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Automatic Steering Corrections to Minimize Injection Oscillations in the Fermilab Antiproton Source Rings

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Abstract

Missteering of a particle beam at injection into a circular accelerator produces coherent betatron oscillations. The beam position monitor system in the Anitproton Source at Fermilab can measure the beam position on each turn around the ring during these oscillations. From the amplitude and phase of the oscillations, corrections to the beamline steering are calculated to remove the oscillations. The analysis includes the case where the horizontal and vertical tunes are quite strongly coupled. This technique has proved to be valuable both in operation of the Fermilab Collider and as an analytical tool.

Introduction

At the Fermilab Collider one of the steps in preparing for a transfer of antiprotons from the Accumulator is to tune the beamline by injecting 8-GeV protons from the Main Ring backward into the Accumulator[1]. The final step in steering the beam is to minimize the coherent betatron oscillations. Without assistance this is often a difficult and tedious process. The pressure to do the job quickly is severe, since during this time we are neither able to run the collider experiments or to stack more antiprotons, yet it must be done well to avoid dilution of the antiproton emittance during the transfer. To assist in the tuning we have developed a system which automates the process for injection into either of the rings of the Fermilab Antiproton Source from any of the four beamlines.

Determining the corrections to the beamline may be broken into two major tasks: to measure the injection error with sufficient detail to allow correction and to calculate the necessary changes to eliminate that error. In the conventional view we need to correct both the position and angle at injection, so in principle we need to measure two quantities and adjust two beamline elements (for each plane).

The injection error could be determined by measuring the beam position on the first turn at two locations separated by about $\pi/2$ in phase advance. We choose instead to measure the beam position at a single location on many successive turns. Making adjustments based on the oscillations has the advantage of letting us work on exactly the property that we are trying to minimize. Using multiple turns allows us to improve the precision of the measurement by, effectively, averaging over many measurements to obtain two parameters. Further, by using a single detector, we remove all questions of cross-calibration between two detectors.

We describe the oscillations we are trying to correct with two parameters, the phase and amplitude. From these numbers and the lattice we calculate the changes to two bending elements which will eliminate the oscillations.

Theory

We consider the two-dimensional space of all simple injection oscillations in one plane. The ideal is a point with zero amplitude. Any finite amplitude oscillation will have a phase. The amplitude and phase characterize the oscillation.

If we start with no oscillation and turn on a single trim in the injection beam line, we induce an oscillation. The phase of the oscillation depends only on the phase advance from the trim to the measurement position. The amplitude of the oscillation depends on the size of the bend in the trim and the relative lattice functions at the two points. A single bipolar trim can move the oscillation vector from the center in either direction along a straight line. A second trim, placed at some other phase (modulo π) relative to the detector, will produce oscillations that lie along a straight line at a different angle.

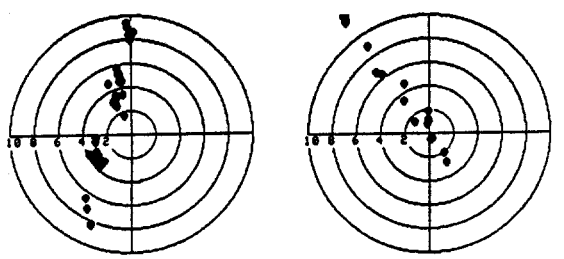

Figure 1: The oscillation vector moves along two different straight lines as two different trim magnets are varied.

Now we adjust two trims. Assuming a linear machine, the position of the beam at the detector on each turn is the linear sum of the changes induced by each of our two trims. We can find the resultant oscillation on our plot by taking the vector sum of the two separate oscillations.

The summing process can be reversed. An arbitrary oscillation vector can be decomposed into the linear sum of two vectors, with the two vectors parallel to the axes defined by the two trims of interest. If we start with the beam oscillating, we can calculate the magnitude of the correction necessary from each trim in order to produce an oscillation with will exactly cancel the initial oscillation in the ring.

This graphic picture of the trimming explains well what can also be understood in other ways. The most important thing to notice is the problem you face if the two trims you are attempting to use are close together in phase and the error oscillation you want to correct is far away from them in phase. Although you can decompose the error into components parallel to the trims, you are likely to run out of range on your power supplies before attaining the desired correction and you may not have enough aperture in the beam line between the two trims to accommodate the deviations.

We can also understand better the traditional tuning process. Given two knobs associated with two trims we traditionally use them alternately to minimize the amplitude of the oscillations, iterating until we are satisfied or bored or tired. If the trims are orthogonal, the ideal, we follow the first path. First we optimize with one trim, then the other, and we are done. It takes a while to find the minimum oscillation amplitude as a function of each trim, requiring measurements at many points along the line. This is especially true of the first trim, since it is likely to have a fairly shallow minimum. If the two trims are not orthogonal, an iterative process must be used, only slowly

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converging. The paramount importance of establishing trims, or combinations of trims, that are orthogonal is thus vividly demonstrated. By contrast, the decomposition of a single measurement can predict the correct settings when the available two-dimensional information is used. Additionally, the placement of trims is less critical.

Measurement of Oscillations

The hardware of the Beam Position Monitor (BPM) system for the Antiproton Source has been described in detail elsewhere[2]. For this measurement we use the section of the electronics which detects the 53 MHz component of the beam (due to the RF buckets) and which is capable of logging the beam position at one detector on each turn of the beam around the ring. This is commonly known as the turn-by-turn (TBT) system.

The goal of the data analysis is to extract an amplitude and phase for the oscillations. A necessary byproduct is the frequency, which also gives the tune of the machine.

A Fast Fourier Transform

The first stage of the analysis is a Fast Fourier Transform (FFT) of the position data. The code derives from that given in Reference 3. A simple peak search for the maximum amplitude gives the fractional part of the tune, q, to within $1/N$ where N is the number of turns. A simultaneous search for the second-highest local maximum attempts to find the frequency of oscillations coupling in from the other plane. At least some of the additional information that we extract using the techniques described below could probably be obtained by a more sophisticated application of FFT theory, but we chose to use the tools with which we were familiar.

Fitting Uncoupled Oscillations

We can fit the simple oscillations to a sine wave using a least squares fit. For a given fixed frequency the problem is a linear least squares fit. We find the best frequency by solving the problem for a few different frequencies near the frequency determined by the FFT.

We take i to be the turn number, ranging from 0 to $N-1$; X_i to be the measured position on turn i; and $x(i)$ to be the position calculated from a pure sine wave. We assume that all positions are measured equally well, since the detector and electronics are identical for all measurements. The quantity to be minimized is then

$$D^2 = \sum_{i=0}^{N-1} (X_i - x(i))^2 \tag{1}$$

and the best fit is obtained when all the partial derivatives of D^2 with respect to each parameter of $x(i)$ are equal to zero.

If we use the functional form

$$x(i) = C_1 \sin 2\pi q i + C_2 \cos 2\pi q i \tag{2}$$

and keep q fixed, then we can quickly take the partial derivatives of D^2 with respect to the parameters C_1 and C_2, equate the derivatives to zero, and solve the two linear equations for the two unknown parameters. We also calculate D^2 for those values of C_1 and C_2.

For a given measurement data set the quantity D^2 is only a function of q. We calculate D^2 for $q = q_{FFT}$, the tune obtained from the FFT; for $q = q_{FFT} - 1/N$; and for $q = q_{FFT} + 1/N$. $1/N$ is the granularity of the measurement of q_{FFT} and is thus an appropriate range. We assume that the dependence of D^2 on q is approximately

$$D^2(q) = D^2(q_0) + \frac{1}{2} D^{2\prime\prime}(q_0)(q - q_0)^2 \tag{3}$$

for small variations of q from q_0, the 'best' value. Having evaluated D^2 for three values of q, we may solve for q_0 (and, if we wanted to, $D^2(q_0)$ and $D^{2\prime\prime}(q_0)$). Using our new value q_0, we solve one last time for C_1 and C_2. To convert C_1 and C_2 into the amplitude and phase that we desire, we equate the two expressions

$$x(i) = C_1 \sin 2\pi q i + C_2 \cos 2\pi q i \tag{4}$$

$$= \mathit{Amplitude} \sin(2\pi q i + \mathit{phase}) \tag{5}$$

and require them to be equal for all values of i.

Fitting Coupled Oscillations

The previous analysis assumes that the effect of coupling between the horizontal and vertical tunes may be neglected. In the Accumulator, where we run very close to the $q_x = q_y$ line and with the tunes coupled quite strongly on the injection/extraction orbit, this is not a reasonable approximation. The Debuncher, as well, suffers from coupling in some modes of operation. We are therefore led to a more complete analysis which includes the effects of coupling.

The basic principle remains the same as with the uncoupled case. We treat the two planes separately. The peak search of the amplitude spectrum from the FFT finds the two highest local maxima. A linear least-squares fit to two sines waves is performed using the two frequencies obtained from the FFT. The frequencies may be refined by seeking better fits to the data with different frequencies.

We write

$$x(i) = A_1 \sin 2\pi q_1 i + B_1 \cos 2\pi q_1 i + A_2 \sin 2\pi q_2 i + B_2 \cos 2\pi q_2 i \tag{6}$$

for the oscillations. The partial derivatives of D^2 are set to zero to produce four linear equations in four unknowns. The two amplitudes and phases are calculated as they were for the uncoupled case.

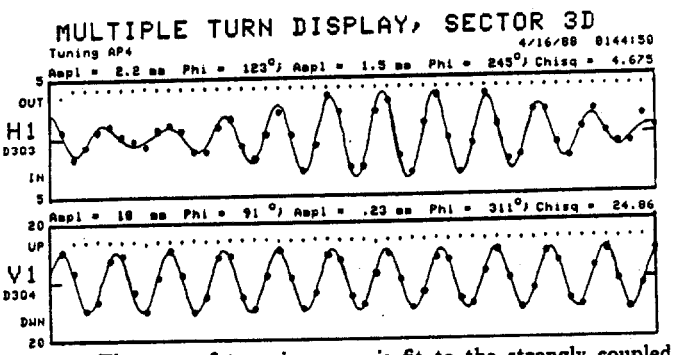

Figure 2: The sum of two sinewaves is fit to the strongly coupled oscillations. The heavy dots are measured points on successive turns; the light line is the fit to the data.

The frequencies determined from the FFT are generally sufficiently precise to allow us to use the amplitude and phase from the linear fits obtained with the FFT frequencies. To improve the frequency (tune) values beyond the precision offered by the FFT, we need to do a two-dimensional non-linear fit. The FFT values provide a good starting point for the frequency fit. We have adapted the subroutine MIGRAD, a variable metric gradient method from the CERN fitting package MINUIT[4] for the fit.

Calculation of Corrections

We use, of course, the standard Courant-Snyder notation of beta functions and phase advances to describe the motion of the beam in the rings. This notation may be extended to a beamline which joins a ring by propagating the parameters in the ring through the magnetic elements up (or down) the beamline. In this notation a bend $\delta\theta$ in the beam line at a point A will propagate down the line and around the ring to point z as a change in the displacement.

$$\delta x_z = \delta\theta_A \sqrt{\beta_z \beta_A} \sin(\psi_z - \psi_A) \tag{7}$$

The oscillation at one measurement point on successive turns is then

$$x_i = \delta\theta_A \sqrt{\beta_x \beta_A} \sin(\psi_x + 2\pi Q i - \psi_A) \quad (8)$$

$$= A \sin 2\pi q i + \phi \quad (9)$$

Canceling oscillations with two trims

So, starting from perfect injection, each trim will induce an oscillation of fixed phase and varying amplitude in the ring as its setting is changed. To correct for an existing oscillation we need only decompose the error oscillation vector into its components parallel to two trim oscillation vectors and set the trims to cancel.

We call the trims A and B. We call the oscillation vectors $\vec{O_A}$, $\vec{O_B}$, and $\vec{O_{error}}$. The condition for cancelling the error oscillations is then simply written.

$$\vec{O_A} + \vec{O_B} + \vec{O_{error}} = \vec{0} \quad (10)$$

To actually calculate we separately set two orthogonal components of the vectors.

$$0 = A \sin(\psi_{BPM} - \psi_A) + B \sin(\psi_{BPM} - \psi_B) + C \sin\phi \quad (11)$$

$$0 = A \cos(\psi_{BPM} - \psi_A) + B \cos(\psi_{BPM} - \psi_B) + C \cos\phi \quad (12)$$

These are easily solved for the trim strengths A and B and simplified by combining products of sines and cosines.

$$A = -C \frac{\sin(\psi_{BPM} - \psi_B - \phi)}{\sin(\psi_B - \psi_A)} \quad (13)$$

$$B = C \frac{\sin(\psi_{BPM} - \psi_A - \phi)}{\sin(\psi_B - \psi_A)} \quad (14)$$

Remembering that the position oscillations are proportional to the invariant oscillation size and $\sqrt{\beta}$ and the effect of a trim is also proportional to $\sqrt{\beta}$, we can substitute back to get trim bends as a function of oscillation amplitude.

$$\delta\theta_A = -\frac{Amplitude}{\sqrt{\beta_{BPM}\beta_A}} \frac{\sin(\psi_{BPM} - \psi_B - \phi)}{\sin(\psi_B - \psi_A)} \quad (15)$$

$$\delta\theta_B = \frac{Amplitude}{\sqrt{\beta_{BPM}\beta_B}} \frac{\sin(\psi_{BPM} - \psi_A - \phi)}{\sin(\psi_B - \psi_A)} \quad (16)$$

We note that these equations confirm several intuitive notions: 1) A trim located at a high β location does not need to be run as hard as one at low beta. 2) We achieve better precision (for a fixed position resolution) by using a BPM at high β. 3a) Trims that are orthogonal to each other in phase advance (modulo π) work best, because they minimize the bends needed from the trims. 3b) Trims that are near to each other in phase advance (modulo π) require more strength. 4) If the phase error matches the location of one trim, then the other trim is not needed.

Reducing oscillations with one trim

The technique of the previous section may also be applied to the problem of minimizing oscillations when only one trim is available. The the residual oscillation may be written as the sum of the initial oscillation plus the trim oscillation.

$$\vec{\text{Residual}} = \vec{O_A} + \vec{O_{error}} \quad (17)$$

We take the square of the amplitude of the residual, in the invariant units of the previous section; differentiate with respect to the trim amplitude A; set the derivative equal to zero to find the minimum residual; and solve for A.

$$R^2 = A^2 + C^2 + 2AC \cos(\psi_{BPM} - \psi_A - \phi) \quad (18)$$

$$\frac{\partial R^2}{\partial A} = 2A + 2C \cos(\psi_{BPM} - \psi_A - \phi) = 0 \quad (19)$$

$$A = -C \cos(\psi_{BPM} - \psi_A - \phi) \quad (20)$$

We then slip in our $\sqrt{\beta}$'s to return to units of trim bends and BPM positions.

$$\delta\theta_A = -\frac{Amplitude}{\sqrt{\beta_{BPM}\beta_A}} \cos(\psi_{BPM} - \psi_A - \phi) \quad (21)$$

Implementation

The data acquisition and data reduction has been described above. The PDP-11 "console" which the accelerator operator uses offers a color text screen with a keyboard and track-ball for most user interaction. A color graphics screen is in the adjacent rack. Our system consists of two programs communicating with each other using RSX-11M system utilities. One program is responsible for data acquisition, fitting the oscillations, and display of the data and fits. The other program handles operator interaction (including control of the former program), monitors the status of the trim elements, and calculates and sends new settings to the trim elements based on the measured oscillations.

The system has been in active use since the start of the 1988-1989 Collider run at Fermilab in June of 1988. The operators find that tuning to remove the injection oscillations now takes only a few minutes whereas in the 1987 Collider run the process often took an hour. At the same time the oscillations are also reduced to a level that was only dreamed of in 1987.

We have found that calculations of corrections based entirely on calculated lattice parameters and trim magnet strength measurements are not perfect. The relative phases and amplitudes, especially in the beam-line, can be improved significanty by measuring the oscillations as a function of trim setting. The source of the errors has not yet been isolated.

Conclusions

Treating oscillations as vectors to be summed or decomposed is a powerful and effective technique for correcting unwanted coherent injection oscillations. Unstable elements can be identitified by looking at the phase of pulse-to-pulse variations. This measurement technique could be exploited to measure lattice parameters along a beam line and around a ring. Simultaneous treatment of both planes in the analysis of coupled oscillations would allow measurement of the coupling strength and phase quickly. We should be able then identify trouble spots and analytically calculate settings for the skew quadrupole correction elements.

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