

MACHINE DEVELOPMENT STUDIES IN THE CERN PS BOOSTER, IN 2016

E. Benedetto, S. Albright, M. E. Angoletta, W. Bartmann, J. Belleman, A. Blas, M. Cieslak-Kowalska¹, G. P. Di Giovanni, A. Findlay, V. Forte, A. Garcia-Tabares, G. Guidoboni, S. Hancock, M. Jaussi, B. Mikulec, J. Molendijk, A. Oeftiger, T. Rijoff, F. Schmidt, P. Zisopoulos², CERN, Geneva, Switzerland
¹also at EPFL, Lausanne, Switzerland; ²also at Uppsala University, Uppsala, Sweden

Abstract

The paper presents the outstanding studies performed in 2016 in preparation of the PS Booster upgrade, within the LHC Injector Upgrade project (LIU), to provide twice higher brightness and intensity to the High-Luminosity LHC. Major changes include the increase of injection and extraction energy, the implementation of a H⁻ charge-exchange injection system, the replacement of the present Main Power Supply and the deployment of a new RF system (and related Low-Level), based on the Finemet technology. Although the major improvements will be visible only after the upgrade, the present machine can already benefit of the work done, in terms of better brightness, transmission and improved reproducibility of the present operational beams. Studies address the space-charge limitations at low energy, for which a detailed optics model is needed and for which mitigation measurements are under study, and the blow-up reduction at injection in the downstream machine, for which the beams need careful preparation and transmission. Moreover they address the requirements and the reliability of new beam instrumentation and hardware that is being installed in view of LIU.

INTRODUCTION

The Proton Synchrotron Booster (PSB) at CERN is the first synchrotron in the LHC proton injection chain and will be given several important upgrades during Long Shutdown 2 (LS2), including an increased injection and extraction energy, and new RF system [1]. This paper discusses a number of important Machine Development (MD) studies that took place in 2016 in preparation for the upgrades. The longitudinal studies are related to mitigation of space charge effects in the PS and the High-Level RF (HLRF) and Low Level RF (LLRF) upgrades. The transverse studies relate to the maximum attainable brightness, and the effect of the 160 MeV injection energy after the upgrades with efforts to build a non-linear model. Finally results related to the transfer of beams to and from the PSB are presented.

LONGITUDINAL STUDIES

PS Space Charge Mitigation

Mitigation of space charge in the PS has been studied with large longitudinal emittances and hollow bunches. Both provide a reduced line density and an increased beam size

from dispersion, leading to a reduction in the transverse tune footprint.

The LIU-PSB baseline requires LHC beams with 3 eVs longitudinal emittance and 205 ns bunch length at 2 GeV [2]. Presently the highest transferable bunch length to the PS is 220 ns at 2.8 eVs emittance, therefore this was the emittance produced in these studies. PSB longitudinal emittance blowup uses phase modulation in a high harmonic cavity. Optimisation of this process provided the first demonstration that bunches can be produced with the 2.8 eVs longitudinal emittance required as shown in the top plot of Fig. 1.

An alternative to large emittances is hollow bunches, as shown in Fig. 1. For a given bunch length, transverse emittance and intensity, it has been shown that hollow bunches suffer from much less emittance growth than parabolic bunches [3]. The hollow bunch production scheme requires a minor modification of the nominal LHC production cycle, using a dipolar parametric resonance to deplete the bunch center. Further studies confirmed the potential to provide larger longitudinal emittances by shifting the parametric resonance towards the end of the PSB cycle.

HLRF and LLRF Studies

New LLRF features for MDs and operation were requested for the 2016 run [4]. The longitudinal blowup scheme was improved to guarantee a phase lock between the C16 and the C02 RF systems. The firmware was also modified to guarantee a reproducible phase after each harmonic change. A new algorithm to move from a fixed injection frequency to the frequency program was implemented, minimising the beam phase oscillations during the transition. The LLRF timings and synchronisations were updated to give the option of studying the effects of some intended LS2 upgrades. Finally, an optimised algorithm was implemented to minimise the beam shaking during the extraction synchronisation process, as shown in Fig. 2.

The optimised extraction synchronisation algorithm highlighted a perturbation at extraction on the PSB outer rings 1 and 4. The perturbation was caused by a magnetic field influence on the Pick-UP (PU) head amplifier, which was eliminated in ring 1 by shielding the phase PU. The same shielding will be installed in ring 4 over the 2017 PSB run, meanwhile a different PU was selected far from the field leak.

A novel operation of the wideband HLRF system as $h = 3$ was implemented, allowing triple-harmonic operation. Pre-

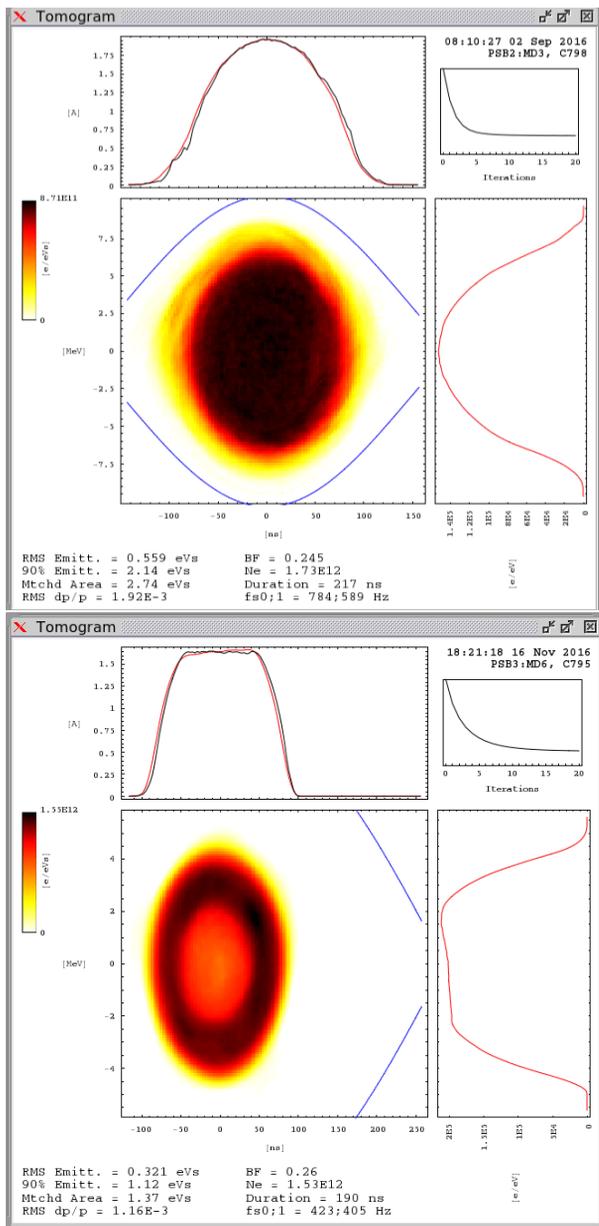


Figure 1: Reconstructed phase space of a bunch with 2.8 eVs emittance (top) and a hollow bunch (bottom) prior to transfer to the PS. The line density projection is shown at the top, and the energy spread to the right clearly showing the difference between parabolic and hollow distributions.

liminary results indicate that this new operational mode reduces losses early in the cycle. More details on the PSB Finemet operation can be found in [5].

TRANSVERSE STUDIES

Brightness

Increasing the injection energy from 50 MeV to 160 MeV with Linac4 gives a factor $(\beta\gamma^2)_{160\text{MeV}}/(\beta\gamma^2)_{50\text{MeV}} = 2.04$ reduction of the space charge tune spread. The LIU baseline

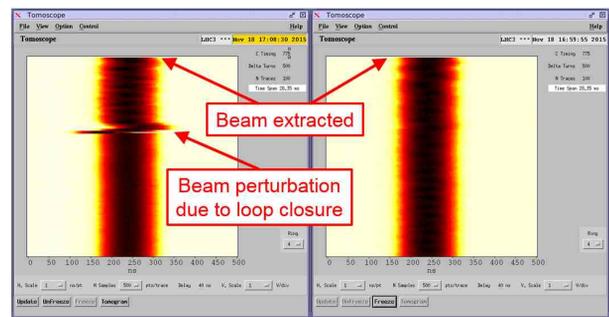


Figure 2: Tomograms of bunches at extraction before (left) and after (right) algorithm optimisation.

is to have the same injection tune spread with twice the intensity for a given emittance [1].

The average transverse emittance versus extracted intensity line of the 25 ns LHC beam, as described in the LHC design report [6], was measured with a rotating wire-scanner at the end of 2015, see Fig. 3. The brightness at the end of 2015 agrees with measurements from 2012 [7], despite a 15% drop in linac current.

Figure 3 also shows emittance versus extracted intensity and a comparison with simulation. The red squares refer to two simulations at 50 MeV injection energy, for the working points (4.28, 4.65) and (4.42, 4.45). The green triangles and blue stars correspond to simulations at 160 MeV, assuming the two working points (4.33, 4.55) and (4.43, 4.60), in comparison with the measured line scaled by a factor 2.

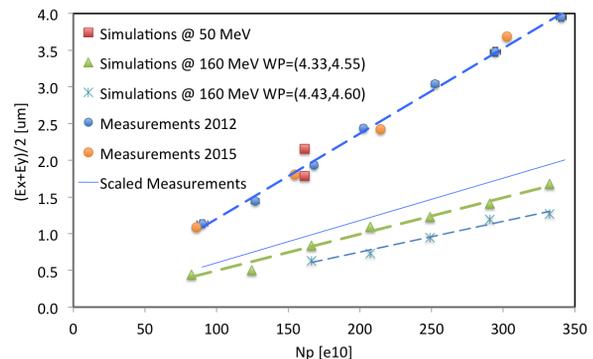


Figure 3: Measured and simulated normalised average emittances versus intensity from 2012 (blue circles) and 2015 (orange circles) [8], with simulations of future behaviour with 160 MeV injection.

Nonlinear Model

To maximise present and future machine performance, better knowledge and optimization of the linear and non-linear models are needed. Systematic studies with turn-by-turn BPMs will be done next year. Preliminary analysis of data coming from the monitors equipped with turn-by-turn readings has been started, in order to derive beta-beating information, commission the hardware and validate the method of the AC Dipole excitation at a low-energy ring [9].

Measurements of the non-linear chromaticity were made on a 160 MeV flat-top cycle and compared with the model, which includes only the main bends, quadrupoles and the chromaticity sextupoles family. Studies were done with two working points, the standard one (4.20, 4.32), and a second special one (3.32, 3.81).

Other Transverse Studies

Several other studies were conducted, in particular to characterize the tail-repopulation mechanism after scraping, discussed in details in [10], and to benchmark the impedance model with beam based measurements.

BEAM TRANSFER STUDIES

Tomography at PSB Injection

Due to the multi-turn injection process no attempt was made to synchronize the injection with the RF. A dedicated cycle was built introducing distributor timings that are synchronized to the RF train, and then count 40 MHz clock ticks reducing jitter to 25 ns. This cycle was used to study the Linac2 to PSB injection process.

It can be proven mathematically [11] that the RF bucket during the first couple of milliseconds after injection is actually a decelerating one due to the fixed RF frequency. By incorporating the acquired understanding of the physics in the first couple of milliseconds, it was possible to perform tomographic analysis after injection.

With a reproducible phase at injection, the process becomes similar to a bunch-into-bucket transfer, which enables monitoring of the energy of the incoming beam and to adapt the injection frequency accordingly. As a consequence, it is possible to evaluate any variation in what is delivered by Linac2 and perform energy matching at PSB injection, see Fig. 4.

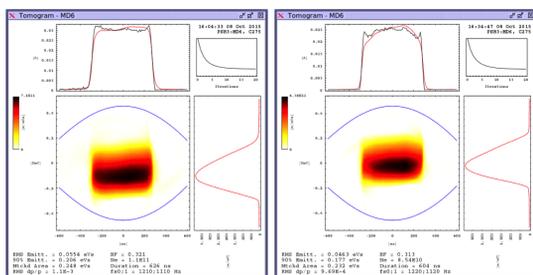


Figure 4: Tomogram at the PSB injection for the initial fixed RF frequency (left) and the corrected RF frequency (right) adapted for a proper energy matching.

PSB Extraction at 160 MeV

During commissioning after the LS2 upgrades, one of the first steps will be the establishment of the closed orbit. As there is no internal dump, the possibility of extracting at 160 MeV rather than losing the beam in the rings was studied. A new optics was calculated for the extraction and the transfer lines to the dump and tested in two dedicated

MD sessions due to the fact that the extraction septum and the quadrupoles in the transfer line cannot work in pulse-to-pulse modulation between 160 MeV and the usual extraction energy of 1.4 GeV. This MD required a lot of preparations, and demonstrated >80% transmission for a beam with intensity of 60×10^{10} p and bunch length of 500 ns, typical values expected for commissioning beams after LS2.

PSB-to-PS Transfer Studies

Several studies were performed in the transfer line from the PSB to the PS. In particular, it was important to measure the magnetic waveforms of the vertical recombination kickers. These studies introduced new methodologies for this type of beam-based measurements and enabled estimation of time margins and vertical emittance blow-up induced by the kickers for the future beams for HL-LHC [12].

Dispersion measurements in the transfer line to the PS and in the measurement line showed good agreement with the dispersion model for rings 1 and 4, while differences up to ~ 0.5 m were observed in rings 2 and 3 [13, 14].

The PS first-turn horizontal dispersion was reduced from 5 m to ~ 2.5 m peak-to-peak by re-matching the quadrupoles in the transfer line, as shown in Fig. 5. This improvement did not affect yet the measured horizontal emittance at PS injection. Further efforts are on-going to better match the optics model with measurements and validate its operational deployment for the 4 PSB rings.

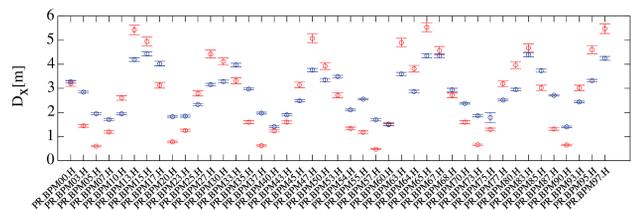


Figure 5: The measured horizontal dispersion (PS 1st turn from PSB ring 3) before (red) and after (blue) the correction.

CONCLUSION

During 2016 a large number of Machine Development studies were carried out to study various aspects of the planned PSB upgrades. These studies focussed on longitudinal, transverse, LLRF, HLRF and beam transfer issues. The studies are ongoing in all cases, but are already providing useful insight into the ability to reach baseline parameters, improving our understanding of the machine, and helping define operational techniques for use in both present and future operations.

ACKNOWLEDGEMENTS

The authors would like to thank the LIU-PSB and operations teams for valuable contributions and useful discussions.

REFERENCES

- [1] K. Hanke et al., “Status and plans for the upgrade of the CERN PS Booster”, in Proc. IPAC’15, paper THPF090.
- [2] “LHC injectors upgrade, technical design report, Vol. I: protons”, edited by J. Coupard et al., CERN-ACC-2014-0337, CERN, Geneva, 2014.
- [3] A. Oeftiger et al., “Flat bunches with a hollow distribution for space charge mitigation”, in Proc. IPAC’16, paper MO-POR023.
- [4] M. E. Angoletta et al., “Operational experience with the new digital low-level RF system for CERN’s PS Booster”, presented at IPAC’17, Copenhagen, Denmark, May 2017, paper THPAV143.
- [5] M. E. Angoletta et al., “Control and operation of a wideband RF system in CERN’s PS Booster”, presented at IPAC’17, Copenhagen, Denmark, May 2017, paper THPAB141.
- [6] “LHC design report”, edited by O. Brüning et al, CERN-2004-003-V-1, CERN, Geneva, 2004.
- [7] B. Mikulec, “Performance reach of LHC beams”, LIU Beam Studies Review, CERN, 28 August 2012, <https://indico.cern.ch/event/200692/>
- [8] E. Benedetto et al., “Space charge effects and mitigation in the CERN PS Booster, in view of the upgrade”, in Proc. HB’16, paper THPM9X0.
- [9] M. McAteer et al., “Simulation and observation of driven beam oscillations with space charge in the CERN PS Booster”, in Proc. IPAC’14, paper THPRO081.
- [10] E. Benedetto, M. Cieslak-Kowalska and P. Zisopoulos, “Tail repopulation measurements in the PSB”, presented at IPAC’17, Copenhagen, Denmark, May 2017, paper WEPVA038.
- [11] S. Hancock, “Tomography at injection in the PSB”, CERN-ACC-NOTE-2016-0040.
- [12] V. Forte et al., “Beam-based kicker waveform measurements using long bunches”, presented at IPAC’17, Copenhagen, Denmark, May 2017, paper MOPIK042.
- [13] V. Forte, “PSB-to-PS transfer studies”, presentation at the Injector MD days 2017, March 23, 2017, <https://indico.cern.ch/event/609486/>
- [14] G. P. Di Giovanni, “Comparative measurements of emittance at the wire-scanners and at the SEM grids in the PSB”, presentation at the CERN Emittance Working Group, December 5, 2016, <https://indico.cern.ch/event/592437>