BROADBAND ANTENNA MATCHING NETWORK DESIGN AND APPLICATION FOR RF PLASMA ION SOURCE*

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Abstract

The RF ion source at Spallation Neutron Source has been upgraded to meet higher beam power requirement. One important subsystem for efficient operation of the ion source is the 2MHz RF impedance matching network. The real part of the antenna impedance is very small and is affected by plasma density for 2MHz operating frequency. Previous impedance matching network for the antenna has limited tuning capability to cover this potential variation of the antenna impedance since it employed a single tuning element and an impedance transformer. A new matching network with two tunable capacitors has been built and tested. This network can allow precision matching and increase the tunable range without using a transformer. A 5-element broadband matching network also has been designed, built and tested. The 5-element network allows wide band matching up to 50 kHz bandwidth from the resonance center of 2 MHz. The design procedure, simulation and test results are presented.

INTRODUCTION

Many RF systems used in charged particle accelerators operate in narrow frequency band and the impedance matching is usually done for a single frequency if the RF load has very high Q-factor. It is interesting to see that a broadband matching could be useful in certain RF applications for accelerator systems. The Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL) is ramping up the beam power to 1.4MW goal with 38mA H- beam current from the rf-driven multicusp ion source. Higher beam current up to 56mA will be required for the future power upgrade plan [1]. The amplifier output impedance has to be matched to the low antenna impedance through an efficient matching network. A well matched RF system is required to increase the reliability and power efficiency of the ion source system since plasma generation is highly dependent on the RF power.

Coil type antennas with high Q-factor are generally utilized in RF plasma ion sources. This high Q restricts bandwidth [2] and makes the system tuning difficult. The impedance of ion source antenna load is highly affected by plasma density [3][4]. Variation on antenna resistance mainly affects the magnitude of S11 parameter as shown in Fig. 1, and any effects on the antenna reactance move the resonance frequency. These factors make the impedance matching and maintaining the matching of ion source antenna a difficult task. Therefore, it is desirable to have good tunability and wide bandwidth with the matching network.

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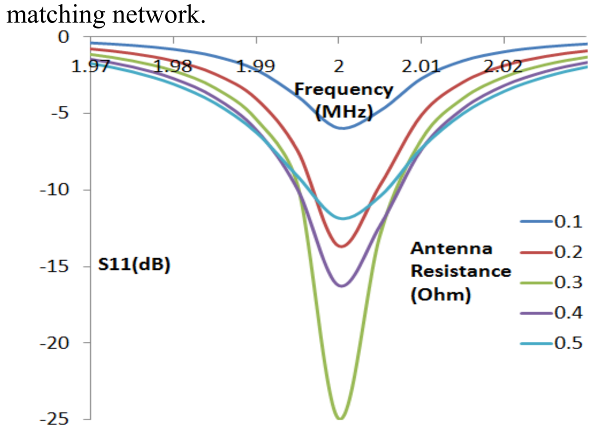


Figure 1: S11 (dB) variations by antenna resistance.

BROADBAND MATCHING DESIGN

The theoretical limitation of available bandwidth for a given reflection coefficient was analyzed by Fano [5]. In this theory, a minimum reflection increases as the system requires wider bandwidth (Fig. 2). Since a Q factor relates the ratio of load reactance and resistance, this theory also demonstrates that Q-Bandwidth product remains constant if same reflection coefficient is assumed.

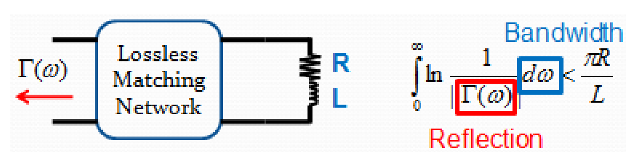


Figure 2: Bandwidth – reflection coefficient relationship.

The relationship between the achievable bandwidth and the number of passive matching network elements is also well known [5][6]. Table 1 shows an example of the bandwidth increase as the number of tuned circuits increases for a special case with the maximum permissible reflection magnitude R>1/3 [6].

Table 1: Comparison of Matching Solutions

Number of Tuned Circuit (n)	*Percent Bandwidth Increase*
1 (=2 lumped elements)	-
2	100 (from n=1)
3	20 (from n=2)
4	9 (from n=3)

This concept can be understood by following the graphical method using Smith Chart [7]. Ellipse 1 in Fig. 3 represents a constant Q trajectory. A simple design is one L-C matching that uses one series inductor and one shunt capacitor to match the load to a reference resistance such as 50 Ohm. Ellipse 2 in Fig. 3 however, utilizes a 3 L-C section matching, and a smaller Q path, which is translated to a wider bandwidth.

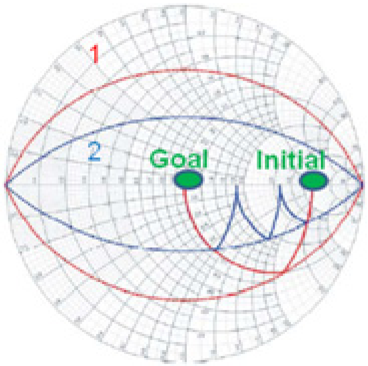


Figure 3: Impedance path on Smith chart (1) n=1, (2) n=3.

EXISTING MATCHING SOLUTION

Two RF systems, pulsed 2MHz and CW 13.56MHz, are combined to have more reliable and efficient operation of ion source in SNS [1]. RF Isolation between 2MHz and 13.56MHz is not discussed in this paper [4]. The nominal load impedance of an antenna is estimated as 0.18 + j8.07 Ohm in present operation.

Series-Inductor and Capacitor Matching (SL-C)

For a flexible impedance matching, two variable elements are required. The existing (SL-C) matching network is configured with a matching transformer (TF), a vacuum variable capacitor (VC) [8], and a fixed inductor (Fig. 4). The TF and VC can be used as tuning elements, however the TF is not easy to tune precisely and introduces ferrite core loss. Element values for an example case are summarized in Table 2. The bandwidth of this type of matching is very narrow and minimum reflection matching may not be possible.

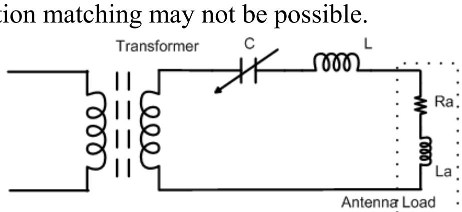


Figure 4: Schematic of SL-C 2MHz matching design.

Table 2: Values of Lumped Elements (SL-C)

Element Name	*Value*
L	2.1 uH
C	2200 pF (Tunable)
Transformer	1:12 (Partly tunable)

BROADBAND MATCHING SOLUTIONS

The lack of precision and the limited bandwidth of the SL-C type matcher provide motivation for new matcher design. The research from LBNL [9] introduced advantage of the capacitive network at 2MHz with high power operation. In this result, a capacitive matching (SL-C-C) is proposed to increase tunability with better efficiency. Since this SL-C-C design still has limited bandwidth, a broadband five-element (5E) network is designed for possible future implementation. The Advanced Design System (ADS) [10] tool by Agilent Technologies is used for circuit design and simulation.

Series-Inductor and Two Capacitor Matching (SL-C-C)

A VC is added to the SL-C type design in this SL-C-C network instead using the TF. This design allows the precision matching and efficiency that is improved over SL-C design by removing the TF. The theoretical minimum reflection is achievable without using the discontinuous impedance transformation of the TF. The number of circuit elements remains the same and similar bandwidth is achieved. Table 3 shows element values of the example design.

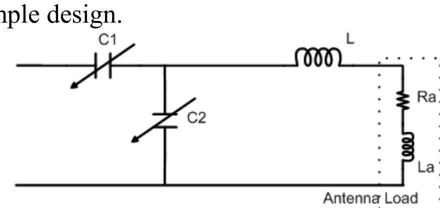


Figure 5: Schematic of SL-C-C 2MHz network design.

Table 3: Values of Lumped Elements (SL-C-C)

Element Name	*Value*
L	1.9 uH
C1	170 pF (Tunable)
C2	2200 pF (Tunable)

Five-Element Matching (5E)

With a fixed inductor, the number of tuneable circuit elements is doubled in the 5E matching. Much wider bandwidth is achievable with this design. Two variable capacitors are used with two fixed capacitors where large capacitances are required (C3 and C4 in Fig. 6). Table 4 shows circuit element values of a design. An inductance is needed for the existing antenna impedance.

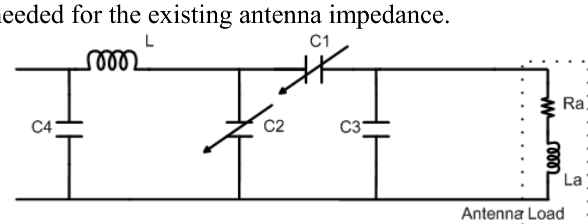


Figure 6: Schematic of 5E 2MHz network design.

Table 4: Values of Lumped Elements (5E)

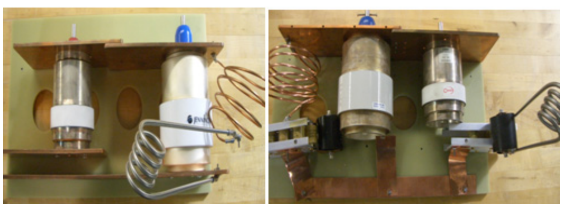
Element Name	*Value*
L	4.9 uH
C1	140 pF (Tunable)
C2	1400 pF (Tunable)
C3	9.7 nF
C4	7.4 nF

TEST RESULTS

The SL-C-C and the 5E designs have been built using real circuit components as shown in Fig. 7. Voltage and current ratings were calculated on the components in both circuits, and these components were selected to withstand up to 100kW peak power. High power test was performed only with the SL-C-C circuit so far since the fixed capacitors in 5E circuit for high power operation were not available.

Low Power Test

The S11 results of SL-C-C and 5E circuits are shown in Fig. 8. The measured bandwidth of the 5E matching network at -15dB is about 40 kHz, which is more than twice the bandwidth of the SL-C-C matching as expected from Table 1. The minimum reflection of 5E increases for the price of the wider bandwidth.



(a) (b)

Figure 7: Test matching circuits – (a) SL-C-C. (b) 5E.

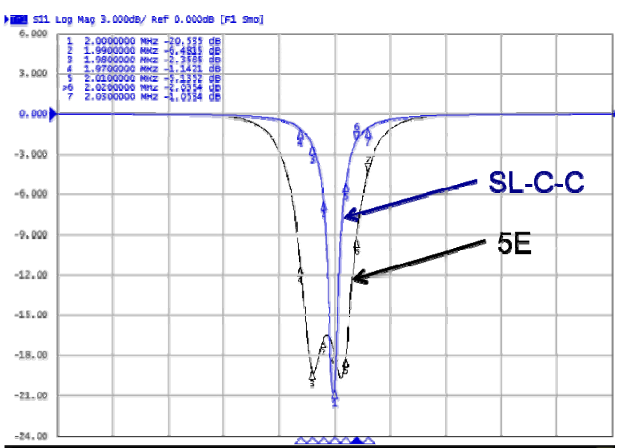


Figure 8: Low power test results.

High Power Test

The SL-C-C matching network was tested up to 60kW peak input power at 6% duty cycle. The network was housed in a metallic chamber (Fig. 9 (b)), and a directional coupler (Fig. 9 (a)) was utilized for measurement of the forward and reflected voltages. Because of limited thermal capacity of the load antenna circuit, a water load with a transformer was used to emulate the antenna load impedance.

(a) (b) (c)

Figure 9: High power test setup - (a) directional coupler (b) matcher in a shielding box, and (c) water load.

The amplitudes of the forward and reflected voltages were measured by an oscilloscope. With this measurement (1.6 / 0.28 V), the S11 is found to be -15.13 dB. The small difference of S11 between low and high power test is caused by an imperfect emulation of the antenna load. The -15dB S11 is still a good matching condition and can be easily tuned by two VC elements.

CONCLUSIONS

Table 5 summarizes a comparison of SL-C, SL-C-C, and 5E networks. The SL-C-C matching has excellent tunability and circuit simplicity, and was successfully high power tested. The 5E matcher has excellent bandwidth and efficiency. A high power verification of this 5E matcher remains as a future work.

Table 5: Comparison of Matching Solutions

Network	*Bandwidth*	*Simplicity*	*Efficiency*	*Tunability*
SL-C	Good	Good	Poor	Poor
SL-C-C	Good	Excellent	Good	Excellent
5E	Excellent	Poor	Good	Good

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