Fusion Engineering and Design 121 (2017) 265–271

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Full length article

Design of a 150T pulsed magnetic field generator device

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ARTICLE INFO

Keywords:
Magnetized laser plasma
Pulsed strong magnetic field device
Electromagnetic analysis
Circuit verification

ABSTRACT

A 150T pulsed magnetic field generator device which can generate a 150T pulsed magnetic field by a single-turn coil with a 3 mm diameter was designed to study the coupling of laser-produced plasma and strong magnetic fields is described. An 880 kA current pulse is discharged into the coil by a pulsed-power system composed of 20 capacitors of 5 μF, electric-trigger switches, and low-impedance strip transmission lines. The structure of the generator was optimized based on the results of electromagnetic analysis. A set of small pulsed discharge system with a 50 kV/5 μF capacitor bank was built to research synchronous trigger and the current curve. The circuit verification experiment was proceeded and the result was revealed to be consistent with theoretical analysis.

1. Introduction

Magnetic field has become a significant tool of modern scientific research since Ampere made the first electromagnet in 1820. The intensity of magnetic field has become an important parameter in the study of physics. Magnetic field is usually divided into two types, steady magnetic field and pulsed magnetic field, according to the pulse duration. The strength of steady magnetic field is relatively weak and can no longer meet the requirements of many science researches. While the strength of pulsed magnetic field can be easily increased and with a half-cycle of milliseconds, it can satisfy the needs of most physical process. However, the magnet is likely to be destroyed if the magnetic field strength exceeds 100T because of the magnetic stress.

Coupling plasma with strong magnetic fields is an important research trend in inertial confinement fusion (ICF), magnetized target fusion (MTF), plasma confinement by magnetic field and Laboratory Astrophysical Physics. For inertial confinement fusion, a strong magnetic field can significantly inhibit the thermal transport of electrons and ions [1–3], thus increasing the temperature of electrons and ions. For magnetized target fusion, embedding a magnetic field in the preheating plasma can suppress heating conduction, while increasing the fusion products of alpha particle energy deposition [4–7].An external strong magnetic field can help to get the plasmas in conditions related to celestial bodies, thus making it possible to simulate some processes in Astrophysics in laboratory [8–10].

A 7 T pulsed magnetic field generator was developed to study the effect of a magnetic field on the evolution of a laser-generated plasma, using a capacitor bank, a laser-triggered switch and a Helmholtz coil pair with a 6 mm diameter in University of Science and Technology of China [11]. A target field exceeded 15Tfor laser-driven flux compression in high-energy-density plasmas has been demonstrated with a capacitor bank, a laser-triggered switch and a single-turn Helmholtz-type coil in Laboratory for Laser Energetics, University of Rochester [12]. An up to 40 T magnetic field was achieved for laboratory astrophysics and inertial confinement fusion studies by a solenoid connected to a pulsed power unit composed of five capacitors at LULI (France) [13]. But until recently, very few laser plasma experiments had been performed under a strong magnetic field.

2. Design requirements

Here we present a design of a 150T pulsed magnetic field generator device. It is designed to explore magnetized inertial confinement fusion on Shenguang-II (SG-II) laser facility [14] at Shanghai Institute of Optics and Fine Mechanics (SIOM) and Shenguang- III (SG- III) prototype laser facility [15] at the China Academy of Engineering Physics (CAEP). Portable pulsed power systems with small volume ($\varnothing 3 \times 3\ mm^3$) and flexible magnetic field configurations are required to adapt different laser facilities and different experiment conditions as shown in Fig. 1. A sub-μs risetime of the magnetic field pulse are needed to meet the requirements of physical experiment process. The destructive coil will be destroyed because of the strong magnetic stress, so a replaceable coil

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http://dx.doi.org/10.1016/j.fusengdes.2017.08.005
Received 6 March 2017; Received in revised form 12 July 2017; Accepted 3 August 2017
Available online 14 August 2017

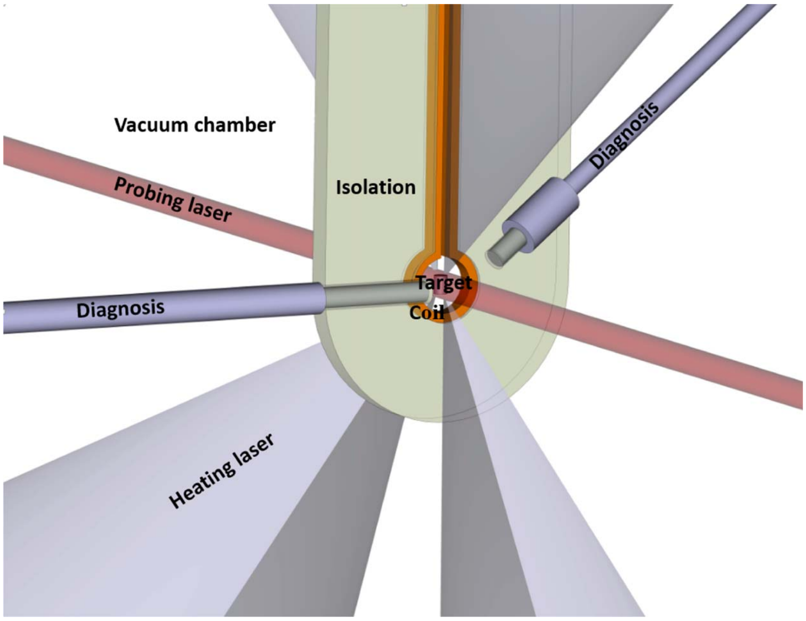

Fig. 1. Schematic of coupling plasma with magnetic field. The target with an isolation layer was heated by heating laser and diagnosed by probing laser and diagnosis.

and a shield for protecting the detecting equipment from the pieces of the coil are needed.

3. Electromagnetic analysis of the circuit

The driver that supplied the current for the magnetic field generator could be considered as a simple LRC circuit, as shown in Fig. 2.

The single-turn coil was bent by a thin copper plate with a polyimide film isolating layer. The parameters of the single-turn coil are shown in Table 1. An electromagnetic analysis about the magnetic line and field strength of the space around the coil was performed. The results showed that a strong pulsed magnetic field more than 150T can be created by the single-turn coil with an 880kA current at the center of the coil. The magnetic line and field strength of the coil with an 880kA current is shown in Fig. 3.

Six capacitors and switches were selected as the power of the circuit according to the theoretical calculation and the parameters of switch. Coaxial cables were selected to connect the power and the single coil. The parameters of the circuit are shown in Table 2. The equations of the circuit can be written as

Table 1
The parameters of single-turn coil.

parameter	value
Inner diameter	3.1 mm
Outer diameter	4.1 mm
Thickness	0.5 mm
Width	5 mm

$$LC\frac{d^2U}{dt^2} + RC\frac{dU}{dt} + U = 0 \tag{1}$$

$$I = -C\frac{dU}{dt} \tag{2}$$

Where U is the discharge voltage and I is the discharge current.

The first period of simulated discharge current in the coil is shown in Fig. 4 with a 25 kV charging voltage of the capacitor. A 950kA current could be generated at 1.2 μs and a strong pulsed magnetic field of more than 150T could be created in the single-turn coil. However, the magnetic field strength has a large gradient with respect to the

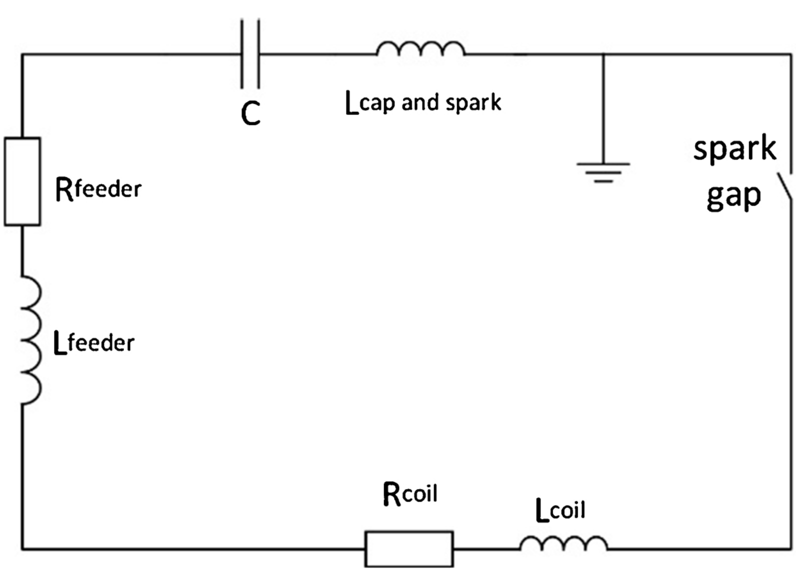

Fig. 2. Simplified schematic of the discharge circuit. The inductance arises mainly from the capacitor, the gas switch, the transmission line and the coil.

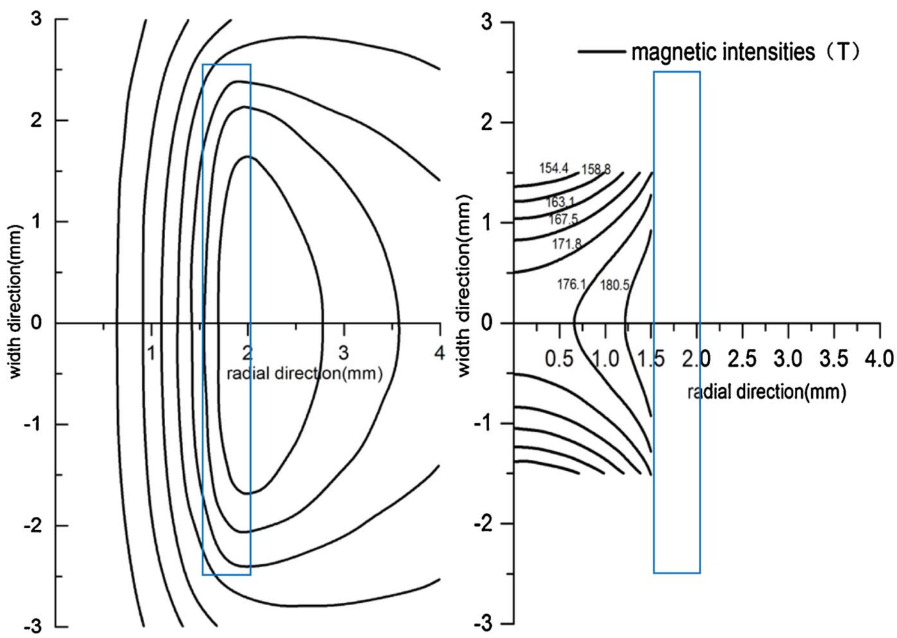

Fig. 3. The magnetic line (a) and field strength (b) around the coil when the current reached 880kA.The magnetic field at the center of the coil was more than 171.8T.

Table 2
The parameters of the circuit.

parameter	value
Coil resistance	$9.05 \times 10^{-5}\Omega$
Feeder resistance	$11.17 \times 10^{-5}\Omega$
Coil inductance	1.05×10^{-9}H
Cap and spark inductance	5×10^{-9}H
Feeder inductance	14.33×10^{-9}H
Capacity	30 μF

distance from the center of the coil. The distribution of field strength at the distance of 20mm–100 mm away from the coil center is shown in Fig. 5. The maximum field strength was only 0.00115T at the range of 100 mm from the center of the coil, so it can be considered that the magnetic field has no effect on the diagnostic device more than 100 mm outside the coil.

4. Structure design

4.1. Capacitors and switches design

Fast discharge capacitors and switches are key components of the pulsed magnetic field generator device. Their performance had direct impact on the performance of the system. The self-healing capacitor (5 μF) has a high energy storage density (≥ 0.5J/cm^3) which is beneficial for the symmetrical arrangement. The working voltage of discharging switch is 50 kV and the peak current is 160kA. The electrodes are uniformly distributed along the circumference, which can balance the magnetic force and ensure even distribution of the spark channels as shown in Fig. 6. Dry compressed air was used to be insulating medium of the gas switch. The insulation of the switch could recover quickly by cleaning the switch with compressed air. The trigger voltage could be changed by changing the gas pressure of the switch.

4.2. Synchronous trigger design

Although the results of theoretical analysis showed that a strong

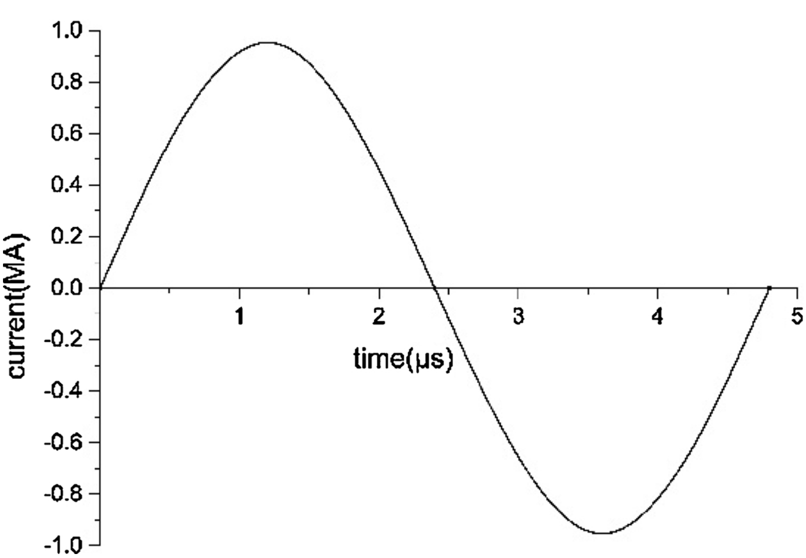

Fig. 4. The first period of simulated discharge current in the coil. A 950 kA current could be generated at 1.2 μs.

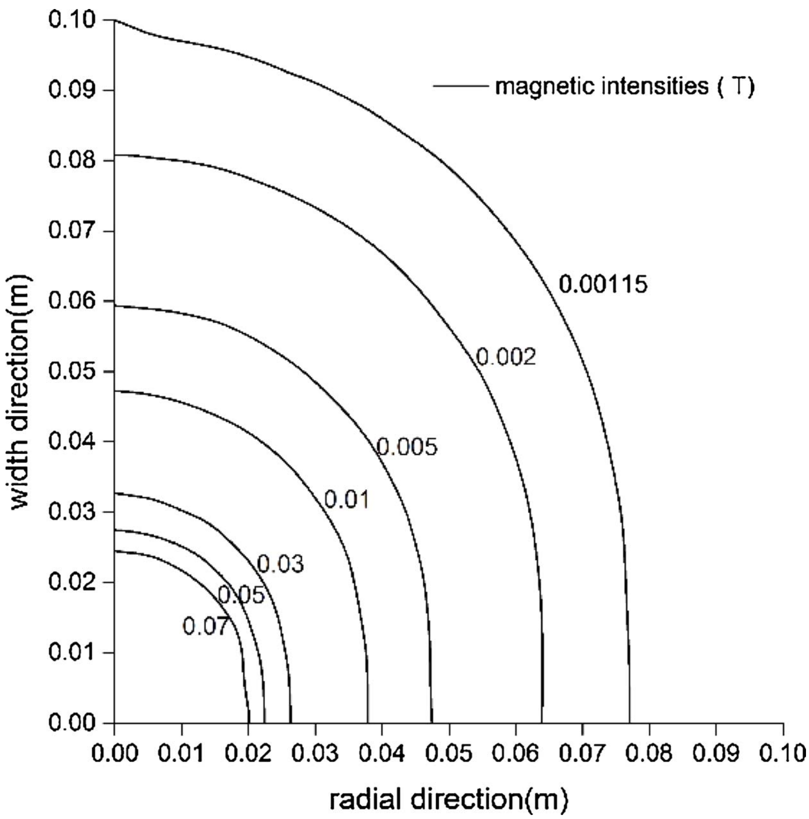

Fig. 5. Distribution of field strength outside of the coil. The magnetic field strength has a large gradient with respect to the distance from the center of the coil.

magnetic field more than 150T can be produced with about six capacitors in parallel, twenty switches and capacitors are connected in parallel as the power supply. We found that the capacitor banks were very easy to break in the experiments. Our power cabinet was out of the Vacuum chamber, twenty capacitor banks could make sure that the broken capacitor banks could be replaced quickly for a long time. Taking the practical situation of engineering application into account, the remaining capacitors are used as redundant backups.

The switches and the single turn coil was connected by low impedance coaxial cables. One end of the coaxial cables were connected to the switch directly. All the outer and inner conductors of the other end was peeled and bundled respectively. The bundle of the outer and inner conductors were welded to the two mountains of the coil respectively as shown in Fig. 7. The feeder and the mountains of the coil was cured with epoxy resin. The coil and two small conductors were cured with epoxy resin together so that it can be replaced easily as shown in Fig. 8. The power supply was placed outside of the chamber due to the space constraints, but the total inductance can be reduced by the connection of the coaxial cables. The synchronous trigger of several circuit was controlled by a hydrogen thyratron.

4.3. Integrated design of pulsed magnetic field generator

A three-dimensional model of pulsed magnetic field generator device was established according to the result of calculation and analysis as shown in Fig. 9. Low impedance coaxial cables were used to connect the switches and the single-turn coil. A driving system which was used to preliminarily position the coil system included an AC servomotor, a ball screw and rectilinear orbit. A six-DOF position adjustable platform was used to regulate the position of the single coil precisely. The flange of the vacuum chamber was connected to the flange of the six-DOF position adjustable platform by a set of bellow component. The replaceable bellow component ensured that the generator could fit Shenguang-II (SG-II) and Shenguang-III (SG-III) prototype laser facility. The transmission lines in the target chamber and the mountain of the coil were cured together by epoxy resin. The coil can be replaced easily because the special design of the mountains of the coil. Because the magnetic field had no effect on the diagnostic device more than 100 mm outside the coil according to the theoretical analysis, the electromagnetic shielding was not necessary.

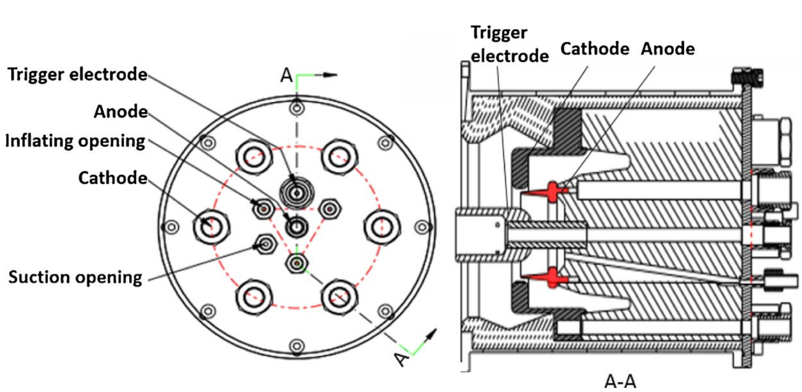

Fig. 6. The structure of the gas switch. The trigger electrode, anode and cathode of the switch are connected with the electrode of capacitor respectively.

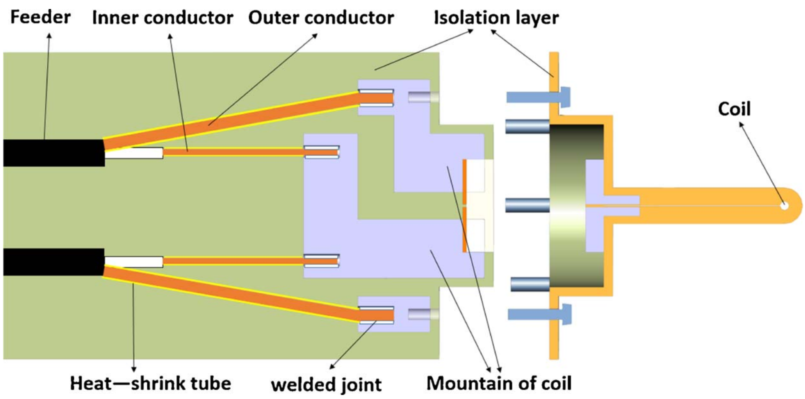

Fig. 7. The connection of the feeder and the mountain of coil. The bundles of the outer and inner conductors were welded to the two mountains of the coil respectively.

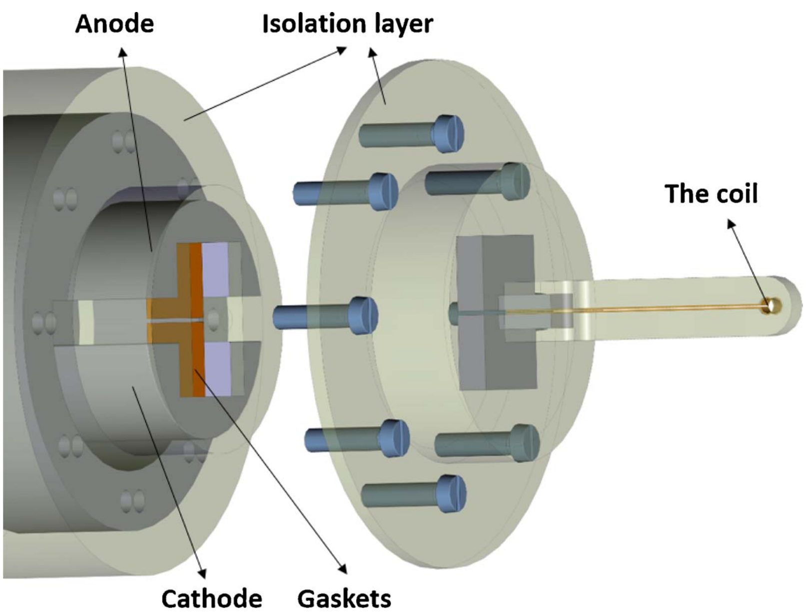

Fig. 8. The connection of the coil and the coaxial cables. The coil was cured with epoxy resin and could be replaced easily.

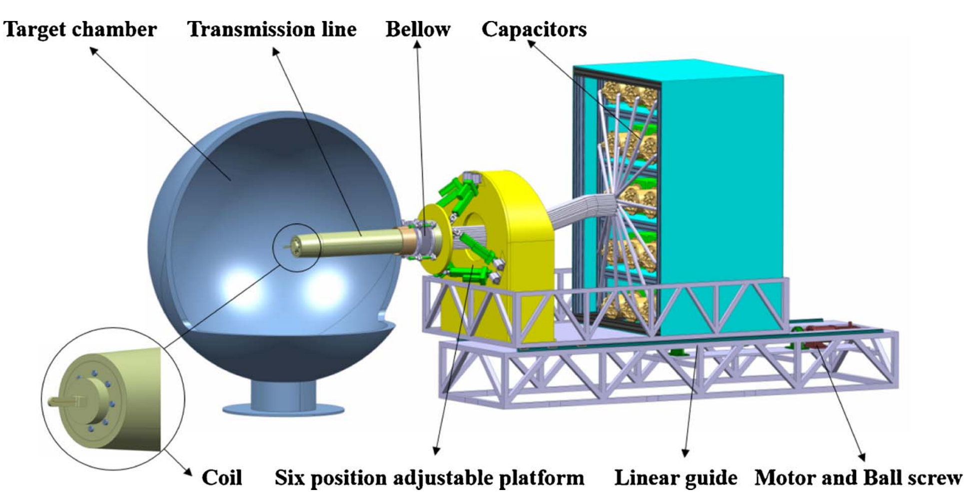

Fig. 9. Three-dimensional model of pulsed magnetic field generator device. The system mainly includes coil system, discharge system, driving system and regulation system.

5. The experiment of verification circuit

In order to verify the analysis results, a small set of experimental platform with two pulse discharge components was designed to obtain test data. The separate discharge assembly with 6.25 kJ energy stored could generate a strong pulsed current by charging the coil with a gas discharge switch.

5.1. The schematic of the measurement system

The schematic of verification circuit is shown in Fig. 10. The trigger circuit was composed of a 40 kV power, an electric-trigger, a filament/hydrogen pressure power and a hydrogen thyratron. The filament/hydrogen pressure power was used to preheat the hydrogen thyratron. The power was used to charge the post capacitor of energy storage. The capacitor could generate a high voltage pulsed signal when the

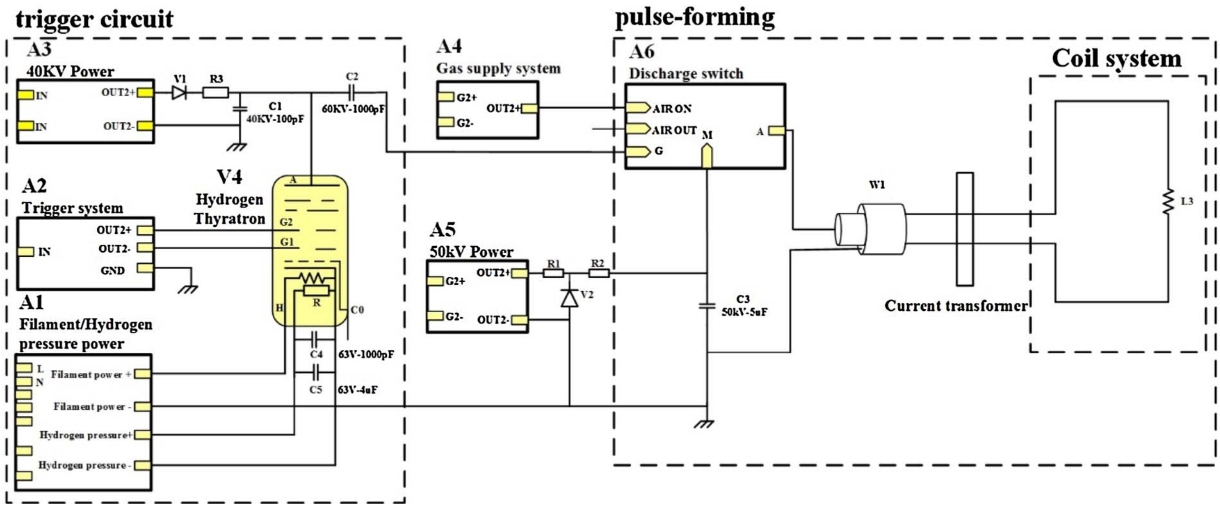

Fig. 10. Schematic of verification circuit. The measurement system includes a trigger system, a pulse-forming system and a charging system.

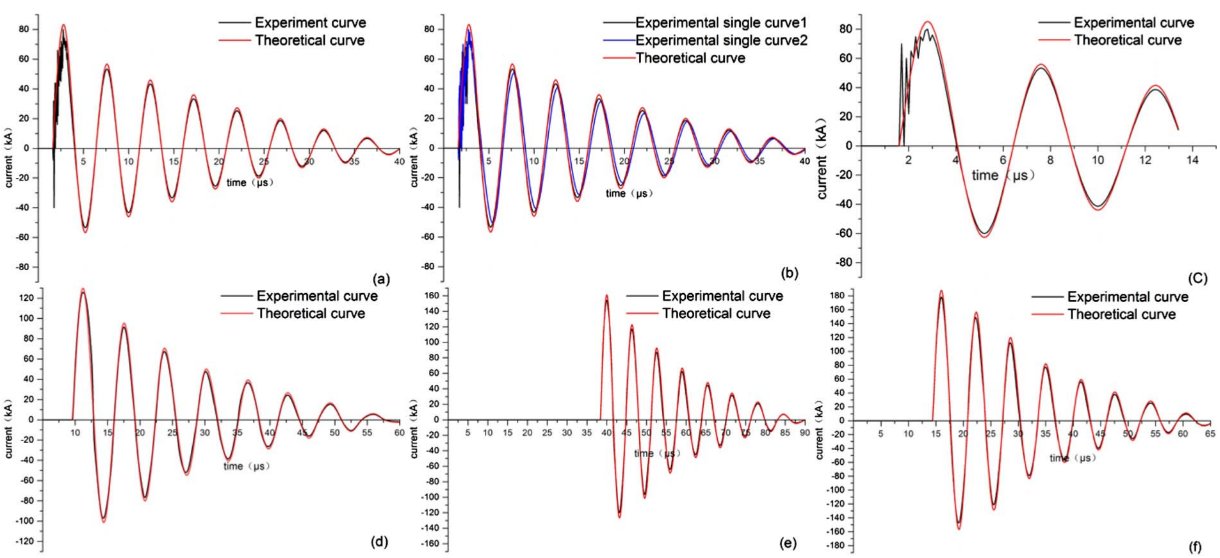

Fig. 11. (a)The single circuit current curve with a 0.05 MPa gas pressure and a 25 kV charge voltage. (b)The two single circuit current curve with a 0.05 MPa gas pressure and a 25 kV charge voltage. (c)The current curve of single circuit when the coil was broken with a 0.05 MPa gas pressure and a 25 kV charge voltage. (d)The total circuit current curve at 0.05 MPa gas pressure and 25kVcharge voltage. (e)The total circuit current curve at 0.05 MPa gas pressure and 30 kV charge voltage. (f)The total circuit current curve at 0.05 MPa gas pressure and 35kVcharge voltage.

hydrogen thyratron was turned on by the trigger. The trigger electrode and cathode of the switch could be turned on when the high voltage pulsed signal exceeds the voltage resistance. The pulse-forming circuit was composed of a 50 kV power, a gas switch and the external load. The gas supply system was used to provide the required gas pressure for the gas switch. The anode and cathode of the switch and the external load were connected by six coaxial cables.

5.2. Test of current curve

A set of small pulsed discharge system with a 50 kV/5 μF capacitor bank was built according to the schematic. Experiments for single and double circuit were conducted separately with a current transformer used to measure the circuit current. The single circuit current curve and the two circuit current curve with 0.05 MPa gas pressure and 25 kV charge voltage is shown in Fig. 11 (a), (b). The current of single circuit reached a maximum of 70kA at about 1.2 μs, in good agreement with the theoretical calculation and there was good consistency between the two single circuits. The noise in the current curve come from the old current transformer. The coil was broken after a series of experiments. The current curve of single circuit when the coil was broken is shown in Fig. 11(c). After repairing and reinforcing the coil, a series of experiments mainly concerning on main circuit were conducted with a new model of current transformer that could eliminate the affection of noise effectively. The total circuit current curve at 0.05 MPa gas pressure and 25 kV, 30 kV, 35 kV charge voltage are shown in Fig. 11 (d)–(f) respectively. The results showed that the total current also linearly increased with the increase of charge voltage. The pulse length grew to 6.4 μs from 4.8 μs owing to the change of resistance and the inductance of the coil after the repairing and reinforcing.

5.3. Test of trigger delay

For the small pulsed system, the trigger delay was the transit time of the trigger signal propagating from the oscillator to the gas switch. The post energy-storage capacitor in the trigger circuit generated a pulsed voltage after the hydrogen thyratron was turned on by the trigger signal. The anode and cathode discharged when the trigger electrode was turned on by the pulsed voltage. So the total trigger delay in this experiment include the time delay of the trigger, hydrogen thyratron

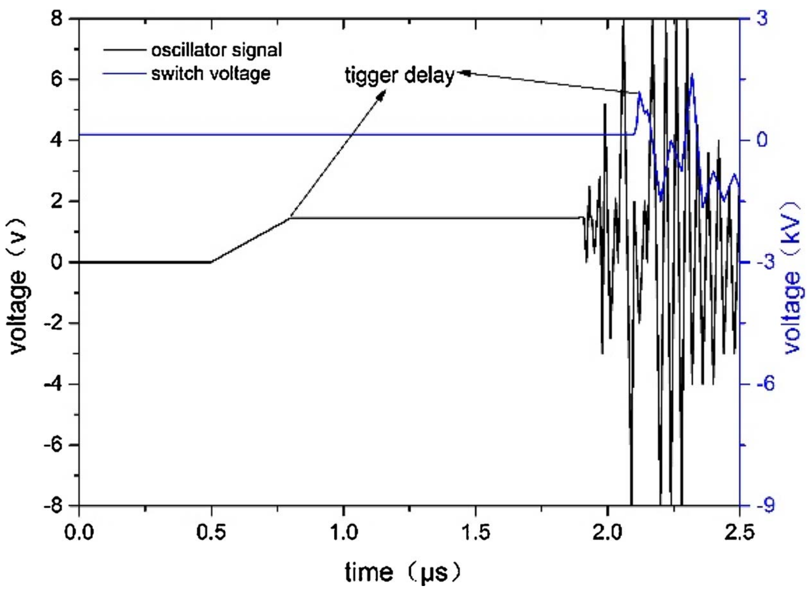

Fig. 12. The trigger delay (1.2 μs) was the transit time of the trigger signal propagating from the oscillator to the gas switch.

and trigger electrode's breakover. Oscilloscope shows that the voltage signal from the oscillator was generated at 0.8 μs and the gas switch was turned on at 2.12 μs. So the trigger delay is 1.32 μs, which is in accordance with the design requirements (Fig. 12).

6. Conclusion

A pulsed strong magnetic field generator which had a 1.2 μs rise-time and a 1.32 μs trigger delay for magnetized laser plasma experiments at Shenguang-II (SG-II) and Shenguang-III (SG-III) prototype laser facility was designed. The device was designed to produce a strong magnetic field of 150 T at maximum in a localized area. The electrical discharge system consisting of an energy storage capacitor and a gas-switch trigger system was coupled with a single-turn coil and the assembly successfully demonstrated the current discharge consistent with the theoretical calculation. The capacitors were placed outside of the chamber due to the space constraints, but the total inductance can be reduced by the special connection of the coaxial cables. A set of small pulsed discharge system with a 50 kV/5 μF capacitor bank was built to verify the analysis results. Preliminary experiments showed that the current curve was consistent with the theoretical analysis and the switch could realize the multiple circuits simultaneous triggering. A more portable design can be provided by employing an optical trigger cable in future works.

Acknowledgments

We acknowledge the support of the Research Center of Laser Fusion, China Academy of Engineering Physics.

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