Preliminary RF characterization of DEMO in-port ion cyclotron heating system for toroidal and poloidal geometry variations

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Ion cyclotron Resonance Heating (ICRH) is one of the auxiliary heating schemes considered for the future DEMOnstration Power Plant (DEMO). The ICRH system in DEMO should couple 50 MW using three equatorial ports. Compared to the ITER one, the current DEMO port design has a smaller toroidal and a larger poloidal extent.

One of the ICRH pre-conceptual design options for DEMO, an in-port antenna based on the current ITER design, is investigated using the ANTITER II code [1]. To make optimal use of the port larger poloidal extent, the possibility to use quadruplets instead of the ITER triplets is explored. The impact on the power coupling is evaluated for two different antenna geometry considering a possible toroidal extension of the antenna in the blanket. The ITER matching-decoupling system is adapted to the new antenna front geometries considered.

Keywords: DEMO, Heating and Current drive, ICRH

1. Introduction

One of the options considered for the ICRH system of DEMO is an in-port antenna of the ITER type. This option is compact, enables to control the relative phase and amplitude imposed to the straps, is load resilient and will benefit of the advanced design phase of ITER. Simultaneously, a Traveling Wave Antenna (TWA) is presently studied as another option [2].

The ITER antenna front face is composed of 24 short straps. The short straps are grouped into triplets by four-port junction (4-PJ) and act as equivalent long straps. Compared to ITER, the standard port of DEMO has (i) a smaller toroidal extension and (ii) a larger poloidal extension [3]. Several antenna configurations could be considered in DEMO depending on the possibility to adapt the toroidal port dimensions (e.g. by enlarging the port entrance or by cutting into the Breeding Blancket (BB)) and by taking advantage of its larger poloidal height. Adapting the antenna front face leads to an adaptation of its matching system.

Section 2 assess the effect of the toroidal and poloidal size of DEMO in front of the "2010low" electron density profile of ITER [4] at a mid-band frequency of 60 MHz prescribed in [5]. Section 3 shows the possible adaptation of the antenna matching system. Conclusions are drawn.

2. Antenna Front Face Sizes

2.1 Toroidal port length and spectrum

The toroidal port length constrains the maximum spacing of the straps which constrains the dominant toroidal wavenumber k_{z0} excited by the antenna with $k_{z_0} = \Delta\phi/S_z$, where $\Delta\phi$ and S_z are the phase and space between straps. The selected dominant wavenumber k_{z0} largely defines the power coupled to and absorbed in the plasma. A larger k_{z0} leads to poorer coupling due to an increased tunneling length of the wave while a smaller k_{z0} leads to poorer core absorption.

Considering the present state of knowledge of ICRH related impurity release, the DEMO antenna should have minimum three straps. Three straps restrict the heating options to a fixed phasing case $(0\pi0)$ with an optimized current amplitude distribution between straps around (1 2 1). A four-strap antenna allows for more phasing flexibility and power distribution between straps which creates new options to minimize impurity release. One promising scheme for DEMO is the $(0\pi\pi0)$ phasing with an even current amplitude distribution between straps. This option should minimize the impurity sources [6], edge modes [7] and should lead to a good compromise between coupling and plasma core absorption.

For our study, we compare the performance of two different antenna toroidal configurations considered on equal terms for DEMO:

1. Option 1: An antenna with the toroidal extension of an ITER equatorial port and the poloidal extension of the equatorial port of a DEMO limiter extent (1.5x2.8 m). This case is close to the TAH antenna proposed in [8].
2. Option 2: An antenna with the toroidal and poloidal extensions of the port of an equatorial DEMO limiter (1.1x2.8 m). Here, the antenna parts dimensions are scaled to fit into the port.

The two antennas layouts considered in ANTITER II are presented in figure 1. Their associated power spectra are presented in figure 2 for the $(0\pi\pi0)$ phasing and another conventional phasing $(0\pi0\pi)$. The second figure illustrates the important influence of the toroidal geometry on the power spectrum and on the overall power coupled to the plasma. It also illustrates the low edge excitation, corresponding to the excitation of low $k_{\parallel}$ wave number in the spectrum, for the $(0\pi\pi0)$ phasing compared to the $(0\pi0\pi)$ one.

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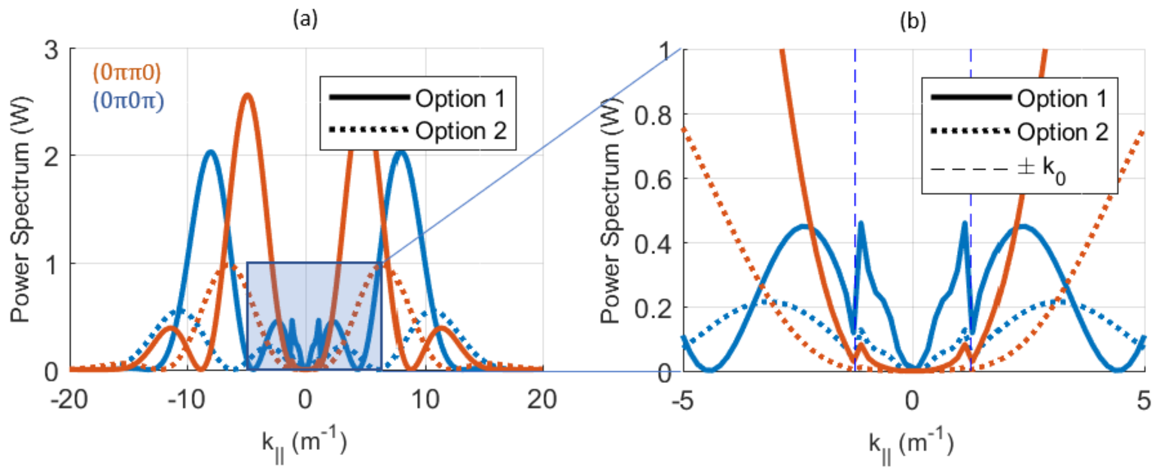

Fig. 2. (a) Power spectrum corresponding to the two different antennas for a 1A excitation of straps and two different phasings. (b) Close up on the coaxial part of the power spectrum.

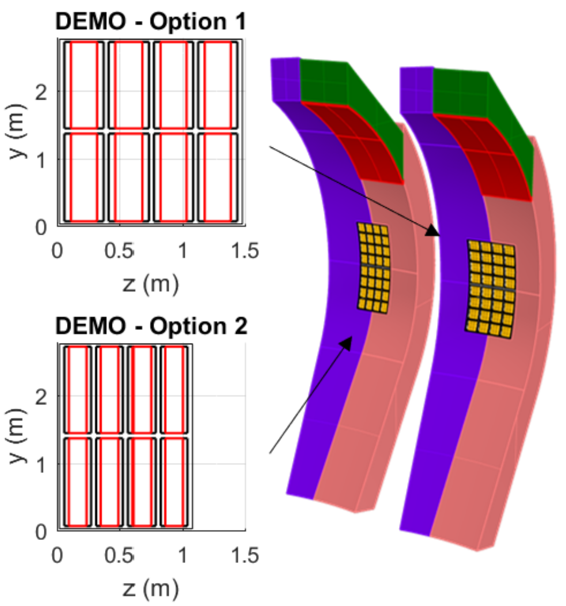

Fig. 1. The two DEMO antenna options considered for analysis. (Left) Strap triplets represented as equivalent long straps in the two different toroidal configurations options considered. (Right) Corresponding side views of the antenna in a DEMO blanket environment.

2.2 Poloidal port length and coupling

To maximize the power radiated by the antenna, reduce the current at the short circuit and reduce the voltage at the feeders, long straps were segmented into triplets in ITER. A low feeder impedance of 15 Ω was chosen to maximize the power transmitted to the plasma while limiting the maximum electric field behind the short strap feeder, inside the 4-PJ line. Given its larger port height, these constraints should be reassessed in DEMO.

The additional poloidal length of DEMO's port roughly corresponds to an addition of two ITER straps. For option 1, this suggests using a segmentation into quadruplets instead of triplets.

The optimal segmentation can be approached using a transmission line model. The strap impedance of a segmentation in n parts of a long strap $Z_{a,n} = R_{a,n} + iX_{a,n}$ has a large reactive part compared to the resistive one $X_a \gg R_a$ and can be computed using ANTITER II. One can then define the minimum conductance G_{min}, representing the maximum power coupled for the maximum voltage V_{max} on line, and the maximum electric field E_{max} on a strap feeding line with characteristic impedance Z_0 as

$$V_{max} = \sqrt{2PZ_0\,VSWR},$$

$$E_{max} = V_{max}/(a\,ln(b/a)),$$

$$G_{min} = 1/(Z_0\,VSWR).$$

Where P is the power on the line, VSWR is the voltage standing wave ratio, a and b are the coaxial inner and outer radius and where b dimensions should not be larger than half of the strap length and width considered. One needs to maximize G_{min} while ensuring that E_{max} do not surpass 2 kV/mm on the line for a given characteristic impedance Z_0.

Figure 3 presents G_{min} and E_{max} as a function of the feeding line characteristic impedance Z_0 for three segmentations n=3,4,5 and a power coupling of 17 MW by ports in the two antenna cases considered in figure 1. The characteristic impedance of 15 Ω used in ITER 4-PJ and the 2 kV/mm electric field limit of the line are also indicated. One clearly sees that, while four straps and 15 Ω impedance looks like a good compromise for option 1, this choice should be reassessed for option 2 and the 17 MW power coupling requirement of DEMO might be a challenge to demonstrate for option 2. Therefore, the last option will be the object of further work.

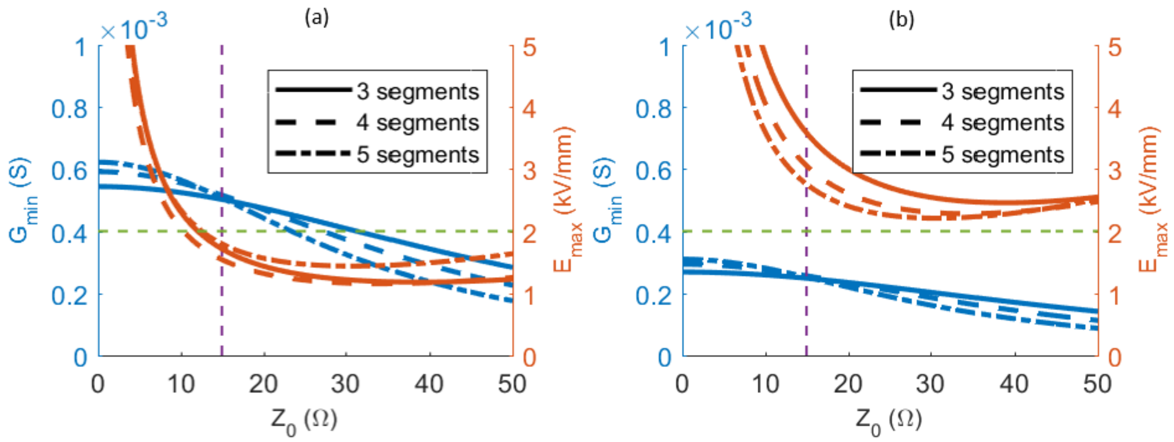

Fig. 3. Maximum electric field E_{max} and minimum conductance G_{min} on the strap side of the PJ as a function of the characteristic impedance Z_0 of the line for three different segmentations n of a long effective strap and 17 MW of coupling for (a) option 1 and (b) option 2.

3. Matching System Considerations

Starting from the antenna front face and going to the generators, the ITER matching system [9] begins right behind the antenna front at the 4-PJ. Up to the bioshield, a service stub on each of the 8 lines provides cooling for the plug and improves the frequency response of the antenna.

Outside the bioshield, in the port cell, a PM stub ensures a lower voltage from the port cell output to a set of six toroidal and four poloidal decouplers. These decouplers are used to ensure the cancellation of power transfer between lines due to mutual coupling between triplets. The decouplers are also used as a feedback control of the voltage and current distribution in the lines. After the decoupler, a two-stub matching system ensures the matching between the load and the generators. Finally, 3 dB hybrids provide resilience to fast load variations, restricting the poloidal phasing to π/2 between two poloidal triplets' pair.

The ITER matching system can be adapted to the DEMO antenna provided small changes in the matching layout. The change of segmentation n of the antenna will imply the implementation of an n+1-port junction. Given the antenna characteristics, the exact position of the service stub to ensure a correct broadbanding will also have to be reassessed.

Nevertheless, an ideal n-port junction can be defined and a first upgrade of the matching system of ITER to the DEMO one using ideal components for a 4-strap segmentation can be made. For 17 MW power coupled to the plasma load of ANTITER, figure 4 shows the maximum voltage magnitude on the transmission lines as a function of the position in the matching system for the (0ππ0) phasing in the case of option 1. Figure 5 shows the voltage imposed on the strap in the same conditions. Figure 6 shows the power coupled to the load as a function of the frequency for a fixed voltage of 45 kV on the transmission lines.

For a 15 Ω n+1-port junction, one can verify the best segmentation anticipated in the previous section for 17 MW coupled. This is done for option 1 in figure 7 where the maximum voltage V_{max} and electric field E_{max} on lines is presented as a function of strap segmentation. One can see that for the option 1, a segmentation in 4 straps leads to the smallest electric field on the PJ. The same method will be applied for option 2 when its front face geometry will be optimized.

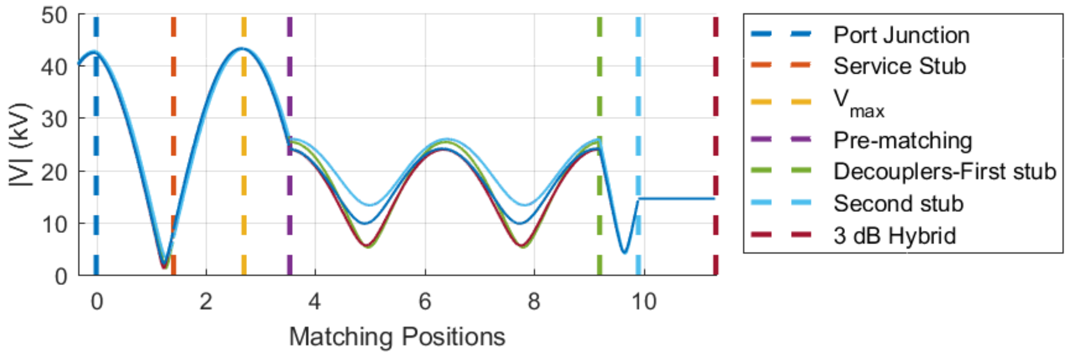

Fig. 4. Magnitude of the voltage along the lines of the matching system for the $(0\pi\pi0)$ toroidal phasing, a $(0,\pi/2)$ poloidal phasing and 17 MW of coupled power using option 1. The multiple curves represents the 8 lines feeding the antenna.

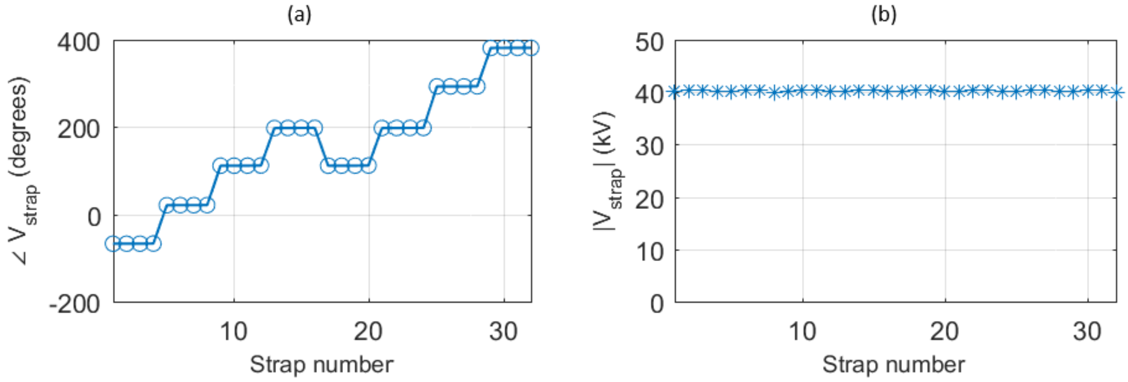

Fig. 5. (a) Phase and (b) amplitude of the voltage imposed on the strap system for the $(0\pi\pi0)$ phasing, a $(0, \pi/2)$ poloidal phasing and 17 MW of coupled power using option 1. Strap numbering is done top down and left to right.

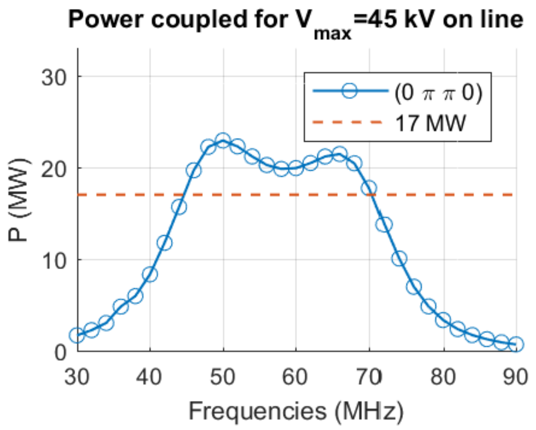

Fig. 6. Power coupled as a function of the frequency of the antenna for a $(0\pi\pi0)$ phasing and a maximum voltage V_{max} on TLs of 45 kV with option 1.

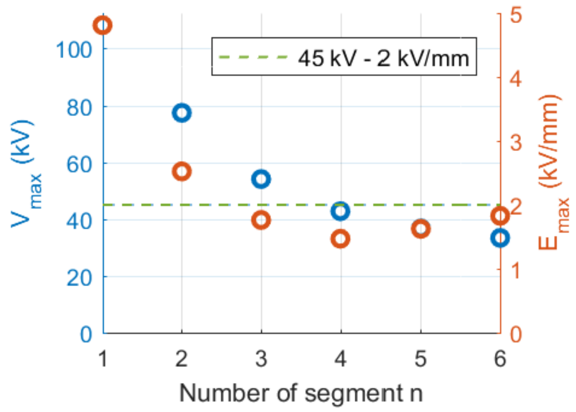

Fig. 7. Maximum voltage V_{max} and Electric field E_{max} on the matching lines for a n+1-port junction of 15 to 20 Ω and 17 MW coupled by the antenna using option 1.

5. Conclusions

The differences between DEMO equatorial port dimensions and the ITER one impose to reassess the antenna front face size which requires to adapt its matching system. Consequently, the definite poloidal and toroidal port extension possible for DEMO are needed for its future development. The antenna performances were analysed for two toroidal sizes options: option 1 benefiting of the toroidal extension of the ITER antenna and option 2 fitting into a DEMO port. Both options benefits from the larger poloidal extension available in DEMO.

The smaller toroidal extent of option 2 affects the power coupled by broadening the antenna power spectrum and decreasing the strap radiating area. The larger poloidal extent of DEMO imposes to reassess the segmentation of long effective straps using quadruplets instead of the ITER triplets in option 1. With the matching system adapted to the new geometry, option 1 can readily couple 17 MW facing the ITER "2010low" density profile on a broad frequency band and within the system tolerances.

The two options presented will be studied in parallel. The front face of option 2 needs to be optimized to see if it can couple the 17 MW per ports required for DEMO. The feasibility of a 5 or 6-port junction also needs to be assessed and its mechanical implication needs to be considered.

Acknowledgments

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