INVESTIGATION AND TEST OF THE POSSIBILITY OF REDUCING THE EMITTANCE OF DIAMOND STORAGE RING

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Abstract

Theoretical and experimental studies have been carried out at the Diamond Light Source to assess the possibility of reducing the emittance of the existing storage ring by means of a change to the optics. The optics solutions obtained so far using a Multi Objective Genetic Algorithm (MOGA) increase the dispersion and the horizontal beta function in the straight sections. While the emittance can be reduced to 2.0 nm, this optics is limited by the operation of high field superconducting wiggler devices. In this report, we present details of the new optics and present results of practical tests. We also compare the theoretical emittance growth due to a wiggler in a dispersive region with the test results.

INTRODUCTION

The Diamond Light Source has been operational since 2007. Its design natural emittance is 2.75nm.rad with working point tunes of Q_x=27.22, Q_y=13.36, for a non-zero dispersion lattice which is the normal operating mode. Since 2011, the storage ring has been operating with two long insertion straights (I09 and I13) which have been upgraded with double mini vertical beta plus horizontal focussing optics [1] moving the working point to Q_x=27.20, Q_y=13.37 (referred to as the 'I0913 optics'). Investigations have been made into further lowering the emittance with the existing layout of magnets if possible, in light of the theoretical minimum natural emittance being ε_{x0} = 0.6nm.rad. The emittance could in principle be reduced by relaxing the dispersion in insertion device straights. As a result however, a further limit on the maximum magnetic field of super conducting wigglers (I15 (3.5T) and I12 (4.2T)) operational in standard insertion straights would have to be imposed where now the limiting magnetic field would be 4.3T for producing degradation of emittance. Initially, the BETA code (ESRF version) was used and later Multi-Objective Genetic Algorithm (MOGA which comes as an ELEGANT based package) based on the NSGA-II algorithm [2] was used to obtain optics solution. The effect of lowering the emittance to 2nmrad would be to increase brilliance on a standard MX beamline by approximately 25% compared with standard optics for 0.3% coupling as shown in figure 1.

OPTICS OPTIMIZATION USING MOGA

MOGA imitates the natural selection process of evolution to provide a set of optimal solutions for determined objectives. For lattice design, small beam emittance, large dynamic aperture and reasonable lifetime are the main objectives. In order to reduce the beam emittance, the horizontal tune Q_x was increased by one integer for stronger focussing of β_x in the bending magnets while the fractional tunes are kept constant (28.20, 13.37) so as to maintain compatibility with the present injection scheme and below the half integer to avoid resistive wall instability which was encountered during commissioning of the I13 optics [1].

In this study, there are two steps of lattice optimization: emittance and dynamics aperture (DA) optimization and non-linear effects and Touschek lifetime optimization. Because the existing Diamond lattice has two modified mini-beta sections, the linear optics optimization was constrained to keep these sections unchanged.

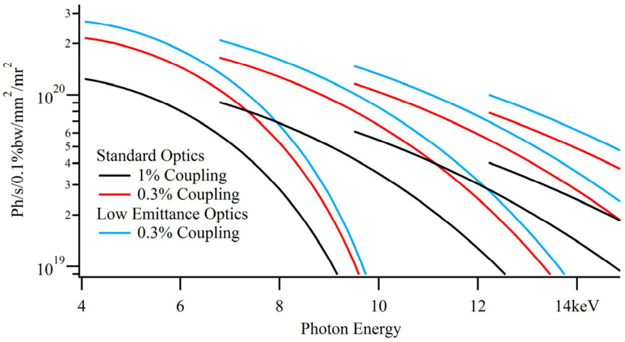

Figure 1: Brightness calculated for a standard MX beamline ID (2m U23) and aperture (150x75µrad^2).

Effective emittance and DA optimization

The effective emittance [3] of an insertion straight of the storage ring is given by;

$$\varepsilon_{eff} = \sqrt{\varepsilon_{x0}^2 + \varepsilon_{x0} H(\eta_x, \eta'_x)\delta^2} \tag{1}$$

Where H is the dispersion invariant in an insertion straight and β_x, γ_x, η_x, η'_x, and δ are the Twiss parameters, dispersion functions and energy spread. By employing effective emittance as one of the objectives instead of the natural emittance, the dispersion function in the straight sections can also be minimized. All ten available families of quadrupoles and six families of harmonic sextupoles were used as variables. In this optimization the summation of the diffusion rate represents not only the dynamic aperture area but also the stability of a particle inside the dynamic aperture [4]. The diffusion rate is given by:

$$d = \log(\Delta Q_x^2 + \Delta Q_y^2)$$

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The optimization results are shown in figure 2. The larger dispersion function produced by the optimization can be observed in the lowest emittance case of ε_{x0} = 2nmrad (ε_{eff} = 2.3nmrad) as shown in figure 3.

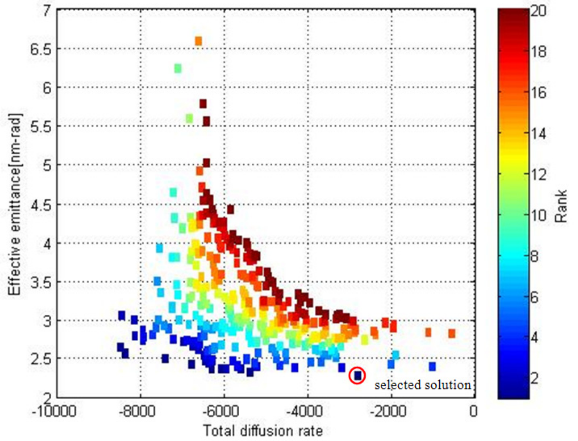

Figure 2: Lattice solutions optimized for effective emittance and total diffusion rate.

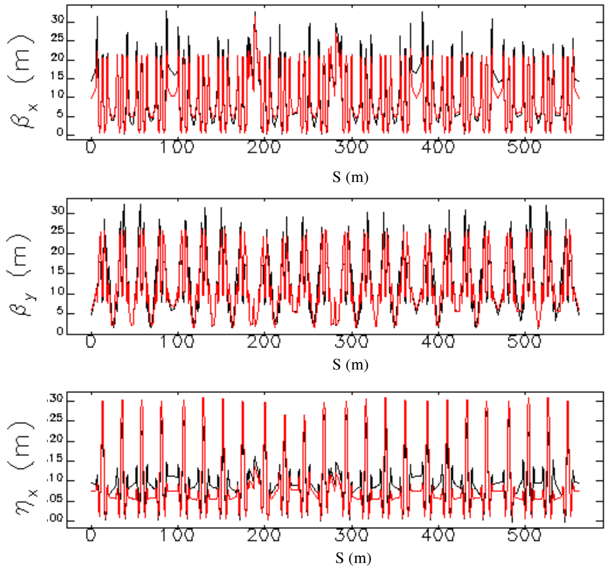

Figure 3: Optical functions for existing Diamond (red) and optimized low emittance optics of ε_{x0}=2nmrad (black).

Non-linear effects optimization

The best solution with small natural beam emittance of 2nm-rad and reasonably large dynamic aperture was selected to be the starting point for the further optimization of dynamic aperture and Touschek lifetime. In this step, the linear optics was fixed to keep the optimized beam emittance. In the nonlinear optimization, only the six families of harmonic sextupoles were used as variables. As in the previous step, the total diffusion rate was used as one of the objectives. From this starting point, MOGA provided an improved solution with larger dynamics aperture and longer lifetime. The process of this optimization is shown in figure 4. The best solution from this second lattice optimization process was chosen for experimental verification in the storage ring.

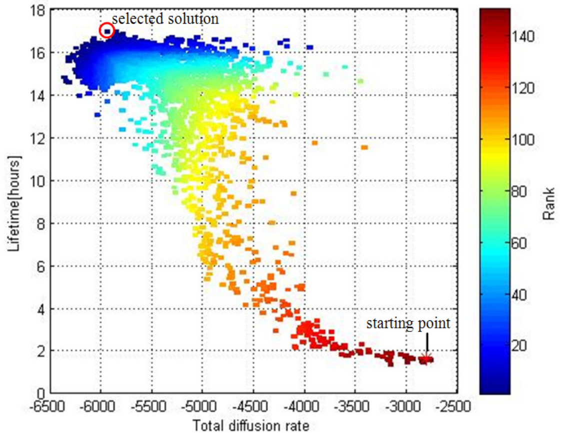

Figure 4: Lattice solutions optimized for Touschek lifetime and total diffusion rate.

MACHINE TESTS OF OPTIMIZED LOW EMITTANCE OPTICS

New Lattice Implementation

The new optimized lattice has been embedded in the middlelayer structure of the storage ring together with other MOGA implementations, for a total of three low emittance cases and two Touschek Lifetime optimizations. This allows an easy definition of the optics in the model which can be used to calculate emittance and energy spread and to run LOCO for subsequent linear fittings of the lattice. When the optics is implemented in the machine for the first time, the new ensemble of quadrupoles and sextupoles are energized starting from the current value of the I0913 optics by adding the difference in currents obtainable from the models of the standard I0913 case and the optimized 2nmrad optic.

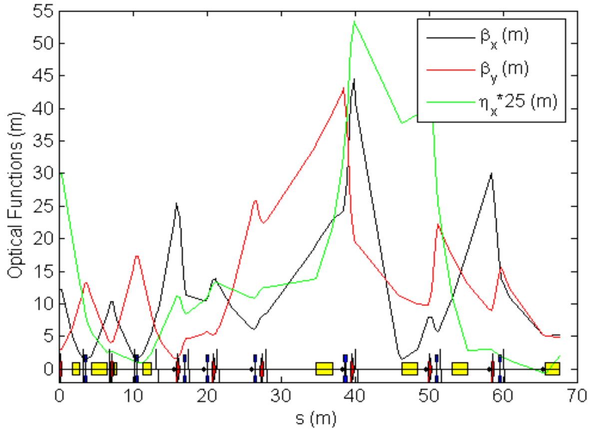

Figure 5: Optical functions of re-optimized BTS with β_x=5.2m at exit of injection septa.

Injection System Changes

The lattice output from MOGA included a horizontal beta function at the middle of injection straight of 14.4m which was a significant increase from the original 9.8m. The injection septum has enough tolerance to accommodate the injected beam with a larger horizontal

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beam size, however this required retuning of the booster to storage ring transfer line (BTS) producing a new beta function of β_x=5.2m instead of 3.2m at the exit of the setpum. The last six quadruples were used to re-optimize the BTS using MADX optics code [5]. Optical functions of the new BTS are shown in figure 5.

Test Results

Initially, injection efficiency was poor but was eventually improved to ~50% after an optics correction with LOCO. After retuning of the BTS and opening the horizontal collimator, it was improved to ~90%. The best beam lifetime achieved during these studies was 9h (in standard conditions, lifetime is around 24h).

The injection efficiency versus tunes was scanned, with the above mentioned efficiency being reached around the design working point (see figure 6). The emittance was measured as described in reference [6] and found to be in good agreement with theory. An image from the pinhole camera is shown in figure 7.

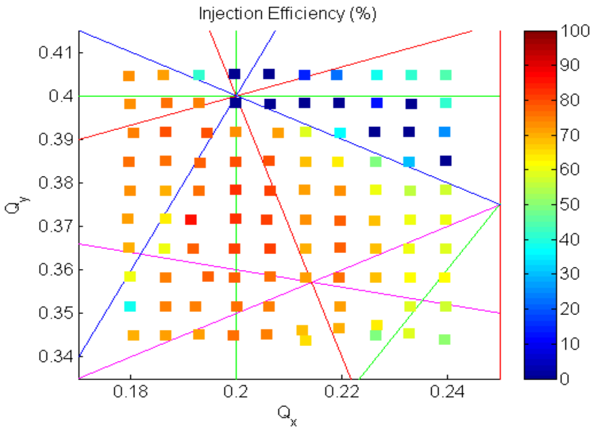

Figure 6: Injection efficiency versus tune for the low emittance optic showing ~90% around the design tunes.

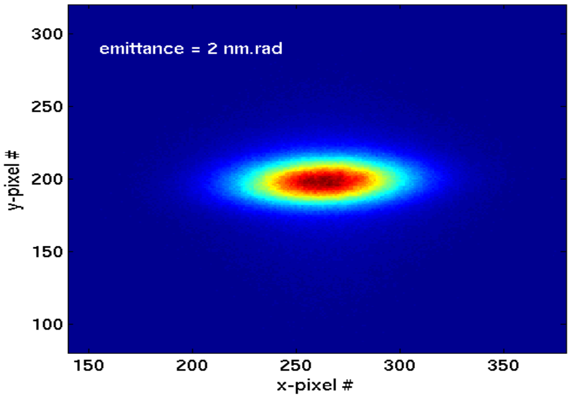

Figure 7: Image of the pinhole camera during low emittance optics tests with measured emittance = 2nmrad.

MEASUREMENTS OF EMITTANCE GROWTH DUE TO WIGGLERS

In the reduced emittance optics, the η_x in the standard insertion device straights was increased, while β_x was decreased. This has lowered the threshold for the wiggler fields to cause emittance growth significantly, thus providing the opportunity to test the standard formulae of emittance growth due to wigglers. The emittance growth ratio is given by [7];

$$\frac{\varepsilon_w}{\varepsilon_0} = \frac{1+\dfrac{I_{5,w}}{I_{5,0}}}{1+\dfrac{I_{2,w}}{I_{2,0}}} \quad ; \text{ Where, } I_{5,w} = \oint \frac{H}{\left|\rho^3\right|} ds \text{ and}$$

$$I_{5,w} = \frac{4H_w L}{3\pi\rho_w{}^3}, \text{ Where, , } H_w = \gamma\eta_x^2 + 2\alpha\eta_x\eta_x' + \beta\eta_x'^2 ;$$

$$I_{2,w} = \oint \frac{1}{\rho^2} ds \quad = \int \frac{\cos^2(k_w s)}{\rho_w^2} ds = \frac{L}{2\rho_w^2},$$

L is the length of the wiggler. The Diamond storage ring currently has two operational high field superconducting wigglers: I12 (4.2T) and I15 (3.5T). The emittance was measured using LOCO with each wiggler energized separately. Results are given in table 1, and show good agreement with theory.

Table 1: Measured and predicted beam emittance

Study cases	Matched Coupling at two pin holes (nm-rad)	Different coupling at two pin holes (nm-rad)	Emittance predicted by theory (nm-rad)
Bare lattice	2.00	2.01	2.0
I15 (3.5T)	2.90	2.92	2.77
I12 (4.2T)	3.26	3.27	3.28

CONCLUSIONS

A low emittance optic with 2nmrad natural emittance was found for Diamond Light Source storage ring using MOGA optimization for the effective emittance and dynamic aperture. It was implemented in the Diamond ring and operated with 90% injection efficiency and a relatively low beam lifetime of around 9h (250 mA, 900 bunches). The theoretical formulae for emittance growth due to a high field wiggler have been verified. Further optimization work is in progress to restore the dispersion invariant of the I0913 optic in order to operate high field wigglers and improve beam lifetime in the low emittance lattice.

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