Possible improvements to the existing pre-injector complex in the framework of continued consolidation

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and

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Main assumptions

- The performance analysis assumes that Linac4 injects into the PSB.
- The target consists of maximising the bunch intensity of the LHC beam with 25 ns spacing.
- Criterion:
  - Control the space charge tune shift
  - Reference parameters
    - $\varepsilon_n = 2.5 \, \mu\text{m}$
    - Bunch length = 180 ns
  - Constraint $|\Delta Q| \leq 0.3$
- For a detailed analysis of Linac4 performance reach see the presentation by M. Vretenar.
Performance reach of pre-injector complex

- Changes since the upgrade of PSB in preparation of LHC:
  - Longitudinal splitting introduced in the PS
  - Harmonic number reduced from 8 to 7 in the PS at injection
  - Six bunches are injected in double batch in the PS

- With Linac4:
  - Maximum intensity/ring (limited by space charge effect at PSB injection): $3.6 \times 10^{12}$ p

How much of this intensity can be injected into the PS respecting the space charge tune shift limit?
Space charge tune shift and energy

Relative change of beam size, $\beta\gamma^2$

Relative decrease of beam size

Maximum space charge tuneshift

Region of interest

Relative field increase in PSB main dipoles
Additional considerations

- \(3.6 \times 10^{12} \times 6 = 3 \times 10^{11} \times 72\): compatible with tune shift criterion if the PSB field can be increased by 40%.
- \(3.24 \times 10^{12} \times 6 = 2.7 \times 10^{11} \times 72\): compatible with tune shift criterion if the PSB field can be increased by 30% (also compatible with hardware capability, see later).
- The change of harmonic number makes it possible to use longer bunches.
- Bunch length increase up to about 200 ns seems realistic (to be confirmed by MDs) and compatible with triple splitting requirements.
- The PSB intensity could be increased proportionally.
PS: transverse instabilities - I

- Nominal LHC beam experiences:
  - Slow losses on injection flat-bottom
  - Transverse instabilities on extraction flat top. Type (single bunch, coupled bunch) still to be determined, but linked with electron-cloud effects.

Interplay between space charge and longitudinal dynamics. Trapping de-trapping phenomena.
PS: transverse instabilities - II

• Nominal performance:
  – $1.3 \times 10^{11}$ p/b with 25 ns: bunches are unstable at top energy if shorter than ~12 ns (rise time few ms).

• Extrapolation to higher intensities:
  – Not easy: it requires a complete study. However, possible cures are:
    • Injection:
      – Improved working point control (tune and chromaticity).
    • Top energy:
      – Control bunch length (avoid too short bunches) and perform bunch rotation faster than with nominal RF-gymnastics
      – Transverse damper
      – Cure electron-cloud effects, e.g., vacuum chamber coating

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PS: longitudinal instabilities - I

- Nominal LHC beam suffers from longitudinal coupled bunch instabilities (dipole mode).
- Nominal performance:
  - $1.3 \times 10^{11}$ p/b with 25 ns spacing are stabilised with the longitudinal feedback system (10 MHz cavities in sections 86 and 96 used for acceleration and for damping the instabilities).
- Extrapolation to higher intensities:
  - In 2009 $\sim 1.4 \times 10^{11}$ p/b with 25 ns spacing were accelerated using the spare 10 MHz cavity in section 11 as a dedicated kicker for the coupled-bunch feedback. A beam with a twice as small $\varepsilon_l$ was successfully stabilised.
PS: longitudinal instabilities - II

• Extrapolation to higher intensities:
  – Assuming scaling of instability threshold as $N_b/\varepsilon_l$, then $\sim 2.8 \times 10^{11}$ p/b should be stable with nominal $\varepsilon_l$ and a dedicated feedback up to top energy.
  – RF manipulations and longitudinal splitting at high energy not tried during the tests because of a too small longitudinal emittance.
  – Detailed study of beam stability during the flat-top RF manipulations is required.
To increase the PSB extraction energy

- **PSB:**
  - Main magnets
  - Main power supply
  - RF
  - Septa and kickers

- **Transfer and measurement line**
  - Magnets
  - Septa and kickers
  - Power converters

- **PS injection:**
  - Septum and kicker
  - Injection slow bump

NB: in this proposal the extraction energy for the ISOLDE beams is unchanged.
PSB, extraction lines, and PS
PSB extraction line: BT

Ejection and recombination:

“Booster Transfer” (BT)
PSB transfer lines: BTP, BTM

Measurement line (BTM)

Booster-to-PS transfer line (BTP)

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Findings:
- Increase of field strength seems feasible
- Field quality is not affected
- Due to higher saturation, the outer rings have to be supplied with a higher current differential than present
- This effect may be reduced by introducing laminated side plates (currently solid)
- This preliminary study is being cross checked with measurements
- Cooling to be reviewed
Findings:
• Increase of field strength seems feasible
• Field quality is not affected
• This preliminary study is being cross checked with measurements
PSB: other magnets

- Special multipole magnets have enough margin.
Power converters

• The main power converter cannot cope with the increased extraction energy. A new one is required. A new trim power converter for the outer rings is also needed.
• NB: the increased Bdot would allow delivering beam to ISOLDE on a 0.6 s basis. Hence, once could envisage:
  • Beam to ISOLDE on 0.6 s PSB magnetic cycle -> a factor of two increase in beam delivered to ISOLDE
  • Beam to PS based on 1.2 s PSB magnetic cycle
• Only a few power converters of transfer lines magnets and septa can be recuperated.
• Hardware consolidation is foreseen (see presentation by S. Baird).
• Synergies with other projects possible.

RF

• The proposed increased energy would bring $f_{rev}$ to 1.81 MHz, hence slightly outside the range of C02 cavities. It can be easily fixed by shifting the whole frequency range.
• A vigorous consolidation programme (see presentation by S. Baird) will be beneficial for the PSB energy upgrade.
Kickers: PSB

Findings:
• Increase of field strength seems feasible
• The rise time of the kickers might increase by 1-5 ns.
• New magnets and tanks are needed.
• The actual tank should also be upgraded to serve as a spare which does not exist for the moment.
• No margin left.

<table>
<thead>
<tr>
<th>Beam kinetic energy (GeV)</th>
<th>Kick multiplicative compared with 1.4 GeV</th>
<th>Required voltage (kV)</th>
<th>Magnet</th>
<th>Switch</th>
<th>PFN</th>
<th>Required current (A)</th>
<th>Magnet</th>
<th>Generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.3</td>
<td>55.25</td>
<td>New magnets &amp; tank</td>
<td>ok</td>
<td>ok</td>
<td>682.5</td>
<td>ok</td>
<td>ok</td>
</tr>
</tbody>
</table>
Kickers: **Transfer line and PS**

Findings:
- Increase of field strength seems feasible
- The rise time of the kickers might increase by 1-5 ns.
- A change of ferrite grade is recommended for BT.KFA10.
- No margin left.
- Increase of strength up to 1.8 is feasible in short-circuit mode, only, but:
  - Flat top ripple increased: 2% -> 3%
  - Rise time increased (2-98)\%: 42 ns -> 68 ns
  - Fall time increased (2-98)\%: 68 ns -> 87 ns
- If the system cannot be used in short-circuit mode, development of 2 new generators is required and 2 new magnets have to be added in the PS. The present system will stay.

<table>
<thead>
<tr>
<th>Beam energy (GeV)</th>
<th>Kick multiplicator compared with 1.4 GeV</th>
<th>Required voltage (kV)</th>
<th>Magnet</th>
<th>Switch</th>
<th>PFN</th>
<th>Required voltage (kV)</th>
<th>Magnet</th>
<th>Switch</th>
<th>PFN</th>
<th>Required voltage (kV per module)</th>
<th>Magnet</th>
<th>Switch</th>
<th>PFN</th>
<th>Module in short-circuit mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.3</td>
<td>55.25</td>
<td>ok, but ferrite change recommended &amp; new tank possibly</td>
<td>ok</td>
<td>ok</td>
<td>36.4</td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
<td>104</td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
</tr>
</tbody>
</table>
Magnets and septa

- Transfer and measurement lines magnets:
  - Margin probably available, but verification is in progress (special care for saturation effects and different energies for PS and ISOLDE).

- Septa:
  - PBS extraction: Enough margin is available (30-40%). Modifications only needed for the internal bus bars and cooling.
  - BT: Strength margin up to 20% maximum. New septa are needed.
  - PS injection: Septum has definitely no strength margin. A longer device should be envisaged, thus implying a re-design of the injection slow bump.

The injection bump is generated by elements in straight sections 40, 42, 43, 44
Implementation

• In general:
  – Three to four years are considered necessary to develop and build the new hardware required for the increase of the PSB extraction energy.
  – One long (eight months) or two short shutdowns to install the new hardware.
Intermediate summary

• Improvement: increase PSB extraction energy (2 GeV) to match new PSB space charge limits due to advent of Linac4. Possibility to generate LHC bunches of $2.7 \times 10^{11}$ p (or even higher with longer bunches) with 25 ns spacing.

• Time line for implementation of new PSB extraction energy:
  – Three to four years (design and construction of new hardware)
  – One to two shutdowns (hardware installation)

• Other areas of study in view of additional improvements:
  – PS working point control.
  – Pulsing PS faster (26 GeV/c in 1.2 s). Potential gain: reduce LHC filling time by 14%-16%.
  – Losses at PS extraction (new thin septum or additional thin septum). Potential gain: reduce the systematic and unavoidable 2-3% losses for high intensity beams for SPS fixed target physics programme.
PS - other improvements: main magnets - I

Courtesy S. Gilardoni

“open” (defocusing) half unit
“closed” (focusing) half unit

Exciting coils in unit U17

Main coil
Narrow defocusing PFW
Wide defocusing PFW

Defocusing Focusing

Pole-face windings
Main coil
Beam
Figure-of-eight loop

Figure-of-eight loop
Narrow focusing PFW
Wide focusing PFW

\[
\begin{bmatrix}
\Delta Q_H \\
\Delta Q_v \\
\Delta \xi_H \\
\Delta \xi_v \\
\end{bmatrix} = A
\begin{bmatrix}
\Delta I_{FN} \\
\Delta I_{FW} \\
\Delta I_{DN} \\
\Delta I_{DW} \\
\Delta I_{8L} \\
\end{bmatrix}
\]
PS - other improvements: main magnets - II

• Under the assumption of a vigorous maintenance plan (see presentation by S. Baird) the PS main magnets will not be a source of limitation for the PS complex.

• However, the pole-face windings and figure-of-eight loop are a potential limitation (but difficult to quantify) as:
  1. No magnetic model exists, yet -> no accurate predictive approach available to specify working point
  2. Five currents are available to control four physical parameters -> optimisation required (or additional parameter to be controlled)
  3. RMS limit for these circuits might prevent using the full capabilities of the new PS main power supply (i.e., 26 GeV/c in 1.2 s). In view of faster cycling, it is worth stressing that the main magnets are also a potential bottleneck (mechanical stress, Eddy currents).

• First two points are being considered: the third one should be addressed too.
PS - other improvements: vacuum pipe layout

- A review of the PS vacuum pipe layout should be made in order to
  - Improve aperture (10% already gained at injection due to increased energy). This effort is already on-going and should be continued.
  - Estimate the potential gain in longitudinal impedance by improving transitions
  - Propose means to combat electron-cloud
PS - other improvements: losses at extraction

- Beam losses for Fixed Target beams have been removed from the electrostatic septum in section 31 (Continuous Transfer -> Multi-Turn Extraction).
- The choice of the longitudinal structure for the SPS (de-bunched beam) has made extraction losses on the magnetic septum unavoidable.
- The losses correspond to about 2-3% of the extracted intensity.
- Possible solutions:
  - One thinner septum in section 16 (anticipated in MTE DR).
  - Two septa: the existing plus a thinner one (electrostatic septum currently used by CT in section 31?)
  - Detailed study (optics and integration) to be performed.
Summary

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