EXPERIMENTAL STUDIES FOR FUTURE LHC BEAMS IN THE SPS

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Abstract

The High Luminosity LHC (HL-LHC) project requires significantly higher beam intensity than presently accessible in the LHC injector chain. The aim of the LHC injectors upgrade project (LIU) is to prepare the CERN accelerators for the future needs of the LHC. Therefore a series of SPS machine studies with high brightness beams were performed, assessing the present performance reach and identifying remaining limitations. Of particular concern are beam loading and longitudinal instabilities at high energy, space charge for beams with 50 ns bunch spacing and electron cloud effects for beams with 25 ns bunch spacing. This paper provides a summary of the performed studies, that have been possible thanks to the implementation of the SPS low gamma-transition optics.

INTRODUCTION

The LHC injectors upgrade project (LIU) aims at consolidating and upgrading the existing accelerator chain at CERN in preparation for the future needs of the LHC. In particular, the future High Luminosity LHC (HL-LHC) will require significantly higher beam intensity and brightness compared to today's operation. For the SPS, the main challenges are instabilities in the transverse and the longitudinal planes, beam loading, electron cloud effects for the 25 ns beam and space charge effects on the long injection plateau for the 50 ns beam due to its higher brightness.

Since the end of 2010, machine studies have been performed using an optics with lower transition energy [1]. In comparison to the nominal SPS optics, which is now referred to as "Q26" optics, as the integer part of the betatron tunes is 26, the working point is lowered by 6 integer units in both planes in the low γ_t optics called "Q20". This yields a reduction of the transition energy from $\gamma_t = 22.8$ to $\gamma_t = 18$, which means an almost 3-fold increase of the slip factor η at injection energy ($\gamma = 27.7$) and an increase by a factor 1.6 at extraction energy ($\gamma = 480$). The intensity thresholds for single bunch transverse and longitudinal instabilities observed in the SPS are expected to scale with the slip factor η. Indeed, a clear improvement of beam stability has been demonstrated experimentally [2]. Since September 2012, the Q20 optics is used successfully in routine operation for LHC filling [3] and will also be the default machine configuration for LHC beams in the future. In addition to the preparations for switching to the Q20 optics for operation, machine studies in 2012 were devoted to high brightness 50 ns beams and high intensity beams with the nominal 25 ns bunch spacing as discussed below.

TRANSVERSE PLANE

50 ns High Brightness Beam

As described in more detail in [3], the operational 50 ns beam delivered to the LHC for physics at the end of 2012 using the Q20 optics had an intensity of typically 1.65×10^{11} p/b at extraction (1.85×10^{11} p/b at injection) and transverse emittances slightly below $1.65\,\mu$m. The corresponding space charge tune shift (Laslett tune shift) on the SPS flat bottom can be calculated as $\Delta Q_x = -0.08$ and $\Delta Q_y = -0.13$ (with the usual 4σ bunch length $\tau = 3$ ns and rms momentum spread of $\delta p/p = 0.0017$). The SPS cycle for LHC beams has a 10.8 s long injection plateau in order to accommodate four injections from the PS before acceleration. To maintain equal beam parameters along the bunch train, beam loss and emittance blow-up on the flat bottom have to be kept as small as possible in a regime with relatively strong space charge.

Thanks to the successful implementation of the "Batch Compression Merging and Splitting" (BCMS) scheme [4] at the end of 2012, the PS was able to provide a beam with 50 ns bunch spacing and similar brightness as envisaged by the HL-LHC/LIU projects. In particular, for an intensity of 1.95×10^{11} p/b and transverse emittances of about $1.1\,\mu$m, an incoherent space charge tune shift on the SPS injection plateau of $\Delta Q_x = -0.10$ and $\Delta Q_y = -0.18$ is calculated. In this case the space charge necktie would overlap with the vertical integer resonance for the usual working point used for LHC beams in the SPS ($Q_x, Q_y = 20.13, 20.18$). A working point scan was thus performed in order to see how much space in the tune diagram is needed to accommodate the incoherent tune spread for minimizing emittance blow-up in the SPS. Figure 1 shows the tested working points on the tune diagram together with the corresponding emittance measurements. First, the horizontal tune was varied from to $Q_x = 20.07$ to $Q_x = 20.23$ while the vertical tune was approximately $Q_y = 20.19$. For each setting, a *single batch* of 24 bunches of the 50 ns BCMS beam was injected in five consecutive cycles with transverse damper on and the transverse beam profiles were measured with the wire scanners in turn acquisition mode (average profile along bunch train) at the end of the 10.8 s long injection plateau. For each plane and each working point, the emittance is determined from a single Gaussian fit of the corresponding overlapped measured profiles and the error bars are determined by the fit uncertainty. While a significant horizontal emittance blow-up was observed for horizontal tunes below $Q_x = 20.13$, practically constant emittances were found for higher horizontal tunes. A similar tune scan

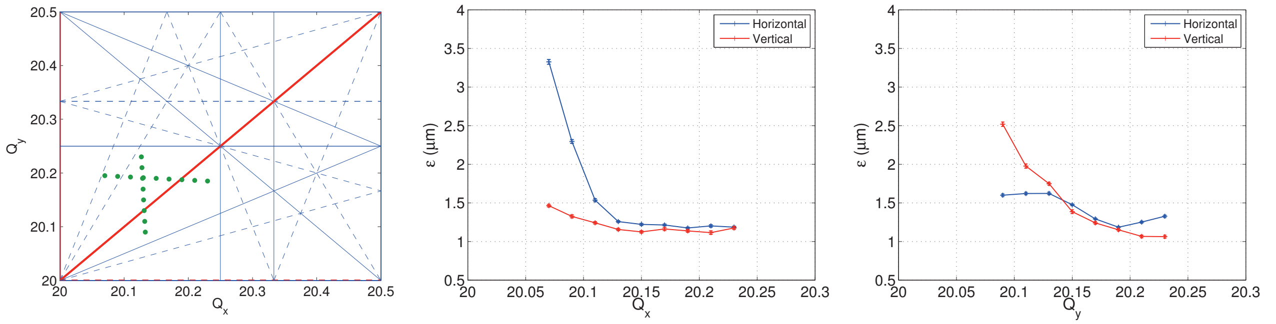

Figure 1: Working point scan with the BCMS high brightness 50 ns beam (1.95×10^{11} p/b): tune diagram (left) with resonances up to fourth order (red and blue lines indicating systematic and non-systematic resonances, respectively, dashed lines corresponding to skew and full lines to normal resonances) together with the tested working points marked by green dots; emittance measurements at the end of the injection plateau for the horizontal (middle) and vertical tune scan (right).

was performed for the vertical plane, where the horizontal tune was kept at about $Q_x = 20.13$. In this case, significant emittance blow-up was found for vertical tunes below $Q_y = 20.19$. Above this tune, the sum of the two transverse emittances was practically constant. These measurements suggest that for the high brightness beam the tunes should be set slightly higher than $Q_x = 20.13$ and $Q_y = 20.19$ in order to minimize the emittance blow-up. Note that for all the working points studied here, the losses on the injection plateau were typically of the order of 1% and the total transmission up to flat top was usually about 93% (without scraping).

The above findings were confirmed with bunch-by-bunch emittance measurements for the same beam but with *three injections* from the PS. Figure 2 shows an example of the emittances along the train for two different working points. While slightly larger emittances were found for the first batch for the working point $(Q_x, Q_y = 20.13, 20.19)$, equal behavior of the three batches was found when setting $(Q_x, Q_y = 20.17, 20.23)$. Note that the bunch-to-bunch variation within the batch origintaes from the pre-injectors.

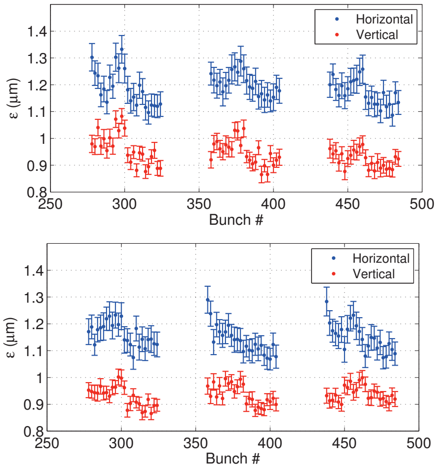

Figure 2: Bunch-by-bunch emittance measurement for $Q_x, Q_y = 20.13, 20.19$ (top) and $Q_x, Q_y = 20.17, 20.23$ (bottom) for three batches of the 50 ns BCMS beam.

25 ns Beams

A series of machine studies was devoted to the nominal LHC beam with 25 ns bunch spacing. During the scrubbing run of the LHC at the end of 2012, the 25 ns beam was regularly extracted from the SPS Q20 optics with four batches of 1.15×10^{11} p/b and transverse emittances of about 2.7 μm [3]. However, fast losses at injection of the third and fourth batch into the SPS together with emittance blow-up at the tail of these batches were observed for intensities above 1.35×10^{11} p/b. This could be related to electron cloud effects as observed in the past, since the machine was never scrubbed for these high intensities [5]. Further studies on this will follow after the long shut-down 1 (LS1).

LONGITUDINAL PLANE

During the last few years many studies with high intensity beams were devoted to the comparison between the Q20 and Q26 optics. During the second half of 2012, the Q20 optics was used for the LHC operational beams. This made the filling of the LHC faster due to better stability and less sensitive to the longitudinal beam parameters of the injected beam (bunch length and longitudinal emittance as well as their spread). As expected [2], bunches of the same intensity had the same average bunch length at the SPS flat top but smaller longitudinal emittance. One of the worries for these small emittances was the IBS effect on the LHC flat bottom, which could lead to transverse emittance blow-up and reduction in the peak luminosity. As a cure batch-by-batch controlled emittance blow-up is now available in the LHC [6].

After LS1, the LHC will most probably be operated with 25 ns bunch spacing and thus in the second part of 2012 the experimental beam studies were concentrated on this beam-type. The threshold of the longitudinal coupled bunch instability is decreasing with energy proportional to $|\eta|/E$. Measurements confirmed that in the low γ_t cycle the instability starts later than in the Q26 cycle. The energy at which the beam becomes unstable depends also on the bunch spacing and therefore on the characteristics of

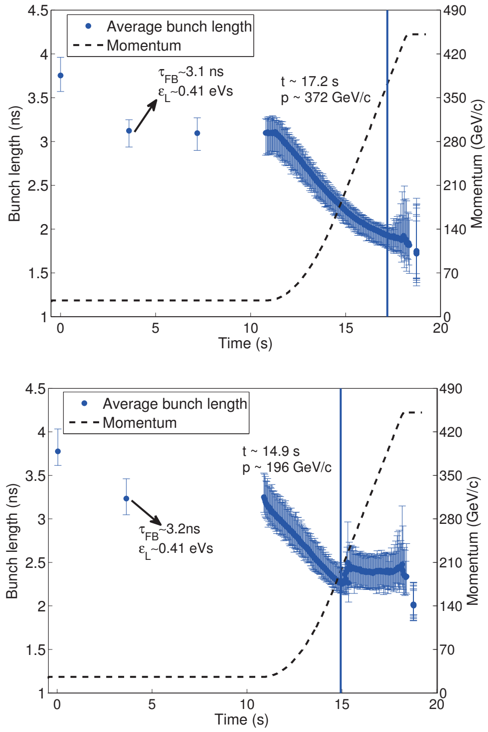

Figure 3: Bunch length evolution during the SPS acceleration cycle for a single LHC batch with 50 ns (top) and 25 ns (bottom) bunch spacing in a single (200 MHz) RF system in the Q20 optics. The average intensity is 1.6×10^{11} p/b for 50 ns bunch spacing and 1.2×10^{11} p/b for 25 ns.

the impedance source responsible for this instability. With the same voltage programme the instability starts for the 25 ns beam at almost half the energy compared to the 50 ns beam, see Fig. 3, while the ratio of total currents in this case is only 1.5. The number of circulating batches seems to be much less important, pointing to a resonant impedance with a quality factor Q in the same range as for the fundamental impedance of the SPS 200 MHz and 800 MHz RF systems (150 and 300) [7].

The 800 MHz RF system in bunch shortening mode is used for beam stabilisation during the entire cycle. For the 50 ns bunch spacing no controlled longitudinal emittance blow-up was necessary in Q20 for intensities below 1.6×10^{11} p/b. Since the 25 ns beam is more unstable, controlled emittance blow-up is required above nominal intensity, i.e. 1.2×10^{11} p/b. Due to the effect of potential-well distortion leading to the incoherent synchrotron frequency shift, this blow-up, performed by band-limited phase noise, is sensitive to the spread in bunch lengths. Bunches which have not been blown up enough become unstable on the SPS flat top. While the bunch-by-bunch variation comes from the RF gymnastics in the PS, the bunches in the batches injected earlier have systematically smaller bunch length due to losses along the SPS 10.8 s long flat bottom. Furthermore, the last batch had a shorter bunch length due to the short time until the start of the ramp. This was eliminated by delaying the acceleration by 300 ms. A 25 ns beam with stable longitudinal conditions and an average intensity of 1.35×10^{11} p/b in four batches was finally obtained at 450 GeV as shown in Fig. 4. This is a new SPS intensity record for the LHC beam.

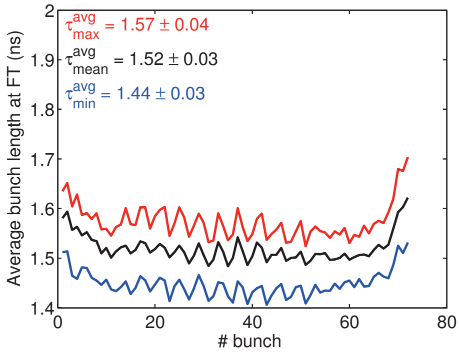

Figure 4: Minimum, maximum and average bunch length along the batch on the SPS flat top for several cycles with 1-4 batches of the 25 ns LHC beam (1.35×10^{11} p/b).

Beam loading during the cycle is one of the serious limitations for the 25 ns beam, in particular before the RF power upgrades planned for 2018, even though the higher matched voltage on the flat bottom in the Q20 optics has a beneficial effect. For high intensity 25 ns beams one of the main concerns at the moment is beam transmission which is significantly decreasing with intensity (below 90%). The origin of these losses is not clear yet but could be the same as for the bunch length reduction on the flat bottom, which might be explained by longitudinal scraping.

SUMMARY AND CONCLUSION

Incoherent space charge tune spreads of $\Delta Q_y = -0.18$ were achieved on the SPS long injection plateau with small losses and equal emittances for three batches of a 50 ns high brightness beam after slightly raising the SPS working point. LHC beams with 25 ns bunch spacing were successfully accelerated to flat top with stable longitudinal beam conditions up to 1.35×10^{11} p/b at extraction. However, transverse instabilities observed at the injection of the third and fourth batch for intensities above 1.35×10^{11} p/b need to be addressed in further studies, together with the transmission which is significantly decreasing with intensity.

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