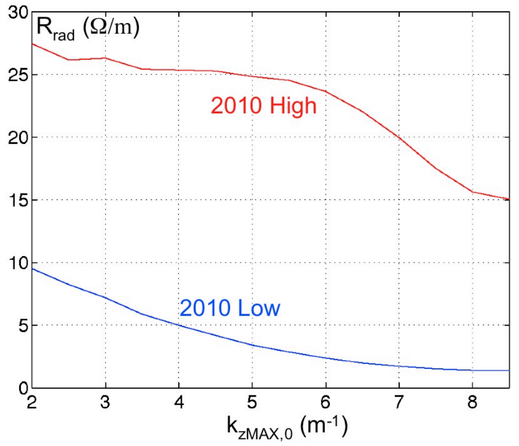

Fig. 4. Distributed antenna radiation resistance versus $k_{zMAX,0}$ for the two plasma profiles of Fig. 2. Same parameters as for Fig. 3.

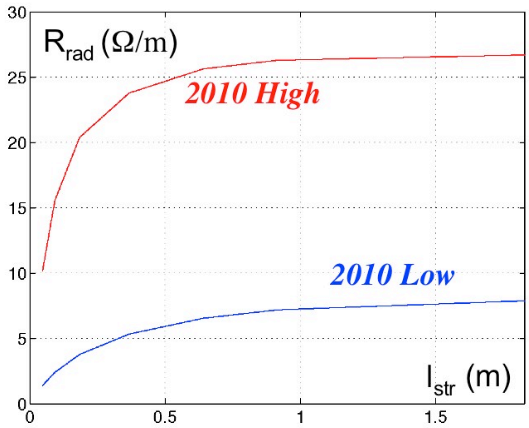

Fig. 5. Distributed antenna radiation resistance versus the strap length for the two plasma profiles of Fig. 2. Same parameters as for Fig. 3.

is too close to k_0 and the contribution of the modes $k_{zmax,-1}$ corresponding to p=-1 when $k_{zmax,0}$ is sufficiently large. Figure 4 compares the dependence of R_{rad} on $k_{zmax,0}$ for the 2 different plasma density profiles of Figure 2. This comparison indicates a power capability ratio exceeding 2.9 and stresses the importance to decrease as much as possible the distance antenna-N_{CO}. For a section of n_{str} straps having same current profile amplitude $|I(y)|$ we have $P_{rad} \propto n_{str} R_{rad} \int_0^{lstr} |I(y)|^2 dy$. This relation is maximized for $|I(y)|$=const and the longest possible strap length l_{str} especially as R_{rad} is an increasing function of l_{str} as shown in Figure 5 for the two density profiles of Figure 2. Effective long straps can be obtained by feeding strap sections near their current antinode as for strap doublets with central grounding and strap triplets connected to 4-ports junctions.

Properties of toroidal arrays used as TWA and their feeding in resonant ring configuration.

An array of self-tuned grounded straps constitutes a slow wave structure, called combline [5], which has already been proposed and tested [6] for fast wave current drive above 100 MHz. The propagation along it relies on its inter-strap mutual coupling. It avoids the individual feed of each toroidal strap: only the first and the last strap of each section are to be connected outside the tokamak to a hybrid junction (see fig. 1b). The structure acts as a passband filter and is equivalent, in his passband, to a section of lossy transmission line, the losses being due to its coupling to the plasma. It also produces the strap current distribution studied in the preceding section (i.e. about same strap current amplitude and same inter-strap phase difference) if it is terminated on its iterative impedance and in the limit of vanishing coupling. Due to coupling to the plasma the strap current amplitude decays from strap to strap. In order to maintain sufficient large strap current amplitude the TWA has to be periodically refueled. The remaining question is how to avoid spoiling a large part of the power source in the iterative impedance? The solution is to close the TWA section on itself through the refueling by the resonant ring configuration (see Fig. 1b). The properties of this feeding circuit are [1]: (i) it terminates all TWA section by their iterative impedance, (ii) it is totally load resilient, the generator(s) seeing the constant iterative impedance as load whatever the plasma loading, (iii) it has its voltage self-adjusted to deliver into radiation the total generator power. In [1] we show an alternative single resonant ring configuration with many sections periodically refueled.

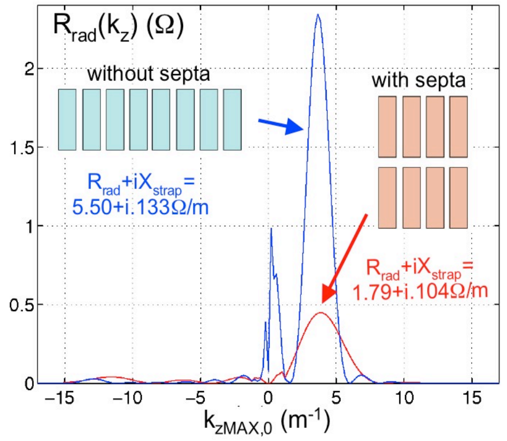

Fig. 6. Comparison of the radiation resistance spectra (with values of resulting distributed strap impedance) for the ITER array (case k_{zMAX} = 3.8m^{-1}) and an equivalent TWA section. Same parameters as for Fig. 2.

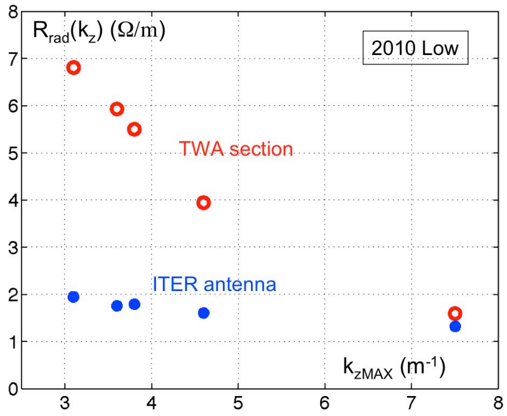

Fig. 7. Comparison of the radiation resistance spectra for the ITER array versus the different k_{zMAX} values selected by the different toroidal phasing cases and the equivalent TWA cases. Same parameters as for Fig. 2.

Comparison of power capability of ITER antenna with TWA.

How the power capability of a TWA antenna expressed by its mean distributed radiation resistance compares with the one of the ITER array of 8 strap triplets [7] for the same radiating surface, for as close as possible the other geometrical parameters and in front of the same reference plasma profile? The comparison is made in Figure 6 for the toroidal phasing giving the same k_{zMAX} There is a significant increase of radiation resistance R_{rad} with the TWA antenna (here factor 2.85) It is attributed to the absence of the vertical septa between the straps (used in the ITER design to reduce mutual coupling effects) and to their thickness. The coupling improvement decreases when $|k_{zmax}|$ increases or more precisely when the inter-strap phasing becomes close to ±π. In this case there is just a voltage node halfway between the straps of the TWA. This effect is apparent in the comparison between the ITER antenna and the TWA equivalent antenna for the 5 main considered phasing cases [7] and it is shown in Figure 7. The value k_{zMAX}=7.5m^{-1} indeed corresponds to an inter-strap phasing of ±π.

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