MICROWAVE BEAM POSITION MONITORS AT SLAC*

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Summary

The design and performance of three types of non-intercepting microwave beam position monitors are described. The monitors locate the transverse centroid of the bunched beam. Monitors of the first two types each consist of two orthogonal position-sensing cavities and one reference cavity. The microwave signals induced by the beam in these cavities are combined in two phase bridges and linearly detected. The video signals are normalized with respect to beam current and transmitted to two control buildings where they are displayed. Thirty-three monitors along the linear accelerator have 0.8-inch apertures, and six special monitors at the end of the machine have 2.0-inch apertures. A third type of monitor has been installed in one experimental area. Waveguide couplers on a 3-inch diameter beam drift tube feed signals to a phase bridge. The bridge sum and difference signals are amplified, detected, and differentially displayed on an oscilloscope. The device can detect 0.004-inch changes in position of a 0.01 mA beam with a response time of 50 ns.

Introduction

Initial SLAC requirements called for two designs of beam position monitors. The first was to have an aperture not smaller than the accelerator structure. Monitors of this design were to be installed principally in the drift-sections at the end of each of the 30 sectors of the linear machine, and be capable of detecting 0.020-inch horizontal and vertical beam misalignments with respect to the machine axis, for beam pulse currents in the range 1 to 300 mA. A second design was required for position monitors to be installed in the Beam Switchyard, where the beam from the linac is channelled to the experimental areas. Performance requirements were similar to the first design, but the monitor aperture had to be as large as possible.

Much of the early exploratory and design work on the SLAC monitors was done by Brunet, Dobson, Lee and Williams.[1] Some of the types of beam sensors considered are illustrated schematically in Fig. 1. They are discussed in the references given.[1,2,3] In spite of greater complexity and cost, microwave monitors were preferred to ferrite-cored differential pulse transformers because much higher sensitivity could be obtained with high Q resonant cavities. Theoretical and experimental investigation led to the choice of TM_{120} resonant cavity sensors for the "in-line" monitors to be installed along the linac. It was decided to make the beam aperture 0.8-inch in diameter.

The resonant waveguide ring was initially chosen for the Beam Switchyard monitors, but its sensitivity deteriorated rapidly as the beam aperture size was increased. It was found that the TM_{120} cavities operated well with a 2-inch diameter aperture, so these were used in the switchyard.

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Each monitor assembly comprises two orthogonally mounted position cavities and one circular cavity operating in the TM_{010} mode. The output of this cavity is independent of beam position, and is used to normalize the position cavity output signals with respect to beam current.

Theory and Design

In-Line Monitors

Overall System Design. The rf-video system is shown in Fig. 2. Semi-rigid coaxial cables transmit the rf signals from the cavities up to the Detector Panel in the Klystron Gallery. Here, the rf signals are converted to video pulses proportional to beam current I_o, and beam current times displacement ($I_o x$ and $I_o y$). The signs of $I_o x$ and $I_o y$ indicate the displacement directions. The Sector Electronics processes the video into a train of three pulses,[3,4] whose heights are proportional to $\ln Q$ (where Q is the charge contained in one beam pulse), x and y. The pulse train is transmitted to the Central Control Room, where it is fed into a multiplexer, together with similar signals from all other position monitors on the linac. The multiplexer samples the $\ln Q$ pulses from each monitor and displays their amplitudes as the ordinates of a dotted line on an oscilloscope.[5] x and y are similarly treated.

Cavity Design. The TM_{120} cavity is formed from a section of waveguide, broad dimension a, narrow dimention b. The guide is closed by shorting planes which are separated by a distance d (approximately one guide wavelength at the accelerator operating frequency). Circular apertures are placed in the centers of the broad faces to permit passage of the electron beam (see Figs. 1 and 3). The beam is tightly bunched at the accelerator frequency.

Power extracted from the beam is given by

$$P_b = \frac{1}{2} \operatorname{Re} \int_{-\infty}^{\infty} E_z I_{RF}^* \, dz \qquad (1)$$

where E_z is the peak value of the electric field along the axis of the electron beam, and I_{RF} is the peak value of the fundamental frequency component of beam current. Since E_z and I_{RF} are in phase, and I_{RF} is twice the average beam current during the pulse, I_o,

$$P_b = E_z I_o b \qquad (2)$$

E_z is related to $E_m(y')$, the maximum electric field in the cavity for a given beam position, y', by

$$E_z = E_m(y') \sin \frac{2\pi y}{d} \qquad (3)$$

y' = 0 when the beam axis coincides with the center of the waveguide apertures, and E_z changes phase by π as the beam crosses the center.

Since the power induced must equal the total dissipated power, P_b may also be expressed in terms of the loaded shunt resistance, R_L, of the cavity:

$$P_b = \frac{1}{2R_L}\left[\int_{-\infty}^{\infty} E_z dz\right]^2 = \frac{\left[E_m(y')b\right]^2}{2R_L} \sin^2\left(\frac{2\pi y}{d}\right) \qquad (4)$$

so that

$$\frac{R_L}{Q_L} = \frac{E_z^2 b^2}{2P_b} \Big/ \frac{2\pi f U}{P_b} = \frac{\left[E_m(y')b\right]^2}{4\pi f U} \sin^2\left(\frac{2\pi y}{d}\right) \qquad (5)$$

where Q_L is the loaded quality factor, f is the frequency and U is the energy stored in the cavity.

Since

$$U = \frac{\epsilon_0 \, a b d \left[E_m(y')\right]^2}{8} \qquad (6)$$

where ϵ_0 is the dielectric constant in vacuum, we have

$$\frac{R}{Q} = \frac{2b}{\epsilon_0 \pi f a d} \sin^2\left(\frac{2\pi y}{d}\right) \qquad (7)$$

The subscripts are dropped because R/Q is independent of the load. P_b must equal the sum of the power P_o coupled out of the cavity and the power P_j lost in the cavity walls, so that

$$P_o = P_b \beta / (1 + \beta) \qquad (8)$$

where

$$\beta = P_o / P_j \; .$$

Combining Eqs. (2), (3), (4), (7) and (8),

$$P_o = \frac{4 Q_L}{\epsilon_o \pi f} \cdot \frac{b}{ad} \cdot \left[\frac{\beta}{1+\beta}\right] I_o^2 \sin^2\left(\frac{2\pi y}{d}\right) \qquad (9)$$

Equation (9) has to be corrected for cavity detuning Δf, finite bunch width α, electron transit time τ and field variation across the cavity. The corrected power output, P'_o, is

$$P'_o = \left[\left(\frac{1}{\sqrt{1+\left(2Q\frac{\Delta f}{f}\right)}}\right)\left(\frac{\sin \alpha/2}{\alpha/2}\right)\left(\frac{\sin \pi f \tau}{\pi f \tau}\right)\cos\frac{\pi x}{a}\right]^2 . \qquad (10)$$

A further correction has to be applied for the field perturbation caused by the beam aperture. In the case of the "in-line" monitors, however, the variation in R/Q from the sine-squared distribution (Eq. 7) was too small to measure.

The circular, re-entrant TM_{010} cavity used for phase reference and normalization is discussed in detail by Altenmueller and Brunet.[6] The power output from the cavity is calculated in the same way as for the position cavities.

One obtains

$$P_o = 2(R/Q)\, Q_L \left[\beta/(1+\beta)\right] I_o^2 \; . \qquad (11)$$

The first three correction factors of Eq. (10) apply. The cavity is made re-entrant to maximize the product $[\sin(\pi f \tau)/\pi f \tau]^2 R/Q$.

Beam Position Monitor Detector Panels. A schematic of this unit is included in Fig. 2. It can be seen that the TM_{010} reference cavity signal is divided four ways: part is used as a reference for sector phase stability, and does not concern us here, part is used for current normalization, and the remainder is divided and used as phase reference in two hybrid rings. The second input arms to these hybrid rings are connected via attenuators and phase shifters to the horizontal and vertical position cavities, as shown. The output signals are detected by coaxial thermionic diodes, which have a linear detection range[7] (index less than 1.15) large enough to monitor beam currents between 1 mA and 300 mA. The differential video output from a balancing network between each pair of diodes is fed to the Sector Electronics. Each network is adjusted to give zero output when the position cavities are disconnected, and each phase shifter is adjusted to maximize the video output (and to select the desired polarity) when a signal is received from a position cavity. In this condition, each hybrid ring is insensitive to small phase changes in the input signals.

Beam Switchyard Monitors

Overall System Design. Beam position monitors are located at six places in the switchyard. Microwave signals from each cavity assembly are transmitted via semi-rigid coaxial cables to a detector chassis mounted nearby and shielded from direct radiation. Polystyrene dielectric is used in the coaxial cables and as much as possible elsewhere in each installation to minimize susceptibility to radiation damage. Video signals from the detector chassis are transmitted to the Data Assembly Building (DAB), where they are processed and displayed (see Fig. 4).

Cavity Design. The theory of operation is the same as for the "in-line" monitors. The 2-inch diameter beam aperture reduces the slope of E_z versus position at the center, and increases field penetration from each cavity into the connecting drift-tubes. For the latter reason, drift-tube lengths had to be increased to 4 inches to avoid cross-coupling.

Beam Position Monitor Detector Chassis Design. This chassis is similar to the "in-line" Detector Panel discussed above, with the following exceptions: (a) the signal from the TM_{010} cavity is used only for amplitude and phase reference at the hybrid rings, and not for normalization, (b) the hybrid ring outputs can be remotely switched to either coaxial thermionic diode detectors or to tunnel diode detectors (tunnel diodes are used for low-level detection, and are chosen primarily because their radiation resistance is better than other semi-conductor devices), (c) the diode video outputs are transmitted directly to DAB, and (d) the phase shifters are motor-driven and remotely controlled.

From Eqs. (9) and (11) we have, for small beam displacements,

$$P_p = \left(K_p I_o p\right)^2 \qquad (12)$$

and

$$P_r = \left(K_r I_o\right)^2 \tag{13}$$

where P_r is the power from the reference cavity at one input to a hybrid ring and P_p is the power from one position cavity (either horizontal or vertical) at the second input to the hybrid ring. In this section, all K's are constants. p is the beam displacement, horizontal or vertical. The phase shifters are adjusted so that the two input signals at each hybrid ring are in phase for beam displacements up and to the right. This condition allows us to write down the signal powers at the two output ports of one hybrid ring as

$$P_A = P_r/2 \left[1 + (P_p/P_r)^{1/2}\right]^2 = u^2 (1+v)^2 \quad , \tag{14}$$

and

$$P_B = P_r/2 \left[1 - (P_p/P_r)^{1/2}\right]^2 = u^2 (1-v)^2 \quad . \tag{15}$$

P_A and P_B are detected by diodes, whose output voltages are given by $V_A = K_A(P_A)^{n/2}$ and $V_B = K_B(P_B)^{n/2}$. Here we assume that the diodes have the same index but different conversion efficiencies. We are interested in forming three quantities: $V_D = V_A - V_B$, $V_S = V_A + V_B$ and $V_N = V_D/V_S$. Using the above equations, and setting $K = K_B/K_A$, we obtain

$$V_D = K_A u^n \left[1 - K + nv(1+K)\right] \tag{16}$$

and

$$V_S = K_A u^n \left[1 + K + nv(1-K)\right] \quad . \tag{17}$$

If the diodes are matched, K = 1 so that, using Eqs. (12) through (15), we have

$$V_D = 2K_A n v u^n = K_D I_o^n p \tag{18}$$

$$V_S = 2K_A u^n = K_S I_o^n \tag{19}$$

and $$V_N = K_N p \tag{20}$$

The above analysis of the detection system applies also to the "in-line" monitors, except that the normalizing signal corresponding to V_S is formed by separate detection of the reference cavity output. In the switchyard the position monitors are used primarily as beam centering devices, so it is sufficient to display V_D on an oscilloscope. However, provision exists for forming V_S and V_N and displaying $\ell n\, Q$, x and y as described by Larsen.[4]

Construction and Installation

In-Line Monitors

Details of the three-cavity assembly are shown in Fig. 3. The cavities, internal drift tubes and water jackets are constructed from OFHC copper. Stainless steel/copper/water interfaces were avoided because of electrolytic erosion. Specified tolerances on resonant frequency and assembly alignment made close dimensional tolerances unavoidable. All dimensions determining cavity size were held to ±.0005 inch for the reference cavities and ±.001 inch for the position cavities. The latter were fabricated from plates, rather than being milled out of solid stock. This method was preferred for reasons of economy and avoidance of leakage "pipes" across the cavity walls. All internal cavity surfaces were machined to a 32 microinch finish. A total indicated runout up to 0.010 inch was allowed between cavity apertures in a completed assembly.

Details of the coupling probe assemblies can also be seen in Fig. 3. The hybrid L-coupling was used in the position cavities because it afforded a wide range of β adjustment by rotating the probe assembly, without being critically dependent upon the current contact between the probe outer conductor and the cavity wall. A conventional loop coupling proved to be more suitable for the reference cavity. The inner conductors of both probe types pass through coaxial-sleeve ceramic vacuum seals. The probe assemblies are welded to stainless steel cups brazed into the cavity walls. Coned transformer sections adapt the position probes to Type N connectors and the reference probes to Type HN connectors.

Each brazed cavity was checked for Q_L and resonant frequency with standard probes before final braze-assembly. Probes selected for that assembly were then inserted and rotated to give the desired Q_L. Q measurements were made rapidly and accurately using a swept frequency display with double sideband suppressed carrier modulation to provide frequency markers at the 3-dB points on the resonance curve. The probe positions were marked and then the probes were welded in place. For final testing, the complete assembly was evacuated and water at 110° F was circulated around the cavities. The resonant frequency of each cavity was adjusted by distorting a specially weakened area of one wall (shown on middle cavity in Fig. 3).

After final testing, each monitor assembly was clamped in an aluminum support bracket and attached by adjustable bolts to an accelerator drift section.

In each installation, the support bracket is aligned by optical tooling apertures with the drift section support girder, which contains a Fresnel zone plate for alignment with a laser beam. It is estimated that the maximum misalignment between the theoretical electron beam axis and the electrical center of a cavity does not exceed 0.020 inch.

Beam Switchyard Monitors (Fig. 5)

Construction of the switchyard cavities is very similar to the "in-line" cavities. Specially developed rf connectors and vacuum seals are used so that the cavity assemblies can be quickly disconnected and removed by means of remote-handling tools. The support and alignment system is also modified to permit quick removal.

Operational Results

The two position monitor systems described above perform in accordance with initial design concepts, and are invaluable aids to establishing and maintaining electron beams through the long machine. No troubles have been experienced with the rf cavities. Some inconvenience is caused by imperfect matching of the coaxial thermionic diodes used for video detection. K (Eq. 16) is a function of rf power, so that even if the diode outputs are balanced at one power level, making $V_D = 0$ for $v = 0$, K differs slightly from unity at other power levels. This gives rise to a spurious position error signal. K also changes with time as the diodes age. The problem is of no consequence in the switchyard monitors, as a remote balancing control is included in the system. However, in the "in-line" monitors, it has proved necessary to add a control which enables all rf position signals to be disconnected from the hybrid rings. The central display then shows the zero errors for each monitor at a given time and beam current. It is now planned to install a remote balance control for each monitor.

Experimental End-Station Monitor

A very large aperture, high sensitivity monitor has been built for measuring horizontal displacements in SLAC End-Stations. The system is illustrated in Fig. 6. The beam sensor is a 3-inch diameter drift tube brazed into the broad walls of S-band waveguide. Common walls are removed to permit beam passage and electromagnetic coupling. The two beam-induced waves travel round the waveguide arms and are combined in a hybrid tee, accurately positioned so that the output signals are equal for a centered beam. The rf signals are converted to 120 MHz IF, logarithmically amplified, detected, and differentially displayed on an oscilloscope. It can be shown that the output for a displacement x is

$$V(x) = 20S \log \tan (2\pi x/\lambda_g + \pi/4) \qquad (21)$$

where λ_g is the guide wavelength and S is the slope of the logarithmic amplifiers in volts per decibel.

The power flow in each arm of the waveguide was measured as 10 μW/mA^2. A 0.004-inch change in position of a 0.01 mA beam pulse could be detected. It is known that greater sensitivity can be achieved at the cost of electrical aperture size by introducing symmetrical reflections in the waveguide arms. This increases the slope of phase versus position near the center of the monitor.

Early tests indicated a response time of 50 ns, but a long trailing edge appeared on the position pulse after the monitor was installed in one End-Station. The trouble was traced to a resonance in the drift tube. It was cured on cold test by inserting a narrow ring of lossy material. It is therefore planned to coat the inside of the tube with lossy iron alloy.

Acknowledgements

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All microwave testing was done by T. C. McKinney, who developed the Q measurement technique mentioned in the paper and coordinated the tightly interwoven schedules of assembly and electrical testing. G. Jackson was responsible for the mechanical layout and prototype construction of Monitor Detector Panels.

The contributions of these individuals and others who assisted them is gratefully acknowledged.

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TYPE OF MONITOR	SCHEMATIC	REMARKS	REFERENCE
SYMMETRICAL MATCHED WAVEGUIDE	TEE, BEAM	LOW SENSITIVITY. DIFFICULT TO CALIBRATE.	1
RESONANT WAVEGUIDE RING	BEAM	GOOD SENSITIVITY. CUMBERSOME STRUCTURE.	1
SHORTED WAVEGUIDE	BEAM	LOW SENSITIVITY. REQUIRES TWO SENSORS PER COORDINATE.	1
TM_{120} CAVITY	BEAM	GOOD SENSITIVITY. ZERO OUTPUT WHEN BEAM CENTERED. SMALL SIZE.	1
SACLAY LOOPS	BEAM	VERY LOW SENSITIVITY. COMPACT: 4 LOOPS CAN BE PLACED IN ONE SECTION.	2
TM_{010} CAVITIES	BEAM	LOW SENSITIVITY. CAVITIES MUST BE EXACTLY MATCHED.	2
DIFFERENTIAL PULSE TRANSFORMER	BEAM	LOW SENSITIVITY.	9

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Fig. 1--Beam position sensors

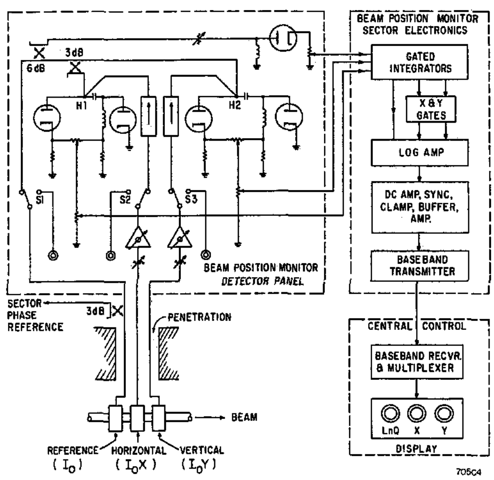

Fig. 2--In-line beam position monitor system

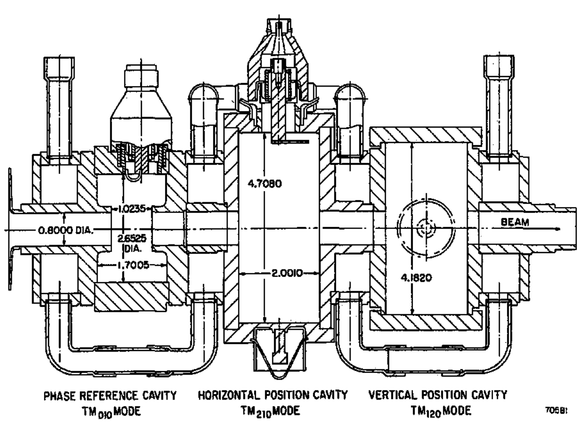

Fig. 3--In-line monitor cavity assembly

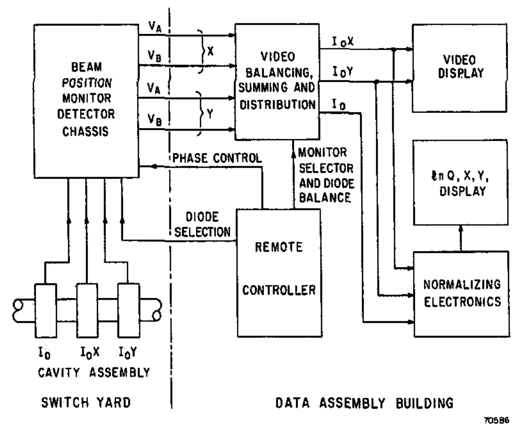

Fig. 4--Switchyard beam position monitor system

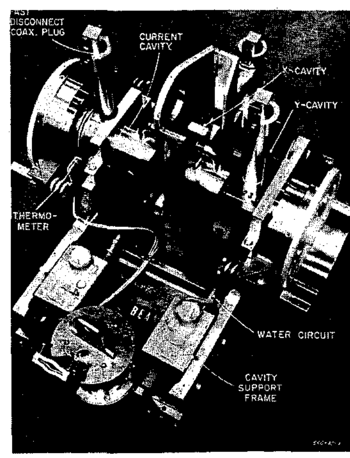

Fig. 5--Switchyard position monitor

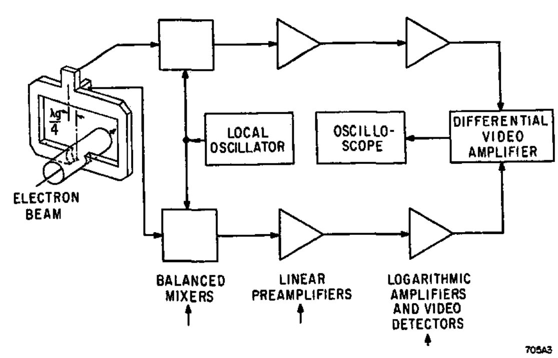

Fig. 6--End station beam position monitor system