Frequency Variable RFQ Operated with TE_{110} Mode

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Abstract

A frequency variable RFQ linac (RFQ) has been proposed as an injector in a future CNS accelerator facility, and the beam dynamics, resonant structure, and radio-frequency (RF) characteristics have been studied. The preliminarily designed RFQ has so long vanes that new resonant structure operated with a TE_{110} mode has been chosen as the candidate. The RF characteristics have been calculated with MAFIA to decide the main component sizes, and the validity of this structure has been verified successfully by the performance test of the 1/4 model cavity.

1. Introduction

A preliminary design study about a future CNS accelerator facility has been started in 1997, and the conceptual design report has been drawn up on July in 1998 [1]. The main feature of the facility is to accelerate intense heavy ion beams to the wide range of the energy.

The main accelerator is a relatively small separated sector cyclotron (SSC), which accelerates 1 pμA Xe^{31+} beam up to 6 MeV/nucleon and 100 pμA O^{5+} beam up to 10.5 MeV/nucleon. The longitudinal acceptance of the SSC has been estimated to be 40 degrees in phase and 1 % in energy spread in case of injecting 650 keV/nucleon O^{5+} beam. Thus, the very small longitudinal emittance is required to the injection beam in the wide range of the intensity. An RFQ is presumed the best candidate to satisfy above requirements, because it captures and bunches an injected DC beam with high efficiency and the longitudinal emittance of the accelerated beam isn't seriously affected by the space charge force.

Therefore, the RFQ has been chosen as the injector, and the beam dynamics, resonant structure and RF characteristics have been studied preliminarily. Further, a 1/4 model cavity has been manufactured, and RF characteristics of the model cavity have been measured to verify the injector design. This paper describes the injector design and the model test.

2. Preliminary beam dynamics design of the injector

Resonant frequency, input energy, and output energy are the most basic parameters defining linac dimensions (diameter and length), and these parameters have been decided according to the following considerations. For the resonant frequency, if the RFQ is operated at the half frequency of the SSC cavity, the longitudinal emittance of the RFQ output beam must be half of the value which is required in being operated at the same frequency. On the other hand, if the RFQ is operated at the double frequency of the SSC cavity, the SSC can't capture half of the injection beam. Therefore, we have considered that the RFQ should be operated at the same frequency as the SSC cavity, and we have chosen the frequency range from 17.25 MHz to 34.5 MHz which is used in existing similar facilities. For the output energy, a higher energy is more desirable to obtain enough space to install various components in the center region of the SSC, but RFQs have a disadvantage that the acceleration field decreases as the beam energy increases. Thus, we have chosen the energy of 650keV/nucleon for O^{5+} beam as the output energy, which is just above the minimum energy to arises no problem of the mechanical design in the SSC center region. For the input energy, we have chosen the energy of 5.4 keV/nucleon for O^{5+} beam, because the energy is high enough to avoid the serious emittance degradation in an injection beam transport line even for the 100 pμA O^{5+} beam.

Table 1 shows the dimensions of the RFQ designed with RFQUIK and PARMTEQ codes, and table 2 lists the operation parameters. The RFQ has a long shaper section of 4.61m to obtain the small longitudinal emittance, and also has twenty cells longer than 10 cm in the accelerator section. Thus, the RFQ has long vanes in spite of the relatively low acceleration voltage about 2 MV.

Table1 Dimensions of the RFQ

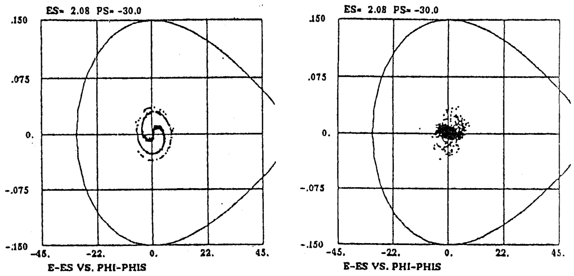
Vane length (m)	8.71
Characteristics bore radius (mm)	26.79
Minimum aperture radius (mm)	8.43
Maximum modulation	4.469
Cell number	230

Table 2 Operation parameters of the RFQ

Ion species	Xe^{31+}	Xe^{31+}	O^{5+}	D^{+}
Charge to mass ratio	1/4.26	1/4.26	1/3.2	1/2
Frequency (MHz)	17.25	21.17	27.93	34.50
Input energy (keV/n)	2.44	3.68	6.40	9.77
Output energy (keV/n)	248	373	650	992
Output energy (keV/q)	1056	1589	2080	1984
Focusing strength	7.0	7.0	7.0	7.0
Inter-vane voltage (kV)	66.0	99.3	130	124

Figure 1 shows the longitudinal emittance of the output beam when the O^{5+} beams of 0 mA and 1 mA are injected into the RFQ. The sufficient transmission ratios above 95% have been obtained, and $\Delta E/E$ and $\Delta\phi$, which are about 3% and 14 degrees in both calculations, are independent on the beam current. Since the product of the two values is almost same as the longitudinal acceptance area of the SSC, it is possible to inject the beam within the longitudinal acceptance through a good bunching system. Then, we have succeeded in the beam dynamics design of the injector.

However, we are not completely satisfied with this design. If we construct the injector with this cell parameters, we have to overcome many problems. For example, we have to consider how to manufacture and align so long vanes within sufficient accuracy. It is also necessary to consider how to remove the RF power consumed on the cavity wall, since the wall loss density of the RF power is concerned to be so high because of the high inter-vane voltage of 130kV. Further design study of the beam dynamics is indispensable to reduce the difficulties to overcome these problems.



0mA injection 1mA injection

Fig.1 Longitudinal emittance of the O^{5+} beams from the RFQ.

3. Study of the resonant structure

3.1 Comparison of the various resonant structures

4-Rod structure and folded-coaxial structure (FC structure) are supposed to be the candidates for the resonant structures operable in a wide frequency range, but we have studied to apply new resonant structure operated with the TE_{110} mode according to the following considerations[2][3][4]. 4-Rod structure has the disadvantage of the relatively low quality factor (Q-factor), because the structure is not a cavity resonator. If we construct the injector in this structure, so much RF power must be required to generate the designed vane voltage. Since the disadvantage may lead a fatal problem, we excluded 4-Rod structure from the candidates. On the other hand, the existing FC structure has a difficulty to be applied to a long RFQ. Since a pare of opposite vanes is supported at the both ends, it is very difficult to align the long vanes in high accuracy. Then, we have to consider how to assemble and align the long vanes, if we construct the injector in the FC structure. This difficulty may become a serious problem, thus, we tried to adopt a new structure to the injector.

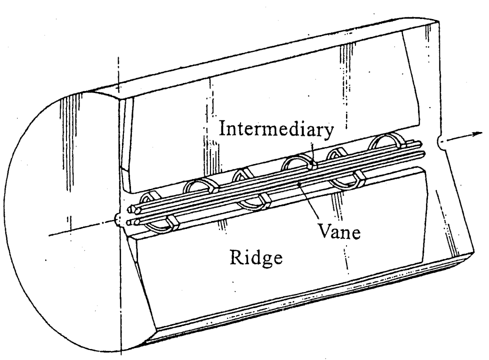


Fig. 2 Scheme of the RFQ operated with the TE_{110} mode.

Figure 2 shows the scheme of the new resonant structure operated with the TE_{110} mode of which fundamental idea is based on the author's patents [5][6]. This cavity is mainly composed of four vanes, two ridges, and many intermediaries. One pare of opposite vanes is joined to the upper ridge by the one group of intermediaries and another is to the lower ridge similarly. When the TE_{110} mode is excited, the voltages of the opposite vanes always become the same, and then the voltages of the adjacent vanes always become the same absolute value in the opposite polarity. Thus, if there is no dimensional error in the distance between the adjacent vanes, a uniform quadrupole field is obtained along the beam axis. These characteristics lead to the advantage that it isn't necessary to tune the quadrupole field with some kinds of tuners. Further, if the both end regions have the same local resonant frequency as it in the center region, the field distribution along the beam axis always becomes flat.

Compared with 4-vane structure operated with the TE_{210} mode, this structure has two features. The first one is that the frequency of the TE_{110} mode never corresponds to the other mode, because the frequency is the lowest in all modes. We have been released from a problem of the mode mixing. The second is that a higher Q-factor and a higher shunt impedance are expected because the current path in the cavity operated with the TE_{110} mode is shorter than it with the TE_{210}.

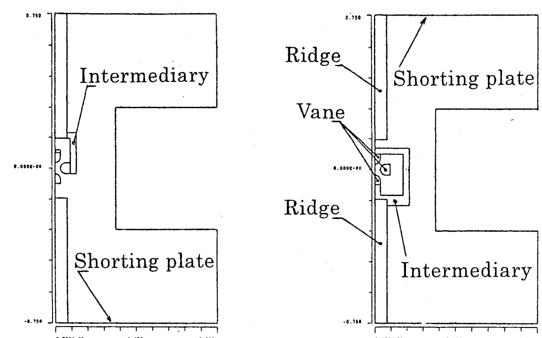


Fig. 3 Half cross sections used in the MAFIA calculation.

3.2 RF characteristics calculated with MAFIA

In order to apply the new structure to the injector, we have studied the RF characteristics with MAFIA simulations. Figure 3 shows an example of half cross sections at the two axial positions, which were used in a simulation. The full cross section are square shapes of 1.6 m in width and 1.5 m in height, and two ridges are positioned at the horizontal center. One pair of the horizontal vanes is joined to the upper ridge and another pair of the vertical is to the lower. Movable shorting plates will be put at the upper and lower boundaries in an actual cavity.

In the study, we tried MAFIA simulations in the two step. In the first step, we calculated resonant frequencies of the two axial infinite models, which have the same structure except for the cavity heights. Here, we decided main component configuration, and calculated the cavity height satisfying the condition that the resonant frequency becomes almost same as 17.25MHz and 34.50MHz. Table 3 shows the calculation result. The resonant frequencies of 35.4MHz and 17.4MHz have been obtained under the condition that the cavity heights are 0.7m and 1.5m respectively. Then, the required frequency range will be obtained by moving the each shorting plate by 400 mm in an actual cavity. The required RF power is calculated assuming that D^+ is accelerated at 35.4 MHz and Xe^{31+} is at 17.4 MHz. The RF power for the D^+ acceleration is relatively large but permissible.

Table 3 RF characteristics calculated with MAFIA

Height of the cavity (m)	0.7	1.5
Width of the cavity (m)	1.6	1.6
Resonant frequency (MHz)	35.4	17.4
Quality factor	8700	18000
Inter-vane voltage (kV)	124	66.0
Required RF power (kW)	286	19.5

In the second step, we calculated resonant frequencies of the two finite models of which axial lengths are 1.27m and cavity heights are 0.7m and 1.5m respectively. The main component configuration in the axial center region is same as it decided in the first step. Here, we tried many simulations and optimized the ridge configuration in the end region to satisfy the condition that the resonant frequency corresponds to it calculated for the same height cavity in the first step. As described above, we decided the center configuration in the first step and the end configuration in the second step.

4. RF characteristics of the model cavity

4.1 Structure of the model cavity

In order to verify the new structure, a model cavity have been manufactured with brass material and the RF characteristics have been measured. The scale of the cross section is 1/4 and the axial length is 1 m. Figure 4 shows the inside view of the cavity. The two horizontal vanes are joined to the upper ridge by the 18 intermediaries and the two vertical vanes are to the lower by the 19 intermediaries. The width of the intermediary located at the axial center is 50 mm which is five times wider than the others. A capacitive circular coupler is located at the side wall facing to the center intermediary, and RF power is fed into the cavity through the coupler. Movable shorting plates as the upper and lower wall of the cavity are divided into the three parts in each side, which can be manually moved independently. The cavity has a lot of tuners to examine the effect on the field distribution. For example, six cylindrical block tuners are installed on each side wall, and two same tuners are on each end wall.

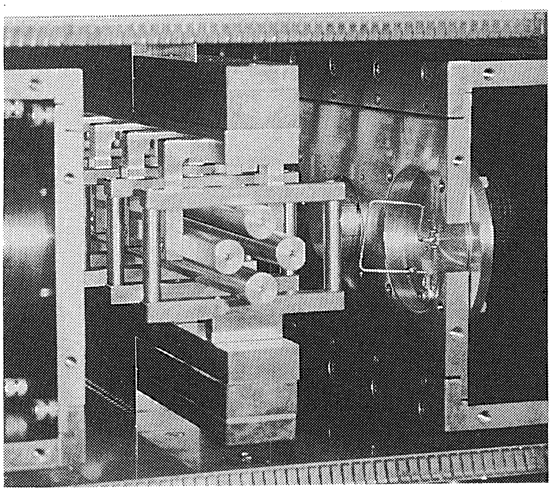


Fig. 4 Inside view of the model cavity.

4.2 Alignment of the vanes

As described before, if this structure has no dimensional error in the distance between the adjacent vanes, a uniform quadrupole field is always obtained. This means that if some dimensional errors exist in it, asymmetricity arises in the field because the field strength is inversely proportional to the distance. Thus, the vanes have been aligned so carefully that the error has been kept within ±90μm.

4.3 Measurement of the RF characteristics

The resonant frequencies and the field distributions have been measured setting the movable shorting plates at various positions. Table 4 lists the typical results of the frequency measurement. Though the frequencies are slightly lower than the theoretical values, the frequency range more than one octave has been obtained by moving the shorting plates by 100mm. This frequency variability almost agrees with the theoretical calculation. Figure 5 shows the field distribution along the beam axis at 68.87 MHz. Very good uniformity and flatness have been obtained without any field tuning by use of tuners. This tendency is independent of the resonant frequency. Concretely, field uniformity is within ±2.4% at 68.87 MHz and ±3.5% at 139.62 MHz. We have succeeded in obtaining the sufficient frequency variability and sufficient field uniformity by the new structure operated with the TE_{110} mode.

Table 4 Resonant frequency of the model cavity

Distance between opposite shorting plates (mm)	Theoretical (MHz)	Experimental (MHz)
175	141.6	139.62
375	69.6	68.87

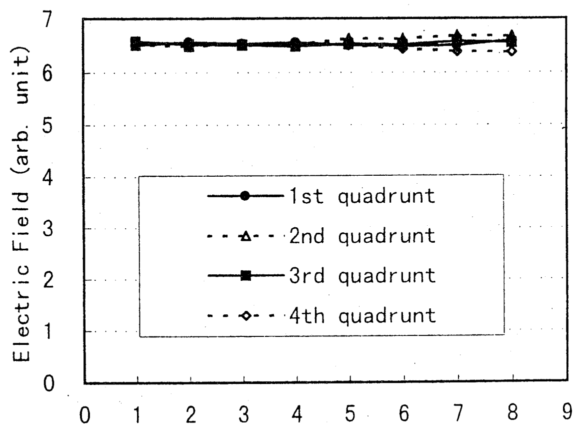


Fig. 5 Field distribution along the beam axis at 68.87 MHz.

5. Conclusions

Beam dynamics, resonant structure, and RF characteristics have been studied about the frequency variable RFQ proposed as the injector in the future CNS accelerator facility. The preliminarily designed RFQ has so long vane that the new resonant structure operated with the TE_{110} mode has been chosen as the candidate. The RF characteristics have been calculated with MAFIA to decide the main component sizes, and the validity of the structure has been verified successfully by the performance tests of the 1/4 model cavity.

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