TURNAROUND FEED-FORWARD CORRECTION AT THE ILC*

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Abstract

The RTML turnaround feed-forward correction scheme, as proposed in the ILC BCD, is considered. Instabilities in the challenging Damping Ring extraction system may give rise to beam transverse bunch-by-bunch jitter, as well as drift across the bunch train. A system is outlined in which the bunch trajectory is measured with an upstream pair of BPMs and corrected with a pair of downstream fast kickers. The beam turnaround time 0.5µs allows signal processing and calculation of the correction. A feed-forward algorithm is formulated and expressions are derived for the main system parameters (BPM resolution, system zero offset stability, kicker voltage, kicker gain compression error) and procedures (matrix measurement, feed-forward gain adjustment). This analysis enables further consideration of the tolerances, and provides a basis for the engineering design.

INTRODUCTION

Trajectories of individual bunches extracted from the Damping Ring (DR) and transported to the end of the Ring-To-Main-Linac line (RTML) may deviate from an equilibrium trajectory due to instability of various DR and RTML subsystems, beam dynamics effects in the DR, etc. A bunch-by-bunch turnaround feed-forward trajectory correction done at the end of the RTML is intended to reduce this deviation so that its residue, having been transported to the Interaction Point (IP), would be acceptably low, within 1/10 of the beam size.

For the extracted beam as 5Hz-rate 1ms trains of 3(6) MHz-rate bunches the trajectory excursions can be characterized through three components: a fast bunch-by-bunch jitter, a drift across a train and a slow train-by-train drift. The latter can be corrected using orbit correction systems available in the DR and RTML. The turnaround feed-forward correction is intended for bunch-by-bunch jitter and drift across a train.

The extraction from the DR is done in the horizontal plane. In this plane, the fast jitter is likely to be due mainly to shot-to-shot instability in the extraction kicks. Slower variation of the kicks across a train causes an intra-train drift. Some spurious vertical component of the kick may produce a vertical jitter as well. Other factors, mainly in the DR, may also cause in either plane a trajectory jitter uncorrelated with the kick jitter. In the ILC BCD [1], it is stated that feed-forward correction is required in both planes.

It is supposed that in the horizontal plane the jitter produced by the kicker exceeds jitter of any other kind. In this case its effect could be reduced by having the betatron phase advance from the Extraction Point (EP) to the IP as a multiple of $\pi/2$. In the vertical plane it is most probably that the total jitter will have a similar component, as well as other significant components. Here it is assumed that for either plane a phase portrait of total variations of the trajectory will occupy some area but will not be simply a linear correlation. Below, the position variations and angle variations are considered as uncorrelated.

Assume arbitrarily, that in the horizontal plane a trajectory rms variation comprising the drift across a train, the slow drift and any additional jitter do not exceed 1σ of the fast jitter. So, the total trajectory rms variation can be taken as $\sigma_t = \sqrt{2}\sigma$.

The correction range is decided by the requirement on the probability of unsuccessful correction at the ILC. Assume that the number of events beyond the correction range 6 per 1000 bunches is acceptable. The correction range comes to $\pm 3\sigma_t = \pm 3\sqrt{2}\sigma$. Below, this range is taken as the basic range for correction in either plane.

Using data from [2], estimate the dynamic correction range. The extracted bunch receives a nominal kick $\theta_K = 0.6\text{mrad}$. For this kick the bunch comes to the septum with displacement about 30mm. Assume the kick jitter $\sigma_{\theta_K} = 0.5\% = 3\mu\text{rad}$ has been achieved. With it, in the septum, $3\sqrt{2}\sigma_{x_K}$ =0.63mm that is about 32 times the 1/10 beam size.

The vertical jitter is expected to be significantly lower than the horizontal jitter. However, the vertical beam size (~17µm in the septum) is also significantly lower than the horizontal beam size (~200µm). So, the dynamic ranges of the horizontal and vertical correction may happen to be required to be approximately the same. The difference between the two corrections is in kicker voltage and BPM resolution. The maximal kicker voltage is decided by the large horizontal jitter but the BPM resolution is decided by the small vertical beam size.

FEED-FORWARD CORRECTION

Take two BPMs, BPM1 and BPM2, in a drift space upstream of the turnaround. For the horizontal feed-forward correction case the position and angle are: x_{BPM1}, $\theta_{\text{BPM1}} = (x_{\text{BPM2}} - x_{\text{BPM1}})/L$ where L is the distance between the BPMs.

Take two kickers K1 and K2 distanced L_K in a drift space downstream of the turnaround. Assume the

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horizontal matrix $\boldsymbol{R}_\mathrm{h}$ that propagates the trajectory parameters from BPM1 to K1 is known. Write:

$$\begin{pmatrix} x_\mathrm{K1} \\ \theta_\mathrm{K1} \end{pmatrix} = \boldsymbol{R}_\mathrm{h} \cdot \begin{pmatrix} x_\mathrm{BPM1} \\ \theta_\mathrm{BPM1} \end{pmatrix} \tag{1}$$

The displacement and angle produced by kickers are:

$$\begin{pmatrix} X \\ \Theta \end{pmatrix} = \boldsymbol{K}_\mathrm{h2} \cdot \begin{pmatrix} 1 & L_\mathrm{K} \\ 0 & 1 \end{pmatrix} \cdot \boldsymbol{K}_\mathrm{h1} \cdot \begin{pmatrix} x_\mathrm{K1} \\ \theta_\mathrm{K1} \end{pmatrix} \tag{2}$$

where $\boldsymbol{K}_\mathrm{h}$ is the kicker matrix.

Write the feed-forward correction as

$$\boldsymbol{K}_\mathrm{h2} \cdot \begin{pmatrix} 1 & L_\mathrm{K} \\ 0 & 1 \end{pmatrix} \cdot \boldsymbol{K}_\mathrm{h1} \cdot \begin{pmatrix} x_\mathrm{K1} \\ \theta_\mathrm{K1} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \tag{3}$$

The kicks required for correction are calculated using the equations (3).

Errors in a real system result in correction errors that can be written as residues: $\delta x_\mathrm{K1} = (x_\mathrm{K1} - X) + dX(Y, \Phi)$ and $\delta\theta_\mathrm{K1} = (\theta_\mathrm{K1} - \Theta) + d\Theta(Y, \Phi)$ where the values x_K1, θ_K1, X, Θ are now taken as values in a real system. The terms $dX(Y,\Phi) << Y$ and $d\Theta(Y,\Phi) << \Theta$ are added to take into account a spurious horizontal kick coming from the independent vertical correction system.

Each residue propagates to the IP as

$$\begin{pmatrix} \delta x_\mathrm{IP} \\ \delta\theta_\mathrm{IP} \end{pmatrix} = \boldsymbol{P}_\mathrm{h} \cdot \begin{pmatrix} \delta x_\mathrm{K1} \\ \delta\theta_\mathrm{K1} \end{pmatrix} \tag{4}$$

with a matrix $\boldsymbol{P}_\mathrm{h}$. Assume each residue has two independent components: a fast jitter and a slow drift. Denoting them with tilde and Δ respectively, for each plane one can write a condition establishing the acceptable error of the feed-forward correction:

$$\begin{cases} \sqrt{<\tilde{x}_\mathrm{IP}^2> + <\Delta x_\mathrm{IP}^2> + <s_{x\mathrm{IP}}^2>} \le \frac{1}{10} \cdot \sigma_{x\mathrm{IP}} \\ \sqrt{<\tilde{y}_\mathrm{IP}^2> + <\Delta y_\mathrm{IP}^2> + <s_{y\mathrm{IP}}^2>} \le \frac{1}{10} \cdot \sigma_{y\mathrm{IP}} \end{cases} \tag{5}$$

where the variances are in brackets, $<s_x^2>$, $<s_y^2>$ are the system noise variances, and $\sigma_{x\mathrm{IP}}$ and $\sigma_{y\mathrm{IP}}$ are the beam sizes at the IP.

CORRECTION SYSTEM PARAMETERS

In this Section, the following relations are used. For the horizontal beam size at K1:

$$\sigma_{x\mathrm{IP}}^2 = \sigma_{x\mathrm{K1}}^2 \cdot \frac{\beta_\mathrm{hIP}}{\beta_\mathrm{hK1}} \cdot \frac{\gamma_\mathrm{K1}}{\gamma_\mathrm{IP}} \equiv \sigma_{x\mathrm{K1}}^2 \cdot \Gamma_x^2 \tag{6}$$

where β is the betatron function value and γ is the Lorentz factor. For some angle variance $<d\theta^2>$

$$<d\theta_\mathrm{IP}^2> = <d\theta_\mathrm{K1}^2> \cdot \frac{\gamma_\mathrm{hIP}}{\gamma_\mathrm{hK1}} \cdot \frac{\gamma_\mathrm{K1}}{\gamma_\mathrm{IP}} \equiv \sigma_{x\mathrm{K1}}^2 \cdot \Gamma_\theta^2 \tag{7}$$

where γ_h is the Twiss parameter. Analogous relations are there for the vertical plane (below, y and φ and index v).

Compact notation as given is used for:

$$R_{11}^2 + \frac{2}{L^2} R_{22}^2 = R_1^2,\ R_{21}^2 + \frac{2}{L^2} R_{22}^2 = R_2^2 \tag{8}$$

$$\sqrt{P_{11}^2 \cdot R_1^2 + P_{12}^2 \cdot R_2^2} = r \tag{9}$$

$$\sqrt{P_{11}^2 \cdot \left| P_{22}^2 - \Gamma_{\theta \text{ or } \varphi}^2 \right| + P_{12}^2 \cdot P_{21}^2} = \rho \tag{10}$$

BPM Resolution

Take the weights of the three components in (5) to be equal. For either plane the BPM rms noise is to be

$$\sqrt{<s_\mathrm{BPM}^2>} \le \frac{1}{10\sqrt{3}} \cdot \sigma_\mathrm{IP} \cdot \frac{1}{r} = \frac{1}{10\sqrt{3}} \cdot \sigma_\mathrm{K1} \cdot \frac{\Gamma_{x \text{ or } y}}{r} \tag{11}$$

Estimation shows that for the vertical plane the right side of (11) is about 1μm. For the horizontal plane it relaxes to ~10μm.

Correction System Zero Offset Stability

Total zero offset of the correction system comprises the zero offsets of the BPMs and kickers and may have additional component coming from errors in the matrix $\boldsymbol{R}$. Being indistinguishable from a beam zero offset, the system zero offset can be corrected to zero, using routine orbit correction means. However, to be successfully eliminated, the system zero offset should be long-term stable. An obvious estimate is that long-term zero offset rms variation should not exceed the BPM rms noise.

To specify an estimate, take again equal weights in (5) and assume that the slow drift component $<\Delta x_\mathrm{IP}^2>$ consists of two approximately equal parts: a drift across the train and some zero offset. Then, for the horizontal plane the latter can be written as

$$\sqrt{<d_{x\mathrm{IP}}^2>} \le \frac{1}{10\sqrt{3 \cdot 2}} \cdot \sigma_{x\mathrm{IP}} \tag{12}$$

An equation system can be obtained for the rms zero offsets $\sqrt{<d_{x\mathrm{K1}}^2>}$ and $\sqrt{<d_{\theta\mathrm{K1}}^2>}$. It yields:

$$\begin{cases} \sqrt{<d_{x\mathrm{K1}}^2>} \le \frac{1}{10\sqrt{3 \cdot 2}} \cdot \sigma_{x\mathrm{K1}} \cdot \frac{\Gamma_x \cdot \sqrt{\left| P_\mathrm{h22}^2 - \Gamma_\theta^2 \right|}}{\rho_\mathrm{h}} \\ \sqrt{<d_{\theta\mathrm{K1}}^2>} \le \frac{1}{10\sqrt{3 \cdot 2}} \cdot \sigma_{x\mathrm{K1}} \cdot \frac{\Gamma_x \cdot P_\mathrm{h21}}{\rho_\mathrm{h}} \end{cases} \tag{13}$$

Kicker Maximal Voltage

To estimate the voltage, take the kickers as being identical to the extraction 50Ω-strip-line kicker prototype described in [2]: the length is 30cm, the gap is 30mm, and the voltage is 150kV for a kick of 0.6mrad. Assuming the kickers are infinitely short, one can write for the voltages:

$$V_\mathrm{K1} = +\frac{x_\mathrm{K1}}{\alpha_1 \cdot L_\mathrm{K}} + \frac{\theta_\mathrm{K1}}{\alpha_1} \text{ and } V_\mathrm{K2} = -\frac{x_\mathrm{K1}}{\alpha_2 \cdot L_\mathrm{K}} \tag{14}$$

where α is the kicker strength. Assuming that K1 is distanced from the EP by a multiple of π/2 which yields

$x_{K1}/\alpha_1 \cdot L_K << \theta_{K1}/\alpha_1$ and reduces the required voltage, the voltage for the $3\sqrt{2}\sigma_{\theta_K}$ kick 13µrad comes to

$$V_{K1max} \approx 3.2\text{kV} \quad (15)$$

Kicker Amplifier Gain Compression Error

The kicker amplifier output voltage can be written as

$$V_{out} = V_{out\ max} \cdot \left[\frac{|g| \cdot V_{in}}{V_{out\ max}} - a_3 \cdot \left(\frac{|g| \cdot V_{in}}{V_{out\ max}} \right)^3 - ... \right] \quad (16)$$

where voltage absolute values are used, and g is the amplifier gain. Typical amplifier gain compression is represented in (16) through the negative cubic term of the polynomial series. For a correction with dynamic range D the error due to the gain compression should be lower than $1/D$. For $D_h = 32$ obtained above,

$$a_3 \le 3 \cdot 10^{-2} \quad (17)$$

MATRIX MEASUREMENT

The matrix $\boldsymbol{R}$ and the kicker matrices $\boldsymbol{K}_{1,2}$ can be individually measured with the beam, using two pairs of BPMs.

To obtain a pair of row matrix components, two different trajectories are necessary. To exclude errors from BPM zero offsets, one can use one more reference trajectory. The BPM scale errors should be taken into account. Express them as $x_{BPM} = (1+\delta_x) \cdot x$ and $\theta_{BPM} = (1+\delta_\theta) \cdot \theta$, where $|\delta_x| << 1$, $|\delta_\theta| << 1$, $\delta_\theta = (\delta_{xBPM2} \cdot x_{BPM2} - \delta_{xBPM1} \cdot x_{BPM1})/L \cdot \theta$. One of the solutions of the $\boldsymbol{R}$ equation system for differences reads:

$$R_{h12} = \frac{1+\delta_{xK1}}{1+\delta_{\theta BPM1}} \left[\frac{(x_{BPM1a} - x_{BPM1}) \cdot (x_{K1b} - x_{K1}) - (x_{BPM1b} - x_{BPM1}) \cdot (x_{K1a} - x_{K1})}{(x_{BPM1a} - x_{BPM1}) \cdot (\theta_{BPM1b} - \theta_{BPM1}) - (x_{BPM1b} - x_{BPM1}) \cdot (\theta_{BPM1a} - \theta_{BPM1})} \right] \quad (18)$$

where the two trajectories are denoted by a and b. As triplets of trajectories, trajectories of three bunches can be used that are different just due to jitter. The matrix elements are averaged over triplets in the train. Another variant is to use three train center-of mass trajectories two of which are intentionally perturbed.

The accuracy of the matrix measurement can be evaluated using the fundamental property $\det = 1$.

FEED-FORWARD GAIN ADJUSTMENT

Assume for simplicity that the matrix $\boldsymbol{R}$ is errorless. The correction residue is:

$$\begin{pmatrix} x_d \\ \theta_d \end{pmatrix} = \left[\begin{pmatrix} 1 & L_K \\ 0 & 1 \end{pmatrix} - \boldsymbol{G} \right] \cdot \boldsymbol{R} \cdot \begin{pmatrix} x_{BPM1} \\ \theta_{BPM1} \end{pmatrix} \equiv \boldsymbol{Z} \cdot \begin{pmatrix} x_{BPM1} \\ \theta_{BPM1} \end{pmatrix} \quad (19)$$

where $\boldsymbol{G}$ in the feed-forward gain matrix.

For condition $x_{K1}/\alpha_1 \cdot L_K << \theta_{K1}/\alpha_1$ used above, the gain acceptable error can be roughly estimated from $|\theta_{K1} - G_{h22} \cdot \theta_{K1}| \le |\theta_{K1}|/D_h$ as $|1 - G_{h22}| \le 1/D_h \approx \approx 3 \cdot 10^{-2}$.

In either plane, the gain can be adjusted and monitored using just the beam jitter being corrected. The correction residue is measured by the BPM pair downstream of the kickers. To exclude the BPM zero offset, one can use in (19) the differences $Tx_n = x_n - x_{n+1}$, $T\theta_n = \theta_n - \theta_{n+1}$ where n and n+1 are the bunch numbers. One can calculate products (index BPM is omitted in (20)):

$$\begin{cases} Tx_{1n} \cdot Tx_{dn} = Z_{11} \cdot (Tx_{1n})^2 + Z_{12} \cdot Tx_{1n} \cdot T\theta_{1n} \\ T\theta_{1n} \cdot Tx_{dn} = Z_{11} \cdot Tx_{1n} \cdot T\theta_{1n} + Z_{12} \cdot (T\theta_{1n})^2 \end{cases} \quad (20)$$

and a similar pair $Tx_{1n} \cdot T\theta_{dn}$ and $T\theta_{1n} \cdot T\theta_{dn}$ for Z_{21} and Z_{22}. If for N increasing, each from four correlation series

$$\left(\sum_{n=1}^{N} T_{1n} \cdot T_{dn} \right) \Big/ \left(\sum_{n=1}^{N} T_{1n}{}^2 \right) \quad (21)$$

converges to zero or at least to $|\varepsilon| \le 1/D_h$, the gains are correct. Otherwise change G_{ij} by small increments/ decrements until convergence occurs.

OUTLOOK

The ILC Turnaround Feed-Forward correction has been briefly considered and its basic features and parameters have been discussed. Some details can be found in [3].

The correction system looks feasible but raises the engineering challenges. In particular, it is necessary to develop a fast bipolar linear amplifier in the kilovolt range, that delivers tens of kW of power in 1ms. Another challenge is to achieve sub-micron resolution and zero offset drift in a low latency single bunch BPM.

In advance of the ILC, tests of the solutions, elements, algorithms and procedures of the system could be done at the KEK ATF. Here a path on the last turn in the Damping Ring and further in the Extraction Line can be used to model the ILC turnaround. [4]

ACKNOWLEGEMENT

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