LASER-BASED HEAVY ION PRODUCTION

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Abstract

Laser ion source (LIS) already has about thirty years history, and has many variety of usages. Since 2000 we have focused on high brightness of induced laser plasma to provide intense highly charged ions efficiently. To take an advantage of the intrinsic density of the plasma, Direct Plasma Injection Scheme (DPIS) has been developed. The induced laser plasma has initial expanding velocity and can be delivered directly to the RFQ. Using this technique, we can provide pulsed very high intensity heavy ion beam with good stability. We achieved 70 mA of Aluminum beam after the RFQ. Also, feasibility of frozen gas target scheme was verified. A design strategy for LIS has been established and the DPIS is ready for use in real operating facilities.

HISTORY

Laser beam has been widely used in an accelerator field as diagnosis device, survey tool, polarizer for electrons, electron beam production and even supplier of direct ion acceleration force. In this article, we focus on ion beam production usage as an ion source among various applications of laser beam.

In 1977 the first utilization of a laser-produced plasma as an ion source was achieved at JINR in Dubna and was followed by ITEP in Moscow and Technical University of Munch in 1988 independently. In 1994, an RFQ linac was used to accommodate ion beams from laser ion source (LIS) at GSI in Darmstadt. At CERN in Geneva, as a part of LHC project high power LIS using 100 J CO_2 laser had been studied intensively under the collaboration with ITEP until 2003[1]. Recently INFN in Catania group started to operate an ECR ion source seeded by laser ablation plasma[2]. In extreme case, some groups presented MeV class acceleration in the laser electric field. In 2005 it was reported by LANL that very high power 30 TW 600 fs laser beam enables to accelerate Carbon ions up to 3 MeV/u [3]. However this approach need to be studied further to apply realistic accelerator complex.

In this stream, since 2000 we have tried to enhance specific advantages of the laser ablation plasma as an ion source. The laser ablation plasma has very high density compared to other plasmas used in different type of ion sources. Because the laser plasma is produced from solid material not from thin gas and this feature gives us to utilize very high brightness ion beams without any extra confinement forces. The another important feature is that the laser plasma has initial expanding velocity normal to the target materials having emitting angle of 20-30 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, direct plasma injection scheme (DPIS) was proposed. The first beam was produced with DPIS and was accelerated by an 80 MHz RFQ in T.I.Tech in Tokyo. The obtained peak current was more than 9 mA from Carbon graphite target using a 4 J CO_2 laser in 2001. Upon this success of the proof experiment, a new RFQ 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 in Chiba, Japan, we could obtain 60 mA of carbon beam with the CO_2 laser. At that time also 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. Last year 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 could provide 70 mA of peak current with good stability. Also frozen gas target technique was tested.

CONVENTIONAL LIS SCHEME

A typical laser ion source consists of a laser system, a target and an extraction electrode like shown in Fig.1. Here we assume that laser pulse duration is from 1 ns to 100 ns range. During 1 ns of laser irradiation, the plasma expands up to 4.5 mm that is much longer than focusing laser spot size, assuming the expansion speed of 100 eV/u which is typical speed of the ion energy included by a laser plasma. This condition means that laser power can be mainly absorbed by electrons in the plasma first and then stepwise ionization occurs. The plasma travels to an extraction region with very large momentum spread and is getting thinner. And then ions can be extracted to form the initial ion beam.

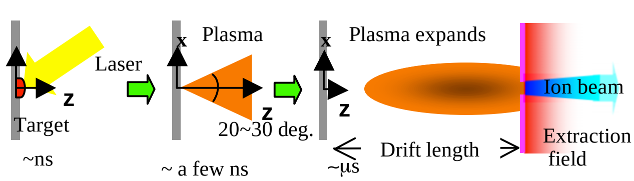

Figure 1: LIS scheme.

PARAMETERS FOR LIS

Laser ion source can provide pulsed intense highly charged heavy ions, but we usually have more strict criterion of ion beam parameters like species, charge state, pulse duration, stability, emittance, repetition rate and current. To obtain specific beam characters for the LIS, we need carefully to choose some parameters listed below.

Target Material

Usually solid material is used as a target. Purity of the target material is very important. It was proved that pure graphite target which has less than 5 ppm of impurity could not show even hydrogen peak in our plasma analysis experiment using a secondary electron multiplier detector. A ratio of isotopes and oxidized surface condition should be taken care of. For instance, it is not easy to get pure beam from Ti target without any special treatment. About beam stability, it is harder from heavier species.

Laser Power

Higher laser power makes more ions. Higher laser power density on the target produces higher charge states and higher velocity of the plasma expansion. We found that each laser has own limitation in heaviness of the target element. We tested two laser systems, a Nd-Glass laser and the Nd-YAG laser. The glass laser could ionized iron with reasonable charge state, but could not produce highly charged ions from heavier materials above iron. For example, Ge and Nb were ionized up to 8+ and 9+ respectively. The YAG laser which has shorter pulse duration could ionize up to silver ions. If we need to get highly charged ions from Ta or Au, more higher power density laser beam will be needed. On the other hand, a few hundred mJ 10 ns laser is enough to provide C^{6+}.

Table 1: Limitation in Heaviness of Species

Laser	**Power**	**Width**	**Ions**
Nd Glass-1062 nm	3.45 J	37 ns	Up to Fe^{17+}
Nd-YAG-1064 nm	2.3 J	6 ns	Up to Ag^{15+}

Wave Length of the Laser

It is commonly said that shorter is better for energy absorption. However the wave length depends on the laser medium. Usually we have more strong constraints from laser availability in the market.

Emittance of the Laser Beam

This parameter affect an achievable focusing spot size just like ion beam optics. Also effect from the wave length should be considered.

Focal Length of the Final Focusing Element

Shorter focal length can provide higher power density. This value is determined by geometrical configuration in the ion source chamber. The focusing element is not allowed to interfere plasma passage.

Plasma Drift Length

A distance between the target and ion extraction point determines ion pulse duration. The laser pulse only has 1 ~ 100 ns and it takes a few μs to travel within this distance for the plasma. More distance makes longer ion pulse and thinner ion density. If you need 10 μs of ion pulse, the length is typically a few m. In this case a higher power laser is needed to compensate 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. These relations were verified well in our experiments.

Solid Angle for Capturing the Plasma Expansion

This value is proportional to the total extracted number of ions because plasma starts from a pin point on the target.

DIRECT PLASMA INJECTION SCHEME

A short plasma drift length dramatically improves the ion capturing efficiency. However in this case strong electric field is required for ion extraction and space charge repulsion force is serious after the extraction. DPIS can overcome these issues. Figure 2 indicates our latest version of the ion source.

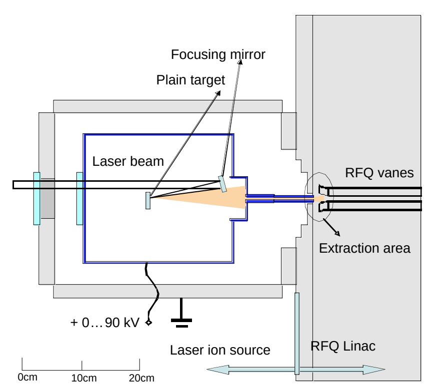

Figure 2: Layout of LIS for DPIS.

A target material hung by a 3D manipulator placed about 30 cm upstream from an entrance of the RFQ. Inside of a vacuum chamber which is directly connected to the RFQ, we have high voltage biased space surrounded by blue line in Fig. 2. A laser beam pass through two coated windows and is focused by a concave mirror. The focused laser beam on the target induces plasma, which expands and towards to the RFQ entrance. Then the plasma is guided by a pipe to the inside of the RFQ tank and then contained ions are extracted. The high voltage parts are all inside of the compact vacuum box and no protection cage is needed.

To obtain matched beam to RFQ input acceptance, incoming beam has to be focused generally. On the contrary, in DPIS scheme, the diverging beam is injected into the RFQ. The extracted beam emittance from the guide pipe changes due to the density variation of the plasma in a single pulse and it is almost impossible to get a perfect matching condition. However using DPIS, the ion density is very high and only overlapped area of the beam emittance and the RFQ acceptance can contain enough number of ions. As a result, we can accelerate intense beam easily without an LEBT including any complex focusing magnet.

RESULTS FROM RECENT BEAM TEST

Since end of the last year, we have studied acceleration of Aluminum ions[4]. In this experiment, the 4 rod RFQ fabricated in IAP and the 2.3 J 6 ns Nd-YAG laser, thales SAGA230, were used. The basic parameters of the RFQ are summarized in Table 2.

Table 2: Basic Design Parameters of the RFQ

Frequency	100 MHz
Total length	2.0 m
Modulated vane length	1.42m
Intervane voltage	120 kV (q/A = 4/12)
I_{out} at 100 mA C^{4+} in	76 mA (pteq-H)
Injection energy	20 keV/u
Extraction energy	100 keV/u
Acceptance	0.14 cm.rad
Aperture	0.655 cm (βλ/3)

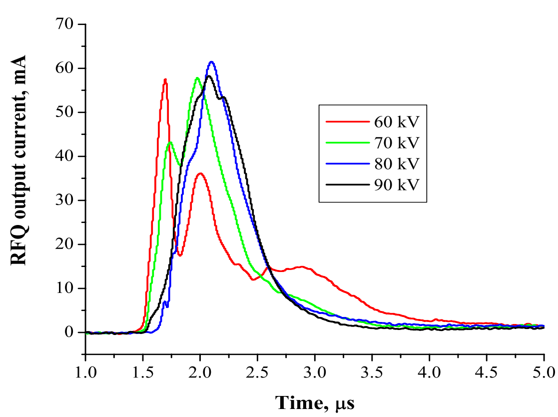

Figure 3: Accelerated beam shape.

Figure 3 shows accelerated currents varying the extraction voltage. Although the laser is capable of producing Al^{12+}, the laser power density was optimized to get Al^{9+}. The extraction voltage of 60 kV matches q/A = 9/27 condition. Due to the changing extraction condition, a dip caused by too high plasma density was observed at lower extraction voltages. The longer plasma drift length will reduce the density at the peak position and longer ion beam pulse might give more total number of ions. Maximum current and pulse duration are 60 mA and 0.65 μs for extraction potentials in the range of 70-90 kV.

The charge state distribution measured using an electro static analyzer situated after the RFQ. Figure 4 indicated analyzed result.

Shot-to-shot reproducibility of output RFQ current amplitude over 150 shots was investigated. The fluctuation was ±6% for total current. In the experiment, RF frequency has been tuned manually. Automatic phase tuning is expected to improve the statistics.

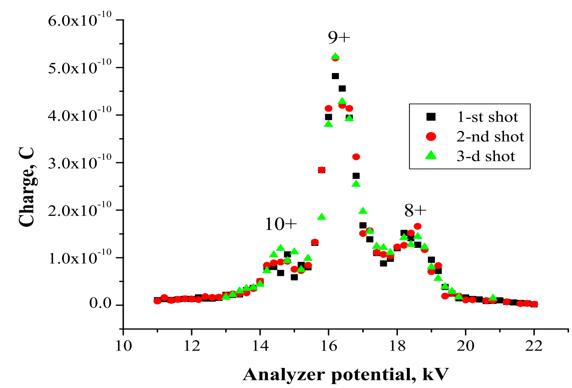

Figure 4: Analyzed accelerated Al beam.

The fraction of Al9+ was about 65% of the total current.

FROZEN GAS TARGET

We also trying to use gas at room temperature as a LIS target. Except He, most of the all the gas can be condensed on cooled substrate. We confirmed that a surface of a cryo-cooled 5 K Cu block can capture rare gases and the frozen rare gas can provide a plasma by laser irradiation. Analysis of the experimental result is in progress.

SUMMARY

The LIS can provide highly charged intense heavy ion beam by choosing various operation parameters. The DPIS is promising approach to obtain high peak current beam with good stability.

Author thanks DPIS collaborators.

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