PROPOSAL FOR CYCLOTRON CASCADE PROJECT

I. Miura, T. Yamazaki, A. Shimizu, K. Hosono, T. Itahashi,
T. Saito, A. Ando, K. Katayama, Y. Misaki and M. Kondo
Research Center for Nuclear Physics, Osaka University, Mihogaoka, Ibaraki, Osaka 567, Japan

Summary

The main components of the new facility are a six separated spiral sector cyclotron (SSC) and a beam storage ring linked to a 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 SSC. 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·Q^2/A MeV, respectively. An emphasis is placed on the production of high quality beams to enable precise experiments.

Introduction

The Research Center for Nuclear Physics is a national "user facility" founded in 1971. The equipments which include a K=140 AVF cyclotron and precise experimental apparatus are available for common use by all researchers in Japan and abroad.[1]

After a decade of operation, RCNP is now receiving strong demands from many users to bring within reach a high precision frontier of nuclear physics in the range of intermediate energies above the threshold of pion production.

In order to meet these scientific needs, a new proposal was put into reality as "RCNP Cyclotron Cascade Project" in the fall of 1985. The project which includes the construction of a K=400 separated sector cyclotron (SSC) as its heart has been endorsed strongly by the Japanese nuclear physics society and by the Science Council of Japan. In August 1986, the Ministry of Education authorized the project to start in the spring of 1987.

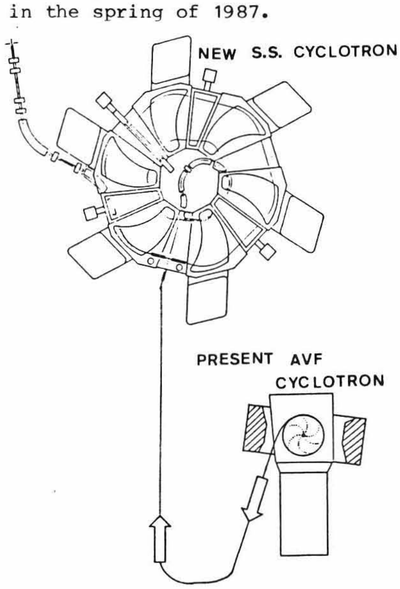

Fig. 1. Concept of cyclotron cascade project.

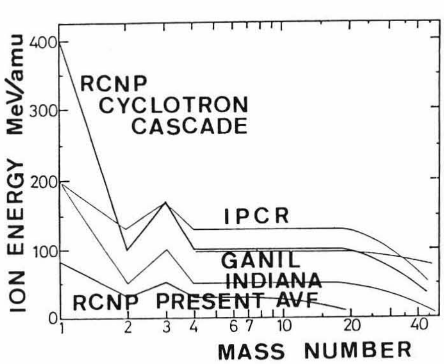

Fig. 2. Expected maximum energies of various ions for cyclotron cascade project and several major projects.

The SSC is energy quadrupler of the present RCNP AVF cyclotron. Figure 1 shows the concept of cyclotron cascade. Protons and alpha particles can be accelerated up to 400 MeV. Injection and extraction radii of the ring cyclotron are 2.0 m and 4.0 m, respectively. Maximum energies of various ions from cyclotron cascade are shown in Figure 2. Figure 3 shows orbit frequencies, acceleration frequencies and harmonic numbers of acceleration in the two cyclotrons for various ions and energies.

Figure 4 shows plan view of the SSC. Three 18°-dee acceleration cavities are used in the SSC. Frequency range of the cavity is 30 ~ 50 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 acceleration frequency to get energy resolution better than 10^{-4}. Figure 5 shows isometric view of the SSC.

A 180°-single-dee acceleration cavity is used in the present AVF cyclotron. The frequency range of the cavity is 5.5 ~ 19.5 MHz, and fundamental acceleration mode is used for protons and alpha particles. Converting the frequency range of the cavity to 30 ~ 50 MHz, the mismatching between the acceleration frequencies will disappear. The characteristics of the cyclotrons are given in Table 1.

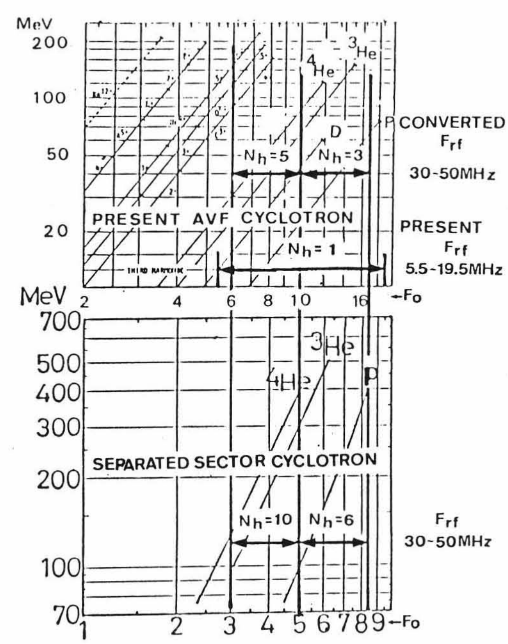

Fig. 3. Orbit frequencies (F_0), acceleration frequencies (F_{rf}) and harmonic numbers of acceleration (N_h) in the present AVF cyclotron and the energy quadrupler (a six separated spiral sector cyclotron (SSC)) for various ions and energies.

For the preparation of ideal injection beams for the SSC, some apparatus[2] for the detailed treatments of the beams are also considered in the injection line.

Small AC switching magnets are employed in the beam transport system to swing beams quickly to another experimental apparatus. The beam storage ring is expected to be used in several modes, that is, cooling mode for high resolution experiments, accumulation mode for studies with high luminosity and acceleration mode to achieve even higher energies.

This paper is a summary for the design studies of the cyclotron cascade. The design study of the lattice of the multipurpose race-track structure beam storage ring is reported elsewhere.[3]

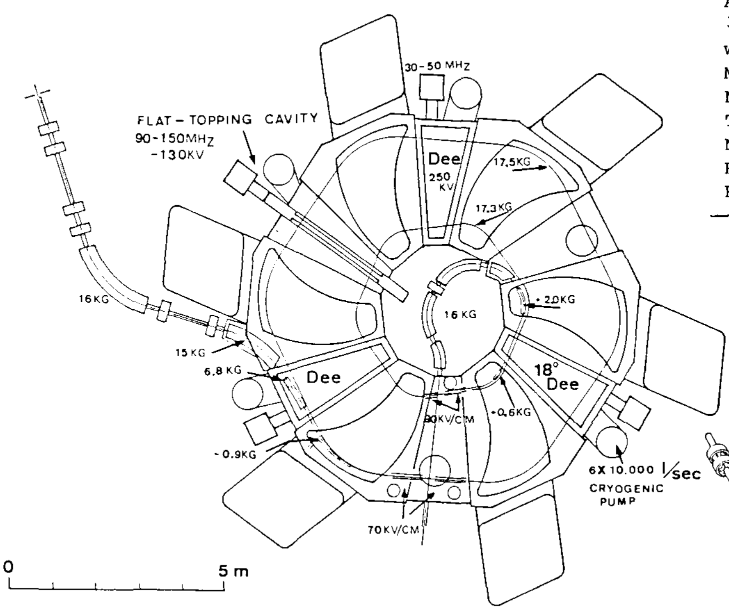

Fig. 4. Plan view of the SSC and maximum field strength of various elements.

Spiral Sector Magnets of the SSC

In the previous proposal[4], a computer code FIGER (artificial magnetic field distribution generator) was used for design. The preciseness of the FIGER was already confirmed by the 1/4.5 scale model magnet study of the four sector SSC.[5]

The sector magnets of the six separated spiral sector cyclotron were also designed by using the FIGER. The radial field distribution without trim coil current is isochronous for 200 MeV proton acceleration.[6] The magnets have 6 cm gaps and Rogowski edges. The total weight of magnets is 2000 Ton. The radial and axial betatron frequencies for maximum energies of various ions in the SSC are calculated as shown in Figure 6.

Thirty five pairs of trim coils follow the Gordon orbits. The trim coils are divided into eight radial region groups. In each group, all trim coils have same radial width (40 or 60 or 80 mm).[6] The radial gaps between trim coils are 5 mm. Each group of coils are driven in series by one large power supply, to reduce construction cost. Twenty seven ground-bypass current controllers are prepared for each of downstream trim coils.

There is an inhibited energy region of proton acceleration at 200 MeV for series driven and ground-bypassed trim coil system. However, the inhibited region can be reduced by use of trim coils in same radial width in each of the groups.

Table 1

Characteristics of cyclotrons

	Injector Cyclotron AVF	SSC 6 SECTORS
No. of sector magnets	3	6
Sector angle	max 52°	22~26°
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	2000
Main coil magnet (kW)	450	450
No. of trim coils	16	~35
Trim coil power (kW)	265	250
No. of cavities	1	3
RF frequency (MHz)	35~50 (6~18)*	30~50
RF power (kW)	120	250×3

* AVF: for present acceleration

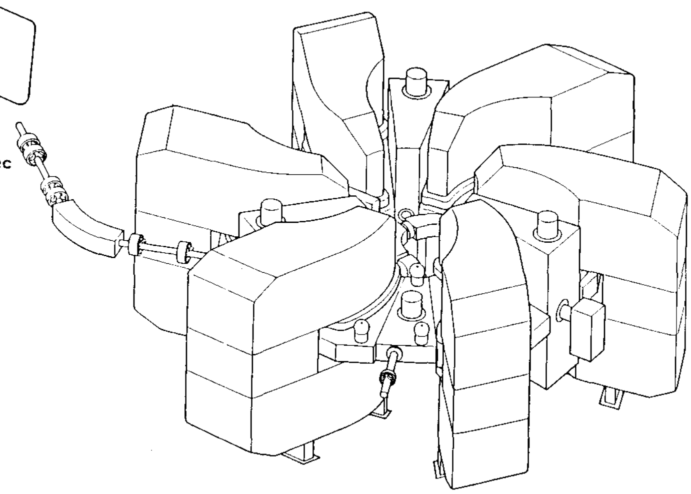

Fig. 5. Isometric view of the SSC.

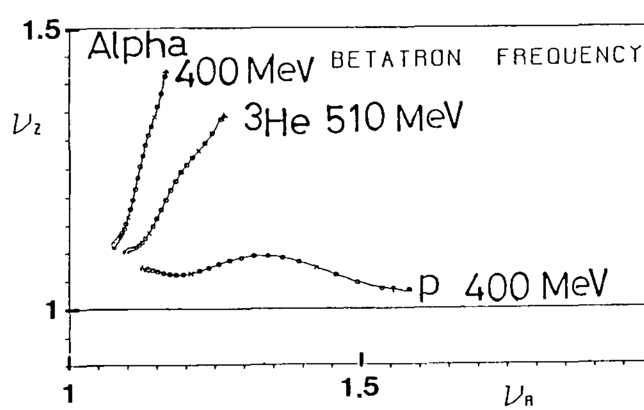

Fig. 6. Radial and axial betatron frequencies for maximum energies of various ions.

The radial gaps of the trim coils and radially stepwise distribution of the trim coil current produce magnetic field errors of isochronous trim coil fields. The computer code TRIM was used to calculate the errors. The maximum amplitude of trim coil field errors was estimated to be less than 3 gauss on ideal setting condition of trim coil current for 400 MeV proton acceleration. The amplitude of phase excursions for acceleration and flat-topping frequencies are 1° and 3° respectively.

Acceleration System

Three 1/2λ type 18°-dee acceleration cavities with a pair of sliding shorts are used in the SSC. Such cavity has a very strong tendency to generate radially concave distribution of acceleration voltage for high frequency. Frequency range of the cavity is 30 ~ 50 MHz. The results of the orbit analyses shows that the concave distribution narrows the phase acceptance for flat-topping.[7]

The cavity structure was investigated by 1/5 scale models to get nearly flat voltage distribution. Conceptional design of electrical and mechanical structure of the cavity has been done.[8]

A single gap H_{101} cavity operating at 90 ~ 150 MHz is to be used for the flat-topping. The cavity has a pair of lips at acceleration gaps and a pair of sliding tuner plates. This kind of cavity generate convex distribution of acceleration voltage. Flat-topping with such cavity also narrows the phase acceptance. However, the effect with flat-topping is not strong, since flat-topping voltage is low.

The radial length of the lips is about 2 m. The RF cutoff frequency of the beam aperture for up-down oscillation is 75 MHz. Consequently, up-down symmetry of the single gap cavity is very important to reduce harmful effect on beam phase probes.

Injection and Extraction

The injection and extraction systems of the SSC satisfy the central-position phase matching condition (dispersion matching). A variable dispersion system follows the extraction system of the SSC, to cancel the velocity dependent momentum dispersion ($D = R_{ex}(1-\beta^2)$) of a relativistic isochronous cyclotron at extraction radius (R_{ex}). The maximum field strength of various elements are shown in the plane view of the SSC, Fig. 4.

Orbit Analyses for Isochronous Fields

The orbital properties of the accelerated beams in the SSC were studied in a simulated magnetic field distribution.

A particle following the equilibrium orbit with acceleration voltage 250 kV was searched at radius of 3.0 m. The particle decelerated down to injection radius 2.0 m to determine the central ray of the injected beam. The injection and extraction systems of the SSC satisfy the central-position phase matching condition. The orbit analyses were done for an ideal case in which the energy width of the injected beam is zero.

The 18°-dee does not satisfy the peak acceleration condition for 6th harmonic acceleration mode of the protons. However the calculated result shows no remarkable radial-longitudinal coupling effect. The sine wave acceleration voltage in the SSC produce energy broadening of 700 keV for 400 MeV proton beams having RF phase width 7°. This energy broadening can be canceled perfectly with only one flat-topping cavity, without evident radial-longitudinal coupling effect. If the phase errors between the cavities are less than ±0.1°, the energy width of the 400 MeV protons is less than 10^{-4}.

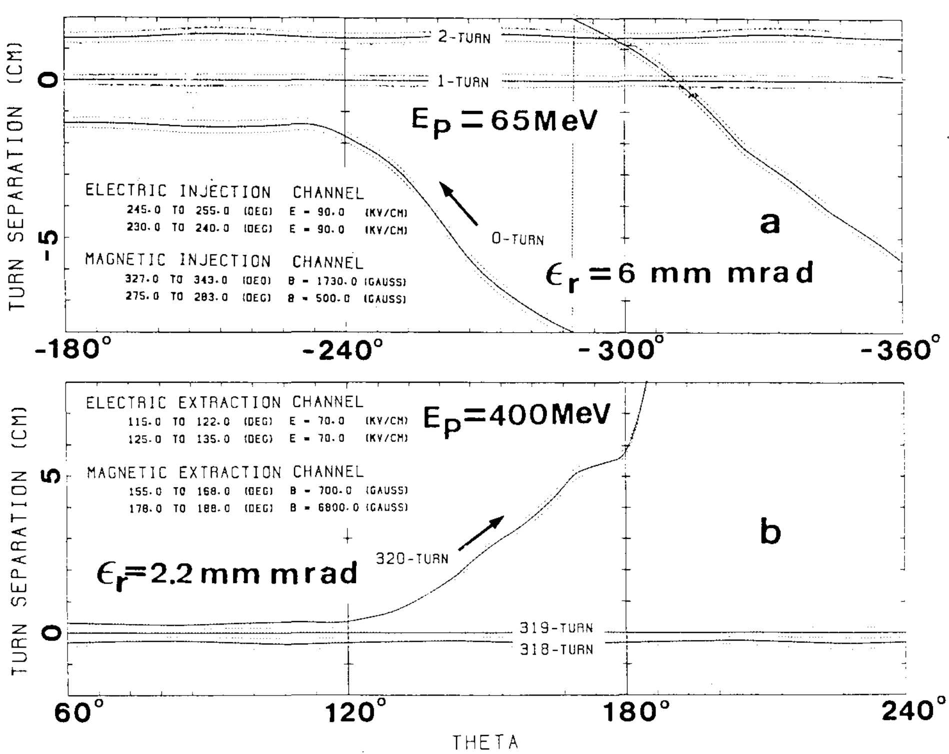

Fig. 7. Turn separations: a) at injection radius, b) at extraction radius

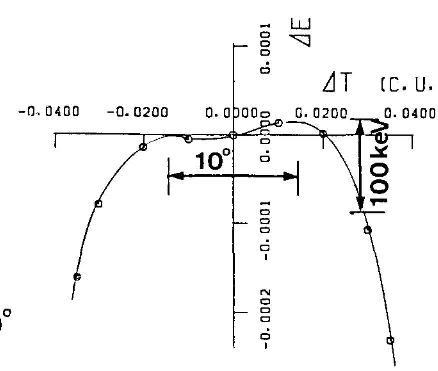

Fig. 8. Energy deviation of the 400 MeV proton beams versus acceleration phases for radial flat voltage distribution.

The orbit properties of the beam along the injection and extraction elements in the SSC also studied. In the electrostatic inflectors and deflectors, the deviation of the beams from linear motion were less than 2 mm. Straight inflection and deflection systems can be used. The turn separations at injection and extraction points are 14 mm and 3 mm, respectively. The single turn extraction can be realized with flat-topping as shown in Fig. 7.

The ratio of the acceleration voltage at extraction and injection radii (V_{ext}/V_{inj}) should not be much larger than 1. At the extraction radius, the energy width of the injected beam will be multiplied by this ratio. Consequently, large phase compression can not be expected.

The wide phase acceptance for single turn extraction mode with flat-topping is desirable to get high intensity beams. The phase acceptance depend much for the radial distribution of the acceleration voltage. Phase acceptance of 20° in width can be expected for flat voltage distribution as shown in Fig. 8. The concave distribution narrows the phase acceptance. A wide phase acceptance can be realized by the convex distribution.

As shown Fig. 6, the axial betatron frequencies for acceleration of 400 MeV protons is always near to $\nu_z = 1$ resonance. The effect of the resonance was studied. The up-down misalignment of magnets should be less than 0.1 mm to keep the axial oscilation amplitude below acceptable level ±1.5 mm.

Effects of Trim Coil Field Errors

The maximum amplitude of the field error for ideal setting of trim coil currents was estimated to be less than 3 gauss. The radial gradient of the error field modulates radial and axial betatron frequencies quickly with radius as shown in Fig. 9. On the other hand, the decelerations with a single gap flat-topping cavity break three fold symmetry of rotation for the accelerated equilibrium orbits for each of turns and shift the center of the equilibrium orbits. These shifts are proportional to the fractional deceleration energy and $1/(\nu_r-1)$. The osciration of the accelerated equilibrium orbit centers drives the radial oscillation of accelerated beams.

Geometrical resonances driving radial oscillation were found[7], when integer multiple of turn separation is equal to the pitch of the trim coils and the integer is equal to $1/(\nu_r-1)$. This oscillation is coherent and is not harmful for beam quality. The radial driving can be canceled by a first harmonic component of the magnetic field or asymmetric arrangement of acceleration cavity voltage.

Vacuum System

The acceleration chamber of the SSC consists 6 magnet chambers, three RF cavity chambers, a flat-topping cavity chamber and two valley chambers as shown in Fig. 4. The gaps between these chambers are sealed by pneumatic expansion seals. The reliability of the seals was verified with model study of the pneumatic expansion seals.[9] After 20 hours of evacuation, the acceleration chamber can be pumped down to 10^{-7} Torr by six 10000 ℓ/sec cryogenic pumps.

Acknowledgment

The authors would like to acknowledge to director H. Ikegami for his encouragement of this proposal. They also wish to thank to all the RCNP staffs especially to S. Morinobu, M. Fujiwara and T. Noro for their heartful help to us.

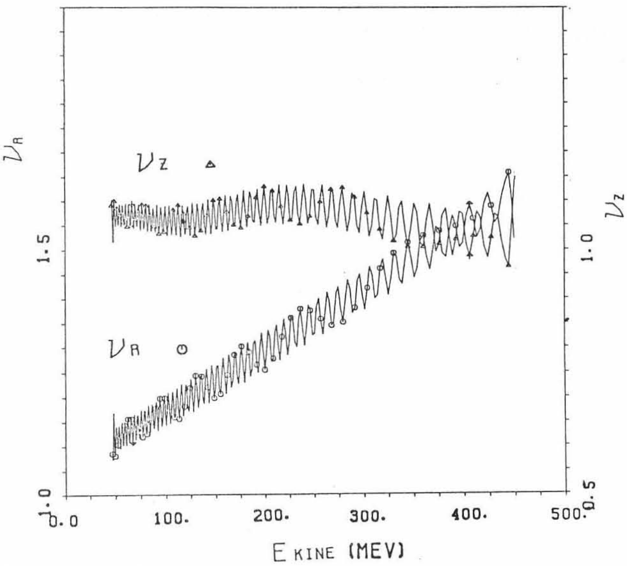

Fig. 9. Radial and axial betatron frequencies for 400 MeV protons in the isochronous trim coil field. Pitch of the trim coils is 45 mm and field modulation is 3 gauss in amplitude.

References

1. M. Kondo, "Recent Developments at the Osaka RCNP 230-cm Cyclotron and a Proposal for a New Ring Accelerator", IEEE Trans NS-26, 2, 1904-1911 (1979).

2. A. Shimizu et al, "Post Injector-Cyclotron Beam Bunching System:, in this conference.

3. A. Ando et al., "Design Study of a Cooling Ring and Storage Synchrotron at RCNP", in this conference.

4. I. Miura et al., "A High Energy Version of RCNP Ring Cyclotron", Proc. 10th Int. Conf. on Cyclotrons and Their Applications, East Lansing (USA) 1984, p.579.

5. K. Hosono et al., "Spiral Sector Magnet of RCNP Ring Cyclotron Project", RCNP Annual Report (1984) p.167.

6. K. Hosono et al., "Spiral Sector Magnet of the Proposed Six Sector Ring Cyclotron", in this conference.

7. T. Yamazaki et al., "Beam Quality Study in RCNP Six-sector Ring Cyclotron", in this conference.

8. T. Saito et al., "RF System of RCNP Ring Cyclotron Project", in this conference.

9. A. Shimizu et al., "Pneumatic Expansion Seal of the Separated Sector Cyclotron Vacuum Chamber", in this conference.