Development of High Voltage and High Current Test Bed for Transmission Line Components

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Abstract. A test bed for testing of MW level transmission line components, based on the concept of standing wave resonator is being developed at ITER-India, Ion Cyclotron Heating and Current Drive (ICH&CD) lab. This test bed can be configured and operated for various lengths of the resonator for optimum requirement. Estimated 32 kV peak voltage and 650 A peak current can be achieved inside the resonator during operation with an input power level of ~ 20 kW. In this paper, detailed design and simulation results of test bed using high frequency simulator Microwave Studio (MWS) is presented. A brief description on implementation plan is described as well.

1. Introduction

The Ion Cyclotron Heating and Current Drive (ICH & CD) system has to couple 20 MW of Radio Frequency (RF) power to ITER [1] plasma for heating and driving plasma current, in the MHz frequency range [2]. The same system will also be used for wall conditioning at lower power level in between plasma shots. India is responsible to deliver total 9 number of RF sources to ITER project, 8 will be used for plasma operation and 1 will be spare. Each RF source will provide 2.5 MW of RF power at Voltage Standing Wave Ration (VSWR) 2:1 in the frequency range of 35 to 65 MHz [3]. A large number of high power transmission line components (3”, 6” and 12”) are required for connecting various stages of RF source. Analytical calculation shows that peak RF voltage and current in transmission line can reach up to 22.5 kV and 450 A during operation at 2.5 MW power level with VSWR 2:1 [4].

To test the passive transmission line components at high voltage and large current, prior to integration with main RF source system, a test bed is required. RF test facilities comprising of stub and phase shifter combination has been developed elsewhere [5, 6] for testing vacuum transmission line (especially vacuum feedthrough) and coaxial transmission line components at high voltages (~ 30 kV or higher). Resonant ring concept has been used at ORNL which utilizes directional coupler to build up high circulating power with very little reflection [7]. Such test stands are usually bulky and require more space. A compact test bed based on standing wave resonator is designed which can be configured and operated for quarter wave (\(\lambda/4\)), half wave (\(\lambda/2\)) and three quarter wave (3\(\lambda/4\)) resonator length. It is basically a “Transmission line resonator” which uses transmission line sections with various lengths and terminations (usually open- or short circuited) to form resonators [4]. Input impedance of the resonator is matched with external RF source (50 Ω) using a tunable matching L-C circuit, which provides impedance matching for different operating conditions at resonance frequency.
The Device Under Test (DUT) (i.e. transmission line components for testing) needs to be connected in-line during operation.

2. Standing Wave Setup Configuration:
Proposed resonator test bed are in three configurations, namely quarter wave \((\lambda/4)\) open circuit stub, half wave \((\lambda/2)\) short circuit stub and three quarter wave \((3\lambda/4)\) open circuit stub. All three resonator configurations can be represented with a series resonator equivalent circuit [4]. A lossy quarter wave or three quarter wave open circuit (half wave short circuit) stub and their series equivalent circuit are shown in figure 1.

![Figure 1](image1.png)

Figure 1. Quarter wave or three quarter wave open (Half wave short circuit) stub (a) layout (b) equivalent circuit.

The stub has characteristic impedance \(Z_0\) and load impedance \(Z_L = \infty\) (open stub). Input impedance of low loss \((al \ll 1 \text{ i.e. tanh}\alpha \sim al)\) coaxial quarter wave \((\lambda/4)\) stub near resonance is given as [4]:

\[
Z_{in} = Z_0 \left[ al + i \frac{\pi \Delta \omega}{2 \omega_0} \right] \quad (1)
\]

where \(\omega = \omega_0 + \Delta \omega\) where \(\Delta \omega\) is small, \(\alpha\) attenuation constant, \(\beta\) propagation constant and \(l\) is distance from load (open circuit). Comparing equation (1) with input impedance of series LCR circuit provides resistance \(R = Z_0 al\) and inductance \(L = \frac{\pi Z_0}{4 \omega_0}\). Similarly for three quarter wave \((3\lambda/4)\) open circuit stub and half wave \((\lambda/2)\) short circuit stub inductance are \(\frac{3\pi Z_0}{4 \omega_0}\) and \(\frac{\pi Z_0}{2 \omega_0}\) respectively with resistance \(Z_0 al\). Unloaded Q for stub is [4]

\[
Q_U = \frac{\beta}{2\alpha} \quad (2)
\]

where for quarter wave \((\lambda/4)\) stub\(\beta = \frac{\pi}{2 l}\), for three quarter wave \((3\lambda/4)\) stub\(\beta = \frac{3\pi}{2 l}\) and for half wave \((\lambda/4)\) stub\(\beta = \frac{\pi}{l}\).

3. Modelling and Simulation
3.1. Quarter wave \((\lambda/4)\) and Three Quarter wave \((3\lambda/4)\) open circuit stub:
Modelling and simulation of 12inch Standing Wave Resonator was performed with CST Microwave Studio (MWS) software. The detail cut view of CST model of 12inch coaxial open circuit resonator is shown in figure 2. Open circuit stub is connected with port 1 (indicated in figure 2) of 12inch coaxial TEE (denoted in figure as TEE1). Length of stub \((l_0)\) is decided depending on the quarter wave \((\lambda/4)\) and three quarter wave \((3\lambda/4)\) mode of operation. Port 2 of coaxial TEE 1 is extended and terminated with a short circuit plunger. Port 3 of TEE 1 connected with a coaxial capacitor. Capacitor is formed by introducing a discontinuity in the inner conductor. The inner conductor in capacitor is made in two
parts; one with larger diameter provides a 29.6 \( \Omega \) section which is fixed and the other 107.7 \( \Omega \) section with smaller diameter slides in and out of the larger diameter section. The overlapping area between two inner conductor sections decides the resultant capacitance of the coaxial capacitor. Inner conductor of 107.7 \( \Omega \) section is extended out of the resonator using Teflon rod (denoted in the bottom right of figure) which will be connected to an external drive for tuning the capacitor. To fulfil the above purpose a coaxial TEE (denoted as TEE2) is used. Port 4 of the TEE 2 is used for extending out the Teflon rod and port 5 is reduced in 3-1/8inch port using a 12inch to 3-1/8 inch reducer. RF power is fed to the resonator through 3-1/8 inch input port.

![CST model of 12inch coaxial open circuit resonator](image)

**Figure 2.** CST model of 12inch coaxial open circuit resonator

Figure 3(a) and 3(b) shows the line diagram and lumped element equivalent of open circuit resonator. Input impedance \( Z_{in} \) of the open circuit stub is matched with the RF source impedance \( Z_0 \) using L-C matching circuit. This matching circuit contains 12inch short circuit stub \( L_o \) and 12inch coaxial capacitor \( C_o \) as shown in figure 2 and 3. The coaxial capacitor is connected in series arm and short circuit stub is connected in parallel arm. Both the circuit components are made tuneable so that they can be used in all three resonator configurations. The characteristics impedance \( Z_o \) of Stub, TEE and reducer section is 50 \( \Omega \).

![Coaxial open circuit resonator equivalent (a) line diagram (b) lumped circuit](image)

**Figure 3.** Coaxial open circuit resonator equivalent (a) line diagram (b) lumped circuit

Figure 4(a) and 4(b) shows smith chart and S-parameter simulation results for open circuit resonator in the quarter wave configuration. Input impedance \( Z_{in} \) of open circuit quarter wave stub at 43.72 MHz (computed at port 3 of TEE1) is 0.87 + j98.99 \( \Omega \). Corresponding equivalent inductance is \( L_{eq} = 360.54 \ \text{nH} \) and required capacitance value to achieve resonance at 43.72 MHz is \( C_o = 36.79 \ \text{pF} \). The input return loss (S11) of resonator at source port at resonance frequency 43.72 MHz is – 28 dB as shown in figure 4(b).
The resonator was simulated in quarter wave configuration for an input RF power of 20 kW. Peak voltage and peak current level inside the resonator were computed using inbuilt current and voltage probes. Distribution of the voltage and current along the length ($l_o$) (see figure 2) of open circuit stub (taking centre of TEE1 as reference) is shown in figure 5(a) and 5(b) respectively. The computed max voltage and current level were ~ 32.1 kV at the position of open circuit and ~ 522.4 A near the TEE1 centre respectively.

With above defined method resonator was simulated for three quarter wave (3λ/4) configuration. Length ($l_o$) of the open circuit stub was increased from ~ 1 m to ~ 4 m. The computed input impedance ($Z_{in}$) of stub is $0.48 + i86.19 \, \Omega$. The equivalent inductance $L_{eq} = 279.88 \, nH$ corresponding capacitance value to achieve resonance at 49.04 MHz is $C_o = 37.67 \, pF$. The peak voltage and peak current level in the resonator reached up to a maximum value of ~ 32.7 kV (at 1.1 m from centre of TEE1) and 651.5 A (at 2.6 m from centre of TEE1) for an input RF power of ~ 20 kW.
Distribution of the voltage and current along the length \( l_o \) of open circuit stub (taking centre of TEE1 as reference) is shown in figure 6(a) and 6(b) respectively.

![Voltage distribution along open stub](image-a)

![Current distribution along open stub](image-b)

**Figure 6.** Distribution along open stub length \( l_o \) (3\( \lambda \)/4 configuration) (a) Peak voltage value (b) Peak current value.

### 3.2. Half wave (\( \lambda/2 \)) short circuit stub

In half wave configuration stub is shorted with a metal plunger at \( \sim 2.55 \)m from TEE1 centre. The computed input impedance \( Z_{in} \) of stub is \( 0.59 + i84.73 \) \( \Omega \). The equivalent inductance \( L_{eq} = 272.25 \) \( nH \) corresponding capacitance value to achieve resonance at 49.56 MHz is \( C_p = 37.91 \) \( pF \). The peak voltage and peak current level in the resonator reached up to \( \sim 32.1 \) kV (at 1.1 m form centre of TEE1) and 646.3 A (near the short position) for an input RF power of \( \sim 20 \) kW. Distribution of the voltage and current along the length \( l_o \) of short circuit stub (taking centre of TEE1 as reference) is shown in figure 7(a) and 7(b) respectively.

![Voltage distribution along shorted stub](image-c)

![Current distribution along shorted stub](image-d)

**Figure 7.** Distribution along short circuit stub length \( l_o \) (\( \lambda/2 \) configuration) (a) Peak voltage value (b) Peak current value

In above three configurations the stub is critically coupled with the external L-C matching circuit at resonance frequency. Thus loaded \( Q \) is approximately half of the value of unloaded \( Q \). The loaded \( Q \) of resonator \( (Q_L) \) computed from simulation is shown in table 1:

| Configuration            | \( Q_L \) of resonator (critical coupling)[4] |
|-------------------------|---------------------------------------------|
| \( \lambda/4 \) open circuit | 6696                                        |
| 3\( \lambda/4 \) open circuit | 7699                                        |
| \( \lambda/2 \) short circuit | 7170                                        |

Table 1. \( Q_L \) of coaxial resonator
4. Implementation as Transmission line test bed
Out of the three resonator configuration, quarter wave and three quarter wave resonators will be used depending on the length of the DUT’s to be tested and the half wave shorted resonator configuration is useful to test shorting plunger and finger contacts in high current conditions. DUT’s will be connected as a part of resonator section along the length (l0) of open or short circuit stub. Figure 8 shows 12 inch directional coupler connected in-line (as an example of DUT). Volume loss and breakdown strength of dielectric supports will be verified. Figure 8 shows position of view ports near the high voltage region for optical arc detection. Analytical calculation shows that copper inner conductor temperature rises up to 185 °C for heat loss of 1.17 kW. Dynamic flow of dry air through annulus region will be used to actively cool the inner conductor. The 4inch gas inserts will be used to inject and take out dry air as shown in Figure 8. The tuning of the coaxial capacitor will be performed through external motor drive attached to extended inner conductor. Minimum tuning accuracy of capacitor is 1mm for fine input matching. For example, a change in overlapping length of 1mm varies capacitance by ~ 420 pF which changes return loss from -28 to -19 dB at source port (in quarter wave configuration). The peak RF voltage level inside the resonator will be measured with calibrated 12inch loop directional coupler and voltage probes installed in the high voltage region shown in figure 8.

5. Conclusion
Test bed for transmission line components based on concept of quarter wave, three quarter wave and half wave resonator is proposed. Detailed design, modelling and simulation conducted using CST MWS. A coaxial type tuneable capacitor is implemented to match the impedance of shorted/open stub with the RF source impedance. With an input power of ~ 20 kW, the peak voltage inside the resonators can be reached up to ~ 32 kV which is above the required 22.5 kV peak voltage level during operation at 2.5 MW with VSWR 2:1. The peak RF current at the short position in the half wave shorted stub is ~ 646 A which is high enough to test the present finger contacts. A detailed description for further implementation of the resonator configurations as a practical transmission line test bed is provided.

References
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