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Development of Liquid Stub and Phase Shifter

S. J. Wang, J. S. Yoon*, B. G. Hong*
Soong Sil University
Seoul, 156-743, Korea

Abstract

The high power RF transmission line components are required for transmitting MW level RF power continuously in RF heating and current drive system which heat the plasma and produce plasma current in fusion reactor. The liquid stub and phase shifter is proposed as the superior to the conventional stub and phase shifter. Experimental results show that they are reliable and easy to operate compared to the conventional stub and phase shifter. There is no distortion of reflected power during the raising of the liquid level. RF breakdown voltage is over 40kV. Temperature increment of the liquid is expected not to be severe. These results verify that the liquid stub and phase shifter can be used reliably in the high power continuous RF facilities.

I. Introduction

High power RF transmission line components are used for various fields which require the high RF power. Key performance required is the maximum voltage and current without breakdown, and accuracy in position reading.[1][2]

Conventional stub and phase shifter have some problem such as fabricating straight coaxial lines, local temperature increase and insulation breakdown when operating for long pulse under high power. To solve problems in conventional stub and phase shifter, innovative research and development has been performed by using liquid instead of gas for insulating dielectric material.

Electric effects of changing mechanical length of transmission line are same to the changing dielectric constant e of the medium or changing the portion of one dielectric material to the other. Liquid stub tuner uses liquid of dielectric constant e at some portion of transmission line and insulation gas of vacuum dielectric constant e_0 at the remaining portion. Let A_L is a normalized length of liquid section located at the shorted side and A_G is a normalized length of remaining gas section. Normalized length is

* Korea Atomic Energy Research Institute, P. O. Box 105, Yusong, Taejon, Korea

defined by $A=fl/b$ where f is operating frequency, l is mechanical line length and b is phase speed in the medium. Characteristic impedance ratio of liquid to the vacuum transmission line is $Z_{0L}/Z_{0G}=1/e^{1/2}$. If the conventional stub tuner shunted at the input of the load is compared to the liquid stub located at the same position, following equation is hold true for the same electrical effect.[1]

$$\frac{1}{\tan 2pA}=\frac{1-\frac{Z_{0L}}{Z_{0G}}\tan 2pA_G \tan 2pA_L}{\tan 2pA_G+\frac{Z_{0L}}{Z_{0G}}\tan 2pA_L} \tag{1}$$

Liquid stub configured to have A_L and A_G as the portion of liquid and gas results same electrical effects with the conventional stub having length A. So A in the equation (1) can be called normalized effective stub length. Figure 1 shows calculated result of equation (1) for 5 different lengths of liquid stubs. A_0 is the mechanical stub length normalized to the vacuum wavelength. Normalized effective stub length A increases with the liquid level. Dielectric constant is chosen to be e=2.72. Large A_0 makes length variation large but there are unnecessary flat region when A_0 is larger than 0.4. To make wider length variation window but mechanically small stub tuner, A_0 =0.3 should be chosen.

The liquid phase shifter is similar to the liquid shorted stub. It uses liquid dielectric material as wave propagation medium at some portion of the transmission line. The difference is that it has 2 symmetrical ports instead of shorted end as the stub has. Phase shift between the 2 ports can be varied by changing the ratio of the length of the liquid section to the total length and is roughly proportional to the ratio if the load is matched. The liquid phase shifter has no advantage when it is inserted at the matched line. Because the liquid phase shifter uses different characteristic impedance of transmission line there are always 2 discrete boundaries having reflection ratio

$$r=\frac{Z_{0G}-Z_{0L}}{Z_{0G}+Z_{0L}}. \tag{2}$$

If the liquid of dielectric constant $e=2.72$ is used, reflection ratio become $r\sim 0.25$ which is not acceptable. But advantages are same to the liquid stub when the liquid phase shifter is inserted at the unmatched line, i.e. used as a part of tuner.

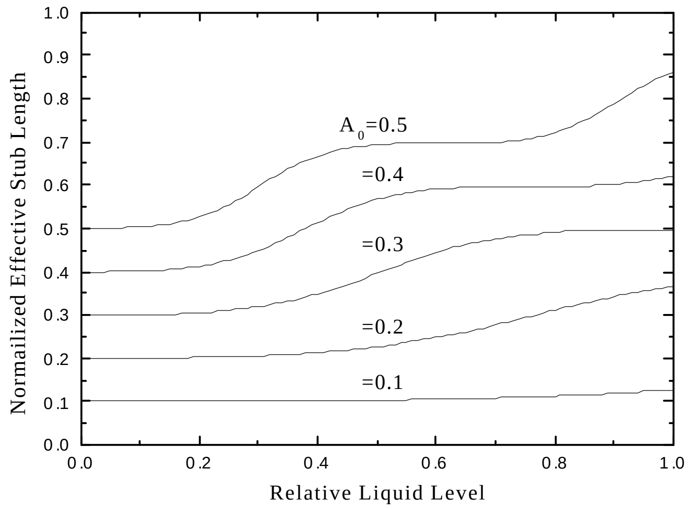

Figure 1. Electrical length of liquid stub with the various stub length.

II. Fabrication of the Liquid Stub and the Liquid Phase Shifter

Silicon oil (Dimethyl Polysiloxane) is used as the dielectric liquid medium. Characteristic of the silicon oil is listed in table (1). The dielectric constant, ***e*** is 2.72 and dielectric loss tangent, *tand* is 10^{-4} in the low frequency at 25°C. Vapor pressure is known to be less than 0.1mHg below 25°C. Low dielectric loss and vapor pressure are the reason of the choice. When RF power is applied to the silicon oil, the temperature will be increased due to the dielectric loss. This topic will be discussed on the conclusion.

4m long stub is fabricated using 6-1/8 ” nominal diameter copper transmission line. One end is electrically shorted and mechanically closed. The other end has flange to meet T-junction. Between both ends, 3m far from the shorted end, separating disc made by Teflon is inserted to stop the diffusion of vaporized oil to the other part of transmission line. The stub is installed vertically so that the potion of the liquid is maintained by the gravity. Liquid in-outlet is located at the bottom, shorted end. 8 capacitive voltage probes and 2 thermocouples are arranged through the holes on the outer conductor.

Voltage probe is made by simple capacitive coupling tip and termination resister. The output voltage V_0 is scaled by

$$V_o = -jwCRV \quad (3)$$

where *w* is operating angular frequency, *C* is coupling capacitance, *R* is termination resistance and *V* is voltage to be measured. Calibration is done with applying low RF power to the stub without liquid and measuring probe output voltage. Comparing the signal with the calculated voltage is shown in figure 2. Empty circles are measured voltages and the solid line is calculated voltage distribution. When the liquid is supplied, coupling capacitance will be increased proportionally to the dielectric constant, and according to equation (3), coupling voltage is known.

The liquid phase shifter is made of 9-1/16" nominal diameter aluminum transmission line. Two identical 3m long liquid phase shifter is connected with U shaped 1.6m spacing elbow as can be seen in figure 3. By the configuration, the position of the liquid phase shifter as well as liquid level can be varied. At the bottom of each phase shifter, there are Teflon disc which separate liquid in upper phase shifter section and gas in lower spacing elbow. Conductor, Teflon and liquid or gas meet at this region. Previous research results[] said this region can be easily damaged by frequent electrical breakdown. The study of the material and shape of the disc will be reported in the near future. Other diagnostic tools and liquid supplying systems are same to the liquid stub.

Specific Gravity (25^{o}C)	0.960
Viscosity (25^{o}C)	50mm^{2}/s
Vapor Pressure (<260^{o}C)	<0.1mHg
Specific Heat (25^{o}C)	0.36cal/g·^{o}C
Thermal Conductivity (25^{o}C)	3.7x10^{-4}cal/cm·sec·^{o}C
Resistivity*	>1x10^{14}Ω·cm
Dielectric Strength*	>50kV/2.5mm
Dielectric Constant (50Hz)*	2.72
Dielectric Loss (tanδ)*	<0.0001

*-Water <50ppm

Table 1. Characteristics of silicon oil (Dimethyl Polysiloxane)

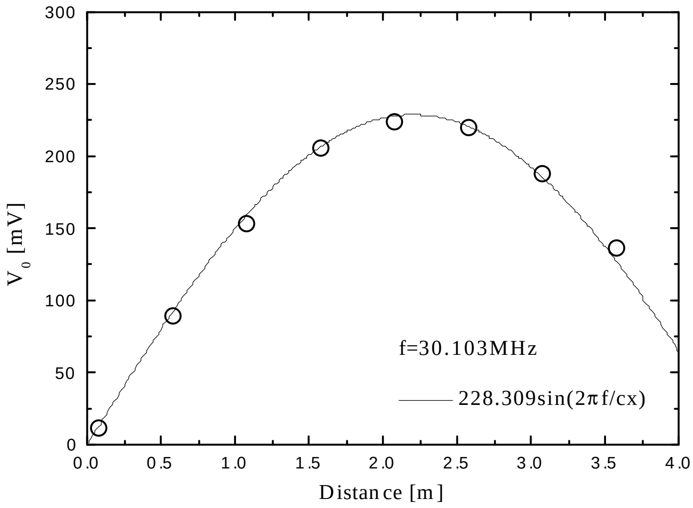

Figure 2. Comparing voltage probe output signals with the calculated voltage along the stub without liquid. Empty circles are measured voltages.

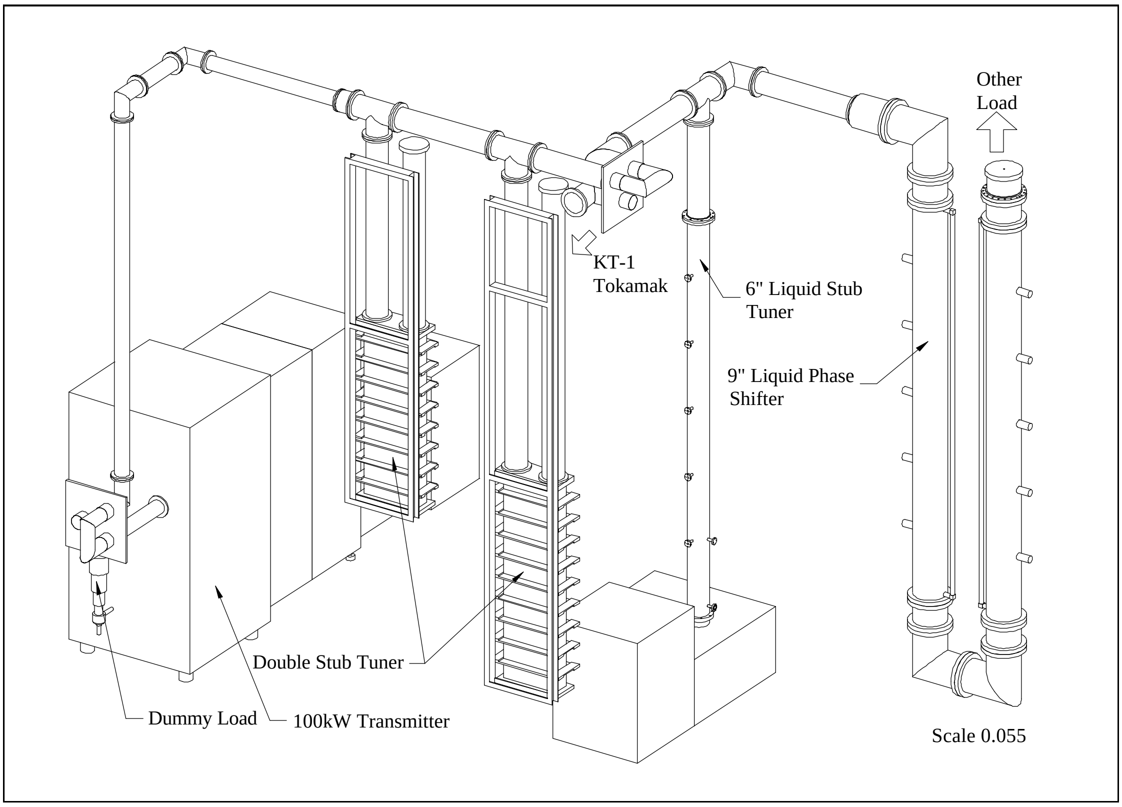

Figure 3. The overall view of the RF test facility

III. Experimental Setup

The overall view of the RF test facility is shown on figure 2. Control cables, oil and gas lines, supporting structures are omitted for simplicity. 100kW power transmitter having 2 intermediate driving stages is capable of producing 28-32MHz RF power continuously. Almost any load, virtually from shorted to open, can be matched to the transmitter output impedance through conventional double stub tuner. Some limitations are frequent, random break down at the voltage larger than 30kV and gradual degradation of the finger stocks. The later limitation causes expecting of tuning position hard and sometimes, unexpectedly, unable tuning at particular load impedance. When RF power is applied, moving contact position is prohibited by the reason.

Liquid stub tuner and liquid phase shifter under developing are shown at the right hand side of figure 3. RF power is switched to either test facility or KT-1 tokamak for ICH study. The length of stub tuner is 4m from the shorted bottom end to the T-junction. Silicon oil can be supplied up to 3m and the flange for the separating disc mentioned on section II is shown. The liquid phase shifter is installed in series to the other transmission line and its output is opened. For the test the other load, i.e. vacuum feed through or ICH antenna under developing, the output of the liquid phase shifter is connected to the load.

IV. Experimental Results

Cold test results of the liquid stub are shown in figure 4 and 5. As liquid level raises, input reactance of the stub varies from –35W to 35W while equivalent line length varies 2m. Equivalent line length is defined as normalized effective stub length in equation (1) multiplied by the vacuum wavelength, i.e. electrical length of the stub at the given frequency. All the results agree exactly with the calculated values.

One notable qualitative result is that there is no distortion of reflected RF power during liquid level raised when the low power, 0dBm, is supplied to the stub. Even a carefully designed finger stock type stub shows severe distortion of reflected power due to the imperfection of the finger stock. This result shows that the liquid stub can be used to match time varying load without disconnect the RF power if liquid level variation speed is faster enough than the load variation speed. Another advantage is that the physical volume of the liquid stub is smaller than the conventional stub. The liquid stub is 4m long and 4-6m variation of electrical length at 30MHz. At least 6m long conventional stub is needed to have the same length variation.

Figure 6 shows voltage distribution of the liquid stub. An empty circle is measured data point with the probe and the solid curve is the fitted result with the data point. Figure 7 is another voltage distribution with the lower RF power than the previous one and all 8 voltage probes are used to measure voltage. This verifies that the fitted curve with a probe data is a reasonable voltage distribution of the system. The highest voltage applied to the stub is ~44kV without electrical breakdown with pulse width 100msec.

With the conventional stub tuner as a part of the RF test facility, the rated voltage is too high to maintain continuously.

Figure 8 shows phase shifting effect of the phase shifter at 30MHz with low power. This test is done with matched load and as mentioned in section I, phase shift is almost linear to the liquid level but not exactly proportional. Voltage applied to the liquid phase shifter is shown in figure 9. The distance is measured from opened end. Maximum voltage at the boundary of liquid and gas exceeds 50kV. As the case of the liquid stub, time duration of the RF power is 100msec.

Table 2 is a major experimental results of the liquid stub and the phase shifter.

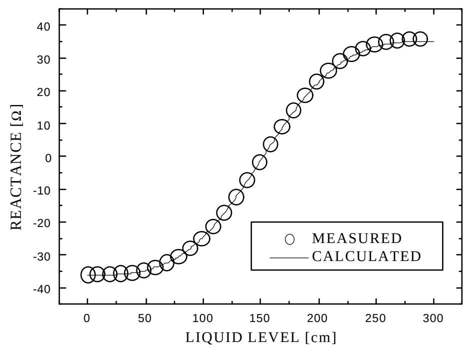

Figure 4. Variation of shorted liquid stub reactance v. s. liquid level

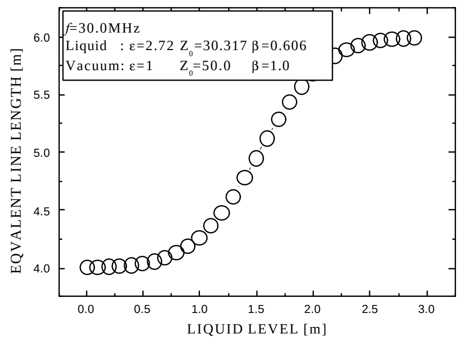

Figure 5. Equivalent line length v. s. liquid level

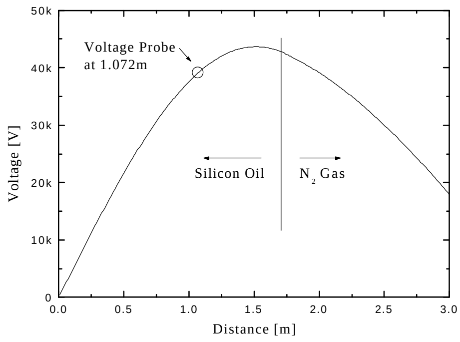

Figure 6. Measured voltage distribution along the stub with high power

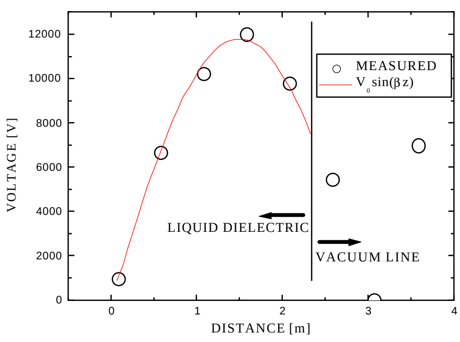

Figure 7. Voltage distribution along the stub with low power

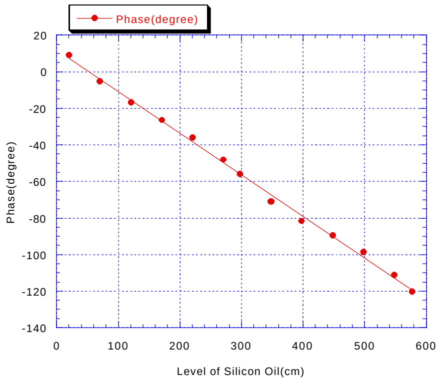

Figure 8. Phase variation of the liquid phase shifter

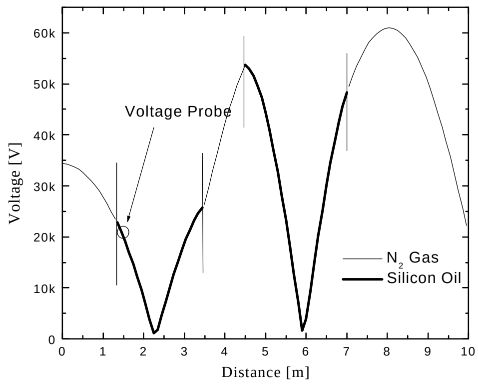

Figure 9. Voltage distribution of the liquid phase shifter

	Liquid Stub	Liquid Phase Shifter
Mechanical Length	4m	8.8m
Length Variation (30MHz)	2m	3.6m
Phase Variation (30MHz)	N/A	130°
Maximum Voltage (100msec)	44kV	53kV

Table 2. Experimental results in liquid stub and liquid phase shfter

V. Conclusion

Dielectric loss of the liquid is small ($10^4 \tan d \sim 1$) but is not ignorable when the RF power is fed continuously. If RF voltage V_{RF} is applied to the coaxial line having radius a and b for the inner and outer conductor, electric field $E(r, z)$ is as following.

$$E(r,z) = \frac{V_{RF}}{\ln(b/a)}\frac{1}{r}\sin(2p\,l_L z) \qquad (4)$$

RF dielectric power loss, P_L is an integration of electric field in equation (4).

$$\begin{aligned} P_L &= \frac{1}{2}ee_0 \tan dw \int_0^z \int_a^b 2pE^2(r,z)drdz \\ &= pee_0 \tan dw \frac{V_{RF}^2}{\ln(b/a)}\left(\frac{1}{2}z - \frac{l_L}{8p}\sin\left(\frac{4p}{l_L}z\right)\right) \end{aligned} \qquad (5)$$

where l_L is RF wavelength in the dielectric medium. If we assume that the surface of liquid is at 1/4 wavelength position P_L becomes

$$P_L = \frac{p}{8} l_L ee_0 \tan dw \frac{V_{RF}^2}{\ln(b/a)}. \qquad (6)$$

When $10^4 \tan d = 2$, $w = 2p \times 30(MHz)$, $\ln(b/a) = 0.835$, $e = 2.72$, and assuming constant dielectric loss and the system is thermally insulated with heat capacity of liquid 0.36cal/g and 5minute continuous power, temperature increment ΔT is

$$\Delta T = 0.012V_{RF}^2,\ V_{RF} \text{ in } kV. \qquad (7)$$

When voltage V_{RF} is 35kV, ΔT is only 15°C and is acceptable.

We developed the liquid stub and the phase shifter for the high power RF components. It is known that they are reliable and easy to operate compared to the conventional stub and phase shifter. There is no distortion of reflected power during the liquid level is raised. As can be seen in table 2 and remembering that the experiment limits come from conventional stub tuner, breakdown voltage is higher than that of the finger stock type stub or phase shifter. Temperature increment of the liquid is expected not to be severe but should be studied experimentally with continuous high power.

Reference

[1] R. Kumazawa et al., Proceedings of the 19th symposium on Fusion Technology, Vol. 1, 617 (1997).

[2] B.G. Hong et al., KSTAR ICRF system for long pulse operation, 10th International Toki conference, Jan. 17 - 21, 2000.