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Coupling control and optimization at the Canadian Light Source

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ABSTRACT

We present a detailed study using the skew quadrupoles in the Canadian Light Source storage ring lattice to control the parameters of a coupled lattice. We calculate the six-dimensional beam envelop matrix and use it to produce a variety of objective functions for optimization using the Multi-Objective Particle Swarm Optimization (MOPSO) algorithm. MOPSO produces a number of skew quadrupole configurations that we apply to the storage ring. We use the X-ray synchrotron radiation diagnostic beamline to image the beam and we make measurements of the vertical dispersion and beam lifetime. We observe satisfactory agreement between the measurements and simulations. These methods can be used to adjust phase space coupling in a rational way and have applications to fine-tuning the vertical emittance and Touschek lifetime and measuring the gas scattering lifetime.

1. Introduction

The electron beam in a synchrotron has properties that we seek to control, such as height, width, tilt and lifetime. We control these parameters through the design and optimization of accelerators by using models. In this paper, we use a linear model of the Canadian Light Source (CLS) storage ring to calculate skew quadrupole settings in order to control the vertical size, tilt and lifetime of the beam.

It is only possible to create an ideal synchrotron in simulation. We strive to make the real machine as close as possible to the ideal one, but this pushes the construction and alignment of the magnets to the highest precision that is technically possible. It is convenient and useful to study an ideal model of a light source because the simplifying assumptions allow for convenient and intuitive parameterizations of beam dynamics.

Even in an ideal electron synchrotron we cannot have zero beam size due to the emission of synchrotron radiation. The horizontal emittance in an ideal electron synchrotron is dominated by the emission of synchrotron radiation in areas of non-zero dispersion giving [1,2],

$$\epsilon_{x0} = C_q \frac{\gamma^2 \left\langle \mathcal{H}_x/|\rho|^3 \right\rangle}{J_x \left\langle 1/\rho^2 \right\rangle} \tag{1}$$

where

$$C_q \equiv \frac{55}{32\sqrt{3}} \frac{\hbar}{m_e c}, \tag{2}$$

$$\mathcal{H}_x \equiv \frac{1}{\beta_x}\left[\eta_x^2 + \left(\beta_x \eta_x' - \frac{1}{2}\beta_x' \eta_x\right)^2\right], \tag{3}$$

J_x is the horizontal damping partition number, ρ is the bending radius of the dipole magnets, β_x is the horizontal betatron function, η_x is the horizontal dispersion, γ is the relativistic Lorentz factor, $\hbar$ is the Planck constant divided by 2π, m_e is the electron mass and c is the speed of light.

Since the vertical dispersion is zero in an ideal electron synchrotron the analogous vertical emittance is zero, $\epsilon_{y0} = 0$. However, even in the ideal case, the vertical beam size does not damp to zero because quanta of synchrotron radiation are emitted with non-zero vertical momenta and the electrons must recoil. This vertical excitation of the electron beam is called the quantum limit of vertical emittance and we write [1]

$$\epsilon_{yq} = C_q \frac{\left\langle \beta_y/|\rho|^3 \right\rangle}{J_y \left\langle 1/\rho^2 \right\rangle} \tag{4}$$

where β_y is the vertical betatron function and J_y is the vertical damping partition number. We also note that $J_y = 1$ for an ideal electron synchrotron and that there is some disagreement in the literature as to the proper form of Eq. (4) with some authors [3] multiplying the right hand side by $\frac{1}{2}$.

The emission of synchrotron radiation also causes an energy spread. The fractional energy spread of the electron beam is given by

$$\sigma_\delta^2 = C_q \frac{\gamma^2 \left\langle 1/|\rho|^3 \right\rangle}{J_E \left\langle 1/\rho^2 \right\rangle} \tag{5}$$

where J_E is the longitudinal damping partition number.

The horizontal and longitudinal phase spaces are coupled through the dispersion function. We add the horizontal beam size contributions due to emittance and energy spread in quadrature to get the horizontal beam size for an ideal electron synchrotron,

$$\sigma_x^2 = \beta_x \epsilon_{x0} + \eta_x^2 \sigma_\delta^2. \tag{6}$$

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Also, the longitudinal beam size depends on the horizontal dispersion through the momentum compaction factor.

The vertical dispersion and betatron coupling are ideally zero, so vertical phase space is completely decoupled from horizontal and longitudinal. The vertical beam size for an ideal electron synchrotron is given by

$$\sigma_y^2 = \beta_y \epsilon_{yq}. \tag{7}$$

If we put numbers into Eqs. (1) and (4) for a third generation light source we calculate values for ϵ_{x0} that are orders of magnitude higher than ϵ_{yq}. For example we use the optics code `elegant` [4] to calculate $\epsilon_{x0} = 17.9$ nm and $\epsilon_{yq} = 1.3$ pm for the nominal CLS storage ring optics. However, when we look at the beam on a synchrotron light monitor, we see that the vertical beam size is significantly larger than that given by Eq. (7). It is clear that our ideal, uncoupled approximation is not sufficient for studying the vertical beam size.

We must consider coupling of the vertical phase space to the horizontal and longitudinal phase spaces. In a real machine, there is non-zero vertical dispersion, η_y. We will therefore have non-zero ϵ_{y0} given by

$$\epsilon_{y0} = C_q \frac{\gamma^2 \left\langle \mathcal{H}_y/|\rho|^3 \right\rangle}{J_y \left\langle 1/\rho^2 \right\rangle} \tag{8}$$

where

$$\mathcal{H}_y \equiv \frac{1}{\beta_y}\left[\eta_y^2 + \left(\beta_y \eta_y' - \frac{1}{2}\beta_y' \eta_y\right)^2\right]. \tag{9}$$

This will give contributions to the squared vertical beam size of $\beta_y \epsilon_{y0}$ and $\eta_y^2 \sigma_\delta^2$.

However, these additional contributions to the vertical beam size still do not give satisfactory results. This becomes especially apparent when operating near the coupling difference resonance $\nu_x - \nu_y = \ell$ where ν_x is the horizontal tune, ν_y is the vertical tune and ℓ is an integer. Near this resonance, the observed vertical beam size becomes very large and we must take into account the exchange of emittance between horizontal and vertical phase spaces.

If we have skew quadrupole strength k_s distributed around the synchrotron, we can calculate the integral

$$\kappa = \frac{1}{2\pi} \oint k_s \sqrt{\beta_x \beta_y} e^{i\left[\psi_x - \psi_y - \frac{2\pi s}{L}(\nu_x - \nu_y + \ell)\right]} ds \tag{10}$$

where ψ_x and ψ_y are respectively the horizontal and vertical betatron phases, L is the ring circumference and s is the longitudinal coordinate. For an ideal machine there are no skew quadrupole terms so $\kappa = 0$. However, a real machine will have non-zero κ and a perturbative treatment of coupling predicts exchange between the horizontal and vertical emittances. If we define

$$\Delta \equiv \nu_x - \nu_y + \ell \tag{11}$$

then emittance exchange occurs at a frequency of

$$\Omega = \frac{1}{2}\sqrt{\kappa^2 + \Delta^2}. \tag{12}$$

The horizontal and vertical emittances become [5]

$$\epsilon_x(s) = \frac{\epsilon_{x0}}{4\Omega^2}\left(\Delta^2 + \kappa^2 \cos^2\left(\frac{2\pi\Omega s}{L}\right)\right) \tag{13}$$

and

$$\epsilon_y(s) = \frac{\epsilon_{x0}}{4\Omega^2}\kappa^2 \sin^2\left(\frac{2\pi\Omega s}{L}\right) \tag{14}$$

giving the sum rule

$$\epsilon_x(s) + \epsilon_y(s) = \epsilon_{x0} \tag{15}$$

which is valid everywhere around the synchrotron and justifies our calling this process emittance exchange.

In the literature, one often sees the maximum emittances expressed as a ratio [5,6],

$$r \equiv \frac{\epsilon_{y,max}}{\epsilon_{x,max}} = \frac{\kappa^2}{\kappa^2 + \Delta^2} \tag{16}$$

and `elegant` calculates κ, Δ and r using the `&twiss_output` command. If we average the emittances over many turns, we get the ratio

$$\frac{\langle \epsilon_y \rangle}{\langle \epsilon_x \rangle} = \frac{\kappa^2/2}{\kappa^2/2 + \Delta^2} \tag{17}$$

which appears in Ref. [7].

We have calculated the contribution to vertical beam size from coupling to the longitudinal phase space through vertical dispersion and to the horizontal phase space through emittance exchange. However, we are still left with an unsatisfactory situation. Even if we are able to combine the various sources of vertical beam size in a meaningful way, the models we have just discussed do not have a mechanism to describe the tilt of the electron beam, which is observed as the corresponding tilt of a photon beam on a diagnostic beamline. The synchrotron light monitor at CLS shows a beam tilt of several degrees.

In this paper, we will study coupling using the full six-dimensional beam-envelope matrix and compare simulated quantities against measurements performed on the CLS storage ring. For simulations, we will calculate the beam-envelope matrix using the optics codes AT [8] and `elegant`. The AT function `ohmienvelope()` makes use of the formalism of Ohmi, Hirata and Oide [9] and the `elegant` function `&moments_output` uses a similar formalism.

We will compare these simulations against measurements using the synchrotron light beam profile monitor and measurements of the beam lifetime and dispersion. The measured vertical dispersion agrees well with the simulations, provided we take special care to ensure that we properly account for the beam position monitor (BPM) gains and horizontal–vertical cross-talk of the BPM signals. We find a useful parametrization for the beam lifetime

$$\frac{1}{\tau_m} = \frac{1}{\tau_g} + \frac{C}{\sqrt{\epsilon_{II}}} \tag{18}$$

where τ_m is the measured beam lifetime, τ_g is the gas scattering lifetime, C is a constant and ϵ_{II} is the vertical-like eigenemittance calculated by the optics codes, which we will discuss at length in the following sections.

2. Coupling calculations

In order to perform any calculations, we need a model of the real accelerator. We use the LOCO algorithm [10,11] to create an effective model of the CLS storage ring. LOCO is an algorithm which takes a model of an accelerator lattice and modifies it so that the simulation outputs a response matrix and dispersion function that is comparable to a measurement of the response matrix and dispersion.

We allow LOCO to adjust the gains and horizontal–vertical cross-talk of the BPMs and the kick strength and the horizontal–vertical cross-talk of the orbit correctors. We also allow LOCO to adjust the strengths and rolls of the lattice quadrupoles. The resulting model is an effective model because there are other sources of coupling, such as vertical dipoles and vertically displaced sextupoles, which we assign to lattice quadrupole rolls. However, the procedure yields a model that is sufficient for our purposes and a more detailed model is likely not possible with the given measured information.

The version of LOCO that we use has AT as its optics code [12], so exporting the resulting lattice is trivial. We also export the lattice quadrupole strengths and rolls to `elegant` and we find good agreement between the two codes when computing machine functions.

Now that we have a model of our accelerator, we can perform calculations on this model. We write the beam envelope matrix using