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DEVELOPMENT OF A SPLIT COAXIAL RFQ FOR THE JHP HEAVY ION LINAC

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ABSTRACT

A split coaxial RFQ (SCRFQ) is being developed as the front-end structure of the heavy-ion linac chain planned in the Japanese Hadron Project (JHP). The features of the INS SCRFQ is that four modulated vanes are installed and that the whole cavity comprises short module cavities. The fundamental problems concerning to the rf and mechanical characteristics were clarified and solved through studies with a cold model. This model was then converted to an accelerating model working at 50 MHz. Acceleration tests using a proton beam showd that the linac had the designed performance. A 25.5-MHz prototype for a JHP machine is now under development. The cavity, 2.1 m in length and 0.9 m in diameter, has been built, and will accelerate ions with a charge-to-mass ratio greater than 1/30 from 1 keV/u to 45 keV/u. From low-power tests so far conducted, we have found that the cavity has good rf characteristics.

1. INTRODUCTION

The heavy-ion linac chain planned in the Japanese Hadron Project (JHP) aims to accelerate radioactive nuclei (exotic nuclei) extracted from an isotope separator on-line (ISOL) from 1 keV/u to 6.5 MeV/u.[1,2] Since the injection energy is so low (v/c = 0.0015) and the ion's minimum charge-to-mass ratio is set at 1/60, an RFQ has been chosen as the front-end structure of the linac chain. The optimized operating frequency of an RFQ for such ions will be 10 ~ 30 MHz; therefore, a split coaxial RFQ (SCRFQ) is suitable for the RFQ, because the cavity diameter becomes small even at such low frequencies.

The principle of the split coaxial resonator was proposed by Müller at GSI.[3] A 1.5-m long SCRFQ with electrodes like drift tubes with focusing fingers was built in 1983.[4] At present, an SCRFQ, 9.5 m in length, is being operated to investigate problems on a high-intensity RFQ and to study plasmas produced by intense heavy ions, favorable drivers for heavy-ion inertial fusion.[5,6] On the other hand, another type of SCRFQ has been developed at INS since 1984.[7] The features of our SCRFQ are as follows: 1) modulated vanes, whose reliability has been verified through experience with

many four-vane RFQ's, are used; 2) a multi-module cavity structure is employed.[8] In the multi-module cavity structure, the vanes running through the whole cavity are supported at boundaries between modules, and hence the vanes have become more stable mechanically. We have thereby solved the problem, peculiar to the SCRFQ, how to align the inner electrodes (vanes in our case) precisely and firmly.

Through studies with a cold model and a 50-MHz proton accelerating model, we have proved that our SCRFQ structure has good rf characteristics, mechanical stability and acceleration performance.[8,9] On the basis of the results obtained with the models, a 25.5-MHz prototype for the JHP heavy-ion linac is now under development. The cavity construction has been completed, and low-power tests are going on.[10]

This paper surveys the layout of the heavy-ion linac complex in the JHP and describes experiments with the cold model and the proton accelerating model as well as preliminary results of low-power tests on the 25.5-MHz prototype.

2. OUTLINE OF THE JHP HEAVY-ION LINAC COMPLEX

The heavy ion linac complex planned in the JHP will accelerate radioactive nuclei as well as stable ones. The layout of the linac complex is shown in Fig. 1, and principal parameters are summarized in Table I.

Radioactive nuclei will be produced by bombarding a thick target with a high-intensity proton beam of 10 μA from a 1-GeV linac. The nuclei vaporized from the target surface are ionized, mass-analysed in an isotope separator on-line (ISOL), and injected to the heavy-ion linac chain. 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, considering the technical feasibilities of an ISOL and an SCRFQ.

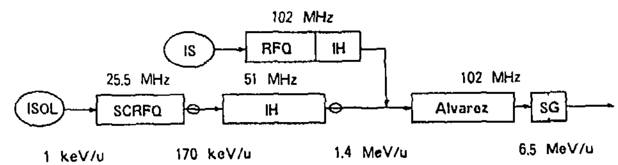

Fig. 1. Layout of the JHP heavy-ion linac complex. Strippers will be located at 170 keV/u and 1.4 MeV/u.

Main parameters of each accelerating structure are listed in Table 2. As shown in Fig. 1, the main stream of the linac chain is composed of a split-coaxial RFQ (SCRFQ), interdigital-H (IH) linacs, Alvarez ones, and single-gap cavities. The heaviest ion is nickel in the present design. Since the above accelerating structures are designed

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

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

Table 2. Main parameters of the accelerating structures.

Main Accelerator Chain

		SCRFQ	IH	Alvarez	Single Gap
Frequency	(MHz)	25.5	51	102	102
Energy	(MeV/u)	0.001 → 0.17	0.17 → 1.4	1.4 → 6.5	
Length	(m)	22	25	35	1.5
No. of tanks		1	5	6	2
Min. q/A		1/60	1/27	1/9	1/9
Heaviest ion*		$^{58}Ni^{+}$	Ni^{8+}	Ni^{17+}	Ni^{17+}
Synchronous phase	(deg)	−90 → −30	−30	−30	−90 ~ +90
Shunt imp. ZT^2	(MΩ/m)	9	50, 150	40	9
Accel. volt.	(MV)	10.1	12.3	18.0	±2.0
Rf power	(kW)	700	80	310	300

* Uranium ions could be accelerated with reinforced rf supplies.

Branch Accelerator Chain

		4-vane RFQ	IH
Frequency	(MHz)	102	102
Energy	(MeV/u)	0.008 → 0.8	0.8 → 1.4
Length	(m)	7	4
No. of tanks		1	1
Min. q/A		1/7	1/7
Synchronous phase	(deg)	−90 → −30	−30
Shunt imp. ZT^2	(MΩ/m)	27	150
Accel. volt.	(MV)	5.5	4.2
Rf power	(kW)	220	40

so as to enable to accelerate very heavy ions up to uranium, only the rf amplifiers should be increased for the acceleration of uranium. In parallel with the main stream, a branch stream consisting of a four-vane RFQ and an IH linac will be set to accelerate stable ions with q/A ≳ 1/7; the output beam is to be injected to the Alvarez linac in the main stream.

Nuclear physicists demand projectile energies ranging continuously from 0.17 to 6.5 MeV/u. The 51-MHz IH and the Alvarez linacs are accordingly divided into short tanks: five IH tanks and six Alvarez ones. By switching off rf powers to tanks, we can change the beam energy at the Alvarez output, but only discretely. In order to smoothen the energy, two single gap cavities will be used.

3. DEVELOPMENT OF THE SCRFQ WITH MODULATED VANES

3.1 Study on a Cold Model

As the first step of the development, a cold model with flat (unmodulated) vanes was constructed to investigate the mechanical and rf characteristics. The model, about 2 m in length and 0.4 m in diameter, consists of four module-cavities. All parts of the cavity were made of brass. The structure of the model is illustrated in Fig. 2.

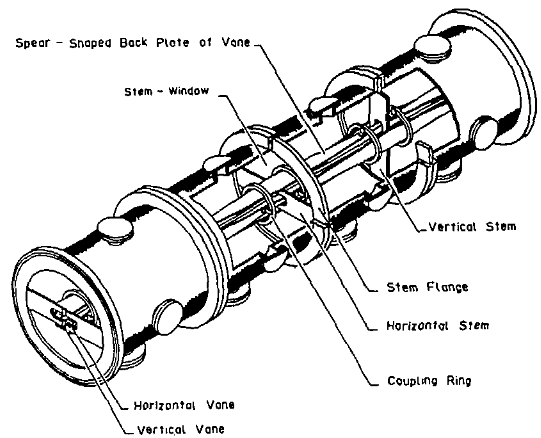

Fig. 2. Structure of the cold model.

The mechanical characteristics were examined through the fabrication, assembling of the parts, and measurement of the accuracy of the vane alignment. The most important issue was whether a satisfactory accuracy of the vane alignment might be attained in our structure. The accuracy was estimated to be better than ±0.1 mm from a measurement of the azimuthal field imbalance. For every quadrants the field strength between neighboring vanes was measured over the vane length, and the resulting field imbalance was ±2.5%.

On the other hand, the rf characteristics were investigated experimentally and theoretically. From experiments on tuning of the resonant frequency, we found that a rough tuning could be performed by changing the areas of the stem-windows (see Fig. 2). The inductance that determines the resonant frequency is remarkably affected by the width of the stems, on which electric current flows. The resonant frequency was 37.1 MHz when the stem windows are open; when closed completely, it increased to 41.8 MHz.

The dispersion characteristics of the resonance modes were measured to examine the mode separation between the fundamental and higher modes. The left figure in Fig. 3 shows the measured profiles of the intervane voltages of various modes (the vertical scale is proportional to the square of the voltage). The flat curve indicates the distribution for the fundamental mode, used for acceleration and focusing. The

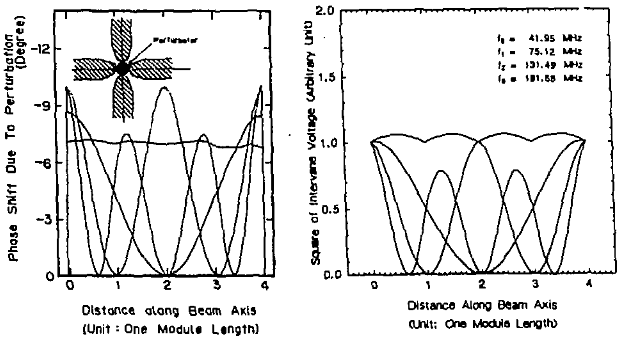

Fig. 3. Intervane voltage distributions for various harmonics. The left figure shows the experimental result, and the right the theoretical one.

flatness of the intervane voltage was within ±2%. The frequency of this mode was f_0 = 41.76 MHz, well separated from the ones of the higher harmonics: f_1 = 76.27 MHz, f_2 = 132.88 MHz, and f_3 = 187.97 MHz. The right in Fig. 3 shows the prediction from an equivalent circuit analysis. The theory explains well the resonant frequencies and voltage distributions of the harmonics.

3.2 Study on a Proton Accelerating Model

As the second step, a proton accelerating model working at 50 MHz was constructed to evaluate the overall performance of the INS-type split coaxial RFQ. The main parameters are listed in Table 3.

The above cold model was converted to the accelerating model by replacing the flat vanes with modulated vanes. The whole inner structure, consisting of the vanes, back-plates and stems, were replaced with new ones made of aluminum alloy. The cavity was not cooled with water because of the low rf power level: an average power of 27 W (270 W in peak) was supplied in the proton acceleration to be described below. The vanes were aligned with an accuracy better than ±0.1 mm, and the field measurement showed that the azimuthal field imbalance was less than ±1%. The unloaded Q-value was 2230, corresponding to a resonant resistance of 18.3 kΩ.

Beam acceleration tests were performed under a pulse operation with a duty factor of 10%. Proton beam with a pulse width of 0.1 ms were extracted from a compact ion source of ECR type. The typical beam current was about 5 μA in peak. The beam was matched to the RFQ acceptance by means of an ion-separator magnet and two

Table 3. Main parameters of the proton accelerating model.

Frequency (f)		50 MHz
Kinetic energy (T)		2.00 → 59.6 keV
Normalized emittance (ε_n)		0.3 π mm·mrad
Intervane voltage (V_{VV})		29 kV
Focusing strength (B)		3.8
Max. defocusing strength (Δ_b)		−0.075
Synchronous phase (φ_s)		−90° → −30°
Max. modulation (m_{max})		2.48
No. of cells		169
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	(0 mA input)	85 %
	(0.1 mA input)	76 %
	(0.2 mA input)	62 %

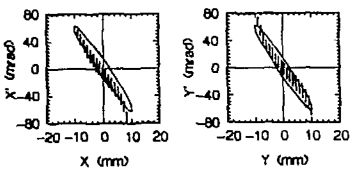

Fig. 4. Input beam emittances. The bars indicate measured profiles, and the ellipses the designed acceptance of $\varepsilon_n = 0.3\pi$ mm·mrad.

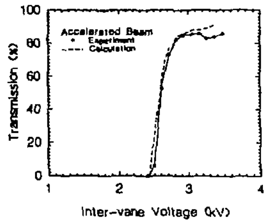

Fig. 5. Transmission efficiencies as functions of the intervane voltage, whose designed value is 2.9 kV.

Einzel-lens doublets. By injecting a beam with emittances shown in Fig. 4, we measured transmission efficiencies as a function of the rf voltage. The result is shown in Fig. 5. The transmission efficiency was 84% at the design voltage of 2.9 kV, and the measured efficiencies agreed well with the result of a PARMTEQ simulation. Both of the output-beam emittances and energy profile agreed with PARMTEQ predictions.

3.3 Construction of a Prototype Model

Main parameters of the prototype model are summarized in Table 4 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 q/A larger than

Table 4. Main parameters of the 25.5-MHz prototype SCRFQ and the JHF machine.

	JHF	prototype	
Frequency (f)	25.5	25.5	MHz
Charge-to-mass ratio (q/A)	≥ 1/60	≥ 1/30	
Kinetic energy ($T_{in} \to T_{out}$)	1 → 170.2	1 → 45.4	keV/u
Normalized emittance (ε_n)	0.6 π	0.6 π	mm·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_{VV})	109.3	109.3	kV
Mean bore radius (r_0)	0.946	0.946	cm
Minimum 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	emA

1/30 from 1 to 45.4 keV/u. The beam dynamics design was performed under the condition that the operation frequency, injection beam energy, beam emittance, maximum intervane voltage and mean bore radius were same as those of the JHP machine except the minimum q/A. When the prototype designed under this condition is constructed, the experimental results will be applicable to the JHP machine ($q/A \geq 1/60$), because the rf characteristics are same as those of the JHP machine.

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 is oxygen-free copper except chrome-copper alloy for the vanes. The structure of the accelerating model was improved as follows: water channels are installed for high power operation (about 70 kW in peak, 10% in duty); and the stems in the proton model have been replaced with stem-flanges. The stem-flanges, supporting the electrodes (the vanes and the back plates), are connected to each other by four spacing rods. Hence the inner structure can be assembled precisely and firmly before its installation into the cavity cylinder.

The module length was determined at 70 cm so that the droop of the vanes caused by the gravity might be less than 35 μm. For the fixed module length, resonant frequencies were calculated for two cases: the all windows are closed or open. The result is shown in Fig. 7. The two curves indicate the upper and lower limit of the frequency range adjustable by changing the window areas of the stem-flanges. The cavity diameter was fixed at 90 cm, because the aimed frequency of 25.5 MHz lies near the center of the adjustable frequency range.

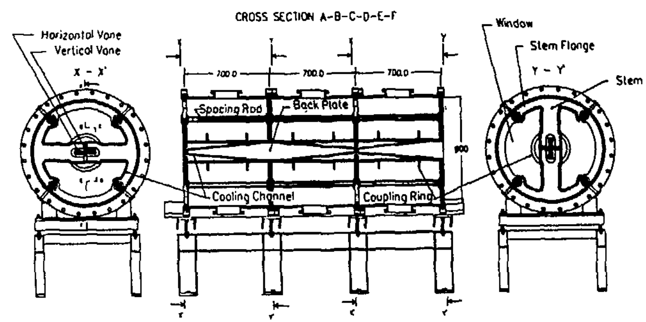

Fig. 6. Structure of the 25.5-MHz prototype.

The cavity construction was completed in the fall of 1989, and we are now conducting low-power tests: frequency tuning of the cavity, Q-value measurement, and field-balance 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 the designed value of 25.50 MHz will be performed by using cylindrical inductive tuners; we have experimentally checked that the frequency increment by 50 kHz is easy. The unloaded Q-value measured 6100 at the frequency of 25.45 MHz; this Q-value corresponded to about 80% of a calculated value. Azimuthal field balance was measured by passing a dielectric perturbator, 5 mm in length and 10 mm in diameter, through the gaps between vanes. From the result shown in Fig. 8, field strengths in the quadrants are same within ±2.5%, and the intervane voltage is estimated to be almost flat over the vane length.

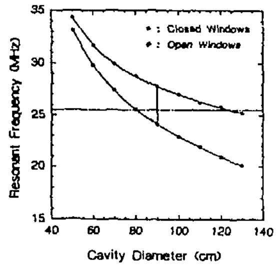

Fig. 7. Calculated relation of the resonant frequency to the cavity diameter. The optimized cavity diameter is 90 cm for the design frequency of 25.5 MHz.

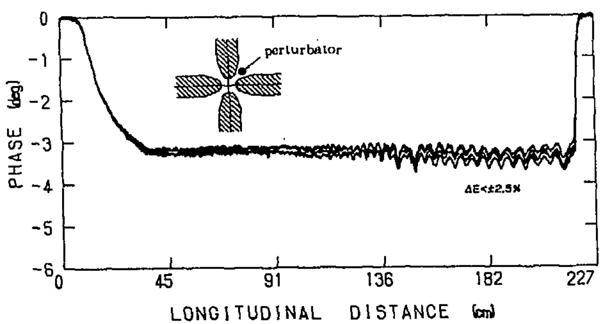

Fig. 8. Measured azimuthal field balance among the quadrants. The phase shift (vertical scale) is proportional to (field strength)^2.

4. SUMMARY

From the results obtained with the cold model and the proton accelerating model, we conclude as follows: 1) application of the modulated vanes to an SCRFQ has become possible by employing a multi-module cavity structure; 2) the INS-type SCRFQ has good rf and mechanical characteristics; 3) acceleration performance for a low-current beam agrees well with the designed performance. As for the 25.5-MHz prototype, the cavity has been already constructed, and it has been comfirmed through cold tests that the rf characteristics agree approximately with the designed ones. Soon after finishing cold-tests for more detailed data, we will conduct high-power tests and then accelerate heavy ions, say N_2^+.

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