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X-pinch experiments with pulsed power generator (PPG-1) at Tsinghua University

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Abstract

The test on an X-pinch device powered by a pulsed power generator (PPG-I) was carried out step by step. In the first step, a brass rod of 6 mm in diameter was used as a load to replace the X-pinch load. The results of the first step shows that all the current, about 200 kA in amplitude, output from PPG-I flows through the load and no breakdown or flashover in vacuum of the load section happens. The waveform of the current from PPG-I measured with a wall resistor coincides exactly with that of the load current measured with a Rogowski coil, which indicates that the calibrations of the wall resistor and Rogowski coil are correct. In the second step, an X-pinch load made of two molybdenum wires of 40 μm in diameter was used. It was found that the distance between the cathode and anode affects considerably the operation of the device. While breakdown in vacuum happens for the distance equal to 30 mm, it works very well for the distance equal to 16 mm. The reason for this phenomenon was given.

Keywords: Pulsed power generator; X-pinch

1. INTRODUCTION

Pulsed power devices like Z-pinch or X-pinch, which we consider in this article, plays an important role in the production of high power particle beams, and are often used as intense sources of radiation for a variety of applications (Korobkin *et al.*, 2005; Yatsui *et al.*, 2005). A very prominent application is in fusion energy (Winterberg, 2006; Kilkenny *et al.*, 2005; Stehle *et al.*, 2005).

An X-pinch is made using two (or more) fine wires (typically 5–50 μm in diameter), which cross and touch at a single point forming an "X" shape, which can than be used as a load for a high current pulsed power generator. The advantage of X-pinch is that it is a very small, bright, sub-nanosecond, X-ray source in the 1–10 keV energy range, and is reliably formed very near the original cross point of the wires. Recent experiments have shown that X-ray radiography of dense plasmas, in which an X-pinch was used as the X-ray source, is an effective diagnostic method (Shelkovenko *et al.*, 2001*a*, 2001*b*).

In our report (Zou *et al.*, 2006), we described the construction and experiments of a pulsed power generator (PPG-I) that could be used to power X-pinch loads. In a report (Liu *et al.*, 2007*a*, 2007*b*), we described the design of the load section housing an X-pinch load, and connecting it to the output of PPG-I. In this article, we describe the preliminary experiments on X-pinch.

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2. EXPERIMENTAL SETUP

As shown in Figure 1, an X-pinch load was powered by PPG-I, which is composed of a 1.2 MV Marx generator, a 1.25-Ohm pulse forming line (PFL), a V/N switch, and a 1.25-Ohm pulse transmission line (PTL). Both PFL and PTL are made of coaxial tubes, 1.67 m in length, using distilled water as insulation. When discharged, PPG-I will deliver a voltage pulse, 110 ns in full width at half maximum (FWHM), and 150–460 kV in amplitude depending on the charging voltage of the Marx generator, to a matched load.

Being composed of an electrode system (two fine wires in "X" shape connecting anode and cathode) inside a vacuum chamber, the load section was sketched in Figure 2. It is a coaxial configuration and a Plexiglas diaphragm is inserted between the PTL and the load section to isolate the water inside the PTL from the vacuum inside the load section. The gap between the cathode and anode can be changed from 15 to 40 mm.

Two current monitors were used for comparison. The first current monitor, called wall resistor, which was made from a foil of stainless steel and installed at the terminal of the outer tube of the PTL, was used to measure the output current

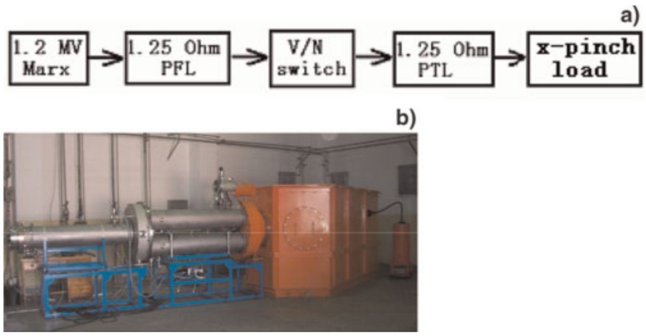

Fig. 1. X-pinch load powered by PPG-I. (**a**) block-diagram. (**b**) photograph.

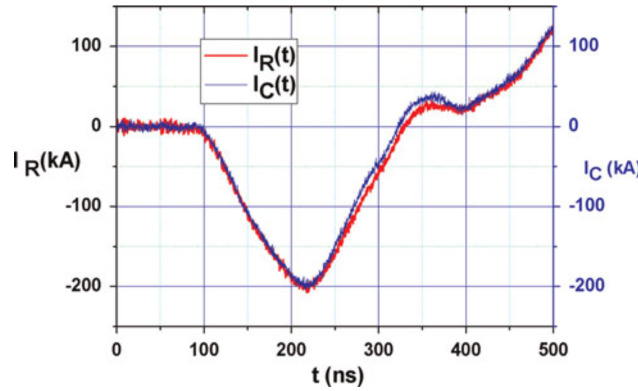

Fig. 3. The comparison of $I_R(t)$ and $I_C(t)$.

of PTL, the second one, a Rogowski coil, was described in detail by Liu *et al.* (2007*a*, 2007*b*), and used to measure the current flowing through the load. A capacitive voltage divider was also placed at the terminal of the PTL in order to measure the voltage applied to the load section.

3. RESULTS AND DISCUSSIONS

3.1. Rod load experiment

In the experiment using an X-pinch load, made of two fine wires, which will be exploded by high current of discharge, and is necessary to open the vacuum chamber to install a new load after each shot of discharge. In order to test the load section with high time efficiency, rod load experiment was performed as the first step of the experiments. In the rod load experiment, the X-pinch load, which was made using two fine wires in an "X" shape, was replaced by a brass rod, which is 6 mm in diameter, and connects the cathode and anode along the axis. With this rod load, we could make as many shots of discharge as we want, without the need of opening the vacuum chamber of the load section.

Figure 3 is the comparison of $I_R(t)$ and $I_C(t)$. $I_R(t)$ is the output current from PTL and was measured with the wall resistor, $I_C(t)$ is the current flowing through the rod load, and was measured with the Rogowski coil. It is clear that both current waveforms are almost exactly the same, which means two things. First, all of the output current from PTL flows through the rod load and no breakdown in vacuum or flashover along the Plexiglas diaphragm happens. Second, the calibrations of the wall resistor and the coil are correct. Since the resistance of the brass rod, 6 mm in diameter and 30 mm in length, is small compared with the inductance of the rod, the load section could be equivalent to an inductance. In this case, we have the following formula:

$$V(t) = L\frac{dI_R(t)}{dt}, \tag{1}$$

where $V(t)$ is the voltage applied to the load section and was measured with the capacitive voltage divider; $I_R(t)$ is the current input into the load section and was measured with the wall resistor; L is the equivalent inductance of the load section. The typical waveforms of $V(t)$ and $I_R(t)$ are shown in Figure 4, from which we could see the relation expressed by Eq. (1). By fitting the data of the measured $V(t)$ and $I_R(t)$ into Eq. (1), L was determined to be about 86 nH.

From the previous experiments, it was known that the voltage pulse applied to a matched load is approximately a trapezoidal waveform, the same as the forward going voltage wave along the PTL. However, the waveform of the voltage pulse applied to a load equivalent to an

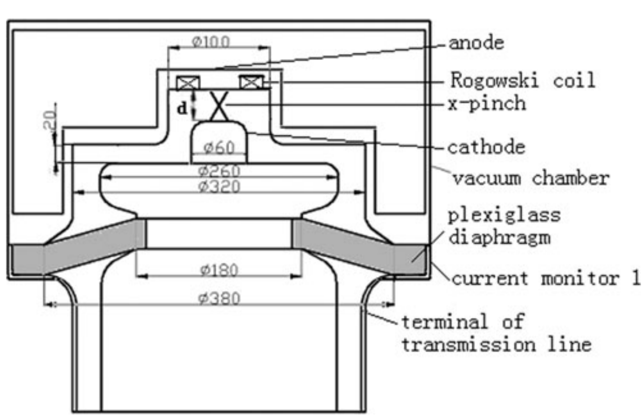

Fig. 2. The sketch of the load section.

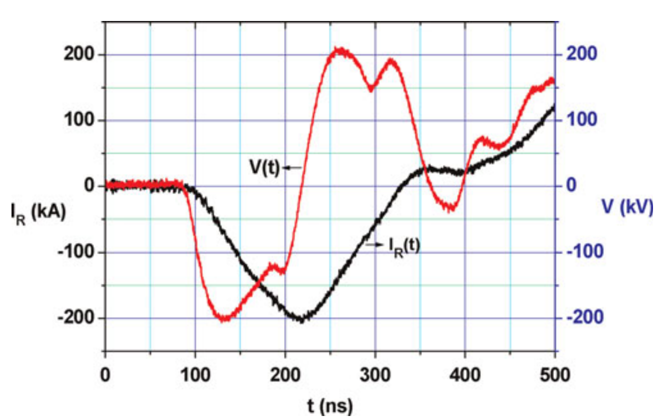

Fig. 4. The typical waveforms of the voltage applied to the load section and the current input into the load section.

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inductance, as shown in Figure 4, is totally different due to reflection, which was confirmed by the results of a numerical modeling, as shown in Figure 5, using a code for circuit simulation, Pspice from Microsim.

In Figure 5, $V_i(t)$ is the forward going voltage wave incident upon a load of 86 nH, the same value as the experimentally determined one; $V_L(t)$ is the voltage applied to the load; $i(t)$ is the load current. Obviously, $V_L(t)$ and $i(t)$ are similar to those shown in Figure 4.

3.2. X-pinch load experiment

An X-pinch load made of two molybdenum wires, 40 μm in diameter, was used. At the beginning, the distance between the cathode and anode, *d*, was 30 mm. As known, the current for exploding and imploding one two-wire X-pinch is usually 100–200 kA, depending on the mass of the X-pinch load. Thus, the current flowing through the X-pinch load was chosen to be about 200 kA in our experiment. Figure 6 shows the waveforms of $V(t)$, $I_R(t)$, and $I_C(t)$.

It was found that the trace of $I_C(t)$, the current flowing through the X-pinch load, begins to depart from that of $I_R(t)$, the current output from the PTL, at the time of about 135 ns when $V(t)$, the voltage applied to the load section, rises to its maximum. From that time on, $I_C(t)$ looks totally different from $I_R(t)$. This phenomenon indicates that somewhere inside the load section breakdown in vacuum or flashover along the Plexiglas diaphragm happens at that time. It seems no big change in the impedance of the load section was seen since $I_R(t)$ did not change abruptly after that time. We concluded that no flashover along the Plexiglas diaphragm but breakdown in vacuum happens, which was confirmed by the fact that no traces of flashover were left on the surface of the Plexiglas diaphragm.

In order to make a rough estimation, where breakdown is most likely to happen, the electric field in the load section was calculated using software Maxwell three-dimensional from Ansoft to see where the field is highest. The distribution of the electric field was given in Figure 7, were we found that the highest field is at the side top of the cathode. If breakdown happens from the side top of the cathode outward to

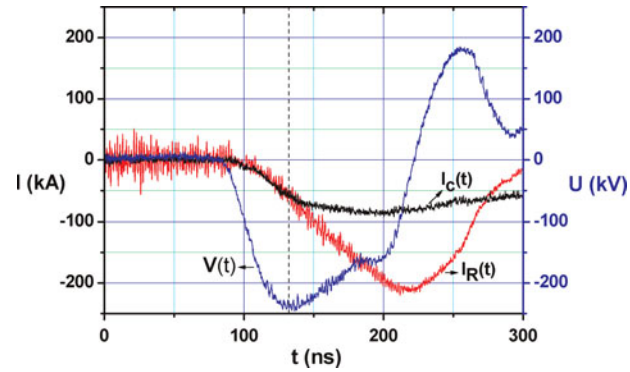

Fig. 6. The waveforms of $V(t)$, $I_R(t)$, and $I_C(t)$ with $d = 30$ mm.

the anode, the impedance of the load section would not change too much after the breakdown, this is just what was observed on the curve of $I_R(t)$ in Figure 6.

We had three possible methods that could be used to avoid this breakdown. The first one, the easiest one, is to decrease $V(t)$ by decreasing the charging voltage of Marx generator of PPG-I, but it will decrease the current. The second one is, to make wider the vacuum gap in the region of the side top of the cathode, but it will increase the inductance of the load section, also leading to the decrease of the current. The third one, the one not straightforward to understand, is to shorten *d*, the distance between the cathode and the anode in the direction of the axis. The reason why the third method could be used to avoid the breakdown is given below.

The load section shown in Figure 2 could be divided into two sections. Section 1 is from the Plexiglas diaphragm on the top of the cathode, and section 2 is from the top of the cathode to the anode. It was found by field calculation that when *d* is shortened, the highest field is always at the same region as shown in Figure 7, and that if the applied voltage is kept to be 200 kV, the value of the highest field for *d* equal to 16 mm is 174 kV/cm, very close to 170 kV/cm, the value for *d* equal

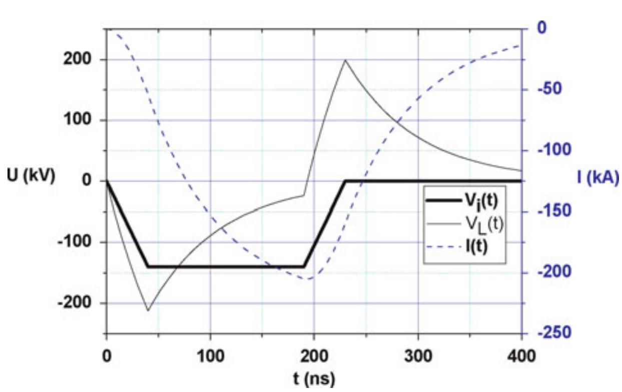

Fig. 5. The results of a numerical modeling with a load equivalent to an inductance of 86 nH.

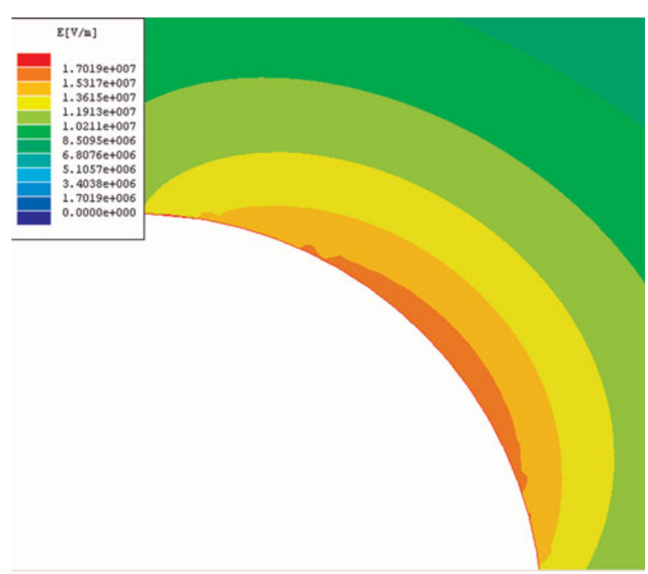

Fig. 7. The distribution of the electric field at the top of the cathode.

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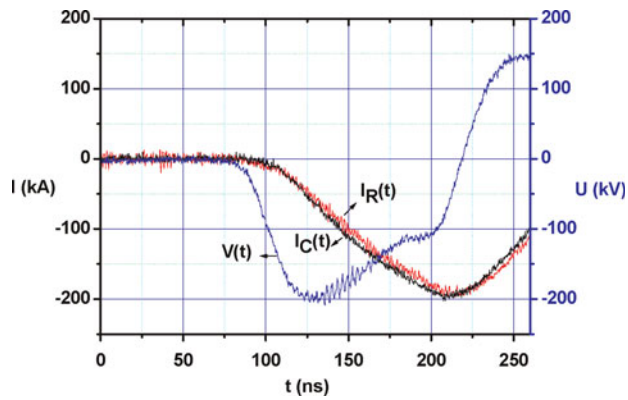

Fig. 8. The waveforms of $V(t)$, $I_R(t)$ and $I_C(t)$ with $d = 16$ mm.

to 30 mm. It is clear that there exists a more uniformly distributed field in section 2 for the shorter *d*. In the view of electrical circuit, the load section could be considered as two impedances in series, Z_1 for section 1, and Z_2 for section 2. While Z_1 is actually a constant inductor that was calculated to be 34 nH, Z_2 could be equivalent to an inductor in parallel with a resistor of two wires making an X-pinch load, and will be decreased as the shortening of *d*. There are two factors affecting the highest field in section 2 when *d* is shortened. The first one is that the voltage applied to section 2 will be reduced due to a reduced Z_2 corresponding to a shortened *d* if the voltage applied to the load section is kept constant, which, in turn, decreases the highest field in section 2. The second one is that the voltage applied to the load section will be reduced due to the reduced impedance of the load section as a result of the reduced Z_2 when the forward going voltage wave incident upon the load section is kept constant, which will further decreases the highest field in section 2.

Figure 8 shows the waveforms of $V(t)$, $I_R(t)$, and $I_C(t)$ with a reduced *d* equal to 16 mm. From Figure 8 we could see that the traces of $I_R(t)$ and $I_C(t)$ almost coincide, which indicates no breakdown in vacuum happens. Although the experimental conditions for Figure 6 and Figure 8 are the same except that *d* was shortened from 30 to 16 mm, the results are much different. It is important to notice that the amplitude of $V(t)$ in the case of Figure 8 is about 200 kV, much smaller than 245 kV, the value in the case of Figure 6, but $I_R(t)$ is about 200 kA for both cases, which means that the impedance of the load section for *d* equal to 16 mm is reduced. All the changes shown in Figure 8 are just what we expected in the above paragraph.

The results of the preliminary experiment show that the X-pinch device runs well. The further experiments are being carried out. The temporal and spatial characteristics of the X-ray emission will be studied with PCD detectors and pinhole cameras in the near future.

4. CONCLUSIONS

The test on an X-pinch device powered by a pulsed power generator (PPG-I) was carried out step by step. In the first step, a brass rod of 6 mm in diameter was used as a load to replace the X-pinch load. The results of the first step show that all the current, about 200 kA in amplitude, output from PPG-I flows through the load and no breakdown or flashover in vacuum of the load section happens. The waveform of the current from PPG-I measured with a wall resistor coincides exactly with that of the load current measured with a Rogowski coil, which indicates that the calibrations of the wall resistor and Rogowski coil are correct. In the second step, an X-pinch load made of two molybdenum wires of 40 μm in diameter was used. It was found that the distance between the cathode and anode affects considerably the operation of the device. While breakdown in vacuum happens for the distance equal to 30 mm, it works very well for the distance equal to 16 mm. The reason for this phenomenon is that Z_2 is reduced for the shortened *d*.

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