

Non-Phase-Difference Rogowski Coil for Measuring Pulsed Plasma Thruster Discharge Current

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Abstract: A Rogowski coil for accurately measuring Pulsed Plasma Thruster (PPT) discharge current up to 20000 A is calibrated. In particular, the phase error in actual practical application ($-4\sim 3\ \mu\text{s}$) of Rogowski coil has been corrected. A non-phase-difference Rogowski coil is presented. It is calibrated that the optimum RC integrating circuit time constant is $\tau=54\ \mu\text{s}$, Rogowski coil sensitivity is $S=9.75\times 10^{-4}\ \text{V/A}$, calibration coefficient is $K=911$, and phase error is less than $\pm 0.1\ \mu\text{s}$. With the assistance of Non-phase-difference Rogowski coil and triple Langmuir probe, Time of flight probe method and Rogowski&Langmuir probe time difference method are used to measure the plasma ejection velocity. The experiment result shows: the PPT discharge theory that the discharge position would move downstream toward the electrode has been proved. The second discharge position is estimated 8.35mm to the PPT Teflon surface.

Nomenclature

τ	=	time constant
S	=	coil sensitivity
K	=	calibration coefficient
v	=	plasma ejection velocity

I. Introduction

ABLATIVE pulsed plasma thrusters(PPT)¹ were first space tested in China on December 7, 1981², and many researches on PPT have been conducted such as pulsed thrust measurement³, plasma diagnostic^{4,5}, PPT propellant species^{6,7} etc. Research on the PPT discharge characteristics has also been in progress⁸. Rogowski coil⁹ is generally used in PPT discharge current measurement¹⁰, which could obtain discharge time, discharge energy, peak voltage, peak time etc. Triple Langmuir probe¹¹ is used for Time of flight probe method which could get plasma ejection velocity. To research on the PPT discharge characteristics, a relationship between plasma velocity and discharge process is established by comparing the waveforms of Rogowski coil and Langmuir probe current curve. Exactly, Rogowski coil measurement results perform characteristics of PPT discharge, and measurement result of the Langmuir probe shows the outside PPT electrode ion velocity characteristics. From this relationship, a more explicit discharge process can be obtained, which is the basic factor to improve PPT efficiency. But the waveforms measured by the Rogowski coil are often ahead of or lag behind the actual current waveform in the practical

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application, leading to phase error ($-4\sim 3\mu\text{s}$). This made it impossible to obtain the comparison waveform of Rogowski coil and Langmuir probe current curve in the discharge process research.

Concerning PPT discharge process, there are three typical views in this field (1) In 1972, American Palumbo¹² and Guman¹³ used high-speed camera on the PPT to study the discharge from formation to finish. Due to the fact that high-speed camera technology was not mature, they only concentrated on the effect of PPT electrodes geometry on its efficiency. The common view at the time was PPT discharge process only has one time discharge; (2) In 1982 American Dawbarn¹⁴ used the high-speed camera to capture the PPT discharge process. In the discharge process there were two groups of different speed plasma. One of the groups is neutral particle, the other is ionized plasma. At the time, PPT discharge process has repeated times of discharge, of which the locations are all along Teflon surface; (3) In 2007 Japanese Hiroyuki Koizumi¹⁵ used high-speed cameras and spectrometers to analyze the PPT discharge process. As a result, it was shown that high density, ablated neutral gas stays near the Teflon surface, and only a fraction of the neutrals is converted into plasma and electromagnetically accelerated, leaving the residual neutrals behind. PPT discharge process has repeated discharge, the discharge position moved to the downstream of the electrodes.

These three views are from a macroscopic point of view using high-speed camera to verify their theory. From the microscopic point of view using plasma diagnostics to explain the discharge process is also very important. Diagnostics of the plasma in PPT has several difficulties because the phenomena are relatively short-lived and the spark plug and the pulsed discharge itself produce considerable electromagnetic noise. Nevertheless, some researchers have succeeded in using Triple Langmuir probes¹⁶ to measure the plasma characteristics. And the studies have produced useful information on discharge process, such as two kinds of plasmoid with different velocities in the PPT plume, which explains the repeatedly discharge exist in PPT discharge process. But Langmuir probes were carried out in the exhaust plume of PPT without discharge time reference in the electrode, which made it impossible to know the discharge process in the electrode. So a non-phase-difference Rogowski coil is required to provide this discharge time reference. Then a relationship between plasma velocity and discharge process can be established.

In our work, a non-phase-difference Rogowski coil is presented. Cooperating with a Langmuir probe, we can analyze the time difference between the waveforms of Rogowski coil and Langmuir probe. With the time difference, plasma ejection velocity could be obtained. These parameters based on Rogowski coil have an accurate response time, and play a vital role on PPT discharge process research. The plasma ejection velocity measured by this method could be compared with Time of flight probe method. This comparison, on the one hand, could verify the accuracy of plasma ejection velocity; on the other hand, it could establish the connection between plasma ejection velocity and PPT discharge current variation. That means we can verify the theory of PPT discharge process according to the relationship between plasma ejection velocity and discharge current.

II. Experimental apparatus

A. Pulsed plasma thruster

A 20J class PPT engineering prototype with rectangular geometry is used in the experiment. The PPT was equipped with Teflon as propellant, oil capacitors capacity of $10\mu\text{F}$, the input voltage of 2000V, discharge time of $12\mu\text{s}$, electrodes length of 26mm. It works in a $\phi 800\text{mm}\times 1000\text{mm}$ size vacuum chamber. The vacuum is below 10^{-2}Pa . The PPT experiment prototype is shown in Figure 1.

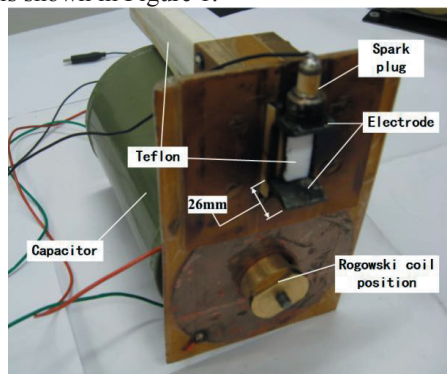


Figure 1. The PPT experiment prototype

B. Non-phase-difference Rogowski coil

The Rogowski coil used in this experiment calls for none-phase error. Its structure and parameters is described below: The outer ring is a PTFE core holder, winding a $4 \times 0.27\text{mm}$ -diam copper wire on a 2-mm-diam polymer rod. The wire is wrapped in 400 turns in two layers. The outer layer uses epoxy resin seal to achieve insulation and anti-hypertension. The end of the Rogowski coil is connected to a RC integration circuit to obtain a linear relationship between the measured value and the discharge current. Pulse current causes the coil to generate the induced current. After the induced current passes through RC integrator circuit, an integral current proportional to the discharge current is obtained.

C. Triple Langmuir probe

Triple Langmuir probes consist of three identical probes placed in the plasma. Tungsten is used as probe collection material. Langmuir probes with 4 different distance measuring point are used to obtain the corresponding signal time difference. The plume plasma velocity of PPT can be calculated through the time difference. Triple Langmuir probe construction is shown in Figure 2.

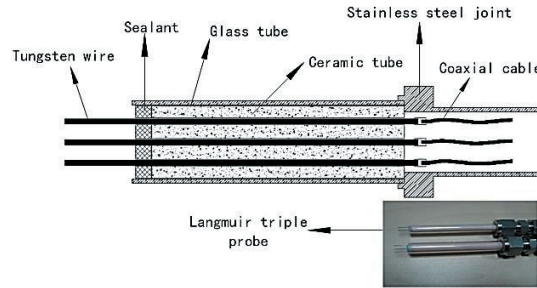


Figure 2. Triple Langmuir probe constructional detail

III. Rogowski coil calibration

The Rogowski coil calibration needs fast leading edge and high-current pulse¹⁷. The actual measurement object is pulsed plasma thruster. In the calibration experiment, the current waveforms measured by the Rogowski coil are often ahead of or lag behind the actual current waveform (measured by resistor shunt) in the practical application. The phase comparison between Rogowski coil and resistor shunt is shown in Figure 3. and Figure 4.

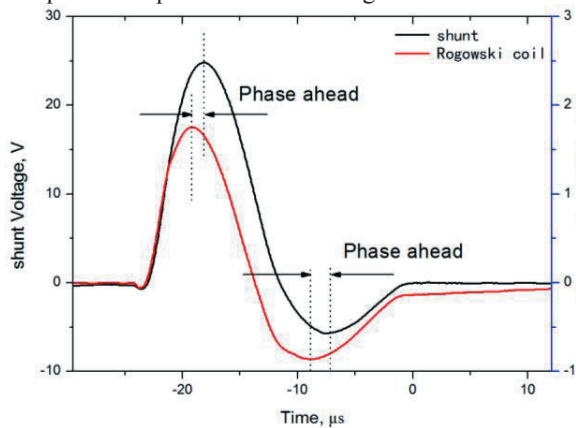


Figure 3. Rogowski coil curve phase ahead

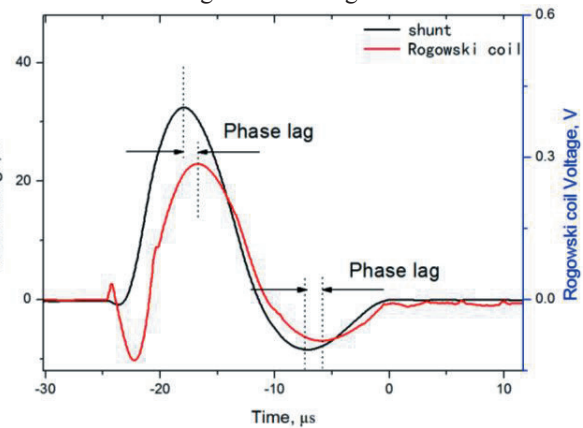


Figure 4. Rogowski coil curve phase lag

Phase error Rogowski coil consists of two parts: (1) Rogowski coil itself is non-ideal device, resulting in some phase errors caused by the manufacturing process, self-inductance, and so on. (2) The non-ideal integrator introduces integrating phase error. Therefore, a series of RC time constants are attempted. The different time constant of the integrating circuit response time is shown in Figure 5.

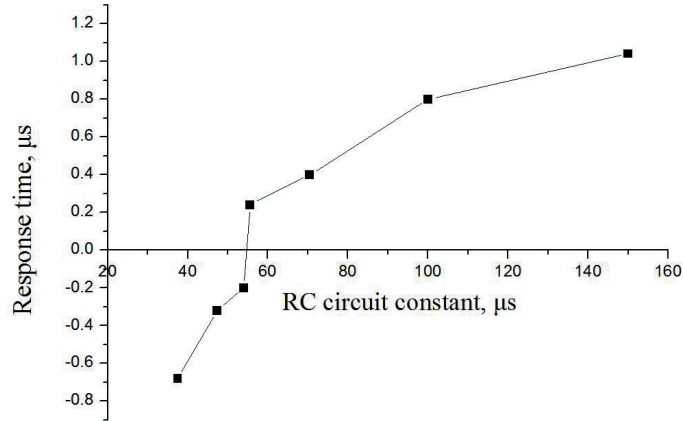


Figure 5. Different time constants of the integrating circuit response time

By dichotomy method the best integration time constant of $54\mu\text{s}$ is obtained. Under this time constant, the phase error is less than $\pm 0.1\mu\text{s}$. The calibration curve is shown in Figure 6.

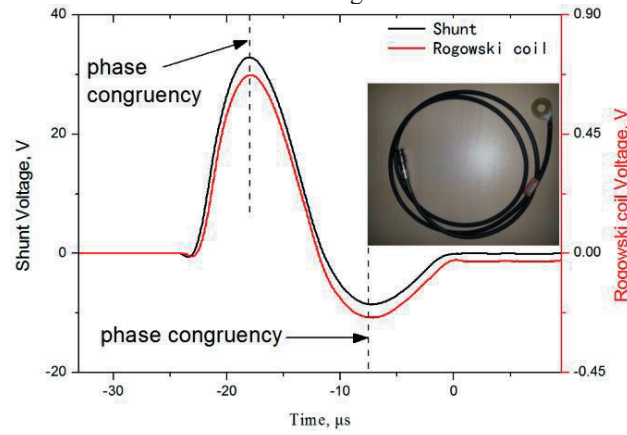


Figure 6. Non-phase-difference Rogowski coil calibration curve

The Rogowski coil is calibrated with sensitivity $S=9.75 \times 10^{-4} \text{V/A}$, calibration coefficient $K=911$, and the phase error is less than $\pm 0.1\mu\text{s}$.

IV. Experimental result

A. PPT discharge current

The Rogowski coil is believed to be non-phase-difference to obtain the PPT discharge current. It was first tested on a PPT for 30 single impulse bits. The PPT discharge parameter is shown in Table 1.

Table 1. PPT discharge parameter

PPT parameter	Value
Discharge energy	20J
Discharge voltage	2000V
Discharge time	$11.730\mu\text{s}$
Discharge variation	1.45%

The PPT discharge current and discharge voltage curves are shown in Figure 7.

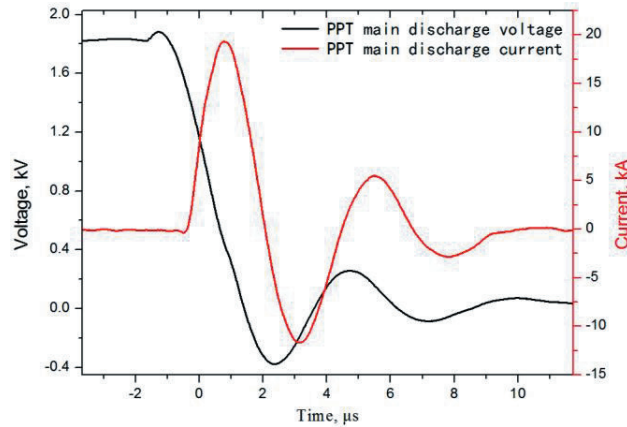


Figure 7. PPT main discharge current and voltage curve

Figure 7 presents the changing trend of PPT discharge current. With the 11.73 μ s discharge time, discharge current exhibits damped trend, and 4 peaks are seen in the discharge curve. PPT main discharge current peak is 19.8kA. Statistical result shows that discharge current standard deviation is 0.293, coefficient variation is 1.45%; discharge time standard deviation is 0.237, coefficient variation is 2.02%. Measurement results show that the PPT discharge process has a good stability and repeatability.

B. Ion ejection speed measured by triple Langmuir probe

Time of flight probe method uses Triple-Langmuir probe placed in different measuring points on the same axis, and obtained time difference in the signal curve. The triple Langmuir probe was placed at 4 different distance measuring points to get the corresponding signal time difference. 4 measuring points are on the center of thruster, Teflon surface, located at 5cm, 8cm, 10cm and 15cm away from the Teflon surface. The triple Langmuir probe measurement result is shown in Figure 8.

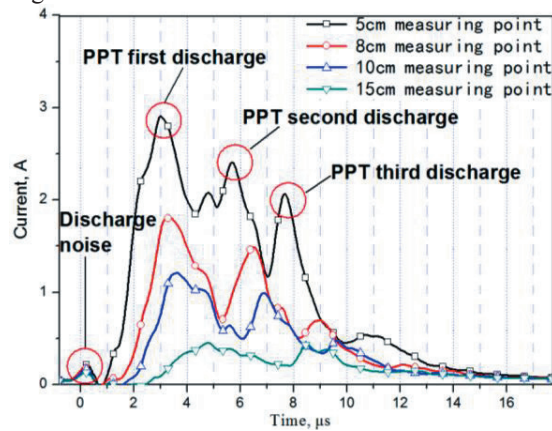


Figure 8. Triple Langmuir probe measurement result

The peak beyond PPT first discharge peak is PPT ignition plug discharge noise. According to the probes measuring points distance difference and corresponding peak time difference, plasma ejection velocity denoted as v_{peak} could be calculated. Because of measuring points of 10cm and 15cm are far away from PPT electrodes, and the third discharge peak signal is too weak, there is no obvious signal collected for 10cm and 15cm Langmuir probe. The results of plasma ejection speed at each measuring point are shown in Table 2.

Table 2 Time of flight probe measurement speed result

	v_{peak1} (km/s)	v_{peak2} (km/s)	v_{peak3} (km/s)
5cm-8cm	58.46	37.97	24.79
8cm-10cm	47.39	46.51	
10cm-15cm	44.21	31.85	
Average	50.02	38.78	24.79

Langmuir probe waveform has three peaks, which means there exists three times discharge in PPT discharge process. The energy of every discharge is weaker than its previous discharge, and there is a time interval between each PPT discharge. The table above calculated plasma ejection speed. There are three repeated discharges during the process. The average plasma ejection velocities are 50.02km/s, 38.78km/s, 24.79km/s.

V. Discussion

Rogowski coil and Langmuir probe time difference method (short for RL time difference method) uses the Rogowski coil and Langmuir probe peak time difference and the distance from Langmuir probe to PPT Teflon surface to calculate the plasma ejection velocity. According to the non-phase-error characteristics of the Rogowski coil, a comparison of current curves between Rogowski coil and triple Langmuir probe can be achieved. And the plasma ejection velocity obtained by phase difference of Rogowski coil and triple Langmuir probe current curves is different from Time of flight probe method. The discharge current curve and Langmuir probe result at 5cm axial distance are compared in Figure 9.

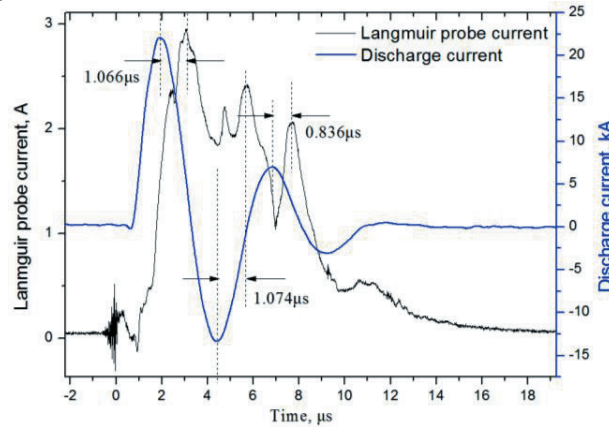


Figure 9. Comparison between Rogowski coil and triple Langmuir probe curve

As can be seen from the comparison of three peaks, time difference between Rogowski coil and Langmuir probe peaks can be obtained. According to the time difference and 5cm axial distance from thruster, we can calculate plasma ejection velocity denoted as $v_{compare}$. The 3 peaks in Langmuir probe current curve and discharge current curve are corresponding to three discharges in PPT. The plasma ejection velocities of three times discharges are compared in Table 3.

Table 3. Comparison between two methods plasma ejection velocities

	Discharge energy(J)	Time of flight probe method	RL time difference method
		v_{peak} (km/s)	$v_{compare}$ (km/s)
First peak	9.41	50.02	46.90
Second peak	5.73	38.78	46.54
Third peak	2.51	24.79	59.78

The data shows that there exists obvious difference between the two series of plasma ejection velocity results obtained by the two methods. For the Time of flight probe method, velocity reduces with the decrease of discharge energy. For the RL time difference method, velocity increased with the discharge energy decreased. It is absolutely that, the plasma ejection velocity calculated by RL time difference method is wrong. Because a direct result of decreasing discharges energy is the decrease of plasma ejection velocity. But the thing worth of attention is that, at the first peak the two velocities, 50.02km/s and 46.90km/s, obtained by the two methods are very close. Then the RL time difference method velocity appeared a wrong increase trend.

The RL method assumes that the discharge occurs at 5cm axial distance from thruster Teflon surface. In fact, a theory proposed that the discharge position would move downstream toward the electrode. Indeed we take the 2.6cm long electrode into consideration. According to the theory that discharge position would move downstream toward the electrode, and in the research paper⁷, at 3.18μs plasma of 3rd half cycle located near the electrode end position. In our study the third discharge is PPT last restrike, so we assume that the third discharge would occurs at the end of electrode. Then the probe distance changes into 2.4cm axial distance from the third discharge position. And the velocity obtained by RL time difference method at the third peak changes into 28.71km/s. In the third peak, velocities of 24.79km/s and 28.71km/s obtained by the two methods are very close this time, which verify the assumptions that discharge will be moved downstream toward the electrode end. This indeed proves that the theory

of discharge position would move downstream toward the electrode. Furthermore, we can assume that the velocity obtained by Time of flight probe method at the second peak is approximately equal to the RL time difference method velocity. Then the PPT second discharge position can be estimated that: $(0.05-d)/(1.074 \times 10^{-6}) = 38.78 \times 10^3$. d is the distance between Teflon surface and second discharge location. The second discharge occurs at the distance of 8.35mm to PPT Teflon surface.

VI. Conclusion

A non-phase-difference Rogowski coil is presented. It is calibrated that the optimum RC integrating circuit time constant is $\tau=54\mu\text{s}$, Rogowski coil sensitivity is $S=9.75 \times 10^{-4}\text{V/A}$, calibration coefficient is $K=911$, and phase error is less than $\pm 0.1\mu\text{s}$. It is first tested on a PPT for 30 single impulse bits. Statistical result shows that discharge current standard deviation is 0.293, coefficient variation is 1.45%. Measurement results show that the PPT discharge process has a good stability and repeatability.

Time of flight probe method and Rogowski coil and Langmuir probe time difference method are used to conduct the plasma velocity measurement experiment. The experiment results show: the theory that PPT discharge position would move downstream toward the electrode is proved. The second discharge position is estimated 8.35mm to the PPT Teflon surface.

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