CHAPTER 5

EXPERIMENTAL SET UP AND RESULTS

Experimental set-up and results from the RF planar coil inductively coupled plasma system are described in this chapter. The diagnostics described here were used to determine characteristics of RF ICP system. Characteristics of the RF ICP system are described in terms of current and voltage of the planar coil. Transition modes of plasma and hysteresis phenomenon are observed.

5.1 Experimental set-up

The RF planar coil inductively coupled plasma system is shown in Figure 5.1. This set-up consists of reactor chamber, RF generator, gas flow control, planar induction coil, impedance matching network, pumping system and diagnostic system.

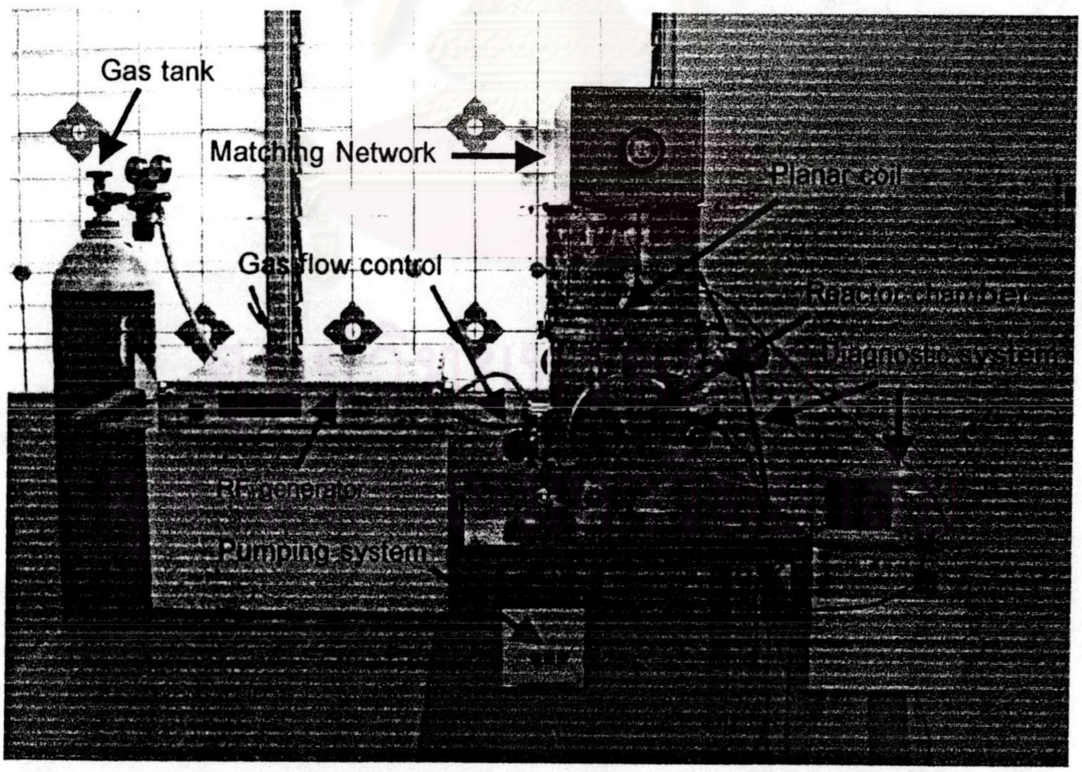


Figure 5.1: The RF planar coil inductively coupled plasma system

5.1.1 RF Generator

RF generator used in this work, is CESAR 1310. The RF generator is operated at 13.56 MHz and is capable of delivering maximum 1000 watts of RF power. The output impedance of this RF generator is 50 Ω to match the available transmission cable and must feed into load impedance. In order to increase the power dissipation in the glow discharge and to protect the generator, a matching network is facilitated. The coaxial cable has stray capacitance and inductance that vary with length and will affect the impedance of the load. So, the coaxial cable used should be as short as possible. To minimized unnecessarily loss and stray capacitance, one-meter coaxial cable was used in this thesis. Figure 5.2 shows CESAR RF generator.

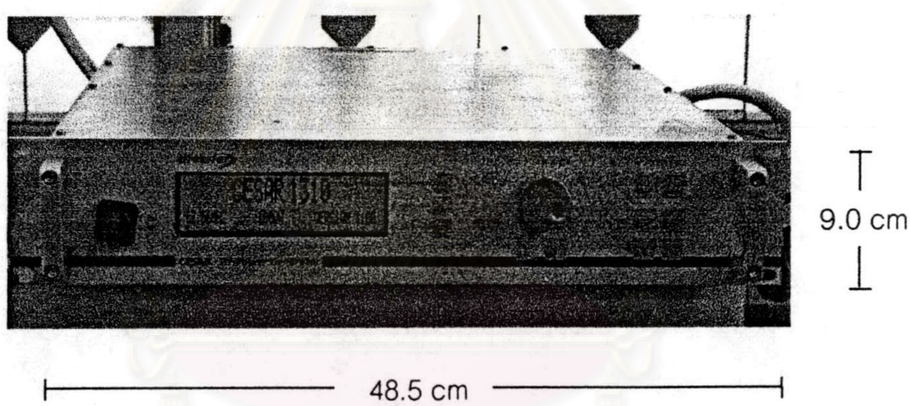


Figure 5.2: RF Generator

5.1.2 Planar coil

The induction coil of the RF-PECVD system is a planar type. The planar coil is a flat helix wound from nearly to the axis to near the outer radius of reactor chamber. It has an ability to produce a disk like uniform plasma that can be scaled up easily [6]. The planar coil is placed outside the reactor chamber over the dielectric quartz plate. The RF power is coupled to the plasma through this quartz window.

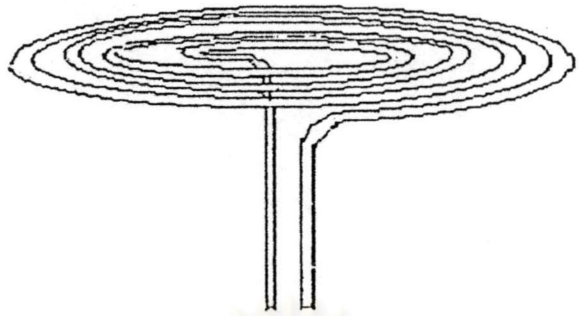
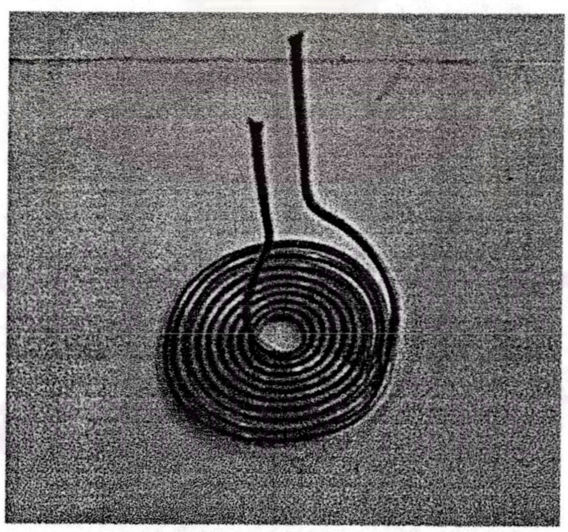


Figure. 5.3: The planar induction coil

In this thesis, the planar coil is 10 turns coil made of 3.2 mm-diameter copper wire with the maximum outer diameter of 9 cm. It located over and near the quartz plate. The current and voltage of the planar coil are measured by a current probe (Rogowski coil) and a high voltage capacitive probe respectively. Output signal will display on an oscilloscope via two 50 Ω coaxial cables.



├── 9.0 cm ──┤

Figure. 5.4: Photograph of planar induction coil

Determination of the inductance of the planar coil

In this thesis, we use a Precision LCR meter, Agilent model 4284A to determine the inductance of the planar coil. The frequency of the Precision LCR meter is varied from 20 Hz to 1 MHz during the measurement. The Precision LCR meter was connected across the terminals of the planar coil as shown in Figure 5.5.

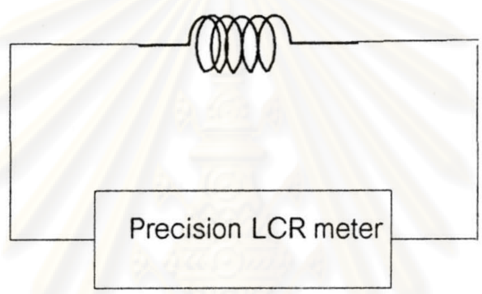


Figure 5.5: Position of the Precision LCR meter for determination of inductance of the planar coil

By varying the frequency of the Precision LCR meter. The inductive reactance of the planar coil; X_L is determined. For each value of the frequency; f, X_L is recorded. Graph of X_L versus f is plotted in Figure 5.6.

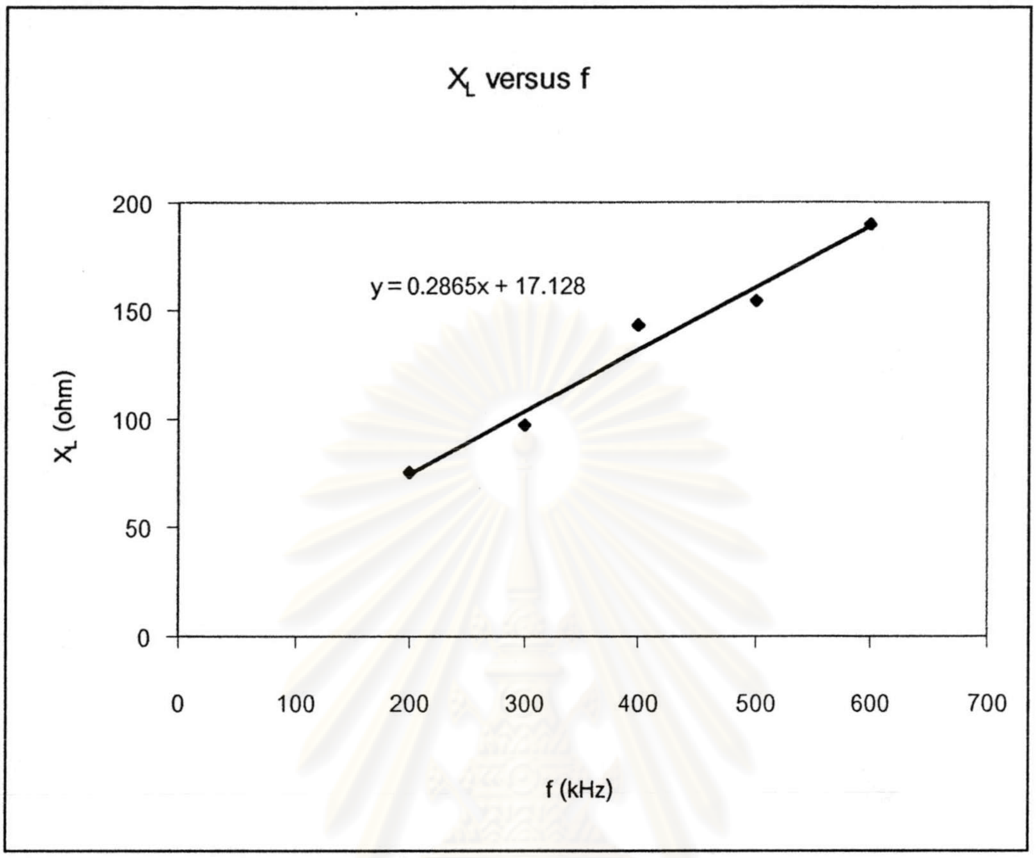


Figure 5.6: Graph of X_L versus f of inductance of the planar coil

From equation,

$$X_L = 2\pi f L$$

Where X_L = inductive reactance of the planar coil

f = frequency

L = inductance of the planar coil

From the linear graph in Figure 5.6, L can be determined as

$$L = \frac{0.2865}{2(1000)\pi} = 45.6 \ \mu H$$

Therefore, inductance of the planar coil is, $L = 45.6 \mu H$

By the resonance principle of LCR circuit, by the simplest way, a variable vacuum capacitor and a transformer are used as matching network.

5.1.3 Matching network

A matching network contains a transformer and a variable vacuum capacitor. They are placed inside a matching cage, acts like a Faraday cage. Since the impedance of plasma will change from time to time, depends on the process condition, so the impedance of the matching network is needed for to tuning over a range of values. Picture of matching cage is shown in Figure 5.7. Matching cage consists of a cylindrical cavity and an aluminum box, This is to reduce the height of dial knob of a variable vacuum capacitor.

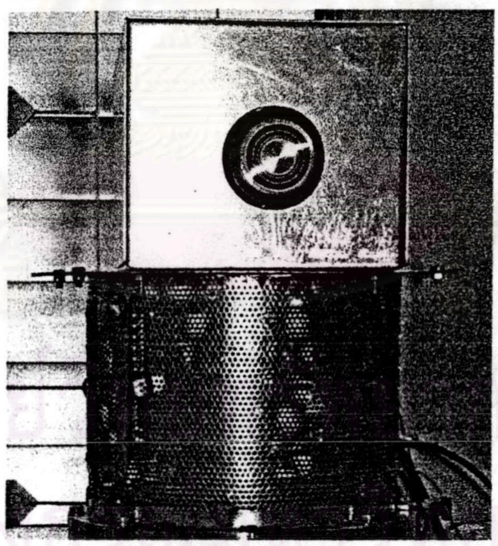


Figure. 5.7: Photograph of matching cage

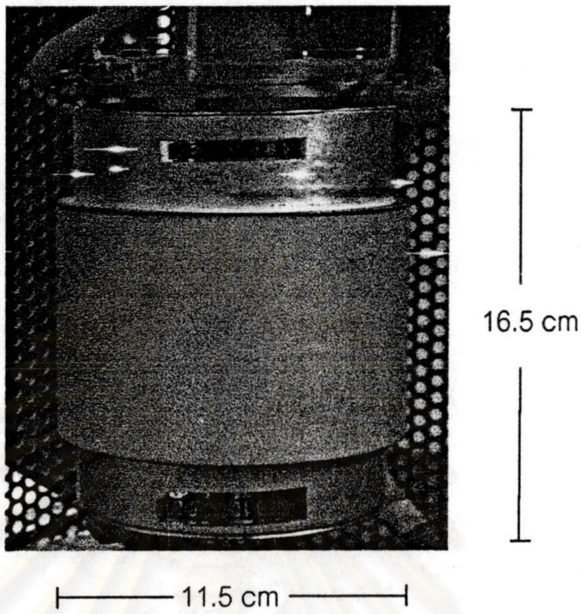


Figure. 5.8: Variable vacuum capacitor

A transformer and a variable vacuum capacitor are placed inside the aluminum box and the induction planar coil is placed inside the cylindrical cavity.

The RF generator is coupling to the planar coil via a 50 Ω coaxial cable through a matching network as shown in figure 5.9. The matching network adjusts the real resistance value, which needed to match the transmission line and RF generator. When ac power transfers to a load L, Z_L is the impedance of plasma, at high frequency, the radiated energy can not be efficiently directed even through a highly directive antenna, so a transmission line is needed to guide the source energy. In this work, the RF generator has output impedance of 50 Ω and a transmission line also has impedance of 50 Ω.

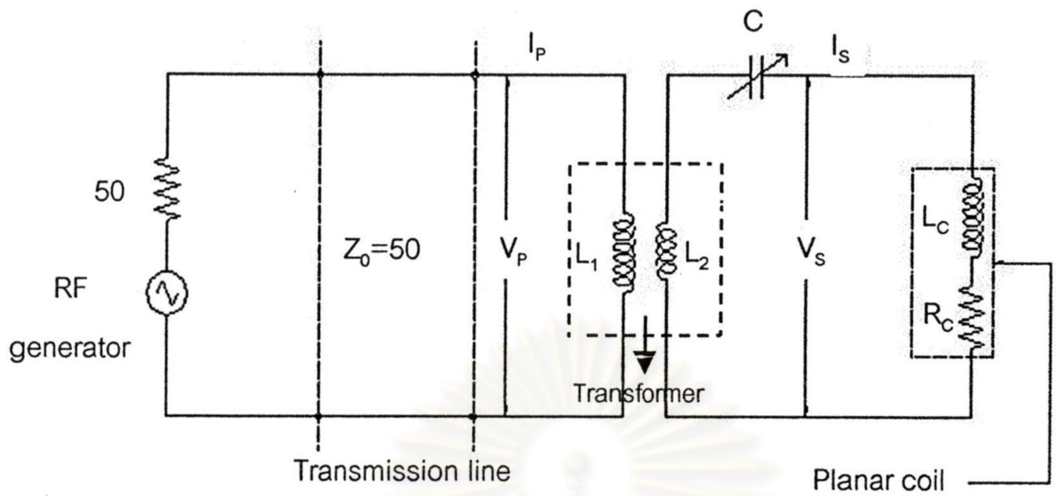


Figure 5.9: Impedance matching network of RF planar coil ICP system [9]

Due to the 50 Ω impedance of the transmission line, a step down transformer is needed to convert this impedance to 1 Ω impedance of plasma. By assumption, plasma is a very good conductor, assume it has 1 Ω impedance. By the transformer theory,

$$\frac{I_S}{I_p}=\frac{V_p}{V_S}=\frac{N_p}{N_S}=h$$

Where h = transformation ratio

N_p = number of turns of the primary circuit

N_S = number of turns of the secondary circuit

We get,

$$h^2=\frac{V_p/I_p}{V_S/I_S}$$

To define, $V_p/I_p=Z_p$ and $V_S/I_S=Z_L$

Where Z_p = impedance of the primary circuit = 50 Ω

Z_L = impedance of the load = 1 Ω

Then,

$$h^2 = \frac{Z_P}{Z_L} = \frac{50}{1}$$

And transformation ratio, $h = 7$

Therefore, the transformer of the matching network is a step down transformer with a turn ratio of primary coil to secondary coil of 7:1.

By the resonance principle of ac circuit, variable vacuum capacitor must be tuned frequently to obtain minimum reflected power. When $X_L = X_C$, resonance occurred. Where X_L is inductive reactance of the planar coil and X_C is capacitive reactance of the variable vacuum capacitor.

5.2 Diagnostic and experimental techniques

Characteristics of the RF ICP system can be explained by the measurement result of the current and the voltage for the planar coil. The Rogowski coil and the high voltage capacitive probe are used in measuring the current and the voltage respectively.

5.2.1 Diagnostic system

The characteristics of system can be explained by measurement result of the current and the voltage of the planar coil. In most plasma experiments, electrical coil current of the system is rapidly varying and large. The simplest way of measuring the current is to place a coil or magnetic pickup loop in the region of the current to be measured. The changing magnetic induction will cause an electromotive force ($d\phi/dt$), where ϕ is the magnetic flux through the coil. By taking the integral of the $d\phi/dt$, the magnetic flux can be obtain since the flux magnitude depends on the current magnitude, which induced the magnetic field. The knowledge of the flux permits the current determination. The Rogowski coil is used in the measuring of the current for the planar coil.

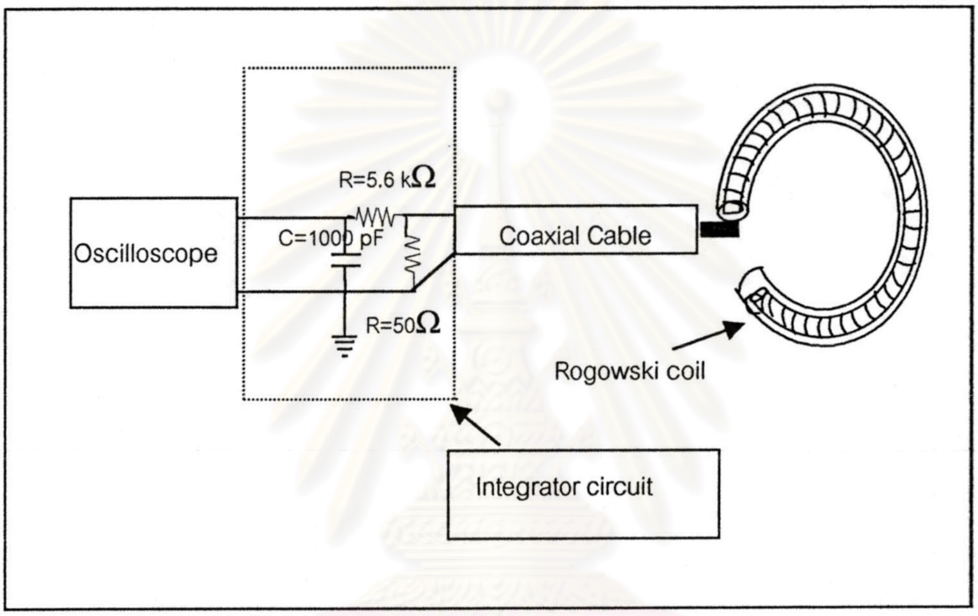


Figure 5.10: A diagram of Rogowski coil and its equivalent circuit

The Rogowski coil is a multi-turn solenoid made from copper wire deformed into the torus shape as shown in Figure 5.10. It is mounted around the planar coil. It is used to measure the coil current by mean of magnetic induction. The signal is recorded via an oscilloscope.

In this thesis, a high voltage capacitive probe is designed to measure the voltage measured across the planar coil. It is mounted across the vacuum capacitor in the matching network box. This divider consists of one-meter coaxial cable, its capacitance is 100 pF and 1 piece of teplon placed between copper plate and base of vacuum capacitor. Diagram of high voltage probe as shown in Figure 5.11. The signal is measured across the 100pF capacitor and is recorded via an oscilloscope. The high voltage probe is used to reduce the signal to a manageable level for the oscilloscope. Although it is more complicate to utilized a capacitive probe, it is required that we have a high impedance voltage probe at RF frequancy. The resistive probe can become less accurate and interface with the matching condition RF frequancy.

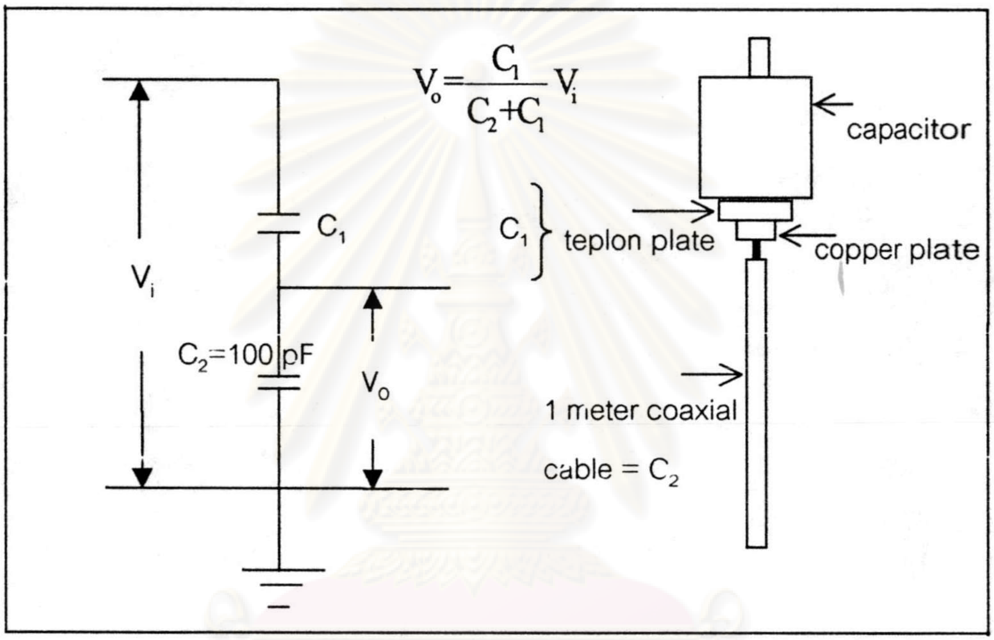


Figure 5.11: A diagram of high voltage probe and its equivalent circuit

5.2.2 Calibration of the Rogowski coil

Although Pearson probe [6] is general used for measuring the current. However, due to its high price and not readily avalaible. Rogowski coil becomes a resonable choice. Rogowski coil used in this work, is calibrated with Pearson probe avalaible in plasma lab at University of Malaya. The circuit is used to calibrate Rogowski coil shown in Figure 5.12.

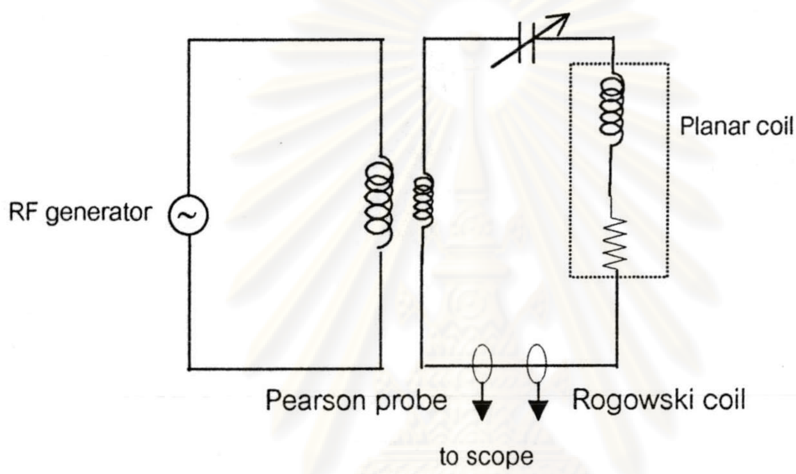


Figure 5.12: Circuit arrangement for calibration Rogowski coil

The Pearson probe and the Rogowski coil are connected to the two-channel oscilloscope. When the capacitance; C varies, current; I varies too. For each value of the C, output voltage of Rogowski coil and a Pearson probe are recorded. The output voltage of Rogowski coil and Pearson probe are shown in Table 5.1. Graph of V_r (voltage signal from Rogowski coil) versus V_p (voltage signal from Pearson probe) is plotted in Figure 5.13.

Output voltage of pearson Probe (Vpp)	output voltage of Rogowski coil (Vpp)
2.56	11.2
2.72	12.0
3.04	14.0
3.28	14.4
3.60	16.4
4.24	18.8
4.72	19.6
5.04	21.2
5.36	23.2
5.84	24.4
6.32	27.2

Table 5.1: The output voltage of Rogowski coil and Pearson probe

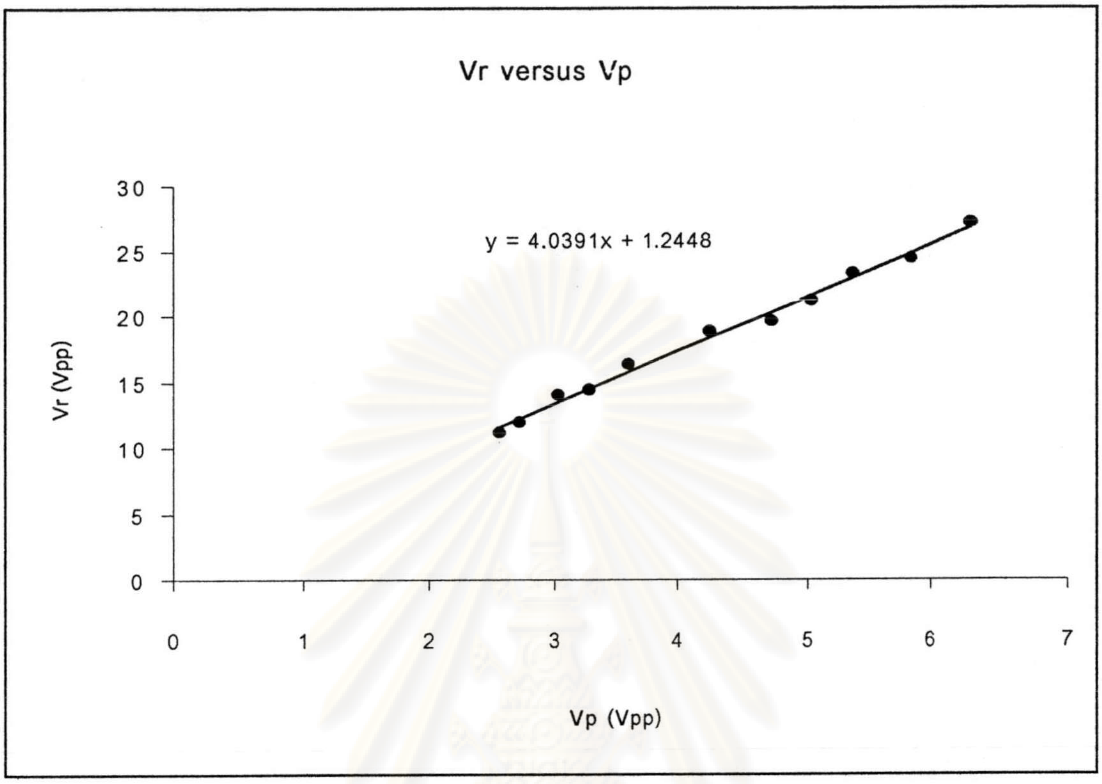


Figure 5.13: Graph of V_r versus V_p for calibration Rogowski coil

From the circuit shown in Figure 5.2, the Pearson probe and Rogowski coil measure the same current; I. Thus,

$$I = K_p V_p = K_r V_r$$

where K_P = calibration factor of the Pearson probe = 2 A/V

V_P = voltage signal from Pearson probe

K_R = calibration factor of the Rogowski coil

V_R = voltage signal from Rogowski coil

Then,

$$K_r = \frac{K_p}{V_r / V_p}$$

From the graph in Figure 5.13, the gradient is $V_R/V_P = 4.0391$. Therefore, K_r can be determined as

$$K_r = \frac{2}{4.0391} = 0.4952 \ AV^{-1}$$

Then, the current value can be obtained by multiply the output voltage from the oscilloscope with 0.4952 AV^{-1}. When 0.4952 AV^{-1} is the calibration factor of the Rogowski coil.

5.2.3 Calibration of the high voltage capacitive probe

In this work, we use a high voltage resistive probe to calibrate high voltage capacitive probe. The high voltage resistive probe provides a 1 V output signal for 1000 V of voltage is measured. The circuit is used to calibrate high voltage capacitive probe shown in Figure 5.14.

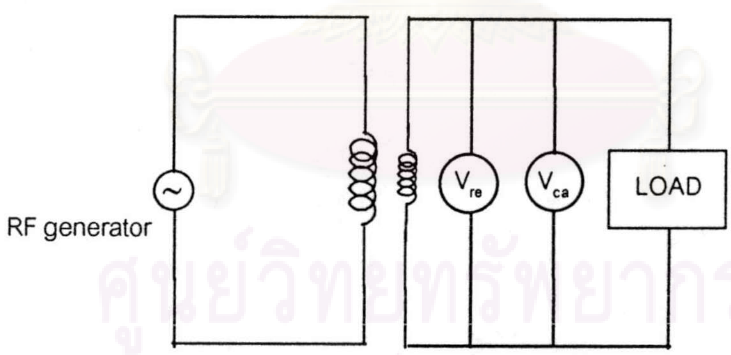


Figure 5.14: Circuit arrangement for calibration high voltage capacitive probe

The high voltage resistive probe and high voltage capacitive probe are connected to a two-channel oscilloscope. When RF power varies, V varies. For each value of the RF power, output voltage high voltage resistive probe (V_{re}) and high voltage capacitive probe (V_{ca}) are recorded. The output voltage of high voltage resistive probe and high voltage capacitive probe are shown in Table 5.2 and graph of $V_{resistive}$ (voltage signal from high voltage resistive probe) versus $V_{capacitive}$ (voltage signal from high voltage capacitive probe) is plotted in Figure 5.15.

Power (watt)	voltage of resistive probe (Vpp)	voltage of capacitive probe (Vpp)
5	223	6.4
10	264	7.4
15	292	8.4
20	341	9.2
25	369	10.0
30	404	11.0
35	425	11.8
40	445	12.4
45	473	13.0
50	494	13.6
55	515	14.0
60	529	14.4

Table 5.2: The output voltage of high voltage resistive probe and high voltage capacitive probe

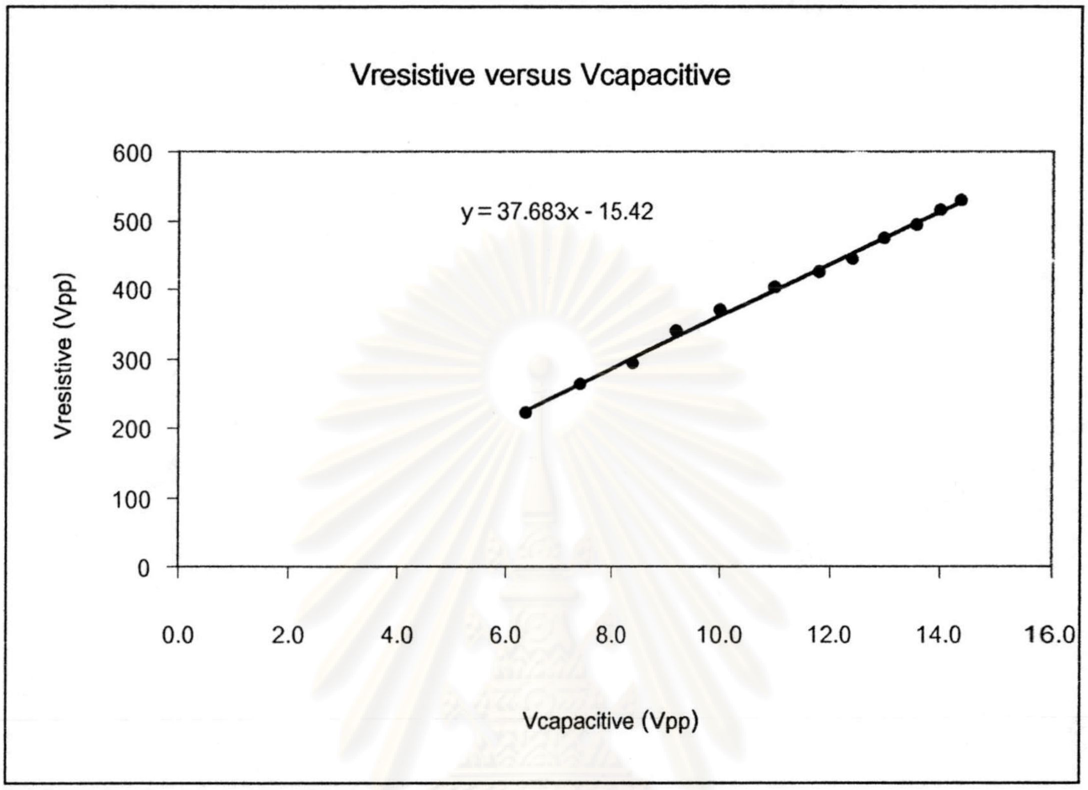


Figure 5.15: Graph of $V_{resistive}$ versus $V_{capacitive}$ for calibration high voltage capacitive probe

From the circuit shown in Figure 5.4, the high voltage resistive probe and high voltage capacitive probe measure the same voltage; V. Thus,

$$V = V_{resistive} = K_{capacitive} V_{capacitive}$$

where $V_{resistive}$ = voltage signal from high voltage resistive probe

$K_{capacitive}$ = calibration factor of the high voltage capacitive probe

$V_{capacitive}$ = voltage signal from the high voltage capacitive probe

Then,

$$K_{capacitive} = \frac{V_{resistive}}{V_{capacitive}}$$

From the graph in Figure 5.15,the gradient is $V_{resistive}/V_{capacitive} =$ 37.683. Therefore $K_{capacitive}$ can be determined as

$$K_{capacitive} = 37.683$$

Therefore, the voltage measurement can be obtained by multiply the output voltage from the oscilloscope with 37.683. When 37.683 is the calibration factor of the high voltage capacitive probe.

5.3 Experimental procedures

When the reactor chamber is closed securely to avoid any leakage. The reactor chamber is evacuated to a low pressure of 7.0 x 10^{-5} torr. Argon gas to be used in this work for diagnosed characteristics of the RF ICP system. Argon gas is introduced into the reactor chamber via gas flow control for 3 minutes. After that, the reactor chamber is evacuated again to pressure of 0.01 torr and repeated the same procedure for three times to minimize the contaminants in the chamber. Introduce Argon gas and adjust the pressure to desire value of 0.55 torr and let the pressure to achieve equilibrium.

Finally, switch on the RF generator and diagnostic instrument. The vacuum capacitor of matching network was tuned frequently to obtain minimum reflected power. Increasing RF power to the RF ICP system until generated the desire mode of plasma. And decreasing RF power again along the same trace. The current and the voltage of the planar coil measured by the calibrated Rogowski coil and the calibrated high voltage capacitive probe, which connect to an oscilloscope. The circuit which is used to measure coil current and coil voltage is shown in Figure 5.16

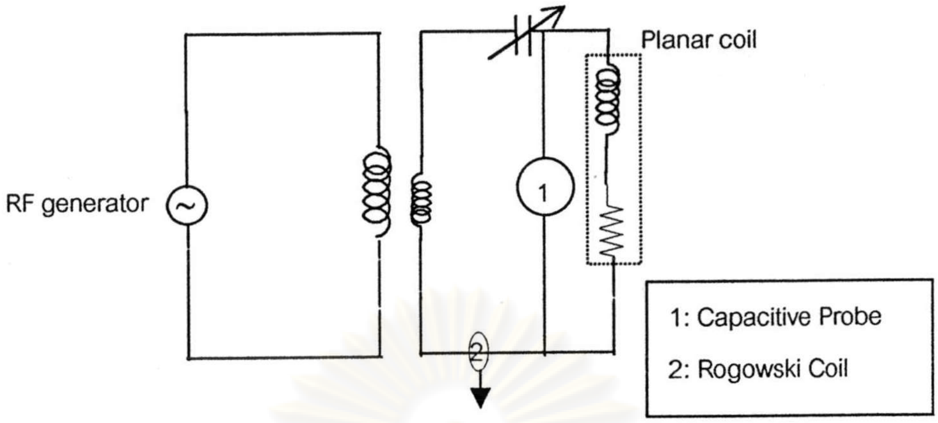


Figure 5.16: Circuit arrangement for measuring of coil current and coil voltage

5.4 Results of current and voltage measurement

Figure 5.17 and 5.18 show the coil current versus power and the coil voltage versus power for argon plasma at pressure of 0.55 torr respectively.

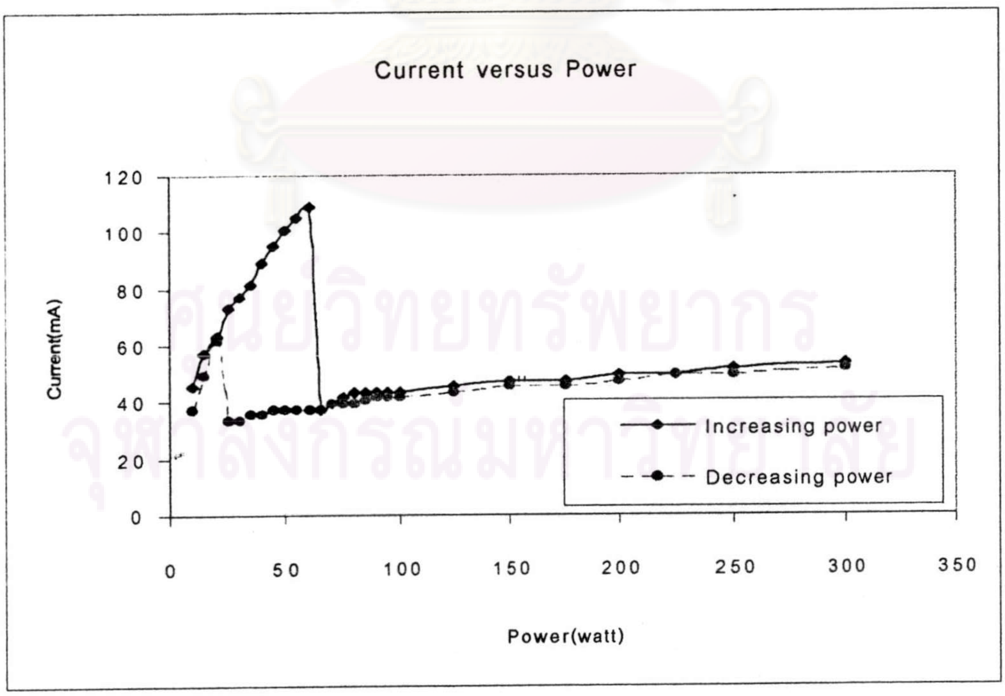


Figure 5.17: Graph coil current versus power at pressure of 0.55 torr

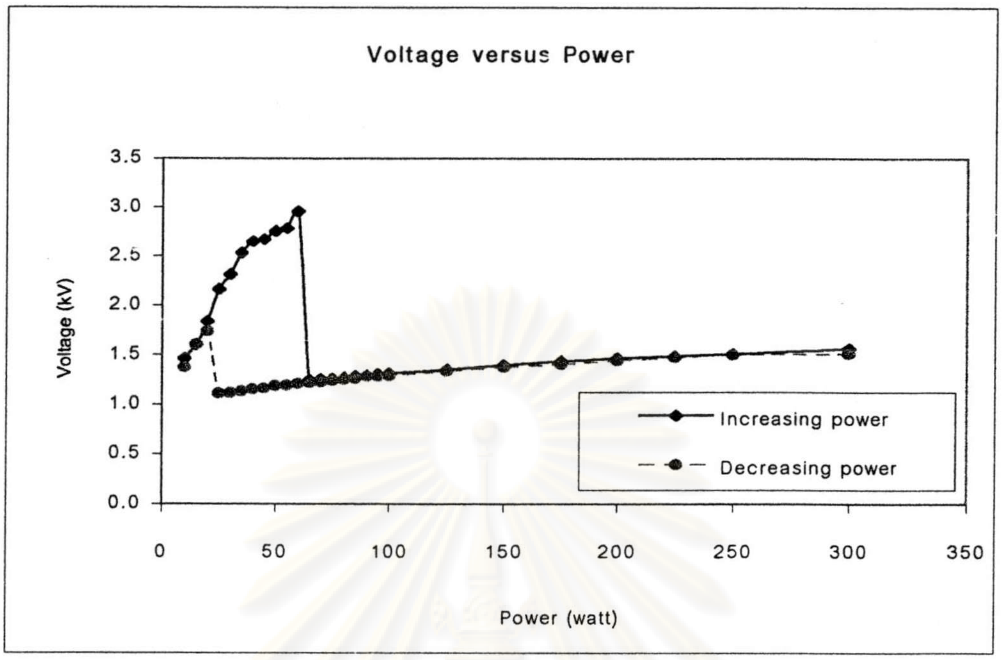


Figure 5.18: Graph coil voltage versus power at pressure of 0.55 torr

From the graph, coil current versus power and coil voltage versus power shown in Figure 5.17 and 5.18, when the RF forward power is increased, the coil current and coil voltage are also increased and the increasing seem to be linear. Furthermore the discharge light emission increases. The faint discharge is operated in the E-mode. When RF power is increased up to a certain value of power, the value of power dependes on the filling pressure of system (about 65 watt at pressure of 0.55 torr), the transition from E-mode to H-mode (forward transition) occurred. The coil current is dropped suddenly, coil voltage is still the same and a dramatic increment of the discharge light emission is observed. The total reflected power is also increased. This is the individual sign of the forward transition mode. These observation are well agreed with observation of Liew Wai Soon [6] and Thien Voon Kwan [7]. When RF power is increased further, plasma luminosity more increased. But the increase is less than the dramatic. Decreasing the RF power along the same trace, discharge light emission decreases. A sudden jump in the coil current has been observed when the power decreased down to a one value of power (about 20 watt at pressure of 0.55 torr) and coil voltage was the same. This implies the transition from H-mode to E-mode (inverse transition) occurred. This observation is also agree with Fayoumi et.al [4]. They reported that the hypothesis phenomenon is observed becauase the forward transition power does not correspond to the inverse transition power.

The faint discharge before the transition mode (E-mode discharge) shows in Figure 5.19, due to the potential difference across the induction coil when forward RF power. When increasing the RF power, transition from E-mode to H-mode occurred. The H-mode is sustained by the induced azimulthal RF electric field. It is produced by the oscillating magnetic field, is produced by the oscillating RF current passes through the coil [5]. Sudden dropping of coil current in the forward of transition mode, due to induced electric field in H-mode is sufficiently strong to generate high-density plasma. The high-density plasma screens out the RF field and causes decreasing inductance of induction coil. The plasma current will induce the coil current to oppose the change, eventually, the coil current decreased.

The shape of the argon plasma is a hemisphere fireball shows in Figure 5.20. Since the electrons tend to diffuse and accelerated radially towards the center because of the curvature of the induction field. Thus, the electrons gain the time-average energy and absorbing the RF power from collisions.

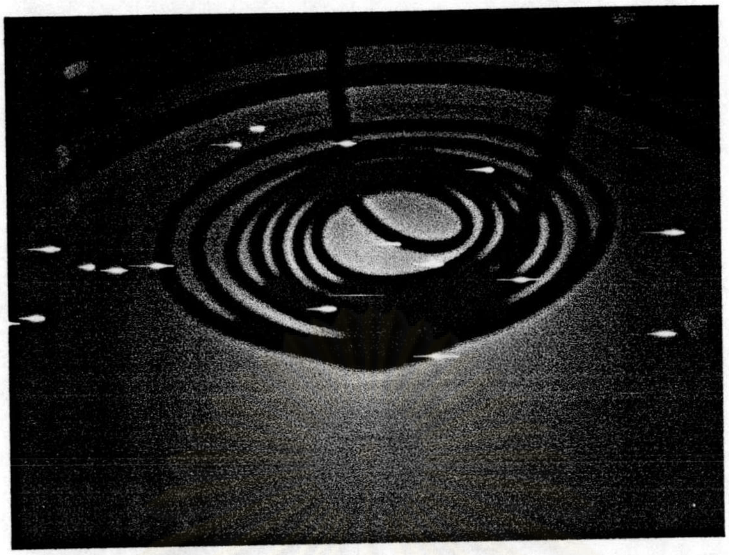


Figure 5.19: E-mode argon plasma at pressure of 0.55 torr

Figure 5.20: H-mode argon plasma at pressure of 0.55 torr