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Review article

Laser ion source for heavy ion inertial fusion

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Abstract

The proposed heavy ion inertial fusion (HIF) scenarios require ampere class low charge state ion beams of heavy species. The laser ion source (LIS) is recognized as one of the promising candidates of ion beam providers, since it can deliver high brightness heavy ion beams to accelerators. The design of LIS for the HIF depends on the accelerator structure and accelerator complex following the source. In this article, we discuss the specifications and design of an appropriate LIS assuming two major types of the accelerators: radio frequency (RF) high quality factor cavity type and non-resonant induction core type. We believe that a properly designed LIS would satisfy the requirements of both types, while some issues need to be verified experimentally.

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Keywords: Inertial fusion; Accelerator; Ion source; Laser ablation; Heavy ion source

1. Introduction

In the past, various scenarios of accelerator complexes for a heavy-ion inertial fusion (HIF) were proposed. The specification for every proposed beam to ignite a fusion condition is more demanding than what we have achieved using the existing accelerator technologies. If we assume 1 MJ beam energy with 1 GeV/u at the final irradiation point, 1 mC beam charge is required. Assuming a 10 μs beam pulse width, 100 A total beam current is required. The desirable current is much larger than the maximum available value provided by a single ion source; therefore, an accelerator configuration using multiple front-ends is envisioned. In other words, an ion source is required to provide a beam current as high as possible to simplify the accelerator complex. In addition, a small transverse beam size is crucial to reduce the size of accelerator components, and consequently, the beam emittance is the most important key to the realization of a HIF power plant. The ion source for HIF must provide a high brightness beam with a large beam current in a pulsed operation mode. To fulfill the requirements, we believe a laser ion source (LIS) provides the most suitable and promising solution.

For the ion species of the driver beam, we propose to use mono-isotopic elements, such as ^{89}Y, ^{93}Nb, ^{103}Rh, ^{127}I, ^{133}Cs, ^{197}Au and ^{209}Bi. For example, if we use lead, which is a typical heavy mass element, it has four isotopes, where ^{208}Pb occupies only 58% of its natural abundance, and the other three isotopes have lighter masses and may cause beam losses somewhere in the accelerator chain. One also needs to consider the chemical stability of the species which is used as a laser target. For example, Ti and Zr capture a large amount of surrounding gases and those impurities may create unwanted ions. Thus, we advocate adopting Au^{+} ions for the HIF driver beams. If a higher charge-to-mass ratio ion is preferred in order to shorten the accelerator, we propose using Nb^{+} rather than requiring beams of Au^{2+}. This is because the laser irradiation conditions to produce charge state 2+ will typically

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produce ions of neighboring charge states. In this article, Au^+ ion beams with currents in the ampere range and good emittance are assumed.

2. Principle of a laser ion source

The first descriptions of laser ion sources can be found in the articles from the 1960's [1,2]. The laser was invented in 1960, and the first laser ion source was proposed within a decade. Therefore, the laser ion source was one of the earliest applications of laser. The principle is very simple. An intense pulse of laser light is focused on a solid target, which is placed within a vacuum vessel. The laser energy is used to ionize the target material and an ablation plasma is induced. Since the laser irradiation period is very short, typically less than a few tens of nanoseconds, the heated plasma does not have time to expand much during the pulse and its density remains high. No extra confinement forces, such as magnetic field, are needed. After laser irradiation, the plasma expands slowly and simultaneously moves away from the target surface, so that the gravity center of the expanding plasma has a velocity perpendicular to the target surface. Fig. 1 shows the expanding plasma emanating from the target to the extraction electrodes. When the head of the plasma plume reaches the extraction voltage gap, ion beam formation starts. This process continues until the end of the plasma plume reaches the extraction electrode. Although the laser irradiation is very short (~10 ns), the pulse width of the extracted ion beams can be extended to the microsecond scale.

3. Driver laser

Historically, CO_2 lasers was used as the driver for laser ion sources [3−5]. They can emit large laser energy with high duty factors and are widely used for industrial machining applications. To obtain high charge state heavy ions, a high temperature plasma is required. This requirement matches the CO_2 laser's capability. The typical wavelength is about 10 μm, which is in the infrared spectral region. Therefore, a vacuum window made from zinc selenide or salt crystal is used, which is transparent for the CO_2 laser wavelength. A CO_2 laser has a gas mixture medium and requires a discharge to obtain a population inversion. Due to the discharge process, special attention is required to obtain good stability. The pulse length is typically more than a few tens of nanoseconds with a long tail. Fig. 2 shows a typical laser pulse of a CO_2 laser (Ushio TEA 10.6 μs 6.4 J). Within the long laser pulse period, the plasma expansion starts. The laser is continuously transferring the energy to the plasma deep within the expanding plasma, so that the plasma is not heated evenly. Therefore, the momentum distribution of the ions in the plasma does not represent a shifted Maxwell−Boltzmann distribution. A CO_2 laser is one of the candidates of driver lasers.

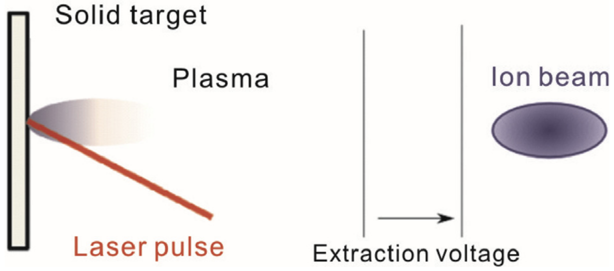

Fig. 1. Principle of laser ion source.

We have been using Q-switched Nd:YAG lasers for ion source application for more than 10 years [6]. Many reliable models in a reasonable cost range are available in market. The fundamental wavelength and typical pulse duration are 1064 nm and 6−10 ns respectively. The laser energy can be controlled easily by changing the interval between the flash lamp trigger and Q-switch timing or the flash lamp's excitation. To minimize undesired target damage, a contrast of the Q-switch is important since a laser leakage before opening the Q-switch may heat the target before starting the main laser pulse. For the HIF purpose, we only need a moderate laser energy because relatively low plasma temperature is required for low charge state ions. The pulse length of Nd:YAG lasers is adequate to achieve thermal equilibrium and the obtained ion pulse shape is quite reproducible. Here, an Nd:YAG laser would be a good driver for HIF.

We have tested shorter pulse length lasers including a sub nanosecond laser system which is equipped with a stimulated Brillouin scattering (SBS) cell [7]. This may result in reduced target consumption; however, we did not yet find significant advantages compared to a typical Nd:YAG laser. The selection of the driver laser is important for the reliable application for HIF and we need to keep an eye on the developments in the laser technology field.

4. Laser target

As mentioned above, we assume solid gold or niobium foils as the target material. The required charge state is only 1+ and the laser power density needs to be controllable between 2×10^8 and 10^9 W/cm^2 for efficient ion production. The laser spot size on the target surface would be several mm in diameter, when we use several hundred mJ of laser energy. In that case, the damage on the target surface caused by a single

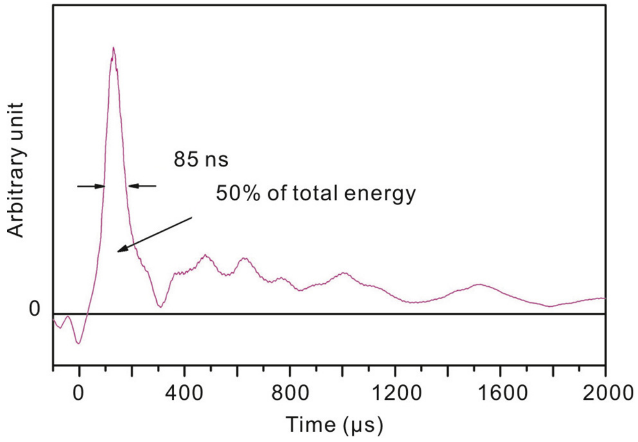

Fig. 2. Typical waveform of CO_2 laser.