REALTIME TUNE MEASUREMENTS IN SLOW-CYCLING ACCELERATORS

D. Herrup*, Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois, 60510

Abstract

Measurement and control of the tunes, coupling, and chromaticities in storage rings is essential to efficient operation of these accelerators. Yet it has been very difficult to make reliable realtime measurements of these quantities. We have built and commissioned the microprocessor-based Generic Finite State Data Acquisition (GFSDA) system. GFSDA provides turn-by-turn data acquisition and analysis of accelerator signals in a way that can be easily related to accelerator operations. The microprocessor is capable of calculating FFTs and correlations in real time. Both the Fermilab Main Ring and Tevatron use open loop tune, chromaticity, and coupling control, and the GFSDA measurements can easily be used to improve the open loop tables. We can add realtime feedback control with simple extensions of the system. We have used this system to make tune measurements closely spaced in time over an entire Tevatron ramp cycle.

1 INTRODUCTION

Accurate and synchronized control of many magnetic and other elements in hadron synchrotrons is one of the major operational problems associated with these accelerators [1]. The Fermilab Tevatron illustrates these issues [2]. The Tevatron operates in two modes - in a fixed target mode in which p's are accelerated to 800 GeV in about 15 sec. and are then extracted for experimental use over a 20 sec. period, and in a collider mode in which it accelerates both p's and $\overline{p}$'s to 900 GeV in 80 sec., undergoes lattice modifications (the low-β squeeze) and stores the beams for up to 12 hours in collisions. Fixed target operation is relatively straightforward since the tune spreads are small and one can tolerate “slightly” inaccurate tune and chromaticity settings. However, in collider running the tune spreads are large due to the full RF buckets and the beam-beam interaction. In addition, time-dependent persistent current effects modify the sextupole moment in the dipole magnets, creating a time-dependent chromaticity even when the Tevatron is not ramping [3].

Maintaining the desired operating point has been difficult because the control is entirely open loop, the basic phenomena causing changes with time are not completely understood (ie., persistent current effects in the superconducting filaments of the Tevatron dipoles), and measurement of the relevant physical quantities (tunes, coupling, chromaticity) has been very difficult. In the Tevatron, measurements have been made with commercially available spectrum analyzers whose output is viewed manually. The spectrum analyzer traces must be correlated in time with the accelerator process. Corrections to the magnetic circuits can then be inserted into the open loop tables for the “next time.” This system has clear drawbacks: it follows changes in the accelerator with a time lag, resulting in non-optimal operation, it is extremely labor-intensive, and the open loop tables do not necessarily have breakpoints at the needed times. Additional breakpoints can be added, but the result will be a set of very long tables which require much effort to tune properly.

A more satisfactory approach to this control problem is to build a data acquisition system that is intimately tied into the accelerator control system and mirrors the accelerator cycles. In this way data acquisition and analysis can be handled automatically, and the relationship between a measurement and the state of the accelerator is evident. One can then easily close the loop to the open loop tables or construct slow, realtime control loops. The Generic Finite State Data Acquisition (GFSDA) system was designed to simplify all these tasks.

2 THE GFSDA SYSTEM

Our goal in designing GFSDA was to design a flexible system that fit naturally into the Tevatron accelerator and Fermilab controls environment [4], allows realtime data processing so that control loops can be implemented if desired, and stores data in a way that allows for easy acces by a user at the Fermilab console system.

GFSDA is primarily a tune measurement system, although it can be used on any accelerator signals. The initial implementation in the Tevatron uses as inputs horizontal and vertical Schottky detectors which measure the transverse beam position oscillations. When fourier analyzed, these signals provide measurements of the betatron tunes. The Tevatron has two horizontal and two vertical detector separated by $\lambda/4$ at the 21.4 MHz resonance frequency. The horizontal and vertical signals are combined in hardware to provide about 20 db of directional rejection, providing as outputs horizontal and vertical p and $\overline{p}$ signals [5] which are digitized by GFSDA. Betatron oscillations in the Tevatron are driven coherently through an un-understood mechanism, and as a result we do not need external excitation to measure the tune. The signals shown in this paper are not Schottky signals but are the driven betatron oscillations.

Currently in the Beams Division at Fermilab, low-level systems such as GFSDA are implemented using embedded microprocessors. A GFSDA system is a VME crate running VxWorks using a 68060 processor with 32 MBytes

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of on-board memory, an 8-channel, 16 bit ADC with on-board memory for 500,000 digitizations per channel, and 128 MBytes of additional memory for data storage. The crate also contains cards necessary for network communications and the receipt of timing and other realtime accelerator data. All microcode is written in C using the MOOC protocol [6].

The software is based around a set of FSMs with a group of states corresponding to different accelerator operations. Each system can be programmed with up to 25 FSMs and 50 states. The FSM is responsible for controlling transitions between its assigned states. The transitions arise either on accelerator timing signals (or a signal plus a time delay), at a fixed time into the state, or by software triggers generated in Fermilab console software. Up to 8 transitions can be specified for a state. Several FSMs can be active simultaneously as long as they are not using the same ADC channels.

Data acquisition, analysis, and storage for user access are handled by the states. States are specified with the transition table discussed in the previous paragraph and data acquisition event rules. The event rules specify the event records used, for instance, to calculate the tune at a given time. Data are collected either on the occurrence of an accelerator timing event (which may occur many times during an instance of a state), at a specified time after the transition into the state, or at a frequency. The data collected are specified by a list of ADC channels, a number of digitizations and the digitization rate, either a fixed frequency or the beam revolution frequency. One can also specify that the microprocessor calculate FFTs in real time on a fraction of the digitizer data, and store in memory only the FFT output from the frequencies of interest. Windowing algorithms can be applied to the raw data and a primitive peak-finding routine can be run on the on the FFT data.

Event records can be spaced very closely in time, with the requirement that data collection for one event end before the next event occurs. This time is a few hundredths of a second. However, the fastest periodic interrupt allowed is 15 Hz, so if event records at a faster rate are desired, they must be specified individually rather than through a single frequency.

The lengths of the event records are determined by the processes being measured. Measurements with 8192 digitizations give a frequency resolution of about 3 Hz. (the revolution frequency is about 47700 Hz.). These long event records must be stored in a manner which permits easy, labelled access to high-level users at the Fermilab console system.

We have solved this problem by associating with each state three circular buffers of sub-buffers, one each for the event rule ADC and FFT data, and one for a Time of Day Stamp (TODS). For each instance of a state, the next available TODS, FFT, and data sub-buffers in their respective circular buffers are chosen. The TODS sub-buffer is filled with a 28 byte string which has the ACNET time of day at which the state was entered. The data and FFT sub-buffers are filled sequentially with the ADC and FFT data from the various event records. When the exit from a state occurs, the two sub-buffers are closed. Upon the next instance of the state, the next available sub-buffers in the circular buffers are chosen. Once all sub-buffers have been filled, they are overwritten in order. This buffering system has several convenient features: the TODS buffer ensure that a console user can easily correlate an instance of a state with other time-stamped accelerator data, the relationship between the three buffers is maintained until they are overwritten in concert, and the circular buffers can be deep enough so that needed data will not be overwritten before it is transferred to the console system and analyzed by the user.

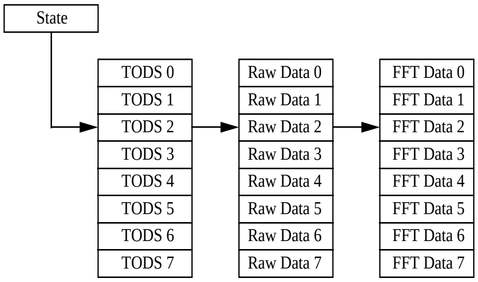


Figure 1: Buffer structure for a state with 8 sub-buffers.

3 HIGH-LEVEL SOFTWARE SUPPORT

In the previous section I described the GFSDA hardware and related microcode. A system as complicated as GFSDA requires significant high level software support to be useable. Also, there are many accelerator applications which require substantial accelerator control, data analysis and display features which at Fermilab only exist at the console level. In this section we will describe the additional software support for GFSDA.

3.1 FSM Specification

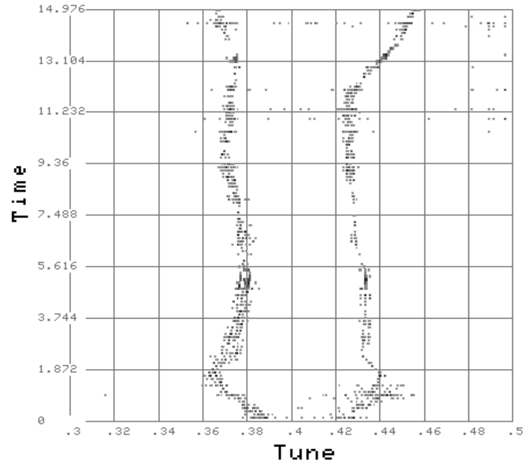
The FSMs and states are complicated software objects. Full specification of a single state or FSM requires over 1 KByte of data, and a single system can contain 50 states and 25 FSMs. We have written a single application to handle all aspects of the FSM programming. This application allows the user to select any of the 25 FSMs in a system, assign the states, and program the data acquisition and transition rules for each state. The programmer also specifies the depth of the circular buffers for TODS and data (raw and FFT) storage. The program also performs various error and consistency checks before loading the microprocessor.

3.2 Analysis Applications

GFSDA itself has only limited data analysis capabilities. Currently these include the ability to calculate a windowed FFT on any fraction of a single event record and a peak-finding algorithm. The real physics analysis of the data must take place at the console level. In addition, through the consoles one has access to all devices in the Fermilab accelerator complex, enabling one to create complete applications for control and measurement.

GFSDA can be used to make a digital spectrum analyzer. An example is the Tevatron Acceleration state within the FSM for fixed target operation. During this state, event interrupts occur at 8 Hz. and we digitize the Schottky signals for 2048 turns. The application to display the data queries GFSDA to determine how many data collection events occurred and how much data are in each event, then reads the data and either displays the FFT or the discrete correlation of the two signals for each event as a function of time through the state. Figure 2a shows a typical example of the tune spectra through the Acceleration state after the correlation analysis has been performed. Two clear tune lines are visible through most of the cycle (The color spectrogram is considerably more informative as it shows the fine structure within a trace. Figure 2b shows the correlation for a single event record.).

[Correlation spectrogram of tunes during the Tevatron ramp.]



[Correlation plot of tunes from a single event record during the Tevatron ramp.]

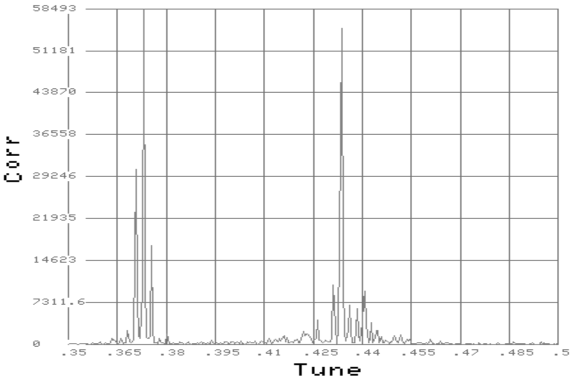


Figure 2: Tune data taken during the Tevatron Energy ramp.

Library routines for GFSDA data retrieval exist, so designing an application to perform a specific analysis function is not difficult. As an example, it would be straightforward to develop a single application to measure chromaticities on the front and back porches. The application would control the RF frequency, data acquisition, tune-finding and the actual calculation of the chromaticities. Measurements could be made at 0.5 Hz., which is adequate for the porches.

4 FEEDBACK

The GFSDA system can easily be the principle component of a slow, realtime control loop. The most logical use for such loops would for tune and coupling control. GFSDA would continue its current functions but with the addition of real pattern recognition to determine the tunes and coupling. The microprocessor analysis would also include a model of the Tevatron consisting of a matrix relating tune and coupling changes with changes in magnetic circuits and a table of “desired” tunes (downloaded from the console system). For each event record, GFSDA would calculate the desired current changes in the circuits, and then output the corrections onto an existing realtime link which communicates with the power supply controllers. Several years ago we built a much simpler system with fewer capabilities using this architecture to do closed loop tune control [7].

5 CONCLUSIONS

We have simplified the problems of tune and chromaticity control in hadron synchrotrons by building a data acquisition system matched to the accelerator operations. The data can easily be correlated with accelerator operations and corrections made either to open loop control tables or through realtime control loops. We have described only the system operating in the Fermilab Tevatron, but an identical system is operating in the Main Ring [8].

6 ACKNOWLEDGEMENTS

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7 REFERENCES

[1] See the Proceedings of the LHC Workshop on Dynamic Effects and their Control, CERN, Geneva, 5-7 February 1997.

[2] G. Dugan, Part. Accel. 26 (1990) 12.

[3] D. Herrup et. al., Phys. Rev. E 49, 5660 (1994).

[4] D. Bogert, Nucl. Instr. and Meth. A247, 231 (1986).

[5] D. Martin et. al., Proc. 1989 IEEE Part. Accel Conf., March 20-23, 1989, (Chicago, IL), 1486.

[6] B. Lublinsky, Nucl. Instr. and Meth. A352, 403 (1994).

[7] D. Herrup et. al., Nucl. Instr. and Meth. A329, 470 (1993).

[8] D. Still et. al., Tune Measurement Methods in the Fermilab Main Ring, Proceedings of this Conference.