

EFFECT OF THE VARIOUS IMPEDANCES ON LONGITUDINAL BEAM STABILITY IN THE CERN SPS

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Abstract

The High Luminosity (HL)-LHC project at CERN aims at a luminosity increase by a factor ten and one of the necessary ingredients is doubling the bunch intensity to 2.4×10^{11} ppb for beams with 25 ns bunch spacing. Many improvements are already foreseen in the frame of the LHC Injector Upgrade (LIU) project, but probably this intensity would still not be reachable in the SPS due to longitudinal instabilities. Recently a lot of effort went into finding the impedance sources of the instabilities. Particle simulations based on the latest SPS impedance model are now able to reproduce the measured instability thresholds and were used to determine the most critical impedance sources by removing them one by one from the model. It was found that impedance of vacuum flanges and of the already damped 630 MHz HOM of the main RF system gave for 72 bunches the comparable intensity thresholds. Possible intensity gains are defined for realistic impedance modifications and for various beam configurations (number of bunches, longitudinal emittances) and RF programs (single and double RF). The results of this study are used as a guideline for planning of a new campaign of the SPS impedance reduction.

INTRODUCTION

One of the main limitations in the SPS is the multi-bunch longitudinal instability during the ramp. In single RF operation (main RF at 200 MHz), the intensity threshold for 72 bunches is approximately $3 - 4 \times 10^{10}$ ppb. To reach the present intensity requirement for the LHC beams (1.2×10^{11} ppb) a fourth harmonic RF system (800 MHz) in bunch shortening mode is used to stabilize the beam. A further increase of the intensity by a factor of 2 is necessary to achieve requirements for the HL-LHC project (2.4×10^{11} ppb). Such a goal requires a good knowledge of the instability sources, as well as a reliable simulation model to do projections for the future.

The development of a longitudinal impedance model was the first step towards understanding the SPS instabilities. A survey of many possible impedance sources and their characterization through RF measurements and simulations was performed [1–3]. Meanwhile, the code BLoND was developed, designed to simulate longitudinal beam dynamics for a wide range of applications including intensity effects [4, 5].

Due to the complexity of the impedance model, it has been tested by comparing simulations with measurements for various cases: with stable [6], as well as unstable single bunch [7]. An important step was to study multibunch instabilities, to identify the most critical impedance sources and

draw guidelines for a possible impedance reduction for the LIU-SPS project [8].

MAIN IMPEDANCE SOURCES

The latest SPS impedance model is presented in Fig. 1. One of the main contributors is the Travelling Wave Cavities (TWC) including their High Order Modes (HOM). The main RF system at 200 MHz is comprised of 2 cavities of 4 sections and 2 cavities of 5 sections, and has a HOM at 630 MHz (damped by a dedicated HOM coupler). In nominal operation, the beam loading in the 200 MHz TWC is compensated by the one turn delay feedback and feedforward systems, which are modelled in the following simulations as a reduction of the 200 MHz TWC impedance by -20 dB.

Next, numerous vacuum flanges (more than 600) of different types are installed in the SPS. All of them contribute mainly at high frequencies (>1 GHz). For simplification these were divided into groups depending on their position with respect to SPS magnets and other devices.

Finally, many kickers are installed in the SPS for various purposes (injection, extraction, ...), and mainly contribute to a broadband impedance. Each of these impedance sources has a different effect on the beam, making particle simulations necessary to study the instabilities. Other smaller impedances (Beam Position Monitors (BPM), etc.) are present in the model but will not be discussed in this paper.

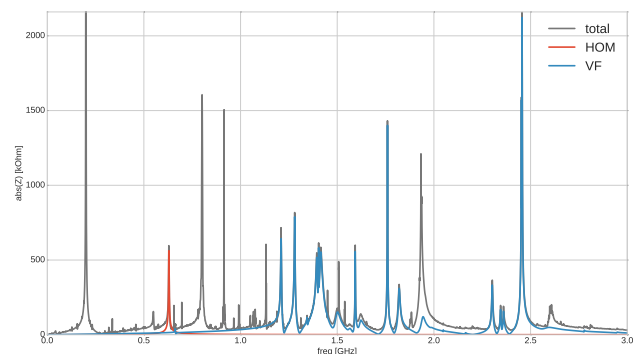


Figure 1: The SPS impedance model, including the Travelling Wave Cavities and HOMs (main at 630 MHz in red), the vacuum flanges (blue), the kickers impedance (background, main contribution coming from the injection kickers MKP).

SIMULATION SETUP

Beam dynamics simulations were done with BLoND using the SPS impedance model. In nominal operation, the LHC beam consists of 4 batches spaced by 225 ns. Each batch is composed of 72 bunches spaced by 25 ns. For this high

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number of bunches the simulation time is a limitation, and as the number of impedance sources is high an extensive number of simulations was needed to assess the effect of each of them. According to previous experimental studies [9] the instability threshold doesn't depend on the number of batches, so the number of bunches in simulations was set to 72. All bunches were generated with the same emittance and intensity, and matched to the bucket including induced voltage. The chosen particle distribution gives a line density close to the measured one.

The RF voltage V_{200} is set to 7 MV (operational value at flat top, corresponding to the limit due to beam loading for the nominal intensity) and the voltage at 800 MHz $V_{800} = 0.1 V_{200}$ in bunch shortening mode. As the instability threshold scales as $1/E$ and reaches minimum at flat top, simulations were done only at flat top (450 GeV/c) for a real time of 2.3 s (corresponding to 100,000 turns in the machine), which is longer than in operation in order to see slowly rising instabilities.

In order to obtain the stability threshold a large range of emittances and intensities was scanned. For each simulation, the bunch length τ was computed for each bunch as a function of time, obtained from Full-Width-Half-Maximum (FWHM), rescaled to $\tau = 4\sigma$ assuming a Gaussian profile). To determine whether a configuration is unstable, the difference between minimum and maximum bunch length $\Delta\tau$ is compared to the average τ_{av} . The instability limit was set to $\Delta\tau/\tau_{av} = 0.12$, which is efficient for the distinction between stable and unstable cases.

PRESENT CONFIGURATION

Simulations at flat top for the present beam and RF configuration, are compared with measurements in Fig. 2 for both single and double RF. Simulations are able to reproduce the instability threshold for 72 bunches for both cases. Results for 24 and 72 bunches are different, especially in double RF, showing that it is not possible to reduce the number of bunches in simulations to further simplify the computing. In single RF, the difference lies within the operational uncertainty (bunch to bunch variation in intensity). As the increase in the intensity threshold obtained from the 800 MHz RF system is large and crucial for the LHC operation, a good knowledge of the RF parameters is important [7]. The reference point for the present configuration is $N_b = 1.35 \times 10^{11}$ ppb with $\tau_{av} = 1.65$ ns.

The effect of the various impedance sources in double RF was tested first by completely removing them in simulations. Results are presented in Fig. 3. As the number of impedance sources is very large, efforts were focused on the ones that are the most critical in terms of beam stability and could be considered for impedance reduction: the vacuum flanges VF (shielding, redesign) and the HOM at 630 MHz (further damping). Completely removing either the HOM or all the VF gives a comparable gain in terms of instability threshold, about 15% for the nominal bunch length ($\tau = 1.65$ ns). For smaller bunch lengths, the gain from removing the vacuum

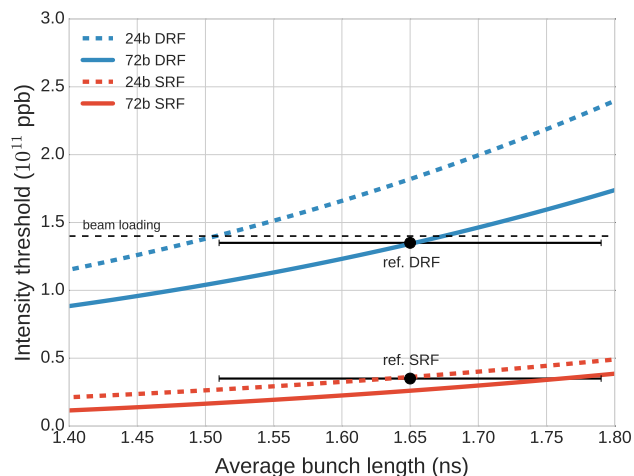


Figure 2: Stability limits for the present operations found by simulations for single and double RF, 24 and 72 bunches at $V_{200} = 7$ MV and $V_{800} = 0.7$ MV, compared with measurements (error bars are the bunch-to-bunch variations, 72 bunches). The horizontal line corresponds to the present limit due to beam loading.

flanges is bigger, their impedance contribution is mainly at high frequencies. As the gain is fairly small, it suggests that the VF and the HOM could have a comparable instability threshold. The next step was to test the combinations of removing the HOM and subsets of flanges (e.g.: between dipole and quadrupole magnets MQF, between BPMs and quadrupoles BPQX, unshielded pumping ports UPP). Removing the HOM and all the VF together gives large gain (40%), confirming that the HOM and VF are both limiting the beam stability. In case of impedance reduction of vacuum flanges, as many as possible should be shielded in all groups. All the remaining impedance sources were tested and their removal gives a small gain, except for the kickers. However, kickers impedance cannot be reduced easily.

The maximum intensity reachable in the SPS is also limited due to beam loading [10]. To overcome this limitation, an RF upgrade is planned and further studies were done to see potential gain of impedance reduction for future RF configurations.

PROJECTION FOR FUTURE RF CONFIGURATIONS

During the Long Shutdown 2 (LS2, 2019-2020), the configuration of the 200 MHz RF system will change (to 4 cavities of 3 sections and 2 cavities of 4 sections) and the RF power will be upgraded [10], reducing the limitation from beam loading and increasing the maximum RF voltage to $V_{200} = 10$ MV for an intensity of $N_b = 2.4 \times 10^{11}$ ppb (25 ns beam). The upgrade will also change the total impedance of the TWC, both for the main harmonic and the HOMs. The main impedance for 3 sections was estimated using [11], while the HOMs impedance was scaled down by 40% with respect to the 4 sections TWC, keeping R/Q constant.

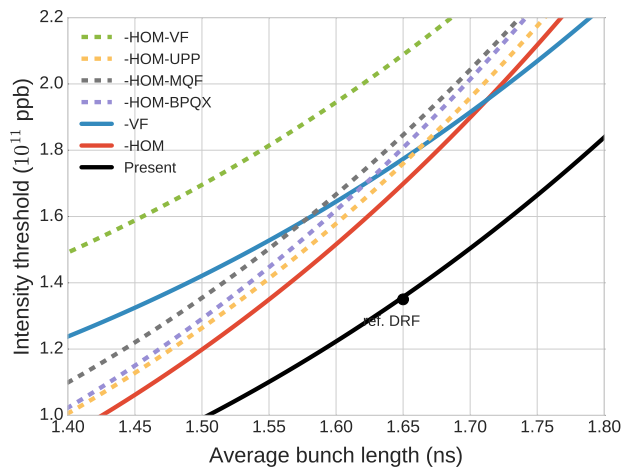


Figure 3: Stability threshold for 72 bunches with $V_{200} = 7$ MV and $V_{800} = 0.7$ MV, for various impedance removal. VF stands for the removals of all vacuum flanges, BPQX/MQF/UPP describes the removal of subsets of the vacuum flanges, and HOM of the 630 MHz HOM.

Results of simulations for the future RF configuration are compared with the current one in Fig. 4. It can be seen that the achievable parameters without impedance reduction would be $N_b = 2.1 \times 10^{11}$ ppb at $\tau_{av} = 1.65$ ns, still below the requirements for the HL-LHC project.

Therefore, an impedance reduction is foreseen to increase further the instability threshold. Again, the effect of the different impedance sources was tested by completely removing them. Results are shown in Fig. 4. Similar to the present 7 MV case, removing either the VF or the HOM at 630 MHz gives a small gain, while removing both is better and would allow reaching the HL-LHC requirements with a small margin. Concerning the kickers, the biggest contributors are the MKPs. A reduction by a factor 2 of their impedance would further increase the beam stability and the margin.

The impedance sources cannot be completely removed so realistic values were used based on a shielding model designed for the most critical vacuum flanges. Its impedance was estimated through RF simulations [2, 3]. Results for the realistic impedance reduction considered now as the LIU baseline are shown in Fig. 4. The reference point after the RF upgrade and a realistic impedance reduction is $N_b = 2.3 \times 10^{11}$ ppb at $\tau_{av} = 1.65$ ns. The gain is even bigger for lower bunches. In operation the bunch to bunch variability may lead to beam configurations where the spread in bunch length is bigger than in simulations. The beam stability would then be limited by the shortest bunches, and the dependence of the intensity with bunch length is important. Finally, there is no margin with respect to the HL-LHC requirements. Further damping of the HOM at 630 MHz would give more margin, but as it is already being damped by a dedicated coupler further damping is difficult. Another source of uncertainty is that some impedance may still be missing from the impedance model according to synchrotron

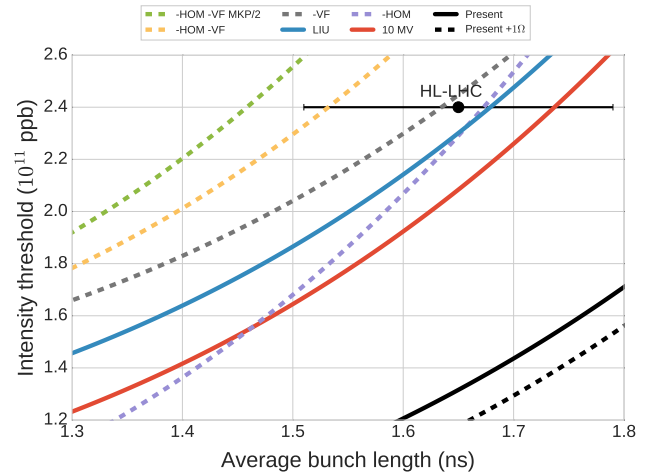


Figure 4: Effect of the removal of different impedance sources with $V_{200} = 10$ MV and $V_{800} = 1$ MV. VF corresponds to the removal of all vacuum flanges, HOM to the removal of the 630 MHz HOM and MKP/2 to the effect of reducing the MKP kickers impedance by a factor of 2. LIU stands for the baseline impedance reduction for realistic models. Lines for the current configuration, and by adding a constant reactive impedance of $\text{Im}Z/n \approx 1 \Omega$ are plotted in black for comparison. The point is the HL-LHC goal.

frequency shift studies [7]. The missing impedance can be estimated as a constant reactive impedance of $\text{Im}Z/n \approx 1 \Omega$, and the effect on the stability for the present configuration is shown in Fig. 4. The effect is to reduce the overall instability threshold, making our prediction slightly more pessimistic whilst remaining in the uncertainty. It shows mainly the minimum margin that should be taken to safely reach future requirements.

The RF upgrade and the impedance reduction make it possible to reach the HL-LHC requirements but with a very small margin, other means to increase it were also studied [8].

CONCLUSION

The simulations using BLoND code and the SPS impedance model are able to reproduce the intensity threshold observed for the LHC beam. According to simulations with the upgraded RF systems and impedance reduction, the HL-LHC goal is achievable, but with a tight margin. The next step is to run simulations during the ramp (8 s real time) with more realistic bunch-to-bunch variation and impedance reduction assumptions.

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REFERENCES

- [1] J. Varela *et al.*, “An Extended SPS Longitudinal Impedance Model”, in *Proc. IPAC’15*, Richmond, VA, USA, May 2015, paper MOPJE035, pp. 360–362.
- [2] J. Varela *et al.*, “Longitudinal Impedance Characterization of the CERN SPS Vacuum Flanges”, in *Proc. IPAC’15*, Richmond, VA, USA, May 2015, paper MOPJE036, pp. 363–365.
- [3] B. Salvant, J. Varela, C. Zannini, SPS Impedance Model Update, Meetings of the LIU-SPS BD WG, CERN, <http://cern.ch/spsu/>
- [4] BLonD, Beam Longitudinal Dynamics code: <http://blond.web.cern.ch/>
- [5] H. Timko *et al.*, “Benchmarking the Beam Longitudinal Dynamics Code BLonD”, presented at the 7th Int. Particle Accelerator Conf. (IPAC’16), Busan, Korea, May 2016, paper WEPOY045, this conference.
- [6] A. Lasheen *et al.*, “Synchrotron Frequency Shift as a Probe of the CERN SPS Reactive Impedance”, in *Proc. HB2014*, East-Lansing, MI, USA, November 2014, paper THO4LR02, pp. 409–413.
- [7] A. Lasheen *et al.*, “Single Bunch Longitudinal Instability in the CERN SPS”, presented at the 7th Int. Particle Accelerator Conf. (IPAC’16), Busan, Korea, May 2016, paper TUPOR009, this conference.
- [8] E. Shaposhnikova *et al.*, “Removing known SPS intensity limitations for High Luminosity LHC goals”, presented at the 7th Int. Particle Accelerator Conf. (IPAC’16), Busan, Korea, May 2016, paper MOPOY058, this conference.
- [9] T. Argyropoulos, “Results of MDs with high intensity 25 ns beam” (22/11/2012), Meetings of the LIU-SPS BD WG, CERN, <http://cern.ch/spsu/>
- [10] E. Shaposhnikova, E. Ciapala, E. Montesinos, “Upgrade of the 200 MHz RF system in the CERN SPS”, IPAC’11, San Sebastian, Spain (2011).
- [11] G. Dôme, “Travelling Wave Drift-Tube Structure for the CERN SPS”, in *Proc. Proton Linear Accelerator Conference 1976*, Chalk River, ON, Canada, 1976, pp. 138–147.