PROGRESS TOWARDS DEVELOPMENT OF PROTOTYPE RADIO FREQUENCY SOURCE FOR ITER ION CYCLOTRON RESONANCE HEATING SYSTEM

[1]AKHIL JHA, [1]MANOJ PATEL, [1-2]AJESH PALLIWAR, [1]ROHIT ANAND, [1]SUNIL DANI, [1]GAJENDRA SUTHAR, [1]KARTIK MOHAN, [1]HRUSHIKESH DALICHA, [1]PARESH VASAVA, [1]ULHAS DETHE, [1]NAVEEN KUMAR MAURYA, [1]DIPAL SONI, [1]SRIPRAKASH VERMA, [1]NAVNIT KUMAR, [1]APARAJITA MUKHERJEE, [1]RAGHURAJ SINGH, [1]KUMAR RAJNISH AND [1]RAJESH G. TRIVEDI

[1]ITER-India, Institute for Plasma Research, Gandhinagar, Gujarat-382428, India
[2]ITER Organization, Route de Vinon sur Verdon, CS 90 046, 13067 St Paul Lez Durance, France

Email: akhil.jha@iterindia.in

1. ABSTRACT

The Radio frequency (RF) source for the ITER Ion Cyclotron Resonance Heating (ICRH) system includes two parallel RF amplifier chains combined at the end stage to deliver an output power of 3 MW at VSWR 1.5 in the frequency range of 40 to 55 MHz [1]. The first of a kind (FOAK) RF source design requires delivery of 3MW RF power for pulse length of 3600 sec with load VSWR of 1.5 at all the reflection phase angles. Further -1dB bandwidth for ±1MHz about any central frequency is required without tuning any cavity elements. The individual RF chain is a cascade of three amplifiers; pre-driver (10 kW), Driver (120 kW), and final stage capable of delivering output power of 1.6 MW in the frequency range of 36 to 60 MHz. Since no single RF tube could demonstrate such performance initially, the qualification of the end-stage tube along with the amplifier chain (for ITER RF source specifications) has been performed during phase 1 (also called the R&D phase) [2] through competitive assessment of Diacrode® [3] and Tetrode [4] based technologies. Further, to execute the next phase (prototype RF source) the end-stage power combiner has been developed indigenously, and rigorous qualification tests have been performed on the prototype combiner [5]. The measured combiner characteristics have been validated with simulation, and performance in power combiner mode at low power (~ 5kW) and in splitter mode at high power (~ 1.5 MW) has been validated. Matched and Mismatched load simulations for the output power of 3 MW at VSWR 1.5 have been performed and corresponding electrical performance assessment of individual RF chains is done. The prototype combiner has been tested for the peak voltage levels (~21.4 kV) arising during worst reflection phase angles through the voltage standoff test setup and based on the experimental feedback the combiner design has been updated to achieve field levels below 1.45 kV/mm. To further indigenize the RF source technology, a pre-driver wide-band solid-state power amplifier stage has been developed and is planned to be integrated with the R&D RF chain. The tube-based driver stage is fabricated through Indian industries (will be part of ITER deliverable at later stages) and has been tested for a rated power level of 120kW at 13kV. The protection cards for vacuum tubes have been integrated with Auxiliary power supplies and have been tested with a driver stage tube (TH 781). The prototype RF source is currently in the design finalization stage and with early procurement activities.

2. TECHNOLOGICAL PROGRESS

As per the recent (2024) re-baselining of the ITER system, the requirement of the RF sources has been divided into two phases with 4 sources at the start of the research operation (SRO) and a balance of 5 sources in the DT phase [6]. 4 sources total will provide RF power of 12 MW out of which 10 MW will be available to couple with the plasma. The tentative layout of the prototype RF source is shown in Figure 1.

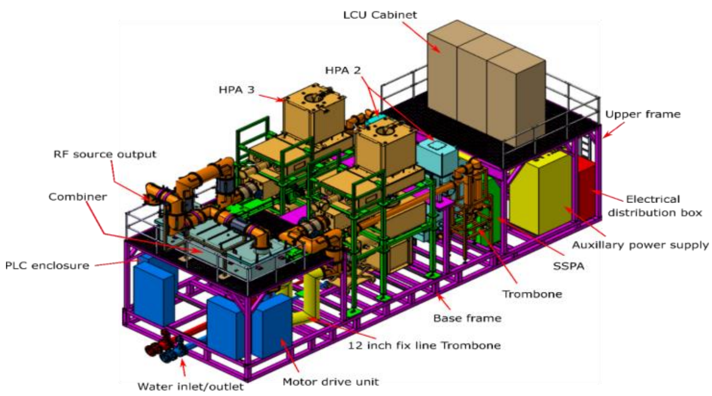
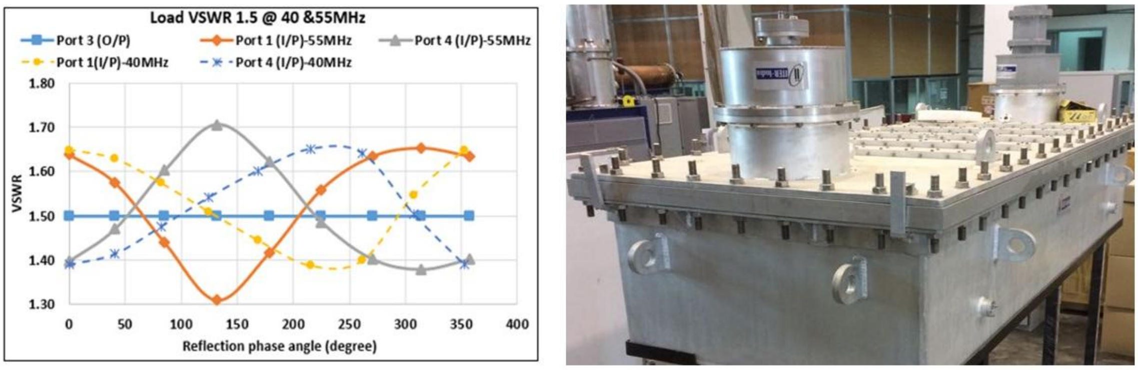


Figure 1: 3D view of RF source layout

As shown in Figure 1, two amplifier chains containing SSPA, HPA2, and HPA3 are combined at the end stage using a developed wideband hybrid combiner. The low-level RF system is accommodated in the SSPA while the control and protection systems are part of the local control unit (LCU). The grid power supplies with its protection circuits for vacuum tubes of HPA2 and HPA3 are accommodated in the auxiliary power supply (Aux PS) cabinet. While the RF design of HPA2 & 3 has been validated in phase 1; performance tests of other subsystems like combiner, SSPA, Auxiliary power supply, and LCU are in the advanced stage and the design will be finalized in the upcoming final design review.

The RF performance of the hybrid combiner was validated through simulation by simultaneous excitation of input ports (1.6 MW) with an external phase difference of 90° over both matched and mismatched loads (VSWR 1.5) [5]. The combiner efficiently combines the input power to achieve the output power of 3 MW over both load conditions with isolation better than -30dB with the load port. However, the VSWR observed at the input ports (RF chain output) is higher compared to load port VSWR as shown in Figure 2(a). Detailed analysis suggests that the individual RF chain electrical performance remains within the acceptable limit for 3.0 MW/VSWR1.5/40-55MHz. The prototype combiner was fabricated shown in Figure 2(b) and was subjected to rigorous qualification tests to verify the RF characteristics and voltage handling conditions.



(a) (b)

Figure 2 (a) VSWR response of the combiner (b) fabricated prototype combiner

The development of SSPA is in the advanced stage and the demonstration of 8 kW power in frequency range of 36 to 60 MHz is already performed with wideband coaxial combiner. Currently, tests are being performed to achieve the required bandwidth and harmonic response. The low-level RF system to control the input phase and amplitude of RF chains/sources is in a mature state and has partially been tested with developed SSPA. The new auxiliary power supply cubical with commercially available power supply units and indigenously developed protection circuits (series switch and negative current) have been tested up to the driver stage with in-house fabricated HPA2. The development of LCU is in the advanced stage with the agreed signal list and hardware architecture. Further signal conditioning modules, PLC-based motor control systems, and FPGA-based RF measurement/control circuits have been fabricated through Indian industries which are undergoing necessary qualification tests. A dedicated safety key management system algorithm has been drafted to define human access control during source maintenance and operation.
Overall the prototype RF source subsystems are in the advanced stage of development with targeted design finalization in the upcoming final design review.

REFERENCES

[1] B. Beaumonta et al., EPJ Web of Conferences, 157, 02002 (2017).
[2] R. Trivedi et al., AIP Conference Proceedings 2984, 030013 (2023).
[3] Thales Diacrod® TH 628 datasheet.
[4] CPI EIMAC 4CM2500KG datasheet.
[5] A. Jha et al., Rev. Sci. Instrum. 94, 024701 (2023).
[6] R.A. Pitts et al., Nuclear Materials and Energy, 42, 2025, 101854