Vol 18 No 1, January 2009
1674-1056/2009/18(01)/0203-06

Chinese Physics B

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2D parameter optimization of Ne-like Cr x-ray laser on slab*

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(Received 3 May 2008; revised manuscript received 19 August 2008)

A method of studying a non-equilibrium x-ray laser plasma is developed by extending the existing one-dimensional similarity equations to the case of two-dimensional plasma study in the directions perpendicular to the slab and along a focal line. With this method the characteristics of pre-plasma are optimized for transient neon-like Cr x-ray laser. It is found that when the duration and the intensity of 1.053 μm pre-pulse are 1.2 ns and 6.5 TW/cm^2 respectively with a delay time of 1.5 ns, the temperature and the temperature discrepancy each approach a proper state, which will provide a uniform distribution of properly ionized neon-like Cr ions before the arrival of pumping pulse.

Keywords: x-ray laser, two-dimensional hydrodynamic evolution, laser plasma
PACC: 4255V, 4260

1. Introduction

Since the first soft x-ray laser was conclusively demonstrated in Ne-like Se[1,2] at 20.6 nm and 20.9 nm using the collisional excitation mechanism in 1984, lots of efforts have been made to study x-ray laser plasmas and great theoretical and experimental progress in developing x-ray lasing schemes have been achieved. Foil targets[1−3] were first successfully used in the experiments. Naval Research Laboratory reduced the power demand of laser to 10^{12} W/cm^2 using the slab target.[4] In order to enhance the yield of XRL, a multiple-laser pulse irradiation scheme was tried. After the proposal of pre-pulse technique,[5] tremendous success was achieved in a large number of experiments in neon-like Ge, Zn, Se, etc.[6,7] Short pulse was introduced in 1996, thereby its efficiency was improved greatly.[8] In the year that followed, a transient scheme was demonstrated and brought on another development in the x-ray laser study:[9] its gain coefficient g arrived at a value as high as 19 cm^{-1}. And then the short pulse was widely adopted as pumping pulse in transient nickel-like and neon-like x-ray laser schemes[10,11] Later on, a longitudinally pumped scheme was proposed and achieved a large amplification of x-ray laser at 18.9 nm, with a total energy being less than 1 J.[12] Recently a new pumping geometry, named a grazing incidence pumping (GRIP), presented another type of table-top x-ray laser for investigation.[13−15]

However the pre-pulse technique dominates the experiments of x-ray laser on slab, and it is found that the character of pre-plasma is a most important aspect for the optimization of x-ray laser. Efforts have been made to study the relations among x-ray laser, pre-pulse, main pulse, and delay time.[8,16−18] The pre-pulse technique in the one-dimensional case may be understood as the fact that the pre-plasma produced by a relatively long weak pulse could relax the density gradient in a delay time by expansion. Then the shallow gradient in the distribution affords a wide gain region and small reflection index which is favourable for the output of x-ray laser.

In the previous work, usually plasma distribution was assumed to be uniform along a focal line and the optimization was made according to the character of plasma in the expanding direction: little attention was

*Project supported by the National Natural Science Foundation of China (Grant Nos 10474137, 10874242 and 10775018), the National Basic Research Program of China (Grant No 2007CB815105), and the Specialized Research Fund for the Doctoral Program of Higher Education of China (Grant No 20070290008).
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paid to the nonuniformity of plasma distribution along the line foci. However in practical experiment the focal line of laser is not so ideal as assumed. The nonuniformity in the focal line will introduce the inhomogeneity into the plasma and then affects the amplification of x-ray laser. In our work, by taking into consideration both the expanding in the x direction (vertical to the slab) and the evolution in the z direction (along the focal line), we investigate the optimal conditions for power output of neon-like x-ray laser.

2. Inhomogeneity of line focus

In the experiments with the pre-pulse technique, the quality of line focus is one of key factors for the successful realization of an x-ray laser. In order to obtain a good line focus, great effort has been made to study optical settings,[19,20] and cylindrical and spherical lenses or cylindrical lens array are usually adopted as shown in Fig.1.

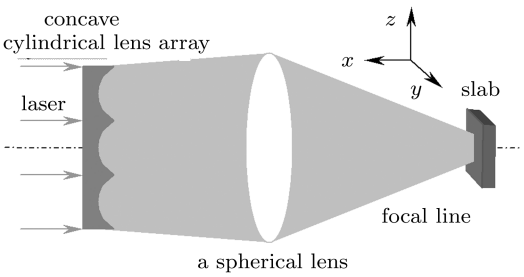


Fig.1. Optical settings in experimental setup.

In practical experiments, whatever optical components are chosen, it is unavoidable to obtain a nonuniform intensity distribution along the focal line. As shown in Fig.2, even with the optimal settings adopted, the intensity distribution is significantly nonuniform.

Figure 2 shows the relative intensity distributions in the z direction, where the horizontal axis represents the position along the focal line, longitudinal axis shows the relative intensity of incident laser, in arbitrary units. From three lines in Fig.2 one can find after optimization the unevenness of incident laser is still obvious. The unevenness caused by both laser facility and optical setup should be considered in practical experiments. One can find that the indention on target, caused by ablation, is due to the uneven incident laser. Generally, the non-uniformity of intensity

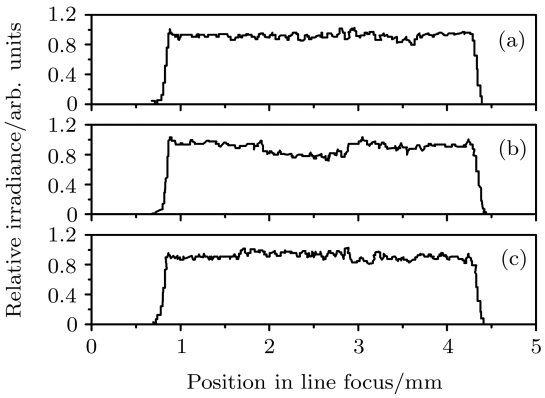


Fig.2. Focal line sampling on 'ShenGuang II' laser facility.

is ±15% of the average,[8] which will bring a noticeable inhomogeneity to the plasma created by laser. However the unevenness could be compensated by the hydrodynamic behaviour of plasma. As studied previously, after the pre-pulse, plasma expands under the action of pressure gradient in the x direction, and the expansion will relax the gradient, thereby leading to more uniform plasma in the x direction. In the same way, the hydrodynamic behaviour will bring uniformity to the plasma also in the z direction, which is important for the gain of x-ray laser too. However the detailed process of this tendency in the z direction has not yet been studied systematically.

3. Model equations

Considering the diffusion and the viscosity of plasma, the expansion of plasma can be described as follows:

$$\begin{aligned}
\frac{\partial \rho}{\partial t} &= -\rho\frac{\partial \upsilon_x}{\partial x} - \upsilon_x\frac{\partial \rho}{\partial x} - \rho\frac{\partial \upsilon_z}{\partial z} - \upsilon_z\frac{\partial \rho}{\partial z},\\
\frac{\partial \upsilon_x}{\partial t} &= -\upsilon_x\frac{\partial \upsilon_x}{\partial x} - \upsilon_z\frac{\partial \upsilon_x}{\partial z} - \frac{1}{\rho}\frac{\partial p}{\partial x} - \frac{1}{\rho}\boldsymbol{\nabla}_x q,\\
\frac{\partial \upsilon_z}{\partial t} &= -\upsilon_x\frac{\partial \upsilon_z}{\partial x} - \upsilon_z\frac{\partial \upsilon_z}{\partial z} - \frac{1}{\rho}\frac{\partial p}{\partial z} - \frac{1}{\rho}\boldsymbol{\nabla}_z q,\\
\frac{\partial T}{\partial t} &= -\upsilon_x\frac{\partial T}{\partial x} - \upsilon_z\frac{\partial T}{\partial z} - \frac{1}{c_V}\frac{p}{\rho}\left(\frac{\partial \upsilon_x}{\partial x} + \frac{\partial \upsilon_z}{\partial z}\right)\\
&\quad + \frac{1}{c_V}H + k\frac{\partial^2 T}{\partial z^2},
\end{aligned} \tag{1}$$

where υ_z, ρ, T, L, p, k, and c_V denote the plasma flow speed in the z direction, the plasma density, the plasma temperature, the plasma characteristic scale, the plasma thermal transport coefficient, and the temperature capacity respectively. The item describing the viscosity is $\frac{1}{\rho}\nabla_z q$, where q =

$C_0^2 L_0^2 \rho \begin{cases} [\boldsymbol{\nabla}\cdot\boldsymbol{v}]^2 & \boldsymbol{\nabla}\cdot\boldsymbol{v} < 0 \\ 0 & \text{else} \end{cases}$, with C_0 being the viscosity coefficient and $L_0^2 \approx \Delta x^2 + \Delta y^2$.

In contrast to the expansion vertical to the slab, the evolution in the z direction is subordinate. So we can take it as a subsidiary effect. In the gain region, the plasma is nearly isothermal along the x direction and speed v_z is mainly determined by the distribution of temperature in the z direction. In addition, we introduce an analytical solution of T and ρ from one-dimensional similarity equations[21−23] as the primary solution of the equations in the x direction. Omitting the technical details one can obtain a set of equations describing the hydrodynamic evolution along the focal line when the ablation is still on, expressed as

$$\begin{aligned} \frac{\partial\rho}{\partial t} &= \frac{1}{L}\frac{\mathrm{d}m}{\mathrm{d}t} - \frac{L'}{L}\rho - \rho\frac{\partial v_z}{\partial z} - v_z\frac{\partial\rho}{\partial z}, \\ \frac{\partial v_z}{\partial t} &= -v_z\frac{\partial v_z}{\partial z} - \frac{1}{\rho}\frac{\partial p}{\partial z} - \frac{1}{\rho}\nabla_z q, \\ \frac{\partial T}{\partial t} &= -v_z\frac{\partial T}{\partial z} - \frac{1}{c_V}\frac{p}{\rho}\left(\frac{1}{t} + \frac{\partial v_z}{\partial z}\right) \\ &\quad + \frac{1}{c_V}H + k\frac{\partial^2 T}{\partial z^2}, \end{aligned} \tag{2}$$

where $\frac{\mathrm{d}m}{\mathrm{d}t}$ is ablation rate[24] that can be considered as a function of position and time.

After the pre-pulse, in the delay time the equations are written as

$$\begin{aligned} \frac{\partial\rho}{\partial t} &= -\frac{L'}{L}\rho - \rho\frac{\partial v_z}{\partial z} - v_z\frac{\partial\rho}{\partial z}, \\ \frac{\partial v_z}{\partial t} &= -v_z\frac{\partial v_z}{\partial z} - \frac{1}{\rho}\frac{\partial p}{\partial z} - \frac{1}{\rho}\nabla_z q, \\ \frac{\partial T}{\partial t} &= -v_z\frac{\partial T}{\partial z} - \frac{1}{c_V}\frac{p}{\rho}\left(\frac{1}{t} + \frac{\partial v_z}{\partial z}\right) + k\frac{\partial^2 T}{\partial z^2}, \end{aligned} \tag{3}$$

that can describe the plasma comprehensively and effectively. And they are easy to solve numerically.

4. Calculation results

The following parameters that are the same as those adopted in Ref.[9] are taken in our calculation, i.e. pre-pulse duration and intensity, which are 1.5 ns and 10^{12} W/cm^2 respectively, and the main pulse intensity and duration, which are 10^{15} W/cm^2 and around 7 fs respectively, under a 'standard' experimental arrangement.

4.1. Average temperature

In an x-ray laser plasma, the ionization is determined mainly by the temperature and the ionization state before the main pulse becomes a key factor for transient neon-like x-ray laser.

In the experiment[9] the main pulse is timed at the falling side of long pulse. Figure 3 gives both the average temperature of the plasma versus time and the scale length versus time. One can find that at 1.5 ns the temperature is around 130 eV at which there could be properly produced plasma for Ne-like stage. The curve in Fig.3(b) shows at 1.5 ns the scale length is nearly 100 μm which is enough to lower the refraction. Based on the previous study, this is well suited for x-ray amplification.

In the following we will check the conditions in the z direction, with the plasma inhomogeneity in practical experiments taken into account.

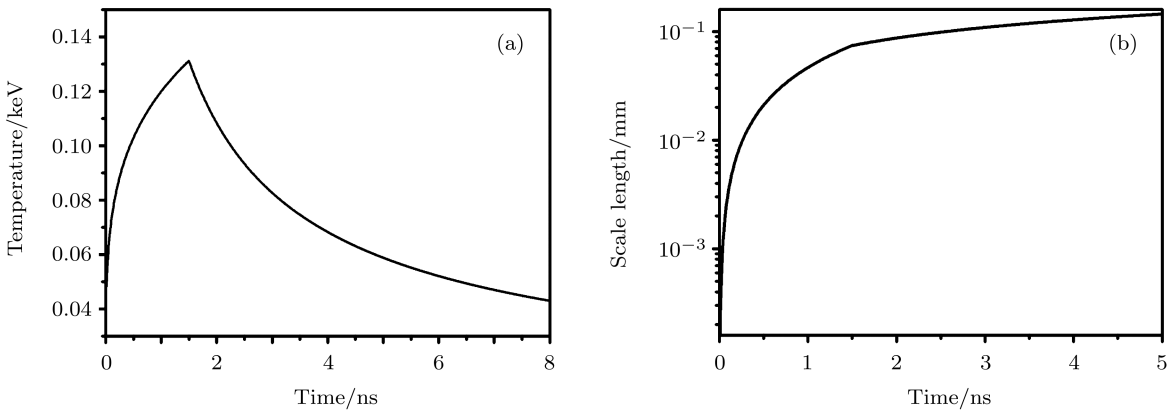


Fig.3. Electron temperature versus time (a) and scale length versus time (b)

4.2. Evolution of temperature in the z direction

Since the amplification takes place in the z direction during the propagation of x-ray photons, the inhomogeneity of plasma will obviously affect the gain of x-ray laser. It can be understood that the uniform distribution of temperature along the line foci is very favourable for the amplification of x-ray because the laser propagates in that direction. According to the practical measurement, we adopt 12% of the average intensity as the inhomogeneity in the calculation and introduce a scrambling spatial distribution of intensity of incident laser pulse into the study of the evolution of inhomogeneity.

Figure 4(a) and the solid line in Fig.4(b) display the temporal evolution of plasma temperature along the focal line. At time 1.5 ns, the average temperature reaches its peak value 131 eV and the distribution of temperature is notably inhomogeneous that prevents the amplification of spontaneous x-ray radiation.

The dashed line in Fig.4(b) shows that at the end of pre-pulse, that is, at 1.5 ns the difference between the maximum and minimum values of temperature is around 14 eV and at 2.5 ns after the pre-pulse the discrepancy is only 2 eV. The range of discrepancy decreases with time after the pre-pulse, which might be caused by both the drop in temperature and the inhomogeneous tendency due to hydrodynamic behaviour of plasma. The solid line in Fig.4(b) shows the evolution of electron temperature versus time, indicating that after the pre-pulse the temperature drops off gradually. Comparing two lines in Fig.4(b) one can easily find that dashed line drops off rapidly, which could support our prediction that hydrodynamic behaviour can bring the homogeneity to the temperature. After 3 ns the variation in temperature in the z direction is very low, implying an ideal homogeneous distribution appearing along the focal line. This suggests that the experimental conditions could be optimized.

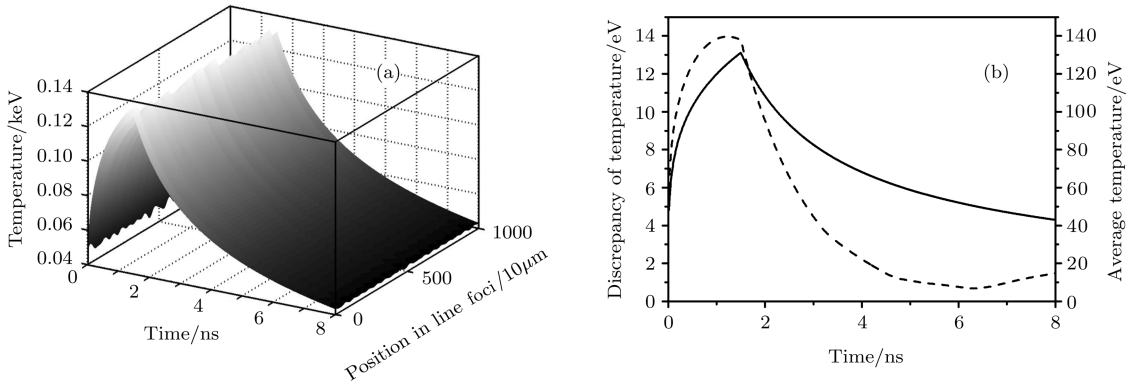


Fig.4. Temporal evolution of plasma temperature distribution and variation in temperature discrepancy in the z direction, where the average intensity of laser is adopted to be 1.0 TW/cm^2 and duration 1.5 ns for neon-like Ti.

4.3. Evolution of electron density in the z direction

Figure 5 shows the evolution of electron density with time. One can see that the density distribution turns uniform much more rapidly than temperature. In Fig.5(b) the dashed line shows that at about 1.8 ns, that is at 300 ps after the end of pre-pulse, the discrepancy in density almost disappears. Under the condition of long pre-pulse (ns) the discrepancy in density in the z direction drops off quickly, and even it turns uniform at the end of pre-pulse and then increases slowly, and it remains at a small value finally. Further calculations show that with a long pulse (longer than ns) the uniform distribution of electron density could be obtained at the end of pre-pulse, which is favourable for solving the refraction problem.

However, compared with the ionization, the refraction is a sub-important factor. Since the ionization state is the most important factor for x-ray laser, the optimization is based on the features of plasma temperature. We optimize the conditions for neon-like Cr x-ray laser by adjusting the temperature (in magnitude and distribution) along the propagation path of x-ray laser.

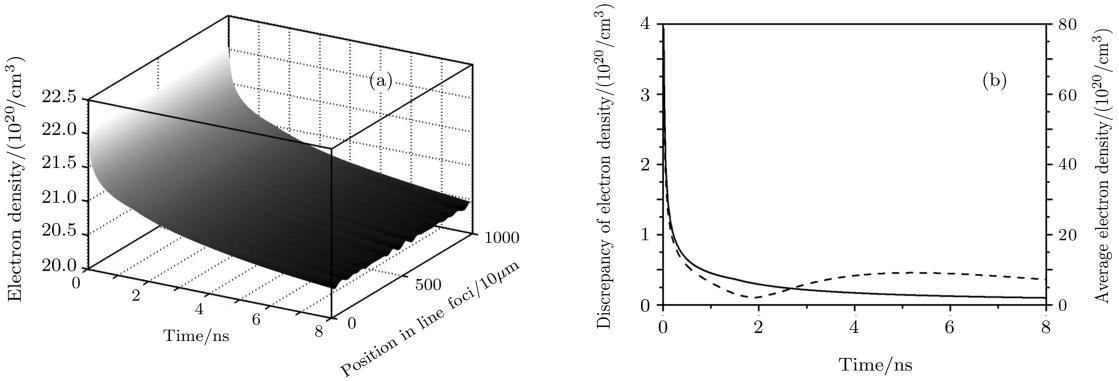


Fig.5. Temporal evolution of electron density distribution in the z direction, where the intensity of laser is 1.0 TW/cm^2 and duration is 1.5 ns for neon like Ti.

4.4. Optimization based on 2D study of plasma evolution

We now study the experimental design of a neon-like Cr x-ray laser by using this model. With a chromium slab target we calculate the temperature on the new condition that the duration and the intensity of pre-pulse are 1.2 ns and 6.5 TW/cm^2 respectively, while the duration and the intensity of main pulse are 7 ps and 2.5×10^{14} W/cm^2 respectively. A delay time of 1.5 ns is introduced between the pre-pulse and the main pulse. The results are given in the followings.

Under the new condition, we find from Fig.6(a) that at 1.5 ns after the pre-pulse the temperature is around 180 eV at which there just could appear the

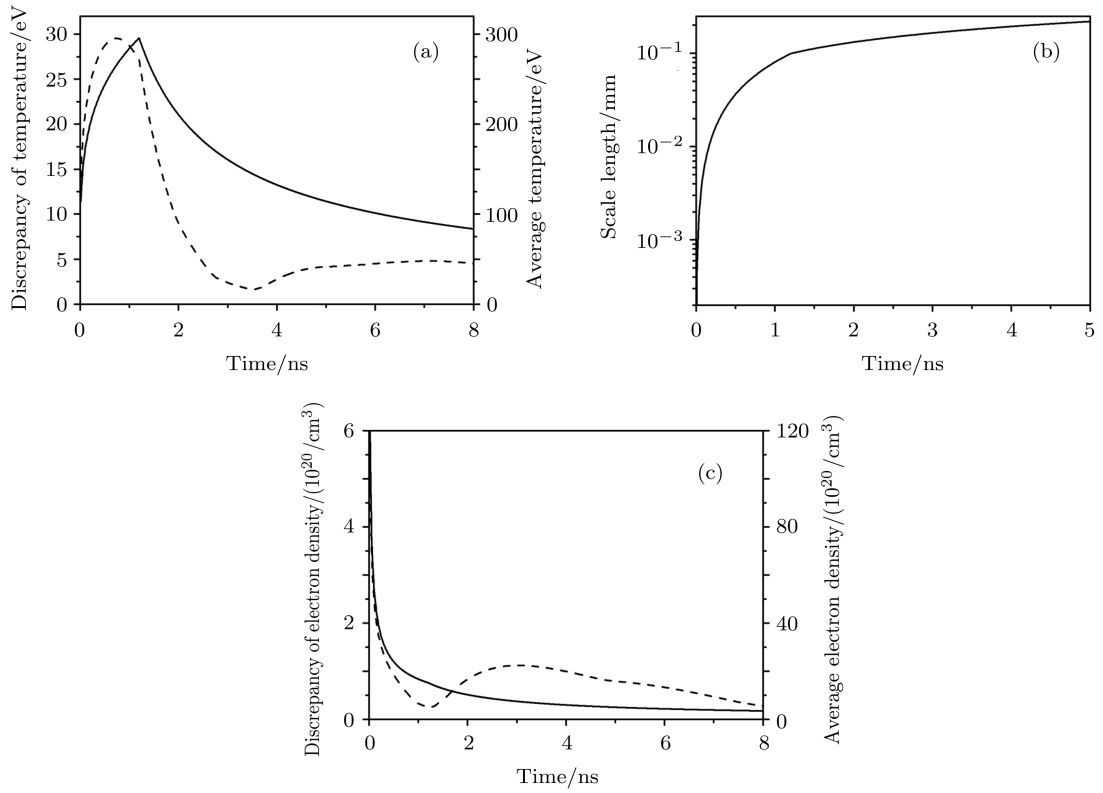


Fig.6. Evolutions of plasma parameters with time, where the durations and the intensities are 1.2 ns and 6.5 TW/cm^2 for pre-pulse at 1.053 μm, and 7 ps and 2.5×10^{14} W/cm^2 for main pulse respectively, with a 1.5 ns delay between the pre-pulse and the main pulse for Cr slab. In (a) the solid line represents the average temperature, while the dashed line refers to the discrepancy of temperature, and in (c) the solid line represents the average electron density, while the dashed line refers to the difference of electron density.

proper ionization for neon-like stage and that the dashed line shows that the range of variation along the z direction is less than 3 eV. Also it can be noticed in Fig.6(b) that the scale length is larger than 150 μm, much longer than the previous one. Figure 6(c) shows the evolutions of electron density and discrepancy in electron density under the optimized condition are almost the same as those in Ref.[9]. But the scale length is larger, and the most important improvement is that the temperature and the discrepancy in temperature along the z direction turn ideal simultaneously at 1.5 ns after pre-pulse, thereby the ionization can properly take place and relatively uniform plasma appears as an ideal medium for x-ray amplification.

5. Conclusions

In this work we have studied the plasma evolution in the two-dimensional case based on 1D similarity equation. We optimize the conditions for a 2D transient neon-like Cr x-ray laser. The character of pre-pulse and the delay time between pre-pulse and main pulse are optimized through studying the evolutions of plasma temperature and density in two directions: parallel and vertical to the chromium slab. We find when the duration and the intensity of 1.053 μm pre-pulse are 1.2 ns and 6.5 TW/cm^2 respectively, at time 1.5 ns after pre-pulse both temperature and temperature discrepancy each approach a proper state and the scale length is also enlarged which will lower the refraction and provide a uniform distribution of properly ionized neon-like Cr ions before the main pulse with a power of 2.5×10^{14} W/cm^2 and a duration of 7 ps reach the gain region.

Acknowledgments

The authors would like to thank Professor Zhang Guang-Cai and Xu Ai-Guo for useful discussion.

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