AN RF VOLTAGE DIVIDER FOR AN
INDUCTIVELY POWERED PLASMA SOURCE

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An RF Voltage Divider for an Inductively Powered Plasma Source

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Abstract
The goal of the project was to develop an accurate radio frequency (RF) voltage divider to measure the voltage drop across an inductive coil. The primary obstacle to overcome was the large radio frequency interference, specifically at 13.56 MHz, generated by the matching network.

1 Introduction

The apparatus is an RF power source used to drive an argon plasma. A three turn coil is used to inductively couple the RF power source across a quartz dielectric window to drive the plasma; see Figure 1. A voltage $V_{\text{actual}}$ is applied over the coil, and a matching network composed of capacitors $C_1$, $C_2$, and $C_3$ is tuned to 50Ω of impedance in order to provide optimum power flow from the power supply to the inductive coil to the plasma. The voltage divider is designed to measure the voltage drop across the coil. However, the use of a high power RF inductive coupling introduces a large amount of RF interference which makes the measurements from the unshielded voltage divider used previously and shown in Figure 2 unreliable and creates a need for shielding.

The voltage measurement is very important because together with a measurement of the root-mean-square current $I_{\text{rms}}$ it yields the inductance of the coil:

$$L_{\text{coil}} = \frac{V_{\text{rms}}}{\omega \cdot I_{\text{rms}}}$$
Figure 1: The matching network circuit. Points A and B correspond to A and B in Figures 2 and 3.

where

\[ \omega = 2\pi \ast 13.56\text{MHz}. \]

The change in coil inductance in the presence of plasma, in turn, is a good indicator of the amount of current flowing through the plasma. Thus, a reliable and accurate voltage measurement is vital.

The first attempt was a one-stage voltage divider without shielding, Figure 2. The inductance was measured to be roughly 440 nH. Unfortunately, this measurement is suspect because of the lack of shielding.

2 Circuit and Design

The circuit of the shielded, two-stage voltage divider is shown in Figure 3. The circuit consists of two dividers rather than one in an attempt to reduce the measurement’s sensitivity to stray impedance. The original divider’s second capacitor, \( C_2 \) in Figure 2, has an impedance of \( X_2 = 1/\omega \ast C_2 \simeq 4\Omega \). At 13.56 MHz, stray inductance in the wire can contribute a substantial enough fraction of 4\( \Omega \) to create an error in the voltage measurement.
Figure 2: Unshielded, one-stage divider.

Figure 3: Shielded, two-stage voltage divider.
Thus, a two-stage divider was designed; the first stage of this divider has a 100 pF capacitor, $C_2$ in Figure 3, with $X_2 \approx 120\Omega$ of impedance, making the divider less sensitive. The second stage of the divider is added to increase the division. The factor of division is given by

$$V_{\text{actual}} = D_1 * D_2 * V_{\text{read}}$$

where

$$\frac{1}{D_1} = \frac{C_1}{C_1 + C_2'}$$

$$\frac{1}{D_2} = \frac{C_3 + C_4}{C_3 + C_4 + C_5}$$

and

$$C_2' = C_2 + \frac{(C_3 + C_4)C_5}{C_3 + C_4 + C_5}$$

The expected voltage on the coil is on the order of one kilovolt. As the output from the voltage divider may later be wired to the inputs of a data acquisition card, which cannot tolerate more than a few volts of input, the values of the capacitances were chosen to give a division of roughly 500:1 or $-54.0$ dB. $C_3$ was added in parallel to $C_4$ in order to allow for a small amount of tuning of the divider. Tuning allows the user to achieve a specific voltage division or, if desired, to compensate for additional capacitance on the readout wire, if desired.

The shielding was accomplished via two small grounded Pamona boxes and BNC-type connectors. The Pamona boxes are simply grounded, conducting boxes used to eliminate RF interference inside the box. The boxes were grounded via a connection to the matching network ground. The BNC connectors are similarly shielded and grounded.

The first, 3 pF capacitor $C_1$ in Figure 3 was kept just outside of the first box because it carries high voltage on its anode. Unlike the the previous, unshielded divider, a long, high inductance lead was required to connect this capacitor to the coil. However, this inductance is tolerable because the inductive impedance is in series with the much higher impedance ($\approx 4000\Omega$) of the 3 pF capacitor.

The two stages were shielded in separate boxes as an extra precaution. Otherwise, the relatively high voltage on the first stage, which is on the order of 30V, may have the effect of a slight capacitive coupling on the second stage, which has a voltage on the order of one volt.
3 Calibration

The voltage divider was initially tuned to roughly 500:1, or $-54.0 \text{ dB}$. The tuning was accomplished with the voltage divider not yet affixed within the matching network. The output from a signal generator set to 13.56 MHz was amplified and measured and the signal was then fed through the voltage divider and measured again.

When the divider was soldered into the matching network, a network analyzer was used to determine the actual division, which at 13.56 MHz is affected by the capacitance of the wires and matching elements. A voltage was applied over the inductive coil, and the response of the divider was measured.

The analyzer determined the division to be $-55.8 \text{ dB}$ or 617:1. Unfortunately, the error in the measurement is rather large – the reading from the analyzer fluctuated from $-55.5 \text{ dB}$ to $-56.2 \text{ dB}$, though the large majority of the values fell between $-55.7 \text{ dB}$ and $-56.0 \text{ dB}$. The best estimate of the division is the average value, $-55.8 \text{ dB}$. The error, based on the deviation of the values, is $0.2 \text{ dB}$ or $\pm 3\%$.

The division of the analyzer was almost independent of frequency in the neighborhood of 13.56 MHz, especially at lower frequencies. Above 30 MHz, the division varied greatly from its value at 13.56 MHz.

4 Data and Error Analysis

The matching network, along with the voltage divider, was inserted into the chamber and an argon plasma was initiated. The plasma length was approximately 7 cm. Voltage measurements with the new voltage divider in place are shown in Table 1. The root-mean-square voltage is given by

$$ V_{\text{rms}} = \frac{V_{\text{read}} \cdot D_1 \cdot D_2}{2^{\frac{3}{2}}} $$

where $V_{\text{read}}$ is the measured peak-to-peak voltage.

A Pearson coil model 411 was used to monitor the current (see Figure 1). It produces a voltage output, from which the root-mean-square current is given by

$$ I_{\text{rms}} = \frac{V_{\text{monitor}} \cdot C_{\text{al}}}{2^{\frac{3}{2}} \cdot K} $$
Table 1: Root-mean-square voltage as a function of power and pressure.

<table>
<thead>
<tr>
<th>Volts</th>
<th>10 mTorr</th>
<th>30 mTorr</th>
<th>50 mTorr</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 W</td>
<td>3.83e2</td>
<td>3.46e2</td>
<td>3.12e2</td>
</tr>
<tr>
<td>100 W</td>
<td>4.59e2</td>
<td>4.14e2</td>
<td>3.94e2</td>
</tr>
<tr>
<td>200 W</td>
<td>5.75e2</td>
<td>5.27e2</td>
<td>5.09e2</td>
</tr>
<tr>
<td>300 W</td>
<td>6.73e2</td>
<td>6.25e2</td>
<td>6.12e2</td>
</tr>
<tr>
<td>400 W</td>
<td>7.68e2</td>
<td>7.14e2</td>
<td>7.14e2</td>
</tr>
<tr>
<td>500 W</td>
<td>8.47e2</td>
<td>8.10e2</td>
<td>8.12e2</td>
</tr>
</tbody>
</table>

Table 2: Root-mean-square current as a function of power and pressure.

<table>
<thead>
<tr>
<th>Amps</th>
<th>10 mTorr</th>
<th>30 mTorr</th>
<th>50 mTorr</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 W</td>
<td>9.28</td>
<td>8.40</td>
<td>7.61</td>
</tr>
<tr>
<td>100 W</td>
<td>11.1</td>
<td>10.2</td>
<td>9.67</td>
</tr>
<tr>
<td>200 W</td>
<td>14.1</td>
<td>13.0</td>
<td>12.7</td>
</tr>
<tr>
<td>300 W</td>
<td>16.6</td>
<td>15.5</td>
<td>15.3</td>
</tr>
<tr>
<td>400 W</td>
<td>20.1</td>
<td>18.9</td>
<td>18.9</td>
</tr>
<tr>
<td>500 W</td>
<td>22.14</td>
<td>21.3</td>
<td>21.4</td>
</tr>
</tbody>
</table>

where $V_{monitor}$ is the peak to peak voltage output and

$$Cal = 10 \times 2 = 20 \frac{A}{V}$$

and

$$K = 1.616$$

The calibration coefficient is the product of the current monitor specification and a factor of two due to a 50Ω terminator that was used during measurements. $K$ represents the high frequency response and is designed to compensate for a shift in calibration at high frequencies; the value of $K$ was obtained from a calibration chart produced by Pearson. The values of the RMS current are shown in Table 2.

The error in the voltage measurement is

$$(\Delta V_{rms})^2 = (\Delta D)^2 \left( \frac{\partial V_{rms}}{\partial D} \right)^2 + (\Delta V_{read})^2 \left( \frac{\partial V_{rms}}{\partial V_{read}} \right)^2 + (\Delta P)^2 \left( \frac{\partial V_{rms}}{\partial P} \right)^2$$
and the error in the current measurement is

\[(\Delta I_{rms})^2 = (\Delta V_{monitor})^2 \left( \frac{\partial I_{rms}}{\partial V_{monitor}} \right)^2 + (\Delta Cal)^2 \left( \frac{\partial I_{rms}}{\partial Cal} \right)^2 + (\Delta P)^2 \left( \frac{\partial I_{rms}}{\partial P} \right)^2 \]

where we estimate

\[\Delta V_{monitor} = \Delta V_{read} \approx 1 \times 10^{-1} V\]

based on fluctuations in the readings.

\[\Delta Cal \approx 1 \times 10^{-2} \times Cal\]

\[\Delta D = \Delta(D_1 \times D_2) = 3 \times 10^{-2} \times D_1 \times D_2\]

The values of power were measured with a Bird Wattmeter 4522; the error in the measurement is 5W. Unfortunately, the dependence of the voltage and current on the power is not known, so it is difficult to arrive at an accurate measurement of error. However, these dependencies can be estimated by adjusting the power values by ±5 W, and recording the change. The dependencies, accurate only to within an order of magnitude, are

\[\frac{\partial V_{read}}{\partial P} \approx 5 \times 10^{-2} \frac{V}{W}\]

and

\[\frac{\partial V_{monitor}}{\partial P} \approx 4 \times 10^{-2} \frac{V}{W}\]

These values are roughly correct over a range of 10 mTorr to 50 mTorr and 50 W to 500 W. These dependencies in turn give us an approximation of the dependencies of \(I_{rms}\) and \(V_{rms}\) on the power. Therefore,

\[\left( \frac{\partial V_{rms}}{\partial P} \right)^2 = \left( \frac{\partial V_{rms}}{\partial V_{read}} \right)^2 \left( \frac{\partial V_{read}}{\partial P} \right)^2 = \left( \frac{\partial V_{rms}}{\partial V_{read}} \right)^2 \left( 5 \times 10^{-2} \frac{V}{W} \right)^2\]

and

\[\left( \frac{\partial I_{rms}}{\partial P} \right)^2 = \left( \frac{\partial I_{rms}}{\partial V_{monitor}} \right)^2 \left( \frac{\partial V_{monitor}}{\partial P} \right)^2 = \left( \frac{\partial I_{rms}}{\partial V_{monitor}} \right)^2 \left( 4 \times 10^{-2} \frac{V}{W} \right)^2\]

Finally, the uncertainties are
Table 3: Coil inductance (nH) as a function of input power and pressure.

<table>
<thead>
<tr>
<th>nHenry's</th>
<th>10 mTorr</th>
<th>30 mTorr</th>
<th>50 mTorr</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 W</td>
<td>484</td>
<td>484</td>
<td>481</td>
<td>483</td>
</tr>
<tr>
<td>100 W</td>
<td>485</td>
<td>476</td>
<td>478</td>
<td>480</td>
</tr>
<tr>
<td>200 W</td>
<td>479</td>
<td>476</td>
<td>470</td>
<td>475</td>
</tr>
<tr>
<td>300 W</td>
<td>476</td>
<td>473</td>
<td>470</td>
<td>473</td>
</tr>
<tr>
<td>400 W</td>
<td>449</td>
<td>443</td>
<td>443</td>
<td>445</td>
</tr>
<tr>
<td>500 W</td>
<td>449</td>
<td>446</td>
<td>445</td>
<td>447</td>
</tr>
<tr>
<td>Average</td>
<td>470</td>
<td>466</td>
<td>465</td>
<td>467</td>
</tr>
</tbody>
</table>

\[
(\Delta V_{rms})^2 = \left(\frac{D_1 \cdot D_2}{2^\frac{3}{2}}\right)^2 [9 \cdot 10^{-4} V_{read}^2 + 7.3 \cdot 10^{-2}]
\]

and

\[
(\Delta I_{rms})^2 = \left(\frac{Cal}{K \cdot 2^\frac{3}{2}}\right)^2 [1 \cdot 10^{-4} V_{monitor}^2 + 5 \cdot 10^{-2}]
\]

The values of \(I_{rms}\) and \(V_{rms}\) determine the coil inductance, shown in Table 3.

The error in the inductance is

\[
(\Delta L_{coil})^2 = (\Delta V_{rms})^2 (\frac{\partial L_{coil}}{\partial V_{rms}})^2 + (\Delta I_{rms})^2 (\frac{\partial L_{coil}}{\partial I_{rms}})^2
\]

\[
(\Delta L_{coil})^2 = \frac{1}{\omega^2 I_{rms}^2} [(\Delta V_{rms})^2 + (\Delta I_{rms})^2 V_{rms}^2 I_{rms}^{-2}]
\]

Using the average values for current and voltage,

\[
\Delta I_{rms} = 9.8 \cdot 10^{-1} A
\]

and

\[
\Delta V_{rms} = 2.4 \cdot 10^1 V
\]

and therefore

\[
\Delta L_{coil} = 4.2 \cdot 10^{-8} H = 42 nH
\]
5 Conclusions

The similarity between the inductance calculated from the voltage measurements of the previous unshielded and the shielded divider lend credibility to those measurements. Though it appears that the RF interference did not distort the values of the voltage significantly, the shielded divider is a more reliable source of data. The error in the measurement of the inductance is significant; a large part of that error is due to the uncertainty in the power measurement.