STATUS REPORT ON RIKEN ACCELERATOR RESEARCH FACILITY

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Abstract

The K540 RIKEN ring cyclotron went into operation with the RILAC as an injector in 1987; two years later another injector of a K70 AVF cyclotron was installed to upgrade the acceleration performance for light ions.

So far 210 MeV protons and twenty kinds of heavy ions ranging from deuteron through erbium with energies of 7 - 135 MeV/nucleon have been delivered for a wide variety of experiments of nuclear physics, atomic physics, nuclear chemistry, material science and radiobiology.

The current status of this accelerator complex is described with an emphasis on recent improvements and developements.

General description of RIKEN Accelerator Research Facility

Figure 1 shows a general layout of the RIKEN Accelerator Research Facility (RARF). The fourteen-year project of constructing this heavy-ion accelerator facility was fully completed in 1989. This facility houses a main accelerator of a K540 ring cyclotron (RIKEN Ring Cyclotron, RRC) and its two types of injectors of a heavy-ion linac (RIKEN Heavy-Ion Linac, RILAC) and a K70 AVF cyclotron. This accelerator system delivers various kinds of heavy-ion beams with a mass range from A=1 to A=209. Maximum energies of protons and helium-3 particles are 210 MeV and 185 MeV/nucleon, respectively. Energy range of heavy-ion beams extends from 7 MeV/nucleon to 135 MeV/nucleon for light lions and to about 20 MeV/nucleon for very heavy ions.

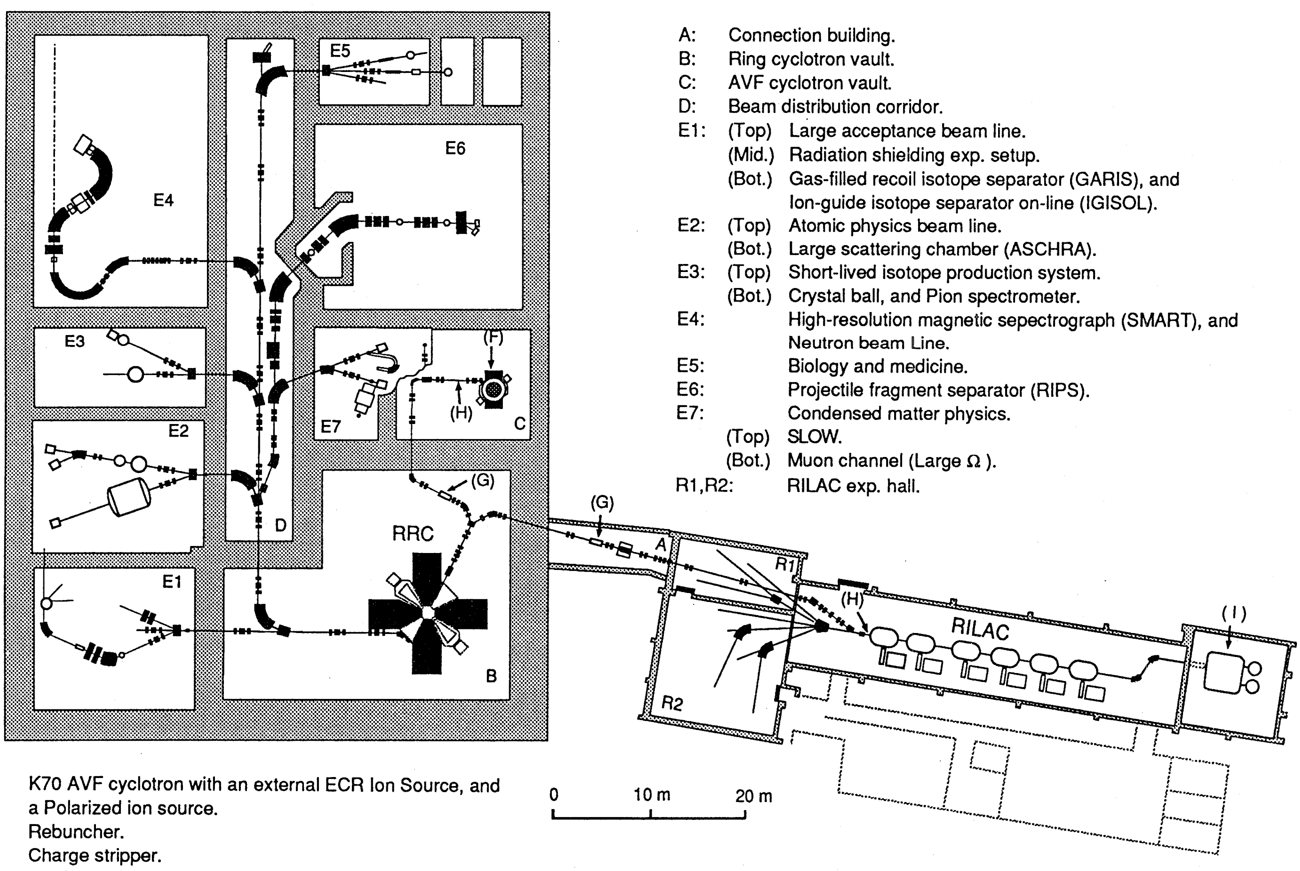
The milestones so far read as follows: The RILAC was completed in 1981, and subsequently started construction of the RRC. In December 1986, the RRC coupled with the RILAC was commissioned. The routine operation of this accelerator complex began in April 1987. In 1987 - 1989, construction of the injector AVF cyclotron and its ECR ion source, fabrication of various experimental apparatus, and extension of beam distribution lines were done. Due to this work beam services were sometimes interrupted. In July 1989 a 135 MeV/nuleon nitrogen beam was successfully extracted from the RRC in the AVF injection. This beam has the largest magnetic rigidity that the RRC is capable of providing, and the highest energy obtained by cyclotrons in the past. Owing to the installation of AVF injector, the design goal of light-ion acceleration has been achieved. Since September 1989, experimental programs have been carried out by using both RILAC and AVF injected beams. In late 1990 an ECR ion source named NEOMAFIOS[1], developed and manufactured by C.E.N.-G., France, was newly installed on a high voltage injector of RILAC, being substituted for an old PIG ion source. Thanks to this installation, the RILAC performance has been greatly improved, and consequently the RRC performance for heavy-ion acceleration has been upgraded.

Up to the present, the RRC has provided 210 MeV protons and twenty kinds of heavy-ion beams ranging from deuteron through erbium with energies of 7.0 - 135 MeV/nucleon for experiments of nuclear physics, atomic physics, nuclear chemistry, material science and radiobiology. High quality beams with transverse emittances as small as 10 mm.mrad, an energy spread of approximately 0.1 % and a pulse width shorter than 300 psec have been extracted.

Recent improvement and operating performance

Ring Cyclotron, RRC

The K540 RRC consists of four straight-edge separate sector magnets and two rf dees. A sector angle of the magnet is 50 degrees; a maximum magnetic field 16.7 kG. Isochronous fields are created by main coils and 26 pairs of trim coils mounted on the pole surfaces. A couple of delta-shaped rf resonators are placed at opposite sides to each other in the magnet valleys. Frequency range of 18 - 45 MHz is tuned coarsely by moving boxes housed inside the resonator, which is our original mechanism for changing a resonant rf frequency[2]. An rf power is fed to the resonator through a 50 ohm coaxial line by a final amplifier



A: Connection building.
B: Ring cyclotron vault.
C: AVF cyclotron vault.
D: Beam distribution corridor.
E1: (Top) Large acceptance beam line.
(Mid.) Radiation shielding exp. setup.
(Bot.) Gas-filled recoil isotope separator (GARIS), and Ion-guide isotope separator on-line (IGISOL).
E2: (Top) Atomic physics beam line.
(Bot.) Large scattering chamber (ASCHRA).
E3: (Top) Short-lived isotope production system.
(Bot.) Crystal ball, and Pion spectrometer.
E4: High-resolution magnetic sepectrograph (SMART), and Neutron beam Line.
E5: Biology and medicine.
E6: Projectile fragment separator (RIPS).
E7: Condensed matter physics.
(Top) SLOW.
(Bot.) Muon channel (Large Ω).
R1,R2: RILAC exp. hall.

F: K70 AVF cyclotron with an external ECR Ion Source, and a Polarized ion source.
G: Rebuncher.
H: Charge stripper.
I: 500 kV Cockcroft-Walton high voltage generator with an ECR ion source (NEOMAFIOS).

Fig. 1. Layout of the RIKEN Accelerator Research Facility (RARF).

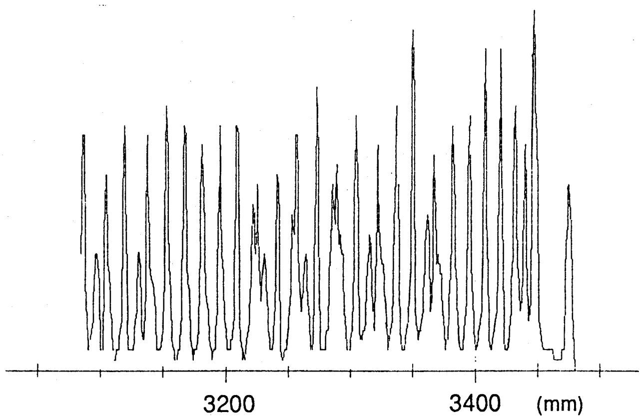


Fig. 2. A turn pattern in the extraction region taken with the radial differential probe for a 135 MeV/nucleon nitrogen beam. The turn at 3475 mm has passed trough the electrostatic deflector.

composed of a 300 kW max. tetrode (SIEMENS 2042SK). At present an rf voltage of 275 kV is generated by a 200 kW power between 10 cm dee gaps at 32.6 MHz, corresponding to 135 MeV/nucleon. An acceleration harmonic number of 5 is used for the AVF injection, while 9 - 11 for the RILAC injection. The RILAC works at the same frequency as the RRC, while the AVF at half of RRC frequency. The large vacuum chamber of 30 m^3 in volume is evacuated by means of fourteen cryopumps of 1.2×10^5 l/sec in total speed to maintain a pressure as good as 10^{-8} Torr. Mean injection and extraction radii are 0.89 m and 3.56 m, respectively; thus a final velocity becomes four times an incident velocity.

An off-centered acceleration technique facilitates single turn extraction. Figure 2 shows an example of turn patterns measured in the extraction region for a 135 MeV/nucleon beam. It is noticed that each peak appearing in the pattern

Table 1. RRC beams during April 1987 - October 1991.

Particle	Charge	RF F (MHz)	h	Energy (MeV/nucleon)	Intensity (pnA)
p	1	38.7	5	210	30
	1	42.2	5	270	-
d	1	24.6	5	70	50
	1	32.0	5	130	10
^{12}C	5	35	9	42	40
	6	32.6	5	135	60
^{13}C	6	35	9	42	10
^{14}N	6	28	9	26	30
	6	35	10	34	30
	6	32	9	35	50
	6	35	9	42	30
	7	26	5	80	100
	7	32.6	5	135	230
^{15}N	5	20.187	10	10.65	20
	6	35	10	34	8
	6	35	9	42	8
	7	24.6	5	70	160
	7	30.5	5	115	30
^{16}O	8	32.6	5	135	60
^{18}O	7	35	9	42	3
	8	24.6	5	70	100
	8	29	5	100	180
^{20}Ne	9	33	9	37	17
^{22}Ne	8	28	10	21	5
^{24}Mg	11	29	5	100	3
	12	29	5	100	12
^{27}Al	13	29	5	100	5
^{40}Ar	11	20	10	10.3	140
	12	28	10	21	17
	13	28	9	26	46
	16	26	5	80	2.5
	17	28.1	5	95	20
^{40}Ca	14	28	9	26	0.7
^{58}Ni	13	18	11	7	2
	8	18	11	7	18
^{64}Zn	20	25	9	20.6	0.5
^{65}Cu	8	18	11	7	3
	18	25	10	17	0.5
^{84}Kr	18	20	10	10.3	4
^{132}Xe	21	18	11	7	2.4
^{136}Xe	23	18	10	8.5	4
	33	28	9	26	1.8
^{166}Er	32	22.3	9	16	2

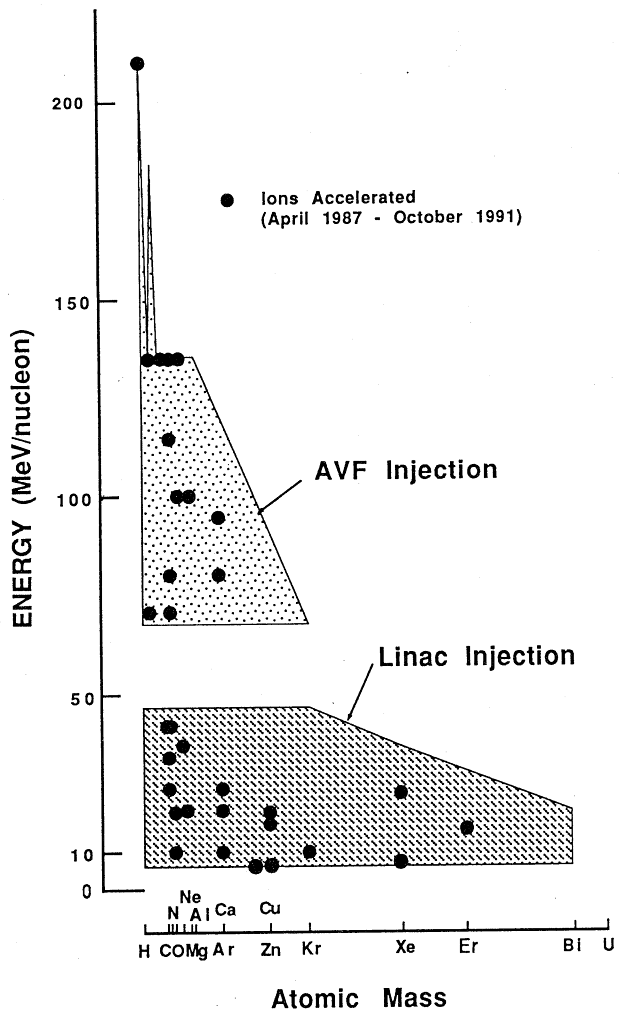


Fig. 3. Energy-Mass curve for the RRC; beams delivered for users are plotted.

contains overlapped three turns, resulting from $\nu_r = 1.3$. The minimum point between the last two neighbouring peaks is carefully adjusted to be positioned at a 0.5 mm thick copper septum of an electrostatic extraction deflector. This is done by changing an rf voltage slightly. In this way we can get nearly 100 % extraction efficiency and high beam quality, even for a top energy beam. Beam transmission efficiency over 70 % is obtained throughout the RRC. The major beam loss is considered to occur in the course of injection due to emittance mismatching or bad quality of an injected beam.

An rf oscillator system has been improved to work stably at 18 MHz which is lowered from a nominal value of 20 MHz; thus the lowest beam energy of 7 MeV/nucleon has been available in the acceleration harmonics of 11.

Trim-coil power supplies have potentiality to create an isochronous field for a 270 MeV proton beam, while accoding to calculations a vertical betatron frequency crosses the dangerous resonace $\nu_z = 0.5$ at 210 MeV and decreases down to 0.2 at the final energy. In order to study the resonance-crossing phenomena, we tried to accelerate protons up to 270 MeV. In this trial, protons were successfully accelerated up to the final energy inside the RRC, but some part of the beam was lost near the resonance-crossing radius, where abrupt vertical shift of central particles was observed. These phenomena will be investigated in further detail.

Table 1 lists the RRC beams used for experiments up to the present. Figure 3 shows plots of ions accelerated on an energy-mass space together with a feasible region of the RRC.

Injector AVF cyclotron

The K70 AVF cyclotron[3] has four spiral sectors and two rf dees with an angle of 85 degrees. Its mean extraction radius of 71.4 cm is four-fifth the mean injection radius of RRC. An rf frequency is tunable from 12 to 24 MHz, and a harmonic number of 2 is used for acceleration. A maximum average field is 17.5 kG. This cyclotron accelerates ions having a mass-to-charge ratio smaller than 4.2 in energy range of 3.8 - 14.5 MeV/nucleon.

The ECR ion source[4] is placed on the floor above the cyclotron vault. The

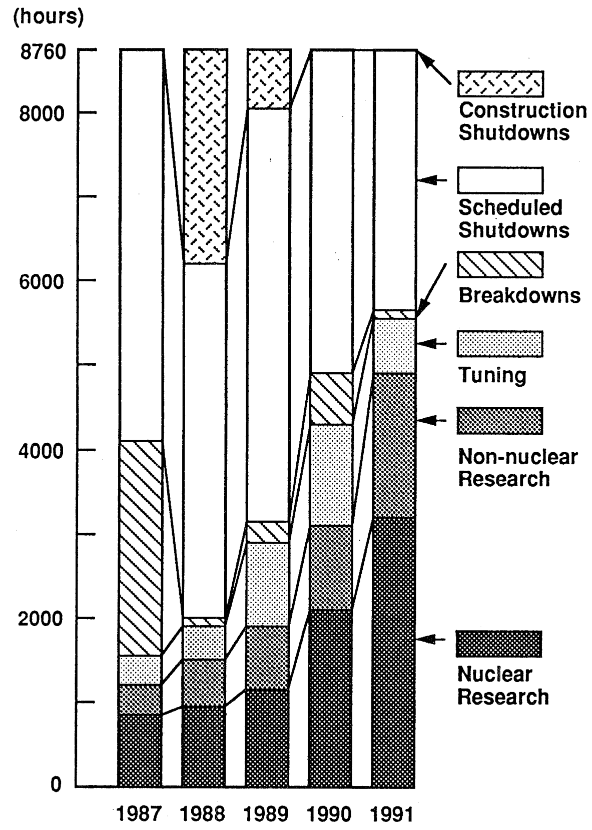


Fig. 4. Statistics of the RRC operation from 1987 to 1991. Operation hours of 1991 are scheduled ones, expecting no more breakdowns as of October 25, 1991.

beam is injected axially into the AVF cyclotron through a spiral inflector. A beam buncher generating a sawtooth-like wave-form rf voltage in a single gap between a couple of mesh plates is placed 2 m upstream from the inflector. A phase compression of a factor of 5 - 6 is obtained by this beam buncher. A beam transmission efficiency between before injection and after extraction is improved significantly in use of the beam buncher; it amounts up to 10 - 15 %. Single turn extraction can be achieved by a carefull tuning, which is indispensable to obtain better beam transmission through the RRC.

The ECR ion source is basically similar in structure to the LBL's[5]. It is of a two-stage configuration and 10 GHz microwaves are applied to both stages. When metalic ions are produced, a ceramic rod made of their oxicide is inserted radially onto a second-stage ECR plasma boundary. Recently it was found that applying of a negative voltage to an electrode housed in a first-stage chamber as well as coating of aluminum and magnesium oxide on a second-stage plasma chamber wall enhance the high-charge state performance[4]. By these means 35 eμA of $^{40}Ar^{12+}$ and 6 eμA of $^{84}Kr^{20+}$ have been obtained, which allows the RRC to deliver approximately 2pnA of 110 MeV/nucleon ^{40}Ar and 70 MeV/nucleon ^{84}Kr beams. This source has been providing a highly-charged very-low-energy beam to atomic physics experiments as well.

A polarized proton/deuteron ion source of an atomic beam type is being assembled about 8 m directly above the AVF cyclotron center. Testing of this ion source will be started in late 1991. R&D work on a polarized ^{3}He ion source is also pursued.

RILAC

The RILAC[6] consists of a Cockcroft-Walton injector and six acceleration tanks of the Wideroe type. An rf frequecy is required to be variable for a coupled operation with the RRC. Its range covers 17 - 43 MHz, while in an injector mode to RRC the lowest frequency used is 18 MHz. A maximum effective rf voltage remains constant at 16 MV in the frequency range up to 34 MHz, and it gradually decreases down to 11 MV at 43 MHz. In the injector mode RILAC is able to accelerate ions having a mass-to-charge ratio smaller than 24 in energy range of 0.7 - 3.7 MeV/nucleon.

Even with a fixed rf frequency, an output beam energy of the RILAC can be lowered by switching off the last one or two acceleration tanks. Accordingly, an output beam energy of the RRC can be lowered below the nominal value obtained with the fundamental acceleration harmonics of 9; the acceleration harmonics of 10 and 11 are used for this purpose.

The NEOMAFIOS is operated at 8 GHz and generates a mirror magnetic field by permanent magnets. It is compact and consumes less electric power than 20 kW, and is therefore suitable for use at the high voltage injector platform. There has been steady improvements in production of a wide variety of ions and high charge states[7]. So far 8 kinds of gaseous ions, helium through xenon, and 30 kinds of solid ions, magnesium through bismuth have been produced. The higher charge states obtained have roughly doubled the acceleration performance for heavy ions in comparison with the PIG ion source. This high-charge-state performance has also enabled us to increase RRC beam energies and intensities for heavy ions. At the RRC minimum energy of 7 MeV/nucleon, no charge stripping is needed for ions of mass-to-charge ratio less than 8.1 owing to the K-value of 460 MeV for a low velocity beam. We applied this acceleration mode to 7 MeV/nucleon $^{58}Ni^{8+}$ and $^{65}Cu^{8+}$ beams, and the intensities obtainable have been significantly increased by a factor of 5 as a result of no beam loss due to the stripping process.

An additional beam buncher[8] is planned to be installed on the injection beam line. It will be operated in a second-harmonic mode to an existing beam buncher. This two-buncher system will enhance a phase compression power so that the beam transmission efficiency through the RILAC is expected to increase by a factor of 2.

Statistics of operation

Figure 4 summarizes the change in yearly operation hours of the RRC from 1987 to 1991. Since 1990 a routine machine-time schedule for the year has almost established, because there have been no interruptions due to construction works. In these two years an extensive improvements have been made for the whole parts of the machine; this work was very effective in quick starting up, stable operation, and easy maintenance. Thereby hours for tuning and breakdown have been cut back so that total effective hours for users is likely to reach nearly 5000 hours in 1991. These hours have been dovoted to proceed nuclear (70 % in portion) and non-nuclear (30 % in portion) experiments. The AVF-injected beam time exceeded the RILAC-injected beam time in a ratio of 7 to 3. Regular long-term overhauls were caried out for 3 weeks in the winter and 6 weeks in the summer.

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