STRUCTURE AND RF CHARACTERISTICS OF THE INS 25.5–MHZ SPLIT COAXIAL RFQ

N. Tokuda, S. Arai, A. Imanishi, T. Morimoto, S. Shibuya†, and E. Tojyo
Institute for Nuclear Study, University of Tokyo
Tanashi, Tokyo 188, Japan
Graduate University for Advanced Studies
Tsukuba, Ibaraki 305, Japan†

Abstract

A 25.5–MHz split coaxial RFQ cavity, 0.90 m in inner diameter and 2.1 m in length, has been fabricated and settled in INS. The electric field for acceleration and focusing is generated by four modulated vanes. In the vane alignment, an accuracy better than ±40 μm (the average bore radius r_0 is 0.946 cm) has been attained. The resonant frequency has been tuned to 25.45 MHz; the frequency will be finally adjusted to 25.5 MHz by using a movable inductive tuner. According to a tentative measurement, the field strengths between neighboring vanes are same within ±1%. This paper describes the cavity structure, the design procedure, and preliminary results on rf characteristics of the cavity.

Introduction

Since 1984, we have been developing a split coaxial RFQ (SCRFQ) at INS. Currently, we see a possible use of this system at the Japanese Hadron Facility. This hadron facility will deliver accelerated beams of unstable nuclei. For the pre–acceleration of ions, whose charge–to–mass ratio is planned to be 1/60 at minimum, a 22–m long SCRFQ of 25.5 MHz will be used.

The idea of the SCRFQ was proposed by Müller in GSI, Darmstadt, and he constructed an SCRFQ and accelerated heavy ions.[1, 2, 3] In his linac, the electric field for acceleration and focusing is generated by drift tubes with focusing fingers. As we reported earlier,[4] we devised a multi–module structure using modulated vanes. In order to demonstrate the capability of our SCRFQ, acceleration tests were conducted on a 50–MHz proton model. Experimental results on output energy, beam emittance, and transmission efficiency agreed with predictions obtained from PARMTEQ simulations.[5]

After the success in the acceleration tests, we decided to construct another SCRFQ that should work high–power operation; the 50–MHz proton model was not cooled, and the acceleration tests were accordingly conducted under a condition of a 230–W rf power in peak and an 8–% duty factor. The 25.5–MHz SCRFQ present here is equipped with water channels so that an rf power of 10 ~ 20 kW in average could be supplied.

The fabrication of the 25.5–MHz SCRFQ cavity, 2.1 m in length and 0.90 m in inner diameter, has been finished. We have so far tuned the resonant frequency to 24.45 MHz and measured the Q–value. The field strengths between neighboring vanes were also examined: the field balance was within ±1% (note that this result is a preliminary one, as will be discussed later). The cavity has settled in INS and is waiting for precise cold tests. After these tests, high–power operations and acceleration tests will be conducted.

Cavity structure

Figure 1 shows the structure of the 25.5–MHz SCRFQ, comprising three modules. The present structure is an improved version of the 50–MHz proton model. The detailed discussion about the structure, as well as the one about the beam dynamics design, is presented elesewhere.[6] From the reference,[6] we will pick up descriptions concerning the cavity's rf characteristics.

The materials for the cavity are as follows: (1) copper–plated mild steel for the cavtiy cylinder and the end disks, (2) oxgen–free copper for the back plates and the stem flanges, (3) copper–plated stainless steel for the spacing rods, and (4) chrome–copper alloy for the vanes. Three different types of rf contactors are used: (1) silver–plated stainless tubes (3.28 mm in diameter) between cavtiy cylinders, (2) copper strips (1 mm × 26 mm) between a stem flange and a cavity cylinder, and (3) shield sprirals between a stem flange and a spacing rod. The cavity parts are bolted together with rf contactors. Between a vane and a back plate, however, no contactor is inserted.

Cavity design

Basic formulae

The structure of the SCRFQ is so complicated that we have not yet a computer code that predicts precisely the resonant frequency of a cavity under design. We hence optimized the cavity geometry by using the equivalent circuit analysis developed at INS.[7] This method was applied to the 50–MHz proton model, and its reliability was verified.[8]

Figure 2 shows the equivalent circuit for the SCRFQ cavity comprising three modules, which are separated by stem flanges. The resonant frequency f_r of the SCRFQ is expressed as

$$f_r = \frac{1}{2\pi\sqrt{L_0 C_0}} , \quad (1)$$

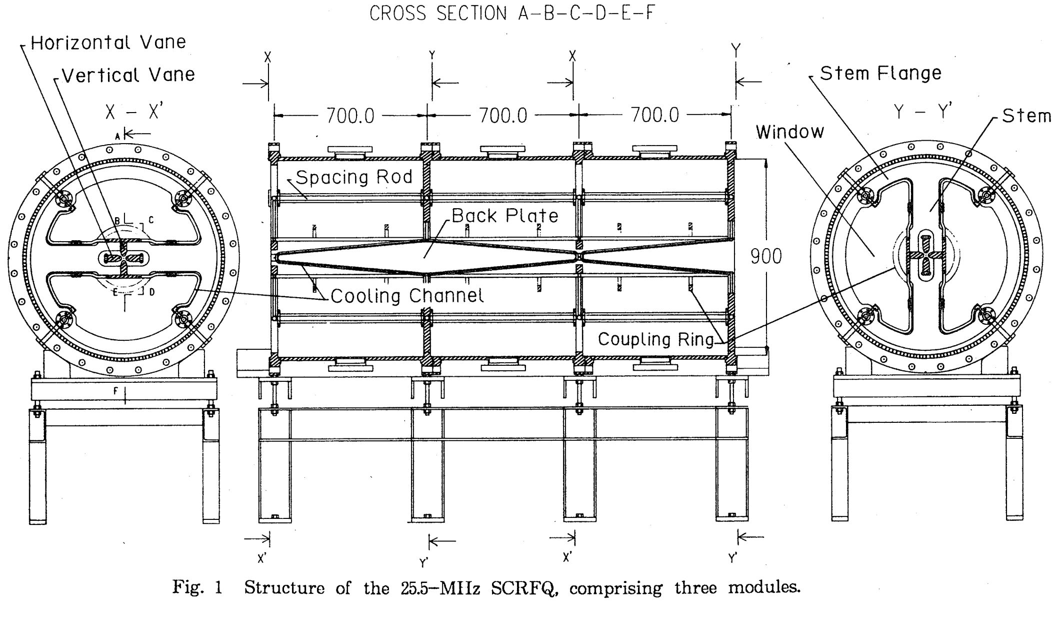

Fig. 1 Structure of the 25.5–MHz SCRFQ, comprising three modules.

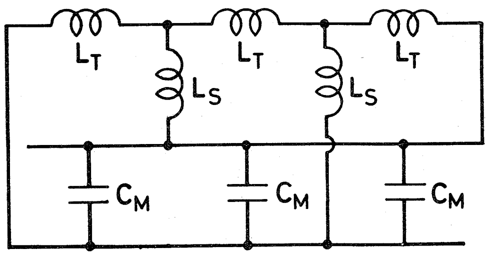

Fig. 2 Equivalent circuit for the three–module SCRFQ cavity.

where L_0 and C_0 are the specific inductance and capacitance. The capacitance C_0 (= $3\,C_M$) is the sum of three capacitances: vane–vane capacitance C_{VV}, vane–ring one C_{VR}, vane–stem one C_{VS}. Among these the vane–vane capacitance is dominant. The vane–vane capacitance C_{VV} is estimated from a SUPERFISH calculation, as will be discussed later. The additional capacitances C_{VS} (vane–stem) and C_{VR} (vane–coupling ring) are calculated numerically on the assumption that electric charge distributes uniformly on the metal surfaces. These capacitances are parallel to the vane–vane capacitance C_{VV}; therefore, the total capacitance is expressed as

$$C_0 = C_{VV} + C_{VS} + C_{VR} \quad . \tag{2}$$

In Fig. 2, L_T denotes the tank inductance associated with the magnetic flux running azimuthally around the inner electrode, and L_S denotes the stem inductance associated with the flux around a stem. The total inductance L_0 is expressed as

$$L_0 = \frac{L_T}{3}\,\frac{L_T + 3L_S}{L_T + \frac{1}{3}L_S} \quad . \tag{3}$$

The tank inductance L_T would approximate the inductance of a simple coaxial cavity:

$$L_T = \frac{\mu_0}{2\pi}\, l_M \ln\frac{r_C}{r_E} \quad , \tag{4}$$

where l_M is the module length, r_C the cavity radius, r_E the radius of the inner electrode (the actual four–piece electrode is here replaced with a cylindrical pipe). In the actual estimation of L_T, however, we calculate the ratio of the magnetic flux around the inner electrode to the current flowing on its outer surface. For simplicity of the calculation, the diamond–shaped back plates are replaced with rectangular plates, and the current density is assumed to be uniform on the plates. The density of the magnetic flux is obtained by calculating numerically the integral that appears in the equation for the Biot and Savart law. The stem inductance L_S is estimated in the same manner. The flux density is summed over the area of a semilunar window of a stem flange.

The amount of the stem inductance varies with the area of the windows, and becomes zero when they are completely closed. Adjusting the stem inductance, we can tune the resonant frequency. The adjustment can be accomplished by attaching metal plates to the stem flanges. This technique was actually employed at the present SCRFQ, as will be described later.

Optimization of the cavity size

In the first approximation, the resonant frequency of the SCRFQ cavity is mainly determined by the tank inductance and the vane–vane capacitance. Our task is therefore to optimize the module length l_M, the cavity radius r_C, and the cross sectional shape of the inner electrode. From the point of view of the fabrication cost, a small cavity radius is desirable, because the cost is roughly proportional to (length l_M) × (radius r_C)^2. A small r_C, however, leads to a long module length (see Eq.(4)), and consequently brings the following problems: the droop of the inner electrode caused by gravity will be large; accurate vane setting will be accordingly difficult; an enlarged vane–vane capacitance and a lengthened current path reduce the Q–value; a small stem inductance L_S leads to a narrower adjustable frequency range. Among these problems, the first two mechanical ones are important. Taking account of these considerations, we fixed first the module length, secondly the vane height, and lastly the cavity radius. The procedure is discussed below, and the resulting geometrical parameters and rf ones are summarized in Table 1.

In the biginning, we got a rough idea about the module length and the cavity radius yielding the aimed frequency of 25.5 MHz. For several values of the module length, the resonant frequency was calculated as a function of the cavity radius. A vane–vane capacitance

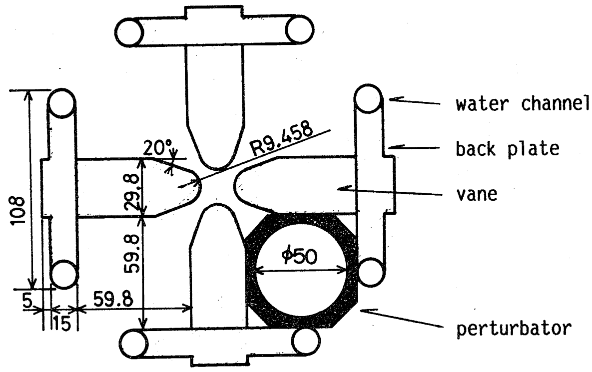

Fig. 3 Transverse cross section of the inner electrode cut at the center of a module. A Bakelite perturbator was set in the measurement of the intervane fields, as will be described later.

of 216.5 pF/m, the measured value at the 50–MHz proton model, was tentatively employed here. The calculation was done for two cases: the windows of the stem flanges are closed or open. We could thereby estimate how widely we can tune the resonant frequency by controlling the stem inductance. As a result, the module length of 70 cm turned out to be optimum under the condition of a smaller cavity radius (40 cm) and a wider tunable frequency range (23 ~ 27 MHz). (Note : the values in the parentheses will be changed later, because the value of the vane–vane capacitance is still tentative.)

For the fixed module length of 70 cm, the cross sectional shape of the inner electrode was optimized so that the droop caused by gravity might be 30 μm or less. Each of the electrode pieces comprizes a vane (chrome–copper alloy) bolted on a back–plate (copper), and is supported by stem flanges at two points. One point is at an electrode end (RFQ entrance for the horizontal electrodes, and exit for the vertical ones), and the other point is 140 cm far from it. This means that every electrode piece has an unsupported end, where displacement of the vanes because of the droop will be large. For various back–plate thicknesses, vane thicknesses and heights, the amount of the droop was estimated from computer calculation, and the cross sectional shape shown in Fig. 3 was employed. The estimated maximum displacement is 32.7 μm for the vertical electrodes and 29.6 μm for the horizontal ones.

For the fixed cross sectional shape of the inner electrode, the vane–vane capacitance was estimated by using a SUPERFISH technique. In the calculation, the inner electrode was installed in an infinitely long cylinder with a radius of 30 cm. The actual electrode has a cross sectional shape varying with the axial distance, because the back–plates are diamond–shaped as shown in Fig. 1. In this model, the cross sectional shape is set to be uniform along the axial distance and to be same as the actual one at the center of a module. The SUPERFISH calculation yielded a resonant frequency f_{SF} of 88.62 MHz. On the other hand, the inductance per unit length approximates

$$L_{SF} = \mu_0 S \tag{5}$$
$$= 82 \text{ nH·m} \quad ,$$

Table 1
Geometrical parameters of the 25.5–MHz prototype cavity and rf parameters for two cases: the semilular windows of the stem flanges are completely open or closed. See Fig. 3 for the cross sectional shape of the inner electrode.

	Closed windows	Open windows
Resonant frequency	27.7 MHz	24.0 MHz
Tank length (3 × l_M)	210.0 cm	——
Inner diameter (2 × r_C)	90.0 cm	——
Radius of inner electrode (r_E)	9.0 cm	——
Total capacitance[1] (C_0)	434 pF	——
Total inductance[2] (L_0)	76.3 nH	101 nH
Unloaded Q–value	10700	7600
Power loss in peak[3]	43 kW	53 kW

Notes : 1) measured C_0 = 454 pF,
2) L_T = 229 nH, L_S = 28.9 nH,
3) estimated for an intervane voltage of 110 kV.

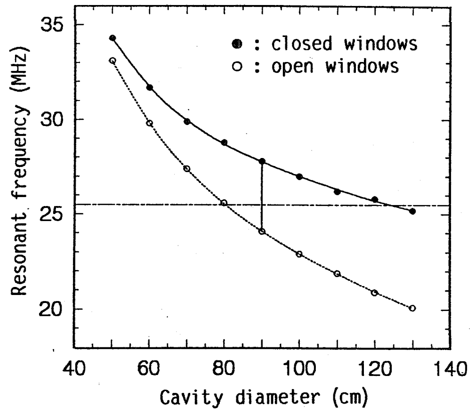

Fig. 4 Resonant frequency as a function of the cavity diameter for the module length of 70 cm and the vane–vane capacitance of 434 pF. From this graph the cavity radius was fixed at 45 cm.

where S is the area of the region between the outer cylinder and the inner electrode. We can thus estimate the vane–vane capacitance:

$$C_{VV} = \frac{l_M}{(2\pi f_{SF})^2 L_{SF}} \quad (6)$$

$$= 157.3 \text{ pF/m} \times 2.135 \text{ m}$$

$$= 335.8 \text{ pF} \quad .$$

The additional vane–stem and vane–ring capacitances were respectively estimated to be C_{VS} = 43.1 pF and C_{VR} = 40.5 pF; consequently, the total capacitance is 419.4 pF. In the subsequent design procedure a slightly larger value of C_0 = 434 pF was used; the correction factor was emperically obtained at the 50–MHz proton model, where (measured C_0)/(estimated C_0) = 1.034. (According to a measurement after the assembling the inner electrode, C_0 was found to be 454 pF.)

The newly obtained capacitance C_0 = 434 pF is smaller than the value of 455 pF (= 216.5 pF/m × 2.1 m), which was used earlier in the optimization of the module length. The cavity radius should be accordingly greater than the previously estimated value of 40 cm. The resonant frequency was re–calculated by varying the cavity radius. From the result, shown in Fig. 4, the cavity radius was fixed at 45 cm. The resulting range of the frequency adjustment is from 24.0 MHz to 27.7 MHz.

Preliminary cold tests

Frequency tuning

Soon after the completion of the cavity, preliminary cold tests were conducted in the industrial firm. In the beginning, the resonant frequency was tuned to 25.45 MHz, by adjusting the area of the semilunar windows.

We measured first the resonant frequency of the cavity with the all windows closed, *i.e.*, the stem inductance is zero. The measured frequency was 28.88 MHz. This value is larger than the estimated value of 27.7 MHz. The discrepancy between the frequencies might be due to the spacing rods, which were not taken into account in the theoretical estimation. The spacing rods reduce the area for magnetic flux around the inner electrode, and hence the tank inductance would be smaller than the estimated value.

Then we removed the four plates closing the four windows of the two stem flanges that separate modules. The closing plates were removed one by one, and the resonant frequency was measured at each time. Every time one plate is taken off, the frequency decreased by 1.1 MHz and finally reached 24.68 MHz. A frequency of 25.76 MHz, obtained when only one closing plate is attached, was closest to the aimed freqecy of 25.5 MHz. This means that the windows should be almost open. We replaced accordingly the original four semilunar plates with narrow strips. Four strips were attached to the stems in the direction parallel to them. The width of the strips were changed a few times until a resonant frequency of 24.45 MHz was attained. With the finally shaped strips the stem width, initially 12 cm, was effectively increased to 21.1 cm. The attained frequency is lower than the aimed frequency by 50 kHz.

Inductive tuners

The above frequency difference can be diminished by using inductive tuners, metal blocks inserted into the cavity so that the tank inductance L_T should be reduced. To evaluate the effect of inductive tuners on the resonant frequency, three cylindrical aluminum blocks were prepared. Each block was 18.8 cm in diameter and 21.7 cm in length. The three inductive tuners, one tuner per module, were attached to the cavity (the distance from the beam axis to the block surface is 30 cm). Then the resonant frequency was measured to be 25.52 MHz, higher than the initial value by 74 kHz. For further frequency tuning, one of the tuners will be replaced with a movable one.

Q–value

The measured unloaded *Q*–value was 6100 without the inductive tuners, and 6040 with them. These values should be compared with 7600, the estimated value in Table 1, because the window areas were reduced a little. Though the cavity consists of parts assembled together with bolts, the obtained *Q*–values is good. The *Q*–values is expected to increase after cleaning the cavity surface through high–power operations.

Field balance

The vanes are aligned with an accuracy within ±40 μm, as was verified through an inspection using a dial gauge. Such a good accuracy should lead to almost same field strengths between neighboring vanes. We measured the field strengths by using the perturbation method. The perturbator was a Bakelite plate (5.95 × 5.95 × 1.36 cm^3) with a hole (5.0 cm in diameter). The perturbator was positioned between vanes, as shown in Fig. 3. The longitudinal positions were the centers of the modules. The frequency shift were hence measured for twelve perturbator positions, 4 (azimuthal) × 3 (longitudinal). A field strength was evaluated by the square root of a frequency shift. For every module, we verified that the field strengths are same within ±1%.

In the above measurement the perturbator was so large that a frequency shift includes the contribution from the field near the edges of back plates, where the field is appreciably strong. In order to eliminate this contribution, we will conduct a more precise measurement: a smaller perturbator should be used and moved continuously in the axial direction.

Acknowledgments

The SCRFQ work is supported in various aspects by the High Energy Physics Division and the Accelerator Research Division of INS. The cavity was fabricated by Sumitomo Heavy Industries, Ltd., and the experiments reported here were performed with help of their staff in Niihama. The computer works were carried out on FACOM M780 in the INS Computer Room.

References

1. R. Müller, *Layout of a High–Intensity Linac for Very Heavy Ions with R.F. Quadrupole Focusing*, GSI–Report 79–7, 1979.
2. R. Müller *et al.*, *Experimental Results with a Very–Heavy–Ion RFQ Accelerating Structure*, Proc. 1984 Linear Accelerator Conf., Seeheim, FRG, May, 1984.
3. J. Jacoby *et al.*, *RFQ–Experiments with Intense Heavy–Ion Beams*, Proc. Int. Symp. Heavy Ion Inertial Fusion, GSI, Darmstadt, FRG, June, 1988.
4. S. Arai, *Split Coaxial RFQ Structure with Modulated Vanes*, GSI–Report 83–11, 1983.
5. N. Tokuda *et al.*, *Acceleration Performance of a 50–MHz Split Coaxial RFQ and the Design of a 25.5–MHz Prototype*, Proc. 1989 Particle Accelerator Conference, Chicago, USA, March, 1989.
6. S. Arai *et al.*, *Design Study of a 25.5–MHz Split Coaxial RFQ*, Proc. 14th Int. Conf. High–Energy Accelerators, Tsukuba, Ibaraki, Japan, Aug., 1989.
7. S. Arai, *Analysis of a Multi–Module Split Coaxial RFQ*, INS–T–464, 1986.
8. N. Tokuda *et al.*, *Development of a Split Coaxial RFQ Linac at INS*, Proc. 3rd Japan–China Joint Symp. Accelerators for Nuclear Science and Their Applications, RIKEN, Wako, Saitama, Japan, November, 1987.