Optimization of power matching and transfer in the helicon plasma discharge

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Abstract. Helicon plasma source is being developed at the Budker Institute of Nuclear Physics SB RAS, Novosibirsk. The parameters are studied of the plasma confined in a mirror trap configuration of the magnetic field at an operating frequency of 13.56 MHz. For matching the antenna impedance and generator load, the Π-type matching box was designed and successfully tested at powers of 20–25 kW. The low reflected power (1–2%) was obtained, as compared to that for the L-type matching network used previously (the reflected power was more than 15% at the generator output power of 18 kW). The triple Langmuir probe is used to determine the plasma density. The plasma resistive characteristics were determined using the Rogowski coil measuring the RF antenna current. In the experiments, the plasma with a density of ~5 $\times$ 10$^{12}$ cm$^{-3}$ and an electron temperature on axis of 10 eV was obtained, and the RF power transfer efficiency was ~85% at the RF power of 25 kW.

1. Introduction

One of the priority fields of the fusion research is the research on the material science technologies. Investigations of the plasma-material interaction (PMI) require the fusion-relevant plasma parameters to simulate the processes on the reactor wall, namely, the long-pulse or steady-state operation regime is required; the plasma should be pure and homogeneous, and its density should be high. The linear plasma devices are inexpensive, as compared to the tokamaks, and satisfy the PMI requirements. The possibility of the dense plasma production and the absence of electrodes make the helicon devices favorable to be used in such linear devices.

The helicon plasma source is based on the inductive discharge with the external constant magnetic field imposed that makes it possible for the helicon waves to propagate inside the bulk plasma, which results in a considerable increase in the efficiency of plasma ionization. In the electrodeless RF plasma sources, the matching system is required to maximize the forward power transferred into the discharge and minimize the reflected power. For these purposes, different types of matching devices are used. However, for the different discharge regimes, the plasma loads are considerably different; a device with a large resonance width is required to match the plasma loads during the jumps between the capacitive (E), inductive (H) and helicon (W) discharge regimes. Another important problem is the efficiency of power absorption in the plasma, since besides the power losses in the matching devices, there are losses due to the power dissipation in the supply network and ohmic heating of the antenna causing its heating. Therefore, the power absorption efficiency is an important characteristic of the plasma operating regime.
The helicon high-power RF source for the PMI studies is being developed and investigated at the Budker Institute of Nuclear Physics in Novosibirsk [1, 2]. The goal of this work was to optimize power matching and to estimate the efficiency of power absorption in the helicon discharge using the Rogowski coil measurements of the RF antenna current and involving the plasma transformer model [3, 4].

2. Experimental setup
The helicon plasma facility developed is presented in Figure 1a. The vacuum volume includes quartz tube 3 (110 mm in diameter, 400 mm in length) with the half-wave helicon antenna 7 (150 mm in length, 0.43 μH in inductance) installed in it and expansion tank 1. The discharge chamber is inside magnetic coils 2, 4, and limiters 5, 8 prevent the plasma from contacting with the chamber wall. Gas (hydrogen) is supplied through the valve near the mirror coil and pumped out through vacuum tank 10. The plasma density and electron temperature were measured using triple Langmuir probe 12, which has galvanic isolation and is installed in diagnostic chamber 9. The magnetic configuration of the facility corresponds to the mirror trap (mirror ratio is approximately 2) with the strong field at the chamber ends and the low-diverging field near the RF antenna (Figure 1b).

![Figure 1. (a) Schematic of helicon facility: (1) expansion tank, (2, 4) magnetic field coils, (3) quartz tube, (5, 8) limiters, (6) gas supply, (7) RF antenna, (9) diagnostic chamber, (10) pumped vacuum chamber, (11) discharge ignition, and (12) axis of the triple Langmuir probe displacement; and (b) magnetic field distribution and field lines in the helicon facility. Current flowing through the coils is 5 A.](image)

The COMDEL CX25000-S RF generator is used as the power supply. The matching boxes of the L- and Π-types were designed to match the plasma impedance and the generator load (section 3.1). To measure the forward and reflected power, the directional coupler was used, which was built-in into the RF generator scheme. The voltage at the RF antenna is measured using the capacitive voltage divider. The RF current at the antenna was measured using the 25-turn-Rogowski coil and the small resistor (1 Ω). The Rogowski coil and the capacitive divider were calibrated using the Tektronix P6015A high voltage meter (1000x, 3 pF) and active resistance 50 Ω.

To determine the resistive plasma parameters, the transformer model of the plasma was used [5, 6]. The plasma load can be written as follows:

\[
R_{pl} = \frac{P_{for} - P_{ref}}{I_{ant}^2} - R_{ant},
\]

where \(P_{for}\) is the forward power, \(P_{ref}\) is the reflected power, \(I_{ant}\) is the RF antenna current and \(R_{ant}\) is the antenna resistance without plasma. The efficiency of the power transfer is as follows:
\[ \eta = \frac{R_{pl}}{(R_{ant} + R_{pl})}. \]

3. Experimental results

3.1. RF power matching

In the previous experiments at the helicon facility, the L-type matching network was used. The maximum forward power reached in the experiments was 20 kW, while the reflected power was 2 kW. The L-type matching network (Figure 2a) includes the variable capacitor connected in series with RF antenna and the second variable capacitor connected in parallel with it. The Π-type matching network includes three variable reactive elements (two capacitors and one inductor). The inductor is a solenoid made of the 6-mm-diameter copper tube winded on the PTFE insulator with the sliding terminal that changes the number of turns used (Figure 2b).

One of the reasons for poor matching is the high Q-factor of the L-type network providing the narrow resonance width that is fatal in the case of the jumps occurring between the RF discharge regimes. One of the main advantages of the Π-type network is the fact that its tuning is less sensitive to the changes in the magnetic field and gas supply as well as to the jumps between the discharge modes due to the low Q-factor as compared to the L-type scheme [7]:

\[ Q_{\Pi} = \frac{R_{in} \cdot \omega \cdot C_{in}}{R_{pl}} \sim 2 \]

\[ Q_{L} = \frac{\omega^2 \cdot L_{ant}^2 \cdot \omega \cdot C_{load}}{R_{pl}} \sim 50 \]

where \( R_{in} = 50 \Omega \) is the generator load, \( C_{in} = 500 \text{ pF} \) is the capacitance of the left capacitor of the Π-type scheme, \( L_{ant} = 0.43 \mu\text{H} \) is the antenna inductance, \( R_{pl} \sim 2 \Omega \) is the plasma load, and \( C_{load} = 870 \text{ pF} \) the capacitance of the capacitor connected in parallel in the L-type scheme.

As a result, for the Π-type scheme, the resonance width turns out to be approximately 0.5 MHz instead of the extremely narrow resonance peak of the L-type scheme, which results in the more stable operation regime without the abrupt discharge terminations and with the slow mismatch of the scheme as the plasma impedance changes. This system can provide good matching even without the automatic tuning of the elements of the matching scheme during the plasma shot.

Figure 2. (a) L-type matching network; and (b) Π-type matching network. \( C_A, C_B \) are the variable capacitors, \( L_A \) is the antenna inductance, and \( R_{pl} \) is the plasma load.
Figure 3. Forward (green) and reflected (yellow) powers during plasma discharge for an output power of 25 kW.

The waveforms of the forward and reflected powers are presented in Figure 3. A smooth gradual increase in the forward power occurs due to the integration circuit built-in into the generator. One can see that the reflected signal has a peak during the first 20 ms associated with the E-H and H-W jumps between the discharge regimes. Thereafter, the reflected power decreases and then slowly increases with changing plasma load of the helicon discharge. The results of experiments on power matching using both matching schemes are shown in Figure 4. The L-type scheme provided the stable operating regime only at powers less than 15 kW and, in this case, the reflected power losses remained high: up to 1 kW at a forward power of 15 kW. With increasing power, the power loss in the transmission line also increases resulting in the lower forward power. As a result, the maximum forward power reached is approximately 20 kW and the reflected power is 2 kW. In the case of using the Π-type scheme, the output power is almost completely transferred into the plasma (24.65 kW of the 25-kW generator power) with the reflected power of 1% of the forward power or even lesser (~300 W). For the Π-type scheme, the antenna voltage is higher and reaches approximately 6 kV, as compared to 4.4 kV for the matching box based on the L-type scheme.

Figure 4. Forward and reflected powers for L- and Π-type schemes and RF voltage at the antenna as functions of generator output power during plasma discharge.

3.2. Plasma load and density measurements
For the power and the external magnetic field varying in the ranges of 10÷25 kW and 0÷400 G, respectively, the discharge resistive characteristics, plasma density and electron temperature were measured. The active and reactive antenna resistances were measured as functions of the output RF power by means of measuring the RF current and voltage without plasma (background pressure was
10^{-6} \text{Torr}). The active antenna resistance turned out to be $R_{\text{ant}} = 0.73 \pm 0.05 \Omega$, and the reactive one was $X_{\text{ant}} = 53.5 \pm 1.8 \Omega$.

The efficiency of power absorbed in the plasma was studied as a function of the magnetic field and output RF power. The plasma density and load as functions of the external magnetic field in the region under the RF antenna at different RF powers are presented in Figure 5. The density sharply increases with increasing magnetic field; the optimal range with the maximum density corresponds to the magnetic fields from 100 to 200 G. With further increase in the magnetic field, the density monotonically decreases. The maximum densities obtained are $2.6 \cdot 10^{12} \text{cm}^{-3}$ (the electron temperature is 11 eV), $4.4 \cdot 10^{12} \text{cm}^{-3}$ (9 eV), $4.9 \cdot 10^{12} \text{cm}^{-3}$ (10.5 eV) and $5.3 \cdot 10^{12} \text{cm}^{-3}$ (10 eV) for powers of 10, 15, 20 and 25 kW, respectively. The plasma load distribution corresponds to the density distribution, but it has more fluctuation. The strongest fluctuations are observed at a power of 25 kW that makes load matching the most difficult. The maximum plasma load was observed for an output power of 25 kW (6.2 $\Omega$), while the lowest one was observed for powers of 10 and 20 kW (4 $\Omega$). As the power increased, a decrease in the plasma load in the high-field range was no longer observed.

![Figure 5](image1.png)

**Figure 5.** (a) Plasma density and (b) plasma load as functions of magnetic field for different powers. Gas pressure is 20 mTorr.

![Figure 6](image2.png)

**Figure 6.** Power absorption efficiency as a function of magnetic field. Gas pressure is 20 mTorr.

We revealed no correlation between the power absorption efficiency and the output RF power, but the maximum efficiency $\eta$ was reached at the maximum plasma density (Figure 6). The highest power absorption efficiency (89%) was obtained at an output power of 25 kW at the approximately optimal magnetic field, and the lowest efficiency was 60% at an power of 5 kW for the high magnetic fields (>340 G).
4. Conclusions
In the experiments, the system for matching the plasma impedance with the generator load was sufficiently improved to optimize the power absorption by the helicon discharge plasma. When using the Π-type matching network, the high matching was reached when approximately 95% of the output power was transmitted into the plasma, and at a power of 25 kW, the stable discharge was obtained. The Π-type scheme has low Q-factor (~2), which makes it possible to obtain power matching in a wide range of parameters (the magnetic field and gas pressure) without the additional adjustment of the matching scheme elements.

For the powers varying in the range of 20÷25 kW and the optimal magnetic fields (150÷200 G), the plasma with a density of ~5 \times 10^{12} \text{ cm}^{-3} and an electron temperature of approximately 10 eV was obtained. In the experiments, the Rogowski coil was used to measure the plasma load and to determine the power absorption efficiency, which turned out to be approximately 85±5%. The rest of the RF power is spent on the heat losses in the power transmission line, match network and RF antenna.

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