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RCNP BEAM CIRCULATION RING

A. Ando, K. Hosono, I. Katayama and H. Ikegami
Research Center for Nuclear Physics, Osaka University
10-1 Mihogaoka, Ibaraki, Osaka 567, Japan

SUMMARY

The RCNP Beam Circulation Ring (CR) is designed for the RCNP Cyclotron Cascade Project[1] as the first step toward a multipurpose storage ring[2] (MSR). In the MSR, electron cooling of a few hundred MeV proton beam or of ~50 MeV/u light heavy ion (HI) beam is the key to prepare a very high quality beam, and the internal target method helps to increase the luminocity in very precise experiments in nuclear and atomic physics. Also, synchrotron acceleration to the energy higher than GeV (proton) or 0.5 GeV/u (HI) gives the feasibility to study nuclear physics with N^* resonance, pion freedom and strangeness.

Combining all these accelerator techniques including foil cooling[3], the RCNP Multipurpose Storage Ring (MSR) will be an active accelerator facility in the intermediate energy region for not only nuclear and atomic physics, but also many interdisciplinary fields.

The RCNP Beam Circulation Ring (CR) is initially constructed as a beam circulator for only few hundred revolutions without any orbit control system. The CR should also operate as a dispersion-matching beam transport line for the very high resolution spectrograph "BIG RAIDEN".

The CR is so designed that the characteristics of the MSR will be achieved, step by step, by the accumulation of improvements and expansions.

DESIGN PRINCIPLES FOR MSR

The particle beams of H_2^+ and light ions partially stripped from the K=400 Ring Cyclotron can be stored and accelerated up to T_P=1.6 GeV or ~0.57 GeV/u. The MSR should have, at least, two very long straight section for electron cooling up to 220 keV (γ=1.43), and for the experiments with an internal target at up to the maximum energy.

The main conditions for the design are as follows, At the target region:

1) variable dispersion (D_T) and variable beta function (β_T) at the target point. (Typically β_T=0.3 m and D_T=-5 m)
2) long straight section (~8 m) for the "BIG RAIDEN".

In the cooling region:

3) variable beta function (β_C) (Typically $\beta_C \simeq 10$ m)
4) doubly achromatic long straight section (~8 m)

Another:

5) long straight sections for injection, extraction and RF acceleration.
6) transition free in the synchrotron acceleration.

To satisfy these conditions, the MSR has a racetrack shape which is a modified type of hexagon shape with the three-fold mirror symmetry. The geometrical scheme is shown in Fig. 1.

CIRCULATION RING

The CR can circulate the beams of the magnetic rigidity up to 3.2 Tm. The elements of the CR are drawn with balck in Fig. 1. The CR has the two-fold mirror symmetry. The quadrant structure is given in Table 1. The typical lattice parameters are shown in Fig. 2, and summarized in Table 2.

The beam from the Ring Cycltoron is injected continuously by charge stripping through a thin foil at the point after about 5° bending in the dipole magnet (B2 in Fig. 1) without any orbit control eleménts such as kickers or bump magnets, and then hits a target. The injected beam repeatedly passes through the stripping foil and the target. There are three collimators at the suitable locations along the CR to clear away a part of circulating particles with an increased emittance and momentum spread due to the passages mentioned above. The energy of the circulating beam is 100 MeV for proton, and ~40 MeV/u for ions. In the case of 30 MeV/u C-beam and 20 μg/cm^2 C-foil, the results of the numerical simmulation are as follows. After 100 revolutions, the r.m.s. emitance increase: $\pi\Delta\varepsilon=(0.25 \sim 0.5)\pi\beta$(mm-mrad), momentum shift: $(\Delta p/p)=0.14(\%)$, where β is the beta (envelope) function at the foil measured in m.

The T_P=100 MeV proton beam is obtained from 200 MeV H_2^+ beam. In this case, the estimates are as follows:

After Nth passage through 20 μg/cm^2 C-foil,

$$\Delta\varepsilon = \beta\theta^2 N \simeq 2.6\times10^{-3}\ \beta N \quad \text{(mm-mrad)}$$

$$\Delta p/p = \beta_L^{-2}\ (dE/dx)*L*N/E \simeq 8\times10^{-7}N$$

$$\theta = 14.1\sqrt{L/L_R}\ /(P\beta_L),\ \beta_L = 0.43$$

$$dE/dX \simeq 8\ \text{MeV}\cdot\text{cm}^{-2}/\text{g}$$

The maximum number of the passages through the stripping foil and the target is determined by the tolerance of experiments. This method would be very effective for detecting very slow recoil paraticles that would be seriously disturbed in an usual target.

The R & D studies toward the MSR are also very important tasks in the CR, such as, for example, internal target, beam handling, RF acceleration with precise phase control, energy loss cooling, measuring system of beam temperature for electron cooling and so on. In these studies, the beam will be collimated at the vertical aperture determined by the gap of the dipole magnet. In the present design, this aperture is ±30 mm, β at the foil is ~13 m and the maximum of β in the dipole magnet is ~ 15 m in the Mode A (Fig. 2-a). These values give the equation for 100 MeV proton beam,

$$(\beta\Delta\varepsilon)^{1/2} = (2.6\times10^{-3}\times13\times15\times N)^{1/2} < 30,$$

that is, N≃1800. The full momentum spread would be 0.15%.

MAGNET DESIGN

The magnets are designed to operate dynamically from the level of Bρ = 1.48 Tm (T_p = 100 MeV) to that of 7.87 Tm (Tp = 1.6 GeV), which is appropriate for the MSR.

Dipole Magnet

The design has changed from the previous one[2]. In the MSR, there should be thirty rectangular magnets. Each core length is 1 m. At the first stage as the CR, twelve magnets are installed, and are also operated as a beam transport line to the "BIG RAIDEN" for up to the maximum energy of the Ring Cyclotron (Bρ = 3.2 Tm). The main characteristics of the magnet are given as follows.

Ring mode	CR	MSR
Bending angle (deg.)	30	12
Sagitta (mm)	66	26
Bρ max. (Tm)	3.2	7.9
ρ (radius of curverture)(m)	~1.9	~4.8
B max. (kG)	16.5	16.5

The gap height(g) is enlarged to 80 mm: 60 mm for the beam aperture, 20 mm for the vacuum chamber and thermo-insulation for ultra high vacuum. At the field level of 16.5 kGauss, the horizonted beam aperture (A) should be, at least, ±50 mm for the stable operation at the CR taking in account of closed orbit distortions. Therefore the good field region at the maximum excitation, 16.5 kGauss, should be about 170 mm, and the pole width is designed to be 380 mm (≈ A+2.5 g). The pole shape will have some suitable shim.

The coils of each pole consist from four pancakes. Each pancake has 20-turn windings. Water flows parallel in these pancakes. The maximum excitation current is 750 A. For a synchrotron mode in the future step of the MSR, these four pancakes are connected electrically parallel, and the maximum current is 3000 A, that is, 750 A for each pancake. The scheme of the cross section is shown in Fig. 3.

Quadrupole Magnet

The bore radius of the magnet is 50 mm. The beam aperture is 45 mm in the both horizontal and vertical plane, and 40 mm radius in the central plane of the magnet pole. The core length is 400 mm. The maximum strength of field gradient is 20 T/m in the MSR, but 8 T/m in the CR which is clear from Table 1. The coil of each pole is a outstretched pancake with 30-turn windings. The cross section is shown in Fig. 4.

The main parameters of the dipole and quadrupole magnet in the CR are summarized in Table 3.

EXPECTED PERFORMANCE

Vacuum

The vacuum system in the CR is not good enough to storage an ion beam for a long time. Assuming that the degree of vacuum is P Torr, the residual gas is nitrogen, and the dominant effect on the beam is due to multiple Coulomb scattering, the effective thickness of redisual gasses reduced at a fixed point in the Ring is obtained as follows.

Suppose the r.m.s. scattering angle of a beam per revolution is θ_0, θ_0 satisfies the equation, $\theta_0 = k\sqrt{L_0}$, where L_0 is the total nitrogen thickness in the Ring measured in the radiation length (X_0), and k is a constant for a given beam. θ_0 should also satisfy the equation, $\bar{\beta}\theta_0 < g$ or $\bar{\beta}\theta_0^2 < A$, where $\bar{\beta}$, g and πA are the average value of the beta function, the minimum aperture and the acceptance. On the other hand, when there is L_1 radiation length of nitrogen at the point where $\beta = \beta_1$, this causes the r.m.s. scattering angle per passage; $\theta_1 = k\sqrt{L_1}$. θ_1 should satisfy the equation, $\beta_1\theta_1^2 < A$. Then, the effective thickness is obtained as, $L_1 = (\theta_1/\theta_0)^2 L_0$. This gives,

$$L_1 = (\theta_1/\theta_0)^2 \rho_0 CP/(P_0 X_0) = (\bar{\beta}/\beta_1)\rho_0 CP/(P_0 X_0),$$

where $P_0 = 760$, $X_0 = 38$ (g/cm^2), $\rho_0 = 5.6\times10^{-5}$ (g/cm^3) and C = 125 (m, circumference of the CR).

At the stripping foil, β_1 is almost equal to $\bar{\beta}$. Then,

$$L1 \simeq 2.4\times10^{-5}\ P.$$

As the 20 μg/cm^2 C-foil has the thickness of 4.7×10^{-7} radiation length, P should be less than 1.9×10^{-3} (Torr) to limit the effect of the residual gas to be less than 10% of the stripping foil.

This estimate gives also the condition of vacuum in the future step of the MSR. If the 1 μg/cm^2 carbon target is used for an internal target, P should be less than 10^{-7} (Torr) to limit the effect less than 1% of the target, because of $\beta_1/\bar{\beta} \simeq 0.01$. Clearly P is linear to the thickness of a target.

The necessary degree of vacuum is also determined by the energy loss of a beam in residual gas. The energy loss of a 40 MeV/u ion beam is about 14 Z^2 MeV·g^{-1}cm^2 in nitrogen, then the momentum shift of the beam after the N-th revolution is estimated as,

$$\Delta p/p = \Delta E/(2T) = 14\ wZ^2N/(80A),$$

where Z and A is the charge and mass number of the beam, and w is the thickness of nitrogen which is given by $w = \rho_0 CP/P_0 \simeq 9.2\times10^{-4}P$ (g/cm^2). Therefore $\Delta p/p \simeq 5.6\times10^{-4}$ PN for the $^{14}N^{7+}$ beam. If the momentum aperture is 5.6×10^{-3}, $PN = 10^{-1}$, i.e., $N = 10^3$ for $P = 10^{-4}$ (Torr). From the above estimates, it is necessary for the degree of vacuum to be less than 10^{-4} Torr in the average through the Ring to keep the 40 MeV/u ion beam in about 1000 circulations.

Beam Intensity

The Ring Cyclotron will accelerate the H_2^+ beam to 200 MeV with the RF frequency of about 32 MHz, which is the 3rd harmonics of the revolution frequency. If the beam current is 0.6 μA, the particle density is $0.6\times10^{-6}/1.6\times10^{-19}/(32\times10^6/3) \simeq 3.5\times10^5$ particle per bunch. The 100 MeV proton beam is obtained from the above H_2^+ beam through charge stripping, and the beam intensity will be 7×10^5 p's per bunch. In the CR, the intensity will be 7.5×10^6 p's per ring after one turn injection because of the revolution period is about 1 μsec. The injected beam immediately becomes coasting because there is no RF acceleration system in the CR.

At the present stage of technology, it is so difficult to monitor a very weak beam current that the 16 slit-type current pickups will be used to confirm the first circulation. Each pickup has four thin plate with the fixed aperture and gives a signal only when the beam hits some plate.

After the stable circulation is achieved, the measurement of Schottky signals from the beam will be very useful. Anyway, the reliable and precise beam monitoring is one of the most important tasks in the CR, and there is enough space for installing any devices to test and develope.

TOWARD MULTIPURPOSE STORAGE RING

The Ring will easily operate as a synchrotron (proton 1.6 GeV) by adding more the same eighteen dipole magnets that are already installed for the CR. Of course there will be an RF acceleration system in one of the straight sections as shown in Fig. 1. The revolution frequency changes from ~1 MHz to ~2.2 MHz for the proton beam in the acceleration from 100 MeV to 1.6 GeV, or ~0.7 to ~1.8 MHz for the Z/A = 0.5 ion beam from 40 MeV/u to 0.5 GeV/u. The necessary voltage is about 4h kV to keep the bucket area about three times of the longitudinal emittance ($\Delta p/p = \pm0.1\%$) where h is the harmonic number, and is ~$1.6/\sin\phi_s$ kV to accelerate the proton beam up to 1.6 GeV in 0.5 sec where ϕ_s is the accerelation RF phase.

Installing more twelve quadrupole magnets of the same standard given in Table 3, all the optics[2] required by the full operation of the MSR will be immediately achieved. In the electron cooling mode with an internal target, the typical values are already described in the previous section.

The vacuum system should be replaced by those of ultra high vacuum for electron cooling or for good storage of an ion beam.

The orbit control system will be also added. Kickers, septum magnets and bump magnets are necessary for the perfect injection by charge stripping. A steering dipole magnet system is necessary for enough beam stacking. Another correction elements are also needed to the stable storage and acceleration, and to keep the good quality of a beam which is already obtained in the Ring Cyclotron or by electron cooling.

There are many elements and systems to realize the full facility of the MSR. The construction of the CR is the starting point, but this CR gives the large and strong basement for any steady effort to bring it to a piece of the frame of the MSR.

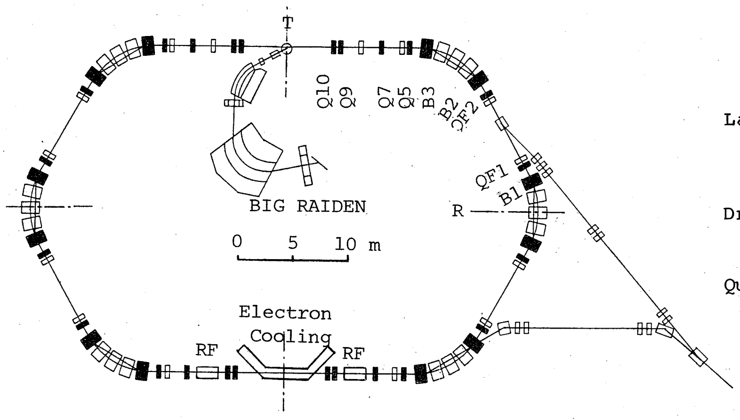

Fig. 1. Scheme of the Circulation Ring and the Multipurpose Storage Ring.

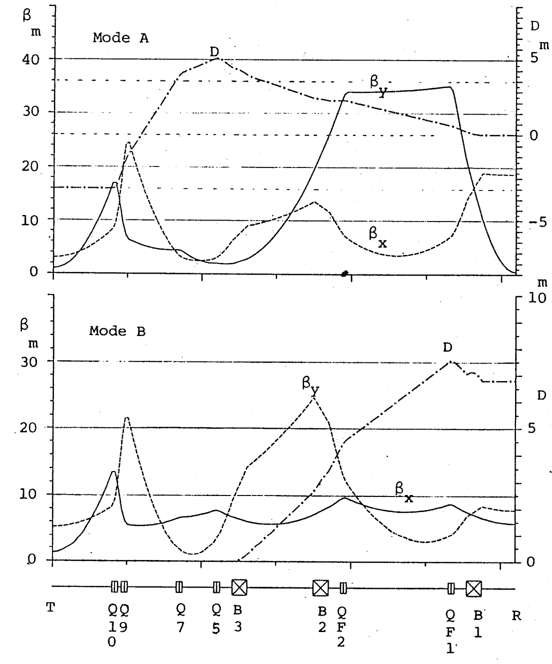

Fig. 2. Lattice Parameters in One Quadrant of the Circulation Ring.

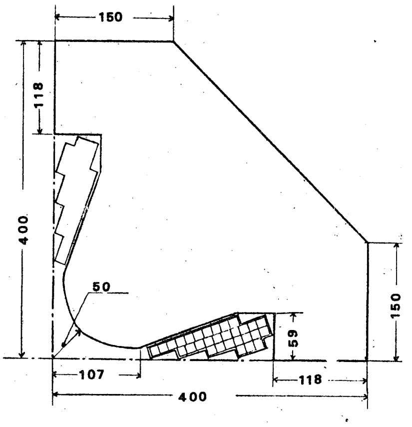

Fig. 4. Cross Section of Quadrupole Magnet.

REFERENCES

1) I. Miura et al., Proc. 11th Int. Conf. on Cyclotrons, Tokyo, 1986, 207.
2) A. Ando et al., ibid., 149.
3) K. Noda et al., ibid., 145.

Table 1

Quadruant Structure of the Circulation Ring

Lattice structure:							
	D4.	Q10	D.25	Q9	D3.3	Q7	
	D2.1	Q5	D.8	B	D2.2	D2.2	B
	D.8	QF2	D6.8	QF1	D.8	B	D2.2

Drift space:	D4.	D.25	D3.3	D2.1	D.8	D2.2	D6.8
length (m)	4.0	0.25	3.3	2.1	0.81	2.219	6.8

Quadrupole magnet (core length is 0.4 m)

	Q10	Q9	Q7	Q5	QF2	QF1
$B'\ell/B\rho(m^{-1})$	0.904	-0.886	0.278	0.226	0.123	0.244 (ModeA)
	0.858	-0.886	0.066	0.135	0.144	0.128 (ModeB)

Dipole magnet : B (rectangular, core length is 1 m)
bending angle 30°
bending radius 1.932 m

Table 2

Typical Lattice Parameters of the Circulation Ring

Circumference			123.4m	
Aperture			$\lvert x\rvert \leq 45$ mm,	$\lvert y\rvert \leq 30$ mm
			Mode A	Mode B
Tune $\nu x/\nu y$			4.1/3.3	3.3/3.7
At a target,	βx	(m)	1.0	1.3
	βy	(m)	3.0	5.2
	D	(m)	-5.0	0.0
Maxima,	βx	(m)	35	14
	βy	(m)	25	25
	D	(m)	7.0	7.5
Transition energy, γ_T			2.5	2.4

Table 3

Parameters of the Dipole and Quadrupole Magnet

		Dipole	Quadrupole
No. of magnets		12	24
Core length	m	1.0	0.4
Field strength	T or T/m	1.65	8
Gap or Bore radius	mm	80	50
AT/pole		6×10^4	9×10^3
Current	A	750	300
Turns/pole		80	30
Hollow conductor		$16-10^{\phi}$	$11-6^{\phi}$
Resistence	mΩ	64	47
Weight, Fe	t	8	1.4
Cu	t	1	0.18

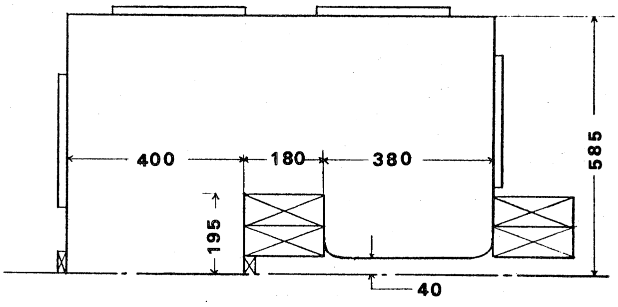

Fig. 3. Cross Section of Dipole Magnet.