UPGRADE OF RILAC INJECTOR

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Abstract

The RIKEN heavy-ion linac (RILAC) has been successfully upgraded by adding a booster linac consisting of six rf-cavities. The maximum beam energy of the RILAC has increased to 5.8 MeV/u, which has made it possible to perform nuclear physics experiments with high-intensity beams in the RILAC facility. The first two cavities of the booster have also upgraded the beam energy of the ring cyclotron (RRC). Heavy ion beams such as krypton are now available at 63 MeV/u after the RRC with an intensity of 100 pnA. Design and rf-characteristics of the booster cavities are presented in this paper.

OVERVIEW

The layout of the present RILAC facility is illustrated in Fig. 1. The main linac[1], which has been operated since 1981, consists of six variable-frequency cavities (RILAC 1 - 6). The maximum voltage gain of the main linac was designed to be 16 MV in the frequency range from 17 to 45 MHz. The rf-amplifiers for the last two cavities (RILAC 5 and 6) were replaced in 1999. The preinjector for the RILAC consists of a variable-frequency RFQ (FC-RFQ)[2] and an 18-GHz ECR ion source[3], which was installed in 1996. The maximum output voltage of the RFQ is 450 kV. Owing to the high performance of the 18-GHz ECRIS, the beam intensity has increased remarkably. In 2004, a new ECR ion source with super-conducting solenoid coils was installed, while the Cockcroft-Walton injector was removed from the beam line.

The booster, consisting of six cavities (Booster A1 – A6), was constructed in 2001[4]. The resonant frequency of the booster is twice that of the main linac. The first two cavities are frequency-variable, whereas the other four are operated at a fixed-frequency. The designed value of the voltage gain is 16 MV. The commissioning of the booster started in 2001, and we got the license for the upgraded operation in March 2002.

Figure 1 also shows the beam transport line[5] and the experimental apparatus. The transport system has one main line, transferring the beam from the RILAC to the ring cyclotron (RRC), and six branches (e1 - e6 in Fig. 1) for various experiments. 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 are under going.

BOOSTER CAVITIES

Design

The booster was designed by considering the beam dynamics and the rf-characteristics of the cavities alternatively. Table I summarizes the main parameters of the booster cavities. The acceptable mass-to-charge ratio (A/q) of the booster was chosen to be the same as that of

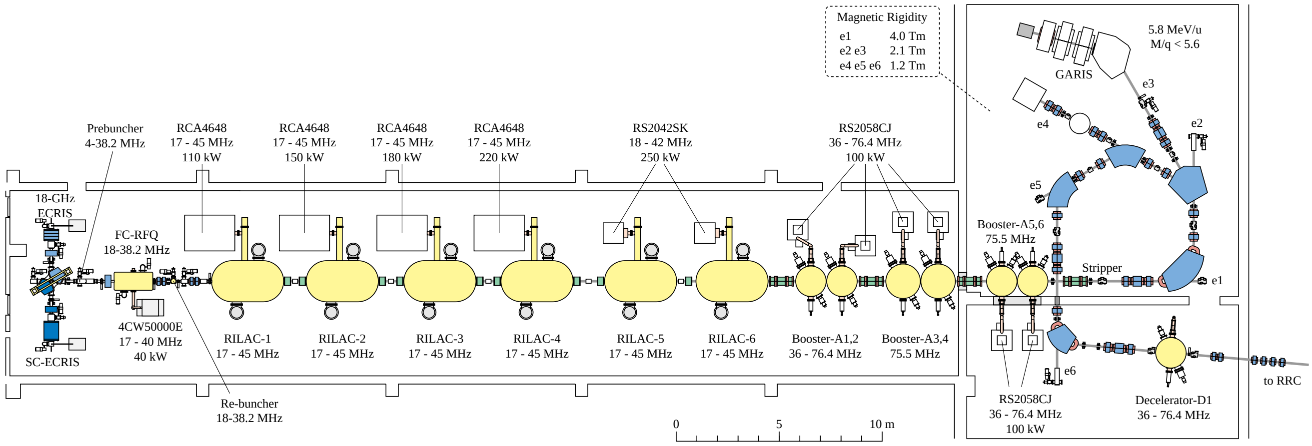

Fig. 1: Schematic drawing of the RILAC facility.

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Table 1: Parameter specifications of the booster cavities.

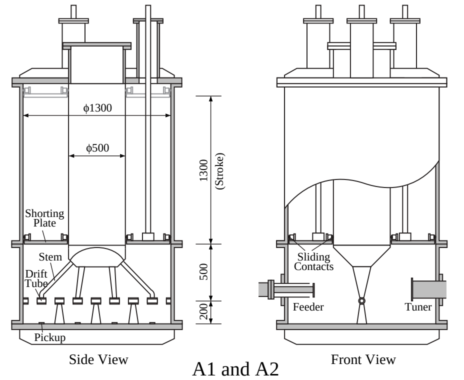
Cavity	*f* (MHz)	*D* (m)	gap	L_{gap} (mm)	V_{gap} (kV)	*ΔV* (MV)
A1	36 – 76.4	1.3	8	80	450	2.82
A2	36 – 76.4	1.3	8	87	450	2.88
A3	75.5	1.5	8	93	470	2.98
A4	75.5	1.5	8	99	470	3.01
A5	75.5	1.3	6	104	500	2.40
A6	75.5	1.3	6	108	500	2.43

D is the cavity diameter (= cavity length), L_{gap} is the gap length, V_{gap} is the gap voltage, and *ΔV* is the effective voltage gain in the cavity.

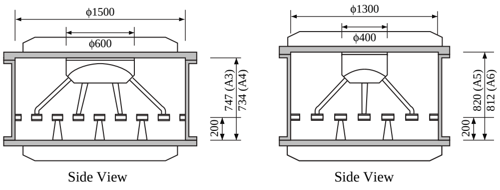
the RILAC; using the booster frequency *f*, *A/q* is expressed as $A/q=32{,}000/f^2$.

The structure of the first two cavities (A1 and A2) is based on a quarter-wavelength resonator with a movable shorting plate, as shown in Fig. 2. The fixed-frequency cavities (A3 – A6) are based in the lower part of the variable frequency cavities. There is no focusing element in the drift tubes, which helps to reduce the rf power losses.

The dimensions were optimized using the computer code MAFIA. The design criteria of the cavities are the following. First, the actual power dissipation should be less than 100 kW, because the cost of the rf amplifier rapidly increases above this value. Second, the inner radius of the cavity should be less than 1.5 meters to reduce the construction cost. Third, the surface electric current on the shorting plate should not exceed 60 A/cm, since sliding contacts are used there. The maximum field on the drift-tube surface has been chosen to be 16 MV/m, which corresponds to 1.6 Kilpatrick (Kp) at the highest frequency of 76.4 MHz, considering the fact that the RILAC has been operated at 1.6 Kp in the cw mode for a long time. The calculations were mainly done for one-half of the cavity, because of the symmetry of the structure. The number of total mesh points adopted in the calculation ranges from 90,000 to 180,000, depending on the position of the movable shorting plate.



A1 and A2



A3 and A4

A5 and A6

Figure 2: Schematic drawing of the booster 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 fixed-frequency cavities 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.

Table 2: Rf characteristics of the cavities

Cavity	*f* (MHz)	*Q*-value	*Q*ratio 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.

Rf Aspects

Table 2 summarizes the rf characteristics of the cavities. 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 (BAL SEAL) into every joint between metallic components. The estimated power losses per cavity are 60 - 90 kW at maximum.

The final amplifier is based on a tetrode (SIEMENS RS-2058CJ) with a grounded-grid circuit[6]. So far, 75 - 80 % of the maximum voltage has been achieved in the cw-mode operation without any significant problems. The vacuum stays in the range of 0.5 – 1.0 τ 10^{-7} Torr in the cw-mode operation.

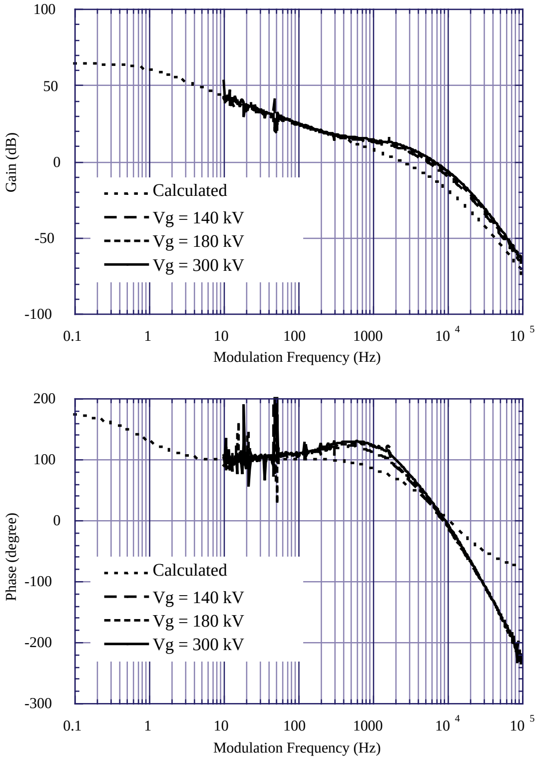


Figure 3: Bode diagram of the open-loop transfer function of the amplitude modulation, measured for the A3 cavity at various gap voltages. The horizontal axis represents the modulation frequency in Hz.

The accuracy of the voltage and phase control of the rf system is chosen to be $\Delta V/V \le \pm 0.1$ % and $\Delta\phi \le \pm 0.1$ degree. These conditions have been checked by using a spectrum analyzer. The stability of the feedback system of voltage control was also examined at several voltage levels, by directly measuring the open-loop transfer function of amplitude modulation[7]. The phase margin of the loop is approximately 30 degrees, as shown in Fig. 3.

UPGRADED PERFORMANCE

Since the commissioning in 2001, the booster has been intensively used for various tests and experiments. The maximum beam power ever achieved through the booster is 1 kW for the Ar^{11+} beam of 5.8 MeV/u with an intensity of 5 pμA. The transmission efficiency of the beam through the booster is usually 100 % within the measurement accuracy.

By using the first two cavities of the booster, it has become possible to operate the RRC in the harmonics of 8 instead of the original number of 9; the extraction velocity can be boosted by a factor of 9/8 at the same rf-frequency[8]. This energy gain is very useful to produce more intense radioactive beams far from stability. For example, a ^{48}Ca beam of more than 100 pnA was accelerated to 63 MeV/u in the search for new isotopes, resulting in discovery of the new isotopes ^{34}Ne, ^{37}Na, and ^{34}Si[9]. Recently, ^{86}Kr and ^{70}Zn beam of 63 MeV/u was extracted from the RRC with the beam intensity of 100 pnA.

The experiments on superheavy elements began in March 2002 with the GARIS at the e3 beam line. First, the beams of ^{40}Ar, ^{48}Ca, and ^{58}Fe with energies of 4.6 - 4.9 MeV/u were used in order to study the characteristics of the GARIS. In July 2002, a confirmation experiment on the synthesis of element 110 started using a ^{64}Ni beam with an energy of 5.0 MeV/u, through the fusion reaction $^{208}\text{Pb} + {}^{64}\text{Ni} \rightarrow {}^{271}110 + \text{n}$[10]. The beam intensity was approximately 1 pμA on the target throughout this experiment which lasted for 1487 hours. From February to May 2003, a confirmation experiment on element 111 was performed using a ^{64}Ni beam on ^{209}Bi Targets[11]. The total service time was 931 hours. Recently, elements 112 and 113[12] have been produced using ^{70}Zn beam of pμA[13]. The booster functioned stably throughout these long-term experiments.

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