THE RCNP RING CYCLOTRON FACILITIES*

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ABSTRACT

The RCNP ring cyclotron is now under construction with a speed of four sector magnets per year. The beams extracted from the RCNP AVF cyclotron will be injected into the ring cyclotron of six sector type. With this accelerator system, high quality beams of $\vec{p}$, $\vec{d}$, ^{3}He and light-heavy ions will be made available up to 400, 200, 510 and 400Q^2/A MeV, respectively, enabling us to start new high precision studies in the field of medium energy. Associated facilities which are also being constructed include a beam circulation ring, linked to an ultra- high precision, dual magnetic spectrograph system, a neutron spectrometer with a 100m long flight path and a secondary particle beam system. The first beam acceleration test will be started in the spring of 1991. The beam circulation ring is expected to be converted into or replaced by a cooler synchrotron which can store particle beams of energy up to 1700 Q^2/A MeV after some developments on the new method of "cyclotron maser cooling". This new cooling scheme is presented in this conference by the present speaker.

INTRODUCTION

The Research Center for Nuclear Physics (RCNP), a national "user facility" founded in 1971 has held a position as one of the most productive research institutes in the fields of high precision nuclear science at sub-intermediate energy and relevant interdisciplinary studies since experimental activities were initiated in early 1976. Thanks to the availability of various beams with high quality from the RCNP AVF cyclotron (K=140, E_p = 85 MeV) and of many sophisticated apparatus which include the world famous spectrograph RAIDEN, the polarization spectrograph DUMAS and the high resolution recoil separator CARP, RCNP has been successful in stimulating the users in Japan and abroad into research activities which have born a great variety of scientific accomplishments.

A dramatic progress of RCNP has took place in assuring a future extension of our high precision frontier of nuclear physics research to medium energies above pion production threshold. A new and decisive project "RCNP Ring Cyclotron Facility" was started in 1987. The main components of the new facility are a ring cyclotron i.e. a six separated spiral sector cyclotron (SSC) and a beam circulation ring linked to a ultra-high precision dual magnetic spectrograph system. The beams extracted from the RCNP AVF cyclotron are transported through one of the beam lines of the present facility and injected into the ring cyclotron as seen in Fig. 1. With this accelerator system, beams of p, d, ^{3}He, alpha and light-heavy ions will be made available in the wide range of energies of up to 400, 200, 510, 400 and 400$\cdot Q^2/A$ MeV, respectively. An emphasis is placed on the production of high quality beams to enable precise experiments.

In August 1987, an order for the ring cyclotron was given to Sumitomo Heavy Industry Ltd. on a four year contract. Another order was given to the same company on a three year contract in September 1988 for beam lines, the beam circulation ring and associated experimental facilities including the magnetic spectrograph GRAND RAIDEN which exceeds, in the resolution, the world highest resolution spectrograph RAIDEN. The beam circulation ring will be converted into or replaced by a cooler synchrotron (K=3000, E_p = 1700 MeV) after some developments on the new method, "cyclotron maser cooling". This new cooling scheme is presented in this conference by the present speaker.

* Construction members of RCNP facilities:
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Open cut and readjustment of the land for construction of buildings for the ring cyclotron facility was finished in March 1988. The design concept of radiation shield of facility is shielding with heavy structure of concrete. The thickness of concrete shield walls is 4.5 m in the ring cyclotron vault and 6 m for the beam damp area (see Fig. 2). The construction of whole buildings will be finished by March 1990.

THE MEANING OF THE RCNP RING CYCLOTRON FACILITIES

The light ion beams especially the proton beam of energy up to 400 MeV to be produced by the ring cyclotron are best suited for studies of nuclear structure and nuclear reaction, because the overall strength of the nucleon-nucleon interaction is weakest and the distortion of the wave function of colliding system is reduced in this energy region. We shall be able to shed a new light on the traditional picture of nuclei by studying the role played by subnuclear degrees of freedom.

Some of the topics in nuclear physics to be covered by the project are i) Pion production mechanism near and above the threshold region, ii) Nuclear structure and reaction at high momentum transfer and short range correlations, iii) Relativistic effects in nuclear structure and reactions, iv) Spin- and/or isospin-dependent correlations from low- to high excitation energies, v) Study of heavy-ion reaction mechanisms in the light of underlying nucleon-nucleon interactions.

The project should certainly support these investigations by facilitating a) the use of various beams to select specific excitation modes, b) polarization experiments as a probe for the spin-dependent structures and c) coincidence measurements to investigate nuclear correlation effects.

The beams are also to be used for the studies in the broad fields of inteerdisciplinary research such as atomic physics, condensed matter physics and medical sciences.

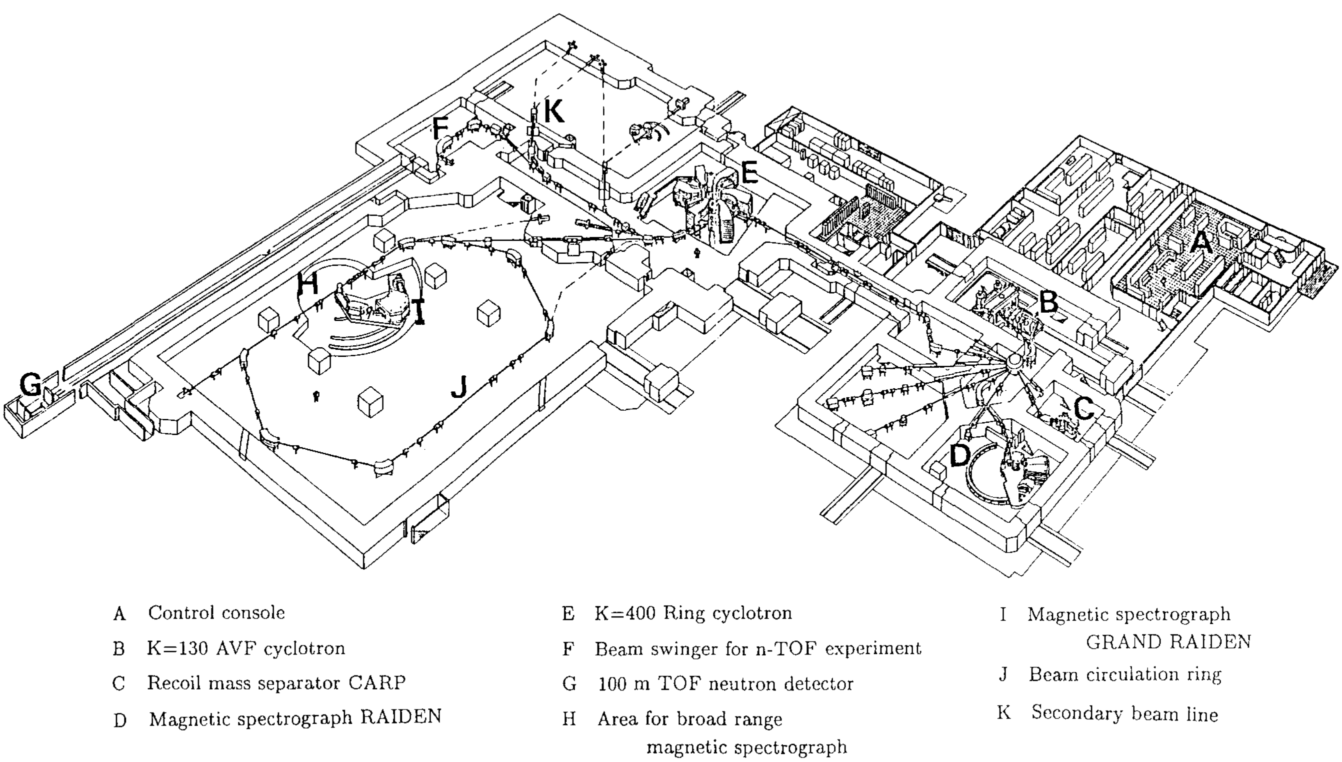

Fig. 1. Overall view of the RCNP ring cyclotron facilities. A ~ D indicate the present facility and E ~ K indicate the new facility now being under construction.

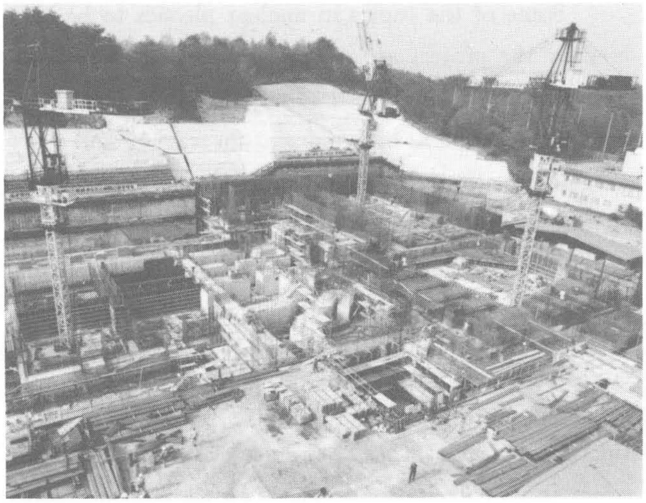

Fig. 2. New building being under construction.

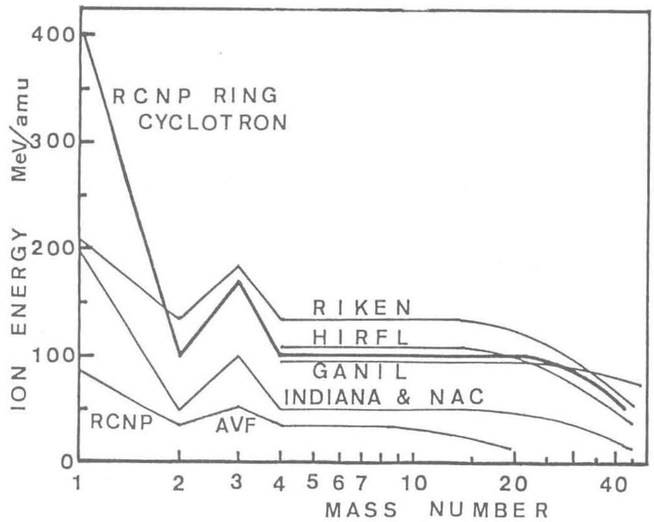

Fig. 3. Maximum energies of various ions to be extracted from the RCNP AVF cyclotron and the RCNP ring cyclotron. Those from several major ring cyclotrons in the world are also shown.

TABLE 1

Characteristics of the cyclotrons

Ring Cyclotron

Maximum energy	p	400 MeV
	d	200 MeV
	^{3}He	510 MeV
	^{4}He	400 MeV
	light-heavy ions	400 Q^2/A MeV
Magnet	Number of sectors	6
	Spiral sector angle	21.9° ~ 27.5°
	Magnet gap	6 cm
	Maximum field	1.75 tesla
	Iron weight	2100 ton
	Main coil power	450 kW
	Number of trim coils	36
	Trim coil power	350 kW
	Injection radius	200 cm
	Extraction radius	400 cm
Acceleration system	Cavity	3 (single gap type)
	Frequency range	30 ~ 52 MHz
	Maximum accelerating voltage	500 kV
	RF power	250 kW × 3
Flat-topping system	Cavity	1 (single gap type)
	Frequency range	90 ~ 155 MHz
	Maximum voltage	170 kV
	RF power	30 kW

AVF Cyclotron (Injector)

Maximum energy	p	85 MeV
	d	70MeV
	^{3}He	175 MeV
	^{4}He	140 MeV
	light-heavy ions	140·Q^2/A MeV
Polarization	$\vec{p}$	$P_y > 80\%$
	$\vec{d}$	$P_y > 80\%$
		(ratio to theoretical limit)
Magnet	Pole face diameter	230 cm
	Maximum average field	1.6 tesla
	Extraction radius	100 cm
	Weight	400 ton
Acceleration system	Frequency	5.5 ~ 19 MHz
	Maximum voltage	80 kV
	RF Power	100 kW

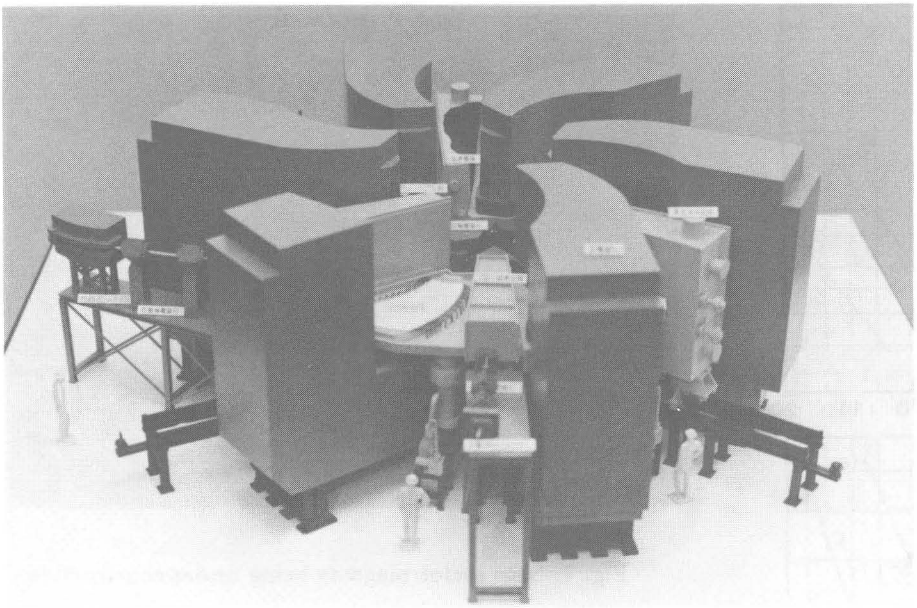

Fig. 4. Scale model of the ring cyclotron.

GENERAL DESCRIPTION OF THE RING CYCLOTRON

The ring cyclotron is an energy quadrupoler of the RCNP AVF cyclotron. Injection and extraction radii of the ring cyclotron are 2.0 m and 4.0 m, respectively. The characteristics of the ring cyclotrons are given in Table 1 together with those of the RCNP AVF cyclotron. The maximum energies of various ions to be extracted from the ring cyclotron are shown in Fig. 3 together with those from several major cyclotrons in the world. Figures 4 and 5 show a scale model and a plan view of the ring cyclotron, respectively. Three single gap acceleration cavities are used in the ring cyclotron. The frequency range of the cavity is 30~52 MHz. Acceleration harmonics of protons and alpha particles are 6 and 10, respectively. An additional single gap cavity is used for flat- topping with third harmonic of the acceleration frequency to obtain energy resolution better than 10^{-4}.

The acceleration chamber of the ring cyclotron consists of 6 magnet chambers, three acceleration cavity chambers, a flat- topping cavity chamber and two valley

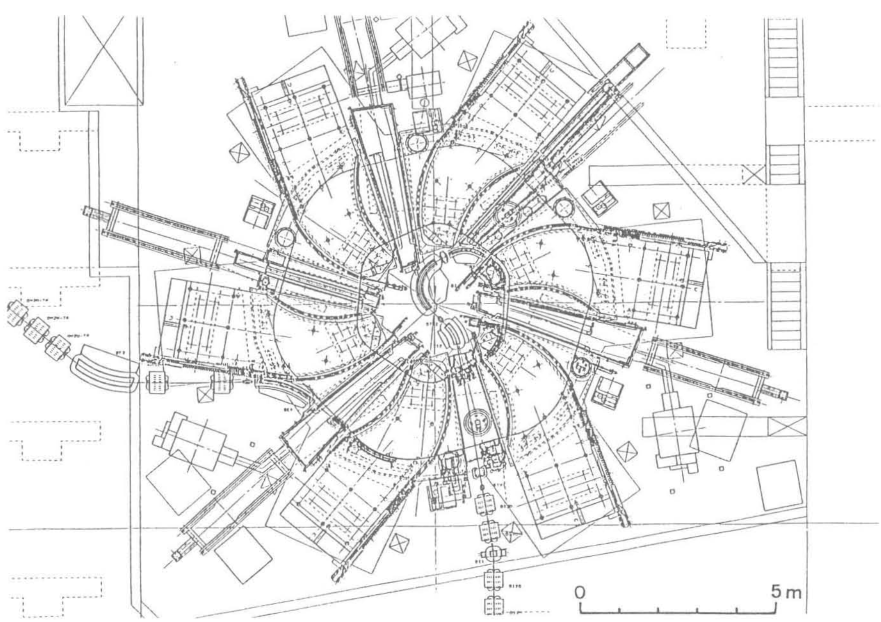

Fig. 5. Plan view of the ring cyclotron.

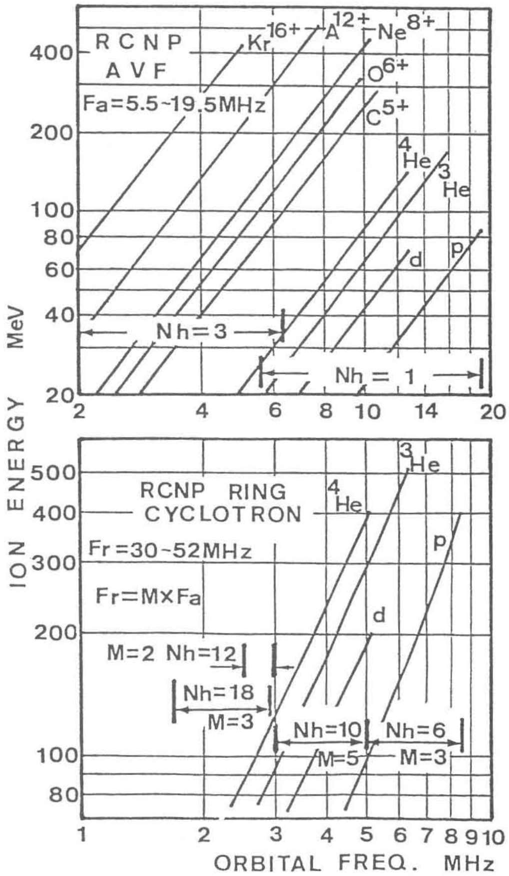

Fig. 6. Orbital frequencies, acceleration frequencies (F_a:AVF, F_r:RING) and harmonic numbers of acceleration N_h in the RCNP AVF Cyclotron and the RCNP ring cyclotron for various ions and energies.

chambers as shown in Fig. 4 and 5. The gaps between these chambers are sealed by using pneumatic expansion seals. The cavity chambers and the valley chambers can be easily extracted from their operating positions along rails. The atmospheric pressure on the radial wall of the cavity chambers is supported by the magnet chambers.

A 180° single-dee acceleration system has been used in the RCNP AVF cyclotron. The frequency range of the acceleration cavity is 5.5~19.5 MHz, and fundamental acceleration mode is used for protons and alpha particles.

Fig. 6 shows orbit frequencies, acceleration frequencies and harmonic number of acceleration in the

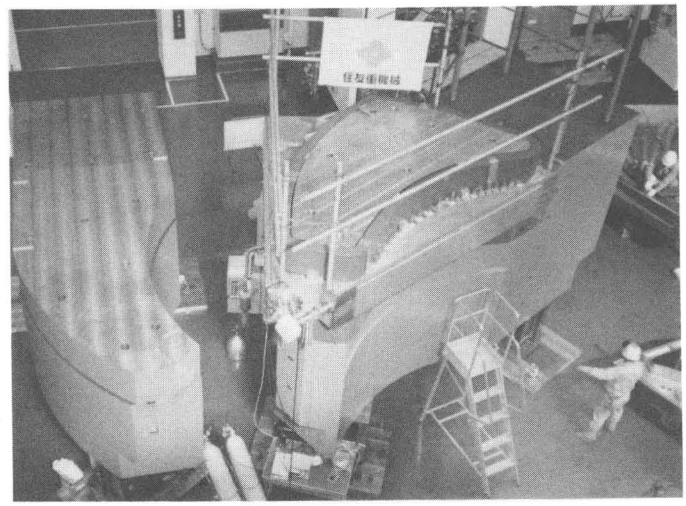

Fig. 7. Two sector magnets being under construction.

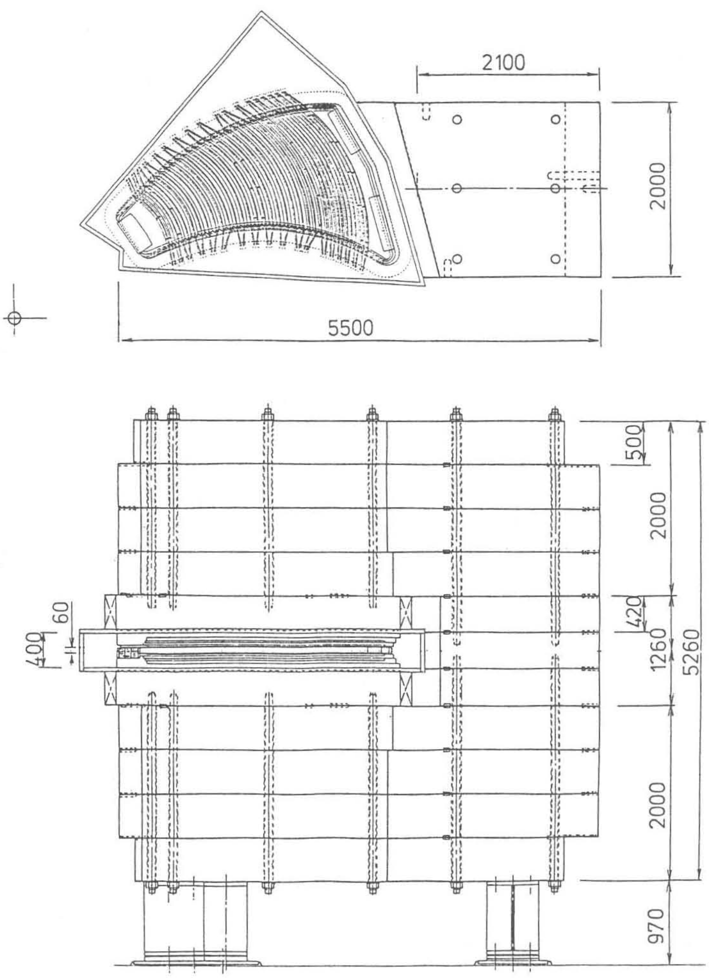

Fig. 8. Shape and geometrical size of the spiral sector magnet.

TABLE 2
Characteristics of the buncher

Frequency	35 ~ 105 MHz
Harmonic number	6
Π mode drift tube	0.5 m
Drift length	72 m
Maximum voltage	105 kV
RF power	10 kW

	Frequency	Beam phase width	
AVF	5.5 ~ 17 MHz	extraction	< 40°
Buncher	35 ~ 105 MHz	at buncher	< 240°
Ring Cyclotron	30 ~ 52MHz	injection	< 30°
		extraction	< 15°

two cyclotrons for various ions and energies. For the preparation of ideal injection beams for the ring cyclotron in longitudinal phase space, a beam bunching system will be introduced. The RF frequency of the buncher (35~105 MHz) is sixth harmonic of acceleration frequency of the RCNP AVF cyclotron. The characteristics of the buncher are presented in Table 2.

In Table 3 is shown the time schedule of delivery of various components of the ring cyclotron. As seen in the table, spiral sector magnets of the ring cyclotron are now under construction with a speed of four sets per year. In Fig. 7 and Fig. 8 are shown two spiral sector magnets being under construction and their shape and geometrical size, respectively. Ultra pure forged iron of carbon content of about 0.002% for the poles and rolled pure iron of carbon content of about again 0.002% for the yokes were produced by Sumitomo Metal Industries, Ltd. A detailed description of the magnets will be seen in the proceedings of this conference.

The injection and extraction system is already delivered. Substantial parts of the acceleration system are also delivered. These are three sets of RF power amplifiers, an acceleration cavity and a flat-topping cavity. (see Fig. 9 and Fig. 10). Most of the acceleration system will be delivered in this fiscal year. Their detailed

TABLE 3
Time schedule of delivery

	FY'87	FY'88	FY'89	FY'90
Main magnet system				
Sector magnet			4 set	2 set
Power supply			1 set	
Field mapper			1 set	
Field data				1 set
Injection and extraction system		1 set		
Acceleration system				
Acceleration cavity		1 set	2 set	
RF Power amplifier	1 set	2 set		
Flat-topping cavity		1 set		
RF Power amplifier			1 set	
RF driving signal				1 set
Valley chamber			2 set	
Vacuum System				
Accelration chamber				
Roughing system			1 set	
Diffusion pump			6 set	
Cryogenic pump		2 set	4 set	3 set
Injection and extraction line				
Turbo molecular pump				3 set
Auxiliary				1 set
Beam diagnostic system			1 set	
Cooling system			1 set	
Control system				
Hardware			1 set	
Software				1 set

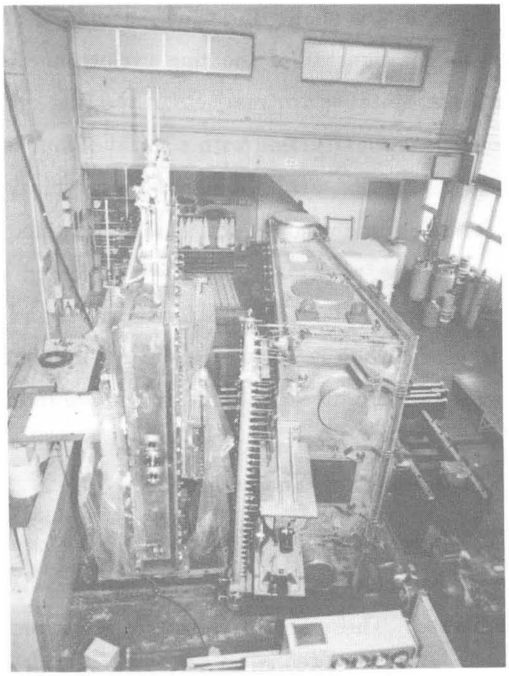

Fig. 9. An acceleration RF cavity and a flat topping RF cavity delivered.

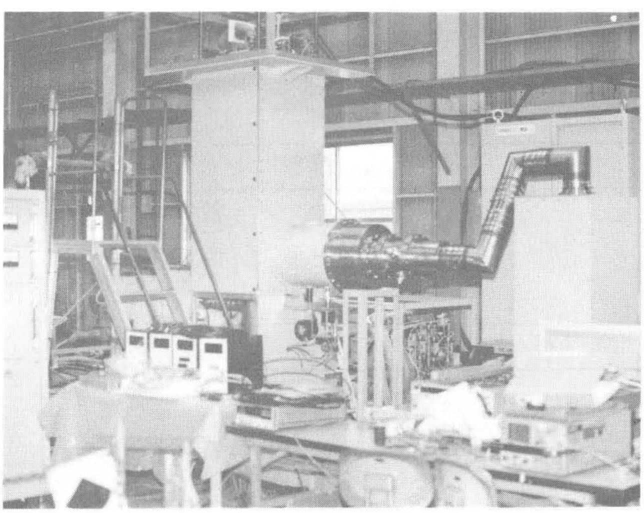

Fig. 10. An RF power supply being tested.

description will be presented in this conference by another speaker. Six sets of cryogenic and diffusion pump systems will also be delivered by 1990. All components of the ring cyclotron will be brought in from early 1990. A 40 ton crab-crane facility will be prepared to maintain the magnet yokes and the cavities. The date for delivery of the ring cyclotron including the distributed intelligent computer control system is March 1991.

EXPERIMENTAL-APPARATUS, BEAM LINES AND CIRCULATION RING

The most important motives of the new facilities is to extend the high precision studies into the intermediate energy region, where the distortion effect of the colliding systems is expected to be the smallest as mentioned before. In order to put such studies into reality, it is important to make a variety of experimental setup possible to allow the selection of kinematical conditions (i.e., selection of momentum, energy and/or mass transfer) as they suit best the specific problems of concern. The observations of the reaction products are desired to be done as exclusively as possible with high enough precision. The possibility of measuring spin observables is also considered to be important.

Based on the discussions made in these viewpoints in the Research Program Committee and in the relevant societies, the following apparatuses, besides the necessary beam lines, were adopted as candidates for construction:

(1) Beam circulation ring.
(2) Magnetic spectrograph GRAND RAIDEN.
(3) Second arm magnetic spectrometer with a large solid angle and a large momentum bite.
(4) Neutron TOF spectrometer with a 100 m long neutron flight path.
(5) pion spectrometer with a large solid angle.
(6) Devices to produce and utilize heavy ion secondary beams.

A decision was, however, made to give construction priorities to those appratuses that would faciliate us to yield scientific output at the earliest stage of operation.

Among the above listed candidates, such appratuses that were considered to fall in this category are the spectrograph GRAND RAIDEN, the neutron TOF spectrometer and a production system of the heavy ion secondary beams. The second arm spectrometer and the pion spectrometer have been left for near future construction and the plan for the circulation ring has been reduced to such a minimum extend that would allow only some basic technical developments. All the apparatuses, however, are currently being designed aiming at their original goals as partly shown in the following section.

Fig. 1 shows the layout of the experimental halls and devices how under consideration. The beam lines shown by the dotted lines are those eliminated from the present construction. These beam lines are scheduled to be constructed with use of magnets in the beam circulation ring when the ring is replaced by the cooler synchrotron. There are three experimental halls. The largest one, the West Hall, is for the beam circulation ring coupled to the spectrograph GRAND RAIDEN and, in future, also to the second arm spectrometer. The East hall is a general purpose experimental hall and one of the beam lines connected to it is to act as a heavy ion secondary beam line. The pion spectrometer will also be installed in the hall in near future. The Neutron Hall located at the top of the figure is connected to a 100 m long neutron flight tunnel. Most part of the building will be built underground.

BEAM CIRCULATION RING

A multipurpose storage ring, cooler synchrotron has been proposed in the RCNP Ring Cyclotron Facilities. Concerning this machine, an important consideration has also been given to the future possibil-

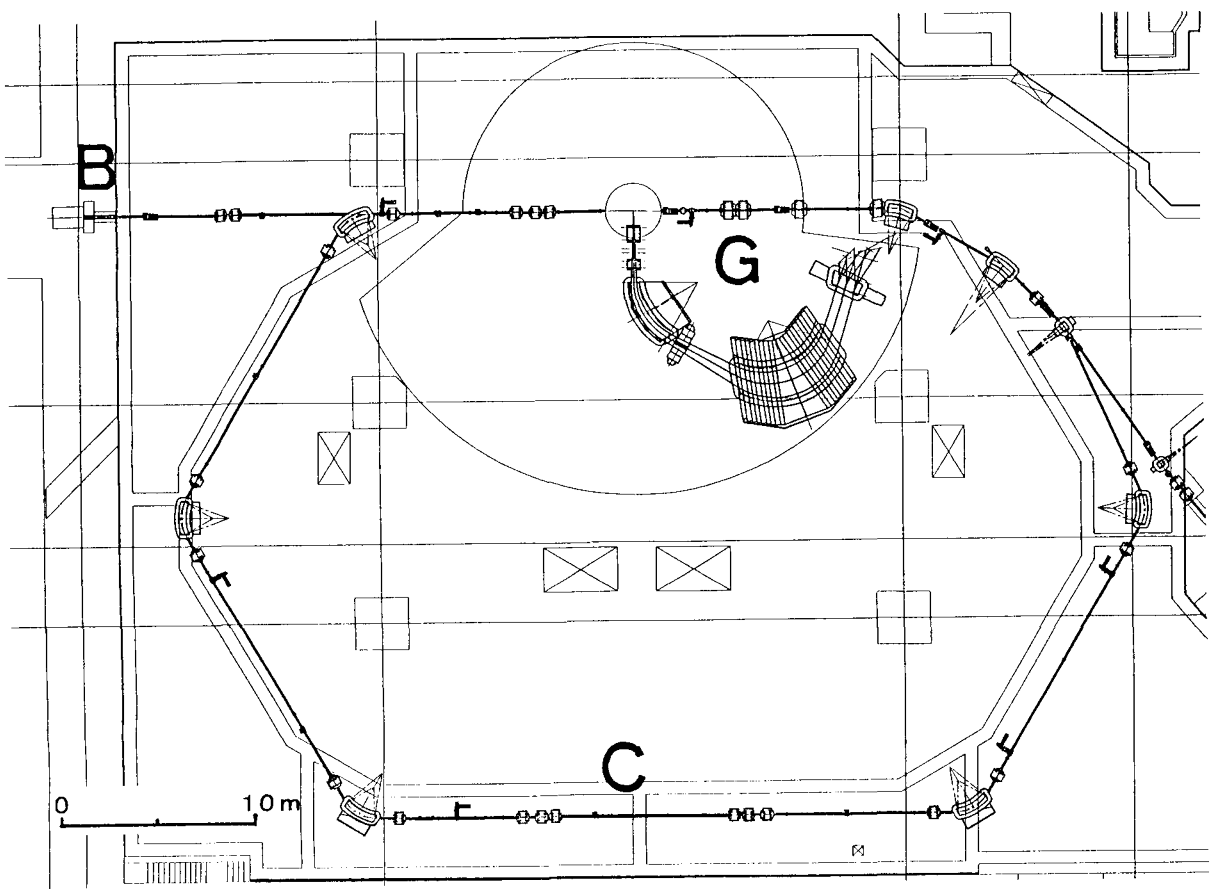

Fig. 11. The beam circulation ring linked to the spectrograph GRAND RAIDEN. B: Beam damp, C: Circulation ring, G: GRAND RAIDEN. Another second arm spectrograph to be linked to the ring is not shown, which will be constructed in near future.

ity to further extend our high precision studies into the GeV energy region. A beam circulation ring consisting of beam line magnets is now under construction as the first stage of the cooler synchrotron. The ring will therefore be used tentatively as a beam line link for the spectrograph GRAND RAIDEN as well as a test ring (see Fig. 11). The circulating ion beams will be injected into the ring from the ring cyclotron through the charge stripping method which will also be employed in the cooler synchrotron in future. One of the significant developments of the cooler synchrotron is, therefore, to put forward this injection method together with those of the new ion beam cooling scheme, "cyclotron maser cooling". The advantage of the beam circulation method with a very thin foil at the target position of the spectrograph GRAND RAIDEN will also be intensively studied with the circulation ring. A full scale AC quadrupole magnet of the cooler synchrotron was already constructed to investigate thoroughly the problems in manufacturing processes and the tolerances of both the mechanical property and field quality.

(a)

(b)

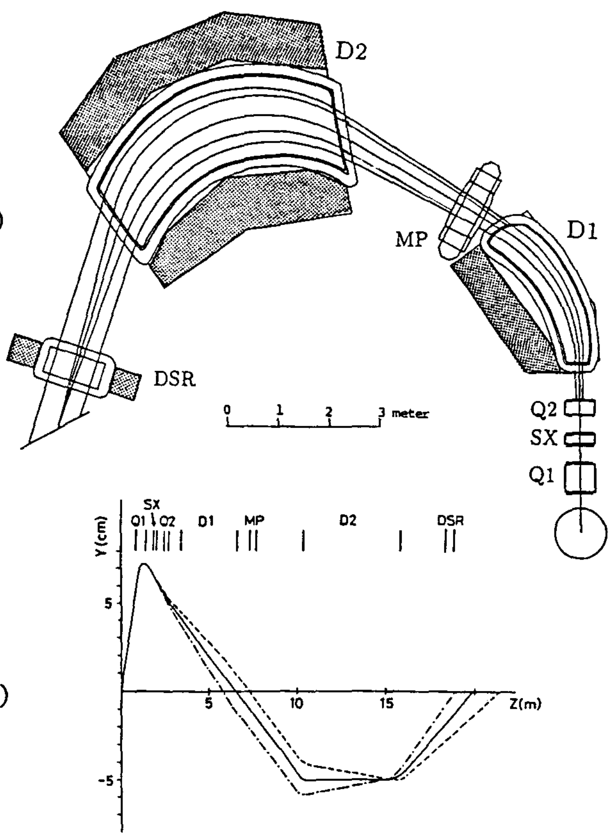

Fig. 12. (a) The layout of the spectrograph GRAND RAIDEN. It consists of two quadrupole Q, sextupole SX, one multipole MP, three dipole D magnets and a spin rotation dipole magnet DSR. (b) Vertical beam envelopes in the spectrograph. The solid, dotted and dash-dotted lines show the vertical heights for the rays with $\phi = 70$ mr, and with $\delta = 0$, +2.5%, and −2.5 %, respectively.

THE MAGNETIC SPECTROGRAPH GRAND RAIDEN

The high resolution ($p/\Delta p$=38000) magnetic spectrograph GRAND RAIDEN being under construction is of QSQDMQ(+D) type as seen in Fig. 12. The spectrograph GRAND RAIDEN exceeds, in the momentum resolution, the world highest resolution spectrograph RAIDEN of which the design value of resolution and the record of performance are 20,000 and 60,000, respectively. The basic ion optical properties of GRAND RAIDEN have been optimized in order to obtain a straight focal plane with the tilting angle of 45° and the vertical height less than 3 cm. The spec-

TABLE 4

SPECIFICATIONS OF THE HIGH RESOLUTION SPECTROGRAPHS AT RCNP

	GRAND RAIDEN	RAIDEN
Mean orbit radius	3 m	1.5 m
Total deflection angle	162°	160°
Angular range	0° ~ 90°	−20° ~ 120°
Focal plane length	150 cm	180 cm
Tilting angle of focal line	45.0°	52°
Maximum magnetic flux density	1.8 tesla	1.6 tesla
Maximum particle rigidity	5.4 tesla·m	2.4 tesla·m
Magnification-vertical	6.0	4.0
-horizontal[1)]	0.56	1.3
Momentum dispersion[1)]	22000 mm	27000
Momentum range	5 %	6 %
Momentum resolution[2)]	38000	20000
Acceptance angle-horizontal	±20 mr	±45 mr
-vertical	±80 mr	±70 mr
Solid angle	~6 msr	~13 msr
Total weight	600 ton	200 ton

1) Values are given along the focal line.
2) The source width is assumed to be 1.0 mm.

ifications of GRAND RAIDEN are presented in Table 4 together with those of RAIDEN. All magnets were made of ultra pure ion of carbon content of about 0.002 %. A multipole magnet of current sheet type is placed between the two dipole magnets D1 and D2 in order to correct aberrations which are caused by the kinematical effect and possible deviations of the magnetic field. In Fig. 13 are shown multipole fields of ideal distribution generated inside the multipole magnet originated by the present speaker.

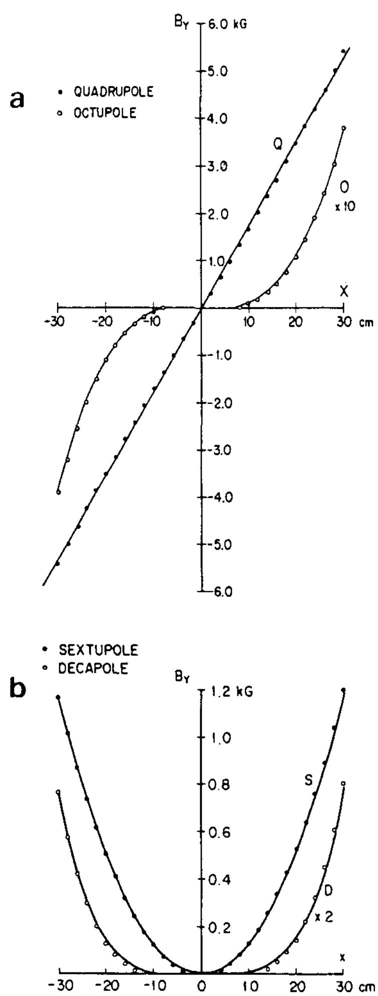

Fig. 13. Measured field distribution in the median plane of the multipole magnet. (a) Quadrupole and octupole field (b) Sextupole and decapole field.

CONCLUSION

It is my great pleasure to have the privilege of calling for kind and constructive collaborations of all the colleagues who belong to the community of science in Japan and abroad. I am sure that those collaborations will lead us to the truly productive 1990's.