Vol 14 No 9, September 2005
1009-1963/2005/14(09)/1856-06

Chinese Physics

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

Effects of drive current rise-time and initial load density distribution on Z-pinch characteristics*

Duan Yao-Yong(段耀勇), Guo Yong-Hui(郭永辉)†
Wang Wen-Sheng(王文生), and Qiu Ai-Ci(邱爱慈)

Northwest Institute of Nuclear Technology, Xi'an 710024, China

(Received 26 October 2004; revised manuscript received 26 November 2004)

A two-dimensional, three-temperature radiation magneto-hydrodynamics model is applied to the investigation of evolutional trends in x-ray radiation power, energy, peak plasma temperature and density as functions of drive current rise-time and initial load density distribution by using the typical experimental parameters of tungsten wire-array Z-pinch on the Qiangguang-I generator. The numerical results show that as the drive current rise-time is shortened, x-ray radiation peak power, energy, peak plasma density and peak ion temperature increase approximately linearly, but among them the x-ray radiation peak power increases more quickly. As the initial plasma density distribution in the radial direction becomes gradually flattened, the peak radiation power and the peak ion-temperature almost exponentially increase, while the radiation energy and the peak plasma density change only a little. The main effect of shortening drive current rise-time is to enhance compression of plasma, and the effect of flattening initial load density distribution in the radial direction is to raise the plasma temperature. Both of the approaches elevate the x-ray peak radiation power.

Keywords: Z-pinch, drive current rise-time, initial load density distribution numerical simulation
PACC: 5255E, 5265, 4765

1. Introduction

Z-pinch can produce a high temperature and high density plasma by passing an intense pulsed current through a wire or wire-array mounted on the generator, and is an efficient approach to producing high-power x-ray radiation. Recently, many laboratories have been performing research works on large-scale generators due to developments in pulsed power technology and computer simulation capability.[1] Z-pinches not only provide an opportunity to study properties of materials in extreme conditions and obtain information about the equation of state and opacities in astrophysics, but also can be of interest to pulsed XUV or x-ray lasers. Z-pinch-produced x-ray radiation may imitate the environment of nuclear detonation and is applied to inertial confinement fusion.[2] A number of theoretical studies[3,4] and numerical simulations[5−9] have been carried out in China, including some experimental research, e.g. Refs.[10,11], to mention only a few here.

A two-dimensional (in r–z plane), three-temperature radiation magneto–hydrodynamics code for the modelling of Z-pinch experiments on Qiangguang-I generator has been developed, and then tungsten-wire array Z-pinch processes[8] and its sausage instabilities [9] have been simulated numerically in detail. The equations, parameters and numerical techniques in this model were given in the Ref.[8]. In this paper, the effects of drive current rise-time and initial load density distribution on plasma temperature, density, x-ray radiation power and energy are highlighted, in order to explore the approaches of increasing x-ray radiation power. Any physical instabilities produced by imploding plasma and any influence by other complicating factors are neglected intentionally, because a comparatively simple physical environment is in favour of discerning the different

*Project supported by the National Natural Science Foundation of China (Grant No 10035020).
†E-mail: gyh661012@163.com

effects of the above two factors. Varying only one parameter while keeping all other parameters constant is one of the unique advantages of numerical simulation, by virtue of which it is easy for us to distinguish the particular effect of any single parameter.

It is very difficult to fully numerically simulate the Z-pinch plasma global dynamical process, for it demands an additional appropriate code that can treat wire melting, gasification and ionization, and amalgamation of wire-array under the action of the prepulse current, but all of which cannot be dealt with in our current code. In our model, initial load density distribution is assumed as a plasma cylinder with uniform density distribution in the azimuthal and the axial directions, but with non-uniform density distribution in the radial direction. Physically, the drive current pulse rise-time can be modified by the combination of generator components and load parameters, and the initial load density distribution can almost be designed artificially before experiment. According to our current diagnoses of Z-pinch experiments on Qiangguang-I generator, we choose such parameters as the initial conditions in our simulations, under which the time-resolution x-ray photograph is clearly taken and the time-dependent radiation power is accurately measured. After comparing the calculated results and the measured ones, we change initial load density distribution or drive current rise-time with all other parameters constant, so that the single parameter effect on x-ray output can be found.

2. Variation of drive current rise-times

One set of typical experimental parameters of Z-pinch on Qiangguang-I generator is as follows. The cylindrical tungsten wire-array load consists of 48 wires with the total mass of 363.6μg and the load diameter R of 1.2 cm, in which each wire has a diameter of 5 μm and a height of 2cm. The drive current rise-time is some 98ns with about 1.6MA in amplitude. The measured x-ray output energy $E_{\rm x}$ is about 30kJ. The measured time-dependent x-ray power $P_{\rm x}$ is given in Fig.1, and the time-resolution x-ray photograph at pinch time in Fig.2.

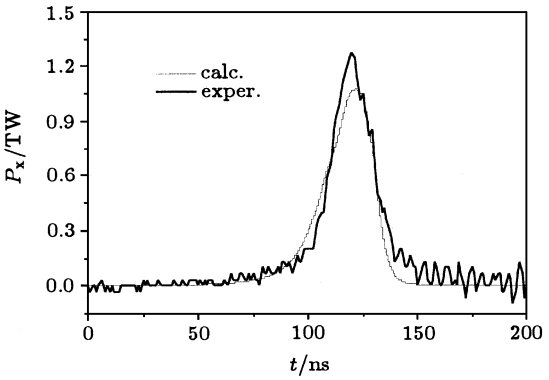


Fig.1. Comparison of experimentally measured time-dependent x-ray power and the calculated one.

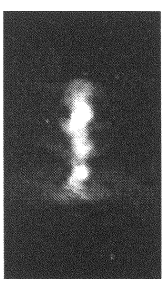


Fig.2. W-array load pinch x-ray time-resolution photograph at pinch time.

In our numerical simulation, the initial load density distribution is assumed as $\rho(r,z) = \alpha r^{\beta}$, where the constant α is determined by total mass conservation law, and $\beta \geq 0$ is the exponential factor denoting the slope of density distribution in the radial direction. The drive current through the load is approximated by a sine function with a period of 4×98ns and current amplitude of 1.6MA. (It should be noted that this approximation to the drive current profile only accounts for the current rise-time and current amplitude which characterize the global distribution, and that the detail in the profile is omitted. Variation of rise-times of the current implies the variation of the full width at half maximum of the current). The exponential factor β in the initial density distribution is assumed as 2, which approximates the initial radial density distribution that increases when $r = 0 \rightarrow R$. The calculated x-ray energy is about 29.45kJ. For convenience of the comparison between the calculated and the measured results, the calculated time-dependent x-ray power is also given in Fig.1. Both the x-ray output energy and the time-dependent x-ray radiation power agree approximately with the corresponding measured ones.

Now, we investigate the evolution of some characteristic quantities of the plasma and the corresponding x-ray radiation for 5 drive current rise-times t_{rt}= 68 ns, 78 ns, 88 ns, 98ns and 108ns, with all other parameters in the simulation unchanged. The 5 symbols in Figs.3–6, τ_1, τ_2, τ_3, τ_4 and τ_5, are used to indicate the corresponding numerical results, where the symbol τ_4 corresponds to the above experimental case. The calculated x-ray radiation energy E_x as the function of time t for the 5 cases is given in Fig.3, the x-ray radiation power P_x in Fig.4, the plasma density ρ_{axis} at the centre of z-axis in Fig.5, and ion temperature T_i at the centre of z-axis in Fig.6. The 4 characteristic quantities—x-ray peak power, x-ray energy, peak plasma density and peak ion temperature at the centre of z-axis—are summarized in Table 1.

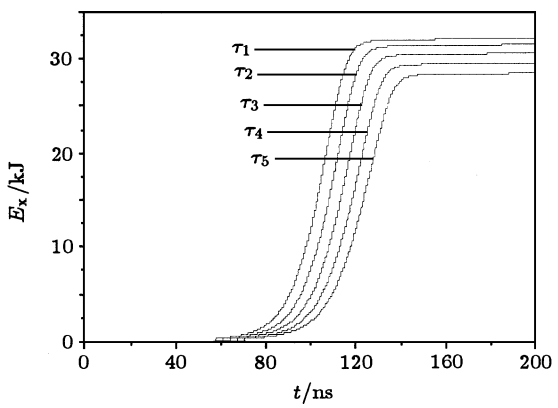


Fig.3. X-ray energy vs time for different drive current rise-times.

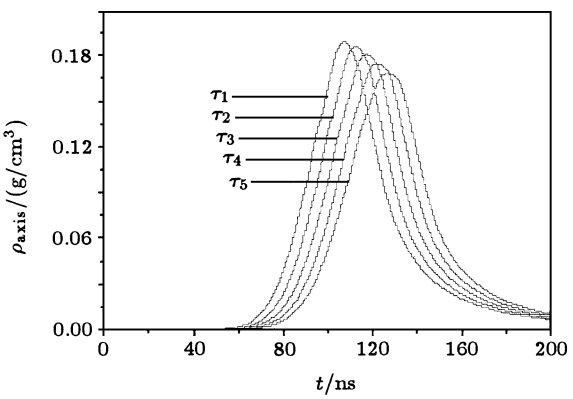


Fig.5. Density at the centre of z-axis vs time for different drive current rise-times.

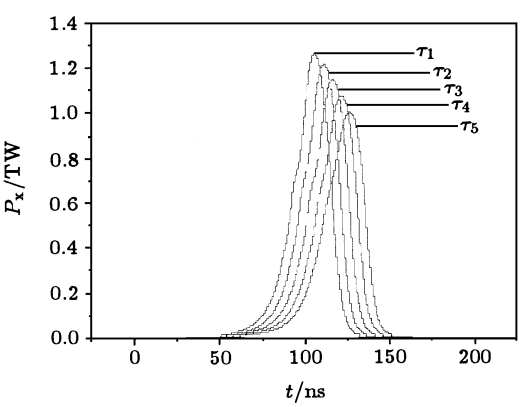


Fig.4. X-ray power vs time for different drive current rise-times.

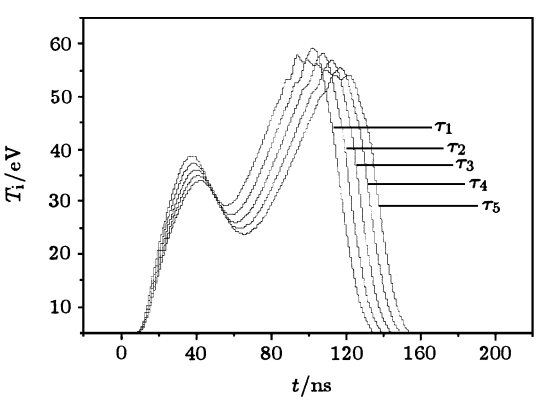


Fig.6. Ion temperature at the centre of z-axis vs time for different drive current rise-times.

Table 1. X-ray radiation and plasma properties for different drive current rise-times.

current rise-time τ_{rt} / ns	x-ray peak power $P_{x,max}$ / TW	x-ray energy E_x / kJ	peak density ρ_{max} / (g/cm^3)	peak ion temperature $T_{i,max}$ / eV
68	1.260	31.97	0.190	58.45
78	1.197	31.35	0.185	57.92
88	1.140	30.40	0.179	56.56
98	1.071	29.45	0.174	55.20
108	0.995	28.35	0.168	54.13

We can observe from the numerical results that x-ray radiation energy, x-ray peak power, peak plasma density, and peak ion temperature increase almost linearly when drive current rise-times decrease from $\tau_{\rm rt} = 108$ns (corresponding to the case of τ_5 in Figs.3–6) to 68ns (corresponding to the case of τ_1 in Figs.3–6). For convenience of quantitative analysis, the percentage increment of the above 4 characteristic quantities are calculated from $\tau_{\rm rt} = 108$ to 68ns, and they are 21.0%, 11.3%, 11.6%, and 7.4%, respectively, where the values of denominators in calculating the percentages correspond to the values in the case of $\tau_{\rm rt} = 68$ns. We can see from the percentages that the percentage increment of the x-ray peak power is the largest among them, and that the smallest is the ion temperature percentage increment. The results show that shortening of drive current rise-time is in favour of x-ray peak power, but with a little influence on ion temperature. On the other hand, the percentage increment of x-ray energy is almost equal to that of plasma density. In short, the shortening of drive current rise-time is one approach to raising the x-ray peak power.

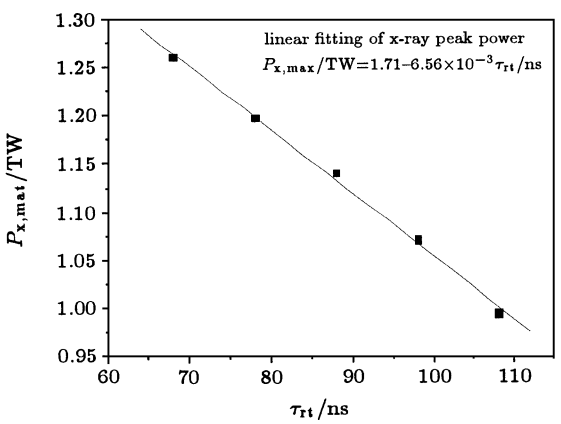


Fig.7. Linear fitting of x-ray peak power as the function of drive current rise-time.

Physically, the shortening of the current rise-time leads to the shortening of implosion time of plasma (see Fig.4), and accordingly, to the shortening of the diffuse time of magnetic field (the diffuse of magnetic field is adverse to the compression of plasma). Because of the shortening of implosion time of plasma, the plasma is more quickly compressed before the plasma temperature has risen up enough (note that the percentage increment of plasma density is larger than that of ion temperature), which makes the load plasma compressed more tightly and the corresponding x-ray peak radiation power increased. In addition, the increments of above 4 characteristic quantities are nearly proportional to drive current rise-time, and this kind of linearly dependent relationship can be drawn from Table 1 and Fig.7, where the numerical fitting formula of x-ray peak power relative to time is $P_{\rm x,max}/{\rm TW} = 1.71 - 6.56 \times 10^{-3}\tau_{rt}/{\rm ns}$.

3. Variation of initial load density distributions

Now, the initial load density distribution is modified while all the other parameters keep constant in current simulations. The variation of initial density distribution is manifested by variation of the exponential factor β. The symbols in Figs.8–9, ρ_1, ρ_2, ρ_3, ρ_4 and ρ_5, are used to indicate the numerical results for 5 different β's, respectively corresponding to β =0.25, 0.5, 1, 2 and 3, and β_4 corresponding to the above experimental case. As the β value decreases from 2 to 0.25, the corresponding initial load density distribution is flatted along the radial direction. The time-dependent x-ray power is given in Fig.8, ion temperature in Fig.9, and numerical fitting of the x-ray peak power relative to time in Fig.10, where the fitting formula can be approximately written as $P_{\rm x,max}/{\rm TW} = 0.7029 + 1.7822\exp(-\beta/1.1671)$. The information about the plasma density at the centre of z-axis and x-ray radiation energy varying with time is omitted to save space, but Table 2 can supply the information we need.

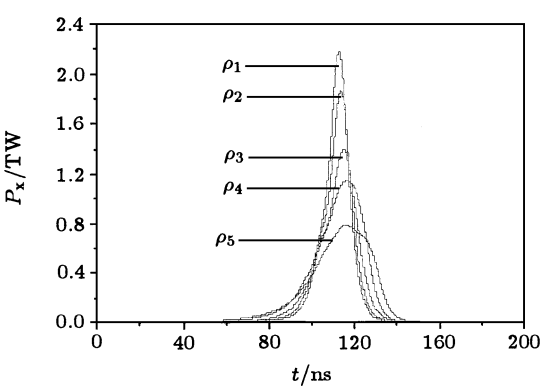


Fig.8. X-ray power distributions in the radial direction vs time for different initial load densities.

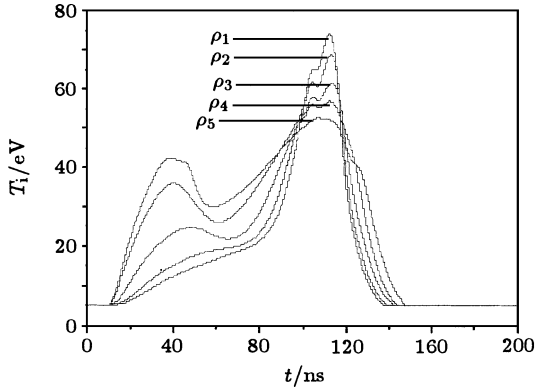


Fig.9. Ion temperature vs time for different initial load density distributions.

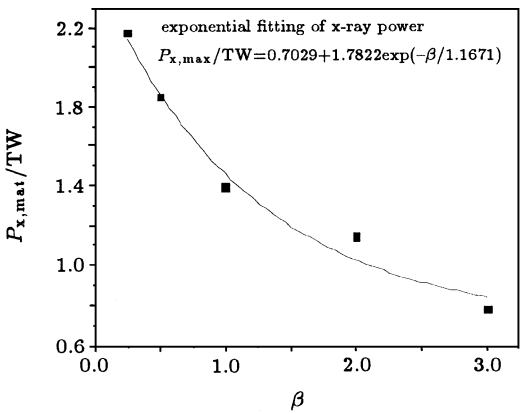


Fig.10. Exponential fitting of x-ray peak power as the function of β.

Table 2. X-ray radiation and plasma properties for different initial load density distributions.

density distribution exponential factor β	x-ray peak power $P_{x,max}$ / TW	x-ray energy E_x / kJ	peak density $\rho_{max}/(g/cm^3)$	peak ion temperature $T_{i,max}$/eV
0.25	2.170	29.60	0.166	73.81
0.50	1.847	28.66	0.170	68.03
1.00	1.392	27.40	0.169	61.18
2.00	1.143	30.40	0.179	56.50
3.00	0.773	26.45	0.170	52.55

As the exponential factor β decreases from 3 to 0.25, indicating that the radial density distribution is gradually flattened, the x-ray peak radiation power ascends sharply (see Table 2 and Fig.8), but x-ray energy fluctuates around 28kJ, changing only a little. This kind of ascend of peak power originates from the reducing of the duration of x-ray pulse. Although the peak density at the centre of z-axis is observed to vary a little, the peak ion temperature at the same position increases rapidly from 52.55eV to 73.81eV (see Table 2 and Fig.9). By comparing these numerical results, we can see that the increase of x-ray peak power is brought about mainly by the increase of plasma temperature rather than the increase of plasma density. It is well known that x-ray radiation comes from the transformation of other kinds of energy. The phenomena may be explained physically as follows. When β is smaller, the radial density distribution becomes more flattened, and the external part of cylindrical plasma implodes softly due to the existence of heavier mass in the internal part of plasma cylinder. Consequently, this figuration is conducive to elevation of the plasma temperature in comparison with the larger β case.

It is generally recognized that staged Z-pinch is advantageous in the stabilizing the plasma implosion.[12] Of course, the point of view is reasonable. Yet we can look round the conclusion from the mechanism of energy transformation. One may consider that staged Z-pinches are in favor of the transformation from other kinds of energy to internal energy, which makes plasma temperature and x-ray peak radiation power rise up rapidly. However, this viewpoint is only heuristic, and further analysis is needed, because the origin of radiation energy in Z-pinches remains a controversial subject.[13]

It may be illuminative to compare different effects of the drive current rise-time and the initial load density distribution. Although both approaches can increase the x-ray peak radiation power, the physical mechanisms are distinctly different. The main effect of shortening drive current rise-time is to increase the pinch plasma density, but the main effect of flattening the radial density distribution is to raise the plasma temperature. In addition, the quantitative trend of x-ray peak power differs also. The former corresponds to nearly linear rise, but the latter to approximately exponential rise.

4. Conclusion

The tungsten-wire array Z-pinch experiment on Qiangguang-I is simulated numerically, and a series of numerical experiments based on a series of drive cur-

rent rise-times and initial load density distributions are carried out in order to study the effects of the two kinds of parameters on Z-pinch plasma properties and x-ray radiation characteristics. The numerical results show that as the drive current rise-time is shortened the x-ray energy, peak radiation power, peak density and temperature at the centre of z-axis grow nearly linearly, but among them the x-ray peak power rises quicker than the other characteristic quantities. As the initial load density distribution alone the radial direction is flattened, x-ray peak power and plasma temperature ascend approximately in exponential form, while x-ray radiation energy and peak plasma density is changed only a little.

It is considered that both approaches can increase x-ray peak power, but the corresponding physical mechanisms are distinctly different. The shortening of drive current rise-time leads to tight plasma compression, but the flattening of initial load radial density distribution leads to the elevation of plasma temperature. In addition, it is suggested that staged Z-pinches not only stabilize the plasma implosion but also improve the energy transformation from other kinds of energy to internal energy. Some of the conclusions in this paper are only preliminary and may or may not be fully reliable in physics, but the proposed explanations might be helpful to the understanding of the physics of Z-pinch and the optimization of Z-pinch experiment design.

References

[1] Liberman M A, De Groot J S, Toor A and Spielman R B 1999 *Physics of High-Density Z-Pinch Plasmas* (New York: Springer) p6

[2] Ryutov DD, Derzon M S and Matzen M K 1998 *Sandia Report* DE98006090 (SAND-98-1632)

[3] Qiu X M, Huang L and Jian G D 2002 *Plasma Sci. Technol.* **4** 1427

[4] Yang Z H, Tian S H and Wu Y P 1998 *Chin. J. Comput. Phys.* **15** 43 (in Chinese)

[5] Ning C, Yang Z H and Ding N 2003 *Acta Phys. Sin.* **52** 1650 (in Chinese)

[6] Wang G H and Hu X J 2002 *Chin. J. High Press. Phys.* **16** 57 (in Chinses)

[7] Zeng Z Z and Qiu A C 2004 *Chin. Phys.* **13** 201

[8] Duan Y Y, Guo Y H, Wang W S and Qiu A C 2004 *Acta Phys. Sin.* **53** 2654 (in Chinses)

[9] Duan Y Y, Guo Y H, Wang W S and Qiu A C 2004 *Acta Phys. Sin.* **53** 3429 (in Chinese)

[10] Kuai B, Cong B T, Zeng Z Z *et al* 2002 *Plasma Science & Technology* **4** 1329

[11] Qiu M T, Kuai B, Zeng Z Z *et al* 2002 *Plasma Science & Technology*, **4** 1529

[12] Ney P, Rahman H U, Wessel F J *et al* 2001 *Phys. Plasmas.* **8** 616

[13] Rudakov L I, Velikovich A L, Davis J *et al* 2000 *Phys. Rev. Lett.* **84** 3326