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B^+ Beam Tests of the "Modified" cw 4-rod RFQ

Hiroshi FUJISAWA*, Kazuhiro NAKAO*,
Masayuki TAMADA* and Takao MATSUMOTO*

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The development of the "modified" 4-rod RFQ linac system has been completed and a series of beam acceleration experiments demonstrated the specified performance of the RFQ linac. The RFQ accelerates light and medium ions to MeV energies for irradiation applications. The linac operates in cw mode at 34 MHz, relatively lower resonant frequency compared with most of the existing proton RFQs. The RFQ cavity withstands up to 50 kW cw rf power. He^+, N^{2+}, C^+ and B^+ ions were successfully accelerated to their goal energies of 84 keV/u: 0.334 MeV, 1.17 MeV, 1.00 MeV and 0.92 MeV, respectively. The maximum beam currents measured at the RFQ output were 32, 13, 220 and 330 pμA for He^+, N^{2+}, C^+ and B^+, respectively with the beam transmission over 80%.

KEY WORDS: RFQ/ 4-rod RFQ/ Beam tests/ Ion acceleration

1. INTRODUCTION

Beam experiments have been in progress since the first successful beam test on December 25, 1992. From that day on, the acceleration tests of He^+, N^{2+} and C^+ ion beams were done roughly in one year period at the ICR, Kyoto University, where the linac system was originally installed. We obtained the beam currents of 32, 13 and 220 pμA for He^+, N^{2+} and C^+, respectively with the beam transmission over 80%. In December 1993, the whole linac system was moved to Kuze factory of Nissin Electric Co., Ltd. to continue with the acceleration tests of a B^+ ion beam. This was so done because the generation of this particular ions uses toxic gas and it required a special exhaust system for safety reasons. The first beam at Kuze factory after the completion of re-assembling and coordination of the linac system was confirmed with a He^+ ion beam in late March, 1994. We then proved with He^+, N^{2+} and B^+ ion beams that the performances of the linac were satisfactory or much better in reference to the data obtained at ICR. Meanwhile our beam emittance monitors were upgraded and re-installed in the linac system—older version lacked resolution in angle but this was corrected in the new ones. We have measured currents, energies, momentum spectra, and emittances of both the input and output ion beams of the linac system. A stability test regarding B^+ beam acceleration was also conducted. A summary of B^+ beam acceleration tests for the "modified" 4-rod RFQ linac is presented in this report.

2. "MODIFIED" 4-ROD RFQ

In 1985, 4-rod RFQ structure has been proposed by a group of Frankfurt University,

* 藤澤　博, 中尾和浩, 玉田将之, 松本貴男 : R & D Division, Nissin Electric Co., Ltd. 575 Kuze Tonoshiro-cho, Minami-ku, Kyoto-shi, Kyoto-fu 601 Japan.

adapting an $\lambda/2$-transmission line as a radio frequency resonant structure[1]. In that concept, a resonant circuit was formed basically with the line capacitance and a pair of inductance shunted at center of the lines. We independently studied a rod-type RFQ structure and came up with a better configuration that was smaller in diameter[2,3]. We call it "modified" 4-rod RFQ structure to distinguish from the Frankfurt model; the features of the "modified" 4-rod RFQ are summarized as follows:

1. an equally-spaced arrangement of the RFQ electrode supporting plates,
2. three dimensional machining of the RFQ electrode tips,
3. eccentrically-situated beam optics axis,
4. de-mountable RFQ electrode assembly,
5. cw operation up to 50 kW.

Our design is to get a relatively small-diameter RFQ suitable for irradiation of light and medium ions with energies up to a few MeV. Table 1 summarizes the specifications of our linac system. Detailed descriptions of our linac design can be found in Ref. 2

Table 1. The specifications of the "modified" 4-rod RFQ linac system.

Injector:	
Ion source	Freeman type
Extraction voltage	50 kV max.
Mass analyzer	90° magnet with sextupole corrections
Focusing elements	four magnetic quadrupole lenses and one Einzel lens
Beam optical lengh	2.5 m, including a beam monitor
Size	1.5 (W)×1.5 (D)×1.8 (H)
RFQ:	
Type	fixed frequency "modified" 4-rod
Frequency	33.3 MHz (design)
Average bore radius	0.8 cm
Focusing strength	6.79
Inter-electrode voltage	54.9 kV
Charge to mass ratio	1/11 (design)
Injection energy	2.73 keV/u
Output energy	83.5 keV/u (w/o half-cell)
Length of electrode	222 cm (w/o half-cell)
Cavity inner diameter	60 cm
rf power	50 kW max.
Operation mode	cw
Transmission	≥80%

3. EXPERIMENTS

3.1 *Setup*

Photo. 1 is a picture of and Fig. 1 is a schematic drawing of the experimental setup of the RFQ linac system. There are five Faraday cups in total to measure the intensity of an ion beam. F1 is retractable and practically works as a beam stopper as well as a beam electrode. F2 and F3 are retractable Faraday cups. F2 and F3 are used to measure the intensity of a beam

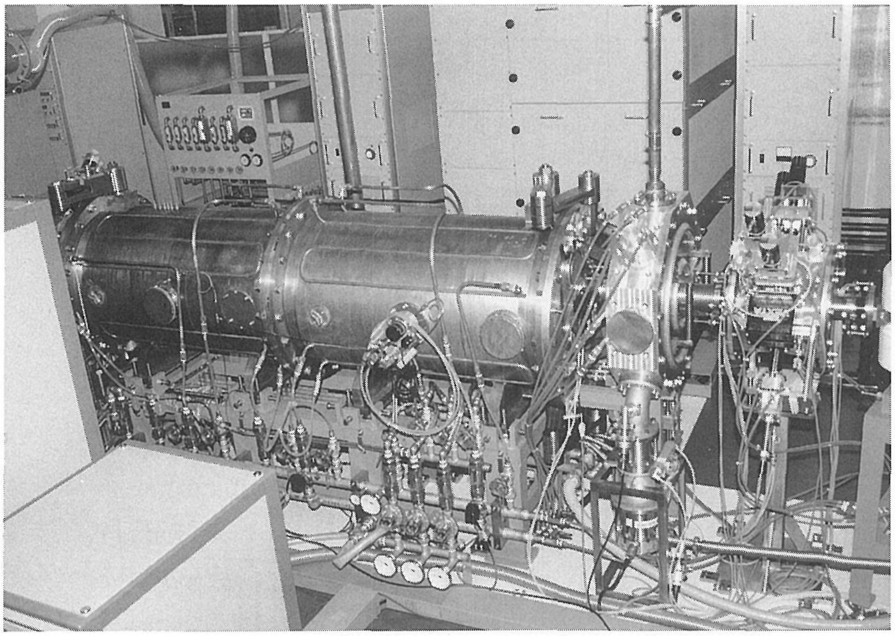


Photo. 1. Picture of the experimental setup at Nissin Kuze Factory.

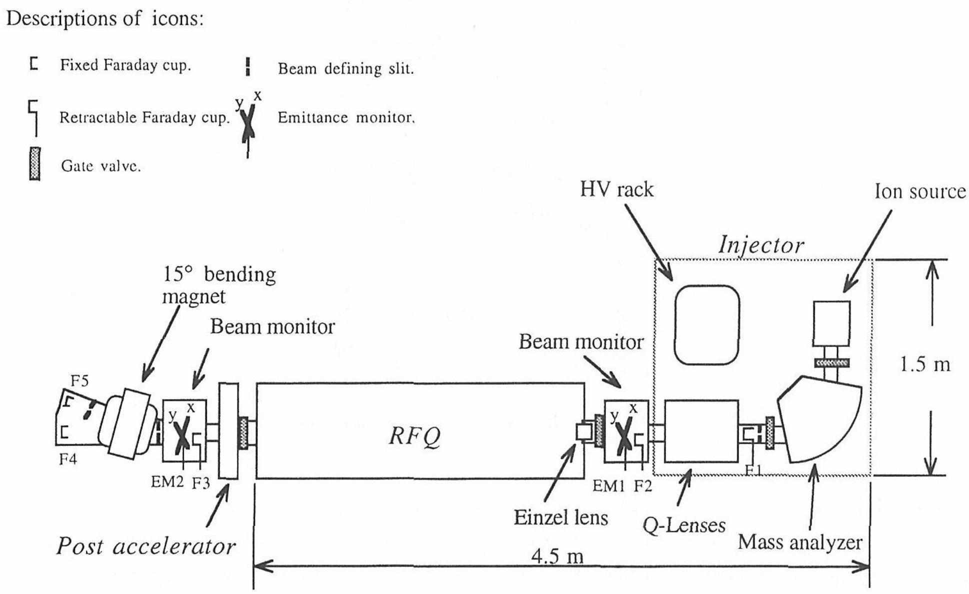


Fig. 1. Schematic drawing of the experimental setup of the RFQ linac system.

at the upstream and downstream of the RFQ, respectively. F4 and F5 are both de-mountable Faraday cup systems and are similar to F2 and F3 in construction. The emittance and orientation in the trace-space of an input and output beam are surveyed using emittance monitors EM1 and EM2, respectively. They are of "two-slits" type, both exactly identical in construction[4]. Table 2 summarizes the specifications of the emittance gears and a schematic

Table 2. The specifications of the emittance monitors.

Slit width	0.5 mm (adjustable)
Thickness of the slits	1.0 mm
Drift distance between the slits	24 mm
Maximum range of the probe span	80 mm
(in reference to the beam optics axis)	±16 mm
Resolution of the probe position	0.01 mm
Maximum linear speed of the probe	0.5 mm/s

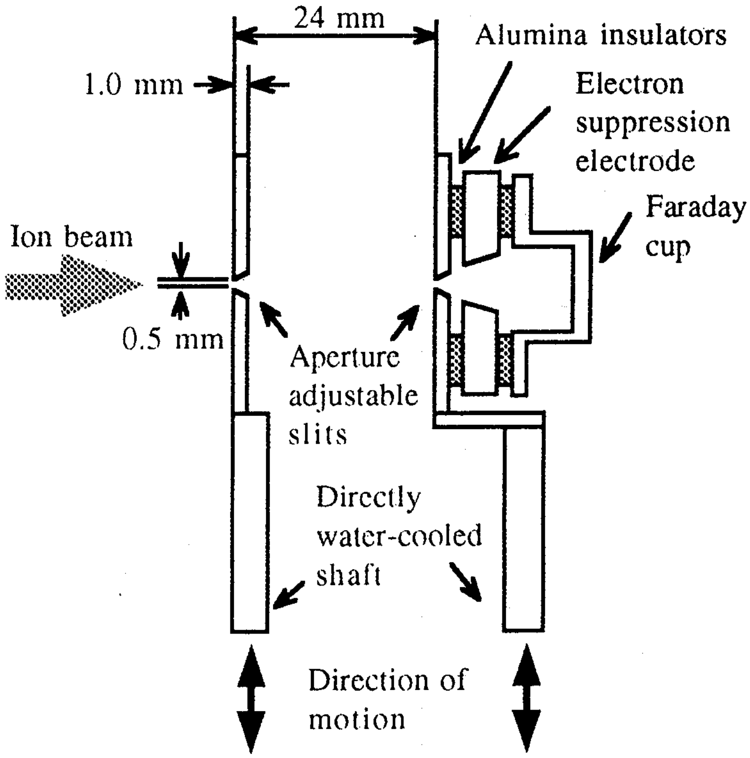


Fig. 2. Schematic drawing of the emittance monitor.

drawing of the system is shown in Fig. 2. The energy of an input beam can be known accurately (better than ±0.5%) by measuring a terminal voltage of the ion extraction high voltage power supply using an appropriate resistor divider. The output beam energy of the RFQ can be estimated by taking a momentum spectrum of a beam with the 15° bending magnet system. Installed at the exit of our RFQ electrodes are half-cells of RFQ[5]. They are expected to suppress the divergence of an RFQ output beam–the effects of the half-cells are to be fully tested in the near future. Shown in Fig. 1 but not explained in this report is the post accelerator of the RFQ. It is basically a $\lambda/4$-rf resonator that further accelerates or decelerates the output beam of the RFQ. The beam tests of the integrated system of the RFQ and $\lambda/4$ resonator have been in part completed at ICR, Kyoto University[6].

Table 3. Typical results of beam intensity measurements.

Ions	Beam currents (pμA)	Beam transmission (%)
He^+	32	86
N^{2+}	13	79
C^+	220	78
B^+	330	80

3.2 *Data*

3.2.1 *Current and transmission*

The maximum current of a B^+ ion beam measured at F3 was 330 μA with 80% beam transmission. The results of current intensity measurements are summarized in Table 3, including previously measured data for He^+, N^{2+} and C^+ ion beams[2].

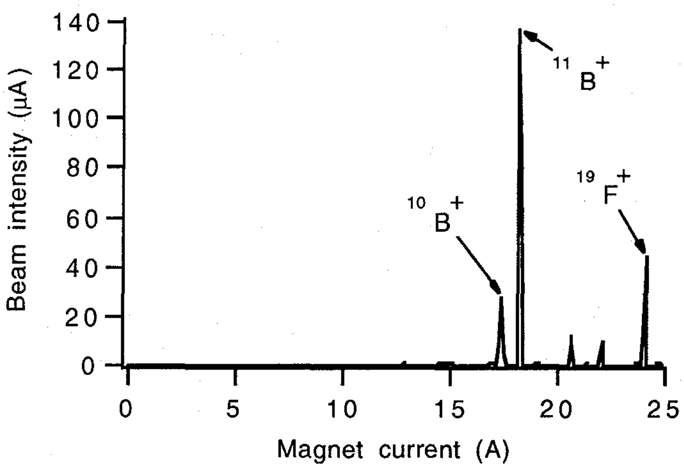


Fig. 3. Momentum spectrum of extracted ions from the ion source at energy of 30 keV.

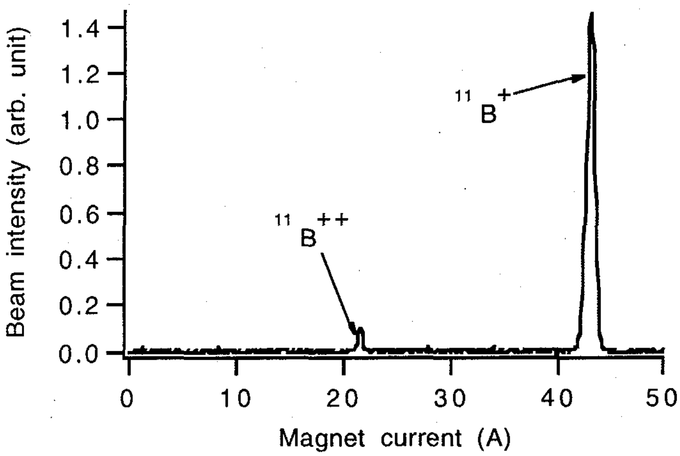


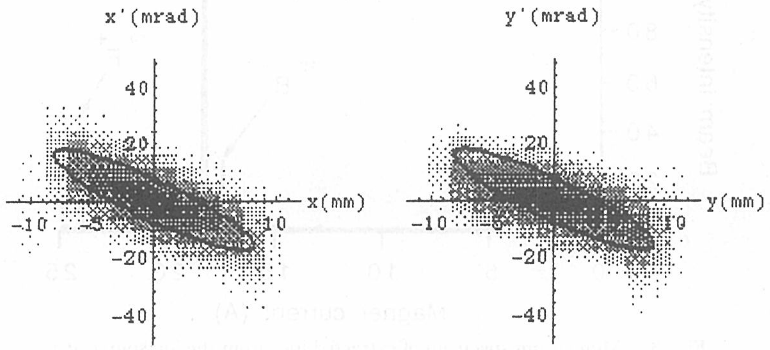
Fig. 4. Momentum spectrum of an accelerated B^+ beam.

3.2.2 *Momentum spectrum*

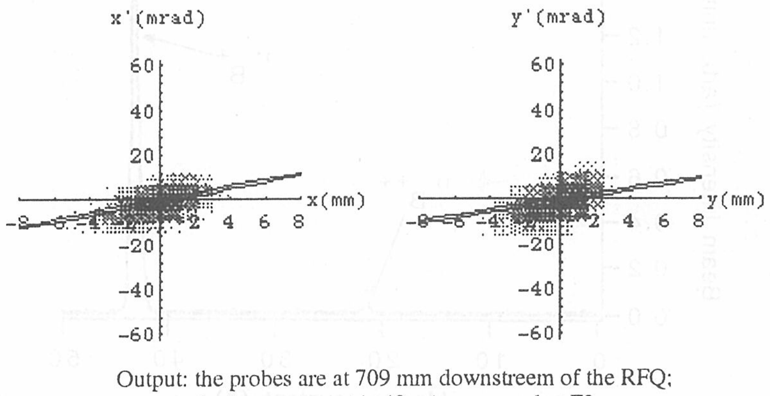
Fig. 3 exemplifies a momentum spectrum of ion beams extracted from the ion sourece operated with BF_3 gas. The measurements were done by recording an ion current with F2 in varying mass analyzer's current. The extraction voltage was set at 30 kV the synchronous energy required for the RFQ injection. The expected mass resolution $M/\Delta M$ of the 15° bending magnet is about 50. F5 measures the analyzed current of a beam which is collimated with the defining slits located both at the entrance and exit of the 15° magnet system. Fig. 4 typifies the momentum spectrum of an accelerated B^+ beam. The energy of the accelerated beam can be approximated by extrapolating from the spectrum of a mono-energetic beam from the ion source with the 15° bending magnet system. The estimated output energy of a B^+ beam is 987 keV$\pm$6%. This is off by +6% from the calculated output synchronous energy. A B^{2+} peak appearing at the half value of the magnet current is dentifiable as a charge-transferred B^+ beam : a small fraction of the B^+ beam from the RFQ collide with the residual gases and becomes B^{2+} ions unchanged in their energies.

3.2.3 *Emittance*

Fig. 5 typifies the results of beam emittance measurements for B^+ ion beams. The



Input: the probes are at 514 mm upstreem of the RFQ;
the beam current is 200 μA measured at F2.



Output: the probes are at 709 mm downstreem of the RFQ;
the beam current is 49 μA measured at F3.

Fig. 5. B^+ emittance data for the input and output of the RFQ.

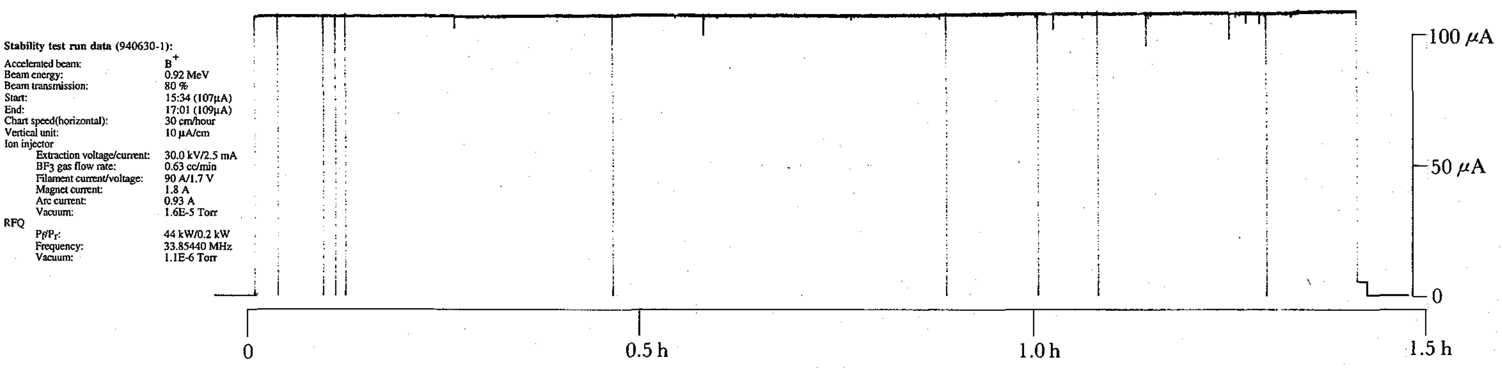


Fig. 6. B^+ beam stability test. The beam current is 100 μA at energy 0.92 MeV. The beam fluctuation is $< \pm 1.0\%$

measurements were done at the probe position of 514 mm upstream of and 709 mm downstream of the RFQ electrode boundaries, assuring 80% beam transmissions through the RFQ. In the figure, the trace-space ellipses obtained from calculations using PARMTEQ and TRACE 3-D[7] are superposed on the raster images of the measured data. The un-normalized emittances represented by the ellipses are 62.7 πmm-mrad for the input in both x- and y-coordinates and 8.6 and 9.7 πmm-mrad for the output in x- and y-direction, respectively. Agreement is quite fair for the input but the other needs further study.

3.2.4 *Stability*

B^+ beam stability test was done at 100 μA for over one hour period. Assuring the beam transmission of 80%, the output beam current of the RFQ was measured at F3 and recorded with a pen recorder. The result was shown in Fig. 6. The deviation from the average value of the beam current is $< \pm 1.0\%$ in the entire run. There are some glitches on the recorded curve, that all arise from high voltage sparks in the ion source extraction electrode. Otherwise, the result is very good.

4. CONCLUDING REMARKS

A series of beam experiments has proceeded successfully. We have obtained over 300 μA of B^+ beam in MeV energy regime with beam transmission $\geq$80%. We hope this result will attract the users of MeV ion implantation. We are currently preparing a simple endstation for a small sample, so that one can do an irradiation experment. Let us know about what your needs are and we may help and assist what you would like to do with our machine.

5. ACKNOWLEDGEMENT

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