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OPERATIONAL PERFORMANCE OF THE LHC PROTON BEAMS WITH THE SPS LOW TRANSITION ENERGY OPTICS

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Abstract

An optics in the SPS with lower integer tunes (20 versus 26) was proposed and introduced in machine studies since 2010, as a measure for increasing transverse and longitudinal instability thresholds, especially at low energy, for the LHC proton beams. After two years of machine studies and careful optimisation, the new Q20 optics became operational in September 2012 and steadily delivered beam to the LHC until the end of the run. This paper reviews the operational performance of the Q20 optics with respect to transverse and longitudinal beam characteristics in the SPS, enabling high brightness beams injected into the LHC. Aspects of longitudinal beam stability, transmission, high-energy orbit control and beam transfer are discussed.

INTRODUCTION

Single and multi-bunch instabilities in both transverse and longitudinal plane are fundamental performance limitations in the SPS for present but, even more, for future LHC-type beams [1]. One of the main ingredients for removing or reducing these instabilities, in the framework of the LHC injectors upgrade project (LIU), was the conception of an optics (named Q20) with lower transition energy and thus larger slip factor, by lowering the integer part of the tune by six units from the nominal Q26 optics [2]. For constant longitudinal parameters, the larger slip factor permitted the 3-fold increase of instability thresholds at low energy and a 60% increase at the SPS flat top for LHC beams, as proved in several machine studies during the last 3 years [1, 3]. This optics became operational during the 2nd part of the 2012 LHC run, as the longitudinal setting up of the LHC beam became increasingly difficult due to the delivered high-intensity of more than 1.6×10^{11} protons/bunch, at the SPS extraction. This paper describes the last steps taken for making the Q20 optics operational, its performance with respect to transverse and longitudinal beam characteristics in the SPS as well as the brightness delivered as measured at the LHC flat bottom.

FINAL STEPS FOR TRANSFER TO LHC

Based on simple scaling arguments, in order to keep the same bunch length in the Q20 optics, the RF voltage should be increased proportionally to the slippage factor. This would already exceed the presently available RF voltage, which which at flat top is at its limit for the LHC beams even for the nominal Q26 optics. On the other hand, controlled longitudinal emittance blow-up is applied in the nominal optics, as the LHC beams suffer from longitudinal multi-bunch instabilities during the ramp at energies above 200 GeV [1, 3]. As the new optics raises the instability thresholds, there is practically no need for applying longitudinal emittance blow-up. Thus, the available voltage is enough (although still at its limit) in order to reach the required bunch length, with the new optics. An example of the measured bunch length distribution is plotted in Fig. 1, for the LHC 50 ns beam (train of 72 bunches), for the Q20 (left) and Q26 (right) optics. The measured average bunch length is similar for the two optics at the SPS flat top, whereas the rms spread with the Q20 optics is smaller.

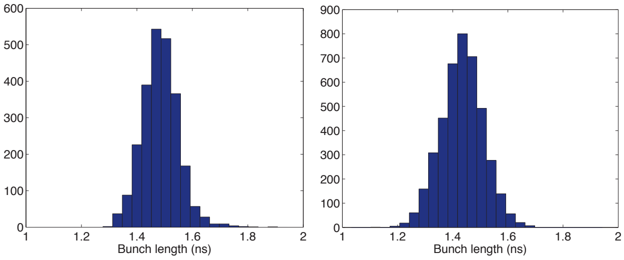

Figure 1: Bunch length distribution for the Q20 (left) and Q26 optics (right) for the LHC 50 ns beam, at SPS flat top.

Although the bunch lengths are similar, the longitudinal emittance ends up being smaller in the Q20 optics, due to its increased stability. This could create a problem in the LHC at flat bottom by enhancing emittance growth due to Intrabeam Scattering (IBS). In a series of measurements for preparing the Q20 optics for transfer and injection to the LHC, it was proven that this effect is small. A further improvement [4] could be achieved by applying a batch-by-batch controlled emittance blow-up [5], which was also implemented at a later stage in the LHC.

The last step for making the SPS optics operational, was the setting up of the extraction conditions (SPS extraction bumps, extraction element settings), the rematching of the TI2 and TI8 transfer line optics and the trajectory optimisation for injection into the LHC [6]. Machine studies showed that the optics difference between the modelled and measured dispersion was small and similar for both optics. The difference of beam trajectory for the two optics in both lines was also quite limited (less than 0.5 mm rms). There were minimal losses in the transfer lines and in the LHC

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at injection. The injection stability was monitored along the 2012 run and was found to be similar for both SPS optics [7]. In conclusion, the tests showed that there was no showstopper and even allowed already in the summer of 2012, the injection of ultra-high intensity single bunches in the LHC with more than 3×10^{11} protons/bunch, and transverse normalised emittances of around 2 μm, for machine development purposes.

OPERATIONAL PERFORMANCE

Transverse Aspects

In the transverse plane, the usual optimisation procedure is followed as for all other SPS beams. The orbit is controlled at injection and in pre-defined points of the ramp, using the SPS orbit correctors. As the orbit correctors become less effective at high energy, the orbit is corrected with a few displaced quadrupoles, at the beginning of the run. This is done for the Q26 optics and the fixed target beam, the trajectory control of which is more critical due to the larger beam sizes. This correction is optimized for an integer tune of 26 and a higher rms closed orbit distortion at flat top was observed for the Q20 optics, as compared to the Q26 optics. This did not present a limitation for operation, though, as the LHC beam sizes are quite small, even in the presence of the Q20 larger dispersion. The fractional part of the tune is the same as for the nominal optics (0.13,0.18) for LHC beams, although a working point moved further away from the integer will become beneficial, especially in the vertical plane, for ultra high-brightness beams having space-charge tune-shifts close to -0.2 [1]. The chromaticities along the SPS Q20 cycles are slightly positive but their control is not so critical due to the enhanced stability of the beam in this optics. The transverse damper settings were also optimized taking into account the different phase advances between kickers and between BPMs with respect to the nominal optics. LHC 50 ns beams with populations of up to 1.8×10^{11} protons/bunch were injected at the SPS flat bottom, resulting to 1.7×10^{11} at extraction, with 3% of the losses corresponding to the beginning of the ramp and another 3% due to a controlled transverse scraping of the beam tails at flat top.

The transverse performance of the Q20 optics for 50 (left) and 25 ns (right) bunch trains, at the SPS flat top is summarised in Fig. 2. The average between the horizontal and vertical emittances measured at the end of the flat bottom for five cycles are plotted as a function of the bunch population at SPS extraction. The error bars include the statistical spread and a generic 10% systematic calibration error. The horizontal axes represent the intensity at SPS extraction. All these beams were transferred to the LHC. The different point clouds correspond to the standard LHC beams (upper) and the high brightness bunches produced by the new batch compression, merging and splitting scheme (BCMS) made available from the PS at the the end of the 2012 run [8]. The expectation curves are extrapolations from the measured PSB performance, taking into account typical budgets for emittance blow up and losses in the PS and the SPS [9]. Although the high-luminosity LHC (HL-LHC) goals for the injectors are even higher [10], they seem within reach in terms of beam brightness.

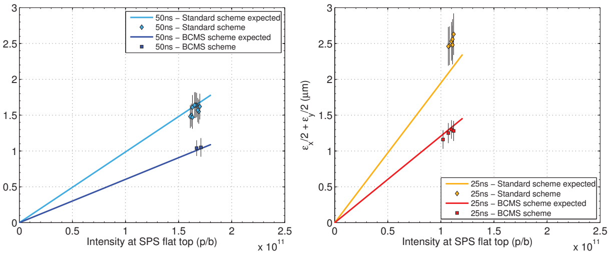

Figure 2: Mean transverse emittance versus intensity at the SPS flat top 50 ns (left) and 25 ns (right) bunch trains. The light blue and yellow points represent measurements taken with the standard beams, whereas the dark blue and red points, measurements performed with high-brightness bunches produced by the BCMS scheme [8].

Longitudinal Aspects

There was a large amount of studies, measurements and optimisation steps performed for the longitudinal setting up of the LHC beams with the Q20 optics [1, 3], steered by the SPS upgrade studies group [11]. During Q20 operation, the voltage at injection was optimised for better transmission (pointing to lower voltage) but also smaller bunch length variation along the PS batches and SPS train (for higher voltage). A slight emittance blow-up was applied to assure stability and reduce the dispersion of bunch lengths at extraction. The beam stability at the SPS flat top is very much dependent on the longitudinal beam distribution coming from the PS. It was observed that bunch dipole oscillations at flat top were reduced for increased longitudinal emittance at the SPS injection. In this respect, continuous monitoring and optimisation of the RF parameters was necessary especially for these high intensities delivered to the LHC.

25 ns Beams for LHC Scrubbing

Apart from the operational 50 ns LHC beam, the 25 ns beam was optimised with the Q20 optics and was regularly delivered to the LHC for the scrubbing run in December 2012. The standard beam with up to 1.25×10^{11} protons/bunch at the SPS extraction showed excellent performance with respect to longitudinal but also transverse characteristics, as shown in Fig. 3, with normalised emittances ranging between 2.5 μm and 3 μm.

LHC BRIGHTNESS

Since the end of September 2012 (after the third LHC technical stop), the SPS started delivering the LHC beams with the Q20 optics. After establishing a clean beam transfer, the number of bunches and bunch intensity gradually increased to around 1.6×10^{11} protons/bunch at the SPS extraction. Due to intermittent problems with the wire scan-

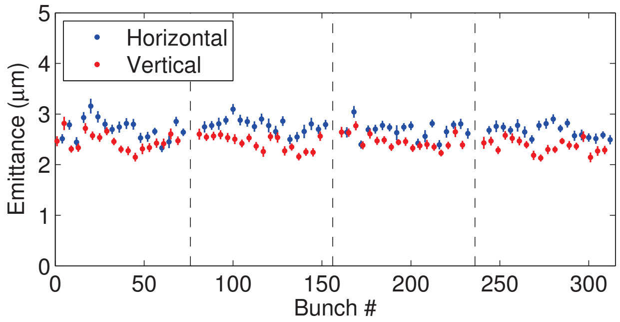

Figure 3: Horizontal (blue) and vertical (red) emittance along the four 25 ns batches in the SPS flat top.

ners at the SPS flat top, it was impossible to have reliable monitoring of the brightness at the SPS extraction. On the other hand, measurements along the rest of the run showed that the injected emittances in the SPS were preserved up to extraction and were similar to the ones at the LHC flat bottom, measured just after injection of the first SPS batches, for both beams. An indication of the increased brightness delivered to the LHC is presented in Fig. 4, where the mean bunch intensity decided by the average transverse emittance is plotted along the different LHC fills, for the second part of 2012. The green triangles represent the brightness delivered in the LHC flat bottom using the nominal Q26 optics, whereas the blue diamonds show the one corresponding to the Q20 optics, for both beams. There was a clear brightness increase at the LHC flat bottom of the order of 15% on average, due to the Q20 optics. It is also worth noting, that the SPS brightness (black crosses) is similar, demonstrating an excellent brightness preservation between the two machines. The luminosity reached record levels (above 7 Hz/nb). However, the expectation for achieving luminosities beyond this level was not fulfilled, as the brightness at the LHC flat top (orange circles) remained constant. In fact, although the specific luminosity of certain bunches was indeed much higher than before, other bunches seemed to have reduced luminosity due to an emittance blow-up along the cycle, related to beam instabilities at LHC high energy [4]. The reason of this blow-up is not yet fully understood and will be addressed in the future (after LS1), for enabling the LHC to digest and preserve high-brightness bunches from the injectors.

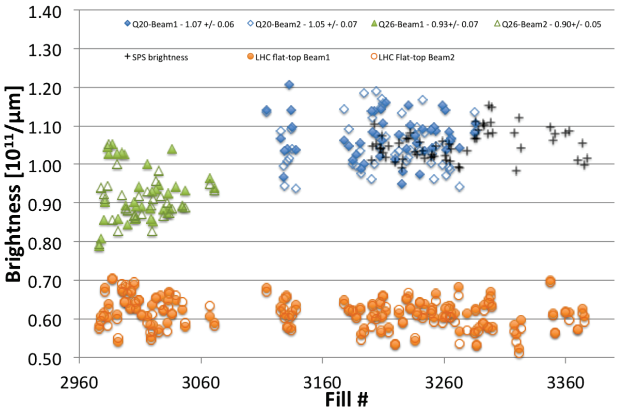

Figure 4: Average intensity over mean emittance (brightness) along the run, during the SPS operation with the nominal (green triangles) and the Q20 (blue diamonds) optics, in the LHC flat bottom and in the LHC flat top (orange circles) for both beams. The SPS brightness since the Q20 deployment is represented by the black crosses.

CONCLUSION

The new low transition energy optics (Q20) in the SPS became operational on September 2012 after two years of careful optimisation. This optics was introduced in order to remove intensity limitations in the SPS, which used to represent the intensity bottleneck in the injector complex. This is indeed an extremely cost-effective solution, as it was shown that there is no major hardware change needed in the SPS. The switch to this new optics was very smooth, allowing very high brightness beams to be delivered to the LHC providing record luminosities. The Q20 optics opens the way for ultra-high brightness beams to be delivered in the HL-LHC era for protons and eventually for ions [12].

ACKNOWLEDGEMENTS

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REFERENCES

[1] H. Bartosik et al., “Experimental studies for future LHC beams in the SPS”, TUPME034, IPAC13 (2013).

[2] H. Bartosik, et al. , “Optics considerations for lowering transition energy in the SPS”, IPAC11 (2011).

[3] H. Bartosik et al., “Experimental studies with low transition energy optics in the SPS”, IPAC11 (2011); “Increasing Instability Thresholds in the SPS by Lowering Transition Energy”, IPAC12 (2012).

[4] M. Kuhn et al., “Investigations of the LHC emittance blow-up during the 2012 proton run”, TUPFI026, IPAC13 (2013).

[5] T. Mastoridis et al., CERN ATS-Note-2012-050 MD.

[6] G. Vanbavinckhove et al.,“Beam transfer to LHC with the low gamma-transition SPS optics”, MOPFI060, IPAC13 (2013).

[7] L. Drosdal et al., “Analysis of LHC transfer line trajectory drifts”, MOPWO033, IPAC13 (2013).

[8] H. Damerau et al., “RF manipulations for higher brightness LHC-type beams”, WEPEA044, IPAC13 (2013).

[9] B. Goddard, “Progress with the upgrade of the SPS for the HL-LHC era”, WEPEA053, IPAC13 (2013).

[10] R. Garoby et al., “Status and Plans for the Upgrade of the LHC Injectors”, THPWO077, IPAC13 (2013).

[11] LIU-SPS Beam Dynamics Working Group, chaired by E. Shaposhnikova, http://paf-spsu.web.cern.ch/paf-spsu/

[12] F. Antoniou et al., “Considerations on SPS low-transition energy optics for LHC ion beams”, TUPME046, IPAC13 (2013).