



CLS Transverse Feedback System

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1.0 INTRODUCTION

1.1 PURPOSE AND SCOPE

This document describes the design and operation of the CLS Transverse Feedback (TFB) system. It presents some commissioning results of the TFB system. The procedures and parameters to set up the TFB controllers for different applications are also covered in this report.

1.2 BACKGROUND

The CLS Transverse Feedback system has been implemented to damp the transverse betatron oscillations associated with coupled-bunch instabilities. It operates in the time domain, which means that the system acts individually on each bunch. The TFB system can also work as a bunch cleaner, wherein selected bunches are anti-damped to leave the storage ring. Another application for the system is to excite selected bunches for transverse tune measurement.

1.3 ABBREVIATIONS

ADC – Analog to Digital Converter
BPM – Beam Position Monitor
DAC – Digital to Analog Converter
FFT – Fast Fourier Transform
FIR – Finite Impulse Response
FM – Frequency Modulation
FPGA – Field Programmable Gate Array
NCO – Numerically Controlled Oscillator
PHS – Phase Shifter
TFB – Transverse Feedback
TFC – Transverse Feedback Controller

2.0 TRANSVERSE FEEDBACK SYSTEM OVERVIEW

2.1 SYSTEM DESCRIPTION

The block diagram of the TFB system is shown in Fig. 1. The system consists of a beam position monitor (BPM), a hybrid front end, an RF front end, Libera Bunch-by-Bunch units, phase shifters, power amplifiers, low-pass filters and kickers. The system is designed to work in the time domain. Therefore, beam instabilities are corrected on a bunch-by-bunch basis.

2.2 FRONT ENDS

The RF signals coming from the BPM buttons are fed into the hybrid front end first. The hybrid front end is fabricated at the CLS and is designed to work around the third harmonic ($3f_{rf}$), where

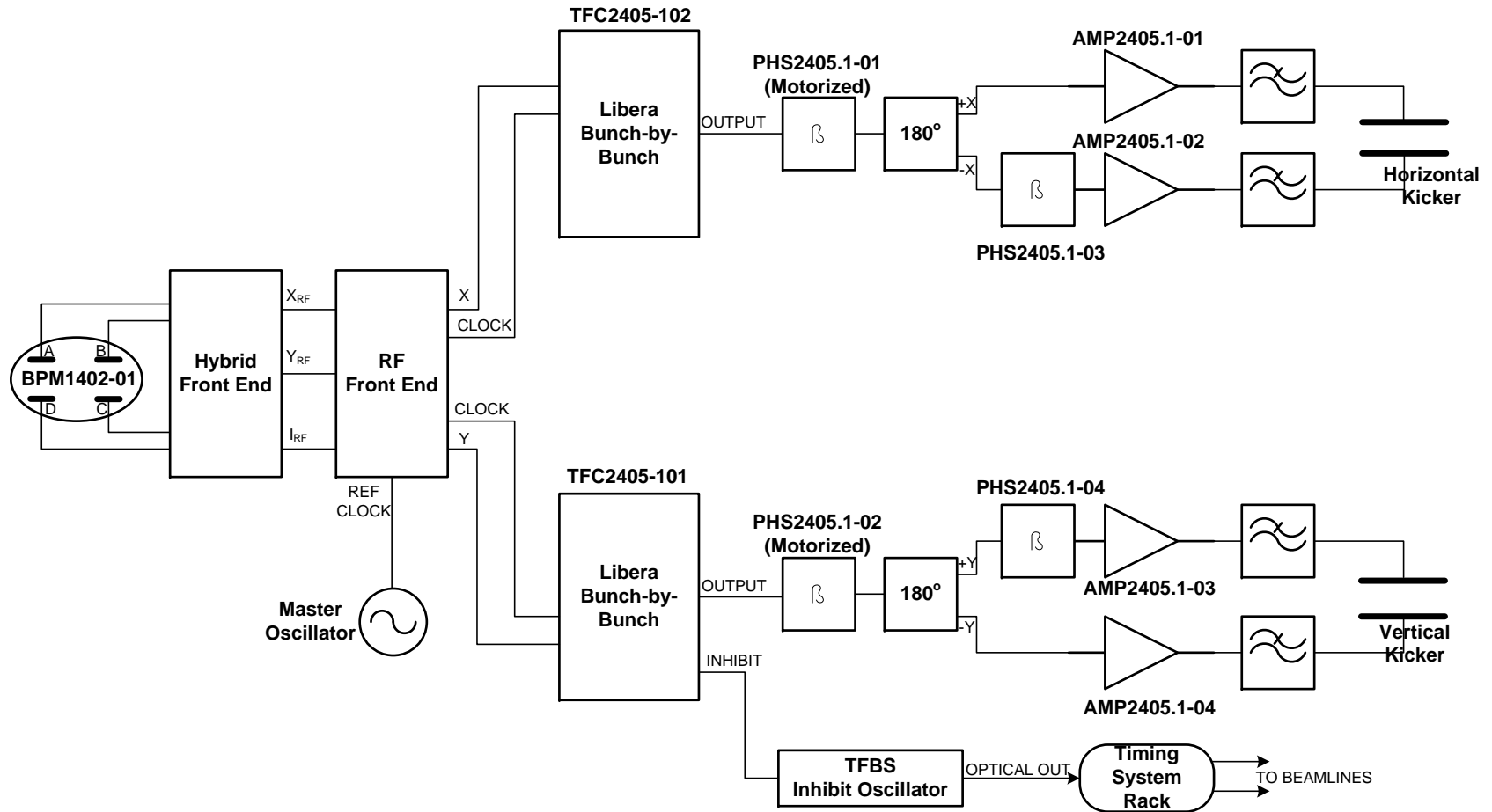


Fig. 1 Block diagram of the transverse feedback system

the whole BPM transfer function has maximum amplitude. The four signals from the buttons are combined in the hybrid front end to obtain the horizontal position signal, vertical position signal and intensity signal. The signals are combined in the hybrid front end according to the following equations:

$$X_{RF} = (A + D) - (B + C)$$

$$Y_{RF} = (A + B) - (C + D)$$

$$I_{RF} = A + B + C + D$$

The RF front end is a Libera Bunch-by-Bunch front end [1], which is designed and fabricated by Instrumentation Technologies. Fig. 2 shows the block diagram of the RF front end. It first filters the signals generated by the hybrid front end. The band-pass filters are centered around 1.5GHz and the 3-dB bandwidth is 400MHz. The filtered signals are then down converted to the base band and filtered again with a low-pass filter. For transverse feedback system, the operation involved in this step is an amplitude demodulation. To make sure the input signals are properly amplitude demodulated, the phase shift of the local oscillator has to be set correctly. It should be noted that the output base band intensity signal is not actually used in the transverse feedback system. This signal will only be used if a longitudinal feedback system is going to be deployed.

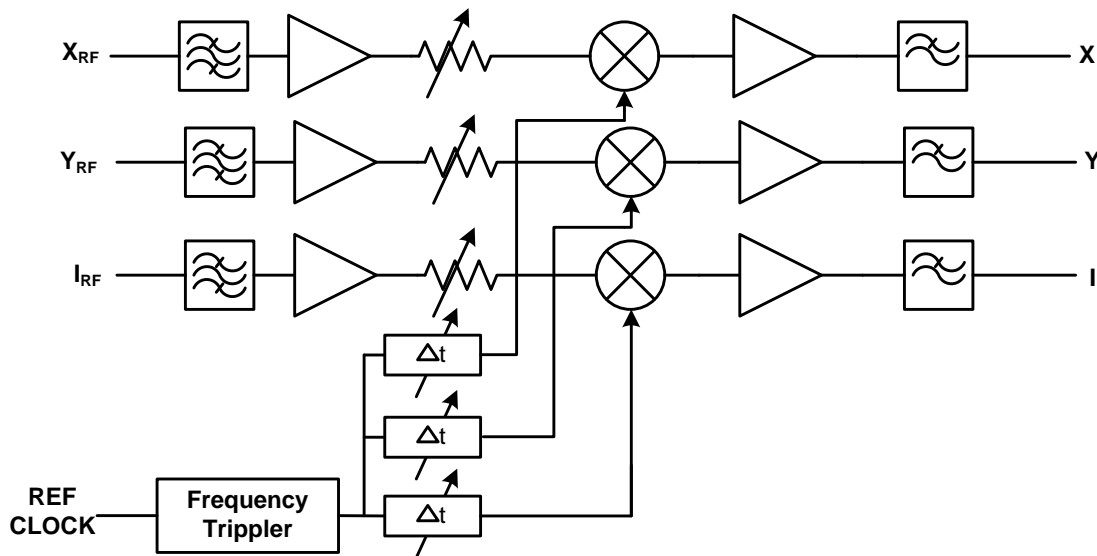


Fig. 2 Block diagram of the RF front end

2.3 LIBERA BUNCH-BY-BUNCH

Libera Bunch-by-Bunch unit [2][3] is a digital feedback processor from Instrumentation Technologies. The base band bunch-by-bunch position signal (X or Y) fed into the unit is sampled by a 12-bit, 500Msamples/s analog to digital converter (ADC). The digitized 500MHz data are demultiplexed into five processing chains, with each chain working at 100MHz, and then digitally processed by a field programmable gate array (FPGA) to calculate the correcting kick signal for each bunch. After processing, the correction data streams are multiplexed and converted to analog signal by a 12-bit digital to analog converter (DAC). Fig.3 shows the block diagram of the Libera Bunch-by-Bunch unit.

Since the CLS storage ring operates with 285 electron buckets, there should be 285 digital filters in the feedback processor and each filter is dedicated for processing one bunch. Each processing

chain in the Libera Bunch-by-Bunch consists of 57 finite impulse response (FIR) filters and each filter is 16 taps long. Filter characteristics can be controlled by setting up filter coefficients.

It is also possible to switch the Libera Bunch-by-Bunch from feedback mode to numerically controlled oscillator (NCO) mode, which is tailored for the needs of bunch cleaning. In this mode, the output sweeps through a predefined frequency range and drives bunches into betatron oscillations.

The input delay, output delay can be adjusted between zero and revolution period in steps of $1/f_{RF}$, which is 2ns. Gain control blocks are implemented with simple binary shifts. Therefore, the output power can be controlled in steps of 6dB.

It is extremely important that the master clock signal is continuously supplied to the Libera Bunch-by-Bunch unit. If this connection fails at anytime, the digital signal processing blocks in the FPGA will lose their synchronization. As a result, the unit has to be restarted.

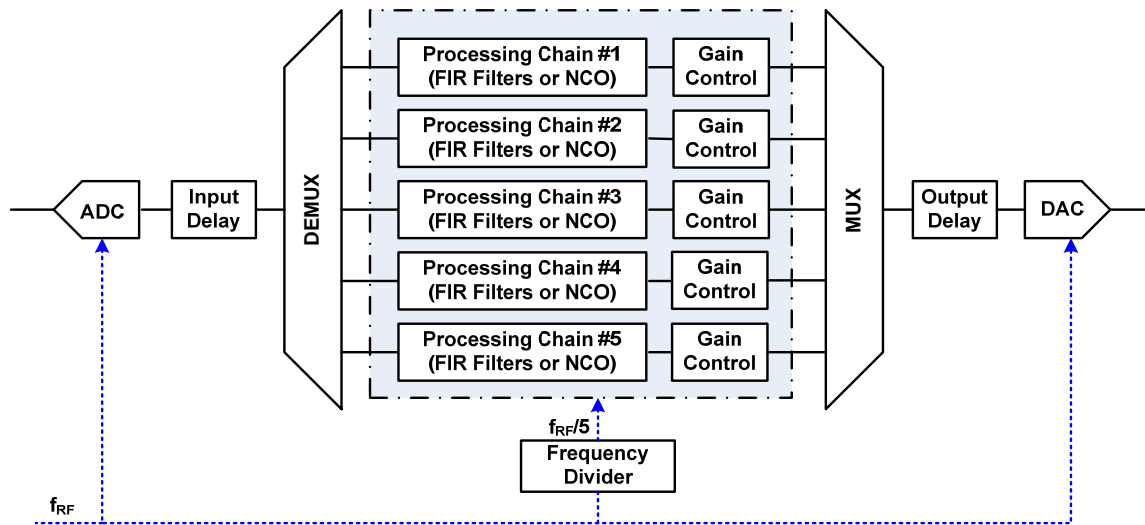


Fig.3 Block diagram of the Libera Bunch-by-Bunch

2.4 PHASE SHIFTERS

There are four phase shifters in the transverse feedback system, PHS2405.1-01, PHS2405.1-02, PHS2405.1-03 and PHS2405.1-04. PHS2405.1-03 and PHS2405.1-04 are manually adjusted to make sure that accurate differential signals are delivered to the horizontal and vertical kicker plates. They don't need to be adjusted again unless an amplifier is replaced in the future.

For transverse feedback application, the signal of a given bunch passing through the feedback chain must arrive at the kicker when, after one or more machine turns, the same bunch passes through it. To achieve this, accurate delay timing is required. However, Libera Bunch-by-Bunch unit can only adjust delay in steps of 2ns. Two motorized phase shifters, PHS2405.1-01 and PHS2405.1-02, are connected at the outputs of the Libera Bunch-by-Bunch units to adjust fine output delay. With these motorized phase shifters, the output delay can be adjusted between 0 and 2ns, with an accuracy of several ps. For bunch cleaning application, accurate delay timing is also necessary because the zero-crossing must occur at the exact moment when the bunch to be retained passes through the kicker. However, the fine output delay introduced will be different from the fine output delay introduced for transverse feedback application because the system is not working in the feedback mode.

2.5 POWER AMPLIFIERS AND KICKERS

The amplifiers are AR model 150A220 with 150W of rated output power and 10kHz-220MHz bandwidth. These amplifiers have a short RF rise time (3 ns), which is important for bunch cleaning. Both the horizontal and vertical kickers are based on the kicker design from the Swiss Light Source, aside from minor changes to accommodate the profile of the CLS vacuum chamber [4].

3.0 BUNCH CLEANING

3.1 BACKGROUND

Time-resolved experiments usually require a high purity single-bunch in the storage ring. Ideally, injecting a single bunch to fill a single bucket in the storage ring is preferred. However, this is not possible with the existing LINAC gun of the CLS because the switching time of the video deflectors is too long. Since single bunch injection cannot be achieved, any unwanted bunches have to be kicked out after injection [5].

3.2 CLEANING MECHANISM

The bunch purification mechanism is based on a frequency-modulated signal that drives the unwanted bunches into betatron oscillation to remove them from the storage ring [6]. Because the bunch tune varies with the bunch charge and the amplitude of oscillation, it is also necessary to modulate the oscillator frequency to ensure all unwanted bunches are eventually driven out. Since the vertical aperture in the CLS storage ring is smaller than the horizontal aperture, bunch cleaning is done in the vertical plane. Two frequency modulation (FM) schemes, sine-wave modulation and linear-ramp modulation, were proposed in [6]. The simulation results show that the linear-ramp modulation is more efficient for bunch cleaning.

In order to remove certain bunches and retain others, a bunch-selection mask is mixed with the frequency-modulated signal. The bunch-selection mask crosses zero when the retained bunches arrive and has a maximum when the unwanted bunches arrive. If an isolated bunch is to be retained, a 180 degree phase shift is introduced to create the zero-crossing. A 180 degree phase shift is necessary because of the limited bandwidth of the power amplifiers. If two or more adjacent bunches are to be retained, zeros are simply inserted into the bunch-selection mask. Fig. 4 presents an example of the bunch-selection mask, where bunches 3, 7, 8 and 9 are to be retained.

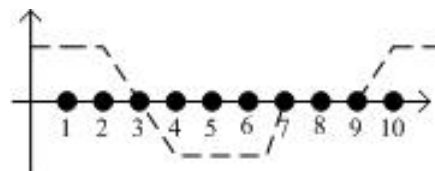


Fig. 4 Bunch-selection mask

3.3 FREE-RUNNING OSCILLATOR IMPLEMENTATION DETAILS

The free running oscillator implemented in the Libera Bunch-by-Bunch is based on a NCO, which is frequency modulated with a saw-tooth signal. The frequency modulated signal is mixed with the bunch-selection mask and goes through a sign function. This implementation is shown in Fig. 5.

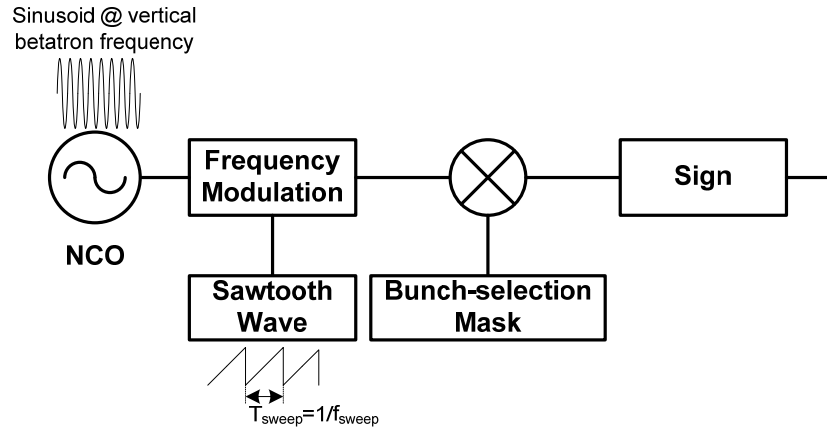


Fig. 5 Free-running oscillator implementation for bunch cleaning

It should be noted that there are several constraints in setting up the free-running oscillator:

1. In principle, the free running oscillator can be tuned to the frequency of any vertical betatron sideband, i.e., $f_{NCO} = (N \pm \nu_0) \cdot f_0$, where N is an arbitrary integer, ν_0 is the vertical fractional tune and f_0 is the storage ring revolution frequency. However, the output frequency of the NCO can't exceed 50MHz due to the fact that the NCO is running at 100MHz.
2. The maximum FM bandwidth, BW_{FM} , is 190kHz.
3. The sweep frequency, f_{sweep} , must be smaller than $\frac{2.98 \times 10^8}{BW_{FM}}$.

Both constraint 2 and constraint 3 are due to the register length limitation of the current FPGA design.

3.4 BUNCH CLEANING RESULTS

Bunch cleaning can be performed during injection or after injection. If the cleaning is done after injection, an arbitrary fill pattern can be established in a few second. A fill pattern monitor [7] is used to measure bunch purities, which is based on a fast X-ray avalanche photodiode detector. Bunch purities of the rejected bunches relative to the retained bunches are 10^{-6} or better, limited mainly by charge leakage from adjacent buckets. The optimized parameters for bunch cleaning are summarized in Table 1.

Table 1. Optimized bunch cleaning parameters

NCO Center frequency	18.105MHz
Drive power	37.5W per plate (150W/4)
FM bandwidth	150kHz
Modulation rate (f_{sweep})	50Hz
Fine output delay (PHS2405.1-01)	760ps

3.5 PERIODIC BUNCH CLEANING AND GATING THE EXPERIMENTS

The test results show that bunch purities will degrade after turning off the bunch cleaning system due to charge leakage from adjacent buckets. Therefore, bunch cleaning has to be performed periodically. For example, bunch cleaning can be turned on for 1 second every minute to keep the average bunch purities significantly better than 10^{-5} . However, the cleaning will also excite the main bunch and this process is transparent to the users because the cleaning is done in the storage ring. An inhibit signal is generated in the Libera Bunch-by-Bunch and supplied to the beamline users allowing them to disregard or inhibit data taking during the cleaning period. Timing diagram of the inhibit signal is shown in Fig. 6. The inhibit signal goes high before the cleaning starts to allow the users stop data taking. The leading time can be specified by the users. The inhibit signal will remain high for a short period after the cleaning stops. An estimation of the following time is 10-20ms. Within the following time, the main bunch is damped down to an acceptable level. Then the users can start data collection again when the inhibit signal goes low.

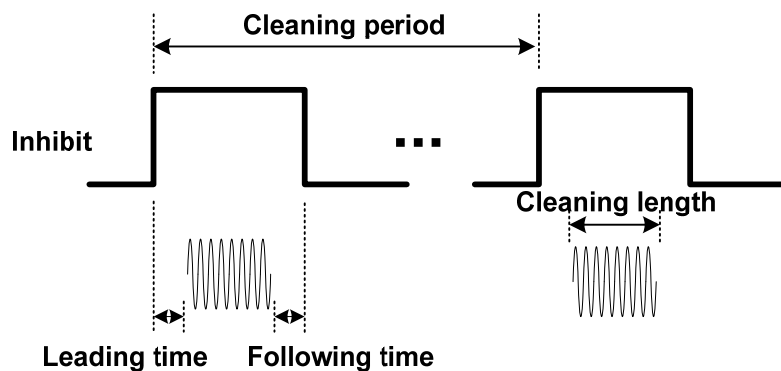


Fig. 6 Timing diagram of the inhibit signal

4.0 TUNE MEASUREMENT

4.1 BACKGROUND

Previously, the beam has to be excited by the injection kicker to determine the transverse tunes. There are several disadvantages in this tune measurement system. (i) The whole bunch train needs to be excited for tune measurement. This is not acceptable during normal operations. (ii) The vertical tune measurement totally depends on the X-Y coupling. It is impossible to determine the vertical tune when the storage ring is running at low current. (iii) There is a risk of beam loss. Therefore, a new tune measurement system was designed as part of the TFB system.

4.2 BASIC PRINCIPLES

In principle, the transverse feedback system can also work in an anti-damping mode to excite the selected bunches for tune measurement. To make the system work in the anti-damping mode, we only need to inverse the kick polarity, i.e., inverse the sign of the FIR filter coefficients. However, there are some problematic issues in this approach. For example, if the targeted bunches are very stable and there is not enough noise from the BPM, the feedback will never be initiated. Consequently, the approach for bunch cleaning has to be used for tune measurement. The obvious questions are: How can we prevent kicking the beam out? Considering the natural damping time is just several milliseconds, how can we trigger the data acquisition before the

beam damps down? Do we need a hardware trigger signal? A simple solution for these questions is to run the system with low power and high modulation rate. By lowering the drive power, the beam will not be kicked out. By increasing the modulation rate, the targeted bunches will be excited again before damping down. Therefore, data acquisition can be triggered by software at anytime. The Libera Bunch-by-Bunch unit starts filling up its history buffer with the bunch by bunch positional data after receiving a software trigger. By analyzing the turn by turn positional data of a specific bunch in the frequency domain, we will be able to find the transverse tunes.

4.3 TUNE MEASUREMENT RESULTS

A single bunch or the whole bunch train can be excited for tune measurement by setting up appropriate bunch-selection mask. The optimized parameters for tune measurement are summarized in Table 2.

Table 2. Optimized tune measurement parameters

	Horizontal	Vertical
NCO Center frequency	17.930MHz	18.105MHz
Drive power	9.375W per plate (150W/16)	9.375W per plate (150W/16)
FM bandwidth	150kHz	150kHz
Modulation rate (f_{sweep})	1kHz	1kHz
Fine output delay	TBD	760ps

Fig. 7 shows the turn by turn positional data of a single bunch excited in the horizontal plane. We can clearly see from this figure that the bunch is excited every 1ms. Fig. 8 shows the FFT analysis results of the excited bunch. Fig. 9 shows the oscillation amplitude plot of the whole bunch train.

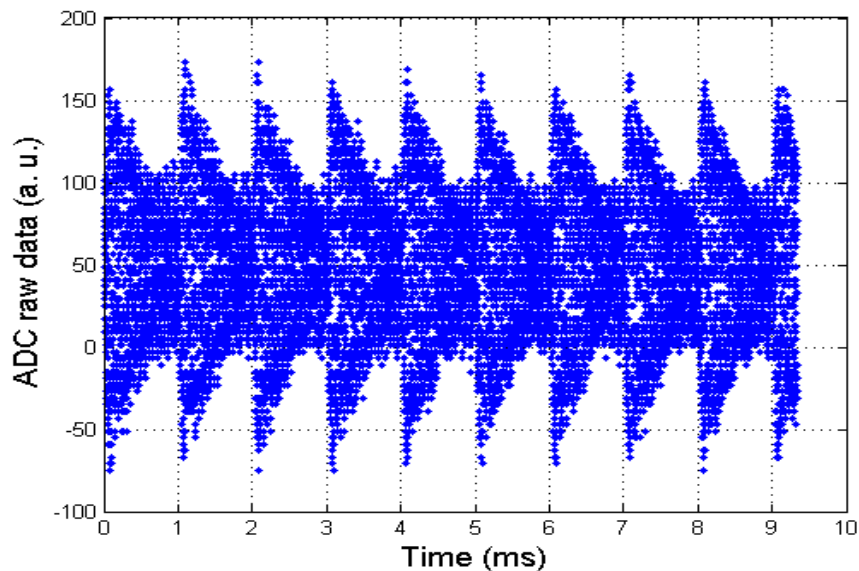


Fig. 7 Turn by turn positional data

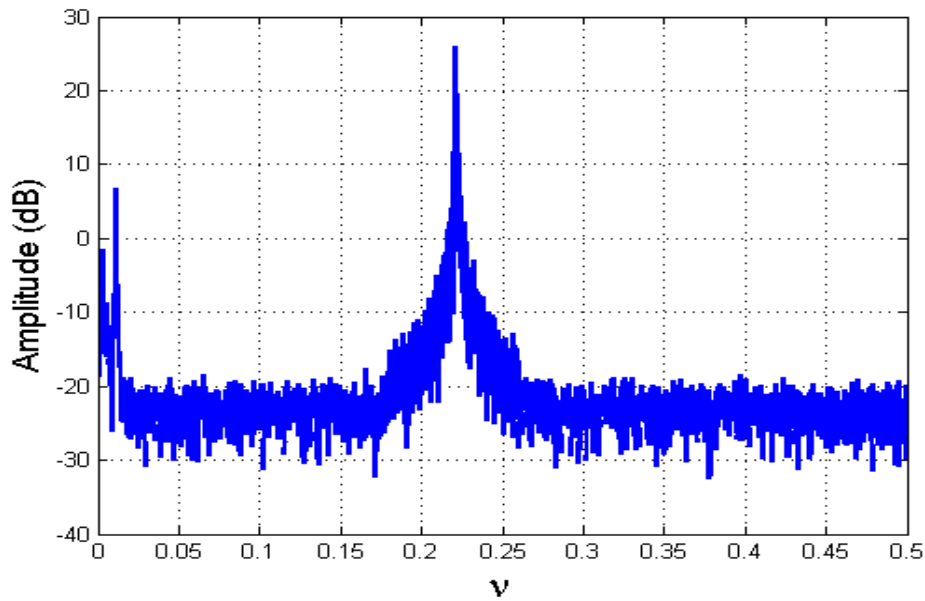


Fig. 8 FFT result

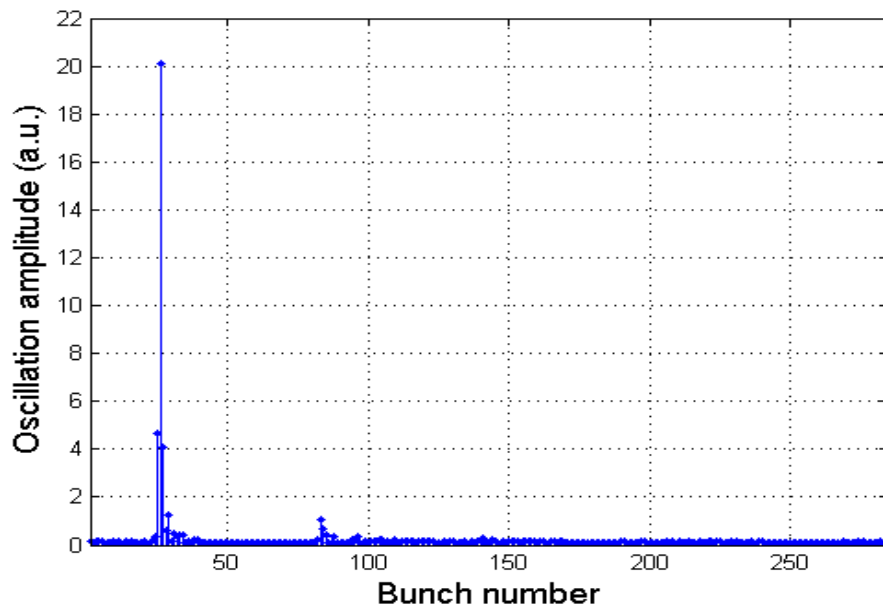


Fig. 9 Betatron oscillation amplitude plot of the whole bunch train

In principle, if we setup appropriate bunch-selection mask to excite a single bunch for tune measurement, all other bunches should stay stable. However, this might not be the case in real life. According to the test results, at least two adjacent bunches are also excited with smaller oscillation amplitude. In reality, the finite bandwidth of the power amplifiers restricts the rise and fall times. As a result, the kick targeted at a particular bunch is directed to the adjacent bunches. Fig. 10 shows this kick overlap effect. Another contributing factor here is the coupling effect between the adjacent bunches. The ultimate goal of the tune measurement system is to use one unstable bunch to determine the transverse tunes during normal operation. Whether this tune

measurement system can be used during normal operation has to be confirmed by some stability-sensitive beamlines.

If only a single bunch is excited, this tune measurement system works when the storage ring current is greater than 10mA. For current lower than 10mA, the whole bunch train has to be excited for tune measurement. In this case, bigger oscillation is introduced because of the kick overlap and coupling effects between bunches.

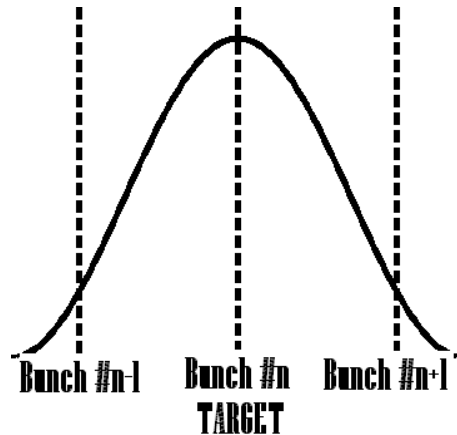


Fig. 10 Kick overlap effect

5.0 TRANSVERSE FEEDBACK

5.1 BACKGROUND

The CLS transverse feedback system is designed to damp the transverse betatron oscillation associated with coupled-bunch instabilities, including the ubiquitous ion trapping and resistive-wall instabilities [8]. In the long run, the system can be employed for stabilizing the beam against instabilities in order to allow operation with moderate chromaticity or higher current. It can also be employed for damping the orbit transients induced by the injection process in the top-up operation.

5.2 BASIC PRINCIPLES

The CLS transverse feedback system is designed to work in the time domain. The correction signal for a given bunch is computed only on the motion of that bunch. Every bunch is measured and corrected at every machine turn. However, the correction kick corresponding to a given measurement is applied to the bunch one turn later because of the delay of the feedback chain. In order to damp the oscillation, the correction signal applied to a given bunch must be proportional to the derivative of the bunch oscillation at the kicker. To calculate the required filter response, both the single-pass betatron phase-advance between BPM and kicker and the additional delay caused by the feedback latency must be taken into account. The digital filter should reject any DC component from the bunch signal to avoid DAC saturation and wasting power to correct a position bias at the revolution frequency. The filter may also be required to have flat response near the operating point to accommodate small tune variations. Ref. [8] discussed how to design appropriate 3-tap, 5-tap, 7-tap and 9-tap FIR filters with all these constraints.

5.3 TRANSVERSE FEEDBACK SYSTEM PERFORMANCE

In order to test the performance of the transverse feedback systems, instabilities have to be introduced into the beam. In the vertical plane, instabilities are introduced by reducing machine chromaticity or filling up the storage ring with 285 bunches. In the horizontal plane, the injection kicker is turned on to induce orbit transients. The optimized parameters for transverse feedback system are summarized in Table 3 and the system performance is described in the following sections.

Table 3. Optimized transverse feedback system parameters

	Horizontal	Vertical
Local oscillator phase	TBD	-136°
Coarse delay	478ns	470ns
Fine output delay	140ps	1320ps
Close loop gain	Varies	Varies

5.3.1 Transverse Beam Profile

During the experiment, vertical instabilities were induced by reducing machine chromaticity and the beam profile was monitored by a CCD camera. Fig. 11 shows the beam profile comparison when the feedback system was off and on. When the feedback system was turned on, it stabilized the stored beam and reduced the vertical beam size.

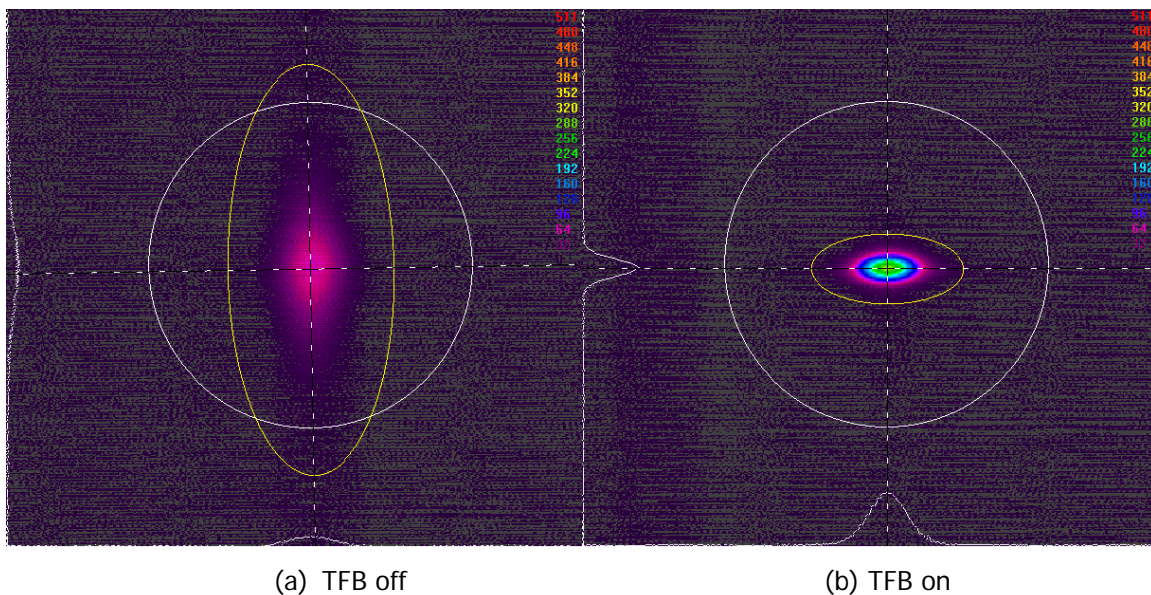


Fig. 11 Transverse beam profile

5.3.2 Betatron Sideband Suppression

Fig. 12 shows the spectrum comparison when the transverse feedback system was off and on. It is clear that the vertical betatron sidebands corresponding to vertical coupled bunch modes disappeared after turning on the feedback system.

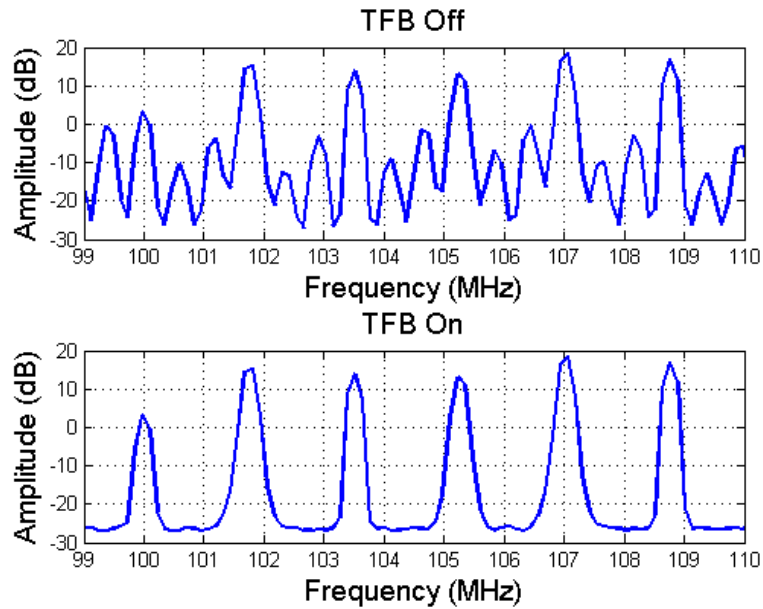


Fig. 12 Vertical betatron sideband suppression

5.3.3 Lifetime Effect

Although the transverse feedback system can effectively reduce the vertical beam size, it would also shorten the beam lifetime, as shown in Fig. 13. It indicates that the storage ring beam lifetime is dominated by Touschek scattering [9][10].

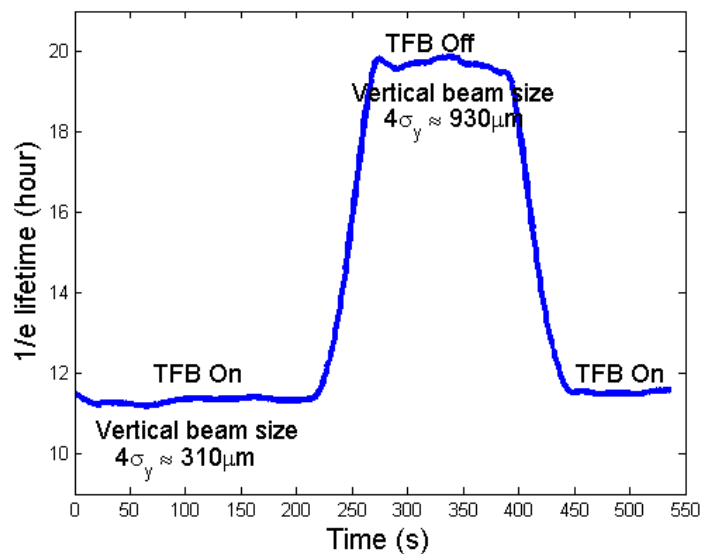


Fig. 13 Lifetime change due to feedback on and off with 200mA stored beam

5.3.4 Horizontal Damping Time Acceleration

The transverse feedback system can also be used to accelerate the damping of the horizontal betatron oscillation induced by the injection kicker during the injection cycle. Fig. 14 shows the damping time comparison when the transverse feedback system was off and on.

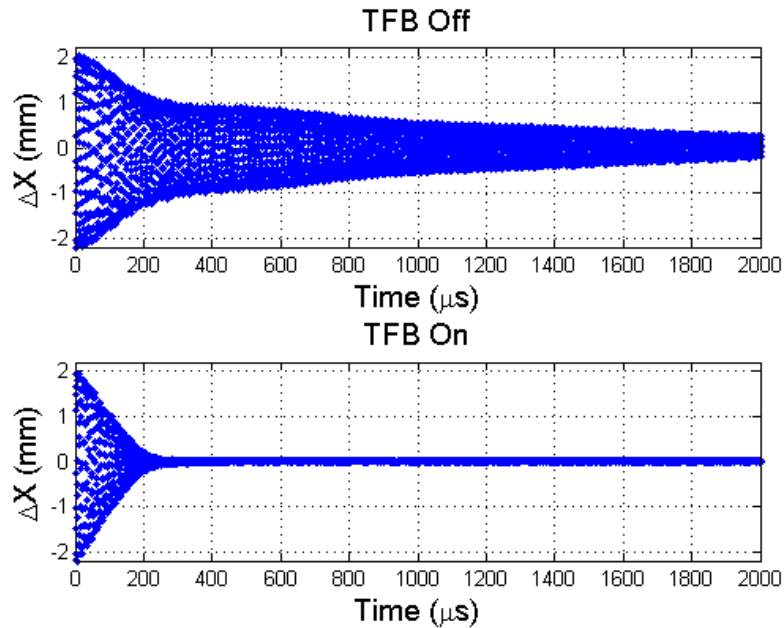


Fig. 14 Damping acceleration

5.3.5 Improved FIR Filter

During the experiment, it was found that we can't turn on the transverse feedback system in both planes if there is a strong coupling between the vertical plane and the horizontal plane. Thus, a small modification to the FIR filter design was necessary. In the new FIR filter, a notch is introduced to the amplitude response [11]. Fig. 15 shows the frequency response comparison between the old and new horizontal FIR filters.

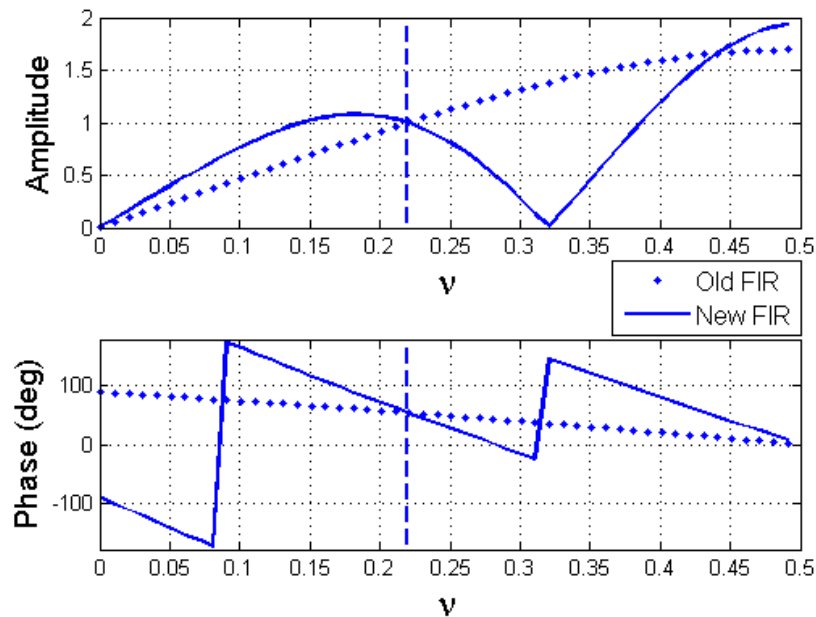


Fig. 15 Frequency response of the new horizontal FIR filter

6.0 OPERATION MANUAL

6.1 POWER AMPLIFIER CONTROL

To operate the transverse feedback system for any application, make sure the transverse feedback system power amplifiers are in **OPERATE** state, as shown in Fig. 16.

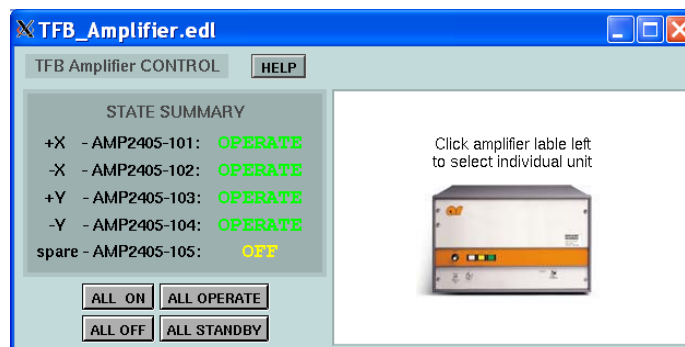


Fig. 16 Transverse feedback system power amplifiers control window

6.2 HOW TO SETUP THE SYSTEM FOR BUNCH CLEANING

6.2.1 Setup Controller

In the **Transverse Feedback System** window, click on the **Bunch Cleaning** tab. Make sure that the vertical transverse feedback controller is in bunch cleaning mode. This is indicated by a green dot in the **Initialization** column, as indicated in Fig. 17. Verify that the **NCO Sweep Frequency** is **50Hz** and the **Output Power** is **-6dB**. If the vertical controller is not in bunch

cleaning mode, click **Setup** and wait until controller setup is done and the **Fine Output Delay** adjustment is finished.

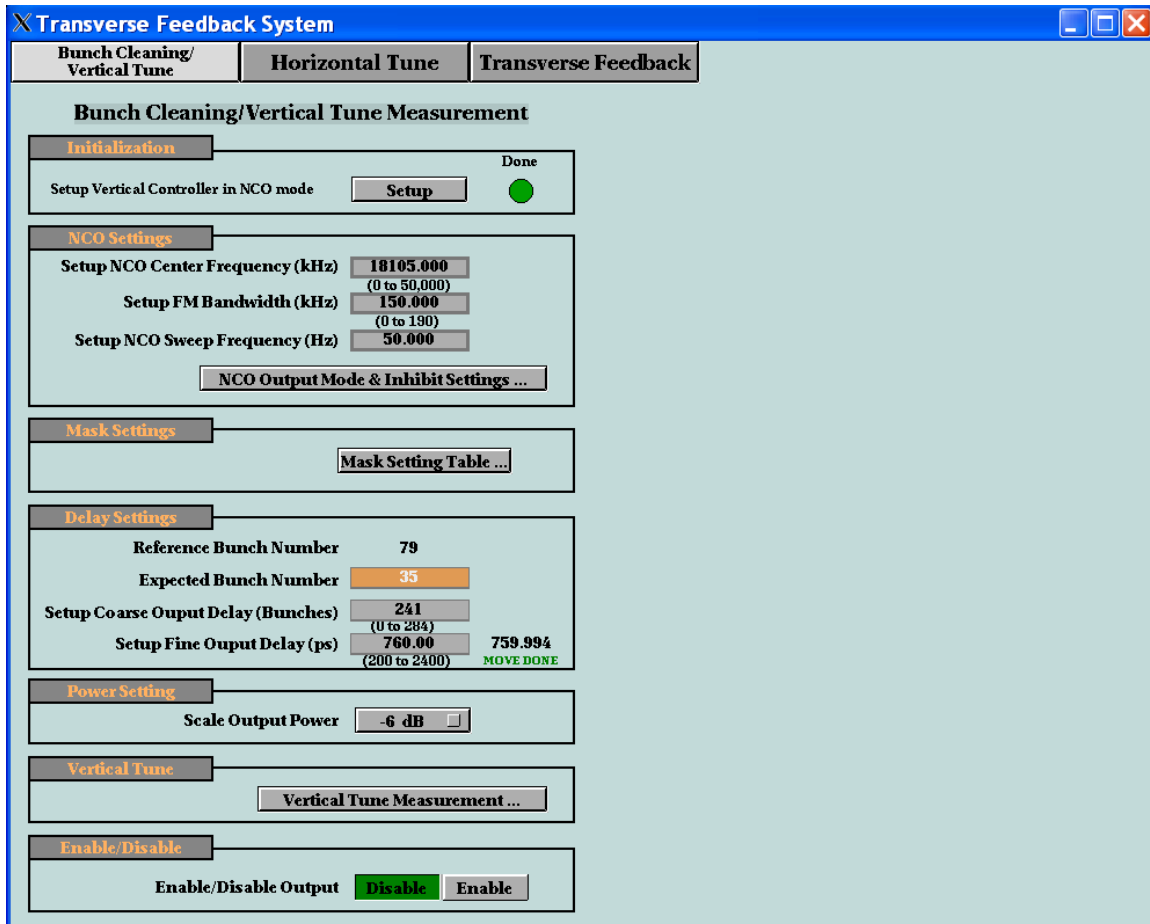


Fig. 17 Bunch cleaning control window

6.2.2 Calibration

To establish synchronization between the machine and the Libera Bunch-by-Bunch unit, the unit has to be calibrated with the fill pattern monitor. This calibration has to be performed again if the machine or the controller restarts. To calibrate the system, open the **Mask Setting Table** and send the bunch-selection mask as **-1: 2 to 143** and **+1: 144 to 285**. With this bunch-selection mask, a single bunch is going to be retained in the storage ring. After the cleaning processing, read the bunch number with the fill pattern monitor and enter this number as **Reference Bunch Number**.

6.2.3 Cleaning

After the calibration, the bunch cleaning system can be used to establish an arbitrary fill pattern. For example, the users might require a single bunch with a specific bunch number for the experiment. In such a case, enter the requested bunch number in the row of **Expected Bunch Number**. The other mostly used fill patterns include three equally spaced bunches and a bunch train with 35 bunches and a single bunch in the row of the empty buckets. The bunch-selection mask for three equally spaced bunches can be **-1: 2 to 95**, **+1: 97 to 190**, **-1: 192 to 230** and **+1: 231 to 285**. The bunch-selection mask for a bunch train with 35 bunches and a single

bunch in the row of the empty buckets can be **-1: 2 to 125** and **+1: 161 285**. The bunch position in these fill patterns can also be adjusted by changing the **Expected Bunch Number**.

6.3 HOW TO SETUP THE SYSTEM FOR TUNE MEASUREMENT

6.3.1 Setup Controllers

To setup the system for vertical tune measurement, click on the **Bunch Cleaning** tab in the **Transverse Feedback System** window. Make sure that the vertical transverse feedback controller is in bunch cleaning mode. Change **NCO Sweep Frequency** from **50** to **1000Hz** and scale **Output Power** from **-6dB** to **-12dB**.

To setup the system for horizontal tune measurement, click on the **Horizontal Tune** tab in the **Transverse Feedback System** window. Make sure that the horizontal transverse feedback controller is in NCO mode. This is indicated by a green dot in the **Initialization** column, as indicated in Fig. 18. If the horizontal controller is not in NCO mode, click **Setup** and wait until controller setup is done and the **Fine Output Delay** adjustment is finished.

6.3.2 Calibration

If a single bunch is to be excited for tune measurement, it is important to know which bunch is being excited. Therefore, both the vertical and horizontal controllers need to be calibrated. The calibration procedure for the horizontal controller is expected to be the same as the procedure to calibrate the vertical controller, which is described in Section 6.2.2. However, this calibration procedure has not been tested for the horizontal controller.

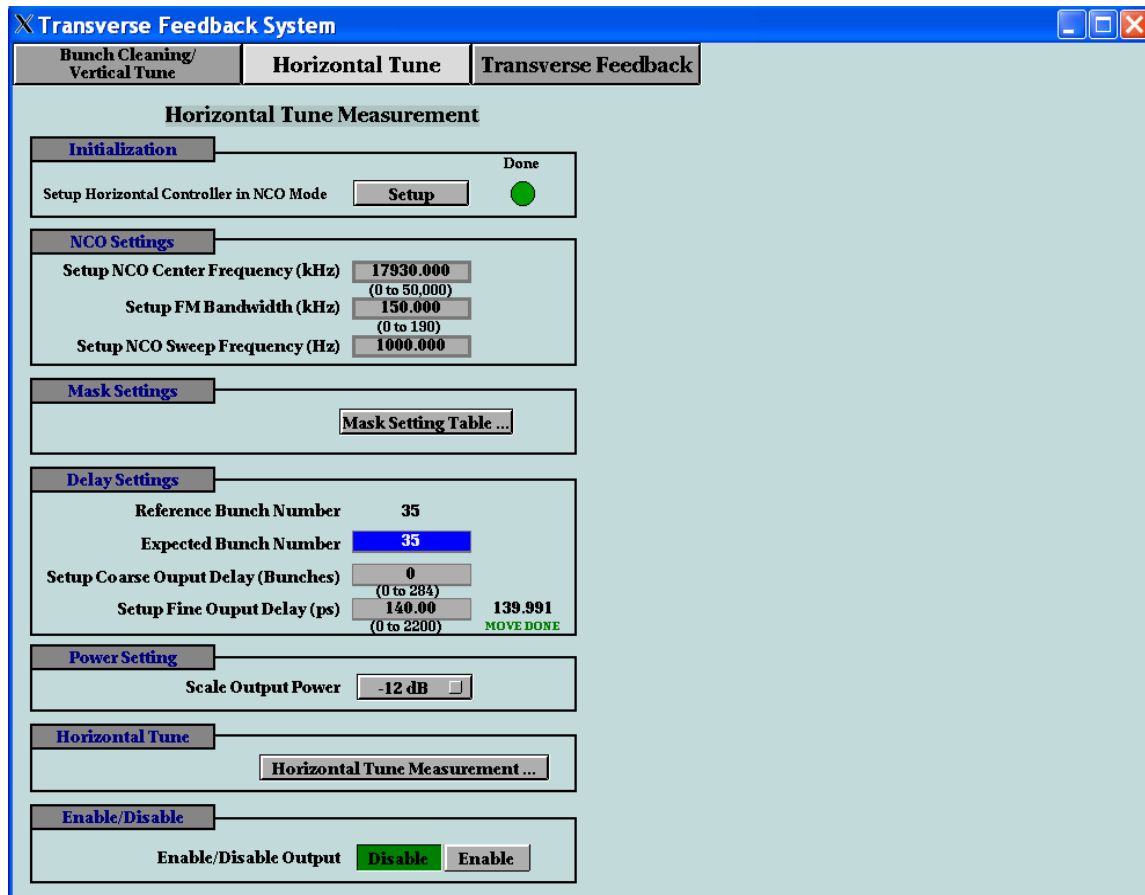


Fig. 18 Horizontal tune measurement control window.

6.3.3 Tune Measurement

To measure the horizontal/vertical tune, open the **Mask Setting Table** and set the mask as **+1: 1 to 1**. Select the bunch that is going to be excited by entering **Expected Bunch Number** and enable output. Open **Horizontal/Vertical Tune Measurement** window and click on **Start** to start data acquisition and analysis process. If the machine is running at low current, it is necessary to excite the whole bunch train for tune measurement. In such a case, the mask should be set as **+1: 1 to 285**.

6.4 HOW TO SETUP THE SYSTEM FOR TRANSVERSE FEEDBACK

In the **Transverse Feedback System** window, click on the **Transverse Feedback** tab. Verify that the transverse feedback controllers are in feedback mode. This is indicated by a green dot in the **Initialization** column in Fig. 19. If the controllers are not in feedback mode, click **Setup** and wait until controller setup is done and the **Fine Output Delay** adjustment is finished. Open **Horizontal/Vertical FIR Filter** control window and load appropriate filter coefficients by clicking on **3-tap**, **5-tap**, **7-tap** or **9-tap** in the **Coefficients** column. According to the tests we have performed so far, we haven't found any advantages of using 5-tap, 7-tap and 9-tap filters. Loading the basic 3-tap filter coefficients seems to be able to meet all the requirements of the transverse feedback system. Fig. 20 shows the horizontal FIR filter control window. Enable horizontal/vertical output and adjust **Output Power** to optimize the feedback performance.

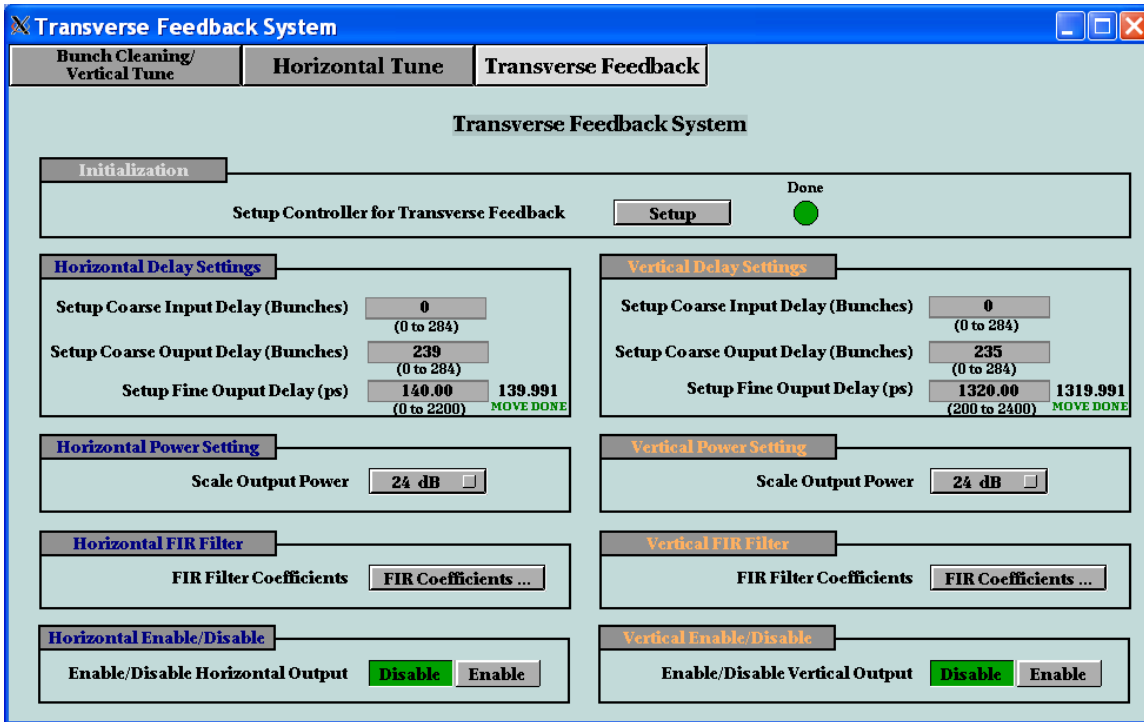


Fig. 19 Transverse feedback control window

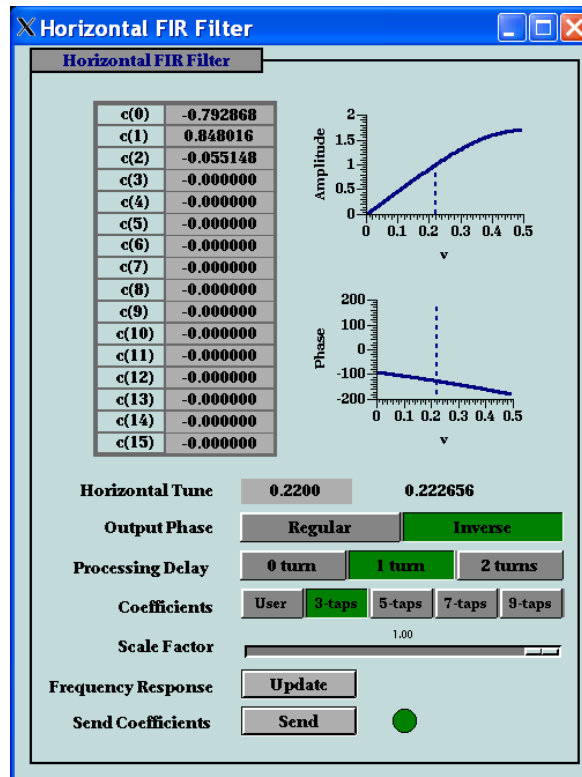


Fig. 20 Horizontal FIR filter control window

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