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**STUDY OF A RAPID CYCLING SYNCHROTRON TO REPLACE THE
CERN PS BOOSTER**

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Abstract

CERN's proton injector chain is undergoing a massive consolidation and upgrade program in order to deliver beams meeting the needs of the LHC Luminosity Upgrade. As an alternative to the upgrade of the existing Proton Synchrotron Booster (PSB), the construction of a Rapid Cycling Synchrotron (RCS) has been studied. This machine would replace the PSB and deliver beams to the LHC as well as to CERN's rich fixed-target physics program. This paper summarizes the outcome of the feasibility study along with a tentative RCS design.

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CERN's proton injector chain is undergoing a massive consolidation and upgrade program in order to deliver beams meeting the needs of the LHC Luminosity Upgrade. As an alternative to the upgrade of the existing Proton Synchrotron Booster (PSB), the construction of a Rapid Cycling Synchrotron (RCS) has been studied. This machine would replace the PSB and deliver beams to the LHC as well as to CERN's rich fixed-target physics program. This paper summarizes the outcome of the feasibility study along with a tentative RCS design.

INTRODUCTION

Following the feasibility study and cost estimate for an upgrade of the existing PS Booster to a beam energy of 2 GeV [1], the question was raised whether a new machine to replace the Booster would be a viable option. The obvious advantage of such a scenario would be not only to replace a 40 year old machine by a new one, but also to commission the machine off-line before connecting it to the downstream Proton Synchrotron (PS) machine, thus minimising risk and down time.

A very preliminary RCS layout with a first suggestion of machine parameters was presented at the Chamonix 2011 workshop [2]. Following these initial suggestions, a study was launched the outcome of which is summarised in [3]. In the study a variant with $4/21$ of the PS circumference was chosen. This would allow operation at $h=1$ and $h=4$, where in a first step $h=1$ is considered the baseline while keeping the option of higher harmonics for future upgrades. The machine would pulse at 10 Hz as originally proposed. As for the geometry of the machine a three-fold symmetry appears preferable, with the straight sections assigned to injection, extraction, and accelerating structures.

In the following sections we describe the machine parameters and technical solutions for some critical equipments and subsystems.

PERFORMANCE

The RCS design goal is to achieve the same beam performance as one PSB ring at 2 GeV for LHC beams with Linac4 as injector [1]. With Linac4 H- charge-exchange injection, extraction energy of 2 GeV, 10 Hz operation and Finemet[®] cavities, beam production

schemes have to be developed and optimized for the downstream PS machine.

LHC Beams

By design, the RCS will match the performance of one PSB ring at 2 GeV for LHC with Linac4 as injector. Therefore the RCS beam characteristics for LHC (25 ns bunch spacing) are $3.3E12$ p/pulse within 2.5π mm.mrad (H/V) and 2 eVs. No problems are expected for single-bunch LHC beams. The baseline scheme for the production of multi-bunch LHC beams is to accelerate one bunch (injected into $hRCS=1+2$ for maximum acceptance and minimum space charge effects) per RCS pulse. Six RCS injections will fill 6 buckets out of $hPS=7$ and the same gymnastics than today will have to be applied afterwards in the PS. Longitudinal blow-up will be required for the production of the LHC multi-bunch beams to achieve longitudinal emittances at RCS extraction of ~ 1.35 eVs or 2 eVs for double or triple splitting in the PS. Controlled transverse blow-up might be necessary as well in case of space-charge limitations at PS injection.

Production of non-LHC beams

A maximum RCS bunch intensity of $1E13$ ppp within $12/8 \pi$ mm.mrad (1 sigma normalized H/V transverse emittances) and 2 eVs is assumed.

For the RCS injection, a preliminary design led to an injection septum with a vertical aperture reduced from 60 mm to 48 mm compared to the PSB at 2 GeV because of the higher repetition rate.

In the case of single-bunch beams, direct losses on the septum could be minimised by a proper choice of the optics and by the reduced physical emittance at 2 GeV w.r.t. 1.4 GeV. In addition, to keep the same radiation levels as today with the same beam intensities, advantage will be taken of the RCS capability to produce smaller transverse emittances.

For the multi-bunch beams filling the PS circumference, the most straightforward scheme is to operate the PS at harmonics 7, and fill it with 7 RCS pulses during 600 ms, similarly to the LHC-type beams.

In this case the maximum possible injected intensity of $7E13$ p into the PS would largely exceed today's record and certainly the ultimate PS potential.

For the Antiproton Decelerator (AD) production beam, 5 bunches (compared to 4 today) would be injected in the PS operating at $h=10$, giving a burst of ideal length to the AD after batch compression at 26 GeV/c.

For the ISOLDE isotope separator, the 10 Hz rate of the RCS will improve the beam power distribution over time and could be more efficient than the present staggered ejection (to be further addressed with target simulations for HIE-ISOLDE upgrade program). In average, more protons per second can be delivered because of the much-increased number of unused RCS pulses while the PS accelerates.

DESIGN CHOICES AND MACHINE PARAMETERS

For civil engineering a triangular shaped ring is most advantageous and was chosen as baseline layout. As illustrated in Figure 1 injection, extraction and RF are each located in one straight section.

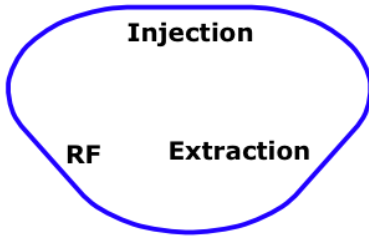


Figure 1: RCS layout.

Optics

The lattice consists of 21 cells – 5 per arc and 2 per straight section - with a cell length of 5.6993 m. Most space-saving for injection/extraction is a FODO cell structure as here the kick of one of the QDs in the straight sections can be exploited. In this lattice only two quadrupole families are used, one QF and one QD. Possible improvements, like the reduction of the vertical beta function and horizontal dispersion and more flexibility for the adjustment of the working point, are expected with more quadrupole families.

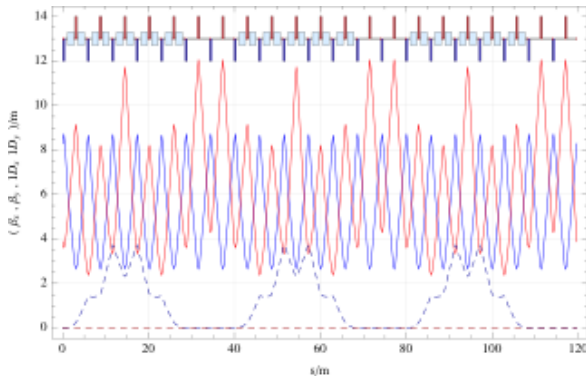


Figure 2: Optics functions around the lattice. The horizontal/vertical beta function is shown in blue/red, the horizontal/vertical dispersion in dashed blue/dashed red.

Injection, extraction as well as the RF system require dispersion free straight sections. The dispersion is suppressed by a phase advance of 2π per arc. Thus with only one QF family the dispersion cannot be fully suppressed in the case of working point adjustments, but stays small for small changes. A full suppression could be achieved by powering the quadrupoles next to the straight section individually. The complete lattice with a working point of $Q_H= 4.205$ and $Q_V= 3.572$ is shown in Figure 2. All lattice and optics parameters are listed in Table 1. The details of the lattice design are reported in [4].

Table 1: Design Parameters

Machine Parameter	Design Choice
Circumference	119.68 m
Number of cells	21
Number of cells per straight section	2
Length of straight section	4×2.35 m
Distance QF-Bend	0.65 m
Phase advance per cell (hor.)	72.1°
Phase advance per cell (vert.)	61.2°
Q_H	4.20505
Q_V	3.57156
Gamma transition	3.60
$\beta_{H,max}$	8.73 m
$\beta_{V,max}$	12.06 m
$D_{x,max}$	3.73 m

KEY ISSUES AND PROPOSED TECHNICAL SOLUTIONS

Magnets

Operating at a frequency of 10 Hz, it is envisaged that the main bending magnets will be able to achieve a field of up to 1.3 T. To achieve this field the magnets must be designed below saturation levels with special attention paid to the construction of the magnetic circuit. In particular it is proposed to use a relatively thin lamination of grain orientated high silicon content steel. The use of this steel with the grain orientation in direction of the majority of the magnetic flux will have the effect of narrowing the hysteresis cycle and increasing the electrical resistance, thus minimising the adverse dynamic effects to within acceptable levels (delay between current and field, field quality perturbation, iron losses etc...).

As per the main bending magnets, the quadrupole magnets will be constructed from a thin lamination of high silicon content grain orientated steel. Limiting the

pole tip field to approximately 0.8 T allows designing a magnet which operates below saturation.

RCS Injection and Extraction

The H- charge exchange injection system comprises a horizontal 4-magnet chicane bump, one magnet painting bump per plane and 3 stripping foils.

The injection system is a novel layout with a 2π chicane bump, housed in two empty FODO cells with a focusing quadrupole in the centre. The circulating proton beam is bumped with an angle across the horizontal axis to be merged with the incoming H- beam.

The extraction system is designed to extract beams with energies at 1.4 GeV and 2 GeV. The extraction is a fast bunch-to-bucket transfer with a kicker and septum system placed around a defocusing quadrupole. A 4 magnet extraction bump alleviates the kick requirements of the kicker and septa magnets by providing a horizontal displacement of 11 mm and an angle of 13 mrad at the septum entrance. The RCS injection and extraction are described in detail in [5].

RF System

The wide frequency range, the fast cycling and the limited available space in the straight sections, suggest the use of high-permeability materials and Finemet[®] is the magnetic alloy of choice because of the high value of its figure of merit, $\mu_p Q f$, which translates into limited losses and high accelerating gradients. In addition, its very low quality factor, Q , allows the entire frequency range to be covered without any tuning system which would, at the specified 10 Hz repetition rate, introduce a substantial additional complexity. Moreover, the wideband characteristic enables multi-harmonic operation. The details of the proposed RF system are reported in [6].

Main Power Converter

Considering the main bending magnets characteristics, two options have been evaluated in the frame of this study.

A resonant system also called a *white circuit* is often used in fast cycling accelerators with a repetition rate of 10 Hz to 50 Hz (ESRF, SRS, J-PARC...). This topology is highly cost effective but does not allow any freedom on the current waveform for operation.

A semiconductor based 4-quadrant converter with local capacitive energy storage as developed for the CERN PS is significantly more expensive but allows more freedom on the current waveform and is well known and understood at CERN.

Civil Engineering and Site

The proposed machine site is downstream of CERN's Linac4. The civil engineering consists of a tunnel (approx. 127 m long), situated 13 m below finished ground level, and a surface building (approx. 54 m long by 32 m wide).

The existing Linac4 tunnel will be modified to allow for connection to the new RCS. Figure 3 shows the proposed RCS site downstream of Linac4.

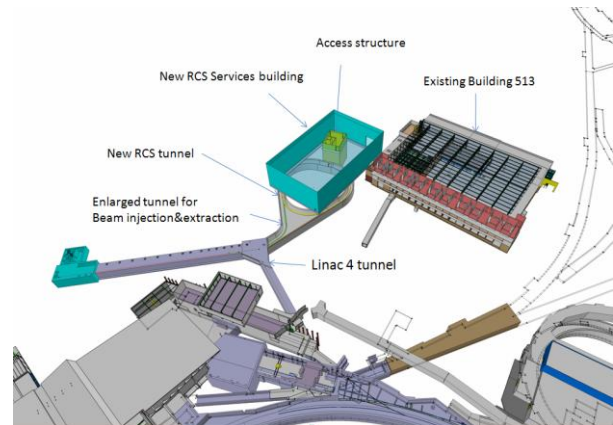


Figure 3: RCS and transfer tunnels.

TIME LINES

A first rough schedule indicates that the project could be completed within 6-7 years from project start if all resources required are made available.

SUMMARY

We conclude that there are no technical show stoppers to build the machine described in this report. We nevertheless note that a number of the proposed technical solutions is challenging.

The RCS would provide the same beam for the LHC as an upgraded PSB at 2 GeV with Linac4 as injector.

For AD and HIE-ISOLDE, advantages are expected with the RCS compared to the PSB at 2 GeV. For other non-LHC beams (mainly high-intensity beams), the effects of the reduced vertical aperture at PS injection and the 10 Hz pulsing of the PS injection kicker would require further study.

REFERENCES

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