BROOKHAVEN NATIONAL LABORATORY

BNL-81502-2008-CP

Laser ion source for low charge heavy ion beams

M. Okamura, A. Pikin, V. Zajic
Brookhaven National Laboratory, Upton NY 11973

T. Kanesue
Kyushu University, Fukuoka 819-0395, Japan

J. Tamura
Tokyo Institute of Technology, Yokohama 226-8502, Japan

Submitted to the 17th International Symposium on Heavy Ion Inertial Fusion (HIF2008)
Tokyo, Japan
August 3-8, 2008

Collider-Accelerator Department

Brookhaven National Laboratory
P.O. Box 5000
Upton, NY 11973-5000
www.bnl.gov

DISCLAIMER

Laser ion source for low charge heavy ion beams

Masahiro Okamura

Brookhaven National Laboratory, Upton, New York 11973, USA

Alexander Pikin

Brookhaven National Laboratory, Upton, New York 11973, USA

Vladimir Zajic

Brookhaven National Laboratory, Upton, New York 11973, USA

Takeshi Kanesue

Department of Applied Quantum Physics and Nuclear Engineering, Kyushu University,

744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan and

RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

Jun Tamura

Department of Energy Sciences, Tokyo Institute of Technology, 4259 Nagatsuta-cho,

Midori-ku, Yokohama 226-8502, Japan and

RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

This work is performed under the auspices of the U. S. Department of Energy.

Abstract

For heavy ion inertial fusion application, a combination of a laser ion source and direct plasma injection scheme into an RFQ is proposed. The combination might provide more than 100 mA of singly charged heavy ion beam from a single laser shot. A planned feasibility test with moderate current is also discussed.

Introduction

An inertial fusion scenario driven by ion beams requires intense beam within short pulse duration. The required ion beam parameters are beyond what we have achieved in the high energy physics accelerator field. Among the various demanded developments for heavy ion inertial fusion (HIF), an ion source study is one of the key issues. We started to explore the feasibility of high current low emittance low charge state heavy ion beam production from a laser ion source (LIS).

In 2000 we started study LIS to provide high current highly charged ion beams for nuclear physics and high energy physics machines. The LIS has two major advantages over other types of ion sources. The first feature is a high plasma density. The LIS creates plasma from dense solid material, while other types of ion sources normally start from gas. A single laser shot from a conventional tabletop laser can generate a large number of ions. For example, a 2 J Nd-YAG laser shot generates about 2 x 10^{14} ions from an aluminum target[1]. The second advantage is that the laser-produced plasma has initial expanding velocity normal to the target. We can transport the laser-generated ions in a neutralized plasma state. To utilize these two advantages, we proposed a new method of combined laser ion production and injection called "direct plasma injection scheme (DPIS)." Figure 1 shows a typical DPIS setup.

A solid target is placed in an electrically isolated enclosure which is directly connected to a radio frequency quadrupole (RFQ) linear accelerator. The target is irradiated by laser shots and the induced plasmas are pushed out from the enclosure into the RFQ cavity. Inside the RFQ cavity, the ions from the neutral laser plasma are extracted by the electric field and are immediately captured by the RF quadrupole focusing force. As a result, the high density ion beam is efficiently accelerated through the RFQ. We demonstrated production of more than 60 mA of highly charged carbon and aluminum beams using the DPIS[2]. We believe that the DPIS is an effective approach also for the HIF, since a space charge problem of the low charge ion beam is more serious. Here we investigate the possibility to use LIS with DPIS for the HIF.

Low charge state heavy ion beam production.

Generally, a highly charged state ion beam is required to obtain efficient acceleration, because the entire accelerator complex becomes small and the construction cost is less. On the other hand, the HIF scenario requires a low charge state of heavy ions that is indispensable to make a deposition of high ion beam power on a target pellet to minimize the space charge repulsion force at a final irradiation stage. This is a unique requirement of the HIF accelerator and it makes beam handling more difficult especially in low energy region. While LIS has been developed to yield highly charged ions, we are investigating low charge low temperature beam production.

A laser system used for the LIS has typically generates ion pulses with duration from 5 to 100 ns. At the very beginning of the laser pulse, a solid target starts to be heated and its vapor to be ionized. The successive laser pulse heats the electrons in the plasma and then a step-wise ionization process occurs within the laser pulse period. To obtain highly charged ions, the laser power needs to be concentrated in a small volume and a high electron temperature is required. However, to produce low charge state ions, the electron temperature should be controlled carefully to avoid excessive ionizations.

Figure 2 shows a typical ion current density detected by a Faraday cup on a distance of 1 m from a Ta target. The output laser power was set to 500 mJ with a second harmonics crystal (532 nm) and the laser pulse duration was 6.2 ns (FWHM). The laser beam had initial diameter of 17 mm and was focused by a convex lens onto the Ta target surface. The focused laser image was 3.7 mm in diameter and the estimated laser power density was 7.6×10^8 W/cm^2. Due to a slow expanding velocity of the plasma and wide velocity spread, the observed ion pulse duration was 42 μs which is much longer than a typical width of the highly charge ion beam pulse. We varied the position of the focusing lens to control the laser power density. The result is shown in Fig. 3. In this measurement, the laser power was fixed at 500 mJ. In this experiment, the lower power density was achieved by enlarging the spot size. Below the 10^8 W/cm^2 of the power density, the ion current was not observed. By increasing the power density, the ion yield increases up to value of power density of 10^9 W/cm^2. Above this value and for the same total laser power the ion yield decreases since the irradiated area on the target decreases. At power density around 10^9 W/cm^2 the singly charged ions occupy more than 95 % of the total ion charge of the beam and the rest was mostly contributed by ions with charge state 2+. To obtain maximum yield efficiency, the laser power density was set to10^9 W/cm^2. We found that the optimum range of laser power density for this application is $10^8 - 10^9$ W/cm^2. Other metal species showed almost the same behavior [3].

We also measured the target material consumption. The same area on the Ta target was exposed to 9000 laser shots. Since the laser spot was large the only the surface layers of the target were consumed. We estimate that 9000 shots reduced the weight of the target by 0.0111 g . The power density and the spot diameter were 7.6x10^8 W/cm^2 and 4.3 mm respectively.

RFQ for low charge ion beams

RFQ linear accelerator was introduced in early 80' and is commonly used as a first stage accelerator in the world. Many electrostatic injector systems have been replaced by RFQs. One of great advantages of an RFQ is its strong transverse focusing force. Once a beam is captured by a transverse force, modulation pattern on the RFQ electrodes produces accelerating force in axial direction and the beam is bunched gradually to form an acceleration bucket. In this report, we focus on method to capture intense beams only in transverse direction, so the effect of the electrode modulation is neglected. For bunching and acceleration of the beam, further discussion will be given in future articles.

We can derive a preliminary space charge limit in an RFQ channel for a continuous cylindrical uniform ion beam. A potential distribution for an ideal static electric quadrupole field can be expressed as,

$$U = \frac{V}{2r_0}(x^2 - y^2).$$

U, V and r_0 are potential at point with coordinates x,y, voltage on the electrode surface and bore radius of the channel. In the RFQ the field is oscillating and the electric RF field in *x* direction is expressed as E_x. The motion of an ion can be described as follows.

$$E_x = -\frac{Vx}{r_0^2}\cos\omega t$$

$$0 = \frac{d^2x}{dt^2} + \frac{qVx}{mr_0^2}\cos\omega t$$

m and *q* are mass and charge of the ion.

Adopting the uniform cylindrical beam with radius *a*, a space charge force is written as

$$F_x = \frac{qI}{2\pi\varepsilon_0 c\beta\gamma^2 a^2}x$$

Here, *I*, ε_0, β and γ are total current of the beam, permittivity of the vacuum, velocity ratio and relativistic factor.

Now the motion equation includes the space charge force;

$$0 = \frac{d^2x}{dt^2} + \left(\frac{qI}{2\pi\varepsilon_0 c\beta\gamma^2 a^2} + \frac{qV}{m r_0^2}\cos\omega t\right)x.$$

This differential equation is known as Mathieu's equation. Condition of beam equilibrium in the channel is balance of the space charge term and the RF focusing term. The field and ion motion in *y* plane is described similarly.

Here we assume our DPIS-RFQ which was built for Carbon beam acceleration. The parameters of the RFQ are summarized in Table 1.

Assuming Ta^{1+} beam with radius of 5 mm, the maximum current in the RFQ was computed as 2.2 mA. Even for zero current ion beam in the RFQ, the betatron oscillation can not reach one full cycle (tune = 0.8) within the length of the RFQ. The charge to mass ratio of the Ta^{1+} beam is 1/181 and for the 100 MHz RFQ it is too small. Figure 4 shows calculated trajectories in a 10 MHz RFQ which has the same parameters as a 100 MHz RFQ except the frequency. The dotted line shows a zero current case and the solid line shows a 220 mA case which is close to the space charge limit in this condition. The derived current limit is only for the transverse confinement. To accelerate the intense beam, the ion beam has to be bunched and then the bunched ions should be concentrated around the accelerating RF phase. To accommodate high current beam, a low frequency RFQ is needed.

Planned experiment using a current setup in BNL.

To confirm the space charge limit of the RFQ and beam injection efficiency, we are planning to use our existing RFQ and LIS. First we will test Ta beam and then will try other species. The planned laser parameters are shown in Table 2. The laser power is 2.0 J and the aperture, which is placed between the LIS and RFQ, has inner diameter 6 mm. The extracted beam shapes were calculated by IGUN [4] and the results are summarized in Table 3. The assumed extraction voltage was 100 kV and all the values in the table are in RMS. Below 200 mA of the current, conversing beams are extracted and the emittaces are larger. In case of 200 mA current, γ is very large. This means that the diverging angle of the beam is steep. The optimum current will be between 100 mA and 200 mA. The detailed preparation for the experiment is in progress.

Summary

A combination of DPIS and low charge LIS can be applied to the HIF scenario. A laser ion source can provide intense low charge state heavy ion beams by carefully selecting a laser power density on a target material. The preferable power density is between 10^8 W/cm^2 and 10^9 W/cm^2. A space charge limit of our RFQ was estimated with a simplified model and the capability of capturing intense beam by a low frequency RFQ was shown. We are planning to test real beam in the near future.

Acknowlegement

The authors would like to thank J. Alessi, E. Beebe, J. Ritter of Brookhaven National Laboratory for useful discussion and are also grateful to H. Kashiwagi of JAEA and R. Becker for helps in the IGUN simulation.

References

[1] Review of Laser Driven Sources for Multi-charged Ions
M. Okamura, S. Kondraschev
2007 Particle Accelerator Conference, Albuquerque, 25-29 June (2007)

[2] Direct plasma injection scheme in accelerators
Rev. Sci. Instrum. 79, 02B314 (2008)
M. Okamura, T. Takeuchi, R. A. Jameson, S. Kondrashev, H. Kashiwagi, K. Sakakibara, T. Kanesue, J. Tamura

[3] MEASUREMENT OF ION BEAM FROM LASER ION SOURCE FOR RHIC EBIS
T. Kanesue, J. Tamura, M. Okamura

2008 European Particle Accelerator Conference, Gennoa, Italy 23-27 June (2008)
[4] http://www.egun-igun.com/

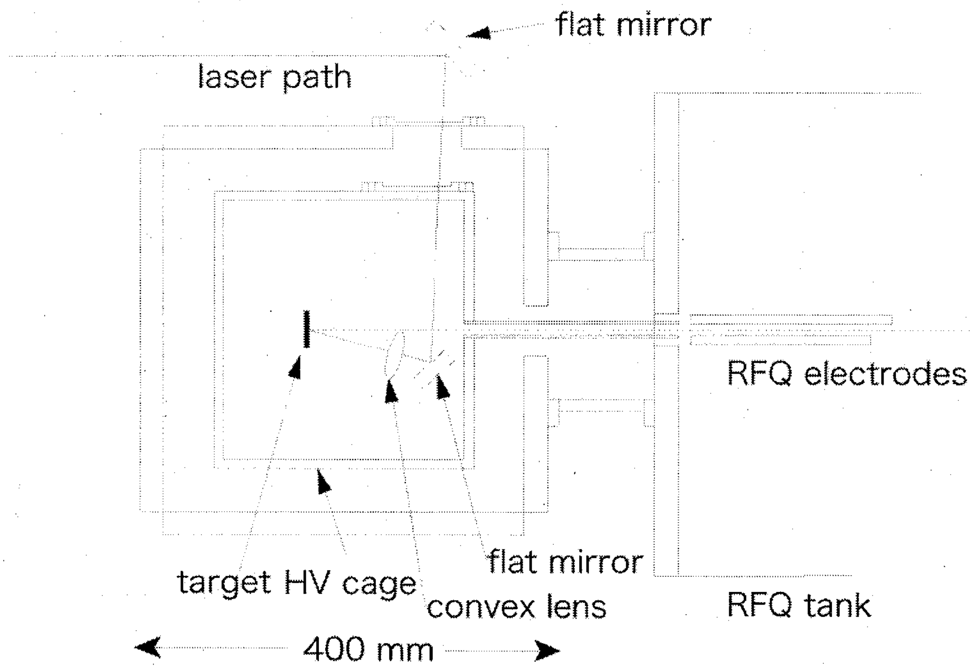

Fig 1 A laser ion source with direct plasma injection scheme.

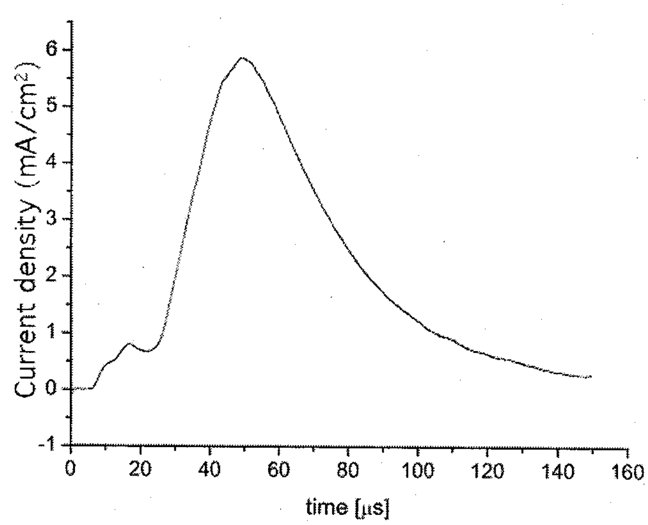

Fig. 2 Ion current at 1 m away from a Ta target.

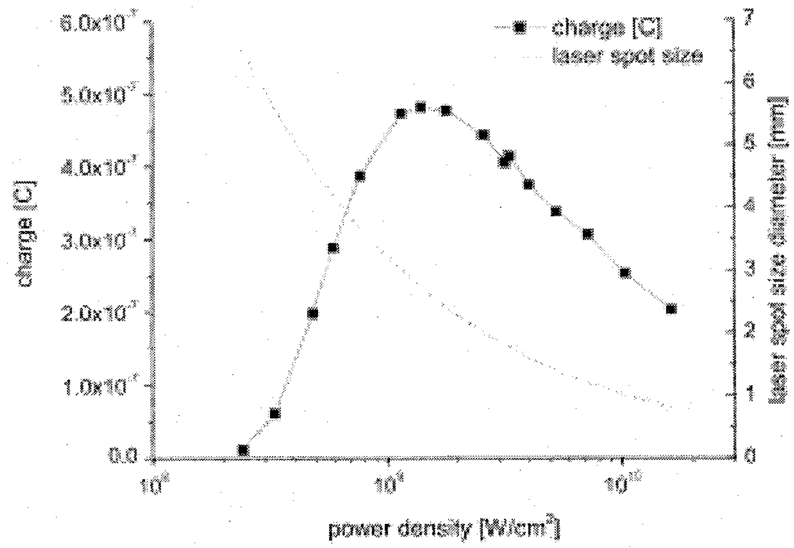

Fig. 3 Total charge yield and laser power density.

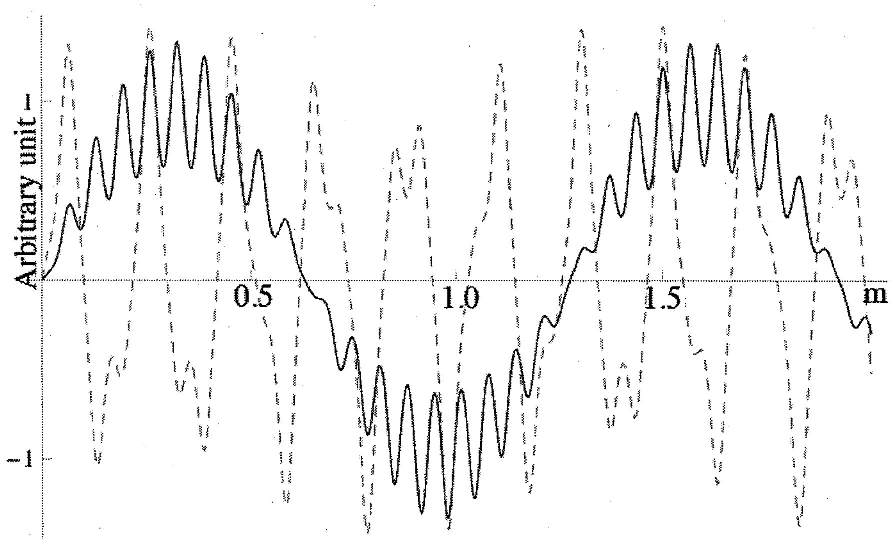

Fig. 4 A general solution of the Mathieu equation which represents 10 MHz RFQ.

Table 1: Parameters of the DPIS RFQ

Frequency	100 MHz
Total length	2.0 m
Aperture	6.55 mm
Inter vane voltage	120 kV
q/m	4/12

Table 2 Planned laser irradiation condition using Ta target.

Current (mA at peak)	10	100	200
Laser power density (W/cm^2)	$2.7x10^8$	$4.7x10^8$	$6.4x10^8$
Pulse width (μm, FWHM)	72	51	43
Number of particles (within FWHM)	$1.2x10^{12}$	$9.8x10^{12}$	$1.7x10^{13}$

Table 3 Twiss parameters at the beginning of the RFQ electrodes.

Current (mA)	α	β (mm/mrad)	γ (mdad/mm)	ε (mm mrad)
10	-0.0772	0.0077	130	25.8
100	-8.82	0.13	610	26.7
200	-107	1.4	8600	3.4