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ZERO DISPERSION OPTICS TO IMPROVE HORIZONTAL EMITTANCE MEASUREMENTS AT THE CERN PROTON SYNCHROTRON

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Abstract

In modern particle accelerators, the horizontal dispersion function is forced to zero at locations with instrumentation measuring the transverse beam distribution, in order to remove the dispersive contribution to the horizontal beam size. The design of the CERN Proton Synchrotron (PS) did not foresee such a zero-dispersion insertion, making it challenging to get a good precision on the beam emittance measurements. In this contribution, we present a new optics configuration, which allows to reach zero horizontal dispersion at the locations of different beam size measurement locations. This can be achieved by powering a set of trim quadrupoles, the so-called Low Energy Quadrupoles (LEQ). We investigate how the resulting optics perturbation affects beam parameters.

INTRODUCTION

The emittance is one of the most important beam parameters for accelerators. Its value must be well known along the injector chain, as a means to identify and study errors that could lead to unexpected emittance blow-ups, as it was observed at PS injection from the PSB for high-brightness beams during Run 2 [1]. The emittance ϵ can be calculated at locations where the beam size $\sigma(s)$ is measured and other parameters are known using the following equation:

$$\epsilon = \frac{\sigma^2(s) - D^2(s)\left(\frac{\Delta p}{p_0}\right)^2}{\beta(s)}, \qquad (1)$$

with $D(s)$ the dispersion function, $\frac{\Delta p}{p}$ the relative momentum spread and β the optical beta function.

Research accelerators that are built in recent times usually contain dispersion suppressors. These are sections of the machine where the dispersion is brought to zero, removing the dispersive contribution from the expression above. The PS does not have such a section and therefore there is a non-zero horizontal dispersion along the whole ring, introducing additional errors in emittance calculations [2,3]. In this study, the LEQs are used to induce a dispersion oscillation leading to zero dispersion at specific beam measurement locations in the PS. This dispersive oscilliation must be optimised so the other optics functions are minimally perturbed while zero dispersion is reached. The optimisation uses the single particle simulation toolkit MAD-X [4,5] to identify the corresponding LEQ-strengths. Going from nominal optics to zero dispersion optics is initially tested using a simulation framework that allows including space charge effects in time dependent optics configurations, here implemented using PyOrbit. [6,7]. The optics are then used in an experimental setting to see if zero dispersion is reached at the desired beam measurement location and to investigate what the effects are on the beam size and emittance while the optics are changed between the nominal and the zero-dispersion configuration.

SINGLE PARTICLE STUDY

The zero dispersion optics are abstracted into a numerical optimisation problem. The quadrupole strengths are a clear choice as optimisation variables for this study. In this manner, the change in optics can be minimised using a quadratic objective function since the induced tuneshift and beta-beating from a quadrupolar variation is directly proportional to that variation:

$$\text{minimize } \delta k_1^2 + \delta k_2^2 + \ldots + \delta k_n^2 ,$$

where δk_i are the strength variations of the individual LEQs. On top of having the quadrupole strength limits as bounds, an additional boundary condition needs to be placed on this objective function that forces the dispersion to zero at a specific location. This bound is created by superimposing the effects of each quadrupole on the dispersion at that location. This bound is of the form

$$D^* = D_0 + \Delta D_{k_1} \times \delta k_1 + \Delta D_{k_2} \times \delta k_2 + \ldots + \Delta D_{k_n} \times \delta k_n, \quad (2)$$

where D^* is the dispersion after varying the quadrupoles which will be equated to zero, D_0 is the initial dispersion and ΔD_{k_i} are the scalars proportional to the effect of a quadrupole variation of size δk_i on the dispersion. A small study was performed to prove that the dispersion beating is directly proportional to the quadrupole variation [8], validating the expression above. Thus a convex quadratic optimisation problem is formed which will force the dispersion to zero and minimally affect the other optics functions. This optimisation problem is solved using CVXOPT [9].

Initially, all 40 LEQs are used in the optimisation. However, the same result can be achieved by using less active quadrupoles. The active number of LEQs is iteratively reduced by one until the quadrupole strength limit is reached. The reduction is realised with the following reasoning: if $|\delta k_i|$ is large for a certain quadrupole, that quadrupole heavily forces the dispersion to zero. Hence, the LEQ with the lowest $|\delta k_i|$ has the least influence in this problem and can be removed from the equations.

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A zero-dispersion simulation starts with the active set that consists of the current LEQ lattice. The quadrupole strengths of the active set, starting from their nominal settings, is then optimized by the numerical optimisation algorithm. The LEQ with the lowest $|\delta k_i|$ is then removed from the active number of LEQs.

This process is repeated, starting from the nominal optics and removing a quadrupole from the optimisation in every step. The beta functions and tunes start showing significant distortions when 10 or less active quadrupoles are used. A compromise is found between the complexity of the zero dispersion optics settings and the perturbation of the optics functions. With this method, zero dispersion optics are found for every Wire Scanner (WS) location in the PS using 15 quadrupoles. The zero dispersion optics for WS in Straight Section (SS) 68 from a MAD-X simulation is shown in Fig. 1.

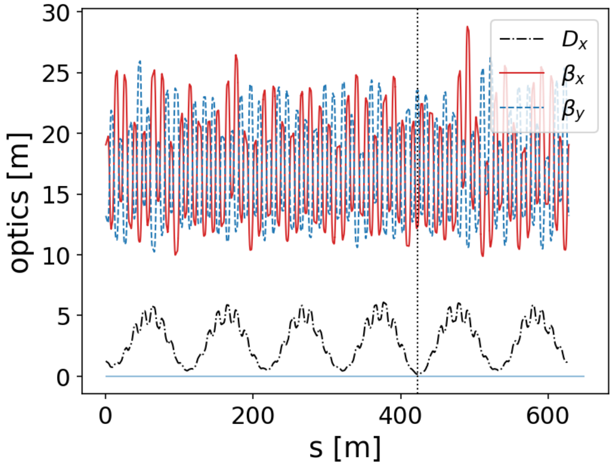

Figure 1: The zero dispersion optics at WS 68 from the single particle simulation achieved by 15 LEQs. The vertical dashed line is the location of WS 68.

THE IMPACT OF DIRECT SPACE CHARGE EFFECTS

The zero dispersion objective was reached using single particle simulations in the previous section. Here, space charge forces are included in the simulations to examine their effect on the dispersion. Experimentally, the dispersion should reach a zero value only when the beam profile is measured. Before and after the measurement the beam must be in its nominal state. Therefore, knobs were developed and implemented into the PS controls system that allows to continuously ramp the LEQ strengths to and from zero dispersion optics. Conducting space charge simulations with the PS model, an experimental procedure is replicated where the beam starts in its nomimal state, it is ramped towards the zero dispersion optics, it is kept there sufficiently long for a beam profile measurement, and it is returned to the nominal optics. The same procedure is repeated for a simulation without space charge forces for comparison. The space charge framework reconstructs the horizontal dispersion from the distribution of the beam by looking at the correlation between the relative momentum spread $\frac{\Delta p}{p}$ and the horizontal position of the beam, while the dispersion from MAD-X is based on the periodic solution of the magnetic lattice. Due to the different reconstruction method, the dispersion will have a small difference between them, even when no space charge is used. The results of the simulations are shown in Fig. 2 and Fig. 3.

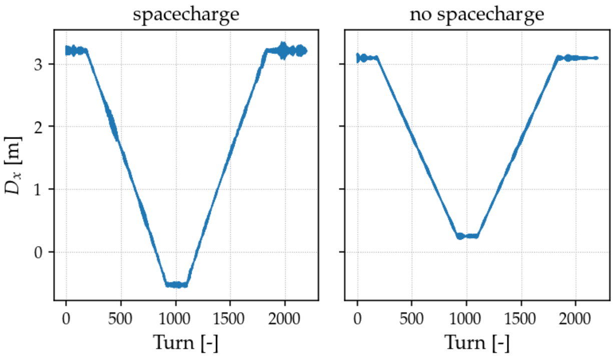

Figure 2: The horizontal dispersion from space charge and non-space charge simulations at the WS at SS 65 using LEQ knobs designed for this location.

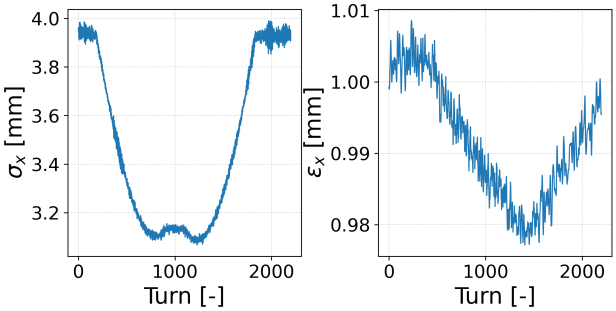

Figure 3: The horizontal beam width and emittance during space charge simulations at WS 65.

Space charge forces cause a larger change in dispersion compared to the non-space charge simulations and even lead to negative dispersion when the knobs are fully ramped. This non-zero dispersion is also visible in the horizontal beam width. This means that in an experimental set-up less magnetic strength will be needed to reach zero dispersion. The emittance shows an unexpected variation during the ramping of the knobs. This is possibly due to the ramping time being too short for an adiabatic process. Nonetheless, zero dispersion is reached and can be tested in the machine. Here, the ramping of the knobs can be done in the order of milliseconds instead of a few turns. This would give better insight on where the unexpected emittance behaviour originates from.

EXPERIMENTAL MEASUREMENTS

Two LEQ knobs are developed to reach zero dispersion at the horizontal WS 54 and 68. The optimisation can reach zero dispersion anywhere along the lattice but the LEQs and their values will change depending on which location is chosen. Thus, the measurement is done at two locations to verify if the ramping of the knobs has similar effects no matter the location. Wire scanner measurements are launched in an interval of 10 ms to measure the beam width before, during and after zero dispersion optics. The ramping of the knobs is done over an interval of 150 ms for both the up and down-ramp with a 150 ms plateau in between. The horizontal dispersion is reconstructed using a Beam Position Monitor (BPM) from the same SS from which the beam position can be taken over multiple cycles while varying the radial steering. Using the slip factor from MAD-X, the momentum error $\frac{\Delta p}{p}$ can be calculated and the local value of the dispersion can be determined. This also allows for the reconstruction of the emittance if the β function is taken from the MAD-X simulation.

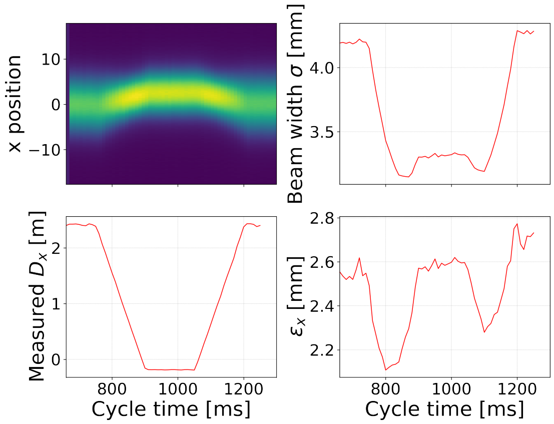

Figure 4: The optics at WS68 using the full range of the zero dispersion knobs while ramping over 150 ms.

Figure 4 shows a visualisation of the WS results over the ramping interval in a waterfall plot. The measurements of the beam size at the WS location and dispersion at the nearby BPM are also shown. Lastly, the emittance is reconstructed. The results from WS 54 are very similar. It can be seen that the dispersion goes below zero when the knob is fully ramped resulting in a small increase of the beam width compared to after the knobs has been ramped down and the beam is returned to nominal optics. The emittance shows an decrease while the knob is being ramped. Additionally, there is a general increase in the emittance over the measurement interval, which is likely due to a non-adiabatic process.

Since there is still an effect on the emittance which we suspect is due to non-adiabatic ramping of the LEQ-knobs, the experimental measurements are done again with a slightly different set-up. Firstly, the ramping of the knobs are done over an interval of 400 ms, which is the largest interval that the flat-bottom of a standard PS cycle allows for. Secondly, the knob values are sampled in search for true zero dispersion and this value will serve as the plateau in the WS measurements. The results for WS54 are shown in Fig. 5 because WS68 had technical issues during the measurement period.

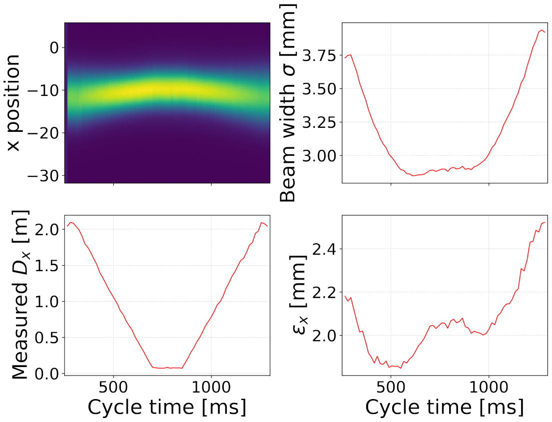

Figure 5: The optics at WS54 using 96% of the zero dispersion knobs while ramping over 400 ms.

Figure 5 presents the same plots as the previous measurement. While the dispersion does not fully reach zero dispersion at the nearby BPM, the beam width profile shows again a small increase at the maximum knob value plateau. This means that at the WS the dispersion went slightly below zero. The emittance profile again shows a decrease while ramping the beam and a general increase over the whole interval. This means that either an adiabatic ramp cannot be reached in the PS or there is another effect that we are not yet aware of.

CONCLUSION

Having a good accuracy on emittance measurements is essential to further improve the performance of the PS in the injector chain. However, the dispersive contribution to the beam size on the horizontal plane is a known source of uncertainties. The performed research helps to deconvolute the dispersive contributions from the beam profile measurements through obtaining zero-dispersion optics with the LEQs in the PS.

The LEQ strengths needed to achieve zero-dispersion optics are obtained by globally minimising the sum of the squares of the quadrupole strength variations from the nominal optics, while keeping the dispersion at zero at the measurement location. The impact of space charge forces leads to a further decrease of the dispersion, making the search for true zero dispersion a non-trivial one. Furthermore there is a decrease of the emittance while the knobs are being ramped and a general increase of the emittance over the measurement intervals that cannot be removed by ramping the knobs over a longer time interval. More optics measurements to benchmark the model are planned. This is necessary before the zero dispersion optics are used to increase the accuracy of emittance measurements.

ACKNOWLEDGEMENTS

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