BEAM-BASED BPM ALIGNMENT

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Abstract

An operational, beam-based, null-measurement, control room procedure designed to steer the closed orbit through the effective (no steer) center of every quadrupole is described. Performance of the procedure is simulated using UAL (Unified Accelerator Libraries). Matching SNS hardware availability, quadrupole strengths are assumed to be trimmable, but only in families, not individually. The accuracy of the procedure is unaffected by geometric and/or electrical misalignment of BPM's (beam position monitors) but calibration of their misalignments is a byproduct of the procedure. Some of the many possible failure mechanisms have been modeled, and have been found not to invalidate the procedure.

DEFINITION OF THE TASK

We are concerned with steering the closed orbit through the centers of all quadrupoles. Magnet imperfection may cause significant displacement of the effective quadrupole center (position of no particle deflection) from its geometric center and electronic imperfection may cause significant displacement of the effective BPM center (position the data acquisition system reports to be zero) relative to *its* center.

In this report, to avoid ambiguity, when "center" is used, be it quad center or BPM center, the meaning will always be *effective* center that is meant. From the control room the absence of steering is the determinant of beam passage through effective quadrupole center and output of zero from the BPM is the determinant of beam passage through the effective center of the BPM. The present paper describes a control room, beam-based, procedure that is independent of the installed BPM alignment and can therefore corroborate, or even supercede, the installation accuracy.

An ideal arrangement would supply every quadrupole with a full "detector/adjuster package" consisting of trim winding, horizontal and vertical kickers, and horizontal and vertical BPM. There is a natural "null measurement" operational procedure that can be performed using a quadrupole (call it quad i, and let its inverse focal length be q_i) endowed with such a package. Taking the quad effective center as origin, let the closed orbit position be (x_i, y_i). The effect of the quadrupole is to cause angular orbit deflections

$$\Delta x_i' = -q_i x_i, \quad \Delta y_i' = q_i y_i. \tag{1}$$

The effect of making fractional change f (absolute change fq_i) in the quadrupole's strength is to introduce a further kink ($\delta\Delta x_i' = -fq_i x_i,\ \delta\Delta y_i' = fq_i y_i$) that changes the closed orbit. This changes not only local position (x_{di}, y_{di}) but also the complete set of closed orbit measurements at all N_d BPM locations, $(x_{dj}, y_{dj}), j = 1, 2, ..., N_d$. A simple operational procedure is then to adjust the local kicker values to "null out" this closed orbit change; the kicker strengths will be $\delta x_i' = -\delta\Delta x_i',\ \delta y_i' = -\delta\Delta y_i'$. In principle the nulling could employ a single BPM (which need not be the i'th) but a more robust (less subject to noise) procedure would be to average numerous BPM's. From the available data one obtains

$$x_i = \frac{\delta x_i'}{f\, q_i}, \quad y_i = -\frac{\delta y_i'}{f\, q_i}. \tag{2}$$

This information can be used to center the beam on the quad, or more practically, if there is a local BPM, to calibrate the BPM so that its electrical center coincides with the quad center, both horizontally and vertically. The BPM will then serve as a secondary, or transfer, standard. After all BPM's have been calibrated in this way they can be used for a grand smoothing that puts the beam through the centers of all quads. Even if a quad lacks a BPM the closed orbit can be adjusted to pass through the quad center, provided there is a local steering elements that can be used for the null measurement.

Unfortunately, in practice, all quadrupoles are not necessarily supplied with the full detector/adjuster package. In the case of SNS, though there are trim windings on all quadrupoles, the quadrupole trims are not individually powered. Rather the quadrupoles are grouped in families of 8 having trim windings powered from a single power supply. The purpose of this report is to generalize the null calibration procedure in this circumstance and to simulate its performance using UAL.

ORBIT SMOOTHING ALGORITHMS

It has to be assumed that there is a control program which uses N_d detectors (BPM's) and N_a adjusters to smooth the orbit, say horizontally, where "smooth" may mean that all measured offsets are zero. More commonly there is a redundantly generous distribution of BPM's so that $N_d > N_a$, so the "badness"

$$B(\delta x_1', \delta x_2', \ldots, \delta x_{N_a}') = \sum_{i_d=1}^{N_d} \frac{x_{i_d}^2}{\beta_{i_d}^{(x)}} \tag{3}$$

can be minimized but not be made to vanish. Here B is expressed as a function of the adjuster deflections $\delta x_1', \delta x_2', \ldots, \delta x_{N_a}'$ since they are the quantities to be varied in order to minimize B. Mathematically this leads to the equations

$$\frac{\partial B}{\partial(\delta x_{i_a}')} = 0, \quad i_a = 1, 2, \ldots, N_a. \tag{4}$$

In this report the UAL algorithm (TEAPOT module) that simulates orbit smoothing is called `hsteer` and the corresponding vertical algorithm is `vsteer`. Programs like this rely on the optical model of the lattice to calculate an "influence function" $T_{i_a}(i_d)$ which is the closed orbit displacement at detector i_d caused by unit deflection at adjuster location i_a. Starting from closed orbit displacements $x^{(0)}_{i_d}$, the effect of applying kicks $\delta x'_{i_a}$ is to produce displacements $x^{(0)}_{i_d}$ given by

$$\frac{x_{i_d}}{\sqrt{\beta^{(x)}_{i_d}}} = \frac{x^{(0)}_{i_d}}{\sqrt{\beta^{(x)}_{i_d}}} + \sum_{i_a=1}^{N_a} \delta x'_{i_a} T_{i_a}(i_d). \tag{5}$$

Letting $Q = (\delta x'_1, \delta x'_2, \ldots, \delta x'_{N_a})^T$ be the (transpose of the) vector of unknowns and substituting Eq. 5 into Eq. 4 yields equations (in matrix form)

$$\mathbf{M}\,\mathbf{Q} = \mathbf{V}, \tag{6}$$

where

$$\mathbf{M}_{ab} = \sum_{i_d=1}^{N_d} T_a(i_d)T_b(i_d), \quad V_a = -\sum_{i_d=1}^{N_d} \frac{x^{(0)}_{i_d}}{\sqrt{\beta^{(x)}_{i_d}}} T_{i_a}(i_d). \tag{7}$$

Solving Eq. 6 yields kicker values which minimize the badness.

BPM ALIGNMENT AT SNS WITH QUADRUPOLES GANGED IN FAMILIES

Consider, for example, the family consisting of the N_q(=8) quadrupoles labeled QFH in the SNS lattice shown in Fig. 1 for which the MAD lattice description file is `BmBasedBPMAlign.mad`. This file differs only from file `ff_sext_latnat.mad` by name changes made for the present simulation. Both files are available at `http://www.ual.bnl.gov`, along with a detailed description of the simulation. The task is to measure all N_d horizontal misalignments and all N_d vertical misalignments. Of course there are also many other quadrupoles, grouped in other families. The procedure described here is immediately applicable to all such families. It is not even required that all nominal quadrupole strengths in the same family be equal or that the fractional trim strengths be equal. But, for this report, these simplifications have been made.

The strategy to be followed is much the same as with a single quadrupole trim. An intentional systematic change of the strengths of the quadrupoles in a single family causes the closed orbit to shift because of the (random and unknown) displacements of the quadrupoles in the family. Using an orbit smoothing algorithm the associated kicker magnets can be adjusted to undo this change. Then the individual quad misalignments can be inferred from the kicker strengths and the nominal quadrupole strengths using Eq. 2. At that time all BPM offsets would be recorded to enable subsequent use of the BPM's as "secondary standards".

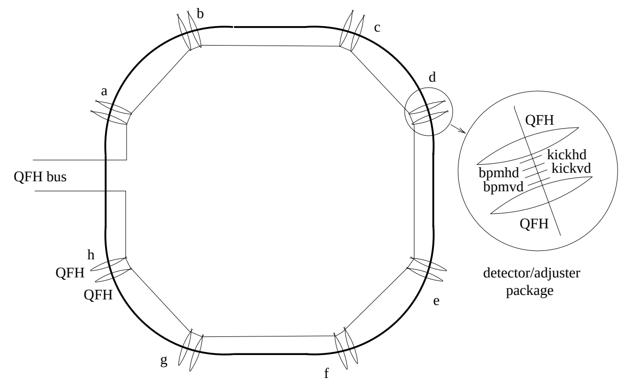

Figure 1: SNS lattice showing the particular family of quadrupoles used in the paper to illustrate beam-based quadrupole alignment when quadrupoles cannot be trimmed individually. The QFH elements are half-quads. In real life the BPM's and kickers would be somewhat displaced from the actual full quads.

Concentrating first on the horizontal measurement, it is essential now to restrict the adjusters being used to precisely those associated with the quadrupoles in the QFH family. Therefore $N_a = N_q$. For noise suppression it would be appropriate to use $N_d >> N_q$ but, for simplicity, we assume $N_d = N_q$. So from here on the term "perfectly smooth closed orbit" is equivalent to $B = 0$ where B is given by Eq. 3 with $N_d = N_q$. Because $N_a = N_d$, the number of Eqs 4 is equal to the number of unknowns. Therefore the equations have a unique solution. If the lattice were ideal (except for the misalignments being investigated) this would be the end of the story. But because of coupling and nonlinearity, when the calculated kicker values are installed the value of B is still found to differ from zero. This may necessitate proceeding by successive approximation.

In any case one eventually achieves the result $B = 0$, be it in simulation or in the control room. Repeating, for emphasis, what has already been implied, this only means that the orbit is perfect *as far as the* QFH *detectors are concerned.* Let us refer to this restricted closed orbit as the "QFH closed orbit". The orbit shown by all BPM's in the ring will not necessarily improve in the successive approximations described in the previous paragraph. In fact, our simulation shows that the closed orbit at points outside the QFH family frequently is made worse by a next approximation. Though disconcerting this is what is to be expected.

In the control room the QFH closed orbit *appears to be* perfectly smooth when all BPM outputs from the QFH family are zero. But this only means that the closed orbit has been adjusted to pass through the electrical centers of every QFH detector.

Next we apply the systematic fractional strength change f to all quadrupoles in the QFH family. This causes the QFH closed orbit to be no longer smooth. Applying `hsteer` and `vsteer` again yields the kicker strengths needed to re-smooth the orbit. Finally the misalignments being sought are given by Eq. 2. This completes the determination of closed orbit displacement relative to quad centers at all quads in the family.

FUNDAMENTAL LIMITATIONS

As with all operational procedure, the BPM calibration can be compromised by world realities. Some BPM's may not function at all and electronic noise will cause fluctuation of the measured positions. These effects are perhaps the ones most likely to limit the practicality of the procedure being described here. For this procedure the absolute accuracy of BPM's is irrelevant, but it is important that their least count correspond to a very small distance—or rather that they be capable of stably and reproducibly recording very small beam position *changes*.

Another practical complication is that BPM's, though physically close to their associated quadrupoles, cannot be precisely superimposed. But, provided they are reasonably close and that signals are available from other nearby BPM's, values can be accurately interpolated to the precise quadrupole locations. Even if vertical quads are restricted to vertical focusing quad locations, and horizontal to horizontal (as is common) there are reliable interpolation procedures to produce the signals assumed in this report. Similarly, even though kickers are not precisely in their ideal locations, the kicker strengths can be appropriately adjusted.

There are other more fundamental effects that potentially limit the practicality of the proposed method. The effect of increasing a quadrupole strength is not just to cause a steering effect proportional to the quad offset. There are also changes in the lattice optics, both tunes and beta functions. At worst the change in quad strength could make the lattice unstable and, at a minimum, the changes in lattice optics will cause the closed orbit fitting programs to be somewhat inaccurate. Such a limitation is already present in the single quadrupole procedure. In the interest of increased signal to noise ratio one wishes to make the quad strength increment fq_i as large as possible, but the need to limit lattice distortion forces one to compromise. Nonlinear elements present in the ring also limit the accuracy of the procedure. Nonlinear elements would not affect the one quadrupole, null measurement, but their presence reduces the accuracy of the closed orbit algorithms. All effects mentioned in this paragraph are subject to investigation using UAL or another simulation code. Our (very limited) investigations started with the guess that a one percent alteration of quad strengths ($f = 0.01$) would be satisfactory. At this level we find the algorithm to be essentially unaffected by changing the chromaticities from their natural (all chromaticity sextupoles off) values to being zero in both planes. Similarly the procedure is little affected by the inclusion or exclusion of magnet imperfections at anticipated levels.

The achievable accuracy can be estimated as follows. Let us concentrate on vertical orbit smoothing. If the lattice is taken to consist of nothing but 90 degree FODO cells and the tune is Q there will be $8Q$ quads altogether, each with its local BPM. But of these only half are close to vertical quads where their accuracy is high and only about half of those are favorably located relative to a particular vertical steering that is being nulled. If the r.m.s. position error at a quad of strength q_i is σ_y, the r.m.s. deviation of the deflection to be nulled for trim factor f is $fq_i\sigma_y$. The downstream displacement caused by such a deflection is

$$\sigma_d \stackrel{\sim}{<} \beta_{\rm typ.} f q_i \sigma_y \tag{8}$$

For individually trimmed quads the $2Q$ "useful" detectors would improve the nulling precision by a factor $1/\sqrt{2Q}$. The effect of being forced to trim the N_q quads in a family will exact a loss of accuracy which will erode this factor to $1/\sqrt{2Q/N_q}$. Incorporating this estimate in Eq. 8, using the estimate $\beta_{\rm typ.} q_i \approx 1$ and solving for σ_y yields

$$\sigma_y \stackrel{\sim}{>} \frac{\sigma_d}{f}\sqrt{\frac{N_q}{2Q}}, \tag{9}$$

as the estimated accuracy with which the closed orbit can be steered through the quadrupole center. Taking the square root factor as 1, the precision with which the orbit can be steered through the quad is approximately the BPM precision eroded by factor $1/f$. With f being of order 0.01 the steering accuracy is 100 times worse than the measurement accuracy. To achieve 0.1 mm steering accuracy will require something like $1\,\mu$m BPM reproducibility. Note, though, that it is *short term reproduceability* not absolute or even long term relative accuracy that is required. Perhaps the required precision could be attained using very low frequency excitation with lock-in detection. Least count precision of the steering power supplies may also be an issue, as the required deflections are very small.

CONCLUSIONS AND COMMENTS

An algorithm for centering the beam on all quadrupoles has been described. The algorithm is applicable even when multiple quad trims are powered from the same bus. Some effects that could potentially cause the algorithm to fail have been investigated. Sextupoles of strength needed to adjust chromaticities to zero have negligible effect. So also do the random and systematic magnetic field errors assumed in the only lattice file investigated.

Other effects, potentially more limiting, have not been investigated. A simulation such as this one could, however, anticipate the degree to which this calibration procedure would be reliable. Electronic noise and stability could be estimated and included. Also instrumentation issues such as the required least count precision of analog to digital conversion could be addressed.