Present status of the RIKEN Ring Cyclotron (RRC)

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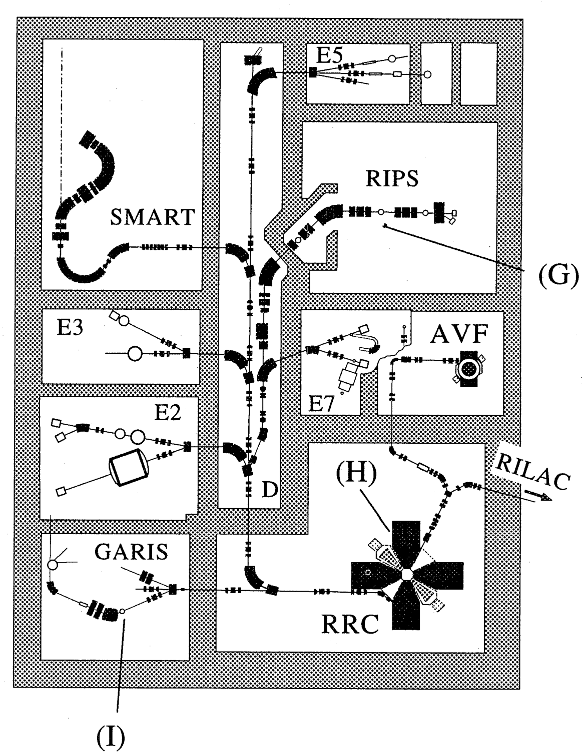
Abstract

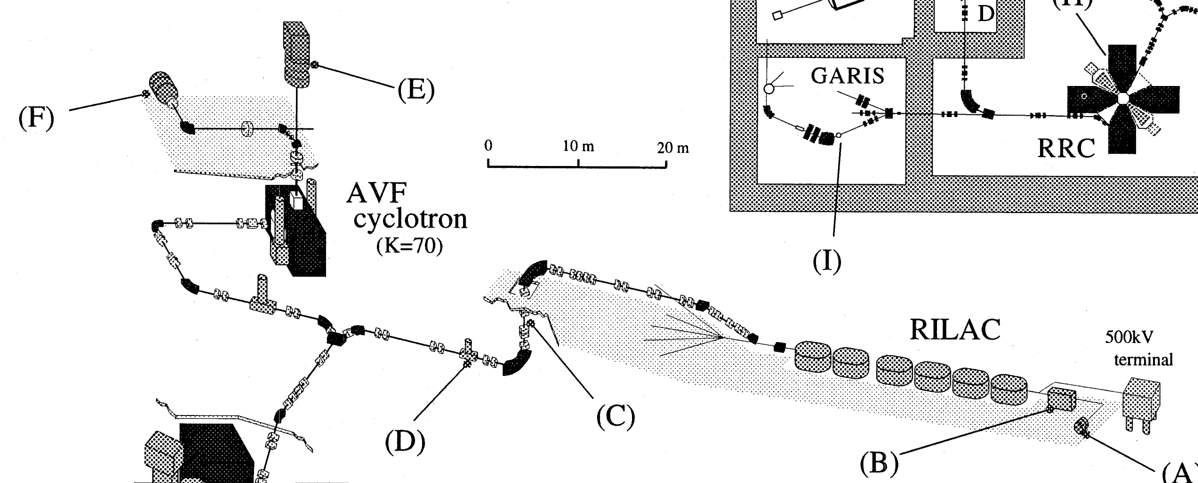
The RIKEN Ring Cyclotron (RRC) has been providing a various kind of beams for thirteen years since 1996 to experiments in many fields, not only nuclear physics but also biology, radio chemistry, atomic physics and so on. The beam intensities have increased over years step by step. Many improvements are required to upgrade the present machine to be matched as an injector to the program of the RI beam factory.

1 Introduction

The RIKEN Ring Cyclotron[1](RRC) was completed in 1986 as a main accelerator in RIKEN Accelerator Research Facility (RARF). The RRC is a K=540 four-separated-sector cyclotron which has the first injector, the RIKEN heavy-ion linac[2](RILAC) which was completed in 1981 and which have been used for acceleration of heavy ions ranging all mass region with energies of 7 ~ 40 MeV/nucleon. After the second injector of a K=70 AVF cyclotron was completed, the RRC began to operate with the full performance in 1989. That is, for relatively lighter ions, the maxmum energy was pushed up to more than 100 MeV/nucleon. For the several kind of beams, the intensities around 1 μpA have been available. A layout of these accelerators is shown in Fig. 1. 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, not only nuclear physics but also biology, radio-chemistry, atomic physics and so on. In nuclear physics, a search for new isotopes has been done extensively and, as the results, more than ten new isotopes were found successfully for





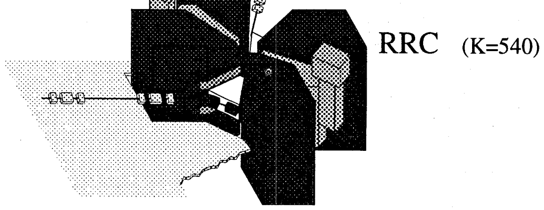


Fig.1 Accelerator system and beam lines in RARF (RIKEN Accelerator Research Facility). See in text for (A) - (H). RIPS: RIKEN Projectile-fragment Separator, GARIS: Gas-filled Recoil Isotope Separator, SMART: Swinger Magnetic Analyser with Rotator and Twister.

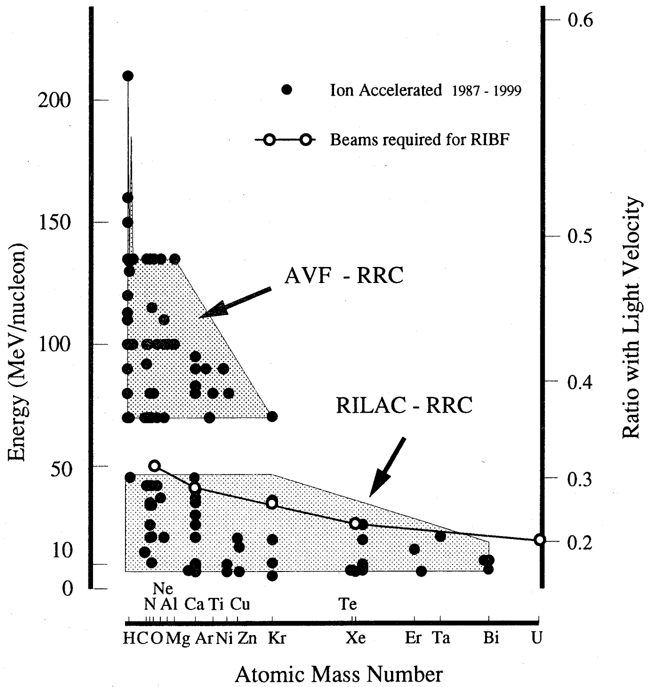


Fig. 2 The performance of RIKEN Ring Cyclotron (RRC). The all beams which have ever been accelerated are shown as solid circles on an energy-mass space.

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

ION	Energy (MeV/n)	RF (MHz)	h	Injector	Intensity (pnA)
pol.d	135	32.6	5	PIS - AVF	>280
^{12}C,^{14}N,^{16}O	135	32.6	5	ECR10 - AVF	500
^{18}O	100	29.0	5	ECR10 - AVF	420
^{40}Ar	95	28.0	5	ECR10 - AVF	70
^{40}Ar	24	27.0	9	ECR18-RFQ-RILAC	2000
^{40}Ar	7.6	18.8	11	ECR18-RFQ-RILAC	2000
^{46}Ti	90	27.5	5	ECR10 - AVF	4
^{48}Ca	70	25.0	5	ECR10 - AVF	7
^{56}Fe	7.6	18.8	11	ECR18-RFQ-RILAC	200
^{58}Ni	7.6	18.8	11	ECR18-RFQ-RILAC	120
^{84}Kr	70	24.6	5	ECR10 - AVF	1
^{84}Kr	5.4	18.7	13	ECR18-RFQ-RILAC	1700
^{136}Xe	26	28.0	9	ECR18-RFQ-RILAC	42
^{136}Xe	7.6	18.8	11	ECR18-RFQ-RILAC	280
^{209}Bi	15	23.9	10	ECR18-RFQ-RILAC	1

ECR10:	10GHz ECR	F in Fig.1
PIS	Polarised Ion Source	D in Fig.1
ECR18:	18GHz ECR	A in Fig.1
RFQ:	Folded Coaxial RFQ	B in Fig.1
AVF:	AVF cyclotron	
RILAC:	RIKEN heavy-ion Linac	

these ten years using RI beams at RIPS (G in Fig1). In the project of RI beam factory[3](RIBF), mass range of RI beam will be extended and it is expected that much more kinds of new isotopes will br found.

RILAC-RRC combination will be an injector to next stage of cyclotron cascade, IRC[4] and SRC[5], in RIBF. Various improvements on RILAC-RRC about beam intensity and quality are required in aim of RIBF.

2 Operation Statistics

Around one hundred kinds of beams have been accelerated for these twelve years with the RIKEN Ring Cyclotron (RRC). 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 an energy-mass space. Among them, some typical beams are listed in table 1 together with beam intensities and accelerator conditions. After beams of 15 MeV/nucleon ^{209}Bi and 70MeV/nucleon ^{84}Kr were successfully accelerated in 1997, the plots in Fig.2 cover almost full range of the available regions for the two injectors, the AVF cyclotron and RILAC, respectively.

A total of machine operation time has been in excess of 6000 hours per year since 1993. A total of the beam delivery time in 1998 amounted to be about 5000 hours. Most of the beam time (>80%) was devoted to nuclear physics experiments. The rest of 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.

The machine operation time in 1999 is estimated to be shorter than 5500 hours due to a two-month shutdown in the spring. The movement of sub-power-station for the existing machines was done in order to prepare a space of RIBF construction.

3 Improvements

An 18GHz ECR (A in Fig.1) and FC-RFQ (B) were installed in 1996 as a pre-injector to RILAC. Available beam intensities of 7.6 MeV/nucleon ^{40}Ar and ^{136}Xe became 2pμA and 280pnA, 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 2pμA are now available on a target (beam power is 2kW) and this beam was used on a test of rotating target which will be used in RIBF.

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

(1) The structure of four-gap drift tube in re-buncher(D in Fig.1), which is located half-way in the beam transport line between RILAC and RRC, was changed to be precisely matched to the harmonic number of RRC. The five sets of drift tube are now prepared for harmonic numbers from 9 to 13.

(2) Beam energy at the exit of RILAC was stabilized

by a feedback loop to an rf phase of one cavity of RILAC [6]. Since a shift of beam energy causes the beam phase fluctuation after drifting along the beam transport line toward RRC, the beam energy can be stabilized if an rf phase of the final cavity is controlled according to the beam phase measured near the re-buncher (C in Fig.1). This method was available for increasing beam intensity especially in the case of low energy acceleration such as 7.6MeV/nucleon ^{40}Ar and ^{136}Xe, because the beam phase fluctuation became relatively large after long time drifting.

In these ways, we recently succeeded in acceleration with a harmonic number of 13. We obtained 5.3MeV/nucleon ^{84}Kr with an intensity of 1.7 pμA, which is used for the research of super-heavy elements at GARIS (I in Fig.1).

A Charge State Multiplier [7] (CSM) will be introduced just after RILAC. The CSM consists of accelerators, a charge stripper and decelerators, which will minimize a beam loss in the process of charge stripping for heavier ions. It will be very important in RIBF to obtain a heavy ion beam with an intensity of 1pμA.

A frequency-tunable (36 - 78 MHz) linac cavity having six or eight acceleration gaps has been designed for CSM accelerator and decelerator. Six cavities of accelerator section will be installed soon after RILAC. The maximum energy at the end of these accelerators will be around 6MeV/nucleon. A stand-alone use of RILAC+CSM accelerator is planed for the experiment of nuclear synthesis of super-heavy elements until the first phase of RIBF is completed in 2003.

Improvements on ECR ion source have been done extensively and steadily.

For the production of metallic-ion beams, the method so-called MIVOC (Metal Ion from VOlatile Compounds) has been tried with the 18 GHZ ECR ion source. Beams of Fe^{7+} and Ni^{8+} were accelerated by RRC using these compounds. We obtained a remarkable improvement on the intensity. Recently a new-type of ECR ion source was installed at injection line of AVF cyclotron. Using a liquid-He-free super-conducting solenoid, the mirror ratio will be a nominal value of 6.0 with B_{max} of 3T and B_{min} of 0.5T. With this high field and mirror ratio, it is expected that a beam intensity is improved moreover. A test of this super-conducting ECR will be started soon.

4 Trouble Shooting

In the first half of operation history of the RRC, many vacuum troubles occured frequently concerning connections of pipes for cooling water or high-pressured air inside rf-resonators. After all the connections were improved by welding directly, a total of trouble shooting time was reduced.

However, in the spring 1999, a serious problem occurred to a west-sided sector magnet (H in Fig.1). A magnetic field of this sector magnet became so unstable due to a layer short-circuit of the lower main coil. Each main coil consists of eleven pancakes, each of which has six-turn two-layer coil. Each conductor was covered with insulation glass tape, and the whole coil was molded with epoxy resin after assembled. Since, at the beginning, the effect was so small and it lasted for a short duration, it was very difficult to find its cause clearly. After the precise measurement of terminal voltages of each coils and the careful search on a surface of the molded coil by the thermoviewing, ultimately a position where the layer-short-circuit had been happening was found exactly. It turned out that the short-circuit occurred at outside of coil and that near to its terminal, fortunately. By removing epoxy resin partialy, the concerning hollow-conductor with a square cross-sectional shape was exposed. After the corner edge of conductors was scraped to make an enough space between them, this trouble was overcome completely.

5 Conclusion

The RRC has been in a successful operation since 1987, providing a variety of beams with its full performance to many users. 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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