RF-DESIGN AND CONSTRUCTION OF NEW LINAC INJECTOR FOR RIKEN RI-BEAM FACTORY

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Abstract

A new linac injector, which will be exclusively used for the RIKEN RI-Beam Factory, has been constructed to increase the beam intensity of very heavy ions such as xenon and uranium. The injector system consists of a superconducting ECR ion source, RFQ linac, three DTLs, and beam transport system including strong quadrupole magnets and beam bunchers. Two DTL resonators were newly designed while existing devices including the RFQ were modified to the other resonators. Direct coupling scheme was adopted for the rf-sytems of the DTLs, where the design study was successfully performed by using the MWS code. This paper focuses on the design procedure of the RFQ and DTLs as well as the results of their high power tests.

INTRODUCTION

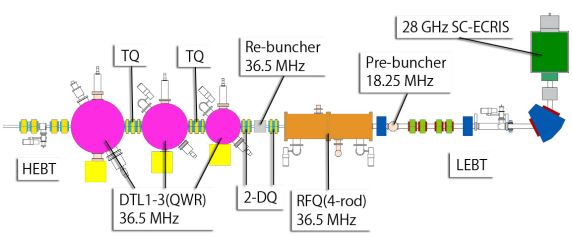

Figure 1: Schematic-layout view of the RILAC2.

A new additional linac injector called RILAC2 has been constructed at the RIKEN Nishina Center so that beam intensity can be increased drastically and RIBF [1] experiments and synthesis of super-heavy element [2] can be carried out independently. As shown in Fig. 1, the RILAC2 consists of a 28-GHz superconducting ECR ion source [3], a low-energy beam transport (LEBT) including a pre-buncher, a four-rod RFQ linac, three drift-tube linac tanks (DTL1-3), a rebuncher between the RFQ and DTL1, a high-energy beam transport (HEBT) from the DTL3 to the RIKEN Ring Cyclotron (RRC) [4], and strong quadrupole magnets that were placed between the rf resonators for the transverse focusing. Another rebuncher is required in the HEBT to focus the longitudinal phase spread at the injection of RRC by a combination of the rebuncher and an existing one. Very heavy ions with mass-to-charge ratio (m/q) of 7, such as $^{136}Xe^{20+}$ and $^{238}U^{35+}$, are accelerated up to an energy of 680 keV/u in the cw mode and injected into the RRC without charge stripping. The rf resonators excluding the pre-buncher are operated at a fixed rf frequency of 36.5 MHz, whereas the pre-buncher is operated at 18.25 MHz. The basic design of the RILAC2 was finished in 2006 [5], and their rf-design has started since the budget was approved at the end of FY2008.

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MODIFICATION OF RFQ LINAC

To save construction cost, we decided to recycle a four-rod RFQ linac which was originally developed by Nissin Electric Co. Ltd. in 1993 [6]. In November 2007, the RFQ system was transferred to RIKEN through the courtesy of the Advanced Research Center for Beam Science, Kyoto University. The RFQ linac can accelerate heavy ions with an m/q of 16 up to 84 keV/u in the cw mode with an rf frequency of 33.3 MHz. The maximum rf input power was designed to be 50 kW(cw). If the RFQ resonator is so modified to have an resonant frequency of 36.5 MHz, ions with an m/q of 7 can be accelerated to 100 keV/u for RILAC2 without changing the vane electrodes. The intervane voltage required for RILAC2 is 42 kV, which is less than the originally designed value of 55 kV. The basic parameters corresponding to the RFQ linac after the conversion are listed in Table 1; the parameter values were obtained by scaling the original values.

Table 1: Basic Parameters Corresponding to RFQ Linac

Frequency (MHz)	36.5
Duty (%)	100
m/q ratio	7
Input energy (keV/u)	3.28
Output energy (keV/u)	100.3
Input emittance (mm·mrad)	200π
Vane length (cm)	225.6
Intervane voltage (kV)	42.0
Mean aperture (r_0:mm)	8.0
Max. modulation (m)	2.35
Focusing strength (B)	6.785
Final synchronous phase (deg.)	-29.6
Unloaded Q	4500 (MWS)
Shunt impedance (kΩ)	63 (MWS)
Required rf power (kW)	17.5 (80%-Q)

For modification of the resonant frequency, we inserted a block tuner into the gaps between the posts supporting the vane electrodes. The size of the block tuner was optimized by 3D electromagnetic calculations using the computer code Microwave Studio 2009 (MWS) and rf measurements using cold-model test pieces made of aluminum. The block dimensions were determined to be 240 mm × 260 mm × 114 mm. The rf power required to excite the rated voltage of 42 kV was evaluated to be 17.5 kW by taking into account 80% derating of the shunt impedance (63 kΩ) determined by the MWS calculation. The maximum output power (40 kW) of the new final amplifier was sufficient for operating the modified RFQ resonator.

The heat load distribution was also evaluated by MWS calculations to decide the cooling conditions. The maximum current density in the block was 32 A/cm, which was sufficiently small. The total heat load estimated for the five blocks was approximately 2.1 kW at the input power of 17.5 kW. The size of the cooling water channel was so chosen that the flow rate of water was approximately 16 L/min; at this flow rate, the water temperature increases only by 2 °C. The cooling capacity was found to be sufficiently high if the value of the shunt impedance degraded to 70%. The block tuner was made of oxygen-free copper; three types of blocks were required by the mounting position. The blocks were mounted on a base with an rf contact provided by coil springs. The water channels in the blocks were connected in series by copper pipes. Figure 2 shows the internal structure of the RFQ linac after mounting the block tuner and water pipe.

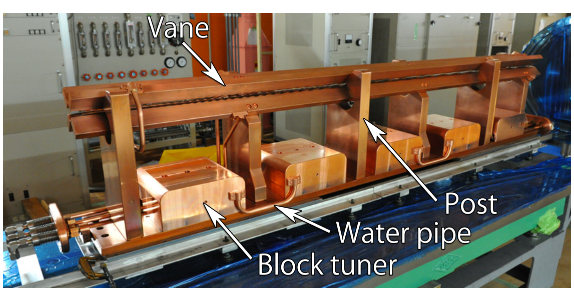

Figure 2: Internal structure of RFQ after mounting the block tuner.

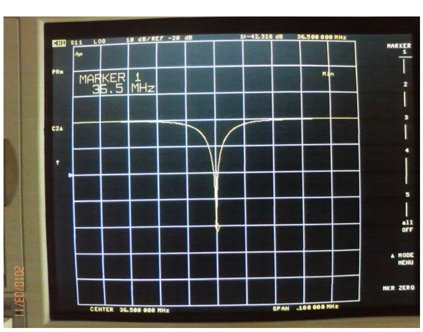

Figure 3: S11 plot measured for RFQ.

A low-power test was performed to evaluate the rf characteristics, and the resonant frequency was found to be changed to 36.5 MHz successfully as shown in Fig. 3. Vacuum level reached 8×10^{-6} Pa with the cooling-water flow. A power amplifier, low-level circuits, and control system for the RFQ were installed and dummy-load test was performed in March 2010. After relocating the resonator of RFQ linac to the AVF-cyclotron vault and connecting the electric-wires and water-pipes, a high-power test was performed in August 2010, and excitation with the rated voltage of 42 kV has been attained successfully.

RF-DESIGN AND CONSTRUCTION OF DRIFT-TUBE LINAC

The structure of DTL is based on a quarter-wavelength coaxial-cavity. Two resonators (DTL1 and 2) were newly designed while the DTL3 was obtained by modifying a decelerator resonator that was developed for a Charge-State-Multiplier system [7]. Table 2 shows the design parameters of DTL. The maximum electric field was kept below 1.2 Kilpatrick. The cavity dimensions were determined by MWS calculations to optimize the rf characteristics. The length of the stem was decided to reduce the asymmetry of the electric field distribution between the gaps.

Table 2: Design Parameters of Three DTL Tanks

	DTL1	DTL2	DTL3
Frequency (MHz)	36.5	36.5	36.5
Duty (%)	100	100	100
m/q ratio	7	7	7
Input energy (keV/u)	100	220	450
Output energy (keV/u)	220	450	680
Cavity diameter (m)	0.8	1.1	1.3
Cavity height (m)	1.32	1.43	1.89
Gap number	10	10	8
Gap length (mm)	20	50	65
Gap voltage (kV)	110	210	260
Drift-tube aperture (mm)	17.5	17.5	17.5
Peak surface field (MV/m)	8.9	9.4	9.7
Synchronous phase (deg.)	-25	-25	-25
Max. power of amp. (kW)	25	40	40

In order to reduce the construction cost and the space occupied by the equipments, a direct coupling scheme was adopted for the rf amplifier. A plate electrode of a tetrode 4CW50000E was directly connected to the capacitive coupler, which was mounted on the cavity. When the coupler and tetrode were connected to the cavity, the resonant frequency decreased because of their series/parallel capacitance. Thus, we had to set the design-target frequency of the cavity such that this decrease in the resonant frequency was compensated. To estimate the decrease in the frequency, at first, modification of the DTL3 was performed by changing the drift-tubes and stems, and rf characteristics were measured with using an original 50-Ω coupler.

The measurement results were compared with the results of MWS calculations which took into account the 50-Ω coupler or the direct coupler, The decrease in the frequency was evaluated to be -225 kHz for using the direct coupler. Including other effect, the cavity length of the DTL3 was determined to actualize the target frequency of 36.6 MHz. A design of DTL1 and 2 was performed only by the MWS calculations based on the experience on DTL3. A target frequency was set to be 36.725 MHz for both DTL1 and 2 including the error of MWS calculations.

The coupler was designed such that the load impedance could be adjusted to approximately 700-1000 + $j0$ Ω with using the tetrode. At first, the coupler position where an impedance was matched to 50 Ω was determined for each cavity by calculating external Q-factor [8] and comparing it with unloaded Q-factor. The result was also compared with the measured one by the DTL3, where the measurement was performed with changing the position of the original coupler so as to reproduce the load impedance, and the calculated position was scaled for the direct coupler by f-matrix calculations. The radius of the coupler electrode were determined by comparing the MWS calculations using a frequency-domain solver on a Smith chart.

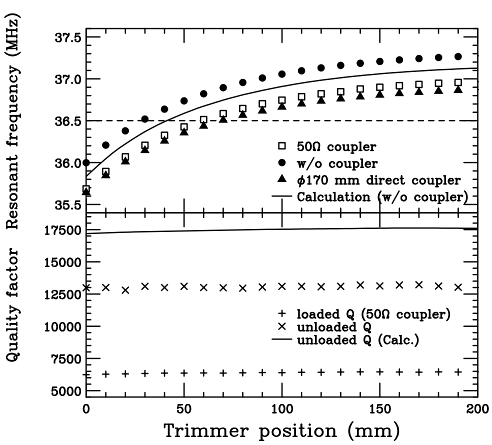

Figure 4: Frequency response of DTL1 as a function of trimmer position.

After fabricating the DTL, a low-power test was performed immediately. Figure 4 indicates the results of the low-power test measurements for the DTL1. The frequency response as a function of trimmer position is plotted in the upper panel. The lower panel presents the quality factors. As shown in the figure, an operation frequency of 36.5 MHz was achieved at the trimmer position of 68 mm by using a direct coupler for the DTL1, that is consistent with the results of MWS calculation. The DTL2 and 3 were also successfully constructed for the operation frequency of 36.5 MHz. The electric-field distribution along the beam axis was measured using a TiO_2 bead by the perturbation method. The results of phase variations for the DTL1 are plotted in Fig. 5. The measured rf characteristics of the DTL are listed in Table 3.

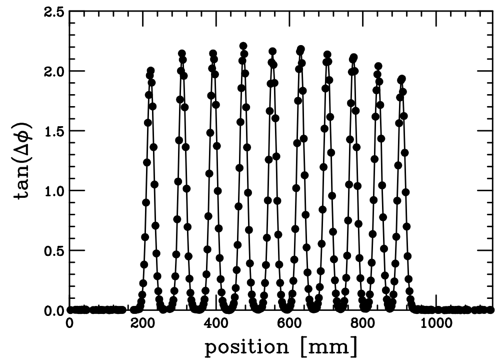

Figure 5: Measurement result of electric-field distribution for DTL1.

Table 3: Measured Rf Characteristics of DTL

	DTL1	DTL2	DTL3
Unloaded Q	13000	20350	22500
Shunt impedance (MΩ)	0.94	1.65	1.72
Effect. shunt imp. (MΩ/m)	135	176	102
Required rf power (kW)	6.5	13.4	19.6

A high-power test was performed with a load impedance setting of 700-1000 Ω depending on the tank. After one day of conditioning, the rated voltages were successfully achieved for every tank. The DTL were installed in the AVF-cyclotron vault in February 2010 and high-power test was performed again.

OUTLOOK

The 28-GHz SC-ECRIS has been installed and cooled. Beam test will be performed before long. The RFQ linac, LEBT, and HEBT are being aligned to the beam line now. Beam diagnosis and control system are also preparing. Two rebunchers are in fabrication. Further conditioning and retunes for the DLT are performed to improve the long-term stability. We plan to start the beam commissioning of the RILAC2 in December 2010.

REFERENCES

[1] Y. Yano, Nucl. Instr. Meth. B 261 (2007) 1009.

[2] K. Morita et al., J. Phys. Soc. Jpn. 73 (2004) 2593.

[3] T. Nakagawa et al., Rev. Sci. Instrum. 79, 02A327 (2008).

[4] Y. Yano, Proc. 13th Int. Cyclo. Conf., 102 (1992).

[5] O. Kamigaito et al., Proc. of PASJ3-LAM31, 502 (2006).

[6] H. Fujisawa, Nucl. Instrum. Meth. A 345 (1994) 23.

[7] O. Kamigaito et al., Rev. Sci. Instrum. 76, 013306 (2005).

[8] O. Kamigaito, Phys. Rev. ST Accel. Beams 9, 062003 (2006).