LONGITUDINAL BEAM LOSS STUDIES OF THE CERN PS-TO-SPS TRANSFER

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Abstract

Bunch-to-bucket transfer between the Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS) is required before beams can enter the Large Hadron Collider (LHC). The overall beam loss at this transfer is currently around 5–10 %, and is increased for higher intensities or larger longitudinal emittances. Previous attempts to reduce the losses with additional RF voltage from spare cavities in the PS were unsuccessful. In this paper, we modelled the complete PS flat-top bunch splitting and rotation manipulations, PS-to-SPS transfer, and SPS flat bottom using end-to-end simulations. Starting from the measured bunch distributions, the simulations provide an accurate insight into the problem and allow direct benchmarking with experiments. As a result, it was understood and confirmed by measurements that shorter bunches do not necessarily lead to better transmission. The particle distribution in longitudinal phase space at PS extraction should be optimised instead. A significant loss reduction of up to 50 % is expected from simulations; experimental studies are on-going to verify these theoretical findings.

INTRODUCTION

Different types of studies to optimise the PS-to-SPS transfer of the LHC beam have been on-going for several years now. Initially, the aim of these studies was to reduce the beam loss in the SPS, which was in the range of 10–40 % [1, 2, 3]. Amongst others, it was attempted to optimise the PS bunch rotation [4], which is done just before extraction in order to fit the PS bunches into the SPS bucket, by creating shorter bunches using additional, spare-cavity voltage for the rotation. Shorter bunches were successfully obtained, however, the transmission remained the same and the underlying reason was not understood at that time.

Nowadays, losses are as low as ~ 5 % at the current intensity of $(1.6\text{–}1.7)\times 10^{11}$ ppb, due to an extensive optimisation of the SPS flat-bottom (FB) RF settings and reduced electron-cloud activity. However, relative losses increase with intensity, so for the future high intensities of the high-luminosity LHC the issue has to be re-considered. Furthermore, a solution which would allow for higher longitudinal emittance is desirable, since both in the PS and the SPS the beam is at the limit of longitudinal stability at the present intensity.

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SIMULATION AND MEASUREMENT STUDIES

The currently operational LHC-type 50 ns-spaced beam has been modelled with single-bunch simulations using the longitudinal tracking code ESME [5]. The averaged, real bunch distributions measured at the PS flat top (FT) have been sampled with 500 000 macro-particles and tracked over the full chain of PS and SPS RF manipulations including adiabatic voltage reduction, a double splitting, and a bunch rotation in the PS, injection and FB in the SPS. Intensity effects have not yet been taken into account. Furthermore, simulations include an experimentally observed emittance blow-up, which may be attributed to the synchronisation process in the PS (for more details, see [6]).

To verify the predictions from simulations, a series of measurements has been carried out this year with 36 bunches of LHC-type 50 ns-spaced beam. The operational intensity of about 1.6×10^{11} ppb (at injection to the SPS) has been used in all experiments, except for measurements investigating intensity dependence. The timings of the PS rotation voltage programme, $t_{40\,\mathrm{MHz}}$ and $t_{80\,\mathrm{MHz}}$ (Fig. 1), have been scanned systematically to find the optimal transmission. To increase the rotation voltage, we investigated two options: operating the spare 40 MHz or the spare 80 MHz cavity.

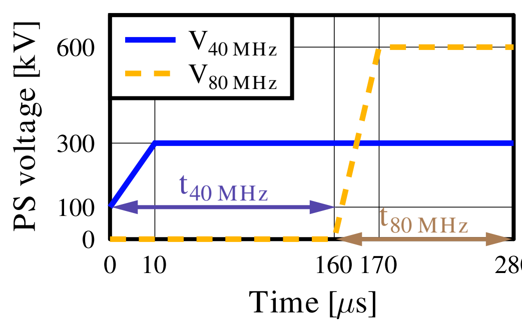

Figure 1: Currently operational PS bunch-rotation voltage programme [4]. The voltage is produced with one 40 MHz and two 80 MHz cavities. A hot spare cavity is available for both the 40 MHz and the 80 MHz RF systems.

Both in simulations and measurements, the bunch length (4σ) has been obtained from a Gaussian fit to the bunch profiles. Experimentally, the transmission has been determined as the ratio of the bunch intensity at 30 GeV/c (the FB momentum is 26 GeV/c) to the injected intensity, in order to include all losses due to uncaptured particles, also those that occur at the beginning of the acceleration ramp. Simulations took only capture and FB losses into account.

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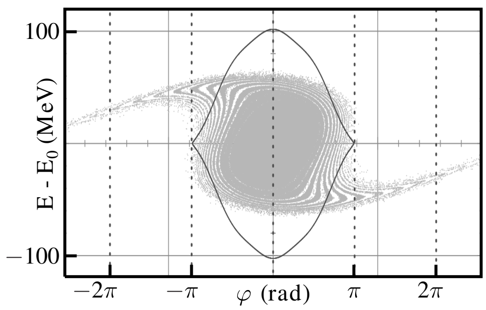

Figure 2: Simulated particle phase-space distribution at injection into the SPS bucket ($V_{200\,\mathrm{MHz}}$ = 2 MV and $V_{800\,\mathrm{MHz}}$ = 0.34 MV in bunch-shortening mode) under operational conditions.

Bunch Distribution Optimisation

The simulated longitudinal phase-space distribution of a typical bunch after the PS rotation, at injection into the SPS bucket is shown in Fig. 2.

This case suggests qualitatively that the capture losses could be dominated by the loss from the bunch tails. Due to the particular shape of the bunches at transfer, a reasonable phase error and energy mismatch at injection were found to have a negligible effect on the losses in our previous studies [6]; hence, perfect injection is assumed in all the simulations presented here.

In principle, by optimising the bunch distribution in longitudinal phase space, the number of particles in the tails can be diminished. Since this distribution is not visible from the measured bunch profiles, the guidance of simulations was essential to find its optimum. Furthermore, simulations suggest that shorter bunches do not necessarily result in better transmission; if the particles in the bunch tails can be brought closer to the bunch centre, the transmission is expected to improve despite of a longer bunch length.

Using the Spare 80 MHz Cavity

Simulation and measurement results using PS rotation voltages of $V_{40\,\mathrm{MHz}}$ = 300 kV and $V_{80\,\mathrm{MHz}}$ = 900 kV produced by in total one 40 MHz and three 80 MHz cavities are shown in Fig. 3. Note that due to transverse losses in the experiments, there may be a quasi-constant offset between the measured and the simulated transmission. Note also that using a spare cavity introduces further impedance to the machine. At the beam intensity of $\sim 1.6 \times 10^{11}$ ppb used in the measurements, the PS is already close to the limit of longitudinal beam stability under operational conditions. To counteract beam instabilities caused by the additional impedance, more controlled longitudinal emittance blow-up has been applied than usual and in simulations;

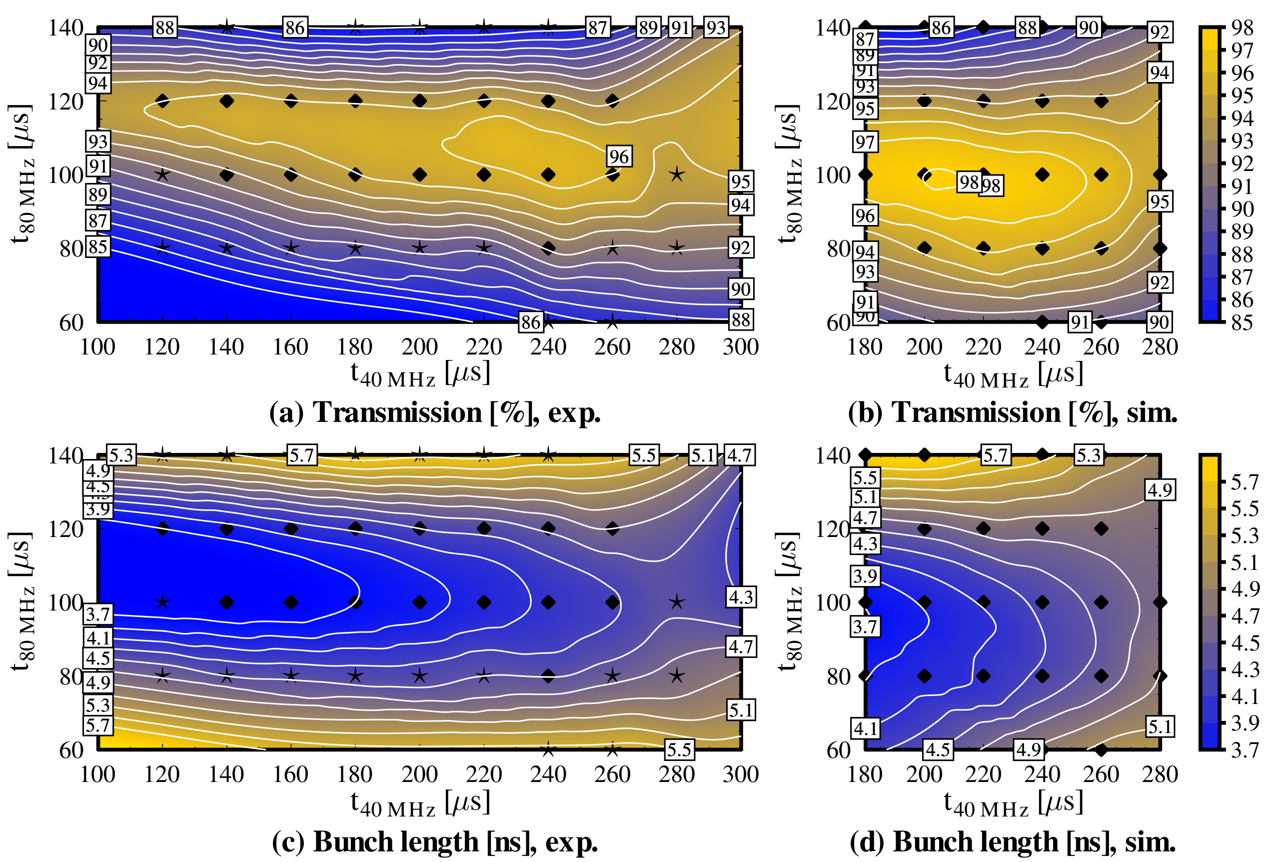

Figure 3: Contour plots of transmission and bunch length as a function of PS rotation timings for $V_{40\,\mathrm{MHz}}$ = 300 kV and $V_{80\,\mathrm{MHz}}$ = 900 kV. Measured and simulated results are shown in Figs. (a), (c) and (b), (d), respectively. In (a) and (c), measurement points marked with stars are averages of 5 measurements, while diamonds mark an average of 10.

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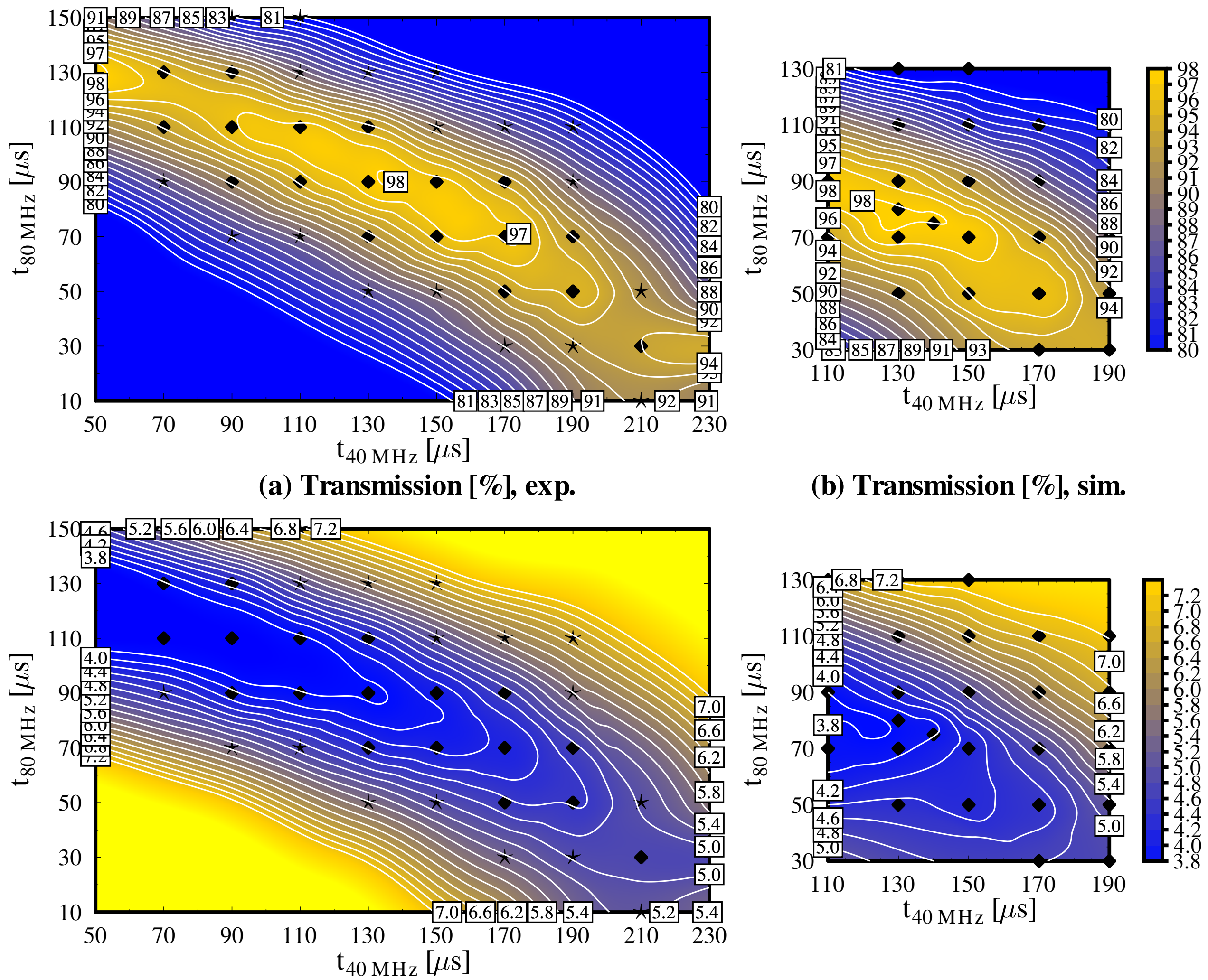

(a) Transmission [%], exp. **(b) Transmission [%], sim.**

(c) Bunch length [ns], exp. **(d) Bunch length [ns], sim.**

Figure 4: Contour plots of transmission and bunch length as a function of PS rotation timings for $V_{40\,\mathrm{MHz}} = 600$ kV and $V_{80\,\mathrm{MHz}} = 600$ kV. Measured and simulated results are shown in Figs. (a), (c) and (b), (d), respectively. In (a) and (c), measurement points marked with stars are averages of 5 measurements, while diamonds mark an average of 10.

hence, simulated bunch lengths are smaller compared to measured bunch lengths.

The optimal transmission region is predicted by simulations around $t_{40\,\mathrm{MHz}} = 200$–$220$ μs and $t_{80\,\mathrm{MHz}} = 100$ μs; experimentally, the values $t_{40\,\mathrm{MHz}} = 240$ μs and $t_{80\,\mathrm{MHz}} = 100$ μs have been found. While simulations predict an increase in transmission from 95.6 % (operational) to 97.9 %, or equally, a loss reduction from 4.4 % to 2.1 %, the experimentally achieved gain is only 95.4 % → 96.3 % in transmission, corresponding to 4.6 % → 3.7 % in loss reduction.

Using the Spare 40 MHz Cavity

By using two 40 MHz and 80 MHz cavities each to produce $V_{40\,\mathrm{MHz}} = V_{80\,\mathrm{MHz}} = 600$ kV, a highly favourable combination of transmission and bunch length can be achieved, see Fig. 4. Also in this case, the predicted and measured optimal timings agree very well: simulated values are $t_{40\,\mathrm{MHz}} = 130$ μs, $t_{80\,\mathrm{MHz}} = 80$ μs, and experimentally, one obtains $t_{40\,\mathrm{MHz}} = 130$ μs, $t_{80\,\mathrm{MHz}} = 90$ μs. The corresponding gain in transmission (loss reduction) is 95.6 % → 98.1 % (4.4 % → 1.9 %) in simulations and 94.8 % → 97.7 % (5.2 % → 2.3 %) in experiments.

Since the overall transmission is very good both in experiments and simulations, the effect of an increased PS rotation voltage is only a few per cent on the absolute scale. The more relevant quantity for our studies is the relative loss reduction, which can be used in estimates of transmission at future intensities. The relative loss reduction achieved with the spare 40 MHz cavity is more than 50 %, just as expected from simulations. In addition, this can be achieved at a bunch length shorter than operational. Why the predicted loss reduction could not be achieved with the spare 80 MHz cavity will have to be studied in future simulations that include intensity effects.

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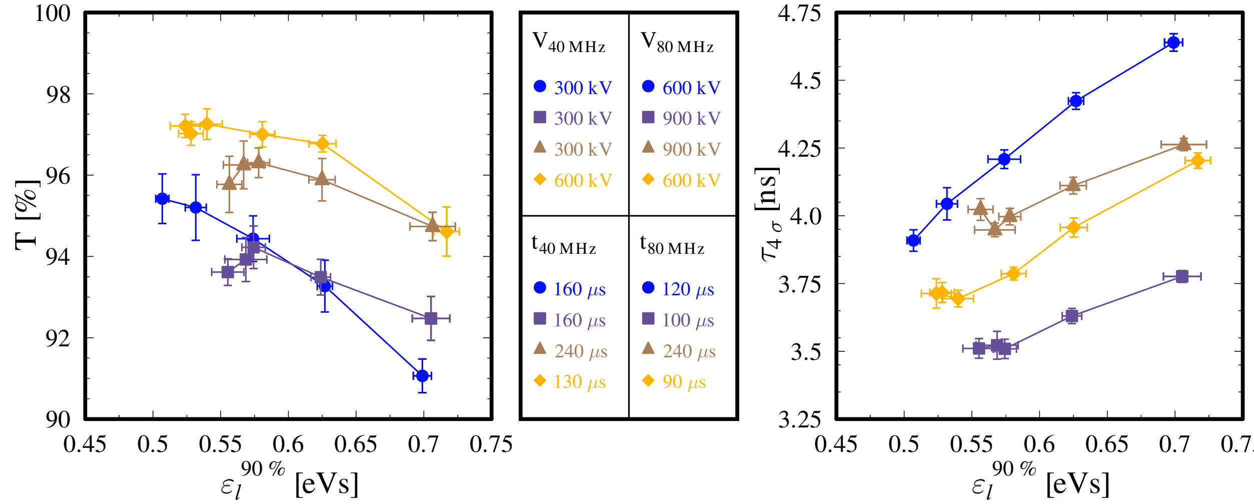

(a) Transmission **(b) Bunch length**

Figure 5: Emittance dependence of transmission at 30 GeV and bunch length at PS ejection for different bunch rotation voltages and timings. Each point is an average of ten measurements. The operational emittance (containing 90 % of the particles) is around 0.5 eVs, prior to the double splitting.

Emittance and Intensity Dependence

At the currently operational intensities, both the PS and the SPS are at the limit of longitudinal beam stability. Instability thresholds in the SPS can be increased significantly by using transverse tunes of $Q_{\mathrm{x,\,y}} = 20$ instead of the present $Q_{\mathrm{x,y}} = 26$. In the PS, using a larger longitudinal emittance is a straightforward option. Hence, it is necessary to know how the transmission behaves as a function of emittance and intensity.

The measured emittance dependence of the transmission and the bunch length for different PS rotation voltages is shown in Fig. 5. The emittance has been varied by changing the amount of controlled emittance blow-up in the PS. The blue circles represent measurements with the operational settings. The violet squares used the spare 80 MHz cavity with bunch-length minimising settings as in the attempts in previous years, and reproduced the earlier findings of an unchanged transmission at a significantly reduced bunch length. With the optimal settings predicted by the simulations (brown triangles), an improvement in transmission can be achieved with the spare 80 MHz cavity. At the same time, the bunch length is similar to currently operational values. With the spare 40 MHz cavity (yellow diamonds), an even better transmission can be achieved with much shorter bunches. Looking at the emittance dependence, the current, operational transmission can be maintained with a 40 % larger emittance, at a similar bunch length, when the spare 40 MHz cavity is used.

The intensity dependence of the transmission has been investigated with the spare 40 MHz cavity and with the operational settings; the results are summarised in Table 1. The operational transmission can be maintained with a 15 % larger intensity with the additional cavity at $\varepsilon_l^{90\,\%} \approx 0.55$ eVs. According to the empirical longitudinal stability scaling in PS, which was found for low intensities, the intensity should scale linearly with the emittance. Hence, in theory, with the above-mentioned 40 % larger emittance, up to 40 % higher intensity could be used in the PS, while maintaining beam stability.

DISCUSSION

Using the spare 40 MHz cavity has several advantages over using the spare 80 MHz cavity:

- Not needed during ion runs (unlike the spare 80 MHz),
- Better transmission,
- Shorter bunches at transfer.

Furthermore, compared to today's operational conditions, with the 40 MHz cavity one can maintain the same transmission with

- Either 40 % larger emittance,
- Or 15 % higher intensity.

Table 1: Intensity Dependence. The emittance $\varepsilon_l^{90\,\%}$ was around 0.55 eVs in all cases.

Intensity	**Transmission**	$\tau_{4\sigma}$
$V_{40\,\mathrm{MHz}} = 300$ kV, $V_{80\,\mathrm{MHz}} = 600$ kV, $t_{40\,\mathrm{MHz}} = 160$ μs, $t_{80\,\mathrm{MHz}} = 120$ μs:		
1.58×10^{11} ppb	(94.9 ± 0.5) %	(4.00 ± 0.04) ns
1.81×10^{11} ppb	(93.4 ± 0.3) %	(4.02 ± 0.03) ns
$V_{40\,\mathrm{MHz}} = 600$ kV, $V_{80\,\mathrm{MHz}} = 600$ kV, $t_{40\,\mathrm{MHz}} = 130$ μs , $t_{80\,\mathrm{MHz}} = 90$ μs:		
1.58×10^{11} ppb	(97.0 ± 0.4) %	(3.63 ± 0.03) ns
1.81×10^{11} ppb	(94.6 ± 0.9) %	(3.71 ± 0.04) ns

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Given that stability is a key issue in the PS at the present intensities, the increase in emittance, which is possible with the new, optimal bunch rotation settings, is expected to provide a significant margin for the future intensity increase. At high intensities, good beam quality in both the PS and the SPS is of utmost importance, too. Especially in the current optics of the SPS ($Q_{\mathrm{x,\,y}} = 26$), the development of instabilities in the SPS is very sensitive to the uniformity and overall beam quality of the beam arriving from the PS. In the $Q_{\mathrm{x,\,y}} = 20$ optics, longitudinal instability thresholds are higher; hence, a controlled longitudinal emittance blow-up might not be necessary in the SPS and the bunch-to-bunch variation of the beam extracted from the PS will be preserved throughout all the SPS cycle. Therefore, in both optics, the PS beam quality has an appreciable impact on the LHC beam quality as well. As a consequence, our once transmission-oriented transfer studies are now more and more concerned with the possible gain in emittance. The operational use of the spare 40 MHz cavity promises improvement in both of them.

Concerning the necessary hardware modifications in the PS, converting the spare 40 MHz cavity to an operational cavity would require only minimal low-level hardware. No hot spare cavity would then remain, however, even if one of the cavities fails, the other cavity could be used with the currently operational settings. Nonetheless, a reliable operation of the 40 MHz cavities would become more important and supports the plan to upgrade their power supplies. Adding a third 40 MHz cavity is another option, which, however, would require significant financial and manpower investment.

CONCLUSIONS

Detailed simulations of the PS-to-SPS longitudinal beam transfer determined the main longitudinal beam loss mechanism in the SPS. The simulations demonstrated that using the minimum bunch length at PS-to-SPS transfer as a criterion for best transmission is not necessarily appropriate; instead, the phase-space bunch distribution should be optimised as a function of the bunch rotation timings used in the PS.

Systematic measurements with 36 bunches of LHC-type 50 ns beam in a short cycle gave reproducible, consistent results. The predicted optimal timings and the qualitative transmission and bunch length behaviour obtained from simulations is in excellent agreement with experimental results. With the spare 40 MHz cavity, a significant loss reduction of about 50 % can be achieved with bunches that are shorter than operational. Alternatively, the longitudinal emittance can be increased by 40 % while keeping the operational transmission, which allows for a stable beam in the PS even at significantly higher intensities.

To better estimate the transmission and emittance requirements at the ultimate intensity required by the high-luminosity LHC, simulations including impedance effects are underway. Due to the recent failure of a 40 MHz cavity in the PS, the new bunch rotation settings could not yet be tested under operational conditions, but they shall be tested as soon as it will be possible.

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