# BUNCH-BY-BUNCH CONTROL OF INSTABILITIES WITH THE ELETTRA/SLS DIGITAL FEEDBACK SYSTEMS

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*Abstract*

The electromagnetic fields associated with the very high intensity electron beams accumulated in state-of-the-art synchrotron light sources can generate Coupled Bunch Instabilities (CBI) through the interaction with the surrounding vacuum chamber and cavity-like structures. CBIs degrade the quality of the beam leading to increased beam emittance, energy spread or even to limitations of the operating current and beam loss. In order to damp any potentially excited transverse and longitudinal mode of oscillation of the accumulated beam, wide-band bunch-by-bunch feedback systems have been developed and installed on the ELETTRA/SLS storage rings. The systems rely on the same type of DSP-based processing electronics, which execute the feedback algorithm and bunch-by-bunch data acquisition. An integrated environment using Matlab has been developed as a unified platform for accessing the feedback equipment from the control room workstations and performing an effective analysis and visualization of the considerable amount of data that can be acquired. A description of the system architecture, of the available diagnostic tools and of the operating experience gained is given.

## INTRODUCTION

Several recent applications of circular accelerators, like particle factories and synchrotron radiation sources, rely on intense bunched beams. They both require the storage of hundreds of bunches at high currents to reach the requested luminosity and brightness respectively. The high circulating current interacting with the vacuum chamber geometry generates intense wakefields that drive beam instabilities, notably Coupled Bunch Instabilities (CBI's). These instabilities spoil the effective beam emittance, induce energy spread of the stored beam and, under unfavourable conditions, they can even limit the maximum achievable current or produce rapid beam losses.

In a basic CBI model, bunches are treated as rigid "macroparticles" oscillating about their nominal centres like coupled mechanical pendulums [1, 2]. For a beam of M bunches, there is a total of M possible modes of motion, each defined by a bunch-to-bunch phase difference $2\pi\mu/M$, where the 'mode number' $\mu$ can assume the values 0, 1…M-1. If observed from a single point in the ring, each mode is associated with a set of frequencies given by

$$\omega_p = \left(pM \pm (\mu + \nu)\right)\omega_0 \tag{1}$$

where p is an integer, $\nu$ the betatron (horizontal $\upsilon_x$, vertical $\upsilon_y$) or synchrotron (longitudinal $\upsilon_s$) tune that represents the (non-integer) number of bunch oscillation periods per revolution and $\omega_0$ the ring revolution frequency. Each mode appears as a number of sidebands of the ring revolution harmonics, but only once in a frequency span equal to $M\omega_0/2$.

In the corresponding time domain description, the equation of motion of the n-th bunch is

$$\ddot{y}_n(t) + d\,\dot{y}_n(t) + (\nu\omega_0)^2 y_n(t) = F(t) \tag{2}$$

where y is the considered transverse or longitudinal coordinate, d represents the natural damping mechanisms, $\upsilon\omega_0$ the betatron or synchrotron frequency and F(t) the driving force from all the bunches.

The goal of an active feedback system is to control the bunch oscillations. The feedback is generally composed of a detecting part that measures the beam instability, a processing stage to determine the correction signal and an electromagnetic actuator that applies the corrective kick back on the beam one or a few turns later.

In line with the description of the CBI mechanism given above, the operation of the feedback can be considered both in the frequency and time domains. In the case of a limited number of clearly identified modes, selective feedback loops ("mode-by-mode" feedback) tuned at the corresponding frequencies can be used to damp CBIs. For rings with hundreds of bunches, that correspondingly have an equivalent number of potentially excited modes, a feedback acting on all bunches and damping all the instability modes is particularly indicated. From a time domain perspective, such a feedback ("bunch-by-bunch" feedback) detects the motion of each bunch and adds a damping term to equation (2) or, in other words, a quantity proportional to the first derivative of the detected oscillation signal. The equation of motion of the n-th bunch becomes

$$\ddot{y}_n(t) + (d + G)\,\dot{y}_n(t) + (\nu\omega_0)^2 y_n(t) = F(t) \tag{3}$$

where G is a term proportional to the feedback gain.

## FEEDBACK ARCHITECTURE

The ELETTRA/SLS (Swiss Light Source) multi-bunch feedback systems are of the bunch-by-bunch type, where the position of the 2ns-spaced 432/480 bunches are independently sampled and corrected. The block diagrams of the Transverse Multi-Bunch Feedback (TMBF) for one of the two transverse planes and of the Longitudinal Multi-Bunch Feedback (LMBF) are shown in figure 1. The systems feature a consistent single-detector-single-actuator architecture based on an identical software programmable processing block. Key differences exist in the front-end and back-end hardware.

The signals from a button Beam Position Monitor (BPM) are composed in a hybrid/combiner network producing wideband signals proportional to the bunch transverse position Y (current I). These are amplitude (phase) demodulated into the RF front-end that works at a 1.5 GHz centre frequency (3 times the ring radio frequency) to provide a baseband (0-250 MHz) bunch-by-bunch signal whose amplitude is proportional to the bunch position (time of arrival or phase) error. With a baseband frequency span of 250 MHz corresponding to $M\omega_0/2$, all possible CBI modes are detected. The bunch-by-bunch signal is then sampled by an eight-bit 500 Msample/s Analog-to-Digital Converter (ADC) and digitally processed. The calculated corrective kick values are symmetrically recombined and transmitted to a complimentary 500 Msample/s Digital-to-Analog Converter (DAC). In the transverse case, an RF amplifier that powers a stripline kicker directly amplifies the DAC output. Quite differently, the LMBF electromagnetic actuator is a cavity-type kicker operating in the 1.25-1.5 GHz frequency band. In order to create an appropriate driving signal the DAC output is amplitude modulated in a lower Single Side Band (SSB) modulator using a coherent carrier at 1.5 GHz. The feedback processes are synchronized by dedicated timing electronics.

## DIGITAL PROCESSING

The basic task of the processing electronics is to calculate the kick values based on the bunch oscillation signals detected by the BPM. In order to add a damping term the correcting kick signal must be shifted by $\pi/2$ betatron (synchrotron) oscillation phase with respect to the position (phase) signal of the same bunch when it passes through the kicker. The processing also rejects the DC “stable beam” component from the BPM signal, which is not used by the feedback and would only lead to a waste of output RF power.

The bunch-by-bunch option, the possibility of using the same processing electronics for the transverse and longitudinal systems of both the accelerators, the needs for flexibility and availability of diagnostic tools have led to the choice of a digital scheme based on software programmable Digital Signal Processors (DSP).

The bunch-by-bunch approach allows splitting the required processing power into several DSPs, where each of them is in charge of a given subset of bunches [3]. The 500 Mbyte/s data flux from the ADC, carrying the position samples of all the 432/480 bunches, is first de-multiplexed into 32-bit FPDP (Front Panel Data Port) channels towards six processing boards. The data on each board is then distributed by means of a programmable switch among four available TMS320C6201 fixed point DSPs. The DSP and, originally, the ADC and DAC are commercial-off-the-shelf VME boards. Following product cessation, a new family of ADC/DAC boards has been developed [4].

Different processing arrangements can be organized. At ELETTRA, the 72 bunch samples arriving at each processing board are passed to the first DSP for on-line acquisition and diagnostics and concurrently split over the three other DSPs that execute the feedback algorithm on the 24 respective bunches. In the case of the SLS, 80 bunches are assigned to each processing board. While the first DSP is again dedicated to on-line acquisition and diagnostics, the bunch samples are split asymmetrically among the three remaining DSPs for feedback operation: 28 bunches to the second and third, 24 to the fourth.

### *Digital Filters*

The correction kick values are first determined by shifting through a digital filter the phase of the signal detected by the BPM. As the filter can be programmed to provide any phase, the operation of the feedback is independent of the relative phase between the BPM and the kicker. In view of this the kicker can reside at any position in the ring

One of the simplest digital filters satisfying the processing requirements given at the beginning of this section is the 3-tap Finite Impulse Response (FIR). It can provide DC rejection and the appropriate phase and gain at the betatron (synchrotron) frequency. The 3-tap FIR filter includes all the essential functionality, however, more complex filters are implemented that address additional issues of transverse and longitudinal beam dynamics.

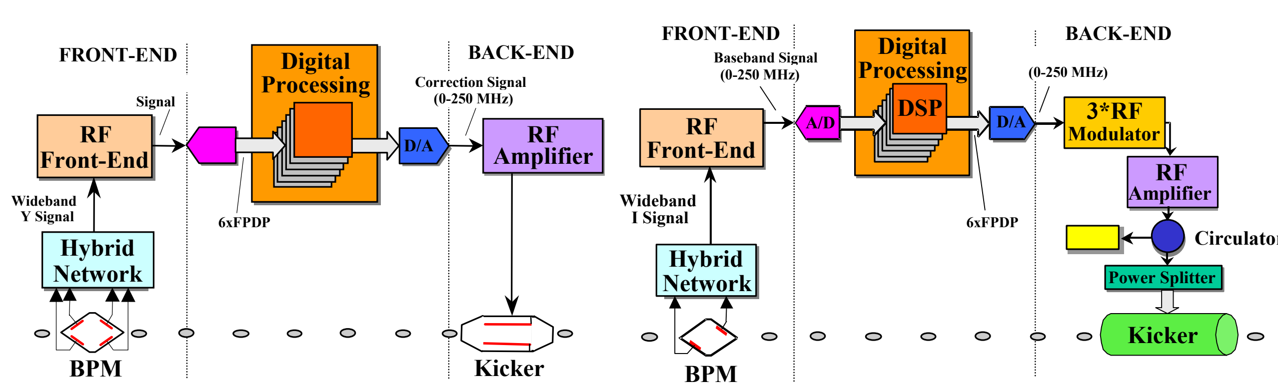


Figure 1: Block diagrams of the Transverse (one plane, left) and Longitudinal (right) Multi-Bunch Feedback systems.

At ELETTRA, betatron tune variations can be observed when opening/closing some insertion devices and during energy ramping from 0.9 to 2 or 2.4 GeV, which move the working point of the digital filter and lead to a degradation of feedback performance. A family of 5-tap FIR filters featuring compensation of tune variation was designed and is currently used. These filters provide the right amplitude and phase in a given frequency interval around the nominal tune. Figure 2 shows the transfer function of a filter where fractional tune changes exceeding ±20% are possible whilst keeping the same damping performance of the TMBF system.

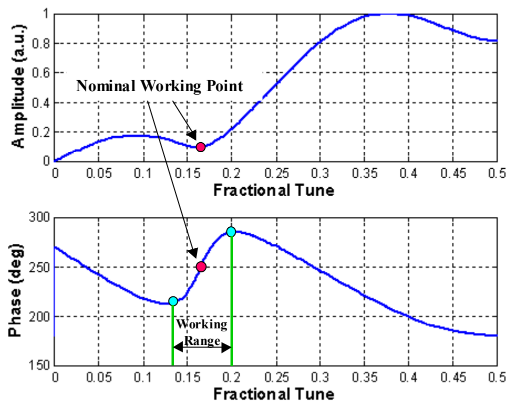


Figure 2: Transfer function of a 5-tap FIR filter featuring compensation of betatron tune variations.

While in the transverse planes the bunches execute a number of oscillation periods per revolution (for ELETTRA, $\nu_x = 14.3$ and $\nu_y = 8.2$), many turns are needed for a single oscillation period in the longitudinal coordinate (for ELETTRA, $\nu_s = 0.009$ at 2 GeV). Such a difference has a significant impact in the processing scheme for the TMBF and LMBF systems. In the transverse case all of the position samples acquired at each machine revolution must be processed in order to calculate the correcting kick signal for a given bunch. In the longitudinal plane the lower synchrotron tune allows to down sample the digital phase error signal from each bunch and to use only one over *n* of the incoming samples to feed the digital filter; the correction signal is accordingly updated once every *n* revolution periods. Thanks to the programmability of the system, the down sampling is carried out via software starting from the input data at the full rate of 500 Msample/s. The down sampling technique increases the time the DSPs have to calculate the correction values and more sophisticated digital filters can be implemented.

A down sampling factor $n = 10$ has been chosen for the ELETTRA LMBF resulting in a down sampled synchrotron tune of 0.09, which allows the digital filter to reject the DC component of the signal and to have at the same time a high gain at the synchrotron tune. A 4th order digital IIR (Infinite Impulse Response) filter is currently implemented (figure 3).

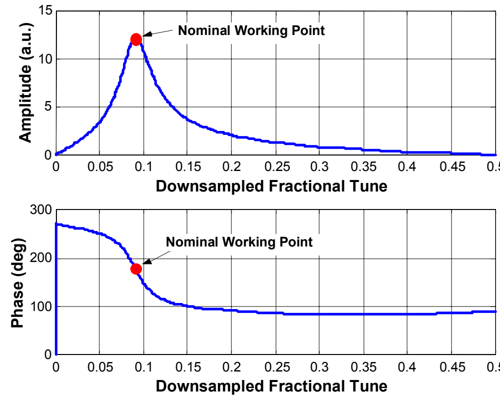


Figure 3: Transfer function of the 4th order IIR filter used for the LMBF, with a down sampling factor $n = 10$.

## OPERATIONAL RESULTS

Two TMBF systems are installed and routinely operate in the vertical and horizontal plane during user shifts at ELETTRA. With the support of the feedbacks a beam free of CBIs is delivered to the users and the improvement in beam quality is verified by the photon spectra of the insertion devices (figure 4).

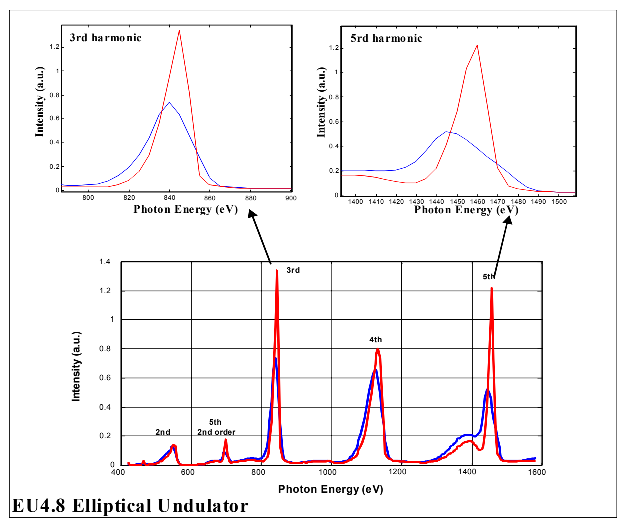


Figure 4: ELETTRA EU4.8 elliptical undulator spectra (gap 20 mm) in the previous user mode (blue line) and with damped CBIs (red line) (135 mA@2.4 GeV).

In view of the production of the new ADC/DAC boards, the digital processing electronics of one of the TMBF systems running the appropriate software has been used for the commissioning of the LMBF. By activating the LMBF from the beginning of the ring injection process, up to 280 mA of longitudinally stable beam at 0.9 GeV have been accumulated at ELETTRA.

The TMBF has been tested on the vertical plane of the SLS. Figure 5 shows the effect of the feedback as seen on the synchrotron radiation pin-hole camera for an 80 mA beam affected by vertical transverse CBIs.

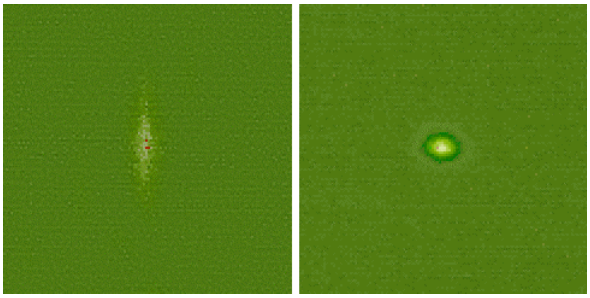

Figure 5: Pin-hole camera images of an 80 mA initially vertically unstable beam at the SLS with TMBF off (left) and on (right).

## SYSTEM INTEGRATION

The 6 DSP, the ADC, DAC and Timing boards corresponding to one system are placed in one VME chassis (figure 6). A VME host computer acts as system supervisor and interfaces the feedback components to the control system through the appropriate protocol: Remote Procedure Call (RPC) and EPICS Channel Access for ELETTRA and SLS respectively.

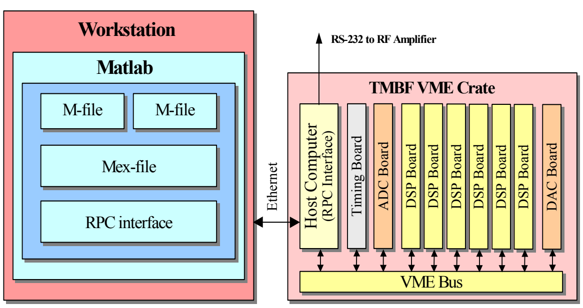


Figure 6: Hardware and software feedback system integration at ELETTRA.

Filter tap values can be changed on the fly by reading/writing the DSP internal memory through the VME bus, without interfering with the currently executing code.

As already mentioned, one of the four DSPs on each VME board is dedicated to data acquisition for on-line diagnostics and 16 Mbytes of fast memory are available for this purpose. The whole system made up of six boards allows 96 Mbytes of bunch-by-bunch continuous data at 500 Msample/s, corresponding to 192 ms, to be recorded in parallel to normal feedback operation.

At ELETTRA, a set of newly developed Matlab commands, implemented as M/Mex-files on top of the RPC protocol, provides access to the feedback equipment from any Matlab session running on the control room UNIX workstations (figure 6). The reading/setting of the digital filter coefficients, the acquisition of an array of bunch-by-bunch position samples of all bunches and of turn-by-turn samples of a chosen bunch are implemented as Matlab commands [5]. This gives an integrated environment for system control, data acquisition, on-line analysis of the acquired data and graphical visualisation of the results.

During routine operation, the feedbacks are easily controlled from the control room panels executing on the UNIX consoles, with the *init*, *run* and *standby* procedures fully automated.

## MEASUREMENT AND BEAM MANIPULATION TOOLS

In addition to the closed loop functionality, the digital feedback processing allows for the implementation of diagnostic features that can be built by appropriate programming of the system. Some of the most significant measurements carried out at ELETTRA are reported hereafter.

### *Wide-band Spectra*

250MHz-wide spectra for complete multi-bunch mode analysis with 1kHz resolution can be obtained in the control room at a repetition rate of about 0.5 Hz. When using the full amount of available recorded bunch-by-bunch data a resolution of 5.2 Hz can be achieved.

### *Growth/Damp Transients*

Growth/damp transients are created by switching the feedback off/on through a proper setting of the digital filter coefficients according to a specified sequence of time intervals. The positions of the bunches during the transients are concurrently recorded by the diagnostic DSPs. Figure 7 shows the spontaneous growth of the oscillation amplitudes of the bunch train for a vertically unstable beam when the feedback is switched off and the subsequent damping effect when the feedback is switched back on. Filter coefficients are set to zero and restored back to their original value after a specified 3.4 ms interval. The bunch train gap can be clearly distinguished.

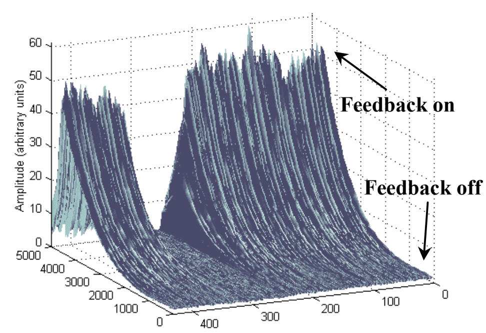


Figure 7: Bunch growth/damp transient of a vertically unstable beam created by switching the feedback off/on.

In figure 8, a transient is analysed in the frequency domain, where the evolution of the unstable vertical mode sidebands of the entire beam spectrum is plotted against time. Rise times and damping rates of coupled-bunch modes throughout the whole operating frequency range can be measured by appropriately fitting the acquired data. Similar transients can also be started with an anti-damping period of positive feedback, which is obtained by inverting the sign of the filter coefficients.

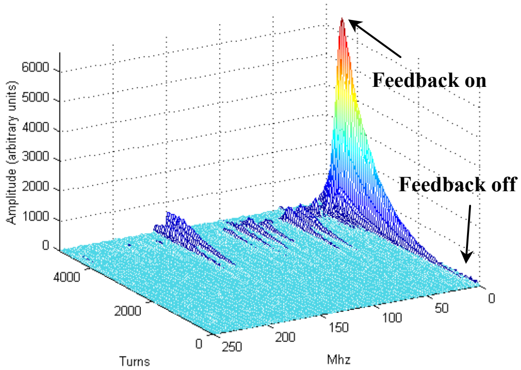


Figure 8: Growth/damp transient of vertical mode sidebands created by switching the feedback off/on.

### *Betatron Tune Measurement, Tune Tracking*

Highly resolved betatron tune measurements can be performed using the TMBF system. In the case of a transversally unstable beam, the spectrum of the turn-by-turn position data of a given bunch clearly reveals a line at the fractional betatron tune. During operation with users, however, the beam is kept transversally stable through the action of the TMBF. In order to measure the tune without affecting the users' experimental activities, a novel diagnostic tool has been developed. It consists of exciting with the TMBF only few selected bunches using an arbitrary downloaded waveform, while the remaining bunches are kept damped by the system itself that is concurrently running. A frequency domain analysis of the turn-by-turn position data of the excited bunches clearly identifies the fractional betatron tune. In the case of figure 9, pink noise with power spectrum centred at the frequency of the vertical tune was used to excite two of the 432 bunches stored in ELETTRA.

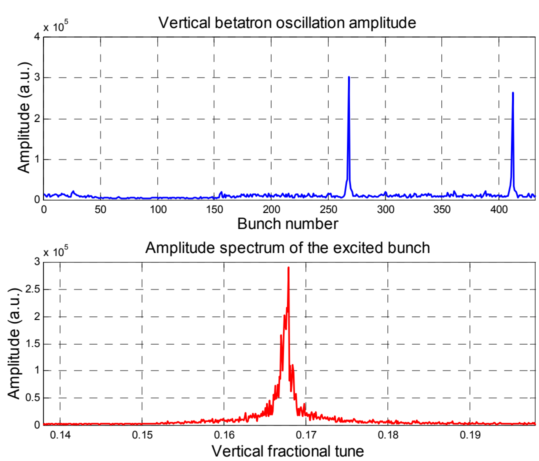


Figure 9: Excitation of two bunches with pink noise. Amplitude of the vertical betatron oscillation component for the 432 bunches (upper) and fractional vertical tune measured from one of the two excited bunches (lower).

The upper graph of figure 9 shows the amplitude of the vertical betatron oscillation component for the different bunches, the lower reveals the fractional tune as measured from one of the two excited bunches.

As a further development an adaptive technique called 'tune tracking' has been implemented in order to keep TMBF operation at its optimum working point even in the presence of large betatron tune variations (e.g., from changes of insertion device gaps or energy ramping). It consists of periodically measuring the tune by using the method just described, calculating the feedback digital filter coefficients according to the updated tune value and downloading these coefficients into the running DSPs.

## CONCLUSION

In the frame of an active collaboration, transverse and longitudinal bunch-by-bunch feedback systems have been developed by ELETTRA and the SLS. The systems are based on the same type of digital processing hardware, which mainly consists of a 500 Msample/s ADC and DAC, programmable data route switches and an array of DSPs running the appropriate software.

At ELETTRA, two TMBF systems are routinely operating during users shifts and have enhanced the quality of the delivered beam. Since the installation of the first TMBF in November 2001, operation of the systems has been effective and reliable.

While a number of DSPs execute the feedback algorithms, the rest of them can concurrently run data acquisition and processing tasks. The availability of up to 96 Mbytes of bunch-by-bunch data allows time and frequency domain analysis with extremely high resolution.

This new integrated mixing of functionalities opens the way for the implementation of different diagnostics and beam manipulation tools. Such tools are well integrated in the accelerator control system and have been used since the commissioning phase for the characterization of the feedback system hardware and for beam physics studies.

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