TESTS FOR LOW VERTICAL EMITTANCE AT DIAMOND USING LET ALGORITHM

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Abstract

We present the results of a campaign of measurements recently performed at the Diamond Light Source, aimed at achieving a low vertical emittance using the Low Emittance Tuning (LET) Algorithm developed for the SuperB factory. The tests have been focused on the comparison of the method to the LOCO algorithm, that is currently used at Diamond. Beam position monitor tilts estimation and multiple coupling response matrices have been introduced in the algorithm in order to optimize the procedure. After a few fast iterations (5-6 min per iteration) using vertical correctors and skew quadrupoles, very low vertical dispersion and emittance coupling, comparable to those obtained by LOCO, have been measured.

INTRODUCTION

The SuperB e^+e^- collider [1] has a project luminosity of $10^{36}cm^{-2}s^{-1}$. This target requires an horizontal emittance of $2.46nmrad$ for LER and $2nmrad$ for HER and a vertical emittance of $6.15pmrad$ for LER and $5pmrad$ for HER. These parameters are well within the reach of third generation light sources. At the Diamond Light Source [2] a vertical emittance of 2.2 pmrad has been achieved [3] using LOCO [4]. In SuperB the introduction of the Final Focus makes this target very challenging and requires very accurate tools to control the emittance. A new LET tool has then been developed and used to study SuperB tolerances [5]. This tool has been tested at Diamond in order to prove the effectiveness of the correction scheme and to compare it to the result obtained by LOCO on the same lattice.

LET ALGORITHM

The LET correction scheme is a modified response matrix method that extends the Dispersion Free Steering (DFS) technique [6]. The correction is based on the SVD inversion of the response matrix determined by the relations:

$$\begin{pmatrix} (1-\alpha-2\omega)\,\vec{y} \\ \alpha\,\vec{\eta}_y \\ \omega\,\vec{\mathcal{ORM}}_{y,\theta_H} \\ \omega\,\vec{\mathcal{ORM}}_{x,\theta_V} \end{pmatrix} = \mathcal{M}_v \begin{pmatrix} \vec{\theta}_V \\ \vec{K} \\ \vec{T} \end{pmatrix} \tag{1}$$

$$\begin{pmatrix} (1-\alpha-2\omega)\,\vec{x} \\ \alpha\,\vec{\eta}_x \\ \omega\,\vec{\mathcal{ORM}}_{x,\theta_H} \\ \omega\,\vec{\mathcal{ORM}}_{y,\theta_V} \end{pmatrix} = \mathcal{M}_x \begin{pmatrix} \vec{\theta}_H \\ \vec{T} \end{pmatrix}$$

where $\vec{x},\vec{y}$ are orbits, $\vec{\eta}_{x,y}$ are the dispersions, $\vec{\mathcal{ORM}}_{x,\theta_H}$ are columns of the orbit response matrix in the plane x, y determined by one or more horizontal (H) or vertical (V) correctors and θ, K and T are respectively corrector strengths, skew quadrupoles gradients and tilts. The parameters α and ω are relative weights between the different quantities to be corrected, and must be taken in account also in the definition of the response matrix. These parameters and the number of SVD eigenvectors are chosen at every correction reiteration, in order to identify the settings producing the best correction. The set of correctors and parameters obtained by SVD of system (1) determines a non-zero orbit which goes off axis in quadrupoles and sextupoles. The resulting feed-down effect minimizes the off diagonal blocks of the response matrix, reaching low coupling (vertical correction) and restoring the design β-functions (horizontal correction). For these reasons we expect an increase of orbit amplitude to gain on dispersion, coupling and β-beating.

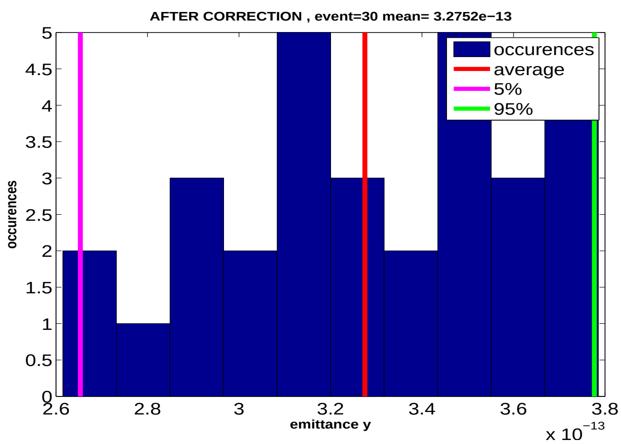
In principle there is no need of skew quadrupole correctors in LET, but in reality it is useful to include them in the tool as they are commonly present in many accelerators and allow further control of large unwanted effects. In addition, they add more degrees of freedom to further minimize orbit, coupling, dispersion and β-beating simultaneously. The $\vec{\mathcal{ORM}}_{y,\theta_V}$ vectors used in LET may be evaluated for any number of correctors, up to all the correctors in the $\vec{\mathcal{ORM}}$ and appended to system 1. The more $\vec{\mathcal{ORM}}$ columns are included in the calculation the longer the time for measurements and to compute the necessary response matrices. In particular it is wise to chose a subset of correctors that includes at least two correctors at a phase advance of $\frac{\pi}{2}$ to avoid the effect of zeros in the orbits generated by the correctors. Using more correctors is also useful to average the correctors rotation effects.

All the matrices used in the correction that will be presented in the next sections are simulated. The simulation of the matrices is done in MADX [7], taking in account the effect of dispersion in the correctors and scaling the strength of the correctors with the β-functions.

Simulations

Simulations of the LET correction have been performed for Diamond before starting the tests. Random misalignments of 50 μm rms in the vertical plane and 70 μm rms in the horizontal plane for quadrupoles and sextupoles (broadly in line with the measured data [8]) have been applied to the lattice and the correction has been performed.

In the simulations also BPM's reading errors of $1\,\mu m$ and BPM's offsets of $50\,\mu m$ in both planes have been included. The results of one iteration of ORM correction and 4 iteration of LET correction (correcting alternatively with horizontal and vertical steerers) applied on 30 different random sets of errors, are shown in Figure 1. The average final vertical emittance obtained starting from the same initial conditions and using the largest 65 SVD eigenvalues, is $5.3\,pm$ for DFS ($\alpha = 0.49\%$,$\omega = 0$) and $0.33\,pm$ using LET ($\alpha = 0.49\%$, $\omega = 0.01\%$). In these simulations also the effect off radiation in correctors is taken in account to evaluate the emittance. The improvement brought by LET correction is then evident.



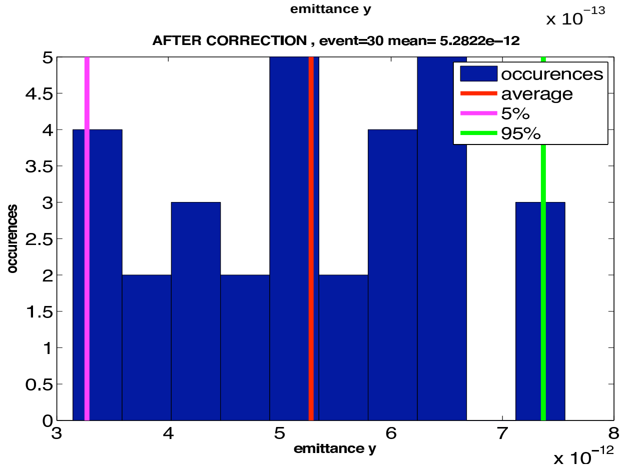


Figure 1: Simulations: for the same 30 initial random sets of misalignment, the correction is performed only with steerers using dispersion free steering (bottom) and LET (top).

MEASUREMENTS

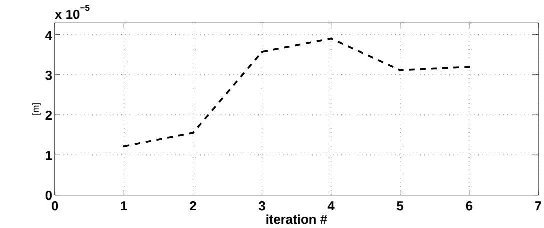
LET has been tested and compared to LOCO during several Machine Development shifts between November 2010 and July 2011. The measurements have been usually performed with a total current of 150 mA stored in 900 bunches. The lattice used for the first measurements is the Diamond lattice modified in the straight section 13, that has tunes $Q_x = 27.230$ $Q_y = 13.180$, 170 BPM's, 170 horizontal and vertical steerers and 96 skew quadrupoles, while in the last two shifts we included the latest modifications in straight section 9, with two more BPMs and with tunes changed to $Q_x = 27.201$ $Q_y = 13.371$. During the various correction iterations beam size at 2 pinhole cameras has been monitored. At the same time the lifetime of the beam was measured to have further characterization of the effect of coupling. Systematic errors due to the dependence of lifetime on the polarization of the electron beam were avoided by recording the lifetime after injection. LOCO estimated tilts have been used in all the corrections up to now.

Table 1: Minimum Achieved Values in the Various Tests

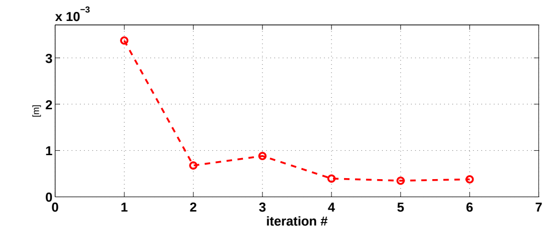
	LOCO	LET
τ	5.86h	5.51h
$\tau * I$	881 mAh	818 mAh
$\frac{\epsilon_y}{\epsilon_x}$	0.37%	0.37%
σ_y	$12\ \mu m$	$12\ \mu m$
K estimated from τ	0.07%	0.06%
ϵ_x	$2.8\,nmrad$	$2.8\,nmrad$
ϵ_y	$1.9\,pmrad$	$1.7\,pmrad$
$\langle y^2 \rangle$	$1\mu m$	$32\mu m$
$\langle \eta_y^2 \rangle$	$700\mu m$	$350\mu m$
iterations	2	5
total time	90 min	30 min

The LET evaluated correction has been applied in steps of 1-10% of the total correction, until improvements were observed. Correction calculations via SVD take a few seconds while measurements times are at most the time of a dispersion measurement plus the time to acquire 2 or few more columns of the ORM. This very short measurement and analysis time allows for fast multiple reiteration of the correction, also needed since the response matrices are simulated with the model. The correction converges after a few iterations. In the case of correction with skew quadrupoles, in Figures 2a,2b,2c we show the standard deviations of the BPM's readings (top), the dispersion (center) and the vertical orbit generated by a horizontal corrector (bottom), as a function of the iteration number. As expected, the orbit is not corrected to zero, while dispersion and the measured ORM off diagonal block columns are minimized. At every iteration the LET parameters α and ω and the eigenvalues cutoff are selected to generate the best improvements as seen on the model. Table 1 shows the best results obtained in the different conditions for the two tools.

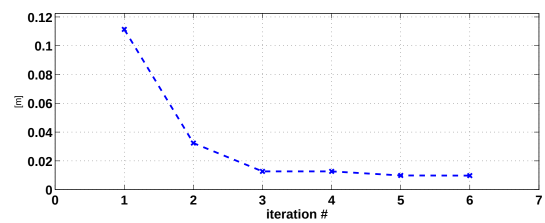
The best parameters for LET are obtained using skew quadrupoles. In fact, after a few iterations, the correction achieves the lowest vertical dispersion ever observed at diamond of $350\,\mu m$ rms. A direct comparison of the two tools may be seen in Figures 2d and 2e that store all the measure-



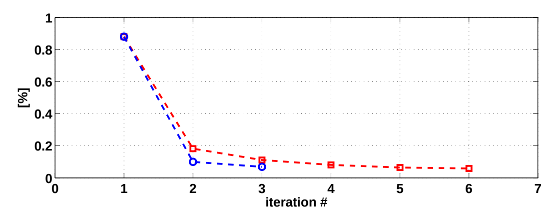
(a) *rms vertical orbit.*



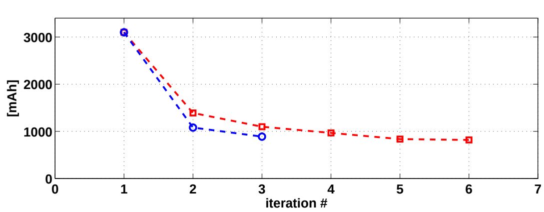
(b) *rms vertical dispersion.*



(c) *rms vertical orbit caused by a Horizontal Corrector.*



(d) *Coupling estimated as in Eq. 2 LOCO (blue) and LET (red).*



(e) *Product of lifetime and current. LOCO (blue) and LET (red).*

Figure 2: Vertical Orbit, vertical dispersion, coupling and lifetime as a function of iteration number.

ments of normalized lifetime (lifetime times current) and the estimated coupling after every correction application. LOCO correction (blue) is applied for 2 iterations varying quadrupoles and skew quadrupoles while LET correction (red) is applied 4 times using skew quadrupoles (the last point is a measurement after injection).

Listed in Table 1 for $Q_y = 13.371$ are the best achieved results. Starting from emittance coupling $K = 0.88\%$, 21.1h lifetime and normalized lifetime of 3150 mAh, both corrections reach $K = 0.37\%$ with pinhole beam size measurement while the lifetime measurement shows for LET 5.51h (818 mAh) and for LOCO 5.86h (887 mAh). However the vertical beam sizes and the coupling values measured at the pinholes are larger than expected for the observed lifetime due to the not optimum adjustment of the point spread function at the moment of the measurements. From lifetimes measurements (after correction $\tau_2 \simeq 6h$) it seems that even smaller beam coupling

$$K_2 = \frac{\tau_2^2}{\tau_1^2} K_1 = 0.06\% \qquad (2)$$

can be achieved, that is a strong indication of a very small vertical beam size and of a vertical emittance of

$$\epsilon_y = K_2 \epsilon_x \simeq 1.7\ pm\,rad.$$

CONCLUSIONS

It is evident how the two correction differ. The LOCO correction is more accurate since it controls the orbit over the whole machine but takes longer times, while the LET algorithm requires more iterations but reach a lower vertical dispersion and similar total coupling within a shorter total time. The parameters expected by the simulations are not achieved in the measurement shown but there is still a very large range of untested solutions and in particular that provided by the simulations that was obtained by alternating horizontal and vertical correction. The influence of corrector tilts may also affect the correction and it is currently under investigation. In the future other test will be required to determine the full potential of the LET algorithm. In this sense we plan to apply the LET procedure also for the Swiss Light Source (SLS). A first promising result has been already achieved [9].

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