RECENT DEVELOPMENTS AT THE OSAKA RCNP 230-cm CYCLOTRON AND A PROPOSAL FOR A NEW RING ACCELERATOR

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Summary

The RCNP cyclotron has been operated satisfactorily for many kinds of nuclear research experiments since the middle of 1976. The versatile machine is able to deliver protons up to 75 MeV, deuterons up to 60 MeV, ^{3}He particles up to 140 MeV, alpha particles up to 120 MeV, ^{12}C ions, ^{14}N ions, ^{16}O ions, ^{20}Ne ions, polarized protons and polarized deuterons.

Beam quality and reliability of the machine were very good. Unscheduled down time was several percent of the scheduled time in 1977. About 30 research experiments were performed in this period and about 150 changes of particle type or energy were practiced to satisfy the requirements of these experiments. The facility has been open to outside users since January 1977.

1. Description of the RCNP Cyclotron

The design and construction of the cyclotron started in 1971 and the first extracted beam was obtained in July 1975.[1)2)] The cyclotron is a three-sector, single-dee machine designed to accelerate various particles over a wide range of energies. The beam energy is variable up to the magnet rigidity limit of 120 Q^2/A MeV for all ions except protons. The maximum energy of protons is limited to about 80 MeV by both the vertical focusing property and the maximum RF frequency. The adjustment of 16 trim coil currents of the main magnet can produce a very good fit to any isochronous field. The wide RF frequency range from 5.5 to 19 MHz permits acceleration of particles with very low energies without an energy gap by using the third harmonic mode.

The resonance conditions for accelerations of various particles are shown in fig.1.

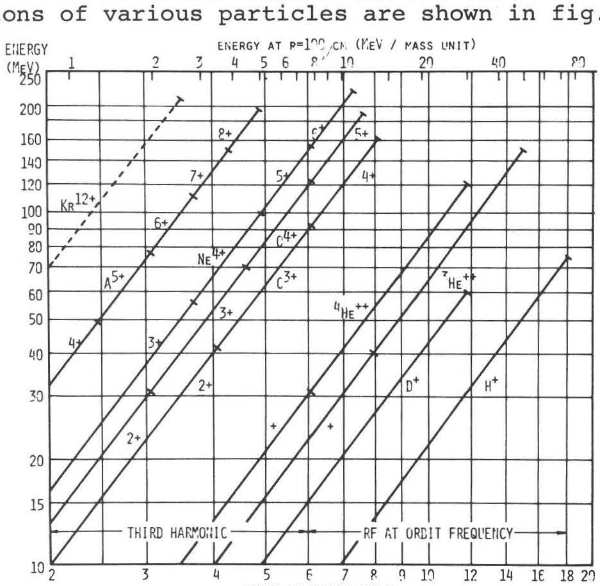
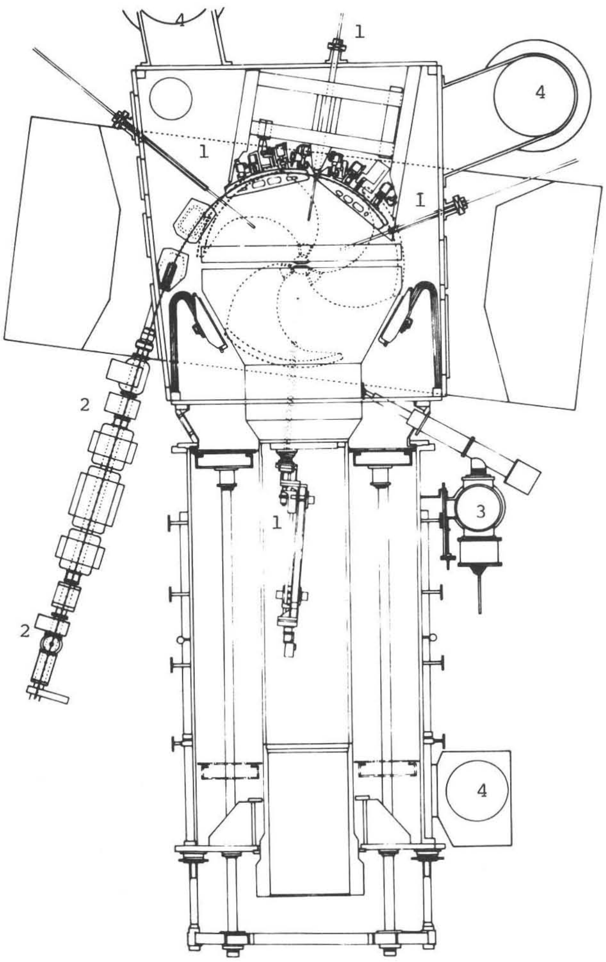


Fig. 1. Resonance conditions for ion acceleration.

The RF system consists of a 1/4 λ mode coaxial resonator with a sliding short and a MOPA system using an RCA 4648 tetrode as a power tube. The accelerating electrodes consist of a 180° single dee, a dummy dee, a dee-insert electrode, a dummy-dee-insert electrode and a movable puller. The performance of the RF system is presented at this conference[3)]. The resonator is shown in fig.2.



1: Beam Probes. 2: Beam Emittance Meas. Device.
3: Power Amplifier. 4: Diffusion Pumps.

Fig. 2 Horizontal cross section of the RCNP cyclotron.

Three types of ion sources are employed to accelerate light ions, heavy ions and polarized ions. One is a normal Livingston type installed axially in the lower yoke. In case of the acceleration of heavy ions, the normal ion source is replaced by a PIG-type heavy ion source. The polarized ion source is located on the second floor outside the cyclotron vault. The polarized beam is axially injected into the cyclotron through a focusing system. The beam is then inflected by 90° at the center of the cyclotron by an electric mirror system which is inserted into

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the cyclotron instead of an ion source.

The vacuum system consists of two 36-in oil diffusion pumps and a 22-in one. For a run of ^{3}He particles, the ^{3}He-recovery system is used and then the main vacuum and the ion source form a closed recirculating system.

The cyclotron and beam transport system can be controlled by a control computer PDP11/40, but they are usually controlled manually using a digital control system. Settings of all power supplies and drivings of the mechanisms are made by stepping motors.

In order to diagnose the beam, the accelerator is equipped with four beam-probe driving systems and an emittance measuring device as shown in fig. 2.

2. Accelerator Performance and Operation

The various kinds of particles have been accelerated within the energy range designed.[4] Particles and energies accelerated in 1977 are listed in table 1 as an example.

Table 1. Particles and energies accelerated in 1977.

Particle	Energy(MeV)
p	45,50,55,60,65,70,75
d	55
^{3}He	70,90,100,110,120
α	40,43,50,58,60,70,79,89,90,100,110,120
$\vec{p}$	40,45,51,52,65,68
$\vec{d}$	52
$^{12}C^{4+}$	160
$^{14}N^{4+}$	128,130
$^{14}N^{5+}$	130,210
$^{16}O^{5+}$	180
$^{20}Ne^{4+}$	90*,95*
$^{20}Ne^{5+}$	150
$^{20}Ne^{6+}$	160
$^{40}Ar^{7+}$	150**
$^{40}Ar^{8+}$	196**

* Third harmonic mode

** Beam acceleration test, third harmonic mode, low beam current (14∿90 enA, extracted)

About 30 experiments approved by the program committee were performed this year. About 150 changes of particle type or energy were practiced to satisfy the requirements of these experiments and the development studies. Time distributions to the accelerated particle type are listed in table 2. Operational time distributions are also shown in table 3. As shown in the table the unscheduled downtime was several percent of the scheduled beam time.

The setting parameters of the cyclotron are given from the control computer PDP11/40 by putting a particle type and its energy into it. The internal beam can be easily obtained using just these parameters and fine tuning of the main coil current.

Table 2. Time distribution of the cyclotron.

Particles	Jan.1977-Dec.1977			Jan.1978-Mar.1978		
	E(MeV)	Time(hr)	%	E(MeV)	Time(hr)	%
p , H_3^+	11∿75	867	22.9	55∿75	392	30.7
d	55	136	3.6			
α	30∿120	664	17.6	70∿120	321	25.1
^{3}He	70∿140	1129	29.9	65∿120	197	15.4
H. Ion (C,N,O•••)	90∿260	478	12.6	13∿210	141	11.0
$\vec{p}$, $\vec{d}$	45∿68	507	13.4	40∿65	227	17.8
	Total	3781	100.0	Total	1278	100.0

Table 3. Operational time distribution of the RCNP cyclotron.

	Jan.1977-Dec.1977		Jan.1978-Mar.1978	
Research experiments	2654 h	30.3%	907 h	42.0%
Beam development	576 h	6.6%	91 h	4.2%
Beam source tests	551 h	6.3%	280 h	12.9%
Total beam time	3781 h	43.2%	1278 h	59.1%
Set-up and maintenance	1168 h	13.3%	237 h	11.0%
Unscheduled shut-down	264 h	3.0%	10 h	0.5%
Scheduled shut-down	3548 h	40.5%	635 h	29.4%
Total	8760 h	100 %	2160 h	100 %
Unscheduled shut-down				
Ion sources	89 h		3 h	
Central electrodes	54 h			
Deflector	40 h			
Probes	27 h			
RF power supplies	26 h		1 h	
Manget power supplies	13 h			
Vacuum and cooling	8 h		2 h	
Beam transport	7 h		2 h	
Primary electric power			2 h	
	264 h		10 h	

In order to get an optimum condition for the extracted beam, fine adjustments are required to No. 1 valley coil current, No. 5 valley coil current, dee voltage, No. 1 deflector voltage and No. 2 deflector voltage. Once the machine comes into operation for an experiment, retuning is generally not necessary for one day or so. The operational data of the accelerator can be obtained by the computer system at any time.

The accelerated beam current is limited to 5 μA for the present to reduce the residual activities and to avoid the unnecessary damage of the machine parts, because adequate current can be transported at the target position with this current. Proton beam current of 50-60 μA was tried a couple of times, but the tips of water-cooled beam probes were melted away due to the concentration of strong heat on a very small volume.

A PIG-type ion source[1] whose cathodes are heat-insulated and kept hot is used to accelerate heavy ions. The $^{12}C^{4+}$, $^{14}N^{4+}$, $^{14}N^{5+}$, $^{16}O^{4+}$, $^{16}O^{5+}$, $^{16}O^{6+}$, $^{20}Ne^{4+}$, $^{20}Ne^{5+}$, $^{20}Ne^{6+}$ and $^{40}Ar^{7+}$ ions were accelerated. The life of the source is 8-24 hours in the case of ^{14}N and ^{20}Ne beams. The life time is usually limited by either the cathode life or the short circuit of the arc by the sputtered material builded up on a gap between the anode and cathode. The sputtering rate of the Ta cathode is about 0.36g/hr and the cathode life is more than 20 hours.

A test of the third harmonic acceleration have been made using H_3^+ ions prior to the acceleration of lower energy $^{20}Ne^{4+}$ ions in the third harmonic mode. The selection of H_3^+ ions from normal proton beam was made by moving the position of the phase defining slits from the normal position to an appropriate position. The center region of the cyclotron is shown in fig. 3. The beam patterns measured with a differential current probe are shown in fig. 4 for both the proton beam and H_3^+ ions.

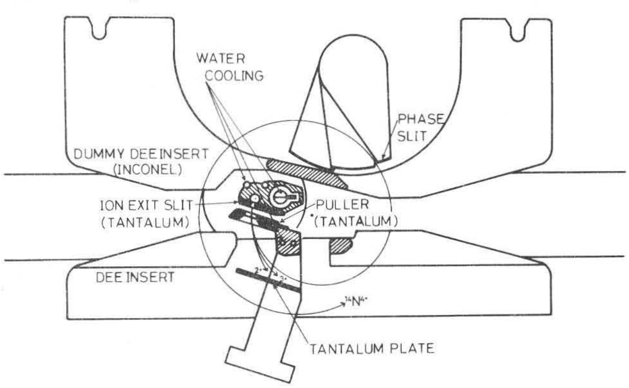

Fig. 3 Center region of the cyclotron.

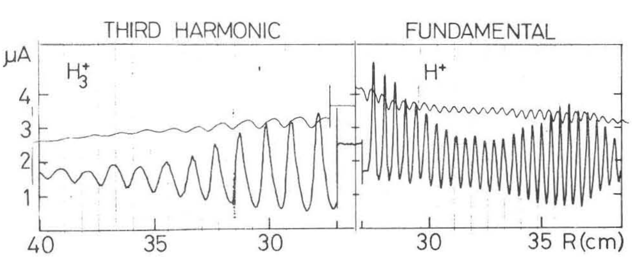

Fig. 4 Differential beam currents vs radius.

The 90 MeV $^{20}Ne^{4+}$ ions were succesfully accelerated in the third harmonic mode and employed for research experiments.

An atomic beam type polarized ion source[5] was constructed two years ago and has been succesfully operated for about 1500 hours. After some improvements in the ion source and installation of a beam buncher in the axial ion injection system[6], polarized proton beam currents are increased to about 110 nA for the extracted beam and about 70 nA on the target. The gain of the beam intensity by the buncher was about a factor of 3. The proton beam polarization is normally between 65 and 75 percent. The most recent results of the beam polarization during the experimental runs are shown in fig. 5.

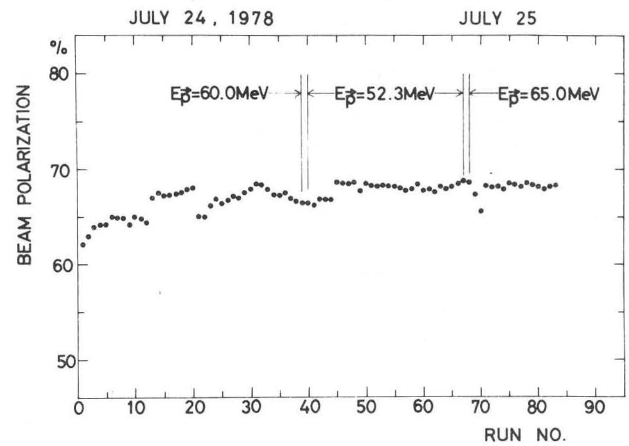

Fig. 5 Proton beam polarization during an experiment.

Vector polarized deuterons were accelerated to 52 MeV and the beam polarization was measured. To achieve vector polarizarion, 1-4 transition was used at the frequency of 12 MHz. The obtained vector polarization of the beam was about 49 percent and the extracted beam current was 30-50 nA.

3. Beam Diagnostics

In order to measure internal beam current, integral, differential and three-finger probes are provided. One of them is mounted on a probe-driving system as shown in fig. 2. A capacitive pick-up phase-probe is constructed to measure the phase of the beam. A phase-meter system of a direct-reading type is also developed. A beam phase history from 5 cm to the extraction radius can be recorded on a chart paper in a few minutes.[7] The block diagram of the phase meter system is shown in fig. 6. A typical result of the beam phase history by the phase meter system is shown in fig. 7 for various values of the outermost trim coil current. Another capacitive pick-up phase probe, sampling type, has also been made to measure the time structure of the beam and the phase history.[8]

The third new method is developed to measure the beam phase structure using gamma-ray time spectra.[9] The internal beam was stopped on a beam probe and the emitted gamma-rays were detected by a plastic scintillator. The photomultiplier anode signal was used for a start signal of the time-to-pulse height converter and the triggered pulse by RF signal was used for a stop signal.

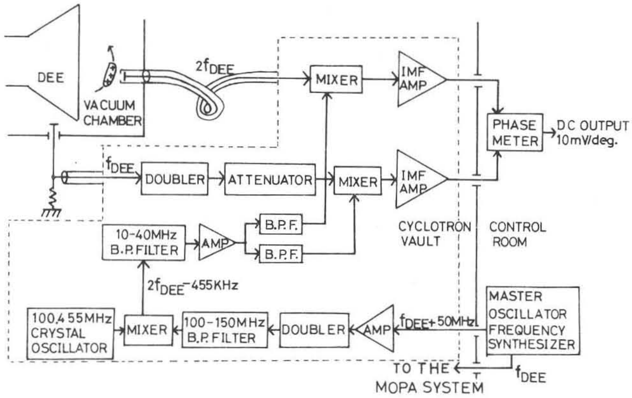

Fig. 6   Block diagram of the phase meter system.

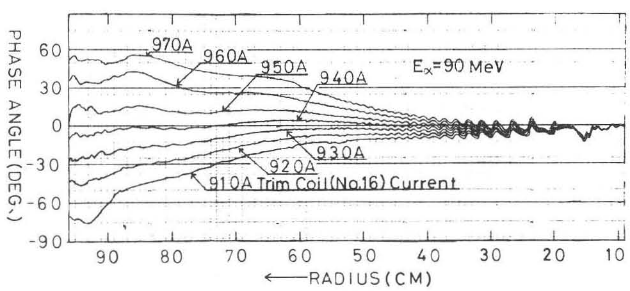

Fig. 7   Beam phase history measured with the phase meter from 10 cm to the extraction radius.

Fig. 8 shows the time spectra of the beams measured by the two different methods. The measurements are in good agreement. As shown in fig. 8, the width of the beam phase is narrowed by using the phase slit system which is shown in fig. 3. Fig. 9 shows the time structure of the polarized proton beam. The effect of the beam buncher is obviously seen in this figure.

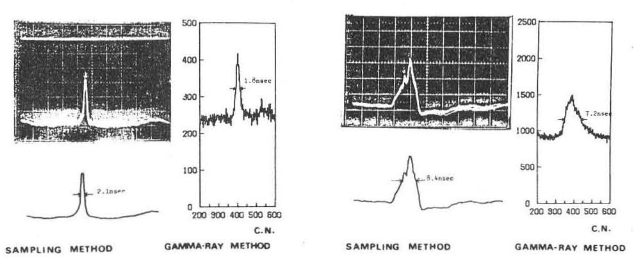

Fig. 8   Time spectra of the beams measured by the sampling method and the gamma ray method.
Right : phase slit open
left : phase slit width small

A technique to measure characteristic x-rays induced by a bombardment of a target by charged particles is applied to beam diagnostics . The x-rays are detected by a Si(Li) x-ray detector or a LEPS (pure Ge) detector. By this method the beam profile can be measured precisely even though the beam size is less than 1 mm × 1 mm.

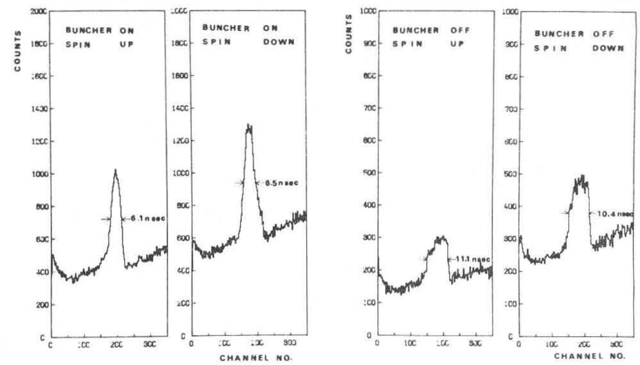

Fig. 9   Time structure of the polarized proton beam.

In order to measure the beam halo at the target position caused mainly by the scattering at the beam-defining slits, we used particular targets which were composed of several foil materials arranged like a mosaic as shown in fig. 10-1. By observing the yields of the characteristic x-rays, the beam currents impinging onto each material are measured. The ratio of the current onto each material (I_x) to the main beam current (I_o) is calculated and shown in table 4.

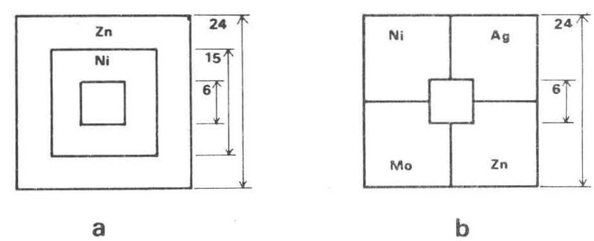

Fig. 10-1   Mosaic targets.

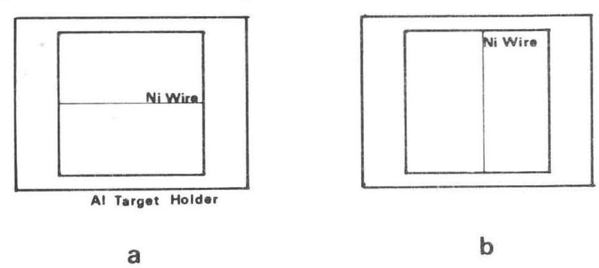

Fig. 10-2   Wire targets.

Table 4.   Distributions of the beam current (I_x) outside the beam spot. I_o : total current

Target (a) in fig. 10-1

	I_x/I_o
Ni	0.00051 ± 0.00007
Zn	0.00006 ± 0.00001

Target (b) in fig. 10-1

	I_x/I_o
Ni	0.000116 ± 0.000033
Zn	0.000049 ± 0.000006
Mo	0.000035 ± 0.000007
Ag	0.000220 ± 0.000023

The results indicate that 10^{-5} part of the beam current outside the main beam spot is detectable. The beam profile is also measured with wire targets shown in fig. 10-2. A nickel wire (0.1 mmϕ) was strung on the target holder vertically or horizontally. To measure the vertical beam profile, the target was moved upward or downward with about 0.1 mm step by the stepping motor. The results are shown in fig. 11. In the vertical beam profile, the beam size of 1.23 mm FWHM is observed and undesirable beam current outside the main beam spot is 10^{-3}–10^{-2} percent.

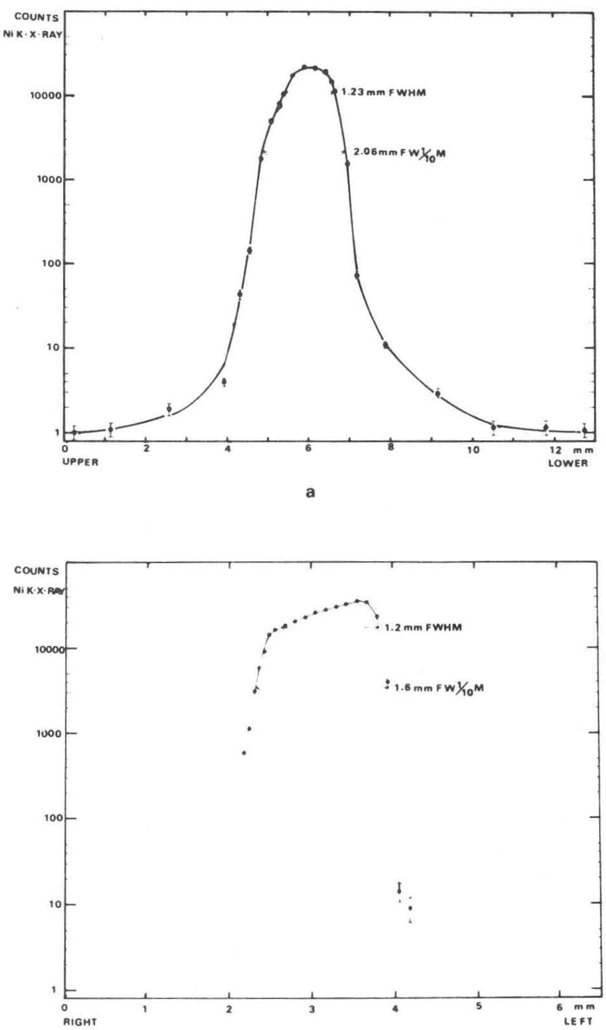

Fig. 11 Vertical (a) and horizontal (b) beam profiles at a target position.

4. Research Equipment

Eleven beam lines designed by H. Ikegami and co-workers[10] are installed in the beam switching yard and four independent experimental areas. The layout of the experimental area, beam lines and experimental apparatus is shown in fig. 12. Both achromatic and dispersive transport of the beam are available for most of these beam lines. The highest beam resolution (0.01% or better) is available at the G-beam line by use of a tandem monochrometer system (momentum dispersion 36.000 mm) formed by the two analyzing magnets in the beam-switching room.

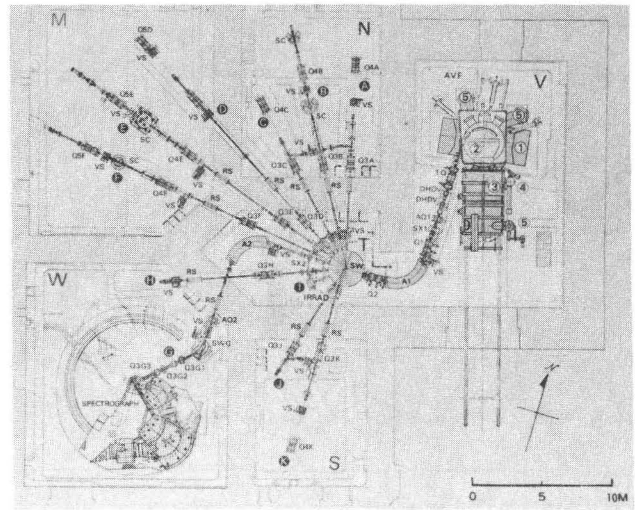

Fig. 12 Layout of experimental areas.
A ∿ K : Beam lines
A_1, A_2 : Beam analyzing magnets
SW : Switching magnet
SC : Scattring chamber

Six beam lines out of eleven lines (labelled A to K) are in use at present.

The B-line is equipped with a small scattering chamber and detector cryostat system mounted on the rotating arms outside the scattering chamber. The polarization monitor system is set up in this line following the scattering chamber.

At the E-line a large scattering chamber (diameter 1040 mm, height 565 mm) is arranged. It is commonly used for investigation of nucleon transfer reactions, few particle reaction problems and heavy ion reactions.

The F-line is mainly used for inbeam spectroscopy studies in which gamma rays, electrons and particles emitted following nuclear reactions are measured.

The original design of the magnetic spectrograph, RAIDEN, was initiated and completed in RCNP.[11] It consists of two quadrupole and two dipole magnets arranged in the QDDQ form. To achieve higher order focusing and kinematical corrections, a novel set of multipole magnets of the current-sheet type are also included. The spectrograph is used in conjunction with the high-resolution G-beam line. The cross-sectional view of the spectrograph is shown in fig. 13. The specifications are listed in table 5.

Table 5 Specifications of the Spectrograph.

Mean orbit radius	150 cm
Angular range	-40°∿140°
Solid angle	13 msr
Maximum Bρ	2500 kG cm
Energy range	14 %
Maximum energy resolution	10000
Total weight	200 ton

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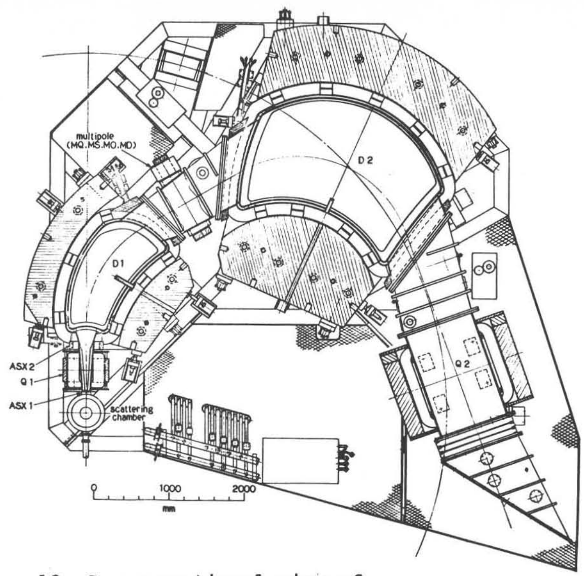

Fig. 13 Cross-sectional view of the spectrograph RAIDEN.

5. Future Accelerator Project at RCNP

Studies on the future accelerator project at RCNP started two years ago. The research program committee of RCNP was consulted to make the next stage plan by the general committee. To extend the research field to higher energy regions than the present RCNP facility, problems in nuclear physics, accelerator technology and research equipments have been discussed. Three accelerator plans have been prepared and reviewed.

The first one is to construct a new injector cyclotron which accelerates heavy ions[12]. The extracted heavy ions from the injector are injected into the present K=120 MeV cyclotron, stripped inside and then accelerated. The efficiency for acceleration of heavy ions will be greatly increased with the injector. The specifications are listed in table 6 and the layout is shown in fig. 14.

Table 6 Specifications of the injector cyclotron.

	Injector		Booster	
	Q_1	E_1	Q_2	E_2
^{20}Ne	4	6.0	10	30
^{40}Ar	6	3.4	16	17
^{56}Fe	7	2.4	19	12
^{84}Kr	8	1.4	23	7

Injector Cyclotron
- K=150 MeV
- MAGNET 300 Ton
- Ave, FIELD 20 kG
- Ext, Radius 0.9 m
- Resonator 2-90° Dee
- RF mode push-push
- Orb, Freq, 2.6 ∿ 8 MHz

Booster Cyclotron
- RCNP 230 cm Cyclotron
- Energy Gain 5

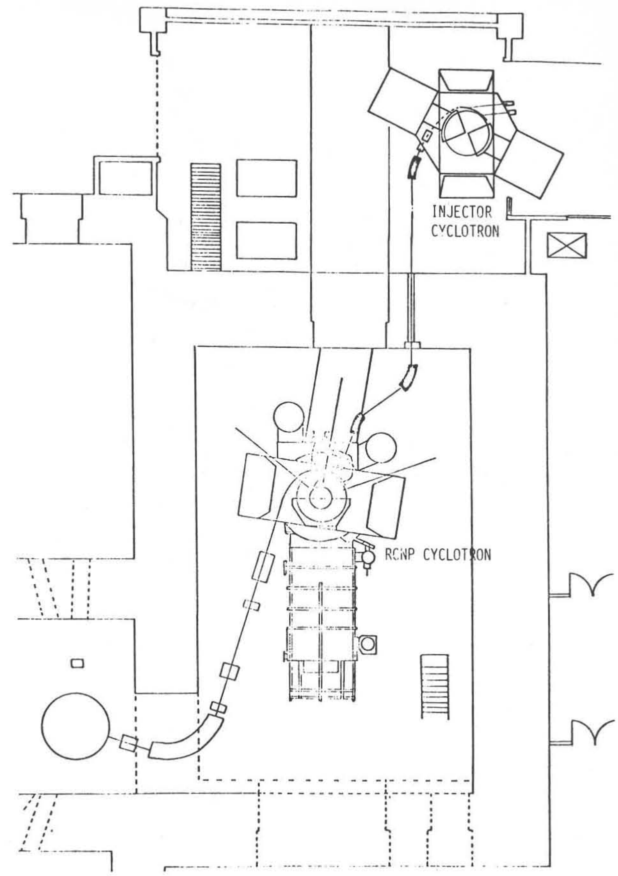

Fig. 14 Layout of the injector cyclotron plan.

The second one is a booster project to the present cyclotron[13]. The booster is a K=300 MeV ring cyclotron and the acceleration energies are approximately doubled. The heavy ions will be accelerated without strippers to save the magnet weight. The specifications are listed in table 7 and the plan view of the ring cyclotron is shown in fig. 15.

Table 7 Specifications of the booster ring cyclotron.

p	150 MeV (200 MeV)
d	150 MeV
α	300 MeV
^3He	300 MeV (350 MeV)
H. I.	$300\frac{Q^2}{A}$ MeV
MAGNET	
Fe	780 ton
Cu	20 ton
HILL GAP	70 mm
B max	16 kG
MAIN COIL	250 kW
TRIM COIL	30 kW
RESONATOR	
2 COAXIAL	
F 12 MHz ∿ 36 MHz	
RF POWER	200 kW
INJECTOR	
RCNP 230 cm Cyclotron	

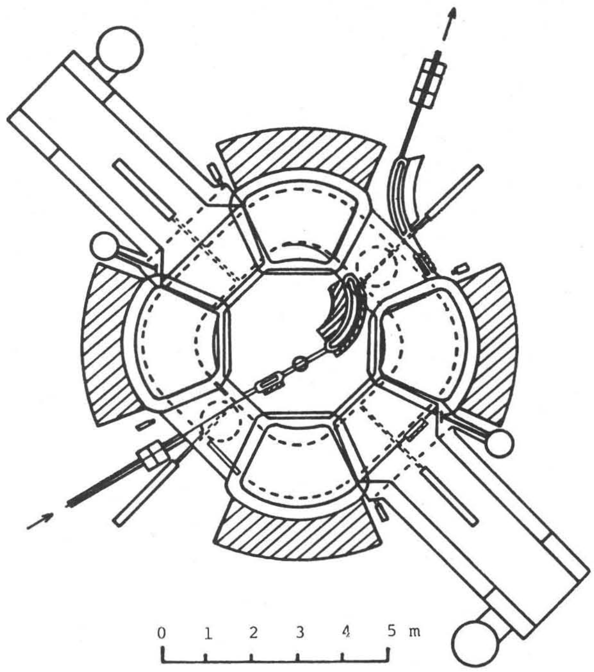

Fig. 15 Plan view of the booster cyclotron.

The third plan is a new ring accelerator complex which consists of a new small injector cyclotron, 1st ring cyclotron and 2nd ring cyclotron. In order to accelerate high energy and high intensity heavy ions, a Wideröe type variable frequency linac is also considered as an injector. This would result in a variable energy machine with K=460 MeV (Heavy Ions). Protons will be accelerated up to 550 MeV and the accelerator can be used as a meson factory. The project is divided into three phases. Phase I consists of an injector cyclotron and the first ring cyclotron. The second ring is added in Phase II. In Phase III the linac will be added. The details of this third plan will be presented at this conference.[14)]

After many discussions, the third plan has been adopted as the future accelerator project at RCNP by the research program committee. The specifications of the accelerator complex are listed in table 8, and the layout is shown in fig. 16.

Table 8 Characteristics of Ring Accelerator

	Injector cyclotron	Ring 1	Ring 2
No. of magnetic Sector	4	4	8
Sector angle		33°	∿19°
Injection radius		1.3 m	3.4 m
Extraction radius	0.65 m	3.4 m	4.7 m
Magnet gap	∿18.5 cm	∿8 cm	∿8 cm
Max. magnetic field	18.5 kG	16 kG	18.3 kG
Magnet weight	160 ton	1200 ton	1600 ton
Main coil power	200 kW	400 kW	600 kW
No. of trimming coils	5	30	60
No. of cavity	2	2	4
RF frequency		20-32 MHz	
RF power	30 kW×2	150 kW×2	200 kW×4
K-value for H. I.	70 MeV	230 MeV	460 MeV

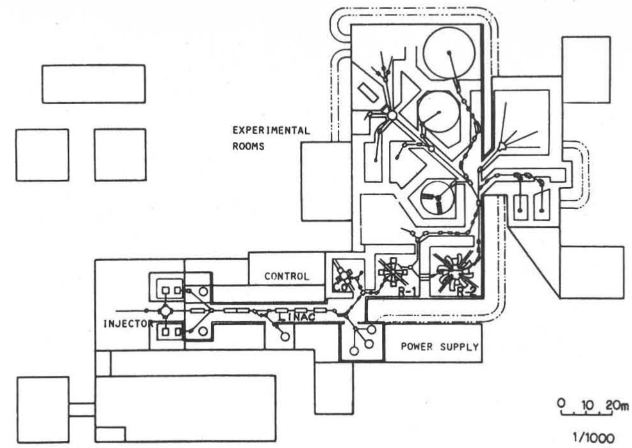

Fig. 16 Layout of the new ring accelerator complex.
Co : injector cyclotron
R-1 : the 1st ring cyclotron
R-2 : the 2nd ring cyclotron

Acknowledgements

I wish to thank Profs. S. Yamabe, H. Ikegami and H. Ogata for their valuable suggestions and discussions. I am particularly thankful to Drs. I. Miura, T. Yamazaki, H. Ejiri, A. Shimizu, I. Inoue, K. Hosono, Y. Nagai, T. Fukuda, T. Itahashi, K. Nisimura, K. Imai and Messrs. T. Saito, H. Sakai, N. Matsuoka and S. Nagamachi for their collaborations.

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** DISCUSSION **

H. BLOSSER: Would you clarify the phrase "the project is adopted"? Is it funded?

M. KONDO: The project is adopted by the research program committee in our institute, but not yet by the government. Government funding is likely.

J.R. RICHARDSON: To focus 550 MeV protons in your ring, I presume you must use some spiral in your sector?

M. KONDO: Yes, we use spiral in our magnets.

R. VADER: What beam currents did you use to obtain your oscilloscope pictures of beam phase pulses?

M. KONDO: In observing pulses with alpha particles, 70 nA is sufficient. In the case of protons the RF frequency is rather high and there is RF pickup at present, so we have not determined the lowest limit. The pictures using protons were taken at 1 μA.

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