ACCELERATION EXPERIMENTS OF A VARIABLE ENERGY RFQ DRIVEN BY AN LC-TANK CIRCUIT

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Abstract

To develop a variable energy RFQ accelerator for MeV ion implantation, an RFQ system driven by an LC-tank circuit was proposed. A feasibility study showed that the beam energy was effectively varied by changing the circuit resonance frequency, and the characteristics obtained in the range of 12 to 15MHz agreed well with the calculated data. On the basis of these results, a prototype RFQ apparatus consisting of the RFQ and the new microwave ion source was constructed. Finally, beam acceleration test results using the prototype machine were given and discussed.

Introduction

The requirements of high-energy ion implantation have been changing recently for different application regions. For instance, MeV implantation of heavy ions is indispensable for latch-up avoidance and soft-error reduction in CMOS memory devices.[1] One method of realizing mA-class MeV ion beams is to accelerate the ions using a Radio Frequency Quadrupole (RFQ) accelerator.[2,3] In a conventional RFQ accelerator, however, the beam energy cannot be varied because the accelerator uses a cavity resonator which operates at a constant frequency. To change the acceleration energy, the frequency must be varied. Therefore, new RFQ structures have been proposed in which the frequency can be varied.[4,5]

We have studied technological parameters required for a variable energy RFQ and have proposed a new RFQ system driven by an LC-tank circuit. The conceptual diagram of our variable energy RFQ system is shown in Fig. 1.[6] The resonance frequency is varied by changing the electrical capacity or the inductance in the circuit.

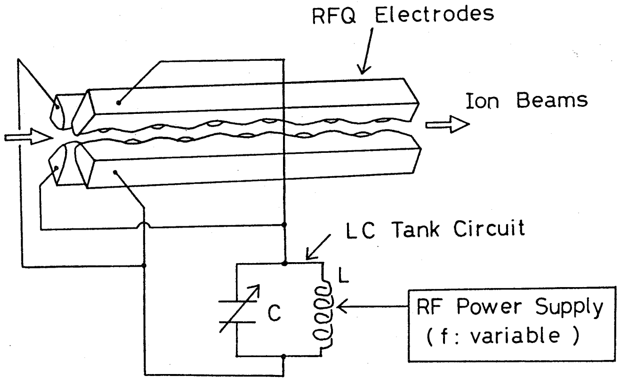

Fig. 1 Conceptual diagram of the variable energy RFQ system.

In order to study the acceleration properties of our RFQ apparatus, beam acceleration experiments were carried out using a small RFQ apparatus. RF power introduced into the small RFQ was limited to less than 4kW. Now, a prototype RFQ machine is being constructed to investigate the technological problems when higher power is introduced into the circuit. In addition, a newly designed microwave ion source is being installed in the prototype RFQ machine, in anticipation of high energy implantation over 1 MeV.

In this paper, results of the work on our variable energy RFQs are presented and future improvement of the system are discussed.

Acceleration Experiments Using Small RFQ

A schematic diagram of the small RFQ apparatus is drawn in Fig. 2.[6] It consists of a microwave ion source, a mass separator, a variable energy RFQ system, a cylindrical energy analyzer and a beam current detection system. The RFQ system contains conventional RFQ electrodes 60cm in length and an LC-tank circuit. Vane parameters such as bore radius, modulation, etc. were calculated so that the injected N^+ beam of 1.3keV could be accelerated to about 50keV at 13.56MHz. Vane parameters are graphically shown in Fig. 3 as a function of cell number. The parameters were calculated for an intervane voltage of 6kV.

In Fig. 2, the LC-tank circuit consists of a one-turn copper coil (ϕ200 x 600mm) and a vacuum capacitor. The resonant frequency was varied by adjusting only the capacity. A 4kW rf power supply was used in this experiment and the frequency could be varied from 12 to 15MHz.

When the frequency is varied, the vane voltage, $\pm V$, is adjusted so as to satisfy the following equation:

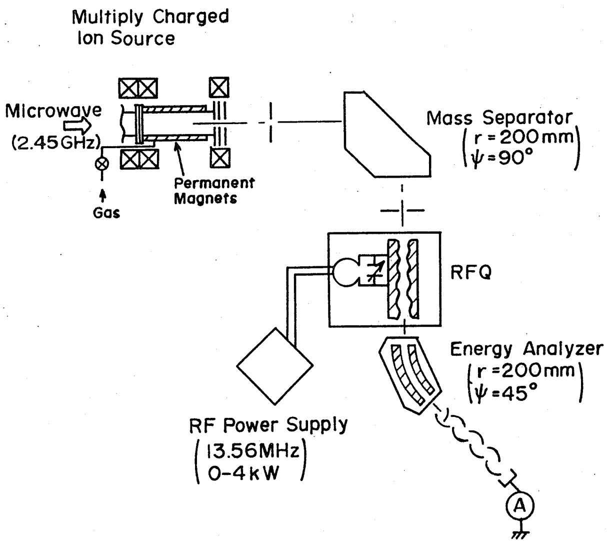

Fig. 2 Schematic diagram of small RFQ apparatus.

$$(qV/M)^{1/2}\cdot f^{-1} = \text{constant}, \tag{1}$$

where q, M and f are ion charge number, ion mass and operating frequency, respectively.

In order to study the acceleration characteristics, N^+ beams of about 0.1μA were introduced into the RFQ system at 1.3keV. When the intervane voltage, at 13.56MHz frequency, reaches 6.2kV, N^+ beams are effectively accelerated to 50.7keV, which coincides with the calculated value. The beam energy spread ΔE/E is about 1.3%, which is comparable with that reported for a conventional RFQ.

The dependence of the N^+ acceleration energy on the frequency was studied in detail and the results are shown in Fig.4. The injected N^+ energy and intervane voltages were adjusted in accordance with Eq.(1). The plotted results show that the beam energy is effectively varied by changing the frequency within the range of 12 to 15MHz.

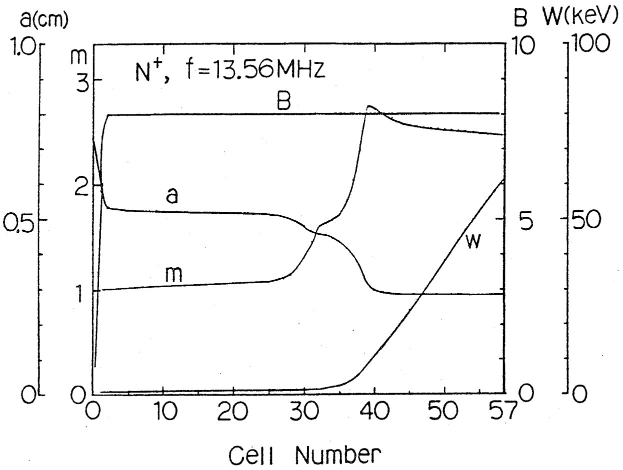

Fig.3 Vane parameters of small RFQ as afunction of cell number.

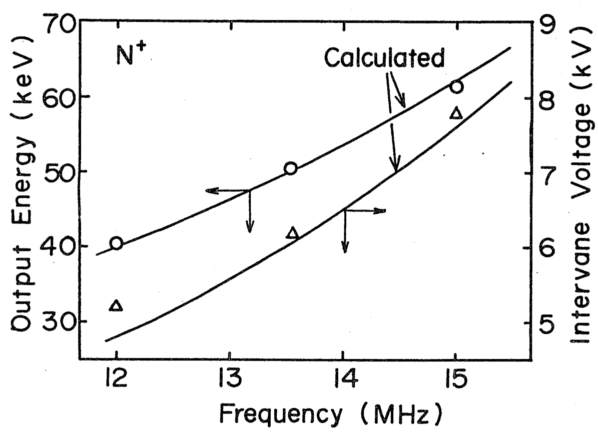

Fig.4 Dependence of N^+ acceleration energy on frequency. ○ and △ denote the experimental data obtained.

Acceleration Experiments Using Prototype RFQ

Intervane voltages sufficient for MeV acceleration are generally several tens of kV for a conventional RFQ. This means that rf power must be increased up to several tens of kW even for our RFQ system. The maximum rf power necessary for MeV acceleration depends on the shunt-impedance of the LC-tank circuit. The prototype RFQ machine is being constructed to assure high power operation in our RFQ system.

Principal parameters of the prototype RFQ are summarized in Table 1 and its structure was basically the same as that of Fig.2. However, the rf power supply of 30kW was used instead of 4kW power supply. On the other hand, the frequency was kept constant at 15MHz and the vane length was increased to 1.3m.

The LC-tank circuit contained a one-turn copper coil(φ200x450mm) and a vacuum capacitor(100-1000pF variable). The shunt-impedance at 15MHz was measured at the absorbed rf power of 17kW and the value is about 30kΩ.

The acceleration properties using the prototype RFQ apparatus were investigated with results shown in Fig.5. Acceleration conditions regarding the incident N^+ energy, intervane voltage, output energy, etc., agree well with the design parameters shown in Table 1. In addition of the N^+ acceleration test, Ar^{3+} acceleration was carried out. The frequency was kept constant at 15MHz. In this experiment, both the injected energy and the intervane voltages were adjusted so that the Ar^{3+} velocity in the RFQ was the same as that of N^+. The measured acceleration energy of Ar^{3+} is 0.75MeV, which agrees with the theoretical value. These results show that the ion beams are effectively accelerated for higher rf power levels. The rf power for MeV acceleration is estimated to be about 60kW for our RFQ system. Furthermore, new RFQ electrodes must be designed depending on the ion species, final acceleration energy and the frequency. These plans have been made to increase the beam energy to the MeV range for our RFQ system.

Table 1 Principal parameters of prototype RFQ

Electrode length	1.3m
Total cell number	49
Ion	N^+
Operating frequency	15MHz
Intervane voltage	26kV
Incident energy	10keV(0.7keV/u)
Output energy	272keV
Normalized emittance	0.01πcm·mrad
Minimum bore radius	0.43cm
Focusing strength	13.0
Maximum defocusing strength	-0.46
m(max)	2.5
ϕ_s	-30°
Transmission	
0 mA	87.4%
2 mA	72.6%

Discussion and Conclusion

In order to satisfy MeV ion implantation requirements, the beam energy must be varied by at least one order of magnitude. Thus, the operation frequency of the RFQ system must be varied by a factor of 3 in magnitude. The frequency range in the final MeV implanter was estimated to be from 10 to 30MHz for our RFQ system. The rf power necessary for acceleration of single charged ions to 1-2MeV would be about 60kW.

As is well known, the RFQ accelerator has the best acceleration efficiency for the energy range of 1-2MeV. To obtain mA beams of 2-4MeV, the introduction of multiply charged ion beams is very useful. Therefore, a new microwave ion source was designed to obtain high-current lower-charge-state multiply charged ion beams.[7,8,9] The typical beam extraction properties of the source are shown in Fig. 6. It was expected that the combination of the new microwave ion source and the variable energy RFQ would result in mA-class implantation of 2-4MeV.

In conclusion, the beam energy was varied by changing the frequency, and the obtained characteristics agreed well with the calculated data. Results showed that a variable energy RFQ driven by an LC-tank circuit would be suitable for application in MeV ion implantation.

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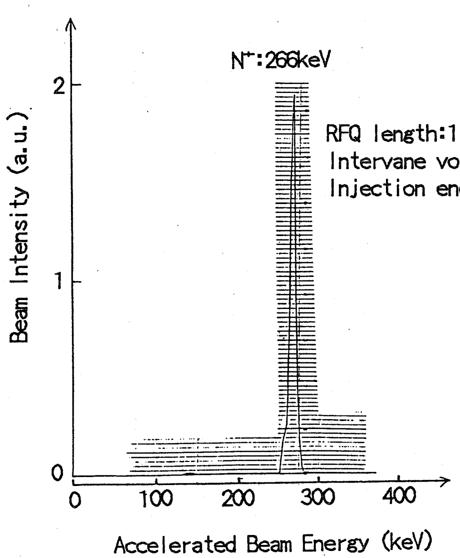

Fig. 5 Energy spectrum of accelerated N^+ beam using prototype RFQ system.

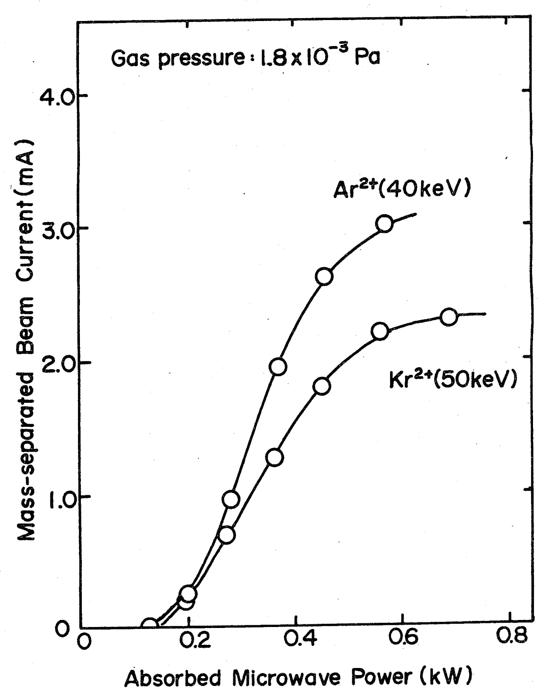

Fig. 6 Beam extraction characteristics of newly designed microwave ion source. Beam currents denote the value after mass-separation.