PRESENT STATUS OF THE RIKEN HEAVY-ION LINAC

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Abstract

The RIKEN heavy-ion linac (RILAC) was successfully upgraded, by adding a booster consisting of six resonators. Various heavy ion beams have been accelerated to the energies around 5 MeV/u with very high intensities. For example, ^{64}Ni beam of more than one particle-micro-ampere is available in the cw mode. The stability of the rf-system, as well as the transmission efficiency, have been improved. On the other hand, we experienced serious problems mainly due to the high rf-power required for the acceleration. Using the upgraded beams, systematic study on search for super-heavy elements is under way; elements 110 and 111 have been produced so far.

1 OVERVIEW

The layout of the RILAC facility is illustrated in Fig. 1. The main linac[1], which has been operated since 1981, consists of six variable-frequency resonators (RILAC 1 - 6). The 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 resonators (RILAC 5, 6) were replaced in 1999.

There are two injectors for the main linac. One is the Cockcroft-Walton injector of 450 kV, which was installed in 1980. On the high voltage terminal, an ECR ion source (ECRIS) of 8 GHz (NEOMAFIOS) is placed. The other is a variable-frequency RFQ (FC-RFQ)[2] with an 18-GHz ECRIS[3], installed in 1996. The output voltage of the RFQ is the same to that of the Cockcroft-Walton injector. Owing to the high performance of the 18-GHz ECRIS, the beam intensity has increased remarkably.

The booster, consisting of six resonators, was constructed in 2000 in order to increase the beam energy[4]. The first two resonators are frequency-variable, whereas the other four are fixed-frequency type. The resonant frequency is set twice as that of the main linac. 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 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 carried out.

The most important feature of the RILAC is that the acceleration is performed in the continuous wave (cw) mode. Another important property is the variability of the frequency, which makes it possible to accelerate various kinds of ions. Available beam energies are summarized in Table 1, along with the maximum mass-to-charge ratio

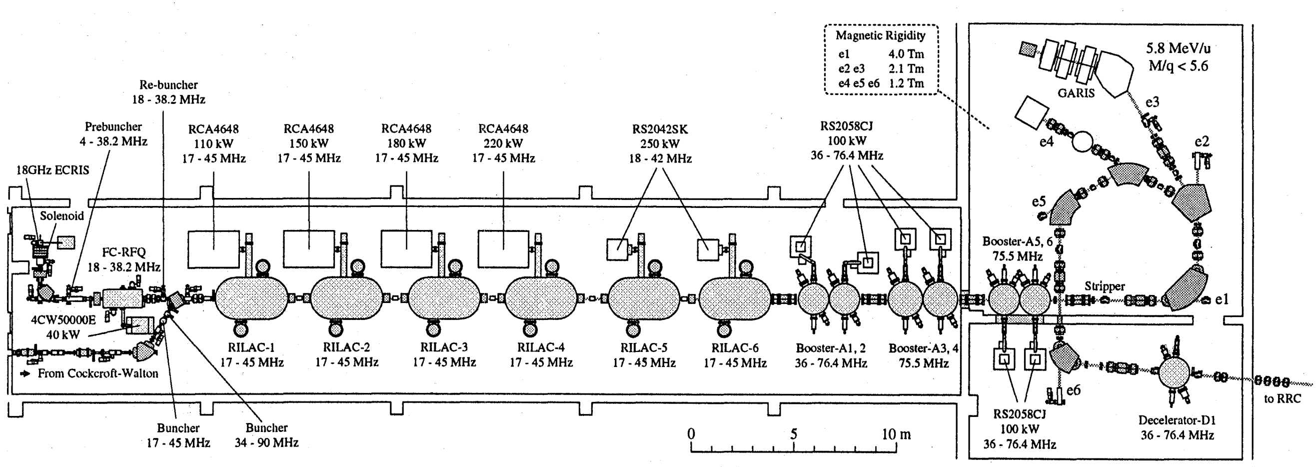

Fig. 1: Schematic drawing of the RILAC facility.

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acceptable by the RILAC.

Table 1: Beam energy in the RILAC facility

Resonators	f (MHz)*	Eout (MeV/u)	M/q**
RILAC (Main linac)	18 - 42	$0.00202 \times f^2$	$8000 / f^2$
RFQ+RILAC +A1+A2	18 - 38.2	$0.00271 \times f^2$	
RFQ+RILAC +A1~A6	37.75	5.8	5.6

*Resonant frequency of the main linac (RILAC 1 - 6).
**Designed value of the acceptable mass-to-charge ratio.

2 OPERATION STATUS

Table 2 shows the statistics of the RILAC operation from January 1 through December 31, 2002[5]. Although we met a lot of problems, the beam time amounts to 4,500 hours.

Table 3 summarizes the number of days allocated to different research groups[5]. Since we got the upgraded license, nuclear physics experiments have become major part of the beam time. The percentage of the beam time used by the RRC was 32 % of the total.

The accelerated ions in the last year are the followings: $^{4}He^{2+}$, $^{40}Ar^{8+, 11+}$, $^{48}Ca^{11+}$, $^{58}Fe^{13+}$, $^{58}Ni^{9+}$, $^{64}Ni^{13+, 14+}$, $^{84}Kr^{8+, 17+, 19+, 20+}$, $^{86}Kr^{20+}$, $^{136}Xe^{18+, 20+, 27+}$, $^{181}Ta^{20+}$, and $^{209}Bi^{20+}$. For more than 95 % of the beam time, the ions were fed by the 18-GHz ECRIS. The beam time of ^{64}Ni amounts to 52 days, which is about 30 % of the total. The ^{86}Kr and ^{48}Ca ions were accelerated by the RILAC together with the booster (A1 and A2) and injected into the RRC with a harmonic number of 8.

Table 2: RILAC operations from January 1 through December 31, 2002.

	No. of Days	%
Beam time	187	51.2
Overhaul and improvement	77	21.1
Scheduled shutdown	68	18.6
Periodic inspection & repair	33	9.0
Total	365	100

Table 3: Beam time allocation.

	No. of Days	%
Nuclear physics	83	44.4
Beam transport to RRC	60	32.1
Radiation chemistry	13	7.0
Material analysis	12	6.4
Atomic physics	11	5.9
Accelerator research	8	4.3
Total	187	100

3 IMPROVEMENTS AND TROUBLES

The transmission efficiency of the beam through the linac, from the 18-GHz ECRIS down to the exit of the booster, was not so good. The typical value stayed around 30 - 40 %. The beam loss mainly takes place in the injector section, from the ion source to the entrance of the main linac.

One of the reasons for the beam loss is considered to be a mismatch of the transverse emittance to the acceptance of the beam line in the injector section. However, the only device with which we could control the beam profile had been the solenoid magnet between the analyzing magnet and the RFQ.

To improve the transmission efficiency, a new solenoid magnet was installed between the 18-GHz ECRIS and the analyzing magnets[6]. The maximum magnetic field on the axis is 0.65 T. As a result, the beam intensity increased by about 50 % at the exit of the analyzing magnet. The transmission efficiency through the linac has also increased; typical value is 50 % now.

We had another problem on the output beam from the RILAC; the longitudinal phase of the beam center was sometimes quite unstable and the injection of the beam into the RRC was difficult. From the measurement for the rf-system of the main linac, it was found that the phase oscillation was large in the region close to the carrier frequency ($\Delta f < 100$ Hz). Therefore, all the phase control units for the main linac were replaced into newly designed ones[7]. After this replacement, the phase oscillation has improved to be less than $\pm$ 0.1° in the whole frequency range. The longitudinal excursion of the beam has become negligibly small.

On the other hand, new problems appeared as the rf-power increased. One of them is that the thin copper sheets (10 cm wide, 7 cm long, 0.3 mm thick), used for the electric contact in the resonators of the main linac, sometimes melted due to the large rf-current. They were replaced with thicker ones in this summer.

Another problem is a self-oscillation of the rf-amplifier of the last resonator of the main linac (RILAC-6); it oscillates at 105 MHz with very high power when the plate stub is set in a certain position-range. A measurement has shown that there is a coupled resonant mode between the grid circuit and the plate circuit, by which the output power is fed back to the input circuit in the positive phase. Although this oscillation is temporary suppressed by mounting dumping resistors in the plate circuit, the problem is not fully solved yet.

4 EXPERIMENTS WITH RILAC

In this section, two topics are briefly represented among the experiments performed with the RILAC.

4.1 Super-heavy element search

Research experiments on super-heavy elements began in March 2002 with 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}Pb + ^{64}Ni $\rightarrow$ ^{271}110 + n. The total service time for the experiments was 1486.5 hours. The 18-GHz ECRIS with the MIVOC (Metal Ions from Volatile Compounds) method[8] and the booster resonators worked actively to provide these beams with high intensity for a very long time. Finally, 14 candidates of decay chains originating from ^{271}110 were observed, and the excitation function of the reaction was measured successfully[9].

The typical beam intensity had exceeded one particle-micro-ampere on the target throughout this experiment. The voltage gain of the booster was 10.6 MV, which was 65 % of the designed value.

From February to May 2003, a confirmation experiment on the element 111 was performed using a ^{64}Ni beam on ^{209}Bi targets. The total service time was 930.5 hours. The excitation function of the reaction was also measured successfully, where 14 candidates of decay chains were observed[10].

4.2 H=8 mode acceleration of the RRC

The harmonics of the rf-system of the RRC is designed to be 9 when the RILAC is used as an injector. The additional velocity gain through the booster makes it possible to operate the RRC in the harmonics of 8, which indicates that the extraction velocity can be boosted by a factor of 9/8 at the same rf-frequency[11]. This energy gain is very useful to produce more intense radioactive beams far from stability. Based on this acceleration scheme, more than 100 particle-nano-ampere of ^{48}Ca beam was accelerated up to 63MeV/u in order to apply to new isotope search, resulting in discovery of the new isotopes ^{34}Ne, ^{37}Na, and ^{34}Si[12]. Recently, ^{86}Kr beam of 63 MeV/u was extracted from the RRC with the beam intensity of 100 particle-nano-ampere.

5 FUTURE PLAN

As mentioned above, most of the beams are provided with the 18-GHz ECRIS. The ion source, however, requires periodic cleaning especially in the MIVOC method, which means that the beam time is stopped during the maintenance.

To make this intercept as small as possible, we are planning to construct another ECRIS and install it in parallel with the present one. The beam line from the Cockcroft-Walton injector will be removed at the same time. A planned layout is shown in Fig. 2. Two analyzing magnets are connected back to back and they are rotated by 90 degree without opening the vacuum chamber. This configuration will allow us to test one of the ion sources while the other is in use for the beam time. The magnets have been already fabricated. The installation will be carried out in the next year.

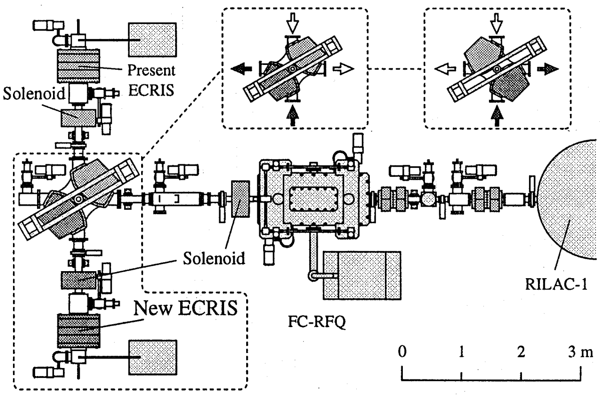

Fig. 2: Planned layout of the new injector with two ion sources.

6 ACKNOWLEDGMENT

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