PERFORMANCE OF THE LOW CHARGE STATE LASER ION SOURCE IN BNL*

M. Okamura†, J. Alessi, E. Beebe, M. Costanzo, L. DeSanto, S. Ikeda, J. Jamilkowski, T. Kanesue, R. Lambiase, D. Lehn, C.J. Liaw, D. McCafferty, J. Morris, R. Olsen, A. Pikin, R. Schoepfer, A. Steszyn , Brookhaven National Laboratory, Upton, NY USA

Abstract

In March 2014, a Laser Ion Source (LIS) was commissioned which delivers high brightness low charge state heavy ions for the hadron accelerator complex in Brookhaven National Laboratory (BNL). Since then, the LIS has provided many heavy ion species successfully. The induced low charge state (mostly singly charged) beams are injected to the Electron Beam Ion Source (EBIS) where ions are then highly ionized to fit to the following accelerator's Q/M acceptance, like Au^{32+}. A LIS has been known as high current high charge state ion source, however we demonstrated it can provide stable long pulse low charge state heavy ion beam with a good emittance.

INTRODUCTION

Laser ion source has been used to deliver high charge state high current beams. In fact, it can provide fully stripped carbon beam with more than a few tens mA of beam current [1, 2]. In spite of the known unique features, we are developing a low charge high brightness laser ion source. In this report we introduce the laser ion source which is providing singly charged heavy ion beams to the electron beam ion source (EBIS) followed by the linacs and the chain of synchrotrons in BNL.

The new laser ion source was nicknamed as "LION" by one of the authors. We started to develop the LION in 2009 since the project was funded by NASA. The NASA has a user facility in BNL which is called as NASA Space Radiation Laboratory (NSRL) and we provide various heavy ion beams from the booster ring to simulate high energy cosmic rays in the NSRL. By installing the LION, the beam species can be switched in a minutes and the facility can operate with more versatile and more flexible modes. Before intfg\roducing LION, all the initial seed beams were provided from a set of hollow cathode ion sources [3]. The typical beam currents were only around ten microamperes with long pulses and the beam transport line from those external sources to the EBIS was designed to accommodate the range of the hollow cathode source's beam current. The LION beams also need to go through the same beam transport line comprised of electro static optics devices with the limited area of good field region. So that the LION needs to provide relatively low current comparing a standard LIS, less than a milliampere, with a very good beam emittance.

In 2014, the first beam from LION was delivered to the EBIS. The beam commissioning was very successful and since then LION has been used to provide various heavy ion beams to the NSRL. In 2015, we installed another laser and additional target to provide gold beam to relativistic heavy ion collider (RHIC). Now most of solid based species and oxygen are supplied by the LION in BNL.

* Work supported by NASA and US Department of Energy under contract number DE-SC0012704.
† email address okamura@bnl.gov

FEATURES OF LASER ION SOURCE

The principle of a laser ion source is simple. In vacuum condition, a solid target is irradiated by a pulsed laser beam and a plasma is formed. The plasma is heated by successive laser irradiation and the plasma temperature becomes higher. The typical total laser pulse width is from sub-nanoseconds to several tens of nanoseconds. By controlling deposited power on the target, the plasma's temperature and expansion speed can be adjusted. For the LION development, we only need singly charged ions and the laser power density was controlled just above 10E8 W/cm^2. We use 850 mJ 6 ns Nd-YAG lasers [4] and the typical spot size is 3 mm to 5 mm in diameter. As we stated, the heating process is defined only by the laser and target. Other factors like effect of vacuum vessel's wall or background confinement forces do not contribute the plasma production. As long as we control the laser stability and target surface condition, stable ion beam can be easily obtained.

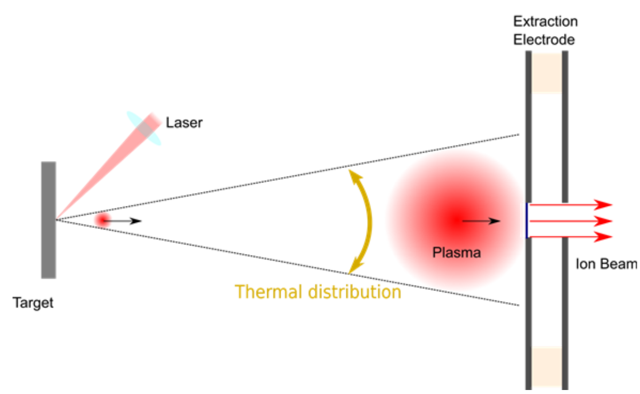

Figure 1: Expanding plasma and extracted ion beam.

Figure 1 shows expanding laser ablation plasma. The gravity centre of the plasma has a velocity perpendicular to the target surface. While the plasma travels from the target to the extraction point, it expands three dimensionally. After the heating stage, each particle in the expanding plasma can be considered to move on the straight path, and the envelope of the entire plasma has conical shape. This conical angle corresponds to the thermal distribution in the plasma. Generally, the solid angle defined by an extraction hole is much smaller than the plasma's expanding angle. As a result, the extracted ion beam has much less thermal distribution which contributes to define the ion beam emittance. The LION has 15 mm of extraction aperture which is 3.3 m away from the target surface. So that the thermal effect in the plasma is negligible in the ion beam collimated by the extraction aperture.

In general, the plasma shape affects uniformity of the obtained ion beam. In case of a laser ion source, the heated plasma occupies only small volume and it is located far from the ion beam extraction point, as shown in Fig. 1. This configuration helps to make a uniform density distribution in the ion beams. The uniform beam distribution also helpful to mitigate an emittance growth.

Since heating time period is with in nanoseconds range, we don't need to use an external confinement force when the plasma is created. At the presence of strong magnetic field, ion beam extraction from the plasma enlarges the beam emittance. We are almost free from this adverse effect. We may use weak magnetic field to guide the expanding laser plasma which will be explained later, however, since the field is so weak or localized, almost no contribution to the beam emittance is expected.

Therefore, we believe high brightness low charge state heavy ion beams can be delivered by a LIS.

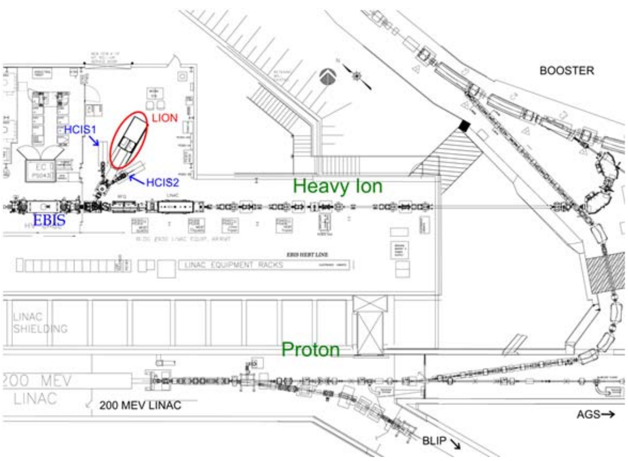

Figure 2: Floor layout of the EBIS injector.

Figure 2 shows the location of LION. Heavy ion beam induced from various solid materials are created by LION and transported to the EBIS [5]. The RFQ and IH-LINAC accelerate stripped heavy ion beam (Q/M > 32/197) up to 300 keV/u and 2.0 MeV/u, respectively [6, 7]. Since there is no analysing magnet before the RFQ, the injected beam to the linacs has charge state distribution around the desired charge state. The charge state selection is done by a set of dipole magnets just before the injection point of the booster ring. A typical charge of Au32+ injected to the booster ring is about 11 nC per pulse.

A cut view of the LION is shown in Fig. 3. At the top of the frame, three lasers were installed in an interlocked safety box. The first laser is for NSRL and second laser is for RHIC. The third laser is a spare for NSRL and can be used to irradiate on the same spot of the first NSRL laser simultaneously since the polarization of both NSRL lasers have right angle. Each laser has 850 mJ and the NSRL target can be shot with nearly twice of 850 mJ.

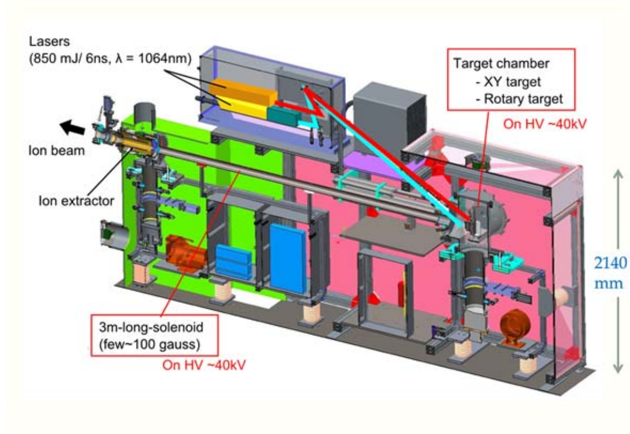

Figure 3: Cut view of the LION.

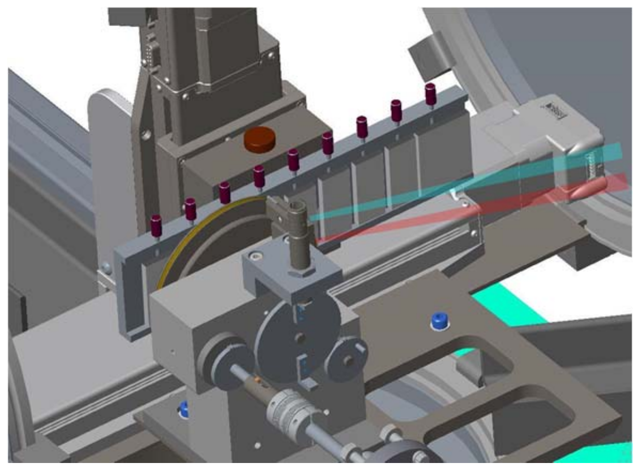

Figure 4: Target station of LION.

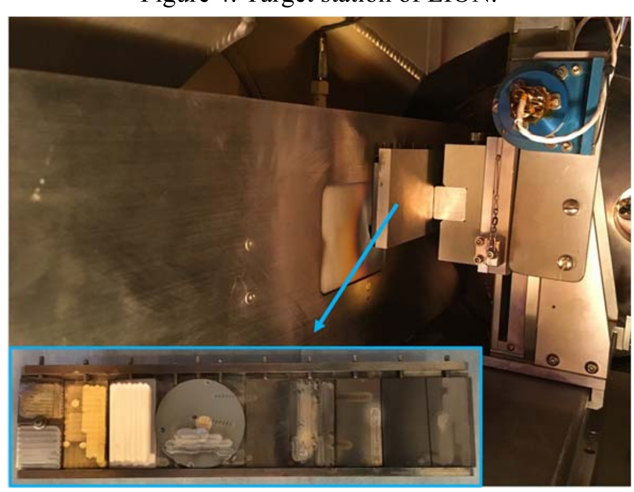

Figure 5: XY stage. Ten material plates are placed in the holder. The wall in front of the target holder is to prevent accumulation of vaporized materials on the target surface.

The laser targets are illustrated at Fig. 4. The shown disk is made of solid gold and is used for the RHIC. In the operation, the disk is driven through gears by a motor which is outside of the vacuum chamber. Behind the gold target, a motorized two dimensional stage is mounted. The photo of the stage is shown in Fig. 5.

The target is usually scanned with slow speeds, typically 0.1 mm every minutes, to avoid a long period of exposure on the same spot and equalize target material consumption over the usable area. The scanning speed is depending of the materials. Alkaline metals can be also used with relatively faster scanning speed as a target [8].

The beam extraction electrodes are at 3.3 m downstream from the target. This long plasma drift section makes a longer ion beam pulse which is requested by the EBIS. The beam performance at the EBIS injection point was measured in the test bench before we fabricated the final version of LION. The design specifications and measured values are listed in Table 1. The measured beam emittance by a pepper pot monitor was 0.043 pi mm mrad (RMS) and the distribution in the phase space is shown in Fig 6.

Table 1: Measured and Required Value of Gold Beam

Required value		
Mass of injected ion	AMU	197
Charge state of interest	+	32
q/A		0.16
Overall efficiency	%	50
Injection time	µs	145
avg inj 1+ current	µA	38.1
total ion charge in species of interest	Coulomb	5.5E-09

Experimental results		
Experimental result of injection time	µs	145
Experimental result of peak current	µA	113
Experimental result of total ion change	Coulomb	1.46E-08
Nor RMS emittance X	πmmmrad	0.043
Nor RMS emittance Y	πmmmrad	0.043
Solenoid	gauss	0
Twin pulse	Yes/No	N

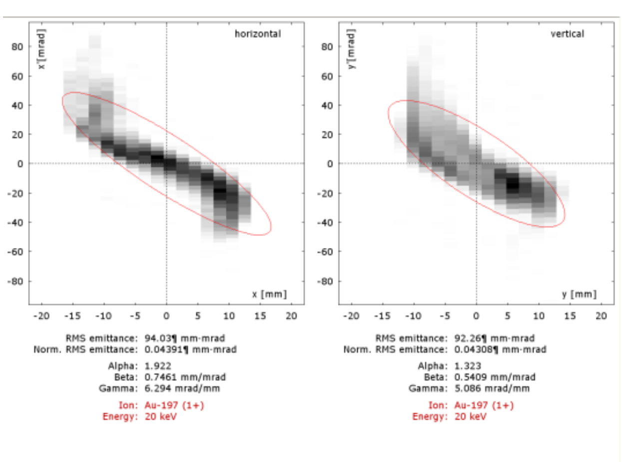

Figure 6: Measured emittance of Au beam after the transport line.

The long drift section between target vessel and the extraction vacuum chamber is connected by a 3 m long static solenoid. The I.D is 76 mm. By applying a few tens of Gauss, the diverging angle of the plasma is slightly shrunk and the beam current is enhanced up to ten times. This is a very convenient knob to adjust the current of the entire beam pulse. Each species has an optimum beam current demanded by the EBIS. For a long time operation, the flash lamps of the lasers are gradually degraded and the target surface roughness becomes coarse. Those slowly changing conditions gently lower the beam current and it can be compensated by the long static solenoid.

Recently, we developed a pulsed solenoid. The pulsed solenoid is triggered by a fast semiconductor switch and can selectively enhance certain part of the beam. For example, the magnetic field can be applied only at the tail of the beam current period and it can maintain almost constant current within a pulse. When we use a chemical compound, like Al_2O_3, as a target, the earlier part of pulse contains more fraction of oxygen plasma and the pulsed solenoid can enhance this particular part of the beam. The both static and pulsed solenoid are illustrated in Figs. 7 and 8 and Table 2.

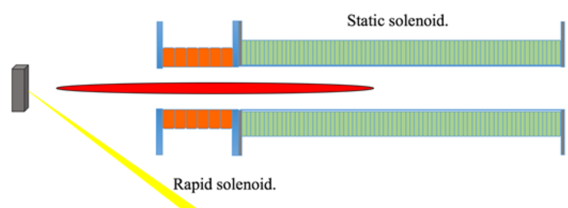

Figure 7: Concept of pulsed and static solenoids.

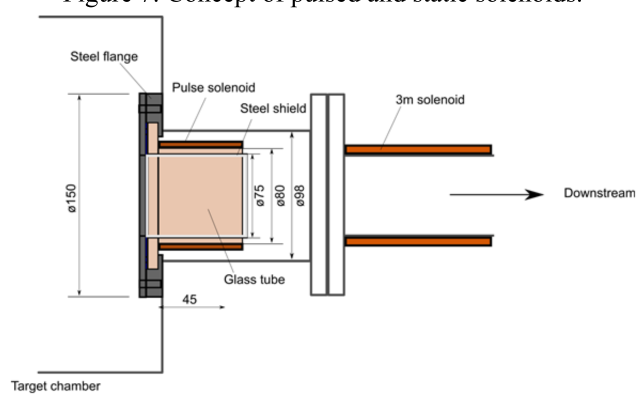

Figure 8: Dimensions of the pulsed solenoid coils.

Table 2: Coil specifications of solenoids

	Static	Pulsed
Magnet length	3 m	45 mm
Inner diameter	76 mm	80 mm
Number of turns	5728	330
Time response	Constant	7 µs

OPERATION OF LION

Since March 2014, LION has been used. Although LION was new concept ion source and we had many small troubles as expected, we could provide various heavy ion beams with almost no down time during the past RUNs.

The Table 3 shows operation days. The Run 17 already started and LION is providing beams to the following accelerators now.

Table 3: Total Days of LION Operation

		Li	B	C	O	Al	Ca	Si	Ti	Fe	Ta	Au
Run14 (since March 25, 2014)	NSRL (days)			2				11	1	18	1	3
	RHIC (days)											33
Run 15	NSRL (days)	1		2			1	18	4	30		6
	RHIC (days)					14						42
Run 16	NSRL (days)		1	5	9			13	5	33	4	1
	RHIC (days)											198

SOME FAILURES

Our experienced failures can be categorized into three group, mechanical, electrical and optics troubles.

Initially, we plan to move the gold target with a constant velocity. However, the continuous revolution of the mechanical shafts destroyed some bearings since those are in vacuum condition. Therefore, we employed step scanning of the rotating target. By applying intermittent rest condition, accumulated heat can be conducted from bearings. We also replaced some ceramic ball bearings to Vespel bushings. In 2016, we found heavy accumulation on the gold target surface. The enlarged photo of the accumulation is shown in Fig. 9. The shown built up was formed from evaporated material, since we have operated for almost two hundred days continuously. Unfortunately some chunk of gold were stuck on the target surface and caused unstable beam condition. For the next run, we modified the target cover and install a carbon fiber brush to scrape off the accumulations. The modified rotary target assembly is shown in Fig. 10.

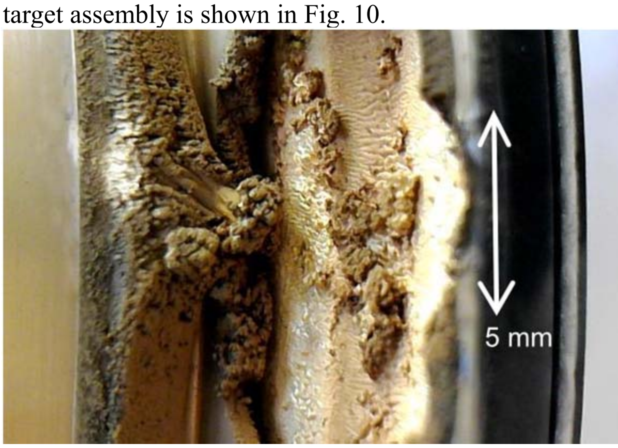

Figure 9: Accumulation caused by vaporized gold.

We experienced some electrical failures including discharge on the high voltage platform, burned high voltage supply connectors and registers, break down of the laser power supplies and sudden stop of some control devices. The most severe trouble was motor failure on the two dimensional stages. In the stage, two stepping motors are used. The failure was similar to the bearing story mentioned above. We started to move the stage with a continuous slow speed. This made the motors very hot and it was visible by the vacuum monitor system. So far, we replaced motors twice and now we end up to use step scan mode as we explained.

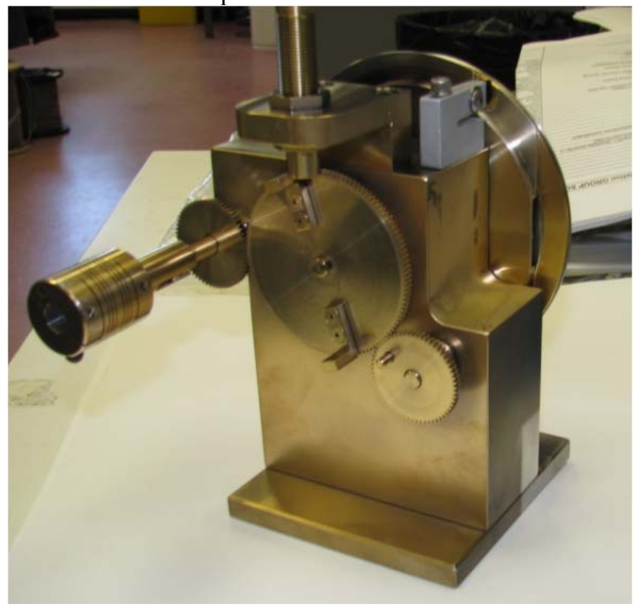

Figure 10: Modified rotary gold target.

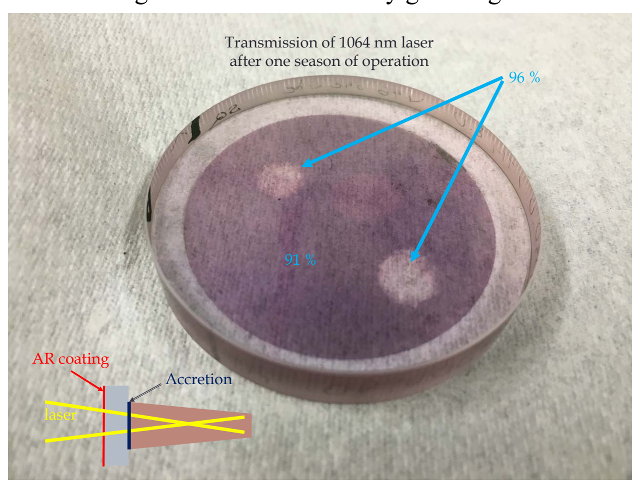

Figure: 11 Used laser window (ϕ = 50.8 mm).

Figure 11 shows used vacuum window for the laser path. The window is 1.8 m away from the target with an angle of 30 degrees from the plasma expanding axis. Since the plasma expands within about 20 degrees and off set position of the window helps to reduce the direct exposure from the dense plasma. Even this condition, after one season's exposure, the window was darken as shown in the picture. The outside surface has AR coating, but inner side has no coating since slight accumulation easily discard the AR condition. On the laser path, the deposited laser energy helps to keep clean the inner surface of the window. The laser transmission on the laser spot reduced 4 %, beside other part of the area absorbs 9 % of the laser energy. We also experienced energy drop on one of laser systems. The laser had been in standby mode for a month with steady temperature of 38 degrees C. This warm water condition could cultivate algae in the water circulation system and degraded the reflectors installed around the laser flash lamps. Now we avoid a long time standby mode and apply UV sanitization when the cooling water is replaced.

Let us note that all the failure experiences had helped us to improve total reliability of LION.

SUMMARY

Since 2014, the new low charge state laser ion source, "LION, " has been operated. Most of all solid based species are supplied from LION in BNL. We demonstrated high brightness and good reliability of laser ion source through the intensive operation period.

ACKNOWLEGEMENTS

In the development stage of LION, the project was helped by many students under the collaboration with RIKEN.

REFERENCES

[1] H. Zhao *et al.*, "New development of laser ion source for highly charged ion beam production at Institute of Modern Physics," *Rev. Sci. Instum.*, vol. 87, p. 02A917, 2016.
[2] T. Kanesue *et al.*, "Laser ion source with solenoid field," *Appl. Phys. Letter*, vol. 105, p. 193506, 2014.
[3] J. Alessi *et al.*, "A hollow cathode ion source for production of primary ions for the BNL electron beam ion source," *Rev. Sci. Instum.*, vol. 85, p. 02C107, 2014.
[4] Quantel Laser, `http://www.quantel-laser.com`
[5] J. Alessi *et al.*, "The Brookhaven National Laboratory electron beam ion source for RHIC," *Rey. Sci. Instum.*, vol. 81, p. 02A509, 2010.
[6] A. Schempp *et al.*, "RFQ and IH accelerator for the new EBIS injector at BNL," in *Proc. 22nd Particle Accelerator Conference (PAC'07)*, Albuquerque, NM, USA, Jun. 2007, paper TUPAN021.
[7] D. Raparia *et al.*, "Commissioning of the IH linac and high energy beam transport of the EBIS based preinjector for RHIC," in *Proc. Linear Accelerator Conf. (LINAC'10)*, Tsukuba, Japan, paper TUP033.
[8] M. Okamura *et al.*, "Calcium and lithium ion production for laser ion source," *Rev. Sci. Instum.*, vol. 87, p. 02A901, 2016.