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DEVELOPMENT AND TESTING OF A LOW GROUP-DELAY WOOFER CHANNEL FOR PEP-II *

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Abstract

The PEP-II High and Low energy rings require active longitudinal feedback to control coupled-bunch instabilities. The driving impedances originate from higher order modes as well as the accelerating fundamental impedance. The PEP-II RF systems use direct and comb loop feedback to reduce the cavity fundamental impedance, though the remaining low-mode impedance is providing the fastest growing unstable modes in both HER and LER. Since commissioning the longitudinal feedback systems have used a dedicated"woofer" channel to apply the low-frequency correction kick via the RF system. The performance of this original controller is limited by the maximum gain that can be supported due to the processing delay (group delay), as well as the difficulty in configuring a common correction controller that acts via two correction paths. A dedicated low-mode signal processing system has been developed to allow higher damping rates. It is a digital processing channel, operating at a 10 MHz sampling rate, and implementing flexible 5 to 14 tap FIR control filters. The design of the channel and initial control filters is presented, as are initial machine experiments quantifying the damping and noise floor of this low group delay woofer system.

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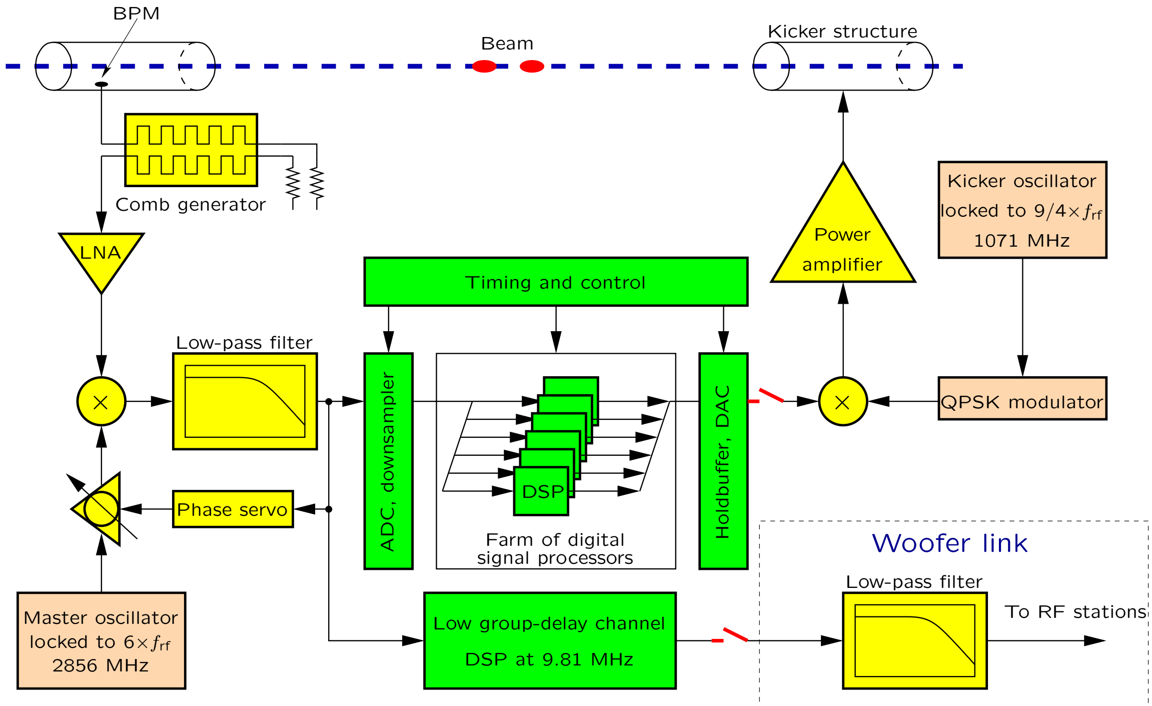

Figure 1: Block diagram of the broadband longitudinal feedback and the Low Group Delay Woofer channel, showing the interconnection and the independent processing of the bunch error signal. The LFB processes all bunches at the 238 MHz rate, while the LGDW processes macrobunch (bandlimited) bunch phase information at a 9.81 Mhz sampling rate

1 Introduction

The LLRF systems in PEP-II implement direct and comb loops to reduce the cavity impedances driving coupled-bunch longitudinal motion. However, the residual impedances still drive unstable low-mode motion at currents above 150 or 200 mA. The broadband longitudinal feedback systems sense this motion, and the broadband correction signal applied to the beam via the broadband kicker helps suppress these instabilities. The original PEP-II LFB and RF design allows the lowest frequency correction to be fed back to the beam via the most effective kicker in this frequency band - the RF klystron/cavity system.

As operating currents have increased the limits of low mode control, and general limits to stability margins, have become evident in the HER and to a lesser extent LER [1]. The HER has added 3 klystrons and 6 accelerating cavities to the original complement of 5 klystrons and 20 cavities. The additional impedance added to the rings, plus the increased operating currents, have driven the development of a special dedicated woofer control path - the Low Group Delay Woofer (LGDW) [2].

2 Low Group Delay Control Filter

The essential control function of the woofer processing channel is to extract a signal component from the broadband longitudinal feedback front end error signal, and generate a correction signal of appropriate gain and phase to sum into the LLRF processing stream. From Fig #1 the LGDW bandlimits the LFB wideband detected bunch phase signal and digitizes the signal using a 9.81 Mhz clock phase-locked to the RF system (72 samples/revolution). The digital stream is processed in a programmable 14 tap FIR filter FPGA using 12 bit data samples with 16 bit coefficients. The filter output is converted back to analog form and passed to the broadband feedback back-end module, which transmits a digital data stream via fiber optic links to the PEP-II RF stations [3]. The 72 samples/turn act as 72 independent feedback channels - in effect the system acts as a macrobunch by macrobunch feedback controller.

The filter includes saturation logic as well as overall normalization (shift gain) functions. Figure #2 shows tap weights and frequency responses for a typical useful control filter. The filter provides DC rejection (sum of tap coefficients is zero) as well as control of the gain and channel phase at the synchrotron frequency. Note that, due to the low group delay response, the filter maximum gain is above the 6 KHz synchrotron frequency, and so the channel is sensitive to out of band (8 to 18 KHz) noise or coherent signals on the beam which can saturate the processing. If the filter center frequency and maximum gain were centered on the synchrotron frequency the delay in the filter channel (the group delay) would concomitantly increase.

This example control filter (14 taps) has a system group delay of roughly 66μsec. (the filter delay plus a 7.3μsec. revolution before the signal is applied by the RF system). By comparison, the broadband feedback system, running an 8 tap filter (but with a downsampling factor of 6) has an system group delay of 170μsec. The LGDW channel allows higher gains (the filter loop itself is stable at the higher gains required to control fast-growing instabilities). An additional benefit is that the woofer filter gain and phase can be optimized independently of the filter characteristics of the HOM control path. These extra degrees of control flexibility is advantageous for both HOM and low-mode control performance and robustness.

3 Implementation

The LGDW prototype has been built using a commercial FPGA development card [4]. The PEP-II FIR implementation was coded using Verilog, and includes a 64Ksample diagnostic memory which can under software control record bunch motion or play out drive sequences for testing/machine experiments. The FPGA design allows two resident sets of filter coefficient files, with a mechanism to select between them based on either logic input or software command. In practice the existing LFB grow-damp record and drive functions, as well as the LLRF fault files, serve as mechanisms to evaluate the performance of the LGDW channel. This approach maximizes the existing software and machine diagnostics investment in the LFB/LLRF systems, however a unique control path was implemented for the LGDW.

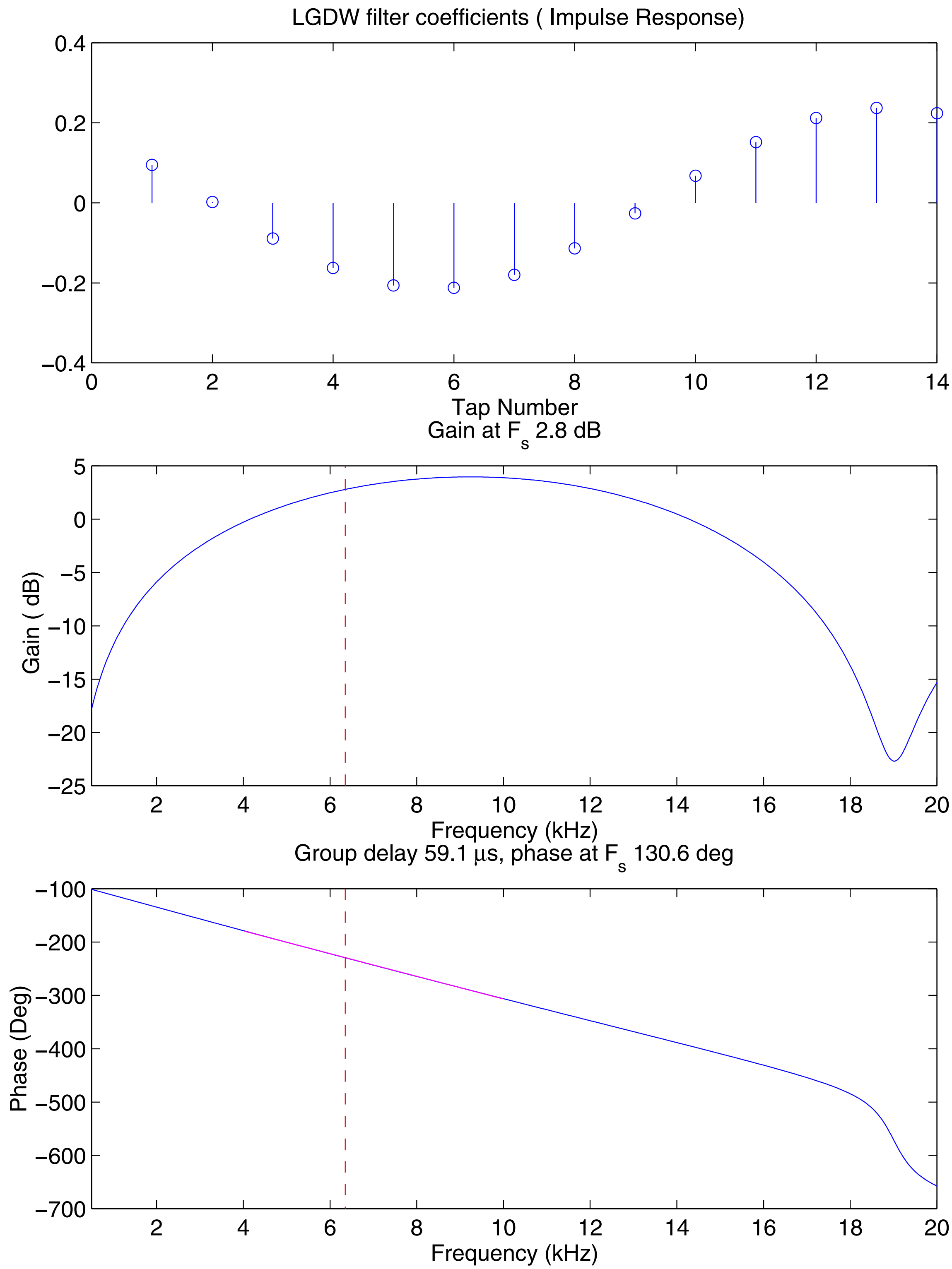

Figure 2: Magnitude and phase responses for a 14 tap FIR filter for the low group delay processing channel. This filter is designed for the PEP-II HER, with a synchrotron frequency of 6.35 KHz. The low group delay filter provides the damping phase shift of 90 degrees at this frequency (including delays in the RF path), though the maximum gain of the filter is found at 12 KHz

Rather than using the VXI packaging of the LFB and LLRF systems, and the VxWorks/EPICS software environment, the LGDW prototype was pragmatically constructed as a stand-alone chassis containing the analog buffer circuitry PC cards plus the commercial FPGA processing card. Control and configuration is via a simple byte-wide parallel port interface to a PC based IOC. The IOC runs Linux and is network accessible via EPICS channel access protocols. A set of top-level operators panels, coded in EPICS, allow the specification of the filter coefficients, the selection of the gain normalization, etc. A save/restore function allows operators to reconfigure the channel as needed to match RF configurations with varied synchrotron frequencies. By using a snapshot recording technique it is possible to measure the rms motion of the beam while the system is in operation.

4 Commissioning of the low group delay woofer

The prototype system was initially tested in December 2003, and an operational prototype was commissioned and installed in the PEP-II HER in April 2004. The commissioning required the optimization of the LGDW channel filter, and the interaction with the broadband feedback requires careful gain partitioning between the two systems.The LGDW has more effective gain for low modes than the broadband all-mode system system but the interaction is not negligible and a useful gain partitioning between the two is required. The commissioning effort included a study of the noise floor in the damped channel to understand saturation effects and the development of bandpass control filters to resistivly damp the low modes in the cavity system. The most sensitive means for adjusting the woofer filter phase and gain is through grow-damp measurements which show the action of the feedback in the damping rate as well as any tune shift.

5 Experimental Results

As part of system commissioning a series of transient-domain instability measurements were taken in the HER at currents up to 1350 mA. Fig. # 3 presents open loop and closed loop measurements over the 700 to 1300 mA range for mode -3 (at these currents due to cavity detuning mode -3 is the most prominent, though a band of low modes is unstable). The growth rates reach roughly 1 ms^{-1} at the 1300 mA current, while the net damping is seen to be roughly 3 ms^{-1}. There is 300 Hz of tune shift between open-loop and closed loop responses at these high loop gains.

For comparison, the damping rates achievable with the original woofer channel (derived from the broadband channel computed correction signal) are roughly 2 ms^{-1} under similar operating conditions. This 50% improvement in damping rates is very significant in allowing abort-free operation of the machine at high currents, and generally allowing greater perturbations and operational margin without the risk of loss of control followed by a beam abort.

With the independent control of the low mode channel through the LGDW it is now possible to do two types of grow-damp measurements. Referring to Fig. # 1, it is possible

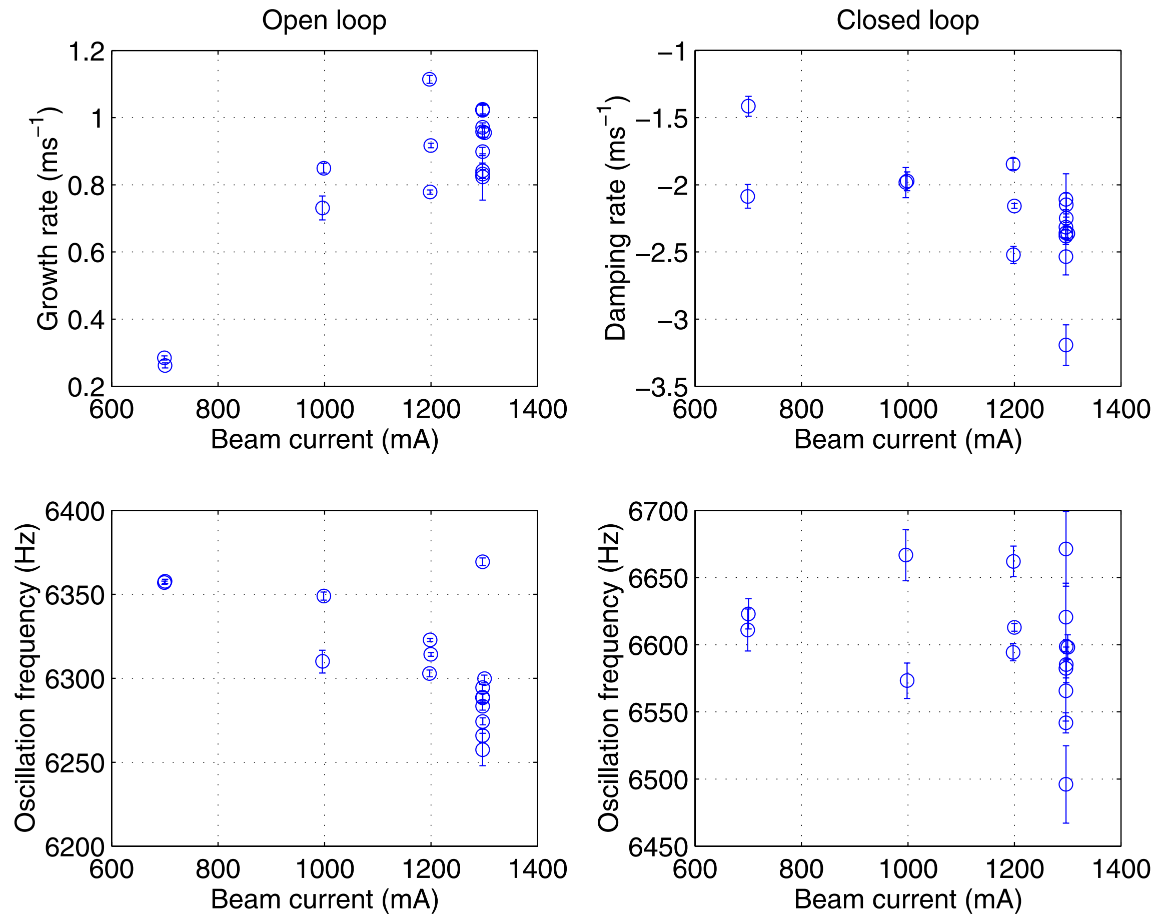

Figure 3: Open-loop growth rates and closed-loop damping rates vs. current for mode -3 in the HER.

to open the control paths through both the LGDW and the broadband feedback, in which case the free motion observed may contain all coupled-bunch modes of the machine. In practice, the fastest-growing modes dominate, and in PEP-II these are all within the RF cavity bandwidth. Measurements done this way give information about low modes, but it is difficult to measure growth/damping from HOM impedances this way, as these are typically smaller and do not grow appreciably in the transients dominated by the cavity fundamental impedance. One technique we have used is to excite known HOM modes to a finite amplitude before doing a grow-damp sequence [5] - but the configuration of the LGDW channel allows an independent measurement of HOM impedance effects by opening the control path in the broadband channel while maintaining the control path through the LGDW. In this technique the HOM-driven instabilities are studied while low modes remain in control. It is not useful to try to open the LGDW control path while keeping the broadband path closed - as the broadband path still has significant gain at the low modes.

One operational benefit in controlling the low modes through the LGDW is that the dynamic range of the LGDW processing, including the RF path through the LLRF system, is greater than through the broadband system. This means that small transients from injections, RF transients or recovery of free grow-damp measurements, are much less likely to saturate the processing, and regaining control of the beam is possible from larger modal amplitudes. This effect makes operation of the system less sensitive to saturation effects and makes the measurement of these rapid growth rates easier, more consistent with a higher measurement SNR.

6 Summary and Future Directions

This prototype processing channel was installed in the HER in April 2004 and has allowed the increase of HER operating current from 1350 mA to over 1550 mA. Beyond allowing this current increase, it has allowed more operating headroom in the processing channel, and allows independent measurement of HOM growth rates previously largely masked by the fast growing cavity-driven modes. The development of the FPGA based channel, using the Verilog tools, and the implementation of the PC-based Linux IOC, with EPICS user interface has created a very solid foundation to build a more sophisticated production LGDW channel. This effort is underway and should be completed in Fall 2004. The production LGDW channels will be based on a larger FPGA platform, and will use the same EPICS-based user interface. These production channels will add functionality through more complex filter channels (up to 32 taps at the 9.81 MHz sampling rate) and also implement some additional beam diagnostic functions as well as periodic beam motion snapshots, a beam kick rms detector, and programmable drive functions.

7 Acknowledgments

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References

[1] P. McIntosh, et al. "PEP-II RF System Operation and Performance," Proc. European Particle Accelerator Conference, Lucerne, 2004

[2] L. Beckman, et al, " Low Mode Coupled Bunch Feedback Channel For PEP-II," Proc. Particle Accelerator Conference, Portland, 2003

[3] A. Young, et al, "VXI Based Multibunch Detector and QPSK Modulator for the PEP-II / ALS / DAΦNE Longitudinal Feedback System" Proc. Particle Accelerator Conference, Vancouver, 1997

[4] GV & Associates, Inc. Ramona, CA

[5] D. Teytelman, et al, " Accelerator Diagnostic Techniques Using Time-Domain Data from a Bunch by Bunch Longitudinal Feedback System" Proc. 3rd European workshop on Beam Diagnostics and Instrumentation for Particle Accelerators (DIPAC 97), Frascati, 1997