OPERATING PERFORMANCE OF THE LOW GROUP DELAY WOOFER CHANNEL IN PEP-II *

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Abstract

In PEP-II collider a dedicated low group-delay processing channel has been developed in order to provide high damping rates necessary to control the fast-growing longitudinal eigenmodes driven by the fundamental impedances of the RF cavities. A description of the digital processing channel operating at 9.81 MHz and capable of supporting finite impulse response (FIR) controllers with up to 32 taps will be presented. A prototype system has been successfully commissioned in the High-Energy Ring (HER) in May 2004. Operating experiences with the prototype and the newly determined limits on achievable longitudinal damping will be discussed and illustrated with experimental data.

INTRODUCTION

Accelerating RF cavities in PEP-II collider are heavily beam loaded and the detuning frequencies in operation exceed the ring revolution frequency. Left unchecked the fundamental impedance of these cavities would excite a very fast longitudinal coupled-bunch instability growth rate for the eigenmode -1 that is unfeasible to control. In order to avoid such strong instabilities PEP-II RF system is equipped with fast impedance reduction feedback loops [1]. These loops provide a significant reduction in the growth rates. However the fundamental-driven longitudinal instabilities are still much faster than the higher-order mode (HOM) driven ones.

Design of the PEP-II longitudinal feedback (LFB) and RF systems provides a path - the so-called woofer - for applying the lowest frequency correction to the beam via the RF klystron and cavity system for a significant gain boost in addition to the wideband kickers. In the operation of PEP-II collider with the continuous increase in stored beam currents the limitations of the existing topology became more and more evident. The main limitation came from the relatively high group-delay of the downsampled LFB processing which limited the achievable damping of the fast low-frequency modes. In addition a shared feedback channel with two different actuators involved a tradeoff between optimal settings for each of the kickers.

A separate low group-delay channel has been designed to separate the wideband and woofer processing - a low group-delay woofer (LGDW). A prototype system has been built, installed and successfully commissioned in PEP-II HER in May 2004 [2]. During the shutdown from August 2004 to March 2005 a production version of the LGDW was implemented and commissioned with beam in both HER and LER in April 2005. In this paper the design of the production system is described and the overall performance of the low group-delay channel is illustrated by the data from both the prototype and the production units.

HARDWARE DESCRIPTION

A block diagram of the low group-delay woofer is shown in Fig. 1. At the heart of the system is an off-the-shelf signal processing board [3]. The board has two identical baseband processing channels equipped with ADCs and DACs. Signal processing and control functionality is housed in two Xilinx XCV800-6 FPGAs. Each FPGA implements a 32-tap FIR filter with two switchable coefficient sets for seamless online controller tuning. Diagnostic features include missing clock detection, PLL lock status, and the FIR output saturation detector. Each FPGA has access to a $128\mathrm{K} \times 16$ memory that can be used to record beam motion. Both hardware (external) and software (internal) triggering is supported.

The analog processing modules implement appropriate band-limiting of the LFB phase detector output and provide the necessary offsets for the ADC and DAC signals. A set of 4 slow DAC channels is available in the system. Two of these channels are used to provide input offset nulling functionality in the front-end electronics.

The sampling clock of 9.81 MHz is generated from the 476 MHz RF reference using a PLL. At the selected sampling rate the low group-delay woofer acquires 72 samples per revolution and has ability to provide feedback control for the lowest 72 eigenmodes (modes from -36 to 36). The effective control range is lower and is determined by the bandwidth of the system actuator - the PEP-II RF system. With the direct feedback loop at nominal settings the closed-loop bandwidth of the RF system is 1.4 MHz allowing for control of the lowest 10 eigenmodes (-5 to 5).

Control and data acquisition interface to the low group-delay woofer is implemented via universal serial bus (USB) using FT245M USB FIFO. A communication protocol implemented in the FPGA and a software driver on the PC side present a high-level abstraction of the interface as a parallel memory-mapped system with 24 bit address and 16 bit data. The protocol allows transparent accesses from a single address to a large contiguous block. Data transfer rates via the interface are 800 kBytes/s for writes and

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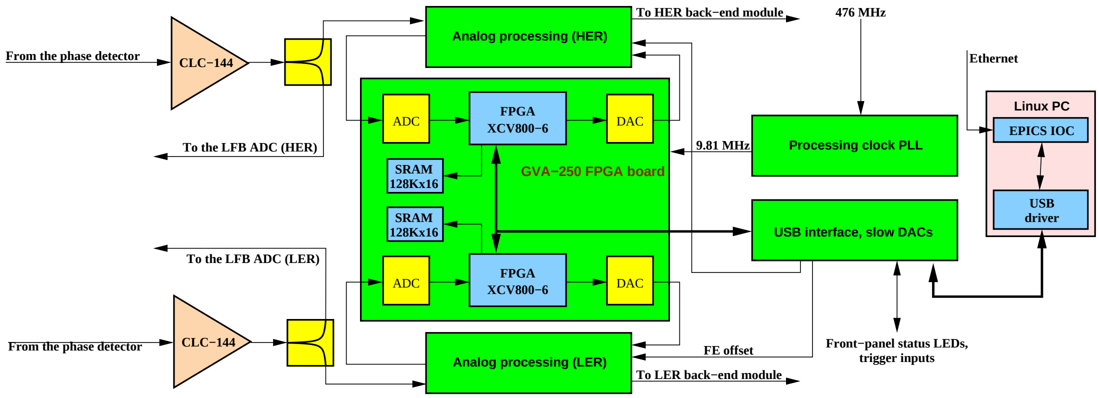

Figure 1: A block diagram of the low group-delay woofer

750 kBytes/s for reads of 128 kWord blocks.

CONTROL INTERFACE

The interface to the LGDW is built using an EPICS soft IOC running on a Linux server communicating to the hardware via USB. A single IOC controls both HER and LER woofer channels through their individual USB interfaces. User interface is implemented in the EDM. The main ring control panel has 32 entry fields for the filter coefficient set 0 or 1. Controls for data acquisition and memory reading and writing are included as well. Error monitoring on the main control panel includes detectors of missing processing clock, PLL unlocked error display, and the DAC saturation indication. All three error monitors are polled at 1 Hz rate and include resettable error counters.

The soft IOC can be set to measure a snapshot of beam motion at a given rate. Maximum duration of the acquired waveform is limited by the FPGA-accessible memory size to 12.8 ms. At the full memory length acquisition the IOC can support 1 Hz readout and post-processing of both the HER and the LER data. The rate is mostly determined by the USB data transfer speed where the full memory transfer takes around 0.34 seconds.

The transferred data vector is post-processed by the IOC subroutine to define four concise plots that are displayed in the waveform panel as illustrated in Figure 2. The first plot is the mean input signal around one revolution obtained by averaging each of the 72 samples per turn over all acquired turns. The data acquisition process in the LGDW is unsynchronized relative to the ring fiducial signal. However the IOC post-processing is designed to realign the data by determining the position in the mean signal with the largest derivative. For a normal ring fill pattern with an abort gap such realignment reliably places the beginning of the bunch train in sample 0. The second plot is the root mean square (RMS) value around the turn. Such display is very useful for determining the parts of the bunch train with marginal control or excessive feedback gain. The signal for the RMS computation is high-pass filtered by the IOC using a 10-tap FIR filter to remove 60 Hz line frequency and harmonics. Since the sampling duration is shorter than the line period of 16.7 ms the raw data shows significant RMS variation due to the unsynchronized sampling of the 60 Hz components in the input signal. Note that the RMS signal very clearly shows the difference between the filled macro-bunches with the RMS around 3 ADC counts and the empty macro-bunch (the gap) at 1.5 counts. The third plot is one of the 72 input channels (high-pass filtered) with the largest RMS value. Finally, the fourth plot shows a quadratically averaged spectrum of all 72 macro-bunch signals.

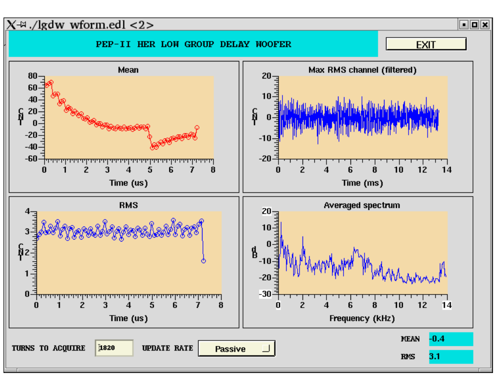

Figure 2: Beam data display for the HER

The IOC also computes the overall input signal average and RMS. The average value is used in an integral feedback loop that adjusts the slow input offset DAC to maintain the fast ADC signal centered.

OPERATING PERFORMANCE

Commissioning of the low group-delay woofer prototype in the HER allowed to raise the beam current from 1350 to 1550 mA. In development testing the LGDW demonstrated damping rates for eigenmode -3 of 3.5 ms^{-1} significantly improving the 2 ms^{-1} limit achieved by the LFB. According to an off-line system model we expect maximum achievable damping on the order of 10 ms^{-1}. Note that the interaction between the LGDW and the LFB described in the next section limits the allowable woofer

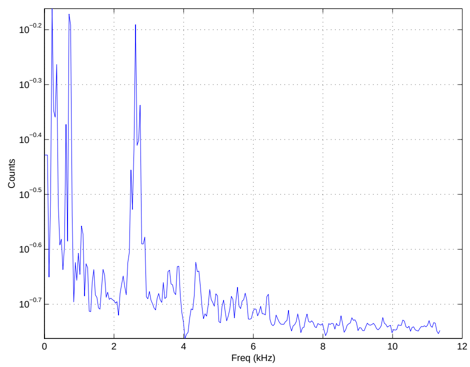

Figure 3: A steady-state closed-loop LER beam spectrum measured at 2050 mA via the LFB system

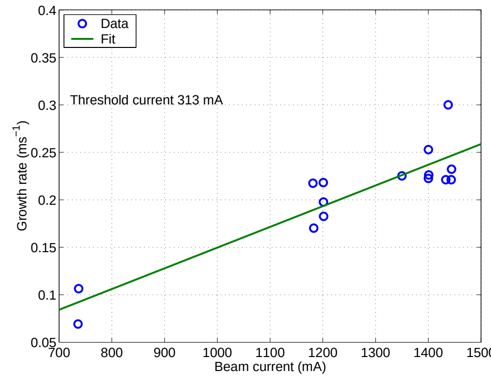

Figure 4: Growth rates of eigenmode 799 in the HER

gain and, as a consequence, the overall damping. That limitation is not critical at this stage of PEP-II operation since the achieved damping rates are still two to four times higher than the open-loop growth rates.

Figure 3 illustrates the performance of the LGDW in the low energy ring. At the synchrotron frequency of 4 kHz the high loop gain of the woofer channel creates a visible notch. Due to the high damping the synchrotron resonance is completely flattened barely rising above the noise floor. The externally driven noise line at 2.6 kHz is currently being investigated.

LFB AND LGDW INTERACTION

During the low group-delay woofer prototype commissioning in May 2004 an unexpected interaction between the bunch-by-bunch longitudinal feedback and the LGDW has been observed. We attempted to maximize the damping of both the LGDW and the LFB and encountered a situation where gains of both channels were limited below the expected levels. After analysis it became clear that the limitation comes from the LFB channel with its high group delay acting on the low-frequency modes which are already heavily damped by the LGDW. To maintain stability the operating gain of the low group-delay woofer had to be reduced to allow the LFB to operate at sufficient gain for HOM control.

HOM GROWTH RATES

LGDW provides a way to quantify the growth rates of the HOMs which in a single feedback configuration are notoriously difficult to measure since their growth rates are 4-5 times slower than those of the low modes. Thus in a single loop configuration open-loop transient growth is dominated by the fundamental-driven modes and to avoid beam loss one is forced to close the feedback loop before the HOMs have evolved above the measurement noise floor. With the two longitudinal feedback loops in operation one can perform the grow/damp measurement opening only the LFB loop so that the low frequency modes are controlled during the transient and the HOMs are allowed to grow.

Measurements of the HOM-driven eigenmode 799 in the HER are presented in Fig. 4. These rates reach 0.3 ms^{-1} and are well within the control range of the bunch-by-bunch longitudinal feedback system. A linear fit to the measured growth rates gives us firstly the threshold current estimate of 313 mA. Secondly the y-axis intercept gives us an estimate for the radiation damping time of 14.5 ms - close to the design value of 13.5 ms. Thirdly from the slope of the growth rate vs. beam current of $2.2 \times 10^{-4}\ \mathrm{ms}^{-1}$/mA we can estimate the driving impedance as 83.8 kΩ. The eigenmode in question is excited by a 0-M-2 mode in PEP-II RF cavities [4]. Bench impedance measurements quote a value of 2.29 kΩ per cavity [5] for a total of 59.5 kΩ.

SUMMARY

A low group-delay woofer channel for PEP-II has been successfully commissioned in both HER and LER providing a significant improvement in low-frequency eigenmode damping. The built-in data acquisition and signal processing features make the LGDW a valuable control room diagnostic tool.

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