X-ray backlighting of two-wire Z-pinch plasma using X-pinch*

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Two 50-μm Mo wires in parallel used as a Z-pinch load are electrically exploded with a pulsed current rising to 275 kA in 125 ns and their explosion processes are backlighted using an X-pinch as an x-ray source. The backlighting images show clearly the processes similar to those occurring in the initial stages of a cylindrical wire-array Z-pinch, including the electric explosion of single wires characterised by the dense wire cores surrounded by a low-density coronal plasma, the expansion of the exploding wire, the sausage instability ($m = 0$) in the coronal plasma around each wire, the motion of the coronal plasma as well as the wire core toward the current centroid, the formation of the precursor plasma column with a twist structure something like that of higher mode instability, especially the kink instability ($m = 1$).

Keywords: X-pinch, Z-pinch, x-ray backlighting
PACC: 5255E, 5270L, 5235P, 9870Q

1. Introduction

The breakthrough in particle beam fusion accelerator-Z (or Z in short), a wire-array Z-pinch that emitted 1.8 MJ x-rays in about 4 ns,[1,2] has sparked the interest in using Z-pinches as x-ray sources for inertial confinement fusion.[3−6] It is generally accepted that the improvement in the load design is responsible for this breakthrough. By using an array with hundreds of fine wires as Z-pinch load, the symmetry of the plasma shell merged by individual wire plasmas is much improved, which reduces the seed level of magneto–Rayleigh–Taylor (MRT) instability.[7−10] However, the detailed processes occurring in seeding MRT instability by the asymmetries related to the discreteness of individual wire plasmas and the manner in which they are merged into a plasma shell are not fully understood. One of the methods for investigating these processes is to backlight Z-pinch plasma using the radiation of a point x-ray source from X-pinch plasma[11−13] or laser-produced plasma.[14,15]

Compared with the x-ray source from the plasma produced by the extremely expensive Z-beamlet laser, which is used for the x-ray backlighting of Z plasma,[16] the x-ray sources produced by X-pinch are affordable to most laboratories and actually have been used in some laboratories for x-ray backlighting of Z-pinch plasma. In order to simulate the prepulse conditions on Z machine, Pikuz *et al.*[17] at Cornell University performed low-current-per-wire experiments in which one to four wires were exploded by a pulse current rising to 4.5 kA in 350 ns and backlighted using X-pinches as x-ray sources. They indicated there to be no detectable plasma forming around 10 μm W wires. Thus, with 300 wires on Z, the 100 ns prepulse will produce little or no W plasma from W wires.[18] Much attention was paid to the high-current-per-wire experiments in which wire arrays were exploded with a fast-rising pulse current ranging from a few tens to one hundred of kiloamperes per wire, and backlighted using X-pinches. The current value per wire in the high-current experiment is similar to that in Z where hundreds of wires were exploded by a 20 MA current and the magnetic field plays an important role in the plasma dynamics. With the x-ray backlighting using X-pinch, Volkov *et al.*[19] in Troitsk obtained the distribution of the plasma density inside a cylindrical wire-array Z-pinch (40 tungsten wires) on Angara-5-1

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facility (2 MA). Lebedev *et al.*[20] at Imperial College studied the effect of core-corona plasma structure on seeding of instabilities in cylindrical wire-array Z-pinches (8–64 wires) powered by mega-ampere generator for plasma implosion experiments generator with a current rising to 1 MA in 240 ns. They concluded that the seeding of perturbations on the wire cores was due to the nonuniform sweeping of the low-density coronal plasma from the wire cores by the magnetic force, which determined the subsequent development of the MRT instability. The experiments were also carried out at Cornell University with linear arrays consisting of 2–8 wires with a current of 15–50 kA per wire.[18] The mass density of the plasma forming around the exploded wires was obtained using a similar method to that given in Ref. [19].

In the present article we describe our experiment on x-ray backlighting of two-wire Z-pinch plasma using an X-pinch as an x-ray source. Two-wire Z-pinch load is the simplest linear wire-array in which there is also the tendency for the current-carrying plasma to be magnetically drawn away from the wires toward the centroid of the current, even though the geometry is not cylindrical. Therefore, the results are relevant to the experiments on cylindrical wire-array Z-pinches. The advantages of using a linear wire-array are no image distortions due to the plane of the array being oriented to the direction perpendicular to the lines-of-sight of the backlighter (X-pinch) and no overlapping images of the wires located at different planes. The backlighting images we obtained show clearly the typical processes occurring in a wire-array Z-pinch.

2. Experimental arrangement

Figure 1 illustrates the experimental arrangement schematically. The experiments were performed on pulsed power generator-1 (PPG-1) that is capable of delivering a pulse current of up to 400 kA to a load in about 125 ns.[21] Two Mo wires of 50 μm in diameter, 10 mm in length and 2 mm in spacing between wires were used as a Z-pinch load, which connected the anode and the cathode at the output of PPG-1. The total current passing through this two-wire Z-pinch load was measured with a Rogowski coil to be in a range of 250–275 kA, corresponding to 125–138 kA per wire. Used as the x-ray source for backlighting, an X-pinch consisting of two 13 μm diameter Mo wires that cross and touch at a single point, thereby forming an 'X' shape, was installed between the anode and the cathode to serve as one of three current-return rods at a position of 60 mm from the Z-pinch.

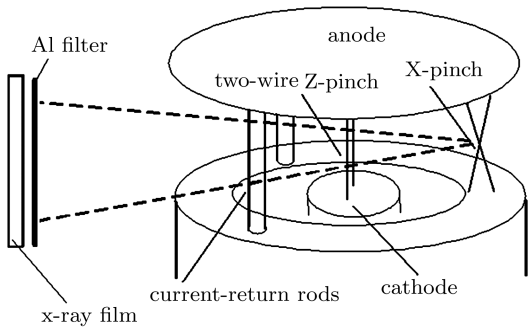


Fig. 1. Experimental arrangement for backlighting of Z-pinch using X-pinch as x-ray source.

The x-ray-sensitive film (KODAK: BioMax-MS) was covered with a 13 μm-thick Al filter to cut off the photons with energies lower than 3 keV, and located at a position of 810 mm away from the Z-pinch. With this geometrical arrangement, the magnification for the Z-pinch image is 14.5. Three diamond photoconducting detectors (PCDs) covered with different filters were used to measure the x-ray pulses of different cut-off photon energies from the X-pinch, and an x-ray pinhole camera was used to record the pattern of the x-ray source. The signals from the Rogowski coil and from the PCDs were fed to a fast digitizing oscilloscope (Lecroy SDA6020) with a bandwidth of 6 GHz and a sampling rate of 20 GS/s.

3. Results and discussion

High temporal and spatial resolutions are required for achieving backlighting images of good quality. The high temporal resolution is determined by the very short pulse duration of x-rays emitted from the X-pinch. The high spatial resolution is dependent on the small size of point x-ray source as well as the geometrical arrangement and the spatial resolution of x-ray film. The x-ray emission from the X-pinch has been studied in our previous paper[22] and the typical results were shown in Fig. 2. Figure 2(a) shows an x-ray pulse of two peaks and about 0.5 ns in pulse width (full width at half magnitude). Figure 2(b) shows the corresponding pattern of x-ray source consisting of two nearly overlapping points, consistent with the two peaks of the x-ray pulse. If the pinhole size of 8 μm is taken into account, the sizes of the point sources should be smaller than 5 μm, which corresponds to a spatial resolution of a few micrometers.[23]

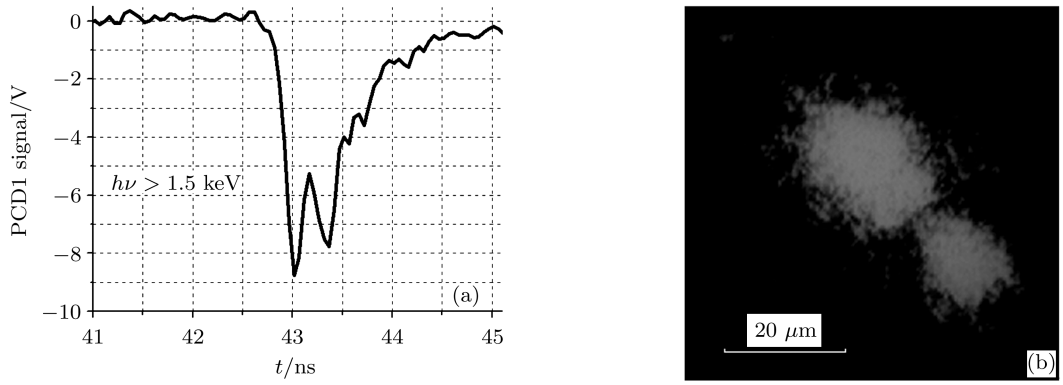


Fig. 2. Typical x-ray emission from the X-pinch. (a) x-ray pulse, (b) pattern of x-ray source.

Figure 3 shows two typical x-ray backlighting images of two-wire Z-pinch for shot Nos. 2009042216 and 2009060417. The time moment when the image was taken was determined by the relative time of backlighter x-ray pulse to the onset of the current flowing through the Z-pinch. The waveforms for shot No. 2009042216 are shown in Fig. 4 from which we know that the image of Fig. 3(a) was taken at the time moment of 61 ns when a current of 155 kA was flowing through the two-wire Z-pinch.

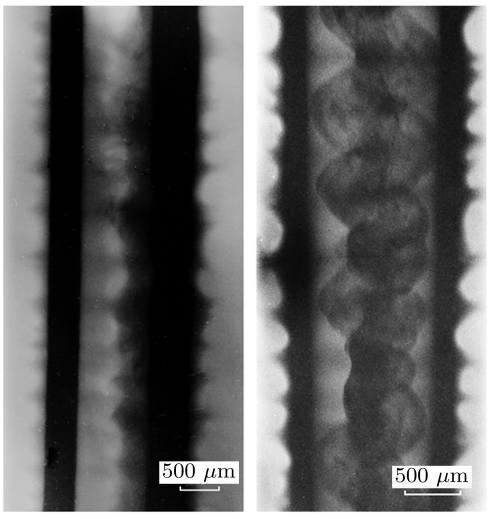


Fig. 3. X-ray backlighting images of two-wire Z-pinch for shot No. 2009042216, 61 ns and 155 kA (a) and shot No. 2009060417, 86 ns and 215 kA (b).

All the processes similar to those occurring in the initial stages of a cylindrical wire-array Z-pinch can be observed in Fig. 3(a), including the electric explosion of single wire, the expansion of the exploding wire, MRT ($m = 0$) stability in the coronal plasma, the coronal plasma as well as the wire core moving toward the current centroid. From Fig. 3(a) we can see

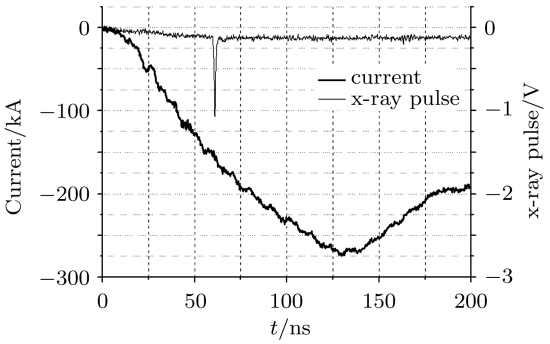


Fig. 4. Waveforms of the x-ray pulse and the Z-pinch current for shot No. 2009042216.

that individual dense wire core is surrounded by low-density coronal plasma produced by the breakdown in the desorbed gases and metallic vapour from the wire surface as a result of the Joule heating, which is a physical picture typical of the electric explosion of single wire. The coronal plasma as well as the wire cores expanded rapidly, and the diameters of these two wire cores were measured to be 410 μm and 580 μm, about 8–12 times as large as their initial diameters of 50 μm (before explosion). It is noted that the wires expanded differently even with using the same wires, which may lead to an asymmetry in the plasma shell merged by individual wire plasmas from a wire-array. Induced by self-magnetic pinch forces as the current increases, MRT stability ($m = 0$) was observed in the coronal plasma that was highly nonuniform axially. The instability pattern around each wire shows a quasiperiodic structure with a wavelength of about 400 μm. It is easy to find that coronal plasma is lo-

cated more in between the two wires than in the other side of each wire, which means the coronal plasma was swept away from the wire to the current centroid by the global magnetic field. To our surprise, the dense wire cores also moved much toward the current centroid at the time as early as 61 ns and the distance between the two wires was shortened to 1.4 mm from the original distance of 2 mm.

Figure 3(b) shows a backlighting image taken at the time moment of 86 ns when a current of 215 kA was flowing through the two-wire Z-pinch. A big difference between Fig. 3(b) and 3(a) is that the massive coronal plasma swept from the two wires was accumulated at the current centroid and formed so called 'precursor plasma'. The axial nonuniform structure in the coronal plasma around the each wire due to $m = 0$ MRT instability led to, in turn, a nonuniform sweeping of the plasma from the wire and a nonuniform precursor plasma with a twist structure something like that of higher mode MRT instability. In addition, these two wire cores were pulled closer with a distance of about 1.2 mm by a stronger global magnetic force due to a higher current and a longer action time than those in the case of Fig. 3(a).

An important phenomenon was observed on some of the x-ray backlighting images and its example was shown in Fig. 5 for shot No. 2009061217. The image was taken at the time moment of 80 ns when a current of 210 kA was flowing through the two-wire Z-pinch. At the bottom, the precursor plasma column is bent. As we know, there are two types of plasma instabilities, i.e. sausage instability ($m = 0$) and kink instability ($m = 1$), they are easier to develop in the pinched plasma column. The kink distortion consists in a perturbation in the form of a bend or kink in the plasma column. Thus, we attribute this bend in the precursor plasma column to the kink instability.

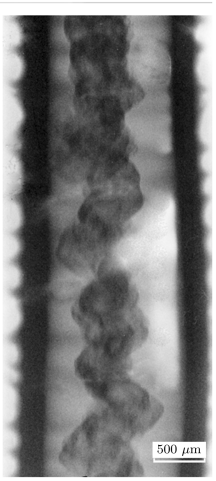


Fig. 5. Kink instability observed at the bottom of the precursor plasma column for shot No. 2009061217, 80 ns and 210 kA.

4. Conclusions

Two 50-μm Mo wires in parallel used as a Z-pinch load are electrically exploded with a pulsed current rising to 275 kA in 125 ns and backlighted using an X-pinch as an x-ray source. The backlighting images show clearly the processes similar to those occurring in the initial stages of a cylindrical wire-array Z-pinch, including the electric explosion of single wires characterised by the dense wire cores surrounded by the low-density coronal plasma, the expansion of the exploding wire, the sausage instability ($m = 0$) in the coronal plasma around each wire, the motion of the coronal plasma as well as the wire core toward the current centroid, the formation of the precursor plasma column with a twist structure something like that of higher mode instability, especially the kink instability ($m = 1$).

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