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Current division between two paralleled X-pinches

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Abstract

In order to use two paralleled X-pinches as X-ray sources for the time-resolved backlighting of wire-array Z-pinch plasma, it is necessary to make these two X-pinches emit X-rays at different but roughly preset time instants. The timing of the X-ray burst from an X-pinch independence of the current, and the wire mass of the X-pinch was investigated. The currents flowing through two paralleled X-pinches were measured and it was found that the total current is almost equally divided between these two X-pinches no matter how different the wires for these two X-pinches are. The reason for the equal current division between two paralleled X-pinches was given based on the inductance calculation of the X-pinch circuit.

Keywords: Timing of X-ray burst; X-pinch; X-ray backlighting; Z-pinch

INTRODUCTION

In 1997, Sandia Laboratories made a breakthrough in particle beam fusion accelerator-Z project. With an efficiency of 16% from the electrical energy to X-ray, 1.8 MJ X-ray energy and 290 TW X-ray pulsed power were obtained in the project (Deeney *et al*., 1998). The interest in Z-pinch-driven nuclear fusion was further enhanced by the breakthrough (Ramirez, 1997). It was well accepted that the use of a wire-array load made from hundreds of fine wires is responsible for this breakthrough. The wire-array was thought to be able to produce a high degree of the initial symmetry in the load mass and the current distribution, which results in a lower "seed level" of magneto-hydrodynamics instabilities. However, the detailed physical processes occurring in the initial stage of the wire-array Z-pinch is still under intensive investigation. The most suitable method to observe these processes is X-ray backlighting of wire-array Z-pinch plasma with a pulse X-ray point source.

It was well-known that the nanosecond pulse discharges are capable of generating high energy electron beams and X-rays (Mesyats *et al*., 2011; Shao *et al*., 2012; Zhang *et al*., 2013; 2014). X-pinch is made using two or more fine metallic wires that cross and touch at a single point, forming an "X"-shaped structure. When a high and pulse current flows through these wires, the metallic vapor plasma from the electrical explosion of the wires pinches at the crossing point, leading to intensive X-rays emit from this point (Zakharov *et al*., 1982). X-pinch is a subnanosecond pulse X-ray point source that is suitable for the backlighting of wire-array Z-pinch plasma (Kalantar *et al*., 1995).

The experiments of using X-pinch as X-ray source to backlight wire-array Z-pinch have been performed on the devices such as MAGPIE (Lebedev *et al*., 2001), Angara-5-1 (Grabovskii *et al*., 2004), COBRA (Douglass *et al*., 2008), and PPG-1 (Zhao *et al*., 2010). In order to obtain the time-resolved images of the X-ray backlighting in single shot of Z-pinch discharge, at least two paralleled X-pinches as X-ray sources are needed. Furthermore, it is necessary to make these two X-pinches emit X-rays at different but roughly preset time instants. It was believed that the instant at which the X-ray emits from an X-pinch is dependent on the current flowing through the X-pinch and the mass per unit length of the X-pinch load. Therefore, it is important to know how the total current is divided between the two paralleled X-pinches made from different wires (material and diameter).

In this paper, the dependence of the timing of the X-ray burst on the current and the load mass of the X-pinch driven by PPG-1 was investigated. The currents flowing through two paralleled X-pinches were measured and it was found that the total current is almost equally divided between these two X-pinches no matter how different the wires for these two X-pinches are. The reason for the equal current division between two paralleled X-pinches was given based on the inductance calculation of the X-pinch circuit.

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EXPERIMENTAL SETUP

The experiments were carried out on PPG-1 that is a pulsed power generator with a nominal current of 400 kA in amplitude and 100 ns in pulse width (FWHM) (Zou *et al*., 2006). A vacuum chamber housing X-pinch load was connected to the output port of PPG-1 (Liu *et al*., 2007*a*; 2008*a*). The previous studies were focused on the characteristic of the X-ray emission from the X-pinches driven by PPG-1 (Liu *et al*., 2008*b*). Now we are focusing on the technical issues relevant to the time-resolved backlighting of wire-array Z-pinch using X-pinches as X-ray sources.

Figure 1 shows the experimental arrangement for investigating the timing of the X-ray burst from an X-pinch. As shown in Figure 1, an X-pinch load made of two crossing wires connects the anode and the cathode in the center. Four current-return rods support the anode plate. A Rogowski coil with a fast time response (Liu *et al*., 2007b) was inserted on the anode plate for measuring the current flowing through two wires of the X-pinch. A photo-conducting detector was aimed at the crossing point of the X-pinch load for recording of the X-ray pulse from the X-pinch. By comparing the waveforms of the current and the X-ray pulse, the timing of the X-ray burst with respect to the start of the current was determined.

Figure 2 shows the experimental arrangement for the time-resolved backlighting of wire-array Z-pinch using two X-pinches as X-ray sources. It is a modification of Figure 1. The X-pinch in the center was replaced by a wire-array Z-pinch which is the object to be imaged. Two current-return rods were replaced by two X-pinches that are the X-ray sources. Two X-pinches made of different wires emits pulsed X-ray at different times. With a time interval, these two pulsed X-rays penetrate the plasma of the wire-array Z-pinch and arrive at the X-ray sensitive films. By this method, two time-resolved images of the wire-array Z-pinch were obtained.

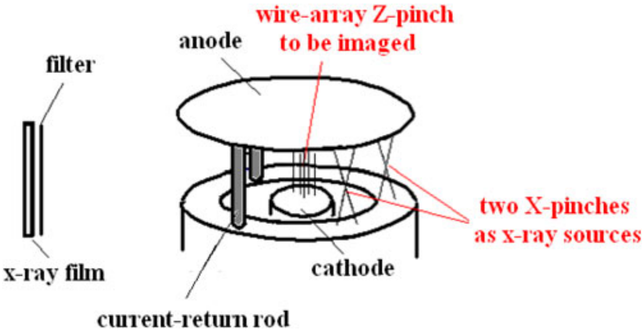


Fig. 2. (Color online) Experimental arrangement for the time-resolved backlighting of wire-array Z-pinch using two X-pinches as X-ray sources.

Figure 3 shows the experimental arrangement for measuring the current division between two paralleled X-pinches. It is a simple modification of Figure 2 by replacing the wire-array Z-pinch in the center with a copper short-circuit rod of 6 mm in diameter. Two Rogowski coils were used to measure the currents flowing through two X-pinches, one coil for X-pinch 1 and the other for X-pinch 2.

RESULTS AND DISCUSSIONS

Timing of X-Ray Burst from X-Pinches

First, we investigated the dependence of the timing of the X-ray burst on the mass of X-pinch load by keeping the current unchanged. Figure 4 shows the typical waveforms of the X-ray pulse and the current for X-pinch loads made of Mo

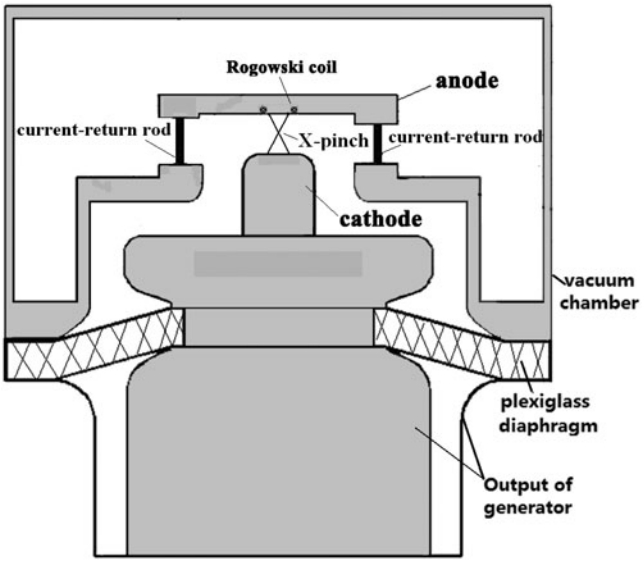


Fig. 1. Experimental arrangement for investigating the timing of the X-ray burst from an X-pinch.

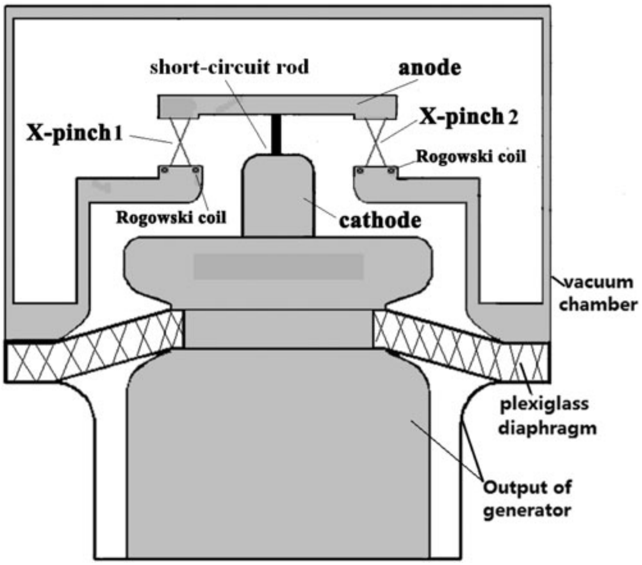
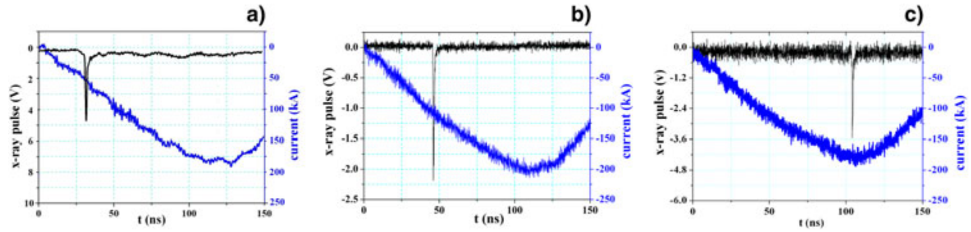


Fig. 3. Experimental arrangement for measuring the current division between two paralleled X-pinches.



13µm Mo wires 25µm Mo wires 50µm Mo wires

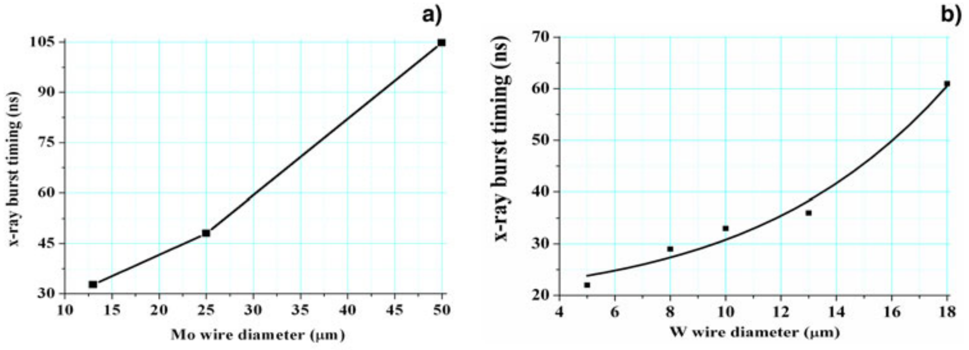
Fig. 4. (Color online) Typical waveforms of the X-ray pulse and the current for X-pinch loads made of Mo wires with different diameter.

Table 1. *Timing of the X-ray burst from the X-pinch made of Mo wires at a current of 200 kA in amplitude*

wire diameter (µm)	Timing of the X-ray burst (ns)				
	shot 1	shot 2	shot 3	shot 4	average
13	30	32	36	—	32.7
25	50	42	48	52	48
50	108	101	105	105	104.8

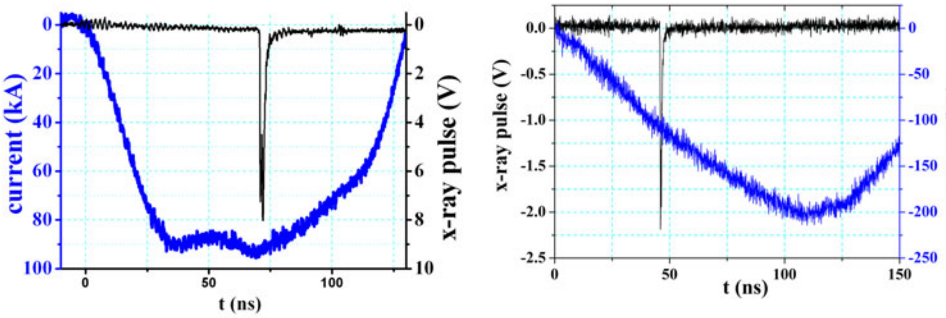
wires with different diameters. The currents flowing through the X-pinch wires were kept at about 200 kA in amplitude. It was found that the timing of the X-ray burst changes a little bit from shot to shot for a given Mo wire and the data were listed in Table 1.

It can be seen from Figure 4 and Table 1 that the timing of the X-ray burst with respect to the start of the current increases from 32.7 ns to 48 ns and finally to 104.8 ns as the diameter of Mo wires increases from 13 µm to 25 µm and finally to 50 µm. The timing of the X-ray burst from the



Mo wires at 200 kA W wires at 100 kA

Fig. 5. (Color online) Timing of the X-ray burst from the X-pinches in dependence of the wire diameter.



95 kA current 200 kA current

Fig. 6. (Color online) Typical waveforms of the X-ray pulse and the current for X-pinch loads made of 25 µm Mo wires through which different current flows.

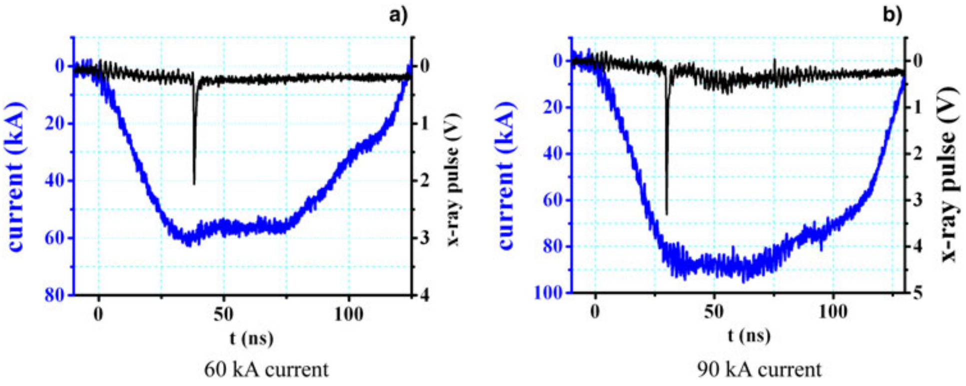


Fig. 7. (Color online) Typical waveforms of the X-ray pulse and the current for X-pinch loads made of 8 µm W wires through which different current flows.

X-pinches in dependence of the wire diameter was shown in Figure 5. Each data point of Figures 5a and 5b are averaged over 4 shots and 10 shots, respectively. It is easy to understand why the timing of the X-ray burst increases with the increase of the wire diameter when the current is kept unchanged. The thicker the wire, the larger is the line mass density to be compressed, which leads to a longer time of the compression for the X-ray burst.

Then, we investigated the dependence of the timing of the X-ray burst on the amplitude of the current by keeping the mass of X-pinch load unchanged. Figures 6 and 7 shows the results for 25 µm Mo wires and 8 µm W wires, respectively.

For 25 µm Mo wires, the timing of the X-ray burst decreases from 72 ns to 48 ns as the current rises from 95 kA to 200 kA. For 8 µm W wires, the timing of the X-ray burst decreases from 39 ns to 28 ns as the current rises from 60 kA to 90 kA.

According to the results mentioned above, it was confirmed that the timing of the X-ray burst from an X-pinch depends on both the current and the load mass of the X-pinch. When two paralleled X-pinches made from different wires (material and diameter) are used as the X-ray sources for the time-resolved backlighting of wire-array Z-pinch plasma, it is important to know how the total current is divided between these two paralleled X-pinches.

Current Division between Two Paralleled X-Pinches

With the experimental arrangement shown in Figure 3, the currents flowing through two paralleled X-pinches were measured with two Rogowski coils. To our surprise, the currents flowing through these two paralleled X-pinches are almost equal, no matter how different the wires used for these two X-pinches are. Two examples were given in Figure 8. Furthermore, the currents flowing through the paralleled X-pinch made of fine wires and the current-return rod of 8 mm in diameter are also almost equal, as shown in Figure 9.

We made a guess at the reason for the equal current division between two paralleled X-pinches. As shown in Figure 10, the total current from the cathode flows to the center of the anode plate through the short-circuit rod. Then, the total current is divided into four parts that go along four strip-like current paths on the anode plate to two current-return rods and two X-pinches. Finally, through the fan-like current paths on the current-return base, four parts of the current meet together at the output of the generator.

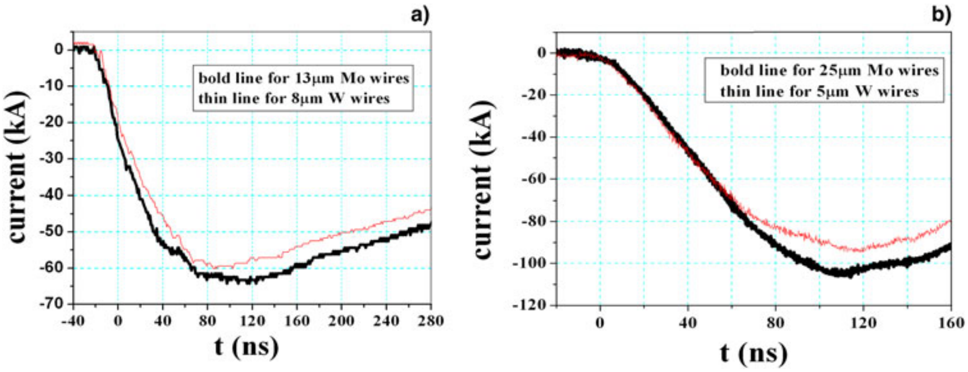


Fig. 8. (Color online) Comparison of the currents flowing through two paralleled X- pinches made of different wires.

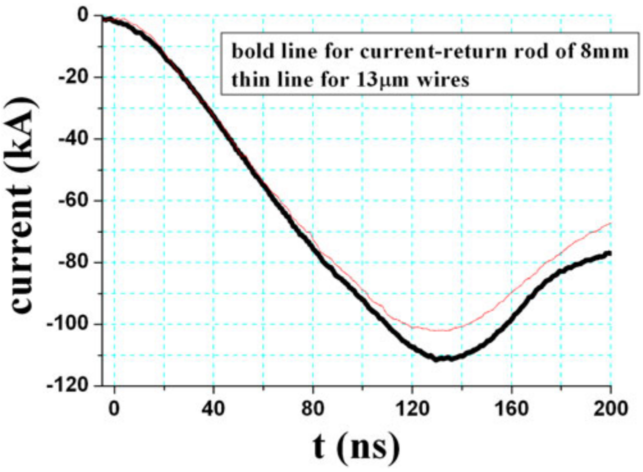


Fig. 9. (Color online) Comparison of the currents flowing through the paralleled X-pinch and current-return rod.

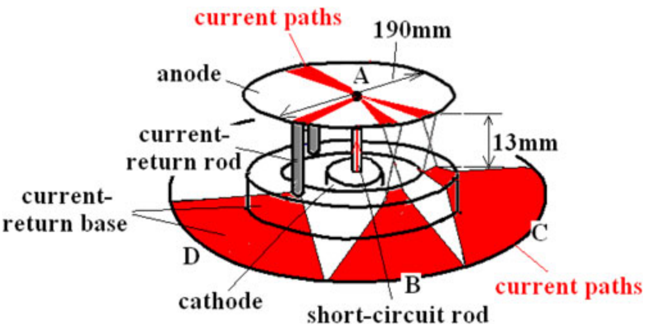


Fig. 10. (Color online) Total current divided into four parts flowing along four strip-like current paths.

For a fast pulse current, the current division mainly depends on the inductance of the paralleled circuits. Obviously, two X-pinches were paralleled not directly but through two relatively long current paths. Now, we consider two paralleled circuits including the X-pinches, circuit A → B and circuit A → C. Since the length of the X-pinch is about 13 mm and much shorter than the length of the current path, the X-pinch makes significantly smaller contribution to the total inductance of the circuit. In this case, the currents flowing through these two X-pinches are almost equal, no matter how different the wires used for these two X-pinches are.

In order to confirm our guess being correct, we calculated the inductance of circuit A → B by the electromagnetic simulation with a code called ANSOFT. Figure 11 shows the results. From Figure 11 it can be seen that the total inductance of circuit A → B decreases from 59 nH to 55 nH as the wire diameter increases from 5 μm to 50 μm. The maximum difference in the total inductance caused by the difference in wire diameter is only 4 nH, very small compared with the total inductance of 55 nH, which cannot considerably change the current flowing through the circuit. Therefore, the currents flowing through circuit A → B and circuit A → C are almost equal, no matter how different the wires used for these two X-pinches are. The similar results were obtained from the calculation of the inductance for circuit A → D. Even though the diameter of the current-return rod is as large as 8 mm, the total inductance of circuit A → D is 53.8 nH, very close to that of circuit A → B, which leads to the experimental result shown in Figure 9.

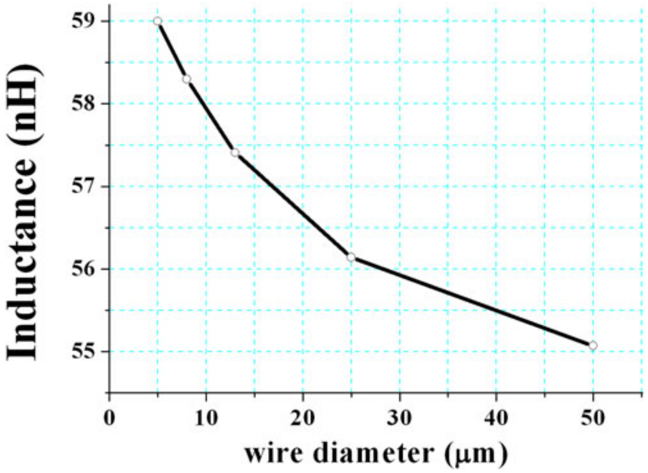


Fig. 11. (Color online) Inductance of circuit A → B in dependence of wire diameter of X-pinch.

CONCLUSIONS

The timing of the X-ray burst from an X-pinch with respect to the current start depends on both the current and the wire mass of the X-pinch. No matter how different the wires used for two paralleled X-pinches are, the currents flowing through these two X-pinches are almost equal, which makes it much easier to use two paralleled X-pinches as X-ray sources for the time-resolved backlighting of wire-array Z-pinch plasma. In this case, the difference in the timing of the X-ray bursts from two paralleled X-pinches depends solely on the difference in wire mass since the current is known and not changed with the change of the wires.

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