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Operation of a Large Area Plasma Source (LAPS) with Oxygen Gas

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ABSTRACT

In this letter, we report on the first operation of an inductively coupled large area plasma source (LAPS) driven by a 13.56MHz traveling wave with oxygen gas. Modified configurations of the antenna coil and the matching network, which are suitable for eliminating the tuning network resonance and obtaining the match with a traveling wave, are described. The required numerical values for tuning elements and matching elements in order to launch a traveling wave are determined under various operating conditions. Results of plasma density measurements for oxygen gas are compared with those for argon gas. Some results for oxygen/argon mixtures are also presented.

1. Introduction

Planar coil, inductively coupled plasma systems are known for their capabilities to generate high density plasmas under low pressure, which leads to increasing processing speed and minimizing contamination. However, when the plasma system is scaled to large sizes comparable to the wavelength of the rf driving power, the plasma generated is inherently non-uniform due to the standing wave effect. To overcome this difficulty, an inductively coupled, large area plasma source (LAPS), driven by a traveling wave, has been designed, constructed and characterized for argon discharges.[1-4)]

In this letter, we report on the first operation of the LAPS with oxygen gas. We modify the configurations of the antenna coil and matching network so that we reduce input power dissipation in the tuning network and obtain a good match with a traveling wave under various operating conditions. The Maple symbolic mathematics program is used to estimate the requirements for the tuning elements and matching elements. For oxygen, argon, and oxygen/argon mixtures, measurements of plasma densities are made with Langmuir probes.

2. Maple program calculation

Figure 1 shows a previous circuit configuration of the LAPS. In order to eliminate the standing wave effect, a tuning network is placed between the matching network and the antenna coil system.

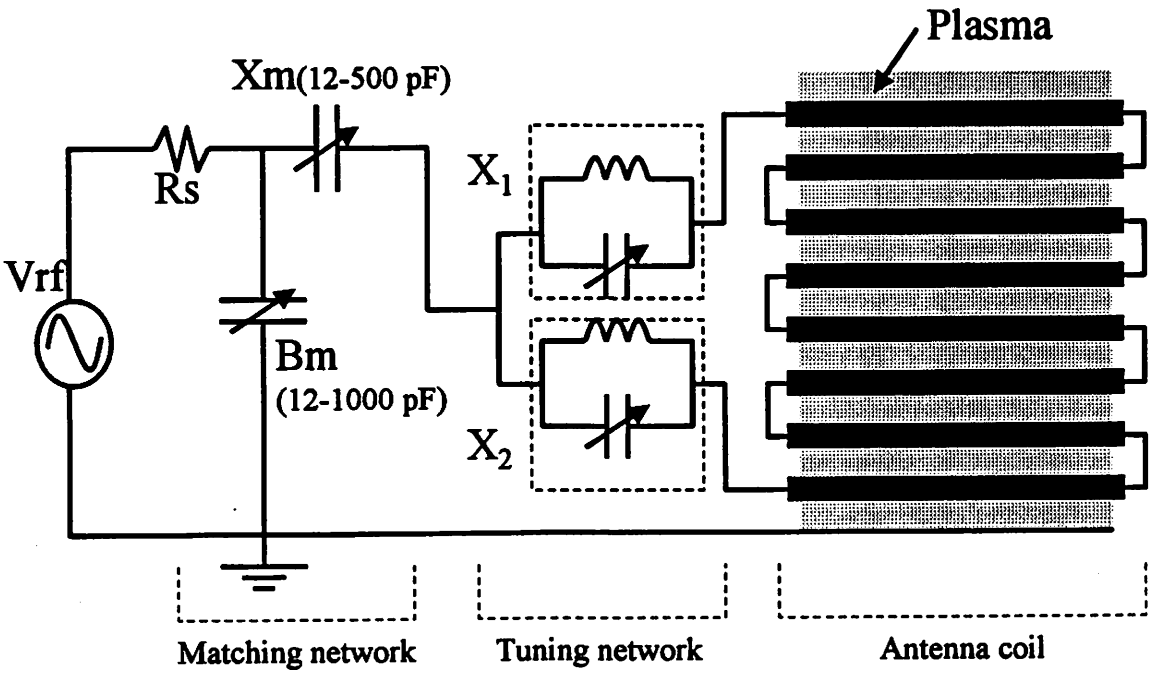
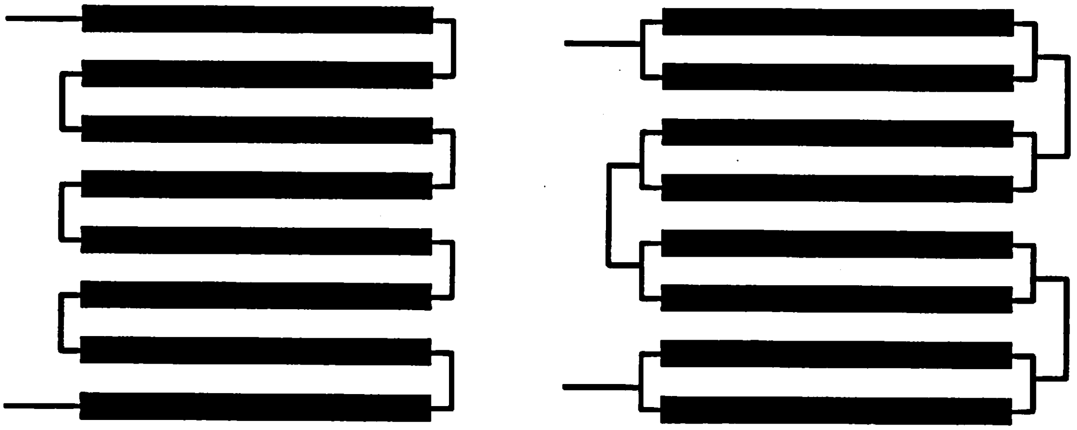


Fig. 1 Circuit configuration of the LAPS for eight rods connected in series.

When all the eight rods are powered, the total transmission line length (L=8.5 m) is around half a wavelength of the rf power frequency, depending on the plasma conditions. Previous calculations and experiments indicated that this results in a resonance in the tuning network, causing a significant fraction of input power dissipation in the tuning elements.[1)] There are several approaches to eliminate the tuning network resonance. One of them is to modify the configuration of the antenna coil and hence the characteristic impedance. Using the Maple symbolic mathematics program, for different antenna coil configurations, we evaluated the tuning elements (X_1 and X_2) and matching elements (Xm and Bm) necessary for launching a traveling wave under various operating conditions. The evaluation was done for two antenna coil systems shown in Figs. 2 (a) and (b), using transmission line model. One, which is the primary configuration, consists of eight copper rods connected in a series path. The other, which is a modified configuration for eliminating the tuning network resonance, is made up of two rods in parallel × four sets in series. We discuss how different transmission line lengths impose different characteristics on the LAPS circuit system.



(a) Eight rods in series. (b) Two rods in parallel X four sets in series (modified).

Fig. 2 Two different antenna coil configurations.

2-1. Transmission line length L=8.5 m

For the LAPS, from the previous evaluation, the plasma density for normal operation ranges from 3×10^{16} to 5×10^{17} m^{-3} for the rf power ranging from 300 to 2500 W.[1)] We thus discuss the requirements for the circuit elements for the above plasma density regime.

For a transmission line length L=8.5 m, which is the length of the primary configuration, figure 3 shows the requirements for the tuning elements X_1 and X_2. As seen in the figure, X_1 and X_2 are inductive in nature, indicating that two variable inductors are required as the tuning elements.

Figures 4 and 5 show the requirements for the matching elements Xm and Bm, respectively. As can be seen in these figures, both Xm and Bm are capacitive in nature. In our system, two variable capacitors with the ranges of 12-500 pF and 12-1000 pF serve as Xm and Bm, respectively.

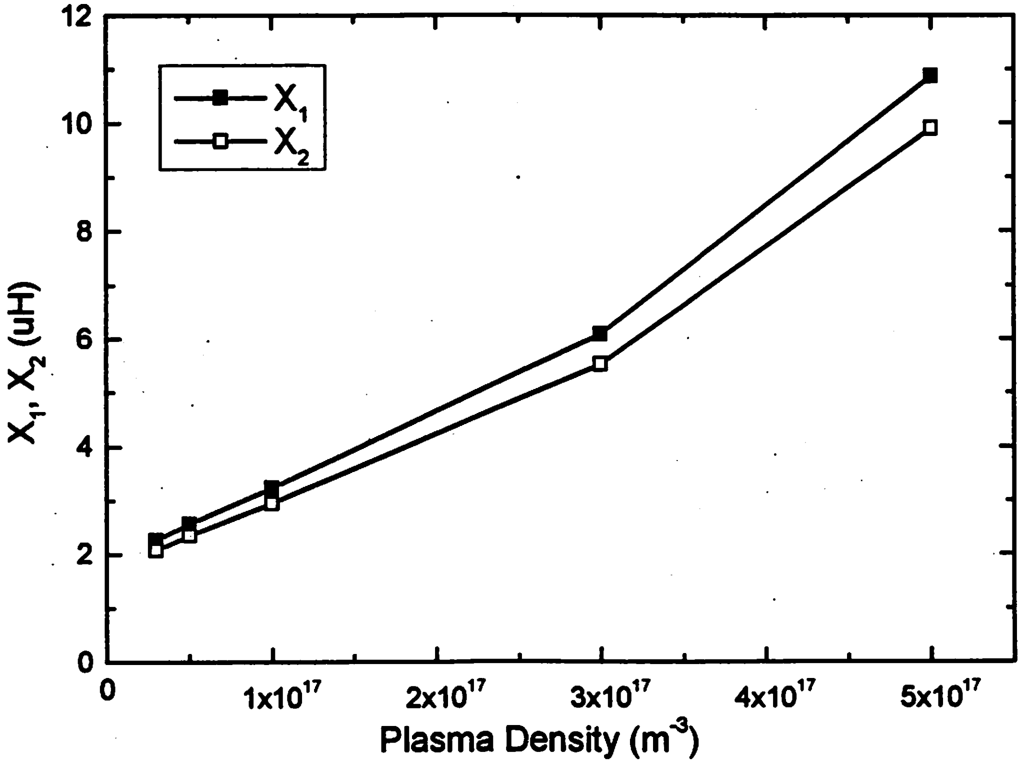


Fig. 3 Requirements for tuning elements X_1 and X_2.
Transmission line length L=8.5 m.

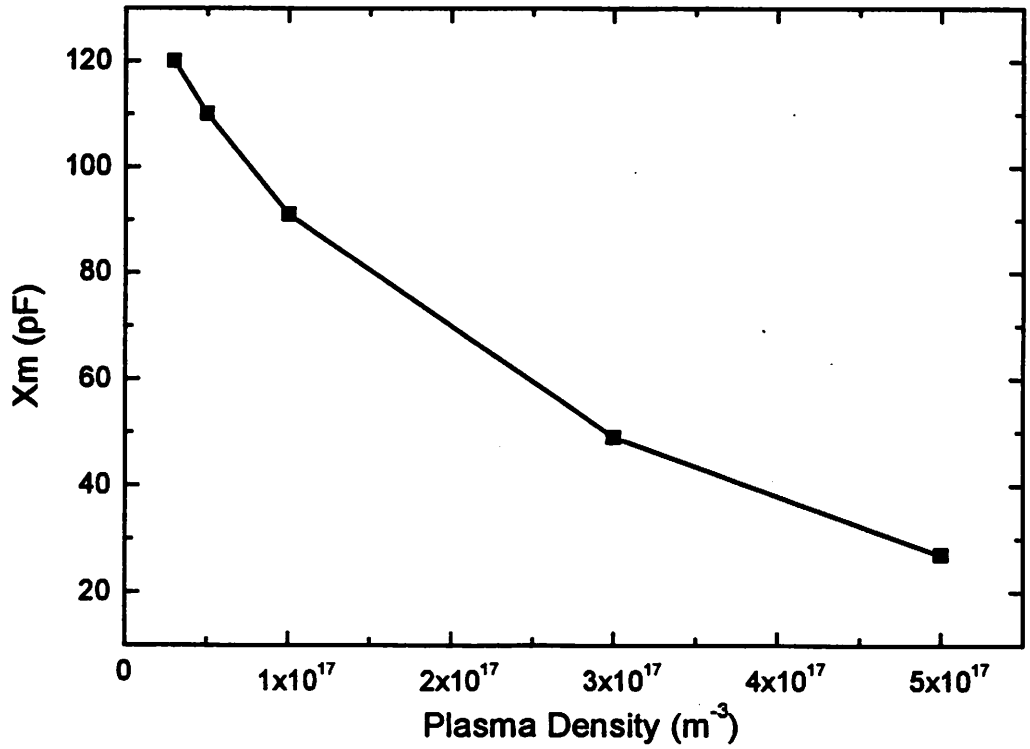


Fig. 4 Requirement for matching element Xm.
Transmission line length L=8.5 m.

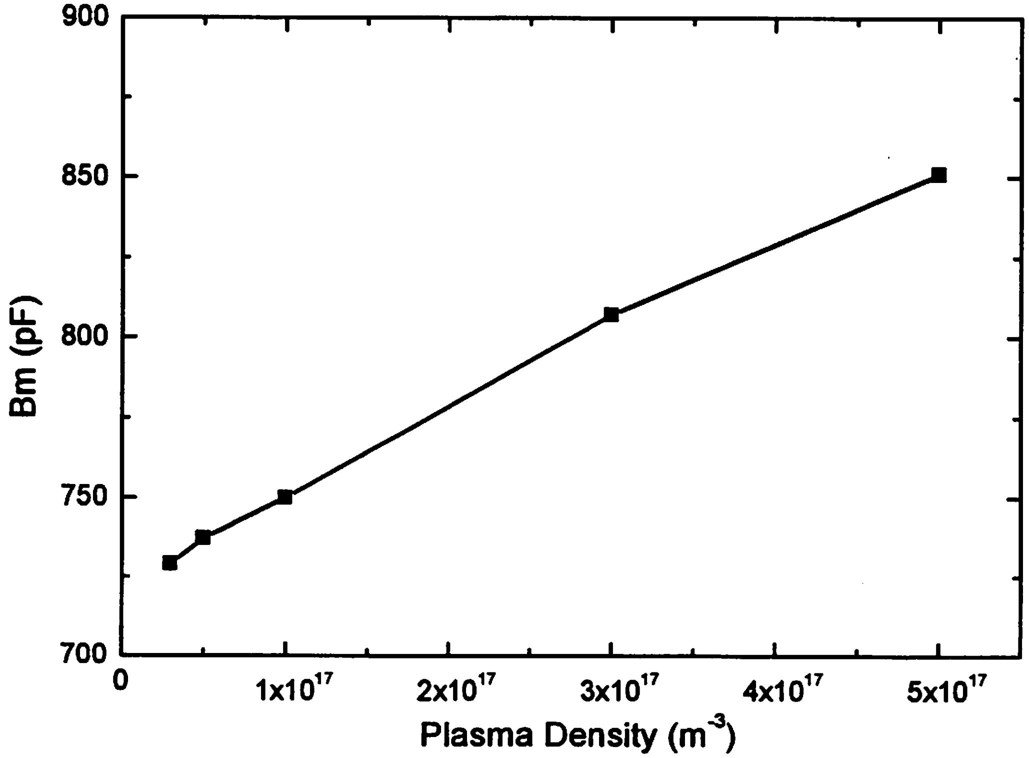


Fig. 5 Reruirement for matching element Bm.
Transmission line length L=8.5 m.

2-2. Transmission line length L=4.25 m

For the modified antenna coil configuration shown in Fig.2 (b), the transmission line length is reduced to be about 4.25 m. The characteristic impedance of the modified configuration is then one half of that for the primary one. This is because the resistance and inductance per unit length of the modified configuration are one half of those for the primary one and the capacitance per unit length is twice that for the primary one.

Figure 6 shows the requirements for the tuning elements X_1 and X_2. In this case, X_1 and X_2 are capacitive in nature, indicating that two variable capacitors are required as the tuning elements.

Figures 7 and 8 show the requirements for the matching elements Xm and Bm, respectively. It is seen in Fig. 7 that Xm is inductive in nature, which indicates that the first series element of the matching network must be a variable inductor. As shown in Fig. 8, Bm is capacitive in nature.

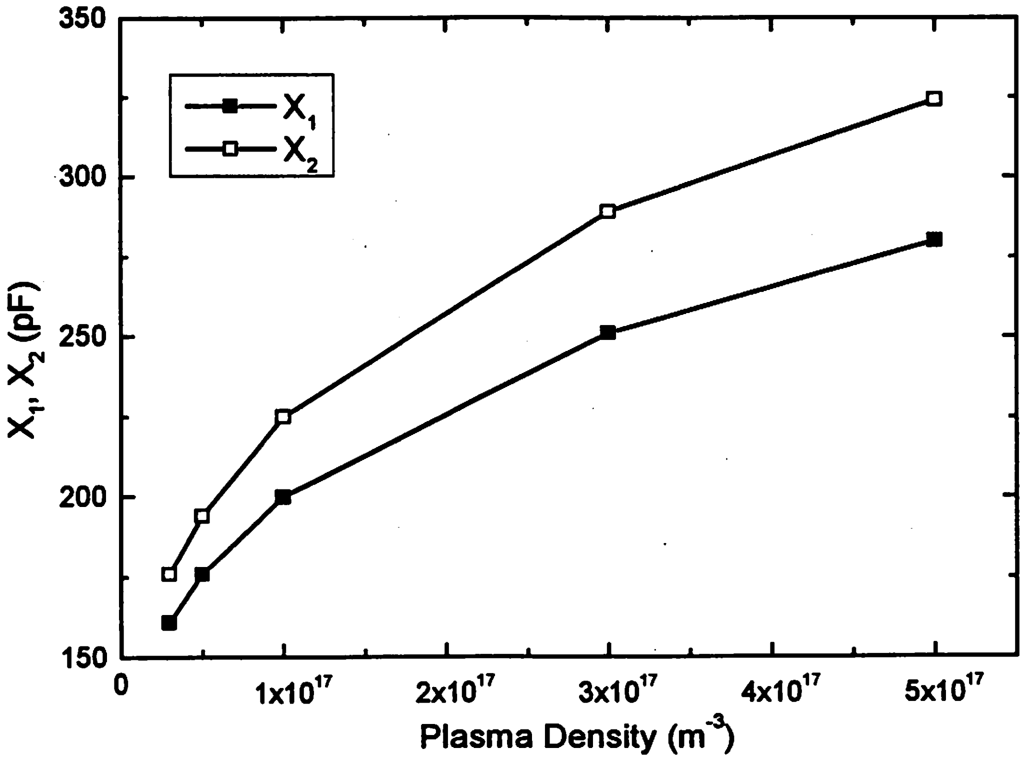


Fig. 6 Requirements for tuning elements X_1 and X_2.
Transmission line length L=4.25 m.

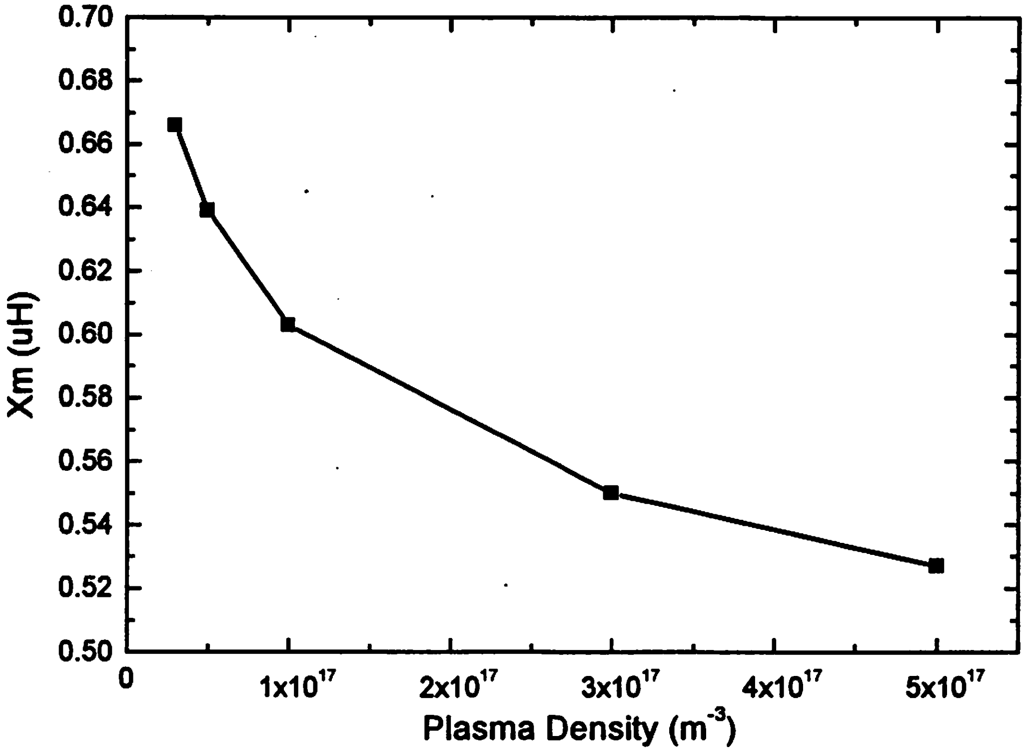


Fig. 7 Requirement for matching element Xm.
Transmission line length L=4.25 m.

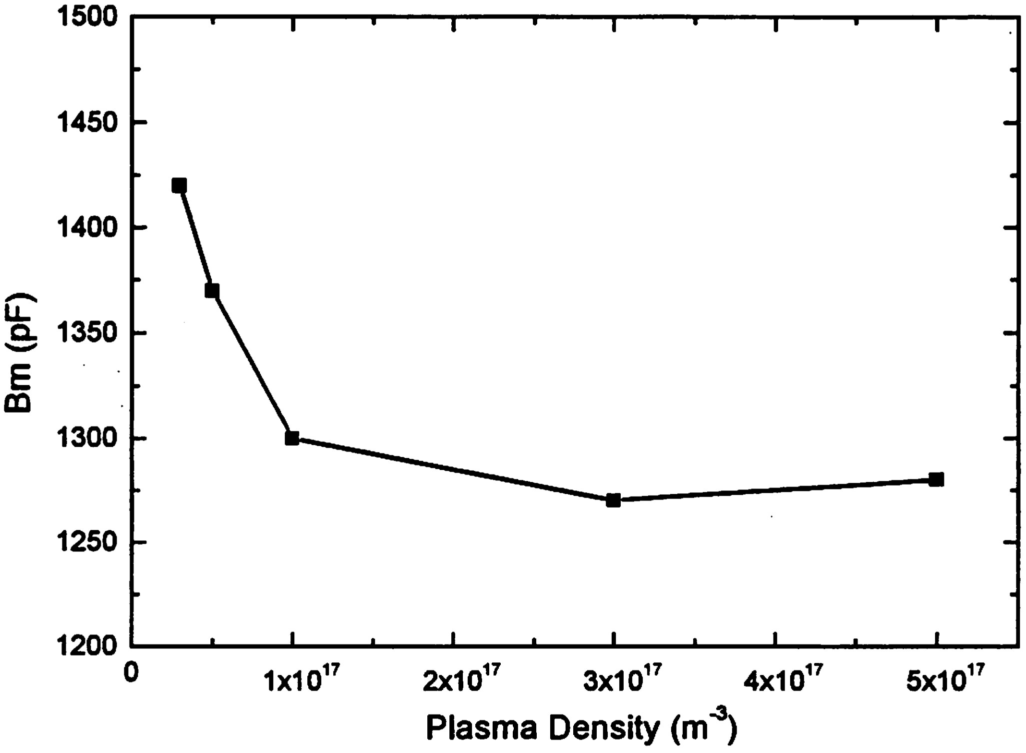


Fig. 8 Requirement for matching element Bm.
Transmission line length L=4.25 m.

From the above discussion, we see that the tuning elements and matching elements must be chosen properly, depending on the transmission line length. A summary is presented in Table 1 to illustrate how different lengths of the transmission line influence the operating conditions of the tuning and matching networks.

Table 1 : Summary of the requirements for the tuning and matching elements, for plasma density ranging from 3×10^{16} to 5×10^{17} m^{-3}.

	X_1	X_2	Xm	Bm
L=8.5 m Primary	2.2-11.0 μH Inductive	2.0-10.0 μH Inductive	27-120 pF Capacitive	730-850 pF Capacitive
L=4.25 m Modified	160-280 pF Capacitive	175-325 pF Capacitive	0.53-0.67 μH Inductive	1270-1420 pF Capacitive

3. Revised matching network for L=4.25 m

From the discussion in section 2, we see, for the modified antenna coil configuration, that the tuning elements must be variable capacitors. Since the tuning network consists of two variable capacitors connected in parallel with two fixed inductors, it provides either variable inductances or variable capacitances in our system. We thus do not need to revise the tuning network. We also see that the first series element of the matching network must be a variable inductor. Furthermore, for the matching

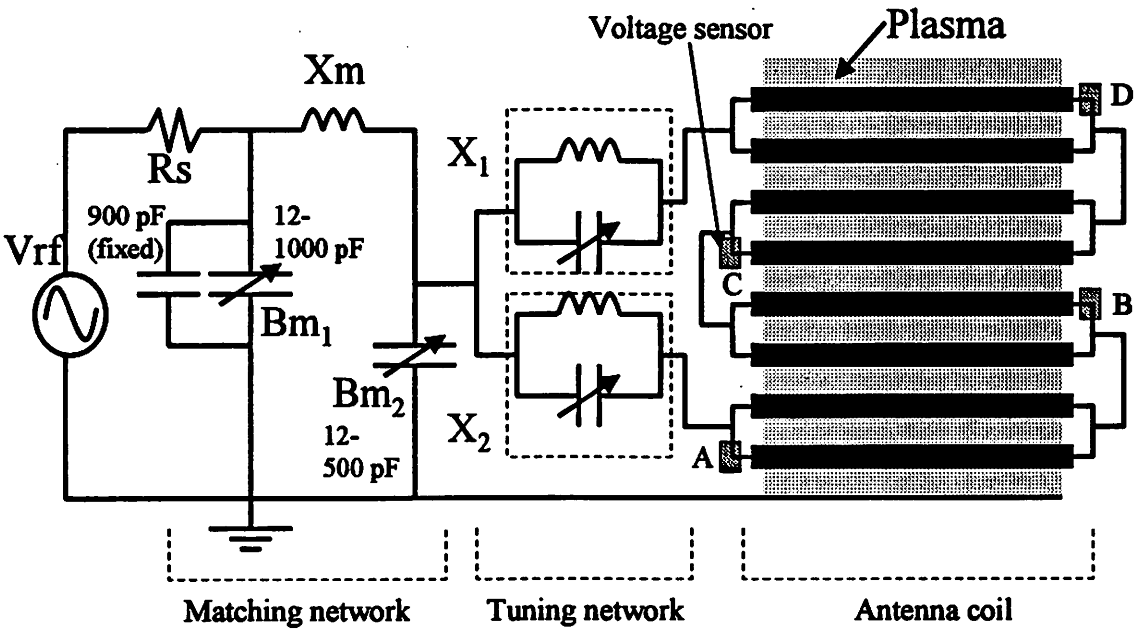


Fig. 9 Revised system configuration of the LAPS for antenna coil length L=4.25 m.

element Bm, capacitance values more than 1000 pF, which are larger than the maximum value of the variable capacitor in our system, are required.

We therefore revise the matching network so that we achieve a match for the modified antenna coil configuration. Figure 9 shows the revised system configuration for the antenna coil of L=4.25 m. The revised matching network consists of three elements. A capacitor (fixed capacitance 900 pF) was connected in parallel with the variable capacitor. The inductance element Xm is a fixed value (0.5 μH), and the two capacitance elements Bm_1 and Bm_2 can be varied to achieve the match.

4. Plasma results

For the modified LAPS configuration shown in Fig.9, we measured plasma densities under various operating conditions with Langmuir probes. Ion saturation currents were used to calculate the plasma densities based on the orbital ion motion model for Langmuir probes.$^{5)}$

4-1. Argon plasma

Figure 10 shows plasma density profiles for various argon gas pressures at an input power of P=700 W. For the three gas pressures, we identified achievement of launching a traveling wave using four voltage sensors (A, B, C, D), shown in Fig. 9, equally spaced along the antenna coil. The tuning network was adjusted so that the voltages from the four sensors were the same. As expected, the plasma density profiles are close to symmetric about the center. It is also seen in the figure that the plasma density increases with increasing gas pressure.

To investigate how the standing wave effects influence plasma density profiles, we measured the density profiles under non-tuned conditions where a standing wave was launched along the antenna coil. Figure 11 shows the density profiles for various standing wave conditions at an input power of P=700 W, and the corresponding voltage distributions along the antenna coil are shown in the inset. As seen in the figure, the profiles are not symmetric and the plasma density is high where the voltage is low. This is because the standing wave current is high where the standing wave voltage is low and the power dissipation along the antenna coil is proportional to the square of the current. From these results, we see that the standing wave pattern can strongly influence the plasma density profile.

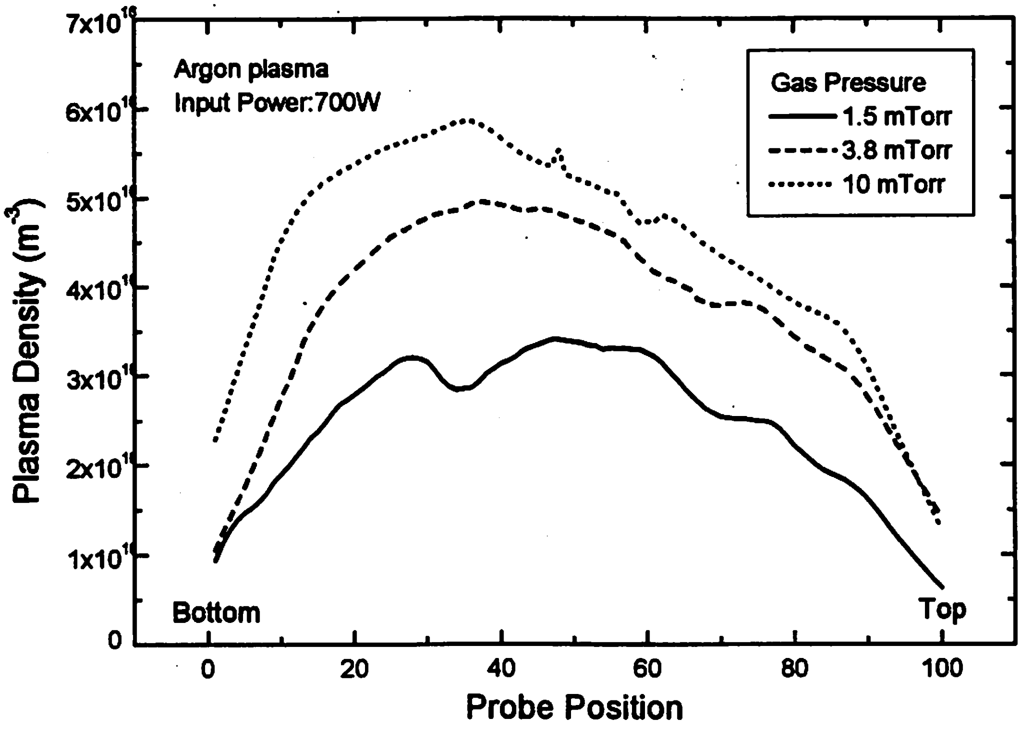


Fig. 10 Argon plasma density profiles for differenet gas pressures at an input power 700 W.

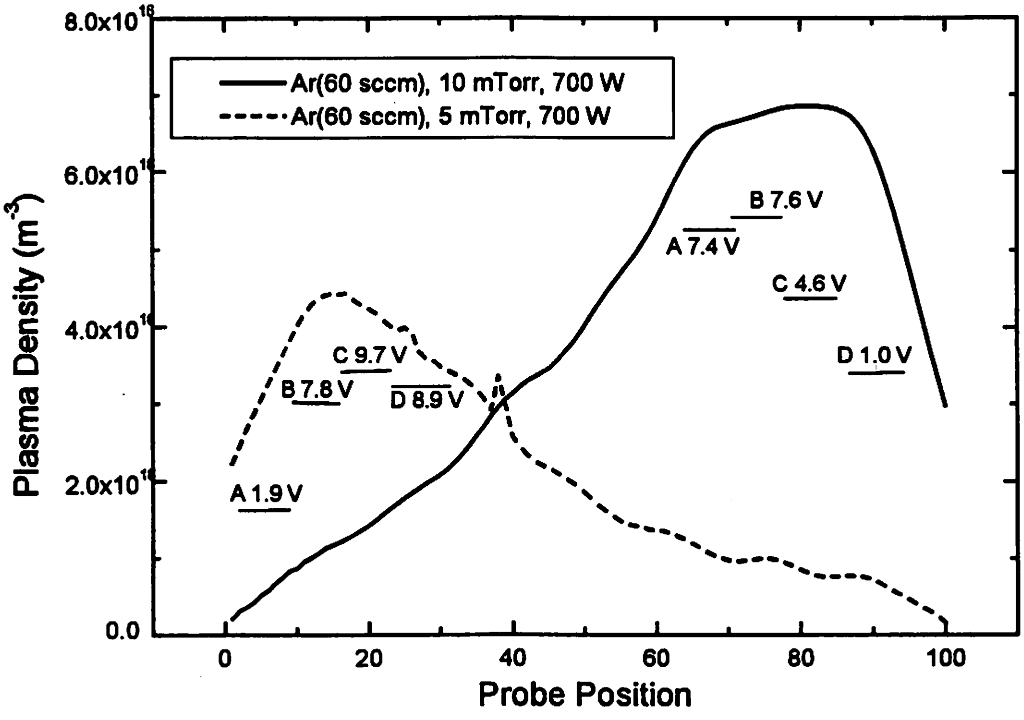


Fig. 11 Argon plasma density profiles for different standing wave conditions at an input power 700 W.

4-2. Oxygen plasma

We now describe the first oxygen plasma results obtained with the LAPS. Figure 12 shows plasma density profiles for various oxygen gas pressures at an input power of P=700 W. For the four gas pressures, we identified the achievement of launching a traveling wave, monitoring voltages from the four sensors to be almost equal. The density profiles are symmetric about the center and the plasma density increases as the gas pressure increases. It is also seen in the figure that the plasma densities are lower than those for argon plasma (Fig. 10) at the same gas pressure.

Figure 13 shows a plasma density profile for a standing wave condition at an input power of P=700 W, and the corresponding voltage distributions along the antenna coil are also shown in the inset. We see again that the plasma density is high where the standing wave voltage is low for this case. This result is also due to the same reason discussed for argon plasmas.

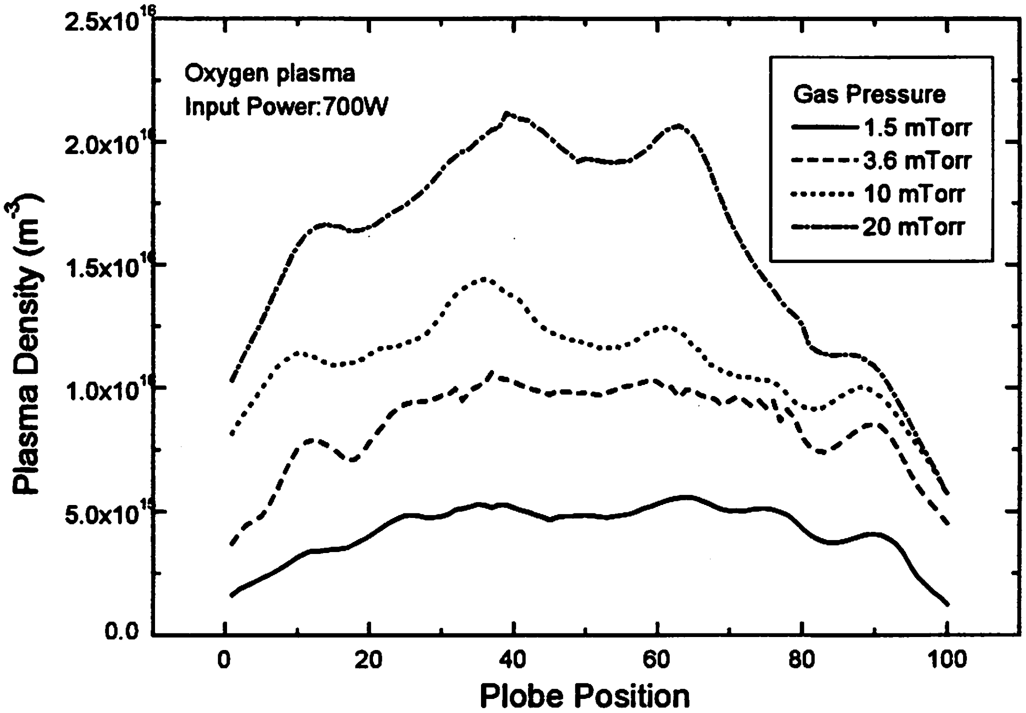


Fig. 12 Oxygen plasma density profiles for different gas pressures at an input power 700 W.

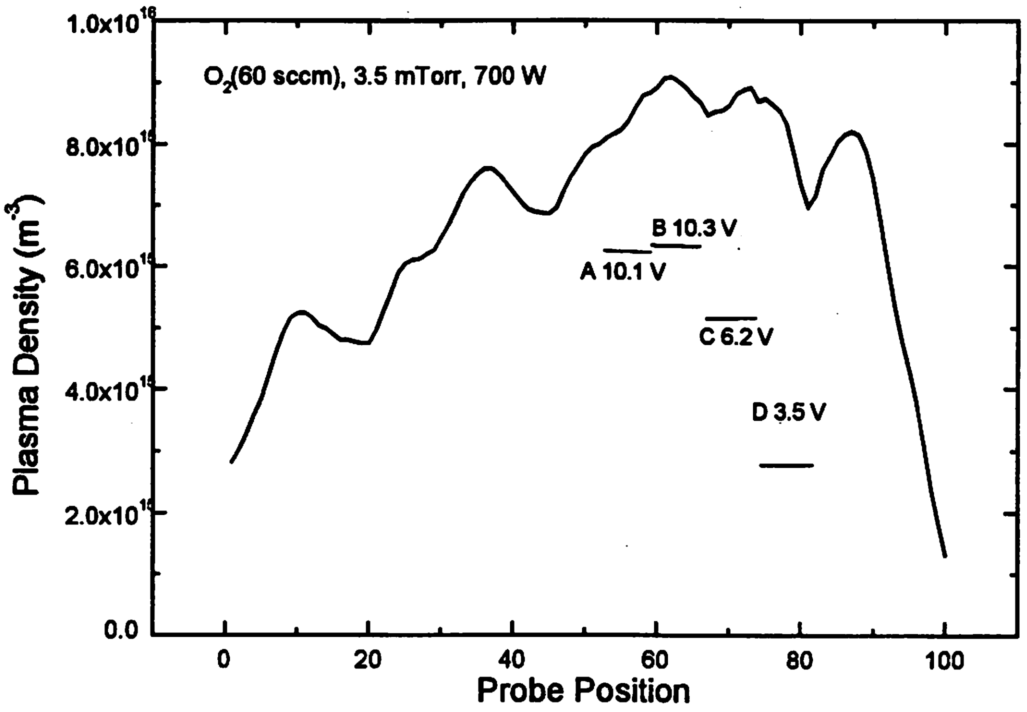


Fig. 13 Oxygen plasma density profile for a standing wave condition at an input power 700 W.

4-3. Oxygen/argon mixtures

It is interesting to measure the plasma density for oxygen/argon mixtures changing the mixture ratio. We measured the oxygen/argon mixture plasma density for different mixing ratios under a traveling wave condition, keeping the total gas flow rate and the input power constant.

Figure 14 shows the oxygen/argon mixture plasma density profiles for different mixing ratios at a total gas flow rate of 60 sccm (gas pressures 3.6-3.8 mTorr) and an input power of 700 W. Figure 15 also shows the result for different mixing ratios at a total gas flow rate of 20 sccm (gas pressures 1.4-1.6 mTorr) and an input power of 700 W. As seen in both figures, the plasma density decreases as the oxygen flow rate increases. In a molecular gas like oxygen, the collisional energy loss per electron-ion pair created can be a factor of 2-10 times higher than for a noble gas like argon at the same electron temperature. This is because, for molecular gases, additional collisional energy losses include excitation of vibrational and rotational energy levels, molecular dissociation, and, for electronegative gases like oxygen, negative ion information.5) Such high energy losses in oxygen plasmas result in lower plasma densities, compared to argon plasmas.

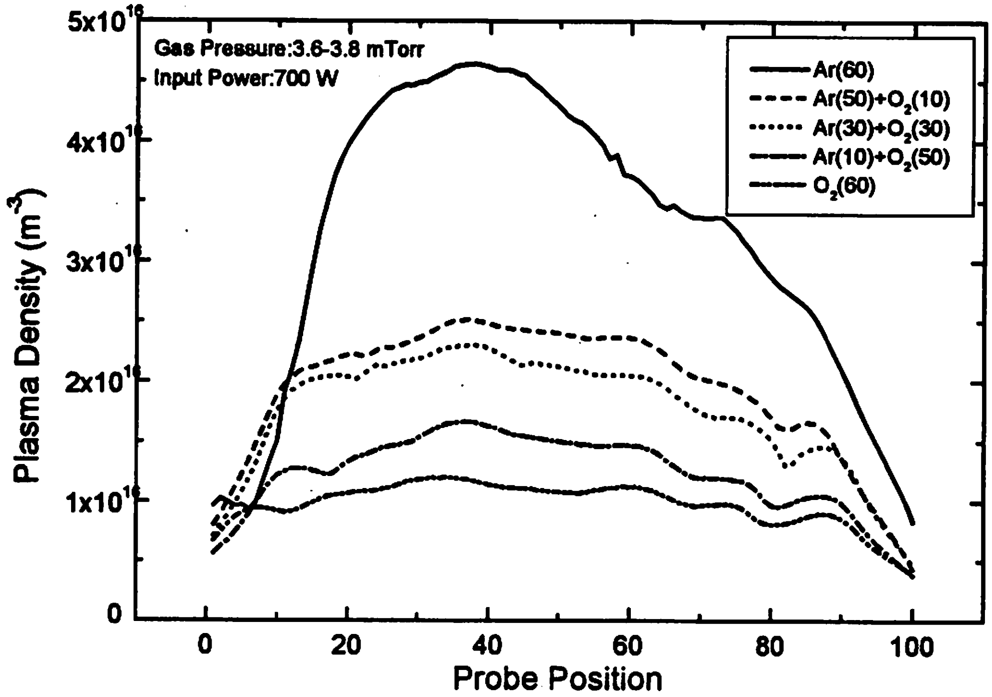


Fig. 14 Plasma density profiles for oxygen/argon mixtures at gas pressures 3.6-3.8 mTorr, for various oxygen/argon flow rates (sccm).

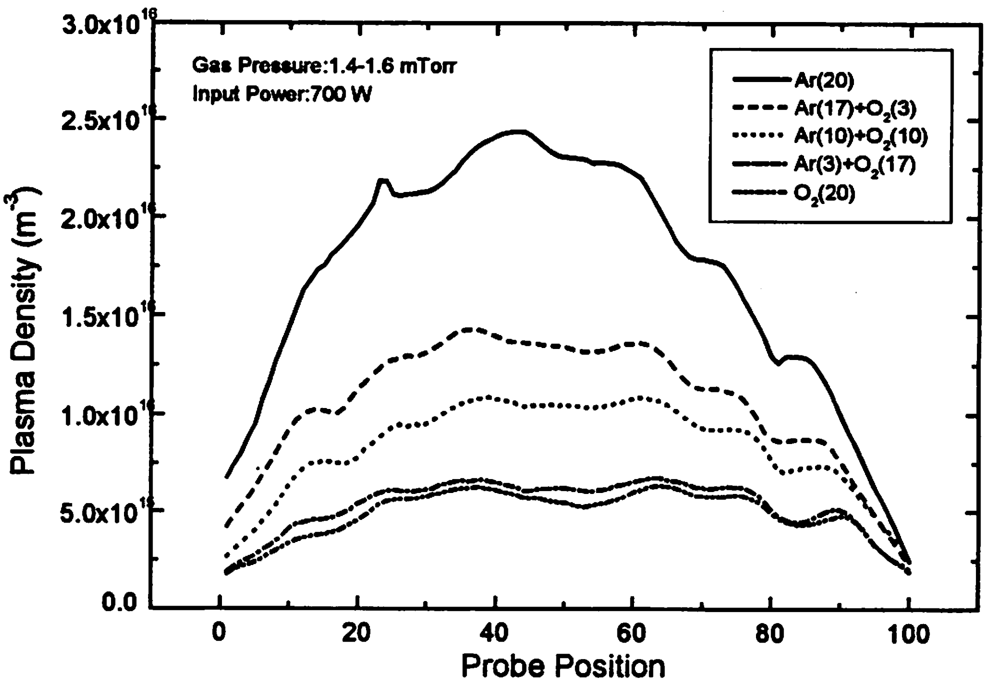


Fig. 15 Plasma density profiles for oxygen/argon mixtures at gas pressures 1.4-1.6 mTorr, for various oxygen/argon flow rates (sccm).

5. Conclusions

We have modified the configurations of the antenna coil and matching network for the LAPS, in order to eliminate input power dissipation in the tuning network and to achieve a match with a traveling wave. Using the revised system configuration of the LAPS, we have successfully launched a traveling wave and obtained symmetric plasma density profiles for oxygen, argon and oxygen/argon plasmas. We plan to do some photoresist etching experiments on the LAPS with an oxygen plasma or oxygen/argon mixture.

Acknowledgements

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