ADVANCE IN THE PROPOSED RCNP RING CYCLOTRON

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Abstract–An intermediate energy particle accelerator complex is being designed as a new accelerator facility of RCNP. This accelerator complex is composed of two separated sector ring cyclotrons and a small injector cyclotron with external ion sources. Protons and light ions can be accelerated up to 550 MeV and 118 MeV/amu, respectively. Magnetic field properties of the sectors were studied with model magnets for the 1st ring and the 2nd ring. Orbital analyses were made using the measured field data. Studies for the RF system were made with a full scale model of the variable frequency single gap cavity. Preliminary studies on the injection and extraction systems of the 1st ring and the injector cyclotron were also made.

1. Introduction–An intermediate energy particle accelerator complex is proposed as a new accelerator facility of Research Center for Nuclear Physics.1) This variable energy accelerator complex covers a wide energy range above the present RCNP cyclotron and accelerates ions from proton through uranium with high intensity and good beam quality. The characteristics of the cyclotrons are given in table 1. The main accelerator of this complex is a two-stage isochronous ring cyclotron system. The 1st ring is designed to provide energies up to 190 MeV and 56 MeV/amu for protons and light ions, respectively. This energy range is extended up to 550 MeV and 118 MeV/amu for protons and light ions with the 2nd ring, respectively. The protons of 550 MeV are available for the meson factory. The 1st ring has four 33° radial sectors. The 2nd ring has eight spiral sectors. Both the ring magnets have 8 cm gap and Rogowski's edges cut stepwise with a numerically controlled milling machine. For these ring cyclotrons, the feasible conceptional design2) was done and intensive design studies with various models are being made.

A 1/3.5 scale model magnet of the 1st ring and a 1/4 scale model magnet of the 2nd ring are used to study various magnetic field properties.3) The analysis based on the measured magnetic field shows a good agreement with the prediction of the modified Spy-Ring code.1)3) Concentric circular trim coils for the model magnet of the 1st ring are made and the isochronous fields are studied.

Preliminary study of injection and extraction systems are made for the 1st ring. The measured magnetic field strength of the model was approximated with the hard-edge and corrections for the soft-edge effect on the orbit property was made.

Variable frequency H_{101}-mode single gap RF cavities with tuning plate are used for the rings. The characterisitics of the cavities are studied with a full scale model.4) The frequency range of the cavities is 20 ∿ 32 MHz. The harmonics used for acceleration in the rings are 4, 6, 8 and 12.1)

The injector for this accelerator complex is required to accelerate protons up to 25 MeV and heavy ions up to 30 q^2/A MeV and 70 q^2/A MeV for the no stripper and the gas stripper mode, respectively. A commercially available AVF cyclotron can be used as an injector of the complex. Design study on the axial injection system for this cyclotron are made to accept higher energy beams. The injection system is essential to the polarized ion and powerful external heavy ion sources. External ion sources are preferable to get a good performance on time structure, energy resolution and emittance of the beam. Then the axial injection system is used for all kinds of ions. Since the extraction radius of the injector is one half of the injection radius of the 1st ring, the harmonics used for acceleration in the injector cyclotron are 2, 3, 4 and 6. Some alternatives of the injector cyclotron such as a separated sector cyclotron with a Cockcroft-Walton are considered.5) However the ordinary cyclotron is chosen as the initial injector on economical reason.

Table 1

Characteristics of the cyclotrons

	INJECTOR CYCLOTRON	1st RING	2nd RING
No. OF MAGNETIC SECTORS	4	4	8
MAGNET FRACTION	1.0	0.37	0.42
SECTOR ANGLE		33°	∿19°
INJECTION RADIUS		1.35 m	3.4 m
EXTRACTION RADIUS	0.68 m	3.4 m	4.7 m
MAGNET GAP		8 cm.	8 cm
MAXIMUM MAGNETIC FIELD	18.5 kG($\bar{B}$)	16 kG	18.3 kG
K-VALUE(INJ) FOR H.I.		30 MeV	230 MeV
K-VALUE(EXT) FOR H.I.	70 MeV	230 MeV	460 MeV
MAGNET WEIGHT	160 tons	1200 tons	1600 tons
MAIN COIL POWER	200 kW	400 kW	600 kW
No. OF TRIMMING COILS	8	30	60
TRIMMING COIL POWER	20 kW	150 kW	200 kW
No. OF CAVITIES	2	2	4
RF FREQUENCY	20 ∿ 32 MHz	20 ∿ 32 MHz	20 ∿ 32 MHz
MAXIMUM VOLTAGE	50 kV	400 kV	500 kV
RF POWER	60 kW × 2	150 kW × 2	200 kW × 4

2. Magnet model studies– A 1/3.5-scale model magnet with trim coils for the 1st ring and a 1/4-scale model magnet for the 2nd ring were made. Fig. 1 shows plan and side views of a 1/4 scale model magnet of the 2nd ring. The magnetic field profiles of the model magnets are measured at eight excitation levels up to 18 kG. Relative strength of the magnetic field on the sectors does not show any remakable staturation effects. Since only one sector of model magnet was prepared for each ring, the magnetic field strength in the valley region was estimated with the simple superposition formula. Orbit analyses of the rings are made using the measured field data.

Fig. 2 and fig. 3 show the calculated radial and axial focussing frequencies for various ions at maximum energies for the 1st and 2nd ring, respectively. The predictions of the modified Spy-Ring code, shown with dashed lines for protons in fig. 2 and fig. 3, show a good agreement with those results of the analyses. However, the sector angle of the 2nd ring must be reduced by 1° to accelerate protons up to 550 MeV.

Twenty five pairs of trimming coils simultaneously excited with five independent currents are prepared for the 1st ring. A method is being studied to realize precise isochronous field for highly relativistic particle using premeasured magnetic field data by one step.3)

3. Injection and extraction system of the 1st ring–The injection and extraction system of the 1st ring are redesigned to fit the high radial focussing frequencies $\nu_r \approx 1.5$. Fig. 4 illustrates the layout of the injection and extraction system for the 1st ring. The injection trajectory for accelerated equilibrium orbit and injection elements in the central region of the 1st ring are also illustrated in fig. 5. The injection system is composed of two bending magnets (BM1, BM2), two magnetic inflection channels (MIC1, MIC2), two quadrupole magnets (Q1, Q2) and an electrostatic inflection channel (EIC). The extraction system is composed of two electrostatic extraction channels (EEC1, EEC2), two magnetic extraction channels (MEC1, MEC2), and a bending magnet (BM3). The characteristics of the injection and extraction elements are given in table 2. The MIC1 and the MIC2 are composed of iron shims and copper hollow conductor in a conventional way. The

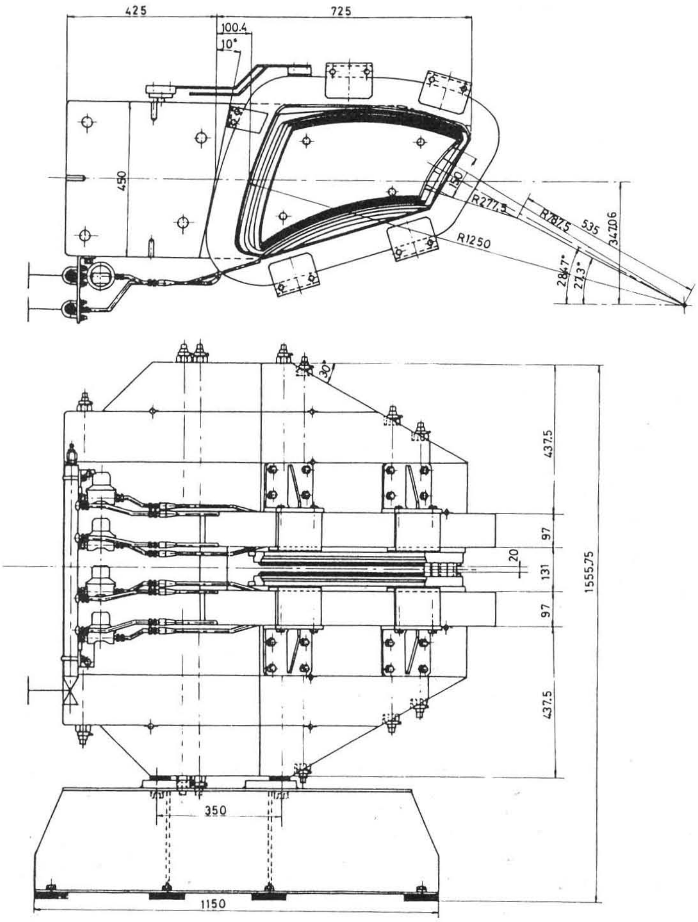


Fig. 1: Plan and side views of the 1/4 scale model magnet of the 2nd ring.

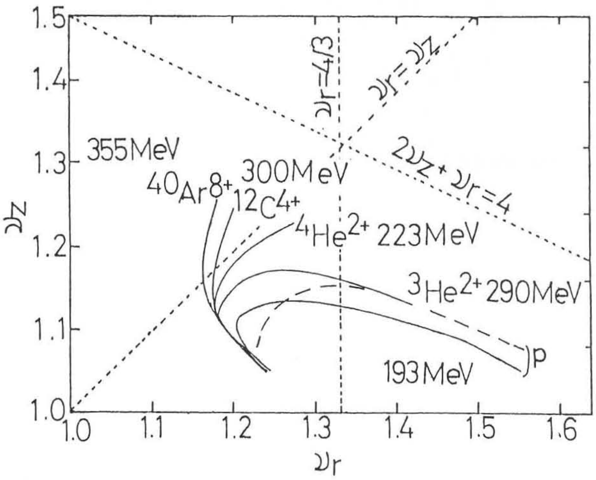


Fig. 2: Calculated radial and axial focussing frequencies of the 1st ring for maximum energies of various ions. Solid lines are results obtained using measured magnetic field data. Dashed line is prediction of calculation using the modified Spy-Ring code.

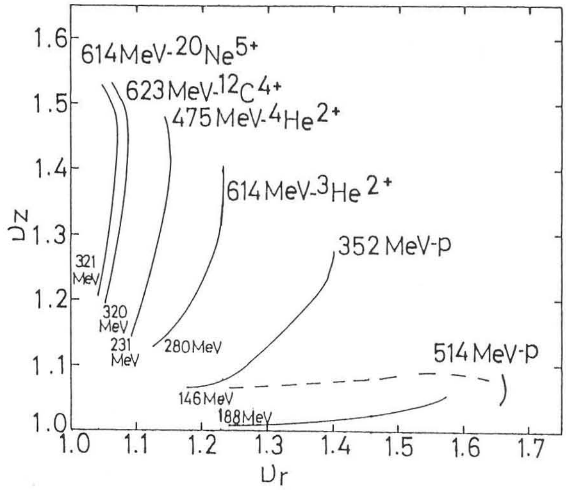


Fig. 3: Calculated radial and axial focussing frequencies of the 2nd ring for maximum energies of various ions. Solid lines are results obtained using measured magnetic field data. Dashed line is prediction of calculation using the modified Spy-Ring code.

Table 2

Characteristics of the injection and extraction elements

	θ_1	length	θ_2	Max. field	effective width Horiz.	effective width Vert.
BM 1	29°	14 cm (10°)	0°	11 kG	5 cm	3.5 cm
BM 2	10°	87 cm (110°)	-21°	17.5 kG	5 cm	3.5 cm
MIC1	9°	78 cm (94°)	16.8°	(16+3.3) kG	3.5 cm	4 cm
MIC2	30°	80 cm (87°)	22°	(16+0.9) kG	3.5 cm	4 cm
Q1		15 cm		1 kG/cm	5 cm	5 cm
Q2		10 cm		0.2 kG/cm	4 cm	2.5 cm
EIC		30 cm (3°)		75 kV/cm	1.5 cm	2 cm
EEC1		50 cm (0.2°)		60 kV/cm	1.3 cm	2 cm
EEC2		80 cm (0.8°)		75 kV/cm	1.5 cm	2 cm
MEC1		75 cm		(16-0.5) kG	2 cm	4 cm
MEC2		60 cm (4.5°)		3 kG+0.5 kG/cm	3 cm	2 cm
BM 3		107 cm (45°)		16 kG	6 cm	4 cm

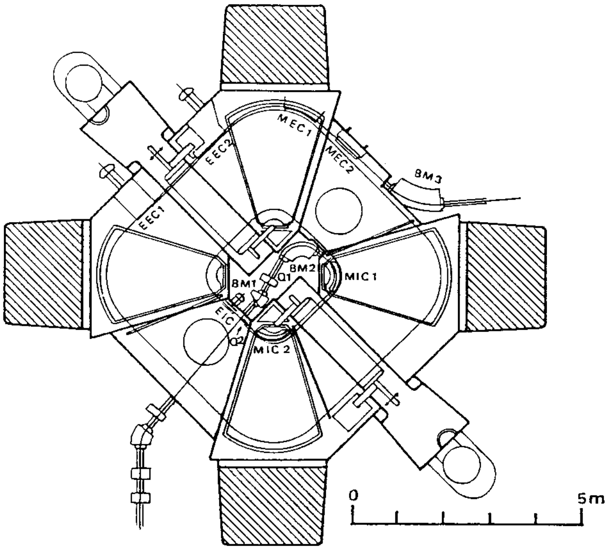


Fig. 4: Layout of the injection and extraction system for the 1st ring.

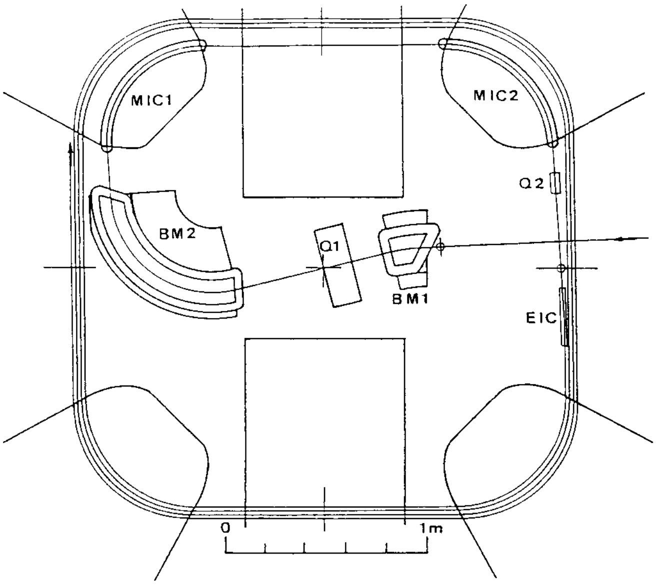


Fig. 5: Injection trajectory of the 1st ring.

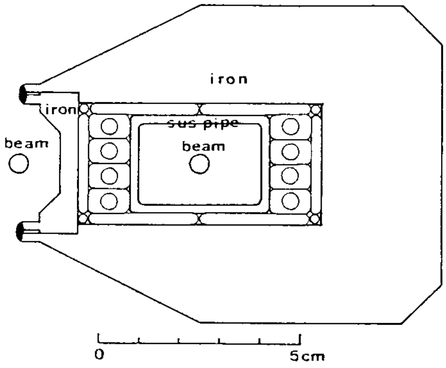


Fig. 6: Cross section of the magnetic extraction channel 2.

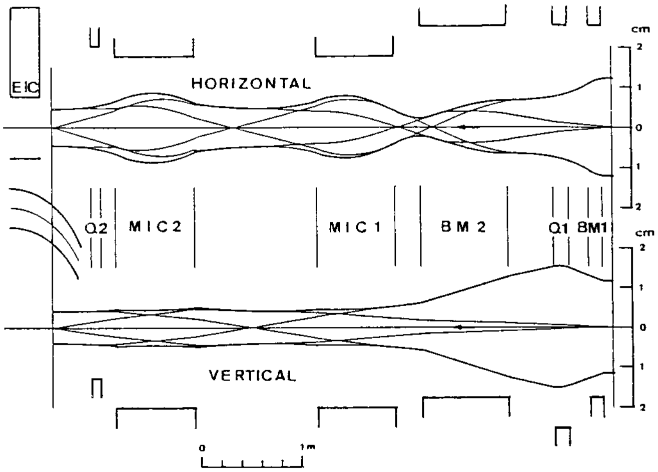


Fig. 7: Beam envelope of injected beam into the 1st ring.

MEC1 is septum coil. The MEC2 has dipole and quadrupole coils, as shown in fig. 6. The dipole coils are made of copper hollow conductor. The quadrupole coils are cooled by the dipole coils through He gas filled in the channel.
A similar structure is also used for the Q2.

The radial dispersion matching[6] on the 'point to point' and 'parallel to parallel' transfer mode was studied using the computer code TRANSPORT. Correction for incident angles of the MIC1 was needed to get the good matching. Fig. 7 shows the beam envelope and the trajectories for the point and parallel beams. A beam having an emittance, 12 mm × 2.8 mrad. in horizontal direction and 12 mm × 1.4 mrad. in vertical direction, is transferred to the injection point as a beam just match the eigen-ellipses, 4.8 mm × 7 mrad. and 4.2 mm × 4 mrad. in horizontal and vertical directions, respectively. The turn separation of the beams on the injection point is 20 mm. The momentum acceptance of the injection system is more than ± 0.5%. These acceptance can be got without precessional motion of the beam. The horizontal beam envelope has a narrow waist between the BM2 and MIC1 as shown in fig. 7. This point is suitable for monitoring the injection beam. At the extraction point in the valley, the turn separation of the beams is only 5 mm. However, the radial focussing frequencies of the 1st ring is very high ($\nu_r \approx 1.5$) on the extraction radius for protons and light ions, as shown in fig. 2. Thus the turn separation of 10 mm can be achieved with proper precessional motion of the beam. The extraction system is designed to extract the beam quickly through only one sector. A long extraction passage is not desirable because of the remarkable change of radial focussing frequencies for particle and energies. As shown in fig. 4 the space between the sector magnet and the cavity is used efficiently for the extraction.

4. RF model study–A full scale model of the variable frequency single gap RF cavity was made to study the characteristics of the cavities and to develop the RF power amplifier for the cavities. Fig. 8 shows the acceleration gap of the full scale model cavity. An oval tuner plate sliding on a stock changes the resonance frequency from 20 MHz to 32 MHz. Fig. 9 shows the resonance frequency, Q-value and input impedance measured at various positions of the tuning plate. The measured Q-values for 20 MHz and 32 MHz are 16000 and 19000, respectively. From the measured Q-values, the maximum RF power losses on the cavities are estimated to be 150 kW and 200 kW for the 1st ring and 2nd ring, respectively. The RF voltage distributions along acceleration gap are measured with the perturbation method. The results of the measurement show the radially increasing RF voltage for all

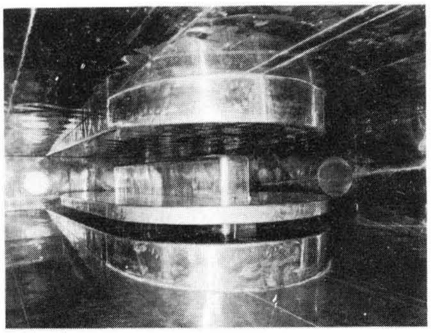


Fig. 8: Photograph of the acceleration gap of the full scale model cavity. The model cavity is rotated. Then the beam axis become vertical.

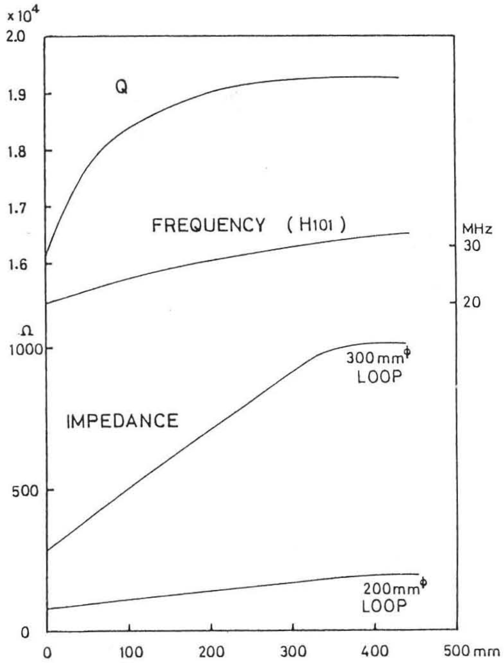


Fig. 9: Resonance frequency, Q value and input impedance measured at various positions of the turning plate.

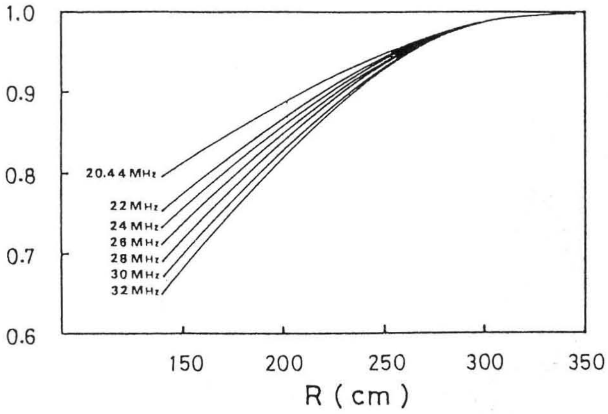


Fig. 10: Measured RF voltage distributions along acceleration gap of the model cavity.

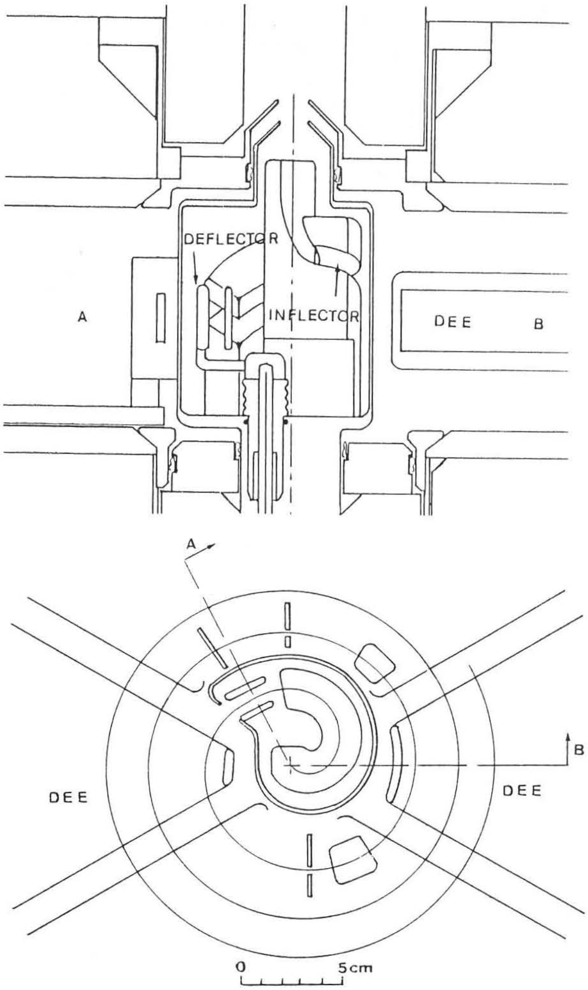
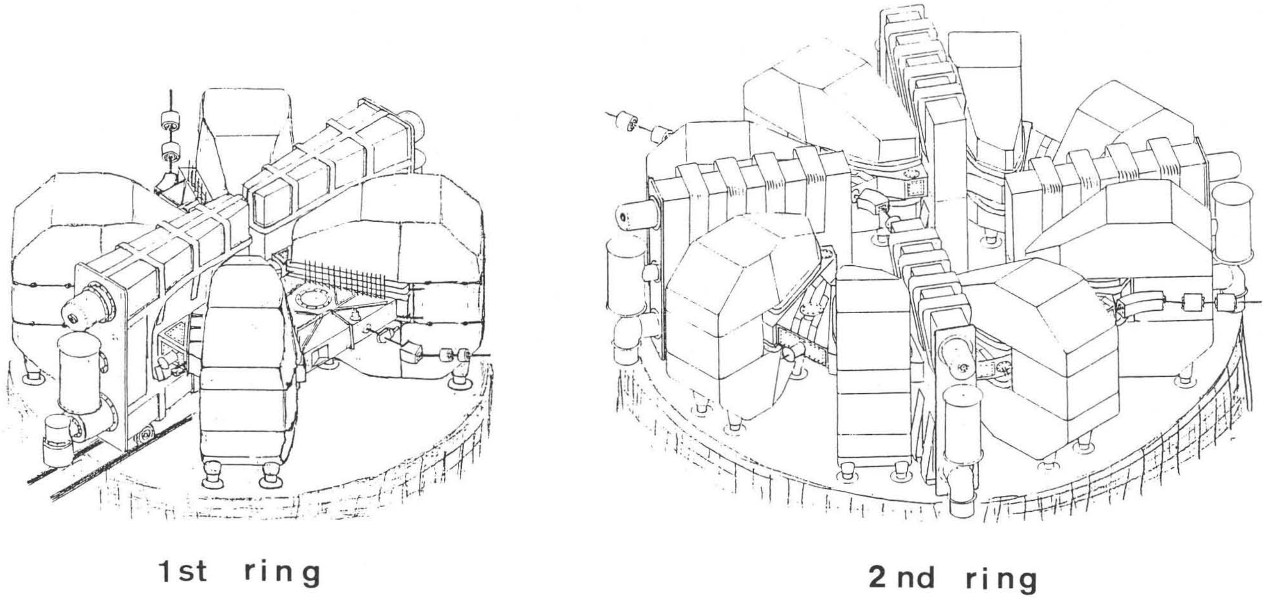


Fig. 11: Cross section and plan view of the central region of the injection cyclotron.

frequencies as shown in fig. 10. Studies for higher multiple oscillation modes of the cavity are also made.4)

5. The injector cyclotron–A commercially available AVF cyclotron is weighed as the initial injector. Design study on the axial injection system for the ordinary AVF cyclotron was made. The injection energy for maximum energy protons was increased to accept high intensity beam. The axial injection hole of magnet is located at the machine center to keep symmetry of the magnetic field. The higher injection energy is preferable to get high intensity and good quality beams. However, available gap of the cyclotron magnet and energy-gain per turn limit the injection energy for the ordinary AVF cyclotron. A Grenoble type7) electrostatic inflector with a small horizontal deflector are designed as fig. 11. For the maximum energy protons of this injector, the average magnetic field is 10 kG and the gap between the magnetic plugs is 16 cm. Consequently, the maximum injection energy of protons is 60 keV. The maximum designed field strength of inflector is 18 kV/cm and the maximum designed field strength of deflector is 16 kV/cm. An example of a good centering beam in the central region is also shown in fig. 11. The accelerating system of this injector cyclotron consists of two dees with angle of 60°. For acceleration of the heavy ions with 6th harmonic mode, these dees can be exchanged for dees with angle of 40°. The peak value of the dee voltage is 50 kV.



1st ring

2nd ring

Fig. 12: Isometric views of the 1st ring and the 2nd ring.

The maximum injection energy of presently operating AVF cyclotrons are distributed from 7.5 keV to 16 keV8). For high intensity beams, the space charge effect is severe. The peak beam currents giving the same space charge effect are proportional to $V^{3/2}(q/A)^{1/2}$, where V is the acceleration voltage9). Therefore the beam intensity can be multiplied ten times by using powerful ion source for the injection energy of 60 keV. The axially injected beams make a constant orbit in the inflection channel. Thus the injection voltage is proportional to B^2q/A for a given system, where B is magnetic field strength. The peak beam currents giving the same effect are accordingly proportional to $B^3(q/A)^2$ for a given system. The minimum value of q/A used for this injector is 8/40. However, available injection beam currents of such heavy ions are very low for useful energy range of this injector. The phase excursion of the beam is very severe for the high harmonic accelerations. A good centering beam can be also achieved for the high harmonic acceleration mode with maximum dee voltage using the deflector and the rotation of the inflection system.

6. Conclusions–The design studies on the proposed accelerator system have made large advance. The results of the studies are promising. The design studies will be done in detail to provide for the construction. Fig. 12 shows isometric views of the 1st ring and the 2nd ring.

7. Acknowledgements–The authors wish to thank the staff of the RCNP for their encouragement and for helpful discussions. The authors wish to acknowledge the usefulness of the many discussions with the SSC construction group of the IPCR.

" DISCUSSION "

G. DUTTO : What is the maximum intensity planned for the proton beam at high energy ?

I. MIURA : We expect 100 µA for 550 MeV proton beam.

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