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Realization of Double-pulse Laser Irradiating Scheme for Laser Ion Sources

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Abstract: A double-pulse laser irradiating scheme has been designed and established for the production of highly charged ion beams at Institute of Modern Physics (IMP), Chinese Academy of Sciences. The laser beam output by a Nd:YAG laser is split and combined by a double of beam splitters, between which the split laser beams are transmitted along different optical paths to get certain time delay between each other. With the help of a quarter-wave plate before the first splitter, the energy ratio between the two laser pulses can be adjusted between 3:8 to 8:3. To testify its feasibility, a preliminary experiment was carried out with the new-developed double-pulse irradiating scheme to produce highly charged carbon ions. Comparing the results with those got from the previous single-pulse irradiating scheme, the differences in the time structure and Charge State Distribution (CSD) of the ion pulse were observed, but its mechanisms and optimization require further studies.

Key words: laser ion source; double pulse; highly charged ion

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1 Introduction

Laser Ion Sources (LIS) are effective sources of highly charged ions, especially refractory metallic ions. Compared with other kinds of ion sources, like electron cyclotron resonance ion source and electron beam ion source, LIS possesses the capability of generating short pulses (μs) of highly charged ions of high intensity (emA) and repetition of 1∼10 Hz, which makes it to be the most promising ion source to realize single turn injection scheme of modern heavy ion synchrotrons[1]. Institute of Modern Physics (IMP), Chinese Academy of Sciences, started to develop a laser ion source for the production of pulsed highly charged heavy ions, which is one of the crucial parts of the High Intensity heavy ion Accelerator Facility (HIAF) project[2]. For LIS, the yield of high charge state ions is one of the key parameters. However, there are two effects limiting highly charged ion yields: plasma shielding and recombination.

When the laser power density is above 10^8 W/cm^2, plasma is generated. Generally, the higher the power intensity of the laser, the higher the plasma temperature and the charge states and energies of ions generated[3]. But plasma shielding effect occurs with the increasing plasma density, and once the plasma electron density reaching the critical value, complete reflection of the incident laser beam may occur[4]. Besides, in the early stage of plasma expanding, the three-body recombination plays an important role and its rate is proportional to $\sim q^3 n_e^2 T_e^{-2/9}$ (here q is charge quantity, n_e electron density and T_e electron temperature), which leads to loss of ions, especially for highly charged ions. After a certain distance plasma spread, the recombination may be neglected, and the charge states of ions should be frozen[5].

In previous work, experimental results on laser induced breakdown spectroscopy showed that ion yield, kinetic energy of ions and electron temperature could be enhanced with double pulse scheme[6]. And double pulse scheme have been used on laser ion source for extending ion beam pulse length for low charge state

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mode[7].The aim of this work, is to build an available double pulse system providing more options for LIS to study how to produce effectively high state charge ions and test the feasibility of this system.

2 Experimental setup

The experimental layout is shown in Fig. 1. A Q-switched Nd: YAG laser, with the wavelength of 1 064 nm, pulse width of 8 ns and energy of 0.5~2.4 J, is used to produce plasma. The total current intensity and time structure of ion pulse are measured by a Faraday Cup (FC) located at 2.86 m downstream with a diameter of 28 mm and the Charge State Distribution (CSD) of ion beam can be measured by an Electrostatic Ion Analyzer (EIA) and an Electron Multiply Tube (EMT) with time of flight method.

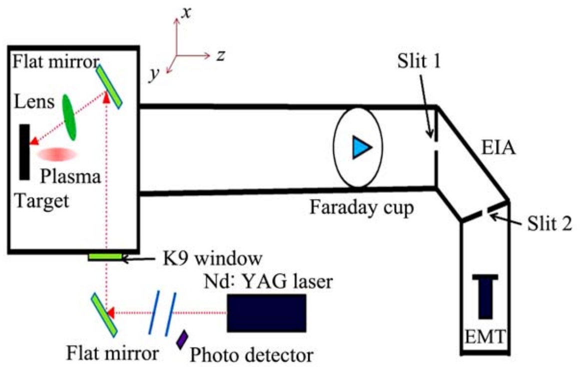

Fig. 1 (color online) Schematic diagram of a laser ion source.

There are mainly two ways to achieve a delay time between two laser pulses: synchronization control system and optical path difference. Synchronization control system, *e.g.* a delay and pulse generator DG535, can be delayed from several ns to 1 000 s with an accuracy of higher than 1.5 ns, while maximum delay only tens of ns is available by controlling optical path difference. In the paper, we use double pulse with a delay time in the order of nanosecond by changing optical path difference because its delay accuracy can reach tens of ps.

Fig. 2 illustrates a view of optical layout of double pulses. This system consists of a Nd:YAG laser, zero-order quarter-wave plate, two prisms, and a series of flat mirrors. To adjust energy radio of double pulses, we use a zero-order quarter-wave plate the optical axis of which can be rotated from 0° to 360° to change p-polarized component and s-polarized component of laser beam from the Nd:YAG laser. When such a laser irradiate on a prism, p-polarized light transmits mostly (> 90%) while s-polarized light is reflected (> 99.5%).

Then one laser beam splits into two that go along different directions. By varying the optical path difference between p-polarized and s-polarized light, the time delay between the two pulses could be adjusted. As shown in Fig. 2 the optical path adjusting of s-polarized component can be achieved by changing the positions of mirror−3, mirror−4. After that, the two beams are combined into the same path with another prism. Here, the optical path difference in the range of 0 ~ 3 m is available, which corresponds to the time delay of 0 ~ 10 ns with a deviation of tens of picosecond. In this way, double laser pulses with different energy ratio and a variable delay time can be obtained.

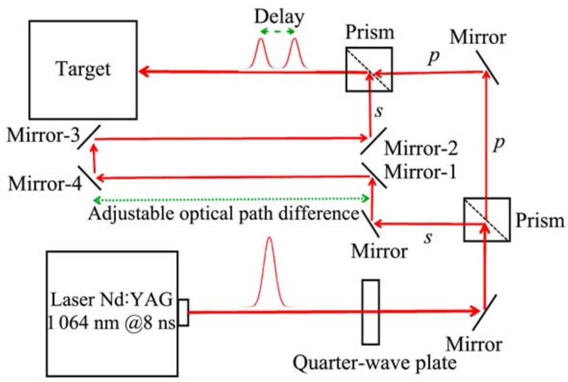

Fig. 2 (color online) A schematic view of double pulse layout on LIS.

3 Experiment results

To verify the feasibility of the double-pulse irradiating scheme, a preliminary experiment was conducted. The 1st and 2nd energy of the double pulses are 0.780 and 0.792 J, respectively, with a delay time of 8 ns. The comparison of double with single pulse laser was carried out, and the single pulse had the equal energy per pulse with that of energy sum of double pulses. Carbon target with purity of 99.9% was used, while other experimental conditions were the same.

3.1 Carbon results with individual pulse and double pulse

The ion pulse structures measured by the FC for carbon ions are shown in Fig. 3. Each plot presented here is the averaged result over tens of laser shots with the exactly same experimental conditions.

Typically, the higher the laser energy, the lower the peak time, and the higher the beam current. However, the time corresponding to peak current 6.38 emA for the 1st pulse and 2nd pulse 5.96 emA are 11.14 μs and 11.71 μs, respectively, while the 1st pulse energy is lower than 2nd pulse energy. The possible explanation could be related to plasma shielding effect. The s-polarized light is reflected by the electron density wall, while p-polarized light is absorbed when an intense laser pulse propagates in near critical density plasma[8].Therefore, it is easy to understand this phenomenon because the 1st pulse is p-polarized light and the 2nd pulse is s-polarized light.

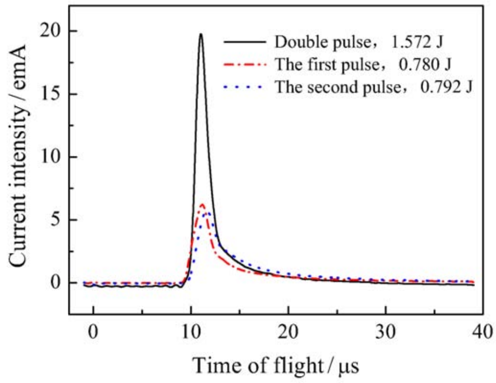

Fig. 3 (color online) Ion pulses for C target with individual pulse and double pulses.

It seems that ion pulse with a shorter arrival time in double pulse mode possesses a higher peak current intensity than the sum of individual pulse. This can be explained by interaction between plasma produced by the first pulse and the second pulse, which leading plasma to absorb a certain amount of laser energy, heat up to high temperature and rapidly expand outward.

The CSD presented in Fig. 4 were considered during the time interval of the Full Width of the sum up currents on the EMT as showed.

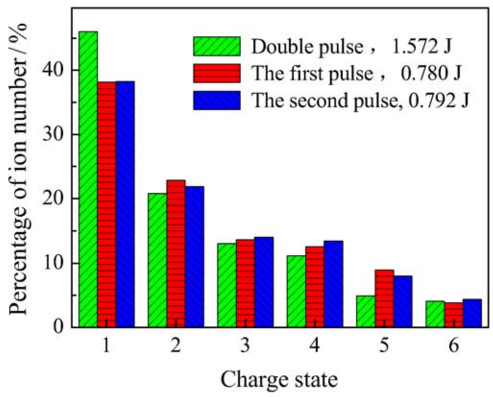

Fig. 4 (color online) CSD of C ion with individual pulse and double pulses.

From Fig. 3 and Fig. 4, we can find that two pulses presented with almost the same energy, pulse duration, and the similar ion pulse structure and CSD.

3.2 Comparison between double pulse and single pulse

The peak current and corresponding time for single pulse is 10.77 emA and 9.71 μs, respectively, while the values for double pulse are 19.87 emA and 10.85 μs, as shown in Fig. 5.

From Fig. 5 and Fig. 6, we may notice the difference in the shape and CSD of ion pulse for single and double pulse at the same experimental conditions (*i.e.* equal energy and pulse width).

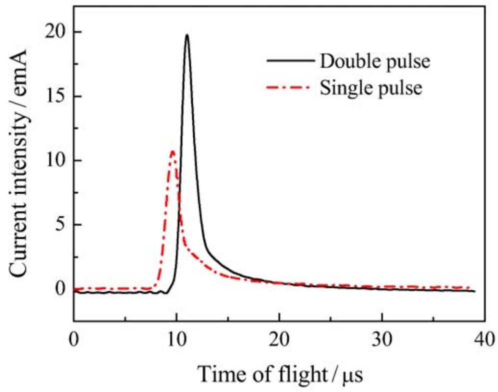

Fig. 5 (color online) Ion pulses for C target with single pulse and double pulses.

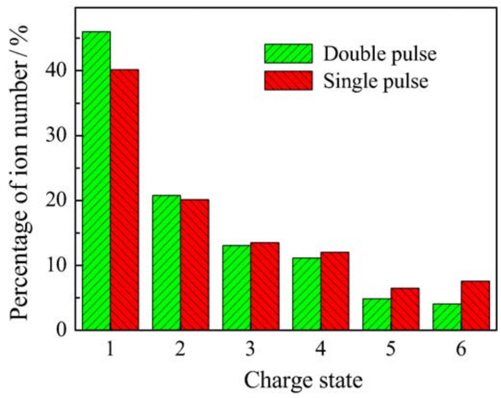

Fig. 6 (color online) CSD of C ion with single pulse and double pulses.

4 Discussion and conclusion

Two pulses with almost the same energy and the same pulse width, generate the similar ion pulse structures and CSD, implying that each pulse of the double pulses can propagate along the designed path and interact with target material. Results show that interaction between plasma produced by the first pulse and the second pulse laser occurs with 8 ns delay occurs. All these tell us that it's feasible to apply double pulse technique on laser ion source. This system can be operated in double pulse mode, single pulse mode as well. The comparison of double with single pulse laser was carried out with the same energy (*i.e.* 1.57 J), and the difference in the shape and CSD between them was observed, but the mechanisms leading to differences require further studies.

In summary, an effective double pulse system for

LIS has been built up and its feasibility has been tested with a preliminary experiment on carbon samples. This system can provide choices for different energy and delay time. In the near future, we will investigate the influences of energy and delay time between pulses on features of ion pulses, especially yields of highly charged ions, for different target materials in detail and achieve optimization.

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激光离子源双脉冲打靶方案的实现

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摘要： 设计并实现了近代物理研究所激光离子源双脉冲打靶方案以产生高电荷态离子束。从Nd:YAG激光器输出的激光束经过一对分光棱镜的分束-合束，通过改变两束光的光程差，得到有一定时间延迟的双激光脉冲。利用四分之一玻片，双脉冲的能量比值可以在3:8～8:3之间连续调节。为了验证该方案的可行性，对C靶进行了初步实验。实验结果发现，与以往单脉冲打靶方案对比，双脉冲方案在离子束的脉冲时间结构和电荷态分布有所不同。但是，导致这些差异的机理和实验的优化还尚需要进一步研究。

关键词： 激光离子源；双脉冲；高电荷态离子

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