A Realtime Feedback Microprocessor for the TEVATRON

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Abstract

A feedback microprocessor has been built for the TEVATRON. Its inputs are realtime accelerator measurements, data describing the state of the TEVATRON, and ramp tables. The microprocessor includes a finite state machine. Each state corresponds to a specific TEVATRON operation. Transitions between states are initiated by the global TEVATRON clock. Each state includes a cyclic routine which is called periodically and where all calculations are performed. The output corrections are inserted onto a fast TEVATRON-wide link from which the power supplies will read the realtime corrections. We also store all of the input data and output corrections in a set of buffers which can easily be retrieved for diagnostic analysis. I will describe use of this device to control the TEVATRON tunes, and discuss other uses.

INTRODUCTION

In hadron colliders such as the Fermilab TEVATRON, the HERA p ring, the SSC and the LHC, a well-defined sequence of operations is needed to take the accelerator from an initial state, without stored beam, to a final state, with stored beam and collisions at the interaction points. There are many intermediate states (such as acceleration), during which accelerator parameters change. It is difficult to construct a single model of the accelerator which applies during all these states. Instead, it is convenient to consider each process separately and construct models for each state. The entire process may be thought of as a finite state machine, with each state corresponding to a different operation and having its own model of the accelerator. In addition, the time scales at which the accelerator parameters change vary from state to state. Changes in accelerator parameters lead to variations in the beam parameters such as the tunes, coupling, and chromaticities. If the beam parameters are not carefully controlled, beam quality will deteriorate. One of the principal challenges of collider operations is to maintain high beam intensities and low emittances through the chain of operations from injection to collisions.

The sequence of operations in the TEVATRON is illustrative of this process[1]. Operations proceed through the following (simplified) set of states: p injection, energizing electrostatic separators to create different helical orbits for p's and $\overline{p}$'s, $\overline{p}$ injection, acceleration, lattice modifications to produce low β^*'s at the interaction regions, and energizing additional separators to create head-on collisions at the two interaction regions. In p and $\overline{p}$ injection, a closed orbit time bump moves the circulating orbit near an injection kicker, and back immediately after injection. Closed orbit changes may be accompanied by betatron tune and coupling changes caused by the non-linear fields of the bending dipoles and sextupoles. Energizing the separators has the same effect. During acceleration, all the magnetic elements are ramped. Although the linear lattice is kept constant, the multipoles change, affecting the tunes and coupling. The closed orbit may also vary. "Squeezing" is the term used to describe lattice changes to create small β^*'s at the interaction regions. In principle, only a restricted set of quadrupoles should be needed for this step. However, since the quadrupole strengths are not precisely known, the exact settings for the quadrupoles cannot always be calculated. The closed orbit may not pass through the centers of the quadrupoles, leading to closed orbit (and tune and coupling) shifts. If during these states the tunes and couplings are not kept away from harmful resonances, emittance growth and/or beam loss will result.

Closed orbit and quadrupole variations also affect the chromaticities. These effects are usually small and do not pose problems for beam stability. However, persistent current effects in the bending dipoles of superconducting accelerators have a large effect on the sextupole moment. During the 1-3 hour TEVATRON injection front porch, the chromaticities change by as much as 70 units. These changes are undone in the first seconds of acceleration. If the chromaticities are too low during these states, head-tail instabilities may develop. If they are too large, the chromatic tune spread may overlap harmful resonances. In both cases, emittance growth and/or beam loss may result.

In all of these cases it is necessary to have accurate tune and chromaticity control. This is usually accomplished with open loop control in the form of tables operating at breakpoints, with linear interpolation between breakpoints. However, this interpolation is often not accurate. The CBA[1] system at Fermilab was constructed to provide tune control with realtime feedback loops.It operates as a finite state machine in which each state corresponds to a specific TEVATRON process. Feedback within a state is performed by periodic calls to the state's data acquisition and feedback routines. Each state also includes a set of buffers in which the measurements and calculations from the feedback routine are stored. All data are available through the Fermilab accelerator control system. We will describe the gen-

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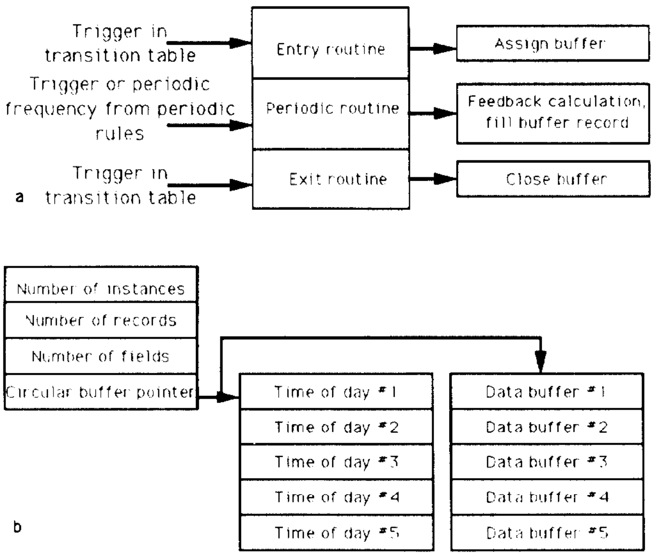

Figure 1: a CBA State Structures and b CBA Buffer Structures.

eral features of the microprocessor software, the way in which it has been incorporated into the TEVATRON control system, and some of the ways in which it has been used.

Features of the CBA System

The hardware standard chosen for CBA was the Intel Multibus II[3] chassis using a Micro Industries 80386 processor card with 8 MBytes of DRAM. We use the MTOS[4] operating system. All software is written in C.

The heart of the finite state machine is a set of states with a transition table and a set of periodic rules and buffers for each state. These structures are illustrated in Figure 1a and 1b. The transition table consists of a list of allowed transitions between states and the trigger which will cause a given transition. Each state can have transitions into up to 8 other states, although a given trigger signal can occur only once in the transition table for a state. The periodic rules consist of a specification of 8 frequencies and timing signals which will cause the periodic routine to be called. The frequencies vary from state to state, depending upon the accelerator processes occurring. For instance, during acceleration the persistent current effects are removed rapidly, and a frequency of several Hz is indicated, but during the squeeze the quadrupole circuits change very slowly and a frequency of 1 Hz is sufficient.

Associated with each state is a set of buffers. The buffer structures consist of a specification of the number of fields, number of records, number of instances of a state which may be buffered before they are overwritten, time-of-day stamps for each buffer, and the data buffers themselves. One buffer is filled for every instance of a state, and after the entire set has been filled, they are overwritten in a circular manner. The number of buffers for each state has been chosen to be large enough so that there is no danger of buffers being overwritten before they have been archived, if desired. The time-of-day stamp is the clock date and time at which the instance of the state occurred. It is stored in a separate circular buffer which maintains the one-to-one correspondence with the data buffers. Each data buffer consists of fields into which the input data, accelerator parameters, and output data may be loaded. A new record consisting of data for all the fields is added to the buffer each time the periodic routine is called.

The computations for each state are performed in the entry, exit, and periodic routines. The entry routine allocates the next available buffer and zeroes the timer which counts time since the start of the state. The exit routine closes the buffer and zeroes the feedback output. The periodic routine consists of routines that read the beam and accelerator parameters, such as the betatron tunes and bending bus current. It also accesses the tables of desired values for beam quantities as a function of time since entry into the state. The desired values and measured values are inputs to the feedback routine, which calculates an error signal. The accelerator model is then used to calculate the feedback current required to null the error signal. These corrections are output in real time to the power supplies and are stored, along with the input data and whatever calculations are desired, in the buffer being used for the particular instance of the state.

TEVATRON Implementation

Figure 2 is a complete diagram of the system as implemented in the TEVATRON. The inputs are a set of phase lock loops whose input is the signal from a set of Schottky detectors[5]. These circuits provide a realtime measurement of the tune. The triggers for the transition tables are read from the global TEVATRON clock (TCLK) and other machine parameters (the bend bus current) are read from the global MDAT link[6]. The realtime corrections are transmitted to the power supply controllers over MDAT. Various control parameters (feedback gains, frequencies, on/off switches, etc.) are downloaded into CBA through the accelerator control network (ACNET). The data buffers are also available to the console system over ACNET.

We have conducted several closed loop tests of CBA. In one such test, we demonstrated that CBA can successfully compensate tune shifts caused by changes in TEVATRON parameters other than the tune circuits. We introduced a single horizontal dipole kick of varying magnitude at one location. In Figure 3a we plot the kick, the position measured on a beam position monitor, and the horizontal and vertical tunes. The kick leads to a maximum tune change of about 0.01. Figure 3b is the same plot with CBA turned on to perform active feedback. The tune shift has been successfully compensated to within 0.002.

Conclusions

We have built a general purpose microprocessor based feedback system which has been tailored to fit the finite state behavior of hadron collider operation. The system will work with any reliable realtime inputs and will provide feedback at up to 60 Hz. Each state has it's own feedback routines which contains a model of that particular accelerator state. We have provided a buffer system which matches the states of the state machine and which contain all information describing the operation of the feedback loop. Closed loop corrections to the power supplies can be output on any accelerator-wide link. This system has been tested and shown to work in circumstances which are useful to accelerator operations.

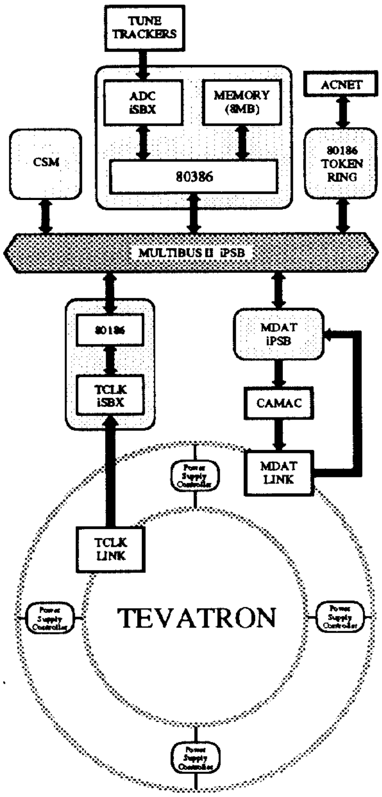

Figure 2: CBA implementation in the TEVATRON.

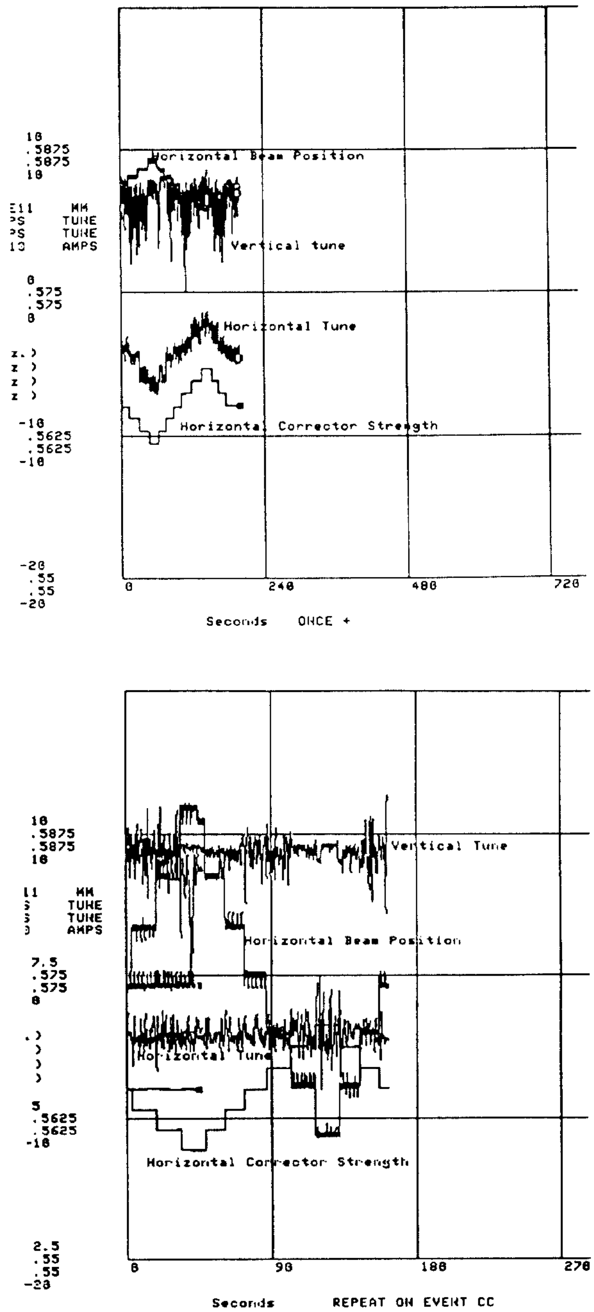

Figure 3: Plots of a horizontal correction dipole, horizontal beam position monitor, and the horizontal and vertical tunes with a CBA off and b CBA on.

References

[1] G. Dugan, Particle Accelerators 26, 12 (1990).

[2] CBA is an acronym for Colliding Beam Adrastus. See R. Graves, THE GREEK MYTHS, vol. 2, Viking Penguin Inc., New York, New York, 1955, p. 377. See also D. Herrup et. al., Real-Time Feedback Control of the Tevatron Tunes and Chromaticities, Proceedings of the 2^{nd} European Particle Acclerator Conference, Nice, June 12-16, 1990, p. 898, and D. Herrup et. al., A Feedback Microprocessor for Hadron Colliders, to appear in Nuclear Instruments and Methods Section A.

[3] Multibus is a trademark of the Intel Corporation.

[4] MTOS is a trademark of Industrial Programming, Inc.

[5] D. Martin et. al., A Resonant Beam Detector for TEVATRON Tune Monitoring, Proceedings of the1989 IEEE Particle Accelerator Conference, March 20-23, 1989, Chicago, IL, and J. Fitzgerald and R. Gonzalez, Tune Trackers for the Fermilab TEVATRON, Proceedings of the 1991 IEEE Particle Accelerator Conference, May 6-9, 1991, San Francisco, CA.

[6] D.G. Beechy and R.J. Ducar, Time and Data Distribution Systems at the Fermilab Accelerator, Nuclear Instruments and Methods in Physics Research A247 (1986), p. 231.