REVIEW OF LASER DRIVEN SOURCES FOR MULTI-CHARGED IONS

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Abstract

Since the first idea of an ion source using laser ablation plasma arose, almost forty years has already passed. It was found that the laser plasma could provide ultra intense beam with high charge state easily. In spite of this advantage, the laser ion source (LIS) has not been accepted by a major stream of the accelerator field. Once the laser plasma produced, it is hard to control the pulse structure. However, accumulated research results by many groups capable us to provide high quality multi-charged ions from LIS now. The LIS suits not only for a large accelerator complexes but also for small facilities. The history of the LIS and a project for LHC at CERN are briefly introduced. Then recent activities about direct plasma injection scheme (DPIS) are explained. Also other works related to LIS are summarized.

ION SOURCES FOR ACCELERATORS

Three types of high current ion sources, electron cyclotron resonance (ECR) ion source, electron beam ion source (EBIS) and laser ion source (LIS), are used for multi-charged beam production. The ECR source is the most popular type and has a great advantage in CW operation. Now, many leading institutes are investing the enormous efforts to develop the ECR sources. The EBIS can supply intense high charge ions with excellent flexibility. The charge state distribution is controlled by changing the ion confinement time and also the beam pulse structure can be manipulated. Among these sources, the LIS has the simplest structure and the pulse current is the most powerful. We believe that the LIS will be accepted more widely in various purposes in the future.

In the category of the LIS, we discuss about basic backward ablation type in this article. There is selective type LIS which uses resonant ionization processes with a particular laser wave length but this is not treated here. Recently, a forward ablation type LIS was developed, which is using a short pulse, fs range, laser with thin target foils. The thin foil is irradiated by laser shots which have very high power density achieved by the short pulse and energetic ions are emitted from the opposite side of the foil. To utilize this scheme in real accelerator complexes, however, further study is still needed. So we focus only the backward ablation LIS.

HISTORY OF THE LIS

The first idea of the LIS was proposed by an English group[1] and Y. A. Byckovsky separately in 1969. In 1977, the first LIS operated to provide heavy ion beams to Synchrophasotron at JINR. In 1988, the beams from LISs were provided to electrostatic accelerators at ITEP and Technical University of Munch independently. In 1994, an RFQ linac was used to accommodate ion beams from LIS at GSI with ITEP group. At CERN, as a part of LHC project a high power LIS using 100 J CO_2 laser had been studied intensively under the collaboration with ITEP until 2003[2].

LASER PRODUCED PLASMA

One of the most important features of the laser plasma is its very high density. The laser plasma is created from the solid target by laser pulse irradiation and is expanded from a pinpoint. On the other hand, in most of all other ion sources, the plasma generated from gas state. If we extract ions near the plasma starting point of the LIS, high brightness of the ion beam can be easily achieved. The initial expanding velocity of the plasma is typically about 100 eV/u with about 100 % of a momentum spread. The laser energy and the power density on the target surface are important parameters those are typically from 100 mJ to a few tens J and from 10^9 w/cm^2 to 10^{13} w/cm^2 respectively. High power irradiation makes large amount of ions and the higher laser power density enables to strip more electrons.

We can make rough estimation of the current from the LIS based on the volume of the evaporated target material by a single laser shot. Using a 3 J Nd:Glass laser, we made a crater on a aluminum target which has 0.2 mm in diameter and 0.1 mm depth. Assuming the crater made by a laser shot has conical shape, the volume corresponds to $2x10^{16}$ ions. If all the evaporated volume is turned into a pulse beam which have charge state 10+ and 1 μs length, the current is about 32200A. In real world, only small portion can be ionized and let us assume this efficiency as 1 % here. Still we have about 300 A of the current. The plasma expands not only for one direction and its diverging angle is about 20 degree. If we apply typical DPIS configuration shown in Fig. 1, the current is estimated as 170 mA which roughly corresponds to experimentally obtained value. We can imagine the brightness of the LIS.

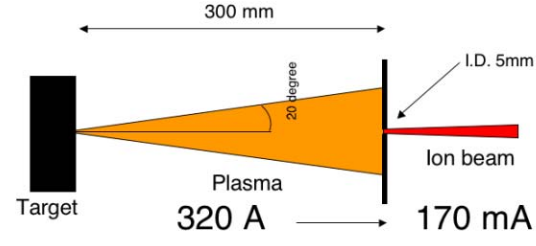

Figure 1: Ion beam current extracted from laser plasma.

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The above discussion also indicates that the distance between the target and the ion extraction point is important parameter to control the beam current. Also the distance defines the ion beam pulse length. The laser pulse only has 1 ~ 100 ns and it takes a few μs to travel within this distance in the plasma state with a large momentum spread. More distance makes longer ion pulse and thinner ion density. If you need 10 μs of ion pulse, the length is typically more than 1 m. In this case a higher power laser is needed to compensate the diluted ion density at the extraction point. The ion pulse width is proportional to the length and a peak current amplitude is inversely proportional to the cube of this value. Figure 2 shows peak currents and pulse widths as a function of the distance.

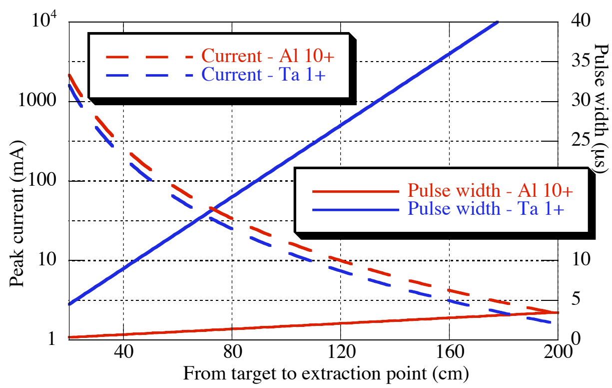

Figure 2: Currents and pulse widths.

Red line: Al^{10+} (3 J, 30 ns, Nd-glass laser, 10^{11} W/cm^2)

Blue line: Ta^{1+} (1 J, 5 ns, Nd-YAG 2ω laser, 10^9 W/cm^2)

LIS FOR LHC

To study the possibility of providing intense lead ion beam to LHC, the high power LIS had been developed. The requirements for the LHC-LIS are in Table 1. We believe this LIS was the most powerful one among the history. To satisfy the long pulse length with the high charge state, specially designed CO_2 laser was constructed. The laser energy was set to 100 J.

Table 1: Required performances for the LHC-LIS

Species	Current	Pulse length	Repetition rate
Pb^{25+}	8 mA	5.5 μs	1 Hz

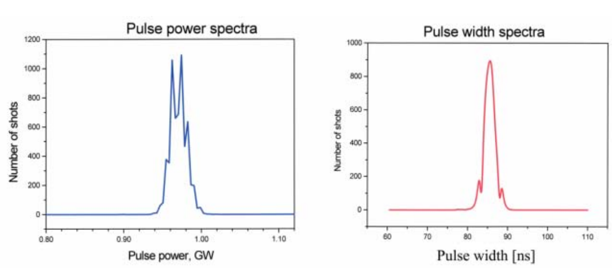

Figure 3: Stability of the 100 J CO_2 laser in generator mode.

In generator mode operation, the obtained pulse width was 88 ns with good stability. Master oscillator – power amplifier mode operation with 0.25 Hz repetition rate performed well. The achieved charge states from a lead target showed from 19+ to 32+ and the charge states 26+ and 27+ showed the highest yield. At the extraction point which is 1.75 m away from the target, Pb^{27+} ions were counted as 2.3×10^{10} with a 34 mm extraction aperture. This project was stopped just before the final completion. This huge LIS was moved to ITEP and is being developed for TWAC project. The obtained knowledge from the intensive research activity in CERN is still giving us valuable information.

USING COMMERCIAL LASERS

To achieve outstanding performance, a specially made high power laser system might be needed. However in this case, much research efforts have to be paid for the laser development. A commercial laser system would be a solution for limited manpower and for restricted cost. In 2005 at RIKEN, we explored the potentials of typical laser systems. Charge states distributions of various species using two commercial laser systems were measured. The specifications of the two lasers are summarized in Table 2. The tested species are ^{12}C, ^{27}Al, ^{48}Ti, ^{56}Fe, ^{70}Ge, ^{93}Nb, ^{108}Ag and ^{181}Ta. Figures 4 and 5 show measured charge states using the Nd-glass laser and the Nd-YAG laser respectively. The Nd-YAG laser has

Table 1: Specifications of the conventional lasers

	Nd-Glass-Laser	Nd-YAG-Laser
Model	B.M.industries SERIE 5000	Thales SAGA230
Max. energy	3.45 J - 30 ns	2.36 J - 6 ns
Wave length	1062 nm	1064 nm
Spot size	10 mm	17 mm
Divergence	0.8 mrad	0.5 mrad
Rep. rate	45 s / shot	10 Hz
Power density	~10^{11} W/cm^2	~10^{12} W/cm^2

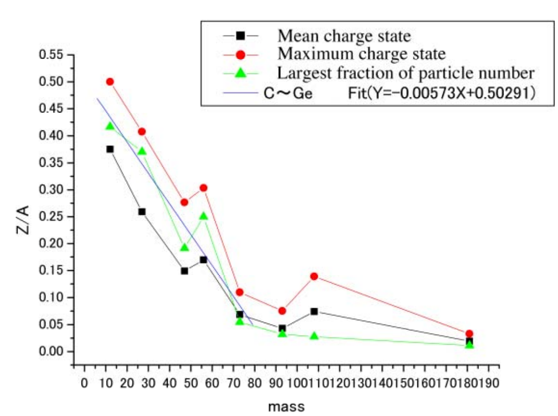

Figure 4: Charge states using the Nd-glass laser.

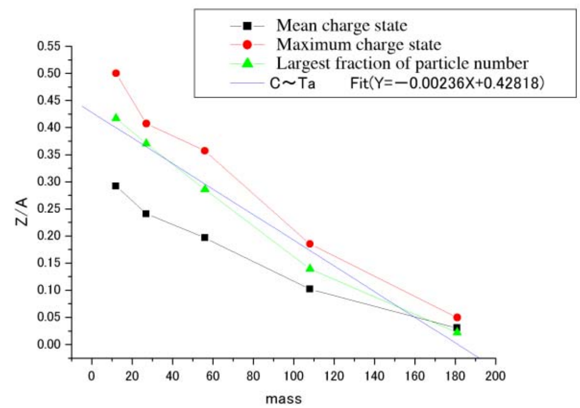

Figure 5: Charge states using the Nd-YAG laser.

one order higher power density than the Nd-glass laser has. In both cases, a focusing lens was placed 100 mm from the targets and the target positions were adjusted to maximize the emitted ion velocities those gave usually the highest charge states yield. In carbon and aluminum measurements, the recorded charge state distribution using both lasers were similar. In iron measurement the highest charge states using both lasers are almost same, but the Nd-YAG iron charge distribution concentrated around the charge state 16+ while the Nd-glass has even distribution starting from 2+ to 17+. Most significant difference was observed in silver measurement. The Nd-glass laser only could ionize up to the charge state 11+, but the Nd-YAG laser provided up to the charge state 20+. The higher power density laser can obtain a certain ratio of a mass number and a charge state number with the heavier species. When the target is very heavy, the laser power density does not affect the charge state distribution well. Both Ta plasmas from the two lasers showed alomst same distribution. To create highly charged ions from heavy material above Ag, a higher power density irradiation is required.

HIGH POWER DENSITY FOR HEAVY MATERIALS

A high power density of a laser irradiation is achieved by a high laser power or by a short laser pulse. Prague Asterix Laser System (PALS) iodine laser satisfies the both requirements simultaneously. The powerful iodine laser emit 1.315 μm, 1 kJ, 400 ps laser pulse and the power density reaches 6×10^{16} W/cm^2 on a target. L. Laska's group demonstrated to produce Pb^{51+}, 19.8 mA/cm^2 and Ta^{55+}, 49.0 mA/cm^2 at 1 m from the targets. They also reported that nonlinear processes significantly influencing ion generation were observed above 10^{14} W/cm^2. Beyond the power density, achievable charge state and plasma expanding velocity suddenly go up[3.4]. However the laser has relatively slow repetition rate and the size is very large for the typical accelerators.

It is not severely difficult to achieve 10^{14} W/cm^2 using a short pulse laser. It is worth to explore the plasma generation conditions with a several ps, several hundred mJ compact laser which will be fit to the accelerator ion source application.

DIRECT PLASMA INJECTION SCHEME

As mentioned previously, the laser ablation plasma has very high density compared to other plasmas in different types of ion sources and has initial expanding velocity normal to the target materials having emitting angle of a few tens degree. We can transport the bright ion beam under the neutralized plasma state condition into the first stage accelerator which is typically an RFQ.

To take these advantages of the laser plasma as an ion source, the DPIS was proposed in 2000. The first beam was produced with the DPIS and was accelerated by an 80 MHz 4-vane RFQ in T.I.Tech that was originally designed to accelerate oxygen ions. The obtained peak current was more than 9 mA from a carbon graphite target using a 4 J CO_2 laser in 2001(Fig. 6). After the proof experiment, a new 100 MHz RFQ shown in Fig. 7 was designed and was fabricated to accelerate hundred mA class high intensity heavy ion beam collaborating with A. Schempp and R. A. Jameson of IAP, Frankfurt university. In 2003, using this new RFQ which was installed at NIRS, we could obtain 60 mA of carbon beam with the 4 J CO_2 laser (Fig. 8). At that time, also a 400 mJ Nd-YAG laser was tested to produce fully stripped carbon beam and the measured result showed that accelerated peak current reached up to 17 mA (Fig. 9). In 2005 the RFQ and the ion source were moved to RIKEN campus in Saitama, Japan and we started to accelerate Al ions. A new 2.3 J commercial Nd-YAG laser (see Table 2) could provide 70 mA of peak current with good stability (Fig. 10).

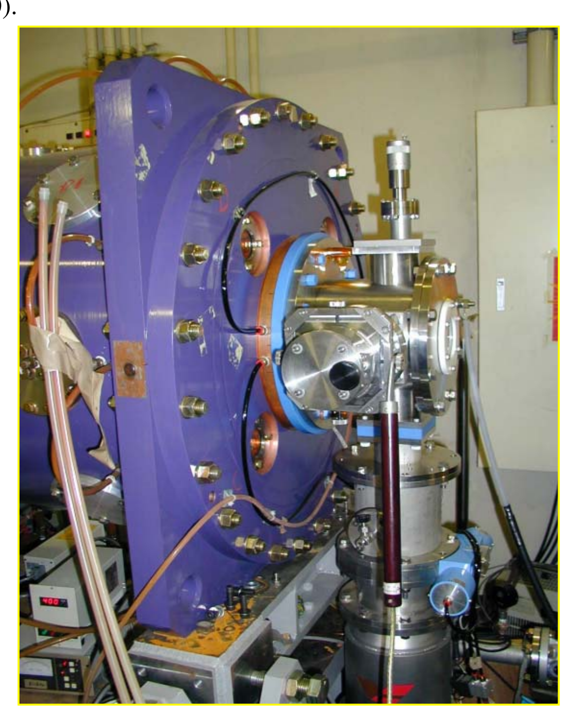

Figure 6: The first DPIS test at T.I.Tech, Tokyo.

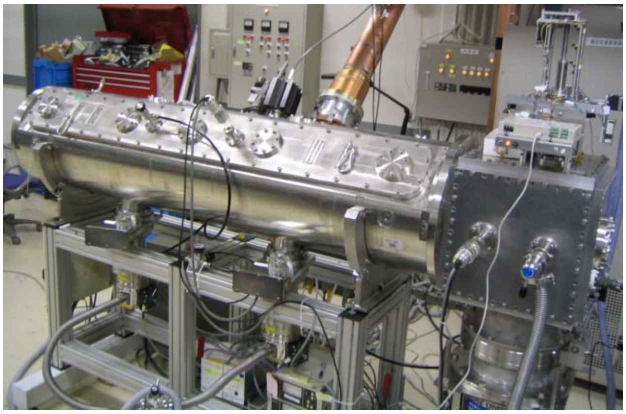

Figure 7: 100Mhz 4-rod RFQ with DPIS-LIS.

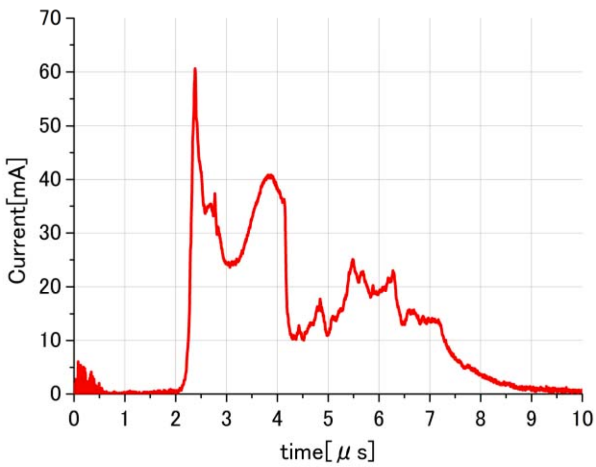

Figure 8: Carbon beam acceleration.

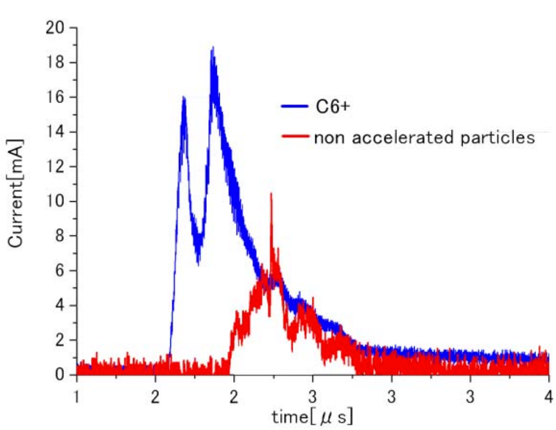

Figure 9: Fully stripped carbon beam acceleration.

All the peak currents indicated here are measured after the RFQ and the beam energy were 100 keV/u for the all cases. The DPIS is quite effective to provide intense heavy ions with short beam pulse, 2 to 3 μs range, which matches to a small scale synchrotron (circumference ~100 m) and a FFAG. In addition, typical commercial laser system is enough to provide highly charged ions up to medium mass species like irons.

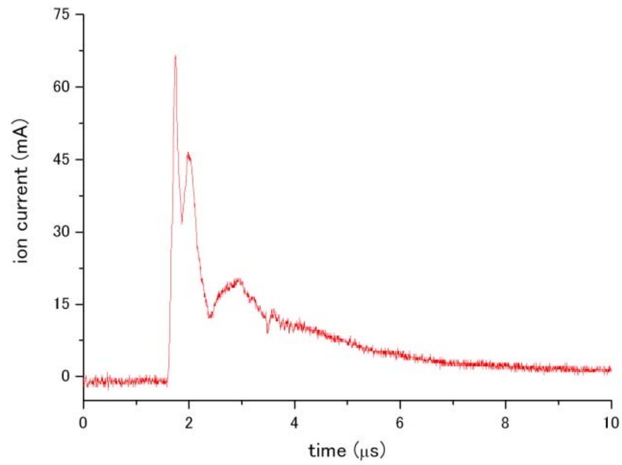

Figure 10: Aluminum beam acceleration.

COMBINATION OF LIS AND OTHER DEVICES

The laser beam can ionize materials those are located electrically isolated places. This feature is good to combine with other accelerator devices. In addition the LIS is also useful to provide stable low charge states beams. Here we introduce a few examples of the LIS applications.

LIS for ECR

An attention-grabbing approach was tried at INFN-LNS. A laser target was placed inside of an ECR chamber and was hit by a 0.9 J-9ns Nd:YAG laser. The applied 18 GHz ECR source was one of the most advanced super-conducting ECRs named SERSE. Au and Ta were used as targets. To reduce the initial momentum of the laser plasma, the targets were electrically biased. The plasma was induced under the strong magnetic field (2.7 T). This hybrid ion source with LIS and ECR produced Ta^{38+} and Au^{41+}[5].

LIS for EBIS

At BNL, a powerful EBIS is being constructed which will be mainly used for RHIC and NSRL. The EBIS has about 2 m long, 6 T super-conducting solenoid and the length of a trap region is designed as 1.5 m. A 10 A electron beam covers the trap region with 1.1×10^{12} electrons and the 5.5×10^{11} ion charges will be captured assuming 50 % efficiency. In case of gold beam production, the required charge state is 32+ which occupies about 20 % of total trapped charge number, 1.1×10^{11} charges, after the ionization process. The total number of ions contained by a single ion source beam

Table 2: Particle numbers of the BNL-EBIS

Ions	$^{12}C^{6}$	$^{28}Si^{14}$	$^{56}Fe^{24}$	$^{197}Au^{32}$	$^{238}U^{45}$
Fraction*	50 %	50 %	50 %	20 %	20 %
Req. #	4.6E10	2.0E10	1.2E10	3.4E9	2.4E9
Inject. #	1.2E11	4.3E10	2.4E10	1.7E10	1.2E10

* Number of desired charges / all stored charges

pulse is $3.44\text{x}10^{9}$ particles and $1.72\ \text{x}10^{10}$ low charge ions are required to be injected as a primary beam from an external ion source. For other species, the particle numbers for the EBIS are summarized in Table 2.

A small LIS can provide enough number of the low charge state particles to the EBIS. The produced charge states can be easily controlled by reducing the laser power density on targets. We tested to produce low charge state plasma from several target materials. Figure 11 shows the Ta plasma result using a Nd-YAG, 532 nm, 0.74 J, 5 ns laser. The Ta target was placed near a focusing lens and the geometrical laser spot size on the target was 13 mm in diameter. Assuming the distance from the target to the extraction point as 2 m, about 100 μs pulse length with more than 500 μA of Ta^{1+} beam in 1 cm^2 extraction aperture is predicted. In this condition, the expected particle number of Ta^{1+} is about $3.7\text{x}10^{11}$ which is more than 20 times of the required particle numbers by the BNL-EBIS as a primary beam. We also confirmed that the used target can be remained smooth surface condition without any craters after more than several hundred irradiations.

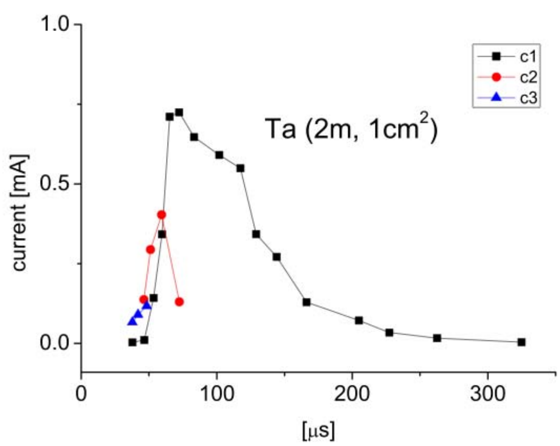

Figure 11: Ta^{1+} production using a LIS.

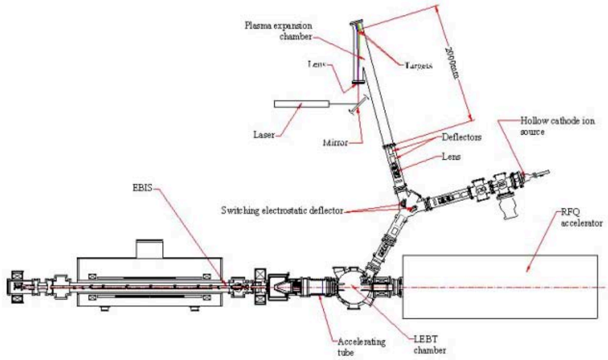

Figure 12: Floor layout plan for the LIS + EBIS.

Figure 12 indicates the LIS installed in the BNL-EBIS apparatus. In the LIS chamber, several targets will be installed. By switching laser path, we can change the extracted species by pulse to pulse basis. Within this year, we plan to built a test LIS for this purpose.

LIS for electrostatic accelerator

At RARAF, Columbia University, a compact LIS is being developed for Singletron which is a single end 5 MV electrostatic accelerator. The laser is Nd-YAG type 100 Hz, 325 mJ, 10 ns. The specially designed cylinder shaped target is driven by a motor in vacuum and survive for a month operation. In spite of relatively high repetition rate and severe vacuum pumping condition, highly charged ions like Al^{10+} are produced without recombination with electrons. This project is to provide single-particle single-cell micro-beam to study fundamental cellular response to irradiation[6].

GAS TARGET FOR LIS

Since 2006, we have been trying to make ices of gases on a cold surface for LIS. Using a 4 K, 1 W cry-cooler, Ne gas was frozen and irradiated by Nd:YAG laser, 0.6-1.2 J, 1064 nm and the Ne plasma was investigated. We succeeded to produce stable Ne plasma with 1 Hz repetition rate. The cold surface was made of Ta sheet to prevent damage from the laser irradiation. A laser shot flushes all the accumulated Ne ice and then enough ice start to condense on the surface again for next laser shot. The target drive mechanism is not required. The obtained current corresponds to more than 100 mA with a typical DPIS configuration.

SUMMARY & ACKNOWLEDGEMENTS

LIS provide highly charged intense pulsed heavy ion beams with a simple structure and suit for any size of accelerator complexes. Also some new approach to combinations with other devices are being studied. The authors thanks all the researchers in the relevant accelerator field and are specially grateful to Prof. L. Laska in PALS, Prof. L. Torrisi in INFN and A. Bigelow in RARAF for providing valuable information.

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