# LATTICE WITHOUT TRANSITION ENERGY FOR THE FUTURE PS2*

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*Abstract*

The Large Hadron Collider (LHC) at CERN will be commissioned very soon. Improvements of the LHC injection complex are considered in the upgrade possibilities. In the injection complex it is considered that the aging Proton Synchrotron (PS) would be replaced with a new fast cycling synchrotron PS2. The energy range would be from 5-50 GeV with a repetition rate of 0.3 Hz. This is a report on the PS2 lattice design using the Flexible Momentum Compaction (FMC) method*. The design is trying to fulfil many requirements: high compaction factor, racetrack shape with two long zero dispersion straight sections, circumference fixed to a value of 1346.4 meters ($C_{PS2}$=15/77 $C_{PS}$ with h=180), using normal conducting magnets and avoiding the transition energy.

## INTRODUCTION

Going through transition energy during acceleration introduces very serious problems as the bunch length becomes very small with very large momentum spread. The longitudinal motion is frozen and due to non-linear chromatic effect particles with different momentum pass the transition at different time creating the longitudinal phase distortions. Instabilities can occur at transition: the fast transverse instability, the microwave instability, electron cloud instability, et cetera. Transition occurs at the moment when the relativistic factor $\gamma$ becomes equal to transition energy $\gamma = \gamma_T$. The equation of the synchrotron motion is:

$$\frac{\delta T}{T_o} = \left(\alpha - \frac{1}{\gamma^2}\right)\frac{\delta p}{p}, \tag{1}$$

where $\alpha$ is the momentum compaction:

$$\alpha = \frac{1}{\gamma_T^2} \approx \frac{1}{C_o}\sum_i \overline{D}_i \theta_i, \tag{2}$$

where $\theta_i$ is a bending angle of the dipole 'i'. A lattice design method to avoid the transition crossing had been previously presented [2]. To avoid transition crossing the transition $\gamma_T$ has to be outside of the range of acceleration or be an imaginary number. This is possible if the total horizontal dispersion through dipoles has negative value: $\Sigma_i\ D_i\ \theta_i, < 0$. The method is best explained by the Floquet's transformation and "normalized dispersion" function [2]:

$$\chi = \frac{D_x}{\sqrt{\beta_x}} \ and\ \xi = D'_x\sqrt{\beta_x} + \frac{\alpha_x D_x}{\sqrt{\beta_x}}. \tag{3}$$

The vector $D'_x\sqrt{\beta} > \theta_i\sqrt{\beta}$ represents the dipole effect on the dispersion function. These vectors need to be within the negative part of the $\chi$ axis making the negative momentum compaction and avoiding the transition.

## PS2 REQUIREMENTS

The PS2 is assumed to be normal conducting machine [1] with a maximum ramp rate of 1.5 T/s, and constraints are presented in Table 1. The demand for brighter and more intense beams requires many different beam manipulations. These impose constraints on the possible value of $\gamma_T$ that can be considered.

Table 1: Constraints for the PS2

| Basic beam parameters | Required | This example |
|---|---|---|
| Kinetic energy: Inj. [GeV] | 4 | 4 |
| Extraction [GeV] | 50 | 50 |
| Circumference [m] | 1346.4 | 1346.4 |
| Transition energy [GeV] | 10 i | 11.6 i |
| Max. Bending field [T] | < 1.8 | 1.73 |
| Max. Dispersion [m] | < 6 | $-4.27 < D_x < 3.26$ |
| Max. Beta functions [m] | < 60 | 53.3 |
| Max. Gradient [T/m] | < 17 | 18.6 |

## LATTICE DESIGN

The racetrack design includes two zero dispersion straight sections for extraction and injection or for the RF control. The lattice design is modular: the arc basic cell provides the negative momentum compaction with a high filling factor and easy chromatic correction. Magnet properties in the arc module are shown in Table 2. The gradients of the strong focusing and defocusing quadrupoles (two doublets in the middle of the module) are $G_f$ =16.4 T/m and $G_d$ =–17.4 T/m, respectively. All dipoles are 3.3 m long, with the maximum magnetic field of 1.74 T. Lengths of the focusing and defocusing quadrupoles, are 1.5 m and 0.8 meters, respectively. Lattice functions of an arc module are shown in Fig. 1. Note that the dispersion function (green color) is oscillating between the positive and negative values with negative part mostly in dipoles. The arc modules use the separated function magnets.

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Table 2: Magnet and arc module properties

| Magnet | l(m) | G(T/m) | $\beta_{@Q}$(m) | $\beta_{max}$(m) | $D_x$(m) |
|---|---|---|---|---|---|
| $Q_{FS}$ | 1.5 | 16.4 | 24.0 | 50.68 | 3.28 |
| $Q_D$ | 0.8 | -17.4 | 45.9 | 45.9 | 0.07 |
| B | 3.3 | 0.0 | 1.74 T | 38.4 | -4.24 |

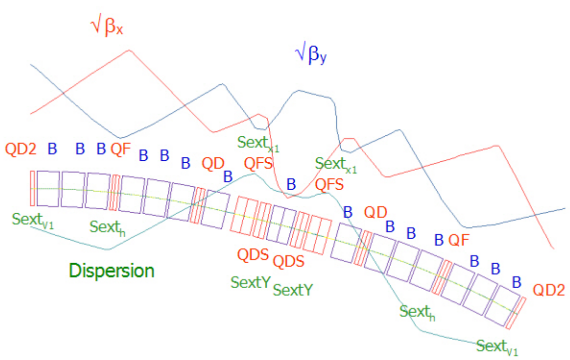


Figure 1: Betatron functions in the arc module.

The oscillation of the dispersion function induces offsets for particles with momentum offsets δp/p=±1%, as shown in Fig. 2.

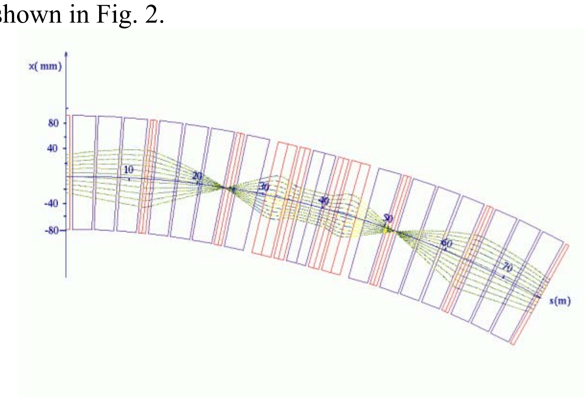


Figure 2: Orbits magnified 100 times in the arc block with different momentum in the range δp/p=±1%.

## *Chromaticity Correction*

The chromaticity correction sextupoles are placed at the positions at the maximum of the corresponding betatron and dispersion functions ($Sext_H$, SextY, $Sext_{X1}$, and $Sext_{Y1}$ in Fig. 1). The strengths of the sextupoles are –0.034 $m^{-2}$, and –0.042 $m^{-2}$, 0.035 $m^{-2}$, and 0.050 $m^{-2}$. The tunes in this example, $\nu_x$~0.809 and $\nu_y$~0.671 produce negligible sextupole induced tune shifts presented as:

$$\nu_x = 0.8089 + 3.60 J_x + 2.66 J_y, \qquad \nu_y = 0.6706 + 2.66 J_x + 3.11 J_x \tag{4}$$

where $J_x$ and $J_y$ are the horizontal and vertical beam actions, respectively. The most favourable horizontal and vertical tunes for the complete cancellation of the variation of tune shift with amplitude in the arc block are $\nu_x$~0.75 and $\nu_y$~0.5.

## *Matching the Arc Blocks to the Straights*

In order to produce zero dispersion in the straight sections a "missing dispersion suppressor" is used. Matching optics is obtained by using the arc block with missing dipoles and positioning the remaining dipoles at locations so as to provide the dispersion function match to the straight section FODO cells. The zero dispersion matching is presented in the normalized dispersion space in Fig. 3. The dipole vectors and their effect on the normalized dispersion are shown in Fig. 3. A slope in the dipole vectors with respect to the χ-axis is due to the betatron phase through the dipoles.

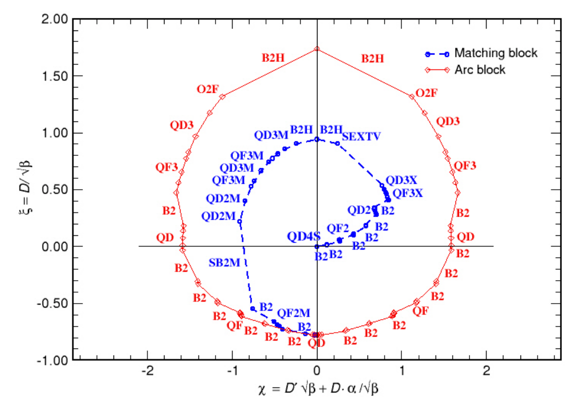


Figure 3: Normalized dispersion for the matching (blue colour) and arc cell (red colour), "B" is the bending magnet, while "Q" is the quadrupole.

The matching sections with arc cells and the straight section FODO cells at the both ends are shown in Fig. 4.

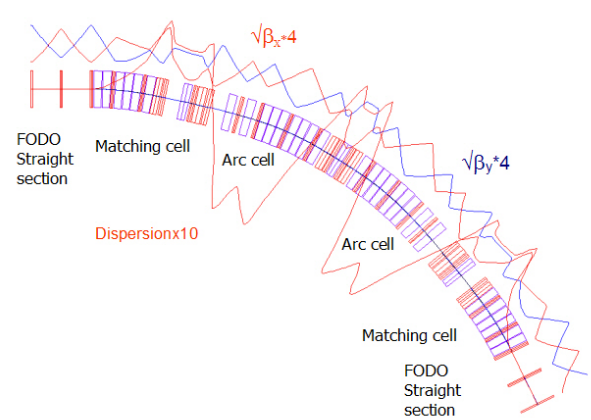


Figure 4: Matching of the arc cells to the zero dispersion straight sections.

Dipoles are displayed in a blue, while the quadrupoles are presented in red colors. The dispersion function is equal to zero at the end of the matching cells or beginning of the straight section FODO cells.

### *The Straight Sections*

The horizontal betatron phase advance per cell in the straight sections is set to $\nu_x$=89.1° to allow easy beam extraction and injection. The vertical phase advance per cell is $\nu_y$=69.1°. For a cell length of 25.2 meters this makes the maximum betatron functions of $\beta_x$=39.8 m and $\beta_y$=45 m. The defocusing and focusing quadrupole lengths and gradients are $l_{QD}$=1.15 and $l_{QF}$=1.05 m, and GD=–14.4 T/m and GF=18 T/m, respectively. The useful drift space between the quadrupoles in the straight section is 11.5 m. Dispersion is zero in the straight sections. The arrangement of cells shown in Fig. 5 presents the straight section matching in more detail. The Fig. 5 shows the betatron functions in the whole racetrack.

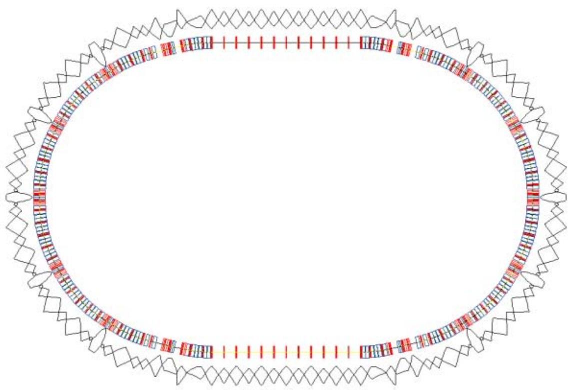

Figure 5: Horizontal and vertical betatron functions in the whole PS2 racetrack.

Dispersion function in the racetrack is shown in Fig.6.

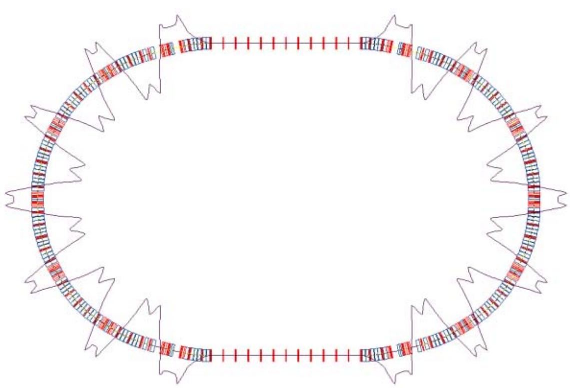

Figure 6: The dispersion function in the racetrack.

### *Chromaticity Correction of the Whole Racetrack*

The horizontal and vertical tunes for the whole racetrack in this lattice are $\nu_x$=14.432 and $\nu_y$ =11.424, respectively. The natural chromaticities of this PS2 example are $\xi_x$ = -20.4 and $\xi_y$=-17.3. The sextupole induced tune variations with amplitudes after the chomaticity corrections are:

$$\begin{aligned} \nu_x &= 14.3218 + 46.0 J_x + 76.0\, J_y, \\ \nu_y &= 11.4237 + 76.0 J_x + 57.8\, J_x \end{aligned} \tag{5}$$

The strengths of the sextupoles are –0.047 $m^{-2}$, and –0.080 $m^{-2}$, 0.035 $m^{-2}$, and 0.050 $m^{-2}$. The correction is without optimization as the previous values of one pair of the sextupoles are unchanged. Possible layout of PS2 is shown in Fig. 7.

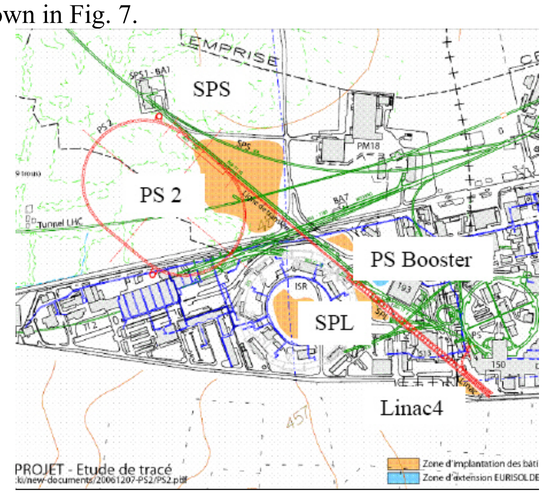


Figure 7: Possible layout of PS2.

## SUMMARY

A PS2 design for a 4-50 GeV accelerator without transition energy would replace the existing aging PS machine. The transition energy is imaginary $\gamma_T$= i 11.57 simplifying the whole acceleration process. It has been previously shown [4] that tunability of this design is excellent. The length of the straight sections is $L_s$=153 meters. Machine parameters are presented in Table 3.

Table 4: Lattice parameters

| $\gamma_T$ | $\beta_x$(m) | $\beta_y$(m) | $\xi_x$(m) | $\xi_y$(m) | $D_x$(m) |
|---|---|---|---|---|---|
| i 11.57 | 53 | 45.5 | –20.4 | –17.3 | 4.3 – 3.3 |

The lengths of two straight sections are 153 m long.

## REFERENCES

[1] S. Hancock, "Gamma at Transition in the Proposed PS2 Machine", http://care-hhh.web.cern.ch/CARE-HHH/LUMI-06/, pp.126-128.

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[3] Y. Papaphilippou, "Optics considerations for PS2", http://care-hhh.web.cern.ch/CARE-HHH/BEAM07/, pp. 153-160.

[4] S.Y. Lee, K.Y. Ng, and D. Trbojevic, "Minimizing dispersion in flexible momentum compaction lattices", Phys. Rev. E, **Vol. 48** (1993) pp. 3040-3048.