CONTROL PATH OF LONGITUDINAL MULTIBUNCH FEEDBACK SYSTEM AT HERA–p

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Abstract

A longitudinal broadband damper system to control coupled bunch instabilities has been developed and installed in the 920 GeV proton accelerator HERA–p at DESY. The control path consists of a FPGA–based digital controller, a vector modulator, a 1 kW power amplifier, a kicker-cavity and the beam itself. The bunch phase signals are sampled by a digital FPGA board with 14 Bit ADCs and 10.4 MHz. Phase calculation for all bunches and offset correction is done by a digital filter realized in FPGA software. The filter has to deal with a slowly changing synchrotron frequency. Here we considered a filter design which treats each of maximum 220 bunches as an independent oscillator which has to be damped. With the FPGA–board output signals a 104 MHz sine wave is modulated. The resulting logitudinal correction kick signal is provided by the kicker-cavity to kick the proton bunches each with its correction kick voltage. Besides the technical details we present first operational experience and the actual system performance in a series of 3 papers (see also [1, 2]).

INTRODUCTION

This paper is part 3 of the series of 3 papers describing the recently successfully installed Longitudinal Multibunch Feedback system (LMBF) at HERA–p. The goal of the longitudinal broadband damper system is to reduce the proton bunch lengths and thus to increase the specific luminosity at the two experiments ZEUS and H1. The beam consists of maximum 220 proton bunches which have to be controlled independently with respect to longitudinal coupled bunch oscillations. Without additional damping of bunch instabilities the bunch length is 1.5 ns or larger at the beginning of a typical luminosity run. Theoretically the bunch length should go down to 0.8 ns, but coupled bunch mode instabilities occur on the acceleration ramp, when the bunch length decreases below 1.5 ns which blow up the beam.
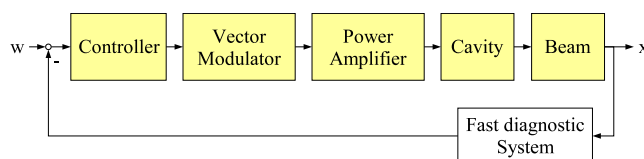

Figure 1: Feedback control loop.

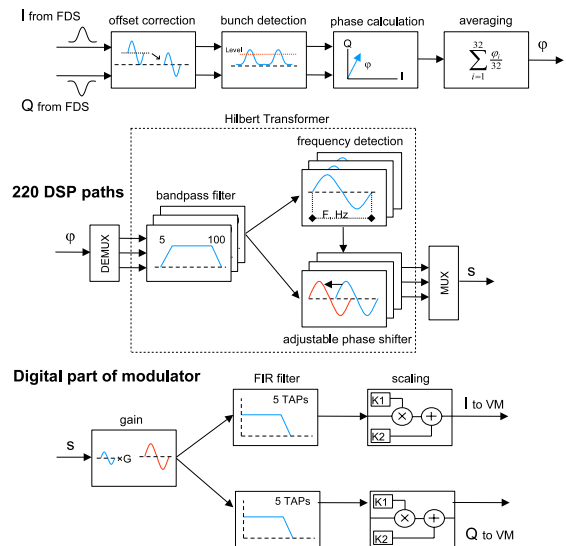* corresponding author: frank.eints@desy.de

Figure 2: Controller algorithm.

The main components of the longitudinal broadband damper system are the controller algorithm implemented in a FPGA–board, a vector modulator (VM), a 1 kW power amplifier, a kicker cavity [2] and a fast longitudinal diagnostic system (FLD) for oscillation and performance diagnostic [3]. Figure 1 illustrates the LMBF control path from the engeeneering point of view.

CONTROLLER

The controller consists of 220 time–multiplexed feedback loops. The controller algorithm can be subdivided into three parts: signal conditioning, 220 independent digital signal processing pathes and the digital part of the modulator, which already prepares for the modulation of the kick-signals. A block diagram of the controller algorithm is shown in figure 2.

The I and Q signals – which contain the amplitude and phase information of the bunches in respect to the 52 MHz reference signal – are provided by the FLD analog hardware by demodulation of the 52 MHz component of the bunch pickup signals and are sampled by the digital hardware with 10.4 MHz. An analog signal offset correction is done independently for all bunches, because each bunch has a different and constant offset during one run period. Bunch detection means to verify whether the I or Q value is above a user defined level. If I or Q value is above

the preset level it will be feed through to the phase calculation unit. If I and Q value are below the user defined level, constant values are provided to the phase calculation unit. The calculation of the picked up phase is done by an arctan(I,Q) algorithm available in FPGA firmware. To reduce phase noise and the internal sample rate a 32 element average is calculated. A demultiplexer then splits the signal up into 220 independent digital signal processing pathes. Each bunch signal is bandpass filtered to reduce noise and Hilbert transformed. The filter has to be able to deal with slowly changing synchrotron frequency (20...80 Hz) [1]. The frequency of the bunch oscillation is detected by the zero-crossing method, where half a signal period is measured and inverted to obtain the frequency. For delay correction an adjustable phase shifter is also implemented here. Then the signal is multiplexed to the output stream.

This digital part of the modulator was extended from two 2–TAP FIR filters, which are essential for the method used for modulation, to 5–TAP FIR filters with additional coefficients for compensation of the unwanted dynamic errors of the power amplifier which turned out to have a slightly nonlinear transfer function. From the correction values for each bunch new I and Q values are calculated and distributed to the inputs of the following analog vector modulation.

Since the bunch distance is 96 ns the bunch signals are sampled with 10.4 MHz sampling rate. Each single bunch is sampled with a rate of 47 kHz, which is the revolution frequency of HERA. The full range of I and Q signals is sampled with 14 Bit resolution. The phase precision for a single bunch sample is about 0.2 degrees due to the noise of the analog signal path and about 0.004 degrees by digital resolution. Therefore the signal conditioning implies averaging over 32 revolutions to improve the signal quality. The internal sampling rate (for one bunch) is therefore reduced to about 1.5 kHz, which is enough for synchrotron frequency detection (20 to 80 Hz) and for generation of the correction signal.

CONTROL PATH COMPONENTS

The VM modulates the 104 MHz reference sine–wave signal with the new calculated I and Q controller output signals. Figure 3 demonstrates the operation principle of the VM.

The 52 MHz HERA–p reference signal is frequency doubled by a diode, filtered by a bandpass filter to improve the noise performance and amplified to adjust the required power level. Then the 104 MHz signal is branched by a power splitter and phase shifted to each other by 90 deg. In principle the VM consists of two 4–quadrant voltage output analog multipliers (AD835) with low multiplier noise from Analog Devices which generate each a linear product of its sine and cosine input signals. The modulated I and Q signals are combined and fed to the 1 kW power amplifier. The 60 dBm–tube amplifier amplifies the VM output
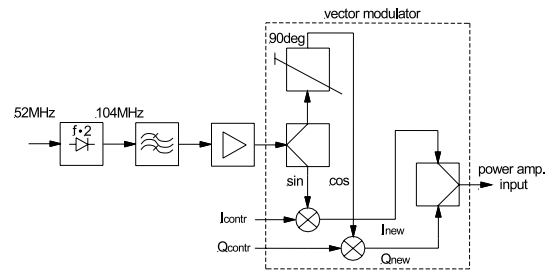

Figure 3: Analog part of the vector modulator.

signal to drive the a kicker cavity. Simulations have shown that in order to control longitudinal proton bunch oscillations approximately 56 to 57 dBm cavity input power will be required. To ensure optimized driving of the amplifier, its transmission characteristic has been measured.
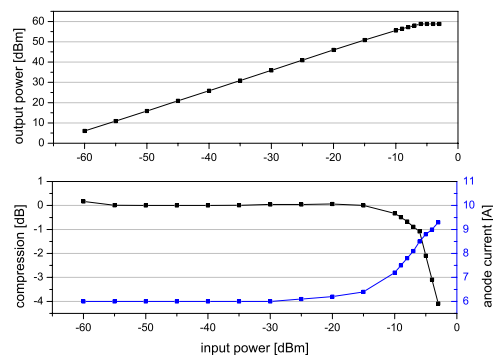

Figure 4: Amplifier transmission characteristic.

The figure 4 shows amplification, compression and anode current characteristics of the tube amplifier. The measured maximum output power is 58.8 dBm. By calibration of the anode current the tube operation point has been adjusted. Figure 5 shows the modulated and amplified correction kick signal (blue curve).
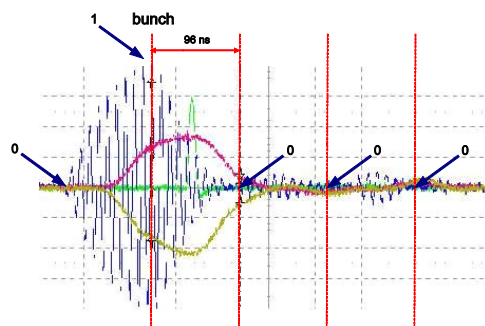

Figure 5: Power amplifier output.

The red and the yellow curves are the demodulated I and Q signals from the correction kick signal. Times where a bunch will pass the kicker cavity are marked.

The minimization of the amplifier ringing has been done

by adjusting filter coefficients of the two 5–TAP FIR filters. In order to not add coupling and ringing to the bunches, the kicker output signal needs to have reached zero after the kick within 96 ns. Also following bunches at multiple of 96 ns must not see any of the signal decay.

In the LMBF the kicker cavity is serving as an actuator. It is designed as a single cell quarter wavelength coaxial line cavity. The cavity has a resonance frequency of 104 MHz, a bandwidth of 7.9 MHz (Q = 13.2) and a shunt impedance of 2780 Ω. [2]

The LMBF controls bunches with regard to amplitude and phase. Thus control path components had to be characterized according to time constant and gain. The table 1 shows the gain and dead time of LMBF components and the used RF–cables. For RF–cabling of the LMBF CELLFLEX low loss foam–dielectric coaxial cable has been used. The 1/2˝and 7/8˝coaxial cables have losses of 2.2 dB/100 m and 1.2 dB/100 m at 104 MHz respectively.

Table 1: Characteristic values of control path.

module	gain	dead time
FPGA–board	variable	
vector modulator (VM)	4.5 dB	
cables VM to amplifier (140 m)	-3.08 dB	700 ns
power amplifier	65.9 dB	60 ns
cables amplifier to cavity (30 m)	-0.36 dB	150 ns
kicker cavity	-0.5 dB	
overall	66.46 dB	910 ns

The overall gain and dead time from the VM input to the cavity output is 66.46 dB and 910 ns respectively.

COMMISSIONING OF THE LMBF

Commissioning of the LMBF includes not only to check the RF–cabling with regard to RF–power distribution, to adjust the required input power levels of the control path components, to tune the cavity resonance frequency finally or to test the power amplifier remote control. An essential part of the LMBF commissioning is the timing adjustment of the controller input and output signals. The controller input sample time has to be synchronized to the 52 MHz signal of the RF–system. Additionally the controller has to be synchronized to revolution frequency of HERA–p (47 kHz). Figure 6 demonstrates the controller output timing adjustment.

The controller output signal has to be synchronized to 104 MHz, which is derived from the 52 MHz signal of the RF–system. For the controller output timing adjustment HERA–p was filled with one bunch train of 10 bunches and only one correction kick signal generated. The blue curve shows the transients of some proton bunches of the bunch train and the correction kick signal, which kicks the first bunch. The red and the yellow curves are the demodulated I and Q signals of the transient longitudinal kicker
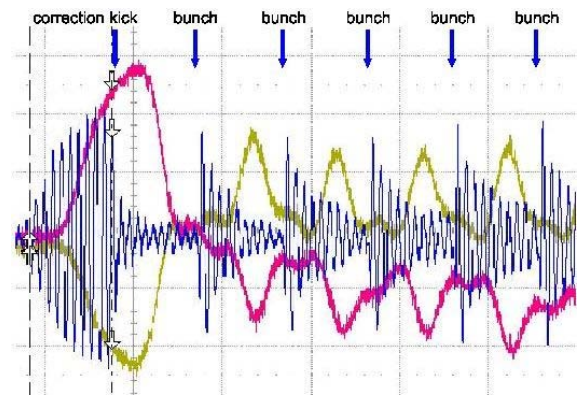

Figure 6: LMBF timing adjustment.

signal. The kicker signal has to be delayed to hit the proton bunches when they pass the gap of the kicker cavity. With a minimum time resolution of 9.6 ns the controller has shifted the longitudinal kicker signal as close as possible to the first bunch of the bunch train. The fine tuning of the timing has been done by variation of the VM output cable length.

OPERATION

In February 2006 the LMBF has been started up successfully. First operation results have shown that the system can reduce the initial bunch length at least from 1.5 ns to 1.0 ns. When the LMBF is switched off the beam is not excited by the kicker cavity through of beam loading. The feedback noise of $\approx$1 V cavity gap voltage can be neglected. The further goal will be to slow down the bunch lengthening over hours. To achieve this the improvement of the LMBF noise performance may help. This can be done by the implementation of a more sophisticated filter in the controller. For further studies the measurement of the loop gain and the beam response function is planned. This can be done by integration of a frequency controlled digital oscillator into the FPGA software, which enables the dedicated exciting of a single bunch while measuring the response of all bunches.

REFERENCES

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