THE DSP-BASED BETATRON TUNE FEEDBACK OF THE RAMPED 1.5 GEV ELECTRON STORAGE RING BODO

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Abstract

The ramped storage ring BoDo is the full energy injector of the 1.5 GeV synchrotron light source DELTA. All ramped booster magnet power supplies, RF power control and beam diagnostics of BoDo are handled by a distributed VME-based DSP (digital signal processor) multiprocessing system developed at DELTA. The VME DSP boards of this system are interconnected by DeltaNet, a novel reflective memory ring network. DeltaNet transmits the measurement data from each DSP board to all other boards in real-time via fibre optic links. The generic hardware and software architecture of the system allows the implementation of different kinds of global real-time feedbacks with correction rates in the range from some 100 Hz to some 10 kHz [1]. This paper presents the architecture and performance of a real-time betatron tune feedback which was implemented with the DSP system. The betatron tune is measured and corrected in both planes at a rate of typically 700 Hz for arbitrary beam optics and energy ramps of BoDo. In combination with the global BoDo orbit feedback [1, 3], the tune feedback increases the performance of BoDo both as an injector and as a testbed for machine studies and newly developed accelerator components.

INTRODUCTION

In 2001/2002 a large part of the control system hardware of BoDo as well the beam diagnostics hardware for betatron tune and orbit measurements were replaced by a newly developed DSP-based system[2] in order to reduce storage ring filling times of one hour or more, to improve the overall reliability and performance of the injector and to simplify operation and tuning of BoDo for the operators.

Generic Hardware and Software Concept

The core of the new booster hardware consists of VME-bus DSP boards ("DeltaDSP", see Figure 1) with a generic architecture that may be used for a variety of different beam diagnostics and control tasks such as tune measurement and feedback, fast global orbit feedback, control of the ramped BoDo power supplies and beam loss measurement. All BoDo DSP boards are connected in a ring-like structure by fibre-optics cables that use DeltaNet, a real-time network that was implemented in an FPGA (field programmable gate array) and that reflects a part of the internal memory of an ADSP-21062 "Sharc" DSP on each board periodically to the internal memories of the DSPs on all other boards with 160 MBaud and typical periods of some 10 μs. DeltaNet also distributes trigger signals and synchronises the board clocks of all DSP boards with less than 10 ns jitter, so that all monitor readings and magnet current changes in Bodo are precisely synchronised.

The low-level EPICS-based control system driver/device support software that was developed for the DSP system also has a generic structure and is common for all applications (tune measurement, orbit feedback, ...). It uses configuration files to adapt the software to each application. The software that is executed on the DSPs is split into a large part that is common to all DSP boards and a smaller application-dependent part. Due to this generic hardware and software architecture, feedback systems in the kHz-range can be implemented with little effort. This is illustrated by the fact that more than 90 percent of the overall DSP code for the betatron tune feedback and for the global orbit feedback is identical. The actual feedback algorithm is executed in a distributed way on all DSP boards that control feedback magnet power supplies. The main difference between betatron tune and orbit feedback is merely the subroutine that calculates the magnet set currents from the monitor data in the reflective memory.

TUNE MEASUREMENT AND CORRECTION

All magnet power supplies of BoDo can have arbitrary current waveforms ("ramps") that are controlled in real-time by the DeltaDSP boards. The maximum and minimum voltages of the dipole magnet power supply result in a minimum length of about 6.5 s for a periodic energy ramp with 60 MeV injection and 1500 MeV extraction en-

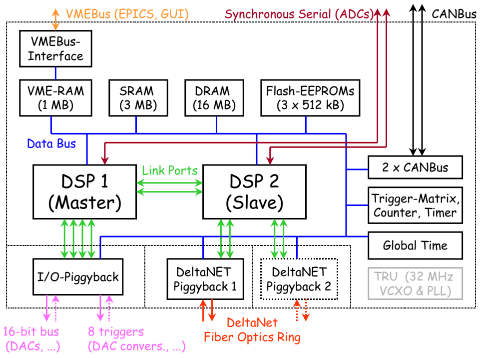

Figure 1: Architecture of the DeltaDSP board.

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ergy. So far the ramps for the quadrupole magnets required manual corrections via lookup tables, with corrections up to several percent every 50 to 100 ms in order to keep the betatron tunes constant. These corrections are necessary due to tune drifts during the ramp that are caused by different current regulation circuits of dipole and quadrupole magnet power supplies, time-dependent orbit drifts in the presence of nonlinear magnet fields of corrector magnets and sextupoles, ion effects, magnet hysteresis and energy- as well as current-dependence of magnet current regulation circuits. In order to avoid beam loss and to guarantee optimal conditions and well-defined beam optics during injection and extraction or for machine physics studies, a betatron tune stability of ±0.01 or less is desired during BoDo energy ramps, with nominal horizontal (x) and vertical (z) betatron tunes of $Q_x = 3.62$ and $Q_z = 2.56$.

In order to simplify booster or storage ring machine physics studies that require different beam energies and booster optics and to simplify the generation, correction and optimisation of new ramps for user operation of DELTA, an automatic tune correction was implemented. Instead of using a feed-forward correction with iterative tune corrections from ramp cycle to ramp cycle or a model-based prediction, a real-time tune feedback was developed. Compared to model-based predictive corrections and iterative feed-forward correction schemes, a real-time tune feedback for Bodo was not more difficult to implement but has the advantage that parameters like beam orbit, extraction orbit bump, sextupole strengths, energy and optics can be changed arbitrarily in real-time during machine physics studies or tuned during user operation of the storage ring without affecting the betatron tunes.

Tune Measurement

The tune measurement system of BoDo is described in refs. [1, 2] and is therefore only mentioned briefly here. BoDo has a revolution frequency of about 5.95 MHz and a harmonic number of 84. The BoDo tune measurement system is based on a DeltaDSP board that excites the electron beam using a diagonal kicker that is driven by the amplified signal of a DSP-controlled DDS (Direct Digital Synthesis) sine function generator (see Figure 2). After beam injection the excitation frequency is swept e.g. from 0 to 3 MHz. The DSP measures the fractional betatron tune frequencies by detecting coherent oscillations of the beam as upper sidebands of the 85th revolution harmonic, where the frequency to be analysed is determined by a second DDS generator that is usually swept in parallel with the first one. The filtered sideband signals of BPM pickups are mixed down to 10.7 MHz and then do DC with logarithmic amplification, so that the DSP can use a 100 kSample/s ADC to detect the betatron sidebands that appear as voltage peaks in the ADC waveform when the beam oscillates coherently.

After a single fast sweep e.g. from 0 to 3 MHz after injection, the DSP detects the fractional tune frequencies using a peak search algorithm and starts to sweep the kicker frequency alternately in two small frequency windows of typically 50 to 100 kHz width around the fractional tune frequencies. Dynamic tracking of these frequencies by the DSP allows to measure both fractional tunes typically 700 times per second. The absolute tune values are obtained from the fractional ones using an optics model. The measured tune frequencies are transferred to all other DSP boards via DeltaNet.

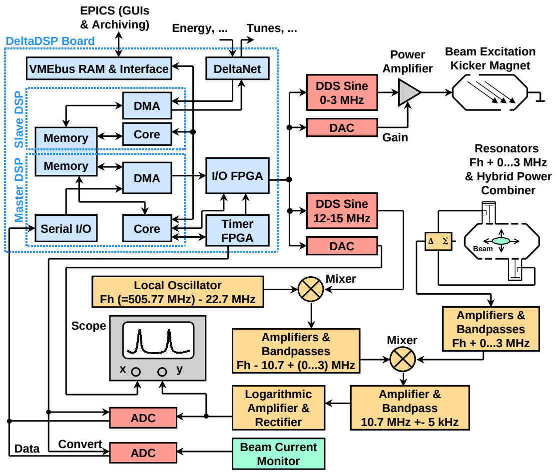

Figure 2: The DSP-based BoDo tune measurement system.

Tune Feedback

The DeltaDSP board that controls the quadrupole power supplies uses the beam energy and betatron tunes received in its reflective DeltaNet memory to calculate suitable corrections for the quadrupole magnet currents. BoDo has a FODO optics with three horizontally focussing ("QF") and three vertically focussing ("QD") quadrupole magnet families with one power supply per family. The tune feedback

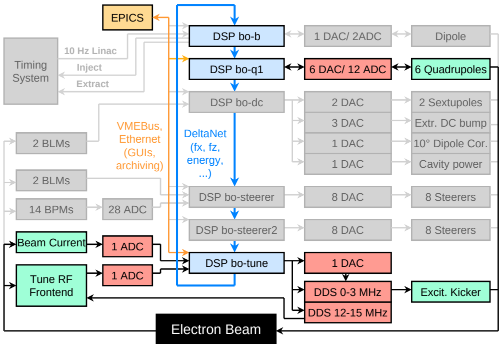

Figure 3: Data flow of the BoDo tune feedback. The "bo-q1" DSP board receives the betatron tunes measured by the "bo-tune" board as well as the beam energy from the "bo-b" board via DeltaNet and keeps the tunes stable during arbitrary energy ramps by adjusting the quadrupole power supplies accordingly. The BoDo DSP boards that are not involved in the tune feedback are shaded grey.

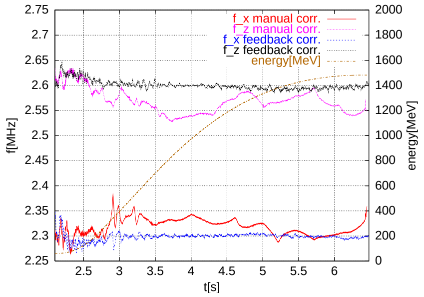

Figure 4: Fractional betatron tune frequencies f_x and f_z measured during an energy ramp from 60 to 1500 MeV, both for a manual tune correction by an operator via quadrupole current lookup tables and for the more precise real-time correction by the tune feedback. 100 kHz correspond to a tune change of ΔQ=0.017.

algorithm corrects the betatron tunes by using two scaling factors S_{QF} and S_{QD} for all QFs and for all QDs. The scaling factors are generated by two PID controllers that use the deviation from the nominal tunes as input error. Since the QFs mainly changes the horizontal tune Q_x and the QDs mainly change the vertical tune Q_z it was not even necessary to use a 2x2 matrix to calculate S_{QF} and S_{QD}, but it was sufficient to calculate S_{QF} from Q_x and S_{QD} from Q_z. Tests with several different beam optics showed that this results in stable and robust feedback operation, with negligible crosstalk between Q_x and Q_z (see Figure 7). The settings for the PID control loop were optimised for the standard BoDo optics, but also worked fine for all other optics that were tested so far.

CONCLUSION

The generic hardware and software architecture of the control and diagnostics systems of BoDo allowed the implementation of a real-time betatron tune feedback with little effort. The feedback corrects the fractional betatron tunes to the desired values with a deviation of less than ±0.01 for the first 100 ms after injection and less than ±0.002 during the remaining part of a worst-case BoDo ramp with the maximum energy gradient of the booster. The feedback proved to be useful both for precise tune and optics control during machine physics studies and for stable performance and easy optimisation and tuning during user operation of the accelerator.

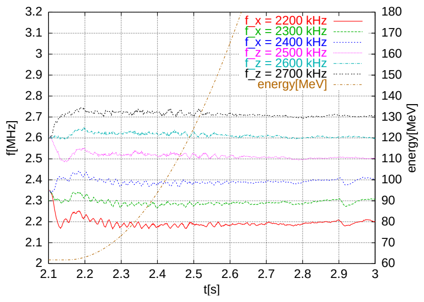

Figure 5: Correction of the fractional betatron tune frequencies by the feedback after injection. The plots are superpositions of three measurements for three different set values for the desired betatron tune frequencies (f_x = 2.2, 2.3 and 2.4 MHz, f_z = 2.5, 2.6 and 2.7 MHz) with identical magnet currents at injection. The feedback needs about 50 ms to adjust the tunes to the desired values after the beam was injected at t=2.1 s.

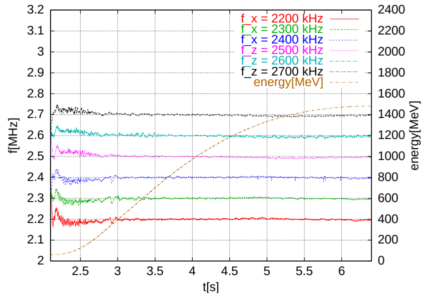

Figure 6: Same measurement as in Figure 5, but with a larger time scale. The feedback keeps the tunes stable during the whole ramp from injection at 60 MeV (t=2.1 s) to extraction at 1500 MeV (t=6.45 s).

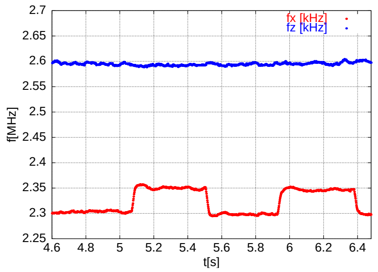

Figure 7: Fractional betatron tune frequencies f_x and f_z with running tune feedback. In order to test the feedback response, the set value for f_x is toggled between 2.3 and 2.35 MHz twice, corresponding to tune changes of 0.008. The feedback moves f_x to the new set value in about 50 ms without significant crosstalk to f_z.

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