HIGH CURRENT RFQ USING LASER ION SOURCE

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Abstract

A new RFQ was built for demonstrating a capability of the "Direct Plasma Injection Scheme". After a few months commissioning period, we could obtain 50 *mA* of Carbon beam from the RFQ. This new heavy ion production scheme could be applied to Cancer therapy facilities and high energy nuclear physics accelerator complexes.

INTRODUCTION

Recently, high current and highly charged state heavy ion sources have been studied intensively in the world. Electron Beam Ion Source (EBIS), Laser Ion Source (LIS) and Metal Vapour Vacuum Arc ion source (MEVVA) are typical sources in this category. Among them, we focused on high brightness of induced plasma in LIS and have studied how to utilize the high density of plasma ablated from solid material.

The plasma is produced by a laser shot on the target and is expanded adiabatically normal to the target surface, with energy of a few hundred *eV*. In the established type of LIS, the plasma drifts with about 100 % momentum spread until obtaining the desired pulse period and then reaches an extraction electrode followed by Low Energy Beam Transport line, LEBT. In order to get about 10 μs of the pulse length, the plasma has to be drifted about 2 *m*. As a result, a solid angle captured by the extraction electrode is very small relative to an emitted angle of the ablation plasma. In addition, we had difficulty overcoming the space charge effect in the LEBT due to highly charged state, voltage limitation in the extractor and relatively higher current compared to standard ion sources, like Electron Cyclotron Resonance (ECR) ion sources.

To prevent the beam loss in the LEBT and take the advantage of the density of the laser plasma, Direct Plasma Injection Scheme (DPIS) has been developed. In general recipe, the beam being injected to an RFQ has to be focused. This scheme is not only for acceptance matching but also having a large beam size in the LEBT to prevent the beam loss caused by the space charge effect. In case of DPIS, we do not need to obey this strategy, because enough injected beam intensity into the RFQ can be achieved even if using diverging injection beam. The diverging beam has a large emittance, but enough beam is accepted by the RFQ. The space charge effect can be neglected during transportation from the source to the RFQ entrance, because the plasma is induced in the box directly attached to the RFQ and the ions fly from the target to the entrance of the RFQ with neutralized plasma state. Moreover the ion source part can be made extremely compact. There are no magnetic or micro wave devices and all the power for ionization is fed by laser light.

Since 2001, we have had experiments to verify the DPIS using an existing RFQ in TITech, Tokyo. Obtained maximum current of Carbon beam was 9.2 *mA* and this value agreed well with our simulation[1]. Upon this experience, we decided to construct a new RFQ to achieve higher current using the DPIS. We believe this new technique will impact the heavy ion accelerator field.

THE NEW RFQ FOR HIGH CURRENT HEAVY ION BEAM

In order to demonstrate the intrinsic performance of the DPIS, the new RFQ was constructed at Institute for Applied Physics, Goethe University, Frankfurt. This RFQ was designed to accelerate Carbon 4+ and 6+. A goal current was set to 100 *mA* with C^{4+}. Operation frequency was chosen as 100 *MHz* by availability of an RF amplifier system. The resonant structure is the 4 rod type, which is well established in IAP and suited for this frequency region and low duty factor operation. It has a reasonably small diameter, and the field distribution is easy to tune. Also it is not difficult to replace vanes in future modification. Total vane length was decided as 2 *m* considering future modification however output beam energy is 100 *keV/u* limited by a radiation safety regulation. The beam is accelerated up to 100 *keV/u* within first 1.42 *m* section and then transported through un-modulated vanes to the end of the RFQ. In the un-modulated section, the accelerated beam is completely de-bunched and this will help to reduce space charge effect in an analyzing section, which will be constructed in the near future. The input energy of the beam is a very important value, because in DPIS a high voltage biased slit is located at the entrance of the RFQ and might cause discharge. Part of the very high intensity plasma is guided through the several mm diameter hole in the biased slit and enter the RFQ. To minimize the beam size emitted from the hole, the slit needs to be close to the vanes. At the same time, we have to avoid sparking and an effect on the resonant cavity. We adopted 60 *KV* as total input beam energy based on our experience. In case of C^{4+}, the value corresponds to 20 *keV/u* as the injection energy. The position of the slit can be adjusted. A picture and summarized design parameters of the RFQ are shown in Fig. 1 and Table 1 respectively. The vane parameters of the RFQ were designed to maximize beam acceptance. These parameters are indicated in Fig. 2. To confirm the particle dynamics in the RFQ, PteqHI was used. This code was developed by one of authors and can simulate multiple charge states simultaneously.

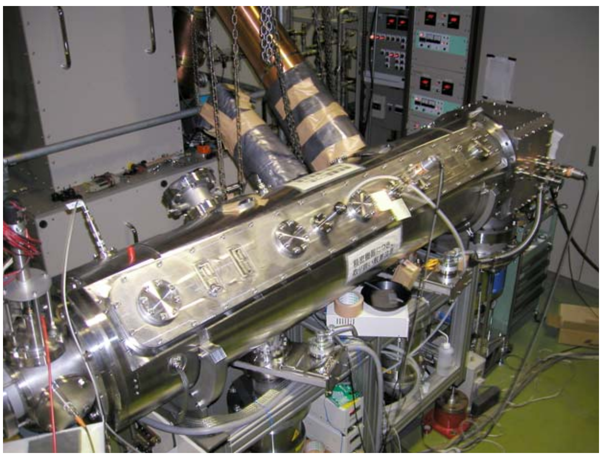

Figure 1: 100 MHz RFQ.

A cube box behind the RFQ is the ion source.

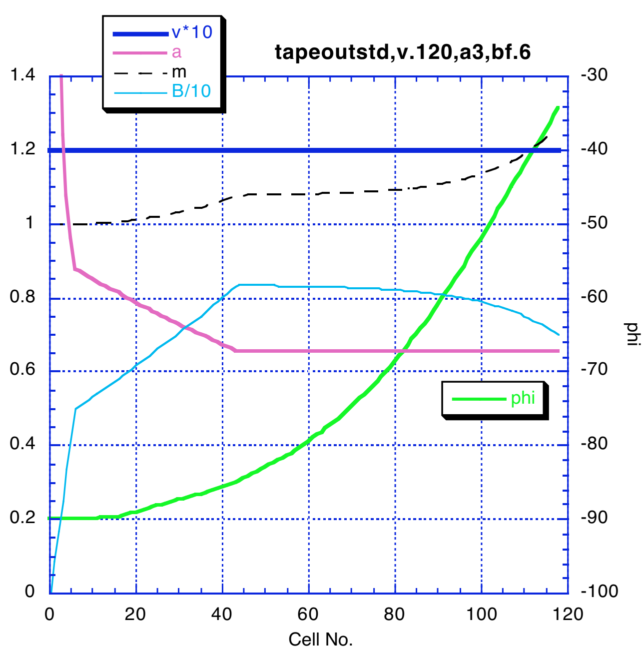

Figure 2: Vane parameters of the RFQ.

Table 1 : Basic design parameters of the RFQ

Frequency	100 MHz
Total length	2.0 m
Modulated vane length	1.42m
Limit of intervane voltage	120 kV
I_{out} at 100 mA C^{4+} in	76 mA
Saturated I_{out}, C^{4+} only	155 mA
I_{in} for saturated I_{out}	~300 mA
Acceptance	0.14 cm.rad
Aperture	0.655 cm ($\beta\lambda/3$)

LASER SYSTEM FOR PLASMA PRODUCTION

We have been investigating two types of laser system for plasma production. Currently a CO_2 laser is used for our experiment. The maximum output energy of the CO_2 laser is 8 J, however emitted energy to the carbon target was measured as 1.2 J with 85 ns (FWMS) of pulse width. Our plasma measurement experiment shows that this condition of the laser system produce mainly C4+ (50 %) and rest of the ions comprised with C5+ (35 %) and C3+ (15%). We can assume that these three charged states ions are injected to the RFQ. We also measured the property of the plasma induced by a Nd-YAG laser system. This laser has output energy of 300 mJ and can produce mainly C6+ (50 %). This laser system is now planed to be used in next DPIS experiment. The measured result also shows that the Nd-YAG laser plasma also can provide enough beam current to the RFQ.

PLASMA TARGET CHAMBER

Ion source parts, including the plasma production solid target and the space which will be filled by the ablated plasma, have to be isolated electrically and kept at high voltage which corresponds to the beam injection energy of the RFQ. 60 kV is applied to the ion source part and this voltage is too high to insulate in the air condition. Therefore, high voltage parts are located in a vacuum box as shown in Fig. 3. The high voltage connector is at the bottom of the TEFLON sleeve that is 30 cm long, and a cable from the high voltage power supply is inserted to the sleeve. The high voltage parts are not shown from outside of the vacuum box. As we mentioned all the fed energy to the plasma is provided by laser shot. This means that both a large terminal stage and safety fence are not needed and the ion source part can be made extremely compact and simple. Behind the vacuum box, laser beam is injected through double NaCl windows and guided to the high voltage region. A concave mirror reflects and focuses the laser beam on to the Carbon target. Then plasma is induced and expanded towards the RFQ. Finally the expanding plasma which can be accommodated by the high voltage slit is injected to the RFQ.

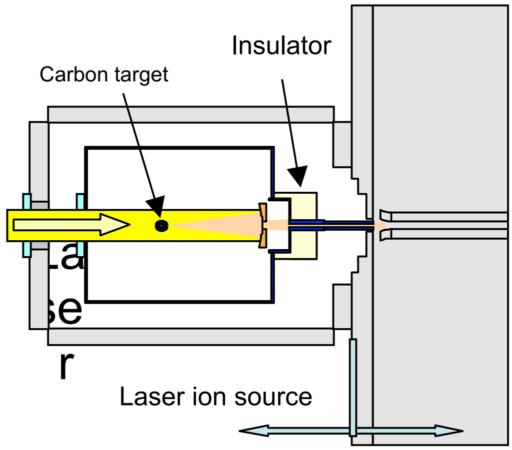

Figure 3: Target Chamber.

ACCELERATION TEST WITH CARBON TARGET

We got the first beam in June 2004 after overcoming sparking problem. The measured peak current reached 30 mA with a slit having 4 mm diameter hole. We optimized various parameters for C^{4+} beam and obtained a maximum peak current of more than 50 mA. In this condition, the inner diameter of the slit is 6 mm. A typical beam shape is shown in Fig. 4. This signal was from a Faraday cup just after the RFQ.

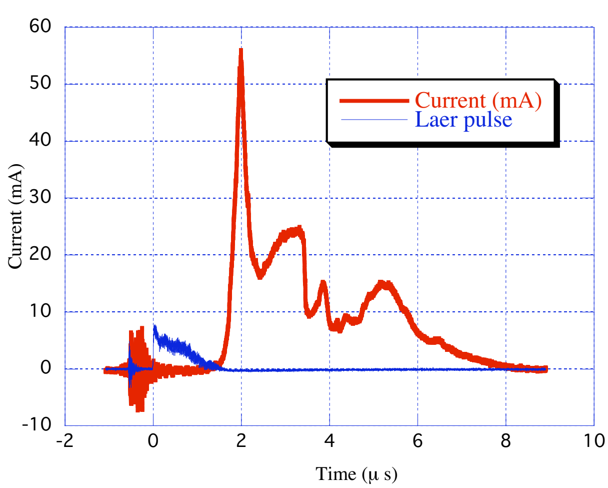

Figure 4: Accelerated beam out of the RFQ.
Red: Current measured by a Faraday Cup after the RFQ.
Blue: Laser pulse shape.

The input current and emittance have not been measured. At the C^{4+} peak, estimates indicate that with a 4 mm extraction slit, ~100 mA with emittance ~0.45 cm.rad enters the RFQ. The RFQ simulation then shows that ~40% is transmitted. With the 6 mm extraction slit, ~200 mA with emittance ~0.6 cm.rad enters the RFQ and ~25% is transmitted. The input estimates are in accord with our analysis of the effect of the dc field in the entrance region of the RFQ. Also, in this regime, output current saturation is expected.

APPLICATION OF THE DPIS

The DPIS can provide intense heavy ion beam efficiently and easily. We expect there will be various applications. Here we emphasize typical applications.

Cancer Therapy

Carbon beam is used in a cancer therapy facility like NIRS. We propose to use the intense carbon beam from DPIS in such a facility. The very high current beam can eliminate the necessity for multi turn injection in a synchrotron. Also enough heavy ions can be obtained after collimation to reduce the beam size. These will make magnets smaller. A laser source can easily produce fully stripped Carbon beam. A contamination of the carbon beam, which is frequently pointed out as an issue, strongly depends on the purity of the solid target in LIS. We expect that DPIS has an advantage in the contamination, because residual gas is not involved in plasma production process, not like ECR or EBIS. The fully stripped carbon beam can eliminate a stripper foil which is usually placed just before the main ring and enables a lower injection energy of the synchrotron to be adopted. Also it can shorten the length of injector linacs. In our next step the Nd-YAG laser is planned to be used to produce C^{6+} beam.

High Energy Physics Accelerator

The DPIS is also applicable to produce heavier species like lead and gold. These kind of heavy species have not been tested yet, however we believe highly charged high current beam can be obtained easily using an adequate laser system. Especially for injecting to a large size synchrotron, a longer beam pulse might be desired. In the case of a solid laser device, several shots with intervals of a few μs can be emitted sequentially and a long beam pulse can be achieved.

REFERENCES

[1] Scheme for Direct Plasma Injection into an RFQ Linac, M. Okamura et al, LASER AND PARTICLE BEAMS, (2002), 20, 451-454

[2] Nd-YAG laser ion source for direct injection scheme, H. Kashiwagi, et al, Review of Scientific Instruments, 75-5 (2004) 1569-1571