OPTIMISATION OF THE DIAMOND STORAGE RING LATTICE

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Abstract

The basic structure of the 3rd generation light source DIAMOND has recently been defined [1]. This paper overviews the optimisation of that structure during the design and specification phase of the project. It describes the linear and non-linear optimisation used to derive a storage ring lattice solution with good dynamic behaviour that simultaneously meets the demands for very high brightness photon beams and adequate lifetime.

1 LAYOUT AND LINEAR OPTICS

The DIAMOND light source is based around a 3GeV storage ring, comprising 24 pseudo double-bend achromat (DBA) cells, set to give a small dispersion in the straight sections. Six of the cells contain longer insertion device straight sections of 8m free space compared to the standard 5m straights; three long straights are used to provide space for RF acceleration, injection and diagnostics (each in a single straight), whilst the other 3 are available for long period or exotic IDs as part of the full complement of 21 user straights [1].

Although in principle the target emittance of <3 nmrad can be achieved whilst maintaining the achromatic condition (the theoretical minimum is 1.9 nmrad), a practical compact design requires some limited dispersion in the straights.

Linear optics selection also included the following constraints:

- Restriction of maximum β-functions to economically provide sufficient apertures for injection and lifetime (Touschek and gas scattering); tailor β-function in long straights to aid injection apertures.
- Limit natural chromaticity and chromatic sextupole strength (maximise β-split).
- Limit dispersion in straights whilst providing target emittance.
- Choose working point compatible with magnet element limits and nonlinear requirements.

Working points satisfying the above requirements, and in regions free of resonances, were examined over a tune range accessible with reasonable quadrupole strengths (between Q_x={22,32} and Q_y={10,13}). These give a degree of confidence that the element specifications will be adequate to provide some flexibility in the optics.

2 NONLINEAR OPTIMISATION

2.1 Selection of Working Point

The small target emittance entails a large natural chromaticity, the correction of which by the chromatic sextupoles induces strong non-linearities and a consequent limitation of the dynamic aperture. A working point of (29.16, 11.35) was initially examined [1,2] with ($5\pi/2$, π) phase advance per cell across the standard straights, and an overall working point set by the phase advance across the long straights. The partial nonlinear cancellation afforded by this interleaved arrangement affords some advantage in providing on-momentum dynamic aperture, but does not provide for a large momentum acceptance. In addition, the relatively large natural chromaticities of (-100,- 42) push up the driving terms that then have to be corrected by harmonic sextupoles in the near-zero dispersion insertions.

By reducing the tune in both planes a reduction in the natural chromaticity is possible whilst allowing some tailoring of the β-functions, the net effect of which is to give an overall improvement in the nonlinear optimisation which is possible. The working point has therefore been moved to a reference design point which provides the same target emittance and similar optical functions in the ID straights as with higher radial tune, but significantly lowers the natural chromaticity. An alternative working point has also been studied with even lower natural chromaticity. Their properties are summarised in Table 1.

Table 1: Alternative working points and their natural chromaticities.

Working Point	Tune	Chromaticity
Original	29.16, 11.35	-100, -42
Reference	27.23, 12.36	-79, -35
Low-Chromaticity	26.29, 12.22	-66, -25

The reference design maintains some cancellation across the standard straights (see Figure 1).

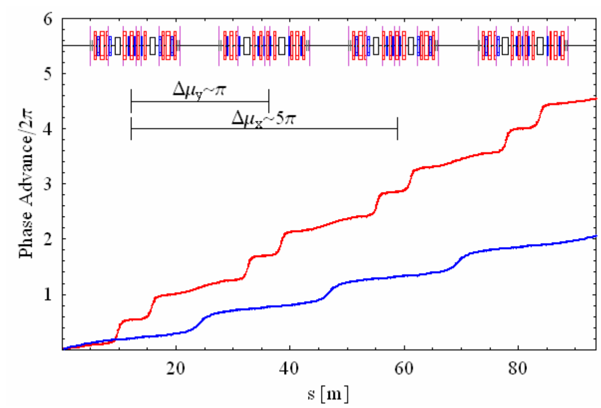

Figure 1: Phase advances across one superperiod for the reference design of DIAMOND.

2.2 Selection of Harmonic Sextupole Families

To first order in sextupole strength there are 9 driving terms in the Hamiltonian, whose strengths are proportional to

$$h_{jklmp} \propto \sum_n^{N_{sext}} (b_3L)_n \beta_{xn}^{\frac{j+k}{2}} \beta_{yn}^{\frac{l+m}{2}} \eta_n^p e^{i[(j-k)\varphi_{xn}+(l-m)\varphi_{yn}]} - \left[\sum_n^{N_{quad}} (b_2L)_n \beta_{xn}^{\frac{j+k}{2}} \beta_{yn}^{\frac{l+m}{2}} \eta_n^p e^{i[(j-k)\varphi_{xn}+(l-m)\varphi_{yn}]}\right]_{p\neq 0}$$

(assuming thin elements), where the integrated strengths of the quadrupoles and sextupoles are b_2L and b_3L respectively; similar expressions can be obtained for the higher-order terms [1,3]. With m sextupole families and n driving terms considered, optimisation reduces to an $m \times n$ matrix problem, the key issue being which of the driving terms it is most important to minimise – i.e. their weightings in some objective function. Minimisation of just the 1st order terms tends to increase the 2nd (and higher) order terms, which have a significant effect upon the overall dynamic properties. When optimising the dynamic aperture, it does not seem to be generally possible to determine a best set of weightings for this objective function independently of the lattice under consideration [4]. In practice a careful manual adjustment of weightings has to be performed for each optimisation problem, and in particular for each candidate working point that is studied.

In DIAMOND, we have chosen to utilise 6 families of harmonic sextupoles (additional to the 2 families of chromatic sextupoles), placed in the near-zero dispersion insertion regions which match into the ID straights. We have limited the total number of families to that required to achieve reasonable dynamic aperture, to reduce the complexity of optimisation and to simplify operational tuning as much as possible. The locations of the harmonic sextupoles are indicated in Figure 2.

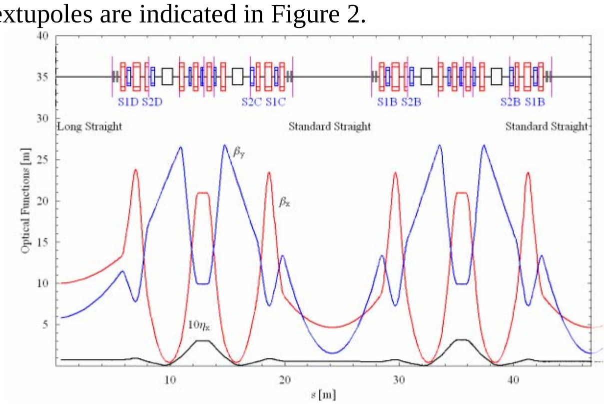

Figure 2: Optical functions in half a superperiod. The location of the harmonic sextupole families is shown (other cells are symmetric).

Notionally we have 8 independent parameters with which to minimise non-linearities, but as well as the obvious engineering limitations on sextupole strengths there are other constraints on the sextupole values which must be taken account of. Firstly, some chromaticity correction is performed by the harmonic sextupoles which reduces the requirement on the notionally 'chromatic-correction' families, but this must be balanced against the relative inefficiency of these harmonic families to perform this. Secondly, the sextupole solutions must also restrict the degree of off-momentum β-beat, which has significant implications on the aperture required for Touschek lifetime if it is not controlled.

2.3 Nonlinear Optimisation

Nonlinear optimisation has to provide:

- Adequate dynamic aperture on-momentum to allow scattered particles to execute sufficient amplitude oscillations for good beam lifetime.
- Adequate momentum acceptance for Touschek lifetime and inelastic gas scattering.
- Control of off-momentum β-functions to limit oscillation amplitudes for scattered particles.
- Limit sextupole strengths to realistic values.
- Relative insensitivity to magnet errors (both in position and strength).
- Limit natural chromaticity and chromatic sextupole strength (maximise β-split).

Numerical optimisation was carried out using a variety of tools, including HARMON (in MAD) [5], OPA [6] and direct evaluation and optimisation of the driving terms. Typically we have found that limits in the on-momentum dynamic aperture can be identified with simple resonance crossing, and that control of tune shifts with amplitude is the principal method of optimising it [7]. To some extent, reducing the detuning at large amplitudes helps to control the tune shift with momentum, but it is nevertheless difficult to provide a large off-momentum dynamic aperture; careful adjustment of the various driving terms is necessary.

2.4 Sensitivity of Sextupole Position

The contributions to the driving terms from each sextupole family depend upon its longitudinal position in the lattice, and will affect the global minimum that can be obtained. In common with studies elsewhere [7], we have found that the dynamic aperture that can be achieved is strongly dependent upon the sextupole position, with 10cm changes in location being significant. Sextupole location has therefore been chosen to simultaneously optimise both on- and off-momentum dynamic aperture within engineering constraints. Both candidate working points – the reference working point (27.23,12.36) and the low chromaticity option (26.29,12.22) – were used to determine these best locations.

3 REFERENCE LATTICE PROPERTIES

The properties of the reference design are summarised in Table 2. The on-momentum optical functions are shown in Figure 2, and their variation with momentum in Figure 3.

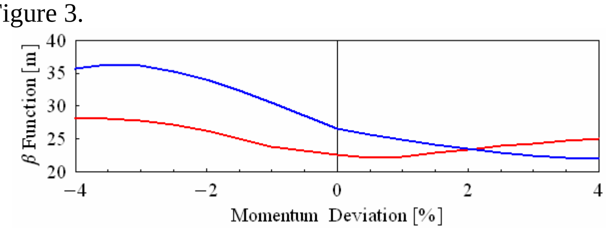

Figure 3: Variation of maximum β-function with momentum.

Table 2: Reference design properties.

Energy	3 GeV
Beam current	300 mA
No. of DBA cells	24
Symmetry	6
Circumference	561.6 m
Harmonic no. (500 MHz)	936 ($2^3.3^2.13$)
ID space	18 x 5 m, 4 x 8.0 m
Dipole field	1.4 T
Natural Emittance	2.7 nmrad
Coupling	1 %
Betatron tunes	27.23, 12.36
Natural chromaticity	-85.7, -39.1
Dispersion (long, short sts)	7.2, 5.2 cm
Momentum compaction	1.6 x 10^{-4}
Natural energy spread	9.62 x 10^{-4}

The optimised dynamic aperture without magnet errors for the reference lattice is shown in Figure 4.

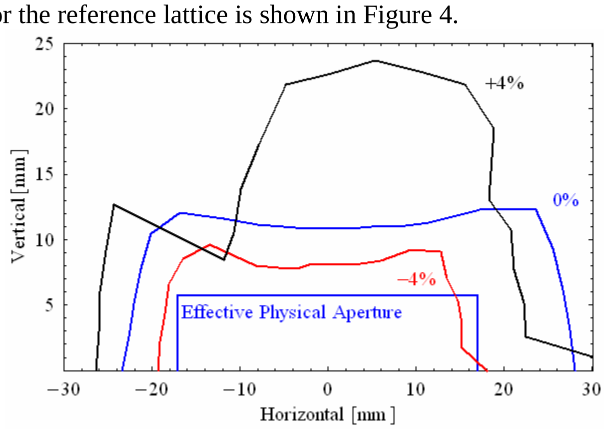

Figure 4: Dynamic aperture for on-momentum particles and for those with +/-4% momentum deviation, calculated at the centre of a long straight (β_x=10.0m, β_y=5.8m). The effective physical aperture presented by the storage ring apertures is also shown.

3.2 Effects of Errors

Using the error set given in Table 3, the effect of errors on the dynamic aperture is shown in Figure 5. Note that in addition to the space required to provide momentum acceptance and Coulomb lifetime, the physical aperture also contains allowances for closed-orbit errors and contingency for alternative working points. It is not necessary to provide a dynamic aperture that exceeds the physical one for either on- or off-momentum particles, only that it is sufficient for injection and lifetime [8]. For instance, particles scattered to large momentum deviations require an aperture which has allowances for the betatron amplitude induced by the momentum change, closed-orbit errors and the small initial (core beam) betatron amplitude.

Table 3: Total assumed alignment errors (after survey).

Quadrupole Transverse Displacement	0.1mm
Sextupole Transverse Displacement	0.1mm
Dipole Transverse Displacement	0.05mm
Dipole Longitudinal Displacement	0.05mm
Dipole Field Error	0.1%
Quadrupole Roll Error	0.2mrad
Dipole Roll Error	0.2mrad
EBPM Resolution Error	1 micron

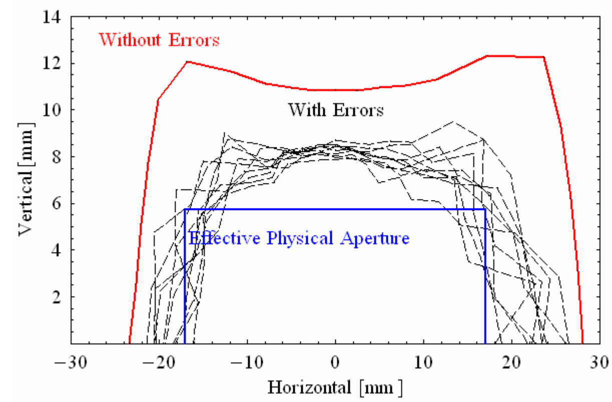

Figure 5: Dynamic aperture for on-momentum particles, showing the effect of 10 random sets of misalignment and magnet field errors [1] calculated at the centre of a long straight (β_x=10.0m, β_y=5.8m). The effective physical aperture presented by the storage ring is shown for comparison.

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