IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

LONGITUDINAL BEAM SIGNAL PROCESSING FOR THE FERMILAB BEAM QUALITY MONITOR

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Summary

A general overview of a new beam monitoring system is presented along with a detailed description of two of the signal processing units used for measuring longitudinal beam properties.

Introduction

Various properties of the main ring beam can be measured with a system which has been developed over the past few years. The system includes three pickups located in the main ring, four signal processing units (two are discussed in detail in this paper), and two have been described elsewhere,[1] two 53 MHz digitizers,[2] and the associated hardware[2] and software which allow one to select among the signal processing units, and to select the particular portion of the beam in the machine to examine The system is referred to as the "beam quality monitor" when one examines various properties of the first turn beam injected from the booster.

An overview of the system is schematically presented in Figure 1. The phase error signal processing unit is hardwired into one of the 53 MHz digitizers, while a software controlled switch chooses which of the other three signal processing units is analyzed by the second digitizer. One is able to remotely select the time in the accelerator cycle at which one starts to digitize, also one can select the particular bunch at which one starts to digitize, how many bunches to digitize (the number can range from 1 to 1113), and finally how many turns that elapse between subsequent digitizations. As an example, one can choose to examine the seventh, eighth, and ninth bunches in the ring, skipping ten turns between digitizations, and starting just after transition. The fast memories contain 1536 locations, and this determines the relationships among the number of bunches to examine, the number of turns to skip between digitizations, and the length of time during the cycle that one wishes to sample.

The cables connecting the pickups to the signal processing units were chosen to minimize signal distortion, and the length of cable as the minimum length between the pickup and the particular unit. In the case of the phase measurement unit (discussed in detail in the third section of this paper) there is an additional signal input, an RF clock. The RF clock input to the unit is from a voltage controlled oscillator (VCO) which has a frequency range during the acceleration cycle from 52.813 MHz to 53.105 MHz. This frequency span necessitated care in balancing the delay between the processing units and the beam pickup, and the delay between the processing unit and the VCO. After the balancing was done a further instrumental effect was found due to sidebands in the VCO (located at $\pm$8.74 MHz from the fundamental and 46 db down in magnitude). We have used two methods to overcome this difficulty: we can use a fixed frequency oscillator without sidebands to monitor injection, or we can use a filter which cuts the sidebands down by an additional 16 db. The first solution means that we can only examine the beam during injection while the second solution has a frequency dependent phase shift during the acceleration cycle due to the response of the filter. For normal beam monitoring the filter is used, however during booster main ring longitudinal matching studies[3] the fixed frequency signal is used.

In concluding this overview of the system it should be noted that a fifth signal processing unit is under development which will permit the monitoring of the intensity of a bunch in the same manner that the other properties of the bunch are monitored.

Width Measurements

The space occupied by each of the bunches within the buckets of the Fermilab Main Accelerator is determined by a bunch width/phase detector. The width detector is part of the beam quality monitor system and converts beam signal data derived from broad bandwidth, long clipping time, stripline monitors into voltage quantities suitable for longitudinal phase space analysis.

Observations of beam signals had indicated that bunch spread existed over a range from about 1/8-to-1/4 of an rf cycle, or from about 2.2-to-5 ns. The width range of the monitor was designed to overlap these observed values and was set to 2-to-8 ns; a phase range of 38-to-153 degrees.

The bunch width detector developes the analog of width/phase as a series of constant voltage levels, one for each bunch, each lasting about 15 ns at a PRF of 53 MHz. The discrete voltage levels developed represent a specific bunch width. A positive zero volt referenced 2 ns trigger pulse is also made available to facilitate the synchronization of other devices such as fast digitizers.

The intensity range over which the width determining device functions is >6:1 (16 db), where the lower threshold is 5 x 10^9 protons per bunch.

Width-to-Voltage Conversion

The method used in the width-to-voltage conversion process is outlined in Figure 2. This block diagram shows the beam signal being split into a number of equal amplitude but unequal delay paths and then the split paths are recombined again by an arithmetic summer (see Ckt. path 1 of Figure 2). This splitting, delaying, recombining process leads to the development of pyramid voltage function whose apex height is proportional to the width of the beam bunch. The pyramid function can be developed in a few nanoseconds, thus making this tech-

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nique applicable to bunch-by-bunch determinations of width. By using fast track and hold circuits activated by beam developed triggers (path 2 in Figure 2), the apex value is determined for individual bunches. Path 3 in Figure 1 contains a peak signal detector and meter which allows beam intensity monitoring.

Figure 3 shows several pyramid functions, each associated with a specific beam pulse width. The figure illustrates the width-to-amplitude-conversion process. The τ_{1n} value shown represents the width.

Design Parameters

The evaluation of important parameters proceeds as follows: The sampling function halfwidth ($\tau_{\Delta S}$, Figure 2) is set to a value no larger than 1/10 the maximum sampling time, $1/f_{rf}$. For the Fermilab machine $\tau_{\Delta S} \leq 0.1/f_{rf}$ = 1.88 ns max.; 1.62 ns utilized. For design purposes a maximum of 80% of the time between sample pulses is used for pyramid development (base width value maximum τ_{BW}), while the remaining 20% is used as a guard against spill over and mixing of adjacent pyramid functions, thus, $\tau_{BW} = 0.8\ 1/f_{rf}$ = 15.2 ns maximum. The base width time of the pyramid is related to the total number, n, of delay cables required, the differential delay in each cable, $\tau_{\Delta C}$, and the width of the beam bunch, τ_B through $\tau_{BW} = (n - 1)\ \tau_{\Delta C} + \tau_B$. The differential delay time, $\tau_{\Delta C}$, is set so as to permit two pyramid steps to be used in establishing the charge on the track-hold capacitor. This measure improves resolution and permits interpolation of the input quantities, therefore, the delay must be half the sampling function halfwidth; $\tau_{\Delta C} = \tau_{\Delta S}/2$ = 0.81 ns. The number of delay cables (and splitter divide ratio), n, can be found from these data as, $n = (\tau_{BW} + \tau_{AC} - \tau_{Bmax})/\tau_{\Delta C}$ = 10 cables; 10-way splitter.

Performance

Figure 4 shows the output of the width module during beam observation. Figure 4 shows a dynamic variation in bunch-to-bunch width phase variation from 2.1-to-4.5 ns, 40 deg-to-86 deg phase. About 40 bunches are shown. The table below indicates the general performance factors for the device.

Performance Factors Summary

Type...Width-to-voltage using pyramid generator
Intensity range...6:1, 3×10^{10}--5×10^{9} protons/bunch
Bunch width range...2-8 ns
Phase range...38-153 deg
Operating pulse repetition frequency (PRF) ...52.8-53.1 MHz
Output sensitivity factor...0.3 volts/ns
Input/output impedance...50/50 ohms
Trigger output...2 ns HW, +0.8 V peak
Resolution...2 deg phase
Accuracy...5 deg phase, estimated

Phase Measurement

The other beam parameter needed for assessment of beam quality is the phase position of the bunch relative to the bucket. This parameter requires the determination of the time difference between the bunch centroid locations and the positive zero crossing point along the gap wavelet. This time quantity is related to bunch phase position, ϕ_S, by $\phi_S = 360\ f_{rf}\ \Delta t$, where f_{rf} is the operational frequency of the gap wave and Δt is the time difference.

The major design difficulty in obtaining the ϕ_S values on a bunch-by-bunch basis is the requirement for obtaining the individual bunch centroid locations in the nanosecond time frame. Methods to derive the analog of time centroids generally involve slow, difficult to implement integrations and divisions.

One method, rarely if ever employed to find centroid values, uses the quadrature property of and network elements of rf circuit devices called quadrature junctions. For sinusoid inputs, the quadrature signal crosses the zero axis exactly at the centroid of the cusps of the input wave.

In general, the zero crossing of the quadrature signal and its correspondence to the centroid location holds well (2%) for most evenly distributed functions such as rectangular pulses, triangular waves, half sine waves, trapezoidal waves, etc., provided the major part of the spectrum of the wave is contained within the bandwidth boundaries of the junction. For the skewed and stepped functions shown in Figure 5, the quadrature signal also approximates the centroid location, but with less accuracy.

The broadband nature of the device permits using the quadrature junction as the building block for determining centroid locations at nanosecond speeds. Figure 6 shows the overall block diagram of the phase monitor system using the junctions technique.

Phase Monitor Circuit

The beam signal is applied to the centroid circuit consisting of a quadrature junction (a 30-80 MHz unit was chosen) and impedance matching networks. The resultant signal is then amplified and limited to increase the zero crossing function slope and to control overdrive. The fast comparator is arranged to sense the positive-going zero crossing wave and discriminate against negative-going crossings. The comparator produces a 2 ns wide signal whose positive-going edge at the 50% point is aligned to the centroid position. Figure 7 shows how the developed centroid pulse signal (lower trace) follows the centroid of the input wave (upper trace) over a 5:1 width ratio; from 10-to-2 ns.

The output from the comparator triggers a 1.5 ns wide bipolar track and hold control pulser whose output is applied to the track and hold so that the gap waveform can be sampled. The track and hold output, V_S, is proportional to the time displacement of the bunch centroid and the gap zero crossing, Δt, and the slope, m, of the wave, i.e., $V_S = Km\Delta t$, volts; where
K = sample and hold gain constant, 0.41
m = slope of gap voltage 0.34 V/ns
Δt= time difference, + when centroid follows gap zero crossing, - otherwise.
The track and hold output voltage is thus 0.139 V/ns.

This signal is amplified to provide an output signal of 1.39 V/ns in a non-return to zero format. The linear range for the phase system is ± 2 ns or ± 37 electrical degrees, a total phase range of 74 degrees. The output characteristic is shown in Fig. 6.

The overall characteristics of the device are tabulated below.

Phase System General Characteristics

Type system...Centroid controlled processor
Intensity range...5×10^{9}-to-5×10^{10} proton/bunch
Time range...± 2 ns about offset point
Time offset range...± 4 ns from gap wave zero + crossing
Phase range...± 37 electrical degrees
Input signal level...4 V p-p nominal max
Input signal detector...50Ω stripline
Output signal...1.4 V/ns, bipolar
Impedance input/output...50/50 ohms

Phase resolution...2 degrees
Phase accuracy...5 degrees

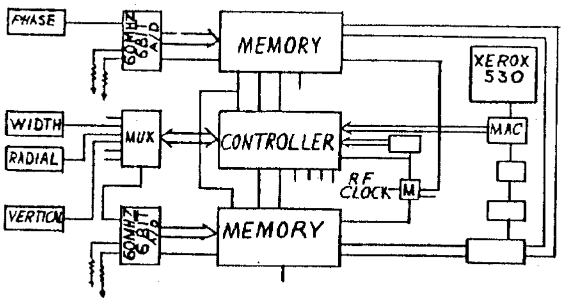

Fig. 1 System Overview

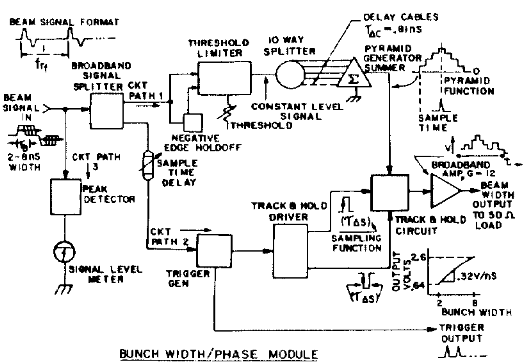

Fig. 2

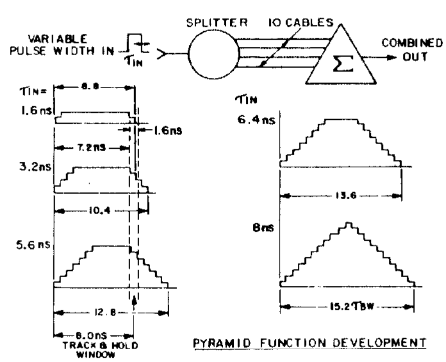

Fig. 3

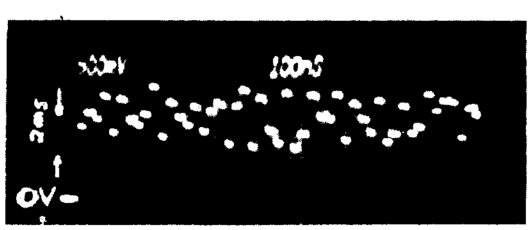

Fig. 4 2 ns/Major Division

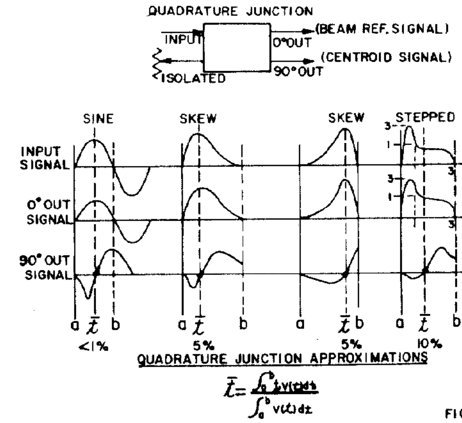

FIGURE 5

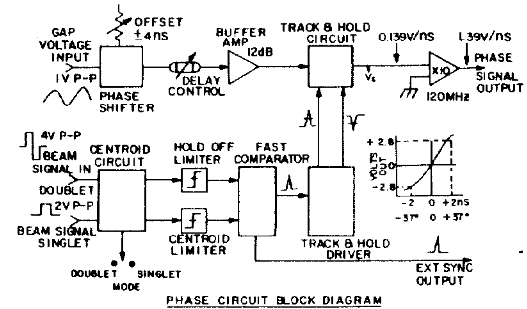

FIGURE 6

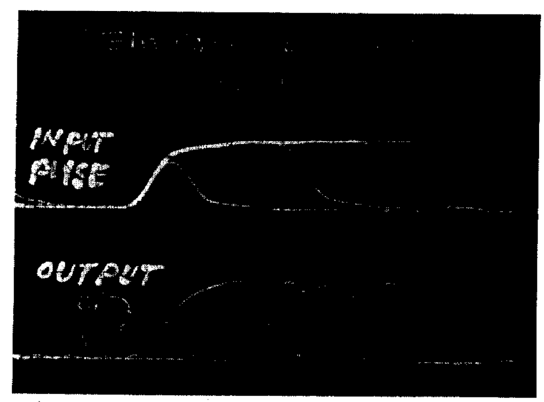

Fig. 7 Centroid signal at 50% tracking input wave.

Acknowledgement

The authors wish to acknowledge the helpful assistance of the Accelerator Division staff, especially Frank Turkot and Stan Pruss.

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