Present status of the RIKEN Accelerator Research Facility (RARF)

M. Kase, A. Goto, T. Kageyama, I. Yokoyama, M. Nagase, S. Kohara, T. Nakagawa, N. Inabe, K. Ikegami, O. Kamigaito, M. Kidera, J. Fujita, A. Yoneda, M. Kobayashi, and Y. Yano

The Inst. of Physical and Chemical Research (RIKEN), Wako, Saitama 351-0198, Japan

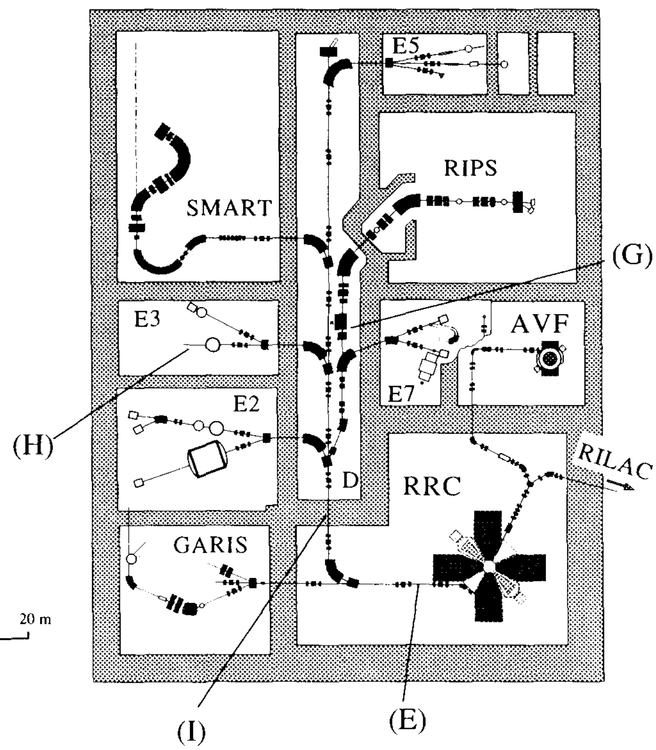
The K540-MeV RIKEN Ring Cyclotron (RRC) celebrated 10 years of successful beam operation in December 1996. The beam intensities have been increased over years to the present levels of about 500 pnA for 135 MeV/nucleon ^{12}C and of 2000 pnA for 24 MeV/nucleon ^{40}Ar. The variation of beam has now exceeded one hundred. These beams have been delivered to users in many fields. Improvements are being and will be made to upgrade the present machine to be matched as an injector to the program of the RI beam factory.

1 Introduction

The first beam of 26 MeV/nucleon ^{40}Ar was extracted successfully from the RIKEN Ring Cyclotron (RRC) in December 1986, when it was coupled with a injector of RIKEN heavy-ion linac (RILAC). The RRC began to work with the full performance in 1989, when the second injector, the AVF cyclotron with a 10 GHz ECR ion source was completed. After the large-scaled experimental instruments such as RIPS, GARIS, and SMART were constructed, the RIKEN Accelerator Research Facility (RARF) was fully completed in 1990 as shown in Fig. 1.

The beams have been delivered to users in many fields of not only nuclear physics but also biology, radio-chemistry, atomic physics and so on. In nuclear physic experiment, most beam time has been devoted into those using RI beams in RIPS. In the project of RI beam factory (RIBF), mass range of RI beam will be extended.

RILAC-RRC combination will be an injector to next stage of cyclotron cascade (IRC & SRC)[1] in RIBF. Various improvements on RILAC-RRC about beam intensity and quality are and will be made in aim of RIBF.



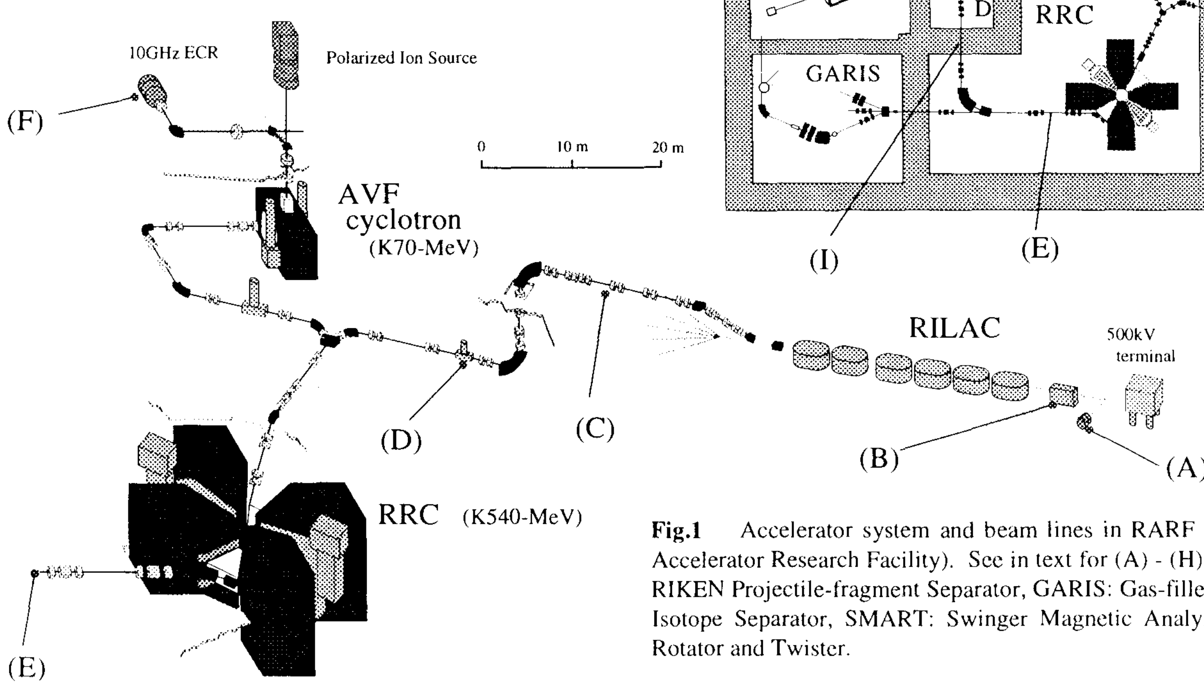


Fig.1 Accelerator system and beam lines in RARF (RIKEN Accelerator Research Facility). See in text for (A) - (H). RIPS: RIKEN Projectile-fragment Separator, GARIS: Gas-filled Recoil Isotope Separator, SMART: Swinger Magnetic Analyzer with Rotator and Twister.

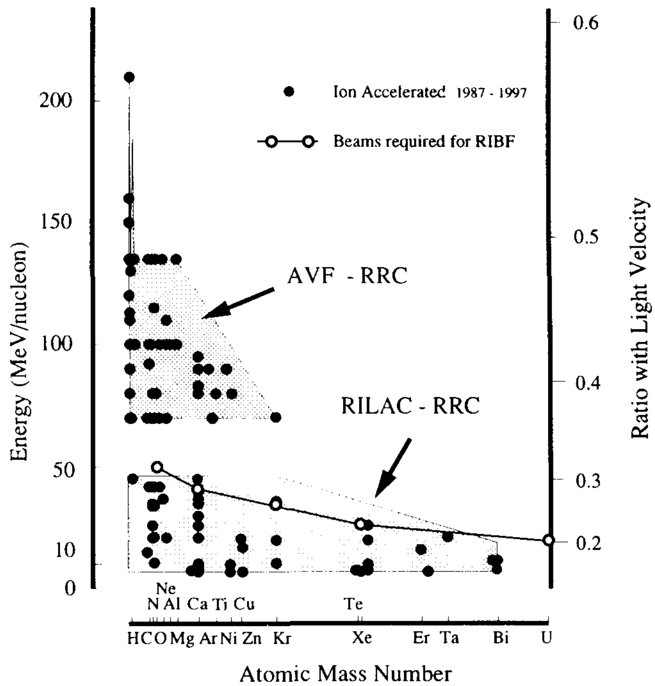


Fig. 2 The performance of RIKEN Ring Cyclotron (RRC). The all beams which has ever been accelerated are shwon as solid circles on an energy-mass space.

Table 1 Typical beams accelerated by RRC and their acceleration conditions.

ION	Energy (MeV/u)	RF (MHz)	h	Operation scheme	Intensity (pnA)
pol.d	270	32.6	5	AVF-RRC	>280
^{12}C,^{14}N,^{16}O	135	32.6	5	AVF-RRC	500
^{18}O	100	29.0	5	AVF-RRC	420
^{40}Ar	95	28.0	5	AVF-RRC	70
^{40}Ar	24	27.0	9	RILAC-RRC	2000
^{40}Ar	7.6	18.8	11	RILAC-RRC	2000
^{46}Ti	90	27.5	5	AVF-RRC	4
^{48}Ca	70	25.0	5	AVF-RRC	7
^{56}Fe	7.6	18.8	11	RILAC-RRC	200
^{58}Ni	7.6	18.8	11	RILAC-RRC	120
^{84}Kr	70	24.6	5	AVF-RRC	1
^{84}Kr	8.5	18.0	10	RILAC-RRC	150
^{136}Xe	26	28.0	9	RILAC-RRC	42
^{136}Xe	7.6	18.8	11	RILAC-RRC	280
^{209}Bi	15	23.9	10	RILAC-RRC	1

2 Operation Statistics

A number of kinds of beams have been accelerated so far with the RIKEN Ring Cyclotron (RRC). There are 25 kinds of elements (Z=1~83) and more than one hundred combinations of ion and energy.

Their masses as well as their energies cover a very wide range as shown in Fig. 2, where the beams accelerated since 1987 are plotted in the region of energy-mass space. Among them, some typical beams are shown in table 1 together with beam intensities and accelerator conditions. After 15 MeV/nucleon ^{209}Bi and 70 MeV/nucleon ^{84}Kr were successfully accelerated in 1997, the plots in Fig.2 are covering almost full of the available regions for the two injectors, the AVF cyclotron and RILAC, respectively.

Machine operation has been in excess of 6000 hours per year since 1993 and amounted to 6500 hours per year in 1997. It is considered to be a practical limit if holidays and maintenance time are taken into account.

The beam delivery time in 1997 amounted to be about 5000 hours. Most of the beam time (86.7%) was devoted to nuclear physics experiments. A high intense beam of intermediate mass (up to ^{48}Ca) with the energies of 70 to 135 MeV/nucleon is requested for RI beam production, and, one the other hand, a wide mass range of beam with energies 7.6 to 10 MeV/nucleon for experiment using fusion reactions.

The rest (13.3%) of the the beam time was devoted to other field experiments, such as medical science, radio-chemistry, health physics, material science, biology, atomic physics. The number of users for biologic research is increasing in recent years.

3 New Topics

3.1 Performance of new pre-injector of RILAC

An 18GHz ECR (A in Fig.1) and FC-RFQ (B) were installed in 1996 as a pre-injector to RILAC[2]. In summer 1997, the extraction voltage of 18 GHz ECR ion source is raised by a factor of two and four vanes of RFQ are converted correspondingly, so that beam intensity will be increased for low energy beams (less than 10 MeV/nucleon) which are required in nuclear physics experiment using fusion reactions. As the results, a beam intensity of 7.6 MeV/nucleon ^{40}Ar and ^{136}Xe became 2 pμA and 280 pnA, which were used for the superheavy element research and for production of a high-spin isomer beam, respectively. Also for 24 MeV/nucleon ^{40}Ar, an intensity of 2 pμA are now available on a target (beam power: 2 kW) and this beam was used on a test of rotating target which will be a production target in RIBF.

3.2 Transmission efficiency of RRC

In order to increase the total efficiency through RRC in the RILAC-RRC, two improvements have been made as follows:

(1) The structure of four-gap drift tube in re-buncher(D), which is located half-way in the beam transport line between RILAC and RRC, was changed to be matched to the harmonic number of RRC. The three sets of drift tube are now available for harmonic numbers, 9, 10, and 11.

(2) Beam energy at the exit of RILAC was stabilized by a feedback loop to the rf of RILAC[3]. Since the fluctuation of beam energy causes the beam phase fluctuation after drifting along the beam transport line toward RRC, the final rf phase can be controlled using a resonator of RILAC according to the beam phase measured near the re-buncher(C). This method was applied in the cases of 7.6MeV/nucleon ^{40}Ar and ^{136}Xe accelerations.

As the results, the beam transmission efficiency through RRC was successfully improved, as well as the beam stability. The beam transmission efficiency through RRC is 70 - 95%, depending on a harmonic number of RRC.

3.3 ECR ion source

For the production of metallic-ion beams, a new method so-called MIVOC (Metal Ion from VOlatile Compounds) [4] was tried with the 18 GHz ECR ion source. Organic metal compounds, whose vapor pressure is high at room temperature, were used, instead of conventional metallic or metal-oxide rod, for charging metal vapor into an ECR plasma. Beams of Fe^{7+} and Ni^{8+} were accelerated by RRC using the compounds of $Fe(C_5H_5)_2$ and $Ni(C_5H_5)_2$, respectively. We obtained a remarkable improvement on the intensity: ten times (e.g., for Ni) compared to conventional method.(A)

The electrically isolated electrode was installed into the plasma chamber of 18GHz ion source. As the results, the enhancement of beam intensity of Ar^{11+} (280eμA) were observed with using electrode at the floating potential.(A)

A design of a new-type of ECR ion source is now under way. Using a liquid-He-free superconducting solenoid, the mirror ratio will be a nominal value of 6.0 with B_{max} of 3T and B_{min} of 0.5T. A hexapole magnet will be used which has 24 segments and is made of Nd-Fe-B permanent magnet. The field strength on the surface of magnets will be 1.4T. With this high field and high mirror ratio, it is expected that a beam intensity is improved moreover. This superconducting ECR will be installed at injection line of AVF cyclotron.(F)

3.4 Small-sized beam

A new focusing element (super-conducting solenoid, 6.8 T·m) was installed in just front of a production target of RIPS, in 1997.(G) Using this, a beam size on the target could be reduced as small as 0.4 mm in diameter with a full intensity.

To meet the requirement from bioscience, a test of high energy micro-beam is going on in the present beam line(H). With a collimator (100μm) on thin copper plate at the exit of RRC(E) and a beam slit at midway of transport (I), a several tens μm sized beam is realized on a target using one-to-one optics, by eliminating a energy-loss beam at the slit (dispersive point).

3.5 Charge-State-Multiplier

In the program of RIBF, in order to get a high intensity heavy-ion beam, Charge-State-Multiplier (CSM) will be necessary between RILAC and RRC (C). In a process of additional acceleration, charge stripping and deceleration, a high intensity heavy-ion beam whose Bρ is matched to RRC injection will be obtained. The first stage of three CSM cavities is now being designed. In summer of 1999, they will be completed and installed after RILAC, and then a test will be done. Twelve CSM cavities will be necessary in total for full-performance of RIBF.

4 Conclusion

After 10-year operation, RRC provides a variety of beams with its full performance. To upgrade the present machine for the future project, many improvements will be made soon, especially in increasing a beam intensity.

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