Radio-frequency electrical design of the WEST long pulse and load-resilient ICRH launchers

Original
Radio-frequency electrical design of the WEST long pulse and load-resilient ICRH launchers / Walid, Helou; Laurent, Colas; Julien, Hillairet; Milanesio, Daniele; Patrick, Mollard; Arnaud, Argouarch; Gilles Berger By, ; Jean Michel Bernard, ; Zhaoxi, Chen; Jean Marc Delaplanche, ; Pierre, Dumortier; Frédéric, Durodié; Annika, Ekedahl; Nicolas, Fedorczak; Fabien, Ferlay; Marc, Goniche; Jonathan, Jacquot; Emmanuel, Joffrin; Xavier, Litaudon; Gilles, Lombard; Maggiora, Riccardo; Roland, Magne; Jean Claude Patterlini, ; Marc, Prou; Robert, Volpe; Karl, Vulliez; Konstantin, Winkler. - In: FUSION ENGINEERING AND DESIGN. - ISSN 0920-3796. - STAMPA. - 96-97(2015), pp. 473-476. ((Intervento presentato al convegno 28th Symposium On Fusion Technology (SOFT-28) tenutosi a San Sebastian, Spain nel September 29th - October 3rd, 2014.

Publisher:
Elsevier

Published
DOI:10.1016/j.fusengdes.2015.01.005

Terms of use:
openAccess
This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)
Radio-Frequency electrical design of the WEST Long Pulse and Load-Resilient ICRH launchers


1. Introduction

The WEST project aims at modifying Tore-Supra (TS) to an X-point divertor Tokamak, equipped with actively cooled tungsten Plasma Facing Units (PFU), with the goal to test divertor components technologies for ITER [1]. In order to generate ITER-relevant high heat fluxes on its PFU, three new ICRH launchers have been designed for WEST, to operate at 3MW/launcher for 30s and 1MW/launcher for 1000s on H-mode plasmas. These new launchers will be to date the first ICRH launchers to offer the unique combination of Continuous-Wave (CW) operation at high power and load tolerance capabilities for coupling on H-mode edge. The Radio-Frequency (RF) design optimization process has been carried out using Full-Wave electromagnetic solvers combined with electric circuit calculations. Cavity modes occurring between the launchers structures and the Vacuum Vessel Ports (VVP) have been evaluated and cleared out.

Keywords: WEST project, ICRH, S/Z parameters, impedance matching.

2. Key parameters of the RF design and encountered trade-offs

2.1 Coupling resistance ($R_c$), coupling resistance per meter ($R_{c/m}$) and straps mean active reactance ($X_s$)
The front-face of each WEST ICRH launcher is an array of 4 straps and is equivalent to a 4-port multipole (shaded black-box in Fig.1). The latter one is described by its 4x4 Z-matrix (or any other matrix called in the following as a RF-matrix) and can be derived from Full-Wave modelling using for instance TOPICA [8,9] at the desired frequency and plasma configuration. This matrix gives a full description of all RF quantities at the inputs of the array and is of a great importance for advanced RF analysis as the simulation of matching algorithms.

Yet, in order to estimate the values of the required matching capacitances \( C_i \) (i=1 to 4) and the I/V/E, and ensure, in a first-order analysis, that the requirements are met; it is very useful to reduce the antenna circuit (connection of RF-matrixes) to a simple lumped-element model. By doing so, this enables the use of the formulas described in section 2.2. The impedances \( Z_{m} = R_c + jX_c \) in Fig.1 are defined as follows. For a given straps Z-matrix and excitation current-vector \( I \), one can extract \( R_c \) (in \( \Omega \)) using equations 1 to 3 (the voltage vector being the product of the Z-matrix and \( I \), \( P \) is the total radiated power by the N=4 straps). \( X_c \) is the mean value of the imaginary parts of the active impedances [14]. Note that 4 identical impedances \( Z_{m} = R_c + jX_c \) crossed by the same current \( I_{0m} \) will radiate the same amount of power as does the array when it is excited by \( I \). \( R_{p_{in}} \) (in \( \Omega/m \)) is then deduced from the ratio of \( R_c \) and a strap’s radiating part’s length \( (D_s = 0.27m) \). It is worth to state that after some algebra one finds that if \( I \) has all its components equal-amplitude, \( R_c \) would be equal to the mean value of the real parts of the active impedances.

\[
R_c = \frac{2}{\sum |I|} \quad (1)
\]

\[
R_c = \frac{\sum I}{2} \quad (2)
\]

One should stress that many definitions of \( R_c \) exist [3,15,16], however the one introduced above is particularly convenient for WEST ICRH launchers as it is valid for any current vector and could be properly compared to the measurements (in the new launchers the voltage probes are located at the straps inputs). Finally, it should be emphasized that, as already outlined in [17], the coupling resistance is mainly a factor of merit indicating that when it is increased (for the same amount of power and at matching) the currents flowing in the capacitors will decrease, however in advanced RF calculations RF-matrixes should be used.

2.2 Capacitances values and I/V/E at matching

After extracting the 4 equal lumped-element impedances \( Z_{m} = R_c + jX_c \), the I/V/E at the straps inputs and the capacitors voltages could be found using equations 4 to 7 (assuming a coaxial connection [18] between the straps and the capacitors). Note that these expressions are given at matching and correspond to peak amplitudes. The capacitances needed to match a poloidal pair of straps (one RDL) could be found using equation 8. In these equations \( R_{int} \), \( R_{ext} \), \( w_{0s} \), \( L_{str} \) and \( Z_{ot} \) are respectively the internal and external radii of the coaxial connection to the series capacitors, the angular frequency, the capacitors self-inductance and the impedance at the bridge.

\[
R_c = \frac{1}{\sqrt{2}} \quad (4)
\]

\[
|I| = \frac{1}{\sqrt{2}} \quad (5)
\]

\[
I = (\frac{\ln(\sqrt{2})}{\sqrt{2}}) \quad (6)
\]

\[
R_c = \frac{1}{|\sqrt{2}|} \quad (7)
\]

As expected, one notices that increasing \( R_c \) and decreasing \( X_c \) are respectively required to decrease the currents and increase the values of the matching capacitances (see section 1). Both increasing \( R_c \) and the reduction of \( X_c \) are needed to decrease the voltages and electric fields. However, it should be emphasized that increasing \( R_c \) has been often accompanied by an increase of \( X_c \). Tradeoff has thus been frequently required between the reduction of the currents on the one hand, and the reduction of the voltages and electric fields and the increase of the capacitances on the other hand.

2.3 ELM-resilience

Lower values of \( R_c \) are expected in H-mode (between ELMs) than in L-mode plasmas (partially due to steeper edge-density profiles [19,20]), followed by a strong and fast increase during ELMs [21]. Figure 2 illustrates that in order to validate VSWR=2 at very low coupling (for instance at \( R_{p_{in}} = 0.75\Omega/m \) indicated by the red vertical solid lines), small values of \( R_c \) should be matched (Fig.2.a and b). However, in these cases, in order to keep VSWR<2 over a wide range of \( R_c \), low impedance values are required at the bridge. Since decreasing \( Z_{in} \) augments the electric fields and harden both the arc-detection at the bridge and the matching (the latter difficulty is due to mutual couplings between the straps [22]), \( Z_{in}=3\Omega \) has been chosen as a compromise (see Fig.2.b).

3. RF optimizations and assessment

3.1 Front-face of the launchers

Various parametric scans have been carried out in order to find a compromise between the increase of \( R_c \) and the reduction of \( X_c \).

![Fig.1. 4-port multipole (shaded black-box), its equivalent lumped-element model (4 impedances \( Z_{m}=R_c + jX_c \), and the matching circuit: the capacitors in series with their self-inductances and ideal bridges (3-branch nodes).](image-url)
The calculations have been made using HFSS, COMSOL [6] combined to SSWICH code [7] and finally TOPICA [8,9] for geometry milestones. Increasing the straps width decreased both R_s and X_s (in agreement with what has been stated in [23]). This is also the case when increasing the straps thickness. A major modification boosting R_s without altering much X_s has been the reduction of the distance between the straps and the Faraday Screen (FS). Shrinking the TS Prototype 2007’s vertical protruding septum also increased R_s, but was accompanied by an increase of X_s (note that an increase of the mutual coupling did not cause major difficulties on the matching). A major modification reducing the value of X_s has been the reduction of the feeder’s length. The geometry has been optimized while keeping E<2MV/m even for currents as high as 140% of the maximum allowed current at the strap’s input (I_{max}=850A peak).

One should note that the front-face has not been specifically conceived to be optimal in terms of RF-sheaths reduction (as in [24]); however effort has been undertaken to choose the optimal FS [25]. In addition, it should be stressed that, in contrast to the analysis performed in [24], self-consistent RF-sheaths calculations have been carried out for WEST ICRH launchers using SSWICH code. A choice has been made between four FS with different transparencies (FST) and rods tilt angles: tilted rods (7°, FST=0.5), horizontal rods (0°, FST=0.5), tilted-and-dense rods (7°, FST=0.25) and horizontal-and-dense rods (0°, FST=0.25); the third configuration has been chosen as it led to minimal power losses attributed to RF-sheaths over the side limiters. The effect of the FST on R_s and X_s has been found to be negligible for transparencies between 0.25 and 0.5, and its effect on X_s has been validated by low-power measurements on a mock-up.

From figure 3 one clearly sees that starting from the TS Prototype 2007, R_s has been boosted to values even larger than those of the TS Classical launchers [3]. Figure 4 validates the requirements on the matching capacitors at the required frequency band (48-60MHz) and for a scan of coupling resistances. R_s deduced from TOPICA simulations and the corresponding capacitances are also illustrated. TOPICA simulations have been made for various L and H-mode plasma profiles. L-mode profiles (1 to 8, with increasing density) are found from X-mode reflectometry measurements [26] in 2007 on the TS Prototype 2007 launcher, while H-mode profiles are deduced from modelling. In the latter case various Line Averaged Densities (n_e) and distances to the separatrix (D_{sep}) are considered. Note that the capacitors self-inductance of 50nH has been intentionally chosen (datasheets give typically 20-30nH) to insure that the requirements on C are met (mainly that C>40nF).

Concerning the power handling capabilities, using equations 4 to 7 (i.e. at matching), one finds that a launcher would operate at 1MW for R_{cpm}>2.6Ω/m without exceeding the I/V/E limits, but requires high coupling to operate at 3MW (R_{cpm}>7.7Ω/m). It should be noted that for frequencies below 60MHz, the limiting factor is the capacitor’s current, while it could be the electric field at higher frequencies.

3.2 Rear-part of the launchers

A major modification has been made on the two-stage (5.3 and 17.7 Ω) Impedance Transformer (IT). Its dimensions have been chosen to transform 3Ω at the bridge’s (BR) input to 30Ω at the RF-Window’s (RW) input, with the largest bandwidth and minimal current-densities, while respecting both E<2MV/m and the mechanical requirements [10]. Some modifications have been performed to the BR, mainly for mechanical reasons, but it has been verified that they do not alter its electrical response. No modifications have been realized either to the RW or to the service-stub.

![Fig.3. Optimization of R_{cpm} at 48MHz. Plasma Scenario 0 corresponds to simulations in vacuum using HFSS, and those going from 1 to 8 to TOPICA simulations with L-mode plasma profiles with increasing density.](image)

![Fig.4. Matching capacitances variation with R_{cpm}. For L-mode, R_{cpm} increases with profiles going from 1 to 8 (increasing density). For H-mode, R_{cpm} increases when n_e increases and D_{sep} decreases. Dashed lines correspond to a scan of R_{cpm}.](image)

![Fig.2. ELM-resilience for various matched coupling resistances (black vertical dashed lines) and impedances at the bridge. The red vertical solid lines correspond to R_{cpm} = 0.75Ω/m.](image)
Figure 5 illustrates Smith charts with the calculated impedances at the RW’s input for various frequencies and BR impedances. It can be noticed that the best-match (VSWR=1) do not correspond to \( Z_0 = 3\Omega \) but rather to \( 3\pm 0.5\Omega \) (Fig.5.a); it is believed to be a combined effect of the final IT dimensions differing from the theoretical ones (compatibility with the manufacturing standards) and the RF-Window. Finally, it is known that a slight reactance might have to be added to \( Z_0 \) (by conveniently setting the capacitors) in order to equalize the straps voltages [4] and enhance the load-resilience [27]; Fig.5 illustrates that this could be achieved without exceeding VSWR=2.

4. Launchers-VVP cavity modes

In [11-13] it has been established for ITER ICRH launcher, theoretically, by simulation as well as experimentally on a reduced-scale mock-up, that cavity modes might be excited between the launcher’s plug and the VVP. In the case of WEST ICRH launchers, it has been found using HFSS Eigen-mode solver that a fundamental cavity mode would exist at \(~35\text{MHz} \) followed by a second mode at \(~100\text{MHz} \). Even though those modes are out of the operation range (48-60MHz), it has been found discerning to up-shift the fundamental mode to sup-100MHz frequencies by establishing a conductive path between the launcher’s rails and the VVP (Fig.6). Note that in WEST’s case, the analyzes were slightly more complicated than in [11-13] since the launcher’s structure and the VVP do not form a shorted coaxial line, but rather a cascade of multi-conductor coaxial lines (analytical formulations are less evident).

5. Conclusion

This paper summarizes the RF design of the WEST ICRH launchers conceived by an international team and led by the CEA/IRFM. Starting from the TS Prototype 2007 launcher, the coupling resistance has been boosted and the nominal frequency optimized to 55MHz with a bandwidth covering the 48-60MHz range. Load-resilience has been enhanced by optimizing the bridge and the two-stage impedance transformer. A Faraday Screen with minimal RF-sheaths power losses over the side limiters has been chosen. Note that the generators are being upgraded and the launchers are equipped with several arc-detection systems. Work is ongoing on the simulation of matching and control algorithms using in-house-developed RF network solvers.

References


![Fig.5. Electrical response of the IT and the RW. The shaded regions correspond to VSWR<2.](image-url)