DESIGN OF A NEW TYPE OF VARIABLE-FREQUENCY RFQ LINAC WITH A FOLDED-COAXIAL RESONATOR

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Abstract

A new type of variable-frequency radio-frequency quadrupole (RFQ) linac that will be constructed as a new injector for the RIKEN heavy-ion linac (RILAC) is proposed. It is designed to accelerate ions with mass-to-charge ratios of 7 to 28 at up to 450 keV per charge by varying its operational frequency from 17 to 38 MHz. The resonator has a folded-coaxial structure, and the resonant frequency is changed by a movable shorting plate. As a result of a low-power test on a half-scale model, the required rf power is found to be 6 kW at 17 MHz, and it increases to 34 kW at 38 MHz in cw operation.

Introduction

The RIKEN heavy-ion linac (RILAC) is rf frequency-tunable between 17 and 40 MHz,[1] which allows us to accelerate various kinds of ions with mass-to-charge (m/q) ratios of 5 to 28 as well as to widely change the energy. A 450 kV Cockcroft-Walton accelerator with an 8 GHz electron-cyclotron-resonance ion source (ECRIS) has been used as the injector of the RILAC.

Very recently, there has been growing demand for much higher beam currents in the RILAC. In order to greatly upgrade the RILAC beam currents, an ECRIS operated at a much higher frequency than 8 GHz is required. Such an ECRIS, however, requires too much electric power to be installed on the high voltage platform. The most favorable solution to overcome the difficulty is to adopt an RFQ (radio-frequency quadrupole) linac as an alternative to the Cockcroft-Walton accelerator.

However, this RFQ linac must be frequency-tunable in the RILAC frequency range. Moreover, it is desirable that the RFQ resonator is as compact as possible at as a low frequency as 17 MHz. To date, very few RFQ resonators have been proposed which satisfy this crucial requirement.[2] In the present paper, we propose a new type of variable-frequency RFQ linac, and report results of a low-power test using a half-scale model.

Design Concept

Let us consider the quarter-wavelength coaxial resonator illustrated in Fig. 1(a). The characteristic impedances in the open-end side and in the short-end side are Z_1 and Z_2, respectively. It is known that, when $Z_1<Z_2$, the resonant frequency is lower than that when $Z_1=Z_2$.[3] In other words, the resonator of $Z_1<Z_2$ is longitudinally more compact than that of $Z_1=Z_2$ for a given resonant frequency.

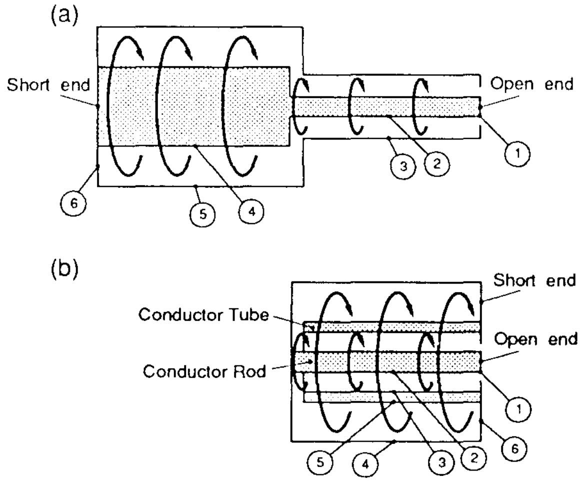

Fig. 1. (a) Quarter-wavelength coaxial resonator. Z_1 is the characteristic impedance of the open-end side and Z_2 is that of the short-end side. In our design, Z_2 is much larger than Z_1. (b) Conceptual drawing of a folded-coaxial (FC) resonator. The corresponding points between (a) and (b) are indicated by numbers of 1 to 6.

The idea proposed is to make the resonator more compact by structurally folding it as shown in Fig. 1(b), keeping the rf characteristics unchanged. We call this resonator a folded-coaxial (FC) resonator. On the inner surface of the resonator wall, a conductor rod is supported by its end. A conductor tube surrounding the rod is fixed on the other side of the resonator wall. The magnetic flux of the fundamental mode runs around the tube and the rod in the same direction, as shown in Fig. 1(b).

The FC resonator is applied to an RFQ linac by replacing the rod with a pair of vanes and by fixing another pair on the inner surface of the tube. Ions are accelerated along the central axis. This type of RFQ linac has the following distinct advantages. Firstly, the resonator is very compact even in such a low frequency region as that of the RILAC, as mentioned above. Secondly, the intervane voltage along the acceleration axis can be made flat enough to obtain high beam-transmission efficiency, when $Z_1<<Z_2$.[4] Thirdly, it can be frequency-tunable over a wide range, because, when one places a movable shorting plate on the short-end side of the larger characteristic impedance (Z_2), the resonant frequency is sharply changed by small movements of the plate.

Variable-Frequency RFQ linac for the RILAC

Resonator design

Figure 2 shows a schematic drawing of the RFQ resonator designed as a new injector for the RILAC. Horizontal vanes are held by front and rear supports fixed on the base plate. Vertical vanes are fixed on the inner surfaces of a rectangular tube which surrounds the horizontal vanes. This tube is supported by four ceramic pillars placed on the base plate. A stem suspended from the ceiling plate is in contact with the rectangular tube. A shorting plate placed around the stem can be moved vertically, which varies the resonant frequency. Radio-frequency power is capacitively fed through the side wall. A capacitive tuner is set on the opposite side of the side wall and two capacitive pickup monitors are set on the base plate.

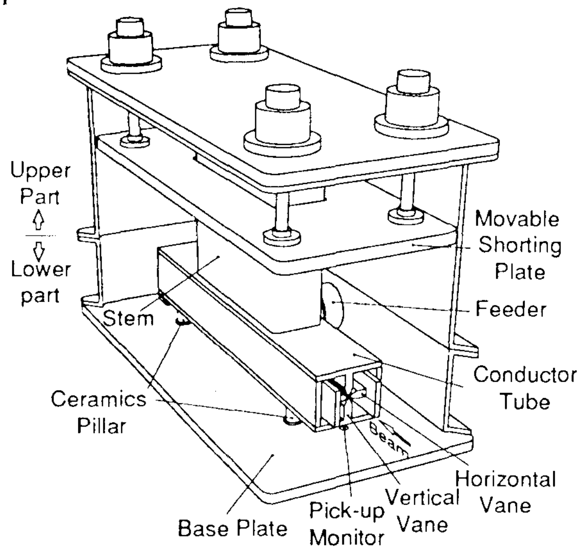

Fig. 2 Schematic drawing of the RFQ resonator designed as a new injector for the RIKEN heavy-ion linac (RILAC). The size is about 1700 mm (L) × 700 mm (W) × 950 mm (H).

The resonator is separable into upper and lower parts, as shown in Fig. 2. The horizontal vanes and the rectangular tube with the vertical vanes are rigidly fixed inside the lower part. The upper part containing the stem and the movable shorting plate can be removed as a unit. This separable structure permits accurate alignment of the vanes and easy maintenance.

The rf characteristics of the resonator were calculated by using the computer code MAFIA. Figure 3 shows a schematic drawing of the calculated magnetic flux of the fundamental mode. The flux flows around the stem, rectangular tube and the horizontal vanes. The direction of the flux is reversed at the middle of the vanes, and the magnetic field vanishes there. This can be well understood if we consider that this resonator consists of the two FC resonators of Fig. 1(b) connected back to back.

According to the calculations, the resonant frequency of the fundamental mode is varied from 17 to 35 MHz by changing the position of the shorting plate with a stroke of 615 mm. The calculated Q-values are 9,700 at 17 MHz and 4,800 at 35 MHz.

MAFIA calculations have shown that the intervane voltage distribution has a sinusoidal profile having the maximum at the middle and the minima at both ends. The difference between the maximum and the minimum voltages is 2% at 17 MHz, and 13 % at 35 MHz. We sought a remedy to maintain high beam-transmission efficiency for this voltage distribution by means of computer simulations with the PARMTEQ program. The remedy is to apply sufficient rf power so that the minimum voltage at both ends exceeds the voltage required for the uniform distribution.

Vertical asymmetry of the field strength also appears in the rectangular tube at the high-frequency region over 30 MHz, reflecting the vertically asymmetric shape of the resonator. This asymmetry is ± 1 % at most and it is expected to yield a negligible influence on the beam-transmission efficiency, considering past experience with RFQ linacs presently in operation.

The accelerating field of the present RFQ linac is a TEM mode, and accordingly an rf magnetic field arises in the region where the beam passes, as shown in Fig. 3 However, the influence of this magnetic field is negligible.[4]

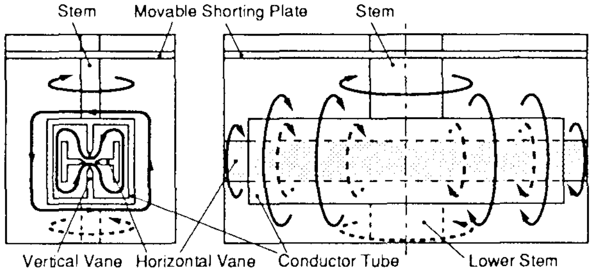

Fig. 3 Calculated magnetic flux of the fundamental mode of the RFQ resonator. The lower stem is used for the high frequency operation.

Vane design

The vane parameters have been optimized so as to obtain high beam-transmission efficiency with moderate power loss and compact dimensions. The key parameters obtained are listed in Table 1. The calculated power losses with the intervane voltage of 33.6 kV are 4 kW at 17 MHz and 18 kW at 35 MHz.

Test Measurement

In order to investigate the rf characteristics of the resonator, a half-scale model has been constructed. In designing the model, the fabrication procedure for the real RFQ linac was also studied. The conductive parts of the model are made of copper (C1100). The vanes have a constant bore radius of 3.85 mm along the acceleration axis, and have been aligned within an accuracy of 30 mm.

Figure 4 shows the measured resonant frequency along with the calculated values. The resonant frequency of the fundamental mode varies between 34.0 and 70.0 MHz by changing the position of the shorting plate by a stroke of 330 mm, which means that the actual operational frequency will be tunable between 17.0 and 35.0 MHz.

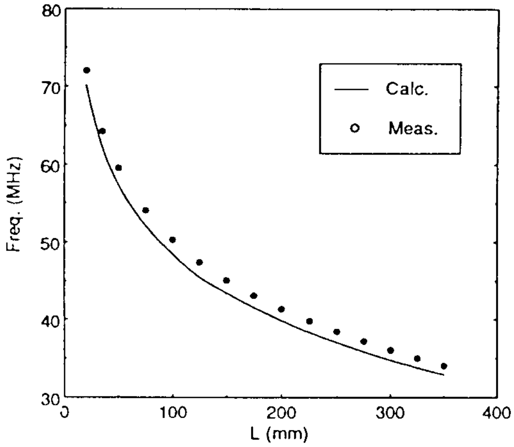

Fig. 4. Measured resonant frequencies (closed circles) and the values calculated using MAFIA (solid line) of the fundamental mode for the half-scale model. L denotes the distance in mm between the top of the rectangular tube and the bottom of the movable shorting plate.

As for the Q-values and the shunt impedances, the calculation overestimates the measured values by about 30 - 50 %.[4] This is considered to result from the fact that the calculation does not realistically treat the roughness of the wall surface and the imperfectness of the electric contact. From the result of the measurement, the power losses of the real RFQ linac are expected to be 6 kW at 17 MHz and 34 kW at 35 MHz.

For the operation of the frequency region above 35 MHz, use of a lower stem shown in Fig. 3 has been found to be effective. In this case, the electric current is shared by the two stems and the power losses become smaller compared to the case using only the upper stem. We have installed two kinds of lower stem in the half scale model and measured the Q-values. The result is shown in Fig. 5. As shown in the figure, the use of the lower stem reduces the power losses at the high frequency region. From this result, the operational frequency can be extended to 38 MHz with the power loss of 34 kW.

Conclusions

We propose a new type of variable-frequency RFQ linac based on the folded-coaxial (FC) resonator. The distinct feature of this RFQ linac is its capability for low-frequency operation and wide frequency-tunability in spite of its compact size.

As a result of the low-power test on the half-scale model, this RFQ linac is suitable for the new injector for the RILAC. It accelerates ions of m/q = 7 to 28 at up to 450 keV/q in the cw mode by varying its operational frequency between 17 MHz and 38 MHz. An 18 GHz ECRIS is to be constructed as a heavy-ion source for this RFQ linac.

TABLE 1
Key Parameters of the RFQ Linac

Vane length	142 cm
Frequency	17.0 - 35.0 MHz
Mass-to-charge ratio (m/q)	7 - 28
Incident energy	10 keV/q
Output energy	450 keV/q
Intervane voltage (V)	33.6 kV
Emittance (not normalized)	145 π mm-mrad
Minimum bore radius	0.417 cm
Mean bore radius	0.770 cm
Maximum modulation	2.7
Focusing strength (B)	6.80
Max. defocusing strength	- 0.30
Final synchronous phase	- 25 deg.
Transmission (0 mA)	96 %

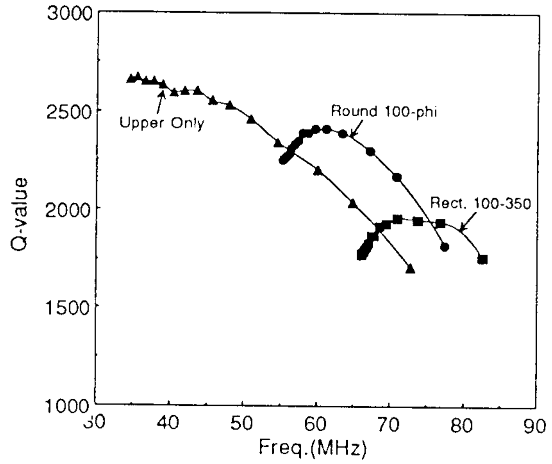

Fig. 5. Measured Q-values of the half-scale model of the RFQ resonator. The triangles are the Q-values only without using the upper stem. The rectangles and the circles are the ones using lower stems of different shapes.

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