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)

THE (7,7) OPTICS AT CERN PS

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Abstract

The PS lattice is composed by one hundred combined function magnets, which set the bare tune of the machine to $(Q_h, Q_v) = (6.25, 6.28)$. Low energy quadrupoles are used at injection to move the tune in a limited working point area. In particular the vertical tune is moved below 6.25 to avoid the structural resonance 8 $Q_v = 50$ coupled with space charge, which leads to strong losses. In view of the high demands in terms of beam brightness for LIU and HL-LHC projects, the interest of exploring different integer tune working area started during last years. During 2016, for the first time, it has been possible to explore the (7,7) tune working area at injection using the auxiliary circuits of the combined function magnets. A finite-element magnetic model, under development, has been used to predict the required currents in order to get the desired optical parameters. In this paper we present the results and issues encountered during the Machine Development (MD) studies about the injection in the (7,7) area along with optics and beam parameters measurements.

INTRODUCTION

The CERN PS has been working reliably for the past 60 years, during its long history it has been upgraded several times to cope with the increasing demands of the downstreams accelerators and experiments. In view of LIU and HL-LHC projects, the injection kinetic energy of the PS will be increased from 1.4 to 2 GeV to mitigate the space charge tune spread of the increased brightness beams. The combined function magnet unit is composed of a focusing and a defocusing half-unit. So called "Pole Face Windings" (PFW) are placed on the pole faces and "Figure of eight Loop" (F8L) are mounted around each half unit. PFWs are used at high field level to compensate the quadrupolar saturation and leakage field, whereas F8L increases the quadrupolar field in one half-unit, while decreasing it on the other half without affecting the integrated bending field. The bare tunes of the machine are $(Q_h, Q_v) = (6.25, 6.28)$. At injection Low Energy Quadrupoles (LEQ) are used to set the tunes in a small area around the bare tune.

A structural resonance coupled with space charge limits the vertical exploitable area between 6.25 and the integer resonance 6 [1]. Injecting the beam above 6.25 lead to strong losses while pushing the tune close to the integer leads to emittance blow-up. In the effort of studying alternative scenario to exploit the full potential of the accelerator, the possibility of changing the integer tune was considered. While it is relatively simple to move the tunes in the (5,7) and (7,5) area using the F8L, which has almost a linear effect, it is much more difficult to move the tunes in the (7,7) area using the non-linear PFWs. Indeed, in normal operation the working point is programmed by relative variations because the relationship between absolute value of the working point and currents in the auxiliary circuits is not known. The last point has also stimulated the collaboration with the magnet group at CERN to continue the development of the magnetic model of the PS in order to predict tunes and chromaticities for a given set of auxiliary currents. In the following section we present details of the PS main magnet and the magnetic cycle of LHC-type beams. Then we introduce the PS injection scheme and the experimental results of the MD1905 for the (7,7) optics.

THE CERN PS MAIN MAGNET

The PS ring is made by one hundred combined function magnets. A picture of the magnet is presented in Fig. 1 and the cross-section of the PFW plate with auxiliary circuits is illustrated in Fig. 2. Each magnet unit is divided into a focusing and a defocusing half unit, half units are composed of five consecutive blocks. The PFWs are divided into four independent circuits, named DN, DW, FN, FW. "F" and "D" represent the focusing and defocusing part where they are mounted, "N" and "W" stand for narrow and wide type of circuit. Wide circuits cover the whole magnetic pole whereas the narrow circuits only cover the part where the iron gap is narrow (smaller aperture). F8L is a winding describing a figure of eight around the focusing and defocusing poles of the magnet. The possibility to power the circuits independently gives control on the tunes, linear chromaticities and one additional parameter, usually Q_h'' or Q_v''. An effective model is constructed with the measurements of the variation of betatron parameters in response of the PFWs and F8L currents at different momentum of the beam.

Figure 1: Picture of the PS combined function magnet unit.

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https://doi.org/10.23727/CERN-Proceedings-2017-002.43

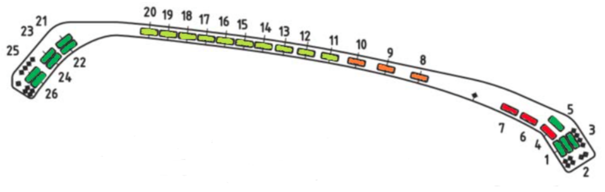

Figure 2: Cross-section of pole-face windings plate. Narrow circuits pole conductors are from 11 to 20 (light green) with return conductors 1-4 and 21-26 (green). Wide circuits are from 8 to 10 (orange) with return conductors 5-7 (red). The small black points are passive circuits that correct the eddy current effects.

Magnetic cycle of LHC-type beams in the PS

The role of the PS in the LHC injection chain (in addition to the acceleration) is to preserve the brightness of the beam and generate the final longitudinal structure of LHC-type beams. The beams are injected at 1.4 GeV kinetic energy and accelerated up to a momentum of 26 GeV/c. The magnetic cycle for the double batch injection scheme for LHC-type beam is presented in Fig. 3, the entire cycle is composed of three basic periods (1.2 s per period), the first batch is injected at 170 ms and the second batch at 1370 ms. After the injection of the two batches, the beam is accelerated on a second plateau for RF splitting. During the second acceleration the PS beam crosses the transition energy around 6 GeV and at top energy the beam is manipulated longitudinally to get the desired bunch spacing before extraction.

LHC-type beams can be produced using the classic scheme of double batch injection (4+2 bunches) in harmonic 7 (h7) followed by triple splitting on the intermediate energy plateau at 2.5 GeV and a double-double splitting at top energy to get the final 72 bunches with 25 ns bunch spacing. An alternative method is the Bunch Compression and Merging Scheme (BCMS) which is characterized by (4+4) bunches injected in h9, the bunches merge in four on the second plateau before triple splitting and a final double-double splitting at top energy to get 48 final bunches.

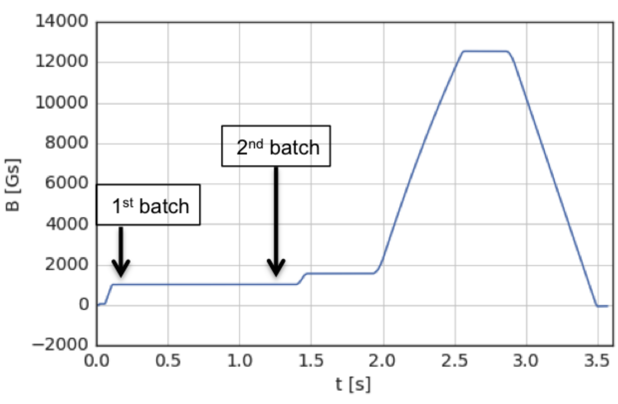

Figure 3: Magnetic cycle of CERN with double batch injection scheme for LHC-type beams.

WORKING POINT OF THE PS

The combined function magnets of the PS set the bare tune to (Q_h, Q_v) = (6.25, 6.28) and natural chromaticities to (ξ_h,ξ_v) = (-0.8,-1). Figure 4 shows the frequency space of the PS, the bare tune is represented by a black point. The blue area around the bare tune is the reachable area of LEQs with currents within ± 10 A. The plot also shows first (full black lines) and second (dashed blue lines) order resonances. The 8^{th} order structural resonances are shown in red and can be written as $aQ_h + bQ_v = 50$ with $a + b = 8$. Several MDs have been performed during last years to characterise the resonances [2, 3], in particular the $8Q_v = 50$ is one of the limiting factor to increase the beam brightness. The outcome of the studies has shown that the structural resonance is coupled with space charge, i.e. intensity dependent, and it leads to strong losses during the long flat bottom if the beam is injected above $Q_v = 6.25$. This resonance limits the exploitable tune area to accommodate the expected Laslett tune spread of about -0.31 or more for LIU and HL-LHC. Figure 4 shows that the (7,7) area is free from structural resonances and, in principle, the area between the integer 7 and the third order resonance $Q_v = 7.33$ could be fully exploitable to place the high brightness LHC-type beam and keep the emittance growth and losses within LIU budget. F8L is linear circuit and can be used to move the tunes in the (5,7) or (7,5) area [1]. These particular cases are not discussed in this paper. PFWs are non-linear elements and not used at injection for regular operation. A basic approach to move the working point would be to ramp the PFWs currents along the flat bottom while measuring the tune in order to approach the working point space towards the (7,7) area. Unfortunately the beam does not survive to several resonances that are present in the machine and are excited by the ramping fields of the PFWs. In particular the resonance $Q_v = 6.75$ leads to a complete loss of the beam.

A finite-element magnetic model has been prepared in OPERA during last years to predict the required currents in the auxiliary circuits [4]. The model successfully reproduce the tune of the bare machine within 1‰ and chromaticity within 30‰. When PFW currents are added to the model, the errors in tune and chromaticity increase. This magnetic model has some limitations: it uses a straight magnet (the real is bent), there is a clear dependence of the multipolar fields on the radius of expansion and therefore the conversion of the integrated fields to multipoles in MADX.

INJECTION IN THE (7,7) WORKING POINT AREA

The PS injection scheme for proton (Fig. 5) is performed with a four bumpers scheme to control the orbit displacement and the slope of the bumped orbit. The septum bends the beam from BT-BTP line by 55 mrad (nominal value) and then it goes through the bumper 43 and 44, a kicker in SS45 operated in terminated mode gives the final 4.3 mrad kick to place the beam on the closed orbit. For a given position and angle of the injected beam at the septum flange the bumpers

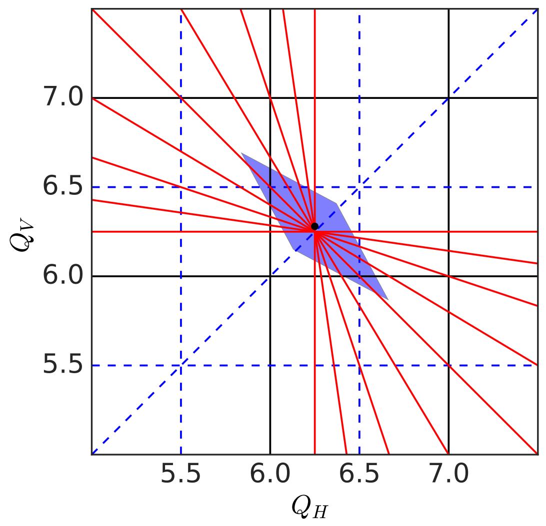

Figure 4: Tune area of the CERN PS. The black point represents the bare tunes of the machine (Q_h, Q_v) = (6.25, 6.28), resonances: integers (black lines), second order (blue dashed lines), 8^{th} order structural (red lines). The blue area around the bare tune represents the reachable area of the low energy quadrupoles at 1.4 GeV.

43, 44 are matched to steer the injected beam with zero horizontal orbit displacement and -4.3 mrad angle in the kicker 45. The bumpers 40 and 42 are then matched to close the bump for the circulating beam. Operationally the strength of the septum, kicker and bumpers are optimized for each different beam to minimize losses and close the bump. An injection steering program is used in operation to minimize injection oscillations and, as consequence, the emittance blow-up due to errors. SEM grids are also used in dedicated MDs to check the betatron and dispersion mismatches of the incoming beam with respect to the periodic optics solutions of the ring at the exit of the septum flange.

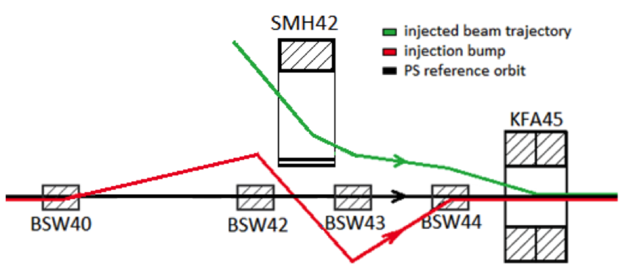

Figure 5: Injection scheme of the CERN PS at 1.4 GeV with bumpers, septum and kicker (not to scale). The injected beam trajectory from the transfer line in green and the bumped orbit in red.

The (7,7) optics changes the phase advances in the machine elements and it is not possible to use, in the standard way, the control room tools to adjust injection and orbit.

During 2015 several tests were performed to inject the beam using different settings of the PFWs currents calculated with the magnetic model. In most of the cases the beam did not survive injection, for one set with about 70 A in the wide circuits and 20 A in the narrow circuits of the PFWs, it was possible to observe part of the beam going through injection and survive for few ms (~ 1k turns). Figure 6 shows the magnetic cycle of LHC-type beam and the intensity of the injected beam. The beam used for this experiment is a clone of the BCMS operational beam, using a single bunch from ring 3 of the Booster with low intensity (25 10^{10} ppb).

The intensity of the beam at injection, presented in Fig. 6, shows that half of the beam is lost at injection and the remaining half is lost after few ms. The orbits, measured in 43 BPMs per plane, are presented in Fig. 7. Each line in the plot is an average over 200 turns after the end of the bump. It was not possible to measure the tunes in a clean way but it is possible to have an indirect measure of the integer part of the tune by counting the number of orbit oscillations around the machine in Fig. 7. This indirect measurement indicates that the tune is close to seven but it is not possible to get the fractional part of it or to understand if it is below or above seven.

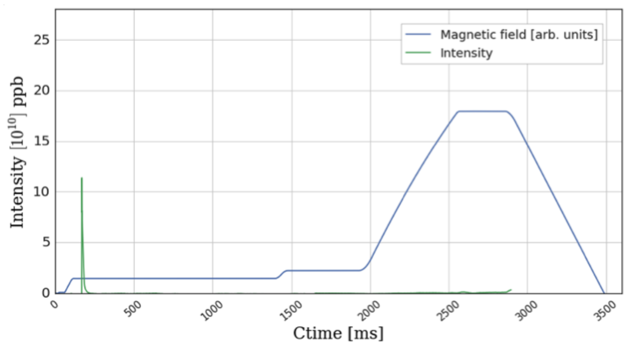

Figure 6: LHC-type beam magnetic cycle (blue line) and intensity evolution of the beam in green. The bunch intensity from the Booster is 25 10^{10} ppb indicating that half of the beam is lost at injection. The beam survives for few ms (~ 1k turns).

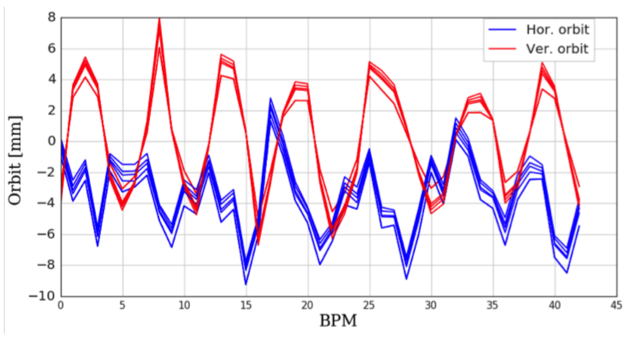

Figure 7: Vertical and horizontal orbit of the beam after injection. Each line is an average over 200 turns after the end of the injection bump which lasts about 500 turns.

In 2016 we continued the MD trying to improve the injection and measuring the optics and beam parameters. The orbits and the signals in the BPMs clearly show that the bump is not closed and the orbit needs to be corrected. As first attempt to correct the injection and orbit of the beam, we measured the response matrices of all injection elements: bumpers, kicker and septum, and the matrices from all orbit correctors in both planes. After applying the calculated corrections we did not observe any improvement in the behaviour of the beam. Several tests on other possible sources of the problem were not successful until we switched off the radial loop of the B-TRAIN, which measures the integrated bending field, seen by the beam. Even with strong losses, part of the beam was surviving along the injection plateau. This effect indicated that the use of the B-TRAIN for this configuration needed to be reconsidered. A further check on the timing of the PFWs currents led us to discover that the fields generated by the PFWs were changing the reading of the magnetic marker (around 60 ms ctime) used to set the B-TRAIN field. Delaying the start time of the PFWs after the magnetic marker solved the problem.

After optimizing the currents in the injection elements and correctors, we were able to inject properly the beam in the PS. An example of intensity along the injection flat bottom for the corrected case is presented in Fig. 8. The beam is dumped on the internal dump at the end of the flat bottom since the ramp and the extraction was not commissioned. The intensity in this case shows that almost no losses occur at injection, the 25 10^{10} ppb from the PSB are transmitted to the PS, some losses are still observed during the injection plateau. The corresponding orbits of the beam are presented in Fig. 9, the plot clearly shows a strong reduction of the peak-to-peak orbit distortion with an oscillation amplitude similar to what is measured with the operational beams in the (6,6) tune area. The setting of the injection elements and PFWs used in the (6,6) operational area and in the new (7,7) area are reported in Table 1.

It is important to note that the maximum PFWs current is limited to 250 A. This means that the beam cannot be accelerated while keeping the PFWs proportional to energy, same argument regards the RMS currents during the cycle (80 A over the supercycle). The highest energy achievable in this condition is about 9 GeV. Even if it is not possible to extract the beam at top energy, the studies of the new working tune area are interesting because they improve our knowledge of the magnetic model and non-linear fields generated by the PFWs. We have also gained experience with the injection optics and the related tools in control room in view of the commissioning of the new injection at 2 GeV.

TUNE AND CHROMATICITY MEASUREMENTS

The measurement of the fractional part of the tune is based on an excitation of the beam and consecutive measurement of the beam response in a fast pick-up over a finite number of turns. The Q-meter software tool in the control room

Table 1: PFWs, septum (SMH42), bumpers (BSW) and kicker (KFA45) settings at injection for the (6,6) and (7,7) WP area.

Element	I [A] ((6,6) area)	I [A] ((7,7) area)
FW	0.0	70.0
DW	0.0	70.0
FN	0.0	19.0
DN	0.0	15.0
BSW40	1030.2	1196.1
BSW42	3773.4	3780.8
BSW43	3090.7	3027.7
BSW44	1142.1	1124.85
KFA45	337.1 [KV]	356.6 [KV]
SMH42	31272.9	31739.2

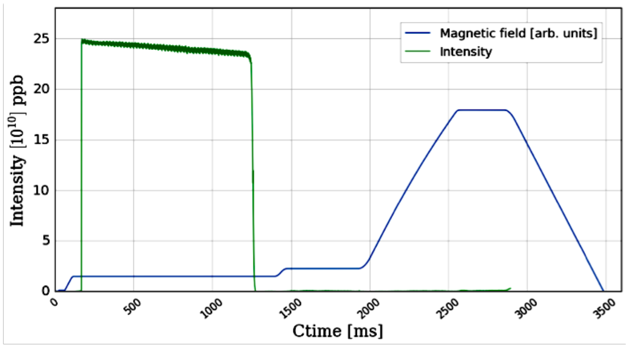

Figure 8: LHC-type beam magnetic cycle (blue line) and intensity evolution of the beam in green. The bunch intensity from the Booster is 25 10^{10} ppb indicating that no losses occur at injection. The beam is dumped on the internal dump at the end of the injection plateau to avoid irradiation of the full ring.

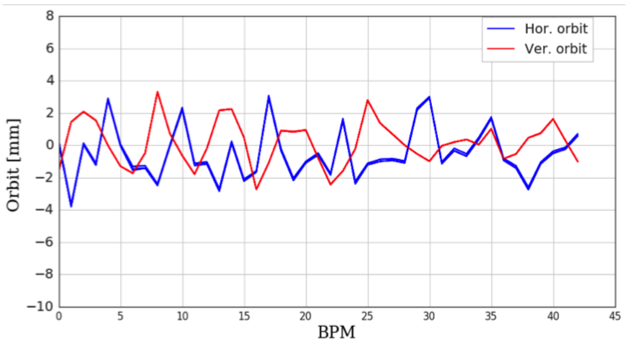

Figure 9: Vertical and horizontal orbit of the beam after injection. Each line is an average over 200 turns after the end of the injection bump which lasts about 500 turns.

calculates the fractional part of the tunes by Fourier analysis of the data. Using the PFW settings in Table1, the Q-meter calculates $(q_h, q_v) = (0.27, 0.16)$. For the following MDs we moved the fractional part of the tunes with LEQs to $(q_h, q_v) = (0.24, 0.22)$. To measure also the integer part of the tune and compare the results of the Q-meter, an advanced method based on multiple BPM data analysis with Numerical Analysis of Fundamental Frequencies (NAFF) algorithm was applied to the transverse data [5,6]. The method does not need to excite the beam, it is very fast and allows to get turn-by-turn tune measurements with also the integer part. The orbit data during the injection bump are chosen due to the largest betatron oscillations. An example of tune measurement with this technique is presented in Fig. 10. The upper plot shows the turn-by-turn evolution of the tunes while the plot below shows the relative errors. In about 40 turns the measurements converge to the values obtained by the Q-meter with a perfect agreement in the horizontal plane and a small deviation of 0.02 in the vertical tune.

A chromaticity measurement was also performed to evaluate the effects of the non-linear PFWs. Indeed the measurements in Fig. 11 show that the horizontal chromaticity has a parabolic shape, the effect is less strong on the vertical plane. The linear chromaticities are comparable to the values measured in the (6,6) area. It should be noted that the Q-meter in the control room does not measure the integer part of the tune and the reported values by the software GUI in Fig. 11 are with the integer 6 by default.

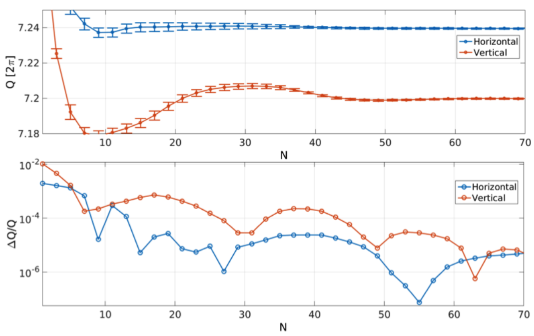

Figure 10: Tunes measurement with advanced multiple BPMs data and NAFF algorithm during the firsts 70 turns.

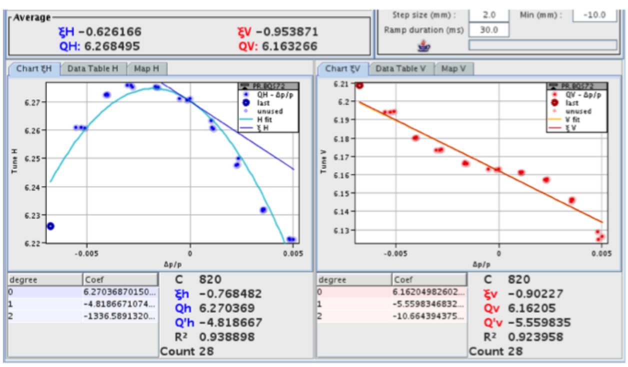

Figure 11: Chromaticity measurement snapshot using the Q-meter in the control room. Note that the tool does not measure the integer tune so it displays 6 by default.

DISPERSION MEASUREMENTS AND INJECTION STEERING PROGRAM

To continue the characterisation of the new optics we measured the dispersion, presented in Fig. 12. We continued our studies using LHCINDIV beam (~ 12^{10} ppb) to reduce irradiation due to the heavy use of the internal dump. The measured points in the plot are in a reasonable agreement with the MADX model at (7,7) (blue line in the plot). The MADX optics model was implemented in the injection steering tool of the PS, named YASP [7], to correct the injection orbit and minimize the oscillations. Apart from some issues uploading the model in YASP due to different naming convention in the element database, the implementation was successful and led to orbit correction at the very first try. The output of YASP showing the orbits in both planes for the first and second turn after correction are presented in Fig. 13, the superposition of the two orbits indicates that the injection steering program works correctly.

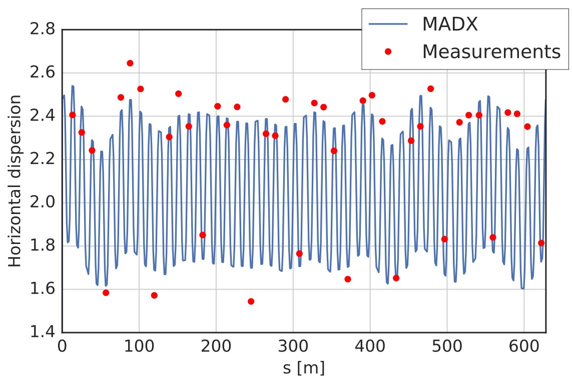

Figure 12: Dispersion measurement in the horizontal plane shows a good agreement with the MADX model.

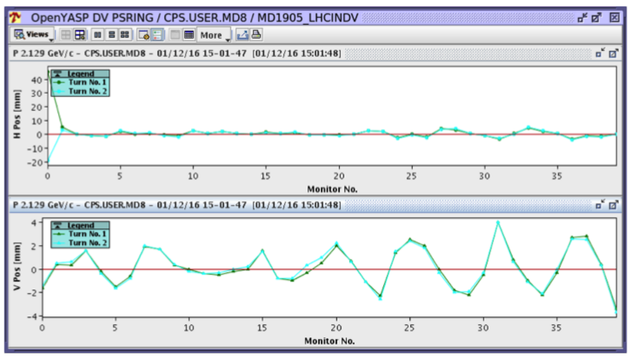

Figure 13: First and second turn orbit from the injection steering program YASP shows an excellent injection oscillation correction.

EMITTANCE MEASUREMENTS AND EFFECT OF THE Q_v = 7.25 LINE ON THE BEAM

To complete the beam characterisation with the new working point in the (7,7) area we measured the emittances at PSB extraction and PS injection to get some indications about the beam mismatch with the new optics. The transfer line is not fully PPM and the only way to inject without mismatch would have been to perform dedicated MDs. Given the complexity of the operation and few MD slots left at the end of last year operation, we decided to leave the transfer line mismatched. The results of the emittance measurements in the horizontal and vertical plane are reported in Fig. 14 and 15, respectively. The vertical axis represents the measurements at PSB extraction while the horizontal one represents measurements at PS injection; the colour scale indicates the bunch intensity. The results indicate a blow-up in the horizontal plane of about 10% and 40% in the vertical. Given the low intensity of the beam, the observed blow-ups are assumed to be mainly from the betatron and dispersion mismatches at injection.

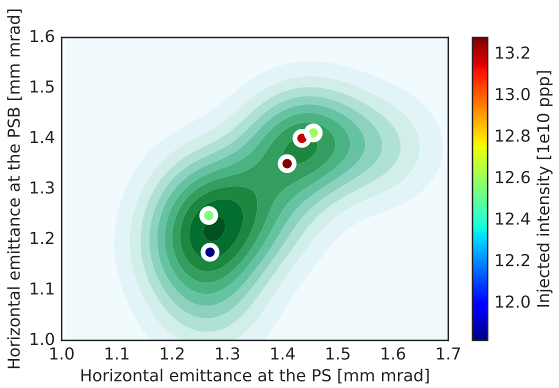

Figure 14: Horizontal emittance measurements at PSB extraction and PS injection. The colour scale indicates the bunch intensity.

An interesting study carried out is the effect of the line Q_v = 7.25. Frequency Map Analysis (FMA) do not show any 8^{th} order resonance but the 4^{th} order with the formation of the 4 islands in the transverse space [8]. To analyse the line we moved the vertical tune just below and above 7.25 (Q_v = 7.245 and 7.255) while measuring the losses between injection and the end of the flat bottom. The results are presented in Fig. 16, for each set of data it is clear a correlation between intensity of the beam and observed losses. In addition the result for Q_v = 7.255 indicates that losses increase above 7.25. Most likely the new observed resonance is a lattice resonance excited by the PFWs currents. A possible way to study the real nature of the Q_v = 7.25 resonance would be to move the tune in the (5,7) area using the linear F8L, and repeat the study for working points above and below 7.25.

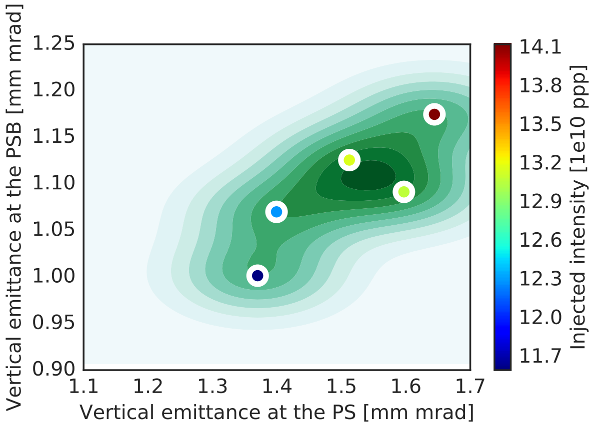

Figure 15: Vertical emittance measurements at PSB extraction and PS injection. The colour scale indicates the bunch intensity.

To complete the study we measured the response matrices of the system. A scan of the tune and chromaticity, adding 2 A on each PFW circuit to the nominal value listed in Table 1, has been performed. The results presented in Fig. 17 show that increasing the current in the defocusing circuits the tunes approach to a common value, while the chomaticity has almost the same values for the wide circuit and inverted values for the narrow circuit. The effects of focusing circuits on the tunes are the opposite; the tunes diverge while the effect on chromaticity is similar, almost same value for wide circuit and inverted values for the narrow one. From these results it is possible to construct a matrix to move tunes and chromaticities in the (7,7) tune area.

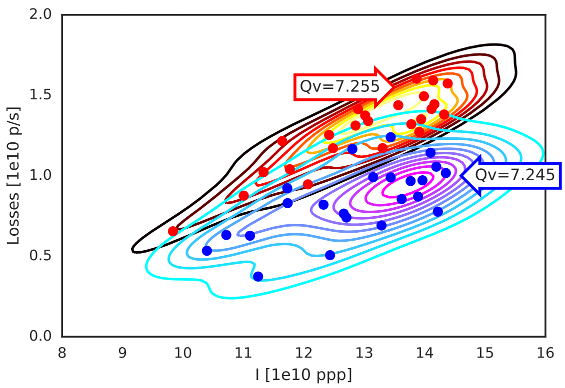

Figure 16: Losses as function of injected intensity for working point above and below Q_v = 7.25.

CONCLUSION

For the first time the injection of LHC-type beam in the (7,7) tune area of the PS has been achieved. The injection issues encountered during the MDs have been useful to understand the procedures to follow in case of operation with the auxiliary circuits at injection. Even if it is not possible to accelerate the beam at top energy, the exploration of

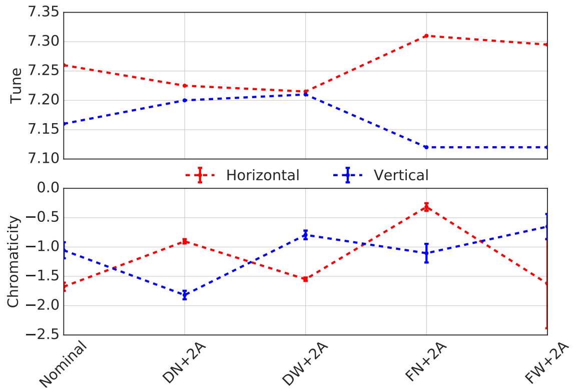

Figure 17: Tune and chromaticity scan adding (individually) 2 A on each PFW circuit to the nominal value listed in Table 1.

the new tune area gives us the opportunity to improve the non-linear model of the PS and the possibility to test the magnetic model over a wide range of currents in the auxiliary circuits. The line $Q_v = 7.25$ is probably a new lattice resonance excited by PFW fields, further studies using the F8L in the (5,7) area could confirm this result.

ACKNOWLEDGEMENT

The authors would like to thanks the OP team for the support during the MDs, the SWAN team for the development of online Python notebooks used for data analysis, Heiko Damerau for the useful discussions during the MDs and Foteini Asvesta for the FMA in the (7,7) area.

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