Laser and Particle Beams (2002), *20*, 451–454. Printed in the USA.
Copyright © 2002 Cambridge University Press 0263-0346/02 $16.00
DOI: 10.1017/S0263034602203171

Scheme for direct plasma injection into an RFQ linac

M. OKAMURA,[1] T. KATAYAMA,[1] R.A. JAMESON,[1] T. TAKEUCHI,[2] T. HATTORI,[3]
AND H. KASHIWAGI[3]
[1]RIKEN, Wako-shi, Saitama, Japan
[2]Center for Nuclear Study, Graduate School of Science, University of Tokyo, RIKEN, Wako-shi, Saitama, Japan
[3]Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology, Okayama, Meguro, Tokyo, Japan

Abstract

A new efficient injection method from a laser ion source to a Radio Frequency Quadropole (RFQ) was proposed and is being tested in RIKEN, Japan. A laser plasma is induced just before the entrance of the RFQ and is injected directly into the RFQ channel. Using an existing RFQ, first verification tests have been completed successfully. Finally, the preliminary specifications for the first RFQ dedicated to the new injection scheme are presented.

Keywords: Heavy ion fusion; Low energy beam transport; Plasma injection; RFQ linac

1. INTRODUCTION

At RIKEN, a laser ion source (Katayama *et al.*, 2000) has been developed. The laser source can provide high intensity heavy ion beams and is well suited for injection into a high energy accelerator complex including a synchrotron, such as a Heavy Ion Fusion (HIF) facility. However, the multiple charge-state beams from the laser ion source have wide energy spreads. Also, the currents and beam profiles change during the pulse (Wolf, 1995). Due to these complex features, it is quite difficult to suppress space-charge effects in a low energy transport line, which usually consists of an extraction system and focusing elements, between the source and the first stage accelerator (Fournier, 2000). To overcome this disadvantage of a Low Energy Beam Transport (LEBT), we have proposed a new injection method called "Direct Plasma Injection Scheme into a Radio Frequency Quadropole (RFQ) Linac." A target material is located in a vacuum chamber, which is directly connected to an RFQ. The chamber is electrically isolated from ground so that a high voltage can be applied to adjust the initial beam velocity to the RFQ design. Plasma is generated by hitting the target with an intense laser beam. After the laser is focused onto the surface of the target, the emitted plasma expands normal to the surface of the target. A strong space-charge effect is not present inside the laser ion source chamber because it is not an ion beam but an electrically neutral plasma which is transported. The emitting angle was expected to be small. If we have a short distance between the target and the entrance of the RFQ, a large fraction of the expanding plasma goes directly into the RFQ channel. At the exit of the extraction aperture, the ions are extracted from the plasma, accelerated by the DC potential, trapped by the RFQ focusing force, and then accelerated up to the design energy. If a complicated LEBT with convergent lens devices is not necessary, the injector can be fabricated less expensively and can be handled very easily.

2. VERIFICATION TEST AT TIT

To verify the feasibility of this scheme, the acceleration test was carried out using the TITech RFQ (Okamura *et al.*, 1994) at Tokyo Institute of Technology, Tokyo, Japan. This heavy ion RFQ, originally designed for $q/A = 1/16$ and a medium current 10-mA beam, is not entirely appropriate to accommodate the intense beam from the laser source. In this experiment, we focused on proving the principle of the new scheme. The general experimental setup is indicated in Figure 1. The main design parameters of the RFQ are listed in Table 1.

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
Vane length (cm)	422
Characteristic bore radius, r_0 (cm)	0.466
Intervane voltage (kV)	78.9
Shunt impedance (MΩ/m)	29.5
Transmission for $q/A = 1/16$ beam 10-mA input	6.84 mA

Address correspondence and reprint requests to: Masahiro Okamura, Beam Physics and Engineering Laboratory, RIKEN, Saitama 351-0198, Japan. E-mail: mokamura@postman.riken.go.jp

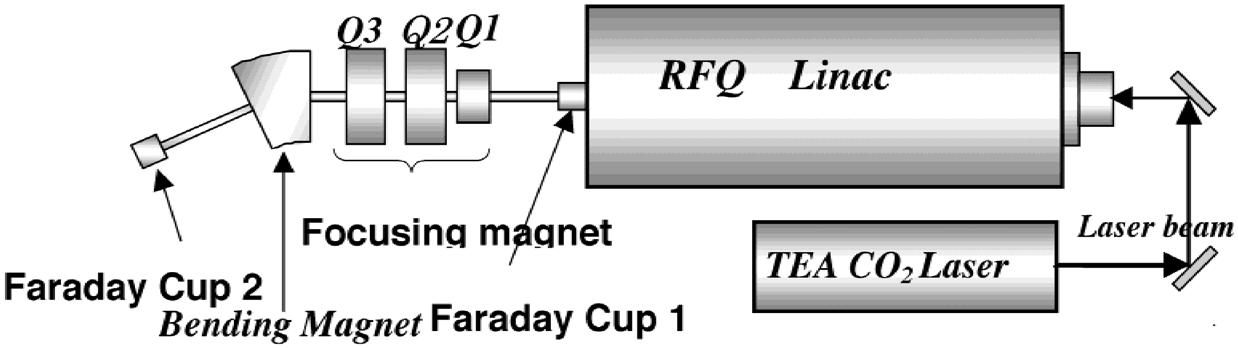

Fig. 1. The layout of the experimental setup.

For this experiment, a 4.1-J TEA CO_2 laser with 38-ns pulse duration was used. The measured total power was 1.1×10^8 W. The diameter of the laser beam is about 50 mm with a hollow center 20 mm in diameter. The laser beam emitted from the TEA CO_2 cavity was guided by two plain mirrors to the plasma target chamber.

As indicated in Figure 2, in the chamber, the laser beam was focused onto the carbon target by a concave donut-shaped mirror installed between the target and the RFQ cavity. The irradiated power density on the target was estimated as 3.35×10^{12} W/cm^2. The ablation plasma is induced from the target surface and expands, passing through the hole of the concave mirror and then through a small slit. This slit, ϕ 4 mm, aimed to scrape the exceeded plasma that cannot fit into the beam channel of the RFQ, and is placed very close (6 mm) to the RFQ vanes. According to the results of our plasma production experiment that had been done in RIKEN, the divergence of the expanding ablation plasma was less than 20°. In this acceleration test, only a small portion of the ablated plasma can go into the RFQ. The injected beam intensity is estimated as shown in Table 2, based on the plasma production experiment in RIKEN (Takeuchi, 2000) and the 324-mm distance between the entrance of the RFQ and the plasma target. To adjust the velocity of the carbon ions to the designed value of the RFQ, high voltage of 15 kV to 35 kV was supplied to the target chamber.

The accelerated carbon beam was observed at the Faraday cup, FC 1, located just after the RFQ. The measured peak current has reached 9.2 mA as shown in Figure 3. The analyzed C^{4+} beam currents at FC 2 are shown in Figure 4. In both graphs, the horizontal scale is the ratio (vfac) of the rf voltage applied to the vanes with respect to the design RFQ intervane voltage. Each line shows the measured current at the voltage applied to the target chamber. The maximum current of C^{4+} beam was recorded at 15 KV target chamber voltage, which corresponds to the designed injection velocity of the RFQ. The total current

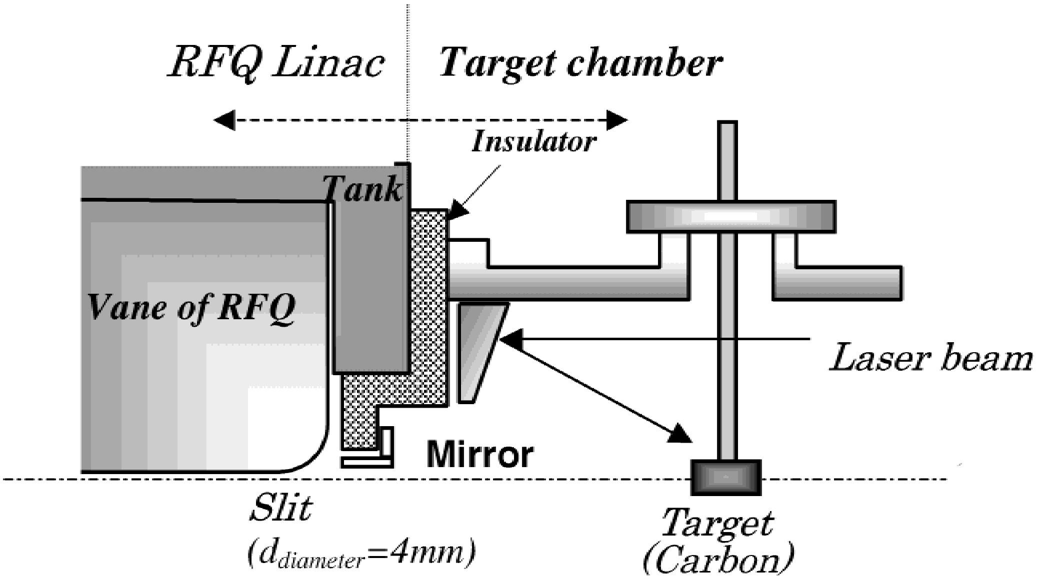

Fig. 2. Plasma target chamber.

Table 2. *Injected carbon ions into the RFQ*

	C^{4+}	C^{3+}
Current (mA)	20.7	4.3

measured at FC 1 shows maximum transmission at 15 kV applied voltage because the main fraction of the injected beam is 4+ ions.

The RFQ performance was simulated using the code named "pteqHI" (Jameson, 2001, 2002), an RFQ simulation code newly modified to handle multiple ion species with different charge, mass, current, and injection energy. The RFQ injection geometry shown in Figure 2 results in elongated DC equipotential contours in the RFQ injection region due to the RFQ vane shape. The emittance at the RFQ injection plane 6 mm from the extraction aperture was computed using a three-dimensional code, with a result about 10 times the geometrical emittance computed using the target spot size and the extraction aperture. Using this emittance as the input to the RFQ, the simulation produced essentially exact agreement with the experimental results at FC 1, Figure 3, over the full range of injection voltages and vane voltage factors. The excellent agreement between experiment and simulation for the RFQ gives confidence for the design of a new, dedicated RFQ.

Some loss in transmission between FC 1 and the analyzed beam at FC 2 was expected; further data analysis is pending. Overall, it was found that the direct injection method performs excellently for the laser ion source.

3. NEW RFQ DESIGN

A new RFQ is being planned for the next step in developing the new scheme. The crucial first step, discussed here, is to define the overall specification and basic parameters such as ion species, current, frequency, and length for a research RFQ that can cover a wide range of investigations for the most economical price. This is difficult because of the large number of parameters available. The detailed design is not finished yet.

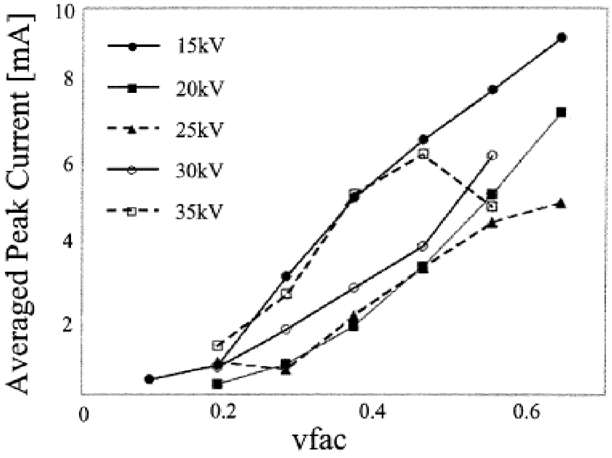

Fig. 3. Total currents just after the RFQ.

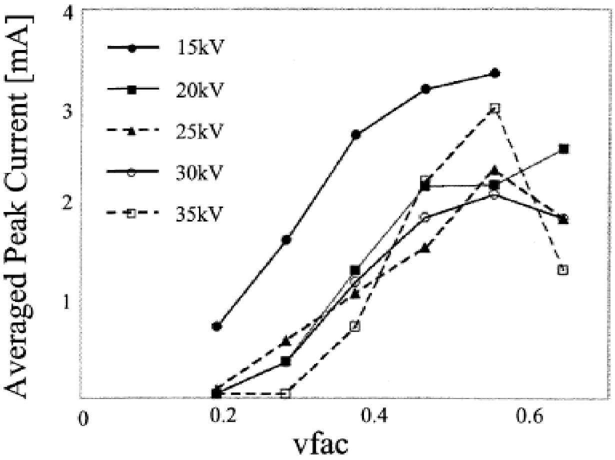

Fig. 4. Analyzed C^{4+} beam current.

To demonstrate the possibility of the Direct Plasma Injection Scheme, the design goal was set to accelerate 100 mA of C^{4+}, which can be provided by our existing CO_2 laser system. The operating frequency was surveyed assuming a low emittance from the source, about 10 mm·mrad, which was obtained from a geometrical emittance analysis of the LIS chamber. Three frequencies, 40 MHz, 80 MHz, and 120 MHz, were compared with various injection beam energies. As expected, we found that higher injection energy will give higher beam transmission. However, 100 kV seems to be a practical maximum voltage on the target chamber. The simulation shows that 80 MHz is good, with more than 95% of the beam transmission expected at 100 kV injection energy and this low injection emittance. About 60% transmission is predicted using the larger emittance found by beam tracking including a realistic three-dimensional DC and RF field map. Improvement of the input conditions and match is in progress and is expected to improve the transmission to the expected value of >90%.

For the mechanical structure, a four-rod type resonator or equivalent will be adopted considering frequency, low duty factor, and cost. Constraint of the length to about 4 m is considered practical. The design studies indicate that this length can be controlled as desired after the frequency and ion species and current are specified, by choosing the input and output energies, and also by controlling the bucket-width to beam-width ratio.

It is anticipated that the same RFQ should be used for later experiments by changing the vanes for perhaps Al ions and ultimately Au ions. Preliminary design work indicates that the 80-MHz frequency and ~4-m length should also produce useful results for these ions. Discussions are in progress with various groups to obtain design comparisons and information concerning structure choice and fabrication possibilities. We hope to complete fabrication of the new RFQ during 2003.

4. CONCLUSION

To capture the intense ion beams from the laser ion source, the direct plasma injection scheme has been proposed. The first accelerated carbon beam was observed successfully and reached 9.2 mA. This method is quite useful to utilize the intense beam from the laser ion source for various applications. A much more intense beam is expected from the dedicated new RFQ.

REFERENCES

Fournier, P. *et al*. (2000). Status of the CO_2 laser ion source at CERN. *Rev. Sci. Instrum.* **71**, 924.

Jameson, R.A. (2001). RIKEN internal reports.

Jameson, R.A. (2002). RIKEN internal reports.

Katayama, T. *et al.* (2000). *Proc. EPAC2000*. p. 68.

Okamura, M. *et al.* (1994). *Nucl. Inst. and Meth. B89*, 1–4, 38–41.

Takeuchi, T. *et al.* (2000). *Proc. EPAC2000*. p. 1622.

Wolf, B. (1995). *Handbook of Ion Source*, p. 147. Boca Raton, FL: CRC Press.