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RECENT DEVELOPMENTS IN MICROWAVE BEAM-POSITION MONITORS AT SLAC*

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Summary

The design, installation and performance of beam position monitors initially installed at SLAC are reviewed briefly. The use of receiver systems to improve the sensitivity of switchyard monitors is described. Two position-monitoring systems developed especially for polarized electron-beam experiments are described : the first is a homodyne system capable of detecting 10 μm beam displacements at 100 μA beam currents, and the second is a traveling-wave monitor with a limiter-normalized output which can be used down to 20 μA.

Introduction

When SLAC was built, beam-position monitors were installed in the drift-sections along the accelerator, and in the beam switchyard. These position monitors are all basically the same type, namely, an assembly of three microwave cavities which resonate at 2856 MHz, the transit frequency of SLAC electron-beam bunches. The monitors have been described in earlier publications.[1,2] However, it will be convenient to review some features of their design, construction and performance here by way of introduction to this paper.

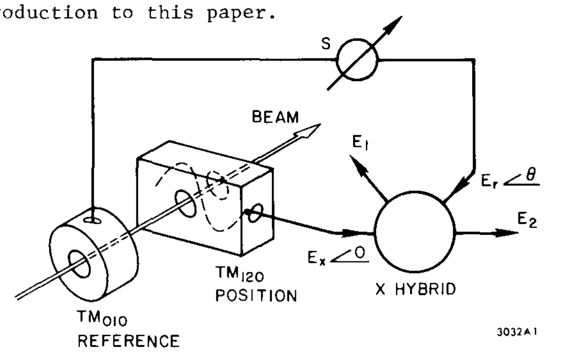

Fig. 1 : Schematic of Resonant Beam Position Monitor

The basic concept is illustrated in Fig. 1. The bunched beam passes through a TM_{010} reference cavity and two TM_{120} rectangular position cavities, aligned orthogonally to detect horizontal (X) and vertical (Y) beam displacements. Only the X cavity is shown in Fig. 1. Complete expressions for the cavity power-outputs are derived in the references given. Here it will be sufficient to observe that for small beam displacements the output of the reference cavity is independent of position, and

$$E_r = k_r I \tag{1}$$

where E_r is the induced signal amplitude and I is the beam current. Similarly, the induced signal amplitude E_x from the X cavity varies approximately linearly with displacement x from the central axis, if the displacement is small :

$$E_x = k_x Ix \tag{2}$$

When these signals are combined in a hybrid as shown, the signals E_1 and E_2 at the output ports are given by

$$E_1^2 = E_r^2/2 + E_x^2/2 + 2\, E_r E_x \cos\theta \tag{3}$$

$$E_2^2 = E_r^2/2 + E_x^2/2 - 2\, E_r E_x \cos\theta \tag{4}$$

If the phase-shifter S is adjusted so that $\theta = 0$ for the beam to the right of center, then

$$E_1 = 1/\sqrt{2}\,(E_r + E_x) = 1/\sqrt{2}\,(k_r I + k_x Ix) \tag{5}$$

and

$$E_2 = 1/\sqrt{2}\,(k_r I - k_x Ix) \tag{6}$$

Clearly, if E_1 and E_2 are detected by identical linear diode networks, the difference between the resultant signals will be a voltage proportional to Ix, and the sum of the signals will be proportional to I. When the beam moves to the left of center, θ changes from zero to π and Ix changes sign, giving the sense of the displacement.

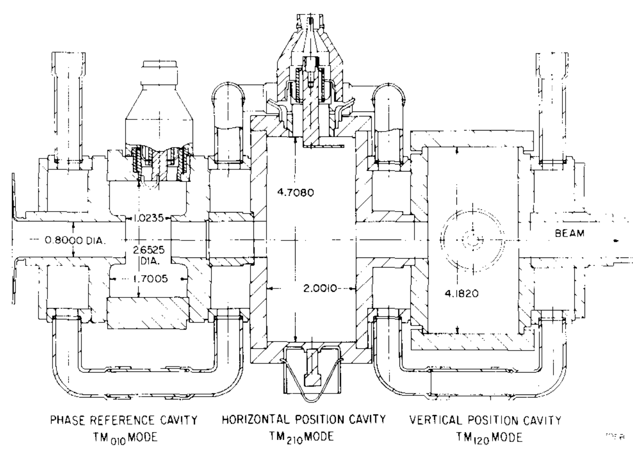

Fig. 2 : Cross section of Resonant-Cavity Transducer

A cross section of a typical monitor cavity assembly is shown in Fig. 2. Thirty-three such monitors, each having a beam aperture diameter of 2.03 cm, are installed along the accelerator. RF signals from each cavity are transmitted through semi-rigid coaxial cables to Detector Panels in the Klystron Gallery, where the signals are mixed and detected to form video pulses proportional to I, Ix and Iy as indicated above. The video pulses are then processed[3] into trains of three pulses proportional to ln Q, x and y. Q is the charge contained in one beam pulse. The information is transmitted to the Main Control Center (MCC), multiplexed[4] and displayed.

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An early modification to the above system was the provision of remote diode-balancing from MCC. The need for frequent rebalancing arose from the poorly-matched time-variable characteristics of the thermionic diode detectors used in the system. For many years, the choice of simple RF detection was limited to thermionic diodes because of the large signal range (45 dB) over which quasi-linear detection was required. The difference network across a pair of mismatched diodes may be balanced at any particular signal (current) level to indicate zero Ix when $E_x = 0$. However, if the current changes, or the diode characteristics vary, balance will be destroyed and a spurious Ix signal will result. The networks are rebalanced by disconnecting E_x at the hybrid (Fig. 1), and adjusting the difference network to give zero output by means of a motor-driven potentiometer. All RF switches and potentiometers are remotely controlled from MCC, and of course the same balancing system is applied to the Y channels.

The accelerator beam-position monitors as described above continue to operate moderately satisfactorily, although it is planned to convert them to hot-carrier diode detection in the near future, and also to use a modulation/synchronous detection system which does not require balancing. This system will be described in detail below.

Six microwave beam-position monitors were initially installed in the beam switchyard. The transducers (i.e., the assemblies of three resonant cavities) have not been modified since the time of installation. They are similar to those described above and illustrated in Fig. 2, with two important exceptions : (1) the beam aperture diameter is 5.08 cm, and (2) the cavity separation is increased to 10 cm to reduce crosstalk. Also, the reference cavity is not re-entrant.

Signal processing for these monitors is also basically as shown in Fig. 1. However, because of the high-radiation environment, the phase-shifters, S, are remotely controlled. A further difference is that by remote switching, two different detector systems can be selected for the hybrid output signals E_1 and E_2. A block diagram of the system is given in Fig. 3. It shows thermionic diodes and solid-state diodes as the alternate detectors. The thermionic diodes are normally used for position monitoring beams in the current range from about 80 mA down to 0.5 mA. The solid-state diodes were initially tunnel diodes, but these have been replaced firstly by point-contact diodes and then by hot-carrier diodes which have greater burn-out resistance and are useful over a lower current range extending down to about 100 μA.

Again, more details are to be found in the references.[1,2] The switchyard monitors do not have provision for electronically normalizing the Ix and Iy signals. Instead, they are delayed by 2 μs and 4 μs respectively from the I signal, so that all three video pulses can be displayed sequentially on one oscilloscope trace. The real time display allows observation of current-and position-changes during the beam pulse. The Ix and Iy pulses can be manually normalized by adjusting the scope gain to keep the I pulse-height constant as the current changes.

60 MHz Receiver Systems

The sensitivities of four monitors in the switchyard have been increased by a factor of 10^3 by the addition of superheterodyne receiver systems. A block diagram of one X-Channel is shown in Fig. 4. The terminals X_A, X_B, X_C and X_D are connected to the corresponding terminals in Fig. 3, and the hot-carrier diodes shown there are removed. The Y-Channel is similarly connected.

The power-dividers and mixers in each receiver are microstrip hybrid-ring circuits on organic substrates developed at SLAC. They are relatively inexpensive to build in-house and have good narrow band performance around 2856 MHz. The same basic circuit is also frequently used as a phase bridge.

The output of the TM_{120} cavities is approximately 50 $\mu W/mA^2mm^2$, or -73 $dBm/\mu A^2mm^2$. The receivers have about 10 dB noise-figures and 10 MHz bandwidths, so that their equivalent noise input is -88 dBm. Thus, allowing 3 dB cable loss, it should be possible to resolve a 1 mm displacement of a 250 nA beam. Measurements have shown that a 1 mm displacement is discernible at 100 nA beam current.

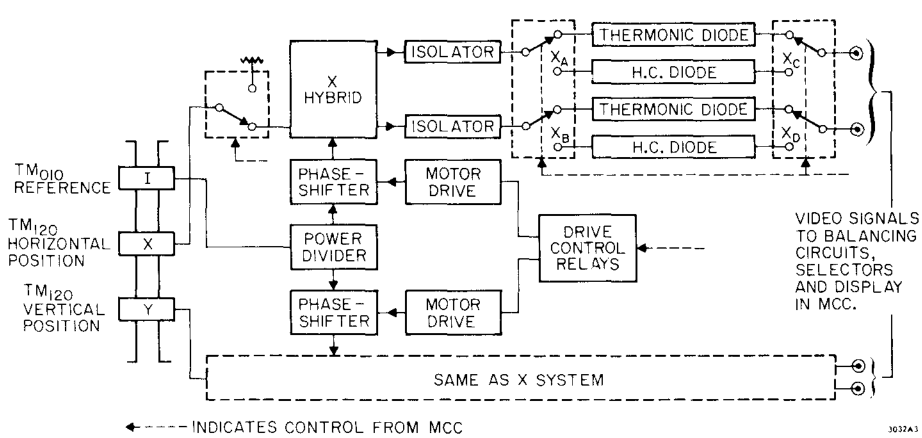

Fig. 3 : Block Diagram of Typical Switchyard Position Monitor System

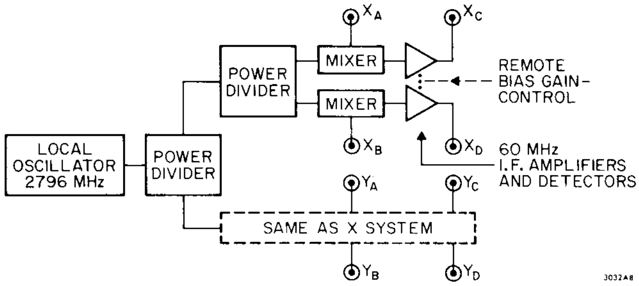

Fig. 4 : Block Diagram of 60 MHz Superhet Receiver

It should be emphasized that these systems offer only improved sensitivity; the position information is still not normalized and zero errors occur when the I.F. channels are unbalanced.

The video outputs of the receiver systems are also summed to give signals proportional to beam-intensity. Besides being used for normalizing, the sum-signals provide excellent beam-current video information. They can be used to detect beam currents down to 10 nA

Homodyne Receiver Systems

In the course of planning an experiment on the inelastic scattering of polarized electrons at SLAC, it became clear that very precise beam-position monitoring would be required to direct the electron beam onto the deuterium target. Two monitors were needed : one placed about 10 m back from the target had to be able to record 10 μm displacements at 100 μA beam current, while a second about 50 m further back had to resolve 60 μm at the same current.

It was determined that a phase-modulation synchronous detection (homodyne) system, coupled to the resonant cavity transducers described above, would best meet the requirements. A block diagram of the system is shown in Fig. 5. The signal from the TM_{120} position cavity, which will be on the order of -73 dBm for a 100 μA beam displaced 10 μm from the center line, is fed into a hybrid which is used as a double sideband suppressed carrier (DSSC) modulator. The modulation is produced by a relatively high-level (10 dBm) 30 MHz CW signal. The DSSC modulation can be considered as 180° phase-modulation at a 30 MHz rate, (with synchronous amplitude modulation which does not significantly affect the detection mechanism). The 30 MHz phase-modulated 2856 MHz cavity signal passes through an isolator (to avoid reflections which can be modulated and re-transmitted as spurious position error signals) to a mixer which is used as a phase-detector. Here it is mixed with a coherent 2856 MHz CW reference signal derived from the accelerator drive system. The latter is fed into the experimental area at 476 MHz, where it is multiplied up to 2856 MHz and distributed to the two homodyne systems. The output of the mixer is a 30 MHz signal.

The phase of the reference signal into the mixer can be remotely adjusted to maximize the output amplitude, which occurs when the input signal vectors are co-linear. The mixer output is amplified and fed into a synchronous detector, where it is phase-compared with part of the original 30 MHz signal. Again, it is necessary to adjust the phase of one 30 MHz signal to maximize the video output from the synchronous detector. A low-pass filter removes the residual 30 MHz signal, and the video passes through a bipolar video amplifier to ADC circuits and the SDS 9300 computer.

The system described may be set up to give positive video polarity when the beam is, say, to the right of center. It is important to note that when the beam is centered, the cavity output and its dependent signals throughout the receiver chain go to zero. No balancing is involved. When the beam moves to the left of center, the cavity output changes phase by 180°, and is followed by the DSSC and mixer output phases. This causes the video output of the synchronous detector to change polarity.

Two double-channel homodyne receivers were built and installed in the experimental area (End Station A). Resonant-cavity transducers were installed in the beam line locations mentioned above and connected by 2.2-cm diameter coaxial cable to the receivers. A photograph of one receiver box is shown in Fig. 6.

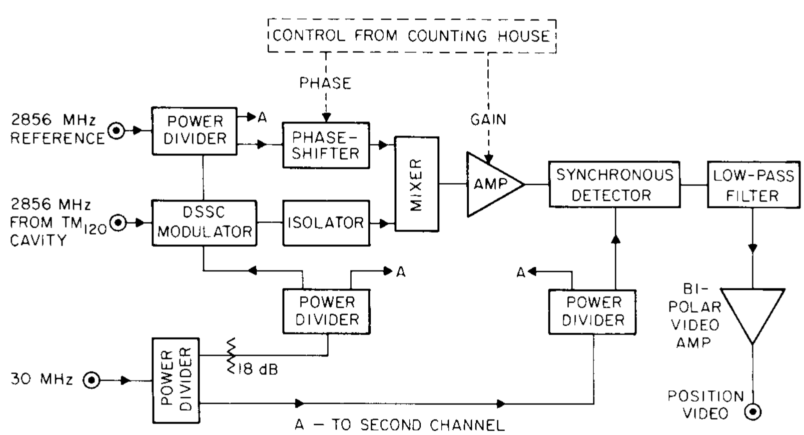

Fig. 5 : Block Diagram of Homodyne Receiver System

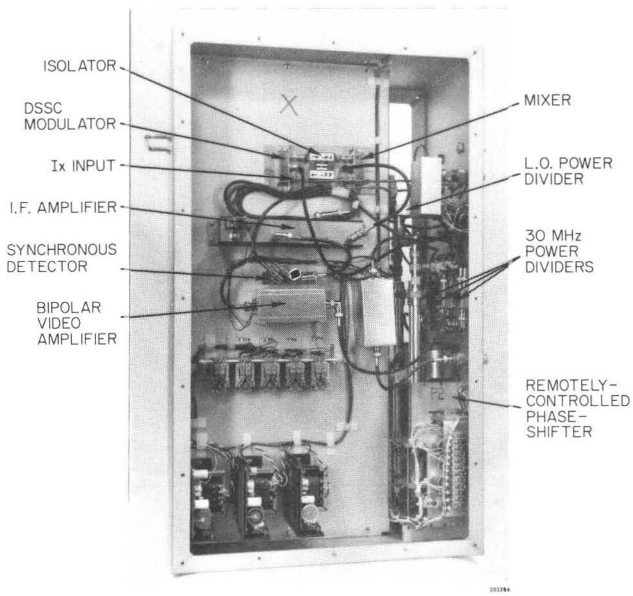

Fig. 6 : Photograph of X-Channel, Homodyne System

The computer was used to analyze the position data supplied by the monitors and to apply corrective steering currents to vernier coils on the beam line magnets. Because of their absolute accuracy, toroids were used to monitor the beam current and thus provide the normalizing information required to compute displacement. In their description of the experiment, Prescott et al[5] note that the two position monitors were sensitive to a few microns displacement. With computer steering, systematic position changes were held to less than 1 μm, and systematic beam-angle changes at the target were less than 0.1μradian.

Traveling-Wave Beam Position Monitors (TWBPM's)

An early form of TWBPM has been described.[1] This monitor was cumbersome and expensive, and was troubled with drift-tube resonances. Nevertheless, the concept of a non-resonant microwave position transducer, easier and less expensive to build than the resonant cavity structures already described, remained attractive. To this was added the idea of simple normalization (i.e., removal of beam-current dependence) by the use of limiter-amplifiers prior to phase detection.

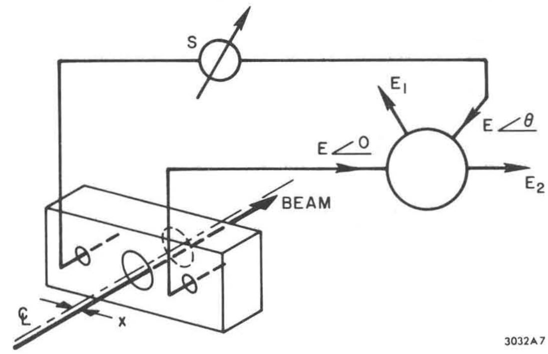

Fig. 7 : Schematic of Traveling-Wave Beam Position Monitor

A schematic diagram of the basic monitor is given in Fig. 7. The transducer is simply a length of S-Band waveguide with beam apertures centrally placed in the broad walls. Each end of the waveguide is terminated by a matched transition to coaxial line, and the two lines are connected to a phase bridge, represented for the moment by a simple hybrid. Using the notation of Fig. 7, the hybrid output signals will be

$$E^2_{1,2} = E^2(1 \pm \cos\theta) \qquad (7)$$

The phase-shifter S is adjusted so that when the beam is centered, $\theta = \pi/2$ and $E_1^2 - E_2^2 = 0$. When the beam moves off center a distance x, the additional phase-shift, ϕ, developed across the hybrid is $4\pi x/\lambda_g$, where λ_g is the effective guide wavelength. Then

$$E^2_{1,2} = E^2(1 \pm \sin\phi) \qquad (8)$$

For small ϕ, $E_{1,2} \sim E(1 \pm \phi/2)$, and

$$E_1 - E_2 = E\phi = kIx \qquad (9)$$

where k is a constant.

A very convenient way of removing the I-dependence is shown in Fig. 8. The $E\angle 0$ and $E\angle\theta$ signals from the transducer are down-converted to 60 MHz and passed through limiter amplifiers before phase detection. One TWBPM based on these ideas has been developed and used in polarized electron beam experiments.[6] Design and performance details follow.

Referring again to Fig. 8: the 60 MHz limiter amplifiers used have an input signal range from -70 dBm to +10 dBm. The levelled output is about +3 dBm

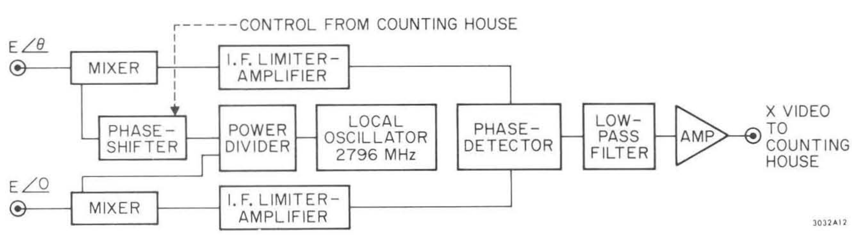

Fig. 8 : Block Diagram of TWBPM Detection System

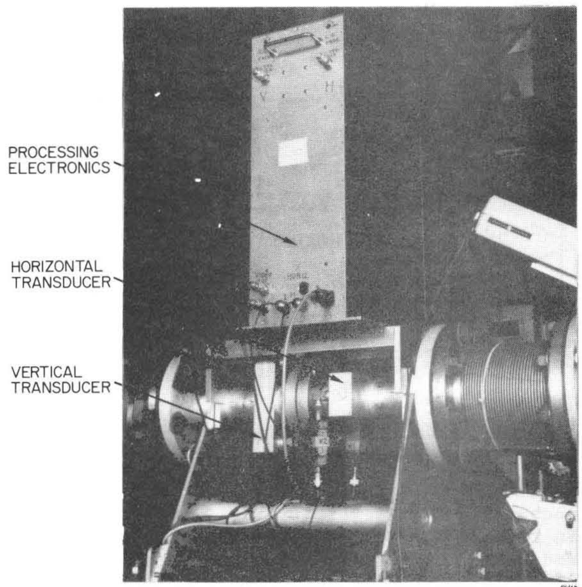

Fig. 9 : Photograph of TWBPM installed in Beam Line

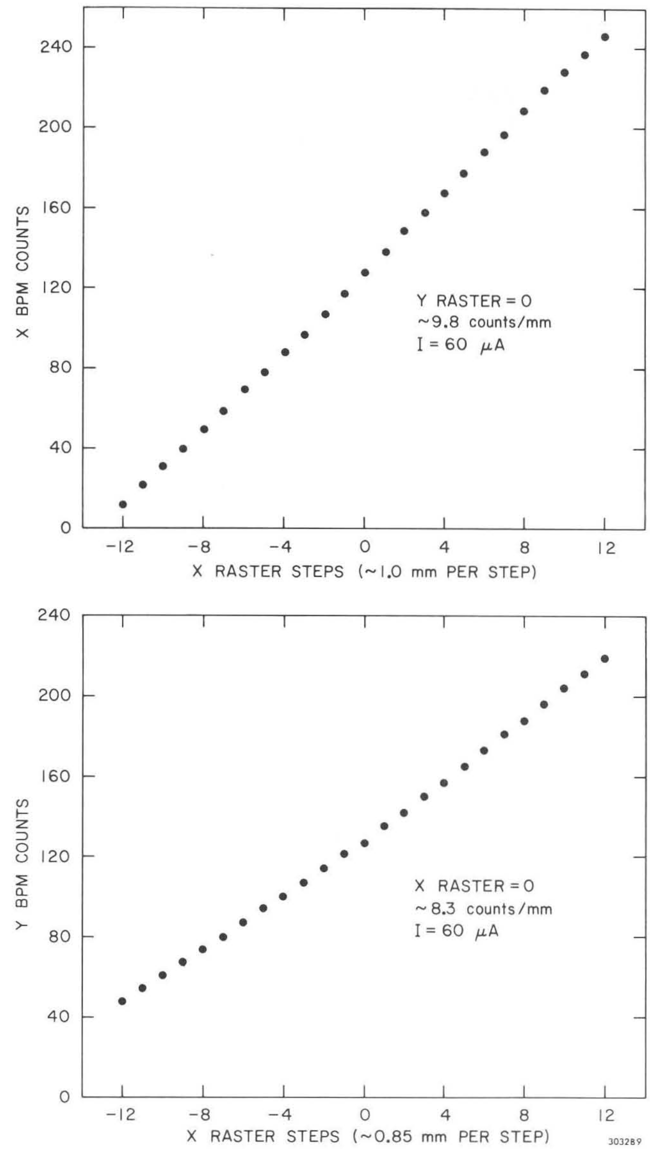

Fig. 10 : TWBPM Output as Function of Beam Displacement

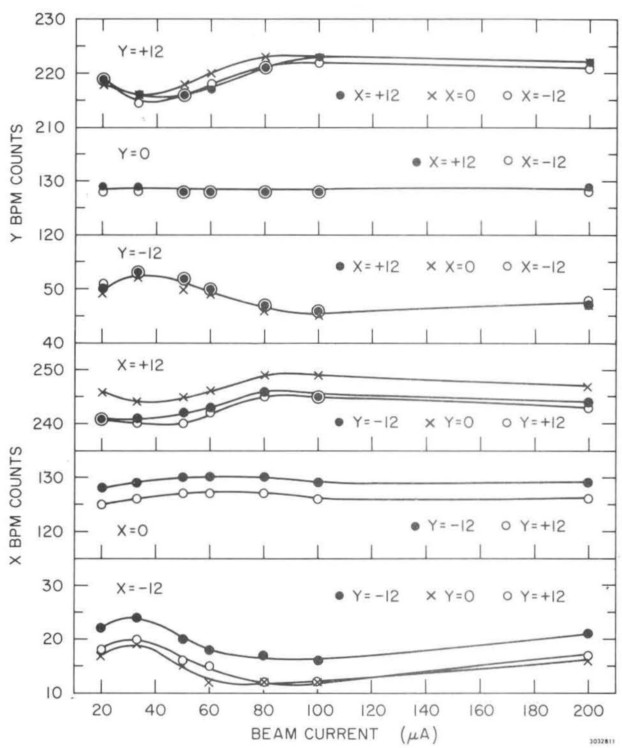

Fig. 11 : Illustrating Current Dependence of TWBPM Output

and the transmission phase-shift over the input signal range is less than 10 degrees. However, the amplifiers in the matched pair used were specified to track to within 3 degrees. Shielding and isolation are important to minimize crosstalk. Separate local oscillators are used for each channel.

Fig. 9 is a photograph of the complete monitor installation in the End Station A beam line. It can be seen that the X and Y transducers are well-separated. The 6.35-cm diameter beam pipe is lined with lossy material to increase isolation between channels. The transducer beam interaction impedance is about 250 ohms, and the differential phase-shift (ϕ) is 2 degrees per mm of beam displacement. The video output of each phase detector is amplified and transmitted to the Counting House (Experimental Control Room). The video is sampled by a 0.5 μs integrate-and-hold gate. The sampled and stretched signal is amplified, converted to an 8-bit word and counted out at a 1 MHz rate into a string of pulses which are fed into a decimal display counter and also into the computer. The phase shifter (Fig. 8) is adjusted so that when the beam is centered the video output is zero and a count of 128 is displayed. A variable-gain amplifier is set so that 0 indicates the beam is left (or down) 13 mm, and 256 indicates right (or up) 13 mm. This particular scale (approximately 10 counts per mm), was chosen to suit the experiment, in which the beam was scanned over a 26-mm square, and the TWBPM was used to monitor the instantaneous beam-coordinates, so that raster-steering corrections could be computed and applied.

The monitor described will detect beam position changes of 0.1 mm (corresponding to approximately 1 count) for beam currents down to 20 μA. The linearity of the monitor in the x = 0 and y = 0 planes is illustrated in Fig. 10. Fig. 11 illustrates the most serious problem remaining with the TWBPM, namely, the variation in indicated beam position as a function of beam current. This variation is about 1 mm maximum, and is roughly proportional to deflection. It is most likely due to imperfect limiting in the amplifiers.

Acknowledgements

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