A HIGH ENERGY VERSION OF 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 artificial magnetic field distributions for the ring 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 has been prepared to make final test. An RF cavity was constructed for the new ring[5]. 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.

Normalized emittance and energy spread for a typical ion beam extracted from ion sources are about 1 mm·mrad and 20eV, respectively. Succeeding in acceleration of the ion beams without notable beam heating, we can get high quality beams directly from the accelerator without any cooling.

However, the RF acceleration makes severe effects on the beam quality. The energy spread of a beam extracted from a conventional cyclotron is wider than the energy gain per turn of the cyclotron. The normalized emittance of the beam is also expanded much by the RF acceleration in the cyclotron.

For single turn extraction mode, the energy spread can be reduced by the restriction[6] and the compression[7,8] of the RF beam phase width or by the flat-topping deceleration with higher harmonic frequency. The emittance expansion can be reduced by using an external ion source with high injection voltage.

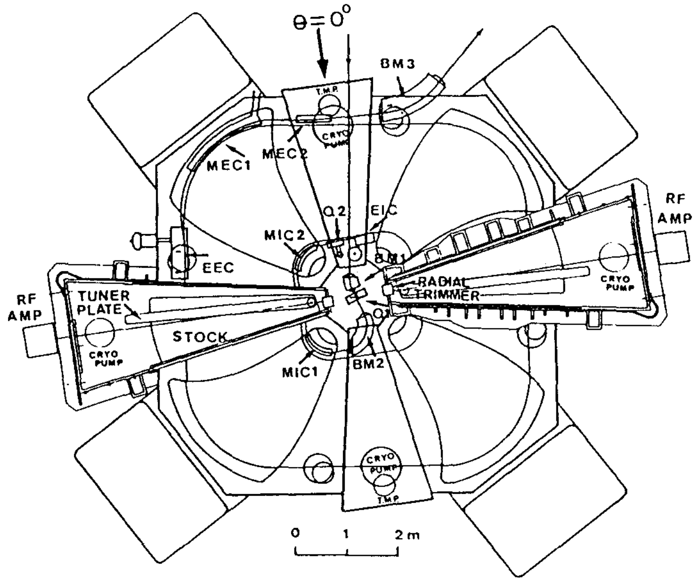

Fig. 1. Layout of the first ring cyclotron.

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	60° × 2	2
RF frequency (MHz)	20 ∿ 33	20 ∿ 33
Voltage max. (kV)	50	500
RF power (kW)	60 × 2	200 × 2

Recently at Indiana[9] and Uppsala[10], 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.

The orbit properties of beams in artificial magnetic field distributions for the first ring are studied with and without acceleration.[11]

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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[4]. A 1/3.5-scale old model magnet for a four-radial-sector ring cyclotron has been converted to a 1/4.5-scale model magnet for the spiral 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[11].

2.3 Acceleration Cavities

An aluminium variable-frequency single-gap cavity for the ring cyclotron was delivered as shown in Fig. 4. 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.

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. An RF power amplifier system was developed. A full-scale model cavity for the old proposal was excited by the amplifier up to breakdown voltage in air (100 kV)[3,4]. The aluminium cavity will be evacuated to a pressure lower than 1×10^{-5} Pa by a 20" cryogenic pump, and excited up to 500 kV by the RF power amplifier[4].

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[10].

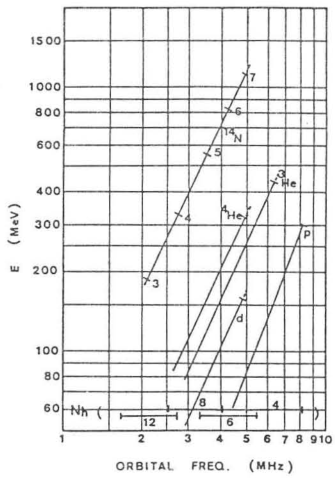


Fig. 2. Ion energy and acceleration harmonics, N_h, as a function of orbit frequency.

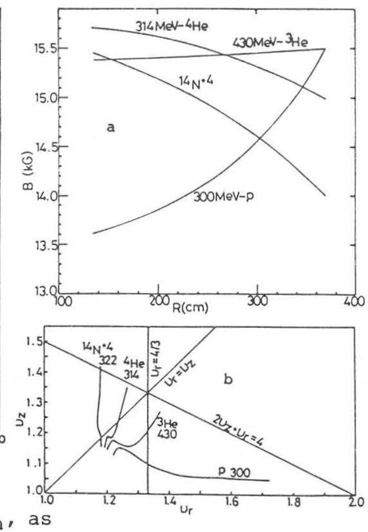


Fig. 3
a: Calculated isochronous fields.
b: Radial and vertical betatron frequencies for maximum energies of various ions.

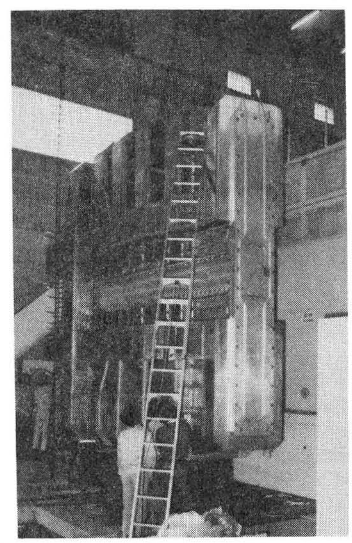


Fig. 4. Aluminium cavity of the ring cyclotron.

An orbit analysis was done for 26.2 MeV proton beams injected into an eigen ellipse (10 mm·mrad) on the equilibrium orbit with acceleration. Fig. 5 shows radial phase ellipses for various azimuth on the first turn. The radial extent of the beams on

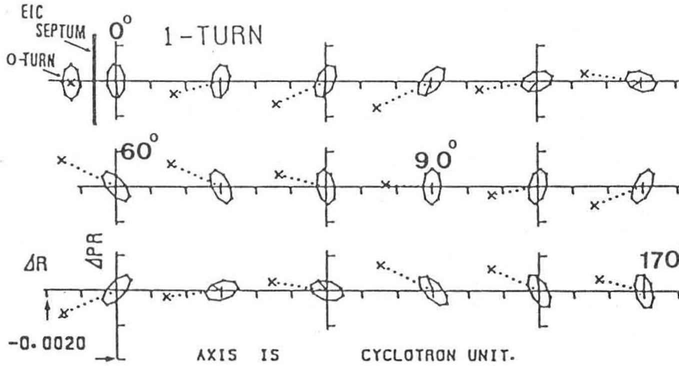


Fig. 5. Radial phase ellipses for various azimuth on the first turn.

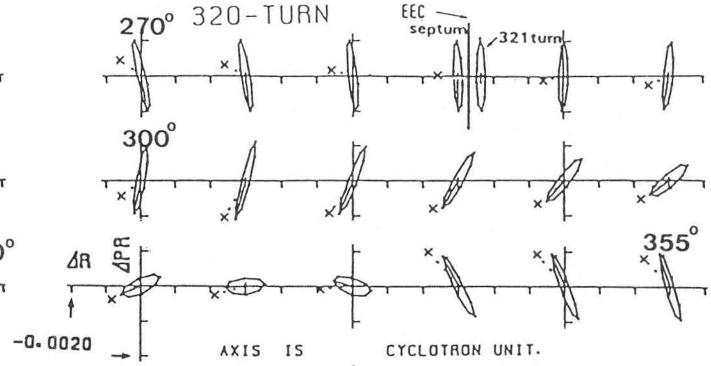


Fig. 7. Radial phase ellipses for various azimuth on the final orbit.

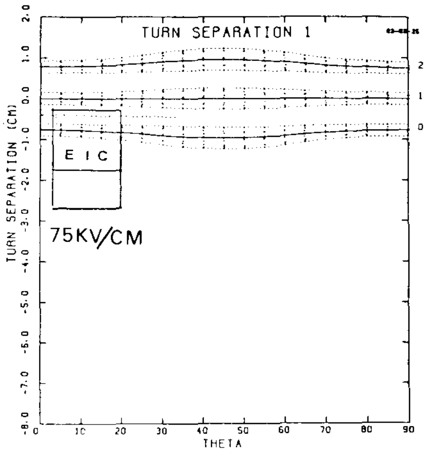


Fig. 6. Radial extent of the beams on the injection radius.

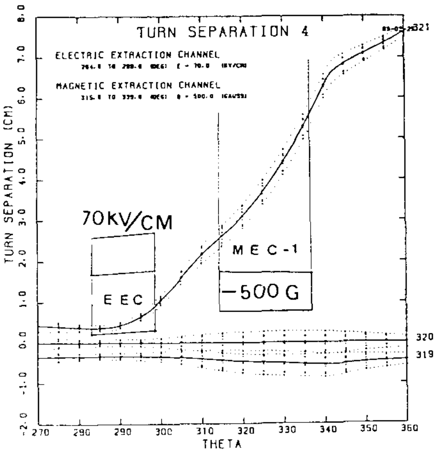


Fig. 8. Radial extent of the beams on extraction region.

the injection radius are shown in Fig. 6. Fig. 7 shows radial phase ellipses for various azimuth on the final orbit. The 300 MeV proton beams can be extracted in single turn mode through an electrostatic extraction channel(EEC) and a magnetic extraction channel (MEC-1) with very high extraction efficiency (∿100%) as shown in Fig. 8. The elements of the extraction system are closely arranged in a quarter section of the ring as shown in Fig. 1, since the radial betatron frequency became near to 2 on the outermost radius as for the acceleration of 300 MeV protons.

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. Main characteristics of the injector cyclotron are also listed in Table 1.

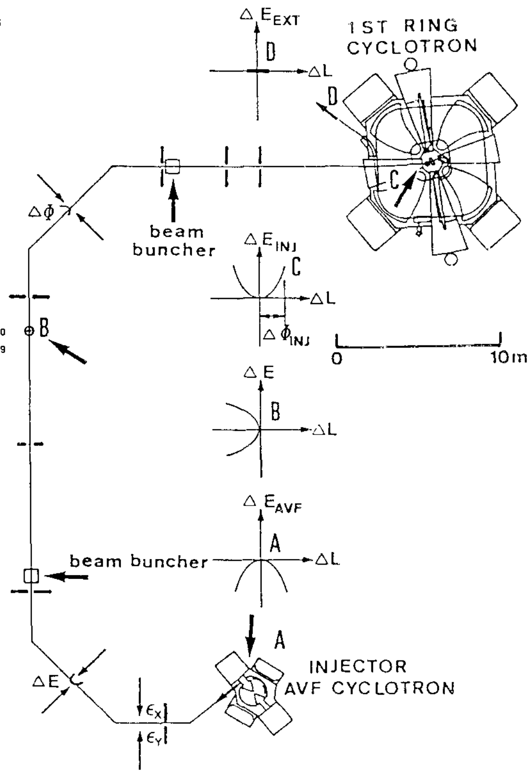
In the central region of a cyclotron with an internal ion source, phase dependent drive for radial betatron oscillation, phase dependent vertical betatron frequency, transversal phase space mismatching and transit time difference make severe effects for emittance and energy spread for the beams in a narrow local RF phase domain.

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. 9. The extracted beam from the injector makes achromatic focusing at the source defining slits. 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 B, as shown in Fig. 9.



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

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

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

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

Fig. 9. New flat-topping method used in the beam transport system between the injector and the first ring.

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.

Fig. 10 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).

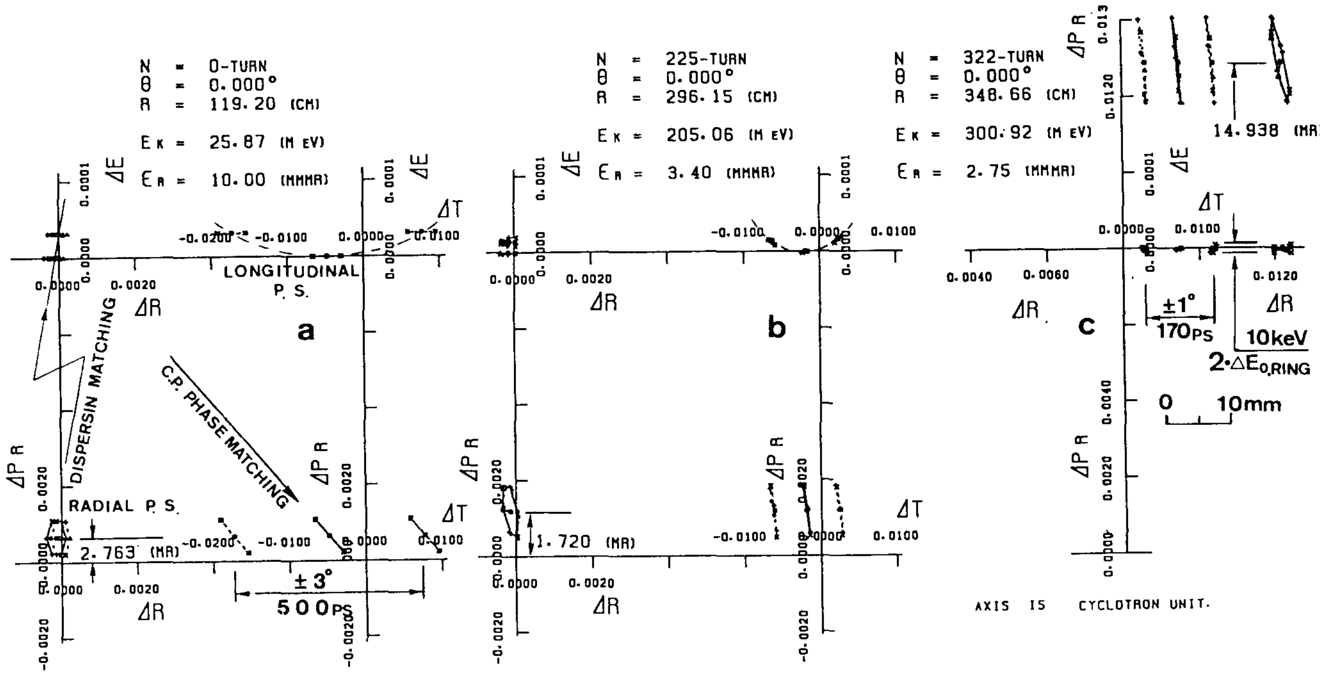


Fig. 10. Compensation of the energy spreads with new method of flat-topping.

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

This method is simple and also suitable for the acceleration of axially or horizontally polarized beams[12] 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. Space Charge Effect

The longitudinal space charge effect makes energy spread[13] and limits the maximum beam current for the single turn extraction mode[14]. For 300 MeV protons, an energy resolution better than 10^{-4} can be obtained up to 1 μA by the flat-topping with the space charge compensation using the RF phase shift[13]. The maximum current is 50 μA for the protons.

7. 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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