The Research Center for Nuclear Physics Ring Cyclotron

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Abstract

The main components of the new facility are a six sector variable energy ring cyclotron and a beam circulation ring linked to a high precision dual magnetic spectrograph system, a neutron TOF facility with a 100m neutron flight tunnel and a heavy ion secondary–beam facility.

The beams extracted from the RCNP AVF cyclotron are transported through one of the beam lines of the old facility and injected into the ring cyclotron. With this accelerator system, beams of p, d, ^{3}He, alpha and light-heavy ions are available in the wide range of energies of up to 400, 200, 510, 400 and 400·Q^2/A MeV, respectively. An emphasis is placed on the production of high quality beams to enable precise experiments.

These beams are extracted with single turn extraction mode with flat-topping. Beam energy width of 80 keV was achieved for 300 MeV proton. Energy resolution of 25 keV and 35 keV were obtained with high resolution spectrograph Grand Raiden by using dispersion matching for 300 MeV and 400 MeV proton inelastic scattering spectra, respectively. A very short polarized proton beam pulse of 150 ps was achieved for neutron TOF experiment.

I. INTRODUCTION

The Research Center for Nuclear Physics was founded in 1971, as a national user facility. A K=140 AVF cyclotron [1] and precise experimental apparatus were used during two decades by many researchers in Japan and abroad. After intensive design study of new facility, "RCNP Cyclotron Cascade Project" [2],[4] was proposed in 1985, to extend the high precision studies into energy region above threshold energy of pion production.

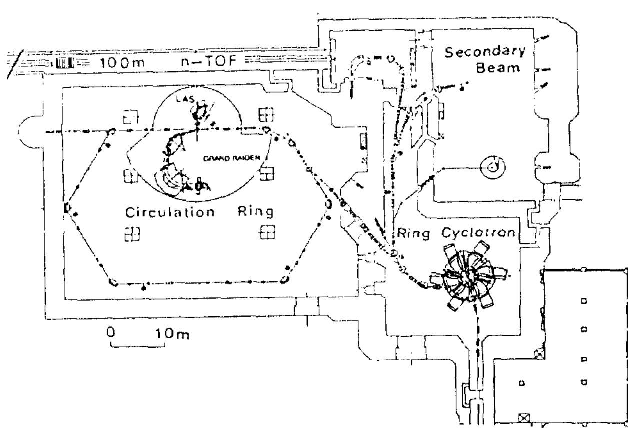

Fig. 1. Plan view of the new facility.

In 1986 the proposal was accepted and the four years cyclotron construction contract was made with manufacturer in August 1987.

The main components of the new facility are a six separated spiral sector cyclotron (ring cyclotron) and beam circulation ring linked to a high precision magnetic spectrograph Grand Raiden (p/Δp=39000,54 kGm) and a Large Acceptance Spectrograph (p/Δp=5000,32 kGm), a neutron TOF facility with a 100m neutron flight tunnel and a heavy ion secondary beam facility, as shown in Fig. 1.

Installation of the ring cyclotron was started in February 1990, immediately after finish of the Ring Cyclotron Hall. On December 1991, the first extracted beam of 300 MeV protons was obtained [7]. Figure 2 shows the photograph of the ring cyclotron.

The new system of the ring cyclotron had been tested and many improvements were made for the initial trouble of operation. These systems work well now and efforts being continued to improve beam quality, intensity and stability of the ring cyclotron.

The ring cyclotron is energy quadrupler of the RCNP AVF cyclotron. Protons and alpha particles can be accelerated up to 400 MeV. Plan view of the ring cyclotron is shown in Fig. 3. Three single gap acceleration cavities are used in the ring cyclotron. Frequency range of the cavity

Fig. 2. Photograph of the RCNP ring cyclotron.

is 30~52 MHz and harmonic numbers of acceleration is 6, 10, 12 and 18. An additional single gap cavity is used for flat-topping with 3rd harmonic of acceleration frequency to get good energy resolution and wide phase acceptance. The phase acceptance is 20° for energy deviation with flat-topping within 10^{-4}.

A 180°-single-dee acceleration cavity is used in the RCNP AVF cyclotron. The frequency range of the cavity is 5.5~19.5 MHz, and fundamental and 3rd harmonic acceleration modes are used. Figure 4 shows relation between orbital frequencies and acceleration frequencies in the AVF cyclotron and the ring cyclotron for various ions and energies. The characteristics of the cyclotrons are given in Table 1.

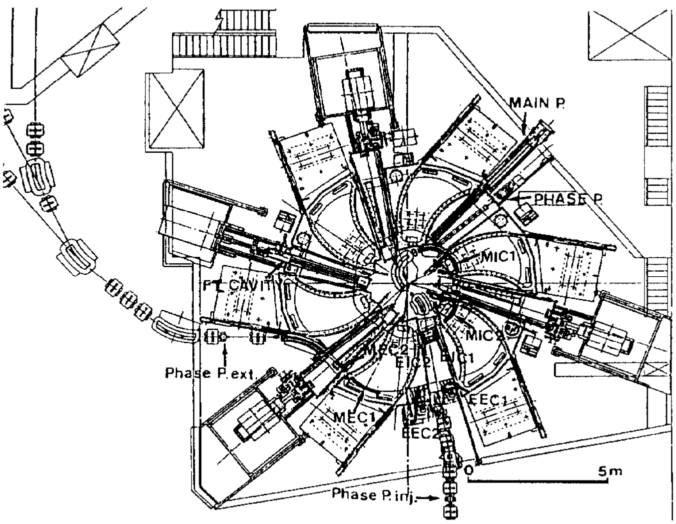

Fig. 3. Plan view of the ring cyclotron.

Table 1 Characteristic of cyclotrons

	AVF	Ring	
No. of sector magnets	3	6	
Sector angle	max 52°	22~27.5°	
Injection radius(cm)		200	
Extraction radius(cm)	100	404	
Magnet gap(cm)	20.7 min	6.0	
Max. Magnetic field(kG)	19.5	17.5	
Proton max. energy(MeV)	84	400	
Alpha particle energy(MeV)	130	400	
^{3}He energy(MeV)	160	510	
Weight of magnet(ton)	400	2200	
Main coil magnet(kW)	450	440	
No. of trim coils	16	36	
Trim coil power(kW)	265	350	
No. of cavities	1	3(Acc.)	1(FT)
RF frequency(MHz)	5.5~19.5	30~52	90~155
RF power(kW)	120	250×3	45

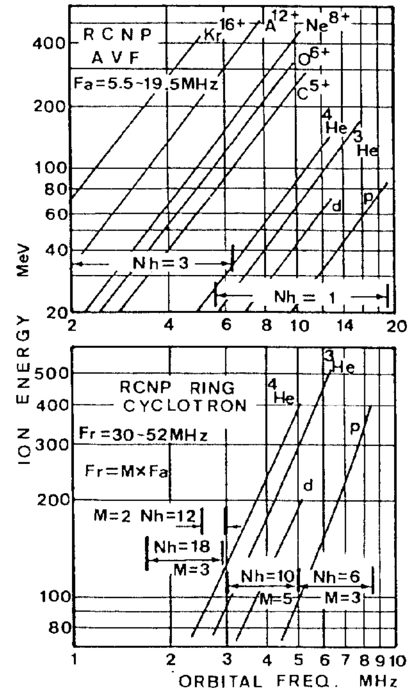

Fig. 4. Orbital frequencies, acceleration frequencies (Fa&Fr) and harmonic numbers of acceleration (Nh) in the RCNP AVF cyclotron and the RCNP ring cyclotron for various ions and energies. M is ratio of the acceleration frequency of the ring cyclotron to the AVF cyclotron.

II. MAGNETS OF THE RING

The magnets of the six spiral sector ring cyclotron was designed by using computer code FIGER (artificial magnetic field distribution generator) and the results of model magnet study of the previous proposal [3]. Figure 5 shows calculated field distribution with the code. The sector magnets are designed as isochronous for 200 MeV proton acceleration without trim coil current. The measured magnetic field distribution are quite satisfactory [8].

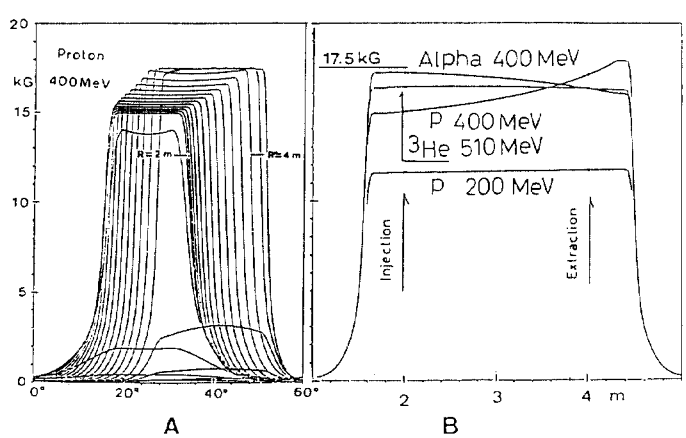

Fig. 5. A: Designed field distribution for 400 MeV proton. B: Designed isochronous fields on hill center for various ions.

Figure 6 shows comparison between betatron frequencies calculated from the measured magnetic field and the designed one.

Figure 7 shows the structure of the spiral sector magnet. 36 pairs of trim coils are mounted on the pole faces by SUS mild-steel welded bolts. Each trim coil is insulated with alumina-ceramics coating. The radial pole edges are shaped stepwise to the Rogowski's curve. The carbon content of the forged poles and rolled iron yokes are 0.004% and 0.002%, respectively. The median plane of the sector magnets are aligned with accuracy of ±0.2 mm. However, on 400 MeV proton beam acceleration, 30~50% of the accelerated beam was lost by axial oscillation driven with median plane error near $\nu_z=1$ resonance, on the orbit

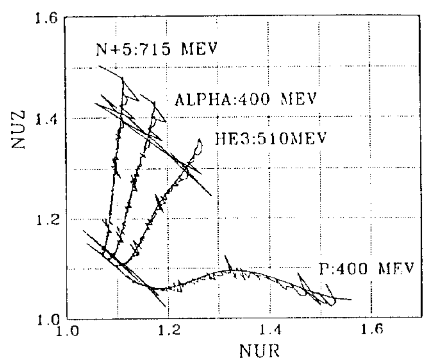

Fig. 6. Comparison between betatron frequencies calculated from the measured field and the designed one.

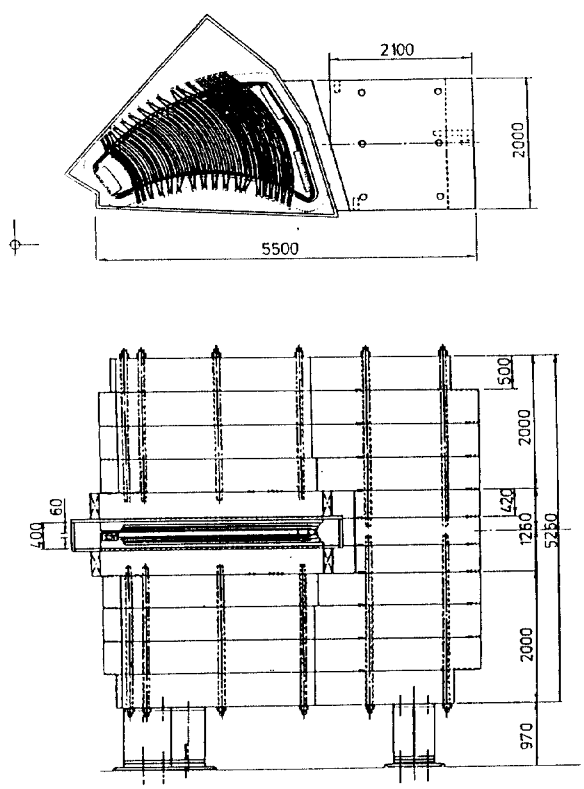

Fig. 7. Structure of the spiral sector magnet.

radius between 3 and 4 m. Three supplementary power supplies are installed to make median plan corrections by supplying different currents for the top and bottom of the auxiliary coil of the main coil on three individual sector magnets.

III. VACUUM SYSTEM

The vacuum chamber of the ring cyclotron consists of six magnet chambers, three acceleration cavity chambers, a flat-topping cavity chamber and two valley chambers as shown in Fig. 3. The gaps between these chamber are sealed by pneumatic expansion seals. These seals are working quite well [5]. The ring cyclotron is evacuated down to 1×10^{-7} Torr by six diffusion pumps with double chevron baffles (2,500ℓ/sec each eq.), three 16 inch cryopumps (6,500ℓ/sec each) with gate value and six 20 inch cryopumps (10,000ℓ/sec each).

IV. ACCELERATION SYSTEM

Figure 8 and 9 show schematic drawing of the acceleration cavity and the flat-topping cavity. The walls of the cavities are made of stainless steel 50 mm in thickness with water cooled copper lining 5 mm in thickness. The walls can not withstand atmospheric pressure under evacuation, so these walls are supported by the magnet chambers. After full assembly of the ring cyclotron, full power test of the RF system and baking of the cavities were made [9]. The variable frequency acceleration cavity is tuned with a pair of rotatable plates. Figure 10 shows radial voltage distributions of the acceleration cavity and the flat-topping cavity. The beam phase compression factor is about 0.5.

The RF power of the flat-topping cavity leaks easily to outside of the cavity, for asymmetric setting of the sliding shorts. RF shields of trim coil feed-through were set on the both side of the flat-topping cavity.

Acceleration frequency of the AVF cyclotron, generated by a frequency synthesizer, is used as clock signal of the ring cyclotron RF system. The clock signal is converted to acceleration, flat-topping, buncher, intermediate and various local frequencies. The intermediate frequency is used in phase control and auto tuning servo systems. Digital phase shifters, 0.03°/step, are working well on 455 KHz intermediate frequency. Achieved stability of cavity voltage and phase are now 10^{-4} and ±0.1°, respectively.

A maximum acceleration voltage of 530 keV was achieved. The turn separation for 400 MeV proton acceleration at injection and extraction points are 10 mm and 3 mm, respectively.

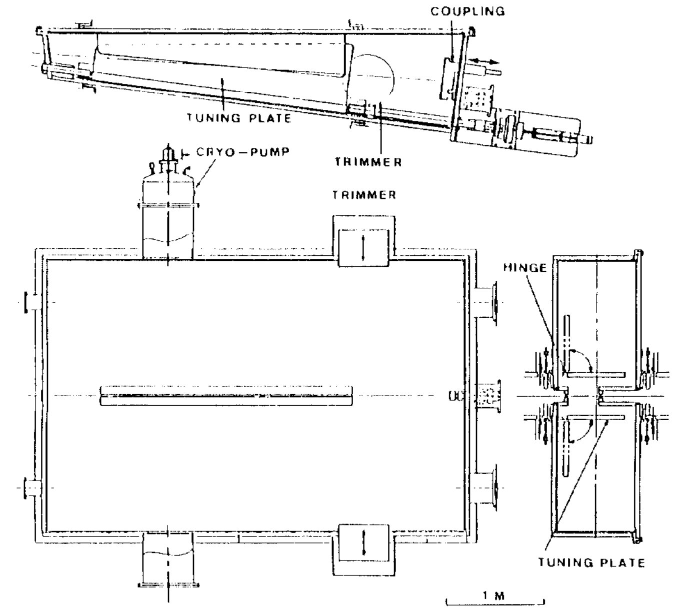

Fig. 8. Schematic drawing of the acceleration cavity.

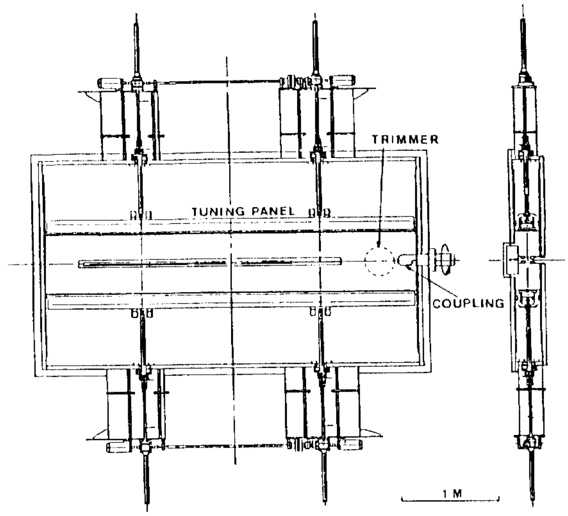

Fig. 9. Schematic drawing of the flat-topping cavity.

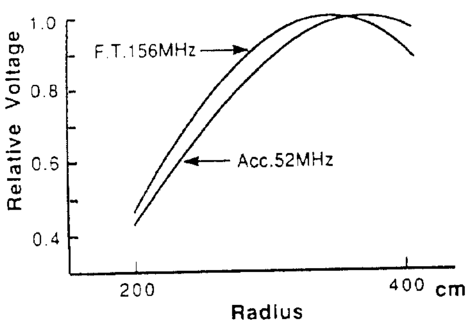

Fig. 10. Voltage distributions of the acceleration cavity and the flat-topping cavity.

V. INJECTION AND EXTRACTION SYSTEM

The maximum designed parameter of the injection and extraction system [6] are shown in Table 2. Various improvement of capability on injection and extraction elements were made in 1992. These system is working satisfactory as designed.

VI. AVF CYCLOTRON

The 20° phase acceptance of the ring cyclotron correspond to 7° and 4° for the acceleration frequency of the AVF cyclotron, since the ratio of acceleration frequency of the ring cyclotron to that of the AVF cyclotron is 3 and 5 for proton and alpha acceleration, respectively.

For internal ion source, an internal phase slit [1] and a post- injector beam buncher [9] (energy modulator with energy selector) are used to limit the beam phase width. A new beam phase selector for axial injection mode was developed as shown in Fig. 11. Efficient phase selection was made down to about 3°.

In order to get high quality injection beam for the ring cyclotron, the six dimensional phase space volume of the injection beam is limited by various slits between the ion source and the ring cyclotron. The beam intensity reduction about 10^{-2} in the process is very serious for polarized beam and heavy ion beam. A new high intensity polarized proton and deuteron ion source, a new axial injection system and injector beam line for the polarized ion source and Neomafios will be installed in August 1994.

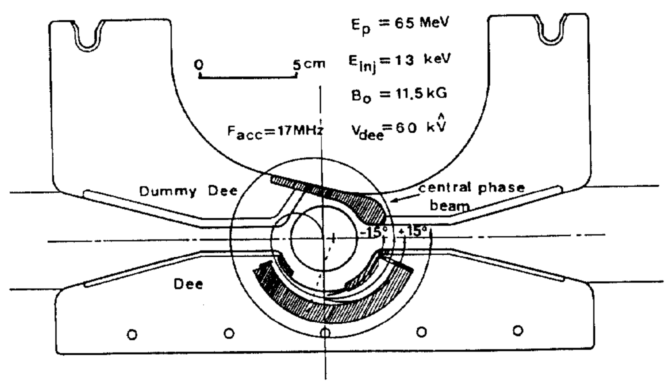

Fig. 11. Beam phase selector for axial injection mode of the AVF cyclotron.

Table 2. Parameters for 400 MeV beam

		Proton	α
Injection	MeV	63.6	86.3
MIC1 ΔB	Gauss	+1730	+1889.3
MIC2 ΔB	Gauss	+550	+551.1
EIC1/EIC2	kV/cm	80	59.1
EEC1/EEC2	kV/cm	70	38
Electrode gap	cm	1	1
MEC1 ΔB	Gauss	-900	-759.3
MEC2 B	kGauss	10	9.187

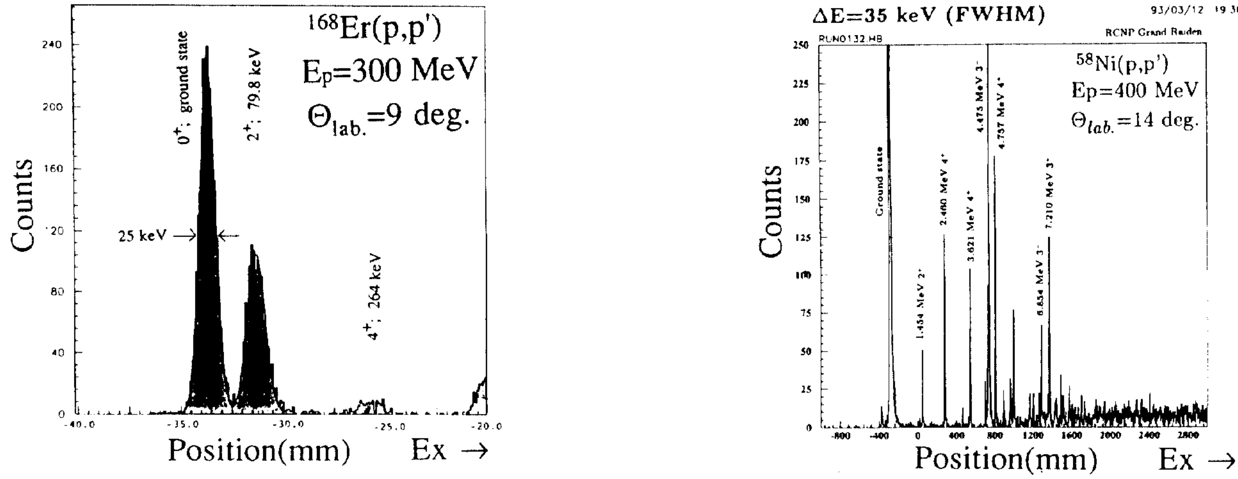

Fig. 12. Obtained Spectra. ^{168}Er(p,p') reaction at E_p=300 MeV and ^{58}Ni(p,p') reaction at E_p=400 MeV.

VII. BEAM DIAGNOSTIC SYSTEM

The commissioning of the ring cyclotron was made with various kind of beam diagnostic elements [10]. Efforts to get good S/N ratio for weak beam down to 1nA were made. A 30 Hz 5th order (30dB/Oct) low pass filter is used for beam current measurement.

For beam phase measurement, noise-free phase signal amplifier for acceleration frequency was used. 5/3 and 8/5 multiple of the acceleration frequency are used for phase measurement of proton and alpha, respectively. A crystal filter is used in IF amplifier of the phase signal amplifier to reduce noise. The output signals are averaged by a digital oscilloscope to reduce thermal noise. Relative phase between beams can be measured with this phase probe for beam current down to 1nA.

VIII. CONTROL SYSTEM

The old control system of the AVF cyclotron is used without any modification. The new computer control system [11] consist of a central computer (system controller, μVAX3500) and four sub-computers (group controller, μVAXII+3·rt-VAX1000). The control functions of the ring cyclotron are distributed to the five computers and many intelligent device-controllers. The new operator console of the ring cyclotron is installed near by the old operator console of the AVF cyclotron.

IX. ACCELERATED BEAMS

Polarized and unpolarized protons, deuterons and alpha particles were accelerated up to the designed maximum energies, 400 MeV, 200 MeV, and 400 MeV respectively. 450 MeV ^{3}He beam was also accelerated.

The beams are extracted with single turn extraction mode with flat-topping. Beam energy width of 80 keV was achieved for 300 MeV proton. Energy resolution of 25 keV and 35 keV were obtained with high resolution spectrograph Grand Raiden, as shown in Fig. 12, by using dispersion matching for 300 MeV and 400 MeV proton inelastic scattering spectra, respectively [12]. A very short polarized proton beam pulse of 150ps was achieved for neutron TOF experiment.

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