Vol 14 No 8, August 2005
1009-1963/2005/14(08)/1613-05

Chinese Physics

© 2005 Chin. Phys. Soc.
and IOP Publishing Ltd

Study of tungsten wire array Z-pinch implosion on Qiang-Guang I facility*

Xu Rong-Kun(徐荣昆), Li Zheng-Hong(李正宏), Yang Jian-Lun(杨建伦),
Xu Ze-Ping(许泽平), Ding Ning(丁 宁), Guo Cun(郭 存),
Jiang Shi-Lun(蒋世伦), Ning Jia-Min(宁佳敏), Xia Guang-Xin(夏广新),
Li Lin-Bo(李林波), Song Feng-Jun(宋风军), and Chen Jin-Chuan (陈进川)

China Academy of Engineering Physics, Mianyang 621900, *China*

(Received 8 September 2004; revised manuscript received 27 April 2005)

The main results of investigation on the tungsten wire array Z-pinch implosion experiment performed on Qiang-Guang I facility in 2003 are reported in this paper. A set of diagnostic equipments including an x-ray power meter (XRPM), a 1D spatial-temporal x-ray meter and a pinhole camera was used to study implosion process and x-ray radiation characteristics of the tungsten wire array. In the experiment, the maximum x-ray yield of 36.6kJ was obtained for an optimizing load with a diameter of 8mm and a length of 20mm, which consists of 32 5-μm-diameter tungsten wires. The experimental results show that the region of x-ray emission decreased at a rate of 6.4×10^6cm/s by analysing the data of the 1D spatial-temporal x-ray meter. It also shows that the peak time of x-ray radiation was prior to the time when plasmas were compressed into a near-axis region.

Keywords: Z-pinch, multi-wire array, x-ray, plasma
PACC: 5270L, 0762, 3220

1. Introduction

Z-pinches are very efficient for producing x ray. At present, many Z-pinch devices have achieved $> 10\%$ conversion of stored electrical energy into x-ray.[1−3] The Qiang-Guang I facility (QG-I) located at Institute of Northwest Nuclear Technology can store up to 260 kJ of electrical energy, and 80 kJ can be delivered into a pinch load. It can be used to investigate the Z-pinch implosion process in the case of light loads, and to carry out studies on the process of plasma formation and merging, plasma instability and its influence on the implosion, spatial structure and characteristics of x-ray radiation, etc. It is useful to check a model of Z-pinch by numerical simulation and to adjust calculation parameters. For searching a way to achieve a high x-ray power and conversion coefficient of x-ray energy, a series of experiments with various loads was performed on QG-I in 2003.

2. Experimental arrangement

It is well known that Z-pinch load mass must match parameters of a pulse power facility to gain a high conversion coefficient of x-ray energy. Heavy pinch load results in slow plasma implosion velocity, while light pinch load results in premature implosion before the pinch current reaches its peak value. Theoretical analysis[4] and one-dimensional (1D) calculations show that QG-I can drive a Z-pinch load with mass of 30μg/cm to 150μg/cm. This means that the array load consisting of 10 to 50 tungsten wires with wire diameter of 5 μm can be used. On the other hand, Deemey's research[5] shows that the x-ray power is closely related to the gap of adjacent wires, thus the x-ray can reach a high yield only if the gap is small enough. According to the above analysis, the experiment on QG-I uses the Z-pinch loads with the diameter of wire array from 6 mm to 10 mm, the wire number from 20 to 40, and initial length of 2 cm.

As shown in Fig.1, a load was installed in the horizontal direction. Taking into account a slight shift of the cathode position from the air state to vacuum state, the length of pinch loads was designed to be self-adjustable with an actual value of 1.8cm. Eight current return rods with a diameter of 7.2cm were

*Project supported by the National Natural Science Foundation of China (Grant No 10035030).

arranged symmetrically to carry the anode-disc current. The cathode of the wire array is fixed to a steel column with diameter gradually changing from 3.0cm (near to the wire array) to 4.5cm at the contact with the cathode-plate of the QG-I. The distance from steel column to anode-plate was chosen as 1cm. In addition, the surface of the steel column was polished to reduce the possibility of discharge.

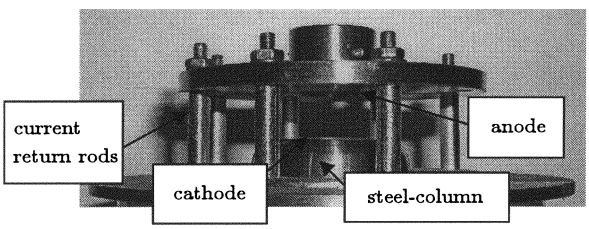


Fig.1. Load configuration, comprising current return rods, cathode, anode and steel column.

In order to observe the features of the x-ray radiation as a function of the initial diameter of wire array, different loads composed of 32 tungsten wires with a diameter of 5μm were used. Three kinds of loads with 6 mm, 8 mm and 10 mm diameter were studied. The x-ray radiation bursts were recorded employing an x-ray power meter and a 5 GS/s Tek.684 A digitizing oscilloscope. A detector, which didn't view the x-ray source of the pinch load to avoid the background disturbance from infrared to ultraviolet rays, was used to record the fluorescence emitted by an x-ray sensitive scintillator. The factors determining time resolution of < 3 ns and a flat energy response are described in Ref.[6]. The radial x-ray images were recorded as a function of time using a 1D spatial-temporal x-ray meter.[7] A pinhole camera was employed to record a time-integrated shadowgraph. A framing camera and a transmission grating were used to record the x-ray images and the time-integrated x-ray spectra, respectively.

3. Experimental results and discussion

Time-integrated pinhole images are shown in Fig.2. The experimentally measured axis length was about 1.6 mm, because a fraction of pinch region near the anode obstructs viewing. There are three individual pinholes covered with 3 μm Al filters, without any filters, and with 0.73μm C_8H_8 add 0.1μm Al filter, respectively. Then, the time-integrated shadowgraph images of > 1 keV in the first pinhole, including visible light in the second, and < 1 keV in the third were obtained. Figure 2 shows that the plasmas were compressed with a better axial uniformity. The emission region according to the middle image was located in a radial scale from 1.5 mm to 2 mm. The x-ray energy of sub-keV or higher was mostly located in a sub-mm radial region according to the other two images. In other words, the x-ray radiation with higher energy mostly came from the pinch center around which the x-ray emission has lower photon energy. In addition, there was no noticeable difference in the final x-ray radiation distribution for the three kinds of loads.

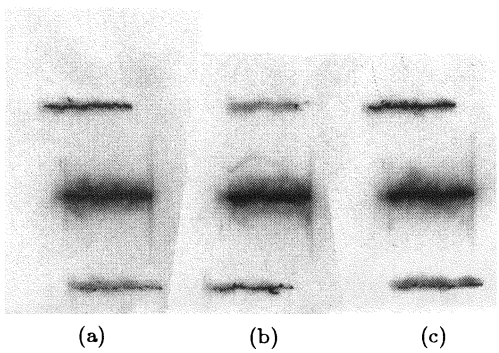


Fig.2. Time-integrated pinhole images with about 50μm spatial resolution for three kinds of loads with different array diameters. (a): D=8 mm; (b) D=10 mm; (c) D=6 mm.

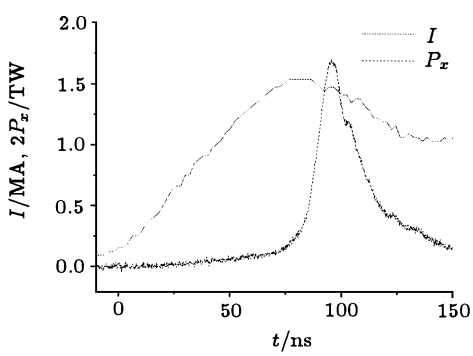


Fig.3. Typical x-ray power waveform obtained by XRPM together with current waveform in shot 03197. The load with a diameter of 8 mm consists of 32 tungsten wires with wire diameter 5 μm.

Under the same condition, the XRPM has the same sensitivity to effectively compare the variation of the x-ray radiation at different pinch loads. Typical waveform of x-ray power, together with load current in shot 03197, are shown in Fig.3.The rise time and peak value of load current in this shot are 62 ns and 1.54 MA. The rise time of x-ray radiation and full width at half maximum (FWHM) are 15 ns and 21 ns, respectively. The time of maximum x-ray power was at 5 ns after the time of maximal load current value.

The power and yield of the x-ray shown in Fig.3 are 0.91 TW and 33.4 kJ, respectively.

The x-ray yield and power as a function of the initial diameter of the wire array are shown in Fig.4 and Fig.5. It is obvious that the experimental data for the same pinch loads have a fluctuation because of the instability of the implosion process. However, on the whole, this fluctuation with value of 0.06 TW, 0.07 TW and 0.21 TW is small compared to the difference of x-ray power between different pinch loads, as shown in Fig.5. It shows, by the way, that the loads prepared in our experiments were well controlled in their quality. Using the well-fabricated wire arrays, Fig.4 and Fig.5 definitely show that the array with diameter of 8 mm has significantly higher x-ray power and yield than the other two kinds of arrays.

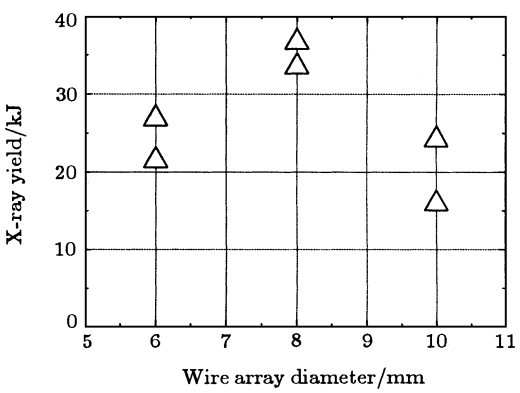


Fig.4. Comparison of x-ray yield as a function of diameter of wire arrays for all six shots.

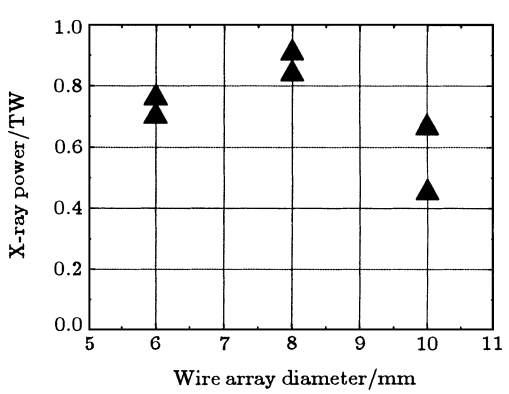


Fig.5. Comparison of x-ray power as a function of diameter of wire arrays for all six shots.

Some characteristic electric parameters are listed in Table 1. The voltage and current listed in Table 1 were composed fundamentally of both incident wave initiated by the generator and reflected wave originating from the difference of the plasma impedance and the input impedance. To a certain extent the difference of electric parameters indicates the difference of pinch process of different kinds of load. Depending upon the pinch load impedance being greater or less than the input impedance, the reflected wave could be positive or negative. However, the reflected wave will extend the electric pulse width at any rate due to the gradual increasing of plasmas impedance during the implosion. As for the extension scale, we assume that it is related to the variation of plasma implosion phase. For example, it is related to the convergence ratio of initial wire array radius to the plasma radius at the time of maximum current, because the plasma impedance gradually increases with decreasing of the distribution radius of plasma. The convergence ratio of 8 mm diameter load was smaller than that of 10 mm and of 6 mm diameter load, as the bigger initial radius resulted in a larger compression ratio in the case of 10 mm diameter load and the earliest compressed plasmas also resulted in a larger compression ratio in the case of 6 mm diameter load.

Table 1. Characteristics of load voltage and current for the three kinds of loads.

load diameter	I		V	
/nm	t_r/ns	Max./MA	FWHM/ns	Max./MV
10	68	1.70	87	0.95
10	68	1.51	93	0.91
8	64	1.63	82	1.08
8	62	1.54	82	1.09
6	64	1.44	85	1.16
6	64	1.44	83	1.11

Radial distribution of x-ray power as a function of time was measured by a 1D x-ray spatial-temporal imaging system with axial and radial fields of view. The axial and radial viewing regions are 2.2 mm and 5.9 mm, respectively. The two typical images obtained in shots 03197 and 03195 for different loads of diameter 10 mm and 5 mm are shown in Fig.6 and Fig.7. It is shown that the initial time of x-ray radiation on the axis was prior to that of near-axis region in Fig.6. Fig.8 shows that the region of x-ray radiation first extended to 1.4 mm, and then gradually decreased at a rate of 6.4×10^6 cm/s and the whole process lasted about 15 ns. As Fig.6, Fig.7 also indicates that the x-ray radiation started from the axis and lasted about 15 ns, first reaching quickly a maximum radial size, then gradually decreasing.

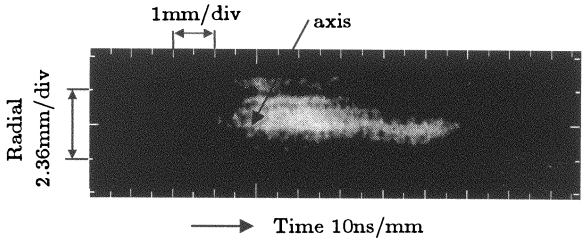


Fig.6. Radial x-ray radiation distribution in shot 3197 with a spatial resolution of 0.15 mm.

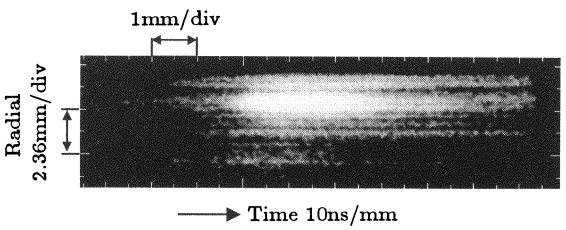


Fig.7. Radial x-ray radiation distribution in shot 3195 with a spatial resolution of 0.15 mm.

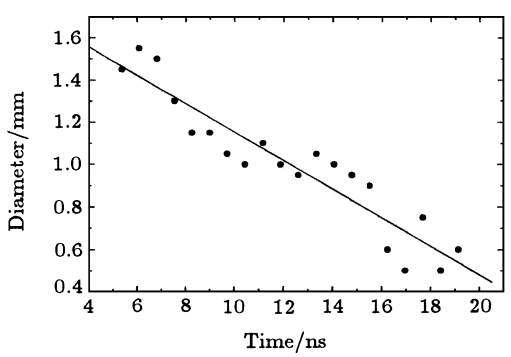


Fig.8. Radial x-ray radiation size reducing as a function of time in shot 3197, the x-ray radiation region was gradually decreasing at a rate of 6.4×10^6 cm/s.

The streak images of x-ray radiation distribution as shown in Fig.6 and Fig.7 lead to the following points:

1) A fraction of plasmas reaches to the axis at a relatively earlier time, the remaining part of the plasmas gradually fills the whole region, then stagnated with x-ray burst. No plasma shell was observed in this experiment, which indicates the non-homogeneity and non-synchronization of the pinch process. This may be attributed to the relatively large gap between adjacent wires, and, as has been confirmed by previous researches, the plasmas breaking away from adjacent wires are not well merged and are compressed individually for loads with fewer wires.

2) The plasmas are distributed in a radial region from 1.4 mm to 1.5 mm for some time corresponding to the scanning images in shot 3197, because the x-ray radiation only comes from the implosion. It means that the convergence ratio r_0/r_1, where r_0 was the initial radius of wire array and r_1 was radius of the plasmas, was from 5 to 7 for loads of 8 mm and 10 mm diameter at this stage. This is relatively small compared with the results of experiments conducted on Angara-5-1 facility. As is well known, the temperature of plasmas was closely related to the convergence ratio r_0/r_1; a higher r_0/r_1 means a higher temperature and a shorter x-ray pulse duration, which is the reason for the relatively wider pulse duration as shown in Fig.3.

3) The strong x-ray emission in a steady radial region lasted about 15 ns, just as shown in Fig.6 and Fig.7. According to the brightness of the scanning images, the radially-integrated x-ray radiation intensity gradually decreased with the decrease of the x-ray radiation region. This means that the strongest x-ray radiation was prior to the stagnation of implosion. A qualitative explanation for this phenomenon is that there exists a equilibrium of outward plasma pressure with the inward magnetic pressure on the boundary as shown in Fig.6, i.e. when internal energy of plasmas and its outward pressure gradually increased with the plasmas pouring into the boundary in the leading edge of load current, the magnetic pressure increased synchronously, resulting in a balance and a steady boundary for a few nanoseconds at this stage. On the other hand, the plasma will deliver its energy in the form of x-ray radiation in the rear edge of the current, which causes a decrease of plasma temperature in this process. While the pinch force also decreased with the decreasing of load current, the balance was kept and lasted for a few nanoseconds. When the balance was broken, the pinch force was dominant, which resulted in the decrease of plasma distribution. Further investigation of this process by means of laser probing with time and spatial resolution is under consideration.

4. Conclusion

1. Experiments with different kinds of loads were successfully performed on the QG-I facility. Maximum x-ray yield was 36.6 kJ for an optimized load with a diameter of 8 mm, consisting of 36 wires with a wire diameter of 5 μm. Because of the relatively small convergence ratio r_0/r_1, FWHM of the x-ray power waveform was larger than 20 ns.

2. The period of most intensive x-ray radiation corresponds to the steady radial region in which the x-ray radiation which sustains for a more or less long

time, and then its intensity gradually decreases with the reduction of x-ray radiation region.

3. The strongest x-ray radiation occurred before the plasmas were compressed into a small region.

Acknowledgements

Thanks to Kuai-Bin, Zhou Chong Pi-Tian and all their group for many useful suggestions.

References

[1] Yoans G 1998 *Sci. Am.* **8** 40
[2] Sanford T W L *et al* 1996 *Phys. Rev. Lett.* **77** 5063
[3] Spielman R B *et al* 1998 *Phys. Plasmas* **5** 2105
[4] Ding N, Yang Z H and Ning C 2004 *Acta Phys. Sin.* **53** 808 (in Chinese)
[5] Deemey C *et al* 1997 *Phys. Rev.* E **56** 5945
[6] Guo C *et al* 2004 *Acta Phys. Sin.* **53** 1331 (in Chinese)
[7] Xu R K *et al* 2003 *Acta Phys. Sin.* 52 1203 (in Chinese)