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**A Longitudinal Bunch Monitoring System  
Using LabVIEW<sup>®</sup> and High-Speed Oscilloscopes**

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# A Longitudinal Bunch Monitoring System Using LabVIEW and High-speed Oscilloscopes

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## Abstract

A new longitudinal bunch monitor system has been installed at Fermilab for the Tevatron and Main Ring. For each machine, a signal from a broadband wall current monitor is sampled and digitized by a high-speed oscilloscope. A Macintosh computer, running LabVIEW-based software, controls the scopes and CAMAC timing modules and analyzes the acquired data. The resulting bunch parameters are used for a variety of purposes, including Tevatron collider luminosity calculation and injection analysis. This paper examines the system in detail.

## INTRODUCTION

Accurate measurements of bunched beam intensities and lengths are necessary for the calculation of luminosity during collider operations. At the relativistic energies of the Fermilab Main Ring and Tevatron accelerators, the signal from a broadband, resistive wall current monitor(1) closely approximates the beam longitudinal profile. These signals can be digitized and processed to obtain the required parameters. An earlier "Sampled Bunch Display" (SBD) system(2,3) used a 1 GHz bandwidth, repetitive-sampling oscilloscope to digitize the signal, which has a maximum 20 dB bandwidth of 250 MHz. Code using a Motorola 68000 microprocessor processed the profile and reported results to the accelerator control system network, or Acnet. This system has operated since 1988.

Technological advances made it possible to upgrade this useful system. In late 1992, the 2 GSample/sec, 500 MHz Tektronix TDS620 oscilloscope(4) was chosen, along with the National Instruments software platform LabVIEW.(5) Longer time slice records of single turns could now be more extensively analyzed at higher speeds. Data refresh rate for the 12 proton and antiproton bunches of a Tevatron store decreased from 90 to 15 seconds. A single bunch mode updates every 1 or 2 seconds, depending on whether profile graphing is on. The longer record captures satellites of the main bunch, or even an entire batch (13 bunches) of uncoalesced beam. Multiple memories and longer records enable acquisitions at many key times during a Main Ring-to-Tevatron injection event, from 13 bunches of 8 GeV beam through the coalesced Tevatron bunch. Single turn acquisitions allow first turn and synchrotron oscillation measurement. During its first eight months of operation, the upgraded system has proven to be quite flexible, while providing results with high accuracy.

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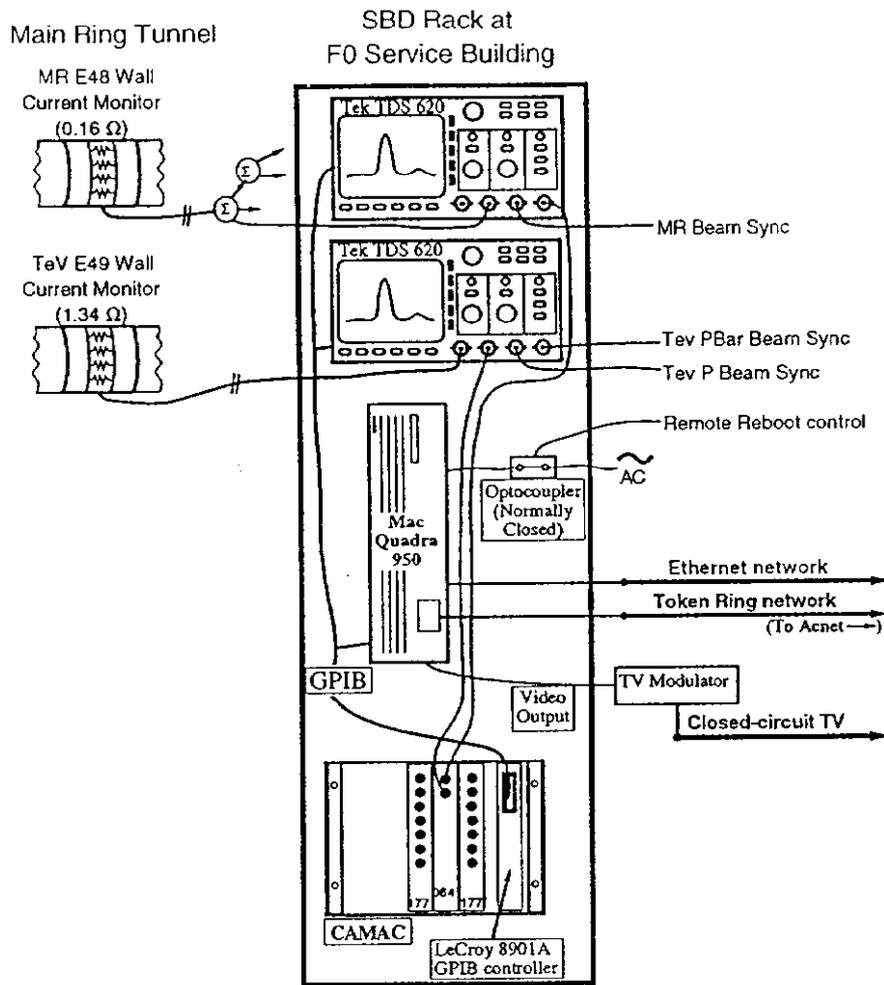


Figure 1. Overview of the new SBD system hardware.

## SYSTEM HARDWARE

The heart of the new SBD system (Fig. 1) is a Macintosh Quadra 950 computer running a program written with the LabVIEW graphical language. The software controls and reads two TDS620 oscilloscopes, one for both the Main Ring and the Tevatron. Besides the high sampling rate and analog bandwidth, the scopes have five memory locations, record lengths of at least 500 samples, and a versatile triggering system.(4) The Main Ring signal comes from a 3 pickoff point, 1.5 kHz-2 GHz wall current monitor, which is shared with other functions. The Tevatron signal comes from a dedicated wall current monitor, an improved 4-point, 3 kHz-6 GHz model.(1) Each signal travels over 100' through low-loss cable to a rack in a service building.

Oscilloscope triggering depends on the mode of the SBD. The default mode cycles through the 12 Tevatron bunches during a store. Two Tevatron beam

synchronization triggers are used with bunch-specific delays. When beam is injected into the Tevatron during a store setup, the SBD is put into an injection mode. Specific timing delays off an accelerator clock event are necessary for the 5 Main Ring and up to 3 Tevatron acquisitions. Each of 8 channels of a CAMAC Tevatron clock decoder pulses a programmable time after an injection event, and these channels are wire-OR combined into two outputs. The main triggers for the scopes are derived from two such decoder modules and a CAMAC S/R flip-flop module. The beam sync pulses act as the delayed triggers, and acquisitions occur after bunch-specific delays.

The Macintosh acts as controller for GPIB communication with the oscilloscopes and CAMAC decoders. The Quadra 950 has a built-in Ethernet interface, while an Apple TokenTalk card allows communication with Token Ring. An in-house interface between the LabVIEW program and the Acnet control network occurs over Token Ring.(6) The video output of the Macintosh is modulated onto Fermilab's closed-circuit TV system.

A remote computer reboot can be accomplished through Acnet by toggling an optocoupler relay and the computer's AC power. The program restarts itself completely when a reboot has occurred.

## SYSTEM SOFTWARE AND MODES

Software development was simplified by using LabVIEW. Besides the graphical programming itself, an extensive analysis library is readily available along with GPIB drivers for the TDS620 scopes. The LabVIEW-Acnet interface, popular among recent Fermilab accelerator instrumentation projects, was very easy to use. Programming the beam profile "waterfall" plots, displayed on the TV system, was trivial with LabVIEW graphical output. The entire program itself is modular, allowing for future additions.

Control system communication to the SBD program takes place through Acnet devices, either as control or reading variables. For example, some variables control the hardware after initialization. Scope gain can be set to automatic or manual, and the number of averages can be selected. CAMAC delays for acquisition timings can be changed. Program calibration types, processing algorithms, number of injection acquisitions, and the program mode can be controlled. Acnet reading variables include all processed data for both cycling Tevatron and injection modes.

During a 6 X 6 store, the SBD continuously cycles through all 12 bunches in 15 seconds. The correct scope gain, trigger, and delay is set for each bunch. The program then waits for completion of a 250 ns, 500 sample acquisition with the specified number of averages. Data is retrieved over GPIB, processed, and made available to Acnet.

The beam can be either uncoalesced (13 bunches) or coalesced (main bunch with satellites). Different processing algorithms exist for each type, and the choice is made through a control variable. In both cases, the boundaries of the 19 nsec RF buckets are carefully defined first. For each bucket, a baseline defined by the edges is subtracted to account for the low frequency cutoff of the wall current monitor. Parameters for coalesced beam include: main bunch intensity, RMS sigma, % area width, longitudinal emittance, and centroid and peak times; leading and trailing satellite intensities and widths; and sum of 5 bunch (main and 4 satellites) intensities. The uncoalesced data are: sum of intensities of 13 bunches;

average width, emittance, and RMS sigma, weighted by intensities; and arrays of 13 elements for the individual intensities, sigmas, widths, and bunch centroid times. The most important parameters above have companion variables with their boxcar averages and standard deviations.

After each cycle, the mode control variable is checked. Mode changes are made either manually or through the sequencer, an Acnet program which orchestrates the entire Tevatron injection process during store setup. Another mode is the aforementioned Tevatron mode on a single, selected bunch. An update rate of 1 second is achieved, or 2 seconds with plotting.

Besides these two Tevatron store modes, other modes acquire both Main Ring and Tevatron data during a proton or antiproton injection. These modes can make up to 5 total acquisitions (coalesced and/or uncoalesced) per machine. The times of the acquisitions can be set for each event, with a minimum spacing of 0.7 seconds. After injection of that specific bunch is complete, an entire Tevatron cycle is done in time for the next bunch injection. The injection acquisitions are processed and the results update the appropriate Acnet reading variables.

## CALIBRATION

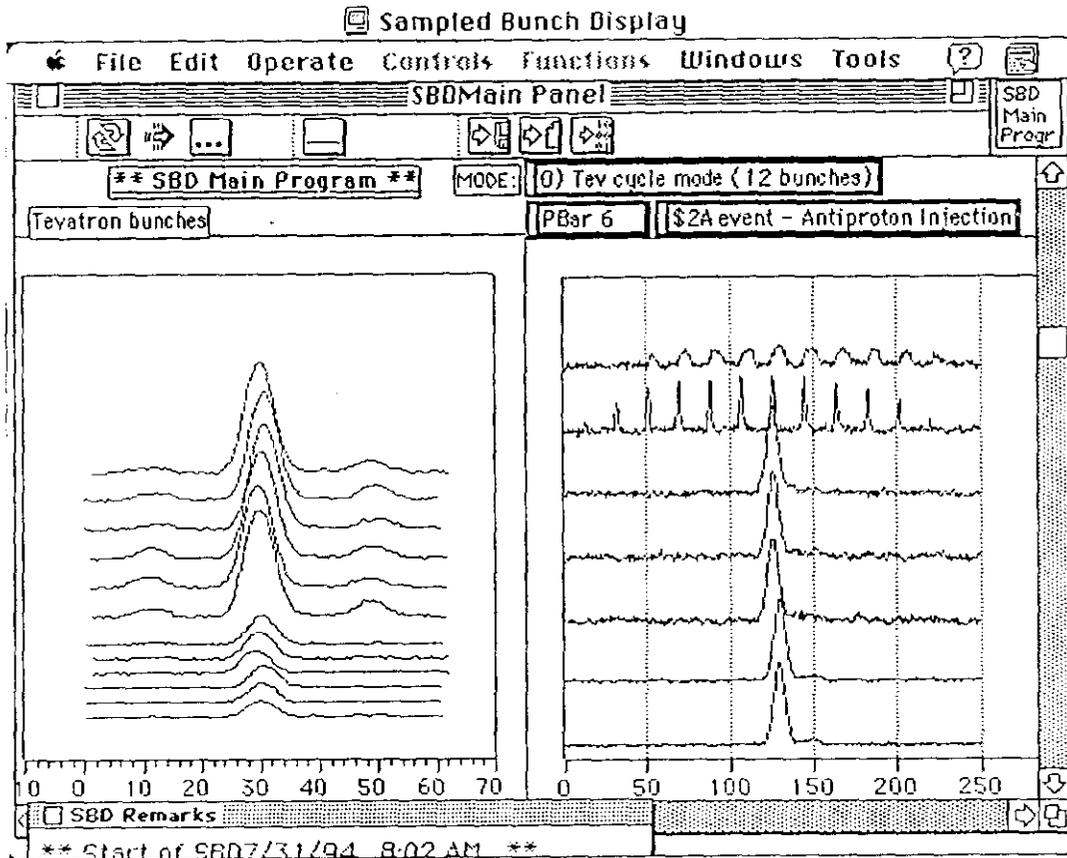
The following procedure, based on the beam spectrum and system frequency response, has been used to calibrate the intensities and widths of the SBD. For each accelerator, the frequency response of the wall current monitor, cable, splitter (if any), and oscilloscope path is measured. The wall current monitor can be readily measured only before tunnel installation. Afterwards, and on a periodic basis, the rest of the path is measured. A calibrated frequency synthesizer injects a set of discrete frequencies into the cable in the tunnel, and the resulting powers are measured on the scope for all relevant gain settings. The power ratios become the transfer function with two dimensions, frequency and scope gain. An off-line simulation program then transmits an ideal gaussian, representing beam, through this system transfer function. The usual SBD algorithms are performed to find the resulting intensities and widths. The ratio of these values to the input gaussian parameters become the intensity and width calibration factors. Also, the ability to perform an "adaptive" calibration exists. The actual acquired waveform is deconvoluted with the transfer function to obtain the theoretical beam profile. Both waveforms are processed, and the intensity and width ratios become the adaptive calibration factors. The adaptive method was found to be too susceptible to noise, so the simulated calibration factors are now used instead.

Variations of 1.5% sigma can primarily be attributed to the effect of noise and 8-bit ADC truncation on the baseline subtraction algorithm. Averaging decreases this fluctuation. The SBD Tevatron intensity sum has been compared with the DC current transformer, which measures with  $\pm 1\%$  absolute accuracy.(7) Agreement has been within  $\pm 1\%$  over many months of operation.

## OUTPUTS AND USES

The data is presented in a number of formats for monitoring and analysis. All Acnet control and reading variables are listed on an Acnet console parameter page, specific to the SBD. Fermilab cable channel 13 (Fig. 2) displays the running averages of the 12 Tevatron store bunch intensities. Cable channel 22





**Figure 3.** Closed-circuit TV channel 22, showing the LabVIEW front panel. Left: plot of all 12 Tevatron bunches, from Proton 1 (top) to Antiproton 6 (bottom). Right: waterfall plot showing time progression of the most recent bunch injected into the Tevatron, from Main Ring injection (top) to Tevatron.

simplified the work. Since the time that the TDS620 oscilloscopes were purchased, even higher performance digitizers have been developed. Hopefully, the SBD program was written to allow for easy replacement, if desired in the future. The system now runs with good reliability, providing high accuracy longitudinal data for Fermilab colliding beam physics.

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