A MODEL TO SIMULATE THE EFFECT OF A TRANSVERSE FEEDBACK SYSTEM ON SINGLE BUNCH INSTABILITY THRESHOLDS*

G. Bassi†, A. Blednykh, V. Smaluk, BNL, Upton, NY 11973-5000, USA
Z. Yang, Department of Physics, Auburn University, Auburn, AL 36849, USA

INTRODUCTION

We discuss a simple algorithm to model the effect of the transverse feedback system (TFS) on beam stability based on a standard implementation of the TFS diagnostics, in which electrostatic or strip-line pickups are used as beam position monitors (BPMs) to detect the position of the beam centroid, and strip-line kickers are used to kick the momentum of the beam in order to suppress any unstable bunch centroid motion (dipole instability). This is accomplished by imposing a specific phase advance relation between the pickup and the kicker. The algorithm is implemented in the particle tracking code SPACE [1] and applied to model the NSLS-II TBS [2]. To mimic the experimental conditions, the kick induced on the bunch centroid at the kicker location requires the knowledge of the amplitude of the dipole motion at the pickup location. This is accomplished by calculating the average momentum of the bunch from the bunch centroid position at previous turns. The additional knowledge of the beta functions at the pick-up and kicker location, together with the desired damping time, completely define the kick strength.

SCHEMATICS OF THE TRANSVERSE FEEDBACK SYSTEM

The goal of a resistive TFS is to suppress betatron oscillations at a given damping rate. A schematic view of a feedback system is given in Fig. 1. A BPM detects the average position of the beam acting a as the detector, followed by a feedback processing to calculate the proper power, suitably amplified, to be delivered to the beam at the kicker location, where electromagnetic fields are induced on the beam with a net transfer of momentum [3]. The NSLS-II TFS is designed to provide a damping time as fast as 200μs to suppress transverse instabilities at the nominal current of 500mA [2].

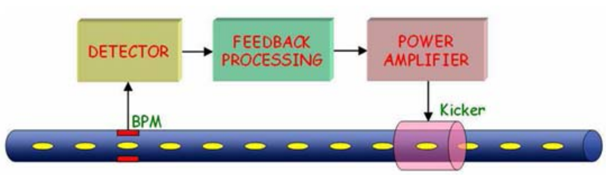


Figure 1: Schematic view of a feedback system [3]

* Work supported by DOE contract DE-SC0012704
† gbassi@bnl.gov

A MODEL OF THE TRANSVERSE FEEDBACK SYSTEM

We now discuss the derivation of a simplified model of the TFS. The model is implemented in the SPACE code for our numerical analysis. Without loss of generality, we limit the discussion to the horizontal plane. We use position x and momentum $p = x'/\omega_\beta$ as phase space variables, where $\omega_\beta = c/\beta_x$ and β_x is the beta function.
Let us assume that the bunch centroids $\langle x_t\rangle = \int dxdpxf(x,p,t)$ and $\langle p_t\rangle = \int dxdppf(x,p,t)$, where f is the transverse phase space density, perform betatron oscillations with constant β_x, then

$$\langle x_t\rangle = \langle x_{t_0}\rangle \cos\omega_\beta(t-t_0) + \langle p_{t_0}\rangle \sin\omega_\beta(t-t_0),$$
$$\langle p_t\rangle = \langle p_{t_0}\rangle \cos\omega_\beta(t-t_0) - \langle x_{t_0}\rangle \sin\omega_\beta(t-t_0). \quad (1)$$

Using turn number n instead of t as independent variable, Eq.(1) can be written as a transfer map from turn n to m

$$\langle x_m\rangle = \langle x_n\rangle \cos 2\pi\nu_x\Delta + \langle p_n\rangle \sin 2\pi\nu_x\Delta,$$
$$\langle p_m\rangle = \langle p_n\rangle \cos 2\pi\nu_x\Delta - \langle x_n\rangle \sin 2\pi\nu_x\Delta, \quad (2)$$

where $\Delta = m - n$ and $\nu_x = \omega_\beta/\omega_0$ is the betatron tune, were ω_0 is the revolution angular frequency. Assume now the bunch performs harmonic oscillations around the phase space origin $(0,0)$, and let A be the amplitude of the oscillations defined as $A^2 = \langle x\rangle^2 + \langle p\rangle^2$. Then A is a constant of motion, $A_t = A_{t_0}$. Consider now the beam at turn n at a kicker location is given a kick in the momentum p according to

$$\langle x_n\rangle^- = \langle x_n\rangle^+, \langle p_n\rangle^- = \langle p_n\rangle^+ + k, \quad (3)$$

where $\langle\cdot\rangle^-$ and $\langle\cdot\rangle^+$ label quantities before after the kick respectively. Let A_K be the amplitude after the kick and A_P be the amplitude before the kick. Here the subscripts K and P refer to quantities evaluated at the kicker and pickup location respectively. It follows, for small kicks ($|\, k \,| << 1$), that $A_K = A_P + 2\langle p_n\rangle^- k + k^2 \approx A_P + 2\langle p_n\rangle^- k$. Thus defining $\Delta A = A_K - A_P$ and assuming $A \approx A_P \approx A_K$, it follows that $\Delta A/A = 2\langle p_n\rangle^- k/A^2$. If we label $\langle p_n\rangle^-$ as $\langle p_n\rangle_K$ (momentum at kicker location) and $\langle x_n\rangle_P, \langle p_n\rangle_P$ as position and momentum of at a pickup location preceding the kicker by the distance S, we have the transformation $\langle p_n\rangle_K = \langle x_n\rangle_P \cos\Delta\varphi + \langle p_n\rangle_P \sin\Delta\varphi$, where $\Delta\varphi = 2\pi\nu_x S/C$, with C the ring circumference. Let us assume now that the kick k is determined by the linear combination

$$k = b_0\langle x_n\rangle_P + b_1\langle x_{n-1}\rangle_P\,, \quad (4)$$

with constant coefficients b_0, b_1. From Eq.(2) it follows that $\langle x_{n-1}\rangle_p = \langle x_n\rangle_p \cos(2\pi\nu_x) - \langle p_n\rangle \sin(2\pi\nu_x)$, thus, by expressing $\langle x_n \rangle_p$ and $\langle p_n \rangle_p$ in polar coordinates, $\langle x_n \rangle_p = A\cos\theta$, $\langle p_n \rangle_p = A\sin\theta$, and averaging over θ, it follows

$$\left\langle \frac{\Delta A}{A} \right\rangle_\theta \equiv \frac{1}{2\pi}\int_0^{2\pi} d\theta \frac{\Delta A}{A}$$
$$= \frac{1}{2\pi}\int_0^{2\pi} d\theta(\cos\Delta\varphi\cos\theta - \sin\Delta\varphi\sin\theta)$$
$$\times\,(b_0\cos\theta + b_1(\cos\theta\cos 2\pi\nu_x - \sin\theta\sin 2\pi\nu_x))$$
$$= \frac{1}{2}(b_0\cos\Delta\varphi + b_1\cos(\Delta\varphi - 2\pi\nu_x)).$$

In order to achieve exponential damping, we impose $\langle \Delta A/A \rangle_\theta = 1/\tau$, where τ is the damping time. From the additional condition of zero kick for $\langle x_n \rangle_P = \langle x_{n-1} \rangle_P$, i.e. $b_0 + b_1 = 0$, it follows that b_0 and b_1 read

$$b_0 = -\frac{2}{\tau(\cos\Delta\varphi - \cos(\Delta\varphi - 2\pi\nu_x))},\quad b_1 = -b_0. \qquad (5)$$

NUMERICAL SIMULATIONS

Numerical simulations with the SPACE code have been done with the TFS model described by Eq.(5). To simplify the analysis, we assume $\Delta\varphi = 2\pi\nu_x$, thus we apply the kick k at turn n according to the bunch centroid position at turn $n-1$ and $n-2$. We discuss the effect of the TFS in single-bunch mode of operation. A broadband resonator model is used to simulate the effect of the short-range wakefields, with parameters chosen to reproduce the experimental results at zero chromaticity obtained during the commissioning of the NSLS-II storage ring with the base lattice [4]. The resonator parameters are $R_s = 18k\Omega$, $f_r = 25$GHz, $Q = 1$ in the longitudinal case and $R_s = 0.9$MΩ/m, $f_r = 30$GHz, $Q = 1$. The RF voltage is 2.6MV. The simulations are done up to 30000 turns, corresponding to few radiation damping times ($\tau_s = 27$ms). Fig.2 and Fig.3 show the last 10 000 turns of the bunch length and energy spread evolution for several bunch currents . Fig.4 and Fig.5 show the bunch lengthening and energy spread increase as a function of single bunch current. The maximum, minimum, and average of the bunch length and energy spread are calculated over the last 5000 turns. The microwave instability threshold is ≈0.3 mA. For a discussion of the dynamics above threshold see [5].

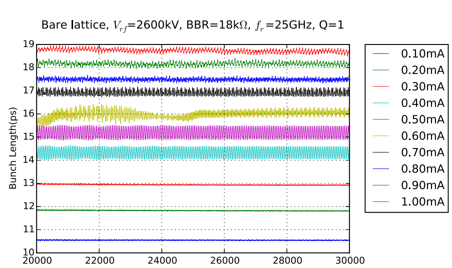


Figure 2: Bunch length vs. number of turns.

Measurements of the vertical tune shift vs. single bunch current from spectra of turn-by-turn data [4], taken with TFS off, are shown in Fig.6. An accumulation threshold is seen at

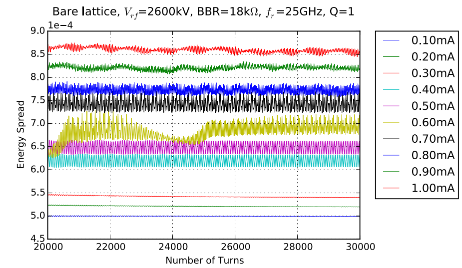


Figure 3: Energy spread vs. number of turns.

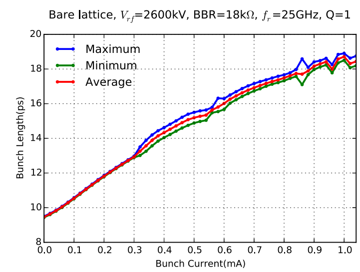


Figure 4: Maximum, minimum and average of the bunch length vs. bunch current.

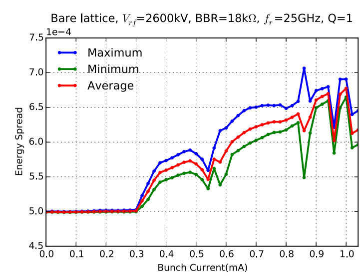


Figure 5: Maximum, minimum and average of the energy spread vs. bunch current.

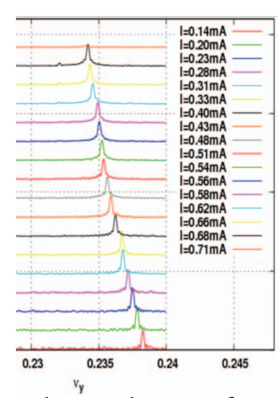
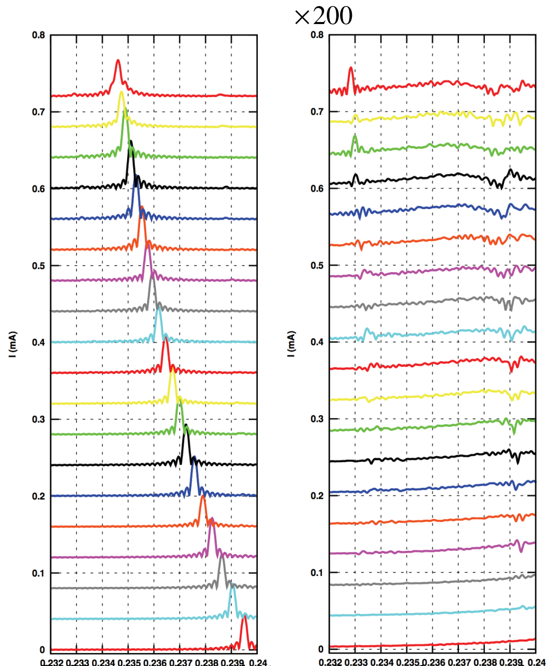


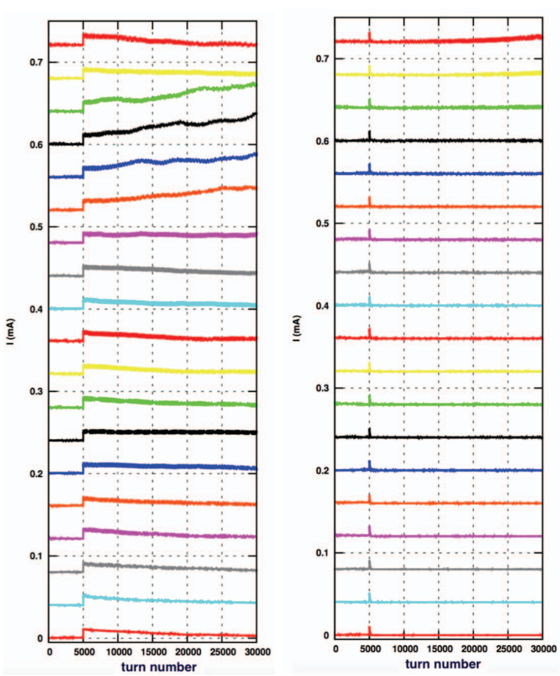
Figure 6: Measured vertical spectra from turn-by-turn data [4].

the single bunch current of 0.71 mA, where the mode 0 and −1 are still well separated, thus far from the TMCI threshold. The comparison with numerical simulations shown in Fig.7a indicates good agreement. Fig.7b shows spectra of the beam transverse motion with the inclusion of the TFS model in the simulations, where the beam is kicked transversely at the 5000 th turn and the TFS turned on with a damping time $\tau = 200\mu$s. The vertical data have been



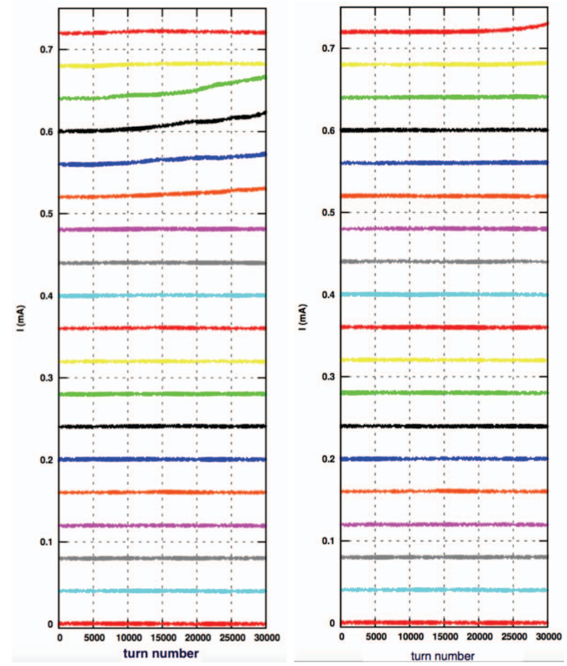
a) b)

Figure 7: Numerical simulations of vertical spectra for several bunch currents without TFS, a), and with TFS, b).



a) b)

Figure 8: Numerical simulations of vertical bunch centroid vs. number of turns for several bunch currents without TFS, a), and with TFS, b).



a) b)

Figure 9: Numerical simulations of vertical bunch size vs. number of turns for several bunch currents without TFS, a), and with TFS, b).

multiplied by 200 times for comparison. Fig.8a and Fig.8b show the vertical bunch centroid vs. number of turns with and without the TFS respectively. It can be seen that the induced betatron oscillations are efficiently suppressed by the TFS, with the exception of the current above 0.7 mA, shown by the red trace. Fig.9a and Fig.9b show the vertical bunch size vs. number of turns with and without the TFS respectively. We observe an increase in the bunch size above 0.5 mA, indicating the presence of a possible quadrupole instability. This might explain the accumulation threshold observed in the measurements. We notice that with TFS the simulations show that the TFS is able, in the bunch current range 0.5 mA-0.7 mA, to suppress not only the bunch centroid motion, but the increase in bunch size as well. A possible explanation can be given in terms of mode coupling. Further studies are required.

REFERENCES

[1] G. Bassi *et al.*,"Self-consistent simulations and analysis of coupled-bunch instabilities for arbitrary multibunch configurations", *Phys. Rev. Accel. Beams*, vol. 19, 024401, 2016.

[2] W. Cheng *et al.*, "Commissioning of bunch-by-bunch feedback system for NSLS-II storage ring", presented at *IIBIC2014*, Monterey, CA, USA, 2014, p. 707-211, paper WEPD27.

[3] M. Lonza and H. Schmickler, "Multi-bunch Feedback Systems", CAS - CERN, 2013.

[4] A. Blednykh *et al.*, "NSLS-II commissioning with 500MHz 7-cell Petra-III cavity", presented at *IPAC'14*, Dresden, Germany, Jun. 2014, p. 1724-1726, paper TUPRIO69.

[5] A. Blednykh *et al.*, "Microwave Instability Studies in NSLS-II", presented at *NAPAC'16*, Chicago, USA, Oct. 2016, paper WEA1CO05, this conference.