Proceedings of the Injector MD Days 2017, Geneva, Switzerland, 23 – 24 March 2017, edited by H. Bartosik and G. Rumolo, CERN Proceedings, Vol. 2/2017, CERN-Proceedings-2017-002 (CERN, Geneva, 2017)

SPACE CHARGE STUDIES IN THE PS

F. Asvesta*, H. Bartosik, H. Damerau, A. Huschauer, Y. Papaphilippou, M. Serluca, G. Sterbini, P. Zisopoulos

Abstract

In this paper the results of Machine Development (MD) studies conducted at the CERN Proton Sychrotron (PS) are presented. The main focus was the investigation of new working points in an effort to characterize and potentially improve the brightness for LHC-type beams in view of the LHC Injectors Upgrade (LIU). Various working points were compared in terms of losses and emittance evolution. Since space charge and the resonances it excites are the main cause for emittance blow-up and losses, tunes close to excited resonances were carefully studied. Mitigation techniques, such as bunch flattening using a double harmonic RF system, were also tested.

INTRODUCTION

Space charge is a dominant effect for low energy, high brightness accelerators. It creates an incoherent tune shift that depends on the line density of the longitudinal beam profile and the transverse beam size. For Gaussian beam distributions it yields [1]

$$\Delta Q_{h,v} = -\frac{r_0 \lambda}{2\pi e \beta^2 \gamma^3} \oint \frac{\beta_{h,v}(s)}{\sigma_{h,v}(s)(\sigma_h(s) + \sigma_v(s))} ds \,, \quad (1)$$

where r_0 is the classical particle radius, λ the line density, e the elementary charge, $\beta\gamma$ the relativistic factors, $\beta_{h,v}$, $\sigma_{h,v}$ the transverse β-functions and beam sizes, respectively. In the PS , at low energy, the space charge tune spread is significant. For the operational LHC25 beam [2] the incoherent space charge tune spread at PS injection, with maximum values $\Delta Q_h \approx -0.20$ and $\Delta Q_v \approx -0.26$, is shown in Fig. 1. The tune spread for the BCMS operational beam [2] is slightly smaller with maximum values $\Delta Q_h \approx -0.18$ and $\Delta Q_v \approx -0.24$. However, the space charge induced tune spread is sensitive to certain parameters, i.e. bunch intensity, bunching factor, transverse emittances and $\Delta p/p$, which may vary from shot to shot.

The main focus of the MDs presented here was the investigation of new working points in an effort to characterize and potentially improve the brightness for LHC-type beams in view of the LIU goals for protons [3]. In 2016, significant blow-up of the horizontal emittance was observed for LHC beams at PS injection [4], which was subject of MDs focused on the beam transfer from the PS-Booster (PSB) to the PS [5]. In this context, tune scans were performed in order to assess the emittance growth of the beam core due to the integer resonances, which might contribute to the observed blow-up. Furthermore, the excitation of other resonances was studied, in particular the space charge driven $Q_v = 6.25$ 8^{th} order

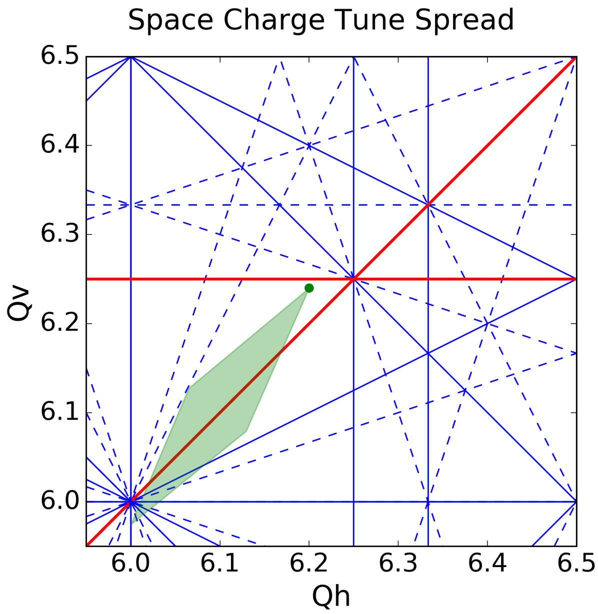


Figure 1: Sketch of the tune footprint for $Q_h = 6.20$, $Q_v = 6.24$ in the PS for the beam parameters of the operational LHC25 beam. Resonance lines up to 4^{th} order marked in blue, the coupling resonance is plotted in red. The red lines at $Q_v = 6.25$ and $Q_h = 6.25$, correspond to 8^{th} order structural resonances.

structural resonance [6], which presently limits the achievable beam brightness in the PS. The chromaticity remained uncorrected during the described MDs.

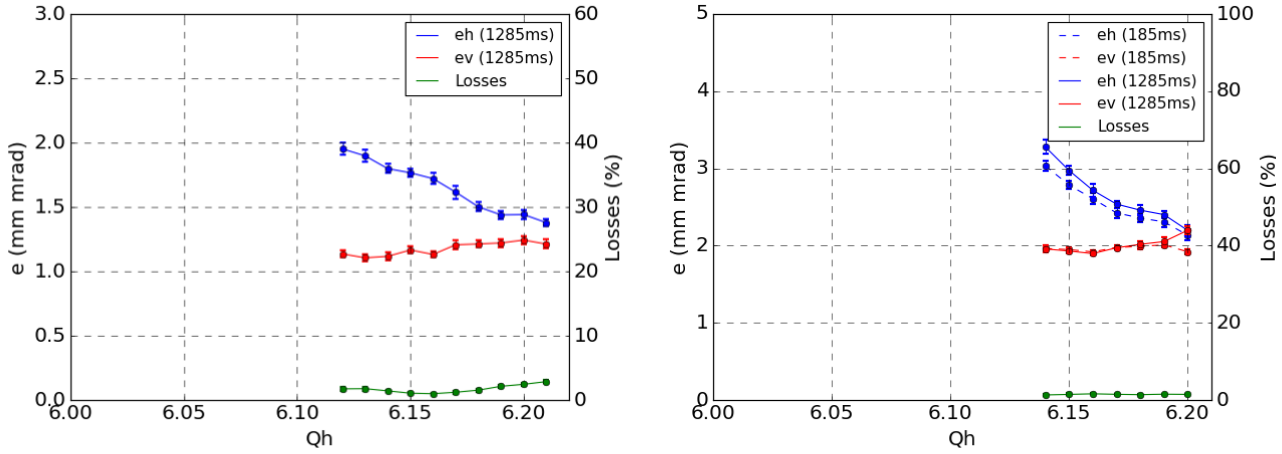
Since the space charge tune spread is proportional to the longitudinal line density, a smaller tune footprint can be achieved by flattening the bunch profile using additional RF harmonics. This was tested by introducing a second harmonic on the flat bottom of a LHC25 type cycle, i.e. a combination of $h = 7$ and $h = 14$ was used.

TUNE SCANS

Single bunches from PSB Ring 3 were used for the tune scans presented here. The machine cycles in the PS were clones of the LHC25 and the BCMS operational beams. For each working point the beam was injected at the corresponding tunes, which remained constant during the entire flat bottom. The evolution of intensity was monitored for both beam types, in order to deduce losses. The horizontal and vertical emittances were evaluated twice during the cycle: Profiles were taken 15 ms after injection at 185 ms, to avoid any secondary effects such as the injection bump [7], and at the end of the flat bottom at 1285 ms, where the second injection would take place. The emittance is calculated from

* foteini.asvesta@cern.ch

https://doi.org/10.23727/CERN-Proceedings-2017-002.37



(a) (b)

Figure 2: Horizontal tune scans using BCMS (a) and LHC25 (b) beams. Horizontal (blue) and vertical (red) emittances at injection (dashed) and at the end of the flat bottom (solid) as a function of the horizontal tune.

the transverse beam profiles using β-functions from the PS MADX-model, the measured dispersion and $\Delta p/p$ as measured with the tomoscope [8].

Horizontal tune scan

BCMS In order to study the effect of the horizontal integer resonance, the horizontal tune was varied while the vertical tune was fixed at $Q_v = 6.26$. The dependence of the transverse emittances and the losses on the tune is shown in Fig. 2a. Although the initial emittances were not systematically measured for this scan, there is no blow-up observed between injection and at the end of flat bottom for the nominal tune $Q_h = 6.20$. However, when the tune is set below $Q_h = 6.19$ horizontal emittance blow-up is observed. As expected from a blow-up of the beam core at the horizontal integer resonance, the vertical emittance and the bunch intensity are clearly unaffected.

LHC25 In Fig. 2b the emittance and losses evolution as function of the horizontal tune are plotted. For these measurements the vertical tune was fixed at $Q_v = 6.24$. The horizontal emittance growth due to the integer resonance is observed for tunes below $Q_h \approx 6.20$, already at the injection measurement. This blow-up is therefore very fast. Comparing the two beams, one can deduce that they behave similarly in terms of losses. However, the emittance blow-up seems to be larger for the LHC25 beam.

Vertical tune scan

BCMS Now the vertical tune is varied, while the horizontal is kept constant. The measurements were split in two parts. For tunes $Q_v < 6.23$, $Q_h = 6.22$, whereas for $Q_v \geq 6.23$, $Q_h = 6.20$. The resulting emittance and losses are shown in Fig. 3a.

As the tune approaches the integer resonance, a large emittance blow-up is observed even for the measurements at injection. The emittance blow-up is also observed for tunes $Q_v \approx 6.23$, but only for the measurements at the end of the flat bottom. The effect disappears when $Q_v = 6.25$. For these working points the losses are negligible.

The study of tunes above $Q_v = 6.25$ clearly shows excitation of the 8^{th} order structural resonance $8Q_v = 50$, as losses and emittance reduction are observed. The highest losses of about 14% are observed at $Q_v = 6.30$. The behaviour is improved for tunes $Q_v > 6.30$, where the losses drop and the emittance approaches the initial values. However, for tunes $Q_v > 6.33$ the emittances don't behave as expected.

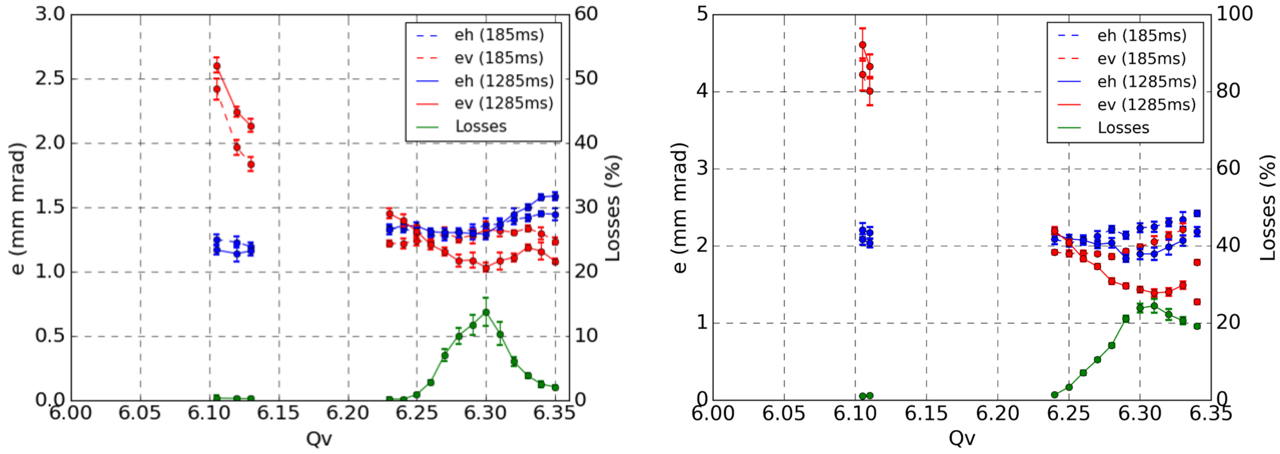
The acquired vertical beam profiles, Figs. 4a and 4b appear asymmetric both at injection and at the end of flat bottom. This could be due to space charge effects or an instrumental effect of the wire scanner [9]. Nevertheless, for tunes $Q_v \approx 6.33$ there are indications for tail formation. This coincides with the reduction of losses and the increase of emittance. Less tail formation is observed for $Q_v = 6.35$.

LHC25 In Fig. 3b the dependence of the transverse emittances and losses on the working point is shown. The horizontal tune was fixed at $Q_h = 6.20$ throughout the scan.

The vertical integer resonance causes blow-up for tunes $Q_v \approx 6.10$. The effect is strong enough to be observed even with the measurements right after injection. Contrary, if the tune is set to $Q_v \approx 6.25$, the blow-up is only observed at the end of flat bottom.

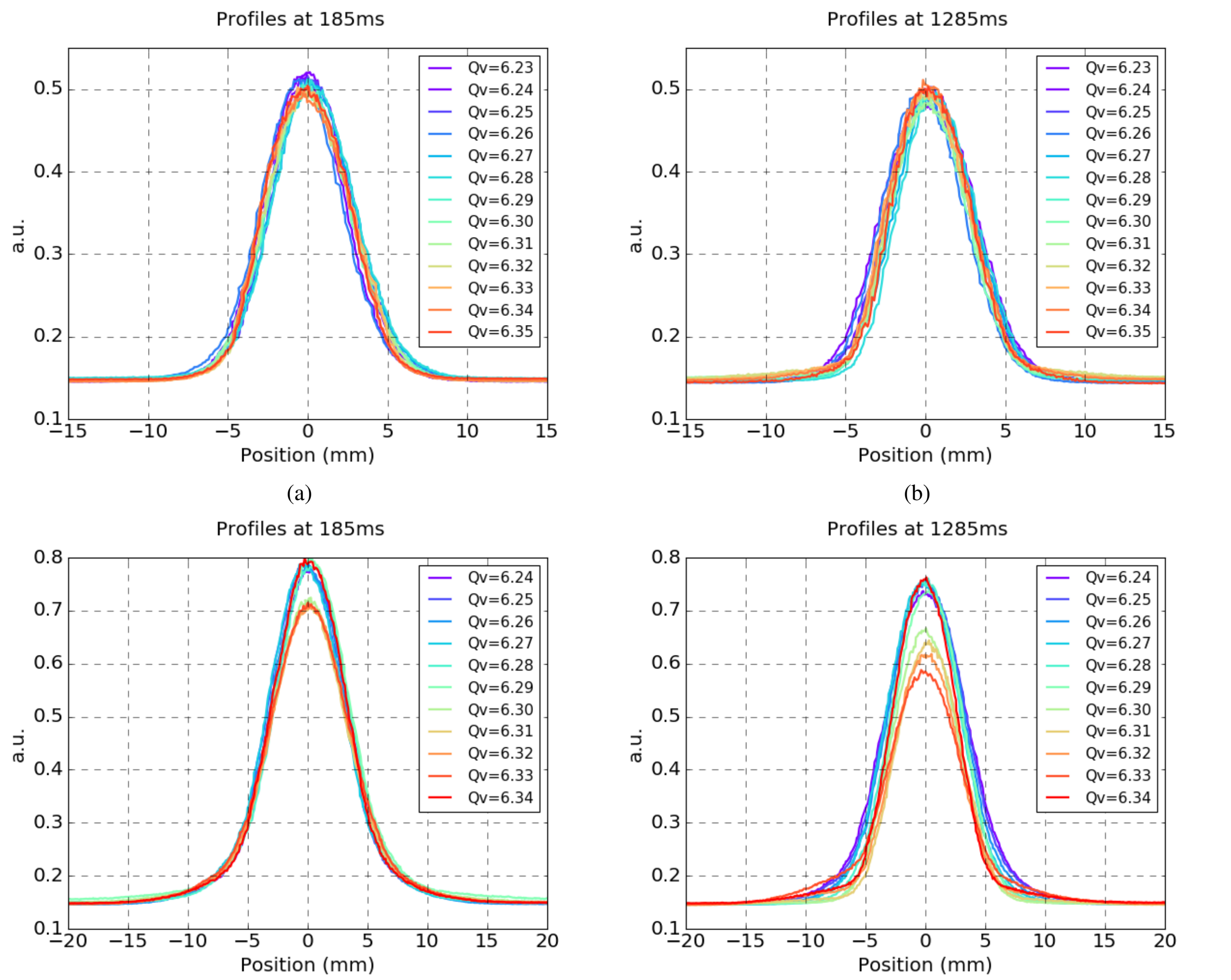
Crossing the structural resonance, notable losses occur even when the tune is set to $Q_v = 6.25$. As the tune is further increased significant losses, almost 25% at $Q_v \approx 6.30$, cause a reduction in the transverse emittances of both planes. The fact that the losses remain significant for tunes $Q_v > 6.31$ could be an indication of a different resonance crossing close to $Q_v = 6.33$ [10].

Thorough examination of the vertical bunch profiles in Figs. 4c and 4d, provides important information for the beam



(a) (b)

Figure 3: Vertical tune scans using BCMS (a) and LHC25 (b) beams. Horizontal (blue) and vertical (red) emittances at injection (dashed) and at the end of the flat bottom (solid) as a function of the horizontal tune. Losses (green) are shown using a second axis.



(a) (b) (c) (d)

Figure 4: Vertical beam profiles at injection (a,c) and at the end of flat bottom (b,d) for BCMS (a,b) and LHC25 (c,d) beams.

quality, as well as a better understanding of the observables. Regarding the beam quality shortly after injection at 185 ms, the profiles deviate from a Gaussian as tails are observed. These tails, which appear regardless of the tune, could be a result of the strong space charge force, some injection phenomena or already generated in the PSB. The bunch is more Gaussian-like at the end of the flat bottom for tunes $Q_v \approx 6.25$, since large amplitude particles are lost. Excitation of the structural resonance modifies the bunch profiles as the amplitude of the signal is reduced, due to losses, and additional tails are formed. The halo formation dominates when the losses start to drop, implying that the particles affected by the resonance are closer to the beam core. The tails at the end of the flat bottom are reduced when $Q_v = 6.34$.

Both beams suffered transverse stability issues for tunes towards the integer resonance and for $Q_v > 6.33$, since the stabilizing effect from the linear coupling resonance was reduced. The consequences of resonance crossing appear stronger for the LHC25 beam, more losses and tail formation. A potential explanation for this could be the difference between the beam sizes. Scans with both beams encourage the study of higher tunes in the future, since the beam quality is observed to improve.

SPACE CHARGE MITIGATION

The incoherent space charge tune spread can be moderated by reducing the peak line density of the longitudinal profile. This may be accomplished by introducing a double harmonic RF voltage. In the case of the LHC25 beam tested here, the RF harmonics were $h = 7$ and $h = 14$ respectively. The voltage in the cavity at the principal harmonic was kept constant at 25 kV while the one in the cavity at twice that harmonic was varied in steps of 6 kV. The voltage in the double harmonic cavity was ramped up at 170 ms and ramped down at 1250 ms. The duration of the ramp was 20 ms, corresponding to several synchrotron oscillation periods. The working point chosen was $Q_h = 6.20$, $Q_v = 6.23$ to enhance the effect of the integer resonance. Throughout the MD the radial loop and the phase loop had to be turned off, as the spectrum of the bunches in the double-harmonic RF unfavorably influence the loops. The modification of the line density profile as function of the RF voltage measured at 190 ms is shown in Fig. 5.

The vertical emittance measurements for these machine settings are shown in Fig. 6. The emittance at injection was only measured once but the initial emittance should not change, as the parameters in the PSB remained constant. The emittance at the end of the flat bottom shows a clear dependence on the voltage of the cavity and hence the line density. The blow-up for the flatter longitudinal profile is reduced by approximately 50%, demonstrating a potential reduction of the incoherent space charge tune spread as the beam is less affected by the integer resonance.

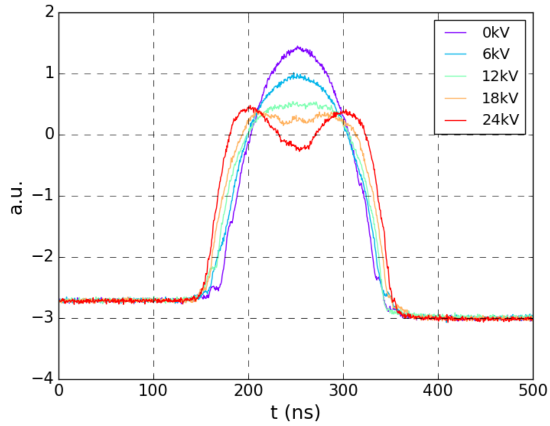


Figure 5: Longitudinal profiles acquired at 190 ms using a double harmonic cavity.

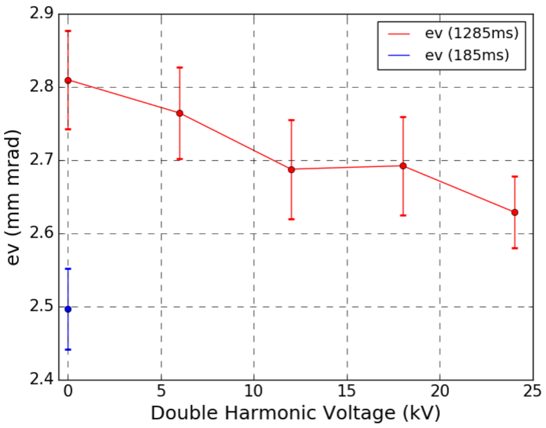


Figure 6: Vertical emittance at injection (blue) and at the end of flat bottom (blue) as a function of the voltage in the double harmonic cavity.

CONCLUSION

Thorough tune scans in both planes towards the corresponding integer resonances have shown the expected blow-up of the emittances. Vertical tune scans for the two LHC beam types, LHC25 and BCMS, show clear excitation of the $Q_v = 6.25$ structural resonance. For the BCMS case the effect manifests only when the coherent tune is set above it. Thus, the best beam performance in terms of brightness is obtained when the working point is $Q_h = 6.20$, $Q_v = 6.25$. Tunes above $Q_v \approx 6.34$ should be studied in future MDs to check whether larger space charge tune spreads can be accommodated. This might require a compensation of the 3^{rd} order resonance at $Q_v = 6.33$ as successfully demonstrated in the past [11]. The beam stability issues encountered for these tunes need to be cured with the transverse feedback system [12]. In the future the impact of chromaticity correction should be studied, as it might reduce the detrimental effects of the structural resonance.

The use of a double harmonic RF system for space charge mitigation seems promising. The issues encountered with the beam phase and radial loops should be further studied so that it can operate throughout the cycle. The BCMS beam could also be tested once the settings of the timing tree and the functions for the harmonic numbers are modified.

ACKNOWLEDGEMENT

The authors would like to thank the PSB and PS OP teams for their help.

REFERENCES

[1] K.Schindl, "Space Charge", *CERN/PS 99-012(DI)*, 1999.

[2] R.Steerenberg *et al.*, "Beams from Injectors in 2016", *LHC Performance Workshop*, 2016.

[3] G.Rumolo *et al.*, "LIU baseline for protons", *LHC Performance Workshop*, 2017.

[4] H.Bartosik *et al.*, "PS emittance blow-up", *Injector MD days 2017*, CERN, 2017.

[5] V.Forte *et al.*, "PSB-to-PS transfer studies", *Injector MD days 2017*, CERN, 2017.

[6] R.Wasef *et al.*, "Space Charge effects and limitations in the CERN Proton Synchrotron", *IPAC'13*, Shanghai, China, 2013.

[7] M.Serluca *et al.*, "Injection Bump Synchronization Study for the CERN PS", *CERN-ACC-NOTE-2016-0006*, CERN, 2016.

[8] S. Hancock *et al.*, "Longitudinal Phase Space Tomography with Space Charge", *Proc. of EPAC'00*, Vienna, Austria, 2000.

[9] M.Cieslak-Kowalska *et al.*, "Interpretation of Wire-Scanner asymmetric profiles in a Low-Energy ring", *CERN-ACC-2016-0109*, CERN, 2016.

[10] A.Huschauer *et al.*, "Working Point and resonance studies at the CERN PS", *IPAC'13*, Shanghai, China, 2013.

[11] A. Huschauer *et al.*, "Identification and compensation of resonances in the CERN Proton Synchrotron", *Space Charge Workshop*, CERN, 2013.

[12] G.Sterbini *et al.*, "Beam-based Performance of the CERN PS Transverse Feedback", 54^{th} *ICFA Advanced Beam Dynamics Workshop*, 2015.