New Source System of Intense Heavy Ion Beams by Using Direct Plasma Injection Method

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Abstract

We have developed a new source system, based on Direct Plasma Injection Method (DPIM), and have succeeded to produce intense Carbon ion beams of the beam current 8 emA for Carbon ion beams with the energy of 214 keV/u. By a charge state analysis with a bending magnet, we found that the accelerated beam includes C^{4+} and C^{3+} of 4.0 emA and 0.8 emA, respectively. From a comparison with simulation, it is suggested that DPIM has effects to suppress the strong space charge effect by intense low energy beam at the entrance of RFQ LINAC.

1. Introduction

Recently, Laser Ion Source (LIS) is being remarked as an initial stage of accelerators for high energy physics and medical science because LIS can produce heavy ion beams with highly charge and intense beam current [1,2]. However, LIS has serious problems concerning beam matching to the subsequent stage accelerator. These problems are followings. The extracted beam from LIS has a wide energy spread, a strong space charge effect, and a rapid time-variation of beam current and beam profile [3]. Therefore, it is difficult to control a low energy beam transport (LEBT) between the LIS and the subsequent stage accelerator. As a result, intense beams from the LIS suffer a large beam loss. In order to resolve such a difficulty, new principle of "Direct Plasma Injection Method (DPIM)" has been developed with a collaboration of RIKEN-CNS-TIT which combined a laser ion source and a Radio Frequency Quadrupole LINAC (RFQ linac).

2. Basic Concept of Direct Plasma Injection Method

A schematic view of DPIM is given in Fig. 1. A target is positioned in a target chamber, which is just connected to an RFQ linac, but electrically isolated by an isolator tube. The laser beam is focused onto a surface of the target, and produces the ablation plasma which flows to the direction of RFQ linac. At the entrance of RFQ linac, ions in the plasma are extracted by RF vane voltage in RFQ linac. Immediately, extracted ions are captured by RFQ focusing force and accelerated up to the design output energy of RFQ linac.

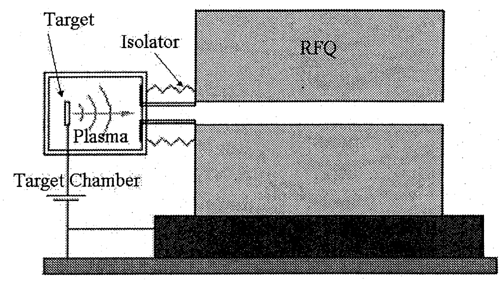

Fig. 1. Basic concept of DPIM

3. Experiment for Direct Plasma Injection Method

The experiment for Proof of Principle (POP) of DPIM has been carried out for Carbon ions. A fig. 2 shows the overview of experimental setup.

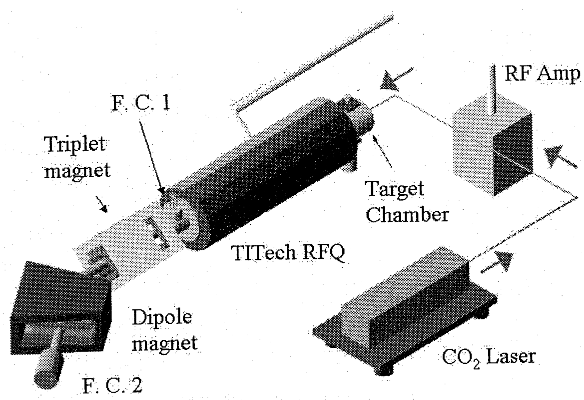

Fig.2. DPIM experimental setup

The laser was a 4.1 J TEA CO_2 laser with 38 ns pulse duration. The measured total power was 1.1 x 10^8 W. The diameter of laser beam from the resonator is about 50 mm and has the hollow at the central axis with the diameter of about 20 mm.

TITech RFQ [4] at Tokyo Institute of Technology, was used in the experiment. The main design parameters of the RFQ are listed in Table 1. The laser beam from the laser resonator is transported by two cupper mirrors, passing through a NaCl window, and is injected into the target chamber as shown in Fig. 3. At the inside of the target chamber, the laser beam is reflected and focused onto the Carbon target (ϕ = 30 mm, thickness = 10 mm) by a hollow focusing mirror. The laser power density on the surface of the target is estimated as 3.35 x 10^{12} W/cm^2. The laser-produced plasma expands passing through each holes of the focusing mirror and a small aperture, and go into RFQ linac channel. The distance between the entrance of RFQ and the target is 264 mm. In order to adjust the initial beam energy of the Carbon ions to the designed input energy of the RFQ, the target chamber is supplied to the high voltage and isolated to RFQ by the isolator. Faraday Cup 1 was installed at the close location after RFQ and the second Faraday Cup 2 was set downstream a triplet quadrupole magnet and an analyzing dipole magnet and was 3.65 m after the exit of RFQ linac.

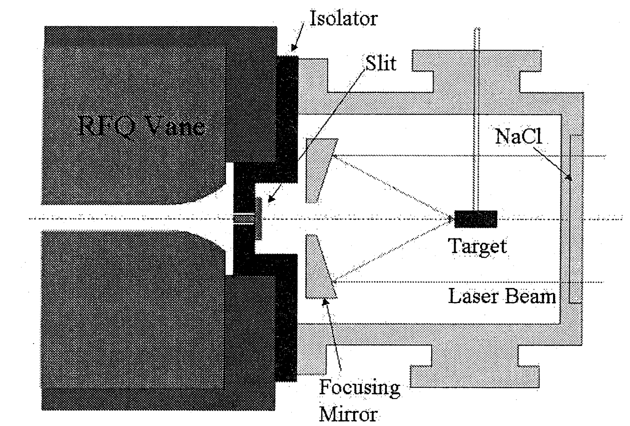

Fig.3. Target Chamber

Table 1 The main parameters of the TITech RFQ

	Designed Values
Charge to mass ratio	≥1/16
Operating frequency (MHz)	80
Input energy (keV/amu)	5
Output energy (keV/amu)	214
Normalized emittance (100%)(cm· mrad)	0.05 π
Vane length (cm)	422
Total number of cells	273
Characteristic bore radius, r_0 (cm)	0.466
Synchronous phase	-90° to -20°
Inter-vane voltage (kV)	78.9
Transmission for q/A=1/16 beam (10 mA)	6.84 mA

4. Experimental Results of DPIM for Carbon Ion Beams

The accelerated Carbon ion beam was observed at the F.C.1. The measured peak current has reached 25 mA as shown in Fig. 4.

Since a distance between the RFQ and the Faraday Cup 1 is very short, the bunched structure appears in the beam signal. After averaging data points for 1 period of 80 MHz and replotting it, we can obtain average peak current of 8 emA with the pulse time width of 1.24 μs. This beam is expected to contains of several charge states such as C^{3+}, C^{4+}, C^{5+} and C^{6+} because Carbon ions with these charge state can achieve RFQ input energy of 5 keV/u under the condition of a target chamber potential (16kV) in this experiment.

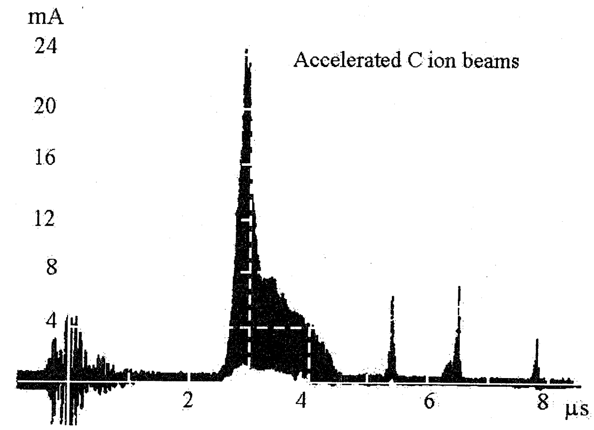

Fig.4. Accelerated Carbon beam signal on F.C.1

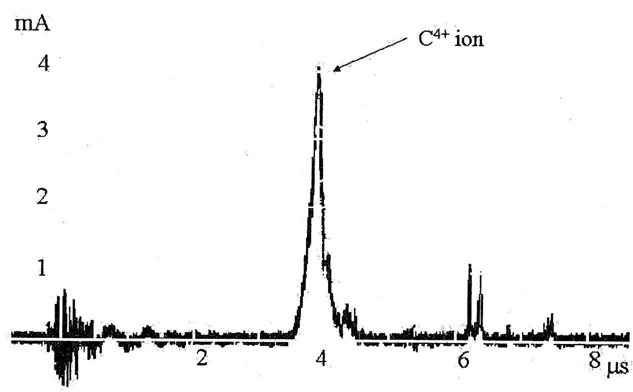

Fig.5. Analyzed C^{4+} beam signal on F.C.2

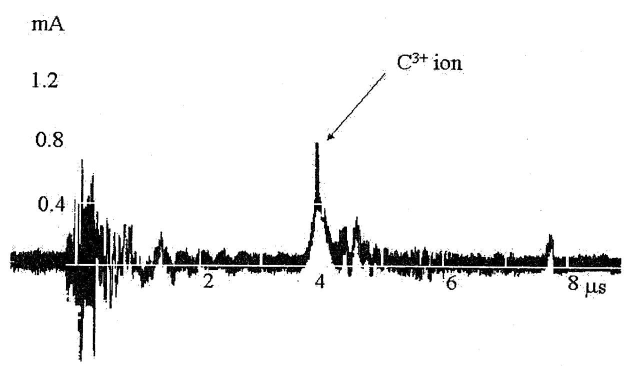

Fig.6. Analyzed C^{3+} beam signal on F.C.2

The analyzed beam can be measured by F.C. 2 located at the 3.65-m downstream the exit of RFQ. Obtained C^{4+} and C^{3+} ion current signals are shown in Fig. 5, 6, respectively. The measured peak current were 4.0 emA and 0.8 emA for C^{4+} and C^{3+} with the pulse width of 0.41 μs and 0.35 μs, respectively. The C^{6+} and C^{5+} ions could not be measured. The distance between the F.C. 2 and the exit of the RFQ is enough to get the de-bunched beam. We confirmed that the Carbon beam can be accelerated with the DPIM.

5. PARMTEQ-HI Simulation

To investigate this new method, beam simulation in the RFQ linac has been done. The standard beam simulation code in RFQs, PARMTEQ-HI was modified to be able to

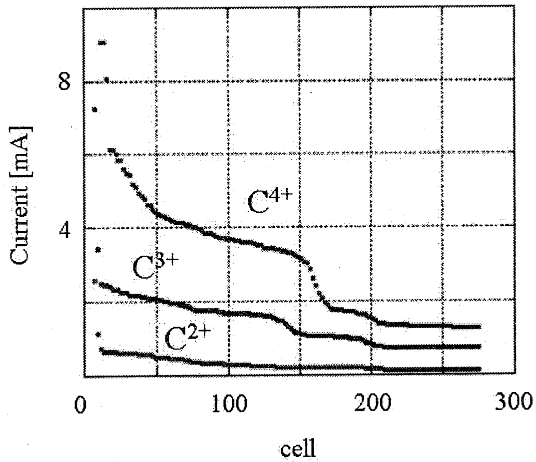

Fig. 7. PARMTEQ-HI simulation result for C^{4+}, C^{3+}, and C^{2+}

simulate various charge states ions simultaneously[5]. In the simulation, we have tried to reproduce the experimental results of the acceleration test. Assumed initial conditions of the injected particles, such as emittances and currents, are determined based on plasma experiment at RIKEN and are summaried in Table2. To simplify the calculation, only three kinds of the particles, C^{2+}, C^{3+} and C^{4+}, were tracked. A result of the modified PARMTEQ-HI simulation is shown in Fig. 7. This graph indicates accelerated currents as a function of the cell numbers. The calculated output currents are 0.14, 0.75 and 1.32 mA for C^{2+}, C^{3+} and C^{4+} respectively.

Table 2 The initial beam parameters for the simulation

	Assumed Values
Total beam current (mA)	93.9
Assumed particles	C^{2+}, C^{3+} and C^{4+}
Fraction (%)	14, 31, 47
Current (mA)	13.1, 29.1, 43.1
Total energy (keV)	32, 48, 64
Emittance (π mm mrad)	9.8, 9.8, 9.8

6. Discussion

The comparisons with the experiment and the simulation are listed in Table 3. All the experimentally measured values are higher than the simulated currents. The most of beam losses are observed within first twenty cells. It seems that there is neutralization effect due to presence of electrons at the entrance of the RFQ. The target chamber was supplied at positive high voltage, however the vane-tips of the RFQ were oscillating with higher voltage. The electron in the plasma can move to the RFQ entrance within some RF phase. Also, some electrons in the plasma can be pulled by positive charges of ions, which firstly proceeded to the RFQ entrance. Thus, it is expected that DPIM has some effects to suppress the strong space charge effect by high charge state and intense ion beam. Further consideration and verifications by means of detailed numerical calculation should be needed.

Table 3 Output beam currents

	Experiment	Simulation
Total (mA)	8.0	2.21
C^{2+} (mA)	-	0.14
C^{3+} (mA)	0.8	0.75
C^{4+} (mA)	4.0	1.32

7. Conclusion

Direct Plasma Injection Method, suppressing the strong space charge effect during the flight path of the low energy highly charged intense ion beams, has been proposed. The acceleration test using DPIM has been done for Carbon ions. The accelerated peak current was 8 mA, which was analyzed as 4.0 mA and 0.8 mA for C^{4+} and C^{3+}, respectively. The observed total current exceeded designed current of the RFQ. The new principle, DPIM, was proved successfully.

Acknowledgement

The authors are grateful to the staff members of RIKEN Beam Physics and Engineering Laboratory for the encouragement and suggestions during the work. They acknowledge to the members of Research Laboratory for Nuclear Reactors in Tokyo Institute of Technology for the many assistance in the operation. They would like to thank Dr. Sergei Kondrashev (ITEP, Moscow) for valuable comments on the properties of the laser-produced plasma.

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