Developments of linear accelerators at RI Beam Factory

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The injection of very heavy ions such as uranium in RIBF[1)] was initially performed with RILAC.[2)] However, the beam current of $^{238}U^{35+}$, which was directly injected into the RRC[3)] without charge stripping, was too low to meet the demand of RIBF users because of the limited performance of RILAC. In addition, a strong demand for more RILAC beam time was made by those engaged in research projects on superheavy elements (SHE) started at the RILAC facility in 2002.[4)] It was obvious that such experiments conflict with the BigRIPS experiments at RIBF, as shown in Fig. 1(a). Therefore, a new injector was required to resolve these problems. By 2006, a basic design study of the new injector involving beam dynamics calculations had been conducted.[5)] Fortunately, the project was approved by the supplemental budget in late FY2008, and we quickly constructed the new injector by the end of FY2009.

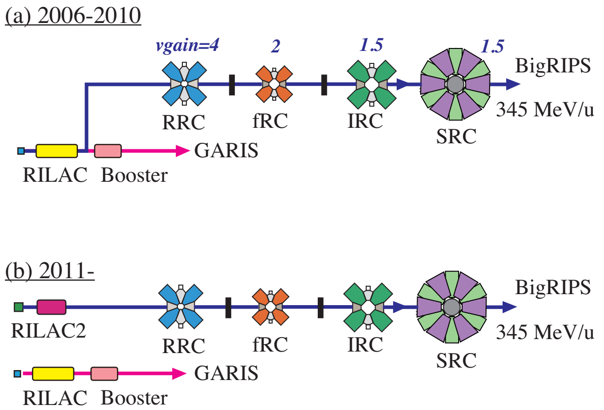

Fig. 1. Accelerator chain of RI Beam Factory. The upper panel (a) shows the uranium acceleration scheme in RIBF and metallic ion beam acceleration for the GARIS experiments until 2011. Both schemes used RILAC. The lower panel (b) shows the acceleration scheme since 2011. Now the uranium beam is injected through RILAC2, while RILAC is almost entirely dedicated to SHE experiments.

The new injector, named "RILAC2," is schematically shown in Fig. 2. It mainly consists of the 28-GHz superconducting ECR ion source,[6)] a low-energy beam-transport (LEBT) line[7)] including a prebuncher, an RFQ linac, and three DTL cavities. An important point in designing RILAC2 was that the required total voltage is as low as 4.6 MV, which is less than one third of that of RILAC; it is sufficient to accelerate ions with a mass-to-charge ratio of 6.8, such as $^{136}Xe^{20+}$ and $^{238}U^{35+}$, up to an energy of 670 keV/nucleon. Therefore, it was possible to reduce the total length of the linac structure to less than 8 m by choosing an rf frequency of 36.5 MHz, instead of the RILAC frequency of 18.25 MHz, whereas the prebuncher is operated at 18.25 MHz in order to match the beam bunch interval to the rf system of the RRC. We have placed the new injector in the AVF cyclotron vault, as shown in Fig. 2, which made the length of the beam transport line to RRC 36 m, less than half that of the RILAC injector. The main parameters of RILAC2 are listed in Table 1.

Table 1. Main parameters of RFQ and DTL cavities.

Resonator	RFQ	DTL1	DTL2	DTL3
Frequency (MHz)	36.5	←	←	←
Duty(%)	100	←	←	←
m/q	6.8	←	←	←
E_{in} (keV/u)	3.28	100	220	450
E_{out}(keV/u)	100	220	450	670
Length (m)	2.3	0.8	1.1	1.3
Gap number	93*	10	10	8
Gap voltage (kV)	42	110	210	260
Aperture (mm)	8**	17.5	17.5	17.5
ϕ_s(deg.)	-29.6†	-25	-25	-25
Power (kW)	18	7	13	20

* Cell number ** Mean aperture (r_0)
† Final synchronous phase

The RFQ linac used in RILAC2, which is based on a four-rod structure, is the one originally developed for use in an ion implantation device in the 1990s.[8)] We modified it to yield a resonant frequency of 36.5 MHz by adding tuner blocks between the posts that support the vanes based on fine electromagnetic simulations.[9)] We also diverted one of the cavities in the Charge State Multiplier[10)] developed for RIBF to the last cavity of the DTLs in RILAC2.

In order to reduce the construction cost and space, we adopted a direct coupling scheme for the rf coupling between the DTL cavities and amplifiers. Since the resonators could not be designed independently from the tetrode amplifier, the frequency shift of the cavities as well as the strength of the coupling were carefully calculated based on computer simulations with the help of a lumped circuit model.[11)] This calculation exhibited excellent agreement with the measured results.

The first beam test of RILAC2 was successfully conducted in December 2010, and the device was fully commissioned in October 2011 using a uranium beam. Since then, RILAC2 has provided intense uranium and xenon beams for nuclear physics experiments at RIBF very stably.[12)] The completion of RILAC2 has also

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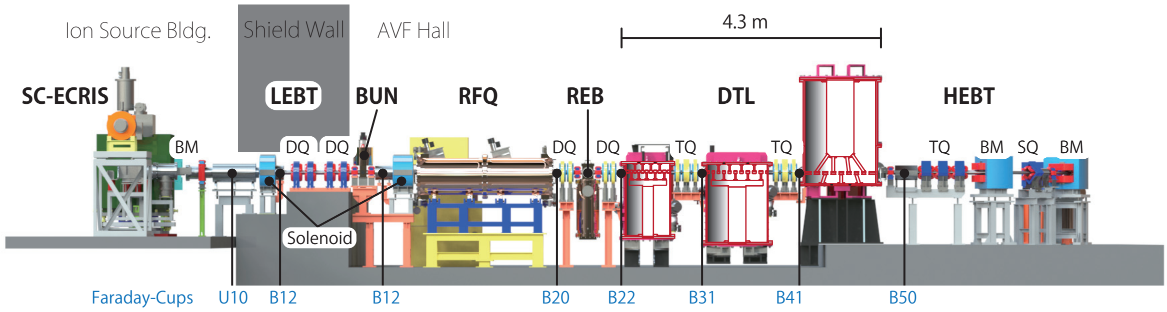

Fig. 2. Side view of the RILAC2 injector. The beam is provided with a 28-GHz ECR ion source and is accelerated through the RFQ and three DTLs. A pre-buncher and a rebuncher are implemented in the linac.

allowed us independent operation of the SHE experiments at the RILAC facility, as shown in Fig. 1 (b). We think that RILAC2 contributed to the third event of the element [113] in 2012[13] to a certain degree.

When the name of the element [113] was proposed as "nihonium" in 2016, a supplemental budget was approved for further investigation of heavier new elements, such as [119] and [120], through a major upgrade of RILAC. The upgrade program includes the construction of a 28-GHz superconducting ECR ion source and two cryomodules that substitute the last four cavities of the RILAC booster. We expect to have very intense metallic beams of vanadium and chromium of more than 5 pμA at 6.5 MeV/nucleon. This upgrade program also aims at mass production of ^{211}At, a candidate medical isotope for radionuclide therapy in the future. For this purpose, an intense beam of ^{4}He at 29 MeV is necessary.

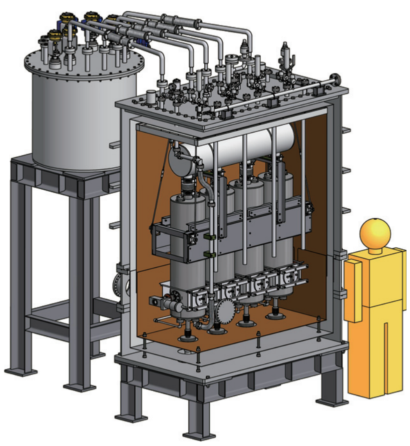

Fig. 3. Conceptual drawing of the cryomodule. Each cryomodule contains four quarter-wavelength resonators (QWRs).

Figure 3 shows a conceptual drawing of a cryomodule, which contains four quarter-wavelength resonators (QWRs). Each QWR operates at a resonant frequency of 73.0 MHz at a gap voltage of approximately 0.8 MV with a power consumption of 4.0 W. The corresponding acceleration gradient is 4.5 MV/m. The inner radius and height of the QWR are 1,090 mm and 300 mm, respectively.

We have investigated the same structure of a superconducting resonator in a proposal of an RIBF upgrade program.[14] A similar structure was also studied, constructed, and tested in the framework of the ImPACT program, [a] and we achieved a very high voltage in a vertical test.[15,16]

The construction of the new devices is in progress. We expect that the upgraded RILAC facility will start operation in FY2019. It will contribute to the intensity upgrade of RIBF in the future.

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[a] Impulsing PAradigm Change through disruptive Technologies Program of Council for Science, Technology and Innovation (Cabinet Office, Government of Japan)