Upgrade project of the AVF cyclotron facility

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1 Introduction

The RCNP AVF cyclotron was constructed in 1973 [1] and has been used for many experimental studies in nuclear physics, atomic physics and interdisciplinary fields. Since the completion of the ring cyclotron in 1991 [2], the AVF cyclotron has been mainly used as an injector of the cyclotron cascade system. The cascade system has provided high quality beams for various experiments. At present, the beam quality extracted from the ring cyclotron is restricted by the performance of the injector AVF cyclotron. An upgrade proposal of the AVF cyclotron facility was approved as a one-year project in 2004 to improve the performance as well as to renew old components which it is now difficult to repair. Following items are included in the project.

1. New accelerating system with a flat-top system.
2. An 18 GHz ECR ion source to produce highly charged heavy ions. A polarized Li^{3+} ion source is developed by ionizing optically pumped atoms.
3. A beam line to deliver beams from the AVF cyclotron to experimental halls of the ring cyclotron facility.
4. An accelerator control system consisting of personal computers connected each other by a local area network.
5. Power supplies for trim coils and beam line magnets.

2 Accelerating system

The flat-top acceleration system of the RCNP ring cyclotron is indispensable for operation of the cyclotron to accelerate high quality beams. The flat-top system operates successfully to provide beams with very low energy spreads and high extraction efficiencies [3]. From our operational experiences, the beam quality extracted from the ring cyclotron is primarily determined by the performance of the injector AVF cyclotron. To improve furthermore the beam quality of the AVF cyclotron, a flat-top system is proposed. A horizontal cross section of the AVF cyclotron is shown in Fig. 1. The AVF cyclotron is of the three-sector type and has a single 180-degree dee with the coaxial quarter wavelength resonator. The acceleration RF power is fed through the main power feeder. An additional FT resonator and a power feeder for the flat-top system are capacitively coupled to the dee electrode at the other side as shown in Fig. 1. The system generates a flat-top voltage by superposing the

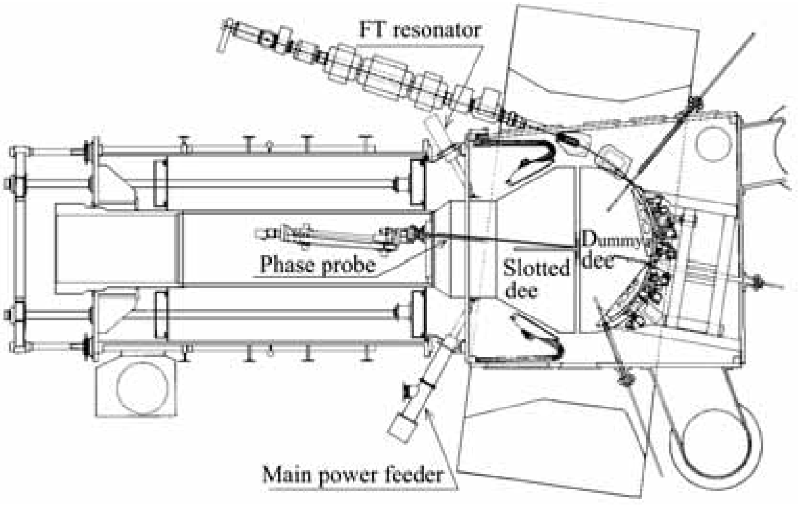

Figure 1: Horizontal cross section of the RCNP AVF cyclotron.

fundamental and odd higher harmonic voltage [4]. Designed flat-top frequencies are of fifth, seventh and ninth harmonic of the fundamental acceleration frequencies. The flat-top system fully covers the frequency range of acceleration.

The possibility of the flat-top system has been examined by using a one fifth scale model resonator. The specifications of the RF system for the AVF cyclotron are summarized in Table 1. The maximum RF power was estimated with the model resonator and an equivalent circuit model analysis. At the lowest frequency of the flat-top system, the voltage or the current density at the resonator is limited by the insulation and cooling power. At the ninth harmonic frequency with the present system, the maximum voltage and current density is 80 kV peak and 50 A/cm, respectively, in the low acceleration frequency region.

Table 1: Specifications of the RF system of the RCNP AVF cyclotron.

Accelerating frequency	6-18 MHz
Max. accelerating voltage	100 kV peak
Max. accelerating RF power	400 kW
Flat-top harmonic number	5, 7, 9
Max. flat-top voltage	5 kV peak
Max. Q-value of flat-top RF power	15 kW
Max. flat-top resonator voltage	80 kV peak
Max. flat-top resonator current density	50 A/cm

The 180-degree dee electrode of the AVF cyclotron may have a transverse resonance mode, of which frequency is in the region of the flat-top frequency. Measured resonance frequencies of the one fifth model resonator are shown in Fig. 2. A transverse resonance mode of frequency 382 MHz is observed in addition to the coaxial TEM mode resonance. This resonance mode has a node at the center of the acceleration electrode, and the RF phase becomes 180 degrees there. Therefore around this frequency region, it is impossible to generate higher harmonic voltage with a flat voltage distribution along the acceleration gap [5]. To get around the difficulty, a new slotted dee is proposed. As shown in Fig. 1, there is a slot at the center of the dee electrode. The one fifth model was used to investigate effects on the voltage distribution caused by the slot. With the slot, the resonant frequency of the transverse mode is reduced about 130 MHz as shown in Fig. 2. No effect is observed for the fundamental mode resonance, nor for the higher mode of the acceleration and flat-top voltage. Because of the structure of the resonator, flat-top resonance modes have the same voltage distribution. So the flat-top system is effective all over the accelerating region [6]. Based on the result of model tests and analyses of the equivalent circuit, the width and the length of the slot was determined to 10 mm and 1000 mm, respectively. Deterioration of mechanical rigidity caused by the slot is estimated to be small. The slotted structure has enough stiffness against the deformation or vibration. There are no jointing insulators at the slot. Figure 3 (left) shows a photograph of the dee electrode and the insert with the slot.

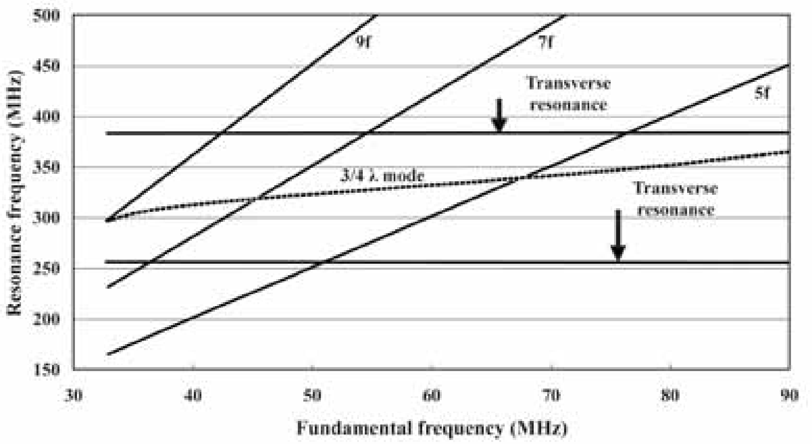

Figure 2: Resonance frequencies measured with the one fifth scale model resonator. Frequencies in the figure are five times larger than those of the actual cavity. Higher harmonic flat-top frequencies are labelled by 5f, 7f and 9f. The dotted curve shows the coaxial TEM mode resonance.

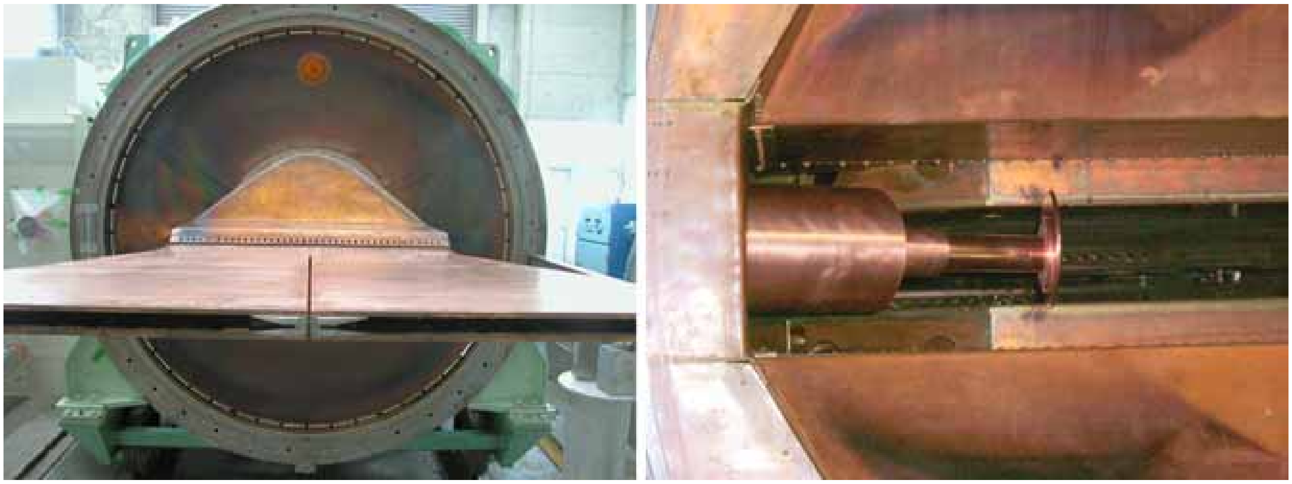

Figure 3: Left: Photograph of the dee electrode and the insert with a slot. Right: Photograph of the flat-top resonator and power feeder.

The flat-top resonator is a quarter wavelength coaxial type which is shown in Fig. 3 (right). The diameter of the water cooled outer conductor is 170mm. The maximum length of the resonator is about 700 mm. A 1 kW transistorized wide band amplifier is used as the flat-top RF power source. Control system for the flat-top RF signal is similar to that of the flat-top system of the ring cyclotron [3]. The tetrode of the main accelerating system is changed from RCA4648 to RS2042SK by Siemens. The maximum power of the main RF source is 400 kW and that of the driver source is 20 kW, which consists of 16 units of transistorized amplifiers.

3 Ion sources

At present, the AVF cyclotron is equipped with an atomic beam type polarized ion source, HIPIS [11], and a 10 GHz Electron Cyclotron Resonance (ECR) ion source which is made of permanent magnets, NEOMAFIOS [8]. The K-value of the AVF and ring cyclotron is 120 and 400 MeV, respectively. The resonance conditions for accelerations of various ions by the AVF cyclotron are shown in Fig. 4. The ratio of the extraction to injection

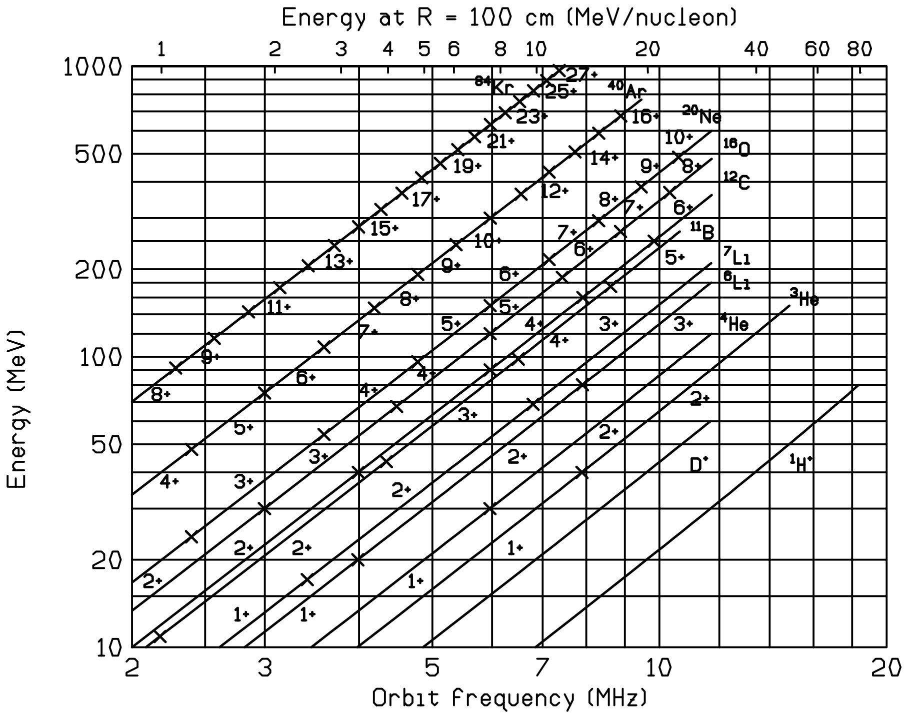

Figure 4: Resonance conditions for ion acceleration by the RCNP AVF cyclotron.

radius of the ring cyclotron is 2 and the ring cyclotron quadruples energies of heavy ions from the AVF cyclotron. The heaviest nucleus ever accelerated by the ring cyclotron is ^{18}O. A new 18 GHz superconducting ECR ion source (SCECRIS) is introduced to provide high intensity heavy ion beams at intermediate energies. The design of the SCECRIS follows RAMSES at RIKEN [9]. However, the inner diameter of the sextupole magnet is increased to 90 mm from 80 mm of RAMSES, and that of the plasma chamber to 80 mm from 70 mm. The field strength of the sextupole magnet at the radius of 36mm is measured to be 820 mT and is high enough to confine the resonance surface in the plasma chamber. At RIKEN, they report the beam intensities of 20 and 5 eμA for Kr25+, 27+, respectively. Higher charged Kr ions than 20+ can be accelerated in the fundamental mode (6-18 MHz) and lower charged ions are accelerated in the third harmonic mode. The RCNP cyclotron facility is expected to become able to provide heavy ions at 1-100 MeV/nucleon with reasonable intensities.

A polarized ^{6,7}Li^{3+} ion source is being developed to expand experimental possibilities on spin- and isospin-excitations of nuclei at intermediate energies. Polarized ^{6,7}Li^{1+} ions are produced by surface-ionizing optically pumped atoms. This technique has been well established at Florida State University [10]. The SCECRIS is utilized as a charge breeder to obtain fully stripped Li ions. Extensive numerical simulations have been performed to estimate the expected polarization, since a depolarization is anticipated in the ECR plasma [**?**]. Polarizations of Li^{3+} ions are expected higher than 50 % and they strongly depend on the plasma parameters [12]. Design of components has been almost completed and they are now under fabrication. Performance of each component will be tested this summer. Laser systems both for pumping and polarimetry have already been purchased.

A beam line from the ion source is designed to manipulate the spin direction of ^{6}Li^{3+} ions. The schematic layout of the line is shown in Fig. 5. The dipole magnet has a bending angle of 110 degrees and the following electrostatic deflector bends ions by 20 degrees in the opposite direction. The magnetic moment (g-factor) of the ^{6}Li nucleus is 0.822. ^{6}Li^{3+} ions are longitudinally polarized after the SCECRIS and the polarization axis is rotated by 90 degrees with the 110-degree bending magnet and is not affected by the electric field of the deflector. Then ^{6}Li^{3+} ions are still polarized along the beam direction after the electrostatic deflector. A Wien filter can be rotated along the beam axis and makes it possible to put the nuclear spin in any direction before injecting the beam into the AVF cyclotron.

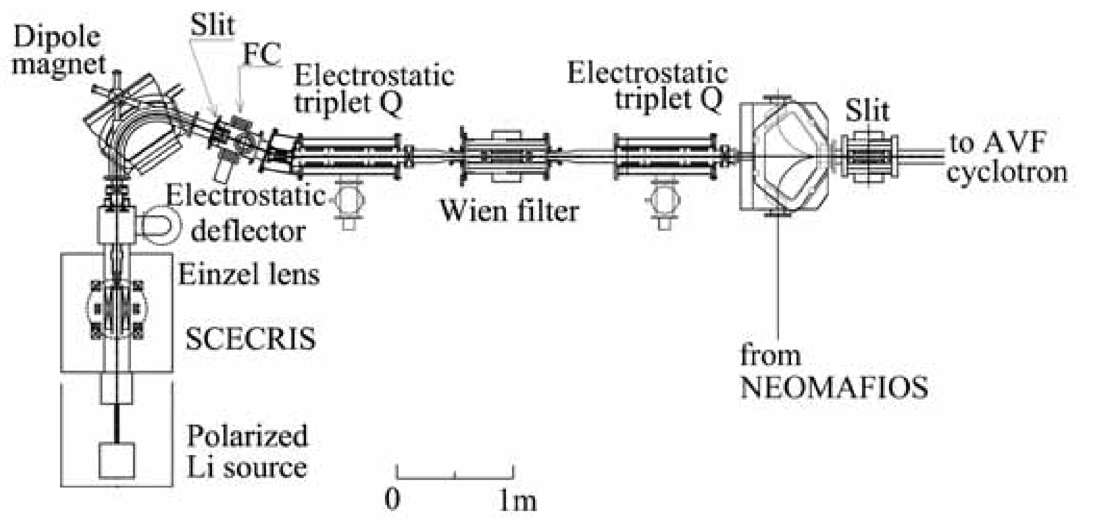

Figure 5: Schematic layout of the beam line from the SCECRIS.

4 New beam line

A new beam line is installed to bypass the ring cyclotron and to directly deliver low energy and high intensity beams from the AVF cyclotron to the experimental halls where such sophisticated apparatuses are available as magnetic spectrometers, the neutron TOF facility, the secondary beam separator, etc. It is expected to increase research possibility at the cyclotron facility. The schematic layout of the beam line is shown in Fig. 6. In addition, the line from the “source point” in the figure to the “focus point” serves to diagnose the quality of the beam which is injected into the ring cyclotron. As mentioned above, the quality of the beam on targets from the ring cyclotron is primarily determined by that of the injected beam from the AVF cyclotron. However, there have been no available diagnostic devices to precisely measure its emittance and energy spread before injection. Two 90-degree dipole magnets have a bending radius of 1200 mm. They have round pole faces to reduce ion optical second order aberrations. The momentum dispersion of the analyzing section is designed to be 12.6 m. Parameters of the AVF cyclotron and the transfer beam line to the ring cyclotron will be optimized by referring to the beam characteristics.

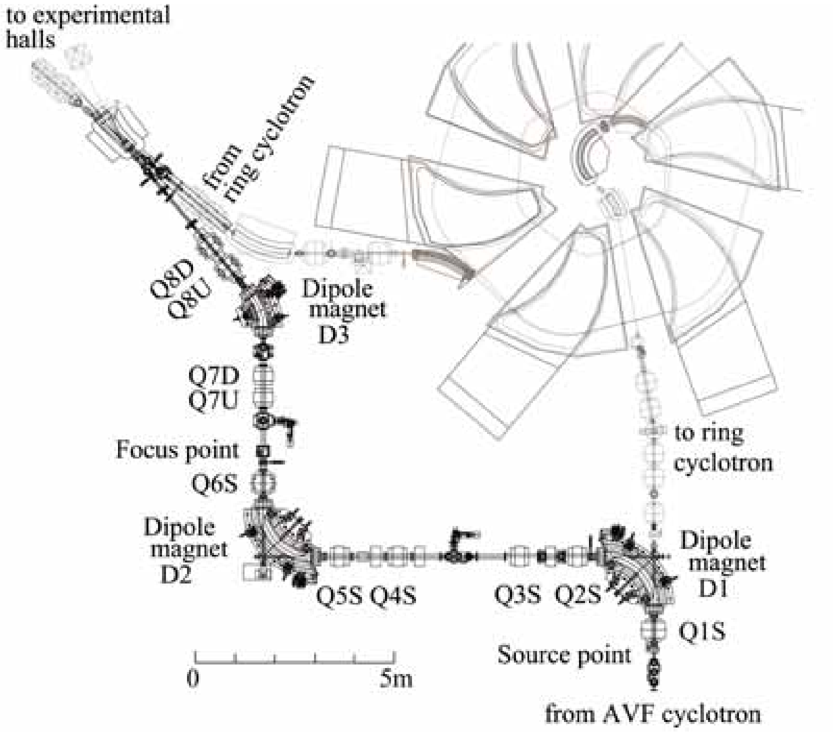

Figure 6: Schematic layout of the beam line to analyze the quality of the beam from the AVF cyclotron as well as to directly deliver low energy and high intensity beams to experimental halls of the ring cyclotron.

5 Control system

The previous accelerator control system consists of a system control unit (SCU) and 6 group control unit (GCU) [13]. They are micro VAX computers and connected to the network system of the computer complex of the cyclotron facility. Recently it has become difficult to support VAX computers and they are replaced by personal computers (PC). The new SCU consists of three equivalent sets of consoles each of which is a cluster of three PC's. The existing message tree communicator (MTC), message tree branchers (MTB) and the universal device controllers (UDC) are still used in the new system, since they are front end devices closely connected to hardwares [14]. For such components newly fabricated in the upgrade project as power supplies, a system of controller and communicator is prepared based on programmable logic controllers (PLC). Two PC's are devoted for monitoring statuses of accelerator components, and for saving accelerator parameters. The InTouch language is used for programing SCU softwares.

6 Power supplies

Thirteen out of sixteen trim coil power supplies were fabricated 35 years ago and it is difficult to repair them today, since most electrical parts are not commercially available. The specifications of new power supplies were determined from intensive studies on beam dynamics in the AVF cyclotron performed for one year. With the newly developed computer code, new sets of trim coil currents were obtained to reproduce isochronous fields. They are used as initial values of trim coil currents, and fine adjustments are enough to get the isochronous fields monitored by the phase excursion of accelerated beams. With this procedure and by reducing the phase spread of the injected beam at the central region of the AVF cyclotron, we can obtain good turn separations at almost whole radius and extract beams in a single turn even for the case of high energy (65 MeV) protons. Table 2 summarized specifications of new power supplies and their stabilities measured for eight hours.

Table 2: Specification of the power supplies for trim coils, dipole and quadrupole magnets

Coil or magnet	Max. current (A)	Max. voltage (V)	Polarity	Stability (/8h)	Ripple
Trim #1	1000	12	no	0.64×10^{-5}	0.29×10^{-7}
Trim #2	500	6	yes	0.78×10^{-5}	0.10×10^{-6}
Trim #3	500	6	yes	0.70×10^{-5}	0.15×10^{-5}
Trim #4	300	5	yes	0.88×10^{-5}	0.81×10^{-5}
Trim #5	300	5	yes	0.78×10^{-5}	1.53×10^{-5}
Trim #6	300	5	yes	0.80×10^{-5}	0.31×10^{-5}
Trim #7	300	5	yes	0.63×10^{-5}	0.51×10^{-5}
Trim #8	300	5	yes	1.00×10^{-5}	0.54×10^{-5}
Trim #9	300	5	yes	0.88×10^{-5}	1.04×10^{-5}
Trim #10	300	5	yes	0.80×10^{-5}	0.28×10^{-5}
Trim #11	300	5	yes	0.48×10^{-5}	0.34×10^{-5}
Trim #12	500	6	yes	0.89×10^{-5}	0.10×10^{-6}
Trim #16	300	5	no	0.48×10^{-5}	0.34×10^{-5}
Mag. channel	1000	6	no	0.79×10^{-5}	0.20×10^{-5}
Dipole A1	450	70	no	0.42×10^{-5}	0.30×10^{-6}
Dipole A2	450	70	no	0.83×10^{-5}	0.13×10^{-6}
Dipole A3	450	45	no	0.69×10^{-5}	0.42×10^{-6}
Quad. magnet	75	45	no	0.40×10^{-4}	0.60×10^{-5}
Quad. magnet	35	40	no	0.30×10^{-4}	0.80×10^{-5}

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