ALTERNATIVE/COMPLEMENTARY POSSIBILITIES

C. Carli, M. Benedikt, H. Damerau, R. Garoby, B. Goddard, K. Hanke, S. Hancock, S. Gilardoni
CERN, Geneva, Switzerland

Abstract

Schemes aiming at increasing the brightness of LHC proton beams available from the PS complex by means alternative or complementary to the standard upgrade path defined after the 2010 Chamonix workshop, based on Linac4 and an upgrade of the PSB to PS transfer energy, are investigated. Compression of batches in the PS after acceleration to an appropriate intermediate energy allows increasing the beam brightness by reducing the length of the batch provided by the PS and thus distributing the available intensity to a smaller number of bunches. Furthermore a study of short Rapid Cycling Synchrotron (RCS) as new PS injector is proposed. The short circumference of one seventh of the PS is on the one hand suitable to reach high beam brightness required and for transfer to the PS. On the other hand the target kinetic energy of 2.0 GeV is a challenging goal.

INTRODUCTION

Present PS Scheme to generate LHC Bunch Trains

The procedure to generate LHC bunch trains in the PS, implemented about 10 years ago to avoid longitudinal microwave instabilities [1] during the initially envisaged debunching rebunching procedure at the flattop, is described in references [1,2,3].

Note that the only RF gymnastics applied are double and triple bunch splittings and transfers to higher harmonics RF systems ("rebucketing") for bunch compression. No harmonic number changes modifying the bunch spacing (without splitting), i.e., batch compression or batch extension, are applied. Hence, the harmonic number of the PS must be a multiple of 7 already at injection.

Furthermore, this scheme does not make optimum use of the available four Booster rings: With single batch PSB to PS transfer, only three instead of the available four Booster rings provide each one two bunches. The situation is similar for double batch transfer where only six out of possible eight $h_{PSB} = 1$ bunches are used. An attempt to use all four Booster rings without batch compression (or extension) is described in [2] for operation with Linac4. The next possible harmonic number of the PS containing the factor 7 at injection is $h_{PS} = 14$*. Three bunches per PSB ring and usage of all four rings allows filling twelve out of 14 PS buckets with one transfer. However, a practical implementation is difficult since (i) the generation of three about equal bunches per Booster ring with an appropriate spacing requiring to superpose three RF harmonics and (ii) the required recombination kicker rise times are not compatible with the existing hardware. Operating the PS with even larger harmonic numbers at injection is ruled out due to PS Booster ejection and recombination kicker limitations. Thus, generation of LHC bunch trains without batch compression or extension and making optimum use of the available four Booster rings seems not feasible without expensive upgrades.

Scenarios presented

The scenarios presented are alternative or complementary to the standard LHC proton injector upgrade path defined as a result of the 2010 Chamonix workshop, comprising Linac4, an increase of the Booster to PS transfer energy and upgrades of PS and SPS. In particular, the following two schemes were studied:

- Batch compression in the PS after acceleration to an appropriate intermediate energy: the starting point for this proposal is the observation that a more efficient use of the four Booster rings is incompatible with RF gymnastics in the PS without batch compression (or extension). Introduction of further batch compression steps after acceleration to an intermediate energy allows further increasing beam brightness. Finally, the total intensity is distributed over a smaller number of bunches provided per PS cycle and thus the beam brightness, is increased.
- Study of a short Rapid Cycling Synchrotron (RCS) as new PS injector: An RCS with a circumference of one seventh of the PS is suitable to fill the PS for the generation of LHC bunch trains (without batch extension or extension). Critical aspects are whether such a machine can reach the target kinetic energy of 2.0 GeV, and provide the required brightness with the 160 MeV Linac4 as injector. Preliminary investigations on such an RCS are reported.

BATCH COMPRESSION IN THE PS

Motivation

Attempts to optimize the usage of the four available Booster rings without batch compression (or extension) did not result in an attractive scheme [2]. Thus, schemes with batch compression [4], i.e. RF gymnastics where the harmonic number in the PS is increased in small steps such that empty buckets are inserted and the spacing between bunches is reduced without splitting, are proposed. Additional batch compression steps further increase the beam brightness available from the PS:

---

[*] Filling four out h_{PS}=7 PS buckets with one single transfer from the Booster, as proposed in another context [4], is ruled out here since the number of bunches is strongly reduced. Note that one of batch compression schemes described yields the same number of bunches per PS batch, but with significantly increased brightness.

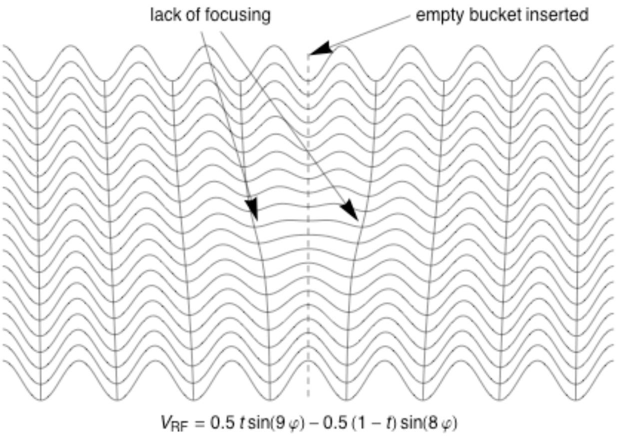
- At injection, as much of the PS circumference as possible is filled with beam to maximize the total intensity for given transverse emittances (most favourable bunching factor).
- After acceleration to an appropriate intermediate energy to reduce direct space charge effects, batch compression is applied to concentrate the available intensity in a fraction of the PS circumference. Hence, LHC bunch trains generated by the PS become shorter and the available intensity is distributed over a smaller number of bunches. The beam brightness is increased.

Even though batch compression schemes can be combined with a Booster energy upgrade, the working hypothesis underlying the schemes presented here is that the beam will be injected into the PS at 1.4 GeV. Eight bunches are injected into the PS to bring the machine close to the transverse direct space charge limit. For operation with Linac2, this is achieved by two PSB batches with one bunch generated per ring. With Linac4 one Booster to PS transfer with two bunches generated per ring will be sufficient[†].

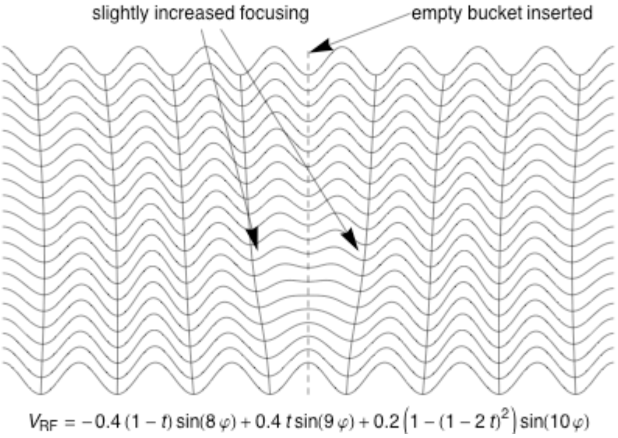
The batch compression schemes presented generate LHC bunch trains with 25 ns spacing. With 50 ns bunch spacings higher intensities (by a factor, which may be smaller than two) per bunch within the same transverse emittances are expected.

General Remarks on Batch Compression

The most favourable bunching factor is achieved by injecting the eight bunches into $h_{PS} = 8$ buckets. However, this is somewhat conflicting with the conditions for efficient batch compression working well with (i) a partially filled machine and (ii) for low harmonic numbers[‡]. The reason is visible in Fig. 1 showing the RF potential during the transition from a harmonic number 8 to 9 to insert an empty bucket at the center. A beating phenomenon is visible in the upper image of Fig. 1 showing the direct transition from $h_{PS} = 8$ (ramped down linearly) to $h_{PS} = 9$ (ramped up linearly) without additional RF components. Longitudinal focusing around stable phases close to location, where the additional empty bucket is inserted, and thus longitudinal acceptance is significantly reduced. The situation can be somewhat improved with the help of an additional RF component as shown in the lower image of Fig. 1 with an additional $h_{PS} = 10$ component. Even thought the batch compression step from $h_{PS} = 8$ to $h_{PS} = 9$ is part of the simulations presented below, feasibility still has to be proven experimantally. Note that the next batch compression step from $h_{PS} = 9$ to $h_{PS} = 10$ is an issue as well due to this beating phenomenon.



Without additional harmonics



With h_{PS}=10 component

Figure 1: Time evolution (mountain range) of the RF potential during batch compression from $h_{PS} = 8$ to $h_{PS} = 9$ with and without additional $h_{PS} = 10$ component.

A Batch Compression Scheme yielding 64 LHC Bunches spaced by 25 ns per PS Cycle

The low energy part of a batch compression scheme yielding 64 bunches spaced by 25 ns per PS cycle is sketched in Fig. 2. Eight bunches are injected into the PS. Injection and first acceleration takes place with harmonic $h_{PS} = 8$ if feasible or with $h_{PS} = 9$. After acceleration to an intermediate plateau, one or two batch compression steps yield eight bunches with $h_{PS} = 10$. Afterwards the bunches are split resulting in 16 bunches at $h_{PS} = 20$. After a final batch compression step the required harmonic number $h_{PS} = 21$ is reached and the beam is accelerated to the flattop. After two more double splitting steps, 64 bunches with 25 ns spacing are obtained (smaller longitudinal emittances and one double splitting step less would yield 32 bunches spaced by 50 ns). With this scheme, each bunch injected into the PS is split into eight bunches for LHC, whereas with the present production procedure each injected bunch is split into 12 bunches. Assuming that the intensity per injected bunch will be similar to present operation and possible limitations other than transverse

---

[†] If the PS is operated with a harmonic number different from $h_{PS} = 8$, the spacing between the two bunches from one Booster ring are adjusted by an additional first harmonic RF component in the Booster.

[‡] From this point of view and for single batch PSB to PS transfer, (with Linac4) filling four $h_{PS} = 4$ buckets is attractive. This option has been ruled out since the RF frequencies required are not possible with the present PS RF system.

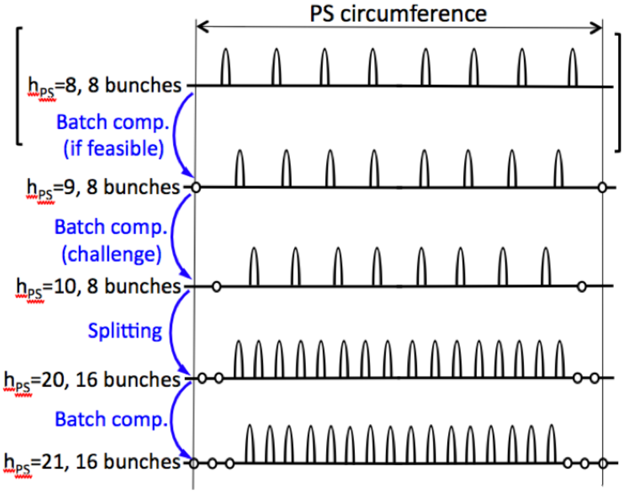


Figure 2: Low energy part of RF gymnastics for a batch compression scheme yielding 64 LHC bunches spaced by 25 ns per PS cycle.

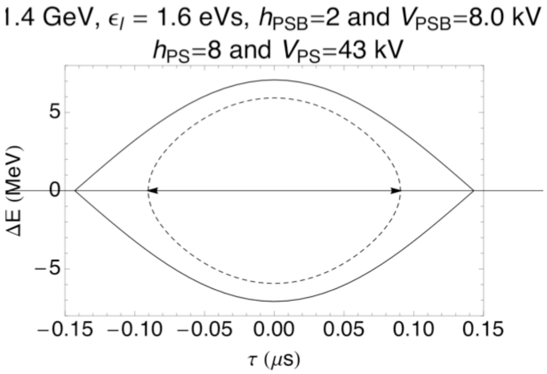


Figure 3: RF buckets occupied by a 1.6 eVs beam at PSB to PS transfer at 1.4 GeV.

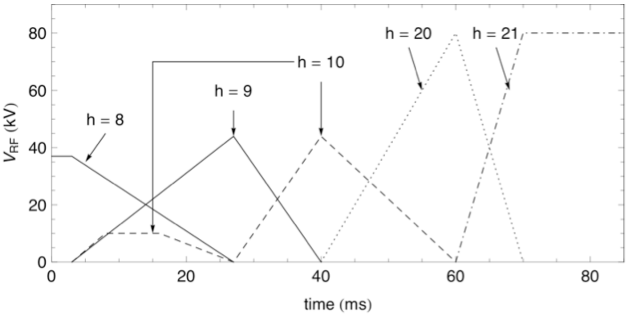


Figure 4: Time evolution of RF voltages for the simulation of the batch compression scheme yielding 64 LHC 25 ns bunches per PS cycle.

direct space charge effects can be solved, one expects a beam brightness increase by a factor 1.5 with respect to the present case An extrapolation from the initial PS design for LHC [6] with later adaptations [1], yields 2.23 10^{11} protons per LHC bunch within 2.5 μm emittances (rms, normalized) at PS injection (the brightness available for the LHC will be lower due to blow-up and losses along the chain)[§].

Assuming a longitudinal emittance of 0.35 eVs per LHC bunch at PS ejection and allowing for blow-up by a factor 1.75, the longitudinal emittance per injected bunch (corresponding to 8 LHC bunches) has to be 1.6 eVs (total). RF Buckets and areas occupied by a beam with 1.6 eVs at transfer shown in Fig. 3 require RF voltages, which appear reasonable in both machines. Acceleration of beams with low harmonic numbers and small longitudinal emittance may imply a temporary increase of the direct space charge tune shift caused by shorter bunches. With a slowed down acceleration to 2.5 GeV and RF voltages extrapolated from the present ones, small temporary increase of the direct space charge tune shift by about 10% has been obtained.

ESME [8] simulations of the gymnastics sketched in Fig. 2 at a 2.5 GeV intermediate plateau have been carried out with the evolution of RF voltages plotted in Fig. 4. Phase space plots for half of the PS circumference, with the center of the batch at the very right, obtained during the simulations are shown in Fig. 5. Even though the time evolutions assumed could be further optimized, the result looks promising with a few perturbations visible on the outer bunches due to non-adiabatic effects and possible temporary reduction of the bucket area.

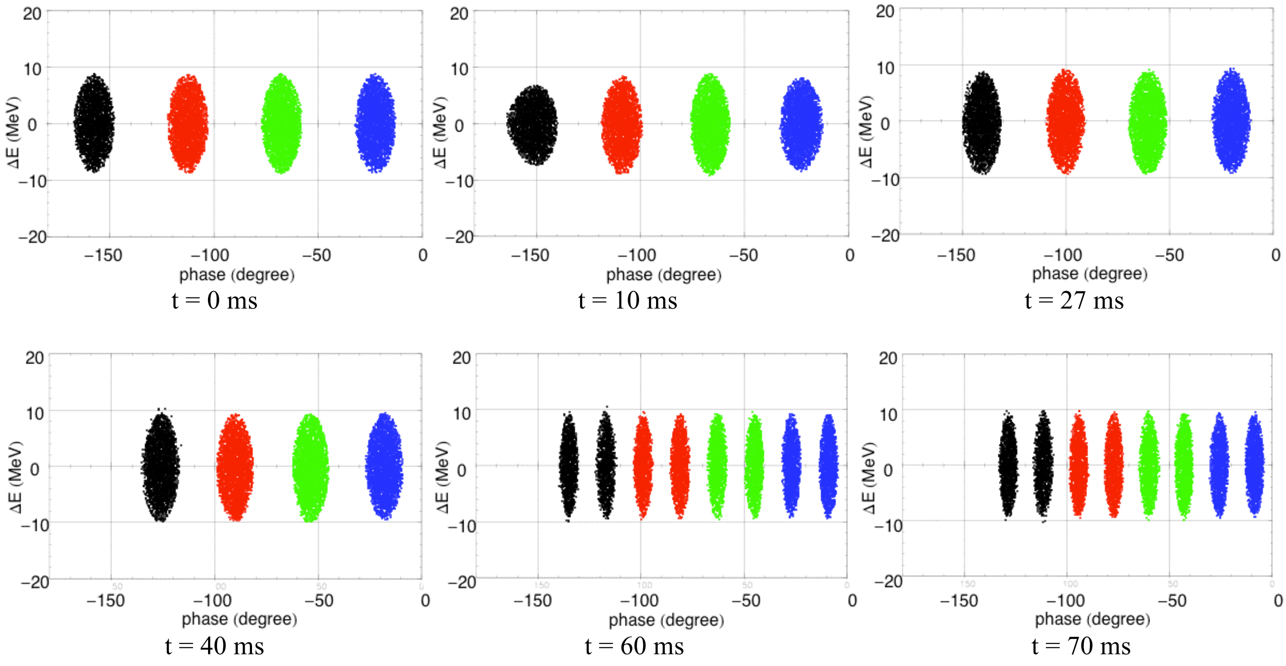
LHC filling with PS batches containing 64 bunches with 25 ns spacing, instead of 72 with the present scheme, has been investigated. A scheme accumulating up four PS batches in the SPS allows injecting 2688 bunches with 25 ns spacing per LHC ring, i.e. about 4% less than with the present nominal filling scheme.

A Batch Compression Scheme yielding 48 LHC Bunches spaced by 25 ns per PS Cycle

The low energy part of a scheme with more compression steps to further increase the beam brightness and yielding 48 bunches spaced by 25 ns per PS cycle is sketched in Fig. 6. Again, eight bunches are injected into the PS. Injection and first acceleration takes place with harmonic $h_{PS} = 8$ if feasible, or with $h_{PS} = 9$. After acceleration to an intermediate plateau, five or six batch compression steps yield eight bunches at $h_{PS} = 14$. Afterwards a special RF gymnastics extrapolated from triple splitting [1] is applied to transform two bunches into three bunches. The procedure can be interpreted as a combination of an incomplete bunch recombination followed by triple splitting. However, both for triple splitting and this procedure transforming two bunches into three, at some moment (at time 90 ms in Fig. 8) the ratio between the three RF components ($h_{PS} = 7$, 14 and

---

[§] This estimates looks somewhat optimistic given present operational experience from the 2010 run [3], but allows comparison with a similar scaling to estimate the intensity of 2.77 10^{11} protons per LHC bunch possible with a Booster energy upgrade to 2 GeV [7]. Note however that the scenario with batch compression does not require double batch PS filling and, thus, the beam stays only for a short duration at injection energy.



t = 0 ms

t = 10 ms

t = 27 ms

t = 40 ms

t = 60 ms

t = 70 ms

Figure 5: Longitudinal phase space plots obtained in ESME simulations during the batch compression process for the generation of 64 LHC 25 ns bunches per PS cycle.

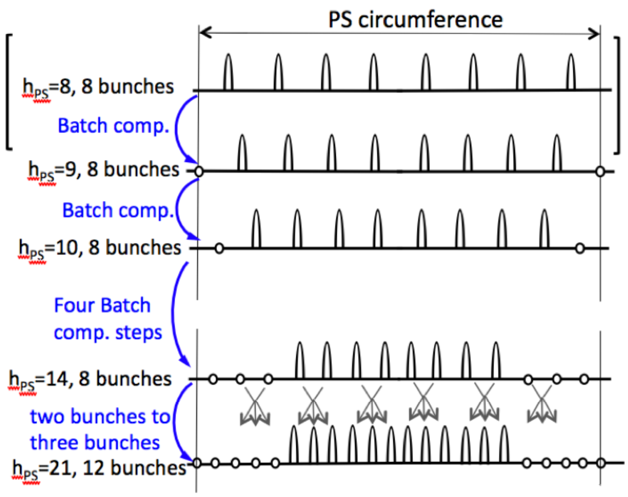


Figure 6: Low energy part of RF gymnastics for a batch compression scheme yielding 48 LHC bunches spaced by 25 ns per PS cycle.

21) involved has to take on values such that three small buckets form within the large bucket. The complexity of the process is not significantly larger than triple splitting, if the starting point is two bunches at $h_{PS} = 14$. Twelve bunches in $h_{PS} = 21$ buckets are accelerated to the flattop. After two more double splitting steps, 48 bunches with 25 ns spacing are obtained (smaller longitudinal emittances and one double splitting step would give 24 buches spaced by 50 ns).

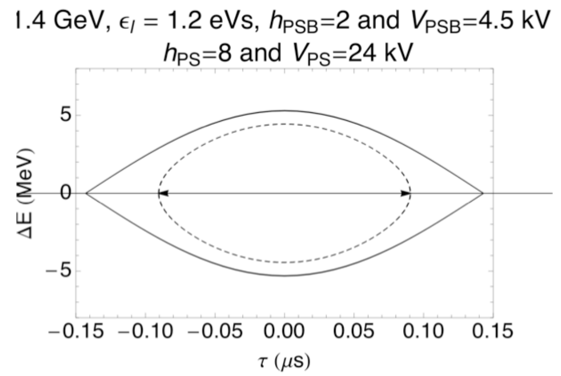


Figure 7: RF buckets and are occupied by a 1.2 eVs beam at PSB to PS transfer at 1.4 GeV.

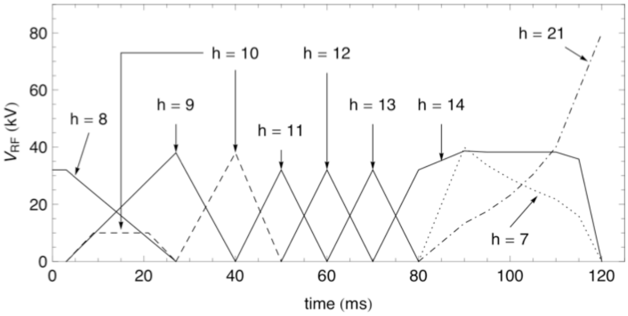
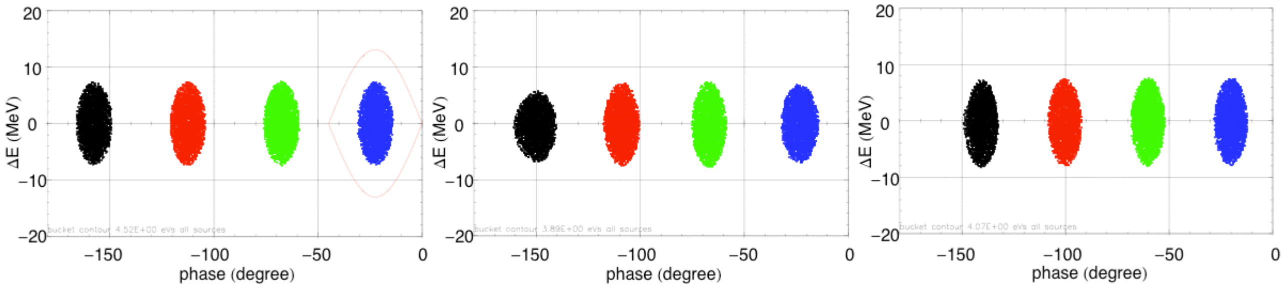
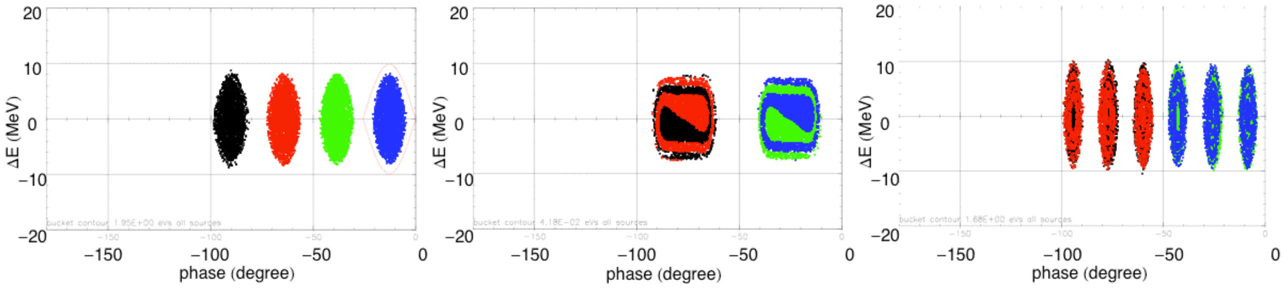


Figure 8: Time evolution of RF voltages for the simulation of the batch compression scheme yielding 48 LHC 25 ns bunches per PS cycle.



t = 0 ms t = 10 ms t = 27 ms



t = 40 ms t = 90 ms t = 120 ms

Figure 9: Longitudinal phase space plots obtained in ESME simulations during the batch compression process for the generation of 48 LHC 25 ns bunches per PS cycle.

With this scheme, each bunch injected into the PS is split into six bunches for LHC, whereas with the present production procedure each injected bunch yields 12 bunches. One may therefore expect a beam brightness increase by a factor 2.0 with respect to the present case and 3.0 10^{11} protons per LHC bunch within 2.5 μm emittances at PS injection (the brightness available for the LHC will be lower due to blow-up and losses along the chain).

Assuming a longitudinal emittance of 0.35 eVs per LHC bunch at ejection and allowing for blow-up by a factor 1.75, the longitudinal emittance per bunch at injection has to be 1.2 eVs. RF Buckets occupied by bunches with 1.2 eVs shown in Fig. 7 require RF voltages, which are somewhat lower in both machines than for other standard operations.

ESME [8] simulations of the gymnastics sketched in Fig. 6 at a 2.5 GeV intermediate plateau have been carried out with the evolution of RF voltages plotted in Fig. 8. Phase space plots obtained with these simulations are shown in Fig. 9. Even though the ESME simulation results of the procedure look very promising, setting up with beam might be tedious and delicate due to the complexity of the RF gymnastics required.

LHC filling with PS batches containing 48 bunches with 25 ns spacing has already been worked out in another context and documented in reference [5]. A scheme accumulating up five PS batches in the SPS allows injecting 2592 bunches with 25 ns spacing per LHC ring, i.e. about 8% less than with the present nominal filing scheme.

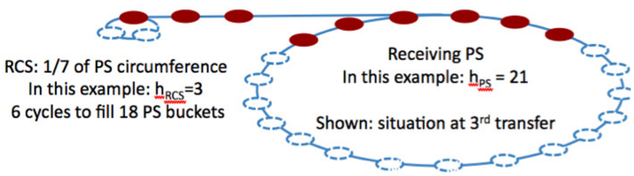
RAPID CYCLING SYNCHROTRON

A short Rapid Cycling Synchrotron proposed as new PS injector is sketched in Fig. 10 and main parameters are given Tab. 1. The motivations and implications of a circumference of only one seventh of the PS are :

- For the generation of LHC beams with 25 ns or 50 ns spacing, it is natural to generate the structure needed for acceleration without complex RF gymnastics by operating such an RCS with harmonic number $h_{RCS} = 3$ and to fill 18 out of $h_{PS} = 21$ buckets with six transfers (see sketch in Fig. 10). Fast RCS ejection and PS injection kickers are required on the other hand to allow this simplification of the RF gymnastics in the PS. The natural choice for the generation of LHC 75 ns beams is to operate the PS with $h_{PS} = 14$ and to fill 12 buckets with 6 transfers from the RCS running with $h_{RCS} = 2$.
- The short circumference is suitable to obtain high brightness beams with low injection energies. Still with the 160 MeV beam from Linac4, the target beam brilliance and the transfer schemes described above, the beam experiences direct space tune shifts larger than $\Delta Q = -0.5$ for a short duration.
- It may be a challenge to reach the target ejection energy $E_{kin} = 2.0$ GeV[**]. To this end, both the bending magnet filling factor and the maximum magnetic field need to be maximized.

[**] A study [9] presented at the 2010 Chamonix workshop ruled out such a short RCS since, at that time, the target transfer energy and beam brightness was even higher.

- An attractive location for the RCS, which requires only short transfer lines, is the inside of the PS ring as sketched in Fig. 1 (the location has to be refined taking PS infrastructure and transfer lines into account).



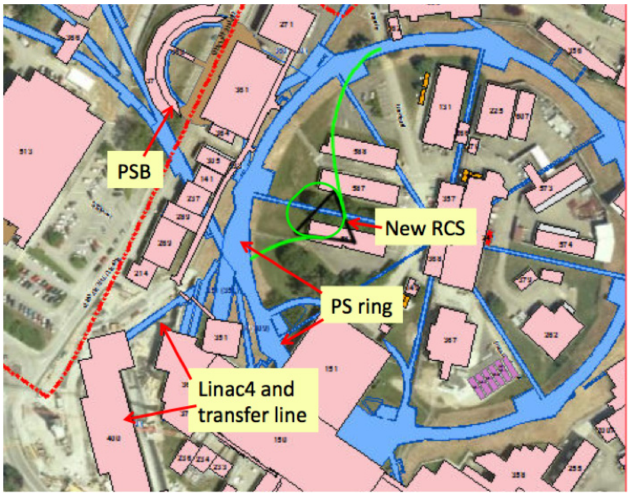


Figure 10: Short rapid cycling synchrotron

Table 1: Main parameter of an RCS

Energy range	160 MeV to 2 GeV
Circumference	(200/7) π m ≈ 89.76 m
Repetition rate	~10 Hz
RF voltage	60 kV
Harmonics	h = 2 or 3
Frequency range	3.48 MHz (h=2 at injection) to 9.5 MHz (h=3 at ejection)
Beam param's for LHC[††] (for lower emittances scale down intensity accordingly)	Intensity: $\leq 12\times2.7\ 10^{11}$ p/cycle Transv. emittance: $\varepsilon^*_{rms} \approx 2.5$ μm Long. em.: $\varepsilon_l < 4\times0.27$ eVs/bunch for 25 ns beams (in practice determined by RCS acceptance)
Lattice	FODO with 15 cells and 3 periods, 4 cells in arc, straight with one cell
Tunes	$4 < Q_{H,V} < 5$
Rel. gamma at transition	~4
Bending magnet filling	56 % (probably optimistic)
Maximum magnetic field	1.16 T (likely to increase)

Magnetic Cycle and Direct Space Charge Tune Shift

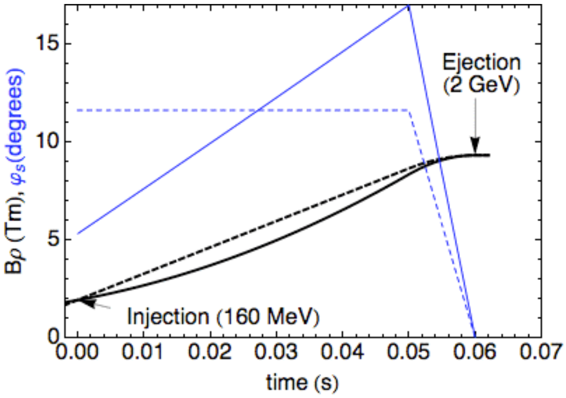


Figure 11: Magnetic cycles (thick curves) and synchronous phases (thin curves) for two ramps assumed for an RCS.

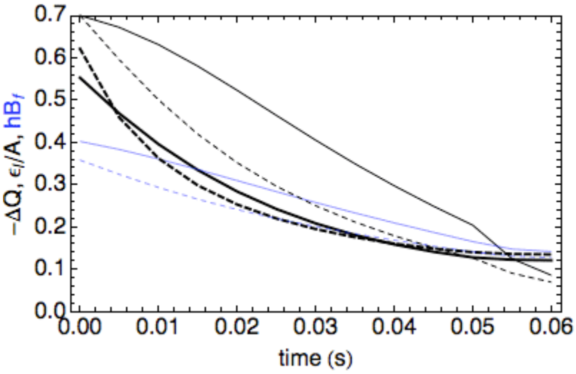


Figure 12: Direct space charge tune shift (thick black lines), ratio between longitudinal acceptance (thin black curves) and bunching factor (thin blue or grey curves) for the two cycles shown in Fig. 11.

For first rough investigations, two magnetic cycles for acceleration within 60 ms (educated guess for 10 Hz repetition rate) have been assumed and are plotted together with resulting synchronous phases in Fig 11: (i) a linear ramp with a 10 ms rounding before the arrival at the flat top (dashed curves) and (ii) a combination of two parabolic pieces to slow down the ramp at injection in order to improve the bunching factor at low energy and, in turn, the maximum direct space charge tune shift (solid curves)[‡‡]. Direct space tune shift have been estimated: (i) adjusting the longitudinal emittance to 70% of the acceptance[§§] at the beginning of the ramp, (ii) transverse emittance and intensity given in Tab. 1 and (iii) estimating the bunching factor from the height of the area occupied by the beam. Direct space charge tune shifts,

---

[††] Parameters expected with Linac4 and a PSB 2 GeV upgrade scaling from the initial proposal from the beginning of the 1990ies to prepare the PS complex for LHC [5].

[‡‡] These magnetic cycles have been used to obtain first estimates. For a thorough study, possible waveforms must be adjusted to the technical limitations of power supplies (and possibly magnets).

[§§] For operation of the RCS with harmonic numbers h_{RCS} = 3 and the generation of 25 ns or 50 ns LHC trains, this procedure yields emittances smaller than the maximum in Tab. 1. For h_{RCS} = 2 and 75 ns trains, the longitudinal emittance obtained is slightly too large for the magnetic cycle with smaller ramp at the after injection.

bucket filling factors (ratio between the longitudinal emittance and acceptance) and bunching factors are shown in Fig. 12.

First Ideas on the Lattice

A large bending magnet filling factor is required to reach the target energy with the short fixed circumference of the RCS. Thus, a FODO lattice being an efficient focusing structure has been chosen. Low periodicity three with three arcs and three straight sections allows reducing the total length of the straight sections. Straight sections are dedicated to injection, ejection and RF systems. The relativistic gamma factor γ_{tr} at transition must be above the one at ejection $\gamma_{ej} = 3.13$ but on the other hand must not be too large to keep the total number of cells reasonable. This is obtained by choosing a horizontal tune Q_H between 4 and 5. The lattice proposed consists of a total of 15 FODO cells implying still a large phase advance per cell. Arcs have a length of 4 cells and straight sections one cell. Lattice functions are shown in Fig, 13.

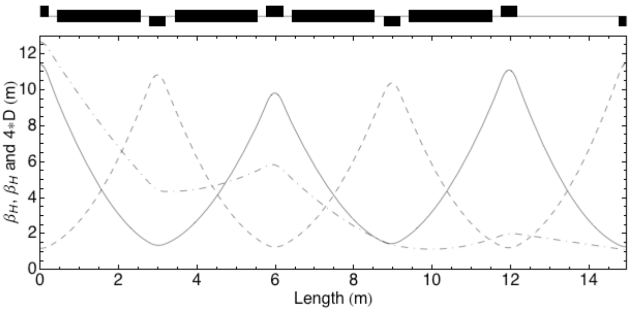


Fig 13: Lattice functions for one half cell extending from the center of the arc to the center of the straight section. Solid, dashed and dot-dashed lines denote the horizontal betatron function, the vertical betatron function and the dispersion.

Since in the arc space has to be made available for correction magnets, possibly instrumentation and other equipment, the bending magnet filling factor of 56% should be considered an optimistic upper limit of what can be achieved. Thus, the maximum bending field of 1.16 T is a lower limit for the one required to reach 2 GeV. A thorough design, allocating sufficient space for all equipments required, is needed for a more realistic estimate.

After a first preliminary study, injection and ejection look challenging, but feasible.

CONCLUSIONS

Batch compression schemes in the PS are a promising option to increase the brightness in the PS without expensive hardware modifications, but require significant manpower to set up the RF gymnastics and to upgrade the beam control system. In particular, the scheme yielding 64 bunches per PS cycle is based on RF gymnastics with a complexity comparable to the present scheme in the PS. Machine experiments are planned for the 2011 run.

First basic parameters of a short RCS to replace the PS Booster have been given. Such a machine looks challenging, but not impossible. A thorough study, comprising in particular investigations on all critical subsystems and on beam dynamics with direct space charge tune shifts exceeding -0.5, is required to clarify technical feasibility and whether an RCS is an attractive option competitive with a Booster 2 GeV upgrade in terms of cost. Advantages of this approach are that a new machine allows for a modern design, good reliability and construction and running-in in parallel with operation of the complex with the existing Booster.

REFERENCES

[1] R. Garoby, Status of the nominal Proton Beam for LHC in the PS, Proceedings of the IXth Chamonix workshop on SPS & LEP performance, (1999).

[2] M. Benedikt, P. Collier, V. Mertens, J. Poole, K. Schindl (editors), Chapter 7 of LHC Design Report, Vol. III, CERN-2004-003-V-3.

[3] R. Steerenberg, Performance reach of the injectors in 2011, these Proceedings.

[4] R. Garoby, New RF Exercises Envisaged in the CERN-PS for the Antiprotons Production Beam of the ACOL Machine, Proceedings of PAC85.

[5] G. Arduini, W. Herr, E. Metral, T. Pieloni, , LHC Project Note 401.

[6] R. Cappi, R. Garoby, S. Hancock, M. Martini, J.P. Riunaud, Measurement and Reduction of Transverse Emittance Blow-up Induced by Space Charge Effects, Proceedings of Particle Accelerator Conference 1993.

[7] G. Arduini, J. Borburgh, J. Burnet, C. Carli, M. Chanel, J. Cravero, H. Damerau, T. Fowler, S. Gilardoni, M. Giovannozzi, S. Hancock, E. Metral, A. Newborough, S. Pittet, L. Sermeus, R. Steerenberg, D. Tommasini, M. Vretenar, Possible improvements to the existing pre-injector complex in the framework of continued consolidation, Proceedings of the Chamonix 2010 workshop.

[8] J. MacLachlan and F. Ostiguy, ESME program, http://www-ap.fnal.gov/ESME/ or
J. MacLachlan, Particle Tracking in E-Phi Space for Synchrotron Design & Diagnosis, Proceedings of the 12th Conf. on Applications of Accelerators in Research and Industry and Fermilab-CONF-92/333 (Nov. 92).

[9] C.Carli, Other scenarios for a partial upgrade of the injector complex, Proceedings of the Chamonix 2010 workshop.