Design of an Inductively Coupled Plasma Discharge Source for a Plasma Physics Laboratory Course

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2016

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A condensed version of this thesis was published in the transactions of the 2016 American Nuclear Society Student Conference
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Introduction

The University of Florida is reintroducing a graduate course, Plasmas and Fusion, to the nuclear engineering curriculum. The course covers theory of plasma physics, and the practical use of plasma systems and fusion devices. Currently, the course is limited to classroom instruction, and could be enhanced by the addition of a laboratory section where students would apply theory learned in class and observe phenomena generated by various plasmas. The purpose of this project is to design an Inductively Coupled Plasma (ICP) Discharge Source, which can be used in future Plasmas and Fusion courses at the University of Florida, beginning in the 2017 spring academic semester, and to design the associated precursory laboratory exercise which demonstrates the theory of inductively coupled plasma and its application in the industry.

An inductively coupled plasma is excited by a magnetic field generated by a radio frequency (RF) current running through an induction coil. The ICP absorbs energy through Joule Heating, whereby free electrons, accelerated by the electric field have multiple collisions with the plasma ions. ICP is commonly used to perform semiconductor manufacturing, etching, and isotope identification. The ICP source can also be used as a teaching tool for studying helium plasma waves in fusion applications. The ICP source is aneutronic, and thus does not emit harmful fast neutrons or radioisotopes making it an ideal choice to study fusion plasmas in an undergraduate laboratory class [1 – 4].

Inductively coupled plasma sources offer several advantages over other plasmas for use as a laboratory experiment. These sources are inexpensive for a teaching application, safe to operate, and useful in a large range of industry applications. ICP sources demonstrate a variety of plasma phenomena and this laboratory experiment would demonstrate several properties, unique to ICP plasma, such as the characteristic emission spectra of plasma gases. These advantages make ICP
sources well suited for a university lab experiment, and a great choice for a hands on addition to the University of Florida Plasmas and Fusion course [1–4]. The University of Florida ICP source design is named Prometheus.

**Project Description**

The goal of this project was to design an Inductively Coupled Plasma Torch which can be used to study plasma phenomena in a demonstrational laboratory experiment. This includes, but is not limited to the intended design for an ICP Torch system, including torch configuration, plasma gas selection, operating conditions such as power output and induction field frequency, component materials selection, and selection of spectroscopic measuring devices.

Additionally, the induced magnetic field by a circular current loop was simulated in a MATLAB program, written by Rao, to calculate the maximum magnetic field strength generated by the copper induction coil [5]. Through this program, students in the University of Florida Plasma Physics course could predict plasma conditions, and practice using the Biot-Savart law to determine the magnetic and electric fields present in the ICP torch as a precursory exercise to the plasma experiment. This program was also used to optimize design parameters of the plasma torch.

Finally, a laboratory precursory exercise was developed for students in future Plasmas and Fusion courses to learn and apply their understanding of inductively coupled plasma theory and applications. This exercise includes background information concerning inductively coupled plasma sources, and a four problem homework set which covers the Biot Savart Law, Paschen curves, matching networks, and emission spectra identification.
Primary Components of Prometheus

Experimental Design

The ICP source design was inspired by the *Inductively Coupled Plasma Discharge in Flowing Non-Argon Gas at Atmospheric Pressure for Spectrochemical Analysis* invention, patented by Meyer and Barnes in 1984 [3]. This ICP design is capable of sustaining inductively coupled non-argon plasma, and performing elemental analysis of aerosol or powdered samples. Meyer and Barnes discuss that excitation of non-argon gas requires the use of an induction field frequency exceeding 40.68 MHz. For this reason, most ICP sources use Argon as the plasma gas, as it has both low ionization potential and thermal conductivity, and can be excited by a 13.56 MHz induction field. Meyer and Barnes’ invention allows for a 13.56 MHz plasma source to generate a non-argon plasma by first initiating an argon plasma and gradually introducing non-argon gas into the containment tube. The University of Florida ICP source design was based off of Meyer and Barnes’ invention so that a 13.56 MHz power supply could be used to study multiple gases. Elemental analysis of aerosol is outside the scope of the experiment, and therefore components of Meyer and Barnes’ device which perform functions exclusively for this purpose are not included in the University of Florida ICP design.

Prometheus has seven primary components: a 13.56 MHz RF power supply, matching network, plasma torch and support stand, spectrometer, gas flow controller system, various gas cylinders, and a Lab View control interface. The RF power source supplies up to 2.5 kW to the induction coil. The matching network serves to both increase the induction frequency of the power supply, and to reduce the percentage of reflected power. A mass flow controller system is used to regulate the flow of plasma gas, coolant gas, and sheath gas into the torch. This system has the capability of accurate, low flow rates, such as 1-3 LPM for the plasma line, 15-30 LPM for the coolant line,
and 0-15 LPM for the sheath line. Several gases are connected to the system. The coolant and sheath gases are compressed air, and the plasma gases include compressed argon, helium, nitrogen, and oxygen. These plasma gases offer a diverse range of energy spectra and are easily excitable with Prometheus. The spectrometer is a Thor Labs Compact CCD Spectrometer, and measures wavelengths in the UV-IR wave range (200-1000 nm) with 2 nm resolution. This information is provided to the Lab View control interface, which also controls the power source, matching network, and flow controllers. Figure 1 displays a block diagram of the experiment.

**Figure 1:** Experiment Block Diagram

**Plasma Torch and Housing Design**

The ICP Torch is custom machined, and is primarily composed of a plastic base, quartz containment and nebulizer tubes, an internal sleeve mount, inlets for coolant, plasma, and sheath gas, and a copper induction coil. Figure 2 shows a 3D representation of the ICP Torch, labeling its primary components.
The ICP torch operates by drawing the plasma, coolant, and sheath gases through three separate inlets on the plastic base, and by using an induction coil, powered by the RF power source to generate a stable plasma at atmospheric pressure. The plasma housing supports two quartz cylindrical tubes: the containment tube and the nebulizer tube. These two concentric tubes provide a physical barrier between the three gases flowing into the torch. The plasma gas enters the torch at low flow rates from an inlet at the bottom of the plastic base within the nebulizer tube until it reaches the induction coil at the top of the device. This gas is the primary component of the plasma generated within the induction coil. Both the coolant and sheath gases enter the torch from inlets on the side of the plastic base cylinder. The coolant gas flows at a higher flow rate than the plasma gas in the narrow region between the containment and nebulizer tubes, and prevents damage and overheat to the containment tube from the plasma within the induction coil. Finally, the sheath
gas is directed along the outside wall of the containment tube, and provides a stabilizing effect to the plasma. Table 1 lists the equipment used to construct Prometheus, including supplier information and technical specifications. Figure 3 displays a schematic drawing of the plasma torch, showing dimensions of the quartz tubes within the plasma housing. Figure 4 shows a cutaway side view of Prometheus, labeling the containment tube, nebulizer tube, sleeve mount, and base handle. The plasma gas inlet leads to the region within the nebulizer tube, and the coolant gas inlet leads to the region between the nebulizer and containment tubes. The sheath gas inlet directs the sheath gas along the exterior of the containment tube.

**Table 1: Prometheus Equipment and Technical Specifications**

<table>
<thead>
<tr>
<th>Component Name</th>
<th>Technical Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.56 MHz RF Power supply</td>
<td>Drytek Model 2600334, 2.5 kW</td>
</tr>
<tr>
<td>Gas Cylinders</td>
<td>Airgas, Size 300, Oxygen, Helium, Nitrogen, Argon</td>
</tr>
<tr>
<td>Mass Flow Controllers</td>
<td>MKS, high accuracy in 5-20 sccm flow rate</td>
</tr>
<tr>
<td>Compact CCD Spectrometer</td>
<td>Thorlabs, Detection Range: 200 – 1000 nm, &lt;2 nm accuracy</td>
</tr>
<tr>
<td>Induction Coil</td>
<td>Hollow copper, water cooled, 0.32 cm tube diameter, 0.56</td>
</tr>
<tr>
<td></td>
<td>tube pitch, 4.5 cm coil diameter, 3.89 cm coil length</td>
</tr>
<tr>
<td>Matching Network</td>
<td>Custom made, forward and reverse power tunable</td>
</tr>
<tr>
<td>Quartz Cylindrical Tubes</td>
<td>Custom Fused Quartz</td>
</tr>
<tr>
<td>O-Rings</td>
<td>Custom Fused Quartz, Teflon</td>
</tr>
<tr>
<td>Plastic Base</td>
<td>Mountain Precision Tool, machine shopped</td>
</tr>
<tr>
<td>Mounting Sleeve</td>
<td>Mountain Precision Tool, machine shopped, Teflon</td>
</tr>
</tbody>
</table>
Figure 3: Plasma Torch Quartz Tubes Schematic (cm)

Figure 4: Prometheus Torch Side View
Optimizing the Design of Prometheus

Induction Coil Design

ICP induction coils have three geometric configurations: planar, cylindrical, and half-toroidal. Prometheus uses a seven turn, cylindrical coil. The number of turns of any induction coil is dictated by a minimum current required to excite the plasma. Lieberman and Lichtenberg suggest that for a cylindrical induction coil this minimum is roughly $10 \text{ Amp-turn-cm}^{-1}$ [2]. This relationship is given in Equation 1:

$$\frac{(I_0 \cdot n)_{MIN}}{\pi \cdot D} = 10 \frac{A \cdot \text{turn}}{\text{cm}} \quad (1)$$

For Prometheus, a maximum radius of 1.8 cm was assumed to determine $n$, as this is the radius used in Meyer and Barnes’ patent. The Drytek RF power source supplies up to 30 A, which was the assumed value for $I_0$, as a higher current minimizes the number of required turns in the coil. After these values are substituted into Equation 1, the minimum number of turns was determined to be 3.768 turns. This number of turns was increased to 4 in Prometheus to simplify design and achieve a more uniform magnetic field. Thus the minimum current required to excite the plasma was reduced to 28.26 A. This current and number of turns is preferred over other possibilities, such as a 14.13 A current paired with 8 turns for two reasons. Initially, the induction coil is to be hand made at the University of Florida, and reshaping a copper coil is a tedious process, and imperfections which could distort the magnetic field, such as crimps in the coil are difficult to prevent or anticipate during the reshaping process. Thus reducing the number of turns minimizes the risk of distorting the coil. Moreover, the induction coil is designed to exhibit properties of a current carrying loop, as defined by the Biot-Savart Law. A lower turn number more closely mimics an infinite loop, which is the reason why a 4 turn induction coil is the best option for this experimental setup. Table 2 lists the design parameters for Prometheus’ induction coil.
Table 2: Induction Coil Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Amplitude</td>
<td>$I_0$</td>
<td>28.26</td>
</tr>
<tr>
<td>Number of Turns</td>
<td>$n$</td>
<td>4</td>
</tr>
<tr>
<td>Coil Diameter</td>
<td>$d$</td>
<td>0.32</td>
</tr>
<tr>
<td>Tube Diameter</td>
<td>$D$</td>
<td>3.6</td>
</tr>
</tbody>
</table>

Matching Network Design

A matching network is a critical component for an inductively coupled plasma source to operate efficiently and safely. The matching network in this experiment connects the power supply to the induction coil. A matching network serves two primary purposes: to maximize the power transfer from the power supply to the induction coil, and to match the generator impedance to the load impedance to reduce the percentage of reflected power. Prometheus uses a standard L type matching network to achieve these goals. Figure 5 displays a schematic of this matching network.

![Matching Network Schematic](image)

**Figure 5:** Prometheus Matching Network

*Circuit Schematic Developed with Do Circuits circuit editor [7]*
For safe operation of Prometheus, this matching network minimizes the reflected power to the radiofrequency generator. The Drytek RF generator has an output impedance of $R_s = 50 \text{ ohm}$, and a typical plasma load impedance is given as $R_p = 2 \text{ ohm}$. The inductor and capacitor are incorporated in parallel to match the generator impedance to the load impedance. This matching network design is more desirable than incorporating a resistor in parallel, as it minimizes power loss to the network and maximizes power delivered to the induction coil. A 115 nH inductor and an 1150 pF capacitor were selected to match the 13.56 MHz power supply. The resulting impedances of the inductor and capacitor are calculated by the governing equations of an L type matching network, as shown in Equations 2 and 3. These values are $X_1 = 9.8 \text{ ohm}$ and $X_2 = 10.207 \text{ ohm}$, respectively. This network achieves matching, and because $R_s > R_p$, the risk of reflected power to the generator has been sufficiently reduced.

$$X_1 = \sqrt{(R_s R_p) - R_p^2} \quad (2)$$

$$X_2 = R_s \frac{R_p}{X_1} \quad (3)$$

**Magnetic Field Simulations**

The principle excitation method of an ICP is through a magnetic field and associated electric field generated by a high current in an induction coil. The properties of the ICP are dependent on the magnitude and direction of the induced magnetic field. The magnetic fields generated by these coils can be approximated with the Biot-Savart law equation for magnetic field in a current carrying loop. This law is shown in Equation 4:

$$dB = \frac{\mu_0 I \, dl \times \hat{r}}{4\pi r^2} \quad (4)$$

The induced magnetic field by a circular current loop was simulated in a MATLAB program, written by Rao [5]. In this program the current amplitude, coil radius, and permittivity may be
varied to show their effects on the magnetic field components strength and direction in the Y-Z plane. Figure 6 displays the Y-component magnetic field strength (BY component), while Figure 7 displays the Z-component magnetic field strength (BZ component). In these figures, the Y-axis is the radial distance in cm from the center of the current loop, and the Z-axis is the distance in cm normal to the plane of the current loop.

As expected, the BY component shows a strong repulsive force with densely packed field lines close to the current carrying wire. These fields would accelerate a charged particle toward the center of the coil. The BZ component also shows the expected magnetic field. In Figure 7, closely packed field lines from z=0 to 6 cm show the presence of a strong magnetic field, capable of exciting a plasma. The density of these field lines suggest a plasma could be excited to a maximum height of 6-8 cm.

Figure 6: Magnetic Field Strength (T) Y (Radial) Component
Laboratory Precursory Exercise

The ultimate goal for the Prometheus ICP source is to be used in a laboratory experiment, coupled with the Plasmas and Fusion course at the University of Florida. A laboratory precursory exercise was written as an educational aid for students to understand the theory by which the Prometheus ICP source was designed, prior to performing experiments in the laboratory. This exercise provides an overview of inductively coupled plasma and its industrial application. Additionally, the exercise includes a four problem homework set which highlights the important components of the experimental design.

Initially, students practice using the Biot-Savart law to calculate the magnetic field components in the center of an induction coil. This problem demonstrates that the magnetic field components along the z axis, passing through the coil are the only components that contribute to the excitation of the plasma. The Paschen curves problem illustrates that all gasses have a characteristic breakdown voltage, and that Argon is a gas with a particularly low threshold breakdown voltage.
In the matching network problem, students learn the importance of impedance matching to minimize reflected power from the induction coil to the generator. The final problem examines a typical emission spectra for various plasma gases. In this problem, students learn how to identify various gases present in a plasma emission spectra. This precursory exercise is presented in its entirety in Appendix C.

**Conclusion**

An Inductively Coupled Plasma source for university laboratory experiments has been designed. Simulations of the induced magnetic field show that an ICP with radius of 1.8 cm and current of 28.6 A could excite a plasma height of 6-8 cm. Additionally, a matching network has been designed to match the impedance of the generator to the load impedance of the plasma. Finally, a precursory exercise has been developed for students in the University of Florida Plasmas and Fusions course to learn and practice their understanding of the theory and application of inductively coupled plasmas.

**References**


Appendix A Nomenclature

CCD = Charge Coupled Device

\( n \) = number of turns in the induction coil

\( D \) = diameter of coil

\( I_0 \) = minimum current in the coil to excite plasma

ICP = Inductively Coupled Plasma

\( \mu_0 \) = Permeability of a vacuum

\( \pi \) = circumference to diameter ratio

\( dB \) = magnetic field of a current element

\( I \) = current in the coil

\( r \) = distance from the current to the magnetic field point of interest

\( dl \) = infinitesimal length of the coil

\( \hat{r} \) = unit vector describing direction of the current vector to the field point
Appendix B Prometheus Torch Diagrams

Part 1 Teflon Base
Model Dimensions in cm

Notes:

1. Add M 2x0.25 mm thread (Pitch = 0.25 mm, thread diameter = 2 mm) to the interior of all three protrusions. (Match thread to the thread used on the exterior of the steel connector - Part 3)

2. Add a standard thread to the screw hole pattern. These screws are used to provide added stability of the sleeve mount and quartz tubes. See Prometheus Reference Drawing for application.
Part 2 Teflon Sleeve Mount
Dimensions in cm

SECTION XSEC0001-XSEC0001
SCALE 0.800
Appendix C Precursory Exercise

ENU 6937/4930

Name: __________________________

Inductively Coupled Plasma Source Experiment

Assignment Description

Complete the following Precursory Exercise prior to the date of the Inductively Coupled Plasma Source Experiment. There will be a quiz on the material presented in this assignment on the date of the laboratory experiment.

Background Information

In this exercise, you will be investigating properties of Inductively Coupled Plasma as it pertains to the laboratory experiment that you will complete in the Plasmas and Fusions course. An inductively coupled plasma is excited by a magnetic field generated by a radio frequency (RF) signal running through an induction coil. The ICP absorbs energy through Joule Heating, whereby free electrons, accelerated by the electric field have multiple collisions with the plasma ions. ICP is commonly used to perform semiconductor manufacturing, etching, and isotope identification.

The ICP source can also be used as a teaching tool for studying helium plasma waves in fusion applications. The ICP source is aneutronic, and thus does not emit harmful fast neutrons or radioisotopes making it an ideal choice to study fusion plasmas in an undergraduate laboratory class [1 – 4]. Inductively coupled plasma sources offer several advantages over other plasmas for use as a laboratory experiment. These sources are inexpensive, safe to operate, and useful in a large range of industry applications. ICP sources demonstrate a variety of plasma phenomena and this laboratory experiment would demonstrate several properties unique to ICP plasma. Figure 1 shows a schematic of the experimental set up of the University of Florida ICP plasma source, Prometheus.
1. Biot Savart Law (induction coil)

The Biot Savart Law can be used to describe the magnetic field strength induced by a current carrying coil. The magnetic field strength of the ICP source can be approximated through the Biot-Savart Law. Figure 2 displays a simple three dimensional diagram which displays the important variables used in the Biot-Savart Law equation.

\[
\frac{dB}{dl} = \frac{\mu_0 I}{4\pi r^2} \left( r \cdot \hat{r} \right)
\]

**Figure 2: Magnetic Field Induced by a Current Carrying Loop**

*Source: ASKIITIANS Engineering Medical Foundation*

The equation below is a general form of the Biot-Savart law. In this equation, \( dB \) is the first derivative of the magnetic field strength in Tesla, \( \mu_0 \) is the constant called the permeability of a vacuum, \( I \) is the current in the coil in amps, \( dl \) is the infinitesimal length of the coil, \( r \) is the distance of the current to the magnetic field point of interest (scalar quantity), and \( \hat{r} \) is the unit vector describing the direction of the current vector to the field point.
Calculate the x, y, and z components of the magnetic field strength in the center of a current carrying coil, given that the current amplitude is 30 A, and the radius of the coil (distance from the center of the coil to the current carrying loop) is 3 cm. Note that the permeability of a vacuum is given as $\mu_0 = 4\pi \times 10^{-7}$ N/A$^2$. Use the equation below to solve for the magnitude of the magnetic field strength in Tesla. Refer to Figure 1 as needed. Discuss the results of the three calculations. Attach additional pages as necessary.

$$
\vec{B} = \frac{\mu_0 I R}{4\pi} \int_0^{2\pi} \frac{z \cos \phi' \hat{i} + \sin \phi' \hat{j} + R\hat{k}}{(R^2 + z^2)^{3/2}}
$$

Hint: What do the vectors $\hat{i}, \hat{j}, \text{and } \hat{k}$ represent? Remember that the x, y, and z components can be solved separately.

2. Breakdown Voltage of Various Gasses and Paschen Curve

In plasma discharge chambers, the excitation of any plasma requires that a minimum induction field frequency is met. This minimum breakdown voltage is a characteristic value for all gases, and is dependent on the pressure of the gas, as well as the gap distance, or the distance between two electrodes. The product of these two values is given the symbol pd. Figure 3 shows the Paschen curves for various gasses.

An inductively coupled plasma is generated through a different mechanism than the aforementioned plasma discharge chambers. In an ICP source, the power supply must operate at a threshold frequency to excite a plasma. However, gases with low characteristic breakdown voltages in discharge tubes also typically have a low threshold frequency in an ICP source. Thus, Paschen curves provide a base knowledge to understand the behavior of various gases in an ICP source.
Figure 3: Paschen Curves for various Gases
Source: G3YNH

Based on the figure above, answer the following questions:

a. What is the breakdown voltage for H\textsubscript{2} in a chamber that is operated at atmospheric pressure with a gap distance of 0.13 cm?

b. You are designing a plasma discharge tube which operates at atmospheric pressure and has a gap distance of 0.921 cm. Your power supply provides an operating voltage of 9000 V. Which of the following gases would breakdown in your discharge tube: air, H\textsubscript{2}, Xe, Kr, Ar? Why?

3. Matching Network Problem

A matching network is a critical component of an inductively coupled plasma source. The matching network in this experiment connects the power supply to the induction coil. A matching network serves two primary purposes: to maximize the power transfer from the power supply to, and to match the generator impedance to the load impedance to reduce the percentage of reflected power. The University of Florida ICP source uses an L type matching network, in which a capacitor and inductor are incorporated into the circuit in parallel to match the impedance of the power supply to the plasma load. The impedance of both the inductor and capacitor are given in the equations below.

\[
X_1 = \sqrt{\left(\frac{R_s R_p}{R_p}\right) - R_p^2}
\]
\[ X_2 = R_s \frac{R_p}{X_1} \]

Figure 4 displays the schematic of a simple L type matching network, similar to the matching network used in the University of Florida ICP source. Answer the questions below based off of this matching network design.

![Schematic of L Type Matching Network](image)

**Figure 4: L Type Matching Network Schematic**

a. For the matching network in Figure 4, what is the impedance value of the inductor (X1) and capacitor (X2)?

b. In the above matching network, impedance matching could be obtained by replacing the capacitor and inductor with a resistor of 2.09 ohms. Qualitatively, why would using a resistor in the matching network NOT be preferred to using the capacitor and inductor? *Hint: What effect does the replacing the capacitor and inductor with a resistor have on how power is delivered to the plasma source?*

4. ICP Spectrum Phenomenon identification

All plasmas gasses have a characteristic emission spectra dependent on the atomic and molecular composition of the plasma. A spectrometer is a measurement device which records the distinct wavelengths that various plasma emit. The energy of these characteristic emissions can be determined from the Planck-Einstein relation, which is shown below. In this equation, Planck’s constant has a value of \( h = 6.626 \times 10^{-34} \) Joule-seconds, the speed of light has a value of \( c = 2.99 \times 10^8 \) m s^{-1}, \( \lambda \) represents wavelength, and \( E \)
represents energy. Figure 5 displays an emission spectra for various gases. Answer the following questions based off of the spectra presented in Figure 5.

\[ E = \frac{hc}{\lambda} \]

![Emission Spectra for Various Gases](source: Nowak [13])

The table below displays the energy emission peaks for Helium and Oxygen. On Figure 5, three emission peaks are labeled with roman numerals I, II, and III. For all three cases, which gas contributes to each emission peak?

<table>
<thead>
<tr>
<th>Element</th>
<th>Emission Energy (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium</td>
<td>2.46</td>
</tr>
<tr>
<td>Helium</td>
<td>2.10</td>
</tr>
<tr>
<td>Helium</td>
<td>1.85</td>
</tr>
<tr>
<td>Helium</td>
<td>1.75</td>
</tr>
<tr>
<td>Helium</td>
<td>1.70</td>
</tr>
<tr>
<td>Oxygen</td>
<td>1.59</td>
</tr>
<tr>
<td>Oxygen</td>
<td>1.46</td>
</tr>
</tbody>
</table>