POSITION MONITORING ELECTRONICS FOR THE STANFORD LINEAR ACCELERATOR*

Raymond S. Larsen and Hugh A. Woods
Stanford Linear Accelerator Center
Stanford, California

This paper outlines the overall beam steering system and lists the design requirements for the position monitoring electronics at the 30 sectors of the accelerator. The operation of the electronics is explained, and the more interesting circuits are described in detail. The performance is summarized.

Introduction

An important problem with the SLAC accelerator is to determine accurately the transverse position of the beam within the accelerating structure. Moreover, since multiple beams of widely different charge will be used, it is essential to be able to observe the position of each beam independently.

Sensors are in use which produce video output signals proportional to the horizontal and vertical position coordinates of the beam measured from the central axis. In the two mile SLAC accelerator, however, the transmission of large numbers of such wideband signals to the control room would be difficult and costly. The approach taken here has been rather to develop a system in which video pulses are processed locally, i.e., at the drift section at the end of each 330' sector, to obtain high level average position signals suitable for transmission over a hardwire telemetry link.

Specifically, the Position Monitoring Electronics to be described normalizes video position pulses from microwave position monitors into 0 to 5 volt, 550 μsec pulses proportional to horizontal position, vertical position and the logarithm of beam charge, over a 1000 to 1 range of charge.

A general description of the beam steering system will first be given.

System Description

Figure 1 illustrates the main components of the beam steering system located at a drift section in the SLAC accelerator, and their connection to the Central Control Room. Three microwave resonant cavities provide RF outputs which are functions of beam intensity (i), intensity times horizontal displacement from the accelerator central axis (ix), and intensity times vertical displacement (iy). These are fed to microwave detector circuitry which produces video outputs directly proportional to i, ix and iy. These signals are processed by the Position Monitoring Electronics to give ln Q, x and y in a serial form, where Q is the total pulse charge. This signal is sent by a baseband telemetry system to a de-multiplexer at the Central Control Room, together with similar signals from the remaining 29 sectors.

The de-multiplexer first samples each of the 30 signals and channels ln Q, x and y into 3 separate oscilloscope displays. A remote control system allows the operator to adjust the steering dipole currents at any sector while monitoring the resulting beam position displacements for the entire machine.

The ln Q display is not a particularly accurate measure of charge. Its utility lies in being able to display simultaneously beams of widely varying charge, such as will be encountered in multiple beam operation of the machine.

It is the main purpose of this paper to describe the operation of the Position Monitoring Electronics. As mentioned, its function is to derive from the video signals normalized position signals in a form suitable for transmission to the Central Control Room.

Design Requirements

The main requirements for the position monitoring electronics are as follows:

(a) The circuit must handle a range of beam charge of 1000:1. The maximum beam pulse amplitude and width are 100 mA and 2 μsec respectively, corresponding to a charge of 2×10^{-7} coulombs. Thus the circuit must handle beam charges down to 2×10^{-10} coulombs. The normalized position signals should be independent of charge over this range.

(b) The maximum beam displacement in the accelerator is taken to be ± 1 cm. The system must be able to resolve changes in position of 1 mm over the upper 40 db of its range, i.e., over a 100:1 range of beam charge.

(c) It is imperative that the on-axis position of the beam be detected with high accuracy. This means that systematic errors and drifts in the electronics which would erroneously indicate a beam displacement, cannot be tolerated. However, a measurement of the exact value of the displacement is of secondary importance, because the system will be used as an aid to placing the beam on axis,

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rather than in accurately determining displacements from the axis.

(d) The electronics must operate on a pulse-to-pulse basis, i.e., at a 360 pps rate. This is because as many as six interlaced beams of widely differing energy and charge will be provided by the accelerator. The electronics must thus be able to perform a complete cycle of operations in 1/360 sec (2.78 msec) with no interaction between data obtained from successive beam pulses. This requirement eliminates the need for beam identification at each sector.

(3) The output signals from the electronics must be suitable for telemetering over a base-band system using standard telephone cable pairs. To allow as great a sampling time as possible in the de-multiplexing circuit, the ln Q, x and y signals must occupy as much of the 2.78 msec as possible.

Circuit Operation

The basic information required from the sector Position Monitoring Electronics is the average value, for each pulse, of the horizontal and vertical beam displacements from the accelerator axis. Accordingly, this circuitry evaluates average position values given by

$$\bar{x} = \frac{\int_o^T (ix)(t)dt}{\int_o^T i(t)dt} \text{ and } \bar{y} = \frac{\int_o^T (iy)(t)dt}{\int_o^T i(t)dt} \qquad (1)$$

where i, ix and iy are functions of time and T is the pulse duration.

This definition of average value differs from the conventional definition which, in the case of a horizontal displacement, is given by

$$x_{av} = \frac{1}{T} \int_o^T \frac{(ix)(t)}{i(t)} dt \qquad (2)$$

However, the beam pulse will be essentially rectangular, so that $i(t) = I$ for $0 < t < T$. In this case, $\bar{x} = x_{av}$. Even in the case where the beam pulse is not rectangular, $\bar{x}$ and x_{av} will not differ appreciably.

The circuit to evaluate $\bar{x}$ is much simpler than that required for x_{av}. In this latter case, instantaneous division in real time is necessary, as well as an averaging process which depends upon the pulse length. These requirements are not necessary when evaluating $\bar{x}$ where, as will be shown, two integrations, followed by division, suffice.

Figure 2 is a block diagram of the position monitoring sector electronics. The three video inputs from the microwave detector circuitry are fed into three gated integrators. These are passive RC integrators having a nominal accuracy of 5% for the widest pulse. The integrator outputs are held for 2.25 msec at which time a clamp pulse clears the information in preparation for the next beam pulse.

The integrator outputs represent

$$\int_o^T i(t)dt, \quad \int_o^T (ix)(t)dt \quad \text{and} \quad \int_o^T (iy)(t)dt$$

Normalization is accomplished by appropriately gating these outputs into a logarithmic amplifier. This amplifier consists of an operational amplifier with input summing resistors and a feedback network consisting of 5 series diodes. The diodes are temperature stabilized in a 70°C component oven.

Since the amplifier summing junction is a virtual ground, the input resistor current equals the diode current. The amplifier output adjusts to the required voltage to supply this diode current:

$$i_d \cong i_o \exp\left(\frac{qV}{kT}\right)$$
$$V \cong C^1 \ln i_d$$

Initially the signal $\int_o^T i(t)dt = Q$ is fed to one of the operational amplifier summing resistors. Absorbing constants of proportionality, the output of the logarithmic amplifier is $V = C \ln Q$.

At a time 850 µsec after the beam pulse, the signal $\int_o^T ixdt$ is gated through a second summing resistor into the amplifier. For i = constant, this signal is proportional to $Q\bar{x}$. Absorbing the proportionality constant into $\bar{x}$, we can write $\int_o^T ixdt = Q\bar{x}$. The logarithmic amplifier output then rises to a new voltage $V = C \ln(Q + Q\bar{x})$. After an additional 550 µsec, the $Q\bar{x}$ signal is removed, and 300 µsec later the $Q\bar{y}$ signal is gated in, producing a level $C \ln (Q+Q\bar{y})$ (see Figure 3).

On gating in the $Q\bar{x}$ and $Q\bar{y}$ signals, the output of the logarithmic amplifier changes by amounts

$$\ln (Q+Q\bar{x}) - \ln Q = \ln(1+\bar{x}) \cong \bar{x} \quad \text{and}$$

$$\ln (Q+Q\bar{y}) - \ln Q = \ln(1+\bar{y}) \cong \bar{y}$$

$$\text{where } \bar{x},\ \bar{y} \ll 1$$

Thus the changes so obtained are directly proportional to the required quantities, that is, the average horizontal and vertical beam displacements.

The series expansion is

$$\ln(1+\bar{x}) = \bar{x} - \frac{\bar{x}^2}{2} + \frac{\bar{x}^3}{3} - \frac{\bar{x}^4}{4} + \ldots\ldots$$

$$= \bar{x} + e$$

The summing resistors are chosen so that the ratios $Q\bar{x}/Q = \bar{x}$ and $Q\bar{y}/Q = \bar{y}$ have maximum values of 1/3 for which $|e| = 14\%$. Thus for the maximum displacement in one direction, $\bar{x}$ and $\bar{y}$ will be 15% high, and for the opposite direction, 15% low.

Circuit Details

Most of the circuits are conventional. Details are given only for the gated integrator and the clamp and range-switch following the logarithmic amplifier.

Gated Integrator

Figure 4 shows the gated integrator and × 1 buffer. The circuit must handle a range of signals from 1 volt to 1 mv with DC offsets limited to less than 1 mv.

The dual emitter chopper transistor Q1 is turned on for 3 μsec to allow passage of the video pulse. The integrator time constant is 20 μsec, or 10 times the maximum pulse width. The gate Q1 closes to isolate the charge on the capacitor. Clamp Q2, which is back biased, and the field effect transistor Q3 present an impedance of roughly 20 Megohms. Therefore the pulse droop in 2 μsec is about 1%.

The FET output is buffered by a bootstrapped emitter follower which has an output impedance of approximately 5Ω. The buffered signal is coupled through a 15 μF low leakage tantalytic capacitor which is restored after each operation by clamp Q6.

At a time 2.25 msec after the beam pulse, clamps Q2 and Q6 simultaneously restore the integrator and output coupling capacitors. The resulting output pulse is temperature stable to better than 1 mv over a wide temperature range.

Loading the output of the buffer causes additional droop. The output coupling capacitor and load resistor are selected to limit this droop to less than 1% for a 550 μsec pulse.

The clamp transistors pose a limitation to the time required to clamp a given sized capacitor. Since in practice the series resistance of Q6 can be reduced only to about 5Ω without introducing an unacceptably large $V_{ee}(sat)$, the restoration time constant for the 15 μF capacitor is about 75 μsec. Hence it is necessary to allow 300 μsec for proper clamping.

Clamp and Range Switch

The output of the logarithmic amplifier contains the desired $\bar{x}$ and $\bar{y}$ amplitudes atop the larger ln Q pulse. To extract this information, the clamp circuit of Figure 5 is used. Initially, the ln Q signal is coupled through C1 into the FET buffer. At a time 550 μsec after the beam pulse, a 300 μsec pulse applied to Q1 clamps C1 to ground, charging it to (ln Q) volts. The clamp is removed, and $\bar{x}$, now varying about ground, is obtained. The operation is then repeated for $\bar{y}$. The resultant output signal is ln Q, $\bar{x}$ and $\bar{y}$ in serial format measured from a common baseline. The buffer, Q2 and Q3, and the output coupling scheme, C2 and Q4, are similar in operation to that of the gated integrator.

At this point, the maximum ln Q, $\bar{x}$ and $\bar{y}$ signals must be equalized in amplitude before being transmitted. This is accomplished in a switched attenuator which reduces ln Q, but not $\bar{x}$ or $\bar{y}$, followed by an adjustable gain DC amplifier. The output of the amplifier is 5 volts maximum for ln Q, stable to approximately 2%, and a nominal 5 volts maximum for $\bar{x}$ and $\bar{y}$. A baseband transmitter couples the signal to a hardwire telephone pair for transmission to the Central Control Room.

Construction

The entire position monitoring circuit is contained in a 10-1/2" high standard 19" rack card file. This chassis also contains circuitry, not herein described, associated with the precise measurement of beam charge.

Printed circuit cards are used throughout. The commercial operational amplifier and power supplies are plug-in modules. The dual 15V and 30V supplies are operated from the 115V AC supply. The diode component oven uses a local 24V DC battery supply.

Separate high quality and power ground systems are employed in order to minimize pickup due to ground currents from the timing logic and clamp drives.

Calibration and Performance

The electronics is calibrated by applying known signals to simulate the microwave monitor outputs. The ln Q output corresponding to a 100 mA, 2 μsec pulse is adjusted to 5 volts. The simulated inputs are then attenuated by 60 db, where a threshold is adjusted to eliminate signals below this level.

The nonlinearity in ln Q for input signals ranging from the maximum to -50 db is approximately ± 1 db. The position signal accuracy is ± 15% for maximum beam displacements, but the zero resolution is better than ± 2% of full scale over the top 40 db of the range. For a ± 10 mm maximum displacement, this is equivalent to a spatial resolution of ± 0.2 mm, over a 100:1 range of beam charge.

In the foregoing, it has been assumed that the microwave circuitry is perfectly balanced over the entire signal amplitude and temperature ranges.

Three prototype circuits have been operating continuously in Sectors 1 and 2 of the accelerator since January 1965. The output signals are transmitted a maximum distance of 600' using baseband telemetry to a temporary control room where steering dipole controls are located. No particular problems have been encountered in the noise and temperature environment of the Klystron Gallery, and no component failures have occurred.

When the beam through the microwave sensors is well collimated, excellent steering signals result, and resolution of 1 mm displacement over a 40 db range of charge is achieved. If the beam is improperly focused, however, the sensor signals are poor and the overall sensitivity of the system is degraded correspondingly.

Acknowledgements

Thanks are due to Mr. John Kieffer for his valuable help in the development and construction of the circuits described.

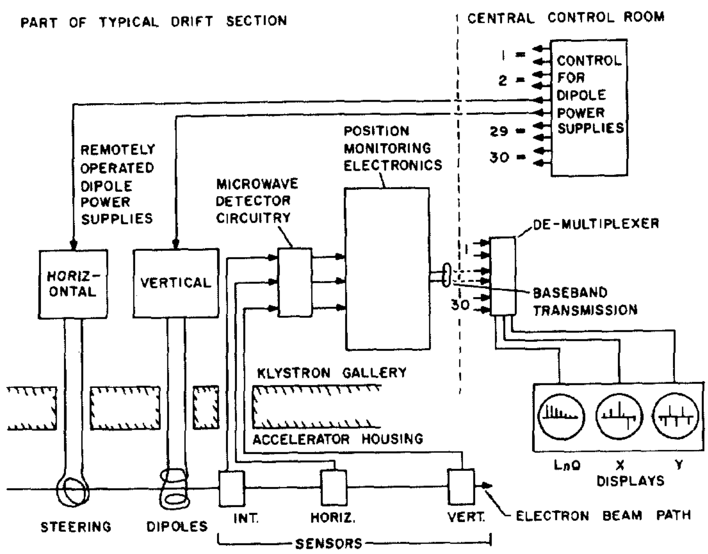

Fig. 1. Beam Steering System.

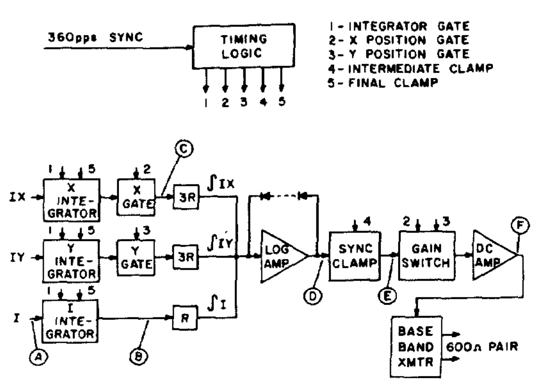

Fig. 2. Position Monitoring Sector Electronics.

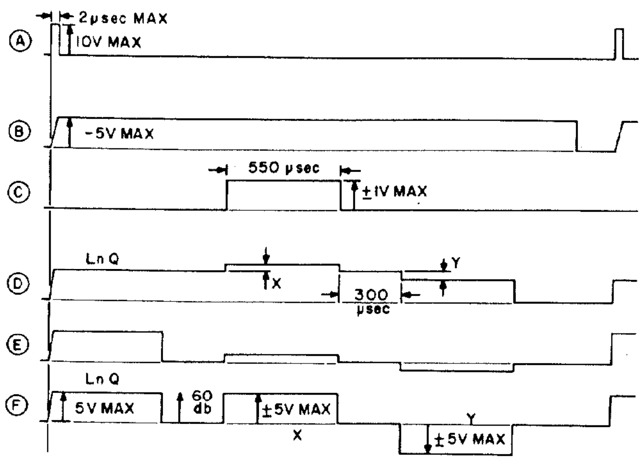

Fig. 3. Waveforms.

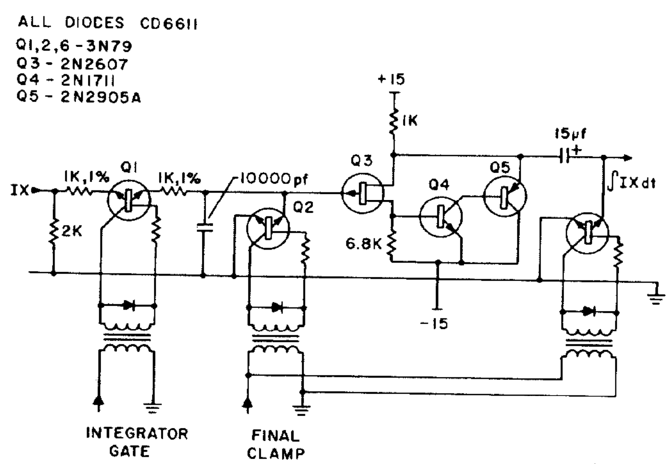

Fig. 4. Gated Integrator Circuit.

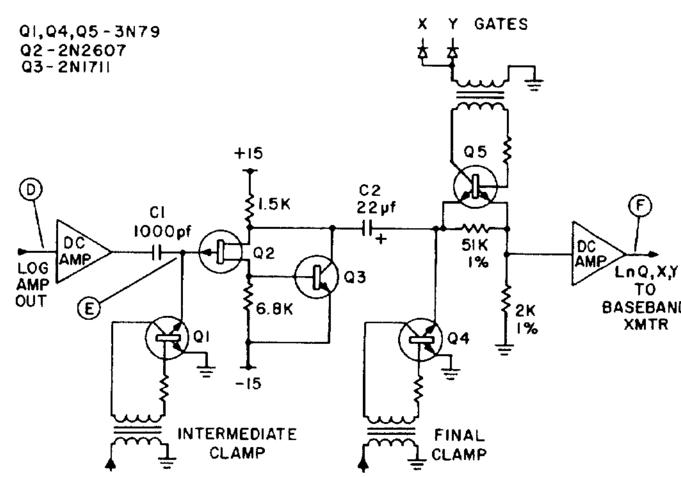

Fig. 5. Clamping Circuit and Range Switch.