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ROUND BEAM OPERATION IN ELECTRON STORAGE RINGS AND GENERALISATION OF MOBIUS ACCELERATOR

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Abstract

"Round beam" rather than a flat beam is preferable for a significant fraction of the beamline users in light sources. It is realised by equally distributing the natural emittance into the horizontal and vertical planes. There are a few approaches for the emittance distribution, and here we explore the so-called Mobius accelerator scheme, where a transverse (horizontal-vertical) emittance exchange results at each turn of beam revolution. The original proposal of Mobius accelerator was based on a set of five (or six) successive skew quadruples, requiring a dedicated long straight section. We generalise the Mobius accelerator to find other possible configurations. Applications to a light source storage ring lattice and a tracking result are also presented.

INTRODUCTION

A significant fraction of the beamline users at Swiss light source (SLS) prefer a "round beam" rather than a flat beam, and hence we study possible options in the context of a planned SLS upgrade, where the storage ring will be replaced with a very low emittance ring while utilising the existing building and injector complex [1]. For a small emittance beam, the emittance growth due to intra bunch scattering (IBS) can be significant, and thus a mitigation of the emittance growth is another motivation.

The coupling scheme is realised by equally distributing the natural emittance into the horizontal and vertical planes. There are a few approaches for the emittance equalisation. One method is to utilise a linear coupling resonance, where the horizontal and vertical emittances are exchanged over a period shorter than the radiation damping time. The other method that we explore in this study is the so-called Mobius accelerator [2].

GENERALISATION OF MOBIUS ACCELERATOR

The Mobius accelerator was originally proposed by Talman [2] and tested at CESR [3]. The transverse particle coordinates are interchanged at a location of the storage ring, and thus an immediate horizontal-vertical emittance exchange results at each turn of beam revolution. The synchrotron radiation induced emittance growth and damping is thus distributed equally among the two modes. The result is each mode has half the natural emittance. The coordinate interchange can be realised with five (or six) successive skew quadrupoles – Mobius insertion − as proposed in [2]. The requirements for the Mobius insertion are

- interchanging the transverse particle coordinates,
- and matching to the closed ring lattice parameters.

The Mobius insertion represented in a 4-by-4 transfer matrix is an off-diagonal block matrix,

$$\begin{bmatrix} 0 & D \\ D & 0 \end{bmatrix} \text{ with } D = \begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix}. \tag{1}$$

The first requirement is obviously fulfilled with the above matrix. The second requirement is fulfilled when the lattice parameters (with skew quadrupoles turned off) are the same for the horizontal and vertical planes at both ends of the Mobius section and when the length L is adjusted to be the length of the Mobius insertion. It is straightforward to switch between the nominal operation mode (flat beam) to the round beam mode, simply turning on and off the skew quadrupoles.

It is of interest to explore possible configurations different from the above mentioned one not only for the Mobius accelerator but also for a coordinate interchange in a beam transport line. For example, a slice emittance measurement can be performed in both planes with a given transverse deflection cavity, which streaks the beam either in the horizontal or the vertical plane.

General Configuration

We assume arbitrary transfer matrices between skew quadrupoles to represent a general beam transport line:

$$(M_e)S_nR_nS_{n-1}R_{n-1}\cdots R_1S_1(M_s) \tag{2}$$

where S is the transfer matrix for skew quadrupole and R is an arbitrary uncoupled transfer matrix, which may include normal quadrupoles. The original configuration with five skew quadrupoles is also represented with the above notation with M being a drift matrix. The matrices M_e and M_s in parenthesis are discussed later.

Multiplying at the transfer matrix in a brute force manner generates many terms in the equations we need to solve. The equations are, however, significantly simplified using the normalised coordinates. The transfer matrix R in the normalised coordinate system is then simply a rotation matrix, and a thin skew quadrupole is represented as

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & -K & 0 \\ 0 & 0 & 1 & 0 \\ -K & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

where K is the normalised skew quadrupole strength, k, multiplied by the length of the magnet, l, and the "effective" beta function,

$$K = \sqrt{\beta_x\beta_y}kl, \tag{4}$$

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The requirements are fulfilled when the transfer matrix for the normalised coordinates becomes

$$\begin{bmatrix} 0 & 0 & \cos\phi_x & -\sin\phi_x \\ 0 & 0 & \sin\phi_x & \cos\phi_x \\ \cos\phi_y & -\sin\phi_y & 0 & 0 \\ \sin\phi_y & \cos\phi_y & 0 & 0 \end{bmatrix}. \quad (5)$$

Equation (5) exchanges a circle in the normalised coordinate with a circle in the other plane, thus the coordinate interchange and the matching are realised.

π/2 Scheme

One of simplest configurations consists of three skew quadrupoles with π/2 phase advances between them in both planes. It is easily found that a transfer matrix corresponding to Eq. (5) is obtained when all three skew quadrupole strengths are set to K=±1, resulting in $\phi_x=\phi_y=\pm\pi/2$.

The scheme is applied to a lattice under development for the SLS upgrade. The lattice consists of 12 cells of seven-bend achromat. The first and the last skew quadrupoles are not in the long drift but in the matching section with normal matching quadrupoles (between the drift and achromat). The centre skew quadrupole is situated in the middle of long drift. Figure 1 shows the original lattice parameters and the ones with a π/2 Mobius insertion. Such configuration may better fit to a drift with other devices, for example rf cavities.

It is noted that, in the fully coupled lattice ($\varepsilon_I = \varepsilon_{II}$), the four beta functions ($\beta_{xI}, \beta_{xII}, \beta_{yI}, \beta_{yII}$) [4] can be conveniently represented by "horizontal" and "vertical" betas ($\beta_x = \beta_{xI} + \beta_{xII},\ \beta_y = \beta_{yI} + \beta_{yII}$).

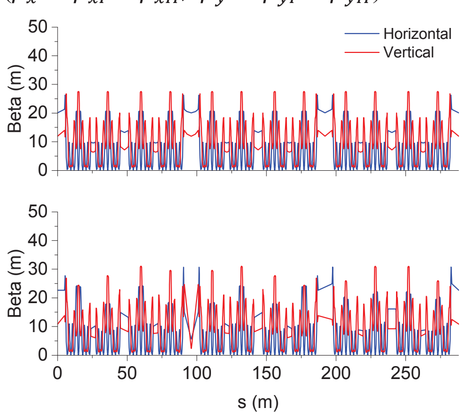

Figure 1: "Horizonal" and "vertical" functions with (bottom) and without (top) π/2 Mobius insertion. The first skew quadrupole is installed at s~89 m and the last one at s~103 m.

Skew Quadrupoles in Matching Section

The number of straight sections is limited and only nine sections are available for the user beamlines at the present SLS. Three straight sections out of 12 are occupied by the injection devices and rf cavities. Therefore the straight section (in a relatively short circumference machine) is highly expensive, and we investigated if the skew quadrupoles can be fully integrated into the matching sections. Figure 2 shows an example of such configuration. Six skew quadrupoles are situated, over two achromat cells, in the matching sections in this example. The skew quadrupoles cannot be situated inside the achromat because unwanted vertical dispersion is excited.

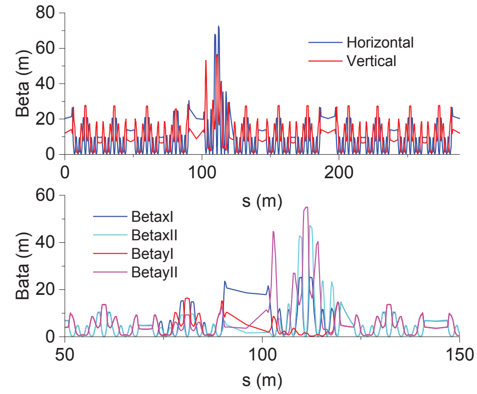

Figure 2: "Horizonal" and "vertical" functions with six skew quadrupoles (top). The first skew quadrupole is installed at s~73 m and the last one at s~120 m. The four beta functions are also plotted (bottom). The mode I and mode II beta functions coincide outside the Mobius section while they bifurcate inside.

In this example, the transfer matrix from the first to the last skew quadrupole actually does not correspond to Eq. (5). It is off-diagonal, fulfilling the first requirement, but the circle-to-circle transfer (matching) is not fulfilled. It is, however, realised with four following normal quadrupoles. Therefore, the Mobius insertion in general does not necessarily fulfil the second requirement when four normal quadrupoles before or after are available for the matching. In other words, "matching" matrix (M_s and M_e in Eq. (2)) can be attached to the beginning and/or to the end of the transfer matrix. In fact, the matching in the original configuration is fulfilled by these matching matrices (realising the same lattice function at both end) while the π/2 scheme relies on the phase advances.

Although the skew quadrupoles can be fully integrated into the matching section as in Fig. 2 the (coupled) beta functions over achromat cells are different from the original optics, and thus the chromaticity and nonlinear correction schemes are largely disturbed. It is under study to adjust the skew quadrupole strengths together with the normal quadrupole strengths to control the beta function between skew quadrupoles. In Fig. 2, the normal skew quadrupoles are only empirically tuned while the beta function reaches about 200 m without the tuning.

ROUND BEAM

The lattice shown in Fig. 1 is examined with tracking using Elegant code [5]. An initial flat beam is tracked over 10,000 turns with synchrotron radiation. Figure 3 shows the horizontal and vertical emittances as a function of turns. It is seen that the emittances are almost equalised

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at 10,000 turns (the damping time corresponds to ~9,700 turns).

We confirmed that the IBS effect is largely mitigated. With a flat beam, the vertical emittance has to be blown up. For the round beam, no additional blow-up is required for the natural emittance of ~180 pm. Figure 4 show the emittance growth due to IBS as a function of bunch current computed using the equations presented in [6], which are implemented to Bmad [7].

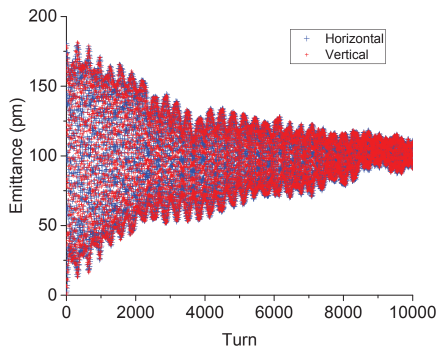

Figure 3: Emittace as a function of the number of turns with synchrotron radiation. The natural emittance is ~180 pm.

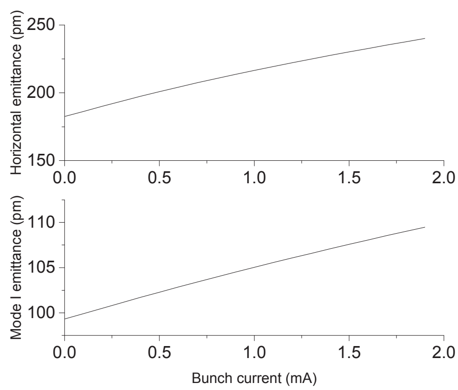

Figure 4: Emittances as a function of bunch current for flat beam (top) and round beam (bottom). A flat beam results in an emittance growth of ~19% at the operation bunch current (~1 mA for 500 MHz rf) while the round beam only 6%. The vertical emittance of the flat beam is blown up to 10 pm.

"MAGIC L"

The length parameter, L, in Eq. (1) depends on the separation between the five skew quadrupole, and it can be varied even for a fixed total length. This feature may be useful, for example, for a fast injection within a long straight section. The separation at the septum is simply proportional to the kicker deflecting angle and to the drift length in-between, which can be effectively increased by a Mobius insertion (five skew quadrupoles).

The round beam operation in light sources requires a (quasi) on-axis injection because of the small vertical gaps of insertion devices. (This is also the case for the round beam with a linear coupling resonance since the emittance exchange should be faster than the damping to form a round beam.) With an off-axis injection, a horizontal separation at the time of injection is immediately brought to the vertical plane and the injection beam will be lost at the small vertical physical aperture. Therefore this feature of "variable length" can be used to decrease the kicker deflecting angle when the longitudinal injection scheme [8], which includes the fast injection scheme, is applied.

Figure 5 shows the effective length as a function of the first and second quadrupole separation. Note that the Mobius insertion of five skew quadrupoles is symmetric [2] about the centre skew quadrupole as also shown in Fig. 5.

In Fig. 5 (top left), the blue dot indicates the point, where the effective length, L, matches to the physical length of the Mobius insertion. Taking a shorter l, the effective length is increased at the expense of stronger excitation of the skew quadrupoles (top right).

SUMMARY

Round beam operation is of interest for a significant fraction of beamline users. We studied the Mobius accelerator and presented a generalisation of the Mobius insertion. A tracking study demonstrated the equalisation of the emittance, and we confirmed that the IBS effect is mitigated with a round beam.

The feature of the original Mobius insertion, "magic L", is discussed in the context of on-axis injection that is essential for the round beam operation in a light source with small vertical gap insertions.

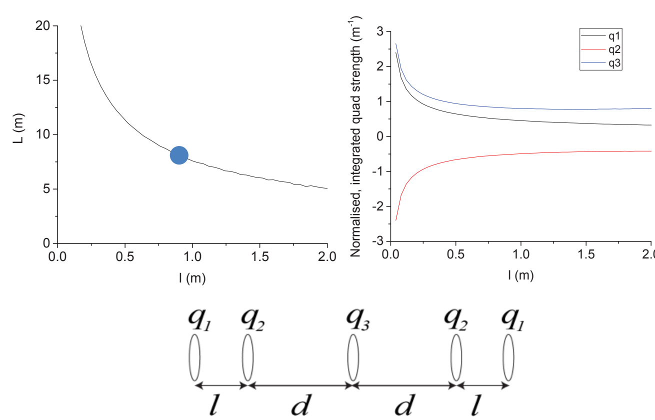

Figure 5: Effective length L as a function of the separation l (top left) together with the configuration of skew quadrupole (bottom). The skew quadrupole strengths (top right), q_1, q_2, and q_3, are found through the equations in [9]. The total length ($2l$+$2d$) is 8 m.

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