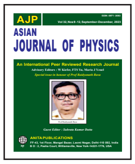

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Development of liquid stub tuner and liquid phase shifter for antenna-plasma impedance matching for high power RF experiments

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Dedicated to Prof B N Basu

Tokamak plasma discharges using radio frequency (RF) power are being very extensively used for plasma pre-ionisation, breakdown, heating and current drive and wall conditioning. For RF heating of plasma, impedance matching plays an important role. Impedance of plasma consists of resistive as well as inductive part. Resistance varies in the range of 0.5 to 5 Ohm, while susceptance part varies from 10 to 200 Ohm. The impedance of RF generator is normally 50 Ohm. This necessitates the matching of plasma impedance with the source impedance for maximum power transfer. The conventional matching is done using conventional stub tuners and conventional phase shifters. At high RF power to the plasma where current is of the order of kA for Ion Cyclotron Resonance (ICR) range of frequencies, conventional stub tuner that have an electric short called plunger, moving between inner and outer conductor of coaxial rigid transmission line develops an arcing. In a similar way as in case of stub tuner, the phase shifter also has finger contacts between the moving inner and outer conductors. Theses finger contacts have spring action in order to make movement feasible between inner and outer conductors. Due to inherent ovality in copper tubes, used for inner and outer conductors, the contact between inner and outer conductors becomes non-uniform and hence many a time gets spark developed for high value of RF current flowing through these finger contacts between inner and outer conductors. In order to avoid these sparks, liquid stub tuner (LST) and liquid phase shifters (LPS) are developed where there is no metallic moving parts. In LST and LPS only liquid moves. As the dielectric constant (ϵ_r) of liquid is different from the air, hence moving liquid changes the wavelength of RF wave being passed in LST and LPS. This in turn changes relative length (l/λ), where l is length and λ is wavelength of the medium in which RF wave is passing. The medium may be air or the liquid being used. This concept is used in LST and LPS for impedance matching at high power ICR frequencies. Here, in this paper we present design and simulation results of LST and LPS.

Keywords: Liquid stub tuner, liquid phase shifter, plasma, impedance matching.
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1 Introduction

Radio Frequency power in the range of few 10's of MHz is required for Ion Cyclotron Resonance Heating (ICRH), Wall Conditioning, pre-ionisation and start-up experiments for plasma. ICR heating has been one of the promising techniques for non-inductive heating for future Fusion Power Reactors called DEMO or DEMOnstration. [1]. Experiments on Joint European Torus (JET) with ITER Like Wall (ILW) for second phase of Deuterium Tritium Experiments (DTE2) have shown that ICRH plays an important role for keeping heavy impurities away from the plasma center for increasing the core ion temperature boosting fusion performance [2]. In super-conducting tokamaks conventional way of wall conditioning like glow discharge etc. does not work in presence of continuous magnetic field. Ion Cyclotron Resonance Frequency (ICRF) plasma discharge assisted wall conditioning has been very promising technique for such tokamaks

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[3]. In Aditya and superconducting Steady State Tokamak-1 (SST-1), RF at 20-100 MHz is being used for pre-ionisation [4] and Ion Cyclotron Resonance Heating (ICRH) [5]. Proper coupling of RF power to the plasma for heating requires impedance matching of RF source impedance to the plasma impedance [6]. Plasma impedance varies in the range of 0.1-10 Ohm resistance and 50-200 Ohm reactance. RF power sources are normally of 50 Ohm impedance [7].

Impedance matching is performed using stub tuners and phase shifters. Conventional stub tuner has a metallic plunger moving between inner and outer conductors. Finger contacts are used in the moving plunger to facilitate the movement of plunger and flow of RF current through it. The finger contacts make the movement of plunger and hence the flow of RF current possible between inner and outer conductors. For Mega Watt level of power for ICR Heating of plasma, RF current of kA magnitude flows between inner and outer conductors through the plunger and the finger contacts. But there is a problem of ovality in inner and outer conductors which are made up of Electronic Tough Pitch (ETP) copper tubes. Due to the ovality, there could be a loose contact between inner and outer conductors and hence there is a possibility of electric spark between inner and outer conductors when the RF current flows between the two. In order to get rid of this problem of spark and subsequent melt down of finger contacts, Liquid Stub Tuner (LST) has been proposed [8].

LST has a dielectric liquid between inner and outer conductors. The wavelength of the RF wave decreases by a factor of $1/\sqrt{\epsilon_r}$, where ϵ_r is the dielectric constant of the liquid. As wavelength decreases by a factor of $1/\sqrt{\epsilon_r}$, relative length (l/λ) of LST increases by the same factor. So in effect, by changing the height of the liquid between inner and outer conductors, the length is changed. This is the concept used in liquid stub tuner. And as there is no movement of metallic part so no chance of any spark between inner and outer conductors.

Similar is the case with Liquid Phase Shifter (LPS). In LPS, the phase angle βl,where $\beta = 2\pi/\lambda$ is changed by changing the liquid height. By varying the height of the liquid between inner and outer conductors, the phase angle is changed [9]. In conventional phase shifter, one set of inner and outer conductors moves inside another set of inner and outer conductors in order to increase or decrease the overall length and hence the phase of the phase shifter. This movement is carried out by using finger contacts between inner and outer conductors and these finger contacts give spark when there is loose contacts. LPS eliminates this problem.

2 Working Principle

A. Liquid Stub Tuner

Liquid stub tuner works on the principle that the wavelength of a travelling wave depends upon the dielectric constant of the medium and it decreases with the increase of the dielectric constant as

$$\lambda = \frac{\lambda_0}{\sqrt{\epsilon_r}} \qquad (1)$$

where λ and λ_0 are the wavelengths of RF wave in liquid and air, respectively. ϵ_r is the dielectric constant of the medium.

The input impedance in a coaxial transmission line is given by [10]

$$Z_{in} = Z_0 \frac{Z_L + jZ_0 \tan\beta l}{Z_0 + jZ_L \tan\beta l} \qquad (2)$$

where Z_{in}, Z_0, and Z_L are input impedance, characteristic impedance and load impedance in the transmission line, respectively.

The input impedance of a short circuited stub ($Z_L = 0$, in the above equation) is given by

$$Z_{in} = jZ_0 \tan\beta l \qquad (3)$$

where $\beta = 2\pi/\lambda$ is the wave number of RF wave passing through the transmission line and l is the length of the transmission line. A liquid stub is formed by filling a liquid (silicon oil in our case) in the short circuited stub as shown in the figure below.

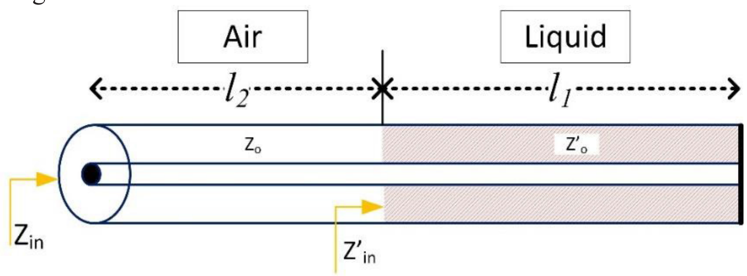

Fig 1. Schematic of liquid stub tuner

The characteristic impedance Z_0' of the liquid part of the stub is given by

$$Z_0' = \frac{Z_0}{\sqrt{\epsilon_r}} \tag{4}$$

As shown in figure, l_1 and l_2 are the lengths of liquid and air part of the stub, respectively.

Z_{in}' is the input impedance at the liquid end of the stub and Z_{in} is the input impedance of the overall stub as shown in the Fig (1). Z_{in}' will be given as

$$Z_{in}' = j\, Z_0' \tan\beta' l_1 \tag{5}$$

where β' is the wave vector in the liquid and is given by

$$\beta' = \beta\sqrt{\epsilon_r} \tag{6}$$

The input impedance Z_{in} at the end of the liquid stub is given by

$$Z_{in} = Z_0 \frac{Z_{in}' + jZ_0 \tan\beta l_2}{Z_0 + jZ_{in}' \tan\beta l_2} \tag{7}$$

where Z_{in}' acts as a load for air part of the liquid stub tuner. Substituting the value of Z_{in}' from Eq (5) into Eq (7), the overall input impedance of the liquid stub becomes,

$$Z_{in} = Z_0 \frac{jZ_0' \tan\beta' l_1 + jZ_0 \tan\beta l_2}{Z_0 - Z_0' \tan\beta' l_1 \tan\beta l_2}$$

Or the normalised impedance or reactance of the stub becomes

$$\bar{Z}_{in} = j\frac{(Z_0'/Z_0)\tan\beta' l_1 + \tan\beta l_2}{1 - (Z_0'/Z_0)\tan\beta' l_1 \tan\beta l_2} \tag{8}$$

As the stubs are connected in parallel in the transmission line so the use of susceptance will make work easier. The susceptance of the liquid stub tuner is

$$\bar{Y}_{in} = j\frac{(Z_0'/Z_0)\tan\beta' l_1 \tan\beta l_2 - 1}{(Z_0'/Z_0)\tan\beta' l_1 + \tan\beta l_2} \tag{9}$$

At 81MHz, λ = 3.7037 meters. For silicon oil with $\epsilon_r = 2.3$, at $l = 0.3\,\lambda$, we get effective length $l = 0.5\,\lambda$ of conventional stub. This is the added advantage of liquid stub that the total length reduces by around 40% [11]. As the resistive part of plasma impedance is very low, so a very high susceptance value is required for matching. For very high susceptance value, the required length in conventional stub is 0 λ or 0.5 λ. Practically, 0 λ or 0 length is difficult to implement. So 0.5 λ is only option. In liquid stub, this 0.5 λ can be obtained with 0.3 λ length, which has an added mechanical advantage at MHz range of frequencies, where λ is in the range of meters.

B. Liquid Phase Shifter (*LPS*)

Conventional phase shifter has two disadvantages for high power applications. The first disadvantage is that one conductor moves inside another to change physical length and hence phase of the propagating RF wave. For high power applications, 6″ or 9″ size conductors are used. Getting copper or aluminium pipes of that size in non-standard dimensions are very difficult because one has to make special dye of that dimension, which will be a costly affair. Secondly, movement of large size conductors is mechanically not easy. Liquid phase shifter for that purpose is a very good alternative, it neither requires non-standard dimensional pipes nor any movement of large size pipes one into another. The wavelength of RF wave in the liquid changes as

$$\lambda' = \frac{\lambda_0}{\sqrt{\epsilon_r}} \tag{10}$$

So the wavelength of RF wave becomes smaller in liquid and hence for small change in length, large phase change is obtained [12,13]. The length in the liquid phase shifter is changed by changing the height of the liquid inside phase shifter and not by the physical movement of the transmission line conductors.

The schematic diagram of liquid phase shifter is shown in Fig 2. The total length of the liquid in the liquid stub is

$$l = 2l_1 + l_2 \tag{11}$$

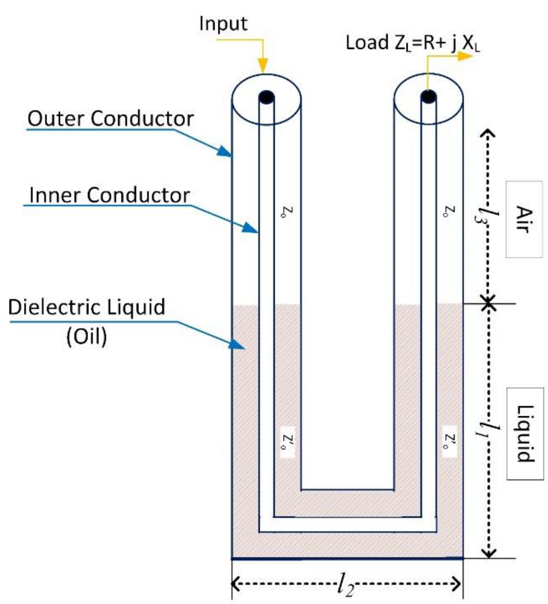

Fig 2. Liquid phase shifter

Total phase shift θ' will be

$$\theta' = \beta' l = \frac{2\pi}{\lambda'} l = \frac{2\pi}{\lambda} \sqrt{\epsilon_r}\, l \tag{12}$$

or

$$\theta' = \frac{2\pi}{\lambda} \sqrt{\epsilon_r}\, l = \beta l \sqrt{\epsilon_r} = \theta \sqrt{\epsilon_r} \tag{13}$$

So the phase shift of the liquid part of the phase shifter will be $\sqrt{\epsilon_r}$ times more than the air dielectric part of the phase shifter and hence the required length for the same phase shift will be lesser in the liquid phase shifter. This is an added advantage along with the electric spark free phase change because in LPS no metallic moving part is there.

C. Matching Requirement of LPS

In order to match a load, the real and imaginary parts of the transformed impedance need to be known at transmission line location. Let the impedance at the end of the LPS is Z_L, where

$$Z_L = R + j\,X_L \tag{14}$$

The impedance will transform as per the following Equation

$$Z_{in} = Z_0' \frac{Z_L + jZ_0' \tan\beta' l}{Z_0' + jZ_L \tan\beta' l} \tag{15}$$

By putting Eq (14) into Eq (15) and separating into real and imaginary parts, the transform impedance at the input end of the LPS will be

$$Re\,(Z_{in}) = Z_0' \frac{R(Z_0' - X_L \tan\beta' l) + R \tan\beta' l\,(X_L + Z_0' \tan\beta' l)}{(Z_0' - X_L \tan\beta' l)^2 + R^2 \tan^2 \beta' l} \tag{16}$$

and

$$Im\,(Z_{in}) = Z_0' \frac{(X_L + Z_0' \tan\beta' l)\,(Z_0' - X_L \tan\beta' l) - R^2 \tan\beta' l}{(Z_0' - X_L \tan\beta' l)^2 + R^2 \tan^2 \beta' l} \tag{17}$$

Here, only the "l" part is variable. So by choosing "l" in such a way that $Re\,(Z_{in})$ = 50 ohm and then putting that value of "l" in Eq (17), the value of reactance or susceptance can be found. The required length of the stub tuner can then accordingly be chosen to cancel out that susceptance value and hence the matching will be achieved.

3 Result and Discussion

It has been observed that LST and LPS are the better options for matching. As there are no moving parts or no finger or spring contacts, so no chance of any electric spark or break down. At high power, electric spark is very common and it gives a frequent system shutdown due to high VSWR. Changing big size stub tuner and phase shifter is also a cumbersome and time consuming process. Other than that, the length of the stub in case of LST has also been reduced as compared to conventional stub. In conventional stub, for complete range of impedance matching, the physical length required is 0.5 λ, while in liquid stub this length reduces to 0.3 λ. As the plasma impedance has very low resistive part, there is a requirement of very high susceptance. This value of susceptance is possible at 0 or λ/2 length of the stub tuner. Getting 0 length is very difficult due to mechanical constraints and hence λ/2 is the only option. At ICR range of frequencies, these stub lengths required for impedance matching are of the order of few meters. By using LST, a reduction of 0.2 λ in physical length, i.e. from 0.5 λ to 0.3 λ, is a substantial reduction.

The measurement of LST of 1.0 m length was carried out. The length of liquid was varied which in turn vary the admittance of LST. The preferred configuration involved connecting the LST in parallel with the main transmission line. This setup effectively cancelled out the imaginary component introduced by the combined load and phase shifter, allowing for accurate admittance cancellation and hence appropriate impedance matching is obtained.

The admittance measurement of the liquid stub tuner was performed using VNA (Vector Network Analyser). The analysis of susceptance produced by liquid level variation in LST has also been performed using MATLAB code for Eq (9). The comparison between simulated and measured values is depicted in the Fig 3, which shows the good agreement between the simulation and experimental data. By utilizing the data, we can infer that varying the liquid height leads to changes in susceptance part of the stub. The varying susceptance provides impedance matching for the system using the liquid stub tuner.

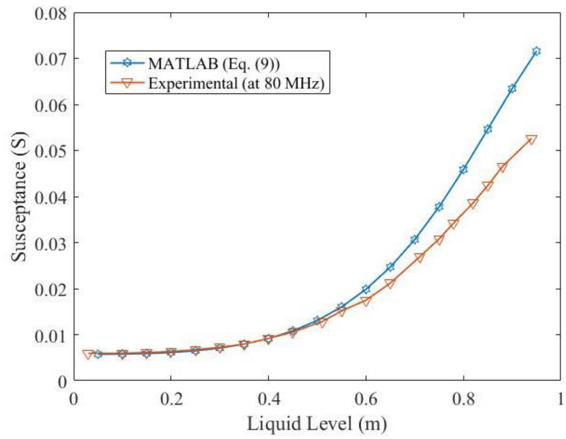

Fig 3. Liquid stub tuner testing at 80 MHz

Fig. 4. Developed liquid phase shifter.

The numerical analysis using MATLAB code has been performed for the liquid phase shifter (LPS) also. The MATLAB code was written for the transform impedance at the input end of the LPS (Fig 2). The resistance and reactance due to the phase shifter and variation of liquid level inside the phase shifter can be drawn by Eqs (16) and (17), respectively. The developed LPS is illustrated in the Fig 4. The characterization will be performed by connecting VNA at one port and the load at another port. The simulation result at 13.56 MHz for the Re(Z_{in}) and Im (Z_{in}) is presented in the Table 1. The liquid height (l_1) has been varied from 0 to 90 cm. The value of l_2 (= 15 cm) was fixed as it was same during the variation of liquid height. We have assumed that the load is connected at one port. The value of the load is taken as $Z_L = 47 + j100$ connected at one port. Experiment will be conducted to check the impedance matching using LST and LPS in comparison to conventional stub tuner and phase shifter. The transmission line size for this testing will be $1\frac{5}{8}''$ rigid coaxial line.

Table 1. Simulation result of transform load at second port due to variation of liquid height into LPS with load, $Z_L = 47 + j100$.

Liquid Height (l_2) in cm	$Re(Z_{in})$	$Im(Z_{in})$
10	6.590	–9.598
20	6.071	-7.271
30	5.626	–5.166
40	5.243	–3.261
50	4.916	–1.533
60	4.636	0.035
70	4.398	1.46
80	4.198	2.769
90	4.031	3.968

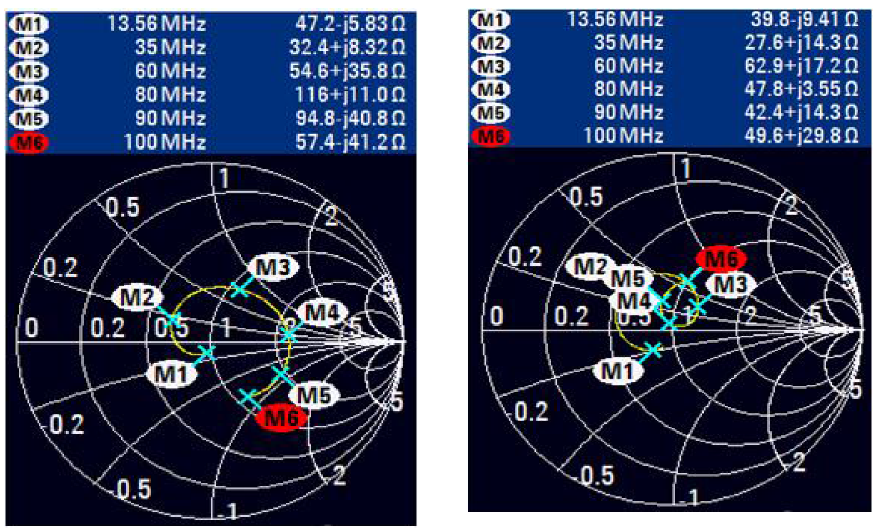

Fig 5. Smith chart plot of LPS for the transform impedance (due to 50 ohm load) for the liquid height (a) l_1 = 25 cm (b) l_1 = 60 cm at different frequencies.

The initial characterization with vector network analyser has been carried out for the developed liquid phase shifter. Figure 5 shows the smith chart plot for the transform impedance due to different liquid level at different frequencies. It can be observed from Fig 5, that the transformed impedance by phase shifter is inductive or capacitive depending upon the frequency of the wave and height of the liquid in the phase shifter. The transformed impedance of LPS observed at 90 MHz for various heights of liquid is listed in the Table 2. It has been observed that for 50 Ohm load at one port, the real part of transform impedance at other port shows the significant variation on changing the liquid level in LPS at 90 MHz (Table 2).

In conventional stub, this change would not have taken place, because the complete phase shifter has uniform characteristic impedance. But in case of liquid phase shifter, the characteristic impedance of liquid part is different from air part, so the overall impedance will change and this change will vary according to liquid height also as per the Eqs (16) and (17). This change will be taken into account in the LST and accordingly the required liquid height will be varied.

Table 2. Experimental result recored on VNA of transform load at second port due to variation of liquid height into LPS with load Z_L = 50 Ohm

Liquid Height (l_1) in cm	at 90 MHz
0	17.24 + 26.23i
10	50.19 + 81.80i
20	66.36 + 98.96i
30	114.65 + 130.03i
40	154.96 + 132.36i
50	163.12 + 114.78i
60	161.01 + 109.88i
70	159.54 + 110.53i
80	152.23 + 97.48i
90	143.95 + 86.25i

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