RECENT ACHIEVEMENTS AT THE RIKEN RING CYCLOTRON

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ABSTRACT

In April 1987 the K540 RIKEN ring cyclotron went into operation with the RILAC as an injector; another injector of a K70 AVF cyclotron was installed in April 1989 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 developments.

1. GENERAL DESCRIPTION OF RIKEN ACCELERATOR RESEARCH FACILITY

The fourteen-year project of constructing the RIKEN Accelerator Research Facility (RARF)[1] was carried to completion in 1989 FY. 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 construction of the RRC was started. 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 conducted. Due to this work beam services were sometimes interrupted. In July 1989 a 135 MeV/nucleon 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. Owing to the installation of the 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[2], developed and manufactured by C.E.N.-G., France, was newly installed on a high voltage injector of the 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 used.

1.1. Statistics of Operation

Figure 1 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 reached 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 carried out for 3 weeks in the winter and 6 weeks in the summer.

2. RECENT IMPROVEMENTS AND OPERATION PERFORMANCE

2.1. Ring Cyclotron, RRC

The 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

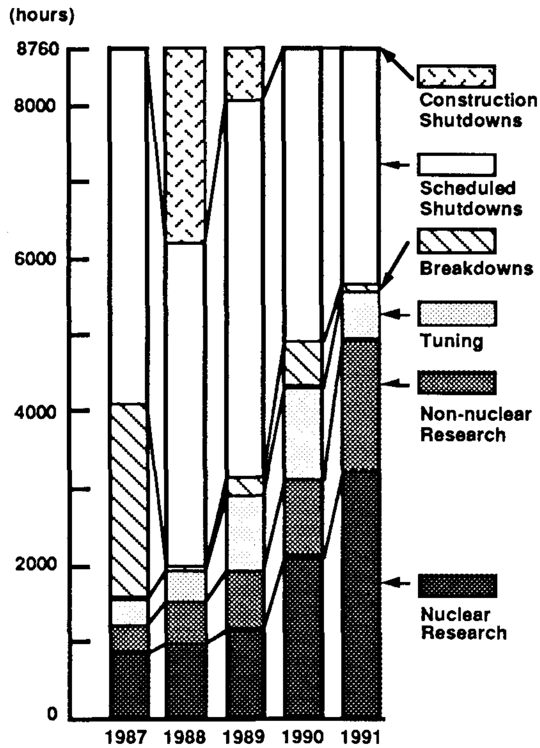

Fig.1. Statistics of the RRC operation from 1987 to 1991.

coarsely by moving boxes housed inside the resonator, which is our original mechanism for changing a resonant rf frequency. An rf power is fed to the resonator through a 50 ohm coaxial line by a final amplifier 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 to facilitate single turn extraction has been established. Such off-centering can be easily obtained by changing a beam inflection voltage at the injection, as illustrated in Fig. 2. It is noticed that each peak appearing in the pattern (c) contains overlapped three turns, resulting from $\nu_r \cong 1.3$. The minimum point between the last two neighbouring peaks is carefully positioned at a 0.5-mm-thick copper septum of an electrostatic extraction deflector. This is done by adjusting 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.

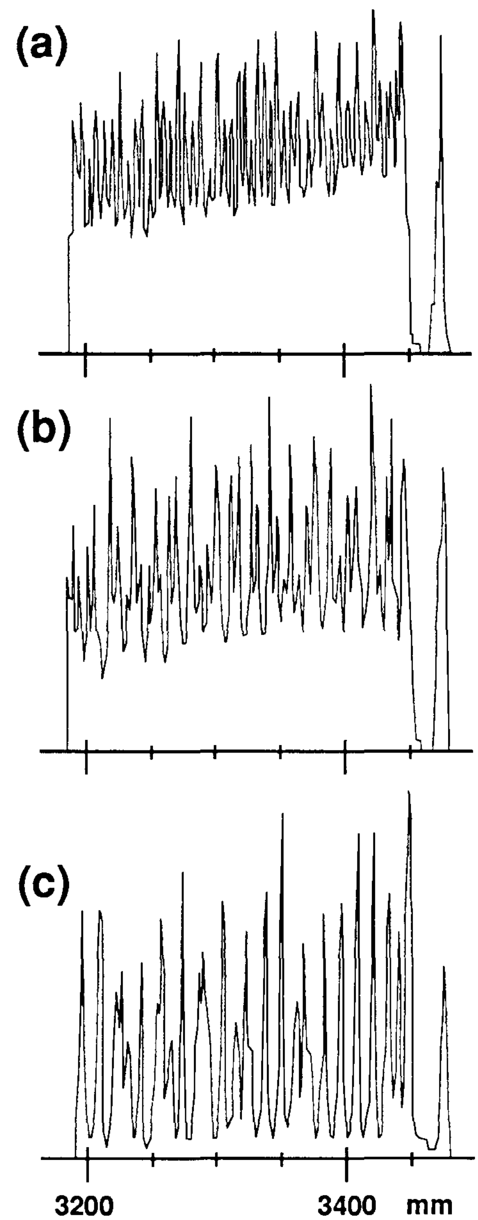

Fig.2. Turn patterns in the extraction region taken with the radial differential probe for a 135 MeV/nucleon nitrogen beam. The last peak appearing at 3475 mm has passed through the electrostatic deflector. (a) a well-centered turn pattern with an average turn spacing of 5.7 mm which is nearly equal to the estimated value; (b) off-centering is driven only by a change of the inflector voltage at injection; (c) the further voltage change followed by a fine adjust of the injection rf phase finally leads clear turn spacings of 15 mm on average.

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 according to calculations a vertical betatron frequency crosses the dangerous resonace ν_z= 0.5 at 212 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

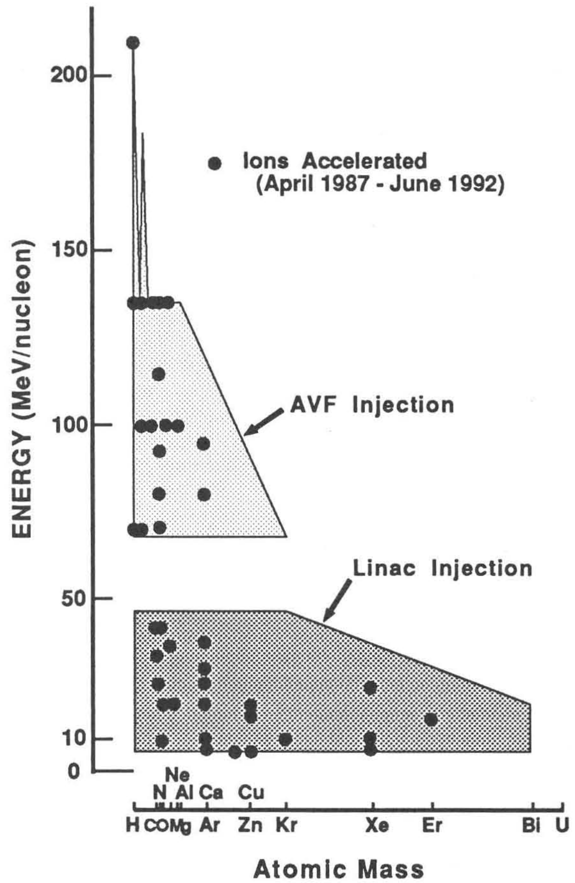

Fig. 3. Energy-Mass curve for the RRC; beams delivered for users are plotted.

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.

Figure 3 shows plots of ions accelerated so far on an energy-mass space where the RARF accelerator complex can stably provide beams. The energy gap between 45 MeV/nucleon and 67 MeV/nucleon is due to an operational instability of the RILAC rf system at frequencies of 39 MHz - 45 MHz.

Beam intensities have been greatly upgraded: e.g. those of 135 MeV/nucleon light-ions and 95 MeV/nucleon ^{40}Ar ions have reached 500 pnA and 50 pnA, respectively.

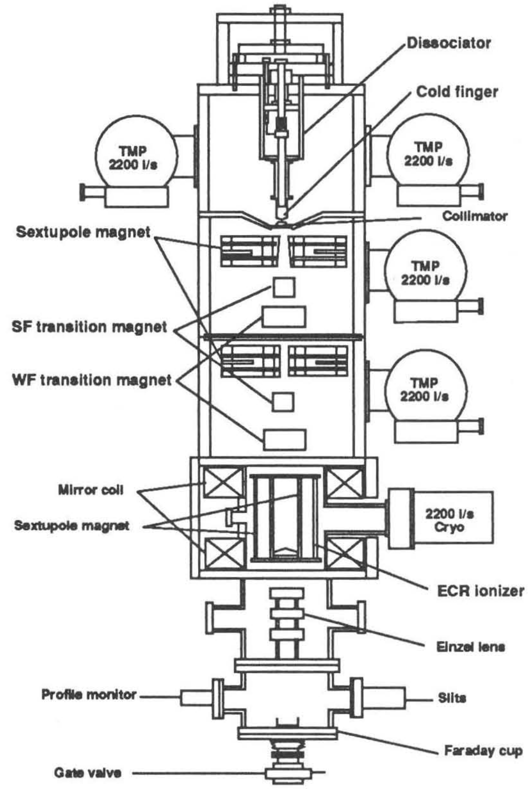

Fig.4. Schematic side view of the polarized ion source.

2.2. Injector AVF Cyclotron

The K70 AVF cyclotron 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 17.0 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 is placed on the floor above the cyclotron vault. The 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 beam transmission efficiency between before injection and after extraction is improved significantly by the use of this buncher which gives a phase compression of a factor of 5 - 6; 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.

This ECR ion source is basically similar in structure to the LBL's[3]. It is of a two-stage configuration and 10 GHz microwaves are supplied to both stages. When metallic ions are produced, a ceramic rod made of their oxide is inserted radially onto a second-stage ECR plasma boundary.

We have studied several methods to upgrade the beam intensity of highly-charged ions. In this improvement works it was found that applying a negative voltage to an electrode housed in a first-stage chamber as well as coating aluminum and magnesium oxide on a second-stage plasma chamber wall enhance the high-charge state performance.[4-5] 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 110 MeV/nucleon ^{40}Ar and 70 MeV/nucleon ^{84}Kr beams with intensities of approximately 2pnA. Recently we have tested "plasma cathode method" by which 80 eμA of $^{40}Ar^{11+}$ could be much stably obtained without any mixing gas.[6] This method has a distinct advantage of very long lifetime and very small gass consumption.

This ECR source is utilized by itself for atomic physics experiments as well.

In May 1992 a polarized proton/deuteron ion source of an atomic beam type was assembled about 8 m directly above the AVF cyclotron center. This source modelled on that of TUNL[7]. Figure.4 shows the schematic side view of the source which consists of a dissociator with a cooled nozzle (~30 K), a pair of sextupole magnets, a pair of weak and strong rf transition units and a 2.45 GHz ECR ionizer. In June the first acceleration test for 14 MeV polarized deuterons were carried out by the AVF cyclotron. A pure vector polarization of 20 % with 30 enA was obtained, which is basically limited to 67%(2/3). An effort is being made to upgrade intensity and polarization.

2.3. RILAC

The RILAC consists of a Cockcroft-Walton injector and six acceleration tanks of the Wideroe type. An rf frequecy is variable for a coupled operation with the RRC. Its range covers 17 - 43 MHz. A maximum effective rf voltage remains constant at 16 MV in the frequency range up to 34 MHz, but it gradually decreases down to 11 MV at 43 MHz. The 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.

At a fixed rf frequency, the RILAC beam energy 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 in 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. It is, therefore, suitable for use at the 500 kV injector platform. There have been steady improvements in production of a wide variety of ions and high charge states. 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 the RRC beam energies and intensities for heavy ions. In addition, when we accelerate ions of mass-to-charge ratio less than 8.1 up to the RRC minimum energy of 7 MeV/nucleon, no charge stripping is preferable owing to the high intensity for the high charge states. Here the RRC has the K-value of 460 MeV for such a low velocity beam. We applied this acceleration scheme to 7 MeV/nucleon $^{58}Ni^{8+}$ and $^{65}Cu^{8+}$, and 7.5 MeV/nucleon $^{40}Ar^{5+}$ beams; 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 will 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.

Although the NEOMAFIOS suits the use inside the high voltage terminal, its performance is much lowered as compared with the 10 GHz AVF ECR ion source. Thus, as the next project, we have decided to construct a new injector consisting of an over 10 GHz ECR ion source and RFQ linac in order to upgrade beam intensity for heavy ions by one or two order of magnitude. Here it is crucial for us to develop a frequency-tunable RFQ. The extreme case required for the RFQ corresponds to the maximum energy 90 keV/nucleon of ions having a mass-to-charge ratio of 5 at 40 MHz. This project is scheduled to complete within two years.

3. References

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