A SIMPLE BEAM POSITION MONITOR SYSTEM FOR CEBAF*

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Abstract

CEBAF is a recirculating linac where the beam passes several times through the linac structures. As a result, up to five beams of different energies may be present in the same linac vacuum chambers simultaneously. One method of distinguishing between the beams involves modulating the current for a time interval of less than one revolution period. In this paper, a very simple low cost beam position monitor system based on the detection of this modulation is presented. Initial results indicate that 1 mm displacements for beam currents of 1 μA can be measured. With the incorporation of several improvements to the present monitor design, the sensitivity is expected to be increased to 1 mm for a 100 nA beam.

Introduction

In the linac sections of the CEBAF accelerator, five CW ($f_{\mathrm{rf}} = 1.5$ GHz) beams of different energies may be present simultaneously in the same vacuum chamber. In order to track the transverse position of a single beam, a method of distinguishing it from the other beams is necessary. This may be accomplished during normal operation of the accelerator by amplitude modulating the CW beam from time to time without interrupting the continuous flow of electrons. The duration of a modulation burst must be less than the circulation time in the machine (4.2 μs). In addition, the time interval between bursts should be greater than five circulations (21.0 μs) so as to allow a given burst to exit the machine before the next one is introduced. A beam position monitor that responds to the modulation frequency provides the capability to measure the transverse position of a single beam from entrance to exit.

The monitors described here consist of simple resonant inductive loops inside the vacuum chamber and operate in the 1-10 MHz range. Because of the simple loop design and relative ease of designing electronics in the 1-10 MHz range, these monitors are excellent low cost alternatives to stripline or cavity monitors which operate at some harmonic of the RF. In view of these cost differentials, it has been proposed that the majority of the CEBAF beam position monitor systems consist of the lower-frequency loop pickups.

The loop monitors, used periodically for steering and corrections, would be complemented with a small number of more expensive, high-frequency, cavity-type pickups for monitoring beam position continuously[1]. The cavity pickups, each consisting of sum and difference mode cavities, are useful mainly in the arcs where the different energy beams reside in separate beampipes. In the linacs, the cavities are only capable of measuring the center of charge of the five beams. However, this information may be used as a qualitative indicator of beam drift for the purpose of activating the modulation and loop pickups for corrections.

A detailed analysis of the resonant inductive loop pickups is given in reference (2) and will not be repeated here. In this paper a brief description of a prototype loop monitor and the preliminary measurement results are presented. In addition, concepts for the final loop pickups and associated front end electronics are discussed.

Inductive Loop Pickups

A single pair of inductive loop pickups is illustrated schematically in Figure 1. Here the inner radius of the beampipe is a and the radial distance to each loop is b. The interaction between the beam current and each loop may be described by the mutual inductances, $M^{\pm}(r,\phi)$, where r and ϕ are the beam coordinates. In addition to the mutual inductances, each loop has associated with it a self inductance, L. The resistive element, R, takes into account losses in each pickup such as finite loop and beampipe conductivities. The intrinsic capacitances of the loops and other parts of the circuit are represented by C. In addition, a $1:n$ turn transformer has been added to each pickup in order to step up the output voltage. The transformer has the same effect as using an n turn loop pickup, but is conveniently located outside the beampipe.

For the idealized pickups of Figure 1, the amplitudes of the steady state output voltages for a sinusoidally amplitude-modulated beam current are given as follows:

$$V^{\pm}(r,\phi) = \omega_o n Q M^{\pm}(r,\phi) I_b \tag{1}$$

where:

$$\omega_o = 1/\sqrt{LC}$$
$$Q = \omega_o L/R.$$

For a finite pulse of modulated current of length τ, the voltages at the end of the pulse are reduced from the steady state values by a factor of γ, where:

$$\gamma = 1 - e^{\frac{-\omega_0}{2Q}\tau} \tag{2}$$

The pickup equivalent circuits of Figure 1 are approximate. Exact equivalent circuits are considerably more complicated because of the non-ideal properties of transformers in the MHz range. External inductances, capacitances, resistances, and frequency-dependent properties of core materials significantly affect the overall ω_0, Q, and n of the pickups. Rather than trying to predict these effects with a complicated equivalent transformer circuit, an optimally sensitive transformer/loop combination is better determined by trial and error procedures in the laboratory.

In order to derive current independent position information, the standard technique of taking difference to sum voltages, V_x and V_y, for the x and y axis pickup pairs is employed:

$$V_x(r,\phi) = \frac{M_x^+ - M_x^-}{M_x^+ + M_x^-} \tag{3a}$$

$$V_y(r,\phi) = \frac{M_y^+ - M_y^-}{M_y^+ + M_y^-}. \tag{3b}$$

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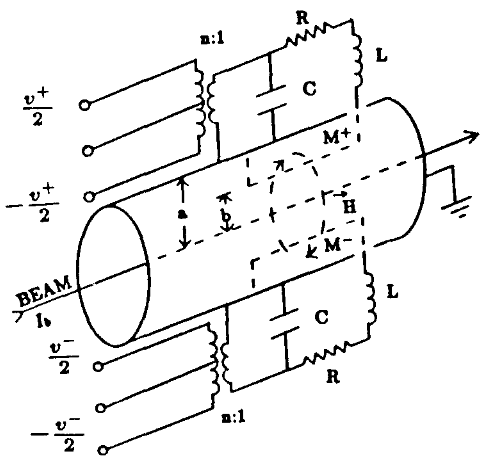

Figure 1 Schematic illustration of inductive loop pickups.

Alternatively, the radial and azimuthal difference to sum voltages may be defined as:

$$V_r(r,\phi) = \sqrt{V_x^2 + V_y^2} \quad (4a)$$

$$V_\phi(r,\phi) = \tan^{-1}\left(\frac{V_y}{V_x}\right). \quad (4b)$$

It can be shown to a high degree of accuracy that V_r is a function of r only and V_ϕ is a function of ϕ only.[2] Because of this separation it is possible to find simple approximate relationships between beam position and V_r and V_ϕ:

$$\phi \approx V_\phi \quad (5a)$$

$$r \approx \sum_{\substack{m=1 \\ \text{odd}}}^{m} a_m\, v_r^m. \quad (5b)$$

The number of terms used in Equation (5b) depends on the desired accuracy in radial position. The coefficients a_m are easily determined through a bench-top calibration employing the standard technique of simulating the beam with a thin current-carrying wire.

Prototype Monitor and Measurement Results

A prototype monitor consisting of four 40-cm-long copper wire loops inside a section of 1 $\frac{3}{8}$" ID stainless steel beampipe was constructed. The 1 $\frac{3}{8}$" ID beampipe will be used typically in the injector and linac sections of the accelerator. The radial distance, b, to each pickup loop in the prototype is 12 mm. Electrical connections to the loops are made with SMA style high vacuum feedthroughs from Ceramaseal.

After considerable experimentation with step-up transformers, it was found that RF impedance matching transformers, commercially available from Mini Circuits, Inc., yielded satisfactory results. As shown in Figure 1, the transformers have center-tapped secondaries so differential first-stage amplifiers may be used to reject common-mode noise. The electronics for the prototype consist simply of two amplification stages per pickup channel. The first stage is a high input impedance (so as not to lower Q) differential video amplifier. The second stage is a high performance op-amp. As mentioned in the next section, a more sophisticated electronics system is envisioned for the final monitor design.

In order to calibrate and test the prototype, a computer-controlled $x-y$ translation stage driven by stepper motors was constructed. The automated stage is capable of positioning the monitor about a fixed current-carrying wire to an accuracy of 0.1 mm. Signals are acquired by computer from each of the four pickup channels via a digital oscilloscope. Calibration, difference to sum voltage computations and position computations are all performed in software.

The basic parameters of the prototype monitor were found to be $f_0 = 6.7$ MHz, Q=12 and $Z_T = 128\ \Omega$. Here, Z_T is defined as the voltage at the output of a transformer divided by the current in a wire physically centered in the monitor. In order to demonstrate the position sensitivity of the pickups/amplifiers, the $+x$ axis channel voltage output was measured as a function of current position along the x axis. The result shown in Figure 2 is for a 1 μA current. Although the signal is slightly noisy, the measurement clearly indicates that 1 mm position resolution for a 1 μA current is obtainable with this type of design. With some improvements to the monitor design, briefly mentioned in the next section, it is expected that 1 mm resolution with a 100 nA beam is possible.

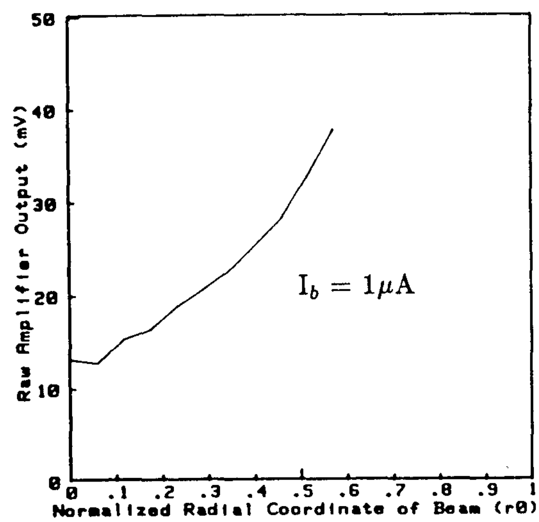

Figure 2 Voltage output of a single channel versus beam position normalized to beampipe radius a.

Another measurement made on the prototype monitor was difference-to-sum voltage versus current position. The results are shown in Figure 3. The measured data (dashed) is x axis difference-to-sum voltage versus current position along the x axis and along the radius at 45°. In addition, the theoretical response is included (solid). The slight difference between the theoretical and measured responses is attributed to the finite conductivity of the beampipe which was not included in the theoretical model. In any case, for small displacements about the center, position is linear with difference-to-sum voltage. For larger displacements, the position/voltage relationship is given quite accurately by Equations (5a) and (5b).

Current and Future Efforts

Initial results indicate that the inductive loop beam position monitors show great promise for use at CEBAF. Presently attention is being turned towards the optimization of the pickups and front end electronics. Concurrently, initial designs for a suitable data acquisition, position computation, and display system are being developed.

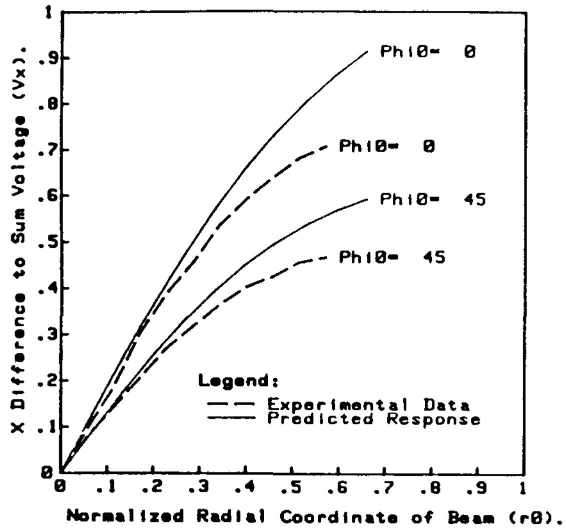

Figure 3 X axis difference-to-sum voltages versus position normalized to beampipe radius a.

The present concept for the final pickups is illustrated in Figure 4. Each loop is separately loaded with a high μ ferrite to increase output voltages while maintaining position sensitivity. The loops themselves are made of copper and are vacuum-deposited directly onto the ferrite blocks. As shown in Figure 4, the copper loops completely encircle the ferrite blocks. By cutting the stainless steel beampipe out of the loop circuit, it is hoped that sensitivity will be increased because of reduced losses. In addition, the copper-deposited blocks are convenient, self-contained units that are easy to mount and align inside the beampipe.

One concept for the final front end electronics is shown in Figure 5.[3] The circuit converts the position dependent amplitudes, V^+ and V^-, into a phase angle which is detected by the output mixer. The DC output from the mixer is proportional to the difference-to-sum of the squares of V^+ and V^-. Position information is derived by applying the same techniques used for standard difference-to-sum measurements. A major advantage of the amplitude-to-phase conversion circuit (due to the limiting amplifiers) is high dynamic range. In addition, the output of the converter circuit contains the current-independent position information directly. Therefore, only two data acquisition channels per monitor are required versus four channels per monitor for systems which compute differences-to-sums in software. Lastly, it is pointed out that all of the components in the amplitude-to-phase converter are easily realized with op-amps.

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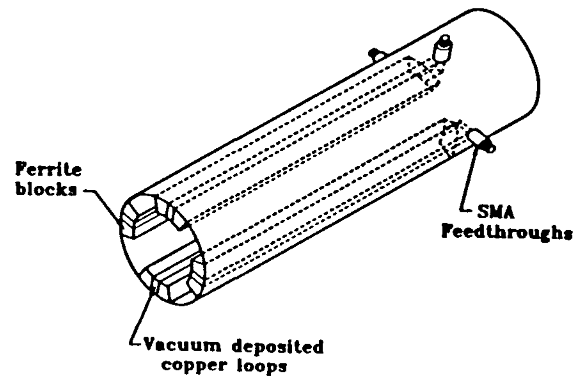

Figure 4 Concept for final pickup design.

References

1. P. Kloeppel, *Beam Diagnostics at CEBAF*, CEBAF TN-0039, August 1986, pgs. 1-6.
2. W. Barry, *Inductive Megahertz Beam Position Monitors for CEBAF*, CEBAF-PR-89-003, November 1988.
3. S. Jachim, Los Alamos National Laboratory, private communication.

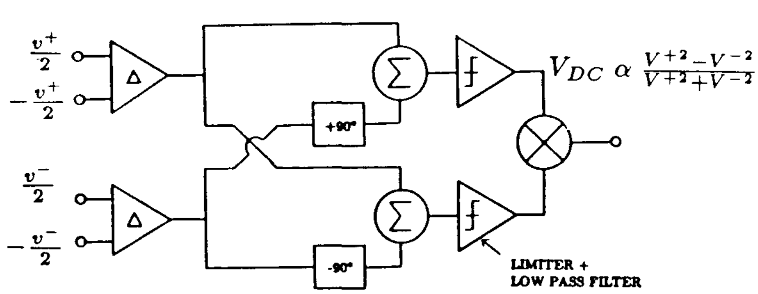

Figure 5 Amplitude-to-phase converter/detector.