PERFORMANCE OF THE NEW COUPLED BUNCH FEEDBACK SYSTEM AT HERA-P

J. Randhahn*, S. Choroba, F. Eints, U. Hurdelbrink, M. Hoffmann, P. Morozov, Y. Nechaev, S. Ruzin, S. Simrock, V. Soloviev, DESY, Hamburg, Germany

Abstract

A longitudinal broadband damper system to control coupled bunch instabilities (LMBF) has been installed in the 920 GeV proton accelereator HERA-p at the Deutsches Elektronen-Synchrotron DESY in Q4/2005. This was one of the attempts to increase the specific luminosity at HERA by reducing the bunch length.

The feedback system is based on a single board FPGA (field programmable gate array) with two ADCs and 2 DACs (each 14 bits resolution) at 52 MHz sampling rate. It was fully automated, in order to relief the operator from manual control during system operation.

During comissioning in Q1/2006 it turned out that the performance goals were reached and the noise introduced due to the feedback corrections and the 1 kW power amplifier was not as much a problem as expected. The proton bunch length is significantly reduced as well as the lengthening of the bunches over runtime since all formaly occuring coupled bunch instabilities could sufficiently be suppressed during the enegergy ramp and the following luminosity run.

System optimization points were found in automatic gain adjustment during acceleration ramp, oscillation level triggering and timing of kicker pulse to bunch.

HERA-P

The layout of HERA-p and all preaccelerators together with their typical fill patterns is shown in [1].

Considerable archived data have been analysed to reveal, which coupled bunch instability modes occur and at what strength. We frequently observed modes 5 and 11 at lower energies, but also very often the mode 164 (HERA has 220 bunch positions) which lead to bunch length blow up at $\approx$ 300 GeV and at $>$ 670 GeV (see [2, 3] and [1]). Growth times of the instabilities are typically more than 2 seconds, hence, a relatively moderate kick voltage ($\sim$ 200 V) is sufficient to damp the oscillations. The synchrotron frequency of HERA-p is typically 35 Hz but can vary from 20 Hz to 80 Hz during acceleration.

Without additional damping the bunch length is about 1.5 ns (FWHM) at the beginning of a typical luminosity run depending on the fill pattern and beam current. With the new feedback system in operation the bunch length could be decreased to 1.0 ns at best (1.2 ns typically, see Fig. 4). Although the bunches get longer during the luminosity run, the integrated luminosity gain is thus up to 5%.

* jean.randhahn@desy.de

THE FEEDBACK SYSTEM

The actual feedback design consists of a fast, high precision bunch centroid phase detector, a 1 kW feedback cavity with 104 MHz centre frequency and 8 MHz bandwidth (FWHM), an I/Q-vector modulator, the low level digital FPGA-board with 14 Bit ADCs and DACs and a cavity transient diagnostics (Fig. 1, see also [1]).

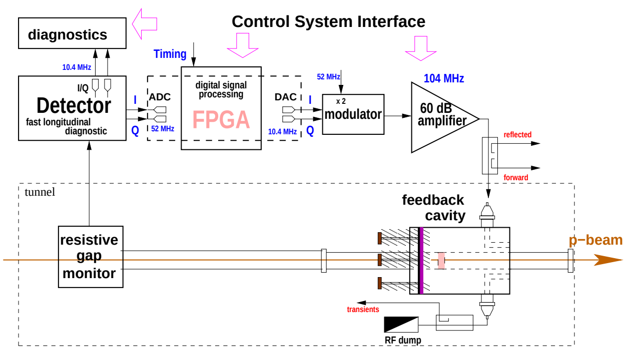

Figure 1: System components of the HERA-p longitudinal coupled bunch feedback system.

The feedback system measures the phases of all bunches and calculates corrections in real time (bunch spacing: 96 ns) which are then applied to the beam via a longitudinal feedback kicker. The controller has to be able to deal with a slowly changing synchrotron frequency (20–80 Hz).

The high precision bunch phase detector has been in operation since 2003. It was designed as a fast logitudinal diagnostics system [2], and its analog RF hardware is now also used for the feedback system. It consists of a 4 GHz bandwidth resistive gap monitor, a 52 MHz bandpass filter with about 30 MHz bandwidth and a 52 MHz I/Q-demodulator.

The controller algorithm

The I and Q components of the bunch signals are sampled by 14 bit ADC's with a rate of 52 MHs which is five times the bunch frequency (10.4 MHz). This oversampling allows baseline reconstruction and signal offset removal. The phase calculation for all bunches is done by FPGA software. It includes a multiplexer and 220 independant digital filters to produce the correction kicks (see Fig. 2). The controller algorithm has to be able to deal with a slowly changing synchrotron frequency (20–80 Hz). The details of the algorithm are presented in [4] and [1].

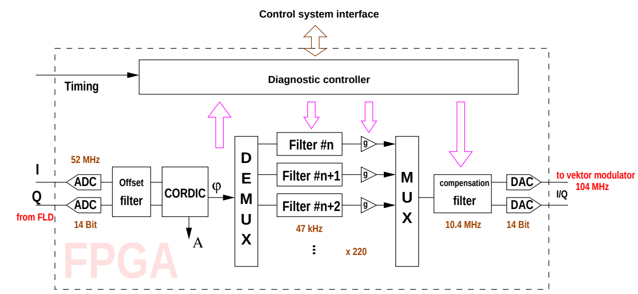

Figure 2: Details of the algorithm implemented in FPGA.

The Feedback Kicker Cavity

We have chosen a 1 kW feedback kicker cavity design with a center frequency of 104 MHz (which is 10 times the bunch frequency, correspondig to a bunch spacing of 96 ns, for details of the kicker design see [5]). The correction kick signal produced by the controller algorithm therefor has to be modulated to a 104 MHz carrier frequency. The modulation principle used works with a cavity of any bandwith if the available power is unlimited. In our case a bandwidth of 8 MHz ($Q = 13$) was realized by externally loading of the cavity with a 50 Ohm wave dump.

The Cavity Signal Modulator

To use full capacity of the kicker system we invented a modulation method which is a combination of digital signal processing and an analog vector modulator. The digital part of the modulator is calculated by the FPGA. The board produces two streams of output which then go to the vector modulator. Its input is calculated in such a way that each bunch sees the desired voltage on top of the 104 MHz sine wave when it passes the kicker. This ensures no waste of power of the feedback amplifier and also makes the kick voltage insensible to individual phase deviations of the bunches due to transient beam loading. The modulation method is straight forward and a simple digital FIR filter with analytically obtained coefficients was used to implement it. The coefficients were finally optimized by measurements to correct for imperfections of the power amplifier. The modulation method then worked pretty well without additional adjustments. The details of the modulation method used for the first time in an multibunch feedback systems are worked out and presented in [6].

The Feedback Middle Layer Server

The feedback server communicates directly with the FPGA-board with the use of the standard libraries supplied with Nallatech's DIME motherboards. The server communicates with the outer world through the TINE protocol to supply the LMFB parameters to the state machine and to the console application. Some of the properties are declared as *writable* to enable the console and state machine to control the FPGA-board's state: to set the amplifier gain, the oscillation level (level above which the phase values for one bunch are considered as valid, means that there is a bunch oscillating here) etc. or to send a command to the feedback server (for example, open or close feedback loop, load/save settings from/to a file an so on).

Figure 3: User interface of the longitudinal coupled bunch feedback system at HERA-p.

Automation

A state machine was implemented as one additional server process which automates the standard operating of the LMFB system. It detects the current state of HERA (from the point of view of LMFB system's settings) by evaluating several global parameters. The *condition matrix* (read from a configuration file) defines a number of states of HERA according to the current values of energy, current and bunch length. To each state correspond the values of the feedback gain and oscillation level to be set at this state. This *settings matrix* is also read from the configuration file. Whenever the state machine detects that the state of HERA has changed, it performs an action according to the *transition matrix*, which contains the information what to do in such a case (open/close feedback loop, set power amplifier high voltage ON/OF, set gain/oscillation level to the right values). When the operation mode of the state machine is set to *Auto*, the command is sent to the feedback server to make the needed actions. If the operation mode is *Manual*, such actions may be fulfilled by an operator from the console application or with the buttons on the graphical user interface (see Fig. 3).

Console Application User Interface

A comfortable display program, written with Visual Basic 6.0 and running on WINDOWS XP workstations was developed both for the control room and offices. There are 5 presentation forms (Fig. 3) which are used to control the parameters of LMBF (about 20 parameters) and to display the current status of the system (about 25 params.), including simultaneous display of the status of each of all possible 220 buckets. Various standard ACOP graphic features and distributions have been implemented as well.

The software completely carries out the automatic control over dynamics changes of LMBF parameters, but the user at any moment can interfere and correct the working mode of the LMBF system. The console application was most actively used during the choice of parameters and algorithms of management and tuning of the hardware of LMBF. Now the system works in an automatic mode.

OPERATION AND PERFORMANCE

The longitudinal feedback is in operation since March 2006. It has proven its capability to suppress all coupled bunch instabilities during the energy ramp of HERA-p and also during hours of beam storage. The bunch lengthening due to diffusion processes is expected to be dominated by intra beam scattering effects, and the contribution of feedback noise during normal operation is hardly noticable. When stable, the feedback system does not kick nor excite the bunches.

The initial bunch length after injection is about 2.4 ns. Without the feedback a multibunch instability (mode 164) showed up at 300 GeV and at 700 GeV with correlated bunch length blow up during a typical energy ramp at HERA-p. With the feedback switched on the instability could be suppesed until the feedback was switched off after some time (t=1050 s) where immediately the bunch length blew up.

It turned out, that the feedback gain needed to be changed during acceleration, because the loop gain changes with energy due to the transfer function of the beam. This was dealt with by implemetation of a gain lookup table. With lower energies too high gains caused feedback-instabilities, because the internal latency caused by the internal synchrotron frequency detection gives a limit here. Also with large oscillation amplitudes the nonlinearities of the longitudinal bucket potential were observed in the way that too big oscillations could not be damped down if the gain was already tweeked to the instability limit.

SUMMARY

The System operation turned out to be very reliable and easy to use. An increase of the bunch lengthening caused by stochastic excitation of the beam by the feedbacks operation or amplified noise was not observed. With only one hardware failure (of the power amplifier) the system could be used the whole rest of the lifetime of HERA, which was about one and a half year.

All though we prepared features which would have supported for beam dynamics studies in HERA-p like the measurement of beam transfer functions, the bunch to bunch coupling functions and the loop gain, instability excitations and selective damping, these featurese were not used because of the limiting beam time scheduled for HERA machine studies.

Also the planned new proton optics, which was designed to further reduce the transversal beam size at the interaction points was not applied to the machine, since this had cost too much time until a stable operation had been established.

Nevertheless the project showed us, that it is nowerdays possible to create a fully functional (longitudinal) bunch to bunch feedback system with a digital signal processing systems which can also fulfill the high noise performance requirements of an hadron accelerator. The feedback was realized without exciting the beam (like with PLL based feedbacks), it is able to track the changing synchroton frequency whenever the beam starts to become instable. This together with the new kicker modulation concept is considered a new experience in accelerator beam control.

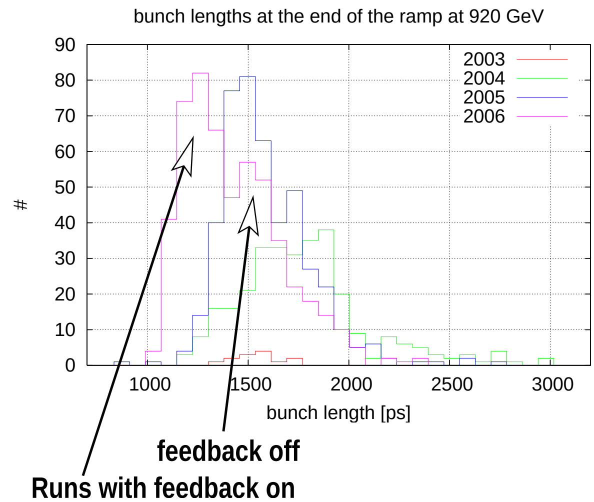

Figure 4: Statistics of bunch lengths for different years of operation of HERA. The bunch length is measured as FWHM of the charge profile of a signal of a resistive gap monitor. In 2006 the feedback system was commissioned and the reduction of bunch length at 920 GeV is visible.

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