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Institute of Space and Plasma Sciences

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Abstract

In our project, we would like to compress a plasma plume to generate the Extreme ultraviolet (EUV) light using a theta pinch. In order to compress the plasma plume, I design a Helmholtz coil to provide the pulsed magnetic field for the theta pinch. Firstly, I calculated the theoretical magnetic field with ideal formula and simulated the magnetic field with COMSOL Multiphysics. The expected magnetic field is more than 3T. To measure the actual magnetic field, we decided to use the B-dot probe for measuring the magnetic field. Before measuring the generated magnetic field, we tested the Helmholtz coil in our pulsed-power system. We verified that the coil can survive after the discharge.

Besides the discharge test of the Helmholtz coil, a Q-switch laser was integrated with the pulsed-power system this year. It is used to take time-resolved images of plasma since it generates a burst of laser light in the order of nanosecond. The Q-switch signal needs to be synchronized with the pulsed-power system so that images are taken at the right time. Therefore, we designed a new optical trigger-pulse generator to solve the problem.

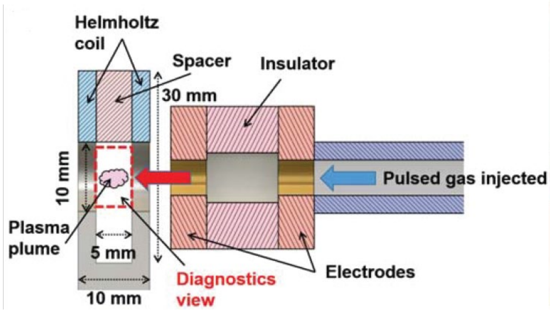
Finally, we made warning signs for two lasers in two different safety classes to remind everyone whether the laser is turned on in the laboratory or not.

Contents

1 Helmholtz coil

In our project, we want to compress a plasma plume using a theta pinch. To compress the plasma plume, we plan to use a Helmholtz coil to provide the pulsed magnetic field as shown in Figure 1. Due to the structure of the Helmholtz coil, we can easily inject the plasma plume and diagnose the plasma from the side. In the future, we can also collect the EUV light from the side. The goal of this project is to build a Helmholtz coil and measure the generated magnetic field when the coil is driven by our pulsed-power system.

(a) (b)



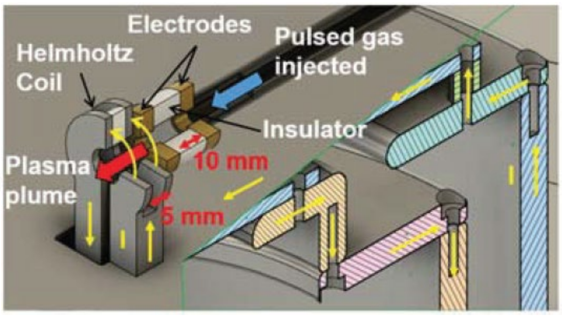


Figure 1 (a) The side view of the Helmholtz coil for the theta pinch. The gap between two coils provide a clear view for diagnostics. (b) The schematic of our proposed EUV light source.

1.1 The principle of an ideal Helmholtz coil

Helmholtz coil is a device that generates a uniform magnetic field over a small area. It is widely used. It is normally used for scientific experiments, magnetic calibration, and to cancel the background magnetic field in experiments. Shown in Figure 2, the ideal Helmholtz coil consists of a pair of circular coils with the same structure and size [1]. The planes of the coils are parallel to each other and the centers of the coils are on the same axis. The distance D between the center points of the coils is the same as the radius R of the coil itself. When the current goes through the two coils in the same direction, it generates a uniform magnetic field in the volume within the coils. The axial magnetic field at the center is the sum of the axial magnetic field from two coils, i.e.,

$$B_z(z=0) = N \cdot \frac{8\mu_0 I}{\sqrt{125}R} \tag{1}$$

where N is the number of turns in the coil, R is the radius of the coil, and I is the current that goes through each coil.

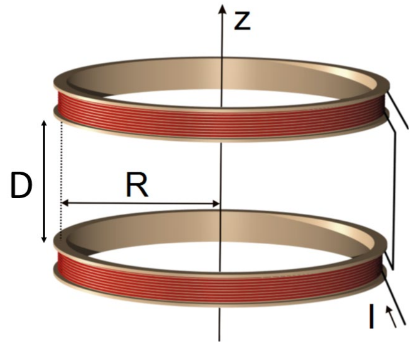


Figure 2 The Schematic of one-axis Helmholtz coil [1].

1.2 The design of our Helmholtz coil

In our experiment, the Helmholtz coil is made of Stainless steel. The Helmholtz coil consists of two coils, one Helmholtz coil horizontal holder, and one bottom coil connector as shown in Figure 3.

(a)

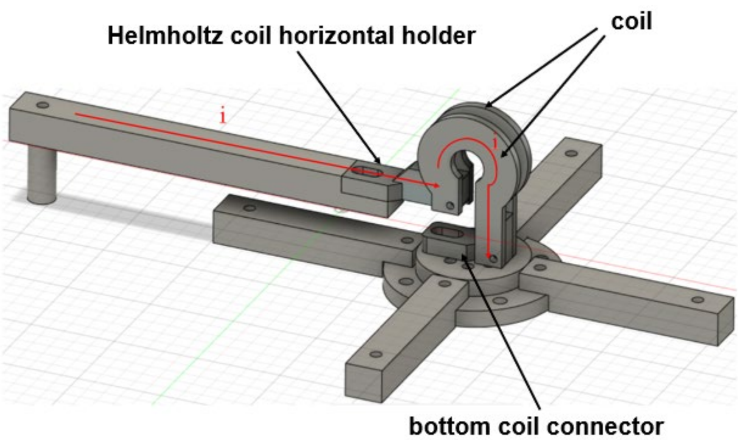


Figure 3 (a) The CAD drawing of Helmholtz coil.

(b)

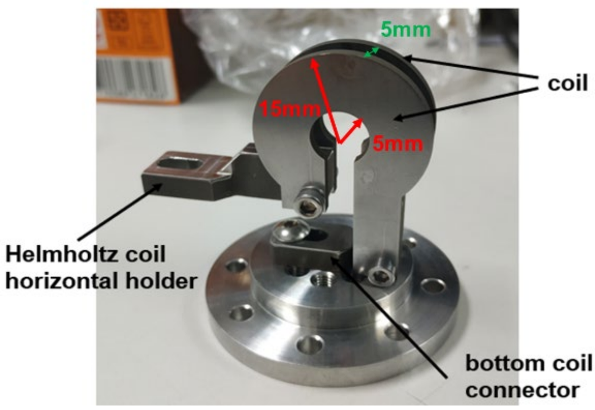


Figure 3 (b) The picture of Helmholtz coil.

As shown in Figure 3, the inner radius of the Helmholtz coil is 5 mm and the outer radius is 15 mm. The separation between two coils is 5 mm. The Helmholtz coil which I designed is not a completed circle and the angle of the outer diameter is 270 degrees, as shown in Appendix [1]. Thus, it is not a typical Helmholtz coil so that the magnetic field may not be as uniform as a typical one.

The Helmholtz coil is connected to our pulsed-power system. When the pulsed current flows through the Helmholtz coil, the coil may expand due to the Lorentz force. Shown in Figure 4, let T as the tension on the coil, R as the inner radius of the coil, Δ as the thickness of the coil, W as the width of the coil, which is into the page and is not shown in the figure, and A =Δ×W as the area of the cross section of the coil. Therefore, the magnetic pressure P_B needs to be balanced by the tension T of the coil , i.e.,

$$R \times \theta \times W \times P_B = T \times \sin\left(\frac{\theta}{2}\right) \times 2 \approx T \times \theta \quad \text{for} \quad \theta \to 0,$$

$$\frac{T}{\Delta \cdot W} = \frac{R \cdot P_B}{\Delta} = \frac{R}{\Delta} \cdot \frac{B^2}{2\mu_0} \leq \text{Tensile strength of stainless steel.} \qquad (2)$$

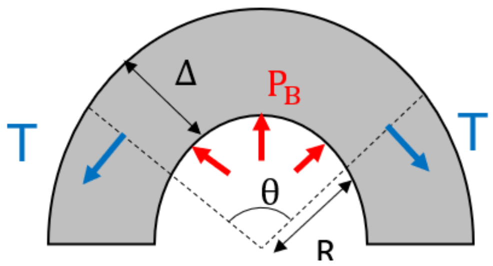


Figure 4 The relation between the tension on the coil T and the magnetic pressure P_B.

The Helmholtz coil needs to be strong enough to hold the tension during the discharge. On the other, two coils are pushed toward each other by the Lorentz force. A plastic spacer between two coils of the Helmholtz coil is used to prevent them crushing to each other

1.3 The theoretical magnetic field

To calculate the expected magnetic field, we have two ideal coils with a radius of 5 mm at -2.5mm and +2.5mm, respectively, and let the 65-kA current flows through each coil. The 65-kA current is half of the expected pulsed current provided by our pulsed-power system. The axial magnetic field distribution of this Helmholtz coil calculated using the equation (3) is

$$B(z) = \frac{\mu_0 I R^2}{2[R^2+(z+2.5\text{mm})^2]^{3/2}} + \frac{\mu_0 I R^2}{2[R^2+(z-2.5\text{mm})^2]^{3/2}} \qquad (3)$$

where R= 5 mm is the radius of the coil, and I=65 kA is the current that goes through each coil. The calculated result is shown in Figure 5.

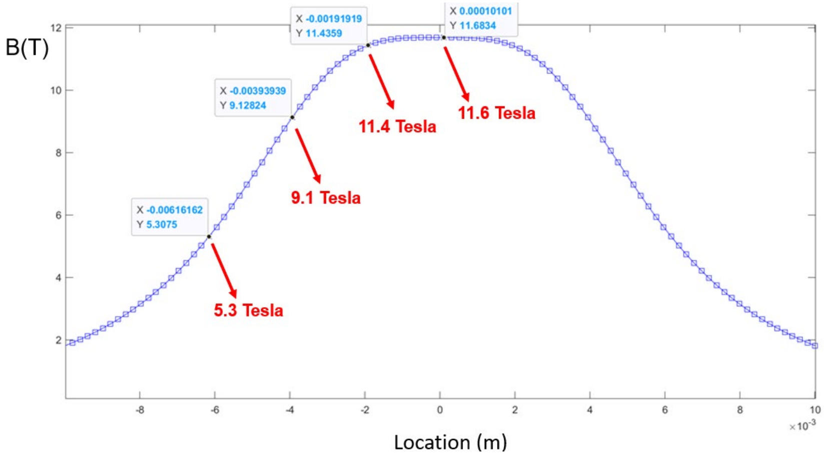


Figure 5 The axial magnetic field distribution of this Helmholtz coil.

The magnitude of the peak magnetic field at x=0 generated from the ideal Helmholtz coil is

$$\mathrm{B}_0 = \frac{8\mu_0 I}{\sqrt{125}R} = \frac{8\mu_0 \cdot (65\times 10^3)}{\sqrt{125}\times(5\times 10^{-3})} = 11.6 \text{ T}. \tag{4}$$

However, the Helmholtz coil which I designed is not an ideal Helmholtz coil. The actual strength of the peak magnetic field supposes to be less than 11.6 Tesla. Since we don't know how the current is distributed in the coils, I calculated the magnetic field generated by two coils with different radius R and different separation d between them as shown in Figure 6. The formula of the magnetic field at z=0 generated from the two coil is

$$B_z(z=0) = 2\times\frac{\mu_0 I R^2}{2[R^2+\left(\frac{d}{2}\right)^2]^{\frac{3}{2}}} \; . \tag{5}$$

(a) (b)

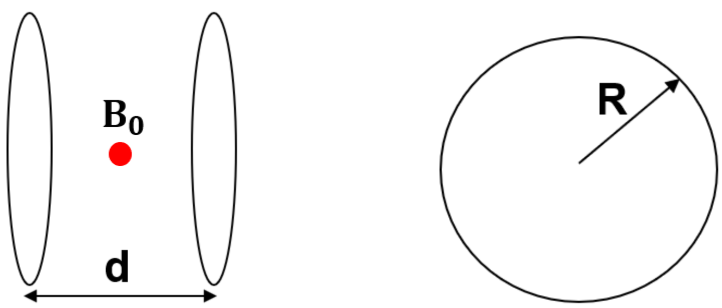


Figure 6 (a) The schematic of the two coils. (b) R is the radius of the coil.

Since the inner radius and the outer radius of my Helmholtz coil is 5 mm and 15mm, respectively. I have R=5, 10, 15 mm. On the other hand, the thickness of the coil is 2.5 mm and the separation between two coil is 5 mm. Therefore, I have d=5, 7.5, 10 mm. According to Table 1, the range of the ideal magnetic field generated from two coils is 4.6 ~ 11.6 T.

Table 1 The ideal magnetic field generated from the two coil.

R(mm) / d(mm)	5	10	15
5	11.6 T	7.4 T	5.2 T
7.5	8.3 T	6.7 T	4.9 T
10	5.7 T	5.8 T	4.6 T

1.4 The simulated magnetic field

In addition to calculating the magnetic field of Helmholtz coil with ideal formula, I want to know the magnetic field of the coil with finite thickness. Therefore, I used a simulation software, COMSOL Multiphysics [2], to simulate the magnetic field generated from the Helmholtz coil.

1.4.1 Introduction of the COMSOL Multiphysics

The COMSOL Multiphysics is a software for Computer Aided Engineering (CAE) simulation of multi-physics coupled analysis. The physics of the software covers electromagnetics, structural mechanics, acoustics, fluids, heat transfer, and chemical industry. The software can analyze the physical properties of different fields in one interface. Besides, the advantage of this software is that the interface is Chinese and simple so that it is easy to use. The interface of the COMSOL Multiphysics is shown in Figure 7.

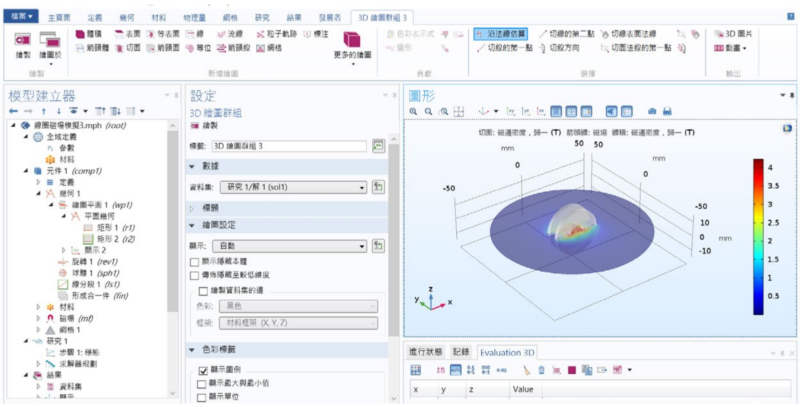


Figure 7 The interface of the COMSOL Multiphysics.

The simulation in COMSOL Multiphysics uses "3+6 modeling steps" to realize simulations for many problems. The number "3" represents the "spatial dimension" "physical interface", and "type of study" of the case that you want to model. The "spatial dimension" of the simulated case can be selected as an option, as shown in Figure 8. Subsequently, the "physical interface" and the "type of study" of the case can be selected as shown in Figure 9 (a) and (b), respectively.

Figure 8 The spatial dimensions can be selected in the COMSOL software.

(a) (b)

Figure 9 (a) The physical interface of the case in the COMSOL software. (b) The type of study of the case in the COMSOL software.

Next, the number "6" represents that there are six steps to model the case in the modeling stage. The steps are "geometry", "material", "physics", "mesh", "solve", and "post-processing". Eventually, you can successfully model the case that you want to study and perform physical analysis of the simulated result.

1.4.2 The procedure of modeling the Helmholtz coil:

1. Add a new file: Model Wizard.
2. Select "space dimension": 3D.
3. Select "physics": Magnetic Fields(mf) in AC/DC.
4. Select "study": Stationary.
5. Enter the interface of COMSOL Multiphysics.

6. Set the "geometry" of the Helmholtz coil and the boundary around the Helmholtz coil.
7. Set the physical dimensions of the Helmholtz coil.
8. Set the element size of the mesh.
9. Compute the physical problem of the Helmholtz coil.
10. Conduct the post-processing.

1.4.3 Benchmark

In order to benchmark the simulation, I modeled a Helmholtz coil with small thickness, and compared the magnetic field distribution with that of an ideal Helmholtz coil with the same dimension. The magnetic field of the ideal Helmholtz coil is calculated using equation (3) introduced in section 1.3.

Figure 10 demonstrates the structures of the Helmholtz coil with small thickness (2.5 mm). Finally, I compare the axial magnetic field of the simulation result with the theoretically calculated axial magnetic field as shown in Figure 11. We can see that the red curve is closed to the blue curve indicating that the simulated magnetic field of the Helmholtz coil with small thickness (red curve) is similar to the theoretical magnetic field of the ideal Helmholtz coil (blue curve) normally. Therefore, we know that the simulation result matches the theoretical calculation.

(a) (b)

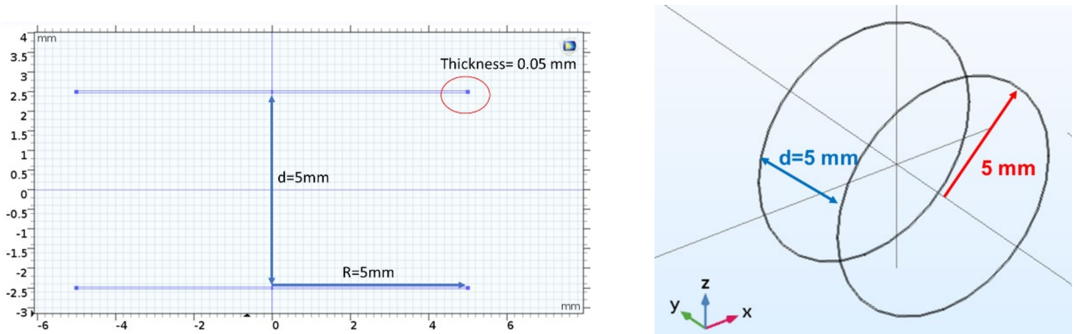


Figure 10 (a) The planar structure of the Helmholtz coil with small thickness. (b) The three-dimensional structure of the Helmholtz coil with small thickness.

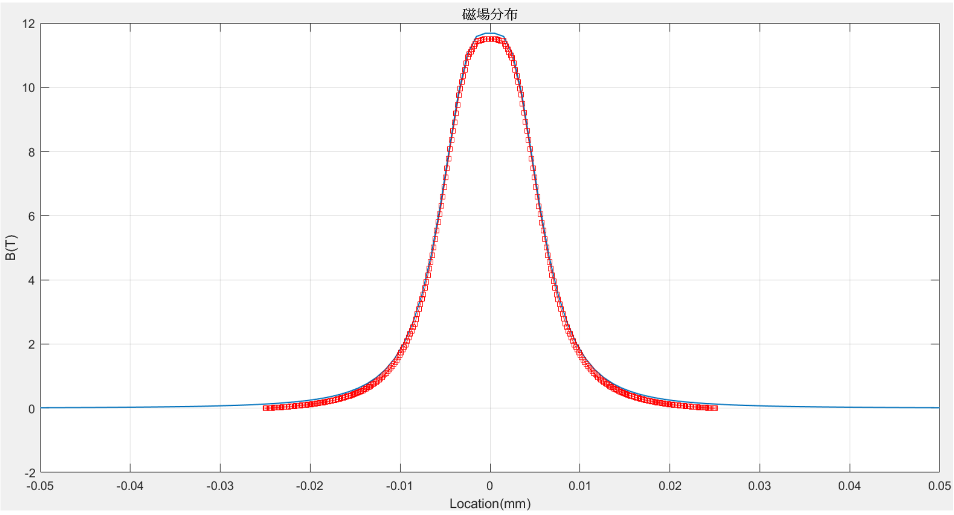


Figure 11 The comparison between the axial magnetic field of the simulation and the theoretical calculated axial magnetic field.

1.4.4 Simulated magnetic field of the actual Helmholtz coil

To be realistic, I simulate the Helmholtz coil whose size is the same as the Helmholtz coil which I designed and is introduced in section 1.2 as shown in Figure 12. Let the 65-kA current flows through each coil and let the current uniformly distributed in the cross section of the coil. The 3-D magnetic field distribution of the Helmholtz coil is shown in Figure 13. The gray structure is the Helmholtz coil. Since the direction of the current is counterclockwise, the direction of magnetic field (red arrow) is in the direction of +y. As shown in Figure 14, the axial magnetic field strength of the Helmholtz coil is surprisingly much smaller than that of the ideal Helmholtz coil. The peak magnetic field is only 3.3 Tesla. It should be the lower bound of the generated magnetic field.

(a) (b)

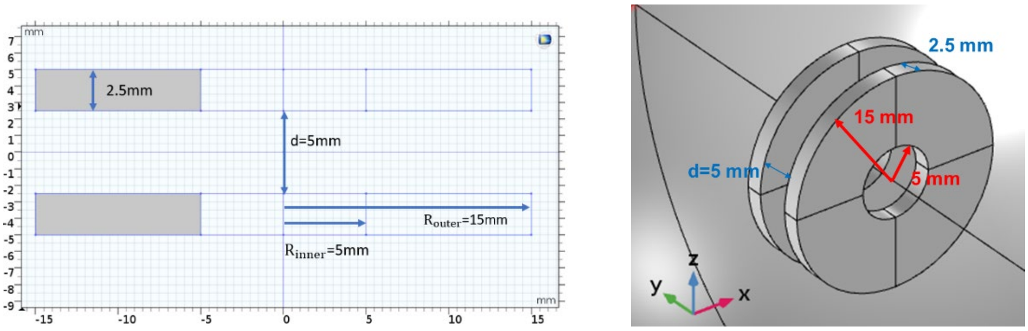


Figure 12 (a) The planar structure of the Helmholtz coil. (b)The three-dimensional structure of the Helmholtz coil.

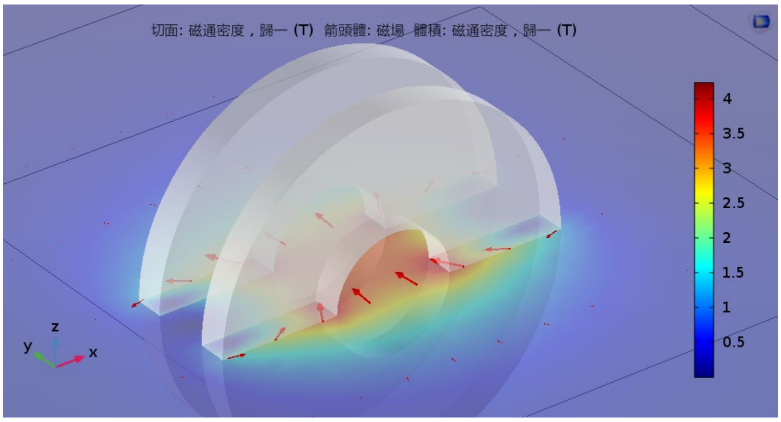


Figure 13 The magnetic field distribution of the Helmholtz coil.

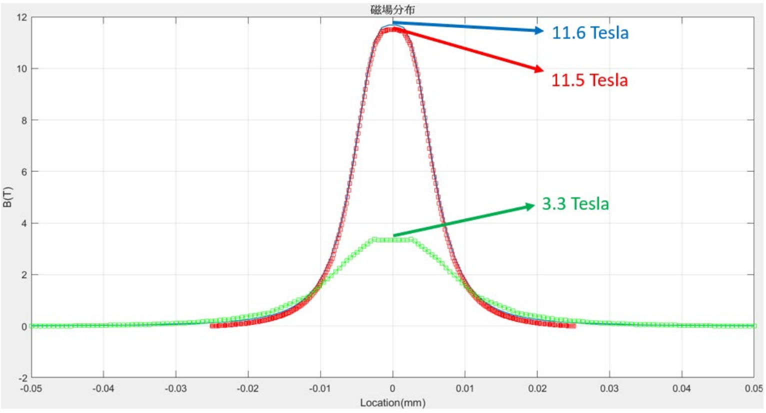


Figure 14 The comparison of magnetic field distribution.

1.5 Helmholtz coil discharge test

Before measuring the generated magnetic field, we tested the Helmholtz coil and see if it can survive after the discharge. We have tested the discharge under three conditions: discharge in atmosphere, discharge under low vacuum, and discharge under high vacuum. In all experiments, the Helmholtz coil is always installed in our pulsed-power system.

In Figure 15, our pulsed-power system consists of twenty 1-μF capacitors, two rail-gap switches, two parallel-plate transmission lines, and a cylindrical vacuum chamber orientated vertically. Two capacitors are first connected in series forming a brick. Five bricks are connected in parallel forming a wing. Finally, two wings are connected in parallel providing a capacitance of 5 μF in total. The discharge current is conducted through the parallel-plate transmission line and the coaxial-transmission line to the center of the cylindrical vacuum chamber for experiments. The system is charged to 20 kV. When it is discharged, a peak current of 135 ± 1 kA with a rise time of 1592 ± 3 ns is generated. The inductance and the resistance of the system obtained from the discharge tests are 204 ± 4 nH and 10.0 ± 0.2 mΩ, respectively. The current is used to drive the Helmholtz coil for generating pulsed magnetic fields [3].

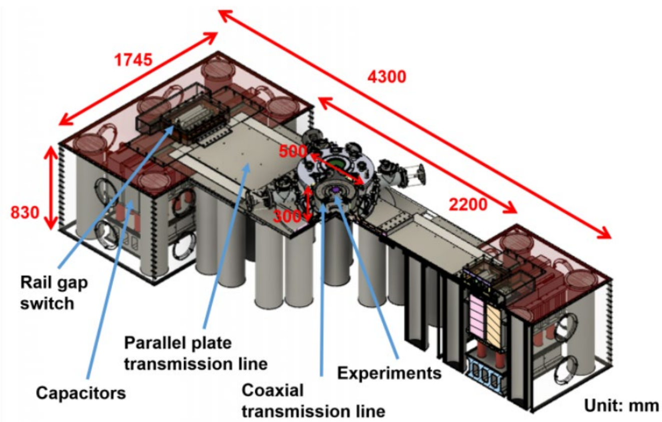


Figure 15 The CAD drawing of the Our pulsed-power system [3].

1.5.1 Discharge in atmosphere

We tested the Helmholtz coil in atmosphere first. We did not cover the vacuum chamber and observed the Helmholtz coil discharge directly from the top of the chamber. When the pulsed current flows through the Helmholtz coil, the coil may expand due to the Lorentz force. If the structure of the coil is not strong enough, the coil will be damaged. Therefore, we need to check whether the Helmholtz coil will survive after each discharge or not. In order to prevent the fragments of broken coil from damaging the chamber, I placed a Polyvinyl Chloride (PVC) tube around the coil and put a transparent acrylic plate on the top as shown in Figure 16.

In experiments, when the system was discharged, the large current flowed through the Helmholtz coil. Sparks were generated as shown in Figure 17.

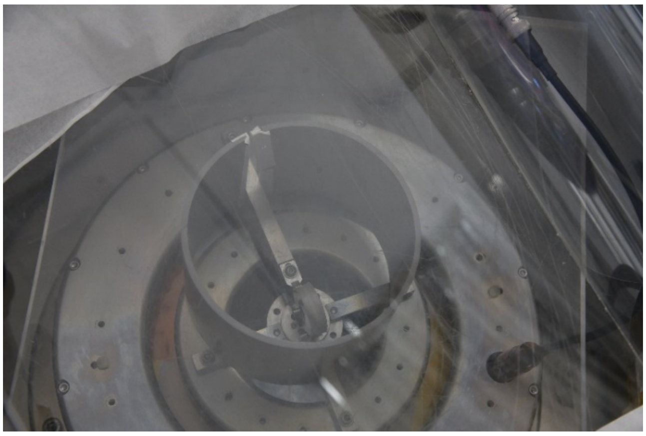


Figure 16 The prevention of damaging the chamber.

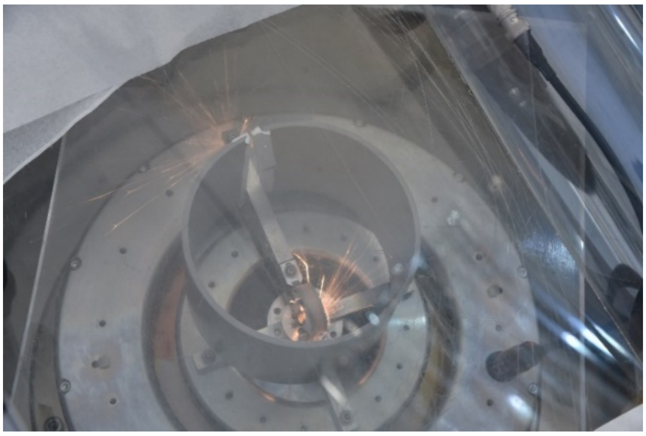


Figure 17 The discharge during the experiment.

During experiments, we measured the voltage of the capacitors in the system with the high-voltage probe, Tektronic P6015A, and the current of the system with Rogowski coil, respectively[4]. Results of the capacitor's charged voltage and the discharge currents are shown in Figure 18 and Figure 19 separately. In Figure 18, except the high-frequency noise occurred at the beginning of the discharge, the system was in an underdamped RLC regime. Unfortunately, the measured current trace was abnormal sometimes as shown Figure 20. The reason I think was that an arc discharge occurred.

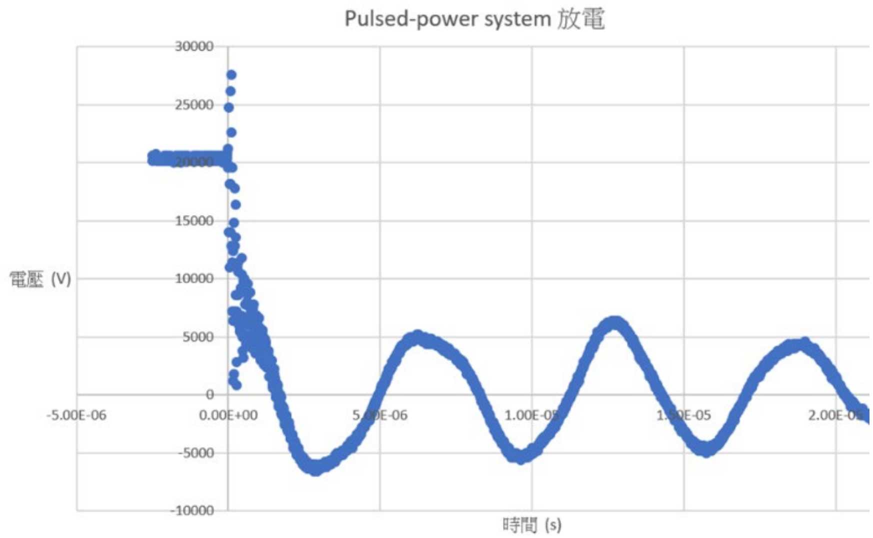


Figure 18 The voltage signal of the system.

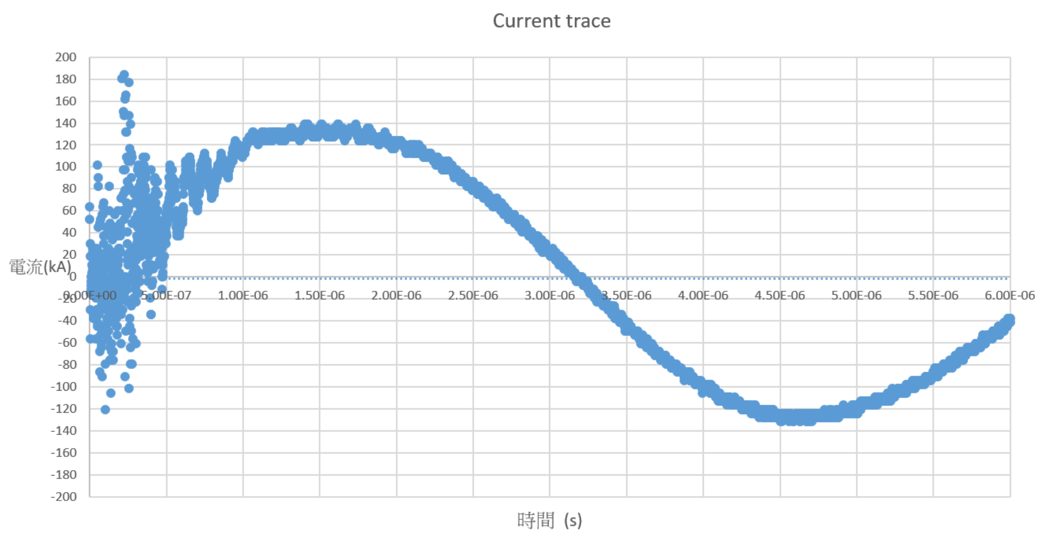


Figure 19 The current trace of the system.

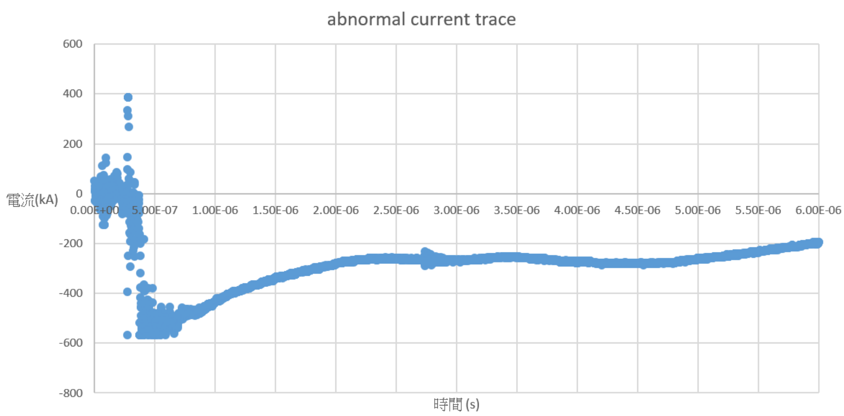


Figure 20 The abnormal current trace of the system.

1.5.2 Discharge under low vacuum

In our project, the plasma plume needs to be generated and preheated first because the theta pinch only compresses a conductor. In other words, plasma needs to be generated prior to the pinch. But, the system of the plasma plume is not completed yet. We would like to directly ionize the argon gas and pinch the plasma at the same time through the electric field generated by the pulsed magnetic field provided by the Helmholtz coil.

From previous experiments of Helmholtz coil discharged under atmospheric pressure, we knew that sparks were generated during the discharge. To reduce the impact of sparks on the experiment, I put some Kapton tape around the Helmholtz coil where there might be arcing. Finally, we closed the vacuum chamber and took the top-view images of the Helmholtz coil discharge using the newly installed raspberry-pi camera [5].

To keep the chamber under low vacuum, I injected a steady stream of argon gas into the chamber using a mass flow controller (氣體質量讀表, KD-1000 1 CH) as shown in Figure 21. The flow rate was 5 standard cubic centimeter per minute (SCCM). On the other hand, only the rough pump was turned on. As a result, the pressure of argon in the chamber was around 0.5 torr. The reason we wanted to have chamber filled with argon with a pressure of 0.5 Torr is in the following.

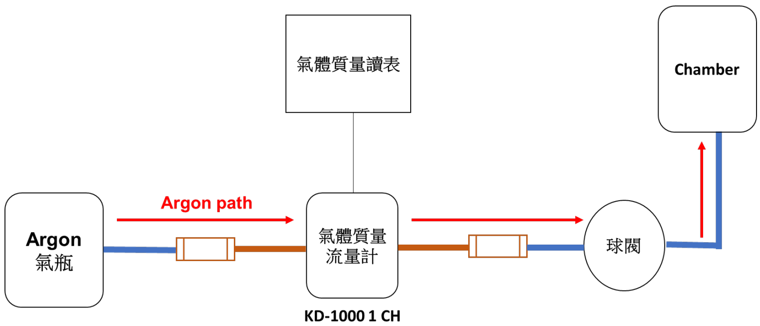


Figure 21 The path of argon gas flow in the system.

Firstly, I want to find out under what conditions argon gas can be ionized using the Paschen curve of argon gas. Paschen curve is a curve that describes the required breakdown voltage V_B of an air gap with a given gap distance (d) and air pressure (P) as shown in Figure 22. Any voltages above the curve can cause a breakdown between the gap. We get the lowest breakdown voltage V_B required for ionization at the lowest point of the curve. Table 2 from the former student, Jun-Yu Chen, shows the lowest breakdown voltage V_B occurs at different products of the gap distance (d) and the air pressure (P). Then, we calculated the required voltage that can be generated by the pulsed magnetic field from the Helmholtz coil.

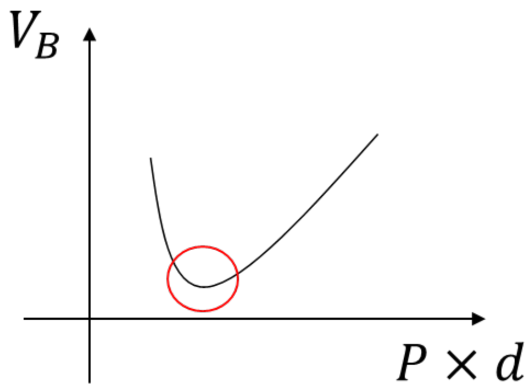


Figure 22　The schematic of the Paschen 's curve.

Table 2　The data of breakdown voltage at the lower edge

間距 d=1 mm 條件下

P × d (torr x mm)	V_B(V)
6.58	58
7.06	59
7.06	57
7.39	58
7.06	60
6.99	60
7.39	60
6.44	62
7.6	62
7.46	64

間距 d=2 mm 條件下

P × d (torr x mm)	V_B(V)
7.04	93
14.92	110
13.98	101
11.52	97
8.24	89
6.44	91
10.4	89
5.7	89
7.64	90
6.44	88

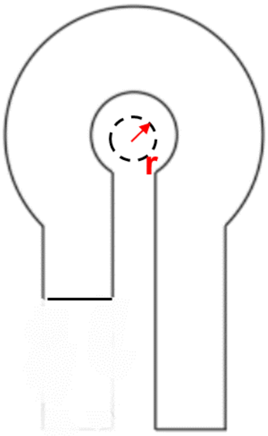
Assuming that the magnetic field generated from the Helmholtz coil discharge is

$$B = B_0 \sin(\omega t) = 3 \ \sin(\omega t) \tag{6}$$

where $\omega = \frac{2\pi}{T} = 2\pi \times \frac{1}{1.6\mu s \times 4} = 9.81 \times 10^5$ rad/s. Three is picked because it is the lowest magnetic field that will be generated as suggested in section 1.4.4. The induced voltage in the Helmholtz coil is

$$V = -\frac{d\phi}{dt} = -\pi r^2 \times [B_0 \omega \cos(\omega t)] = -\pi r^2 \times [3 \times (9.81 \times 10^5) \cos(\omega t)]. \tag{7}$$

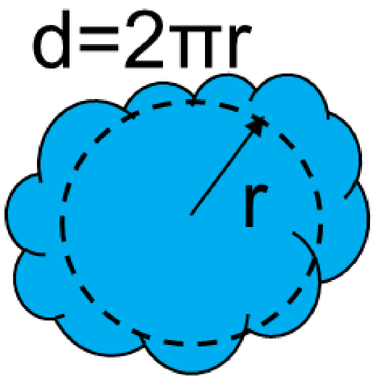
Magnitudes of induced voltages of psudo circles with different radii in space are shown in Figure 23.



Radii, r (mm)	Induced voltage, V (volts)
1	-9.2 cos(ωt)
2	-36.9cos(ωt)
3	-83.2cos(ωt)
4	-147.9cos(ωt)
5	-231.1cos(ωt)

Figure 23 The magnitude of induced voltage at the different radius.

I defined the circumference of the psudo circle in the Helmholtz coil as the gap of imaginated electrodes as shown in Figure 24. Furthermore, I assumed that the magnetic field generated from the Helmholtz coil is uniform in the space. Under the assumption, if the induced voltage is larger than the breakdown voltage at a specific pressure, the argon gas would be ionized becoming plasma.



r (mm)	d (mm)
1	6.28
2	12.56
3	18.84
4	25.12
5	31.40

Figure 24 The schematic of the perimeter of the argon gas among the Helmholtz coil.

In Table 2, the breakdown voltage $V_B = 110\ \mathrm{V}$ that is the largest breakdown voltage when $P \times d$ is 14.92 (torr × mm). The estimated specific pressure is

$$P = \frac{14.92}{25.12} = 0.59\ \text{torr at } r = 4\ \text{mm},$$

$$P = \frac{14.92}{31.4} = 0.47\ \text{torr at } r = 5\ \text{mm}. \tag{8}$$

The estimated specific pressure is around 0.5 torr. Therefore, we kept our vacuum chamber at ~0.5 torr. Shown in Figure 25 is the side-view photo during the discharge. Unfortunately, the phenomenon of theta pinch did not occur in the experiment, In other words, the argon gas was not pre-ionized by the induced voltage. On the other hand, it was found that the glow discharge occurred in the chamber.

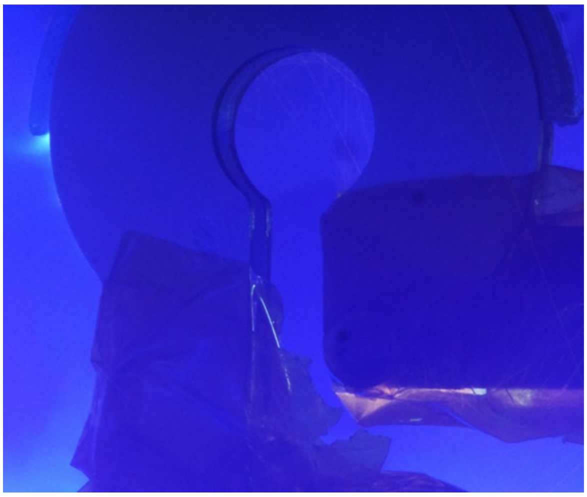


Figure 25 The side-view photo of the experiment.

1.5.3 Discharge under high vacuum

In this series of experiments, we did not inject argon gas into the chamber. However, we pumped the chamber down to 10^{-6} torr, which was at high vacuum. Similarly, we observed the glow discharge occurred in the chamber as shown in Figure 26. Fortunately, all current traces on the oscilloscope was normal as shown in Figure 27. Because the frequency of the current trace changed before and after ~7 μs, we suspected that the inductance of system has changed and the current path has also changed. Since the glow discharge in the chamber happened after 1.6 μs, which should not influence the theta pinch that will happen in the first quarter period.

(a) (b)

Figure 26 (a) The top-view photo in the experiment. (b) The side-view photo in the experiment.

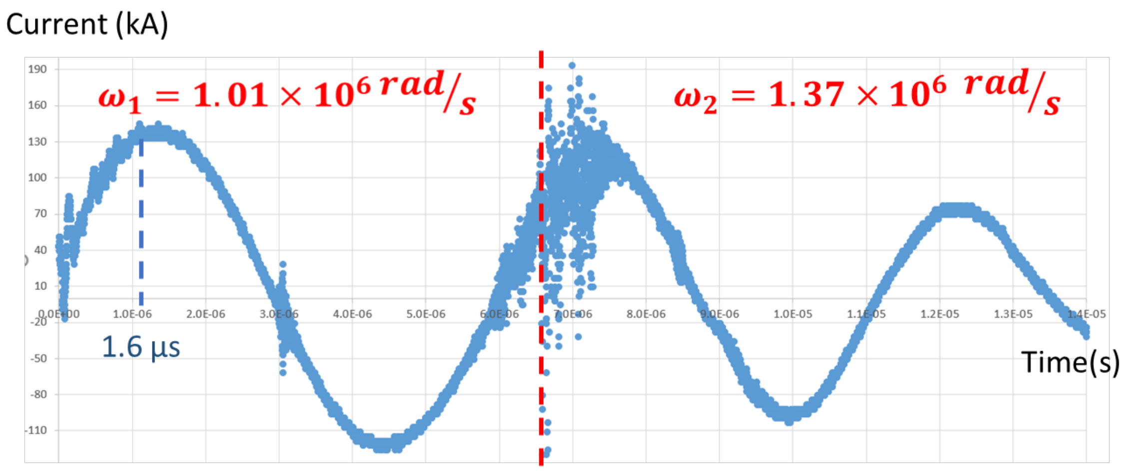


Figure 27 The one of the discharge currents measured with the Rogowski coil.

2 The B-dot probe

In our research, the magnetic field generated from the Helmholtz coil is important for the theta pinch. It needs to be measured. Thus, we decided to use the B-dot probe for measuring the magnetic field.

In many plasma experiments, the main parameters of the experiment include the magnitude of currents, magnetic and electric fields inside and outside the plasma. B-dot probes are electromagnetic sensors which are used to measure magnetic field in wide frequency ranges.

A B-dot probe is normally a single-turn coil made of enameled copper wire. The operating principle of the B-dot probe is based on Faraday's law. When magnetic flux through the B-dot probe changes in time, an electromotive force V_{ind} is induced in the B-dot probe as shown in Figure 28. The magnitude of the induced voltage is proportional to the time derivative of the magnetic flux ϕ:

$$V_{ind} = -\frac{d\phi}{dt} = -N \cdot \frac{d\int \vec{B} \cdot d\vec{A}}{dt} = -NA\frac{dB_{avg}}{dt} \tag{9}$$

where $\phi = N\int \vec{B} \cdot d\vec{A}$, and N is the number of turns of coils in the B-dot probe.

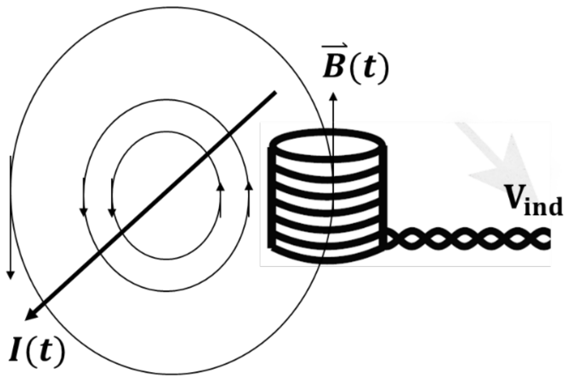


Figure 28 The schematic of the B-dot probe [6].

If the cross section of the B-dot probe is a constant in time, the averaged magnetic field sampled by the B-dot probe is given by $B_{avg} = \frac{\int \vec{B} \cdot d\vec{A}}{A}$,i.e.,

$$B_{avg} = -\frac{1}{NA}\int V_{ind}\,dt \equiv C_{calib}\int V_{ind}\,dt \tag{10}$$

Therefore, as long as we know the calibration factor C_{calib}, we can obtain the magnitude of the magnetic field at the location we measure by integrating the induced voltage of B-dot probe with time.

2.1 The design of the B-dot probe

In my design, the B-dot probe is a single-turn coil which is made of enameled copper wires with a diameter of 0.5 mm. The B-dot probe has only one turn and the diameter of the B-dot probe is 10 mm. The terminals of B-dot probe are twisted forming a twisted pair. The twisted pair can reduce the attenuation and noise during transmission, and improve the ability to suppress external electromagnetic interference [7]. The RG 58 coaxial cable is used to connect the terminals of the twisted pair of the B-dot probe. Therefore, we can observe the induced voltage on the B-dot probe directly from the oscilloscope. Finally, the magnetic field is obtained by integrating the induced voltage using a RC integrator in time as shown in Figure 29.

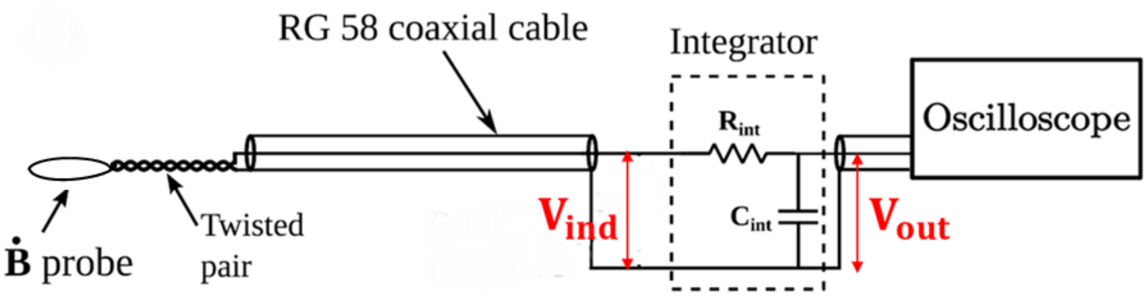


Figure 29 The circuit of the B-dot probe with a integrator.

2.2 Calibration of the B-dot probe

Before using the B-dot probe to measure the magnetic field of the Helmholtz coil, the B-dot probe needs to be calibrated by a known magnetic field.

2.2.1 The magnetic field generated from a solenoid

I made a solenoid to generate a known magnetic field source as shown in Figure 30. When the current passes through the solenoid, a uniform magnetic field is generated inside the solenoid. The solenoid is made of a PVC tube with a diameter of 34 mm and a electrical wire with a cross section of 1.25 mm^2. The length of the solenoid is 21 cm with 65 turns of coil in total. In other words, the number of turns per unit length (n) of the solenoid is 309.5 turns/m. The measured resistance and inductance are 0.1 Ω and 15.14 μH respectively. They were measured by a RLC meter (LCR-6300 by 華鳴儀器設備有限公司). According to the formula of an ideal solenoid, the magnetic field inside this solenoid is

$$B(t) = \mu_0 \cdot nI(t) = \mu_0 \cdot 309.5 \cdot I(t) = 3.889 \times 10^{-4} \times I(t) \quad T \qquad (11)$$

where μ_0 is the permeability of vacuum, I(t) is the current passes through the wire, and B(t) is the magnetic field generated inside the solenoid.

Additionally, in order to measure the magnetic field inside the solenoid, I drilled a hole on the solenoid and put the probe of the Gauss meter (WT10A) into the hole. The direction of the magnetic field lines of the measured magnetic field is perpendicular to the Hall element at the front end of the probe of the Gauss meter as shown in Figure 31. To make sure that every time when we measure the magnetic field, the probe is inserted to the same location, I made a support using the 3D printer as shown in Figure 32. The computer-aided design (CAD) drawing of the support is provided in Appendix[5]. The support is first inserted through the hole on the side of the solenoid into the solenoid. Then, the probe of the Gauss meter is inserted into the support. In Figure 33(b), the probe (red dash square) is fixed inside the solenoid and the sensor (blue circle) on the probe is at the center of the cross section of the solenoid.

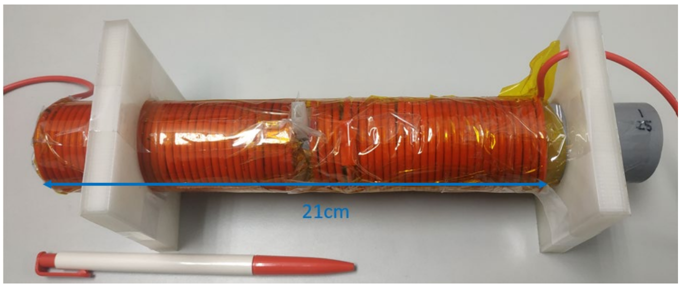


Figure 30 The picture of the solenoid.

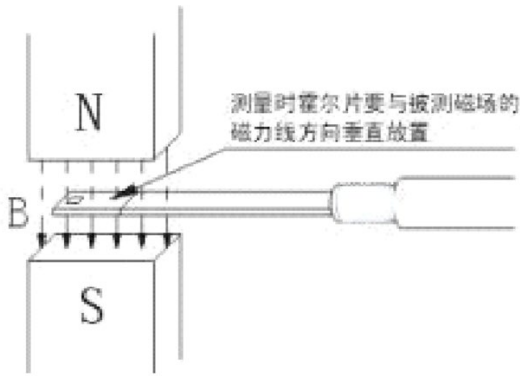


Figure 31 The way to measure the magnetic field with the Gauss meter [8].

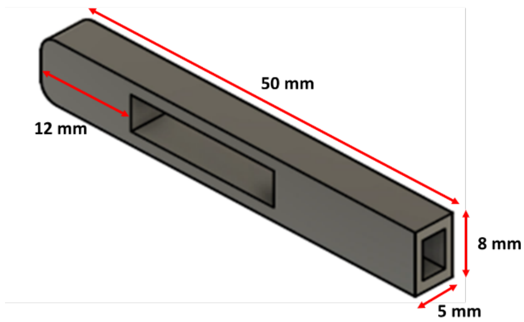


Figure 32 The CAD drawing of the support.

(a) (b)

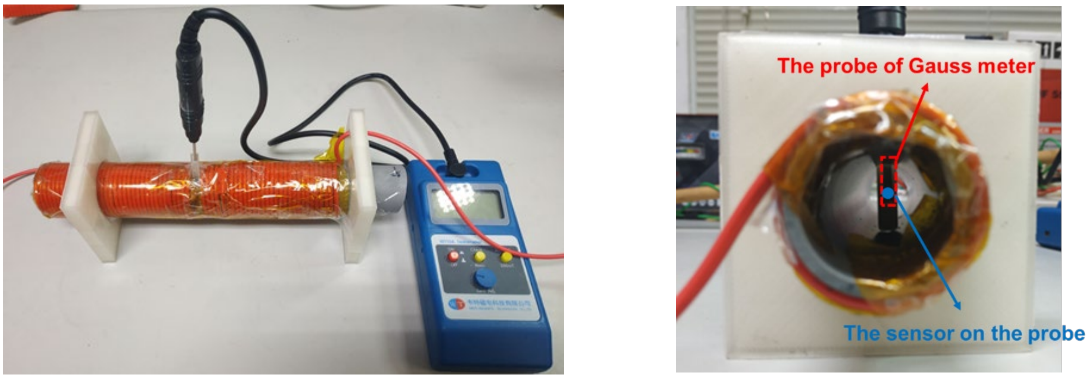


Figure 33　The probe of the Gauss meter is fixed in the center of the circular section of the solenoid.

The circuit that was used to produce direct current (DC) that flowed through the solenoid is shown in Figure 34. In experiments, I adjusted the output voltage of the power supply and recorded the magnetic field displayed on the Gauss meter and the current displayed on the power supply simultaneously. The results of the magnetic field inside the solenoid is shown in Figure 35.

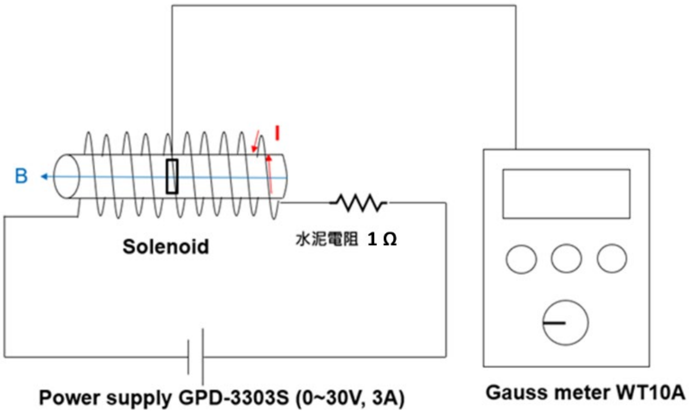


Figure 34　The circuit of the experimental set up.

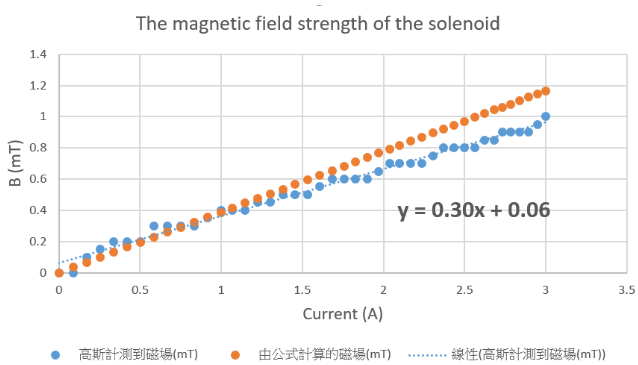


Figure 35　The results of the magnetic field generated inside the solenoid.

In Figure 35, the orange data is the theoretical magnetic field calculated from equation and the blue data is the measured magnetic field recorded from the Gauss meter. Because the smallest unit that the Gauss meter can measure is $0.1\ \mathrm{mT}$, the data of the measured magnetic field is stepped. The formula of the fitted curve is

$$B = 0.30 \cdot I + 0.06\ (\mathrm{mT}). \tag{12}$$

Because a hole was drilled in the solenoid, it may result in a reduction and nonuniformity of the magnetic field. Therefore, the difference between the orange data and the blue data could be the nonuniformity in magnetic field inside the solenoid.

2.2.2 Calibration of the B-dot probe in a low alternating current (AC)

The circuit for calibrating the B-dot probe is shown in Figure 36. The function generator is connected to the solenoid through a 1Ω cement resistor. Cement resistors are high-power resistors and are generally used in workplaces that allow high power and high current. The cement resistor is for measuring the current $I(t)$ on the circuit via measuring the voltage V_R across the cement resistor.

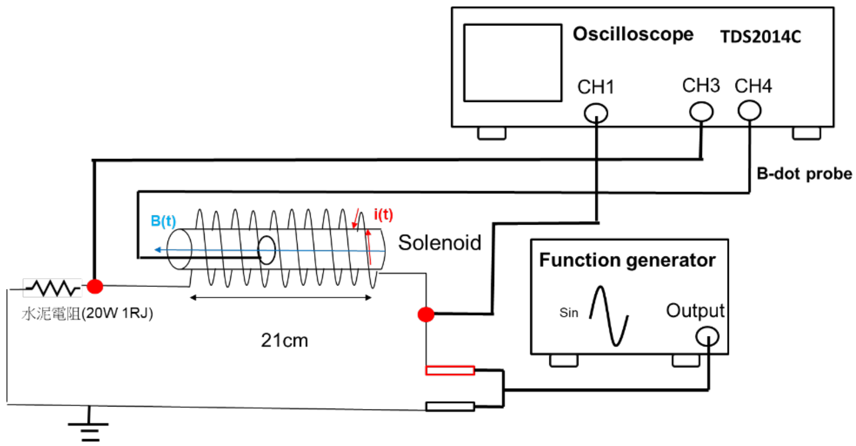


Figure 36 The schematic of the experimental set up.

In Figure 37, the V_R across 1Ω cement resistor is a sine wave because the V_{in} from the function generator is also a sine wave. We can get the current $I(t)$ directly from voltage V_R, i.e., $I(t) = V_R(t)/R$. Next, we put the B-dot probe in the solenoid at the same location where we inserted the probe of the Gauss meter in the solenoid. Therefore, from equation (12), we can get the magnetic field from the current measurement. Thus, we can calibrate the B-dot probe using the referred magnetic field.

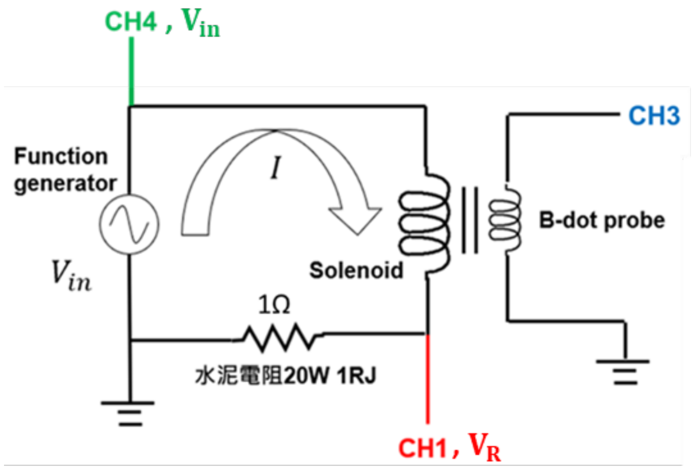


Figure 37 The circuit for calibration of the experiment.

In experiments, I set the input V_{in} with the different peak-to-peak voltage V_{PP} and the different frequency f in the function generator. I measured the V_R across the cement resistor and V_{ind} on the oscilloscope. Table 3 is the list of parameters I used. Data are stored in the folder "2022.3.14_B-dot probe".

Table 3 The setting on the function generator.

編號	Frequency(kHz)	Vpp	示波器檔名
1	100	5	ALL0000
2	100	6	ALL0001
3	100	7	ALL0002
4	100	8	ALL0003
5	100	9	ALL0004
6	100	10	ALL0005

編號	Frequency(kHz)	Vpp	示波器檔名
7	150	5	ALL0006
8	150	6	ALL0007
9	150	7	ALL0008
10	150	8	ALL0009
11	150	9	ALL0010
12	150	10	ALL0011

編號	Frequency(kHz)	Vpp	示波器檔名
13	156.2	5	ALL0012
14	156.2	6	ALL0013
15	156.2	7	ALL0014
16	156.2	8	ALL0015
17	156.2	9	ALL0016
18	156.2	10	ALL0017

Since the rise time of the peak current of our pulsed-power system is 1.6 μs, the calculated frequency is

$$f = \frac{1}{T} = \frac{1}{1.6\mu s \times 4} = 156.25\ \text{kHz}. \quad (13)$$

The result of the NO.13 data, V_{PP}=5 V and f =156.2 kHz, is shown in Figure 38 as an example. Other results are given in Appendix[7]. The red curve and the blue curve represent the V_R across the cement resistor and the induced voltage V_{ind} of the B-dot probe, respectively.

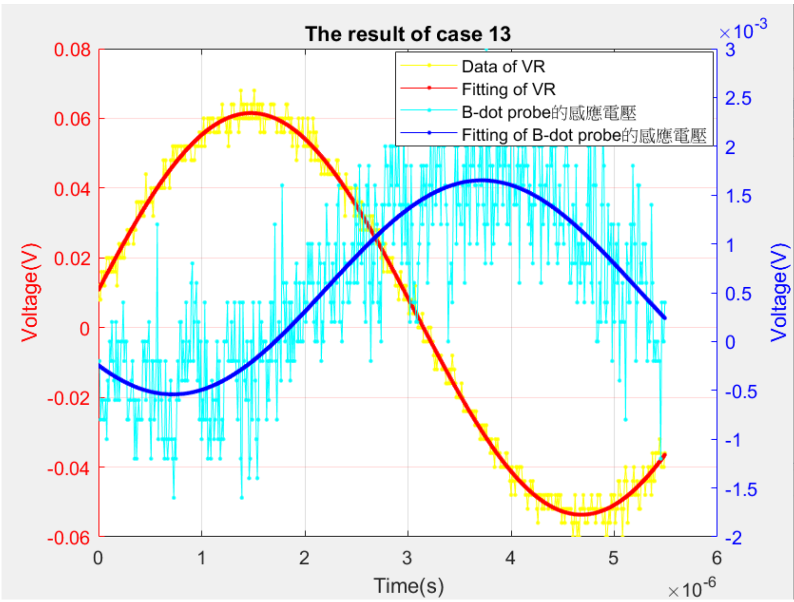


Figure 38 The result of case 13 in the experiment.

After curve fitting using MATLAB, we got

$$V_R = V_{R,0}\sin(2\pi f_1 + \varphi_1) + d_1 \quad (14)$$

where $V_{R,0} = 57.5 \pm 0.3$ mV, $f_1 = 1.56 \times 10^5$Hz ,$\varphi_1 = 0.1 \pm 0.0$,and d_1 =3$\pm$1 mV, and

$$V_{ind} = -V_{B,m}\sin(2\pi f_2 + \varphi_2) + d_2 \quad (15)$$

where $V_{B,m} = 1.09 \pm 0.01$ mV, $f_2 = 1.56 \times 10^5$Hz. $\varphi_2 = 0.8 \pm 0.1$, and

$d_2 = 0.5 \pm 0.1$ mV.

From Equation (12), the referred magnetic field inside the solenoid is

$$B(t) = 0.30 \cdot \frac{V_{R,0}\sin(\omega t)}{R} + 0.06 = 0.30\, I(t) + 0.06 = 0.30 I_0 \sin(\omega t) + 0.06$$
$$= 0.017\sin(\omega t) + 0.06\ [\mathrm{mT}] \qquad (16)$$

The theoretical induced voltage V_{ind} of the B-dot probe is

$$V_{ind} = -\frac{d\phi}{dt} \equiv -\beta \cdot \frac{d}{dt}\left(\int \vec{B}(t)\cdot d\vec{A}\right) = -\beta \cdot A \cdot \frac{dB(t)}{dt}$$
$$= -\beta \cdot (\pi \cdot r^2) \cdot \omega \cdot 0.3 I_0 \cos(\omega t)$$
$$= -\beta \cdot [\pi \cdot (5 \times 10^{-3})^2] \cdot (2\pi \cdot 1.56 \times 10^5) \cdot 0.017\cos(\omega t)$$
$$= -\beta \cdot (7.85 \times 10^{-5}) \cdot (9.8 \times 10^5) \cdot 0.017\cos(\omega t)$$
$$= -\beta \cdot 1.30\cos(\omega t)\ [\mathrm{mV}] \qquad (17)$$

In order to obtain the factor β, I plot the induced voltage V_{ind} versus $(\pi \cdot r^2) \cdot \omega \cdot 0.3 I_0$ with the different I_0 as shown in Figure 39. The slope of the fitted curve is 1.0 indicating that the factor $\beta = 1$. In other words, $B = -\frac{1}{A}\int V_{ind} dt$. The all results of different frequency are shown in Figure 40. We find that the data of other frequencies are also linear. The slope of the fitted curves is 0.8.

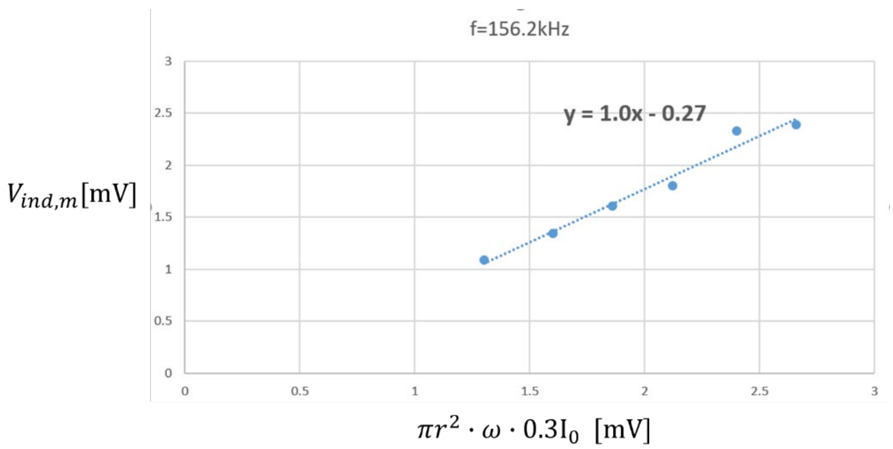


Figure 39 The results of experiments in frequency f=156.2kHz.

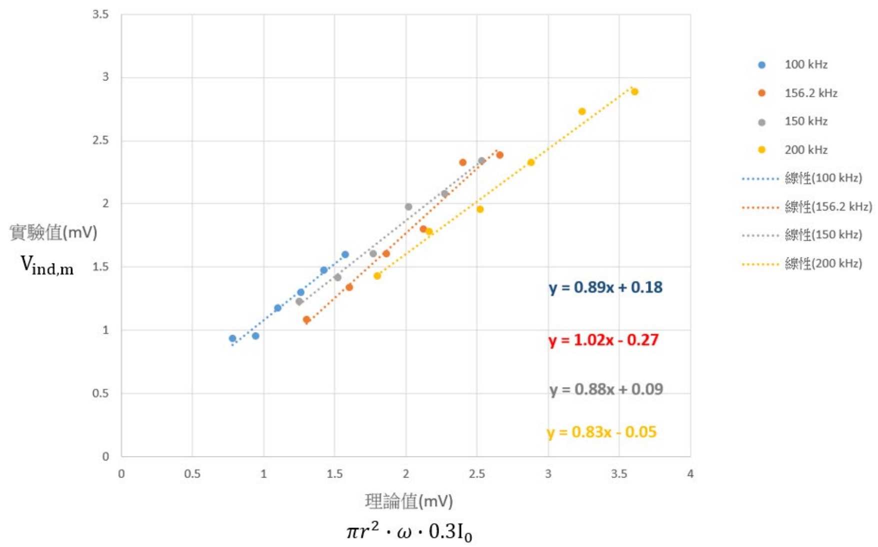


Figure 40 The results of experiments in different frequency.

3 The new optical trigger-pulse generator

A Q-switch laser was integrated in the pulsed-power system this year. It is used to take time-resolved images of plasma since it generates a burst of laser light. The gain media of the laser is pumped by a flashlamp. The flashlamp needs to flash with a frequency of 10 Hz to provide a stable laser output. Therefore, the function generator is used to generate a 10-Hz Transistor-transistor logic (TTL) signal with a pulse width of 35 μs as the timing fiducial signal. The flashlamp of the laser is synchronized with the timing fiducial signal for providing the stable laser output.

On the other hand, the Q-switch needs to be activated to generate the burst of the laser light. The time difference between triggering the Q-switch and triggering the flashlamp controls the energy output of the laser. After testing, we have the Q-switch triggering signal 390 μs after the flashlamp triggering signal to produce the proper energy output. In addition, the Q-switch signal needs to be synchronized with the pulsed-power system so that images are taken at the right time. It is essential that we need to synchronize the triggering signal to the pulsed-power system with the flashlamp using the timing fiducial signal.

We design a new optical trigger-pulse generator to trigger the pulsed-power system first. Then, we use the pickup coil to pick up the time that the pulsed-power system is activated. Finally, we use the picked up signal to trigger the Q-switch laser with a proper delay. The relation chart of triggering the system is shown in Figure 41.

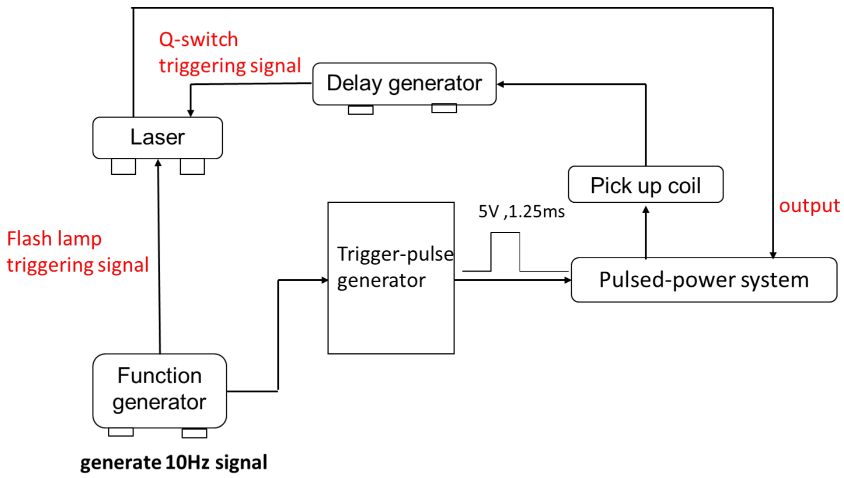


Figure 41 The relation chart of triggering the system

The time sequence of triggering the pulsed-power system is shown in Figure 42. At the beginning, a square optical trigger-pulse signal with a width of 1250 μs is generated by the optical trigger-pulse generator. A slow high-voltage pulse is generated 55 μs after the square optical trigger-pulse signal. Then the fast high-voltage pulse is generated couple nano-seconds after the slow high-voltage pulse generated. Finally, the pulsed-power system is triggered. It takes 1305.5 μs to trigger the pulsed-power system and the peak current is generated 1.6μs after the pulsed-power system is triggered.

The new optical trigger-pulse generator listens to the 10 Hz signal from the function generator. When the fire button of the new optical trigger-pulse generator is pressed, it will wait for the first timing fiducial signal after the fire button is pressed. Then, the square optical trigger-pulse signal is sent out 99084 μs after that timing fiducial signal. Thus, the Q-switch signal of the Q-switch laser is synchronized to the current output with a time difference of 1305.5+Δt-916≈390 μs between the Q-switch signal and the flashlamp.

In experiments, a delay generator is used to provide the required delay Δt to trigger the Q-switch laser so that we can take the image at a specific time.

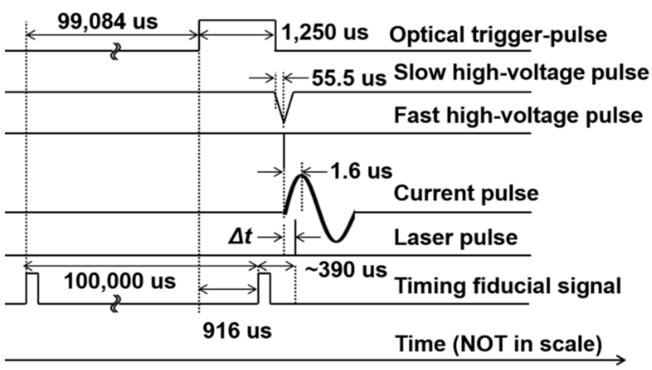


Figure 42 The time sequence of triggering the system [9].

3-1 The design of the new optical trigger-pulse generator

The original optical trigger-pulse generator, which is made by the former student, Yen-cheng Lin, is the initiator for our pulsed-power system. In order to synchronize the trigger pulse to the 10-Hz timing fiducial, I added some components.

The added components are:

1. One switch for Laser (SW-Laser).
2. One LED for Laser (LaserLED).
3. The pin12 of Arduino-nano board is used for listening the 10-Hz signal from the function generator.

As shown in Figure 43, I made the new optical trigger-pulse generator. Shown in Figure 44 is the circuit of the new optical trigger-pulse generator. An Arduino-nano board is used as the main component of the new trigger-pulse generator. The Arduino-nano board is suitable to generate the 1.25-ms pulse. The board is preprogrammed to be controlled by switch buttons, to control LED indicators providing the information of different modes of the generator and provide the pulse importantly. Three switches, two toggle switches as the "SW-Standby" and "SW-Laser", and one push button switch as "SW-Fire".

Figure 43 The photo of the new optical trigger-pulse generator.

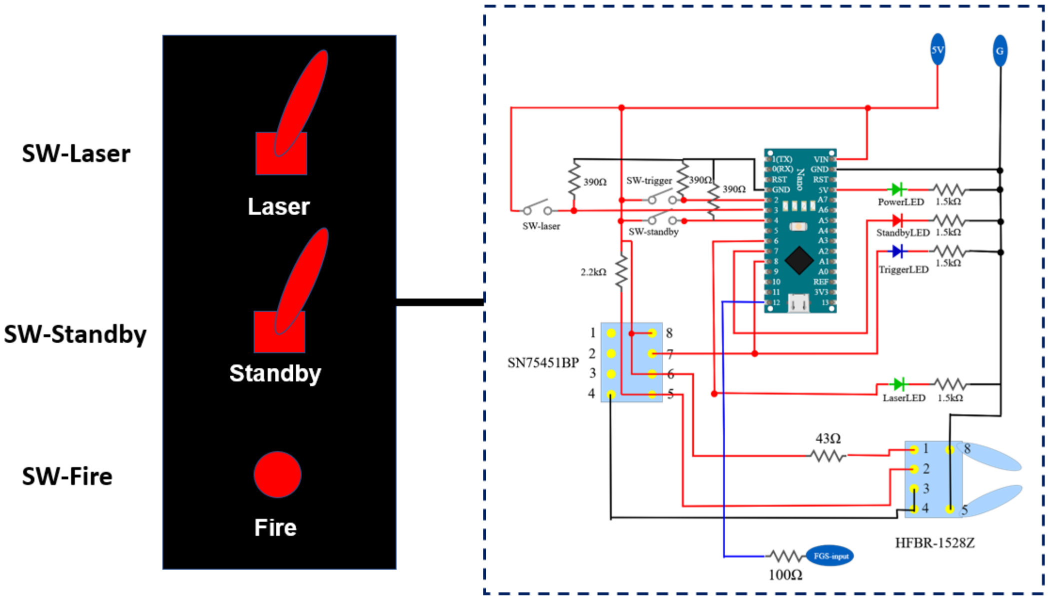


Figure 44 The circuit of the new optical trigger-pulse generator.

3-2 The operation of the new optical trigger-pulse generator

The new optical trigger-pulse generator has two mode: “ normal ” mode and “Laser” mode. The “normal” mode is the use of the new optical trigger-pulse generator without using the laser. The system is in this state when the SW-Laser is at "OFF" state. Contrarily, the “Laser” mode is chosen when we need to take time-resolved images of plasma with the laser. When the toggle switch (SW-Laser) is switched at "ON" state, the system is in the “Laser” mode. In Figure 45, when we pressed the fire button of the new optical trigger-pulse generator, it would send out one 1250 μs optical trigger-pulse 99084 μs after the first timing fiducial signal of the 10 Hz of the function generator.

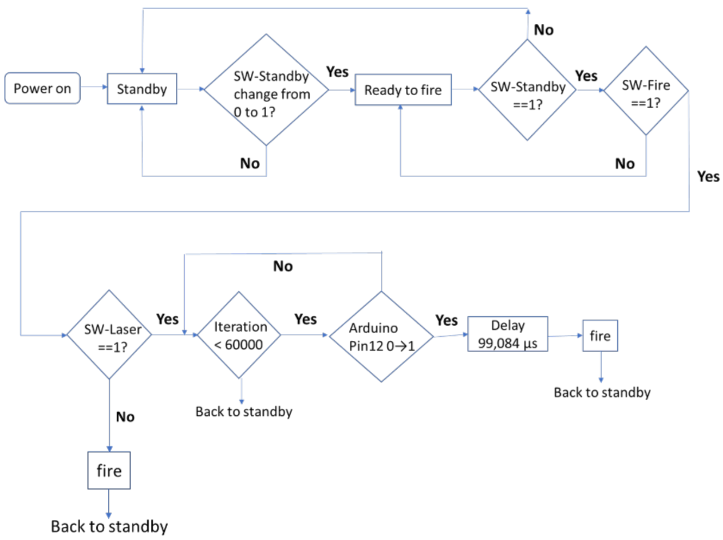


Figure 45 The flow chart of the new optical trigger-pulse generator.

The procedure of operating of the new optical trigger-pulse generator:

1. The new optical trigger-pulse generator is power on.
2. The "powerLED" on the generator is light up (green light).
3. The toggle switch (SW-Laser) is switched to ON state.
4. The system is transited to the "Laser" mode from "normal" mode.
5. The "LaserLED" on the generator lights up (green light).
6. The toggle switch (SW-Standby) is switched from the OFF state to ON state.
7. The system is transited to the "Ready to Fire" mode from "Standby" mode.
8. The "StandbyLED" on the generator is lights up.
9. The fire button is pressed.
10. Fire. (send a 1.25-ms square pulse signal)

5 The warning sign of lasers

Over the past year, we had integrated the laser in our pulsed-power system to take images of plasma. Laser has good collimation and high energy density. If we use the laser improperly, it will cause serious damage to our eyes when our eyes are exposed to direct or scattered light beams. For example, retinal burns may cause visual impairment or blindness. The degree of damage varies depending on the wavelength and energy of the laser. We have two lasers in the Lab. One is the continuous-wave (CW) He-Ne laser. The wavelength is 633 nm. The other one is an Nd:YAG Q-switch laser. The power is 2W. Therefore, we made warning signs for two lasers in two different safety classes to remind everyone whether the laser is turned on in the laboratory or not.

The warning sign for lasers usually indicates different safety class according to the danger of the laser light given in Table 4. The higher class means more dangerous. The CW He-Ne laser we have is a 2^{nd}-class laser. The Q-switch laser we have is a 4^{th}-class laser. Two different signs are needed. The two warning sign are shown in Figure 46

Table 4 The classification of danger in different lasers [10].

等級 1	在合理範圍內且可預測的條件下是安全的。
等級 1M	除了使用光學器具的情況下可能會發生危險之外，與等級1相同。為302.5nm ~ 4000nm波長範圍的雷射。
等級 2	低能量。平常因人類對光線產生的眨眼等厭惡反應，可以保護眼睛且較安全。為400nm ~ 700nm波長範圍的低能量可視光雷射。
等級 2M	除了使用光學器具的情況下可能會發生危險之外，與等級2相同。為400nm ~ 700nm波長範圍的可視光雷射。
等級 3R	雙眼直接觀察雷射光的話可能會發生危險。雷射輻射上限值(AEL)為等級1和等級2的五倍以下。
等級 3B	雙眼直接觀察的話通常會發生危險。
等級 4	高能量(大約超過0.5W)。擴散反射也會發生危險。 可能會引起擴散反射，造成皮膚受傷及發生火災的危險。

(a)

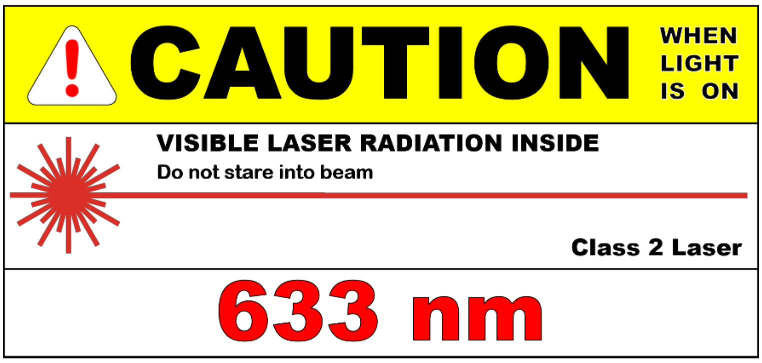


Figure 46 (a) The warning sign for 2^{nd}-class laser

(b)

Figure 46 (b) The warning sign for 4th-class laser

The two warning signs of lasers were completed by me and my classmate, Ming-Hsiang Kuo, as shown in Figure 47. He was responsible for the circuit construction and the production of the switch of warning lights while I was responsible for making the body of the warning signs. The two warning signs are made of acrylic plate with a thickness of 15 mm. I stuck the label of laser warning light on the acrylic plate with double-sided tape.

(a)

(b)

Figure 47 (a) the two warning signs of lasers were on the wall at the Laboratory area of our laboratory. (b) the two warning signs of lasers were suspended from the ceiling at the office area of our laboratory.

I divided our laboratory into the Laboratory area and office area. The Lab area is where we ordinarily do the experiments and solder electronic circuits. On the other hand, the office area is where we analyze the data and do paper works. The floor plan and the three-dimensional figure are respectively shown in Figure 48 and Figure 49. The two yellow squares represent the locations of the two warning signs of lasers.

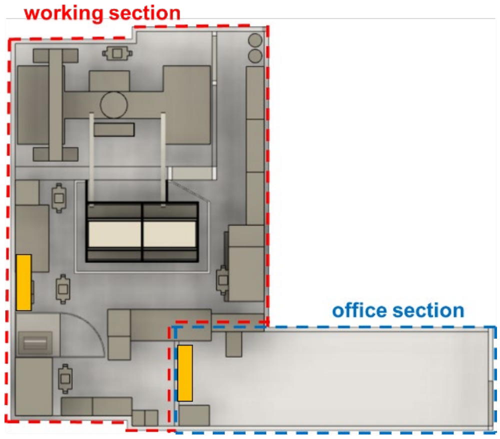


Figure 48 The floor plan of PPL laboratory

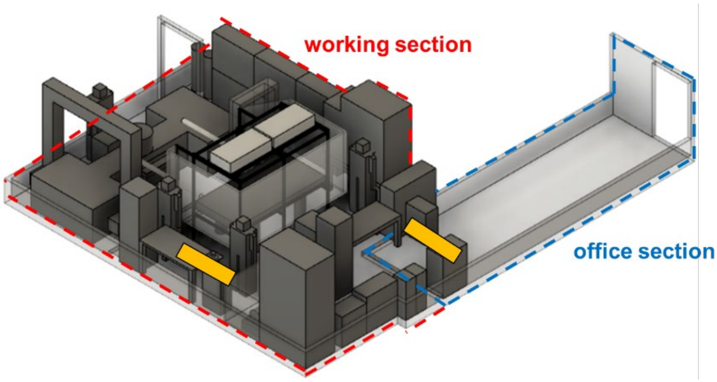


Figure 49 The three-dimensional figure of PPL laboratory

When we use the lasers, we must turn on the warning signs. The laser warning signs in the Lab area and the office area will both light up to remind everyone that lasers are being used as shown in Figure 50 (a) and (b).

(a)

(b)

Figure 50 (a) the two warning signs of lasers were turned at the Lab area of our laboratory. (b) the two warning signs of lasers were turned at the office area of our laboratory.

5 Future works

We are going to finish the calibration of the B-dot probe with the solenoid driven by a high current and get the magnitude of the calibration factor C_{calib}. Then we can obtain the magnetic field at the location we want to know by integrating the induced voltage of B-dot probe with time. Finally, we will measure the magnetic field generated by the Helmholtz coil with the B-dot probe.

6 Summary

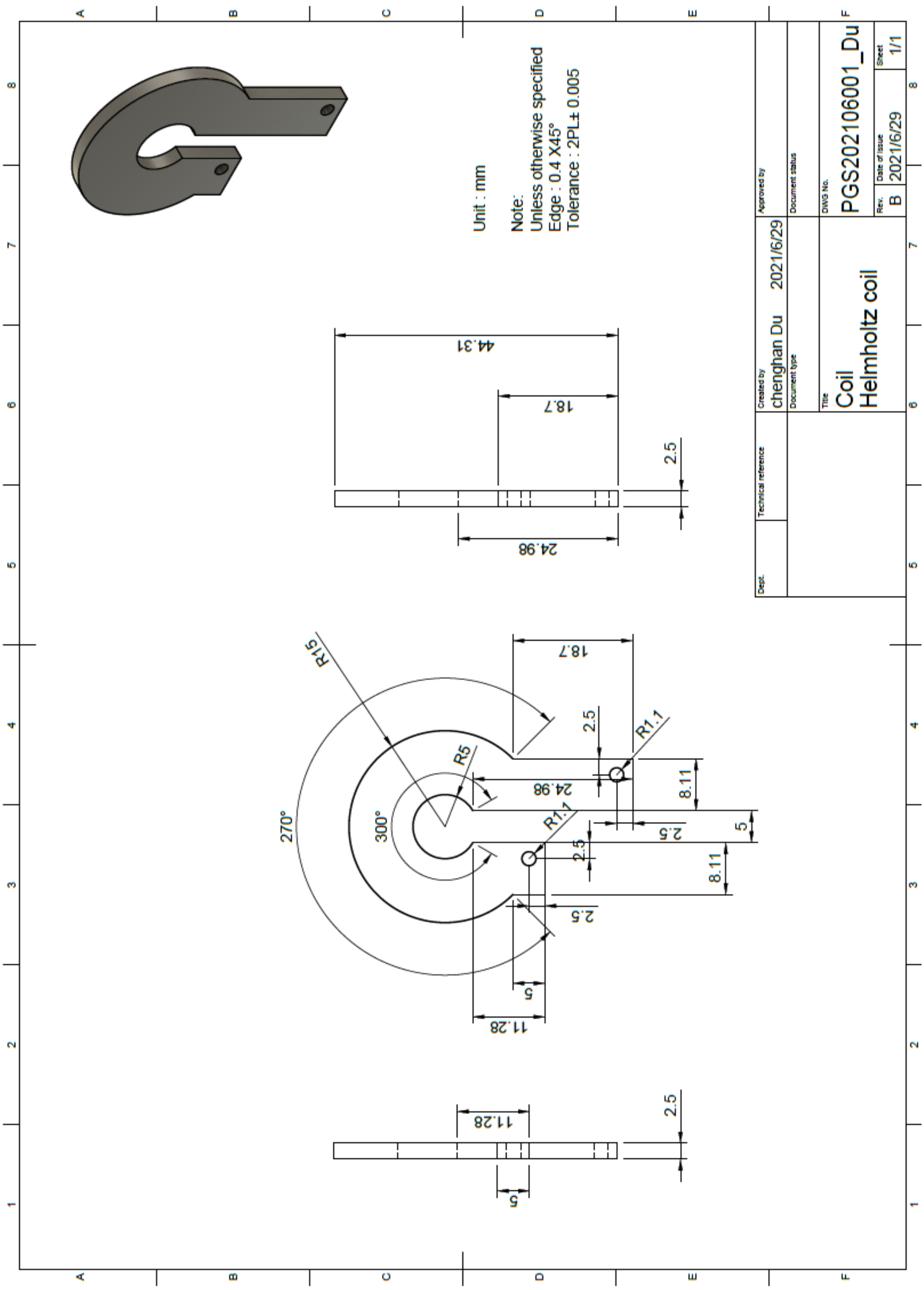
In the report, we have finished making the Helmholtz coil. In experiments, the Helmholtz coil survived after each discharge. The result indicated that the structure of the coil is strong enough to hold the tension during the discharge. The magnetic field generated from the Helmholtz coil is important for the theta pinch. We calculated the ideal magnetic field generated at the center of two coils. I got 4.6 ~ 11.6 T using the theoretical formula. Additionally, in order to be realistic, I simulated the Helmholtz coil whose size was the same as the Helmholtz coil I designed with COMSOL Multiphysics. The peak magnetic field was only 3.3 Tesla. It will be the lower bound of the generated magnetic field.

In order to measure the magnetic field generated from the Helmholtz coil, we decided to use the B-dot probe. Firstly, I made a solenoid to generate a known magnetic field source. The solenoid can generate the magnetic field B=0.30·I+0.06 (mT). Next, I did the experiments of calibrating of the B-dot probe in a low alternating current. Because the current $I(t)$ passed through the solenoid is not related to the differential of the induced voltage of the B-dot probe completely, I only consider the amplitude of the current and induced voltage of the B-dot probe. I ploted the induced voltage V_{ind} versus $(\pi \cdot r^2) \cdot \omega \cdot 0.3 I_0$ with the different I_0. The slope was equal to 1. It indicated the theoretical induced voltage matched the measured induced voltage in experiments.

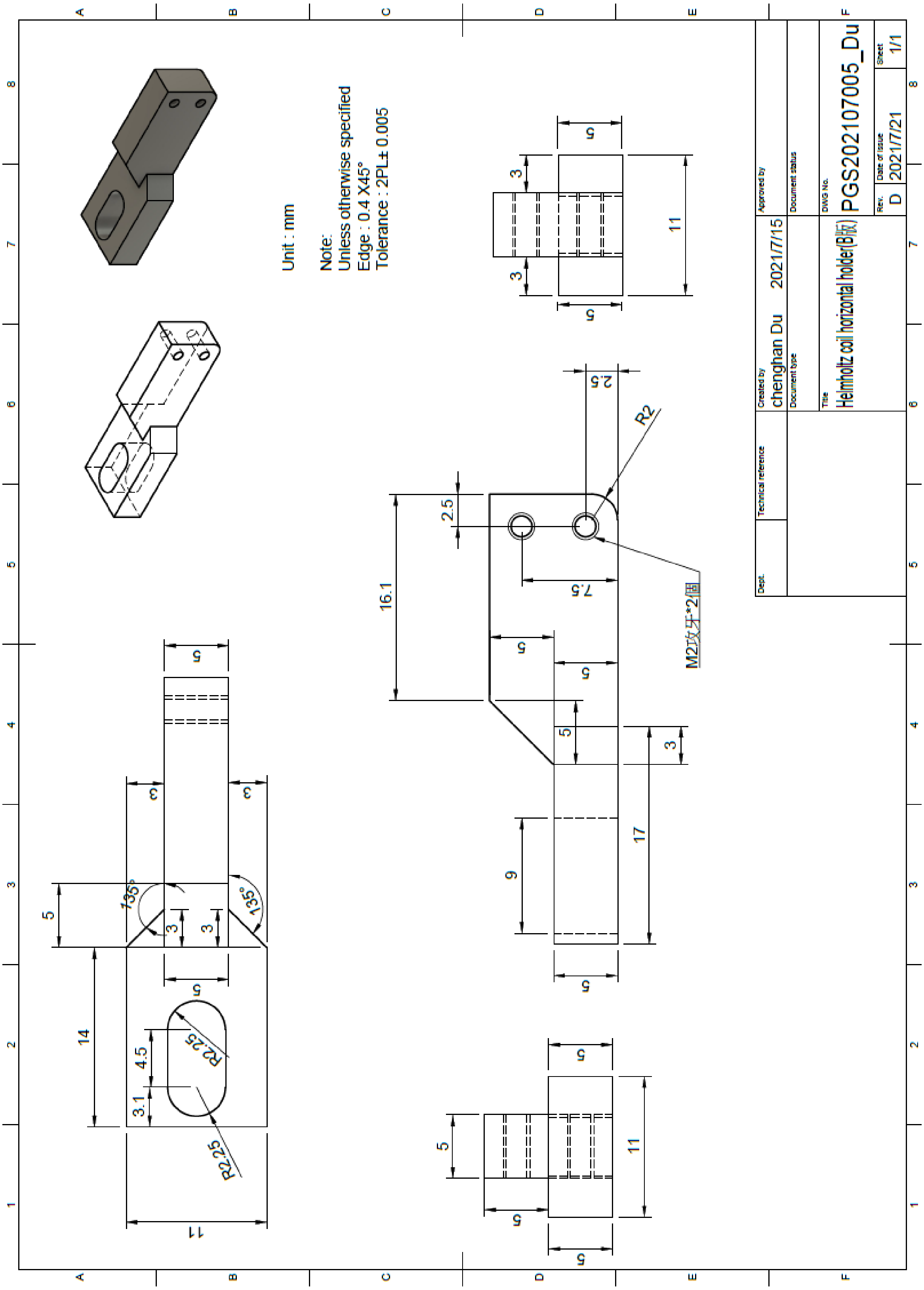
Further, a Q-switch laser was integrated to the pulsed-power system this year. It is used to take time-resolved images of plasma since it generates a burst of laser light. The time difference between triggering the Q-switch and triggering the flashlamp controls the energy output of the laser. After testing, we have the Q-switch triggering signal 390 μs after the flashlamp triggering signal to produce the proper energy output. The flashlamp of the laser was synchronized with the new optical trigger-pulse generator for providing the stable laser output. Finally, we made warning signs for two lasers in two different safety classes to remind everyone whether the laser is turned on in the laboratory or not.

7 Appendix

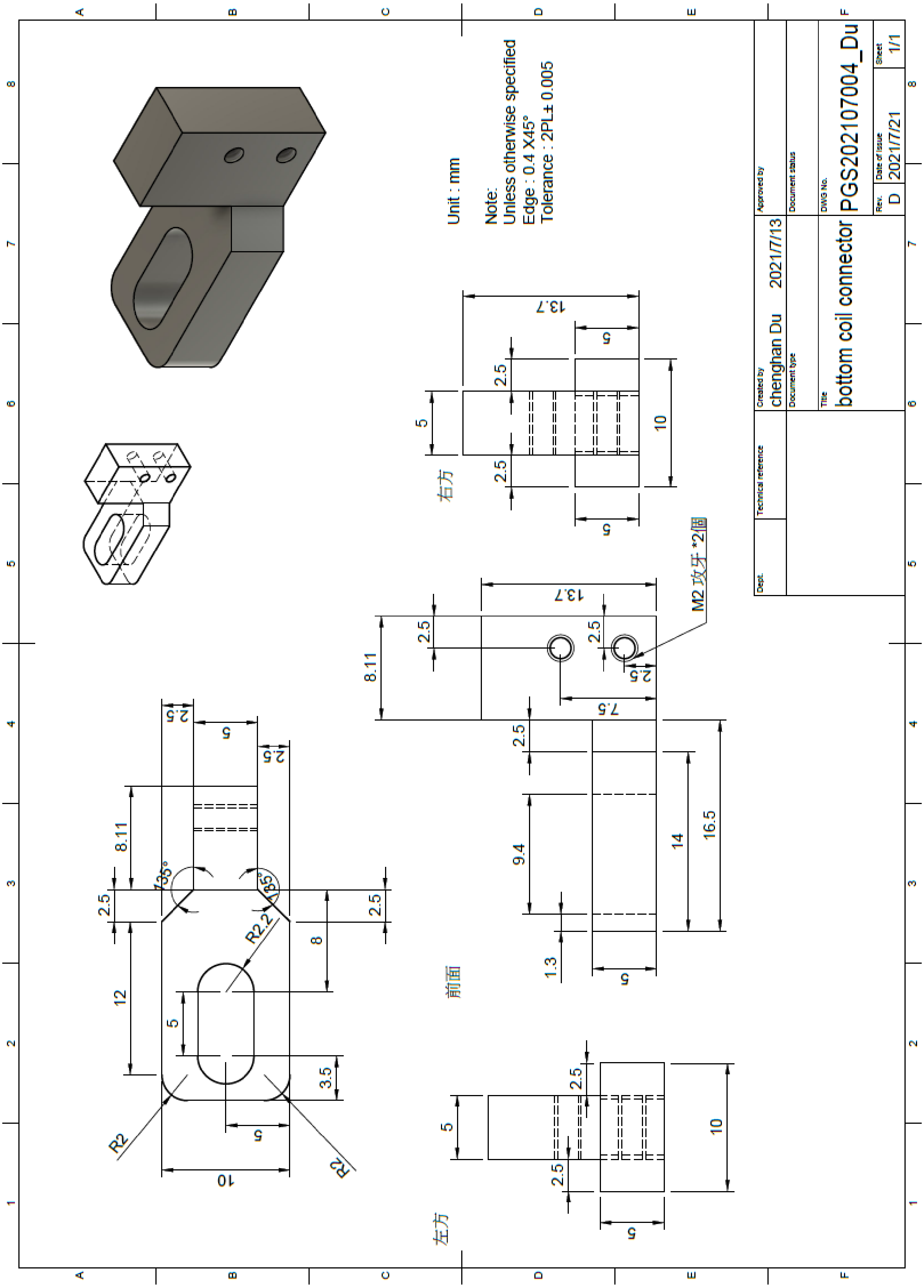
Helmholtz coil_ coil[1]



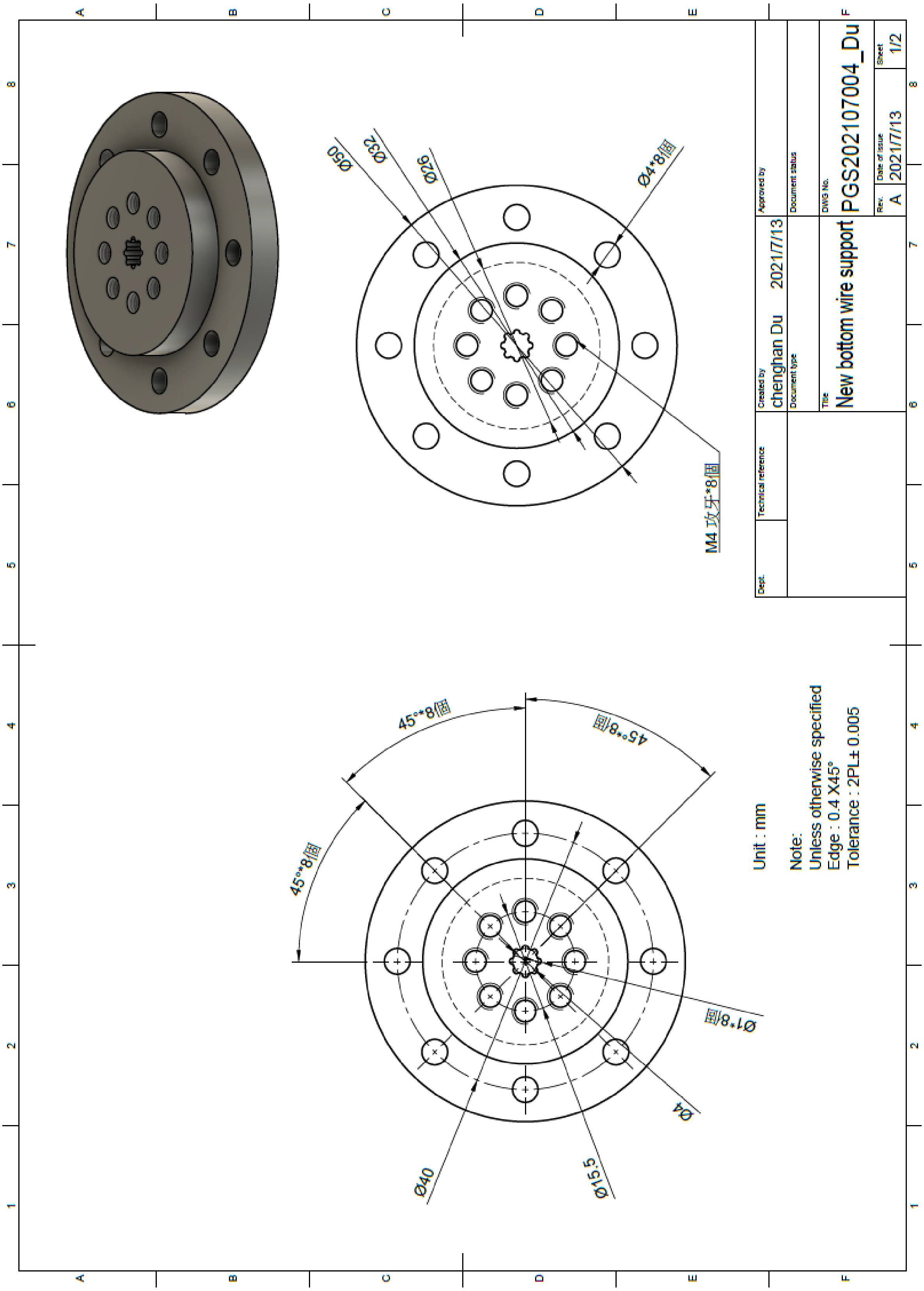
Helmholtz coil_ Helmholtz coil horizontal holder[2]



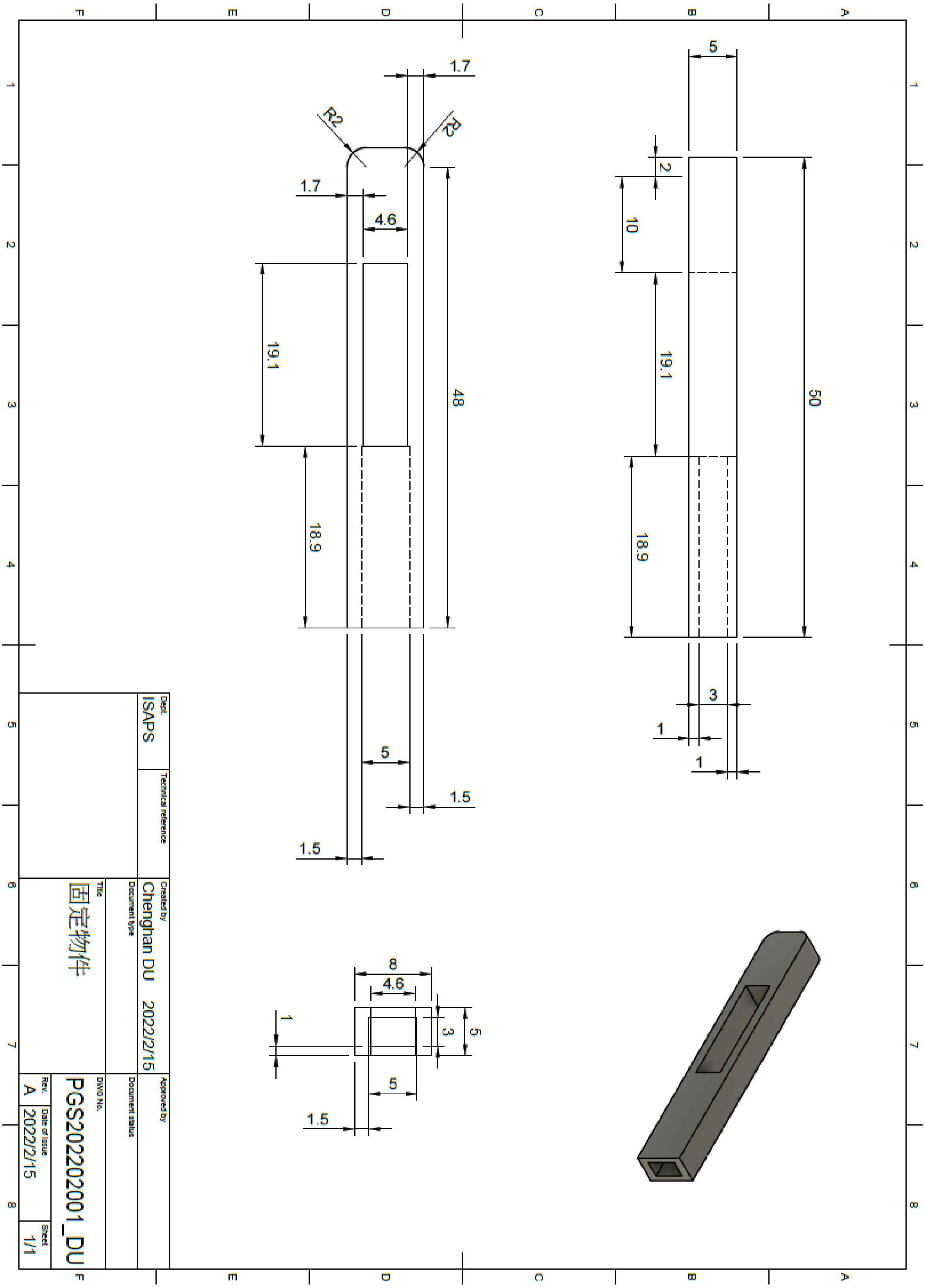
Helmholtz coil_ bottom coil connector[3]



New bottom wire support[4]



The support of Gauss meter probe[5]



The code of triggering the pulsed-power system while synchronizing with the laser[6]

```
* Pin definition:
 *                output: 8 - TLED - trigger indicator
 *                        7 - SLED - standby indicator
 *                        6 - LaserLED - Laser synchronization indicator
 *                input: 12 - FGS - (10 Hz) Function generator input
 *                        2 - triggerpin - trigger switch (push button)
 *                        4 - standbypin - standy switch (toggle switch)
 *                        3 - laserpin - laser synchronization switch (toggle
switch)

int TLED = 8;
int SLED = 7;
int LaserLED = 6; // by Po-Yu, pin for the syncrhonization status LED
int FGS =12; // by Po-Yu, Cheng-Han's code
int triggerpin = 2;
int standbypin = 4;
int laserpin = 3; // by Po-Yu, pin to read the synchronization status of with the laser.
int t0 = 0;
int s0 = 0;
int t1 = 0;
int s1 = 1;
int t2;
int s2;
int st;
int tt;
bool b1;   // by Po-Yu, buffer1 of storing the signal of the function generator.
bool b2;   // by Po-Yu, buffer2 of storing the signal of the function generator.
int laserstatus;   // by Po-Yu, status of the synchronization with laser. 0-without laser;
1-with laser.
int triggerflag; // by Po-Yu, status of triggering
int ittriger; // by Po-Yu, a counter to prevent that the status stuck at the firing mode

void setup()
{
  pinMode(TLED, OUTPUT);
```

```
  pinMode(SLED, OUTPUT);
  pinMode(LaserLED, OUTPUT);    // by Po-Yu, laser synchronization indicator
  pinMode(triggerpin, INPUT);
  pinMode(standbypin, INPUT);
  pinMode(FGS, INPUT); // by Po-Yu, read the signal from the function generator
  pinMode(laserpin, INPUT);
  Serial.begin(9600);
}

void loop()
{
 t2 = digitalRead(triggerpin);
 s2 = digitalRead(standbypin);
 laserstatus = digitalRead(laserpin);    // by Po-Yu, read the laser synchronization status.
 digitalWrite(LaserLED,laserstatus);    // by Po-Yu, indicate the laser synchronization
status.
 st = s2-s1;
 tt = t2-t1;
 if (s0==0)
 {
  if(st==1)
  {
    s0 = 1;
    s1 = s2;
    digitalWrite(SLED,s0);
  }
  else
  {
    s1 = s2;
  }
 }
 else
 {
  if (st==-1)
  {
    s0=0;
    digitalWrite(SLED,s0);
    s1 = s2;
```

```
}
else if (tt==1)
{
  t0=1;
  if (laserstatus==0) //by Po-Yu, output the trigger pulse WITHOUT synchronization.
  {
    digitalWrite(TLED,t0);
    delayMicroseconds(1250);
    digitalWrite(TLED,0);
  }
  else //by Po-Yu, output the trigger pulse WITH synchronization.
  {
    triggerflag = 1;
    ittriger = -30000;
    while (triggerflag ==1 && ittriger < 30000 )   //the loop will stop after 10000 iteration to prevent being stuck in the loop
    {
      boolean b1 =digitalRead(FGS);
      if(b1 == LOW)
      {
        boolean b2 =digitalRead(FGS);
        if(b2 == HIGH)
        {
          //delay 98.972 ms in total, 98.972 = 98 m + 972 us
          delay(98);
          delayMicroseconds(972);
          digitalWrite(TLED,HIGH);
          delayMicroseconds(1250);
          digitalWrite(TLED,LOW);
          triggerflag = 0;
        }
        ittriger = ittriger + 1;
      }
    }
  }
  t1 = t2;
  s0 = 0;
```

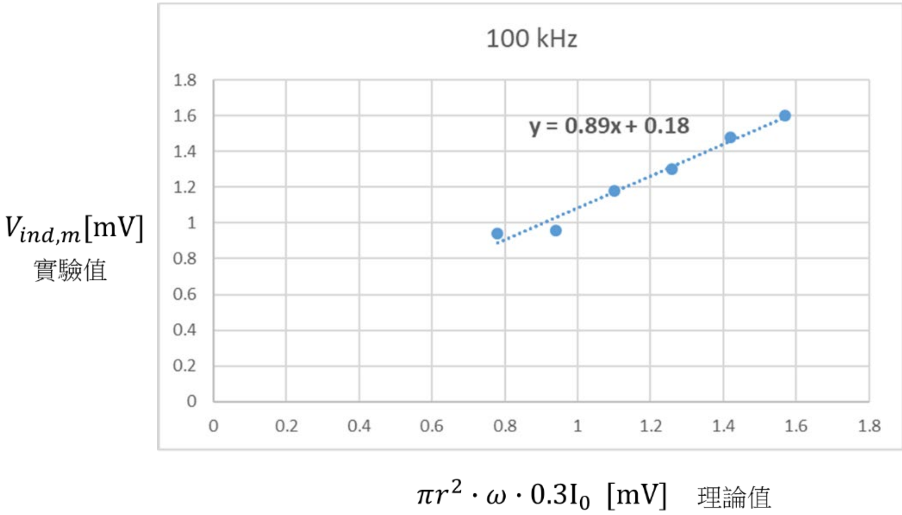
```
      digitalWrite(SLED,s0);
    }
    else
    {
      t1 = t2;
    }
  }
}
```

Calibration of the B-dot probe in a low alternating current (AC)[7]

-Data are stored in the folder "2022.3.14_B-dot probe".

(1) Results (function generator f=100 kHz)

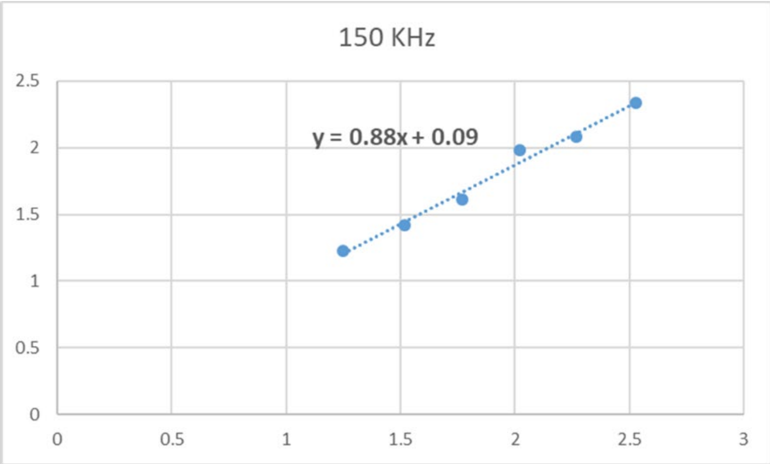
實際值100kHz(mV)	理論值(mV)
0.94	0.78
0.96	0.94
1.18	1.1
1.3	1.26
1.48	1.42
1.6	1.57



(2) Results (function generator f=150 kHz)

實際值150kHz(mV)	理論值(mV)
1.23	1.25
1.42	1.52
1.61	1.77
1.98	2.02
2.08	2.27
2.34	2.53

$V_{ind,m}$[mV]
實驗值

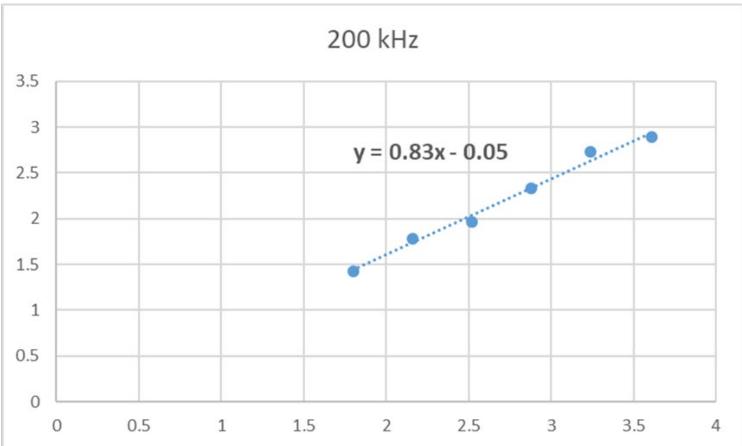


$\pi r^2 \cdot \omega \cdot 0.3\mathrm{I}_0$ [mV] 理論值

(2) Results (function generator f=200 kHz)

實際值200kHz(mV)	理論值(mV)
1.43	1.8
1.78	2.16
1.96	2.52
2.33	2.88
2.73	3.24
2.89	3.61

$V_{ind,m}$[mV]
實驗值



$\pi r^2 \cdot \omega \cdot 0.3\mathrm{I}_0$ [mV] 理論值

8 Reference

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