UPGRADE OF RIKEN HEAVY-ION LINAC FOR NUCLEAR PHYSICS EXPERIMENTS

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Abstract

The RIKEN heavy-ion linac has been upgraded for nuclear physics experiments, by adding six booster cavities followed by a new beam line with six experimental courses. Intense beams of heavy ions having mass-to-charge ratio of less than 5.6 will be accelerated up to 5.8 MeV/u. The booster can be also used to extend the energy range of the ring cyclotron for the ion beams of medium-heavy elements. Acceleration tests have been carried out since May 2001.

1 INTRODUCTION

The RIKEN heavy-ion linac (RILAC) has been used for the low-energy experiments mainly in the field of atomic physics, as well as for an injector to the K540 MeV ring cyclotron (RRC) for more than fifteen years. By varying the rf frequency from 17 to 40 MHz, the RILAC accelerates various kinds of ions up to 4 MeV/u at maximum.

In the RI-beam factory project, a system called "charge-state multiplier (CSM)" has been proposed to extend the energy range of heavy-ion beams[1]. It is a combination of a booster linac, a charge stripper and a decelerator linac, which is placed between the RILAC and the RRC. By use of this system, the most probable charge-state of the beam after the stripper is shifted upwards, and the beam energy from the RRC can be extended to a higher value than that obtained with the present stripper.

The design study of the CSM started in 1997. Two years later, three cavities of the low energy part were constructed, which have shown good rf characteristics such as a wide variability of the frequency and high *Q*-values[2].

In 1999, construction of the booster cavities of the high-energy part started, prior to making the full structure of the CSM. The aim of this decision is to initiate the experiments as soon as possible, using very intense beams from the booster with energies around the coulomb barrier of atomic nuclei.

2 CSM CAVITIES

2.1 Design Parameters

The conceptual drawing of the CSM is given in Fig. 1. It firstly accelerates the ion beams from the RILAC to increase the stripping energy, and then decelerate the stripped ions down to the initial energy, as mentioned above. The total accelerating voltage required for the booster is 16 MV and that for the decelerator is 8 MV.

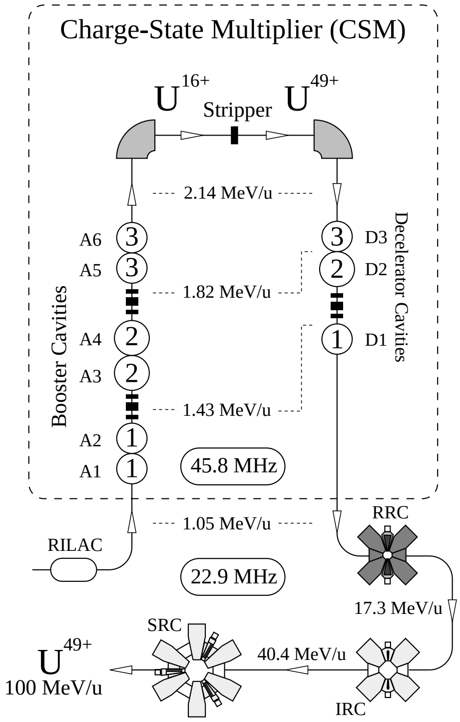

Figure 1: Conceptual drawing of the CSM. The cavities are represented by open circles. The numbers in the circles indicate the "unit" of the CSM. The energy and frequency are chosen for the uranium acceleration up to 100 MeV/u after the SRC, as an example. The stripping efficiency in the CSM is 12 % in this case.

The booster and decelerator of the CSM are divided into three "units", each of which contains two rf cavities of the booster and one cavity of the decelerator, as shown in Fig. 1. The acceptable mass-to-charge ratio (*A/q*) of the booster was chosen to be the same as that of the RILAC; using the CSM frequency *f*, *A/q* of the booster is expressed as $A/q=32{,}000/f^2$. On the other hand, that for the decelerator is given by $A/q=16{,}000/f^2$.

The input and output energies of each cavity are proportional to the square of the frequency. Table 1 summarizes the coefficients of this relationship. The number of gaps of the third-unit cavities is chosen to be six so that the cavity length can be made less than 1.3 m.

Table 1: Design parameters of the cavities.

Cavity	C_{in} [a)]	C_{out} [b)]	V_{gap} (kV)	L_{gap} (mm)	gap	ϕ_s (deg)
A1	5.00	5.88	450	80	8	-25
A2	5.88	6.78	450	87	8	-25
D1	6.78	5.00	450	83	8	-155
A3	6.78	7.71	470	93	8	-25
A4	7.71	8.65	470	99	8	-25
D2	8.65	6.78	470	96	8	-155
A5	8.65	9.40	500	104	6	-25
A6	9.40	10.16	500	108	6	-25
D3	10.16	8.65	500	106	6	-155

a) The input energy is given by
E_{in} (MeV/u) = $C_{in} \times f^2 \times 10^{-4}$,
where f is the CSM frequency in MHz.
b) Same as a) but for the output energy.

The required gap voltages are approximately 500 kV, as shown in Table 1.

2.2 Cavity Structure

The designed structure of the cavities is based on the quarter-wavelength resonator with a movable shorting plate. Each cavity in the same unit has the same shape and dimensions except for the drift tubes. There is no focusing element in the drift tubes, which helps to reduce the rf power losses.

Using the computer code MAFIA, the dimensions were optimized so that the frequency range from 36 to 76.4 MHz could be covered. However, the cavities in the high-energy units (A3 – A6) were constructed only partially; it is sufficient to make the lower parts to get the maximum beam energy required for our purpose. They are operated at a fixed frequency of 75.5 MHz.

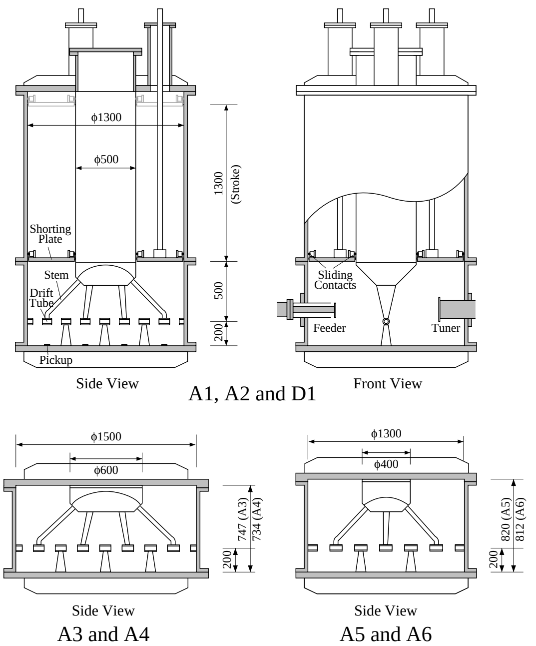

Figure 2: Schematic drawing of the CSM cavities.

Almost all the components are made of oxygen-free copper. The base plates are made of steel and plated with copper by 50 μm. The drift tubes have an inner diameter of 35 mm and an outer diameter of 55 mm. They are aligned within an accuracy of +/- 0.15 mm. Every cavity-wall in the high-energy units is cut from a single piece of copper block in order to avoid possible vacuum leakage and to keep the machining accuracy.

The water channels are arranged based on the heat analyses. The total water flow per cavity is 600 l/min. Each cavity is equipped with a turbomolecular pump of 520 l/s and a cryogenic pump of 4000 l/s. The vacuum stays in the range of 0.5 – 1.0 $\times 10^{-7}$ Torr in the cw-mode operation.

Table 2: Rf characteristics of the cavities

Cavity	f (MHz)	Q-value	Qratio [a)]	P [b)] (kW)
A1	76.4 - 36.0	19,000 – 22,700	0.64 – 0.72	80 – 63
A2	76.4 - 36.0	18,500 – 22,500	0.64 – 0.72	86 – 64
D1	76.4 - 36.0	18,600 – 22,600	0.63 – 0.73	84 – 62
A3	75.5	25,000	0.78	67
A4	75.5	24,200	0.78	72
A5	75.5	23,700	0.76	63
A6	75.5	23,100	0.77	67

a) Ratio of the measured Q-value to the calculated one.
b) Power loss estimated at the maximum gap voltage given in Table 1.

2.3 Rf Aspects

Table 2 summarizes the rf characteristics of the cavities. From the measurement, it was found that the measured frequencies are greater than the predicted values by the MAFIA code by 3 %. The measured Q-values are 60 - 80 % of the calculated ones, which is considerably good in spite of the complicated structure of the cavities. One of the reasons for this is that we have inserted rf contacts of spring type into every joint between metallic components. The estimated power losses per cavity are 60 - 90 kW at maximum.

High-power tests of the cavities have been performed since September 2000, using the power amplifier of 100 kW[3]. So far, 70 % of the maximum voltage has been achieved in the cw-mode operation without any significant problems.

3 BEAM LINE[4]

The beam line in the RILAC facility has been completely replaced by a new transport system as shown in Fig. 3. It has one main line, transferring the beam from the RILAC to the RRC through the CSM, and six branches (e1 - e6 in Fig.3) for various experiments.

Four quadrupole triplets (TQ1 – TQ4 in Fig. 3) have been constructed and placed next to the booster cavities, for which high field-gradient of 25 T/m is required to focus the beam against the strong defocusing effects of the rf cavities. Every quadrupole magnet of them is also provided with a steering function by applying different currents to the four individual poles.

An important feature of the main line is the “e”-shaped magnet array, which provides achromatic and isochronous transport from the stripper to the entrance of the decelerator cavity (D1). Owing to these characters, complicated coupling between the longitudinal and the horizontal motion of the beam can be eliminated. Three dipole magnets, indicated by BM90, SW, and BM85 in Fig. 3, were newly fabricated, which produce the maximum magnetic field of 1.6 T in the pole gap of 60 mm.

Among the six beam lines, the e3 beam line is dedicated for the gas-filled recoil isotope separator (GARIS), where the experiments of search for super-heavy elements will be carried out.

4 PRESENT STATUS

The first beam test of the booster was performed using a carbon beam on May 22, 2001. So far, carbon beams have been accelerated up to 5.8 MeV/u with an intensity of one particle-micro-ampere. When the boosters are fully excited at the maximum voltage, the ion beams having mass-to-charge ratio of less than 5.6 will be accelerated up to that energy.

The booster is also applicable for the extension of the beam energy from the RRC, because the harmonic number in the RRC can be increased to 8 and 7 from the present value of 9. For example, a krypton beam of 66 MeV/u will become available when we use the A1 and A2 cavities. The decelerator cavity would be useful for that purpose, because the stripping efficiency is very sensitive to the beam energy in this energy region.

5 ACKNOWLEDGMENT

The fabrication and heat analyses of the cavities, as well as the design and fabrication of the rf amplifiers, were done by Sumitomo Heavy Industries, Ltd.. The dipole magnets and the quadrupole triplets were fabricated by TOKIN and TOSHIBA Corporation, respectively.

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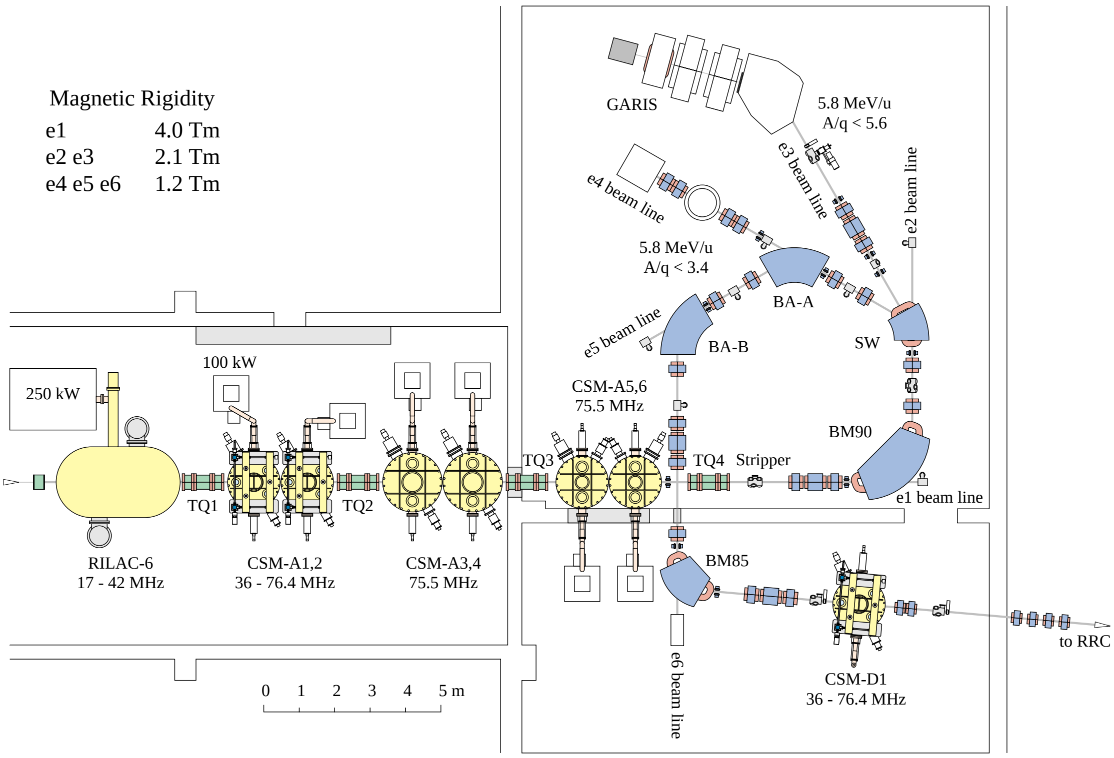

Figure 3: The new beam transport system in the RILAC facility along with the CSM cavities. The values of the magnetic rigidity acceptable in the six beam lines (e1 – e6) are also indicated.