Alternative/complementary Possibilities

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

- Introduction
  - Present PS scheme for nominal LHC bunch trains
  - Alternative/complementary Scenarios
- Batch Compression schemes in the PS
  - Filling 8 out $h_{PS}=8$ or $h_{PS}=9$ PS buckets?
  - Compression to $h_{PS}=10$ and generation of 64 bunches
  - Compression to $h_{PS}=14$ and generation of 48 bunches
- RCS as new PS Injector
- Summary and Outlook
Introduction
PS scheme for LHC bunch trains

- Present PS scheme (end of the 1990ies)
  - Acceleration to flat-top with $h_{PS}=21$
  - One or two double splitting at flat-top for 50 ns or 25 ns trains
  - No debunching/rebunching at flat-top (to avoid instabilities)
- (75 ns LHC beams with double splitting injection energy, $h_{PS}=14$ acceleration)
- Scheme to use all four Booster rings (and single PSB to PS transfer) without batch compression or extension
  - Factor 7 in PS harmonic at injection
  - Proposed (R.Garoby and M.Benedikt):
    - Three bunches per PSB ring fill 12 out of $h_{PS}=14$ PS buckets
    - Implementation difficult:
      1. Short kicker rise times and
      2. Generation of three bunches in the PSB with unequal spacing

PS circumference

$h_{PS}=7$, 6 bunches (single or double batch injection)

$h_{PS}=21$, 18 bunches

RF gymnastics at injection energy for 25 ns and 50 ns LHC bunch trains
Introduction
Alternative/complementary Scenarios

- Scenarios presented here:
  - Alternative/complementary to extrapolation of present scheme to higher brightness using Linac4 and PSB 2 GeV upgrade
  - Batch compression in the PS to increase brightness after acceleration to a suitable energy
    - Abandon factor 7 in PS harmonics to (i) use all four PSB rings (with single batch transfer) and (ii) use batch compression to increase brightness
    - Fill as much as possible of the PS circumference at injection
    - Batch compression after first acceleration to an appropriate energy
    - Reduced number of bunches per PS cycle -> Higher intensity per bunch and, thus, brightness
  - Short Rapid Cycling Synchrotron (RCS) as new PS injector

- General considerations
  - Transverse direct space charge effects assumed the dominant limitation
  - Possible brightness scaled from 1993 design for LHC beams in PS
    - No gains assumed (conservatively) from single batch PS filling (short flat bottom)
  - Intensity estimates per LHC 25 ns bunch, 2.5 μm transverse rms emittance out of PSB
    - Smaller emittance beams with intensities reduced by the same factor
    - For LHC 50 ns beams, larger intensities possible (by a factor probably <2!)
Batch Compression Schemes in the PS
Insertion of an empty bucket with fully filled $h_{PS}=8$ PS

- Batch compression (or extension) works well:
  - With a partially filled machine (conflicts with aim to fill most of circumference at injection)
  - Low harmonic numbers reducing number of harmonic number changes (aspect in favor of $h_{PS}=4$ or $h_{PS}=5$. . . discarded due to large acceptances and low frequencies)

- Is $h_{PS}=8$ to $h_{PS}=9$ compression with eight bunches feasible?!
  - Simulation presented later with $h_{PS}=10$ component to (slightly) allow/facilitate this process
  - RF potential around PS circumference (mountain range of time evolution)

Lack of long. focusing due to beating (slightly) reduced with $h_{PS}=10$

Pure transition from $h_{PS}=8$ to $h_{PS}=9$

Additional $h_{PS}=10$ (20%) component

$$V_{RF} = 0.5 t \sin(9 \varphi) - 0.5 (1 - t) \sin(8 \varphi)$$

$$V_{RF} = -0.4 (1 - t) \sin(8 \varphi) + 0.4 t \sin(9 \varphi) + 0.2 \left(1 - (1 - 2t)^2\right) \sin(10 \varphi)$$
Batch Compression Schemes in the PS
Compression to $h_{PS} = 10$ and generation of 64 bunches

- Injection and first acceleration with $h_{PS} = 8$ or $h_{PS} = 9$
- Potential brightness increase: $12/8 = 1.50^*$
  - Corresponds to PSB upgrade: 1.4 GeV to 1.77 GeV
  - Brightness per bunch for 25 ns trains out of PSB
    - $\varepsilon^* = 2.5 \, \mu m$ and $2.23 \times 10^{11}$ or
    - $\varepsilon^* = 1.90 \, \mu m$ and $1.7 \times 10^{11}$

- Estimate of longitudinal parameters at injection for 25 ns trains
  - Every bunch split into 8 LHC bunches with 0.35 eVs
  - 1.6 eVs per injected bunch allows a factor 1.75 blow-up

*) With $h_{PS} = 8$ at injection, compared to present situation with Linac2 and double batch PSB to PS transfer

With $h_{PS} = 8$ at injection, compared to present situation with Linac2 and double batch PSB to PS transfer
Animation combining phase space plots from ESME simulations

- Showing half the PS circumference between -180° and 0°
- Voltages adjusted to keep sufficient acceptance (no parasitic bunches in simulation)
- No space charge
- $E_{\text{kin}} = 2.5$ GeV (working hypothesis with 1.4 GeV injection)
Batch Compression Schemes in the PS
Compression to $h_{PS} = 10$ and generation of 64 bunches

- Buckets and bunches at injection (neglecting direct space charge)
  - RF voltages in PSB and PS adjusted
    - for longest possible bunches and
    - matching between machines
      (low RF voltages an issue?)

- Acceleration in PS
  from 1.4 GeV to 2.5 GeV plateau
  - Acceleration slowed down to keep longer bunches
Batch Compression Schemes in the PS
Compression to $h_{PS} = 10$ and generation of 64 bunches

LHC Filling pattern for 64 bunches per PS cycle

- Accumulation of (up to) four PS cycles in SPS
- Number of bunches per LHC reduced by ~4% from 2808 to 2688
- More “PACMAN” bunches
Batch Compression Schemes in the PS
Compression to $h_{\text{PS}} = 14$ and generation of 48 bunches

- Potential brightness increase: $12/6 = 2^*$
  - Corresponds to PSB upgrade: 1.4 GeV to 2.22 GeV
  - Intensity per bunch for 25 ns trains and 2.5 μm: $3.0 \times 10^{11}$

- Estimate of longitudinal parameters at injection for 25 ns trains
  - Every bunch split into 6 LHC bunches with 0.35 eVs
  - 1.2 eVs per injected bunch allows a factor 1.75 blow-up

*With $h_{\text{PS}}=8$ at injection, compared to present situation with Linac2 and double batch PSB to PS transfer

RF gymnastics at an appropriate intermediate energy (hypothesis 2.5 GeV)
(Injection and first acceleration with $h_{\text{PS}}=8$ or $h_{\text{PS}}=9$)
Batch Compression Schemes in the PS
Compression to $h_{PS} = 14$ and generation of 48 bunches

Animation combining phase space plots from ESME simulations

- Showing half the PS circumference between $-180^\circ$ and $0^\circ$
- Voltages adjusted to keep sufficient acceptance (no parasitic bunches in simulation)
- No space charge
Batch Compression Schemes in the PS
Compression to $h_{PS} = 14$ and generation of 48 bunches

- Buckets and bunches at injection (neglecting direct space charge)
  - RF voltages in PSB and PS adjusted
    - for longest possible bunches and
    - matching between machines (low RF voltages an issue?)

- Acceleration in PS
  from 1.4 GeV to 2.5 GeV plateau
  - Acceleration slowed down to keep longer bunches
Batch Compression Schemes in the PS
Compression to $h_{PS} = 14$ and generation of 48 bunches

LHC filling for 48 bunches per PS cycle already worked out in
LHC Project Note 401 (G. Arduini, W. Herr, E. Metral, T. Pieloni)

- Accumulation of (up to) five PS cycles in SPS
- Number of bunches per LHC reduced by ~8% from 2808 to 2592
- More “PACMAN” bunches

\[
\begin{align*}
\Delta t_1 & \quad 9 \quad \text{bunches missing} \\
\Delta t_2 & \quad 40 \quad \text{bunches missing} \\
\Delta t_3 & \quad 154 \quad \text{bunches missing}
\end{align*}
\]

Total number of bunches: 2592

\[
\begin{align*}
&
\{[(48b + 9e) \times 2 + 31e] \times 1 + [(48b + 9e) \times 5 + 31e] \times 2\} \\
+ &
\{[(48b + 9e) \times 4 + 31e] \times 1 + [(48b + 9e) \times 5 + 31e] \times 2\} \times 3 \\
+ &
\{114e\} = 3564
\end{align*}
\]
Short RCS as new PS Injector

RCS: 1/7 of PS circumference
In this example: $h_{RCS}=3$
6 cycles to fill 18 PS buckets

- Challenge to reach target kin. energy 2 GeV
- High brightness for given injection energy (for harmonic number $h_{RCS} > 1$):
  - $h_{RCS} = 3$ to fill 18 out of $h_{PS} = 21$ buckets (short kicker gaps) or
  - $h_{RCS} = 2$ to fill 12 out of $h_{PS} = 14$ buckets
- Rep. rate ≈10 Hz (required for Linac4 as well)

(RCS with circumference 4/21 or 3/14 times the PS might be of interest)
Short RCS as new PS Injector

Magnetic cycles assumed
- Solid: Injection with half the average dB/dt, two pieces of parabolas joining at $t = 0.05$ s
- Dashed: constant dB/dt except rounding during last 10 ms
- Synchronous angles for $V_{RF} = 60$ kV and circumference 1/7 of the PS

Direct space charge tune shift along ramp
- Long. emittance adjusted to fill 70% of bucket
  - Compatible with maximum long. emittances
- $\epsilon_{rms}^* = 2.5 \mu$m and $2.7 \times 10^{11}$ per LHC 25 ns bunch
- With constant RF voltage along cycle
  - Estimation of height of phase space area occupied by beam used for
  - Estimation of bunching factor and tune shift

- If tune shifts too large for schemes with six transfers
  - Switch to $h_{RCS} = 1$ and $h_{PS} = 14$ with 12 transfers

Longitudinal matching at transfer to be studied

Time evolution of tune shift (black), bunching factor blue and bucket filling (red).
Short RCS as new PS Injector

- First investigations on lattice
  - Periodicity three
    - Straight sections for injection, RF and ejection
  - FODO lattice with 15 cells for efficient focusing
    - Large bending magnet filling factor (~56%)
  - Tunes around or a bit larger than 4 for suitable transition energy
    - With injection working point of present PSB
      - up to ~110° phase advance per cell
      - ... effect on space charge limit?

- Result
  - Working point of PSB at injection
    - $\gamma_{\text{transition}} = 3.61$
  - 2.1 m long bends
    - Field at 2 GeV: 1.16 T
  - 0.4 m long quads with $|k| \sim 1.4$ m$^{-2}$
    - quads with ~ 1 T at $r = 75$ mm
  - 25 cm between quads and bends
  - 2.6 m between quads in straights

- Injection/ejection look feasible ... still challenging (preliminary study by B.Goddard)

Lattice functions for one half-period: solid line denotes $\beta_H$, dashed one $\beta_V$ and dot-dashed one 4*D
### Tentative list of main RCS parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy range</td>
<td>160 MeV to 2 GeV</td>
</tr>
<tr>
<td>Circumference</td>
<td>$(200/7) \pi \text{ m} \approx 89.76 \text{ m}$</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>~10 Hz</td>
</tr>
<tr>
<td>RF voltage</td>
<td>60 kV</td>
</tr>
<tr>
<td>Harmonics</td>
<td>$h = 2$ or $3$</td>
</tr>
<tr>
<td>Frequency range</td>
<td>3.48 MHz ($h=2$ at injection) to 9.5 MHz ($h=3$ at ejection)</td>
</tr>
<tr>
<td>Beam parameters for LHC</td>
<td>Intensity: up to $12 \times 2.7 \times 10^{11}$ protons/cycle</td>
</tr>
<tr>
<td>(for lower emittances scale down intensity</td>
<td>Transv. emittance: $\varepsilon^*_{\text{rms}} \approx 2.5 \mu\text{m}$</td>
</tr>
<tr>
<td>accordingly)</td>
<td>Long. emittance: $\varepsilon_i &lt; 12 \times 0.27$ eVs (determined by acceptance for most cases)</td>
</tr>
<tr>
<td>Lattice</td>
<td>FODO with 15 cells and 3 periods, 4 cells in arc, straight with one cell</td>
</tr>
<tr>
<td>Tunes</td>
<td>$4 &lt; Q_{H,V} &lt; 5$</td>
</tr>
<tr>
<td>Relativistic gamma at transition</td>
<td>~4</td>
</tr>
<tr>
<td>Bending magnet filling factor</td>
<td>56 %</td>
</tr>
<tr>
<td>Maximum magnetic field</td>
<td>1.16 T</td>
</tr>
</tbody>
</table>
Summary

- **Batch compression schemes to increase brightness in PS**
  - Scheme yielding 64 bunches per PS batch
    - Brightness increase compared to present situation: 1.5
    - Reasonable complexity of RF gymnastics
  - Scheme yielding 48 bunches per PS batch
    - Brightness increase compared to present situation: 2
    - Complex RF gymnastics with many batch compression steps
  - RF gymnastics to be refined (time for cavity tuning, of RF voltage functions ...)
  - Implication (slow initial acceleration, time for gymnastics) on PS cycle?
  - Tests (with double batch transfer) possible without expensive hardware upgrades ...
    - ... but significant manpower and efforts from the PS RF team and MD time required!
  - Potential to combine PSB energy upgrade with batch compression
    - Requires double batch PSB to PS transfer

- **Rapid Cycling Synchrotron as new PS injector**
  - Very first estimates only possible within time available
    - Some parameters (e.g. bending filling factor and magnetic field) challenging ....
    - ... but no showstopper identified for the moment, Linac4 has to cycle faster as well
  - Feasibility needs to be answered after a more thorough study
Batch Compression Schemes in the PS
Compression to $h_{PS} = 10$ and generation of 64 bunches

$t = 3\text{ ms (start)}$

$t = 13\text{ ms (during 1}^{\text{st}}\text{ compression step)}$

$t = 27\text{ ms (pure } h = 9)\text{)}$

$t = 33\text{ ms (during 2}^{\text{nd}}\text{ compression step)}$

$t = 40\text{ ms (pure } h = 10)\text{)}$

$t = 50\text{ ms (splitting)}$

$t = 60\text{ ms (pure } h = 20)\text{)}$

$t = 65\text{ ms (during last compression step)}$

$t = 80\text{ ms (pure } h = 21)\text{)}$