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A LOW FREQUENCY BEAM POSITION MONITOR*

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Summary

The beam position monitor described here is inductively driven by the 1.7-microsecond pulse envelope of a relativistic electron beam. Its principal virtues seem to be its simplicity, its inherently fixed zero position, and its adaptability to wide apertures. In the form presented, it has a 3.5-inch clear aperture; its minimum sensible beam current × beam displacement is about 2×10^{-4} ampere-millimeters; its ultimate spacial resolution is 0.1 millimeter.

Introduction

Inductive type beam position monitors take on very diverse forms[1] as they are adapted to measuring beams in differing apertures, and to utilizing beam modulation in different frequency regions.

This monitor is designed to measure the x and y transverse displacements of the centroid of an electron beam within a clear circular aperture of 3.5 inches diameter. The beam can be any size or shape within this aperture, but it is expected to be a circular pencil of nearly parallel rays, about 1/4 inch in diameter.

The beam current modulation to be utilized is in the form of rectangular pulses from 0.5 to 2 microseconds in length, repeated up to 360 times per second.

In the first application, this monitor measures the position of a positron beam, just ahead of a liquid hydrogen target in which the positrons annihilate to form a monochromatic photon beam. The photon energy is directly related to the production angle, which is defined critically by the position of the primary beam in the target.

Operating Principles

The principle of operation is illustrated in Fig. 1. If the beam current b passes through the center line of the pickup loop as shown, the magnetic lines of force f surrounding the beam pass symmetrically up and down through the plane of the loop, and no emf is induced in it. If the beam is displaced an amount x as at b', the symmetry is broken, and some net lines of flux, such as f', cut through the coil, and induce an emf proportional to x. This is best expressed as a mutual inductance between the beam current and the coil, proportional to the beam displacement:

$$M = 8 \times 10^{-9} \ell x/W \quad \text{henries}, \; x \ll W \qquad (1)$$

The linear relation between x and M indicates that a distributed beam will produce a signal proportional to the displacement of its centroid, as long as the beam is contained within the linear response region of the aperture.

The amount of electrical power which can be produced by the pickup depends on M and also, in an inverse way, on the self-inductance L of the loop. The output power is:

$$P_\omega = (M^2/L)\, \omega\, i^2_{b\omega} \cos\phi \qquad (2)$$

where $i_{b\omega}$ is the beam current, and cos ϕ is the power factor, which depends on the loading hung on the pickup. ω refers to any frequency component of the beam current. It is clear, then, that to obtain the maximum power out, we should maximize the value of M^2/L, which is purely a function of the pickup loop geometry. Referring again to Fig. 1, M is maximized by bringing the loop wire in as close to the beam as possible, while L is minimized by making the loop "wire" into a broad metal strap, of width S.

Equation (2) can be translated into physical dimensions by using (1) for the value of M, and using approximately for L:

$$L = .004\, \ell \ln(2W/S) \qquad (3)$$

(L is in henries; ℓ, W and S are in centimeters.) Equation (2) then becomes

$$P_\omega = \frac{1.6 \times 10^{-14}\, \ell x^2\, \omega\, i^2_{b\omega} \cos\phi}{W^2 \ln(2W/S)} \qquad (4)$$

(ℓ, x, W, S in cm, i_b in amperes, P_ω in watts). Note that the power is proportional to the length ℓ of the loop.

The Pickup Assembly

The geometry of the actual pickup loop assembly is shown in Fig. 2. A vertical and a horizontal pickup loop (y and x) are incorporated into a single unit, which is milled out of a piece of copper tubing. The intimate electrical connection between the two loops produces no cross-talk, because it is at the balanced center of each loop. The cylindrical geometry of the straps allows a maximum of clear space for the beam, consistent with maximum beam coupling.

Local Amplifier Electronics

In order to attain the sensitivity required for this monitor, it was necessary to limit amplifier noise to be negligible compared to thermal noise, and to avoid pickup of interfering signals from nearby power equipment. Both considerations dictated that a local amplifier be placed adjacent to the pickup loops, in a well-shielded envelope. Since the pickup is located in a radiation environment of the order of hundreds of roentgens per hour, it was felt that transistor amplifiers should be avoided, due to long-term radiation damage which transistors are reported to suffer. Fortunately, in the frequency and impedance range natural to this device, vacuum tubes presently have a lower noise figure than do transistors, so we are well off on both counts to use vacuum tubes in the local amplifier.

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Integration Requirement

Since this is an inductive beam pickup device, it follows that a trapezoidal beam current pulse, as shown in Fig. 3a, will produce an emf in the pickup loop whose shape is the time derivative of the beam current, as in 3b. If one wishes to obtain a pulse shape analogous to that of the original current, it is therefore necessary to perform an integration on this emf waveform, to restore the original waveform, as in 3c.

Frequently beam induction instruments are designed with this integrating function built into the pickup loop itself, as would be the case in Fig. 1, if a low value resistor R were shunted across the loop terminals. If the time constant of the loop, L/R, were long compared to the current pulse duration, this would perform the desired integration. This would be done at the expense of signal amplitude, however, since the L/R integrator performs its function by acting as a low-pass filter. One clearly can obtain a much improved signal-to-noise ratio, then, by passing the emf signal (Fig. 3b) through the early amplifier stages in this form, and only passing it through an integrating filter after it is amplified well above the level of amplifier noise.

Figure 4 is a scheme of the entire electronic system of the monitor. Note that the local amplifier systems for x and y each consist of a low-noise preamplifier, a pulse waveform integrator, and an output amplifier. The latter delivers pulses to a long coaxial cable at a level of ten volts maximum. The preamplifier contains a $\times 10$ relay-operated gain switch, to enable the remote display user to keep the signal level in the optimum range.

The Preamplifier and Input Circuit

Figure 5 gives the schematic circuit of the preamplifier. The first stage is a cascode circuit, which is used for its low effective input capacitance.

The Amperex 7788 tube used is rated to have a noise equivalent input resistance of 60 ohms, and about 100 ohms performance is realized in this circuit. If the tube can be driven from a source whose resistance is high compared to 100 ohms, the amplifier will not add important noise contributions to the inherent thermal noise from the source.

A pulse transformer is used to raise the voltage level of the pickup loop by a factor of 10 before entering the amplifier. One is limited in the step-up ratio which may be used, by the fact that the effective loop inductance is multiplied by the square of the turns ratio; this lowers the ringing frequency of the input circuit, which should be kept above the pass band being used. The ringing frequency is

$$f_r = (2\pi)^{-1} (N^2 L C)^{-1/2} \qquad (5)$$

where N is the turns ratio, L is the loop inductance, and C is the amplifier input capacitance. L for our loop, including the connecting straps, is 0.5 microhenry, and C is 20 picofarads; with N = 10, this results in a ringing frequency of five megacycles, which is at the top of the desired frequency pass band of the system.

Instead of using a 10:1 pulse transformer, of course, the pickup loop could have been made as a ten-turn coil; however, then the inter-turn capacitance of this coil becomes important in lowering the ringing frequency, and the loop becomes more complicated to support rigidly. Since pulse transformers of nearly ideal properties can be made using modern materials, the advantage in performance lies in using them, instead of a multiple-turn pickup coil.

Integrator

The pulse integrator is of classical design,[2] having a decay time constant of 20 microseconds. The effect of the integrator on random noise is rather startling. Assume that the noise (both amplifier noise and thermal noise) is "white", i.e., that there is equal noise power in all equal frequency intervals. The integrator circuit is a filter, having a 1/f characteristic. After passing through the integrator, the noise will have a 1/f spectrum within the band pass of the system, greatly emphasizing the low frequency noise.

Sensitivity Calculation

Using the expression (1) for the mutual inductance, one obtains for this device, a mutual inductance of 3.2×10^{-8} henries per cm of beam displacement. The voltage impulse obtainable from the establishment of a current Δi in a mutual inductance M is

$$\int e\,dt = M\Delta i = 3.2 \times 10^{-8} \ \text{volt-seconds per ampere-cm} \qquad (6)$$

(think of the establishment and disestablishment of beam current Δi as causing the upward and downward voltage impulses in Fig. 3b). Letting the impulse time for this circuit be $dt \simeq 0.2 \times 10^{-6}$ seconds, we get from Eq. (6) that the sensitivity for fast impulse beam current changes is 0.16 volts per ampere-cm at the loop, or 10 times this after the pulse transformer: e = 1.6 volts per ampere-cm, at the grid of the first tube.

Since the thermal noise referred to this point is about 5 microvolts rms, the noise equivalent signal could be taken as that produced by a beam of 3×10^{-5} amperes, displaced by 0.1 cm (3×10^{-5} ampere-millimeters).

In practice, it was found that the minimum size of beam pulse which could be reliably discerned by eye on a single oscilloscope trace was about 2×10^{-4} ampere-millimeter. As one might expect, it was about equally difficult to resolve a signal in the presence of noise, whether one looked at the signal before being integrated or after. One can resolve a much smaller signal, of course, if one observes it at a high repetition rate so the eye can average out the noise of many sweeps.

Calibration and Testing

It is very convenient with this monitor to simulate a beam by passing a wire down its center, carrying electrical current pulses. The sensitivity may be accurately calibrated in this way. The electrical center of the pickup assembly is located precisely by finding the wire position for zero pickup. The electrical center is moved to coincide with the center of its housing, by moving the ends of the pickup straps by means of adjustment screws.

The limitation on ultimate space resolution of this monitor is determined by the fact that the signal does not quite go to zero, when the beam is on the center of the pickup. This is principally due to electrostatic pickup from the charge of the beam, which is not quite balanced out. A perfectly shielded and balanced pulse transformer would eliminate it completely, in principle. The ultimate resolution for this instrument is limited to about one-tenth millimeter, by this effect.

Signal Processing Logic

It is evident from the nature of the inductive pickup mechanism used that the signals will be proportional to the beam intensity, as well as to the beam displacement. For this reason, the horizontal displacement signal out of the local x amplifier in the block diagram of Fig. 4 is labeled "Ix".

Since a signal is desired which is proportional simply to the displacement x, it is necessary to develop an intensity signal, I, and to develop logic which will divide the "Ix" signal by the I signal. This is the function in Fig. 4 of the "x normalizing circuit."

The I signal is generated by a toroidal pickup coil located in the same housing as the position pickup. It is located just "upstream" of the assembly shown in Fig. 2. It takes up about 2 inches of longitudinal beam space. Figure 4 indicates how this signal is amplified locally, then transmitted to the remote readout location, where the above-indicated logic is performed. A similar logic is applied to the "Iy" displacement signal.

Figure 6 indicates how the normalizing logic is performed. The I signal is passed through an Automatic Gain Control amplifier circuit, which develops an AGC signal; the latter is a slowly varying voltage obtained from rectifying intensity pulses. Its decay period is about 0.1 second, or 36 accelerator pulse periods. The gain control element to which this AGC signal is applied is a photoresistor controlled by a lamp. The gain control is thus driven in such a way as to have a gain proportional to 1/I.

This same AGC signal is then used to drive matched gain control units in the Ix channel and the Iy channel, so that each of the latter signals is effectively divided by I, to give out a pure x or y displacement signal. The three photoresistor lamp units are matched to have identical gain to within ± 10%, over a 10:1 dynamic range of beam pulse sizes.

The x and y outputs of this logic system are dynamic pulses, which display beam displacements which occur either from one pulse to the next, or which occur during one pulse. The time resolution for observing beam motion is about 0.2 microsecond. This could be improved by a factor of 10, with some sacrifice in sensitivity.

Figure 7 is a photo of the beam pickup assembly, looking straight down the bore. The four pickup straps are prominent. Figure 8 is an overall picture of the pickup housing, with the three local amplifiers mounted above it. A tightly bolted rectangular shielding box fits over the electronics. It is removed for purposes of this photo.

Acknowledgements

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References

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2. Electronics, Elmore and Sands, McGraw-Hill Publishing Co., 199 (1949).

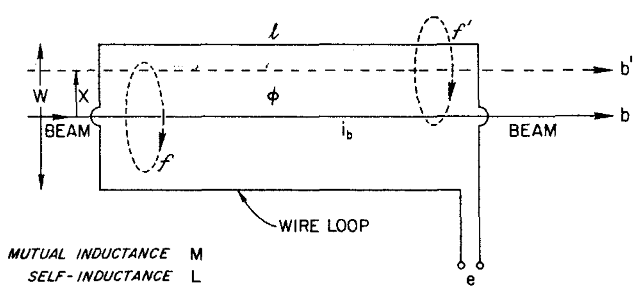

Fig. 1. Principle of inductive position pickup.

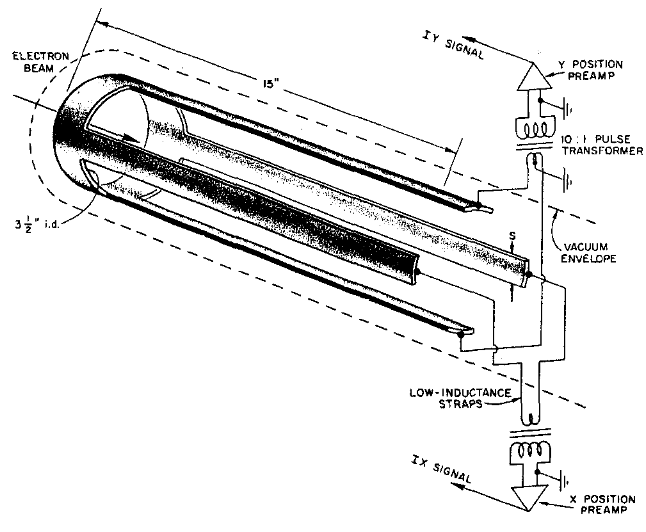

Fig. 2. Pickup loop assembly.

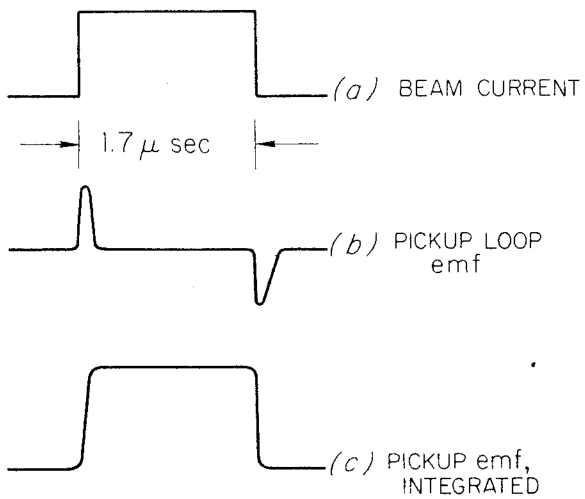

Fig. 3. Pulse waveforms in local amplifier.

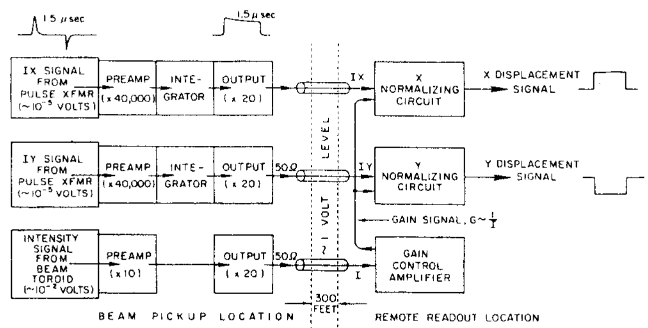

Fig. 4. Electronics block diagram.

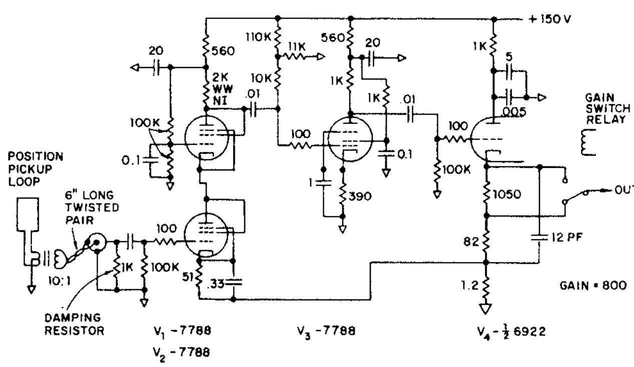

Fig. 5. Low noise preamplifier.

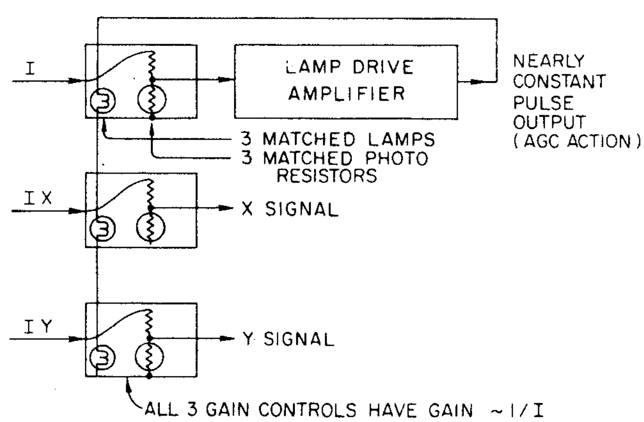

Fig. 6. Normalizing circuit block diagram.

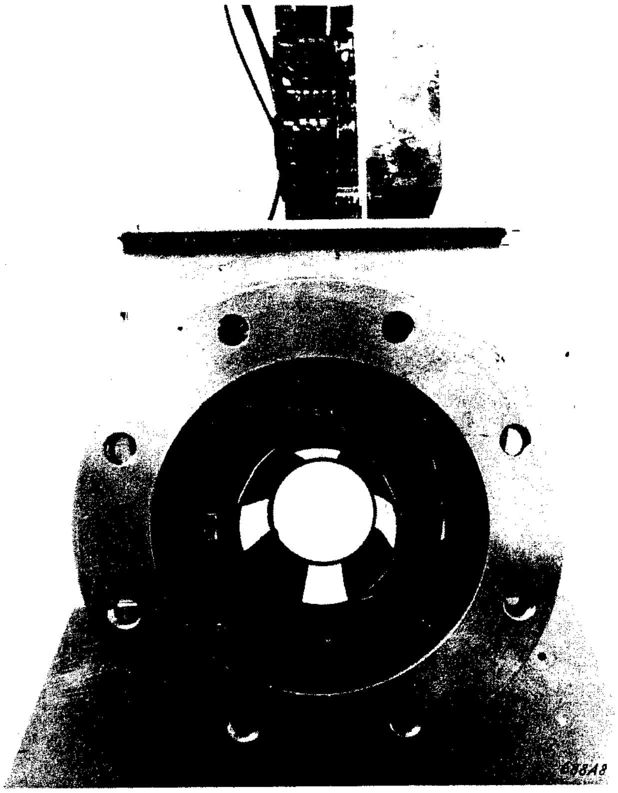

Fig. 7.

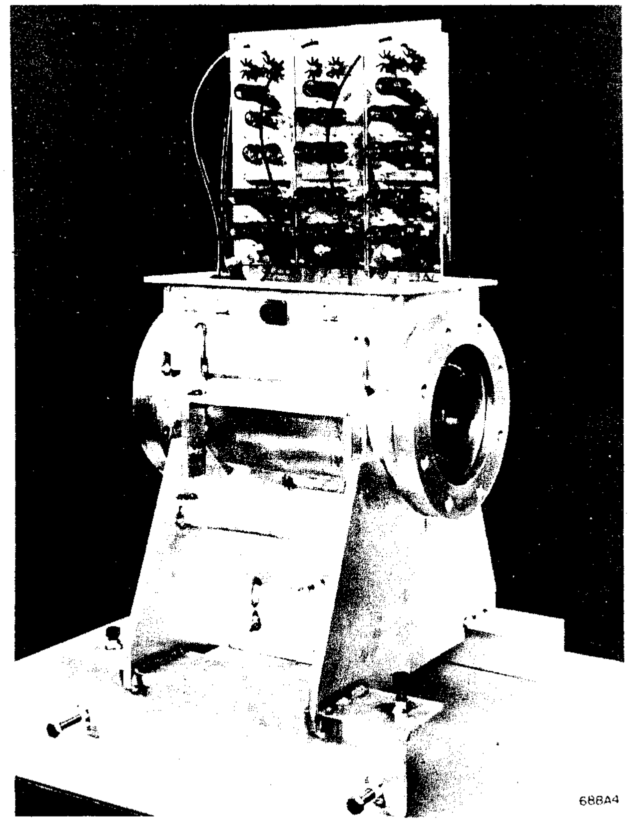

Fig. 8.