

RCNP CYCLOTRON FACILITY

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Abstract

The Research Center for Nuclear Physics (RCNP) cyclotron cascade system has been operated to provide high quality beams for various experiments. In order to increase the physics opportunities, the Azimuthally Varying Field (AVF) cyclotron facility was upgraded recently. A flat-topping system and an 18 GHz superconducting Electron Cyclotron Resonance (ECR) ion source were introduced to improve the beam's quality and intensity. A new beam line was installed to diagnose the characteristics of the beam to be injected into the ring cyclotron and to bypass the ring cyclotron and directly transport low energy beams from the AVF cyclotron to experimental halls. A separator is equipped to provide RI beams produced by fusion reactions at low energy and by projectile fragmentations at high energy. Development has continued to realize the designed performance of these systems.

INTRODUCTION

The Research Center for Nuclear Physics (RCNP) is a national users facility founded in 1971 and is the major research institute for nuclear physics in Japan. RCNP, as a national laboratory, is open to all users in Japan and from abroad. The cyclotron facility is its major facility and consists of an accelerator cascade and sophisticated experimental apparatuses. Research programs cover both pure science and applications. Demands for industrial applications have been growing more and more.

A schematic layout of the RCNP cyclotron facility is shown in Fig. 1. The accelerator cascade consists of an injector Azimuthally Varying Field (AVF) cyclotron ($K=140$) and a ring cyclotron ($K=400$). It provides ultra-high-quality beams and moderately high-intensity beams for a wide range of research in nuclear physics, fundamental physics, applications, and interdisciplinary fields. The maximum energy of protons and heavy ions are 400 and 100 MeV/u, respectively. Sophisticated experimental apparatuses are used like a pair spectrometer, a neutron time-of-flight facility with a 100-m-long tunnel, a radioactive nuclei separator, a super-thermal ultra cold neutron (UCN) source, a white neutron source, and a RI production system for nuclear chemistry. Such ultra-high-resolution measurements as $\Delta E/E=5 \times 10^{-5}$ are routinely performed with the Grand-Raiden spectrometer by utilizing the dispersion matching technique. The UCN density was observed to be 10 UCN/cc at the experimental port at a beam power of 400 W. The white neutron spectrum was calibrated and the flux was estimated to be 70% of that obtained at Los Alamos Neutron Science Center (LANSCE) in the USA.

Neutrons are used for the radiation effect studies on integrated circuits and so on.

User's demands on the beam characteristics are expanding rapidly: ultra-high resolution, high intensity, a variety of heavy ions, and so on. Since there are no slits or collimators in the beam lines after the ring cyclotron, the beam quality on targets is determined by the characteristics of the beam from the AVF cyclotron. The injector upgrade program for these items is in progress [1-3]:

1. a new acceleration system with a flat-top system,
2. an 18 GHz Electron Cyclotron Resonance (ECR) ion source to produce highly charged heavy ions,
3. a polarized Li^{3+} ion source,
4. a beam line to diagnose the beam characteristics from the AVF cyclotron and to deliver low energy beams to the experimental halls,
5. renewal of power supplies of 13 trim coils and magnetic channels,
6. renewal of 100-kW power supplies for the analyzing magnet and the switching magnet
7. renewal of the accelerator control system by using a PC-based distributed system with a network.

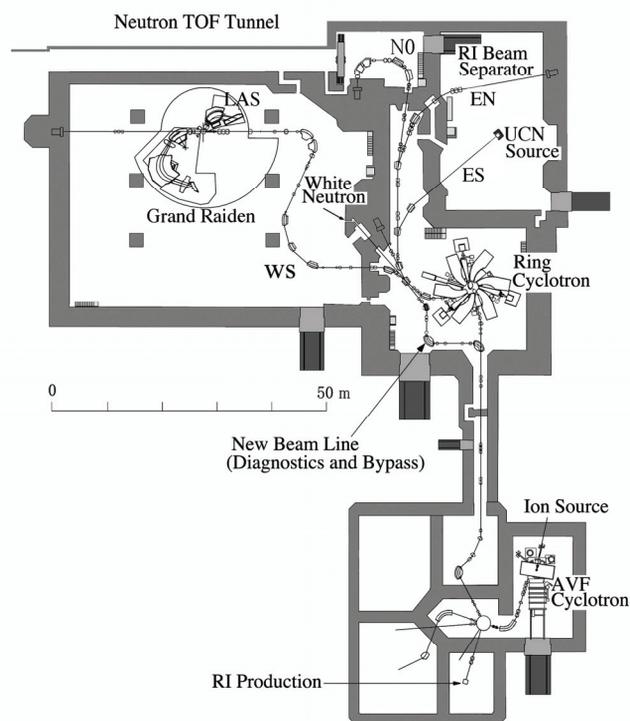


Figure 1: Layout of the RCNP cyclotron facility.

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ECR ION SOURCE

An 18 GHz superconducting ECR ion source was installed in order to increase beam currents and to extend the variety of ions, especially for highly-charged heavy ions, which can be accelerated by RCNP cyclotrons. The production development of several ions beams and their acceleration by the AVF cyclotron has been performed since 2006.

Fig. 2 shows a cross sectional view of the source. The source was designed based on RAMSES [4] at RIKEN, but the inner diameter of the hexapole magnet and of the plasma chamber were extended to 90 and 80 mm, respectively, due to the experience with their development. The mirror magnetic field is produced with four liquid-helium-free superconducting coils, which are cooled by two Gifford-McMahon refrigerators and which are installed in a cryostat chamber covered by iron magnetic shields. Upstream coil 1 (U1) and downstream coil (D) are of the same size and are excited in series by using a common power supply. Central coil (C) and upstream coil 2 (U2) are excited by using independent power supplies, and the mirror magnetic field distribution is controlled quite flexibly. Typical simulated (by TOSCA) magnetic field inductions created on the axis by each coil are shown in Fig. 3. Typical operating currents are 36.3 A, 36.9 A, and 60.5 A for the U1+D, C, and U2 coils, respectively. The maximum current for each coil is 66 A.

The permanent magnet hexapole is of the Halbach type, with 24 pieces of NEOMAX-44H material. The radial field strength is 1.0 T on the stainless-steel plasma chamber's inner diameter. The diameter and the length of the plasma chamber are 80 mm and 380 mm, respectively.

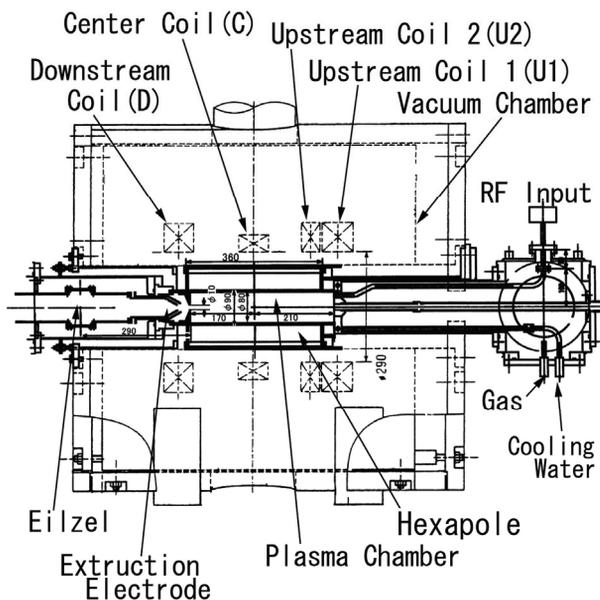


Figure 2: Cross-sectional view of a liquid-helium free 18 GHz superconducting ECR ion source.

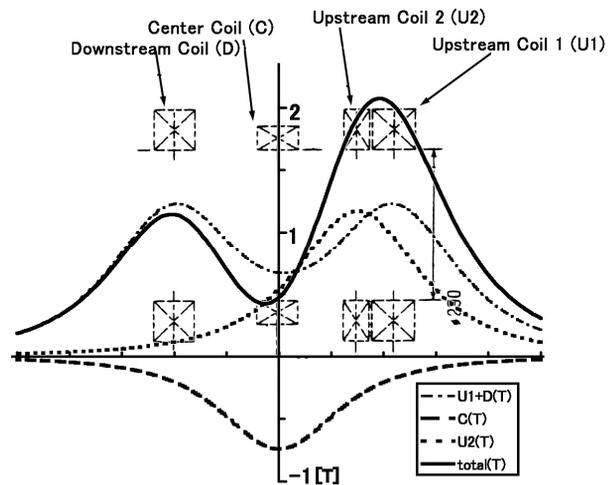


Figure 3: Simulated magnetic field distribution.

In order to improve the performances of the source, a liner was inserted. Tests have been performed with two different thicknesses and materials (1 and 3.5 mm; pure aluminium and aluminium coated with Al₂O₃). In the latter case, it was difficult to get stable operation due to discharge or degassing from the liner.

A bias probe was installed on the beam axis on the injection side. The maximum applicable voltage is -500 V relative to the plasma chamber, and the probe position is variable between 120 and 220 mm from the center of the C coil. The optimum position is located at 170-190 mm, which corresponds to the position of the maximum mirror field. The extraction system is composed of two electrodes and can be moved along the beam axis. An einzel lens is placed downstream of the extraction electrode.

The ion beams extracted from the source are analyzed by using a dipole magnet (AM) and are measured in a Faraday cup (FC) placed at the image focal point of the analyzing magnet. Fig. 4 shows the typical charge-state distribution of ⁸⁶Kr ions obtained by using oxygen as a gas mixing. Table 1 summarizes the performance of the source. ⁸⁶Kr^{21+, 23+} ions were accelerated for the first time by using the AVF cyclotron and were delivered to user's experiments.

In order to produce metallic boron-ions, a test by using the MIVOC (Metal Ion from Volatile Compounds) method [5] was performed using o-carborane (C₂B₁₀H₁₂). Its vapor pressure was around 1-2 Torr at the room temperature. The stable flow of the vapor from the o-carborane powder to the plasma chamber enabled us to produce a stable boron-ion beam. The o-carborane was put in a glass vessel directly connected to the plasma chamber via a buffer tank. A helium support gas was used as the mixing gas. Different support gases were tested to optimize the ¹¹B⁵⁺ intensity. With oxygen, we were not able to produce ¹¹B⁵⁺; with hydrogen, the current was divided by three with respect to the current for helium.

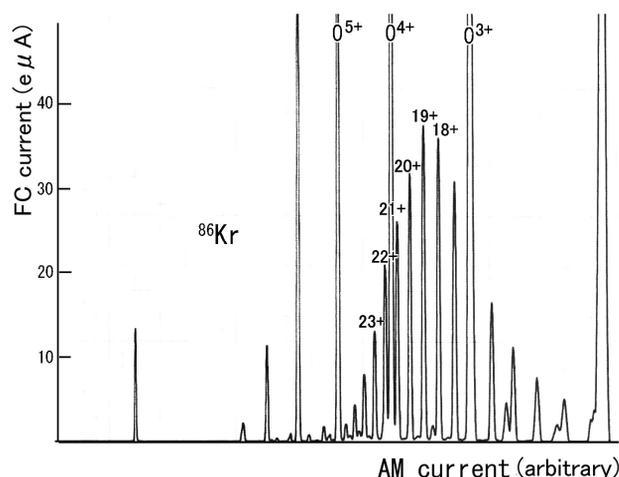


Figure 4: Charge state distribution of ^{86}Kr ions with a 700-W RF power and oxygen mixing.

Table 1: Ion Currents (μA) Obtained by the RCNP 18 GHz ECR Ion Source

	RF						RF
	2+	3+	4+	5+	6+	7+	(W)
^{11}B	1.3	4.1	9.3	8.2			400
^{12}C			410	115			500
^{15}N		167	477	725	117		500
^{16}O	10	178		779	517	27	500
^{18}O		88	235	475	673	39	500
	11+	12+	13+	14+			
^{40}Ar	188	70	17	3			500
	20+	21+	22+	23+	24+	25+	
^{86}Kr	32	26	21	13	8.1	4.5	600
	28+	29+	30+	31+	32+	33+	
^{136}Xe	11.3	10.6	8.8	6.2	4.2	2.3	770

FLAT-TOPPING ACCELERATION SYSTEM

A schematic layout of the main and the flat-top resonators of the AVF cyclotron is shown in Fig. 5. An additional flat-top cavity of a coaxial movable-short type is capacitively coupled to the main resonator on the opposite side of the main power feeder for fundamental-voltage production. The flat-top cavity has a length of 700 mm and an outer diameter of 170 mm. A full stroke of the shorting plate of the flat-top cavity is 100 mm. The coupler electrode and the inner conductor of the flat-top cavity are shown in Fig. 5. The gap between the coupler electrode and the inner tube of the main cavity can be changed from 0 to 155 mm. Fine adjustment for 50 Ω impedance matching is accomplished by using a tuner with a full stroke of 40 mm.

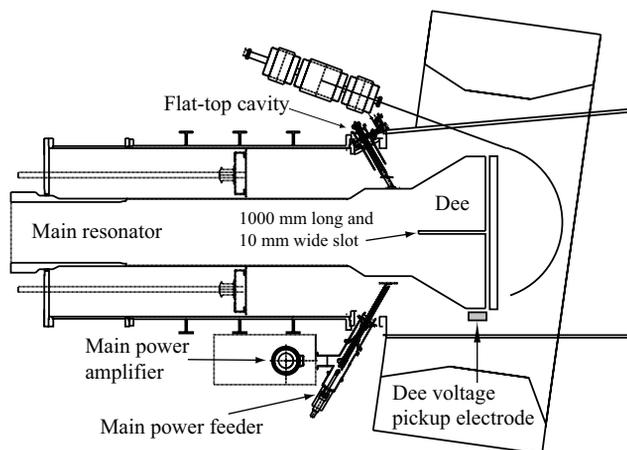


Figure 5: Layout of the RCNP AVF Cyclotron.

A flat-topped dee voltage waveform can be generated by superimposing a harmonic voltage on the fundamental one [6]. The main parameters of the RF system are listed in Table 2. The RF power from a 10-kW transistor amplifier is transmitted to the flat-top resonator through a coaxial waveguide (WX39-D). The input impedance is adjustable by changing the capacitance of the feeder capacitor between 5 and 250 pF. Impedance matching of the 50- Ω transmission line from the flat-top cavity to the main resonator is optimized by adjusting the positions of the coupler, the shorting plate, the tuner, and the feeder capacitor. Impedance matching can be achieved over a wide range of harmonic frequencies from 50 to 80 MHz. Hence, the fifth, seventh, and ninth harmonic modes are available for production of the flat-topped voltage waveform. Such higher order harmonic modes have an advantage of saving power for the harmonic voltage production, because the n -th harmonic voltage required for flat-top waveform production is $1/n^2$ of the fundamental one [7].

A parasitic resonance mode is known to exist originally around 76 MHz. This resonance is generated in the transversal direction of the dee electrode axis. There is some possibility of the parasitic resonance's interference with the fifth harmonic voltage production for the flat-top acceleration of higher energy protons. In order to shift the transversal resonance frequency to around 55 MHz, we replaced the original dee electrode with a new one with a 1000-mm-long and 10-mm-wide slot along the electrode axis, as shown in Fig. 5.

New dee-voltage pickup electrodes were installed near the acceleration gap of the dee electrode. The four pickup electrodes were mounted on a copper block facing the side of the dee electrode. Two pickup electrodes were designed to have a pickup signal level ratio of $1/10^4$ and are used for fundamental voltage regulation and RF reference signal supply to users and control systems of a beam buncher and a beam chopper. The pickup signal with a ratio of $1/10^5$ is used for monitoring the flat-top voltage waveform at the console in the operating room.

Other pickup electrodes provide a harmonic signal for the low-level control of the flat-top resonator.

Table 2: Main Parameters of the RF System

Fundamental frequency	6 - 18 MHz
Maximum acceleration voltage	60 kV peak
Flat-top: harmonic number	5, 7, 9
Flat-top: harmonic frequency	54 - 80 MHz
Flat-top: maximum harmonic voltage	5 kV peak
Flat-top maximum Q-value of resonator	2000
Flat-top: maximum RF power	10 kW
Flat-top: maximum voltage of resonator	80 kV peak
Flat-top: maximum current density	50 A/cm

The performance of the flat-top acceleration system was investigated in power tests using the following fifth harmonic frequencies: 77.084 MHz for 53 MeV protons (to be accelerated up to 300 MeV by using the ring cyclotron), 50.582 MHz for 44 MeV deuterons (200 MeV), 58.250 MHz for 88 MeV $^3\text{He}^{2+}$ (420 MeV), and 50.720 MHz for 87 MeV $^4\text{He}^{2+}$ (400 MeV). We have also succeeded in generating the seventh and the ninth harmonic voltages at 71.008 MHz for 87 MeV $^4\text{He}^{2+}$ (400 MeV) and 60.750 MHz for 19 MeV deuterons (80 MeV), respectively. An example of a flat-top voltage waveform observed at 77.084 MHz is shown in Fig. 6.

Development of a flat-top accelerated beam is now in progress. In order to obtain a high-quality beam with an energy spread of less than $\Delta E/E = 5 \times 10^{-4}$, a beam phase width has to be defined within several RF degrees by using two pairs of phase defining slits placed in the center region of the AVF cyclotron, which causes a sharp decrease in the beam intensity. In the case of fundamental acceleration, the beam phase width must be reduced to 4 RF degrees or less. The beam phase acceptance can be increased to more than 10 RF degrees by the flat-top acceleration within the limits of the phase acceptance of the ring cyclotron. In both cases, the beam buncher installed in the injection beam line plays a significant role in increasing the beam intensity. The flat-top acceleration and single-turn extraction from the AVF cyclotron are indispensable for producing a high-quality beam from the ring cyclotron.

The 300 MeV proton beam, accelerated using the injection beam of flat-top-accelerated 53 MeV protons, was transferred to a gold target in an achromatic mode, and the energies of elastically-scattered particles were analyzed with the Grand-Raiden spectrometer for a beam-quality evaluation. The energy resolution of the elastic peak was estimated to be $\Delta E/E = 1 \times 10^{-4}$. The beam intensity of the high quality proton beam was remarkably increased by a factor of four.

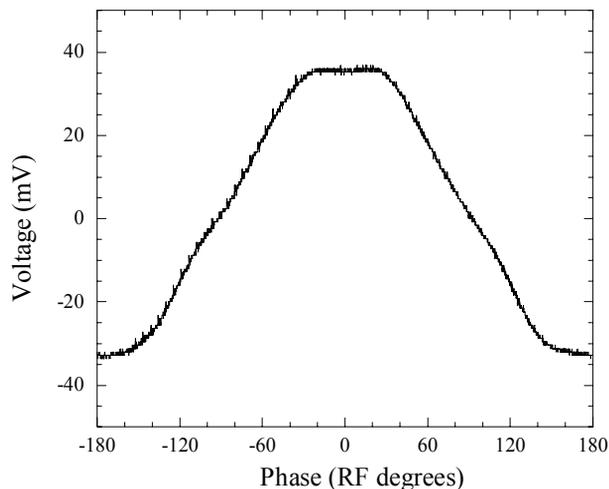


Figure 6: Example of the flat-top voltage waveform observed at 77.084 MHz with the dee voltage pickup electrode.

DIAGNOSTIC AND BYPATH BEAM LINE

A new beam line was installed to bypass the ring cyclotron and to directly deliver low-energy, high-intensity beams from the AVF cyclotron to the experimental halls, where sophisticated apparatuses are available. It is expected to increase research opportunities at the cyclotron facility. The schematic layout of the beam line is shown in Fig. 7. In addition, the part from the “source point” in the figure to the “focus point” serves to diagnose the quality of the beam injected into the ring cyclotron. As mentioned above, the quality of the beam on target from the ring cyclotron is primarily determined by the characteristics of the injected beam from the AVF cyclotron. However, there were no available diagnostic devices to precisely measure the emittance and energy

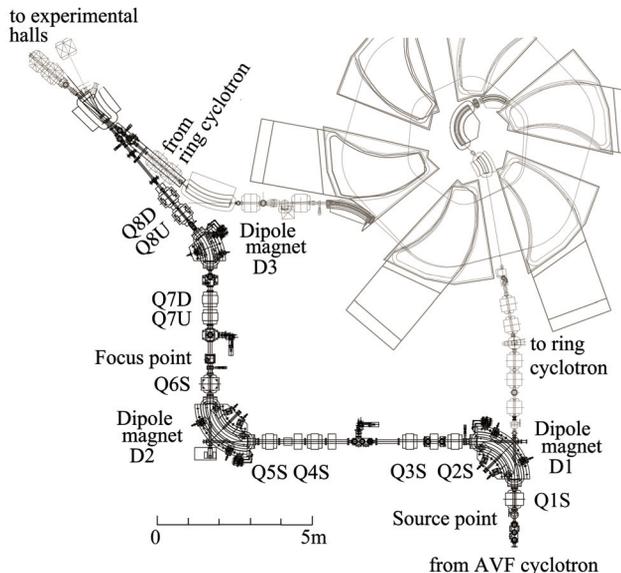


Figure 7: Schematic layout of the beam line to analyze the quality of the beam from the AVF cyclotron and to directly deliver low-energy, high-intensity beams to the experimental halls of the ring cyclotron.

spread before injection. Two 90-degree dipole magnets have a bending radius of 1200 mm. They have round pole faces to reduce the ion optical second-order aberrations. The momentum dispersion of the analyzing section is designed to be 12.6 m. The parameters of the AVF cyclotron and the transfer beam line to the ring cyclotron can be optimized by referring to the measured beam characteristics.

SUMMARY

The upgrade of the RCNP cyclotron cascade has been successfully started and is being continued. The beam quality and the intensity of 300 MeV protons have been improved by using flat-top acceleration in the AVF cyclotron. Developments are being performed to apply the system to other beams. An 18 GHz superconducting ECR ion source has been commissioned to increase the beam intensity of highly-charged heavy ions; a 7.5 MeV/u $^{86}\text{Kr}^{23+}$ beam was delivered to experiments. A new beam line has been installed to diagnose the beam characteristics from the AVF cyclotron and to help match it to the acceptance of the ring cyclotron. It also makes 10÷400 MeV protons and 1÷100 MeV/u heavy ions available for a variety of research in nuclear physics, fundamental physics, and interdisciplinary studies.

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