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Laser ablation ion source for heavy ion inertial fusion ☆

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ABSTRACT

Laser ion source (LIS) is one of the promising candidates for the front end of heavy ion inertial fusion power plant. A LIS can provide low emittance high current heavy ion beams. Based on the performance of an existing LIS, the feasibilities of the ion source of heavy ion inertial fusion plant are investigated assuming both induction accelerator scheme and radio frequency (RF) accelerator scheme. By combining recently developed techniques, we can design LIS both for the induction and RF accelerator schemes.

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1. Introduction

There have been numerous proposals and ideas for realization of a heavy ion inertial fusion driver. The proposed schemes heavily depend on the target design and it is not adequate to assume a particular configuration of the driver at this time. In general, the driver can be categorized into two types. The first is based on induction linear accelerators. The induction cavity can handle ampere class beam current, however inducible voltage per length is limited. The other type proposal is to adopt radio frequency (RF) accelerators. The RF cavity can generate a high electric field, though the accelerated beam current is typically much less than induction accelerators. The front-end design of the driver is demanded to supply their required beam specifications for each type. We investigate the feasibilities of a laser ion source (LIS) which satisfies the requirements both for induction and RF scenarios with the latest available technologies.

2. Requirements for the front end

We assume that the beam energy of 1 MJ is required at 1 GeV at the target. The ion source is needed to provide 1 milli coulomb in total. To mitigate a space charge repulsion force at the final irradiation on the target, singly charged heavy ion, like uranium, bismuth or gold, is assumed [1]. Also, charge state 2+ particle is suggested to adopt as a design particle, since it may reduce the entire machine length half. The demanded charge is too large to provide from a single accelerator and we need to prepare multiple accelerator systems. Here we assume two hundreds beam lines in the initial stage of system. The required beam pulse lengths from the ion source are assumed as 20 μs for the induction scheme and 50 μs for the RF scheme. The design goals are summarized as in Table 1. The repetition rate is 10 Hz for all the cases.

3. Design parameters of laser ion source

Fig. 1 shows how laser plasma is converted to a heavy ion beam. Typically a laser system used in the LIS provides from 5 to 100 ns laser pulse. On the target surface, plasma is created and heated until the laser beam ends. The generated charge state distribution depends on the plasma temperature which can be controlled by a laser power density on the target. To induce mainly single charge state ions, the laser power density needs to be adjusted between 10e8 and 10e9 W/cm^2. Multiple charges require a higher laser power density. The laser irradiation duration is short, however the expanding plasma moves slowly and μs range ion beam can be easily obtained [2]. This mechanism helps to obtain a low ion beam emittance. Although the plasma has to have a certain temperature in the ionization process, it becomes cold at the extraction point in the laser ion source. Also the LIS had another important feature. The plasma is induced from solid material not from gas. So the emit ion density is much lager than other gas based ion sources.

To design a laser ion source which suits for a particular purpose, we have several variables to characterize its performance.

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We review those parameters and confirm some scaling laws regarding to the design.

- Laser energy
  Total laser energy per shot is almost proportional to total ion yield. By adopting a powerful laser system, we can increase the ion beam current easily. However, in case of the HIF scenario, the required repetition rate is 10 Hz and there is a limitation of the laser energy by temperature control of the laser medium.
- Plasma drift length
  The plasma drift length is defined as the distance between the target surface and the beam extraction point. The length is proportional to ion beam pulse width and inversely proportional to cube of the beam current as expressed at formula (1). If a plasma drift length is shortened to the half, the ion beam pulse becomes half and the current increases eight times. This is the most important constraint of the lase ion source. It is easy to make a high current LIS by shortening the length, however a longer ion beam pulse length requirement severely reduces the current. For the pulse length required by HIF is typically short and this feature mitigate the constraint.

  $$I \propto L^{-3} \tag{1}$$

- Laser power density
  The plasma temperature strongly depends on the laser power density. The unit of the density is commonly expressed W/cm^2, although the unit is not SI. To provide single charge state ions, the density is adjusted to from 10e8 to 10e9. Above 10e9 W/cm^2, multiple charge state ions appear. Also the plasma expansion velocity can be controlled by changing the density.
- Area of the extraction hole
  Simply a beam extraction area promotional to the extracted current.

Table 1
Required performance for HIF ion sources.

Driver type	Induction	Induction	RF	RF
Number of ion sources	200	200	200	200
Charge state	1+	2+	1+	2+
Beam current	250 mA	500 mA	100 mA	200 mA
Pulse width	20 μs	20 μs	50 μs	50 μs

4. Solenoid factor

Except the parameters listed above, a useful knob to design a LIS was introduced in 2009 [3]. The plasma has an initial velocity

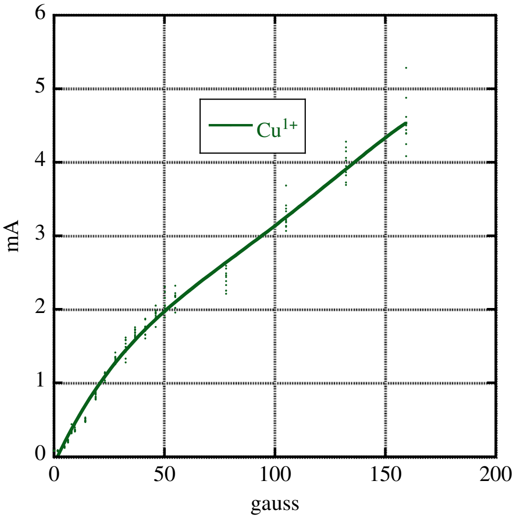

Fig. 3. Solenoid field and beam current.

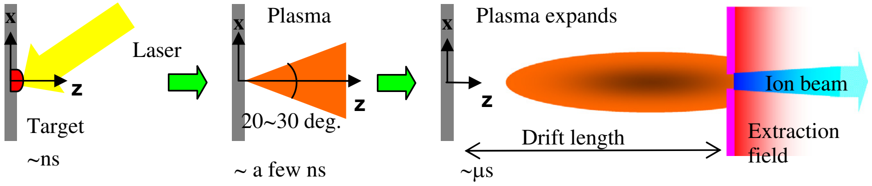

Fig. 1. Laser plasma and beam extraction.

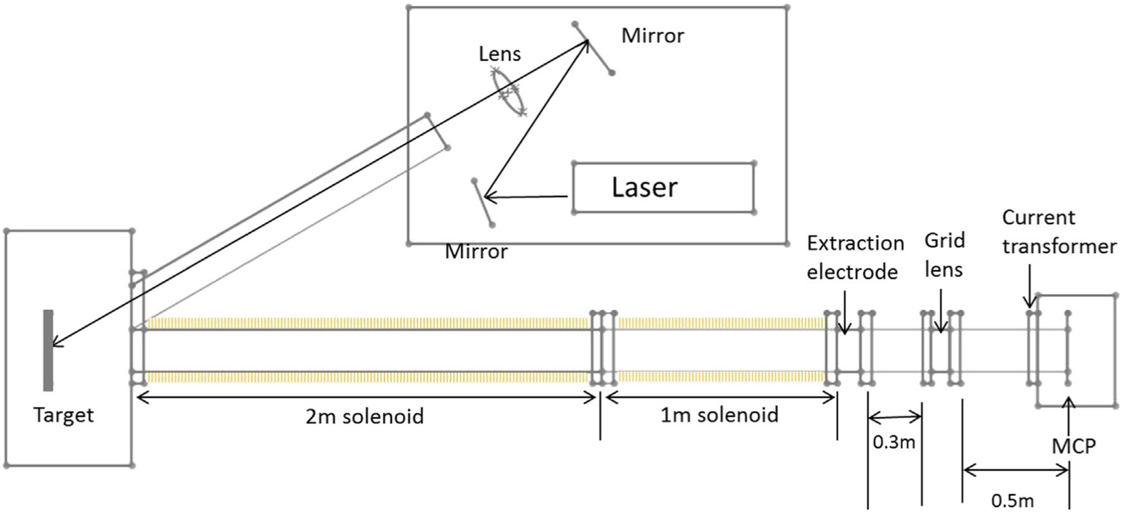

Fig. 2. Experimental set-up.