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Abstract

A split coaxial RFQ (SCRFQ) is being developed for accelerating unstable nuclei with a charge-to-mass ratio larger than 1/60 from 1 to 170 keV/u in the JHP heavy-ion linac. The SCRFQ is equipped with modulated vanes to generate ideal quadrupole and accelerating fields. The fundamental problems on the SCRFQ have been clarified and solved through studies on a cold model, and the excellent accelerating performance has been confirmed by using a proton accelerating model working at 50 MHz. A 25.5-MHz prototype for the JHP SCRFQ is now under development. The prototype, 2.1 m in length and 0.9 m in diameter, will accelerate ions with a charge-to-mass ratio larger than 1/30 from 1 to 45 keV/u. Low-power tests conducted so far show that the prototype cavity has good rf characteristics.

1. Introduction

The acceleration of unstable nuclei (exotic nuclei) is planned in the Japanese Hadron Project (JHP) [1,2]. In order to accelerate unstable nuclei from 1 keV/u to 6.5 MeV/u, a heavy-ion linac complex has been designed. The layout of the linac complex is shown in Fig. 1, and principal parameters are listed in Table 1.

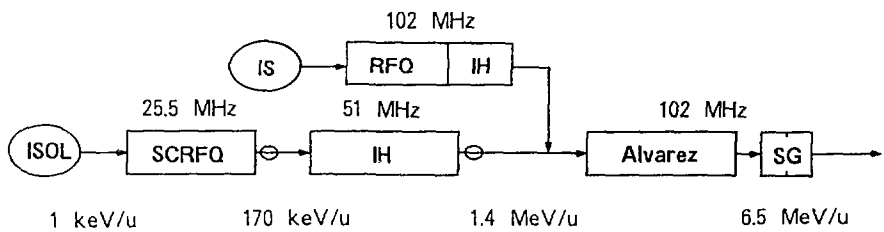

Fig. 1. System structure of the JHP heavy ion linac.

Table 1. Principal parameters of the JHP heavy-ion linac complex.

Output energy	0.17 ~ 6.5 MeV/u	Continuously
Intensity		
(unstable nuclei)	10^4~ 10^{12} ions/sec	Surface ionization, ECR, Plasma
(stable nuclei)	≤ 10^{15} ions/sec	ECR
Current limit	$0.047/(q/A)$ emA	Space charge limit in SCRFQ
Mass number	≤ 60	
Charge-to-mass ratio	≥ 1/60	Single-charged ions from ISOL
Beam emittance	0.6π mm·mrad	Normarized
Duty factor	10%	
Total accelerator length	~120 m	

Unstable nuclei will be produced by bombarding a thick target with an intense proton beam of 10 μA in average current from a 1-GeV linac. The nuclei vaporized from the target surface are ionized by an ion source of surface ionization type or plasma type. The ions with a single charge are preaccelerated up to 1 keV/u, and mass-analysed with an isotope separator on-line (ISOL). The ions passed through the ISOL are injected to the heavy-ion linac. The injection energy and the minimum charge-to-mass ratio (q/A) of the ions have been determined to be 1 keV/u and 1/60, respectively, by considering the technical feasibilities of the ISOL and the heavy-ion linac. As shown in Fig. 1, a main accelerator chain, which is used for unstable nuclei, is composed of a split-coaxial RFQ (SCRFQ), interdigital-H (IH) linacs, Alvarez ones, and single-gap cavities. Since the injection energy to the linac is very low ($v/c = 0.0015$) and the charge-to-mass ratio of the ions is very small ($q/A = 1/60$), we have chosen an SCRFQ as the front-end structure of the linac chain.

A merit of the RFQ is to enable to accelerate low-velocity particles with a good transmission efficiency because of its strong focusing. However, in case of accelerating ions with a q/A as small as 1/60, the RFQ must be operated at a low rf-frequency of 10 ~ 30 MHz. An SCRFQ is well suited for such an RFQ because the diameter of the cavity becomes small even at low frequency. The size of the JHP SCRFQ working at 25.5 MHz is compared with that of a four-vane RFQ at the same frequency in Fig. 2.

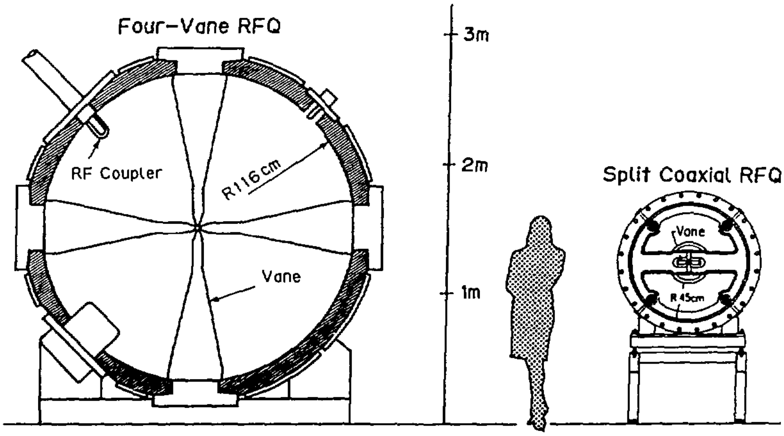

Fig. 2. Comparison between the sizes of 25.5-MHz RFQ's: the JHP SCRFQ and a four-vane RFQ.

The idea of the SCRFQ, using a split coaxial resonator as an RFQ cavity, was proposed by Müller [3] at GSI in the development of an RFQ for research of heavy-ion inertial fusion. At the present time, the SCRFQ at GSI is being operated to investigate the accelerating characteristics and to study the plasmas produced by intense heavy-ion beams [4,5]. In the RFQ, electrodes like drift tubes with focusing fingers are used to generate accelerating and focusing fields.

On the other hand, another type of SCRFQ with modulated vanes has been developed at INS since 1984 [6]. The features of our SCRFQ are summarized as follows: 1) it is equipped with modulated vanes, whose reliability has been confirmed through experience with many four-vane RFQ's; and 2) a multi-module cavity structure is employed to install easily and precisely the modulated vanes in the cavity. Through studies on a cold model and a proton accelerating model, we have proved that this type of SCRFQ has good rf characteristics, mechanical stability and acceleration performance [7,8]. On the basis of the results obtained so far, an SCRFQ prototype for the JHP heavy-ion linac is now under development. The cavity has been already completed and the cold test is being conducted [9].

2. Multi-module Split Coaxial Cavity

The concept of the multi-module split coaxial cavity has been created in the development of an SCRFQ with modulated vanes. The principle of the split coaxial resonator proposed by Müller is understood from the transformation of the $2 \times \lambda/4$ TEM cavity to the split coaxial cavity. Both electrodes of a re-entrant cavity are split into two diametrically opposed pieces, respectively, and a four-conductor quadrupole line is made by combining two pieces on one side with those on the other side, as illustrated in Fig. 3. The voltage difference between adjacent electrodes is almost flat along the beam axis, and the generated electric field is four-pole symmetry. Most important feature of the split coaxial resonator is to have larger inductance compared with other structures with same cavity radius, such as four-vane structure or 0-mode $\lambda/4$ structure.

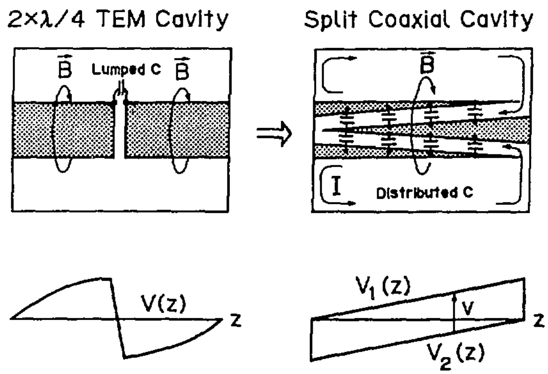

Fig. 3. Principle of a split coaxial resonator.

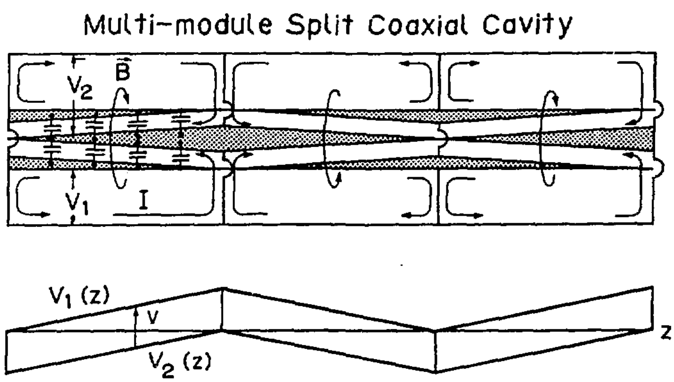

Fig. 4. Conceptual diagram of a multi-module split coaxial cavity resonator.

However, the split coaxial resonator has a structural defect that the long electrodes are supported only at one point on the end wall of the cavity, as seen in Fig. 3. Therefore, it is difficult to install the vanes directly to the above split coaxial resonator. Then, by connecting the split-coaxial resonators more than three, we have enabled to support the vanes at points more than two, as illustrated in Fig. 4. This structure is called a multi-module cavity structure: the whole cavity comprises several module cavities, and the vanes running through the whole cavity are supported at several points with good mechanical stability. We have thereby solved the problem, peculiar to the SCRFQ, how to align the electrodes (vanes in our case) precisely and firmly.

3. Studies on a Cold Model and a Proton Accelerating One

We have constructed a cold model and a proton accelerating one to examine fundamental problems on the INS-type SCRFQ and to evaluate its overall performance. The cold model, about 2 m in length and 0.4 m in diameter, consists of four-module cavities. The structure of the cold model is illustrated in Fig. 5.

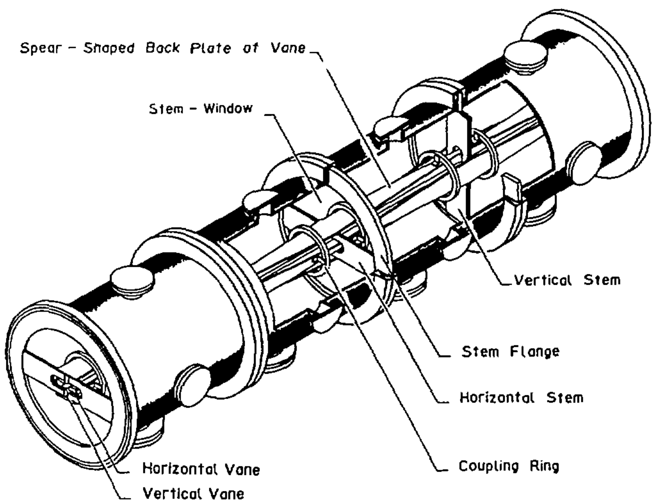

Fig 5. Structure of the cold model.

The cold model was equipped with flat vanes suitable for fundamental studies of the cavity resonator. Spear-shaped back plates are used to improve the uniformity of the current density of the inner conductor along the beam axis, and to strengthen the support of the vanes. Coupling rings are used to short opposite electrodes and to fix the distance between the opposite vanes precisely. The all parts of the cavity were made of brass.

The cold model was converted into a proton accelerating model working at 50 MHz, by replacing the flat vanes with modulated vanes. The main parameters are listed in Table 2. The inner structure consisted of modulated vanes, back-plates of the vanes, stems, and coupling rings; they were made of aluminium alloy. The cavity was not cooled with water because an rf power supplied to the cavity was only 27 watts in average. The unloaded Q-value was 2230 after rf conditioning. Beam acceleration tests were performed under the pulse operation with a duty factor of 10%. A proton beam with a pulse width of 0.1 ms were produced by a compact ion source of ECR type.

Following experimental results were obtained by using two models: 1) the cavity has good mode separation and good field stability; 2) the vane alignment was accomplished with an accuracy better than ±0.1 mm; 3) good field balances were obtained azimuthally and longitudinally owing to precise vane alignment (error of the azimuthal field balance is less than ±1% in the proton model); 4) a rough tuning of the resonant frequency of the cavity could be performed by changing the area of the stem-windows, defined in Fig. 5; and 5) low-current (~5 μA in peak) beam tests showed that the accelerating performance agreed well with a predicted one by PARMTEQ simulations.

Table 2. Main parameters of the proton accelerating model.

Frequency (f)	50	MHz
Kinetic energy (T)	2.00 → 59.6	keV
Normalized emittance (ε_N)	0.03	πcm·mrad
Intervane voltage (V)	2.9	kV
Focusing strength (B)	3.8	
Max. defocusing strength (Δ_b)	−0.075	
Synchronous phase (φ_s)	−90 → −30	deg
Max. modulation (m_{max})	2.48	
Number of cells (radial matcher)	168 (10)	
Vane length	205.19	cm
Mean bore radius (r_0)	0.541	cm
Min. bore radius (a_{min})	0.294	cm
Margin of bore radius (a_{min}/a_{beam})	1.15	
Transmission (design) (0.0 emA)	85	%
(0.1 emA)	76	%

As for the theoretical studies, following results were obtained: 1) an equivalent circuit model was developed to explain the dispersion relation between resonant frequency and harmonic number, and the longitudinal distribution of the inter-vane voltage in each mode; and 2) design method of the cavity structure was improved so that the resonant frequency could be predicted with an accuracy better than few percent.

4. Construction of a Prototype Model

Main parameters of the prototype model are summarized in Table 3 in comparison with those of the JHP SCRFQ. The prototype, 2.1 m in length and 0.9 m in diameter, comprises three-module cavities and will accelerate ions with a q/A larger than 1/30 from 1 to 45.4 keV/u. The main purpose of the construction is to obtain the know-how for practical use of SCRFQ. Issues to be studied are summarized as follows: 1) to examine the dynamic range of the inter-vane voltage, 2) to examine the cooling efficiency of the cavity in relation to the power level and the duty factor, 3) to evaluate the performance of the vanes made by two-dimensional cutting, and 4) to improve the cavity structure of the proton model for easier assembling and for high-power operation.

Table 3. Main parameters of the prototype model.

	JHP-machine	Prototype	
Frequency (f)	25.5	25.5	MHz
Charge-to-mass ratio (q/A)	≧1/60	≧1/30	
Kinetic energy (T)	1 → 170.2	1 → 45.4	keV/u
Normalized emittance (ε_N)	0.6	0.6	πmm·mrad
Vane length (L)	22.3	2.135	m
Number of cells	537	136	
Kilpatrick factor (f_K)	2.2	2.2	
Intervane voltage (V)	109.3	109.3	kV
Mean bore radius (r_0)	0.946	0.946	cm
Min. bore radius (a_{min})	0.618	0.521	cm
Margin of bore radius (a_{min}/a_{beam})	1.15	1.20	
Focusing strength (B)	3.0	6.0	
Limiting current (I_{lim})	3.0	2.5	mA

The GENRFQ method was used as a design principle of the beam dynamics to bunch a dc beam in a short distance quickly. Furthermore, the beam dynamics design was optimized so as to machine the vanes by using a two-dimensional cutting technique.

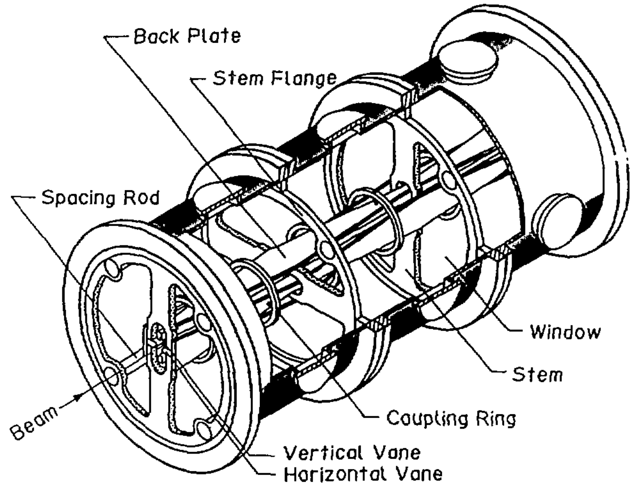

Fig. 6. Structure of the 25.5-MHz prototype model.

The structure of the prototype is shown in Fig. 6. The material of the tanks is mild steel plated with copper, and that of the inner structure except the vanes is oxygen-free copper. The vanes are made of chrome-copper alloy. Compared with the proton model, the cavity structure was improved at the following points: 1) water channels are installed for the high power operation (about 70 kW in peak, 10% in duty); and 2) the stems have been replaced with stem-flanges. The stem-flanges supporting the electrodes, consisting of the vanes and spear-shaped back plates, were arranged at equal distances by four spacing-rods. Hence, the inner structure was assembled precisely and firmly before installation into the cavity tanks. The module length was determined so as that the droop of the vanes due to the gravity might not exceed 35 μm. The diameter of the cavity was designed so as that the resonant frequency of 25.5 MHz is located between frequencies given by two cases: the semilunar windows of the stem-flanges are completely closed or open. Main geometrical and rf parameters are summarized in Table 4. As for the rf parameters, design values for the two cases are compared with measured ones after tuning of the cavity.

Table 4. Main geometrical and rf parameters of the prototype.

	DESIGN VALUES FOR TWO CASES		MEASURED ONES
	Closed windows	Open windows	After tuning
Resonant frequency	27.7 MHz	24.0 MHz	25.45 MHz
Number of modules	3	--	--
Tank length	210.0 cm	--	--
Inner diameter of tank	90.0 cm	--	--
Vane thickness	3.0 cm	--	--
Radius of inner-electrode	18.0 cm	--	--
Total capacitance	434 pF	--	454 pF
Total inductance	76.3 nH	101 nH	86 nH
Resonant resistance	142 kΩ	116 kΩ	84 kΩ
Unloaded Q-value	10700	7600	6100
Power loss (at 110kV)	43 kW	53 kW	66 kW

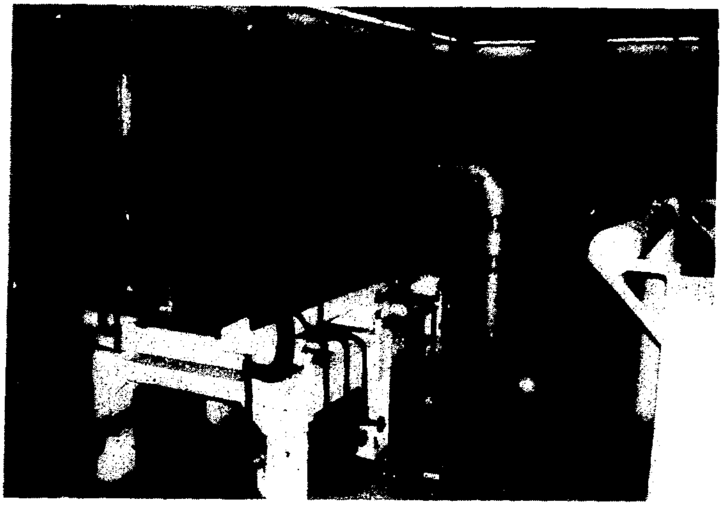

Fig. 7. The prototype model set in the experimental hall.

The cavity construction was completed at the end of 1989. Fig. 7 shows the cavity set in an experimental hall of INS. So far, low-power tests have been conducted for frequency tuning of the cavity, field-balance measurement and Q-value measurement. We have tuned the resonant frequency to 25.45 MHz by adjusting the area of the stem-flange windows. Fine tuning of the frequency to 25.50 MHz will be performed by using inductive tuners of cylindrical metal blocks. The unloaded Q-value was measured to be 6100 at frequency of 25.45 MHz whose value corresponded to about 80% of a calculation. Azimuthal field balance was measured by moving a dielectric perturbator, 10 mm in length and 20 mm in diameter, along the vanes used as a guide, as shown in Fig. 8. Four curves corresponding to inter-vane fields in each quadrant are drawn in the figure and they seem to be almost overlapping each other because the error of the field balance is very small. The resulting azimuthal imbalance were within ±1%.

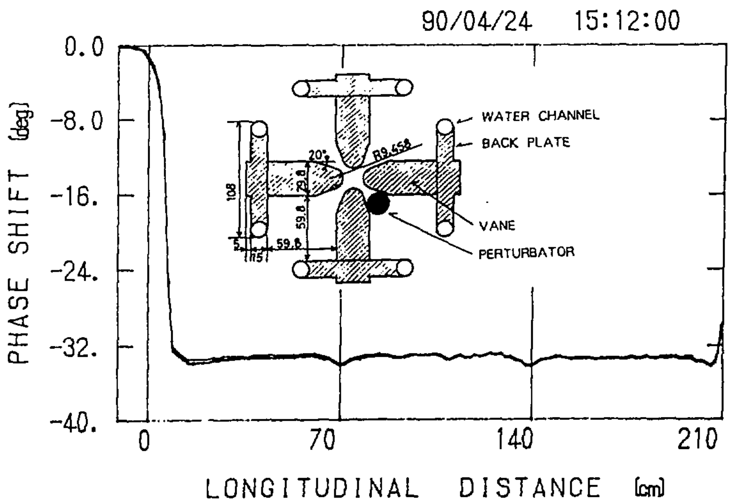

Fig. 8. Azimuthal field balance.

5. Summary

From the results obtained so far in our SCRFQ development, we conclude as follows: 1) the application of the vane-type electrode to an SCRFQ has become possible by employing a multi-module cavity structure, 2) the INS-type SCRFQ has good rf and mechanical characteristics, and 3) acceleration performance for a low-current beam agrees well with a designed performance. As for the development of the prototype, the cavity has been already completed, and it has been confirmed by the cold test that the rf characteristics agree approximately with the designed ones.

Acknowledgments

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