

LINEAR OPTIMIZATION AND TUNABILITY OF THE PS2 LATTICE

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Abstract

The PS2 lattice, based on Negative Momentum Compaction (NMC) arc cells is being optimized in order to accommodate a new all-doublet long-straight section (LSS) design. Apart from smoothing the optics and enabling different tuning solutions for H- injection, the optimization focuses on increasing the available magnet-to-magnet drift space and reducing the quadrupole types and strengths. The variation of lattice parameters for a wide range of working points is presented.

INTRODUCTION

The design of PS2, a separated function conventional magnet synchrotron potentially replacing the existing PS at CERN, is currently under study. One of the key features of the PS2 is the negative momentum compaction (NMC) lattice avoiding transition energy crossing. As part of the CERN injector complex upgrade, the PS2 should deliver beams with significantly higher intensity. Since the intensity of each bunch for the LHC beam will be roughly doubled with respect to the PS, the kinetic energy of the injected protons is increased from 1.4 GeV to 4 GeV for obtaining similar space charge induced incoherent tune shift. An optimized filling pattern of the subsequent SPS for delivering LHC bunch trains is achieved with a circumference of 1346.4 m (15/77 of the circumference of the SPS), considering a top energy of about 50 GeV. The maximum bending field of the dipoles is thereby limited to 1.7 T and the maximum gradients to 16 T/m with a pole tip field of 1.2 T for the quadrupoles in the arcs. Compared to previous lattice versions, the magnet-to-magnet drift spaces are increased to 0.8 m between dipole magnets and 1.3 m next to quadrupole magnets for facilitating the installation of vacuum pumps, correction magnets and beam instrumentation. The vacuum chamber of the PS2 has an elliptical shape all along the ring: In dipoles and focusing quadrupoles, the full apertures are 12.6 cm and 6.5 cm and in defocusing quadrupoles 11 cm and 7.5 cm for the horizontal and vertical planes, respectively. Special vacuum chambers with wider aperture will be designed for the straight sections. Considering the high intensity fixed target beam with normalized emittances of $\epsilon_x = 9$ mm-mrad and $\epsilon_y = 6$ mm-mrad, peak values of the β -functions of around 60 m in both planes and a maximum dispersion function D_x of 6 m correspond to roughly 3σ geometrical acceptance. However, it should be emphasized here that the particles are painted into the phase space at injection allowing for a uniform-like distribution and thus relaxing the requirements on the geometrical acceptance.

LINEAR BEAM OPTICS

The current baseline for the nominal lattice of the PS2 has a twofold symmetry with tunable arcs and two zero dispersion long straight sections (LSS). Each of the arcs consists of five basic NMC cells and two dispersion suppressor modules. The working point of the machine is tuned by adjusting the phase advances in the NMC cells and matching the dispersion suppressors to the optics of the straight sections. The mirror symmetric LSSs are based on two pairs of quadrupole doublets [1] formed by wide aperture magnets with a length of 2.4 m. As opposed to an old version based on FODO cells, this design avoids the crossing of transfer lines while reducing the length of each of the straight sections by 40 m. This in turn gives more flexibility in the dispersion suppressor modules, allowing for smooth optics and increased drift spaces between the main magnets all around the ring. A sketch of the new layout of the LSS is shown in Fig. 1. As required by the general layout of the LHC injector complex, beam transfer systems will be installed in the same LSS of the PS2. The tunability of the straight sections is therefore limited by phase advance constraints between injection/extraction elements. In particular, they accommodate for H⁻ charge exchange injection, fast ion injection and fast, slow and multiturn ejections. In the case of the conventional charge exchange injection with a stripping foil in the center of the straight section, the width of the foil can be minimized by mismatching the optics functions between injected and circulating beam. The solution presented in Fig. 2 (top, left) provides advantageous optics functions in the foil area while keeping the phase advances between extraction elements suitable for all scenarios.

The layout of the basic NMC cell is based on two FODO cells which are linked by a central insertion of quadrupole doublets [2]. Imposing negative dispersion at the entrance of the module leads to negative momentum compaction. A high packing factor is achieved by filling the module with

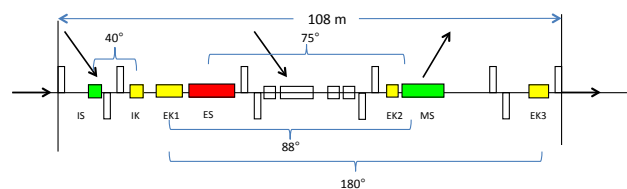


Figure 1: Schematic sketch of the arrangement of injection/extraction elements together with the phase advances in the new all doublet long straight section of PS2.

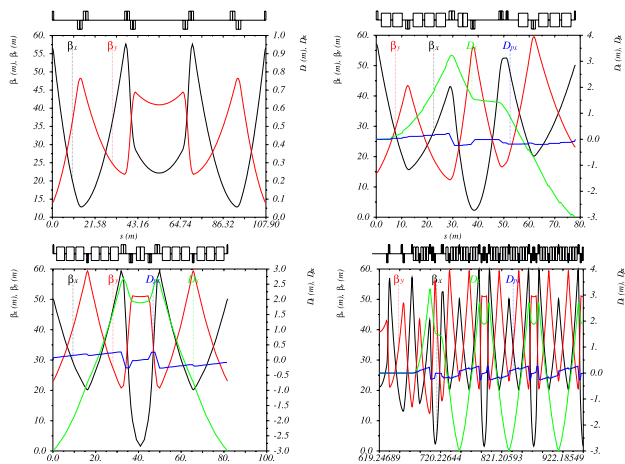


Figure 2: Optics functions of the nominal PS2 lattice, with the LSS (top left), the dispersion suppressor module (top right), the basic NMC cell (bottom left). A quarter of the PS2 ring (bottom right) is shown for the nominal working point $(Q_x, Q_y) = (11.81, 6.71)$ with $\gamma_t = 25.3i$.

13 dipole magnets, three of them placed in each half FODO cell and one in the center of the doublet insertion. Optimizing to maximum gradients of 16 T/m results in three types of quadrupoles for the four families with lengths of 0.8 m, 1.6 m and 2.2 m and a total length of the basic NMC cell of 81.8 m. A plot of the optics functions of the module tuned to a phase advance of $\mu_x = 0.75 \cdot 2\pi$ and $\mu_y = 0.43 \cdot 2\pi$ and a γ_t of $18i$ is shown in Fig. 2 (bottom, left).

A dispersion suppressor module on either side of the NMC arc is needed for matching the optics to the LSS. The length of this cell is fixed by the circumference to 78.1 m. A plot of the optics functions is shown in Fig. 2 (top, right). The first and the last quadrupole is shared with the LSS and the adjacent NMC cell, respectively. Ten dipole magnets and six independent quadrupole families based on the same types of magnets as used in the arc cells are needed to achieve the matching constraints.

The optics functions for the nominal working point of the PS2 with tunes of $Q_x = 11.81$ and $Q_y = 6.70$ with $\gamma_t = 25.3i$ are plotted in Fig. 2 (bottom, right) for a quarter of the circumference. The ring consists of 170 dipole magnets with a length of 3.69 m and a maximum bending field of 1.7 T at top energy. The 116 quadrupole magnets are grouped to 15 families. Four different types of magnets are needed, the wide aperture magnets are required for the LSS while the three remaining types are used in the arc cells, where none of them exceeds a maximum gradient of 16 T/m. The natural chromaticities of $\xi_x = -21.5$ and $\xi_y = -11.0$ may be compensated with relatively weak chromaticity correction sextupoles, as they are installed at locations with high dispersion. The nominal working point is located in the tune space avoiding low order systematic resonances. Figure 3 shows the relevant part of the tune diagram. Since the 3rd-order resonance

in the horizontal plane at $Q_x = 11.66$ is not structural, the area above $Q_x = 11.5$ allows for high efficient resonant slow extraction. Considering the space charge tune shift necktie, a good location for the working point is found just below the diagonal. The actual choice of the working point $(Q_x, Q_y) = (11.81, 6.71)$ is based on non-linear dynamics studies. A comparison of chromaticity correction schemes including the evaluation of dynamic apertures, off-momentum β -beat, Hamiltonian driving terms and frequency map analysis is reported in [3]. Depending on the stop band width of $Q_x = 12$, it may become necessary to move the working point of the machine closer to the half integer (11.5). An alternative working point can be found around $(Q_x, Q_y) = (11.25, 7.20)$. However, the resonance at $Q_x = 11.33$ is structural which may affect the efficiency of the resonant slow extraction.

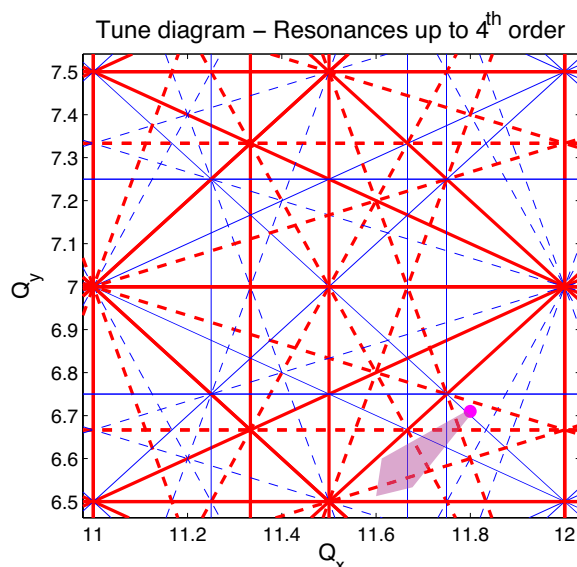


Figure 3: A part of the tune diagram including resonance lines up to 4th order. Red and blue lines indicate systematic and random resonances, respectively. Solid lines are normal and dashed lines are skew components. The pink dot represents the nominal working point.

TUNING FLEXIBILITY

A tunability study of the above described linear lattice is performed. The working point of the machine is tuned by changing the phase advances of the basic NMC cell and matching the dispersion suppressor module to the LSS injection optics. A complete picture of the achievable tuning range is obtained from a Global Analysis of all Stable Solutions (GLASS) [4]. In the case of the PS2 NMC lattice, basically four knobs determine the tune of the machine, i.e., the quadrupole gradients of the four families of the NMC module. Thus, a four dimensional parameter space has to be explored. A good compromise between CPU time and precision is obtained when scanning the normalized gradients in steps of 0.001 m^{-2} , i.e. checking a total of 10^8

possible combinations. In practice, the scan over one of the gradients is split into individual jobs which are run in parallel, where in each of the jobs the three remaining gradients are varied in a loop. For each configuration, the stability of the basic NMC cell is checked within a MADX script. If the solution is stable and the maximal β -functions are below 75 m (upper limit for a geometrical acceptance of 3σ of the high intensity beam), the dispersion suppressor is matched to the straight section. In case a solution is found where the maximal β -functions in the suppressor are also below 75 m, the geometrical acceptance is computed with the APERTURE module in MADX, using the fixed target beam parameters at injection, i.e. normalized emittances of $\epsilon_x = 9\pi$ mm mrad, $\epsilon_y = 6\pi$ mm mrad and momentum spread of $\delta p/p = 0.643\%$. The actual geometries of the two types of vacuum chambers are assigned to each magnet accordingly. In addition, 20% β -beat and 5% parasitic dispersion are assumed. These values are to be considered as pessimistic compared to the values observed in the chromaticity and orbit correction studies on the same lattice [3]. For each of these solutions, the main parameters of the ring together with all the quadrupole gradients are stored to a file. All valid solutions are obtained by filtering the solutions where the quadrupole gradients in the suppressor module are below 16 T/m without changing sign and where the number of beam sizes accepted by the vacuum chamber is at least 3.3. This data-set is then queried against certain properties of interest.

One of the most interesting parameter changing with the tune is the transition energy. Figure 4 shows γ_t for all solutions in the tune diagram. The smaller flexibility in the horizontal plane is due to the additional constraint of periodicity of the dispersion function, limiting the number of possible solutions. This explains also the clear dependence of γ_t on the horizontal tune. The smallest reachable value of $\gamma_t = 18i$ is obtained for $Q_x \approx 12.5$, while γ_t goes up to

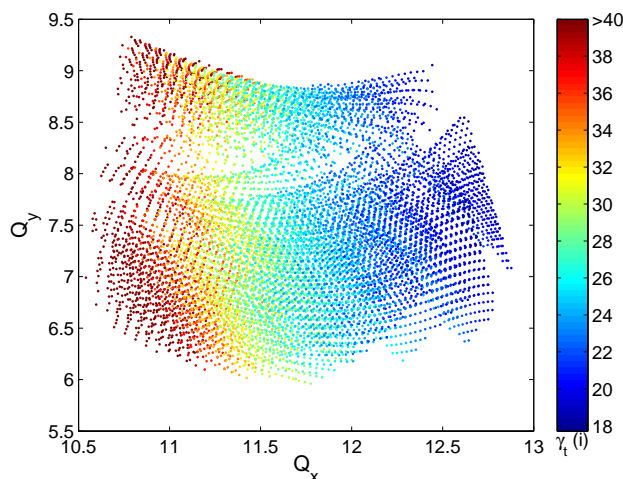


Figure 4: Optics solutions for the nominal PS2 lattice. The color-code indicates the value of γ_t as function of the beta-tron tunes, with values above $40i$ represented by dark red.

$80i$ for tunes around $Q_x \approx 10.5$. It should be emphasized however that for all the working points, γ_t can be adjusted by a few units.

A very important parameter concerning the machine protection and beam quality is the geometrical acceptance of the ring. Figure 5 shows N_σ , i.e. the number of beam sizes fitting into the vacuum chamber, as a function of the beta-tron tunes. As described before, the beam parameters of the high intensity fixed target beam are used for this calculation. A large number of solutions is found with a maximal geometrical acceptance between 3.3σ and 3.5σ . Higher values are observed for solutions in the center of the tuning range with peak values of 3.8σ . As comparison, the nominal working point has $N_\sigma = 3.6$.

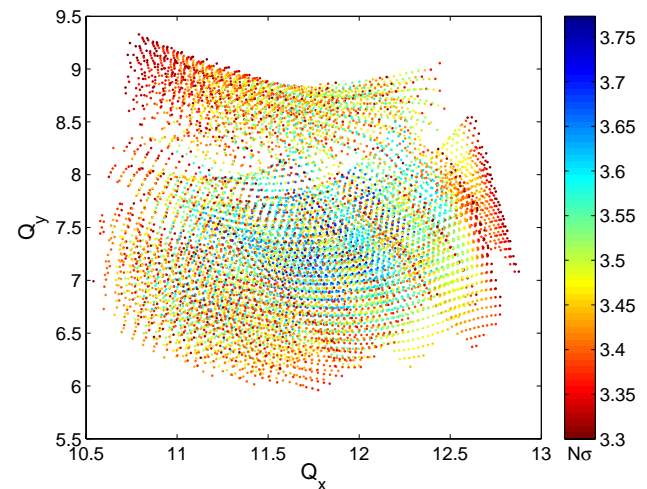


Figure 5: Geometrical acceptance of the solutions for the high emittance fixed target. The color-code shows the number of beam sizes fitting inside the vacuum chamber.

CONCLUSION

In conclusion, the nominal lattice of the PS2 study has reached a high level of optimization concerning the magnet-to-magnet drift spaces as well as the maximum bending fields and quadrupole gradients. The lattice provides very high flexibility for choosing a working point, covering more than 2 units in the horizontal and more than 3 units in the vertical plane. Since the available aperture is limited, geometrical acceptances for the fixed target beam do not exceed 3.8σ . However, the particles will be painted to a uniform-like distribution in phase space at injection. Therefore, aperture limitations may not be an issue.

REFERENCES

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