ANALYSIS AND DESIGN OF THE MATCHING UNIT FOR AN RF DRIVEN PLASMA SOURCE FOR FUSION PURPOSE

H.K. Yue, D. Li, D.Z. Chen*, K.F. Liu, J. Huang, X.F. Li, C. Zhou, C.R. Wang, M.W. Fan
State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology, Wuhan 430074, Hubei, P.R. China

Abstract

An RF driven plasma exciter for producing negative ions, aiming for plasma heating and current drive in neutral beam injectors for fusion applications, is in developing in Huazhong University of Science and Technology. In order to couple effectively the RF power to the exciter, the matching unit is designed to match the impedance of the exciter to that of the RF coaxial line. Firstly, a FEM model was built to estimate the equivalent circuit parameters of the exciter. Numerical predictions were compared with a small experimental setup to verify the accuracy of the FEM model. Based on the numerical results, the RF coil and the matching components were carefully designed. Finally, the matching circuit for the source is developed and will be tested.

INTRODUCTION

Negative ions based neutral beam injectors (N-NBI) are required for the plasma heating and current drive for International Thermonuclear Experimental Reactor (ITER) and other future fusion devices with beam energies of more than 100 keV/nucleon [1]. Compared with filamented arc sources, radio-frequency (RF) sources have fewer parts, only including a source body, an RF coil and a matching unit. And the RF generator and the RF transmission line are much simpler than an arc power supply. Therefore, RF sources are cheaper and basically maintenance-free in operation which fits well with the remote handling requirements of ITER. For this reason and because of the success in the development of the RF negative ion source at Max-Planck-Institut für Plasmaphysik (IPP, Germany), the RF sources were chosen as the ITER reference source in 2007 [1]. IPP has developed three different test negative ion sources: BATMAN, MANITU and RADI, and is constructing a new test facility called ELISE [1, 2, 6]. For the purpose of investigation and talent cultivation, an RF driven plasma exciter for producing negative ions is in developing in Huazhong University of Science and Technology (HUST), as the first step towards a ITER required negative ion source.

The RF system is a key part of the exciter, and it contains the RF power generator, the transmission line, the matching unit and the RF coil (see Fig. 1). The RF power generator output RF power at 1 MHz to the transmission line. The matching unit matches the impedance of the exciter to the transmission line so as to assure the maximum of the RF power transmission to the RF coil.

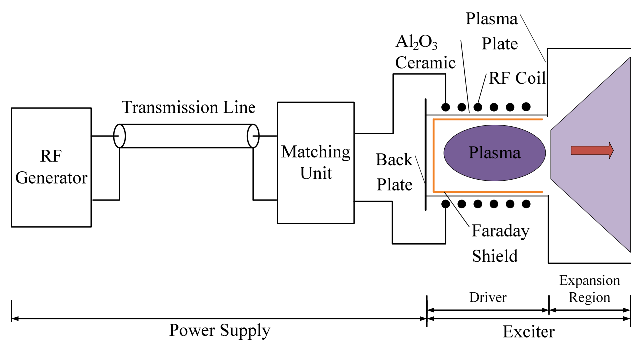

Figure 1: Schematic drawing of RF system of the exciter.

The equivalent RF load can be represented with the series of a resistance R_D and an inductance L_D (see Fig. 2) [2, 3, 4], thus the impedance is $Z_L=R_D+jwL_D$, The task of the matching unit is to transform Z_L to 50 Ω which is the impedance of the transmission line. To design the matching unit, the range of equivalent resistance and inductance is must be estimated before construction. In this paper, a finite element method (FEM) model was built to estimate the equivalent circuit parameters of the excite. The FEM prediction is verified with a small experimental setup. According to the numerical results, three different kinds of matching unit schemes have been designed and compared, and one of the three is under implementation.

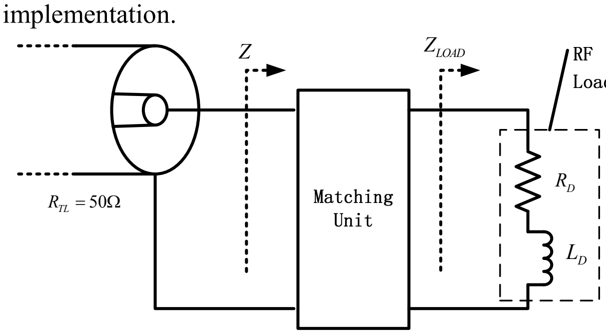

Figure 2: Equivalent circuit of the RF Load.

ESTIMATION OF THE EQUIVALENT IMPEDANCE OF RF LOAD

The FEM Model of the Exciter

An air-core transformer model is often used to estimate the impedance of the RF exciter, which considers

*Email: dzhchen@mail.hust.edu.cn

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the RF coil as the primary side and the plasma as the secondary side with a single turn with current flowing through the thin layer of the surface due to the skin effect. However, because the current is not uniform at the plasma surface, the transformer model can not give good accuracy. So the FEM is used to calculated the electromagnetic field of the RF exciter.

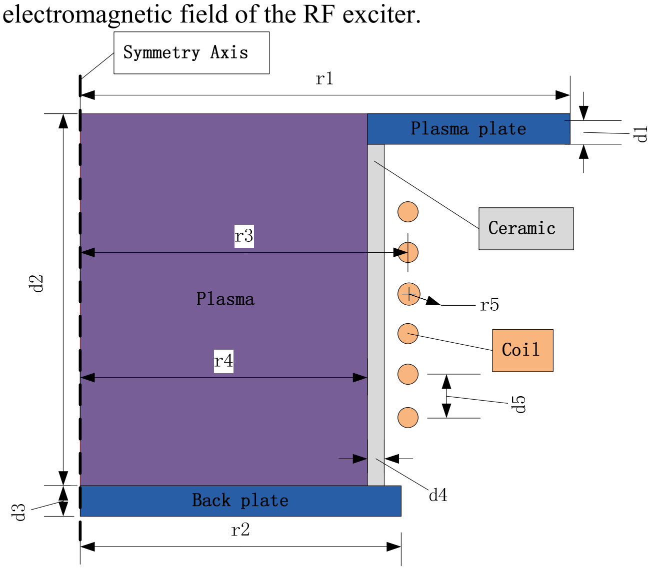

Figure 3: Schematic drawing of the FEM model.

A FEM model is built to calculate the equivalent impedance of RF load. As is shown in Fig. 3, the plasma in the driver is regarded as conductor whose permittivity and conductivity depends on the physical parameters of the plasma[5]. The RF coil is made of copper, and the plasma plate and back plate is made of stainless steel.

Magnetic energy W_M and the power loss P_L are calculated through FEM results. Then the equivalent resistance and inductance can be got based on Eq. 1 and Eq. 2:

$$L_D = \frac{2W_M}{I^2} \quad (1)$$

$$R_D = \frac{P_L}{I^2} \quad (2)$$

Verification of the Model's Accuracy

A small experimental setup was built to verify the accuracy of the FEM model. The sizes of the setup are as follows: *r1*=100 mm, *r2*=60 mm, *r3*=57 mm, *r4*=50 mm, *r5*=1.4 mm, *d1*=3 mm, *d2*=127 mm, *d3*=3 mm, *d4*=5 mm, *d5*=4.4 mm.

The model is built in ANSYS to simulate the unexcited plasma. Under the circumstances, neutral gas is actually in the driver.

The calculative equivalent impedances and the measuring ones by vector network analyzer (VNA) were shown in Table 1.

Table 1: Calculative Results by ANSYS and Measuring Ones by VNA

Turn (N)	*L*(μH)		*R*(mΩ)	
	ANSYS	Measure	ANSYS	Measure
4	2.905	2.827	76.00	99.05
5	4.164	3.589	101.0	123.7
6	5.555	4.932	129.0	151.3
7	7.054	6.851	166.0	172.8

As is shown in Table 1, the measuring inductance is less than the calculative one, and the error is less than 15% . For the resistance, the calculative result is less than the measuring one, and the error is less than 20%.

Because of the material's stress-strain, the setup's coil space of turns usually is greater than it in the FEM model, so it is the main reason for the inductance's error. The error of the resistance is mainly caused by line resistance.

Estimation of the Equivalent Impedance of the Exciter

According to the actual exciter whose sizes is similar to RADI, the model shown in Fig. 3 was also established in ANSYS to calculate the range of equivalent impedance. The sizes of the exciter are as follows: *r1*=260 mm, *r2*=170 mm, *r3*=154 mm, *r4*=142 mm, *r5*=3 mm, *d1*=20 mm, *d2*=170 mm, *d3*=20mm, *d4*=8 mm, *d5*=10 mm.So the calculative equivalent inductance is 7.52 μH~10.92 μH, and the equivalent calculative resistance is 3.31 Ω ~ 10.47 Ω.

However, based on the numerical results and experimental data on RDAI [2], the range of the exciter's inductance expanded and was estimated from 6 μH to 13 μH and the range of the exciter's resistance was estimated from 1 Ω to 5 Ω.

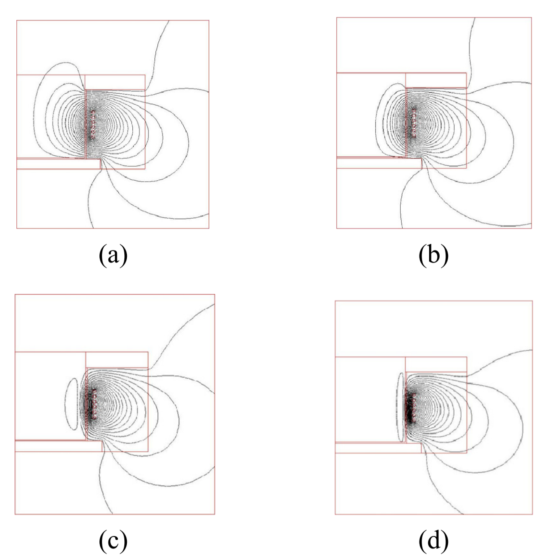

Figure 4: RF magnetic field in different ionization rates. *x* is the ionization rate of the plasma in the driver. (a), *x*=0; (b), *x*=0.001;(c), *x*=0.01;(d), *x*=0.1.

Figure 4 shows the distribution of RF magnetic field in different ionization rates of the plasma in the exciter. The figures clearly shows the magnetic field is squeezed and far away the center of the driver with the increase of the ionization rates.

ANALYSIS OF MATCHING UNIT FOR THE EXCITER

Three Kinds of Impedance-matching Networks

Three different impedance-matching networks were considered (see Fig. 5). The first scheme of matching network shown in Fig. 5(a), is composed of two variable capacitors; the series one is called C_S, and the parallel one is called C_P. The second one shown in Fig. 5(b), adds an transformer between C_S and C_P, whose ideal ratio of transformation is *n*. The third one shown in Fig. 5(c), changed the position of the two capacitors.

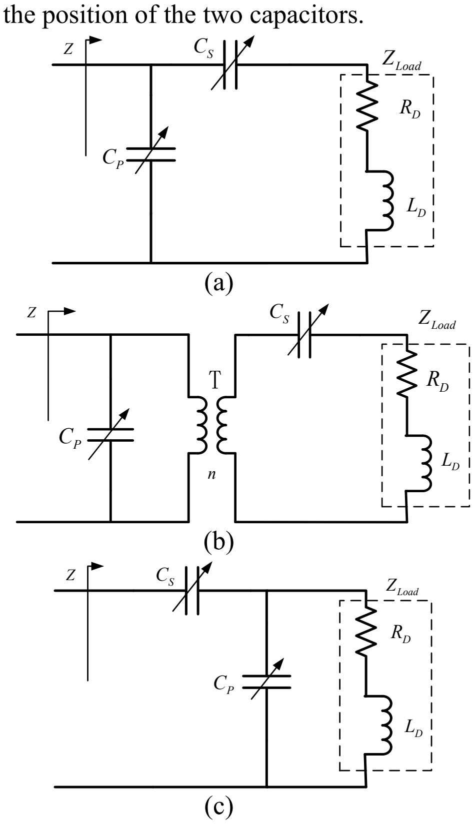

Figure 5: Three kinds of impedance-matching networks. (a) is the first scheme call No.1. (b) is the first scheme call No.2. (c) is the first scheme call No.3.

Analysis and Compare of the Three Schemes

The three schemes require different capacitors' adjustable range which is listed in Table 2 .Under the condition that 90kW output power is completely absorbed by equivalent resistance R_D, the voltage across the capacitors and the current flowing through the ones are also listed in Table 2.The values in Table 2 of voltage and current are all root mean square (RMS) values and approximate.

Table 2: Parameters of the Capacitors for the Three Schemes

		No.1	No.2	No.3
C_S	C_S(nF)	2.2~4.9	2.1~4.2	0.4~1
	U(kV)	4~22	4~22	4~25
	I(A)	140~300	140~300	40~45
C_P	C_P(nF)	10~16	2.0~4.4	1.6~3
	U(kV)	2.1	0.8~2.1	5~25
	I(A)	120~280	10~80	90~260

As is shown in Table 2, because of high power, the capacitors had to bear high voltage and withstand heavy current. Vacuum capacitors whose capacity is usually below 2 nF meet the requirements, but they are expensive. In order to reduce costs, the scheme's cost is a very significant consideration.

In the three schemes, No.2 and No.3 require lower electric parameters, and it means lower cost. But in No.3 scheme, the two capacitors require higher voltage than it in No.3 scheme, especially the C_P, so it costs more.

To sum up, No.2 scheme is chosen, which is under implementation and will be tested in future weeks.

SUMMARY

In this paper, a FEM model is built to calculate the equivalent resistance and inductance of the RF exciter. Then, a small experimental setup is constructed to testify the FEM model's accuracy. The calculated inductance agree well with the measured results. The range of the equivalent impedance is estimated. Three different matching networks are considered and compared. The scheme with a transformer is chosen for implementation.

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