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IMPEDANCE CHARACTERISTIC ANALYSIS AND MATCHING NETWORK DESIGN FOR A 100 mA H⁻ ION SOURCE

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Abstract

China Institute of Atomic Energy (CIAE) has developed a series of multi-cusp H^- ion sources (IS) with DC beam intensity ranging from 3 to 18 mA for high intensity proton cyclotron uses such as cyclotron PET application, neutron source and boron neutron capture therapy (BNCT) facilities. Based on the previous experiences, a new project of radio frequency (RF) antenna driving ion source has been launched for pulse accelerator research. This new ion source is expected to provide over 100 mA peak intensity H^- beams of 60 keV and a longer maintenance interval than conventional filament-driving ion sources above. Impedance matching is indispensable for efficient RF power coupling in the whole working process of the ion source for high-intensity H^- beam extraction. In this paper, impedance characteristic of the IS antenna with various plasma loading is analysed. Eight typical matching topologies are discussed on their electrical requirements. A type-L and a type-γ network are finally selected for the 2 MHz and 13.56 MHz chains respectively. This design may provide a better compromise between the matching performance and the cost of implementation for a wide dynamic loading range. Design of the network is evaluated on the power delivering efficiency in each of the two RF chains and isolation between one and the other. The IS structure and near-future work plan are also presented.

INTRODUCTION

A high-intensity H^- ion source driven by internal RF antenna is under development at CIAE. Design of this new ion source is based on a high-compatibility test-bench which shares similar plasma discharging chamber, magnet layout and extraction system with the conventional filament-driving ion sources [1]. An internal enamel-coated solenoid antenna of 2.5 turns would be applied for the new IS in replacement of the filament, expecting for a longer life-time (> 50 hours) immersed in large-volume plasma. This overall design is shown in Fig. 1.

To obtain a peak intensity over 100 mA, an 80 kW 2 MHz solid-state amplifier (SSA) is adopted in generating large-volume RF coupled hydrogen plasma. And in each pulse interval, from every falling-edge to the following rising-edge, the plasma would be kept *simmering* by a CW 500 W 13.56 MHz amplifier module, aiming to reduce the probability of large-volume plasma generation failure. This module would be set ON at the very beginning for plasma ignition and throughout the whole working process of the ion source. Shifting of the plasma discharging state follows the rule that shown in Fig. 2.

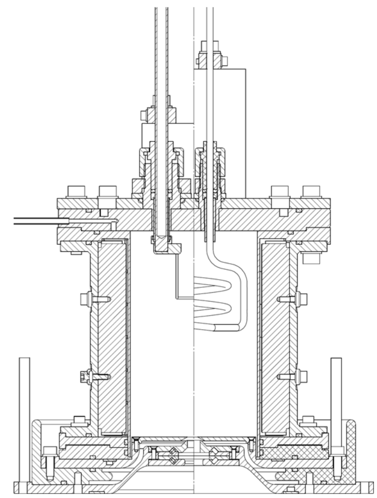

Figure 1: CIAE high-compatibility multi-cusp ion source test-bench. Left: filament driving design. Right: antenna driving design.

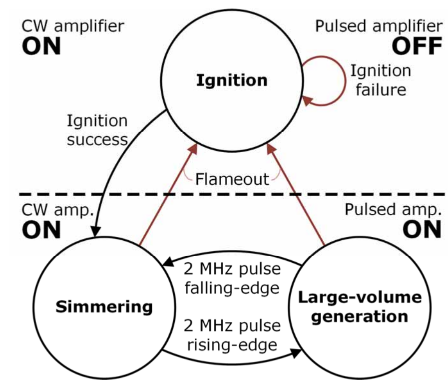

Figure 2: Plasma working states flow.

As the impedance of IS antenna varies dramatically from one discharging state to another, matching networks for the 2 MHz and the 13.56 MHz chains should be designed separately. Each of the networks demands a rather large adjustable matching range to cover most of possible antenna impedances with corresponding plasma loads. Efficient RF power delivery from the 50 Ω transmission-line system to the antenna could be attained only via careful designs of these matching networks, based on the reliable estimates of the IS antenna impedance characteristic. This paper is analysing the equivalent resistance and inductance of the antenna with different plasma loads, comparing basic matching network topologies, presenting and evaluating the design for the new 100 mA ion source.

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IMPEDANCE CHARACTERISTIC OF THE ION SOURCE ANTENNA

In the newly developing 100 mA ion source, hydrogen plasma would be produced by inductive discharging, in which an axial alternating magnetic field would be generated by the RF current through the ion source solenoid antenna. This time-domain sinusoidal magnetic field would further induce a vortex electric field which accelerates the electrons in the discharging chamber and makes the ionization occur. The transformer theory of plasma discharging [2] views the antenna and inductive coupled plasma (ICP) load as the primary and secondary side of a transformer. In this case, the equivalent resistance and inductance of the IS antenna will increase and decrease respectively as hydrogen plasma raises. However, these two values may display the opposite trends when much larger RF power is applied to the plasma load [3-7].

In our design of the ion source, the resistance and inductance of the unloaded 2.5-turn antenna prototype are estimated as 0.013 mΩ and 0.313 μH respectively. While for the large-volume plasma generation state and the plasma simmering state, the values may be decided as 1.2 Ω with 0.8 μH and 0.4 Ω with 2 μH. Matching range for each of the two RF chains is always of demand due to the unpredictability of the impedance. Therefore, impedance coverages of 0.5~2 Ω with 0.2~2 μH and of 0.03~5.56 Ω with nearly any μH levels are separately set for the 2 MHz pulsed chain and the 13.56 MHz CW one. Frames of matching network would be then discussed and compared in the context of these two RF chains on their electrical requirements.

MATCHING NETWORK TOPOLOGIES

In order to minimize the cost and power consumption of the matching network for each chain, dual-capacitor topologies, in type-L or in type-γ form, as the simplest ones, have been taken into account for RF power coupling. For the high-voltage extraction of H^- beam, electrical isolation of the ion source from the grounded solid-state amplifiers is to be established by transformers. Thus, addition of one such component in the networks is also considered.

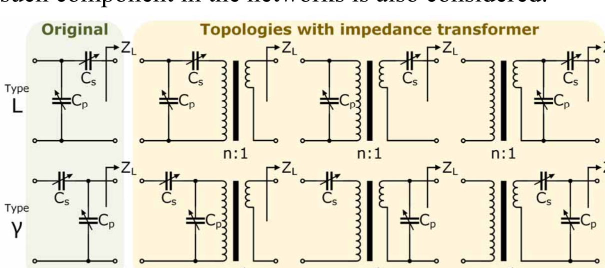

Figure 3: Dual-capacitor type-L and -γ matching networks with or without an impedance transformer. C_s stands for the series capacitor and C_p stands for the shunt one.

The only eight two-port matching network topologies that can be obtained by two capacitors with or without a transformer, as shown in Fig. 3, are evaluated on their requirements of capacitance and RF voltage and current endurance in each of the two chains. Analysis of the impedance matching equation for each network topology in either 2 MHz or 13.56 MHz chain yields the shunt and series capacitance requirement when the assumed equivalent impedance of RF antenna perfectly matched to the 50 Ω system. Corresponding RMS voltage and current are also calculated to evaluate such electrical endurance demands.

Addition of an inductor in series with the IS antenna is found of help to extend the matching coverage, reaching some of the small values that the equivalent inductance of the antenna and plasma load may occur. Analysis of the eight matching topologies with proper additional series inductances for the 2 MHz and 13.56 MHz chains has yield their dominant advantage and disadvantage to be chosen for the network, listed in Table 1, from either comparation of every matching equation or observation of the contours of needed capacitances and of voltage and current endurance requirements, shown later in Fig. 5 and 6.

Table 1: Advantage and Disadvantage of the 8 Matching Network Topologies in the 2 MHz and 13.56 MHz Chains

Topology	Advantage	Disadvantage
80 kW 2 MHz Chain		
Type-L, original	Original	Very large C_s and C_p (tens nF)
Type-L + Trans. on load side	Lower C_s and C_p	Unbearable RF voltage on C_s
Type-L + Trans. inserted	Well balanced	
Type-L + Trans. on source side	Lower C_s	Very large C_p (tens of nF)
Type-γ, original	Much lower C_s and lower C_p	Tuning difficulty
Type-γ + Trans. on load/source side or inserted	Much lower C_s and C_p	Tuning difficulty and unbearable voltage on C_s
500 W 13.56 MHz Chain		
Type-L, original or + Trans. on load/source side or inserted	Small or very small C_s; smaller C_p for ones with a transformer	Unbearable voltage on C_s
Type-γ + Trans. on load side or inserted	Smaller C_s and C_p	Unbearable voltage on C_s and C_p
Type-γ + Trans. on source side	Well balanced	Patience needed when tuning

A type-L matching network with one 3:1 transformer inserted between the capacitors is finally chosen for the 80 kW 2 MHz chain. And a type-γ one with one 3:1 transformer on the source side is selected for the 500 W 13.56 MHz chain.

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DESIGN AND EVALUATION OF THE MATCHING NETWORK

Design of the entire matching network is shown in Fig. 4, in which three ports can be seen totally:

- Port 1 – Pulsed 80 kW 2 MHz input, 50 Ω.
- Port 2 – Ion source antenna, impedance unknown.
- Port 3 – CW 500 W 13.56 MHz input, 50 Ω.

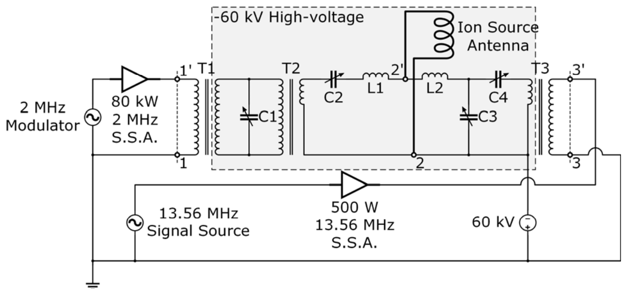

Figure 4: Design of the matching structure.

Matching capacitances for the 80 kW 2 MHz chain and corresponding electrical endurance requirements of this structure can be draw into contours as in Fig. 5. One may directly read out needed parameters of each element in this matching network for every specific antenna impedance range. Similar analysis for the 500 W 13.56 MHz chain yields the results presented in Fig. 6. Less than six adjustable vacuum capacitor of 1500 pF and 2 smaller (< 100 pF) ones are expected for the matching box's implementation.

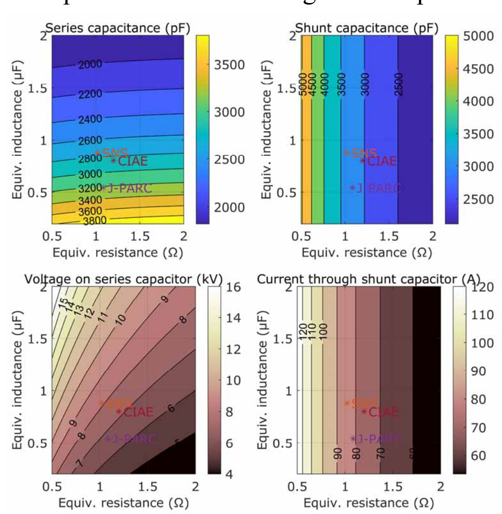

Figure 5: Electrical requirement contours of the series and shunt capacitors in the type-L matching network with 3:1 transformer for the 80 kW 2 MHz chain. Impedances of projects marked by coloured stars.

Evaluation of the RF power deliver efficiency in each plasma discharging states and the power isolation, especially from port 1 to 3 is given out by simulation based on LTspice XVII. The S21, S23 and S31 curves for this 3-port network are shown in Fig. 7, which strongly support the feasibility of each of the RF chains and the sufficient isolation between one and the other.

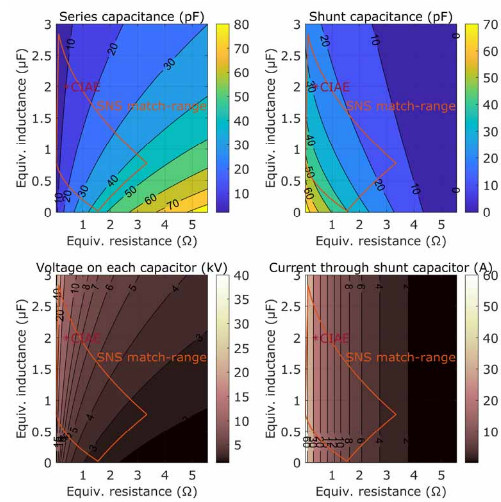

Figure 6: Electrical requirement contours for the type-γ network for the 500 W 13.56 MHz chain.

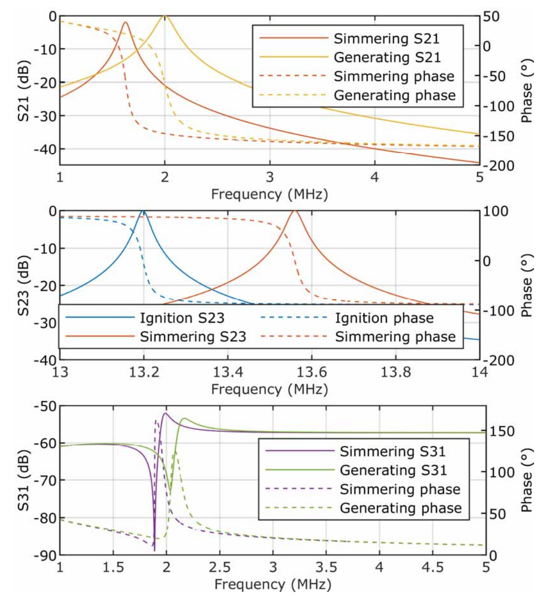

Figure 7: S21, S23 and S31 of the matching network

Moreover, analysis of the S-parameters indicates that when shifting from the plasma simmering state to the large-volume generation state, or from the cold ignition state to the simmering state, RF power delivering efficiency may decline dramatically if the frequency is kept constant. Therefore, a slight increase of the driving frequency may be of help in changing from one plasma working state to another.

CONCLUSION

In the project of a RF-driving 100 mA H^- ion source, a dual-channel impedance matching network is designed to realize a matching coverage of large impedance range. Evaluations show that such a structure provides a balance between its matching performance and the cost of implementation. Simulation proves the network's feasibility, and indicates that proper modulation helps to improve the generating efficiency of RF driven hydrogen plasma.

Mechanical and water-cooling connections between the IS antenna and matching box should be taken into careful account for safety purpose. Remote controlled motors are planned to be installed to adjust the matching box for the ease of impedance matching.

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