Determining the resistance of X-pinch plasma*

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The current and the voltage of an X-pinch were measured. The inductance of the X-pinch was assumed to be a constant and estimated by the calculation of the magnetic field based on the well-known Biot–Savart's Law. The voltage of the inductance was calculated with $L \cdot \mathrm{d}i/\mathrm{d}t$ and subtracted from the measured voltage of the X-pinch. Then, the resistance of the X-pinch was determined and the following results were obtained. At the start of the current flow the resistance of the exploding wires is several tens of Ohms, one order of magnitude, higher than the metallic resistance of the wires at room temperature, and then it falls quickly to about 1 Ω, which reflects the physical processes occurring in the electrically exploding wires, i.e., a current transition from the highly resistive wire core to the highly conductive plasma. It was shown that the inductive contribution to the voltage of the X-pinch is less than the resistive contribution. For the wires we used, the wires' material and diameter have no strong influence on the resistance of the X-pinch, which may be explained by the fact that the current flows through the plasma rather than through the metallic wire itself. As a result, the current is almost equally divided between two parallel X-pinches even though the diameter and material of the wires used for these two X-pinches are significantly different.

Keywords: electrical explosion of wires, X-pinch, Z-pinch

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1. Introduction

In 1997 a breakthrough was achieved by Sandia Laboratories in the PBFA-Z project which got promising parameters of 1.8-MJ X-ray energy with an efficiency of 16% from electrical energy to X-ray energy and 290-TW X-ray pulsed power.[1,2] The breakthrough has sparked an interest in inertial confinement fusion (ICF) driven by the powerful X-rays from Z-pinches.[3] An improvement of the Z-pinch load was thought to be responsible for this breakthrough. A wire-array load made by using hundreds of fine wires provides a high degree of initial symmetry of the load and the current distribution, leading to a lower "seed level" of MHD instabilities. However, the detailed physics of the wire-array Z-pinch is still under intensive investigation. Knowledge of the basic implosion parameters, such as wire core expansion rate, mass ablation rate, and growth of MHD instabilities, in wire-array Z-pinches is of great importance in understanding the physics of the implosion. One of the methods for obtaining these parameters is to backlight Z-pinch plasma with the emission from a point X-ray source.

X-pinch plasma is produced with a high and pulsed current flowing through two or more fine wires that cross and touch at a single point, forming an "X"-shaped structure.[4] A sub-nanosecond pulsed X-ray point source is usually formed at the crossing point of the wires.[5] The experiments on X-ray backlighting of wire-array Z-pinches using an X-pinch as the X-ray source have been performed on facilities such as MAGPIE,[6] Angara-5-1,[7] COBRA,[8] and PPG-1.[9] The experimental arrangements for the X-ray backlighting are more or less the same. A wire-array Z-pinch, used as the object to be imaged, was placed between the anode and the cathode of a vacuum diode powered by a pulsed high current generator. The anode plate is normally mounted on return-current rods, but for these experiments two of these rods were replaced by two X-pinches used as the X-ray backlighters, so as to obtain two time-resolved images in a single shot of discharge.

The key point of the design to use two X-pinches for time-resolved X-ray backlighting is to make these two X-pinches emit X-rays at different but roughly preset time instants. As we know, the X-ray burst for a given X-pinch load occurs at a roughly reproducible value of the current from pulse to pulse[5] and the timing of the X-ray burst with respect to the start of the current flow scales linearly with the mass per unit length of the X-pinch load.[10,11] Therefore, it is important to divide the current suitably among the parallel X-pinches and return-current rods and to choose the right wires for these two X-pinches since the timing of the X-ray burst from an X-pinch is current and wire-mass dependent. For this reason, people need

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to know how the current is allocated among the parallel X-pinches and return-current rods. It is well known that the current division among parallel circuits is inversely proportional to the impedance of each circuit, and thus the problem is determining the impedance for each circuit. Obviously, either a return-current rod or an X-pinch is equivalent to a resistor in series with an inductor. While the resistor and inductor for the solid metallic return-current rod are relatively easy to calculate, these parameters for the exploding wires of an X-pinch are difficult to determine. The only published research on the evaluation of X-pinch impedance was done by Aranchuk and his coworkers.[12,13] They treated an X-pinch as an inductor and evaluated the inductance by assuming the measured voltage across the X-pinch being determined mainly by the inductance, but their assumption is still open to debate and speculation because little quantitative data have been accumulated on the resistance of the exploding wires.

In this article, we present research on determining the resistance of an X-pinch and show that the inductive contribution to the voltage of an X-pinch is less than the resistive contribution. We also show that the wire's material and diameter have no strong influence on the resistance. Because this is true, the current in our experimental setup is almost equally divided between two parallel X-pinches even though the diameter and material of the wires used for these two X-pinches are significantly different.

2. Experimental setup and method

The current work was carried out on the PPG-1 facility in which the cathode and anode of a vacuum diode were connected to the output of a nominal 400-kA, 100-ns pulsed power generator.[14] Before the modification for this experiment, the anode plate was mounted on four return-current rods. For the present work, these four return-current rods were replaced by one X-pinch load and three supporting rods made of insulating material. The experimental arrangement for determining the resistance of the X-pinch is sketched in Fig. 1. The geometrical parameters of the vacuum diode were detailed elsewhere.[15]

Since the experiment was not for X-ray backlighting of wire-array Z-pinches, for convenience, a short-circuit rod rather than a wire-array Z-pinch was connected in between the anode and the cathode. The short-circuit rod was 6 mm in diameter and was made from copper. The current flowing through the X-pinch, $i(t)$, and the voltage across the X-pinch, $V(t)$, were measured respectively with a Rogowski coil and a capacitive divider that were carefully calibrated.[16,17] The construction of the capacitive divider is shown in Fig. 2. The cylindrical divider consists of two capacitors, C_1 and C_2. The voltage ratio of the divider was calibrated to be 246 with C_1 equal to 2.93 pF and C_2 equal to 724.2 pF.

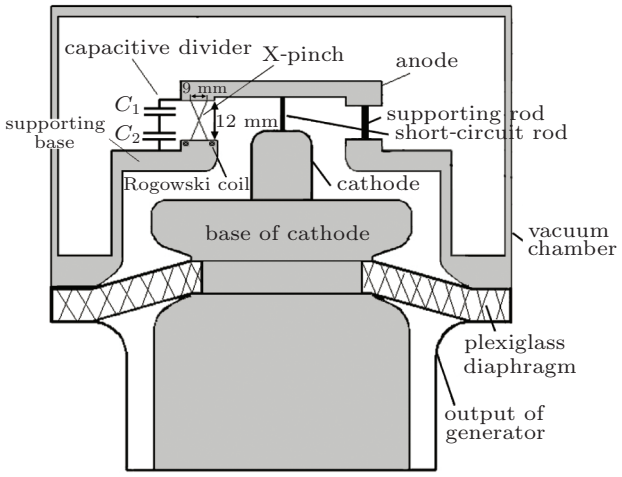


Fig. 1. Experimental arrangement for determining the resistance of an X-pinch.

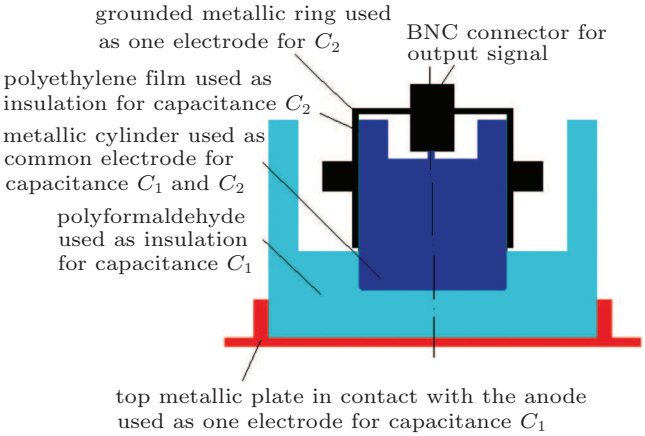


Fig. 2. (color online) Construction of capacitive divider.

It was known that the resistance of the exploding wires of an X-pinch is current-dependent, for this reason, a photoconducting diode (PCD) was installed to monitor the X-ray burst from the X-pinch so as to ensure the current flowing through the X-pinch was in the range high enough to emit X-rays. All waveforms were recorded with a digital oscilloscope of DSO9254A from AGILENT with a bandwidth of 2.5 GHz and a sampling rate of 10 Gs/s (1 Gs = 10^{-4} T).

The voltage across an X-pinch can be expressed by the sum of the resistance voltage and the inductance voltage of the X-pinch:

$$V(t) = R(t) \cdot i(t) + \mathrm{d}\left[L(t) \cdot i(t)\right] / \mathrm{d}t, \tag{1}$$

where $R(t)$ and $L(t)$ are the resistance and the inductance of the X-pinch, respectively.

According to the definition of inductance, $L = \Phi/I$, the inductance can be determined by the calculation of the magnetic flux Φ produced by current I· The magnetic flux produced by two crossing wires of the X-pinch was calculated in the following way.[18] First, the current-flowing wires were divided into many short elements of current. The magnetic field at any point $P(x, y, z)$ in space produced by one current element

can be calculated with the well-known Biot–Savart's Law and expressed by[19]

$$\boldsymbol{B}(x,y,z)\big|_{\text{by}\,I\cdot\mathrm{d}l}=\frac{\mu_0 I}{4\pi}\cdot\frac{\mathrm{d}\boldsymbol{l}\times\boldsymbol{r}_0}{r^2},\tag{2}$$

where $I\cdot\mathrm{d}l$ is the current element; $\boldsymbol{r}$ is the vector from the current element to point P; $\boldsymbol{r}_0$ is the unit vector of $\boldsymbol{r}$.

Second, the resultant magnetic field at the point P, $\boldsymbol{B}(x,y,z)$, was obtained by the addition of the magnetic fields produced by all current elements and expressed by

$$\boldsymbol{B}(x,y,z)\big|_{\text{by}\,I\cdot l}=\frac{\mu_0 I}{4\pi}\cdot\int_l\frac{\mathrm{d}\boldsymbol{l}\times\boldsymbol{r}_0}{r^2},\tag{3}$$

where $I\cdot l$ is all current elements.

Finally, the magnetic flux was calculated with the integration

$$\Phi=\int_S\boldsymbol{B}\cdot\mathrm{d}\boldsymbol{s},\tag{4}$$

where S is the area of the X-pinch circuit and the area is encircled by the base of the cathode, the cathode, the short-circuit rod, the anode, X-pinch, the supporting base, and the plexiglass diaphragm.

For the X-pinch shown in Fig. 1, the inductance was calculated for different wire diameters. The dependence of the inductance on the wire diameter is plotted in Fig. 3. In our experiments, the diameter of wires ranges from 8 μm to 25 μm, the corresponding inductance of the X-pinch varies from 13.4 nH to 14.4 nH.

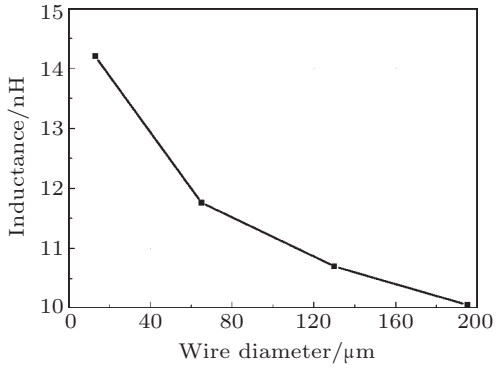


Fig. 3. Dependence of inductance on the wire diameter of X-pinch.

As we know, during the time from the current beginning to the X-ray burst of X-pinch, the shape and the size of the wire core remain almost unchanged, but the current sheath in the plasma surrounding the wire core has a relatively large lateral dimension compared to the initial diameter of the wire.[20,21] Most of the current flows through the highly conductive surrounding plasma rather than the highly resistive wire core. Although the time-dependent distributions of the current in the surrounding plasma and the wire core are not clearly known, this is not important for the estimation of the X-pinch's inductance since the current distribution determines only the inner inductance that is much smaller than the outer inductance. For instance, the inner inductance per meter is about $\mu_0/8\pi$ if the current is uniformly distributed in a current channel.[19] For our X-pinch, made of two parallel wires about 12-mm long, the inner inductance is only about 0.3 nH. For this reason the inner inductance was ignored in our inductance calculation. As shown in Fig. 3, the inductance changes from 14.4 nH to 10 nH when the wire diameter changes from 8 μm to about 200 μm. But the inductance will not change much, even when the size of the current-carrying channel around the wires is considered. For the reasons mentioned above and for simplicity, the time-varying inductance of the X-pinch was treated as a constant inductance approximately equal to the initial wire inductance. In this case, equation (1) was simplified to

$$V(t)=R(t)\cdot i(t)+L\cdot\mathrm{d}i(t)/\mathrm{d}t,\tag{5}$$

where L is a constant inductance.

With the value of inductance known from Fig. 3, the resistance can be determined by using

$$R(t)=\frac{V(t)-L\cdot\mathrm{d}i(t)/\mathrm{d}t}{i(t)}.\tag{6}$$

3. Results and discussion

Four different wires (8-μm W wire, 13-μm W wire, 13-μm Mo wire, and 25-μm Mo wire) were used as X-pinch loads in the experiments. Figure 4 shows the typical waveforms of the measured current, the voltage and the X-ray burst that were obtained with an X-pinch load made of two 13-μm W wires. The time reference of $t=0$ was set at the instant in time when the current begins to rise. As can be seen, the X-pinch emits the X-ray burst at $t=56$ ns when the current flowing through the X-pinch is about 60 kA.

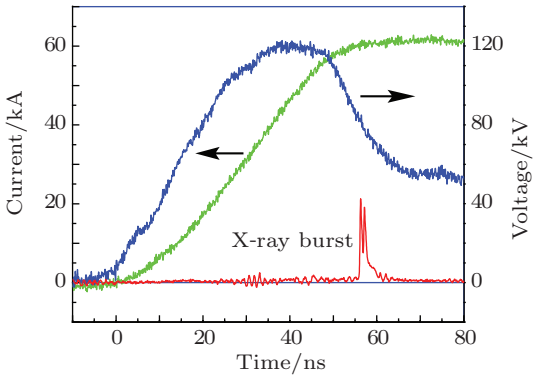


Fig. 4. (color online) Typical waveforms of the measured current, the voltage, and the X-ray burst.

The corresponding impedance and resistance of the X-pinch as functions of time are presented in Fig. 5. The

impedance $Z(t)$ was obtained simply by $V(t)/i(t)$ and the resistance $R(t)$ was determined with Eq. (6). For reference, the waveform of the current is also given in Fig. 5.

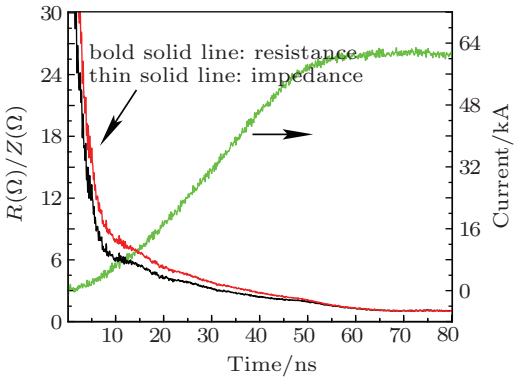


Fig. 5. (color online) Time-varying impedance and resistance of X-pinch made of two 13-μm W wires.

It is well known that when a high current pulse passes through a metallic wire an electrical explosion of the wire occurs.[22,23] As this takes place, the wire, because of its inertia, is overheated throughout its volume or in some regions and evaporates as if exploded. During the evaporation, the metallic conductivity of the wire quickly decreases, resulting in wire resistance increasing by several orders of magnitude. As the metallic vapors quickly expand, especially in vacuum environment as is the situation of the X-pinch, the pressure in the channel falls and, when the voltage across the wire becomes equal to the breakdown voltage of the metallic vapors, an arc discharge is initiated. The variation of resistance shown in Fig. 5 clearly reflects the above-mentioned processes in the exploding wires. At the start of the current flow the resistance of the exploding wires is higher than 30 Ω, ten times as high as the metallic resistance of two 13-μm W wires at room temperature. Then the current increases and resistance falls quickly to about 1 Ω due to a breakdown in the metallic vapors along the wire surface, leading to a transition in the current's path from the highly resistive wire core to the highly conductive plasma.

It is important that the resistance is only a little bit lower than the impedance, indicating that the inductive contribution to the voltage of the X-pinch is less than the resistive contribution. This was further confirmed by the following estimation. From the current curve shown in Fig. 5 we can see that the current rises up linearly with time in the time-range from 20 ns to 40 ns, which means a constant time derivative of the current, $\mathrm{d}i/\mathrm{d}t$, in this time-range. Since $i(t = 20\ \mathrm{ns})$ and $i(t = 40\ \mathrm{ns})$ were found to be about 17 kA and 47 kA, respectively, the constant $\mathrm{d}i/\mathrm{d}t$ was calculated to be 1.5 kA/ns. According to Fig. 3, the inductance of two crossed wires of 13 μm in diameter is 14.2 nH, so the contribution of the inductance to the X-pinch voltage was estimated to be about 21 kV, lower than 26% of the X-pinch voltage in consideration of the X-pinch voltage rising from 80 kV to 120 kV.

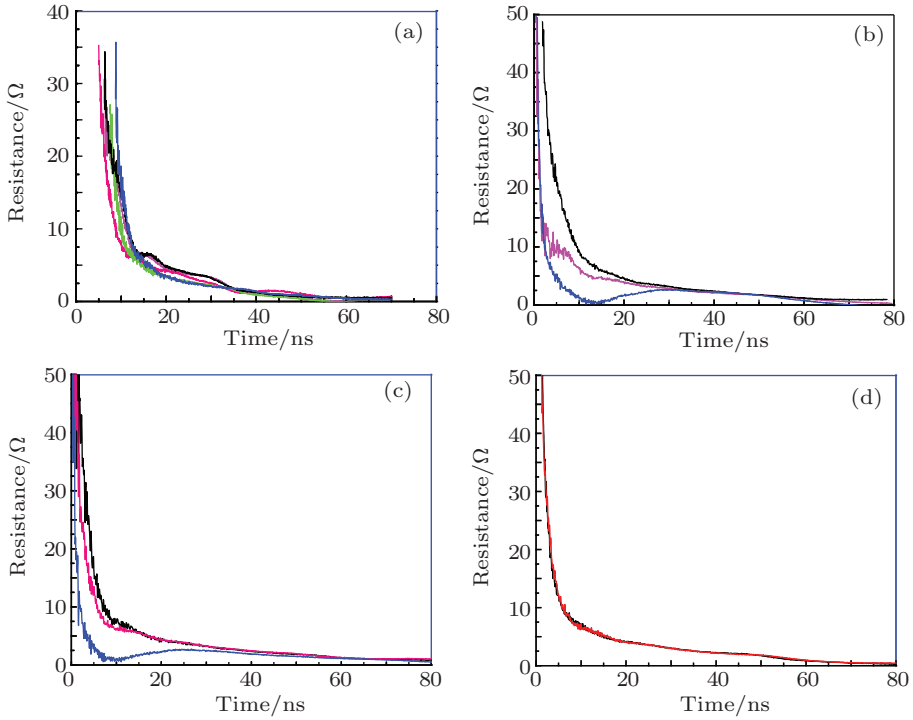


Fig. 6. (color online) Resistance as a function of time for the different wires used as X-pinch loads: (a) 13-μm Mo wires, 5 shots; (b) 25-μm Mo wires, 3 shots; (c) 13-μm W wires, 3 shots; (c) 8-μm W wires, 2 shots.

Figure 6 shows the resistance as a function of time for different wires used as X-pinch loads through which approximately the same current flows. Roughly speaking, all the curves have similar shapes, indicating similar processes, i.e., electrical explosion and then a breakdown in the produced metallic vapors. While the resistance curves for 13-μm Mo wires and 8-μm Wu wires from different shots [Figs. 6(a) and 6(d)] almost overlap, those for 25-μm Mo wires and 13-μm Wu wires [Figs. 6(b) and 6(c)] look more distinctive.

For comparison of the resistances of the X-pinches made of the different wires, all the curves shown in Fig. 6 were put together in Fig. 7. Except for two or three curves, all nearly overlap, which means the material and diameter of the wires we used have no strong influence on the resistance. The reason for these similar resistance curves may be that the current flows through the plasma produced by the breakdown in the metallic vapors along the wire surface rather than flowing through the residual core of the wire itself. A similar result was obtained by Schekovenko and his coworkers who found no strong influence of the wires' material on X-ray burst timing.[9]

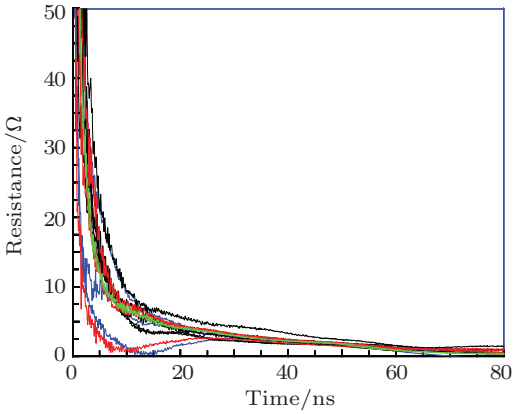


Fig. 7. (color online) Comparison of the resistances of X-pinches made of different wires.

In order to verify the above-mentioned results, we measured and compared the currents flowing through two parallel X-pinches. It was found that the two currents are almost the same even though the diameter and material of the wires used for these two X-pinches are significantly different. Figure 8 is an example. The experimental conditions for Fig. 8 are as follows. Two X-pinches and two return-current rods were paralleled. One X-pinch was made using two 8-μm W wires and the other using two 13-μm Mo wires. The total current output from the pulsed generator was 256 kA in amplitude. From Fig. 8 we can see that there is no big difference between these two currents. The rough equality in both X-pinch currents supports our finding that resistance is dominant in X-pinch impedance and the wire material and diameter have no strong influence on the resistance.

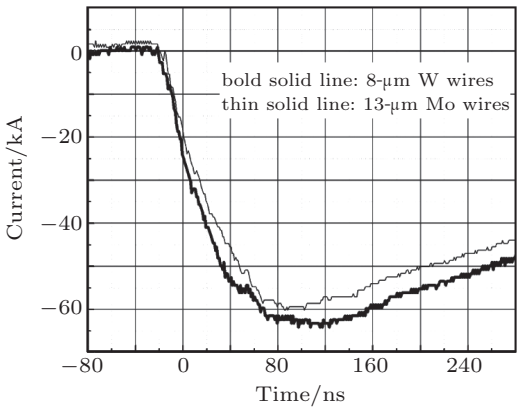


Fig. 8. Comparison between the currents through two parallel X-pinches.

4. Conclusions

At the start of the current flow the resistance of the wires is several tens of Ohms, one order of magnitude, higher than the metallic resistance of the wires at room temperature, and then it falls quickly to about 1 Ω, which reflects the physical processes occurring in the exploding wires, i.e., after the breakdown, there is a redistribution of current, which in the main begins to flow in the region of hot plasma. Our estimation with a simple inductance model shows that the inductive contribution to the measured X-pinch impedance is less than the resistive contribution at least during the initiation phase. For the wires we used, the wires' material and diameter have no strong influence on the resistance. As a result, the current is almost equally divided between two parallel X-pinches even though the diameter and material of the wires used for these two X-pinches are significantly different.

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