DESIGN STUDY OF A COOLING RING AND STORAGE SYNCHROTRON AT RCNP

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Summary

A multipurpose storage ring is designed in the RCNP Cyclotron Cascade Project.[1] The particle beams from H_2^+ to light ions are accelerated in the K=400 separated sector cyclotron, and are injected into this cooling ring/storage synchrotron by charge stripping through thin foil. The 400 MeV proton beam can be stacked by the transversal multiturn injection.

The ring is essentially designed as an electron cooling ring, but will be operated in another two modes, i.e. an acceleration synchrotron mode and a circulation mode. The fundamental characteristics of the ring are described for three modes of operation.

Cooler Mode

Lattice

The lattice of the cooling ring has a race-track structure with mirror symmetry, and is shown in Fig. 1 and Table 1. There are twelve 30° bending magnets and thirty-six quadrupole magnets. The entrance and the exit angle of each bending magnet are 3.75°. The free spaces for the spectrograph (BIG RAIDEN) and the cooling region both have the length of 8 m. The ring has also four long straight sections (LSS) of 6.8 m and two double-achromatic straight sections (ASS) of 4.7 m. Two of LSS's are dispersion-free and one of them is the region for an RF acceleration. Table 2 summarizes the main parameters of the ring in the cooler mode operation. Figure 2 shows the lattice parameters along the ring.

The beta function (β_T) and the dispersion (D_T) at the target are typically 0.3 m and -5 m. These values are easily varied with the constraint of $|D_T/\sqrt{\beta_T}| \simeq 10$, but the drastic change of D_T with the fixed β_T of 0.3 m causes a huge β_x in LSS. When the parameters at the target point are matched at some waist point in the LSS, the lattice functions at that waist point should satisfy the relation,

$$D/\sqrt{\beta_x} = (D_T/\sqrt{\beta_T})\cos\psi \ , \quad \sqrt{\beta_x}\, D' = (D_T/\sqrt{\beta_T})\sin\psi,$$

where ψ is the phase advance of the radial betatron oscillation between these two points.

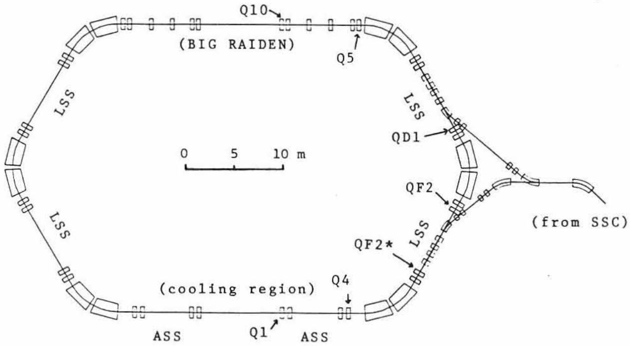

Figure 1 Scheme of the ring.

Table 1

Half structure of the cooling ring

L4.	Q1	D.4	Q2		
L4.7	Q3	D.4	Q4	D.8	
(B)	QD2*	D.4	QF2*	L3.4	
L3.4	QF2	D.4	QD2		
(B)	QF1	D.4	QD1	L3.4	
L3.4	QD1	D.4	QF1*	(B1)	
Q5	D.25	Q6	L1.8	Q7	L1.8
Q8	L1.7	Q9	D.25	Q10	L4.

(B)	= D.7	B	D.4	B	D.7
(B1)	= D.7	B	D.4	B	D.4

length of quadrupole magnet	0.4 m
bending magnet	
bending radius	4.7746 m
bending angle	30°
entrance and exit angle	3.75°

† The characters L and D denote drift spaces, and the number following them means the length in meter. The Q and B denote a quadrupole and a bending magnet, respectively.

Table 2

Typical parameters for a cooler mode operation

Circumference	125.2 m		
Tunes	ν_x=3.12	ν_y=4.20	
	at a target	at a cooling region	
Dispersion (D/m)	-5	0.0	
Beta function (β/m)	$\beta_x=\beta_y$=0.3	β_x=9.85, β_y=10.0	
Maximum values			
in regular cells	β_x=20.4	β_y=16.7	D=5.65
in bending magnets	β_x=103	β_y=15.7	D=2.63
in the ring	β_x=104	β_y=15.1	D=5.65
Transition energy	γ_T = 4.868		

Strength of quadrupoles

name	$B'\ell/B\rho(m^{-1})$	name	$B'\ell/B\rho(m^{-1})$
QF1	0.1970	Q1	-0.4152
QD1	-0.2040	Q2	0.3975
QF2	0.4962	Q3	-0.3001
QD2	-0.4995	Q4	0.2318
QF1*	-0.1316	Q5	1.0897
QF2*	0.5222	Q6	-1.255
QD2*	-0.5374	Q7	0.6673
		Q8	0.1949
Q10	0.7643	Q9	-0.9603

Figure 3-(a) and 3-(b) show the variations of the tunes and the maximum beta's for the small change of D_T. The electron cooling will demand precise adjust of the beam size in the cooling region. This adjustment is done by varying the beta functions in that region, and then causes the change of the operating tunes as shown in Fig. 3-(c).

The vertical acceptance of the ring is limited by the gap height of the dipole magnet, and the radial one is determined by the bore radius of the quadrupole magnet in LSS. The magnets are designed so that the transversal acceptances are both 30 π mm-mrad.

The stability of the betatron oscillations and the problems caused by the sextupole correction are examined by the method of Collins' distortion function[2], and are confirmed to be no problem.

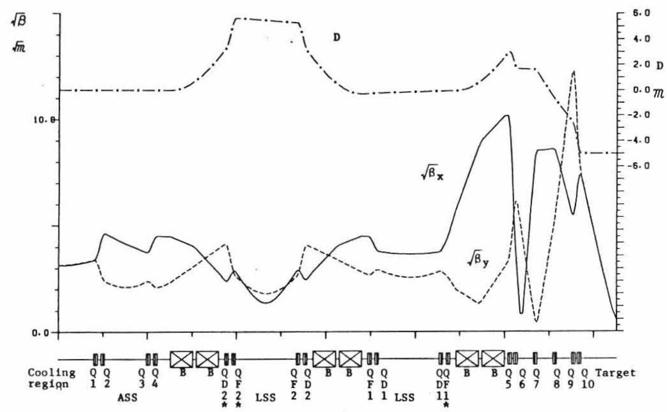

Figure 2 Lattice functions of the ring in the cooler mode.

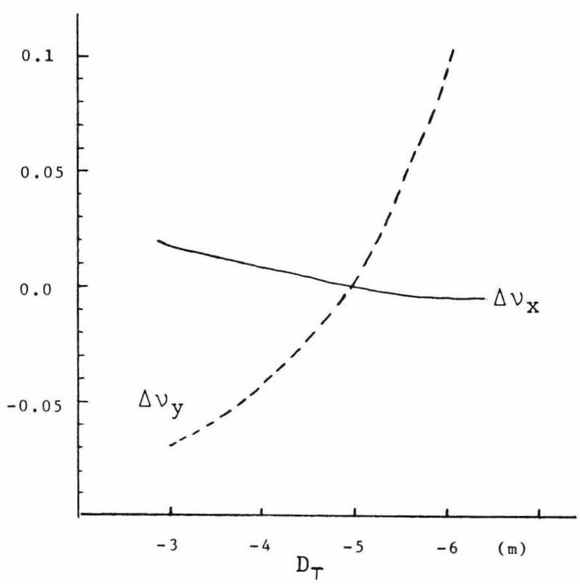

Figure 3-(a) Tune shifts due to the change of D_T under the fixed condition β_T = 0.3(m) and β_c = 10(m).

Injection

The beam of 1 μA from the K=400 six sector cyclotron (SSC) is injected into the ring through a thin foil by charge stripping. The particles and its energy is expected as,

Particle	p	$^{12}C^{6+}$	$^{14}N^{7+}$	$^{16}O^{8+}$	$^{20}Ne^{10+}$
Energy(MeV)	100	~500	~700	~600	~700

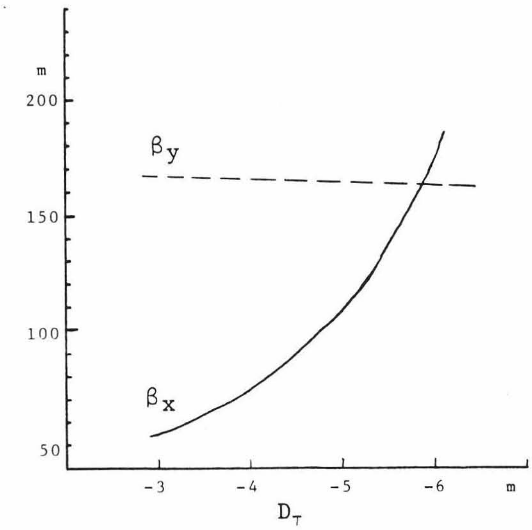

Figure 3-(b) The maximum of the beta functions versus D_T with the same condition of Fig.3-(a).

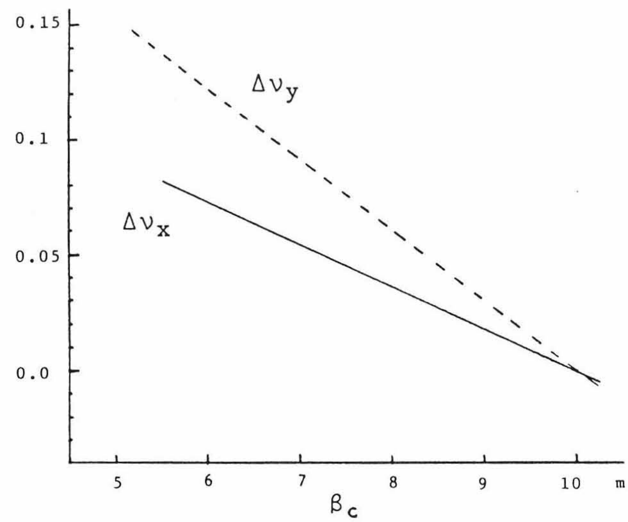

Figure 3-(c) Tune shifts due to the changes of beta functions in the cooling regions under the fixed condition of β_T = 0.3(m) and D_T = -5(m).

The proton beam is obtained from the 200 MeV H_2^+ beam with the emittances of π mm-mrad in both planes. The injection is continued until the emittances of the accumulated beam grow up to the acceptance of the ring by the multiple scattering through the stripping foil, and then the beam driven out of the stripper. Assuming the carbon foil of ~20 μg/cm^2 as the stripper, the property of the 100 MeV proton beam is as follows,

Intensity	6×10^9 protons per ring
Emittance	30 π mm-mrad
Momentum spread $\Delta p/p$ (full spread)	2×10^{-3}

For the 400 MeV proton beam, the transversal multiturn injection should be considered, but the intensity is estimated as 2.5×10^8 p's/ring at most.

Electron Cooling

The characteristics of electron cooling for the 100 MeV proton beam are described in the following. Suppose the beam is prepared as described above, the beam before electron cooling has the velocity spread given as follows;

$$\text{transversal} \quad : \nu_\perp \approx 2.2 \times 10^7 \text{ cm/sec,}$$
$$\text{longitudinal} : \nu_\parallel \approx 1.3 \times 10^7 \text{ cm/sec.}$$

The cooling times are estimated from the experimental results[3] as,

$$\tau_\perp \text{ (transversal)} \approx 1 \text{ sec,}$$
$$\tau_\parallel \text{ (longitudinal)} \lesssim 0.1 \text{ sec.}$$

Another estimation of cooling time is possible by a simple theoretical model, which leads to,[4]

$$\tau_\perp = \frac{3}{4\sqrt{2\pi}} \frac{e\beta\gamma^2}{r_e r_p L\eta j} \left(\frac{T_e}{mc^2}\right)^{3/2} ,$$

where β and γ are the Lorentz kinematical factors, r_p and r_e are the classical radius of proton and electron respectively, L is the Coulomb log, η is the ratio of the cooling region to the circumference, j is the electron current density, T_e is the temperature of the electron beam, and e and mc^2 are the electric charge and the rest energy of electron, respectively. Substituting the specific numbers; β=0.429, γ=1.107, L=10, η=5/125=0.04, j=0.51 A/cm^2 and T_e=0.2 eV, this equation gives, $\tau_\perp \approx 0.7$ sec.

Table 3

Property of electron beam

Current	10 A
Diameter	5 cm
Current density	0.51 A/cm^2
Particle density	~2.5 × 10^8/cm^3
High voltage	≤100 kV (~250 kV)†

† for 400 MeV proton

Equilibrium with an Internal Target

In the following estimate, an internal target is assumed to be so thin that the most probable energy loss rate of the 100 MeV proton beam is much less than the drag rate due to the electron beam. Therefore the longitudinal velocity of the most protons instantaneously equal to that of the surrounding electrons. On the other hand, the longitudinal velocity of each electron shifts from the central value by the amount determined by the space charge effect of the electron beam itself. That is, the fundamental structure of the longitudinal distribution of the proton beam is assumed to be mainly determined by the space charge of the electron beam.

The r.m.s. scattering angle at the target with the thickness of x radiation length is

$$a \simeq 7.4 \times 10^{-2}\sqrt{x} \; .$$

The transversal equilibrium r.m.s. emittance ($\pi\varepsilon_\perp$) is obtained by the equation,

$$d\varepsilon_\perp/dt = -2\varepsilon_\perp/\tau_\perp + \beta_T a^2/T_0 = 0,$$

that is,

$$\varepsilon_\perp = 0.5\ \tau_\perp \beta_T a^2/T_0,$$

where T_0 is the revolution period.

For the multiple scattering is symmetric between the transversal planes, the r.m.s. emittances in the both planes are equal to $\varepsilon_\perp$. On the other hand, the equilibrium energy of the beam with the transversal oscillation amplitude $\hat{x} = \hat{y} = \sqrt{\beta_c\varepsilon}$ shifts due to the space charge effect of the electron beam[5] by,

$$E = K\varepsilon, \quad K = \frac{ne^2}{8\varepsilon_0}\left(1 + \frac{\ell_c^{\,2}}{12\beta_c^{\,2}}\right)\frac{M}{m}\,\beta_c \qquad (1)$$

where n is the electron density, ℓ_c is the length of the cooling section, M and m are the mass of proton and electron, and ε_0 is permittivity of free space. Assuming the Gaussian distribution of proton beam in the transversal planes, the emittance distribution can be derived as,

$$dN/d\varepsilon \propto \varepsilon e^{-\varepsilon/\varepsilon_\perp} . \qquad (2)$$

Substituting Eq.(1) to Eq.(2), the longitudinal distribution is obtained as,

$$dN/dE \propto Ee^{-E/K\varepsilon_\perp}.$$

The 1/e spread of energy (ΔE) is given by,

$$\Delta E = K\varepsilon_\perp .$$

Numericaly, these are,

	100 MeV p beam	400 MeV p beam
$\varepsilon_\perp/x$	8.2 × 10^2	6.7 × 10^1
K (eV)	4.6 × 10^9	2.8 × 10^9
$\varepsilon_\perp$(x=10^{-8})(mm-mrad)	8.2	0.67
ΔE (keV)	38	1.9

Acceleration Mode

The proton beam can be accelerated up to 1.6 GeV. The typical parameters of this mode operation are shown in Table 4.

Table 4

Parameters of accelerator mode

Tune	ν_x = 3.87,	ν_y = 3.26
Transition	γ_T = 4.6	
Maximum	β_x 32.3 m	
	β_y 17.9(in cells) / 48.2(in the ring)	
	D 5.8(in cells) / -8.1(in the ring)	

Strength of quadrupoles

name	B'ℓ/Bρ(m^{-1})
QF1, QF1*, QF2, QF2*	0.48
QD1, QD2, QD2*	-0.48
Q1 = -Q2	-0.374
Q3 = -Q4	-0.174
Q5 = -Q6	-0.727
Q7	-0.517
Q8	0.897
Q9 = -Q10	1.143

For the foil cooling with synchrotron oscillation[6] at high energy, the injected beam must be cooled at first by the electron beam in order to prepare a pencil beam. The balance between the electron cooling time and the growth rate by the intrabeam scattering determines the equilibrium emittances. Numerical calculations based on the formula by Bjorken[7] are repeated to give the grow-up-time of ~1 sec in the transversal planes and $\lesssim$0.1 sec in the longitudinal one. Then the 100 MeV proton beam after electron cooling will have the r.m.s. emittances as,

radial	~0.1 π mm-mrad,
vertical	~0.025 π mm-mrad,
momentum spread	~0.003 %

RF System

The stacked beam is adiabatically captured in an RF bucket, and accelerated up to 1.6 GeV in about 0.5 sec. The typical design values of an RF system are shown in Table 5.

Circulation Ring Mode

The ring will be initially operated as a circulation ring because of the construction schedule under the limited finance. Table 6 shows the parameters of this mode with an internal target. This mode can also be operated to change time structure of the beam from the SSC, and in this mode the lattice can also be excited as in the accelerator mode given in Table 4.

The ring has been designed to satisfy the following conditions;

1) variable dispersion and variable beta-functions at the target point,
2) very long straight section with high dispersion for the large magnetic spectrograph (BIG RAIDEN),
3) variable beta-functions in the cooling region,
4) very long and doubly achromatic straight section for electron cooling,
5) another long straight sections with high dispersion or with double achromaticity for injection, extraction and RF acceleration etc.

Therefore the ring has a race-track shape which is a modified type of hexagon with the three-fold reflection symmetry, and the geometrical outline becomes somewhat similar to those of COSY[8] and ESR[9].

Table 5

RF system for proton beam

Revolution frequency		
at 100 MeV injection	~1.0	MHz
at 1.6 GeV flat top	~2.2	MHz
Voltage and Hamonics	V/h $\simeq$ 4 *)	kV
Minimum voltage	$V\sin\phi_s$ = 1.6 kV	

*) Necessary for keeping the area about three times of the longitudinal emittance ($\Delta p/p = \pm 0.1\%$)

Table 6

Parameters of circulation ring mode

Tune $\nu_x = 3.14$, $\nu_y = 4.16$

Transition $\gamma_T = 4.5$

Functions at a target

$\beta_T = 0.3$ m

$D_T = -5$ m

Strength of quadrupoles magnets

name	$B'\ell/B\rho(m^{-1})$	name	$B'\ell/B\rho(m^{-1})$
QF1=-QD1	0.2	Q4	0.1998
QF2=-QD2	0.4936	Q5	1.0116
QF1*	-0.1666	Q6	-1.2013
QF2*	0.4867	Q7	0.6276
QD2*	-0.4903	Q8	0.3151
Q1	-0.4427	Q9	-1.0064
Q2	0.4181	Q10	0.8062
Q3	-0.2680		

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