Longitudinal Beam Loss Studies of the CERN PS-to-SPS Transfer

Helga Timkó
CERN

in collaboration with

Heiko Damerau, Theodoros Argyropoulos, Thomas Bohl, Steven Hancock, Juan Esteban Müller, Elena Shaposhnikova
Outline

- Introduction and motivation
  - Studies in the past and now
- Methods
  - Simulations and measurements
- Optimisation of the PS bunch rotation
  - Using spare cavities
- Emittance and intensity dependence
- Implications and conclusions
Continuous efforts to optimise the PS-SPS transfer for several years

*In the past:* the aim was to reduce losses
  - For low SPS capture voltages, losses were unacceptable, up to 20-40% (2004)

**Nominal LHC intensity**

(~1.2 \( \times \) 10\(^{11} \) ppb), 25 ns

**E. Shaposhnikova et al.:**
**Capture loss of the LHC beam in the CERN SPS**

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**Graph:**

- **Losses % at 30 GeV**
- **Capture voltage MV**
- **Points:**
  - 30.07
  - 15.10
  - 23.07
Motivation (2)

- **Now:** only ~5 % losses for the nominal intensity (due to long optimisation and less e-cloud)
  - However, relative losses increase with intensity ⇒ will be an issue
    - Higher intensity → $\varepsilon_1$ → more losses
    - Beam loading → deformation of bucket → more losses
  - Using a larger $\varepsilon_1$ is desirable also for stability in the PS & SPS

- **In measurements till 2011** no loss reduction could be achieved by changing the PS bunch rotation settings
  - Idea: shorter $\tau$ using higher voltage for the PS bunch rotation
  - Result: even though $\tau$ got significantly shorter, loss remained the same
  - This scheme didn’t work and it wasn’t understood why…
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Simulations

- The LHC-type 50 ns and 25 ns beam has been modelled with ESME
  - Single bunch simulations, without intensity effects
  - Using averaged, real bunch distributions, measured at PS FT (with the tomoscope)
  - Full tracking of PS & SPS RF manipulations
    - PS: adiabatic voltage reduction, double splitting(s), bunch rotation;
    - SPS: FB, in some cases also ramp

- Capture losses dominated by losses from the bunch tails
  - Shorter bunches do not necessarily result in the best transmission
- Need to optimise the particle distribution in phase space – not visible from bunch profiles, sims. needed!

Operational bunch-to-bucket transfer
Measurements

- First measurements started in 2011, several sessions in 2012
- *Dedicated cycle* for measurements in parallel with operation
  - 36 bunches of 50 ns spaced LHC-type beam
  - Intensity: \( \sim 1.6 \times 10^{11} \) ppb (except for intensity studies)
  - Varying the PS rotation timings \( t_{40\, \text{MHz}} \) and \( t_{80\, \text{MHz}} \) to optimise the distrib.
  - Using the spare 40 MHz or the spare 80 MHz cavity in the PS to increase the rotation voltage
    - Operational: 1×40 MHz, 2×80 MHz cavities
- **Bunch length:**
  - at PS ejection
- **Transmission:**
  - (intensity at 30 GeV) / (injected intensity)
  - In the simulations:
    - only capture + FB losses

![Operational PS voltage at bunch rotation](image)
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Option 1: Use the spare 80 MHz cavity

- Simulations predict: optimum at $t_{40\text{MHz}} = 200-220 \, \mu s$, $t_{80\text{MHz}} = 100 \, \mu s$
- Gain compared to operational settings:
  - $T = 95.6 \% \rightarrow 97.9 \%$; $L = 4.4 \% \rightarrow 2.1 \%$

(a) Transmission [%], end of FB

(b) Bunch length [ns] at PS extraction
Option 1: Measurement results

- Optimal settings for
  \[ V_{40\text{MHz}} = 300 \text{ kV}, \]
  \[ V_{80\text{MHz}} = 900 \text{ kV}: \]
  \[ t_{40\text{MHz}} = 240 \mu\text{s}, \]
  \[ t_{80\text{MHz}} = 100 \mu\text{s} \]

- Gain compared to operational settings
  \[ T = 95.4 \% \rightarrow 96.3 \% \]
  \[ L = 4.6 \% \rightarrow 3.7 \% \]

- N.B. constant offset of transverse losses
Option 2: Use the spare 40 MHz cavity

- Simulations predict: optimum at $t_{40\text{MHz}} = 130 \, \mu\text{s}$, $t_{80\text{MHz}} = 80 \, \mu\text{s}$
- Gain compared to operational settings:
  - $T = 95.6 \% \rightarrow 98.1 \%; \, L = 4.4 \% \rightarrow 1.9 \%$

(a) Transmission [%], end of FB
(b) Bunch length [ns] at PS extraction
Option 2: Measurement results

- Optimal settings for
  \[ V_{40\text{MHz}} = 600 \text{ kV}, \]
  \[ V_{80\text{MHz}} = 600 \text{ kV}; \]
  \[ t_{40\text{MHz}} = 130 \mu\text{s}, \]
  \[ t_{80\text{MHz}} = 90 \mu\text{s} \]

- Gain compared to operational settings
  \[ T = 94.8 \% \rightarrow 97.7 \% \]
  \[ L = 5.2 \% \rightarrow 2.3 \% \]
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Now we understand the results of previous years…

Earlier MDs with spare 80 MHz cavity optimised only $\tau$

(a) Transmission

(b) Bunch length
Spare 40 MHz cavity: Emittance dependence

- Gives a better transmission and shorter bunches!

Operational transmission even with ~40% larger $\varepsilon_i$!
Spare 40 MHz cavity: Intensity dependence

- About ~15% higher intensity with the same transmission

<table>
<thead>
<tr>
<th>Voltage (kV)</th>
<th>t_{40} (µs)</th>
<th>t_{80} (µs)</th>
<th>ε_{l}^{90} %</th>
<th>T (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 × 5.5</td>
<td>160</td>
<td>120</td>
<td>(0.539 ± 0.006) eVs</td>
<td>(4.00 ± 0.04) ns</td>
</tr>
<tr>
<td>2 × 5.5</td>
<td>200</td>
<td>120</td>
<td>(0.546 ± 0.005) eVs</td>
<td>(4.23 ± 0.03) ns</td>
</tr>
</tbody>
</table>

1.58 × 10^{11} ppb, V_{40 MHz} = 300 kV, V_{80 MHz} = 600 kV

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<tr>
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<tbody>
<tr>
<td>2 × 5.5</td>
<td>160</td>
<td>120</td>
<td>(0.567 ± 0.010) eVs</td>
<td>(4.02 ± 0.03) ns</td>
</tr>
<tr>
<td>2 × 5.5</td>
<td>200</td>
<td>120</td>
<td>(0.611 ± 0.008) eVs</td>
<td>(4.23 ± 0.03) ns</td>
</tr>
</tbody>
</table>

1.81 × 10^{11} ppb, V_{40 MHz} = 300 kV, V_{80 MHz} = 600 kV

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<th>t_{40} (µs)</th>
<th>t_{80} (µs)</th>
<th>ε_{l}^{90} %</th>
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<tr>
<td>2 × 5.5</td>
<td>130</td>
<td>90</td>
<td>(0.550 ± 0.012) eVs</td>
<td>(3.63 ± 0.03) ns</td>
</tr>
<tr>
<td>2 × 8.5</td>
<td>130</td>
<td>90</td>
<td>(0.612 ± 0.012) eVs</td>
<td>(3.84 ± 0.02) ns</td>
</tr>
</tbody>
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1.58 × 10^{11} ppb, V_{40 MHz} = 600 kV, V_{80 MHz} = 600 kV

W/ spare 40 MHz cavity

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<th>Voltage (kV)</th>
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<th>t_{80} (µs)</th>
<th>ε_{l}^{90} %</th>
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</tr>
</thead>
<tbody>
<tr>
<td>2 × 5.5</td>
<td>130</td>
<td>90</td>
<td>(0.551 ± 0.007) eVs</td>
<td>(3.71 ± 0.04) ns</td>
</tr>
<tr>
<td>2 × 8.5</td>
<td>130</td>
<td>90</td>
<td>(0.550 ± 0.007) eVs</td>
<td>(3.83 ± 0.02) ns</td>
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Using the spare 40 MHz cavity has some clear advantages over the 80 MHz cavity:

- Better transmission
- Shorter bunch length
- Emittance margin: 40 % (!)
- Intensity margin: 15 %
- Spare 40 MHz cavity not needed for ions (unlike the spare 80 MHz)

The new scheme still needs to be tested in an operational cycle

Even if beam losses currently don’t cause concerns, stability is a key issue at the present intensity, both in the PS & SPS

- Maybe the spare 40 MHz cavity could be a solution?
  - Empirical longitudinal stability scaling in the PS (at low intensities): \( N_b/\varepsilon_1 = \text{const.} \Rightarrow \text{in theory, could gain up to 40 \% in intensity} \)
PS hardware requirements

- Using a spare 40 MHz cavity requires only minimal low-level hardware modifications
  - Low-cost solution
  - Improved operational availability of the 40 MHz cavities is important (e.g. new power supplies)

- Do we need to have a spare cavity?
  - If a cavity fails, we still can go back to the currently operational settings

- Adding a 3\textsuperscript{rd} 40 MHz cavity to the PS is an option, too
  - But: at significant cost and manpower effort
Conclusions

- Simulations determined the loss mechanism of the PS-SPS transfer and agree very well with previous and present measurement results.

- The \textit{optimum phase space particle distribution} at PS extraction has been obtained by simulations, and confirmed by experiments:
  - Can significantly \textit{improve the transmission}
  - Or provide a \textit{\sim 40\% emittance margin} while keeping the same transmission.

- Has the potential to \textit{improve beam stability} in the PS and, hence, allows for higher-intensity beams with good quality, which is important for the LHC.

- Once the spare 40 MHz cavity is available again, the new scheme still \textit{needs to be tested under operational conditions}.

\textbf{Thank you!}