IDENTIFICATION AND REDUCTION OF THE CERN SPS IMPEDANCE

E. Shaposhnikova, T. Argyropoulos, T. Bohl, A. Lasheen, J. Repond, H. Timko,
CERN, Geneva, Switzerland

Abstract

The first SPS impedance reduction programme has been completed in 2001, preparing the ring for its role as an injector of the LHC. This action has eliminated microwave instability on the SPS flat bottom and later nominal beam could be delivered to the LHC. The High Luminosity (HL-) LHC project is based on beam with twice higher intensity than the nominal one. One of the important SPS intensity limitations are longitudinal instabilities with minimum threshold reached on the 450 GeV flat top. In this paper the work which was carried on to identify the impedance sources driving these instabilities is described together with the results expected from the next campaign of the SPS impedance reduction planned by the LHC Injector Upgrade (LIU) project.

INTRODUCTION

The LHC beam with 4 batches of 72 bunches with nominal intensity of 1.2×10^{11} p/b and spaced at 25 ns is operational in the SPS and was used by the LHC. During special machine development (MD) sessions the SPS has been able to deliver at top energy (450 GeV) up to four batches with bunch intensity of 1.4×10^{11}. This beam had nominal longitudinal and smaller than nominal transverse emittances.

The baseline LHC upgrade (HL-LHC) scenario is based on the SPS beam with 288 bunches of 2.3×10^{11} p/b spaced at 25 ns or 144 bunches of 3.6×10^{11} p/b at 50 ns [1].

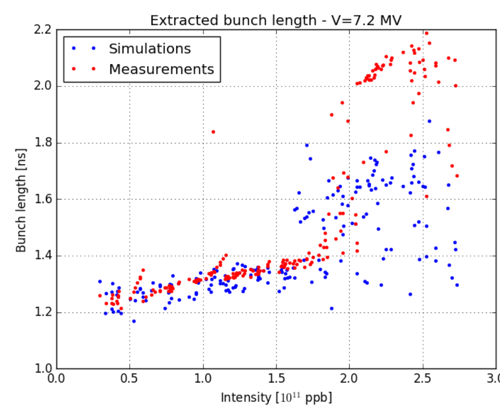
Presently the intensity of the LHC beam is limited by beam loading in the 200 MHz Travelling Wave cavities. In the frame of the LIU (LHC Injectors Upgrade) project [2] the 200 MHz RF system will be significantly upgraded. The plan includes the shortening of the existing long cavities from 5 to 4 sections together with doubling of the total RF power [3]. These modifications should allow the beam intensity of 2.4×10^{11} p/b to be accelerated to the top energy, but without any margin due to longitudinal instabilities which lead to emittance blow-up. This beam should be injected into the 400 MHz RF system of the LHC. To avoid increase of relative particle losses in the LHC, the average bunch length at the SPS extraction should not exceed the present value of 1.65 ns achieved with available voltage of 7 MV.

Longitudinal beam instabilities observed during acceleration ramp have extremely low threshold (6 times below the nominal intensity). Even recently the impedance sources driving this instability were not exactly known [4]. In the present operation the LHC beam is stabilised by the 4th harmonic (Landau) RF system operating in bunch-shortening (BS) mode and controlled longitudinal emittance blow-up, however for the HL-LHC beam the longitudinal emittance needed for beam stability could be too large for acceleration and extraction to the LHC. So during the last few years significant efforts went in identification of the impedance sources driving longitudinal instabilities and building the reliable impedance model of the SPS. The results of these studies are presented below.

LONGITUDINAL INSTABILITIES

Single-bunch Instability

A strong dependence of bunch length on intensity is observed on the SPS 450 GeV/c flat top for single bunches with intensities similar to that required for the LHC upgrade scenarios. This bunch lengthening exists in both single and double RF operation and could not be explained by the potential well distortion from the defocusing voltage due to the SPS reactive impedance with ImZ/n=3.5 Ohm [5]. The results of measurements imply that the threshold of microwave instability is hit during the acceleration cycle. The threshold depends on voltage program used for acceleration [6] and on the flat top is higher for the larger RF voltage. For bunches with longitudinal emittance (2σ) of 0.27 eVs the threshold of fast instability is around 1.8×10^{11}, see Fig.1.



bunch intensity

Figure 1: Measured (red) and simulated (including ramp, blue symbols) bunch length at 450 GeV/c as a function of intensity for a single bunch in a single 200 MHz RF system with 7.2 MV. Voltage program with 7 MV during the 2nd part of the ramp.

Taking into account slow-developing instability during the ramp, for bunches with injected emittance around 0.25 eVs the threshold on the flat top is close to 1.0×10^{11} in a single 200 MHz RF system and to 1.2×10^{11} in a double RF operation with voltage ratio around 0.1 [6].

ISBN 978-3-95450-178-6

Multi-bunch Instability

The longitudinal multi-bunch instability observed in the SPS during acceleration has a very low intensity threshold: one batch of 12 bunches at 25 ns spacing with 4×10^{10} p/b and nominal injected longitudinal emittance (0.35 eVs) is unstable on the SPS flat top. Higher intensities become unstable during acceleration ramp (see Fig. 2).

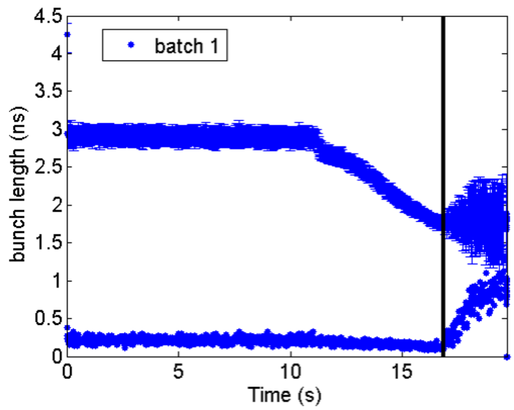


Figure 2: Longitudinal instability of 12 bunches spaced at 25 ns during the SPS ramp (from 26 to 450 GeV/c) in a single RF. Top trace: average bunch length, bottom: maximum bunch length deviation in the batch. Beam with average $N_b = 1.2 \times 10^{11}$ becomes unstable at 265 GeV/c.

Extensive beam measurements were performed recently with the goal to gain more information about possible impedance sources driving multi-bunch instability by studying dependence of its threshold on different machine and beam parameters, and in particular on the number of bunches in the batch and the length of the gap between the batches. The studies were conducted in a single RF system to minimise uncertainties related to the parameters of the 800 MHz RF system.

All measurements presented below were done in the new SPS optics Q20, in operation since 2012, having lower transition gamma γ_t (18 instead of previous 22.8) [7]. In this optics the gain in stability for a given longitudinal emittance is a factor of 2.8 at flat bottom and 1.8 at flat top (proportional to $\eta = 1/\gamma_t^2 - 1/\gamma^2$). Indeed significant increase in both transverse and longitudinal beam stability was obtained on the flat bottom. However for stability of the LHC beams on the flat top, a controlled emittance blow-up during ramp is still required in addition to operation of the higher harmonic RF system.

As can be seen from Fig. 3, 12 bunches with average bunch intensity N_b in the range $(0.5 - 2.0) \times 10^{11}$ and emittance ~ 0.32 eVs became unstable over a wide energy range during acceleration in a single RF system.

Bunches used for measurements in different MD (Machine Development) sessions had very different intensities (a factor 4 variation) and slightly different bunch length (2.8 ns ±5% variation on the flat bottom), but during

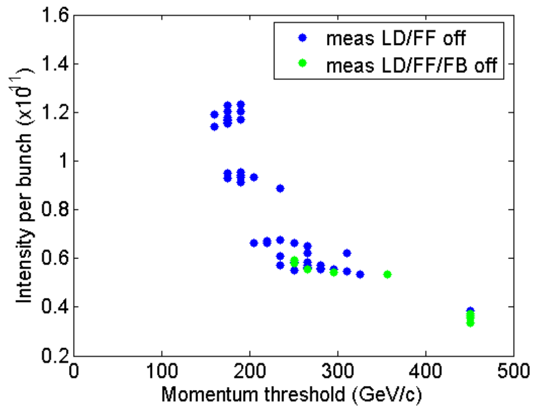


Figure 3: Threshold bunch intensity for 12 bunches as a function of beam energy during the SPS acceleration ramp in a single 200 MHz RF system. Measurements with longitudinal damper and feed-forward system off (blue dots), and without feedback in addition (green dots).

acceleration they all became unstable in the range (150-300) GeV/c. As expected from the calculated threshold for the coupled-bunch instability [8], the instability threshold clearly depends on beam energy E: more dense bunches become unstable earlier in the cycle. Far from transition energy the instability threshold scales roughly as $N_b \sim 1/E_{th}$, see Fig. 4, with minimum reached at the flat top energy.

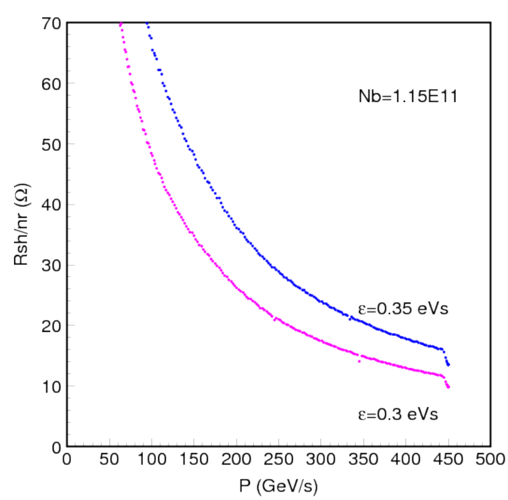


Figure 4: Coupled-bunch instability threshold R_{sh}/n_r ($n_r = f_r/f_0$ with $f_{r,0}$ being resonant and revolution frequencies) as a function of beam energy for bunch emittances of 0.3 and 0.35 eVs in a single 200 MHz RF system with a constant voltage of 6.5 MV above 100 GeV/c.

It was observed previously [4], that the instability threshold doesn't depend on the number of batches in the ring, at least for 50 ns spaced bunches with 250 ns batch gaps. A comparison of instability threshold $N_b E_{th}$ for batches with different number of bunches is shown in Fig. 5. Due to

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sharp reduction of threshold during ramp batches with different bunch intensity appear unstable roughly at the same energy during ramp. This threshold was also measured for two batches of 12 bunches spaced at different distance, see Fig. 6, and no significant variation in threshold could be recorded. The short-range wake is compatible with the main and HOM (630 MHz) impedances of the 200 MHz RF system which have, correspondingly, quality factors of 150 and 500. The impedance of the fundamental mode is significantly reduced by feed-back and feedforward systems and impedance of this HOM is already well damped by dedicated damping loops installed in all cavities. Nevertheless, as confirmed by particle simulations performed at the SPS flat top with 72 bunches using code BLonD [9], the total impedance of 300 kOhm of the HOM at 630 MHz is one of the main sources of multi-bunch instability in the SPS. The measured sharp dependence of intensity threshold on energy can be also reproduced in simulations with realistic model of the main 200 MHz impedance. The simulations show also that for 24 bunches the instability threshold is 30% higher than for 72 bunches [10].

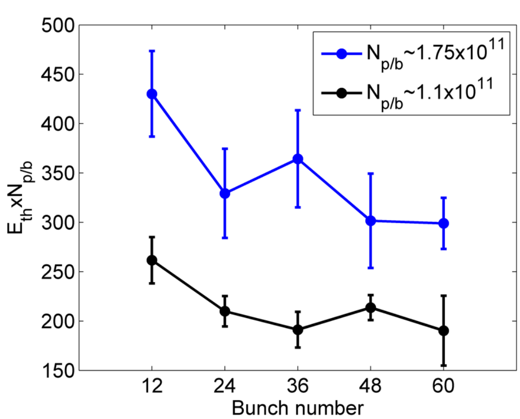

Figure 5: Instability threshold $E_{th}N_b$ for two different values of average bunch intensities N_b as a function of number of bunches spaced at 25 ns.

Measurements with Long Bunches

To identify possible sources of microwave instability various beam measurements were performed in the SPS. Microwave instability leads to an uncontrolled emittance blow-up and was one of the main intensity limitations for the SPS as an injector of the LHC. At that time the inter-magnet pumping ports were identified as a source of this instability by measuring the spectrum of long (~ 25 ns) single bunches injected into the SPS with RF off and intensity $\sim 2\times10^{10}$, above the instability threshold [11]. After shielding of 1000 pumping ports the microwave instability with RF on was not seen anymore on the 26 GeV/c SPS flat bottom for the LHC bunches up to an intensity of 2.0×10^{11}. The threshold has been also increased due to the Q20 optics.

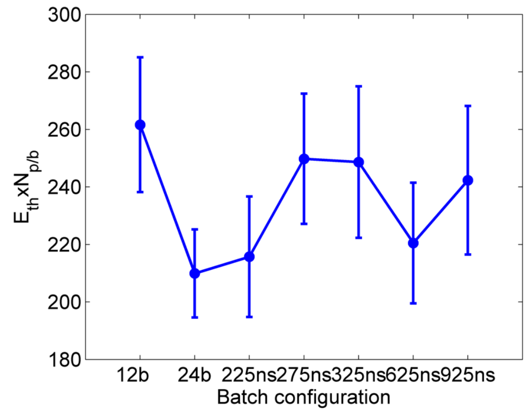

Figure 6: Instability threshold $E_{th}N_b$ for 12 bunches and different gaps between the two batches of 12 bunches (0, 225, 275, 325, 625 and 925 ns).

During developing of instability with RF off, unstable mode spectrum has a center frequency close to the resonant frequency of the impedance $\omega_r = 2\pi f_r$ and a width given by either the impedance width $\omega_r/(2Q)$ or by the bunch length τ (if $1/\tau \gg \omega_r/(2Q)$) [11]; hence longer bunches allow better resolution of resonant peaks, see Figs. 7, 8. In 2001, when the majority of pumping ports were shielded, practically no high frequency peaks were seen for intensity below 8×10^{10}. However, for higher intensities, bunch modulation at 1.4 GHz appeared.

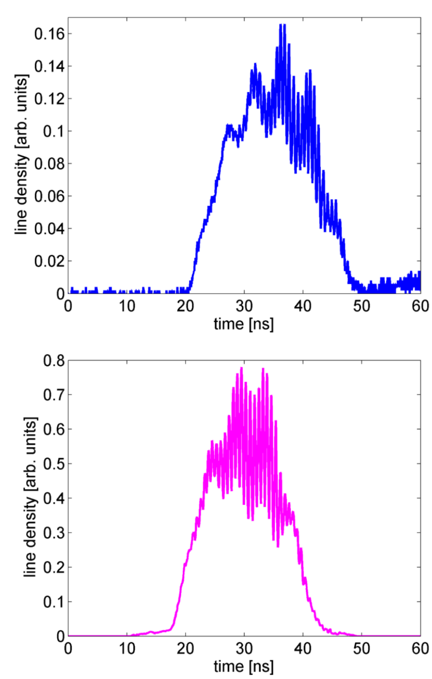

Figure 7: Line density modulation of long bunches ~ 400 turns after injection into the SPS with RF off in measurements (top) and simulations using full SPS impedance model (bottom). Bunch intensity $\sim 1\times10^{11}$.

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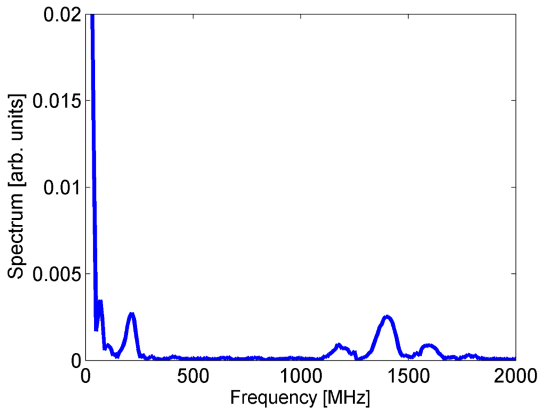

Figure 8: Fourier spectrum during developing of bunch instability shown in Fig. 7 (top).

Since microwave instability was again observed in the SPS, this time during acceleration of high intensity single bunches, measurements with long bunches injected into SPS with RF off were carried out to get more information about possible impedance sources [12], [13]. It was suspected that microwave instability is most probably driven by a resonant impedance at 1.4 GHz with peak in unstable bunch spectrum observed already in 2001. These measurements were repeated at intensities above 8×10^{11}. The possible parameter range of impedance (R_{sh} and Q) was narrowed down using a comparison of particle simulations with beam measurements [12], however the source of this impedance was not known till 2014, when it had been identified as an impedance of the SPS vacuum flanges. A layout survey of the whole SPS ring has been carried out to determine the total number and type of various vacuum flanges and to estimate their impedance contribution [14]. Most of these accidental cavities are damped by ceramic resistors to reduce the Q-factor and risk of coupled-bunch instabilities. Nevertheless the main impedance source responsible for longitudinal multi-bunch instabilities was identified to be vacuum flanges (VF) [10, 15].

Table 1 shows the most significant resonances found in the vacuum flanges [14]. The first two and the last rows of the Table show resonances in the cases where vertical and horizontal Beam Position Monitors (BPV and BPH, respectively) nearby are involved. Radiation losses are dominant for all enameled flanges having relatively low Q values (< 400). Higher Q values have been found for the non-enameled flanges. The resonances can also be divided in three groups: around 1.25 GHz, 1.4 GHz and 1.6 GHz, all visible in Fig. 8, however peaks around 1.4 GHz give the biggest contribution to the SPS impedance.

In the present SPS impedance model shown in Fig. 9, the vacuum flanges together with the 200 MHz and 800 MHz cavities are the three dominant contributors to the resistive impedance. The main contributions to the impedances with high R/Q are from the kicker magnets and again the 200 MHz cavities. The particle simulations performed using this model can reproduced most of observed features (see e.g. Fig. 1), but there are also indications that some inductive impedance with Im$Z/n \sim 1$ Ohm is still missing in the present model [6].

Table 1: The total impedance R_{sh} and quality factor Q of the dominant resonances of the SPS vacuum flanges with n identical elements in the ring. All these flange have enamel coating (except both "QF-QF" types) and attached bellows (except "QF-QF-nb"). Short or long damping resistor is placed inside bellows (except "BPV-QD" and "QF-QF-nb").

	Flange type	n	f_r [GHz]	R_{sh} [Ohm]	Q
1	BPV-QD	90	1.21	630	315
2	BPH-QF	39	1.28	1030	400
3	QF-MBA	83	1.41	1600	268
4	MBA-MBA	14	1.41	300	285
5	QF-QF	26	1.41	3765	1820
6	QF-QF-nb	20	1.61	590	980
7	BPH-QF	39	1.62	120	120

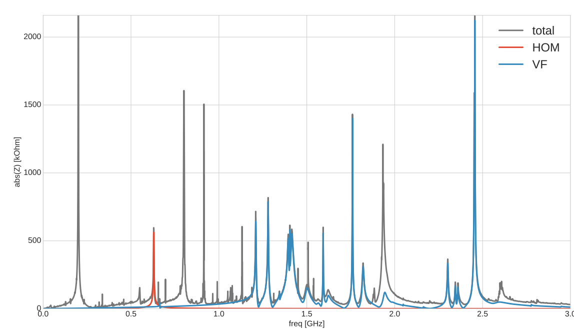

Figure 9: Present SPS longitudinal impedance model. Blue trace: contribution from the vacuum flanges (VF).

IMPEDANCE REDUCTION

The instability thresholds found from macroparticle simulations using code BLonD [9] at the SPS flat top for 72 bunches and a realistic SPS impedance model are shown in Fig. 10. The threshold found for one batch of 24 bunches is 30% higher [10].

As one can see, even with increased longitudinal emittance, possible due to RF upgrade, stability cannot be guaranteed for all bunches in the batch, mainly due to large bunch length spread along the SPS batch coming from controlled longitudinal emittance blow-up in presence of the beam loading in the 200 MHz TW RF system [16].

There are nine main types of flanges in the SPS and they can be divided into two large groups (with approximately 400 and 240 flanges each) by the shape of the main adjacent vacuum chambers (QD or QF), see Table 1. The present baseline of the LIU project [2] is to shield 240 QF-type vacuum flanges which have resonant impedances with the highest R/Q. The implementation will start during

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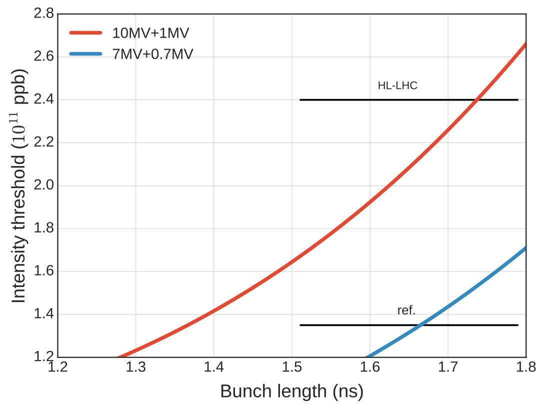

Figure 10: Instability threshold on the SPS flat top as a function of bunch length from particle simulations (code BLonD) with 72 bunches in a double RF (BS mode) for voltages of 10 MV (red line) and 7 MV (blue line) at 200 MHz and 10% value at 800 MHz. Black dots: beam parameters required by HL-LHC and those achieved in the SPS and used as a reference.

the end-of-year stops and will be completed in the long shutdown 2 (2019-2020). Since the majority of SPS flanges are insulating (enamel coating) with adjacent bellows, the shielding options depend on necessity to preserve isolation (gaps) or possibility to short circuit at least some of them (for details of ongoing investigation see [17]).

The instability thresholds found from particle simulations for the present SPS impedance model with realistic impedance reduction are shown in Fig. 11 for the situation after the RF upgrade (with 10 MV at 200 MHz). For main resonant peaks of $\sim$ 130 insulating QF-flanges a reduction of R/Q by at least a factor 20 was assumed. After shielding, the impedance of non-insulating flanges and of un-shielded pumping ports was assumed to be zero. Reducing the quality factor Q of the 630 MHz HOM in the 200 MHz RF system by a factor of 3 could further increase the instability threshold. However their damping is already very good and it is difficult to improve it significantly [18].

Additional ways of reaching longitudinal beam parameters required by the HL-LHC at extraction from the SPS were also studied [15] and include increased RF voltage in the 800 MHz RF system, bunch rotation on the SPS flat top and new SPS optics with intermediate γ_t.

Other potential intensity limitations in SPS (as e.g. from interception devices and e-cloud effect) also exist and are under studies. They were not discussed here.

SUMMARY

The SPS impedance was significantly reduced in the past in preparation of the SPS as an LHC injector. A new SPS impedance reduction campaign is planned now for the HL-LHC project, which requires bunch intensities twice as high as the nominal one. One of the known intensity limitations is a longitudinal multi-bunch instability. The

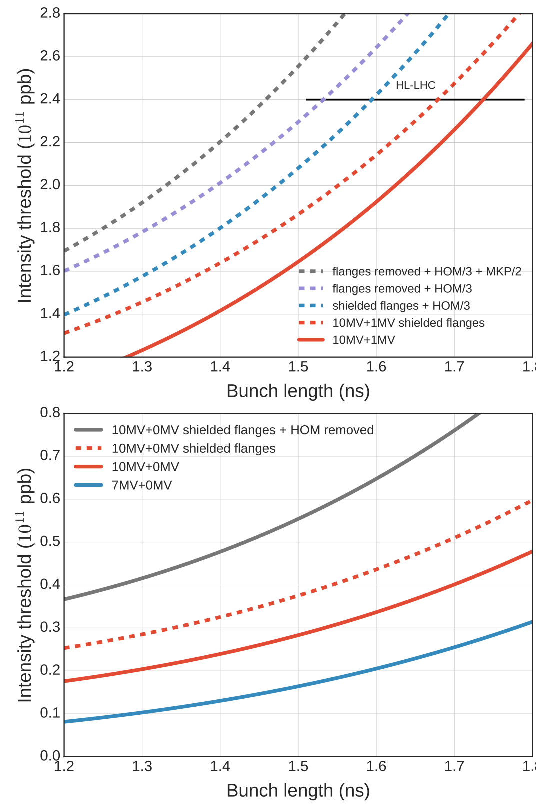

Figure 11: Top: instability threshold on the SPS flat top as a function of bunch length from particle simulations with 72 bunches in a double RF (BS mode) for voltages of 10 MV at 200 MHz and 1 MV at 800 MHz after RF upgrade (red). Dashed lines: different options of impedance reduction. Bottom: similar cases in a single RF system.

instability is presently cured using the 4th harmonic RF system and controlled emittance blow-up and its threshold will be increased after the foreseen upgrade of the 200 MHz RF system, but reaching the HL-LHC parameters cannot be assured without improving the machine impedance. The impedance sources responsible for this instability were identified using beam-based impedance measurements and implementation of their shielding and damping is foreseen during the next long shutdown.

ACKNOWLEDGMENTS

The work on impedance reduction involves many people and is coordinated by the LIU-SPS coordination team. The installation of shielding will be performed by CERN Vacuum Group. We are grateful to members of the LIU-SPS Coordination team and BD Working Group for useful discussions. We would like to thank R. Calaga, F. Caspers, A. Grudiev, T. Kaltenbacher, E. Montesinos, T. Roggen, B. Salvant, Y. Shashkov, J. Varela, C. Vollinger and C. Zannini for their contributions to SPS impedance measurements and calculations. We are grateful to H. Bartosik, H. Damerau and J. E. Muller for help in beam measurements. Special thanks go to the BLonD developers.

ISBN 978-3-95450-178-6

REFERENCES

[1] High-Luminosity Large Hadron Collider (HL-LHC): Preliminary Design Report edited by G. Apollinari *et al.*, Geneva, CERN (2015).

[2] “LHC Injectors Upgrade", Technical Design Report, Vol.I: Protons, edited by J. Coupard *et al.*, CERN-ACC-2014-0337 (2014).

[3] E. Shaposhnikova, E. Ciapala, E. Montesinos, “Upgrade of the 200 MHz RF system in the CERN SPS", *in Proc.* IPAC’11, San Sebastian, Spain (2011).

[4] E. Shaposhnikova *et al.*, “Longitudinal instabilities in the SPS and beam dynamics issues with high harmonic RF systems", *in Proc.* HB2012, Beijing, China (2012).

[5] T. Argyropoulos, “Longitudinal microwave instability in a multi-RF system", *Proc. HB2014*, East-Lansing, MI, USA (2014).

[6] A. Lasheen *et al.*, “Single bunch longitudinal instability in the CERN SPS", *in Proc.* IPAC’16, Busan, Korea (2016).

[7] H. Bartosik *et al.*, “Low gamma transition optics for the SPS: simulation and experimental results for high brightness beams", *in Proc.* HB2012, Beijing, China (2012).

[8] E. Shaposhnikova, “Longitudinal stability of the LHC beam in the SPS", CERN SL-Note-2001-031 HRF (2001).

[9] BLonD, Beam Longitudinal Dynamics code: http://blond.web.cern.ch/

[10] A. Lasheen *et al.*, “Effect of the various impedances on longitudinal beam stability in the CERN SPS", *in Proc.* IPAC’16, Busan, Korea (2016).

[11] T. Bohl, T. Linnecar and E. Shaposhnikova, Measuring the resonant structure of accelerator impedance with single bunches, PRL, v.78, N16 (1997).

[12] T. Argyropoulos *et al.*, “Identification of the SPS impedance at 1.4 GHz", *in Proc.* IPAC’13 (2013).

[13] E.Shaposhnikova *et al.*, “Identification of high-frequency resonant impedance in the CERN SPS", *in Proc.* IPAC’14, Dresden, Germany (2014).

[14] J. E. Varela, “Longitudinal impedance characterization of the CERN vacuum flanges”, *in Proc.* IPAC’15, Richmond, VA, USA (2015).

[15] E. Shaposhnikova *et al.*, “Removing known SPS intensity limitations for high luminosity LHC goals", *in Proc.* IPAC’16, Busan, Korea (2016).

[16] T. Argyropoulos *et al.*, Controlled longitudinal emittance blow-up in a double harmonic RF system at CERN SPS, *in Proc.* HB2010, Morschach, Switzerland (2010).

[17] T. Kaltenbacher, F. Caspers, C. Vollinger, Machine element contribution to the longitudinal impedance model of the CERN SPS, *in this Proc.* (2016).

[18] T. Rogen *et al.*, The SPS 200 MHz TWC impedance after the LIU upgrade, *in this Proc.* (2016).

ISBN 978-3-95450-178-6