LINEAR OPTICS DESIGN OF NEGATIVE MOMENTUM COMPACTION LATTICES FOR PS2

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Abstract

In view of the CERN Proton Synchrotron proposed replacement with a new ring (PS2), a detailed optics design has been undertaken following the evaluation of several lattice options. The basic arc module consists of cells providing negative momentum compaction. The straight section is formed with a combination of FODO and quadrupole triplet cells, to accommodate the injection and extraction systems, in particular the H- injection elements. The arc is matched to the straight section with a dispersion suppressor and matching module. Different lattices are compared with respect to their linear optics functions, tuning flexibility and geometrical acceptance properties.

LATTICE DESIGN CONSTRAINTS

The upgrade strategy of the Large Hadron Collider (LHC) [1] is heavily based on the renewal of the CERN injector complex including the replacement of the old Proton Synchrotron (PS) with a new ring (PS2). Some basic parameters guiding the optics design of PS2 are displayed in Table 1. A proton beam with kinetic energy of 4 GeV will be injected directly from the Super-Conducting Proton Linac (SPL) [2], accelerated up to 50 GeV and extracted towards either the SPS or a dedicated experimental area. The LHC ion beams should be injected from the existing ion complex. The injection and extraction energy choice is driven from space charge tune-shift and instability considerations in the PS2 and SPS [3]. The ring circumference is fixed to $3000\pi/7$m, i.e. 15/77 of the SPS circumference (2200πm) for better filling and synchronization purposes [4]. After a detailed analysis and review process [5], a lattice that avoids transition was considered as the preferred option. Several versions of Negative Momentum Compaction (NMC) lattices aiming to low imaginary transition values were first considered [7, 8]. This was based on the need for fast synchrotron motion to achieve the high energy longitudinal manipulations necessary for the LHC bunch pattern production, with an RF system similar to the one of the actual PS. Considering a pre-choped beam from the SPL with the required bunch spacing and accelerated with a 40MHz RF in the PS, relaxes the constraint on the transition energy which has still to be flexible allowing fast RF gymnastics. This option imposes a challenging large tunability RF system for accelerating the ion beams as well, with RF frequency range from below 20MHz up to 40 MHz. The NMC arcs are filled with conventional dipoles not exceeding 1.7 T and quadrupoles with pole tip fields below 1.2 T, at a radius of 70 mm. The beta functions and dispersion should be kept below 60 and 6 m respectively to assure conformable geometrical aperture. Finally, and taking into account space constraints for correctors and instrumentation, coil ends and vacuum equipments, the drift space around quadrupoles is set to at least 1.2m and dipoles are separated with a drift of 0.6m.

Table 1: Lattice constraints for the PS2.

Parameter [unit]	value
Injection kinetic energy [GeV]	4
Extraction kinetic energy [GeV]	50
Circumference [m]	1346.4
Transition energy [GeV]	Imaginary
Maximum bending field [T]	1.7
Maximum quadrupole gradient [T/m]	17
Maximum beta functions [m]	60
Maximum dispersion function [m]	6
Minimum drift space for dipoles [m]	0.6
Minimum drift space for quads [m]	1.2

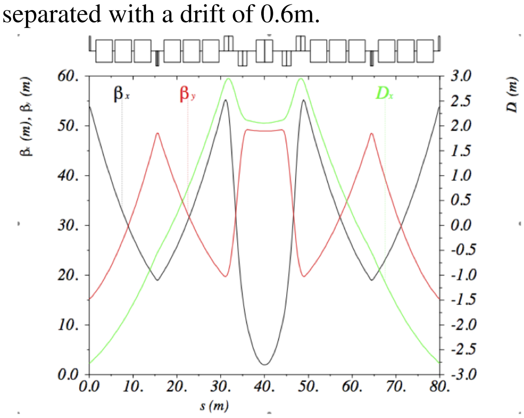

Figure 1: Horizontal (blue), vertical (red) beta functions and dispersion (green) of the NMC module

PS2 RING OPTICS

The backbone of the NMC ring is the arc module whose optics is shown in Fig. 1. The total length is 80m and five of these cells form the arc. The design is based on a combination of FODO cells and quadrupole doublets (in total 4 quadrupole families). The bending strength is varied between these two structures, in order to create a dispersion oscillation. Imposing a negative dispersion at the entrance of the module, drives the momentum compaction factor α_c

to negative values. Three dipoles in the FODO part of the NMC is the best choice for reducing dipole lengths to below 4m, but the module gets slightly longer. The inclusion of central bends in the middle of the cell has the advantage of increasing the dipole filling factor but also has an impact on the final α_c value, as this point is associated with high positive dispersion. The best compromise was found by including a single central bend. This module alone provides a relatively low transition energy of $\gamma_t = 26i$. In order to achieve low imaginary transition energies, focusing has to be increased resulting to high phase advances especially in the horizontal plane with $\mu_x = 267°$ and $\mu_y = 158°$. The maximum betas and dispersion are kept below 55m and 3m, respectively.

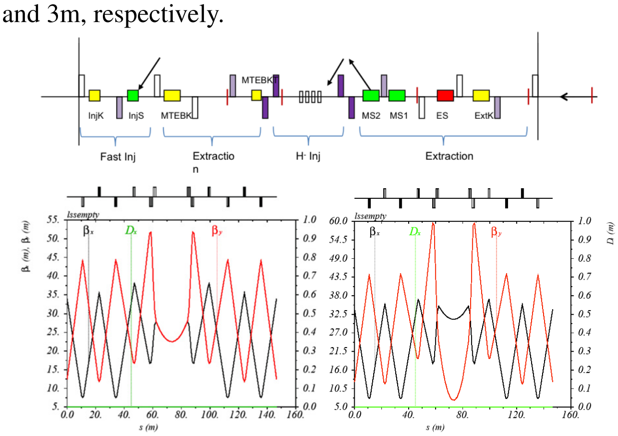

Figure 2: Layout of the injection-extraction LSS (top) and optics (bottom) for accommodating an injection scheme with foil (left) or laser stripping (right).

The two long straight sections (LSS) will be filled with RF cavities, injection and extraction elements. The general layout of the future LHC injector chain implies to install all PS2 injection and ejection elements in the same long straight section. In consequence, the LSS has to be long enough to accommodate all beam transfer systems and protection equipment like dumps or even collimators [9]. On the top of Fig. 2, the layout of the injection and extraction LSS is displayed. The different systems enable the H^- charge exchange injection, fast ion injection and fast, slow and multiturn ejections. The LSS is around 145m long, formed by a series of FODO cells with 90° phase advance and a central quadrupole triplet with a long drift to house the H^- injection system. Two options are considered for stripping (foil and laser) [10] with two optics alternatives, presented in the bottom part of Fig. 2. In the usual stripping by foil option, the width of the foil can be minimized by a mismatch of the optics functions between the injected and circulating beam, imposing $\beta_{x,y} \approx 22.5$m at the injection point (Fig. 2 bottom, left) and injected beam beta of $\beta_{x,y} > 10$ m. Considering laser stripping, the laser peak power is proportional to the vertical beam size if the beam-laser interaction is horizontal and an optics with minimum vertical beam size at the waist is necessary (Fig. 2 bottom, right). This latest optics is limited by the available aperture at the last two triplet quadrupoles which in any case have to be enlarged to accommodate the injected/extracted trajectories.

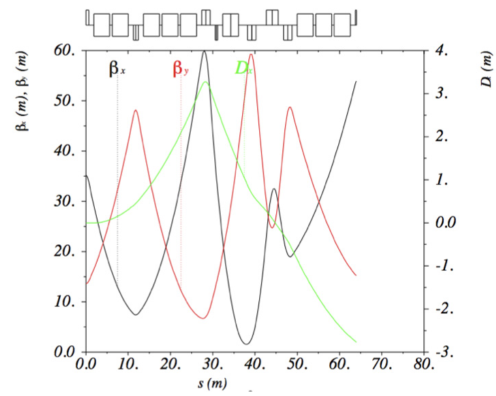

Figure 3: Horizontal (blue), vertical (red) beta functions and dispersion (green) of the dispersion suppressor.

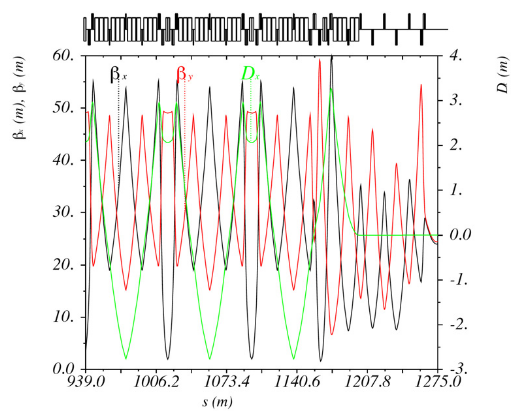

Figure 4: Horizontal (blue), vertical (red) beta functions and dispersion (green) of one quarter of the PS2 ring.

The link between the LSS and the NMC arcs is provided by dispersion suppressor and matching cells. The dispersion suppression can be also achieved by fixing the total phase advance of the arc to a multiple of 2π [11] as in the J-PARC main ring [12]. Although this option provides a compact arc and partial resonant compensation, the additional dispersion oscillations induced lead to larger maximum dispersion and aperture requirements. This option also would necessitate wide tuning flexibility of the LSS which is limited in the PS2 case by the beam transfer constraints. The optics of the tuned cell can be found in Fig. 3. The first half of the suppressor is similar to a NMC half module for zeroing dispersion and matching to the straight section optics. Six independent quadrupole families are needed to achieve the matching constraints, while keeping the maximum beta functions to reasonable levels.

The optics functions for a quarter of the ring are plotted in Fig. 4 for tunes of $Q_x = 13.25, Q_y = 8.21$ and transition energy of $\gamma_t = 36i$. The ring is composed of 166, 3.78m-long dipoles with 1.7T field at top energy, 132 quadrupoles in 17 families of 6 types with maximum gradients of 18T/m. The natural chromaticities are not high $(\xi_x, \xi_y) = (-22, -13)$ considering that dispersion is large enough allowing efficient correction with low chromatic sextupole strengths.

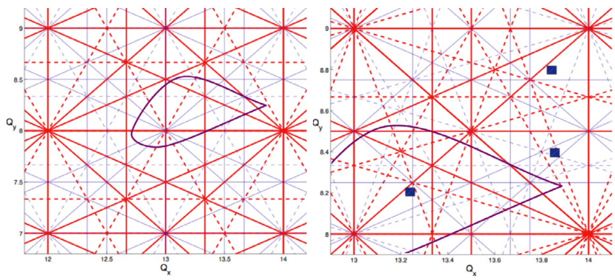

Figure 5: Tune space area with resonance lines up to 3rd order (left) and zoom around the chosen working point with resonances up to 4th order (right).

The working point is chosen such as to avoid low order systematic resonances. The tune space considered is presented in Fig. 5. The red and blue lines represent systematic and random resonances. The solid lines are normal resonances and the dashed lines are skew. From the left plot where resonances up to 3rd order are traced, it is inferred that the best integer tunes are $(Q_x, Q_y) = (13, 8)$ and, as usual, resonance free space is found close to the diagonal. A zoom around this area is shown on the right plot, where resonances up to 4th order are traced. The actual working point sits very close to the 4th order (2,-2) systematic resonance. The horizontal 3rd integer resonance is also systematic and this may affect the resonant slow extraction efficiency. Although DA with sextupoles seems not to be affected [13], a working point below the diagonal and above the half integers (13.5,8.5) may be advantageous. However, it is difficult to be reached with present beta function and space constraints and without retuning the LSS optics. The purple curve represents the area enclosing around 50 matched working points tuned by changing the phase advance of the NMC module. In this way, the transition energy is varied from 25 to 100i. For the lower transition energy (higher horizontal tune), the maximum vertical beta function exceeds 70m in a single location of the dispersion suppressor (Fig.6 left). The horizontal chromaticity is slightly increased by 10% (Fig.6 right).

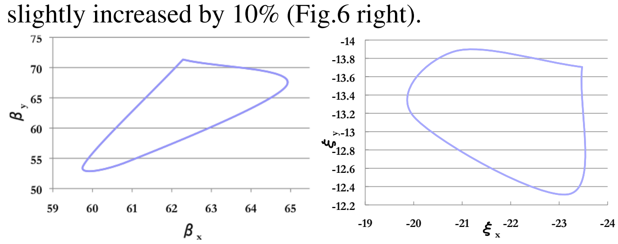

Figure 6: Limits of the horizontal versus vertical beta function maxima (left) and chromaticities (right).

For reducing the effect of systematic resonances, a 3-periodic ring may be considered. The optics for this option are presented in Fig.7. The optics for the straight section is similar to the racetrack design but shortened by removing 2 FODO cells by either side. The NMC module is identical with slightly smaller drift space between

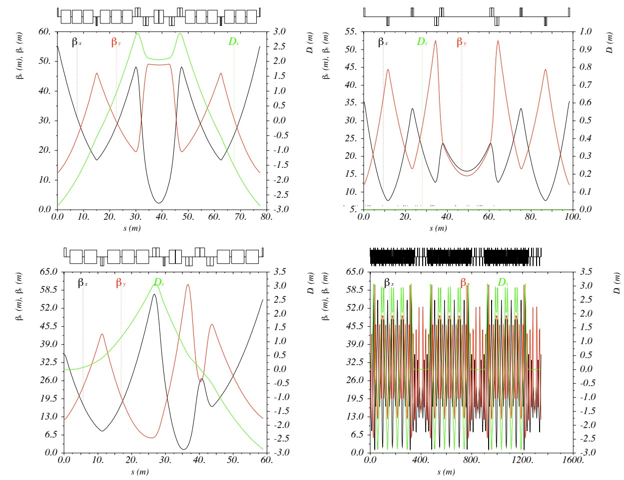

Figure 7: Optics of a 3-periodic PS2 module (top left), LSS (top right), suppressor (bottom left) and ring (bottom right).

dipole and quad (1.1 instead of 1.2m), thus reducing the total length to 77.5m. Each arc is formed by 3 such modules. This module achieves $\gamma_t = 25i$ for similar phase advances (270° and 163.7°). The minimum dispersion is slightly larger and the beta functions the same as for the nominal ring. The dispersion suppressor is shortened by reducing drift space between magnets. The final ring has a $\gamma_t = 38i$ and is tuned for $(Q_x, Q_y) = (14.25, 9.3)$ The number of dipoles is slightly increased (172) and their length reduced. The number of quads remains identical. The slightly bigger chromaticities of -22.8 and -15.7 should not affect the design. The final choice of this alternative will be driven by non-linear dynamics simulations including space-charge and space constraints for the beam transfer elements.

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