Design and development of the actively cooled ion cyclotron travelling wave array system for WEST

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Abstract. This paper presents the preliminary design of the Ion Cyclotron Range of Frequency (ICRF) Travelling Wave Array (TWA) system for the WEST facility. The TWA system aims to address the limitations of current ICRF launchers, focusing on improved coupling, reduced voltages and RF sheaths and enhanced reliability. The project is staged in two phases: first, a direct feeding scheme will be used, and later a resonant ring feeding circuit will be installed. This paper outlines the main milestones, plasma scenarios, RF design and mechanical challenges along with the experimental program planned for the WEST TWA system.

1 Introduction

Ion Cyclotron Range of Frequency (ICRF) heating has proven to be a valuable tool in fusion experiments due to its compatibility with high-density plasma (no density limit), excellent absorption and proven experience in various scenarios such as plasma heating (including dominant ion heating), wall-conditioning [1] or assisted breakdown [2] . Recent results show that ICRF can also reduce turbulence and improve the fusion reaction rate [3] . In addition, the required technology for continuous wave (CW) operation is readily available, even for high-magnetic field machines. Furthermore, modelling of the RF performances of an antenna for a given plasma has been extensively benchmarked in many fusion experiments and is nowadays very reliable and accessible with commercial software.

However, current ICRF launchers suffer from several ch*allenges, making them incompatible with fusion plants, such as low coupling conditions, large RF voltages inside the launchers (arcing issues), metallic impurity production (plasma pollution). Finally, current launcher technologies rely in “in-port” designs, which require a large volume that could be instead dedicated to Tritium breeding [5] .

To solve all of these challenges at the same time, an innovative, remarkably different from traditional resonant ICRF antennas could potentially bring improvements to all the above challenges. It consists of sections of Travelling Wave Arrays (TWA), directly embedded in the blanket modules spread around the fusion plant. This arrangement of antennas reduces the power density for the same power coupled to the plasma, and thus the related RF electric fields [5] . The risk of electric arcing is thus reduced, and the reliability of the antennas is increased [6] . The reduced electric fields also reduce impurity production from RF sheaths, and the radiated spectrum can be optimised to reduce undesirable parasitic coaxial modes [7] . Additionally, the antenna does not require tunable elements close to the plasma. Using the same proven modelling tools as current ICRF systems, a TWA is predicted to have many advantages in terms of coupling and reliability due to its lower power density, intrinsic load resilience, optimised parallel wavenumber spectrum and inherent operational simplicity. Furthermore, the antenna could be placed far from the plasma, reducing the incoming flux, therefore reducing further plasma-wall interactions.

In 2021, a high-power mock-up of a TWA antenna was successfully tested under vacuum conditions at high RF power in the TITAN test bed at CEA/IRFM [4] during a EUROfusion Enabling Research activity led by LPP-ERM/KMS [7] [8] and manufactured by ASIPP [9] . The mock-up has been tested up to 2 MW for 3 seconds, corresponding to the maximum power available from the radio-frequency wave generator. While not actively cooled, this mock-up sustained several consecutive RF pulses of 500 kW for 60 seconds [10] without loss of performance, validating the modelling tool chain. The next logical step is hence to test an ICRF TWA antenna on plasma. As the TWA launcher toroidal extension is larger than a usual in-port launcher, it requires a sufficient space between the vacuum vessel and the plasma to be installed. Distinctly from other machines, WEST offers sufficient space between the plasma edge and the vacuum vessel on the

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low field side to integrate a TWA antenna [10] [11] . WEST is thus an ideal test bed for proving this concept in a tungsten (W) environment relevant for fusion plants.

A project to design and procure an ICRF TWA system for WEST has started in May 2024. This project is performed in an international framework constituted by LPP-ERM/KMS, DTU, ASIPP and led by CEA/IRFM.

Section 2 of this paper gives an overview the project objectives and requirements. The RF launcher design is detailed in Section 3. A preliminary mechanical design is described in Section 4. Finally, the last section addresses the list of foreseen experiments to be conducted in WEST.

2 Project overview and specifications

The goal of the WEST TWA project is to test two TWA ICRF launchers on WEST plasmas. Figure 1 shows an overview of the relevant WEST internal components, with the two TWA launchers located next to the ECRH launcher. The project is staged into two phases. During the first phase, called *direct feeding* phase, each launcher will be fed by one existing WEST high-power ICRF source, and the uncoupled power will be directed to water-loads. This phase will allow a demonstration of the coupling performance, the load resilience properties of the launchers (for example during ELMs), the RF sheath minimisation and high peak coupled power performance. As the launchers have a 12 MHz operational bandwidth, this phase will also allow testing frequency changes during plasma operation and real-time frequency control. It is also envisaged to test Ion Cyclotron Wall Conditioning (ICWC) technique, which could potentially benefit from the launcher's large toroidal extension. In a second phase, a *resonant ring* [12] will be implemented to feed the launchers, which allows recirculation of the uncoupled power. With this configuration, all the RF power generated by the sources is expected to be coupled to the plasma (minus RF losses), hence optimising the overall power efficiency of the system [13] , a key issue for fusion plants.

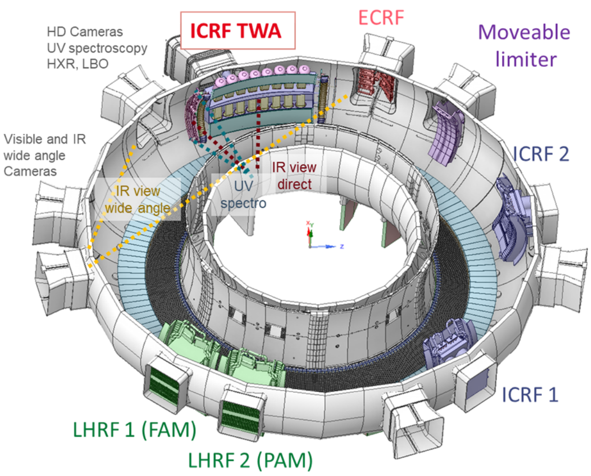

Figure 1. Overview of the location of the IC TWA launchers in the WEST tokamak. The two TWAs are top/bottom positioned.

The WEST TWA ICRF launchers will replace one existing WEST ICRF launcher located in the Q4 port. As WEST is a superconducting machine running long plasma pulses [14] , the launchers and their components must all be actively cooled.

Feeding the launchers using a resonant ring structure increases the RF input power specifications (Figure 2). Hence, the launchers' input power specifications are defined to be compatible directly with the second phase. Assuming 50% single transit coupling (cf. next section), which corresponds to situations in which the WEST plasma is located 6 cm away from the launcher edge limiter tips, both launchers are designed for an input power of 6.0 MW / 30 s (3.0 MW/launcher) and 2.0 MW in steady-state. The maximum power is constrained by the limited space inside the vacuum vessel, which restricts components size, necessitating compact and efficient designs but also imposing some constraints on the maximum electric field they can handle. The TWA concept itself allows for higher power density. The steady-state limitations of the WEST TWA come from either RF feedthroughs (recovered from the removed WEST antenna), the RF plant or the connecting transmission lines (which are not cooled). The launcher material is bare stainless steel without coating facing the plasma, to be as relevant as possible to future fusion plant requirements. During the first phase of the project (direct feeding phase), the launchers will cope with an input power of 3.0 MW during 30 s (1.5 MW/launcher) and 1.0 MW in steady-state (0.5 MW/launcher), which gives large operational margins with respect to their design specifications.

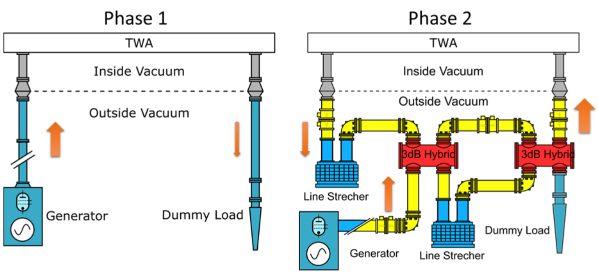

Figure 2. RF Feeding schemes of a TWA launcher. Left: direct feeding. Right: Resonant Ring feeding.

3 RF launcher design

The frequencies and the radiated wavenumber specifications come from the WEST ICRH scenarios, mainly Hydrogen minority heating of Deuterium plasma. Analytic and full-wave modelling have shown that the optimum frequency and parallel wavenumber are respectively between 55 and 57 MHz and between 8 and 10 rad/m [15] .

The RF design is based on 3D inhomogeneous and anisotropic cold plasma full-wave modelling, benchmarked using WEST equilibria and density profiles and WEST ICRF data [15] . Figure 3 shows the frequency response of the launcher, with the normalised coupled, reflected, and transmitted powers for different radial outer gap (ROG) values. The ROG is defined as the shortest distance between the last closed flux surface and the antenna limiter. The WEST ICRF TWA launchers will operate within a 12 MHz bandwidth (defined for a Standing Wave Ratio (SWR) lower than 1.2:1) centred on 57 MHz.

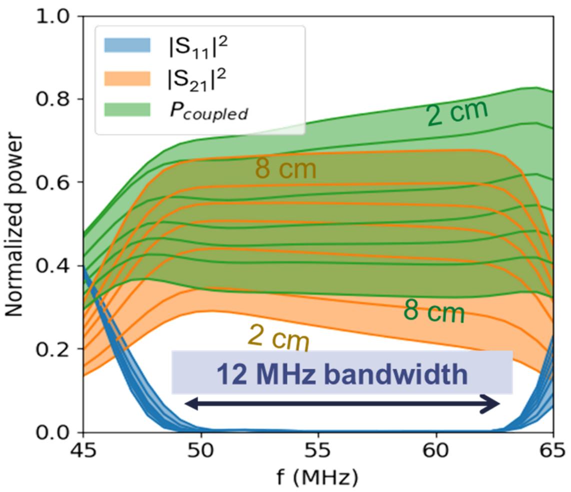

Figure 3. Squared magnitudes (normalised powers) of S11 (reflected, blue), S21 (transmitted to dummy load in the first phase of the project, orange), and coupled power to the plasma (green) as a function of the frequency for several ROG values. Port 1 is the feeding port of the TWA and port 2 the output port. The bandwidth is defined for SWR <1.2:1.

Sensitivity studies have been conducted on the launcher dimensions and assembly tolerances, and show large tolerances on the RF response of the launchers. Using a real WEST plasma equilibrium and a density profile shifted from the launcher (with respect to the edge limiter tip), the ratio of the coupled power to the plasma to the input power (called *single transit coupling*) varies from 80% to 30% depending on the plasma distance to the launcher from 2 cm to 8 cm (Figure 5). The coupling performance of the TWA launcher has also been compared with the current WEST ICRF launchers (Figure 4). Using the same experimental density profiles and the same definition of the ROG, modelling shows that the TWA launcher coupled power will be higher than the current WEST ICRF antenna in all cases.

These results show that the TWA launcher can couple RF power even if the plasma is located far away from the launcher. In addition, and in contrast to classic resonant ICRF launchers, the electric fields of the TWA launcher do not increase as the plasma gets further away from the launchers. In addition to reduced plasma/wall interactions as the plasma is further away from the launcher, the impurity production will be minimised with these launchers [15] .

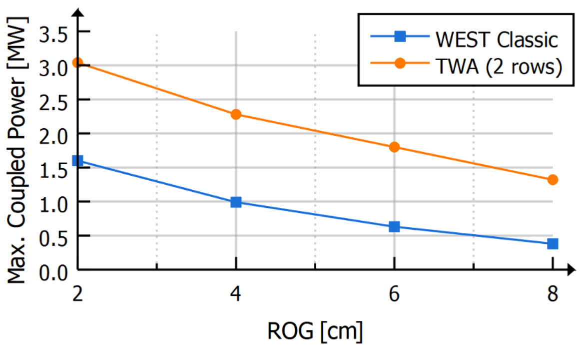

Figure 4. Comparison of the expected coupled power (orange) of the TWA launchers with the WEST current ICRF launcher (blue), for several ROG distances.

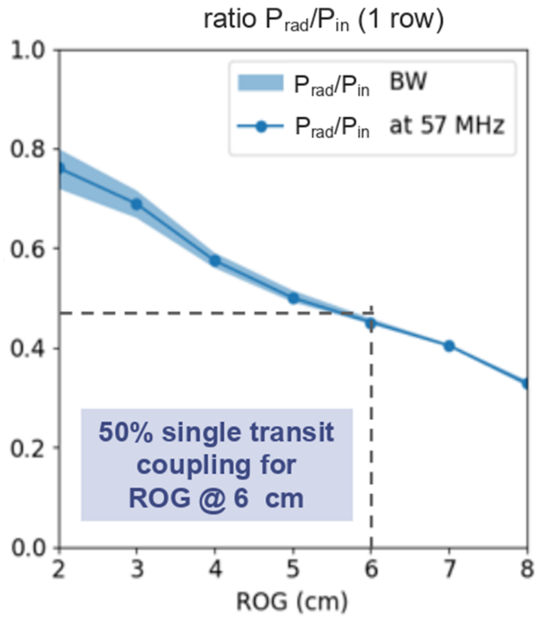

Figure 5. Single Transit Coupling (ratio of coupled power to the input power) for several ROG values.

Each launcher is made of 8 toroidal straps (Figure 6), which produce a narrower spectrum than classical ICRF antennas, enhancing directivity and reducing parasitic uncoupled power. In addition, the radiated spectrum power density has been minimised in the range [$-k_0$; k_0] to reduce coaxial modes' excitation [7] , where $k_0=\omega/c$. The electric field has been optimised to not exceed 2.5 MV/m at maximum power for the second phase of operation, assuming an input power lower than 3.5 MW, coming from the sum of the powers from one amplifier to the recirculated power. This brings large operational margins for the first phase, where the input power will be lower than the maximum RF source transmitted power (2 MW). The total RF losses are of the order of 6% of the input power and are mostly located in the launcher box and straps (which are all in stainless steel without coating).

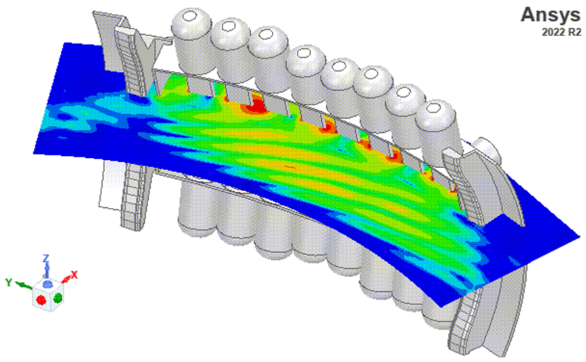

Figure 6. Illustration of electric field magnitude on a plane cutting through the middle of the upper launcher box [15] .

4 Preliminary mechanical design

To fit into the WEST vacuum vessel using a single port for the feeding lines and supporting structure (Figure 7), the TWA launchers are designed as cantilevered structures. This design requires robust engineering to handle the launcher's own weight and, in particular, disruptions and Vertical Displacement Events (VDE) loads. Electromechanical loads have been modelled using representative WEST case load specifications on a 60° large periodic toroidal sector.

All the elements of the launchers must be water-cooled to ensure long pulse operation capabilities and manage heat dissipation effectively. The launcher elements will be cooled with the WEST hot water cooling loop (70°C during operation and 200°C during baking). Only a section of the inner conductor of the launcher transmission line will be cooled with cold water due to mechanical constraints (but not during baking). In addition to RF heat loads (RF losses), both convective and radiative loads from the plasma have been modelled. Due to the large TWAs toroidal size and the reuse of the current antenna edge limiters, convective loads are expected inside the latter. These convective loads will be mitigated using horizontal limiter tiles located above and below the launchers' antenna boxes. The launchers are designed to handle up to 0.16 MW/m^2 of radiative loads in steady-state. To speed up and simplify the assembly and to minimise risks, the design is made such as to maximise the number of components assembled and tested outside the vacuum vessel.

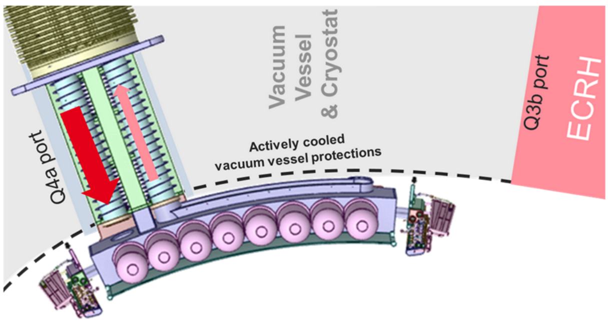

Figure 7. Illustration of the top view of a WEST TWA launcher. The large red arrow is the RF input, the smaller one is the RF output.

5 Diagnostics and arc detection

The launchers and their operation will be monitored using several dedicated or already present WEST diagnostics. RF measurements, including input/output power, strap electric fields, and reflectometers embedded in between the two launchers, will allow us to assess coupling and power deposition. The existing WEST visible spectroscopy system will allow monitoring one side of the Tungsten antenna limiter. Finally, the standard set of WEST infrared cameras [17] will allow for to survey of the launchers, with a partial or a wide-angle coverage (Figure 8), to watch for their thermal responses and to detect hot spots.

Modelling shows that any arc occurring inside the launcher will immediately detune it, increasing the reflected power. Hence, reflected power will be used at the main arc safety interlock to temporarily stop the RF sources. Additional arc detection systems, such as Sub-Harmonic Arc Detector or pressure increase in the vacuum parts of the transmission lines, as in the current WEST launchers [16] , will be used in complement.

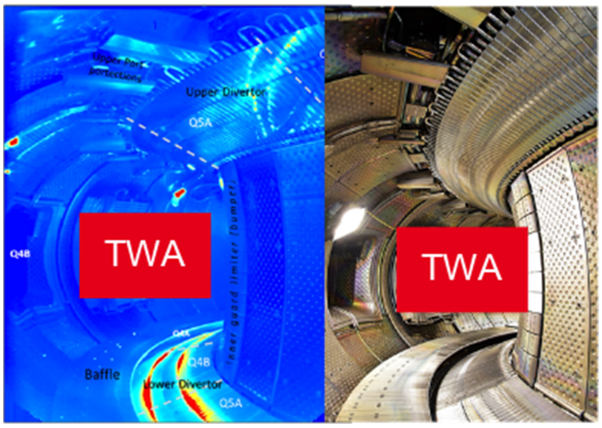

Figure 8. Illustration of the Infra-Red coverage of the TWA with the WEST wide-angle camera.

6 Experimental program

The foreseen experimental program associated with the operation of the TWA launchers in WEST includes a comprehensive set of experiments to characterise the performance and capabilities of the system. The coupling properties of the launchers will be characterised for various plasma properties (shapes and distances). The system heating efficiency will be investigated, as well as the effect of poloidal phase difference to enhance power deposition. The electric field in the antenna and the impurity production will be monitored and compared directly to classic WEST IC launchers on the same WEST plasma scenarios. Synergies with the other two ICRF launchers will be explored (using different RF frequencies for example) and with the other WEST heating systems (Lower Hybrid and Electron Cyclotron). The possibility of using the launchers for turbulence control will also be investigated, using fast ions generated by the TWA launchers to stabilise plasma and improve confinement. Finally, the TWA system will be added to the WEST plasma control system [19] and the real-time frequency change will be tested to assess the capability to change RF frequency in real-time to control or sweep the power deposition, enabling new operational scenarios.

7 Conclusion and perspectives

The TWA system for WEST represents a significant advancement in ICRF technology, addressing key limitations of current launchers. With a staged approach and comprehensive diagnostic tools, the TWA system aims to enhance coupling, reduce RF sheath voltages, and improve reliability. The experimental program promises exciting insights into plasma heating and control, paving the way for future fusion power plants.

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