BNL-112613-2016-JA

Laser ion source for high brightness heavy ion beam

Masahiro Okamura

Submitted to Journal of Instrumentation

August 2016

Collider-Accelerator Department

Brookhaven National Laboratory

**U.S. Department of Energy
USDOE Office of Science (SC),
Nuclear Physics (NP) (SC-26)**

Notice: This manuscript has been co-authored by employees of Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. Department of Energy. The publisher by accepting the manuscript for publication acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party's use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Laser ion source for high brightness heavy ion beam

Masahiro Okamura,^a

^a *Brookhaven National Laboratory,*

Upton 11973 NY, USA

E-mail: okamura@bnl.gov

ABSTRACT: A laser ion source is known as a high current high charge state heavy ion source. However we place great emphasis on the capability to realize a high brightness ion source. A laser ion source has a pinpoint small volume where materials are ionized and can achieve quite uniform low temperature ion beam. Those features may enable us to realize very small emittance beams. In 2014, a low charge state high brightness laser ion source was successfully commissioned in Brookhaven National Laboratory. Now most of all the solid based heavy ions are being provided from the laser ion source for regular operation.

KEYWORDS: heavy ion; laser plasma; ion source.

Contents

1. Introduction	1
2. Intrinsic features of a laser ion source	2
2.1 Ionization principle	2
2.2 Pinpoint ionization	2
2.3 Space charge effect	2
2.4 Ion temperature of ion beam	3
2.5 Space charge limit of beam current	3
2.6 Background magnetic field at beam extraction	
2.7 Application to direct plasma injection scheme	4
3. Low charge high brightness heavy ion laser ion source in BNL	
3.1 Feasibility study of the laser ion source	
3.2 Performance of the laser ion source	Error!
Bookmark not defined.	
4. Summary	Error! Bookmark not defined.

1. Introduction

The laser ion source is one of typical applications of intense pulsed lasers. A solid target is irradiated by a laser shot and ablation plasma is formed. Of course the induced plasma contains electrons and ionized target materials. Generally greater laser power density on the target makes hotter plasma and this leads to create higher charge state ions. Those induced multiple charged ions can be extracted by applying a static electric field and are guided to make a stream called ion beam. This simple scheme is the principle of laser ion source and was invented around fifty years ago[1,2]. However laser ion source has never been employed by a major project in the history. In 1990's, the laser ion source had most intensively been investigated by European Organization for Nuclear Research (CERN) and Institute of Theoretical and Experimental Physics (ITEP), because the laser ion source was a candidate for the large hadron collider (LHC) project. At that time, a capability of high charge beam production from the laser ion source was mostly emphasized. Unfortunately the laser ion source development was stopped in 2004, although they could demonstrate production of the desired ion beam using lead target[3]. Since then, the laser ion source was faded from many researchers minds.

As explained above, a laser ion source is recognized as a high charge state ion source. This is true, however one can say a laser ion source has a great potential to provide very high brightness beam. In this article, we will explore intrinsic advantages of a laser ion source to achieve a high brightness beam. Then our latest laser ion source will be introduced which is now delivering heavy ion beams to relativistic heavy ion collider (RHIC) and NASA space

radiation laboratory (NSRL). Since last year, all the solid based heavy ions are being provided by the laser ion source in Brookhaven National Laboratory (BNL).

2. Intrinsic features of a laser ion source

2.1 Ionization principle

Typical laser irradiation duration is from a sub-nanosecond to a few tens of nanoseconds. The beginning of laser irradiation makes a seed of plasma. The following photon stream penetrates up to a plasma cutoff density and then bounced back. The laser energy is converted to the plasma temperature within this region mainly by inverse Bremsstrahlung process. So the ionization duration is very short which corresponds the laser pulse length. During the ionization process, the plasma is not confined by any external forces and its density is very high because the plasma does not have enough time to expand from a tiny volume heated by the focused laser energy.

2.2 Pinpoint ionization

As mentioned above, volume of ionizing plasma is quite small. Then induced plasma expands three dimensionally and the gravity center of the expanding plasma moves away from the target surface. The expanded and diluted plasma reaches an electric field region and only ions are extracted as an ion beam. Generally the extracted ion beam has a certain pattern of the ion density due to the shape of the plasma ionizing process. For example, electron cyclotron resonance (ECR) ion source use a sextupole transverse confinement magnetic field and this makes plasma triangle shape. The extracted beam is always affected by the shape of its original plasma's triangle shape[4]. On the other hand, a laser ion source has a pinpoint plasma generated far behind the beam extraction. The distance between the pinpoint source and the extraction is usually much larger than the size of the ion beam. This condition makes a uniform ion density of the extracted ion beam.

2.3 Space charge effect

A laser ion source can provide intense ion beam and such intense beam is strongly affected by space charge effect. The space charge effect is considered as the most harmful issue to transport heavy ion beams at a low velocity. This is true, but is not a rigorous expression. Assuming uniform ion density in a round shape beam, the space charge force can be simply expressed as,

$$E_r = \frac{\rho r}{2\epsilon_0} \quad (1).$$

E_r , ρ , r and ϵ_0 are electric field of radial direction, charge density, radial position and permittivity of free space, respectively. As seen in the formula, there is no azimuthal dependence and the induced field is expressed by the linear function of the radial position. This means the space charge force of the uniform round beam exists but does not cause emittance growth due to nonlinear forces. The expanded size of the beam by the linear space charge effect can be easily compensated by a low aberration focusing element. An extracted uniform beam from a laser ion source satisfies this condition.

2.4 Ion temperature of ion beam

In the ionization process, plasma temperature needs to be high enough to achieve a desired charge state of ions. When a very high charge state of ions is required, the plasma temperature reaches several hundreds of electron volts easily. Of course, a laser ion source is not an exception. To provide highly charged ions, we need to attain a high temperature by applying a very large laser power density on the target surface. In the ionization process, the plasma temperature should meet the criteria, however the induced plasma which contains the ions will be diluted and cooled while it moves to the extraction point. Figure 1 shows a schematic view of our new laser ion source installed at BNL, which will be explained later in this article. The ionizing point is 3.3 m away from the beam extraction hole that is 15 mm in diameter. At the ionizing point, the plasma temperature has Maxwell-Boltzmann distribution and expands and moves toward to the extraction point[7]. The expanding angle of the plasma has typically ± 20 degrees and the temperature distribution corresponds to this expanding angle. In the distributed plasma flux by its temperature, the selected plasma only by ± 0.13 degree of the extraction hole, which is ± 7.5 mm at 3.3 m away from the ionizing point, can go through. So the thermal distribution within a slice of the selected and extracted beam became almost negligible.

Figure 1 Schematic view of plasma expansion in BNL laser ion source

2.5 Space charge limit of beam current

To extract charged particles, an available beam current is restricted by space charge limit [5,6]. From static plasma, the limit is expressed by the famous three halves law as,

$$J = \frac{4}{9} \epsilon_0 \sqrt{\frac{2q}{m}} \frac{V_a^{3/2}}{d^2} \quad (2).$$

In the formula, J , q , m , V_a and d are limited current density, charge of a particle, mass of a particle, applied voltage between the extraction electrodes and the distance of the electrodes, respectively. This formula is derived from the Poisson's equation with zero velocity of the initial charged particles. In case of a laser ion source, the ions already have velocity toward to the extraction region and this makes slight difference in the formula as,

$$J = \frac{4}{9} \epsilon_0 \sqrt{\frac{2q}{m}} \frac{(\sqrt{V_0} + \sqrt{V_0 + V_a})^3}{d^2} \quad (3),$$

where V_0 is the total kinetic energy which is characteristic of the initial ion velocity at the sheath. The space charge limit with an initial charged particle velocity has been studied by Jaffe [8], Benilov [9] and Liu[10]. The formula 3 was explicitly derived by Jaffe in the reference 3. Figure 2 shows a space charge limit versus initial velocity of Au^{1+} beam. The horizontal scale shows the total energy of a gold ion. As seen in the graph, ablation laser plasma's expanding condition helps to provide more intense beam than other ion sources those use static confined plasmas.

Figure 2 Extractable beam current density and initial velocity of plasma.

2.6 Background magnetic field at beam extraction

In many cases, plasma is confined by a magnetic field and a beam extractor directly faces to the confined plasma. This typical configuration superimposes magnetic field on the electric beam extraction region. Such situation always affects on the beam emittance. When a particle escapes from the extraction region, the particle may cross the magnetic field fluxes since the field exists around the region. By crossing every magnetic field, the velocity direction of the particle bends slightly. Let's suppose the existence of an axial magnetic field concentric to the beam extractor. At the center of the extractor, which is at the beam core, a particle is extracted freely and does not need to cross the magnetic field since the particle is extracted at the center of the solenoidal magnetic field. However, once a particle extracted at an off centered position, the particle must cross the magnetic field flux and get a azimuthal velocity component referenced to the beam direction. This component is easily derived applying Gauss's law as,

$$V_{\theta} = \frac{1}{2} \frac{q}{m} B_z r \quad (4),$$

where B_z and r are axial magnetic field flux density and radial position. For instance, a C^{6+} ion is extracted at 5 mm from the center of 1 T axial magnetic field, the obtained azimuthal velocity is about 870 eV which is not a negligible value comparing to a typical extraction voltage. Figure 3 shows the relationship of the solenoidal field strength at the beam extraction region and normalized beam emittance of the extracted beam of C^{6+} . The horizontal scale shows radius of the extraction hole. We will explain our solenoidal field beam current enhancement later in the

article, but the field strength of our case is only around ten Gauss and almost no emittance growth is expected. This aspect is the great advantage of a laser ion source.

Figure 3 Beam emittance and background magnetic field at the beam extraction.

2.7 Application to direct plasma injection scheme

We have studied high current heavy ion beam acceleration using a combination of laser ion source and radio frequency quadrupole (RFQ) linear accelerator which is named as direct plasma injection scheme (DPIS). In the DPIS, laser ablation plasma is created and expands toward an RFQ without beam extraction. The ionized particles are delivered within plasma state to the first stage accelerator and the beam extraction is done in the resonant cavity of the accelerator. As a result, space charge force in a low energy transport section can be avoided and very intense beam can be captured by strong focusing force of the RFQ. We have demonstrated to accelerate more than 5×10^{10} of C^{6+} ions with a single 2 J laser shot [11]. This scheme is one of unique applications of laser ion source[12]. A low charge state heavy ion production with a laser ion source and DPIS is considered as a candidate of high brightness drivers for heavy ion inertial confinement fusion scenario [13].

3. Low charge high brightness heavy ion laser ion source in BNL

3.1 Feasibility study of the laser ion source

In 2007, we started to investigate low charge state heavy ion beam production from a laser ion source. At that time, electron beam ion source (EBIS) was being built. The EBIS uses 10 A of electron stream to strip off electrons from injected and captured heavy ions. To provide various species to the NSRL, two external hollow cathode ion sources were prepared. However hollow cathode sources use gas discharge and the used noble gas which may contaminate and sacrifice the electron beam trap capacity. Also only single species can be used as a cathode

material and to switch several species, cathode material has to be changed with breaking vacuum. So new external heavy ion source was strongly desired. By controlling laser irradiation condition, we found that various low charge state heavy ion can be produced which has more than 100 times of beam current than that of the hollow cathode sources without increasing beam emittance. Figure 4 shows the test setup of the low charge state laser ion source.

Figure 4 Test setup of low charge state ion source

The laser source was required to provide a few hundred micro A of beam current and a few hundred micro seconds of the pulse width. The tested all solid based ion beams have fulfilled these basic requirements with good beam stabilities. To test the performance of the beam transport section to the EBIS, the identical test transport was assembled and the performance was confirms. For example, the measured RMS normalized beam emittance by a pepper pot monitor at the end of the transport line was $0.072 \pi \text{ mm mrad}$ for horizontal and $0.077 \pi \text{ mm mrad}$ for vertical. The beam current profile is shown at Figure 5 and the peak current reached at $285 \mu\text{A}$. In the test, beams of C, Al, Si, Cr, Fe, Cu, Ag, Ta and Au have been measured. The detailed conditions were described in the past publications[14.15].

Figure 5 Beam current profile of Fe1+ beam. The peak between two vertical red lines are supposed to be injected to the EBIS.

3.2 Performance of the laser ion source

We commissioned the new low charge state laser ion source in 2014[16]. The first gold beam was successfully and smoothly delivered. In 2015, we upgraded the source to provide different beams to the NSRL and RHIC simultaneously (Figure 6). Usually the RHIC requires gold beam for 24 hours to warm up the entire accelerator chain. The RHIC is a superconducting collider synchrotron and its circumference is 3.8 km. At the moment two major experiments, PHENIX and STAR are being operated. At the injection period of the RHIC, the laser source needs to operate at 5 Hz for 8 pulses or 12 pulses per every 4 seconds. The source needs to operate at least for a few months to a half-year continuously. The NSRL needs various kinds of ions. To meet the requirement, we usually install more than ten species in the source. The sample photo is shown in Figure 7 which shows alumina for oxygen, Ca, Au, Li, Si, B, Ti, Fe, Ta, C. This target assembly is scanned by two dimensional motorized system in the vacuum condition.

Figure 6 Hadron accelerator complex for RHIC and NSRL at BNL.

Figure 7 Laser target assembly for NSRL

Figure 8 shows the entire view of the source. Three 850 mJ Nd-YAG lasers are installed. One is for RHIC, the other is for NSRL and the last one is for spare. The plasma expanding section was made by a 3 m long stainless steel 75 mm I.D. pipe. The entire pipe was winded by a 2 mm diameter conductor to form the solenoid coil which can enhance beam current about ten times. This coil was designed to be energized at several Gauss, however it could be pushed to several times higher field strength depends on the operation condition and the species. At the beam extraction chamber, excessive plasma and neutral gas can evacuate by a dedicated turbo pump. The total days of the operation in RUN15 for multiple species, aluminum for RHIC, and gold for RHIC reached 99, 24, and 96 days respectively [17].

Figure 8 Low charge state laser ion source

The new low charge state laser ion source keeps providing high brightness heavy ion beam at BNL.

4. Summary

Laser ion source have been considered as a high charge state ion source in the history. In addition, we confirmed several advantages of the laser ion source to achieve high brightness beam. At BNL a new low charge state heavy ion laser source is being operated routinely as a high brightness laser ion source.

Acknowledgments

The research was supported by NASA, U.S. Department of Energy, The experiments and fabrications were done by many colleagues in BNL and many students who joined the project. The author thanks to L. Torrissi of Messina University and K. Horioka of Tokyo Institute of Technology for useful discussions.

References

- [1] Y. A. Byckovsky, V. F. Eliseev, Y. P. Kozyrev, and S. M. Silnov, “Laser generator of multi-charged ions for accelerators,” Sov patent 324 938 (8 June 1969).
- [2] N. J. Peacock and R. S. Pease, *J. Phys. D* 2, 1705 (1969).
- [3] B. Sharkov and R. Scrivens, *IEEE Trans. Plasma Sci.* 33, 1778 (2005).
- [4] P. Spadtke, R. Lang, J. Maeder, J. Roßbach, K. Tinschert, Proceedings of ECRIS08, Chicago, IL USA THCO-B02
- [5] C. D. Child, *Phys. Rev.* 32, 492 (1911).
- [6] I. Langmuir, *Phys. Rev.* 2, 450 (1913).
- [7] L. Torrissi, S. Gammino, L. Andò, L. Làska, *J. Appl. Phys.* 91, 4685 (2002)
- [8] G. Jaffe, *Phys. Rev.* 65, 91 (1943).
- [9] M. S. Benilov, *Plasma Sources Sci. Technol.* 18 (2009) 014005 (14pp)
- [10] S. Liu, R. A. Dougal, *Journal of Applied Physics* 78, 5919 (1995)
- [11] T. Kanesue, Y. Fuwa, K. Kondo, M. Okamura, *Applied Physics Letters* 105, 193506 (2014)
- [12] T. Sako, A. Yamaguchi, K. Sato, A. Goto, T. Iwai, T. Nayuki, K. Nemoto, T. Kayama, T. Takeuchi, *Rev. Sci. Instrum.* 87, 02C109 (2016)
- [13] M. Okamura, M. Sekine, K. Takahashi, K. Kondo, T. Kanesue, *Nuclear Instruments & Methods in Physics Research A* 733 97-102 (2014)
- [14] K. Kondo, T. Kanesue, J. Tamura, and M. Okamura, *Rev. Sci. Instrum.* 81, 02A511 (2010)
- [15] K. Kondo, T. Yamamoto, M. Sekine, and M. Okamura, *Rev. Sci. Instrum.* 83, 02B319 (2012)
- [16] T. Kanesue, et al., Proceeding of IPAC2014, WEOAB01
- [17] M. Okamura et al., Proceeding of HIAT2015, THM1C03