DESIGN STUDY ON A COOLER-SYNCHROTRON AT RCNP

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Abstract

In order to extend the present activities at RCNP, we have started a study for a future accelerator towards a new high-precision frontier for quark-lepton nuclear physics in the range of multi-GeV energies. An RCNP future accelerator will have multi-functions, and will be as flexible as possible and characterized as a protons/electrons/light ions/polarized ions cooler-synchrotron-collider. A conceptual design of a collider is described.

1 INTRODUCTION

At the Research Center for Nuclear Physics (RCNP), Osaka University, extensive researches have been performed on nucleon meson nuclear physics at intermediate energies since the completion of the K400 ring cyclotron in 1992. Recently, experimental studies with multi-GeV ion and electron beams are discussed in order to extend present activities at the RCNP. A candidate of the next accelerator is considered to be a collider which combines the function of a cooler ring. For this purpose, a design study on a protons/electrons/light ions cooler-synchrotron-collider is being carried out on the basis of an ion optical theory. Such an accelerator shall meet the following requirements;

- Two-ring configuration,
- Multi-functions,
- Variable focusing modes,
- Multi-particles, and
- Variable energies.

Particle species should include electrons and polarized ions in addition to ordinary particle species such as protons and light ions. Orbital motion of electrons in synchrotrons for ions is considered to be stable if the synchrotron radiation loss of electrons in bending magnets is compensated by the rf system because a dynamical aperture of synchrotrons for ions is large enough to accommodate the small-size electron beam.

A two-ring configuration is very flexible because various functions are allowed so as to transfer the beam between two-rings and to operate independently of each other. In this paper, conceptual designs of both a single ring and an electron-nucleus colliding ring are described.

2 CONCEPTUAL DESIGN OF RINGS

2.1 Single Ring

At present, a design study on a cooler-synchrotron is being focused on a very attractive structure with a figure of eight configuration which seems to be a combination of two rings having opposite bending directions as described in the next subsection. A half of the figure of eight configuration ring is closed separately to give a flexibility to the most extreme, because two separate rings can work independently on each other and give opportunities to accelerate different kinds of ions or electrons simultaneously. Each synchrotron is designed for the maximum energy of 5 GeV for protons. The 45 degrees arc section consists of cells of a doublet lattice OFDBFBDFO and its mirror symmetric lattice, and is a double achromat. The full 180 degrees arc section accommodates four units of achromatic cells, and the double achromatic condition is then satisfied at straight sections. A straight section has a mirror symmetry about the center and has a betatron phase advance of 2π in both transverse planes. Some specifications are given in Table 1. The chromaticity is corrected by two families of sextupole magnets, one focusing and one defocusing.

Table 1: Parameters of a ring

Closed Orbit Perimeter C [m]	427.75
Average Radius R [m]	68.08
Maximun B ρ [T $\cdot$ m]	19.55
Maximum Momentum [GeV/c]	5.86
Betatron Tune Value	
ν_x	10.35
ν_y	6.9
Momentum Compaction	0.00628
Transition γ	12.62
Maximum Betatron Amplitude	
β_x [m]	53.8
β_y [m]	31.9
Maximum Dispersion Function	
D_x [m]	2.48
D_y [m]	0.0
Natural Chromaticity	
Q'_x	-13.4
Q'_y	-14.1

Optimization of lattice parameters is under way with particle tracking simulations. Each ring is also studied for functions of injection, acceleration, extraction, storage and cooling. Layout of the ring is shown in Fig. 1 and Figure 2 shows β and dispersion functions of the unit arc cell.

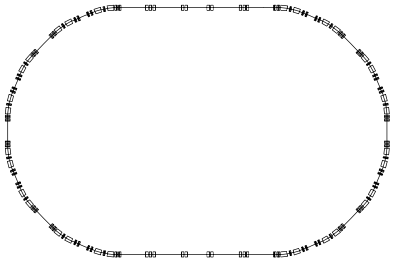

Figure 1: Layout of a single ring.

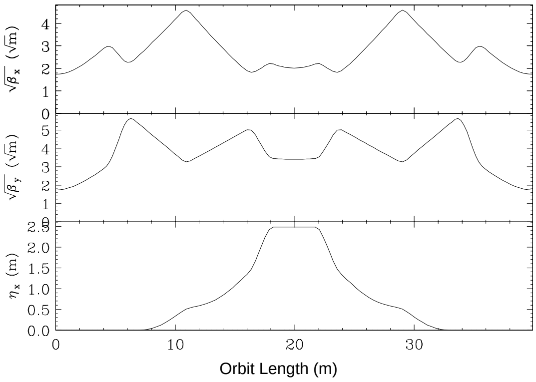

Figure 2: β and dispersion functions of the unit arc cell.

2.2 *Figure of Eight Configuration Ring*

A “figure of 8” configuration synchrotron is proposed to meet these requirements from the accelerator's point of view. This configuration is appropriate to accelerate polarized ions. Details of design study on a synchrotron system will be described in the paper.

A design study on a proton/light ions/electron cooler-synchrotron is being carried out at the RCNP on the basis of an ion optical theory. A figure of eight configuration ring was proposed to accelerate polarized ions up to multi-GeV energies without depolarization. A half of the ring is closed separately to form a synchrotron by itself.

When two rings are connected to shape the figure of eight, S-shape connecting sections are inserted instead of straight sectins. Each connecting section has anti-mirror symmetry and has tune values of 1.5 and 1.0 in the horizontal and the vertical plane, respectively. This section is again a double achromat. Layout of the ring is shown in Fig. 3. Lattice parameters for arc cells are identical to those of the single ring described in the previous subsection. Dispersion function changes its sign at the connecting section. In order to correct the chromaticity, polarities of sextupole magnets are then reversed for the left and right ring in Fig. 3, respectively. Further investigation on the lattice design is being continued to make the ring work as a collider.

2.3 *Electron-Nucleus Collider*

In the feasibility studies of electron-nucleus colliders, parameter sets were calculated by taking account of the beam-beam instability, the space charge effect, synchrotron radiation losses, the beam cooling and the intrabeam scattering [1].

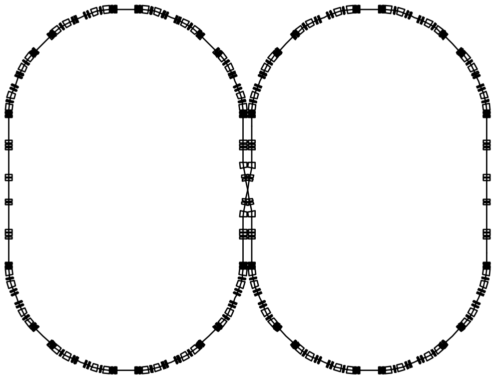

Figure 3: Layout of the figure of eight ring.

If the lumonosity is expressed in terms of the energy of the colliding particles in their center of mass reference system ($\sqrt{s}$), it is found that there is an optimum ion energy to give the maximum luminosity for each value of $\sqrt{s}$. The luminosity has a maximum which occurs when $\Delta\nu_L(\gamma_i)$ = $\xi_e(\gamma_i)$ = $\xi_i(\gamma_i)$ for two interaction points [1]. In the conceptual design, the center of mass energy is assumed 10 GeV for the electron-proton collision and the optimum proton and electron energy is calculated to be 13.9 and 1.8 GeV, respectively. In the present design, however, both the electron and proton energies are fixed at 5 GeV. In this energy region, the ion bunch densities are restricted by so-called Laslett tune shift for ion bunches. General parameters of ion and electron rings of the present design are listed in Table 2. The maximun magnetic rigity is 20 T · m.

Table 2: General parameter list of a collider.

Closed Orbit Perimeter [m]	428
Collision Frequency [MHz]	60
χ = ϵ_e / ϵ_i	1
Curvature Radius in Bending Magnets [m]	12
Maximun B ρ [T · m]	20
β-function at IP [m]	0.1
β-function at Cooling Section [m]	200
Rms Bunch Length [m]	0.1
Beam-beam Parameter ξ_i	0.05
Electron Energy [GeV]	5
N_e ($\times 10^{11}$)	1.0
Electron Beam Current [A]	1
Synchr. Radiat. Energy Loss per Turn [MeV]	4.7
RF-Power [MW]	4.5

In the conceptual design studies, parameter sets were calculated for cases electron-proton, electron-deuteron and electron-^{40}Ca^{20} operational modes of the collider. Results of the calculations are listed in Table 3. In all cases, high luminosity performance larger than 1$\times$ 10^{31} 1/ [cm^{2}s] is feasible, but encounters various problems. For example, a medium energy electron cooling device is inevitable to ensure small enough emittances and short enough cooling times of ion bunches.

Table 3: Parameter set for an electron-ion collider, calculated assuming that $(\Delta\mu_L)_{th} = \xi_i$.

Ion Species	p	d	^{40}Ca
$\sqrt{s}$ [GeV/u]	10.0	5.6	1.55
Specific Luminosity ($\times 10^{20}$) [1/cm^{2}s]	1.3	1.3	1.3
N_i ($\times 10^8$)	16.7	6.5	0.33
Ion Beam Current [mA]	16.0	6.2	6.3
Ion Energy [GeV/u]	5.0	3.14	3.14
Emittans [nm]	46	36	36
Beam-beam Parameter ξ_e ($\times 10^{-4}$)	8.3	4.1	4.2
Density of Cooling Beam ($\times 10^8$) [1/cm^3]	2.3	1.1	0.058
Current of Cooling Beam [mA]	312	126	6.4
RMS Beam Radius [cm]	0.30	0.27	0.27
Current Density of Cooling Beam [A/cm^2]	1.1	0.55	0.028

3 SPIN TRACKING

The figure of eight configuration ring gives a nice performance for the acceleration of polarized ion beams, because depolarization resonances of ion beams are avoided in principle due to opposite precession of a spin vector in two rings. Full Siberian snakes are usually used to keep particle polarizations during acceleration. At multi-GeV energies, however, strong fields are required for a solenoidal magnet when a type-1 snake is employed [2]. For a type-2 or -3 snake, orbit excursions in the snake magnets are quite large and gaps of dipole magnets should be impracticably large to accommodate particle orbits. In order to confirm the advantage of the present configuration, preliminary investigations were performed on the spin trackings using the spinor algebra to examine whether the spin polarization of protons is conserved in the acceleration through intrinsic and imperfection resonances.

The equation of motion of the spin vector $\vec{S}$ through a magnetic field is given by the BMT equation [3]

$$\frac{d\vec{S}}{ds} = \vec{S} \times \vec{\Omega} \tag{1}$$

where the precession frequency vector $\vec{\Omega}$ is

$$\vec{\Omega} \equiv \frac{1}{B\rho}[(1 + G\gamma)\vec{B}_\perp + (1 + G\ )\ \vec{B}_\|] \text{ and } G = \frac{g}{2} - 1, \tag{2}$$

$\vec{B}_\perp$ and $\vec{B}_\|$ being the parts of the field perpendicular and parallel to the particle velocity. The spin motion is conveniently described by the SU(2) spinor formalism. In the spinor representation, a spin vector component is derived by

$$\vec{S}_i = \psi^\dagger \vec{\sigma}_i \psi, \tag{3}$$

where $\vec{\sigma}_1$, $\vec{\sigma}_2$, $\vec{\sigma}_3$ are the Pauli spin matrices. Equation of the spinor is then given by:

$$\frac{d\psi}{d\theta} = \frac{i}{2} H\psi \ = \ -i\frac{\lambda}{2}(\vec{\sigma} \cdot \hat{n})\psi. \tag{4}$$

Solution of the spinor equation is obtained as v

$$\begin{aligned} \psi(\theta) = & \quad M\psi(0) \\ M = & \quad \exp[-i(\tfrac{\lambda}{2})(\vec{\sigma} \cdot \hat{n})\theta] \qquad . \\ = & \quad \cos(\tfrac{\lambda\theta}{2}) - i(\vec{\sigma} \cdot \hat{n}) \sin(\tfrac{\lambda\theta}{2}) \end{aligned} \tag{5}$$

Spin-tracking calculations were performed assuming the normalized emittance of 10 π mmmrad, and the vertical closed orbit distortion (COD) of 1 mm (FWHM) [4]. It was found that only a 5 % partial snake with a solenoid was enough to keep the proton polarization which was longitudinal at the straight section opposite to the snake solenoid magnet. It should be stressed that partial snakes in this case can overcome intrinsic depolarizing resonances as well as imperfection resonances. In the pioneering studies at IUCF, partial Siberian snakes were used to overcome weak imperfection resonances. However, weak partial snakes were not able to overcome intrinsic resonances.

4 SUMMARY

A figure of eight configuration ring was proposed to accelerate polarized ions up to multi-GeV energies without depolarization. A half of the ring is closed separately to form a synchrotron by itself. This gives a flexibility to the most extreme, because two separate rings can work independently on each other and give opportunities to accelerate different kinds of ions or electrons simultaneously. In the feasibility studies of electron-nucleus colliders, parameter sets were calculated for cases electron-proton, electron-deuteron and electron-^{40}Ca^{20} operational modes. High luminosity performance larger than 2× 10^{31} 1/ v[cm^{2}s] is feasible, when a medium energy electron cooling device becomes available to ensure small enough emittances and short enough cooling times of ion bunches.

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