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CASCADE CYCLOTRON MAGNET

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Summary

A brief study of a separated-sector cyclotron has been made. The total weight of a cascade system of the separated-sector cyclotrons is reduced when the beam is accelerated up to a half of the final energy with the injector cyclotron. Such a large injector system has also some unique features other than its weight.

Introduction

A 230-cm isochronous cyclotron has been constructed and has worked well at the RCNP of Osaka University[1). Recently, however, a large accelerator has been required for research of nuclear physics or so-called intermediate energy physics. A separated-sector cyclotron is an example of such a large accelerator. One of the authors (I.M.) has measured magnetic fields of a sector magnet at the Faculty of Science of Osaka University[2) and pointed out that the volume of the magnet of a single-stage cyclotron becomes too large and it is not so appropriate to get good focusing properties for both heavy and light ions. The present paper is one of the brief examinations of the large cyclotron which shows that the difficulties may be reduced by a cascade system which has a large injector. The volume of the magnet and other unique features of the cascade cyclotrons are discussed in the following sections.

Volume of the Magnet

The following assumptions are made to simplify the problem. The cross section of the magnet yoke is equal to the pole area. The magnet is of a C-type sector and its angular width is θ. The outer radius of the yoke is R_M and the height is h. The radii of the injection and extraction are Ri and Re, respectively. The inner radius is assumed to be equal to Ri and the magnet gap and coil spaces are neglected. Then the volume of the sector magnet V_M becomes

$$V_M = \pi(R_M^2 - R_i^2)\frac{\theta}{2\pi} h = \frac{(R_e^2 - R_i^2)^2}{R_e}\theta \qquad (1)$$

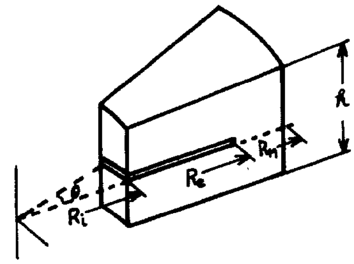

fig. 1
A simplified sector magnet

The angular width θ is assumed to be a half of a unit sector,

$$\theta = \frac{\pi}{N} \qquad (2)$$

where N is the number of the sectors of the system. Thus the total volume of the N sector magnets V_{MT} becomes

$$V_{MT} = NV_M = \pi\frac{(R_e^2 - R_i^2)^2}{R_e} \quad . \qquad (3)$$

In the case of the cascade system, the averaged field strength of the first ring at the extraction radius R_{e1} is assumed to be equal to that of the second ring magnet at the injection radius R_{i2}. The charge state of the ion is also assumed not to be changed between the injector and the final ring. Then the radius R_{i2} comes to be equal to the radius R_{e1},

$$R_{i2} = R_{e1} \quad . \qquad (4)$$

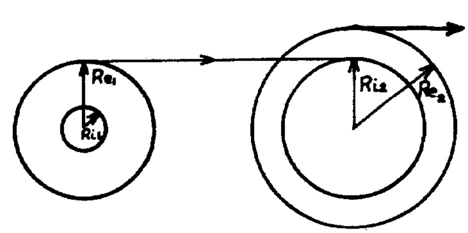

fig. 2
A cascade-ring system

Thus the total volume of the cascade magnet system V_T becomes

$$V_T \equiv V_{MT1} + V_{MT2} = \pi[\frac{(R_{e2}^2 - R_{i2}^2)^2}{R_{e2}} + \frac{(R_{i2}^2 - R_{i1}^2)^2}{R_{i2}}], \qquad (5)$$

where sufficies 1 and 2 show the first ring and the second ring. If the injection radius of the first ring R_{i_1} is small, eq. (5) becomes

$$V_T \simeq \pi \left[\frac{(R_{e2}^2 - R_{i2}^2)^2}{R_{e2}} + R_{i2}^3\right] . \qquad (6)$$

The total volume V_T in eq. (6) comes to be a minimum with an appropriate value of R_{i2} when R_{e2} is given. That is

$$V_T(\min) \simeq 0.6\,\pi R_{e2}^3 \quad \text{at} \quad R_{i2} \simeq 0.69\, R_{e2} . \; (7)$$

On the contrary, the maximum value of the volume is

$$V_T(\max) \simeq \pi R_{e2}^3 \text{ at } R_{i2} = 0 \text{ or } R_{i2} = R_{e2} \qquad (8)$$

which corresponds to the case of a single ring system.

From eq. (7) we can easily understand that the extracted energy of the first ring cyclotron should be chosen to be nearly a half of the final energy. For example, the magnet weight of the combined system composed of a K = 250 injector and a K = 500 final ring is lighter than that of a single-stage K = 500 ring magnet. This conclusion changes little if the injector is replaced by a solid-pole cyclotron of which the azimuthally averaged field is nearly two times stronger than that of the separated-sector cyclotron.

Cascade ring

An injector is often very small as compared with the main accelerator, but the cascade cyclotrons composed of a large injector mentioned above has some good features other than its weight.

(i) Each sector magnet is small and the fabrication is easy. (ii) Energy gain in each ring is not so large. The power of the trim coil can be reduced. (iii) Adopting an appropriate configuration some resonances for example $\nu_Z = 1$, can be avoided. An example has been studied which is composed of a six-sector ring and an eight-sector ring as shown in the following section. (iv) The injector itself is independently usable to research. Each proper experimental area for the respective rings can be set up. This system can be used as the multi-purpose accelerator system.

A three-stage ring system can be considered, but the construction may be rather complicated. SIN cyclotron[3] has a little large injector but the main ring has been designed for proton beams only. If a larger injector is chosen as discussed above, a multi-particle accelerator can be designed to avoid the resonance. On the other hand, if a standard size cyclotron already exists, an energy booster by factor two or three can be designed with ease for multi-particle acceleration at relatively low cost. Examples are discussed in the following section.

Examples

A small case

An existing K = 120 cyclotron is assumed to be used as an injector. This cyclotron is able to accelerate light ions and heavy ions. The booster ring cyclotron is chosen to be a K = 300 ring. The ring is easily designed to accelerate heavy ions and light ions but the proton energy may be limited to 200 MeV to avoid the $\nu_Z = 1/2$ resonance. An example of a six-sector ring and of nearly 30° of a sector width has been examined. Vertical betatron frequency of the ring exists between $\nu_Z = 1$ and $\nu_Z = 1/2$. The weight of the ring magnet is estimated to be approximately 600 tons. Main characteristics are shown in table 1.

Table 1. A small case

injector	K = 120 (K_F = 75)
booster	K = 300 (K_F = 200)
number of sectors	6
hill angle	30°
injection radius	2 m
extraction radius	3.17 m
magnet weight	6 × 100 t
hill field	16 kG
averaged field	8 kG
betatron freq.	$1 < \nu_r < 1.25$
	$1/2 < \nu_z < 1$
orbit freq.	3 MHz ∿ 9 MHz

A big case

A big cascade system has also been examined which includes different kinds of injectors and two cascade ring cyclotrons. One injector is a small isochronous cyclotron for light ions, and the other is a heavy ion linear accelerator followed by a foil stripper. The first ring is of a K = 250 six-sector and the second is of a K = 600 eight-sector magnets slightly modified to have flared and spiraled pole faces to get good focusing properties. Preliminary computer analyses have been made for the system. Ions from proton through uranium might be accelerated without crossing any resonance. Main characteristics of the system are shown in table 2.

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Table 2. A big case

light ion source	heavy ion source
K = 30 cyclotron single dee 6 ∿ 18 MHz R_e = 0.5 m	20 MV linac 16 ∿ 22 MHz
	foil stripper

		ring 1	ring 2
K_{max}		250	600
Number of sectors		6	8
Number of cavities		3	4
RF		16 ∿ 33 MHz	16 ∿ 33 MHz
orbit freq.		< 11 MHz	< 8.2 MHz
orbit radius (m)		0.75 → 2.2	2.9 → 4.4
magnet weight		600 t	1500 t
betatron freq.		$\nu_r + \nu_z < 2$ $\nu_r - 2\nu_z < 0$ $\nu_r > 1$	$\nu_z > 1$
Proton	energy	13.7 MeV→143 MeV	143 MeV→489 MeV
	hill field	13.6 kG →14.3 kG	15.9 kG→18.0 kG
Alpha	energy	19.8 MeV→181 MeV	181 MeV→459 MeV
	hill field	16.3 kG →15.7 kG	17.4 kG→16 kG
heavy ion	energy	K = 30 → 250	K = 250 → 600
	hill field	16 kG → 15 kG	16 kG →14 kG

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