LATTICE DESIGN OF A RCS AS POSSIBLE ALTERNATIVE TO THE PS BOOSTER UPGRADE

M. Fitterer, CERN, Geneva & KIT, Karlsruhe,
M. Benedikt, H. Burkhardt, C. Carli, R. Garoby, B. Goddard, K. Hanke, H. Schönauer, CERN, Geneva,
A.-S. Müller, KIT, Karlsruhe

Abstract

In the framework of the LHC Injectors Upgrade (LIU) a new rapid cycling synchrotron as alternative to the PS Booster has been proposed. In this paper we present the lattice constraints and requirement as well as the current status of the RCS lattice design and beam dynamics studies.

INTRODUCTION

Motivated by the feasibility study of an upgrade of the existing PS Booster to a beam energy of 2 GeV [1], a study of a new machine as replacement of the PS Booster was initiated [2]. First a circumference of 1/7 of the PS circumference was considered but in the end rejected due to insufficient space for diagnostics, vacuum equipment etc. For this reason a longer variant of 4/21 of the PS circumference was chosen. The ratio of 4/21 to the PS circumference implies operation with a fundamental harmonic number of $h = 1$, set as baseline of the performed studies, or $h = 4$. In this first design phase of a machine the main interest lies in obtaining a rough estimate for space and hardware as well as performance limitations and a study of different basic options, which is presented in this paper.

PERFORMANCE AND HARDWARE LIMITATIONS

The PS Booster not only produces the beams for the LHC, but also for a variety of other experiments all with different requirements. The beam parameters required from the RCS for LHC and most challenging non-LHC beam(s) are listed in Table 1 and the general machine and magnet parameters in Table 2.

Table 1: High brightness beams required from the RCS. N_b is the number of particles per pulse, $\epsilon_{N,x,y}$ the normalised hor./vert. rms emittance at extraction, ϵ_l the long. emittance and σ_l the bunch length.

	LHC	**non-LHC**
N_b	3.3×10^{12}	1.0×10^{13}
$\epsilon_{N,x,y}$	2.5/2.5 mm mrad	12/8 mm mrad
ϵ_l	2.0 eVs	2.0 eVs
σ_l	180 ns	180-230 ns

GEOMETRY AND GENERAL LAYOUT

Three different geometries were considered for the RCS: A racetrack with a two-fold symmetry, a triangle with a three-fold symmetry and a square with a four-fold symmetry. Higher symmetries were discarded as the straight sections would not allow sufficient space for injection and extraction.

Table 2: RCS machine and magnet parameters.

Energy	0.16-2 GeV
Circumference	119.68 m
Repetition rate	10 Hz
Max. dipole field	1.3 T
Max. pole tip field quadrupoles	0.8 T

RCS BASELINE OPTION

For a first study [2] the three fold symmetry was chosen for civil engineering reasons, which we will refer to as "RCS Baseline Option".

Table 3: RCS Baseline Option optics parameters.

Hor./Vert. tune	4.42/3.57
Gamma transition	3.93
Max. hor./vert. β-function [m]	8.69/12.34
Max. hor. dispersion [m]	3.33
Max. hor. dispersion (straight) [m]	0.31

Optics and Layout

The lattice of the RCS Baseline Option consists of a regular 21 cell FODO lattice with only two quadrupole families. The dipoles are moved next to the defocusing quadrupoles in order to minimize the dispersion. The dispersion is suppressed over 2π phase advance per arc. The optics are shown in Fig. 1 (left).

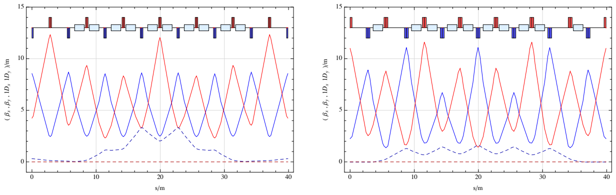

Figure 1: 21 cell FODO lattice with a three-fold symmetry. Only one superperiod (out of three) is shown.

By adjusting the tunes to the chosen WP of $Q_x/Q_y = 4.42/3.57$ allowing for a maximum space charge tune shift of $-\Delta Q_x/\Delta Q_y = 0.39/0.54$ without crossing an integer resonance, the dispersion does not fully vanish but remains small enough for injection, extraction and the installed RF. Vertical beta-beating is caused by the edge focusing from the dipole magnets and can be corrected using more quadrupole families. The optics parameters for this option are listed in Table 3.

Longitudinal Dynamics

The longitudinal emittance of 2 eVs required by the PS creates a conflict with a limit encountered at injection: The technique of longitudinal painting with Linac4 foresees linear energy sweeps within 20 μs, which cannot exceed $\pm$1.2 MeV. A reasonably filled (painted) $h = 1 + 2$ bucket of this height can hold about only 1.2 eVs. To overcome this difficulty a fast emittance blow-up by an additional 200 MHz RF cavity is foreseen. The cavity is locked to an integer harmonics of the revolution frequency jumping by one unit whenever required to keep the frequency within the bandwidth of the cavity [3].

Another potential difficulty arises for the LHC beams from the fact that the PS requires bunch lengths up to 180 ns ($\Delta\phi = \pm 77°$). The matched RF voltage of a bunch of area 2 eVs is about 2 kV and the synchrotron frequency as low as 150 Hz. Consequently, stretching the RCS bunches to this length near flat top is no longer an adiabatic process. For this reason fast bunch rotation preceding extraction is preferred: Dropping the voltage from 60 kV to 14 kV rotates the bunch from initially $\Delta\phi = \pm 36°$ to the desired length in 0.8 ms.

Space Charge Estimates and Non-Linearities

The defocusing due to space charge forces creates a tune spread which extends in general from the bare working point to a maximum tune shift, which is the one that experience the particles with vanishing betatron amplitudes. In the present PSB, it reaches values of about 0.5 in the vertical plane. From this experience one can infer that the RCS will allow tune shifts of this order, perhaps even a little more as the beam is accelerated much faster.

In Table 4 are compiled the computed tune shifts during the critical phase till 5 ms for the most critical beams. The incoherent space charge tune shift was estimated by:

$$\Delta Q = -\frac{N_b}{\epsilon_N} \cdot \frac{r_p}{4\pi\beta\gamma^2} \cdot \frac{FGH_{x,y}}{B_b} \qquad (1)$$

where N_b is the number of protons per bunch, ϵ_N the normalized emittance, β and γ the Lorentz factors and B_b the bunching factor defined as the ratio between the average to the peak line density of a single bunch. F is the image factor with $F \approx 1$, G the transverse distribution factor with $G = 2$ for Gaussian and $G = 1$ for a uniform distribution and H the Aspect ratio factor given by $H_x \propto \langle \beta_x / \left(a\left(a+b\right)\right)\rangle$ and $H_y \propto \langle \beta_y / \left(b\left(a+b\right)\right)\rangle$. Although better transverse distributions can be painted with H- injection, Gaussians have been assumed in both transverse planes. The emittances used in the calculations have been reduced by 20% with respect to the nominal ones to provide some margin for blow-up or minor losses.

The maximum vertical tune shift of -0.54 of the LHC beams appears somewhat risky, but it should be borne in mind that a transverse Gaussian is a pessimistic assumption compared with the distributions made possible by transverse painting.

Table 4: Space charge tune shifts and bunch area during early acceleration for the RCS Baseline Option.

t [ms]	$\mathbf{V_{rf}}$ **[kV]**	$\mathbf{B_b}$	$\mathbf{-\Delta Q_x/\Delta Q_y}$ LHC	non-LHC
0	10	0.482	0.36/0.52	0.37/0.45
2	20	0.421	0.33/0.54	0.39/0.48
3.2	22	0.424	0.32/0.52	0.37/0.46
5	25	0.428	0.29/0.46	0.33/0.4

The effect of typical magnet non-linearities should be negligible in an RCS compared to the effect of space charge. For 2nd- and 3rd-order stopbands it can be estimated from the results of magnet measurements from which the number and the placement of the correction magnets can be inferred. What remains to be checked is the effect of eddy currents in the dipole vacuum chamber: For a maximum, the natural chromaticities of $\xi_x/\xi_y = -3.60/-3.84$ are shifted to $\xi_x/\xi_y = -1.78/-6.30$. These chromaticity values should not require any correction.

ALTERNATIVE SCENARIOS

Alternative lattice options have been studied to increase the transition gamma and reduce the Twiss functions, especially the maximum horizontal dispersion. The lattices studied can be divided depending on their dispersion suppression scheme and the choice of the periodic cell. Again, the dispersion in the straight sections can be suppressed by a phase advance of $n \cdot 2\pi$ per arc, which we call the "2π Scheme" in the following, or a "missing bend scheme". As basic cell types FODO and doublet cells have been considered. All lattices have a total number of cells between 20 and 22 since this delivers enough space for injection, extraction and the installation of the RF and, on the other hand, is sufficient to obtain acceptable maximum beam sizes and transition energy. In all lattices only two quadrupole families are used for this first study.

Cell Design

For comparison between doublet and FODO structures a 20 cell lattice with a four-fold symmetry was used. The dispersion is suppressed by a 2π phase advance per arc. In all options the dispersion is reduced by shifting the bendings towards the defocusing quadrupoles and the comparison was made for this configuration. For a FODO structure two configuration exist, one with a focusing quadrupole (Fig. 2 (upper left)) and one with a defocusing quadrupole in the centre of the straight section (Fig. 2 (lower left)).

Because of the dispersion suppression over a phase advance of 2π per arc, the dispersion is smaller for the version with the focusing quadrupole in the centre of the straight section.

A doublet structure as shown in Fig. 2 (upper right) in general requires twice the quadrupole strength of a FODO structure, but offers the advantage of smaller Twiss functions and a slightly higher gamma transition, here 5.2 for FODO and 5.5 for doublet.

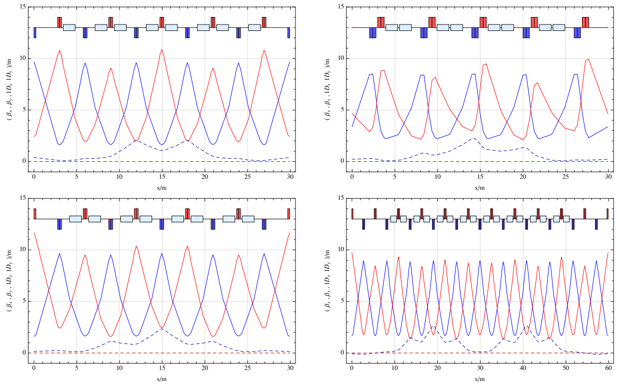

Figure 2: Lattices with two-fold symmetry and 22 cells (lower right) and four-fold symmetry with 20 cells. Only one superperiod (out of two respectively four) is shown.

Beside the reduction of the Twiss function, the required space for the H$^-$ injection is an important selection criterion and was decisive in the case of the RCS. For a FODO structure with the defocusing quadrupole in the center of the straight section the required space could be reduced by 2/3 with respect to a scheme with a simple straight section [4].

2π *Scheme*

By suppressing the dispersion over a $n \cdot 2\pi$ phase advance per arc, the symmetry, the total number of cells N_{tot} and the number of cells per straight section N_{st} and arc N_{arc} determine the optics, i.e. the horizontal tune $Q_{x,\text{id}}$ and therefore the transition gamma and the phase advance per cell ϕ_{c}. Discarding all lattices with a tune and thus transition gamma below 3.6 and a phase advance higher than $100°$ per cell, only the options listed in Table 5 are left. The tunes $Q_{x,\text{id}}$ in Table 5 obtained with zero dispersion in the straight sections are not suitable for a synchrotron with strong direct space charge effects and therefore all tunes have been adjusted taking a maximum space charge tune shift of $-\Delta Q_x/\Delta Q_y = 0.39/0.54$ into account.

In the case of the two-fold symmetry the option with 22 cells is preferred over the 20 cell option because it offers more straight sections, lower Twiss functions and a smaller dispersion in the straight section as the optimal tune of 5.5 is closer to the design value of 5.41. The optics of the 22 cell two-fold symmetry version are shown in Fig. 2 (lower right), the three-fold symmetry option, which was chosen as RCS Baseline Option, in Fig. 1 (left) and the four-fold symmetry option in Fig. 2 (lower left). The Twiss functions are the smallest for the four-fold symmetry, which offers also the most space in the tune diagram due to its high symmetry, but could be tight for injection. The two-fold symmetry option has the most regular Twiss functions, but a low symmetry and almost no suppression of resonances. Because of the higher phase advance per cell the two- and four-fold symmetry also deliver a higher gamma transition what could be advantageous for a stable longitudinal motion.

Table 5: List of possible options using the 2π scheme for dispersion suppression.

Sym.	$\mathbf{N}_{\text{tot}}$	$\mathbf{N}_{\text{st}}$	$\mathbf{N}_{\text{arc}}$	$\mathbf{Q}_{\mathbf{x},\text{id}}$	ϕ_{c}	$\mathbf{Q_x/Q_y}$
2	20	2	8	5.0	90	5.42/5.59
	22	3	8	5.5	90	5.42/5.59
3	21	2	5	4.2	72	4.42/3.57
4	20	1	4	5.0	90	5.41/4.56

Missing Bend Scheme

All options using the 2π scheme have a high horizontal dispersion, which greatly increases the aperture in the quadrupoles. One possibility to reduce the dispersion is to use a dispersion suppressor. As space is scarce a "missing bend scheme" as illustrated in Fig. 1 (right) has been proposed as alternative here explicitly to the RCS Baseline Option.

The dispersion is matched by varying the length of the straight section replacing the missing bend. Compared to the RCS Baseline Option the dispersion is roughly halved, but the beta functions become very irregular, which could be again diminished by allowing for more quadrupole families. As the cells per straight section are reduced from two to one, the injection and extraction become challenging, but one could think of novel schemes using supportively the dipole next to the dispersion free straight sections.

SUMMARY

Different lattice options for a RCS with a circumference of 4/21 of the PS circumference have been studied. The three-fold symmetry version with a 2π dipsersion suppression scheme has been chosen for civil engineering reasons as baseline for the study of hardware and equipment [2]. The other proposed symmetries, namely a two- and four-fold symmetry, and a three-fold symmetry with a missing bend dipsersion suppression scheme are also feasible options all with advantages and disadvantages.

REFERENCES

[1] K .Hanke et al., "Study of an Energy Upgrade of the CERN PS Booster", these proceedings, IPAC'11.

[2] K .Hanke et al., "Study of a Rapid Cycling Synchrotron to replace the CERN PS Booster", these proceedings, IPAC'11.

[3] R. Cappi, R. Garoby, E. Shaposhnikova, "Experimental study of controlled longitudinal blow-up", CERN/PS-40 (RF)

[4] B .Goddard et al., "Injection and Extraction Considerations for a 2 GeV RCS at CERN", these proceedings, IPAC'11.