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The Simulation and Analysis of the Z-pinch Experiments on Qiang-Guang-I Facility

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Abstract: The Z-pinch implosion series experiments have been carried out successfully on the Quang-Guang I facility (QG-I) using tungsten wire-array loads with difference high. It is verified experimentally that the x-ray power of tungsten wire array has no vary obviously as difference high. Based on the measured electric current waveform, one dimension magneto-hydrodynamic simulation （MARED code） shows that the power of x-ray radiation increases with the electric current for the same loads. However, it was not obtained by the experiment. From comparing the experiments with computation results, we conjectured that the electric current measured on the QG-I facility pass through the load partly, did not all pass through one.

1. INTRODUCTION

Z-pinches are very efficient laboratory x-ray sources. The wire-array Z-pinch has in a very short time achieved remarkable performance, and represents a most effective way of coupling stored magnetic energy into soft x-radiation with conversion efficiency of about 15% from the wall-plug.[1,2] As same other small-scale facilities at Imperial College and Cornell and TRINITI, Z-pinch series experiments have been conducted at 1.5MA with aluminium and tungsten wire arrays on the QG-I facility.[3] The QG-I located at Institute of Northwest Nuclear Technology can store up to 260 kJ of electrical energy, and about 80 kJ can be delivered into a pinch load. We use it to investigate the Z-pinch implosion process in the case of light loads with mass of 30 to 150 μg/cm, 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.. The dynamics of the wire-array Z-pinch self-constriction process depend mainly on the following parameters of the system: the length and initial radius of wire-array load, the initial load mass, and the amplitude and rise time of the electric current through it. For searching a way to achieve a high x-ray power and conversion of x-ray energy, a series of experiments with various loads has been performed QG-I from 2002 to now. The experiments can also be useful to check a model of Z-pinch by numerical simulation and to adjust calculation parameters. It is well known that the application of simulations of Z-pinch implosions should have at least two goals: first, to properly model the most important physical processes occurring in the pinch allowing for a better understanding of the experiments and second, provide a design capability for future experiments. We have developed a MHD code (called as MARED code[4]) for simulating Z-pinches in two dimensions which has reproduced important feature of the measured experimental current drive, radiation pulse shape, peak power and total radiated energy. Using MARED code to simulate one dimension (1D) Z-pinch implosion process employs essentially only one free parameter which is plasma resistivity. Currently we are applying this capability to the analysis of recent QG-I experiments. The code results provide insight into the nature of the pinch plasma prior to arrival on-axis, during thermalization and development after peak pinch time.

2. MAIN EXPERIMENTAL RESULTS AND SIMULATION ANALYSIS

To investigate the implosion dynamics of tungsten (W) wire array Z-pinch and the characteristics of x-ray radiation, the experiments were performed on the QG-I facility, and 1D MHD simulation was carried out by MARED code.

We report and discuss mainly the results of x-ray radiation measurements in Z-pinch experiments on QG-I with load current of 1.29 ~1.52 MA. The x-ray radiation power obtained on the Z-pinch implosion experiments is very important. The measurements were conducted by using an x-ray power meter (XRPM). The x-ray power waveform measured indicates a change of x-ray radiation, presents the magnitude of the x-ray power, the rise time of x-ray radiation, full width at half maximum (FWHM) and the time of maximum x-ray power (we defined it as the implosion time).

On the QG-I's experiments, arrays with mass of 121μg/cm consisting of 32 5μm W wires were arranged in a circle of radius 4mm between electrodes separated by 15mm, 20mm and 25mm. In order to observe and research implosion processes, a set of diagnosis equipments were employed. Such as, the XRPM was used to obtain the x-ray radiation pulse power. A time-resolved pinhole camera (2ns gate time with 10ns separation) was used to obtain soft x-ray images, which was filtered by 2μm polypropylene and was sensitive to 100ev-10kev photons.

Under the same conditions, the XRPM has the same sensitivity to effectively compare the variation of the x-ray radiation at pinch loads with different length. Typical waveform of x-ray power together with load current in shot 05159 is shown in Fig.1. The rise time and peak value of load current in this shot are listed in Table 1. The time of maximum x-ray power was at 10.25ns after the time of maximal load current value. The power and yield of the x-ray shown in Fig. 1 are 0.42TW and about 16kJ, respectively. In Table1,"dt" presents the interval between the time of the x-ray peak power and the time of the load current peak value.

Table 1. Characteristics of x-ray power and current for three kinds of difference length wire array

Shot No.	Length (mm)	Power (TW)	FWHM (ns)	X-ray Energy (kJ)	Current Peak Value (MA)	Rise Time (ns)	dt (ns)	Energy Efficiency (%)
05151	15	0.43	21.1	13.7	1.29	67.21	19.55	5.28
05152	15	0.52	13.9	13.8	1.45	66.66	13.55	5.30
05153	15	0.16	42.9	8.5	1.52	81.74	-34.75	3.29
05163	15	0.45	19.5	16.2	1.52	70.75	-1.75	6.21
05156	20	0.19	28.6	10.5	1.51	79.71	-35.75	4.03
05157	20	0.53	25.5	19.3	1.33	73.09	16.05	7.41
05158	20	0.45	20.2	17.4	1.29	113.2	-42.75	6.69
05159	20	0.42	22.5	15.9	1.33	93.7	10.25	6.13
05162	25	0.45	18.0	13.7	1.47	71.94	6.25	5.25
05164	25	0.51	22.7	19.7	1.29	82.89	3.05	7.59
05165	25	0.15	30.6	12.4	1.37	54.95	2.85	4.76

The x-ray powers of the wire-array loads with different length are shown in Fig. 2. It is obvious that the experimental data of the same pinch loads have a fluctuation because of the instability of the implosion process. From Tab.1 and Fig.2, we found that firstly, the x-ray power measured by XRPM were not sensitively depend on the change of the load length. Secondly, with the load current increasing, however, the x-ray power and total x-ray energy were not certainly increased. Specially, for shots 05153, 05156 and 05165, though the currents become larger, but the x-ray power was down. This is a mystery, if we acknowledge the truth that total x-ray energy output is determined by the current, the x-ray pulse width must be decrease in order to optimize the x-ray power on any given pulsed-power accelerator. When we realized the facts of experimental processes of the three shots on QG-I that the initially setting loads have some trouble, for example, twisting the wire array of shot 05153, making the array of shot 05165 incline, and so on, the mystery goes away. Therefore, the three shots belong to abnormal discharge of Z-pinch implosion, shown as Fig.3, on which displays the soft x-ray emission during the implosion of 32 5μm W wire array. In order to compare, the image of normal discharge of shot 05164 is also shown in Fig.3.

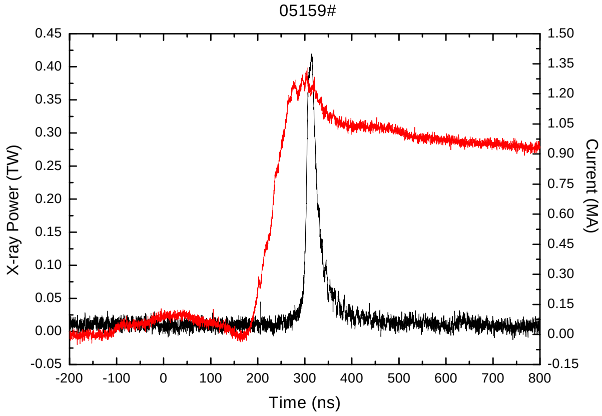


Fig.1 Typical x-ray power waveform obtained by XRPM together with load current waveform in shot 05159, the load with a diameter of 8mm consists on 32 W wire with diameter 5μm and length 20mm.

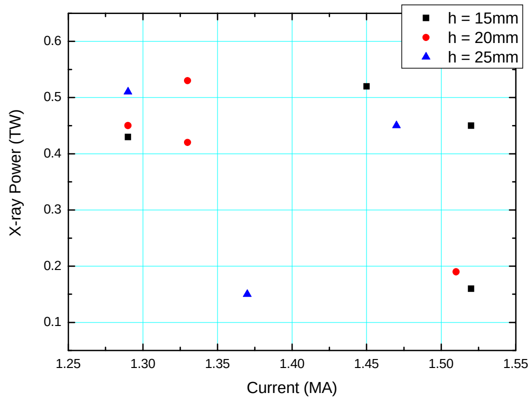


Fig. 2 Comparison of x-ray power as a function of load current of wire arrays for all shots with difference length.

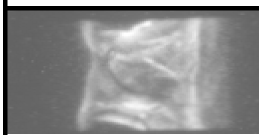
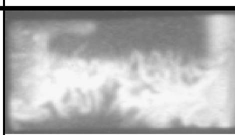
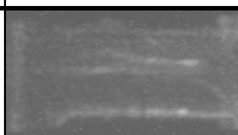
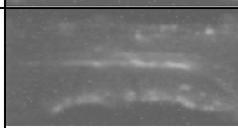
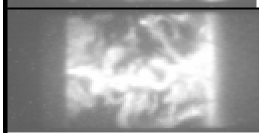
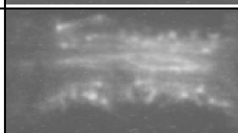
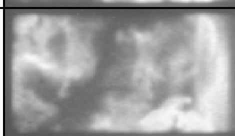
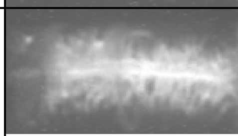
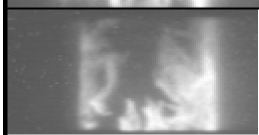
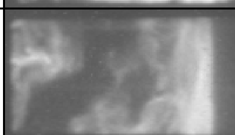
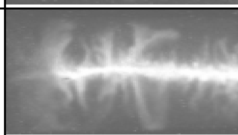
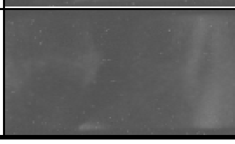
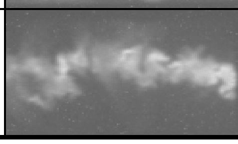
a. 05153#(*l*=15mm, 1.52MA, 0.16TW)		b. 05165#(*l*=25mm, 1.37MA, 0.15TW)		c. 05164#(*l*=25mm, 1.29MA, 0.51TW)	
Anode Cathode	ns/μm	Anode Cathode	ns/μm	Anode Cathode	ns/μm
	-38.8/ 100		-13.8/ 150		-50.6/ 150
	-28.8/ 100		-3.8/ 150		-40.6/ 150
	-18.8/ 100		+6.2/ 150		-30.6/ 150
	-8.8/ 100		+16.2/ 150		-20.6/ 150
	+1.2/ 100		+26.2/ 150		-10.6/ 100
	+11.2/ 50		+36.2/ 100		-0.6/ 100
	+21.2/ 50		+46.2/ 100		+9.4/ 100

Fig.3 X-ray pinhole time-resolved camera images of shots 05153, 05165 and 05164. Diameters of the pinholes in images are ϕ50μm, ϕ100μm and ϕ150μm. Time each image is measured with respect to the time of the X-ray peak power measured in XRPM.

In any case, the experiment of W wire array on QG-I represent the x-ray powers were not increased by rising load current. That is, the wire array implosion with larger load current measured did not imply it obtained larger x-ray power. Whereas, the simulation results by MARED code shown that the x-ray power and x-ray radiation total energy are increasing with the load current increasing, shown as Fig.4, for the same loads under the same simulation conditions. In theory, it is reasonable conclusion because the Z-pinch system should be keep the energy conservation. As we know that, when the QG-I facility starts with a certain amount of energy from a capacitor bank and this energy gets divided up between the magnetic field energy and kinetic energy of the particles in the plasma. If the measured load current become rising, the x-ray power and total energy going down, it concluded that there be not all measured current through the load. The phenomena may be caused by the limitation of measurement technologies. By this token, measuring accurately the magnetic field and load current during implosion processes is very important to analysis and understand the Z-pinch physics.

3. CONCLUSION

On the QG-I facility, the Z-pinch implosion series experiments have been carried out successfully. It is verified experimentally that the X-ray power of W wire array measured by XRPM has no vary obviously as difference length. Based on the measured electric current waveform, 1D simulation using MARED code shows that the power of x-ray radiation increases with the electric current for the same loads. It is reasonable in theory due to the energy conservation of a Z-pinch system. However, the lowest x-ray power was obtained, and the maximal current was measured for once discharge experiment. From comparing the experiments with computation results, we conjecture that the electric current measured on the QG-I facility pass through the load partly, did not all pass through one.

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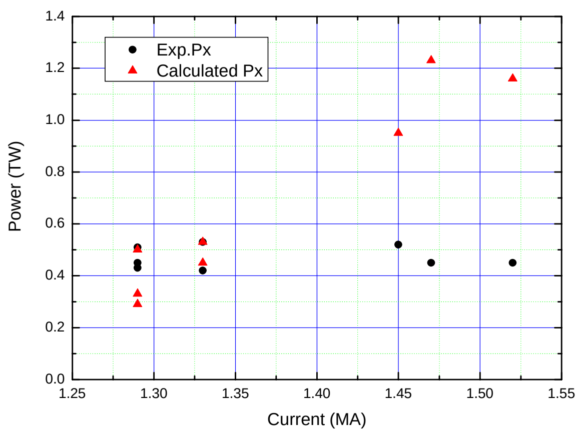

Fig.4 The calculated and measured the x-ray power as a function of load current.

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