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Preliminary design of an impedance matching circuit for a high power rectangular RF driven ion source

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ABSTRACT

Within the framework for the development of a radio frequency driven positive ion source for fusion applications, KAERI is currently constructing a new high power large area radio frequency ion source. An impedance matching circuit maximizing the power transfer to a plasma in the ion source, while taking into account the technical feasibility, is preliminarily designed at a conceptual level. In order to estimate the plasma load impedance and design parameters, an integrated model composed of the hydrogen plasma global model, the two-dimensional electromagnetic model, the relative plasma dielectric constant calculation module, and the impedance matching circuit module is developed for the ion source with a rectangular tube geometry. By employing this design model, the design parameters dependent on RF input powers of up to 50 kW are investigated and the preliminary design is assessed.

1. Introduction

Compared to filament arc driven ion sources, radio frequency (RF) driven ion sources are favorable for fusion applications because they are free from maintenance-related problems [1]. This has led the Korea Atomic Energy Research Institute (KAERI) to develop an RF driven positive ion source for replacing an existing filament arc driven ion source for a neutral beam injection system [2–5]. Within this framework, KAERI is currently constructing a new high power RF ion source as illustrated in Fig. 1(a) and (b).

In order to cover a rectangular ion extraction area of 35 cm in width and 17 cm in length, a rounded rectangular configuration, rather than a multi-source configuration [1,6], has been chosen as the geometry of the RF driven ion source driver on account of its simplicity. A rounded-rectangular quartz tube of 44 cm in inner width, 26 cm in inner length, 20 cm in height, and 6 mm in thickness is used as an antenna window. An internal copper Faraday shield with a thickness of 3 mm is employed to protect the quartz tube from the plasma heat load. An RF power supply is designed to supply RF power of up to 50 kW at a frequency of 2 MHz to an antenna coil of five turns through an impedance matching circuit.

In the RF driven ion source system, the impedance matching circuit plays an important role in providing the maximum power transfer between the RF power supply and a plasma load, and in protecting devices from damage by overvoltage or overcurrent due to the high reflected power. The design of an impedance matching circuit for high power RF driven ion sources in particular requires more careful consideration since the voltages and currents of the circuit components can be high and large and thus damage in case of mismatching can easily occur. Many research groups in recent years have studied and designed impedance matching circuits for high power RF driven ion sources [7–13]. Unfortunately, however, few researchers have addressed and designed the impedance matching circuit for high power rectangular RF driven ion sources while taking into account plasma load impedance. In this paper, plasma load impedances of the RF driven ion source driver are investigated using a hydrogen plasma global model and an electromagnetic (EM) model, and then the impedance matching circuit for the ion source is designed at a conceptual level. The remainder of this paper is organized as follows: A brief description of the developed models is given in Sec. 2. Model results as well as the conceptual design are presented and discussed in Sec. 3. Finally, a summary can be found in Sec. 4.

2. Model description

We have developed an integrated model in an attempt to calculate the plasma load impedance of the KAERI RF driven ion source and then to design its impedance matching circuit based on the calculation results. The model consists of two models (i.e., a hydrogen

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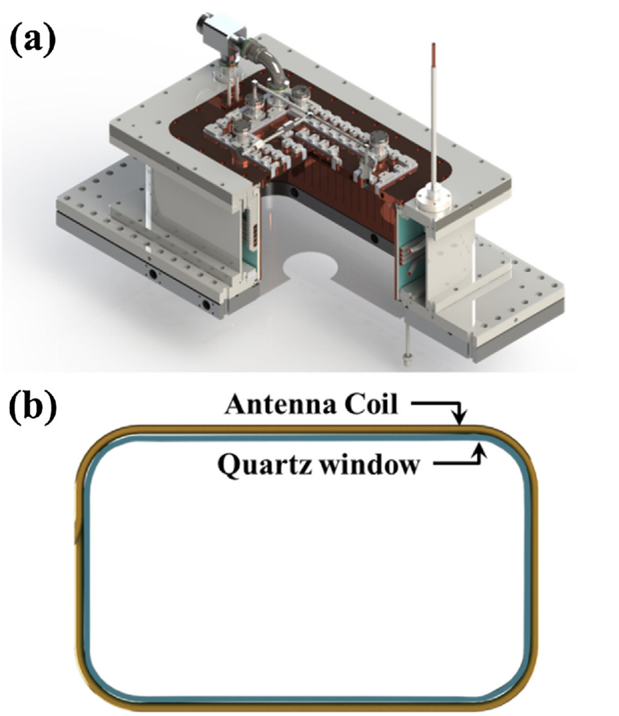

Fig. 1. (a) A schematic diagram of KAERI RF driven ion source driver with an internal copper Faraday shield, a quartz window, and an antenna coil of five turns. (b) A top view of the quartz window and antenna coil.

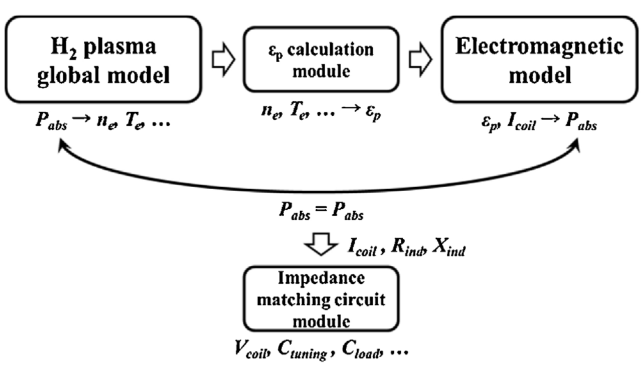

Fig. 2. Flow chart of an integrated model for the design of the impedance matching circuit. See the text for the notations.

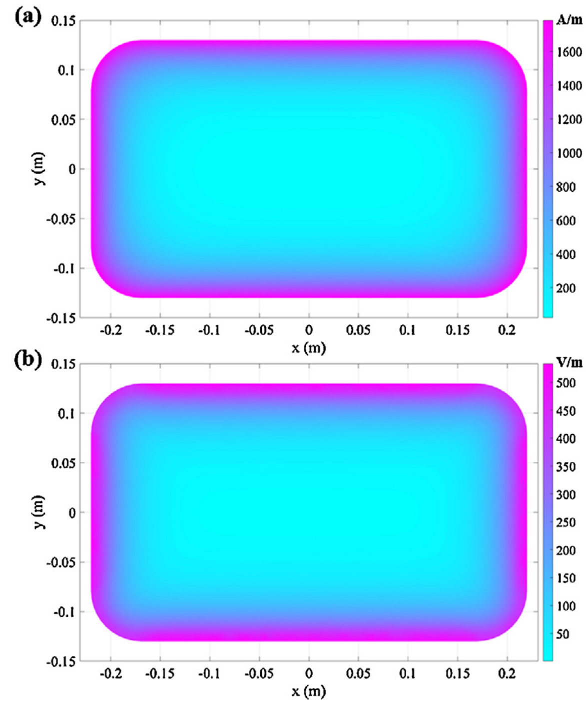

Fig. 3. Modulus of the electromagnetic fields, i.e., (a) magnetic field intensity (A/m) and (b) electric field intensity (V/m) for P_{abs} = 10 kW and I_{coil} = 84.75 A.

plasma global model and a two-dimensional (2-D) EM model) and two modules (i.e., a relative plasma dielectric constant calculation module and an impedance matching circuit module) as shown in Fig. 2.

For a given RF power absorbed by the discharge P_{abs}, the global model can be used to calculate electron temperature T_e and species densities including electron density n_e in hydrogen plasmas as described in detail in Ref. [14]. We revised the global model developed for a cylindrical geometry by modifying the effective diffusion length, the effective area, and the dimensionless ion flux factors to apply to the ion source with the rectangular tube geometry. The pressure was set to 0.5 Pa. With calculated values of T_e and the species densities obtained from the global model, the relative plasma dielectric constant calculation module computes the electron–neutral collision frequency ν_{en}, the stochastic collision frequency ν_{st}, the electron–ion collision frequency ν_{ei}, the effective collision frequency $\nu_{eff} = \nu_{en} + \nu_{st} + \nu_{ei}$, the effective driving frequency ω_{eff}, and the electron plasma frequency ω_{pe}, and consequently provides the relative plasma dielectric constant [15]

$$\varepsilon_p = 1 - \frac{\omega_{pe}^2}{\omega(\omega_{eff} - j\nu_{eff})}, \tag{1}$$

where ω is the driving frequency.

In the EM model [15,16] based on an EM theory of the inductive discharge, EM fields, the plasma load impedance, and P_{abs} are calculated in the system composed of the antenna coil, the antenna window, and the plasma by solving Maxwell's equations in Cartesian coordinates. We assumed an ion source that has a very thin antenna window and a uniform plasma with a Maxwellian electron energy distribution. It was also assumed that the plasma is purely inductive and that there is no external magnetic field. We suppose that the magnetic field induced by the antenna coil is directed in the z-direction. Thus, the induced electric field in the plasma is so transverse to the z-axis that it has components in the x- and y-directions in the model. Source-free Maxwell's equations are the governing equations in this EM model. Assuming that all the fields varying in time t are proportional to $e^{-j\omega t}$ and combining Maxwell's equations (i.e., Faraday's law and Ampère's law) to eliminate the electric field, the equations are reduced to a time-independent Helmholtz equation for the magnetic field:

$$\nabla^2 \tilde{H}_z + k_0^2 \varepsilon_p \tilde{H}_z = 0, \tag{2}$$

where $\tilde{H}_z$ is the complex amplitude of the magnetic field intensity along the z-axis and $k_0 \equiv \omega/c$ (c: the speed of light) is the wavenumber in free space. The boundary condition values at the edges of the plasma were given by the magnetic field at the edges created by the given antenna coil current I_{coil}. We took the field at the edges to be a real number in order to set it the reference for the phase of the magnetic field. The model uses MATLAB 2016b (Mathworks Inc., Natick, MA, USA) as a partial differential equation solver for obtaining the magnetic field profile in the plasma by solving Eq. (2); see Fig. 3(a). The amplitudes of the x and y components of the electric field intensity, $\tilde{E}_x$ and $\tilde{E}_y$, were calculated by using the