100KEV-CLASS HEAVY ION ACCELERATION USING VARIABLE ENERGY RFQ

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Abstract

Ion beam acceleration using a variable energy RFQ was carried out in the range of a few hundred keV. The RFQ system consisted of an LC resonance circuit and water-cooled 4-vane RFQ electrodes. N^+ and Ar^{2+} energies were continuously varied from 150 to 300keV and 550 to 740keV, respectively, by changing the resonance frequency of the circuit. The effective value of the bunched beam current reached 0.6 mA for Ar^{2+} ion. The Ar^{2+} peak current of the bunched beam was about 3.0 mA at 740keV.

Introduction

The requirements of MeV 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 ULSI memory devices.[1] In order to meet these requirements, we have developed the variable energy RFQ driven by an LC resonance circuit.[2,3] One of the final goals in our RFQ development is to obtain the variable beam energy from 0.5 to 4 MeV for phosphorus ions. The planned phosphorus beam current is 1 mA at an energy of 2 MeV. In addition, we plan to accelerate metal ions such as Al, Ti, etc. up to 2 MeV. The goal should be accomplished by 1993.

Heavy ion beam acceleration using the conventional rf linear accelerator has been reported.[4,5] However, the obtained beam current is usually limited to less than 0.4mA and the acceleration energy cannot be varied because of the constant frequency operation.

Our feasibility study with small RFQ electrodes (60 cm) under low rf power introduction (~4 kW) has shown that the beam energy can be varied in the range of a few tens of keV by changing the frequency. On the basis of the results, we have newly designed two types of RFQ electrodes to confirm the high-current acceleration in the range of a few hundred keV.

In this report, the acceleration characteristics using the new RFQ electrodes are described. Future modifications to obtain mA-class MeV ion beams are also discussed.

Experimental apparatus

A schematic diagram of the experimental apparatus is drawn in Fig.1. The apparatus consisted of the new microwave ion source for multiply charged ion beam production, mass-separator, Q-lens system, RFQ accelerator containing a water-cooled LC resonance circuit, and electrostatic cylindrical energy analyzer. Acceleration beam current was measured with a 50 Ω Faraday cup instead of the energy analyzer. LC resonance circuit consisted of two variable capacitors and a one-turn copper coil (φ200 x 210 mm). The resonance frequency could be changed by adjusting the capacitance.

A 100kW power supply was used in the experiments. The operation frequency was continuously varied from 10 to 30MHz. The rf power was introduced into the LC resonance circuit through a matching box. Two RFQ electrodes (1.3 m, 2.3 m) were utilized to investigate the energy variation and acceleration current increase in the 100 keV range. Design parameters of the 2.3 m RFQ are listed in Table 1. This RFQ electrode was intended to increase the acceleration current. The normalized emittance was selected to be as high as possible under the condition that an acceleration energy of over 500keV should be obtained. The value of 0.05 πcm·mrad was five times larger than that for the feasibility study case.

In Fig.1, the beam emittance and its diameter were controlled by adjusting the Q-lens focusing parameter. The experimental beam emittance ranged from 0.03 to 0.05 πcm·mrad for Ar^{2+} ions.

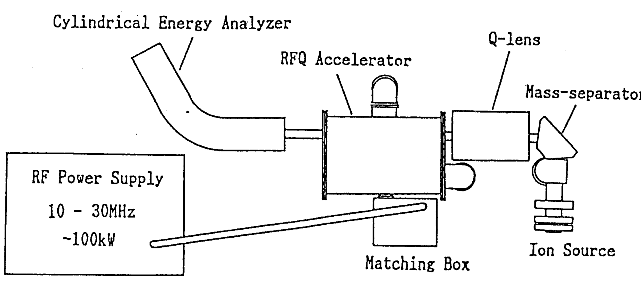


Fig. 1 Schematic diagram of experimental apparatus.

Table 1 Main parameters of RFQ

Vane length	2.3m
Frequency (f)	15MHz
Ion	N^+
Incident energy	35keV
Output energy	541keV
Intervane voltage (V)	45kV
Normalized emittance (ε_n)	0.05πcm·mrad
Min. bore radius	0.55cm
Max. modulation (m_{max})	2.5
Focusing strength (B)	13
Max. defocusing strength (Δ_b)	-0.45
Final synchronus phase (ϕ_s)	-36.5°
Transmission	
0 mA	81%
3 mA	82%
5 mA	77%

Experimental results

Energy variation characteristics of N^+ and Ar^{2+} ions were measured as a function of frequency. The results are shown in Fig. 2. In this experiment, an RFQ electrode 1.3 m in length was used, which was designed to accelerate N^+ ions of 10 keV to about 270 keV. The frequency was varied from 12 to 16 MHz. The incident energy and intervane voltages were adjusted so as to satisfy the following equation:

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

where q, M, V and f are ion charge number, ion mass number, intervane voltage and operation frequency, respectively.

In Fig. 2, the circles denote experimental data and the solid lines, calculated values. The N^+ acceleration energy was varied from 170 to 300 keV. The energy variation is in good agreement with the calculated line, i. e. proportional to f^2. The Ar^{2+} energy reaches 740 keV at 16 MHz.

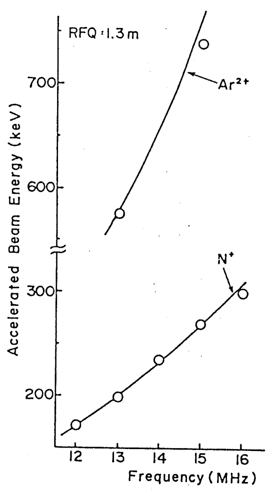


Fig. 2 Dependence of beam energy on frequency.

Experimental acceleration current for the 1.3 m RFQ was less than 0.1 mA because of miss-matching between the injected beam emittance and the designed RFQ acceptance. Thus, in anticipation of a current increase, acceleration experiments with a 2.3 m RFQ electrode were carried out. The wave form of the bunched beam current was measured with a 50Ω Faraday cup and 1GHz oscillo-scope. A typical wave form for accelerated N^+ ions is shown in Fig. 3. The accelerated beams are well bunched and the peak current is 2.5 mA.

In Fig. 3, the experiment was carried out, at 10.4 MHz, which differed from the designed frequency. This is because the new LC resonance circuit for the 2.3 m RFQ had an unexpected high inductance due to long feed lines. Improvement of the circuit structure is mow in progress.

The dependence of N^+ acceleration current on the absorbed rf power was measured and the results are shown in Fig. 4. The rf power necessary for N^+ ion acceleration at 10.4 MHz is calculated as about 7 kW from the necessitated intervane voltage and shunt impedance of the circuit. The results show that the effective value of the bunched beam current reaches 0.54 mA at about 8 kW.

In order to investigate the acceleration properties of multiply charged ions, the wave form of the bunched Ar^{2+} beam current was also measured. These results are shown in Fig. 5. The data indicate that the Ar^{2+} beams are well bunched and that the effective current reaches 0.6 mA at 740 keV. The peak current is about 3 mA.

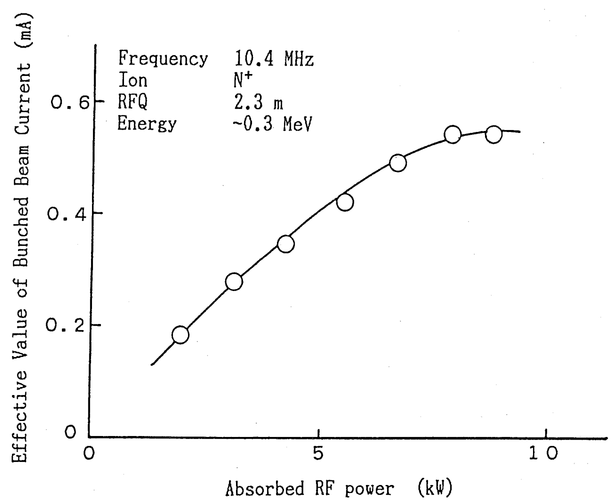


Fig. 4 Dependence of acceleration current on rf power

In these experiments, the respective injection energy of N^+ and Ar^{2+} ions was limited to 17 keV and 24 keV because of the low frequency operation. It has been observed that the injection current strongly increases with the extraction voltage of the ion source.[6] Therefore, the operation frequency increase due to improvements of the LC circuit structure would easily increase the acceleration current to the mA order.

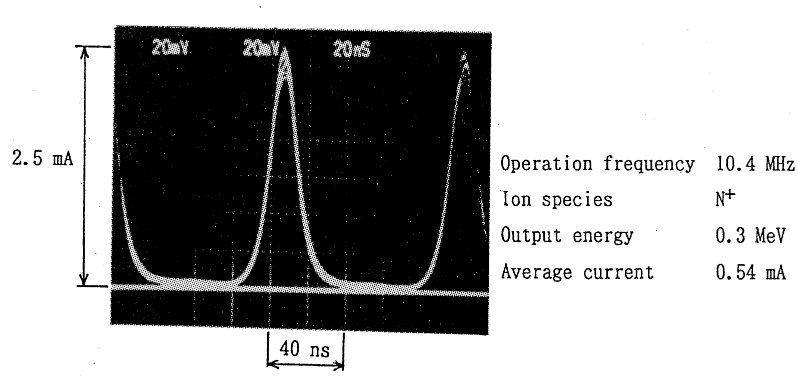
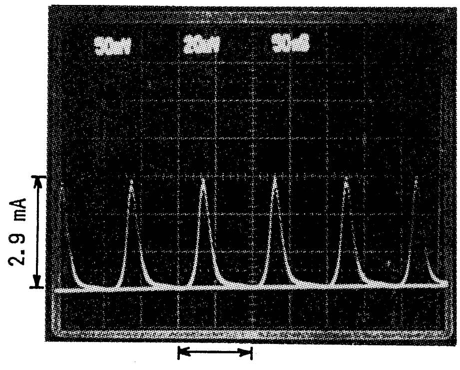


Fig. 3 Wave form of accelerated N^+ beam current.
Beam current was measured with 50Ω Faraday cup.



Operation frequency	10.4 MHz
Ion	Ar^{2+}
Output energy	0.74 MeV
Average current	0.6 mA

Fig. 5 Wave form of accelerated Ar^{2+} beam current.

Discussion and conclusion

For the development of a variable energy RFQ accelerator for MeV ion implantation, it is necessary to generate an intervane voltage in the range of 60-90 kV. The shunt impedance of the LC resonance circuit must be as high as possible to decrease the rf power. The maximum shunt impedance and rf voltage are 70 kΩ and 40 kV at 15 MHz, respectively. When the circuit is composed of only the 2.3 m RFQ electrode and one-turn copper coil, the impedance increases to 84 kΩ which is sufficient to generate the necessitated intervane voltage with a low power of less than 50 kW. In addition, Ar^{2+} ions have been accelerated to 1.4 MeV using the 84 kΩ LC circuit system. Therefore, improvements of the LC circuit structure, now in progress, would contribute to decreased rf power.

In conclusion, it wadss demonstrated that ion beams could be accelerated to the range of a few hundred keV using our variable energy RFQ system. The acceleration properties agreed well with the calculated values. The effective value of the bunched beam current was over 0.5 mA. An operation frequency increase would increase the acceleration current to the mA order.

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