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DEBUGGING REAL ACCELERATORS ☆

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Particle losses and emittance growth in the injection process can result from mismatched injected beams arising from quadrupole errors in the ring and injection line. We describe a method, based on carefully analyzing the BPM–corrector response matrix, which allows to accurately determine quadrupole errors and, at the same time, determine BPM and corrector calibration errors as well as the BPM resolution. Results from SPEAR, NSLS, ALS, and CELSIUS will briefly be described.

Keywords: Beam optic; Diagnostic

1 INTRODUCTION

The injection process into a circular accelerator depends critically on the knowledge of the orbits and the beam optics in both injection transport line and the ring. Bad steering, beta mismatch, and other effects can result in beam loss and increased emittance. The latter is caused by filamentation due to energy spread and amplitude dependent tune-shifts. In the absence of damping, the emittance after

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chromatic filamentation ε in terms of injection errors[1] is given by

$$\varepsilon = \frac{\varepsilon_0}{2}\left[\frac{\beta_i}{\beta_0}+\frac{\beta_0}{\beta_i}+\beta_0\beta_i\left(\frac{\alpha_0}{\beta_0}-\frac{\alpha_i}{\beta_i}\right)^2\right]+\frac{1}{2}\left[\gamma_0 X_i^2+2\alpha_0 X_i X_i'+\beta_0 X'^2\right], \tag{1}$$

where $\alpha_0, \beta_0, \gamma_0$ are the Twiss parameters of the ring and $\alpha_i, \beta_i, \gamma_i$ those of the incoming beam. X_i, X_i' is the orbit of the incoming beam relative to the design orbit, and ε_0 is the emittance of the incoming beam.

In order to minimize these detrimental effects we need to understand the diagnostic and correction elements in both transfer line and ring as well as possible. We review a method for calibrating BPM and correctors as well as determining quadrupole gradient and roll errors. This method allows to construct a faithful model of the hardware in the tunnel, which, in turn allows development of more efficient and reliable correction methods.

2 RESPONSE MATRIX ANALYSIS

In order to obtain detailed information about BPM, orbit correctors, quadrupole gradients, and other parameters we carefully compare the BPM–corrector response matrix, measured by varying a corrector and observing the changing BPM signal, with model predictions from MAD[2] or other beam optics modeling programs. The response coefficients are calculated by propagating the closed orbit change due to a corrector to a BPM. This leads to $\hat{C}^{ij}_{12/34} = [R^{ij}(1-R^{jj})^{-1}]_{12/34}$, where index 12 refers to the horizontal and 34 to the vertical plane. R^{ij} is the transfer matrix between the corrector and the BPM and R^{jj} is the full-turn matrix starting after the corrector location. In addition, a horizontal corrector kick Θ_j changes the length of the closed orbit by $\eta_j\Theta_j$, where η_j is the dispersion at the corrector. In the presence of RF the beam's energy changes by $\Delta p/p = -\eta_j\Theta_j/(\alpha-1/\gamma^2)C$ in order to keep the revolution frequency constant, where α is the momentum compaction factor, γ is the normalized energy, and C is the circumference. This energy shift will be visible at BPM i as an additional orbit shift, proportional to the dispersion η_i at the BPM.

Thus, the complete response is given by

$$C_{12}^{ij} = \left[R^{ij}(1 - R^{jj})^{-1}\right]_{12} - \frac{\eta_i \eta_j}{(\alpha - 1/\gamma^2)C}. \tag{2}$$

Clearly, the second term will be important in many accelerators, particularly at low energy and near transition.

The analysis is done by two codes, CALIF[3] and LOCO[4]. CALIF sets up equations that relate the measured ($\bar{C}^{ij}$) and the model (C^{ij}) response coefficients in a Taylor-series

$$x^i \bar{C}^{ij} y^j = C^{ij} + \sum_k \frac{\partial C^{ij}}{\partial g_k} \delta g_k, \tag{3}$$

where x^i is the BPM scale, y^j is the corrector scale, and g_k is the quadrupole gradient error. The derivative can be calculated in differencing two MAD runs. CALIF then does a linear fit to either $\{x^i, \delta g_k\}$ while keeping y^j fixed or to $\{y^j, \delta g_k\}$ while keeping x^i fixed. This process is iterated while adjusting the BPM resolution errors until the χ^2/DOF is close to unity.

LOCO[4] fits for the deviations of the scales from unity $\Delta x^i, \Delta y^j$, and the gradient errors δg_k with measured BPM resolution error bars using

$$\bar{C}^{ij} = C^{ij} + \sum_k \frac{\partial C^{ij}}{\partial g_k} \delta g_k + C^{ij} \Delta x^i - C^{ij} y^j. \tag{4}$$

As a further refinement LOCO also fits for the energy change from the correctors due to the presence of RF. Equation (4) shows a global degeneracy between BPM and corrector scale errors, which leads to a degenerate linear system, which can, however, be solved using Singular Value Decomposition solvers[5]. Moreover, note that g_k can be any parameter, it need not necessarily be a gradient, but could equally be the length of a drift space, offset in a sextupole or any other parameter.

Equations (3) or (4) can be cast into a linear set of equations of the standard form $\vec{y} = A\vec{x}$, where $\vec{y}$ is based on measured data and $\vec{x}$ is the vector of parameters to be found. The solution is simply

$\vec{x} = (A^{\mathrm{T}}A)^{-1}A^{\mathrm{T}}y$, where $(A^{\mathrm{T}}A)^{-1}$ is the covariance matrix [5], containing the errors on the fitted parameters.

3 EXPERIENCE

We will now discuss four accelerators where the response matrix analysis has been successfully applied.

3.1 SPEAR

In SPEAR there are 30 horizontal and 30 vertical correctors, 26 BPM reading both horizontal and vertical beam positions, which can be used to obtain a maximum of 1560 in-plane response coefficients from orbit perturbations of up to 3 mm. Using CALIF iteratively 60 correctors (or 52 BPM) and 8 quadrupole family errors were fitted for. It was possible[3] to determine gradient errors on the order of one percent with an accuracy of 10^{-3}. Corrector calibrations were found to be up to $10 \pm 3\%$ off and BPM calibrations by up to $5 \pm 3\%$. The iterative process allowed to determine the BPM resolutions to about 0.1 mm vertically, and 0.3 mm horizontally. These BPM resolutions are mostly due to systematic errors, not included in the fit, which were attributed to the BPM resolution in the iterative procedure. Putting the deduced gradients in a modeling code the model tunes agreed with the real tunes as determined by a spectrum analyzer to within 0.004. Taking the difference orbits and analyzing them took about two hours. There were, however, some shortcomings of that analysis: (i) the closed orbit was not controlled properly in the presence of strong sextupoles; (ii) the energy shift from correctors was not taken into account, which probably accounts for the larger horizontal BPM resolution error. Model fitting using LOCO is currently carried out with improved BPM, more stable power supplies, and a re-aligned ring.

3.2 NSLS X-ray Ring

There are 51 X and 39 Y correctors and 48 X and 48 Y BPM in the X-ray ring together with 56 quadrupoles and 32 sextupoles. In total

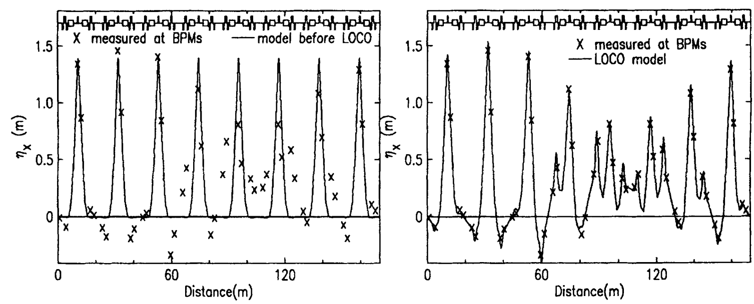

FIGURE 1 The horizontal dispersion in the NSLS X-ray ring compared to the design dispersion (left) and to the dispersion of the fitted model (right).

8640 in- and out-of-plane response coefficients were analyzed by LOCO[4] to fit for quadrupole gradients and roll, BPM calibration, roll, and crunch[4], corrector scale, roll, and longitudinal position, sextupole offsets, and energy change due to correctors. A total of 626 parameters were fitted and the BPM resolution was about 1.2 μm. The fit resulted in a χ^2/DOF of about unity, and the quadrupole gradients were found to an accuracy of 4×10^{-4}, roll angles to better than 1 mrad, calibrations to better than 5×10^{-3}, and the longitudinal position of the correctors to better than 2 mm. The gradient uncertainties translate into a relative error on the beta functions of about 10^{-3}. These remarkably accurate results were used to restore the symmetry of the X-ray ring lattice, and reduced the horizontal emittance by a factor of two[6]. Figure 1 shows the measured dispersion compared to the design model and to the model fitted with LOCO.

3.3 ALS

There are 94 X and 70 Y correctors and 96 X and 96 Y BPM in the Advanced Light Source together with 48 sextupoles, 72 quadrupoles, and the gradient in the bending magnets, treated as a single fit parameter. This yields 15 744 in-plane response matrix elements. Using LOCO, the following parameters were fitted[7]: quadrupole gradients, sextupole offsets, energy shifts from correctors, BPM and corrector calibrations. The measured orbits agreed with the final model predictions to within 3 μm, which is four times the BPM resolution. The

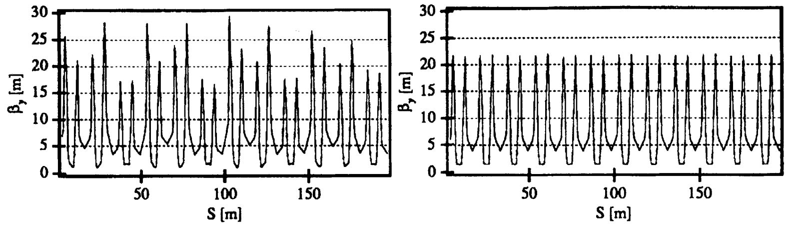

FIGURE 2 The vertical beta functions in ALS before (left) and after (right) correction.

analysis showed variations of more than 1% in a group of quadrupole power supplies which was subsequently verified by current measurements. Furthermore, the found model showed beta beat of 19% which could subsequently be corrected. The validity of the correction was then verified by measuring difference orbits and analyzing them again. The original and corrected beta functions are shown in Figure 2. The corrected lattice had significantly higher symmetry and improved injection efficiency.

3.4 CELSIUS

There are 12 X and 8 Y correctors and 10 X and 10 Y BPM in CELSIUS[8] together with 8 quadrupoles and 12 pole face windings on solid core combined function bending magnets. Using CALIF we fitted for BPM and corrector calibrations only and found BPM calibration errors of up to 50%, BPM with wrong polarity, and a corrector which is three times stronger than assumed previously.

4 OTHER APPLICATIONS

The out-of-plane response matrix data C_{14}^{ij} and C_{32}^{ij}, which correlate vertical correctors with horizontal BPM and vice versa, can be used to correct the coupling. The measured out-of-plane data are fitted by the available skew quadrupolar correction magnets and the negative of the fitted skew gradients are used in order to compensate the observed data. This scheme was tested on LHC, version 2 lattice[9] in which the systematic skew gradient from the dipoles was corrected by normal means and then a random variation with rms equal to the systematic skew gradient (truncated at 2σ) was added. The perturbed lattice showed a width of the difference resonance of 0.025 and significant beta beat. After correction the width was reduced to 0.003 and the beta beat considerably less.

The response matrix analysis is applicable to transport lines as well[10,11]. As example, we use a short beam line with eight 60° FODO cells where the pattern

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(QF, XCOR) – (QD, YCOR) – (QF, BPM) – (QD, BPM)
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is repeated four times. In a test, the gradients of eight QF are increased by 1% and random calibration errors were assigned to all correctors and BPM. It turned out that fitting for the gradient scales alone works very well, but fitting for gradients, correctors and BPM calibrations simultaneously did not find the gradient errors. Instead, the fitting determined all corrector calibrations a little too strong and all BPM calibrations a little too weak. Redoing the fitting by assuming the beam line is circular (i.e. using C^{ij}'s rather than R^{ij}'s) this degeneracy is removed.

5 CONCLUSIONS AND OUTLOOK

Bad steering and beta mismatch at injection causes emittance growth by filamentation. Instrumental deficiencies that contribute can be effectively diagnosed by measuring and analyzing the corrector–BPM response matrix. In particular, quadrupole gradient errors and corrector and BPM calibration errors can efficiently be determined as has been verified at SPEAR, NSLS, ALS, and CELSIUS. At NSLS, the uncertainties in the gradient errors correspond to 10^{-3} relative errors in the beta functions. Analyzing the response matrix can also be used to analyze transport lines and to experimentally decouple a ring.

The presented method has been tested on moderately large accelerators. The question arises, how big accelerators can be handled. One way is to use all available BPM, but use a reduced set of correctors. In this way the required computer memory needed to solve the linear equations is reduced. In the decoupling analysis of LHC only 32 correctors were used, but 556 BPM were used. A careful analysis of the scaling of the memory required, accuracies involved and the computing time will be done in the future.

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