RCNP RING CYCLOTRON

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Abstract

The energy range of the proposed first ring cyclotron has been extended up to 300 MeV for proton. Four spiral-sector flared magnets are used for the new ring. The orbit properties of beams in the ring and the injector cyclotron were studied with and without acceleration.

An energy resolution better than 10^{-4} can be obtained with a new method of flat-topping without flat-topping deceleration for the beams which had a phase width of ±6° before the injection to the ring cyclotron.

1. Introduction

An intermediate energy particle accelerator complex has been designed as a new accelerator facility at RCNP. This accelerator complex is composed of two separated sector ring cyclotrons (the first ring and the second ring) and a small injector cyclotron with external ion sources. The detailed designs of the system have already been reported[1,2,3].

Recently some modifications to the original design for the first ring have been performed and new sector magnets have been designed to achieve energies up to 300 MeV and 85 MeV/amu for protons and light ions respectively[4]. Fig. 1 illustrates the layout of the first ring cyclotron. The shape of the sector was designed by using artificial magnetic field distributions.

A 1/4.5-scale model magnet for the spiral ring cyclotron is used for final test. An RF cavity was constructed for the new ring. The phase compression ratio of the cavity is variable around the value of 3.

The characteristics of the cyclotrons are given in Table 1. Variable-frequency single-gap cavities are used for acceleration. The frequency range of the cavities is 20 to 33 MHz. Fig. 2 shows the orbital frequencies and the harmonics used for acceleration in the first ring cyclotron.

The aim of this accelerator system is to get high quality beams of protons and light ions accelerated up to the intermediate energy region for precise nuclear studies in high resolution.

Recently at Indiana and Uppsala, electron cooler rings are being constructed to cool down the beams below to 10^{-4} in beam energy spread.

In the proposed system, the energy spread of the beam from the injector cyclotron can be precisely compensated to below 10^{-4} in fractional energy spread by using new method of flat-topping without flat-topping deceleration.

2. Ring Cyclotron

2.1 Spiral Ring Magnets

New spiral sector magnets for the first ring have been designed to accelerate 300 MeV protons on the condition of $\nu_z>1$. The magnets have 6 cm gaps and Rogowski edges. Orbit properties of the ring were studied using artificial magnetic field distributions of the ring generated with the code FIGER. Fig. 3 shows the calculated isochronous field and the radial and vertical betatron frequencies for maximum energies of various ions. The orbit analyses based on the measured magnetic field of the 1/4.5-scale model show that the design of the magnet is satisfactory[5].

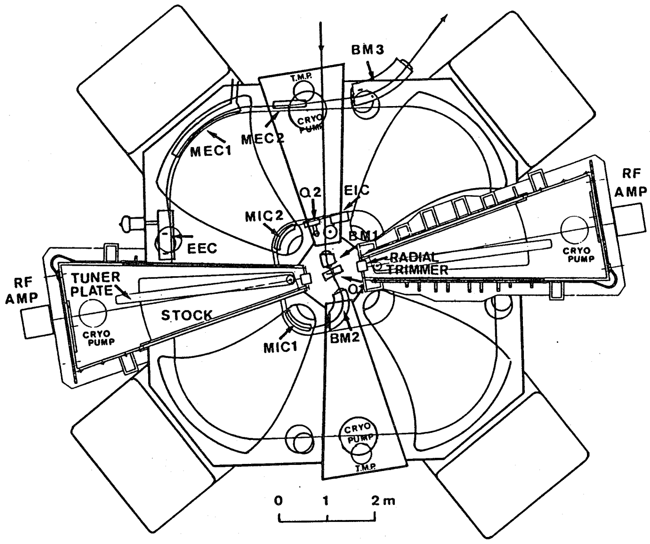


Fig. 1. Layout of the first ring cyclotron.

2.2 Orbit Analysis

A computer code FIGER was developed to generate the artificial magnetic field distribution for a desired sector of the cyclotron. The betatron frequencies were calculated numerically for both the measured field and the corresponding artificial field from injection radius through extraction radius. These results are in an extremely good agreement with each other.

Computer codes ISOCH and ACCEL were developed to study the orbital properties of the ring cyclotron with and without acceleration, respectively[6].

2.3 RF System

An aluminium variable-frequency single-gap cavity for the ring cyclotron is used for an full power test of the RF acceleration system. The resonance frequency of the cavity covers a frequency range of 20 to 33 MHz with a rotatable tuner plate sliding on a stock as shown in Fig. 1.

Table 1
Characteristics of the cyclotrons

	Injector AVF	First Spiral Ring
No. of sector magnets	4	4
Sector angle		34°∿ 39°
Injection radius (cm)		135
Extraction radius (cm)	67.5	375
Magnet gap (cm)	13.0	6.0
Magnetic field max. (kG)	20.0	15.5
Proton energy max. (MeV)	26	300
Alpha energy max. (MeV)	38	340
K-value	70	280
Weight of magnet (tons)	120	1600
Main coil power (kW)	200	350
No. of trim coils	8	35
Trim coil power (kW)	20	160
No. of cavities	2	2
RF frequency (MHz)	20 ∿ 33	20 ∿ 33
Voltage max. (kV)	50	500
RF power (kW)	60 × 2	200 × 2

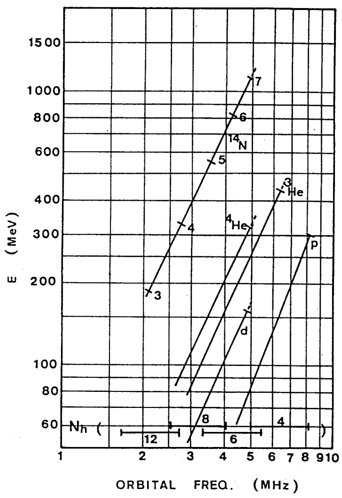


Fig. 2. Ion energy and acceleration harmonics, N_h, as a function of orbit frequency.

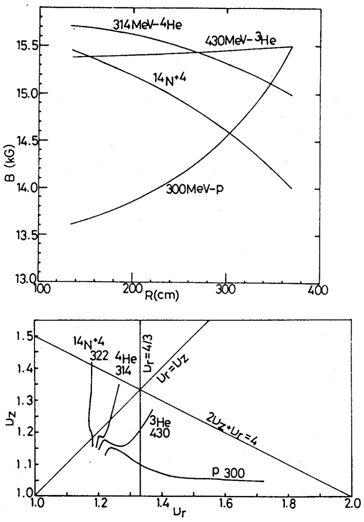


Fig. 3
a: Calculated isochronous fields.
b: Radial and vertical betatron frequencies for maximum energies of various ions.

Frequency ranges and voltage distributions were investigated by using 1/10-scale models. The cavity is designed to be able to adjust phase compression ratio around the value of 3 by a radial trimmer as shown in Fig. 1. The cavity was evacuated to 1×10^{-6} Torr with a 10 in. diffusion pump[7]. An RF power amplifier system was developed and the cavity was excited by the amplifier up to 200 kV after 50 hrs conditioning[8]. The aluminium cavity will be evacuated to a pressure lower than 1×10^{-7} Torr by a 20 in. cryogenic pump, and excited up to 500 kV by the RF power amplifier.

2.4 Injection and Extraction

The injection and extraction systems are also illustrated in Fig. 1. The injection system is similar to the one of the previously proposed first ring cyclotron[1] and satisfies the central-position phase matching condition[9].

3. Injector Cyclotron

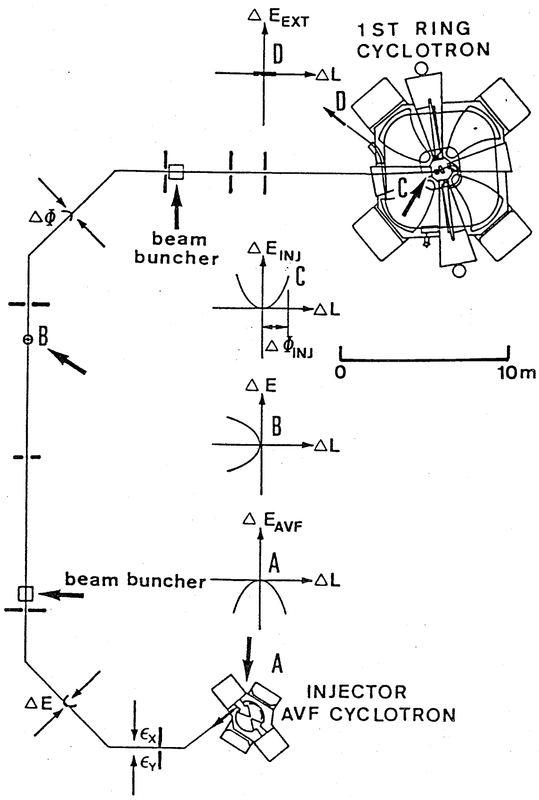
An AVF cyclotron with external ion sources has been designed as the injector. An axial injection energy of 60 keV is used for maximum energy protons[1]. A small test magnet was prepared and the magnetic field distribution in the central region of the injector cyclotron was studied[10]. Main characteristics of the injector cyclotron are also listed in Table 1.

The analysis of the orbit properties down also for the injector cyclotron. The results show that the azimuthal dee width should be matched for peak voltage acceleration condition.[11] In the central region of a AVF cyclotron, the c.p. phase matching condition make a confusion cased by large fractional energy gain. However, the c.p. phase matching condition is fulfilled automatically for the axial injection.

A well centered fine beam can be accelerated through wide RF phase in the injector cyclotron by using the relatively high axial injection voltage. The emittance of the beam at extraction radius can be kept below a few mm·mrad for narrow local RF phase domain. The energy gain is 200 keV/turn for 26 MeV proton. The extracted beam can be let to have a unique number of turn through a phase width wider than ±6°.

4. Beam Transport System

The beam transport system between the injector and the first ring forms an achromatic transport system as shown in Fig. 4. The extracted beam from the injector makes achromatic focusing at the source defining slits.



$$\Delta E_{AVF} = -\frac{1}{2}(\Delta\phi_{AVF})^2 \pm \Delta E_{0.AVF}(\phi,\Delta R,\Delta P_R,I)$$

$$\Delta E_{EXT} = \frac{1}{2}(\Delta\phi_{INJ})^2 E_{INJ}\underbrace{\left(a - \frac{E_{EXT}-E_{INJ}}{a^2\cdot b\cdot E_{INJ}}\right)}_{0} \pm a\cdot\Delta E_{0.INJ} \pm \Delta E_{0.RING}(\phi,\Delta R,\Delta P_R,I)$$

$$a = \frac{\Delta\phi_{INJ}}{\Delta\phi_{EXT}} = \frac{V_{EXT}}{V_{INJ}} \simeq 3 \qquad \Delta\phi_{EXT} = \frac{1}{a}\Delta\phi_{INJ} \qquad \frac{1}{a^2\cdot b} \simeq \frac{1}{4}$$

$$E_{INJ} = E_{AVF} \qquad \Delta E_{INJ} = -\Delta E_{AVF} \qquad \Delta\phi_{INJ} = -\Delta\phi_{AVF}$$

Fig. 4. New flat-topping method used in the beam transport system between the injector and the first ring.

The emittance can be limited by the slits and aperture slits followed the injector cyclotron. The injection system of the ring also makes dispersion matching. Then, perfect achromatic transversal matching can be made.

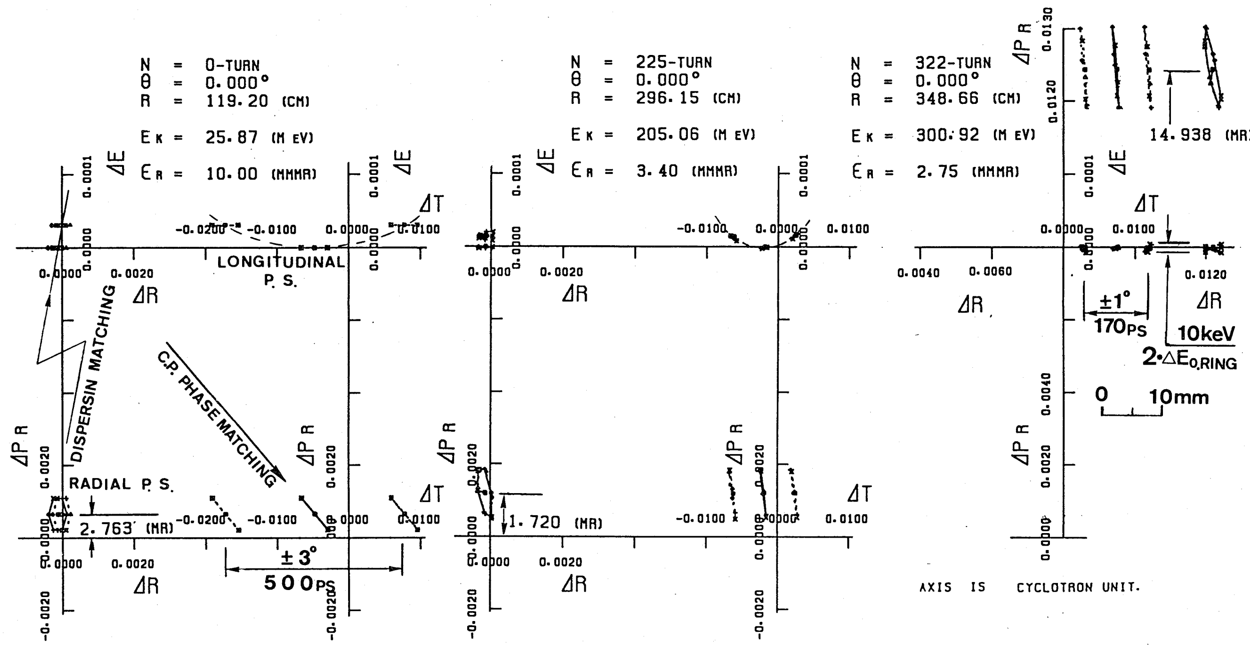
For longitudinal phase space, 'point to point' and 'parallel to parallel' transfer is performed between the extraction point A and the injection point C by two beam bunchers, and the sign of the energy differences are inverted between the source point A and the image point C, as shown in Fig. 4.

The transport system has two 90°-bending achromatic systems. The energy spread and the RF phase width can be restricted by slits at the first and the second dispersive point, respectively.

5. New Method of Flat-topping

The inverted beam energy spreads at the injection point of the ring are multiplied by the phase compression ratio ($V_{ext}/V_{inj} \simeq 3$) after the acceleration in the ring. The energy gain of the ring is about 12. The beam energy spreading in the ring are reduced nearly to 1/4 with the phase compression effect.

The energy spreads can be compensated perfectly in the ring by adjusting the phase compression ratio. This method corresponds to perfect six dimensional phase space matching from ion source to target and can be said to be a programmed dynamic cooling.



a: 26 MeV protons at injection point b: 205 MeV internal protons c: 300 MeV extracted protons

Fig. 5. Compensation of the energy spreads with new method of flat-topping.

Fig. 5 shows results of the calculations in radial, longitudinal and their coupled phase space. The injected beam (26 MeV proton) has the phase width of ±3°(500 ps) and the radial emittance of 10 mm·mrad. The extracted beam (300 MeV proton) has the energy spread of 10 keV, the radial emittance of 3 mm·mrad and the phase width of ±1°(170 ps).

This method is simple and also suitable for the acceleration of axially or horizontally polarized beams and multi-charged beams.

The emittance and the phase width and also the energy spread for extracted beams of the ring can be improved by using the slits in the low energy (E_p=26 MeV) beam transport system between the injector and the ring.

6. Conclusion

The beam extracted from the proposed system can be used directly for the nuclear studies in high energy resolution of 10^{-4}, and can fill the electron cooler ring in 2 μs with four turns injection mode for beam resolution better than 10^{-4}.

The electron cooler can be operated in ultra high resolution mode, if we reduce the number of storaged particles and target thickness. For moderate energy resolution of 10^{-4}, the direct beams has advantage of high reaction yield more than 10^2 times of the electron cooler ring.

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