SIMULATION OF LONGITUDINAL COUPLED-BUNCH INSTABILITIES IN BESSY-II

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Abstract

The longitudinal bunch dynamics in the BESSY-II storage ring was studied in view of the planned installation of a bunch-by-bunch feedback system.

A simulation of coupled-bunch instabilities was performed to study the effectivity of the feedback system in the presence of beam-loading effects and under the influence of noise and phase detection errors as well as transient effects during injection.

1 INTRODUCTION

BESSY-II is a high-brilliance synchrotron radiation source in Berlin-Adlershof. Commissioning of the storage ring has started in April 1998 [1]. Later in 1998, a digital longitudinal feedback system will be installed to counteract multibunch oscillations resulting from the interaction of the beam with higher-order modes (HOMs) of the four DORIS-type pillbox cavities.

Time domain simulations were performed to study multibunch instabilities and the effectivity of the feedback system under circumstances that are not easily accessible by analytical methods. Even the simple case of a beam with bunches of equal charge requires a numerical treatment once the bunch sequence is interrupted by an ion clearing gap. Other issues include unequal bunch charges, noise on the rf voltage, phase detection errors or saturation of the feedback amplifier. Not only the steady-state behavior is of interest but also transient effects e.g. when bunches are injected with a phase or energy offset. Previous studies in a similar context can be found in e.g. [2] [3] [4].

2 THE SIMULATION

2.1 Beam Loading

The voltage induced by a Gaussian electron bunch of charge q_i and rms duration σ interacting with a cavity mode m of angular frequency ω_m, shunt impedance R_m and quality factor Q_m is given by

$$v_{i,m} = 2k_m q_i \exp\left[-\omega_m^2\sigma^2\right] \quad \text{with} \quad k_m = \frac{\omega_m R_m}{2Q_m}, \quad (1)$$

where k_m is the loss factor. According to the fundamental theorem of beam loading, half of this voltage acts back on the bunch during its passage. With Δt being the time elapsed since the passage of the preceding bunch and $\tau_m = 2Q_m/\omega_m$ being the cavity filling time, the iterative procedure

$$\begin{aligned} V_{i,m} &= -\frac{1}{2}v_{i,m} + U_{i-1,m}\exp\left[\left(i\omega_m - \frac{1}{\tau_m}\right)\Delta t\right] \\ U_{i,m} &= -\frac{1}{2}v_{i,m} + V_{i,m} \end{aligned} \quad (2)$$

yields the (complex) voltages $V_{i,m}$ acting on a bunch. The voltages $U_{i,m}$ left behind in the cavity can be initialized to zero or to estimated values and will approach steady state values after some iterations. Equation 2 is an approximation for weakly damped modes with high Q-values (cf. [2]).

The induced voltage for the fundamental ($m = 0$) mode is usually compensated by applying a tuning angle [5]

$$\tan\Psi = \frac{2IR_0}{1+\beta}\frac{\sin\phi}{V_s}\cos\phi, \quad (3)$$

where I is the d.c. beam current, β is the coupling coefficient, V_s is the voltage required to account for radiation losses, and ϕ is the synchronous phase angle. The required generator voltage is given by

$$V_g = \left(\frac{V_s}{\cos\phi} + \frac{2IR_0}{1+\beta}\cos\phi\right)\cos\Psi. \quad (4)$$

V_g and Ψ are controlled by slow feedback loops.

For $m > 0$, there is no such compensation and, depending on the HOM frequency, the induced voltage may excite multibunch oscillations.

2.2 Longitudinal Bunch Dynamics

The motion of bunch i in longitudinal phase space (E_i, ϕ_i) is iterated in time steps $t_\circ$:

$$\begin{aligned} E_i(t) &= E_i(t-t_\circ) + q_iV_g\sin\phi_i + q_i\,\mathrm{Re}\sum_m V_{i,m} \\ & \quad -q_iV_s - 2q_iV_s\frac{E_i(t-t_\circ)-E}{E} + q_iV_{fb} \\ \phi_i(t) &= \phi_i(t-t_\circ) + 2\pi\alpha h\frac{E_i(t)-E}{E}, \end{aligned} \quad (5)$$

where E is the nominal beam energy, V_g is the generator voltage, V_{fb} is the voltage kick from the feedback system, α is the momentum compaction factor and h is the harmonic number.

Since a synchrotron oscillation period in BESSY-II equals ~150 turns, $t_\circ$ is conveniently set to the revolution time.

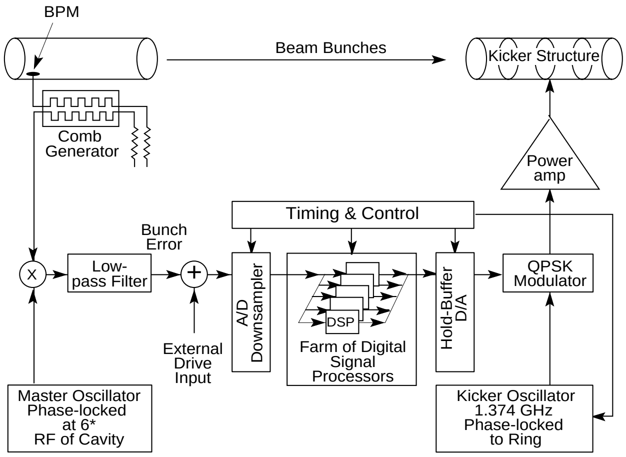

Figure 1: Feedback system (courtesy SLAC LFB group).

2.3 Feedback Model

The longitudinal feedback electronics developed for the ALS (Berkeley), PEP-II (Stanford) and DAΦNE (Frascati) [6] will be used in combination with a kicker cavity developed for DAΦNE [7] and modified for a bunch frequency of 500 MHz [8].

Figure 1 shows a block diagram of the feedback system. The model includes phase detection errors, the 8-bit digitization and downsampling of the moment signal (phase·charge), the FIR (finite impulse response) filter implemented in an array of digital signal processors, the QPSK (quad phase shift keyed) modulation of the 1374 MHz carrier signal and the properties of the kicker cavity.

The correction signal given by the n-tap FIR filter reads

$$y_i = \sum_{j=0}^{n-1} c_j \, x_{i-j} \, , \tag{6}$$

where x_{i-j} are digitized samples of the moment signal and the filter coefficients are set to [9]

$$c_j = c'_j - \frac{1}{n} \sum_{l=0}^{n-1} c'_l \quad \text{with} \quad c'_j = \sin\left[2\pi \, k \, \nu_s (j+\delta)\right] . \tag{7}$$

Here, k is the downsampling factor, ν_s is the synchrotron tune, and δ accounts for the finite sampling time and other delays in the process.

The relevant storage ring and feedback parameters are given in table 1. The frequency response of the 5-tap filter is shown in figure 2. Optimum damping requires a maximum response and a 90° phase shift at the synchrotron frequency, while a zero d.c. response is required to suppress constant phase offsets.

3 RESULTS

For the present purpose, a single HOM with $Q = 40000$ near 800 MHz, coinciding with the upper synchrotron sideband, was assumed.

Table 1: Beam and feedback parameters.

Beam energy E	1700 MeV
Beam current I	0.4 A
Rf frequency f_{rf}	499.6 MHz
Harmonic number h	400
Momentum compaction factor α	$7 \cdot 10^{-4}$
Bunch length σ	5 mm
Radiation loss V_s	290 kV
Synchronous phase angle ϕ	$80°$
Synchrotron tune ν_s	0.0067
Downsampling factor k	30
Number of coefficients n	5
Kicker central frequency $f_\circ$	1374 MHz
Kicker shunt impedance R_s max.	1000 Ω
Kicker qualtity factor Q	5.6
Nominal/effective power P	250/125 W

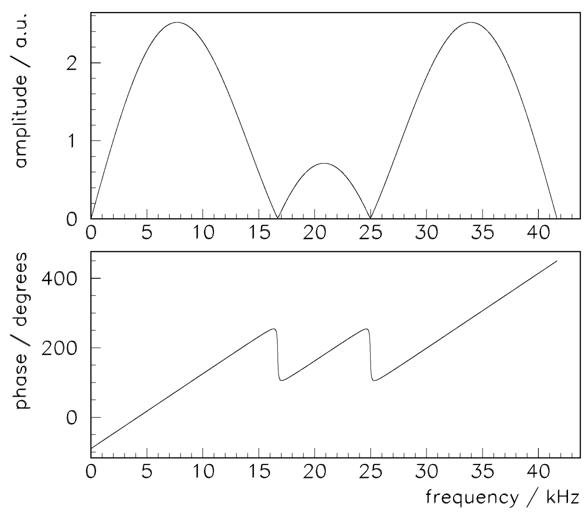

Figure 2: Frequency response of the 5-tap FIR filter.

3.1 Effect of the Bunch Structure

The BESSY-II filling pattern consists of 320 bunches and an ion clearing gap of 80 buckets. Assuming 320 bunches of equal charge (1 nC, corresponding to $I = 0.4$ A), the simulation was initiated with fundamental mode detuning according to equations 3 and 4, which is valid for a complete filling. Due to the presence of a gap, the generator voltage and the tuning angle settle at new values, and each bunch has a different synchronous phase. As shown in figure 3, the range of phase variation is 38 mrad. The corresponding variation in synchrotron frequency is of the order of 1 Hz and its decoherence effect is insignificant. The same is true for unequal bunch charges.

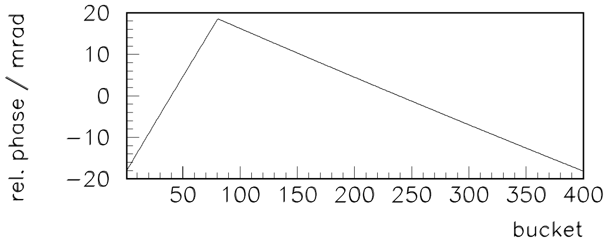

Figure 3: Relative synchronous phase with 20% bunch gap.

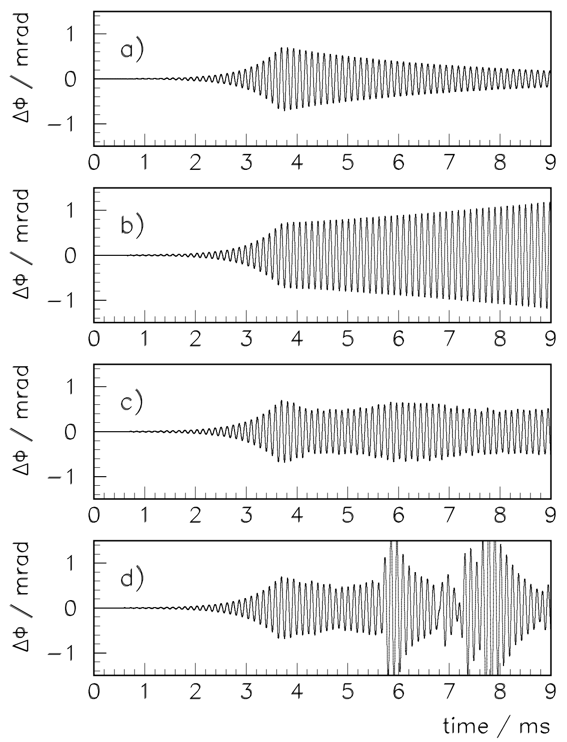

Figure 4: Phase oscillation driven by a cavity HOM and damped by the feedback system after $t = 3.6$ ms (see text).

3.2 QPSK, Digitization Error and Noise

The kicker is operated using a 1374 MHz carrier, which is shifted by 90° after every bunch (QPSK modulation). Due to this phase shift, the slowly decaying voltage applied to a bunch does not perturb the next, but only the second next bunch. Given a cavity filling time of 1.3 ns, only 5% of the voltage is left after 2 rf periods.

Figure 4 shows the phase oscillation of a bunch growing at a rate of 1700 s^{-1}, until the feedback loop is closed at time $t = 3.6$ ms. Using the QPSK scheme (4a) the oscillation is damped, while – in this particular example – the feedback is not sufficient if pure amplitude modulation is applied (4b).

In order to study the effect of phase detection errors, the feedback system was set to a relatively high gain of 150 kV/rad (i.e. the full kicker voltage of 500 V was applied at a phase offset of 3.3 mrad). In figure (c), the digitization errors of the A/D and D/A conversion were introduced. With a full detection range of 120 mrad to allow for phase variations within the bunch train, one bit corresponds to 0.47 mrad. The oscillation appears to be confined within a 1 mrad band.

In figure (d), a random noise source of 1 mrad rms width was switched on, which causes occasional bursts but does not lead to an unstable beam.

3.3 Injection Transients

In the multiturn injection scheme of the storage ring [10], a train of 160 bunches with a few mA of current are added to the already stored beam at a rate of 10 Hz. The centroid energy or phase offset of the injected and the already stored electrons in the respective buckets is usually small and easily damped. The simulation shows that the influence on the other buckets due to the wakefields of the injected bunches is insignificant.

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