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# IMPROVED LOW-ENERGY OPTICS CONTROL FOR TRANSVERSE EMITTANCE PRESERVATION AT THE CERN PROTON SYNCHROTRON

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*Abstract*

Preservation of the transverse emittances across the CERN accelerator chain is an important requirement for beams produced for the Large Hadron Collider (LHC). In the CERN Proton Synchrotron (PS), high brightness LHC-type beams are stored on a long flat bottom for up to 1.2 seconds. During this storage time, direct space charge effects may lead to resonance crossing and subsequent growth of the transverse emittances. Previous studies showed an important emittance increase when the PS working point is moved near integer tune values. Subsequent simulation studies confirmed that this observation is caused by an interplay of space charge effects and the optics beatings induced by the Low Energy Quadrupoles (LEQ). A new optics configuration using these quadrupoles to reduce the optics beating and the emittance growth was developed and experimentally validated. The results of simulation and experimental studies are presented in this contribution.

## INTRODUCTION

The initial tune correction scheme of the PS consisted of 50 LEQs placed symmetrically around the machine, which consists of 100 combined function magnets. As a result, the beta beatings induced from quadrupoles with a 90° phase advance between them would compensate for eachother [1–3]. During the course of the PS' runtime new installations required 10 LEQs to be removed, breaking the lattice symmetry and increasing the optics beatings. Previous studies have shown that the large emittance blow-up generated at working points near integer values in the PS are caused by an interplay of the increased optics beatings due to the irregular distribution of the LEQs and space charge effects [4–7]. Beams with high tune-spread will cross the integer resonance which is the case for the high-brightness beams that are used in the LHC. These beams are therefore limited to the usable working point range [8]. In the presented study a new LEQ-configuration was explored to reduce the optics beatings and increase the flexibility of the PS in terms of working point control.

The optics beatings will be reduced by various optimisation techniques using the single particle simulation tool MAD-X [9, 10]. All promising configurations will then be tested in a simulation framework that includes space charge effects by tracking a particle bunch using PyORBIT [11] through a magnetic sequence with nodes for space-charge calculations. At the nodes, the beam distribution is calculated and dependent on the distribution, the particles receive a coulomb kick [12]. This framework is used to correctly model the direct space charge tune spread and hence investigate the effect on emittance growth. Finally, the most promising LEQ configuration is tested experimentally.

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## LEQ OPTIMISATION

In the current operational configuration, the LEQs are installed at the end of 40 out of 100 straight sections, just before the combined function magnet units. Of the 100 straight sections, 12 have room for a quadrupole to be installed. Additionally, many of the straight sections that are unoccupied could house two LEQs. These additional possibilities are considered in the presented calculations. The working point of all configurations are moved close to integer resonance ($Q_x = 6.1, Q_y = 6.1$) using the LEQs where the focusing and defocusing quadrupoles respectively have the same strengths. This ensures that the optics beating is large causing and increased emittance growth to be observed in the space charge simulations.

### *Parameterisation of the Optics Beatings*

For the following optimisations, the amplitude of the beating of the three main optics functions in the PS ($\beta_x, \beta_y, D_x$) need to be represented by a single real value. Presuming that if a minimum of this value is found, the optics beatings for the corresponding configuration is minimised. The following representation is used here:

$$\xi = \frac{\sigma(\beta_x) + \sigma(\beta_y) + \sigma(D_x)}{3}, \tag{1}$$

Where $\sigma$ is the standard variance of the optics function between brackets. Other representation were tested but this one gave better representations. Since the beatings are essentially describing large variations of the optics functions, large beatings will result in increased standard variations. The effectiveness of this representation is shown in Fig. 1 where the ideal 50-LEQ and current 40-LEQ configuration are compared.

For extra clarity, $\xi$ is normalised to $\xi^* = \frac{\xi}{\xi_0}$ where $\xi_0$ is the bare machine lattice where no optics beating is present at a working point of ($Q_x = 6.21, Q_y = 6.24$).

### *Optimisation Algorithm*

The formulation of $\xi^*$ allows the optimisation of the LEQ positions to be solved by a numerical constrained optimisation algorithm, such as the Zeroth-Order Optimization (ZOOpt) package for Python [13]. The positions of the 40

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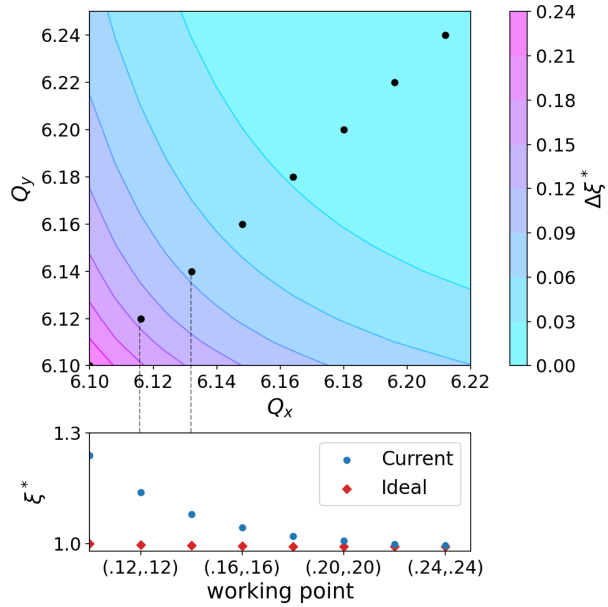


Figure 1: $\xi$ for both current and ideal configurations when the working point is moved closer to the integer resonance, with $\Delta\xi^*$ being the difference between both configurations.

quadrupoles are the optimisation variables and $\xi^*$ serves as the objective function. In principle, this problem would be best handled by a discrete optimisation problem since the quadrupole positions have discrete values but this type of algorithm is generally more complex and proved to be incompatible with MAD-X or cpymad, the MAD-X interpreter for python [14–16]. As a consequence, the positions of the quadrupoles have to be considered as a continuous function during the optimisation, meaning that the algorithm can place them anywhere along the ring. In every simulation step the quadrupoles are then re-located to the nearest available straight section resulting in a feasible LEQ configuration. And the $\xi^*$ value of this LEQ configuration is calculated and used in the optimisation.

The optimisation was run multiple times with a random initial guess, often resulting in a better $\xi^*$ value compared to the current configuration. These potential configurations required many LEQs to be removed and installed in different positions, which would be a very time consuming endeavor. Especially since the new configurations need to be experimentally tested first. Therefore, a new constraint is added to the study: the new quadrupole configuration will need to remain as similar as possible to the current configuration. Only the best result of the optimisation algorithm study is further investigated using space charge. The changes to the current lattice are shown in Table 1. Since this configuration was found using the optimisation algorithm, we will name it the optimised configuration.

### *Iterative Prediction of $\xi^*$*

The added constraint that the current LEQ configuration can only be changed minimally causes the optimisation algorithm above to be unusable. Instead the optics beatings of LEQ configurations close to the current configuration are directly computed using the optics beatings equations [17]. These equations are used to predict the effects of removing or adding a single quadrupole to the lattice. This procedure of predicting the optics by changing one quadrupole is then repeated on potentially promising configurations from the previous iteration. This can be done multiple times, leading to a branch-like structure where the branching depth equals the number of changes made to the initial magnetic lattice. This technique is used until branching depth 5, to keep the computational time down. The results of the branching study are also shown in Table 1. Removing only one quadrupole, the one located in Straight Section (SS) 90, has a notably large improvement. Whereas the configurations with more changes have only a slightly lower $\xi^*$ value. This is not true for the 2-change configuration, which will be omitted from further studies since this configuration has a significantly higher $\xi^*$ value compared to the others.

Table 1: Changes to the current lattice to get new potential configurations based on the optimisation study and the branching study.

| | **remove LEQ in SS** | **add LEQ in SS** | $\xi^*$ |
|---|---|---|---|
| **0 changes** | | | 1.2460 |
| **1 changes** | 90 | | 1.1141 |
| **2 changes** | 56 | 86 | 1.1707 |
| **3 changes** | 10, 90 | 26 | 1.1097 |
| **4 changes** | 10, 90 | 26, 36 | 1.1094 |
| **5 changes** | 21, 22, 90 | 13, 14 | 1.0908 |
| **Optimised** | 55, 72, 95, 99, 100 | 13, 14, 25, 26, 63 | 1.1037 |

## EMITTANCE BLOW-UP DUE TO SPACE-CHARGE FORCES

The LEQ configurations of Table 1 need to be tested using the space-charge framework. The framework will compute the emittance until 5ms after injection to ensure enough time for the emittance to grow, repeating this process in a static tune scan of the transverse planes. The transverse distribution of the injected beam is rematched for the corresponding working point and for each quadrupole configuration. The measured longitudinal beam distribution of the current configuration was used, leading to an additional small beam mismatch. The final emittances of the transverse tune scans are presented in Fig. 2 at the locations of the Wire Scanners (WS).

Although the beam blow-up is still present, both planes show some reduction for the new configurations. Most notable is the reduced vertical emittance growth. Every configuration except for the 4 changes lattice shows a reduction of more than 50 % compared to the current lattice. Note that the blow up reduction is better for $Q_y = 6.10$ compared to other values, since 6.10 is the vertical tune value used in the optimisation. Going below this tune-value it is probable that the effects of the integer resonance become too large

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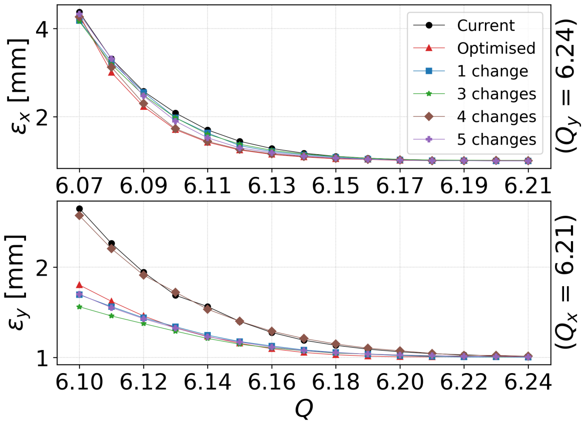


Figure 2: Evolution of the normalised emittances 5 ms after injection obtained with space-charge simulations using different quadrupole configurations.

and the beam gets lost. The 3 changes lattice shows the best vertical blow-up reductions of 65 % close to the integer tune compared to the other lattices, while the horizontal emittance shows the least amount of improvement for most of the scan. The opposite can be said about the 4 changes lattice, where the vertical emittance shows no improvement and the horizontal blow-up does show improvement ( $\approx$ 33 %). At the moment both $\beta$-functions have equal contributions to $\xi^*$, but further improvements in one of the planes could be found at the cost of the other plane by putting additional weights in the $\xi$ definition. Nonetheless, the 1-change and 5-change configuration show a general emittance blow-up reduction in both planes.

## EXPERIMENTAL MEASUREMENTS

The 1-change configuration discussed above is not only easily testable but also has a significant improvement on the emittance blow-up. Using this configuration, tune scans are experimentally performed. The tune scans are limited by the maximum strength of the LEQs. This measurement is compared to the current lattice and a setup where the optics are controlled by the Pole Face Windings (PFW), i.e. circuits on the combined function magnets that can introduce quadrupole and higher order components. They are an additional means for tune and chromaticity control, mostly used at higher energies and they induce a negligible amount of beta beating. One of the conclusions from the study that developed the space charge framework was that the simulation showed no emittance blow-up at all when the working point was controlled with the PFWs. Experimentally, emittance blow-up is expected when using PFWs since there is still going to be resonance crossing. For this reason, the PFW-setup can be used as a benchmark for the least amount of blow-up right after injection since the higher-order effects are not yet present at this point. A large space charge tune spread of $(\Delta Q_x, \Delta Q_y) \approx (0.17, 0.33)$ during injection in the PS was achieved by the beam parameters of the CERN Proton Synchrotron Booster to ensure resonance crossing for all measurements. The wire scanners were launched at 5ms

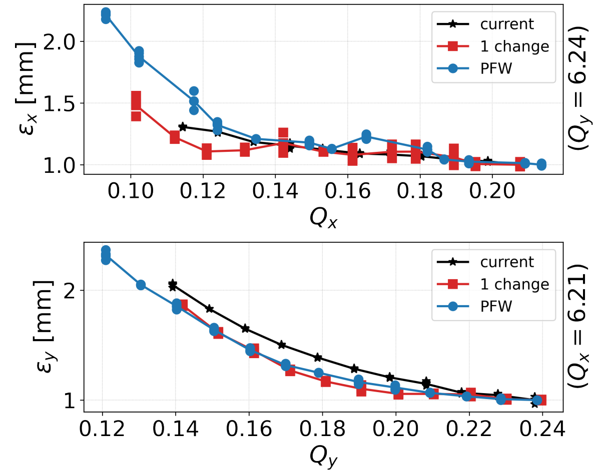


Figure 3: Experimental results of the tunescans for the current PS lattice performed using the LEQs, the PFWs and the 1-change configuration. The scans are performed with WS 64V and 65H.

after injection where the emittances of the working point (6.21,6.24) are $(\epsilon_x, \epsilon_y) \approx (1.2, 0.84)$.

In Fig. 3 the reduction of emittance blow-up near the integer resonance is mainly present on the vertical plane, similar to what the simulations show. The PFWs and the 1-change configuration even have comparable values, proving that the blow-up due to beta beating has a smaller effect on the vertical plane while using the new LEQ optics configuration. The horizontal plane shows little improvement of the emittance blow-up for both the PFWs and the 1-change configuration.

## CONCLUSION

The PS experiences emittance blow-up for working points near the integer resonances. This is caused by an interplay of space charge effects and the optics beating induced by the irregular positions of the LEQs around the ring. A repositioning of these LEQs was investigated to reduce the emittance blow-up. This reduction was realised through an optimisation algorithm or by iteratively either removing or adding an LEQ to the current lattice. To compare the quadrupole configurations with each other, an objective function $\xi^*$ was defined that quantifies the optics beatings based on the standard deviations of the $\beta$ and dispersion functions of the machine. As a result, configurations were found with small $\xi^*$ that were then simulated including space charge forces. In all cases, the emittance blow-up was reduced for at least one of the transverse planes. The most notable configuration was the one where the LEQ in SS 90 is removed. Experimental verification of this configuration showed important mitigation of the vertical emittance blow-up, which is an extremely encouraging result for the operation of high-brightness LHC-type beams.

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## REFERENCES


[1] E. Regenstreif, "The CERN Proton Synchrotron Part 1", CERN Yellow Reports: Monographs, CERN, Geneva, Switzerland 1959. doi:10.5170/CERN-1959-029

[2] E. Regenstreif, "The CERN Proton Synchrotron Part 2", CERN Yellow Reports: Monographs, CERN, Geneva, Switzerland 1960. doi:10.5170/CERN-1960-026

[3] P. Bossard, "Etude et realisation de quadrupoles d'injection", https://edms.cern.ch/document/1751471/1/.

[4] H. Rafique, F. Asvesta, H. Bartosik, A. Huschauer, and M. Kaitatzi, "MD4224 High Brightness in Space charge meeting: PS integer experiment 2019", https://indico.cern.ch/event/810583/.

[5] H. Rafique, F. Asvesta, H. Bartosik, A. Huschauer, and M. Kaitatzi, "Approaching the Integer Tune in the Proton Synchrotron to Probe Space Charge at Injection in LIU-PS Beam Dynamics WG meeting 36 2019", https://indico.cern.ch/event/857161/.

[6] F. Schmidt and F. Asvesta, "Space Charge Resonance Analysis at the Integer Tune for the CERN PS", in *Proc. HB'21*, Batavia, IL, USA, Oct. 2021, pp. 124–128. doi:10.18429/JACoW-HB2021-MOP20

[7] F. Asvesta and H. Bartosik, "Space charge studies in the PS", doi:10.23727/CERN-Proceedings-2017-002.37

[8] F. Asvesta and H. Bartosik, "Identification and characterization of high order incoherent space charge driven structure resonances in the CERN Proton Synchrotron", *Phys. Rev. Accel. Beams*, vol. 23, p. 091001, Sep. 2020. doi:10.1103/PhysRevAccelBeams.23.091001

[9] L. Deniau, H. Grote, G. Roy, and F. Schmidt, "User's Reference Manual 2020", https://mad.web.cern.ch/mad/webguide/manual.html/.

[10] L. Deniau, H. Grote, G. Roy, and F. Schmidt, "MAD Web Page", https://mad.web.cern.ch/mad/.

[11] A. Shishlo, S. Cousineau, *et al.*, "The Particle Accelerator Simulation Code PyORBIT", *Procedia Computer Science*, vol. 51, pp. 1272-1281, 2015. doi:10.1016/j.procs.2015.05.312

[12] H. Rafique, "MD4224 Light github repository" (forked on 26-07-2020). https://github.com/HaroonRafique/MD4224_Light/.

[13] Y. Liu, Y. Hu, H. Qian, Y. Yu, and C. Qian, "ZOOpt: Toolbox for Derivative-Free Optimization". doi:10.48550/arXiv.1801.00329

[14] J. Nocedal and S. J. Wright, *Numerical Optimization*, second. ed. New York, NY, USA: Springer, 2006.

[15] S. Boyd and L. Vandenberghe, *Convex Optimization*, Cambridge University Press, 2004. doi:10.1017/CBO9780511804441

[16] "cpymad Web Page", https://hibtc.github.io/cpymad/.

[17] W. Van Goethem, A. Huschauer, and P. Van Mechelen, "Improved low energy optics control at the CERN Proton Synchrotron", https://cds.cern.ch/record/2806164/.