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PRELIMINARY LATTICE DESIGN FOR THE RAPID CYCLING SYNCHROTRON IN THE SPPC

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Abstract

The Rapid cycling synchrotron (p-RCS) is the first synchrotron of the accelerator chain in the proposed Super Proton-Proton Collider (SPPC) project. It will provide high-energy and high-power beams for the injection to the downstream accelerators for SPPC collision with the required beam characteristics such as bunch spacing, bunch population and emittance, but also serve an independent application program with less restricted beam characteristics and a higher beam power of 3.4 MW. With a designed energy range of 1.2-10 GeV and a repetition rate of 25 Hz, the lattice design plays a mandatory role in beam dynamics. In this paper, three types of linear lattice for the p-RCS, which are based on the basic FODO modules, triplet modules and negative momentum compaction (NMC) factor modules, respectively, are compared. Taking into consideration the longitudinal beam dynamics which requires as a large absolute of phase slippage factor as possible at the extraction energy, the NMC lattice is considered a preferable solution.

INTRODUCTION

SPPC (Super Proton-Proton Collider), as the second phase of the CEPC-SPPC study project in China, is envisioned to be an energy frontier machine to succeed the Large Hadron Collider (LHC), with a center-of-mass energy of 125 TeV and a nominal luminosity of 4.0×10^{34} $cm^{-2}s^{-1}$, to explore the physics beyond the Standard Model [1]. As the first synchrotron of the SPPC accelerator chain, the p-RCS is a rapid cycling synchrotron with a repetition rate of 25 Hz and a designed energy range from 1.2 GeV to 10 GeV. Its goal is to provide the downstream accelerators with the required beam properties for SPPC collision. Additionally, it could serve as an independent beam application program with a higher beam power of 3.4 MW.

To meet the design goal of the p-RCS, the lattice design plays a critical role in the transverse beam dynamics. On the other hand, the study on the SPPC longitudinal beam dynamics [2] indicates that the absolute value of the phase slippage factor at the p-RCS extraction is required to be as large as possible during the longitudinal matching between the p-RCS and the downstream synchrotron--MSS. Otherwise, the RF voltage at the p-RCS extraction would be very low, leading to extremely heavy beam loading. As the phase slippage factor η is closely related to the momentum factor α_p, which is a critical lattice parameter, special attention is paid to the lattice design. In this paper, we will present and compare three types of linear lattice designs for the p-RCS, which are based on the basic FODO modules, the triplet modules and the negative momentum compaction (NMC) factor modules, respectively.

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DESIGN GOALS AND REQUIREMENTS

The p-RCS lattice needs to be specially designed to meet both the requirements of the layout and transverse beam dynamics and those from longitudinal beam dynamics. The following are the specific requirements:

- Maximize the absolute value of the phase slippage factor η, to satisfy the longitudinal phase space matching between the p-RCS and the MSS.
- The circumference is about 1000 m, with the injection and extraction kinetic energy of 1.2 GeV and 10 GeV, respectively, and a repetition rate of 25 Hz.
- The total length of dispersion-free long straight sections (LSS) is better more than one-third of the circumference for accommodating RF cavities, injection, extraction and collimation systems.
- The extraction energy is well below the transition energy to prevent the longitudinal instability caused by the transition energy crossing, i.e., $\gamma_t > 11.66$ with γ_t the transition gamma, or the average dispersion $\overline{D}_x < 1.13$ m.
- The rms transverse geometric emittance at injection energy is 10 πmm· mrad, while the ring acceptance is 100 πmm·mrad.
- The maximum field strength of the main dipole magnets is limited to about 1 T, and the vertical beta function β_y at dipoles should be as small as possible to reduce the magnet gap and manufacturing cost.
- The maximum pole-tip field of the quadrupole magnets is limited to about 0.4 T, and a smaller number of quadrupole families is favored.

With these considerations, three possible design schemes for the p-RCS lattice have been conducted.

POSSIBLE LATTICE SCHEMES

Lattice with FODO Modules

The FODO lattice is the most widely used lattice, especially in high-energy synchrotrons, due to its simplicity, flexibility, and good beam dynamics stability. Additionally, the standard FODO focusing structure can utilize the minimum families of quadrupoles.

In a standard FODO cell, the average dispersion over the cell is [3]:

$$\overline{D}_x = \frac{L_c\theta_c}{4}\left(\frac{1}{\sin^2\mu/2} - \frac{1}{12}\right) \tag{1}$$

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where L_c, θ_c and μ are the length, bending angle and phase advance of the FODO cell. Normally, a 90° phase advance per FODO cell is utilized for proton synchrotrons with equal horizontal and vertical emittance $\varepsilon_x = \varepsilon_y$, and the p-RCS is the case. As a result, the product of the cell length and bending angle must meet the condition of $L_c\theta_c < 2.36$ m due to $\overline{D}_x < 1.13$ m, which imposes a strict constraint on the FODO cell. With this consideration, the entire ring is designed to comprise 6 superperiods, each with 13 equidistant FODO cells and a length of 161.20 m. Figure 1 shows the optical function in one superperiod.

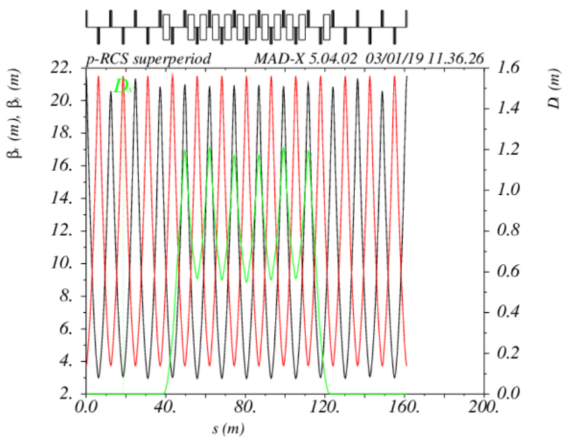

Figure 1: One superperiod composed of FODO modules.

The superperiod consists of 12 identical dipole magnets. Ten of these magnets are located in the 5 FODO cells of the middle arc, while the remaining two magnets are situated in the two dispersion suppressor cells on either side of the arc. Each dipole has a length of 3.2 m and a curvature radius of 36.669 m.

The 26 quadrupoles in one superperiod are divided into two families: focusing quadrupoles (QF) and defocusing quadrupoles (QD). Each quadrupole has the same length of 1.08 m, but the QF and QD have different field gradients of 8.83 T/m and 8.15 T/m, respectively. This differentiation helps the dispersion suppressor cell attain zero dispersion in the LSS. The dispersion-free LSS of the entire ring has a length of 446.4 m, providing ample room for the installation of injection, extraction, RF, and collimation systems.

The maximum beta function is about 21 m, indicating a beam pipe inner radius of 46 mm under an acceptance of 100 πmm·mrad. The transition gamma is 15.13, resulting in a phase slippage factor of -2.99×10^{-3} at extraction. The betatron tunes are (22.13, 18.97), which can be adjusted by slightly modifying the strengths of the LSS quadrupoles.

Lattice with Triplet Modules

A triplet cell can provide the equivalent focusing and small waist points in both the horizontal and vertical planes. Therefore, this type of lattice is beneficial to produce very long drifts and leads to small apertures for dipoles, which is utilized in facilities such as CSNS/RCS [4], ESS/AR [5], etc.

Considering that the total length of the dipole magnets is fixed and the constraint of $\overline{D}_x < 1.13$ m, the length of one superperiod composed of triplet cells cannot be too long. This is because both the maximum and average dispersion increase with the length of the superperiod. Therefore, the p-RCS ring was ultimately designed with 10 superperiods, each consisting of 6 triplet cells with a length of approximately 16.12 m per cell. The superperiod lattice composed of triplet cells is shown in Fig. 2.

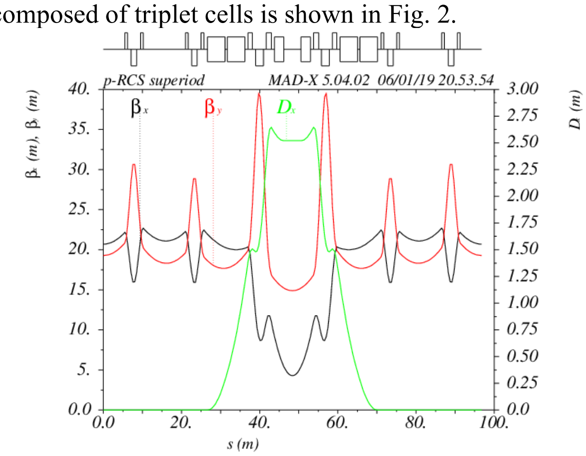

Figure 2: One superperiod composed of Triplet modules.

Each superperiod includes 6 dipole magnets with the same curvature radius of 36.287 m. However, they are categorized into two types based on their lengths and apertures. The two bending magnets located in the middle are 2.4 m long with relatively small apertures, while the four bending magnets situated on the sides are 4.5 m long with relatively large apertures. The central cell reserves 4.4 m drift space for installing a momentum collimator if needed.

The superperiod comprises 18 quadrupoles, divided into 5 categories. Among them, the QF and QD of the 12 quadrupoles in the LSS belong to two categories, with lengths of 0.7 m and 1.4 m, and magnetic field gradients of 5.97 T/m and 5.83 T/m, respectively. The 6 quadrupoles in the middle are symmetrical about the midpoint. The 3 quadrupoles on the left side of the midpoint belong to three families, with lengths of 1.12 m, 2.02 m, and 1.32 m, and magnetic field gradients of 6.14 T/m, 6.23 T/m, and 6.39 T/m, respectively.

The total LSS length is 532.4 m. The transition gamma is 13.41, which leads to the phase slippage factor at extraction is -1.79×10^{-3}. The betatron tunes are (10.27, 7.74).

Lattice with NMC Modules

A lattice with a negative momentum compaction (NMC) factor is another common way to avoid transition crossing, along with giving a large absolute value of the phase slippage factor. A modular approach for the NMC lattice has been well developed [6], which is based on resonantly correlated functions of the orbit curvature and the gradient modulation of quadrupoles [7], and successfully applied to the J-PARC/MR [8], the design of CERN/PS2 [9], etc.

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The NMC module comprises three cells, with two FODO cells (with different focusing and defocusing strengths) on both sides and an optical matching cell with a missing bend in the middle, which is centrally symmetric. The matching cell is composed of two quadrupole doublets, with gradients different from the ones in the FODO cell. Thus, four quadrupole families in the NMC module are utilized to control the transition gamma, the horizontal and vertical phase advances. This could help achieve a dispersion-free straight section without a special suppressor and implement the convenient sextupole chromaticity correction scheme.

With these considerations, the lattice function of an NMC module for the p-RCS ring was preliminarily designed, see Fig. 3(a). The length of the module is 47 m, with a maximum quadrupole strength of 6.55 T/m and a bending magnet length of 4.8 m. The horizontal and vertical phase advances are specially designed as $3\pi/2$ and $5\pi/4$, respectively. Each module has 4 identical bending magnets with the same length and curvature radius of 4.8 m and 36.669 m, respectively.

The superperiod consists of 4 NMC modules to automatically suppress the dispersion in the LSS, see Fig. 3(b). The LSS in one superperiod is 134.4 m long, which is composed of 9 FODO cells but can have independent and adjustable optical parameters based on the requirements.

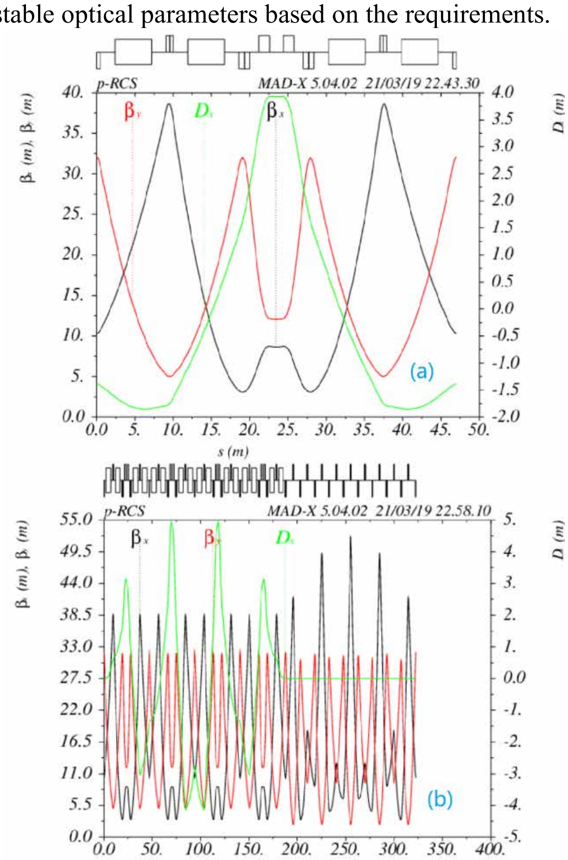

Figure 3: (a) NMC module, (b) One superperiod composed of NMC modules.

Such 3 superperiods form the whole p-RCS ring with a circumference of 967.2 m. The transition gamma is 12.2*i*, giving the phase slippage factor of -1.41×10^{-2} in the extraction.

COMPARISON

The main characteristics of the three types of linear lattice designs are summarized in Table 1. The FODO-module lattice has minimum quadrupole families and the smallest maximum beta function and beta function at dipoles, indicating the minimum apertures for the quadrupoles and dipoles. Neverthelss, it utilizes a total of 156 quadrupoles and gives a relatively small absolute of phase slippage factor. The triplet-module lattice requires the most types and quantity of quadrupoles due to the most superperiods utilized and provides the smallest absolute value of the phase slippage factor. In comparison, the NMC lattice seems favorable from the perspective of longitudinal beam dynamics since it provides the largest absolute value of phase slippage factor, even though the maximum beta function and beta function at dipoles are relatively large.

Table 1: Comparison of Different Types of Lattice

Lattice type	FODO	Triplet	NMC
Circumference (m)	967.2	967.2	967.2
Number of superperiods	6	10	3
Number of quadrupoles	156	180	138
Families of quadrupoles	2	5	4
β_{max} (m)	21	40	52
β_y at dipoles (m)	15.7	19.4	22.2
Total LSS length (m)	446.4	532.4	403.2
Transition gamma γ_t	15.13	13.41	12.2i
η at extraction ($\times 10^{-3}$)	-2.99	-1.79	-14.1

SUMMARY

Three types of linear lattice, based on the FODO modules, the triplet modules and the NMC modules, have been designed for the p-RCS. All of them meet the basic design requirements, but the NMC lattice is considered a preferable solution from the perspectives of longitudinal dynamics that requires as a large absolute of phase slippage factor as possible at the extraction energy. However, the linear lattice also needs to be re-evaluated when the global parameters like the betatron tunes and nonlinear beam dynamics are involved, which is the next step in the future.

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