UPGRADES OF THE RF SYSTEMS IN THE LHC INJECTOR COMPLEX

H. Damerau*, M. E. Angoletta, T. Argyropoulos, P. Baudrenghien, A. Blas, T. Bohl,
A. Butterworth, A. Findlay, R. Garoby, S. Gilardoni, S. Hancock, W. Höfle, J. Molendijk,
E. Montesinos, M. Paoluzzi, D. Perrelet, C. Rossi, E. Shaposhnikova
CERN, Geneva, Switzerland

Abstract

In the framework of the LHC Injector Upgrade (LIU) project the radio-frequency (RF) systems of the synchrotrons in the LHC injector chain will undergo significant improvements to reach the high beam intensity and quality required by the High-Luminosity (HL) LHC. Following the recent upgrade of the longitudinal beam control system in the PS Booster (PSB), tests with Finemet cavities are being performed in view of a complete replacement of the existing RF systems in the PSB by ones based on this technology. In the PS a similar wide-band Finemet cavity has been installed as a longitudinal damper. New 1-turn delay feedbacks on the main accelerating cavities to reduce their impedance have also been commissioned. Additional feedback and beam control improvements are foreseen. A major upgrade of the main RF system in the SPS by regrouping sections of its travelling wave cavities, increasing the number of cavities from four to six, will reduce beam-loading and allow higher intensities to be accelerated. This upgrade includes the installation of two new RF power plants and new feedback systems. All upgrades will be evaluated with respect to their expected benefits for the beams to the LHC.

INTRODUCTION

After the upgrades within the LIU project [1] the intensity of the LHC-type beams is expected to double in the injector chain. However, the longitudinal parameters, bunch length and longitudinal emittance, remain similar. This implies an important increase in longitudinal density and the need to significantly upgrade the RF systems in all accelerators of the LHC injector chain [2] to cope with an intensity of more than $2 \cdot 10^{13}$ ppb instead of the present $1.3 \cdot 10^{13}$ ppb with $25\,\text{ns}$ bunch spacing [3, 4].

Although an extensive number of alternatives for the production of LHC-type beam with various RF manipulations has been studied [5, 6], the original scheme for nominal LHC beam [7] remains the baseline. In total $4 + 2$ bunches, one per the PS Booster (PSB) ring, undergo triple splitting in the PS and batches of 72 bunches spaced by $25\,\text{ns}$ are delivered to the SPS. Up to four of these batches are accelerated to an energy of $450\,\text{GeV}$ in the SPS and extracted towards the LHC.

* heiko.damerau@cern.ch

PS BOOSTER

The PSB presently accelerates up to $1 \cdot 10^{13}$ ppb in a single bunch eventually doubling with its connection to Linac4. It is equipped with three ferrite-loaded cavities per ring. Two of these are operated at $0.59 - 1.75\,\text{MHz}$ ($h = 1$) and twice that frequency for the second harmonic cavity. A further ferrite-loaded cavity at about $6 - 16\,\text{MHz}$ serves for controlled longitudinal blow-up. Almost the entirety of the RF systems in the PSB is affected by the upgrades. The beam-control system has been exchanged by a fully digital low-level RF (LLRF) system [8, 9, 10] during the recent long shutdown (LS1). On the high-power side the replacement of the ferrite-loaded cavities at $h = 1$ and $h = 2$ by Finemet cavities covering both harmonics simultaneously is being prepared.

Beam Controls

Each of the four PSB rings is equipped with a largely independent beam control system, implementing beam phase, radial and synchronization loops. It generates drive signals for the three ferrite-loaded cavities, as well as for present and future Finemet systems. With the start-up after LS1, fully digital beam control systems have been successfully commissioned for all beams on all rings. Figure 1 shows an overview of the new, modular digital beam control of the PSB. For each ring it consists of three digital signal processing (DSP) boards with slots for ADC, DAC or digital synthesizer mezzanine modules. The different beam
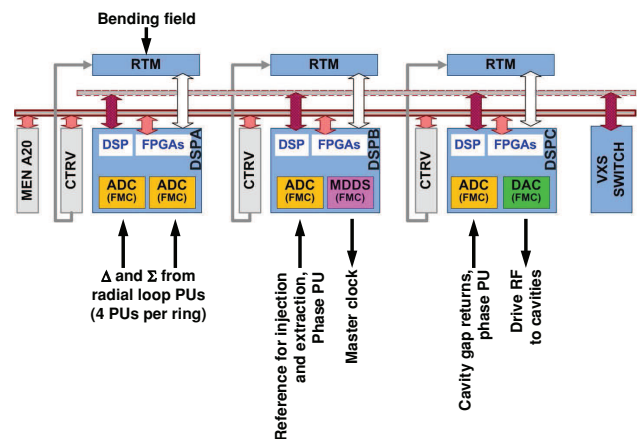

Figure 1: Digital beam control implementation in the PSB. RTM: Rear Transition Module, MDDS: Master Direct Digital Synthesizer, MEN A20: processor card, CTRV: timing card, VXS: VMEbus-switched serial standard.

and cavity controls loops are distributed over the DSP systems. The first signal processing board (Fig. 1, DSP A) takes care of the frequency program and the radial loop. The beam phase and synchronization loops for injection and extraction are integrated in DSP B, while DSP C generates the drive signals to the RF cavities and reads back the cavity gap returns. The modular approach of the beam control allows to add further DSP units to integrate more PU signals or to drive more cavities. An additional DSP board equipped with one ADC and one DAC module is added for processing Finemet signals and implementing four or more cavity loops.

Flexibility and stability are the key advantages of the upgraded beam control system. All control parameters, like sensitivities, loop gains and phases are settable in pulse-to-pulse (PPM) so that optimum parameters can be chosen for each beam type. The flexibility goes well beyond the choice of parameter settings. As the loops are implemented in DSP firmware, the system is reconfigurable so that extensions, like new algorithms for synchronization, can be added without hardware change.

Finemet Cavities

The aging ferrite-loaded cavities and their power amplifiers would require significant upgrades to cope with the increased beam-loading after the second long shutdown (LS2). Replacing them by Finemet cavities driven by solid state amplifiers [11] is thus the preferred upgrade path for the high-power RF system, which will significantly simplify the hardware and its maintenance. Due to the large bandwidth of Finemet cavities, no tuning will be needed and the frequency of both main RF systems at $h = 1$ and $h = 2$ can be covered by one cavity. Only the cavity for longitudinal blow-up would remain with traditional ferrite technology. A first prototype Finemet cavity (5 cells, Fig. 2, left) has been installed in ring 4 of the PSB and tested with beam in 2012. Driven by the digital LLRF, it
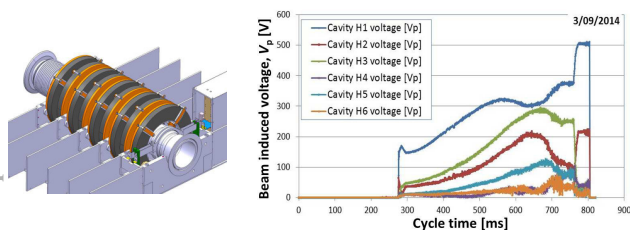

Figure 2: Sketch of the 5-cell Finemet cavity used for beam tests in 2012 (left). The last Finemet ring is not shown to leave the view to the gap. Beam induced voltage (right) at the first six harmonics during acceleration of a single bunch with $7.3 \cdot 10^{11}$ ppb as recorded by the digital LLRF. Injection is at 275 ms and ejection at 805 ms.

has been demonstrated that, together with the ferrite-loaded cavity at reduced voltage, a beam intensity of $4.6 \cdot 10^{12}$ ppb could be handled. The Finemet cavity delivered a voltage of about 2 kV. Since the amplitude control loop was only

closed around $h = 1$, a distortion of the gap voltage without noticeable effect on beam quality was observed.

These encouraging results [12] led to the installation of a 10-cell cavity with new amplifiers and an improved fast RF feedback during LS1. This second prototype delivers sufficient voltage for acceleration on $h = 1$ to replace the ferrite-loaded cavity or to serve for bunch flattening at $h = 2$. Due to the large bandwidth of the Finemet cavity, the digital LLRF will servo the gap voltage at different harmonics simultaneously. Two voltage control (AVC) loops at the first two harmonics, as well as further loops to reduce the beam induced voltage at higher harmonics are foreseen, easily possible with the digital LLRF. Figure 2, right shows a first measurement of the beam induced voltage during the cycle at the first six harmonics. A series of beam tests to verify reliability and limitations of the prototype Finemet cavity is planned for 2015. The decision whether to move to a Finemet-based acceleration system or to upgrade the existing ferrite-loaded cavities will be taken by the end of 2015.

PS

The final bunch spacing for the LHC is prepared by RF manipulations in the PS. Acceleration and these manipulations are achieved with, in total, 25 RF cavities (11 × 2.8 − 10 MHz, 2 × 20 MHz, 2 × 40 MHz, 3 × 80 MHz, 6 × 200 MHz and a Finemet wide-band cavity). Two major limitations are observed with LHC-type beams [13]. Firstly, longitudinal coupled-bunch (CB) instabilities are excited during acceleration, after transition crossing and on the flat-top. Secondly, differing transient beam-loading behaviour of the cavities for bunch-splittings causes an unequal bunch population along the batch. To suppress CB instabilities a Finemet cavity has been installed as a wide-band longitudinal kicker. In addition to increase the direct feedback gain, improved 1-turn delay feedbacks for the 10 MHz cavities have been commissioned. Similar feedbacks are foreseen for the cavities at 20 MHz, 40 MHz and 80 MHz.

Beam Control Improvements and Upgrade

Gradual improvements have been implemented in the longitudinal beam control to follow the demand for more complicated RF manipulations for the LHC-type beams [14, 15]. Figure 3 illustrates the measured evolution of the bunches during the batch compression, merging and triple splitting (BCMS) manipulations in closed loop. It involves RF systems at $h = 7, 9, 10, 11, 12, 13, 14, 21$ and requires beam phase and radial loops at harmonic 7, 9, 11, 13, 21. RF manipulations involving even more harmonics will be tested during the 2014/2015 runs. To keep full flexibility of the beam control and to assure reliable operation for HL-LHC, a complete replacement of the LLRF by a fully digital system is planned during LS2.
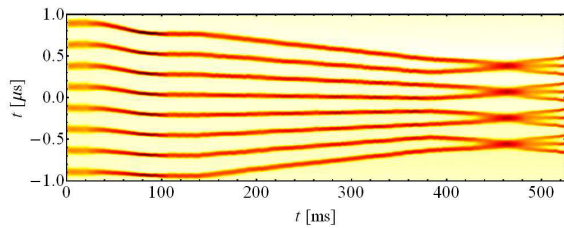
Figure 3: Measured bunch profile evolution during batch compression, merging and triple splitting (BCMS).

Direct RF Feedback

To reduce the residual impedance of the RF cavities all $10\,\text{MHz}$, $20\,\text{MHz}$, $40\,\text{MHz}$, and $80\,\text{MHz}$ systems are equipped with direct RF feedback around the amplifier. The maximum gain, ranging from $24\,\text{dB}$ to more than $40\,\text{dB}$, depends on the bandwidth requirement and the delay of the amplifier chain. Extensive studies have been performed for the $10\,\text{MHz}$ cavities and a possible increase of the feedback gain (at least $3\,\text{dB}$) has been demonstrated. Further improvements are foreseen before any cavity in the PS ring will be equipped with the new feedback circuit. The direct feedbacks of the $40\,\text{MHz}$ and $80\,\text{MHz}$ RF systems are also being reviewed. The feedback amplifiers are located in separated alcoves, but could be moved closer to the cavity to reduce delay in the signal path.

1-Turn Delay Feedbacks

During LS1 a first generation 1-turn delay feedback [16] has been replaced by new flexible hardware based on programmable logic (FPGA) making it applicable to all beams, notably the LHC-type beams accelerated on $h = 7$ and $h = 21$ with various intermediate harmonics for RF manipulations.

It consists of a comb filter periodic with the revolution frequency to pass only the revolution frequency harmonics and synchrotron frequency side-bands, a notch filter to remove any gain on the RF harmonic and an automatic delay to make the total loop delay equal to the time-of-flight of one turn. The simulated and measured open-loop transfer function of the feedback system is shown in Fig. 4, left. Closing the feedback system around the cav-
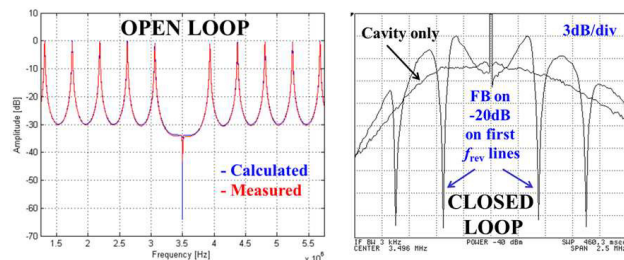

Figure 4: Simulated/measured open-loop transfer function (left) and closed-loop transfer function of the 1-turn delay feedback for the $10\,\text{MHz}$ cavities.

ity (Fig. 4, right) shows the cavity transfer function with the impedance reduction at the revolution frequency lines. The new 1-turn delay feedback has been commissioned on all eleven $10\,\text{MHz}$ cavities during the 2014 start-up.

The new feedback hardware will also be installed on the high-frequency cavities. The impedance of the $40\,\text{MHz}$ and $80\,\text{MHz}$ cavities with their mechanical short-circuit, which cannot be moved in PPM, will be reduced by 1-turn delay feedback.

Coupled-Bunch Feedback

To suppress the CB instabilities observed during acceleration and on the flat-top a new feedback system is under development [17]. To cover all possible CB oscillation modes, a Finemet cavity as a wide-band longitudinal feedback kicker has been installed in the PS during LS1. The six cavity cells are designed for an RF voltage of about $5\,\text{kV}$ in the range from $0.4\,\text{MHz}$ (f_{rev}) to $5\,\text{MHz}$ ($f_{\text{RF}}/2$).

The digital LLRF for the Finemet cavity will detect synchrotron frequency side-bands indicating CB oscillations and feed them back to the beam via the Finemet cavity. Additionally, a multi-harmonic beam-loading compensation feedback based on a bank of narrow-band filters at the relevant revolution frequency harmonics is being tested to reduce the shunt impedance of the wide-band cavity. Due to the large bandwidth requirement and the signal delay between cavity in power amplifiers, direct feedback would only be possible with low gain. Figure 5 illustrates the spectrum of the cavity voltage induced by a short single bunch. At the four harmonics at which a prototype beam-
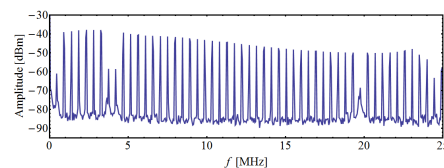

Figure 5: Beam induced voltage in the PS Finemet cavity of a single bunch close to transition. The prototype beam-loading compensation is set to harmonics $h = 1$, 8, 9 and 42, reducing the induced voltage by approximately $20\,\text{dB}$.

loading compensation is programmed, significant reduction of the beam induced voltage is measured, compatible with the gain of the open-loop transfer function. First beam tests with the new CB feedbacks have started in 2014 and it will be made operational during the 2015 run.

SPS

The main RF system of the SPS at $200\,\text{MHz}$ consists of travelling wave cavities made up from sections of crossbar structure cells [18] driven by tetrode amplifiers. The maximum RF voltage for a given input power depends on cavity length and beam current. In view of the increased intensity for LHC-type beams in the SPS, the sections will be rearranged to shorter cavities [19]. The RF system at

200 MHz is complemented by two travelling wave cavities at 800 MHz (200 kW per cavity) delivering about $10-15\%$ of the main RF voltage. The phase between both RF systems must be precisely controlled during acceleration for optimum beam stability and blow-up. The LLRF system of the 800 MHz RF system has therefore been redesigned.

RF Power Considerations

Presently in total 18 cavity sections are arranged to two 4-section and two 5-section cavities with a continuous power of 0.7 MW per cavity. However, this configuration leaves no margin for intensity increase [20] as the maximum amplifier power is reached with a bunch population of $1.2 \cdot 10^{11}$ ppb (25 ns spacing). To keep longitudinal stability during acceleration, the longitudinal emittance is increased from 0.35 eVs to 0.5 eVs by controlled longitudinal blow-up. At higher intensity, due to beam-loading, the voltage per cavity becomes insufficient, especially for the long 5-section cavities [21].

During LS2, the travelling wave cavity sections will therefore be rearranged in four 3-section and two 4-section cavities, using two additional spare sections and reducing the beam coupling impedance by 18%. Moving from four to six cavities requires two additional RF power plants with an RF power of 1.6 MW delivered to the 4-section cavities. Civil engineering for a new building is progressing. The four 3-section cavities will be powered by the existing amplifiers. Their present continuous power limit of 0.7 MW increases to 1.05 MW when operated in pulsed mode (LHC-type beams only fill up to $4/11$ of the circumference).

The bucket area during acceleration with four 3-section and two 4-section cavities at maximum RF power is illustrated in Fig. 6 for various bunch populations. At a bunch
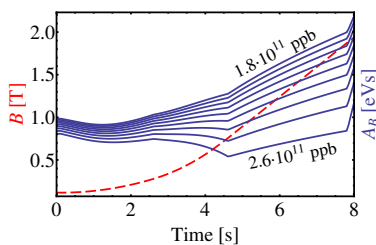

Figure 6: Bucket area (blue) for bunch populations from $1.8 \cdot 10^{11}$ ppb to $2.6 \cdot 10^{11}$ ppb at maximum RF power ($1.05/1.6$ MW) during the acceleration cycle (2014, $\gamma_{tr} = 18$, 25 ns bunch spacing). From one trace to the next, the number of protons increases by $0.2 \cdot 10^{11}$ ppb.

population of about $2.5 \cdot 10^{11}$ ppb the bucket area does not increase during acceleration anymore, leaving no margin for controlled longitudinal emittance blow-up. It is therefore being considered to decrease the ramp rate (Fig. 7) to gain in longitudinal acceptance or to raise transition energy to $\gamma_{tr} = 20$ [5].
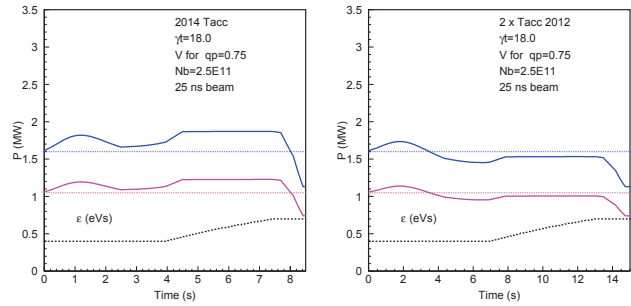
Figure 7: RF power requirement for a bunch population of $2.5 \cdot 10^{11}$ ppb during the cycle (2014, left) and for twice longer acceleration (right).

The bunches must be shortened to 1.7 ns (4σ Gaussian fit) prior to extraction to fit into the 2.5 ns long buckets in the LHC. Again the maximum achievable voltage is reduced by beam-loading with increasing beam current (Fig. 8). At the same time, taking the voltage reduction by potential-well distortion (PWD) and the single-bunch instability due to loss of Landau damping into account [20], the RF voltage required for constant bunch length rises linearly with intensity [22, 23]. The measured beam parameters
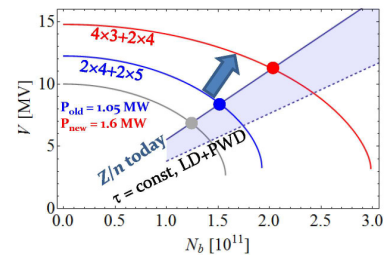

Figure 8: RF voltage versus beam current (in units of bunch population for 25 ns spacing) for present and upgraded cavity configuration together with the linearly increasing voltage requirement. The equivalent RF current for the bunch spacing τ_{bb} is $I_{RF} = 2 N_b e_0 / \tau_{bb}$.

at $1.3 \cdot 10^{11}$ ppb and 7 MV for 1.7 ns long bunches (2012) are the reference point for instability line in Fig. 8. With the present longitudinal emittance and no increase in bunch length nor ramp time, the maximum achievable bunch population after the RF upgrade is estimated to $2.0 \cdot 10^{11}$ ppb.

Significant effort has been made to identify sources of longitudinal impedance [24, 25] driving instabilities. Figure 9 shows the measured amplitude projection of the bunch spectrum as observed when injecting long bunches into the SPS. While the impedance at 200 MHz due to the RF cavities are well understood, the vacuum flanges (about 550) have been identified (Fig. 9) as most probable source for the important peak at 1.4 GHz. The seven flange types all have a resonance frequencies from 1.2 GHz to 1.6 GHz with shunt impedances from $120\,\Omega$ to $2.8\,k\Omega$. Possible shielding to reduce their R/Q is being investigated. Assuming an impedance reduction of approximately
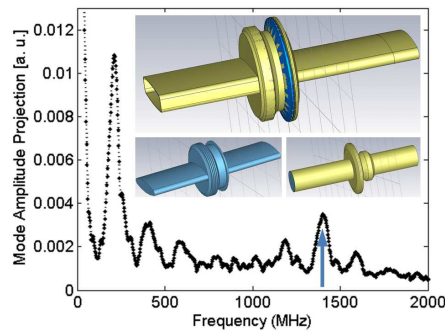
Figure 9: Bunch spectrum of 25 ns long bunches injected with RF off and different types of SPS vacuum flanges.

Figure 10: Simplified diagram of the RF loops around one 800 MHz cavity.

50 % could raise the bunch population to $2.4 \cdot 10^{11}$ ppb for LHC-type beams with 25 ns spacing.

Bunch rotation is studied as complementary approach to achieve short bunches at transfer to the LHC. In the context of the plasma wake field experiment AWAKE at the SPS, single bunches of $2.8 \cdot 10^{11}$ ppb have been successfully compressed from 2.2 ns to 1.2 ns [26]. Tracking simulation studies with multi-bunch beams indicate that bunches of $2.3 \cdot 10^{11}$ ppb could be compressed from 2.2 ns to 1.6 ns average bunch length applying a voltage step from 5 MV to 10 MV [5]. These simulations include effects of the SPS impedance as well as the feedback and feed-forward systems of the 200 MHz RF cavities.

Feedbacks and Beam Controls

In the framework of the upgrades, new LLRF systems will be installed for both, 200 MHz and 800 MHz systems. Priority has been given to feedback and feed-forward [27] of the 800 MHz cavities as precisely controlling their phase with respect to the 200 MHz RF system is essential for the stability and quality of LHC-type beams. The phase must be kept constant with respect to the 200 MHz RF voltage along the batch to achieve bunches with equal parameters. Uniform controlled longitudinal blow-up requires the same synchrotron frequency distribution for all bunches.

A new multi-function feedback controller has been developed which contains an I/Q-loop for the cavity field control, as well as a comb-filter based feedback including a cavity filter to compensate the frequency response of the travelling wave structure and a direct RF feed-forward demodulating the beam signal from a PU. Figure 10 sketches the main loops around one 800 MHz cavity. Additionally, the feedback controller contains a polar loop to correct amplitude and phase drifts of the high power amplifiers (four inductive output tubes). The new LLRF has been installed on one cavity and commissioning has started. Both cavities will be operational with the new hardware by mid 2015.

CONCLUSIONS

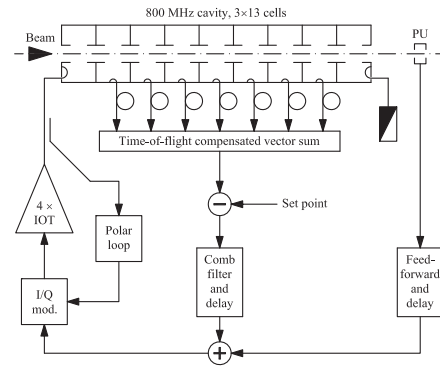The RF systems in the injector chain will be improved to reach a bunch population beyond $2.0 \cdot 10^{11}$ ppb with 25 ns bunch spacing for HL-LHC. First upgrades were put in place during LS1, but the major part will be implemented during LS2.

REFERENCES

[1] R. Garoby et al., IPAC2012, p. 1010.

[2] E. Jensen, Chamonix 2012 LHC Performance Workshop, CERN-2012-006, p. 261.

[3] G. Rumolo et al., Review of LHC and Injector Upgrade Plans (RLIUP), p. 17.

[4] G. Rumolo et al., Chamonix 2014 LHC Performance Workshop, to be published.

[5] T. Argyropoulos et al., Chamonix 2014 LHC Performance Workshop, to be published.

[6] H. Damerau et al., Review of LHC and Injector Upgrade Plans (RLIUP), CERN-2014-006, p. 127.

[7] M. Benedikt et al., CERN-2004-003.

[8] M. E. Angoletta et al., IPAC2010, p. 1461.

[9] M. E. Angoletta et al., IPAC2010, p. 1464.

[10] M. E. Angoletta et al., IBIC2013, p. 575.

[11] M. M. Paoluzzi et al., IPAC12, p. 3749.

[12] M. M. Paoluzzi et al., IPAC2013, p. 2660.

[13] H. Damerau et al., HB2010, p. 193.

[14] H. Damerau, et al., IPAC10, p. 2716.

[15] H. Damerau et al., IPAC2013, p. 2600.

[16] F. Blas, R. Garoby, PAC91, p. 1398.

[17] H. Damerau et al., IPAC2013, p. 1808.

[18] G. Dôme, LINAC76, p. 138.

[19] E. Shaposhnikova, et al., IPAC2011, p. 2014.

[20] E. Shaposhnikova, http://paf-spsu.web.cern.ch/paf-spsu/meetings/2013/m11-07/SPSRF_US1_BD.pptx.

[21] T. Bohl, Chamonix 2000 SPS and LEP Performance Workshop, CERN-SL-2000-007-DI, p. 58.

[22] E. Shaposhnikova, LHC Project Note 242.

[23] E. Shaposhnikova, SL-Note-2001-031 HRF.

[24] T. Argyropoulos et al., IPAC2013, p. 1793.

[25] E. Shaposhnikova et al., IPAC14, p. 1416.

[26] H. Timko et al., IPAC2013, p. 1820.

[27] P. Baudrenghien, G. Lambert, Chamonix 2000 SPS and LEP Performance Workshop, CERN-SL-2000-007-DI, p. 94.