CEBAF-PR-89-004

A BEAM POSITION MONITOR FOR LOW CURRENT DC BEAMS

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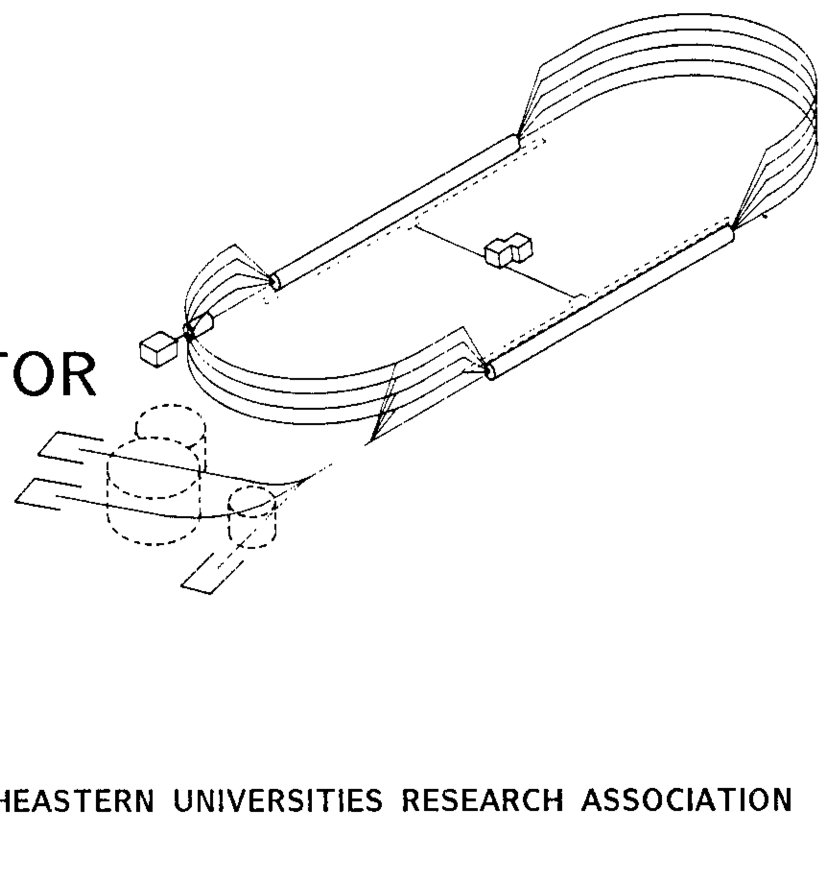

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CEBAF

Newport News, Virginia

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The 4 GeV recirculating linac, CEBAF, is presently under construction and will produce a CW beam with average current between .1 and 200 μA. In order to measure beam position, the beam current will be amplitude modulated at a frequency of 10 MHz. The modulation is detected by an inductive loop type monitor with electronics sensitive only to the modulation frequency. The first tests with beam from the CEBAF injector indicate that beam position can be measured with an accuracy of .1 mm at a modulated beam current of 1 μA.

Introduction

CEBAF is a five pass pair of recirculating electron linacs with an energy gain of 800 MeV per pass. The bunch length is one degree of the 1.497 GHz RF or 1.85 psec. With one bunch per RF cycle, the beam current spectrum consists of a line at DC, f_{rf}, and integer multiples of f_{rf}. For frequencies well into the tens of GHz, the amplitudes of the current harmonics are equal to I_{av}, the average or DC component of the current.

Traditionally, a beam position monitor for this type of beam current would consist of a microwave device, such as a quarter wave stripline or transverse mode cavity, operating at f_{rf} or one of its harmonics. Alternatively, by amplitude modulating the beam at a relatively low frequency (in this case 10 MHz) beam position can be determined with pickups and electronics operating at the lower modulation frequency. Because of relaxed mechanical tolerances on 10 MHz pickups compared to microwave pickups and the availability of low cost electronic components in the 10 MHz frequency range, a beam position monitor system of this type is expected to have a significantly lower overall cost than a system employing striplines or cavities. In addition, this system has the added advantage of being able to detect separately the position of each of the five different energy beams which reside in the CEBAF linacs simultaneously. This is accomplished simply by pulsing the amplitude modulation for a period of less than one circulation time in the machine (4.2 μsec). In addition, the time interval between pulses of modulation should be greater than five circulations (21 μsec) to allow one pulse to exit the machine before the next one is introduced.

The CEBAF monitor system will consist mainly of low frequency monitors that respond to an amplitude modulated beam. The pickups themselves consist of simple, inductive loops inside the beam pipe resonated externally at a frequency of 10 MHz. The loop monitors will be used mainly for machine tune up and periodic orbit corrections. When not performing these tasks, the beam modulation is turned off and the loop monitors become inactive. To complement the loop monitor system, a small number of cavity monitors operating at $2f_{rf}$ will monitor beam position continuously. In the event of a drift in beam position, the cavity system will activate the modulation and loop monitor system in order to make corrections.

Inductive Loop Pickups and Front End Electronics

Figure 1a schematically illustrates a single pair of inductive loop pickups used to measure one of the transverse coordinates, x or y, of the beam. As shown, voltages $V^{\pm}$ are developed through the position dependent mutual inductances, $M^{\pm}$, between the beam current and each loop. The loops are loaded externally with L and C to resonate at $f_0 = 10$ MHz. The series resistance, R, represents the small losses present in the circuit. It is easily shown that $V^{\pm}$ at resonance are given by

$$V^{\pm} = \omega_0 Q M^{\pm}(r_0, \phi_0) I_b \qquad (1)$$

where r_0, ϕ_0 are beam coordinates

The functional dependence of $M^{\pm}$ on beam position is derived in reference [1].

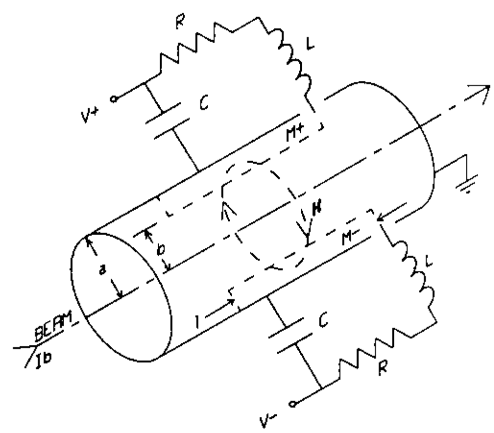

Figure 1a: Schematic of Inductive Pickups

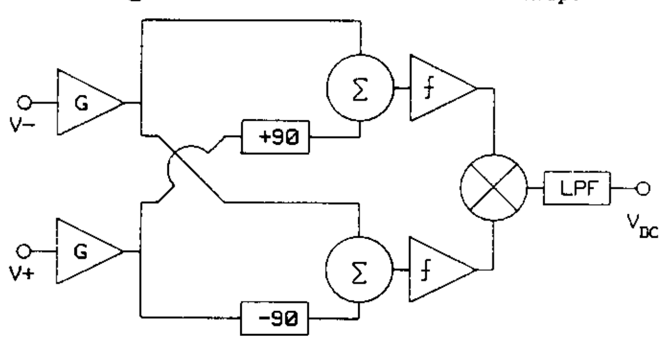

Figure 1b: AM/PM Converter/Detector

Several figures of merit (impedances) in common usage for electromagnetic pickups are defined and evaluated for the pickup circuit of Figure 1a in Table 1. In addition, Table 1 contains typical numerical values of these impedances for a prototype inductive loop monitor. Relevant physical parameters of the prototype are a=18 mm, b/a=.7 and ℓ=40 cm.

Table 1 Impedances for Loop Pickups

Parameter	Definition	For Loop Pickup	Typical Value
R_s/Q	Gain Bandwidth	$\sqrt{L/C}$	200Ω
Q	Quality Factor	$\omega_0 L/R$	50
$Z_\parallel$	$(V^+ + V^-)/I_b$	$(M^+ + M^-)R_s/L$	160Ω
$Z_\perp$	$\frac{\partial}{\partial x_\perp}\big\|_0 (V^+ - V^-)/I_b$	$2Z_\parallel/a$	18Ω/mm

Figure 1b contains a block diagram of the front end electronics used with the inductive loop pickups. The 10 MHz voltages, $V^\pm$, are first amplified by low noise, ultra-high input impedance amplifiers. The remainder of the circuit constitutes an amplitude to phase converter/detector whose purpose is to produce a DC voltage that is proportional to the x or y coordinate of the beam and is independent of the magnitude of the beam current. The AM/PM circuit converts the 10 MHz signals, $V^\pm$, into two amplitude independent signals whose relative phases contain the relative amplitude information, V^+/V^-. The phase and therefore V^+/V^- is detected by the output mixer and low pass filter.

An analysis of the circuit shows that the DC output is given by the following expression:

$$V_{\rm DC} = V_0\left(\frac{4}{\pi}\tan^{-1}\frac{V^+}{V^-} - 1\right) \qquad (2)$$

In equation (2), V_0 is the magnitude of $V_{\rm DC}$ when V^+ or V^- is zero and is adjustable. For the circuits used with the CEBAF pickups, V_0 is set to 5 V. From (2) it is also seen that V^+ and V^- appear as a ratio, therefore, $V_{\rm DC}$ is independent of the magnitude of the beam current. It can be shown that except for large beam displacements, $V_{\rm DC}$ is related to beam position as follows:

$$V_{\rm DC} \approx \frac{2V_0}{a} X_\perp \qquad (3)$$

where a = beam pipe radius

$X_\perp$ = x or y coordinate of beam

Laboratory and Beam Measurements of the Position Monitor

The position sensitivity of the prototype monitor described in the previous section was first tested using the standard technique of simulating the beam with a thin current carrying wire. In order to perform the tests accurately and efficiently, 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 .1mm.

Figure 2 presents the results of the wire measurements on the CEBAF prototype pickups and AM/PM detector circuit. V_{DC} normalized to V_0 is plotted (dashed) as a function of radial position (normalized to a) of the wire for two azimuths, $\phi_0 = 0^0, 45°$. In addition, the theoretical response of the monitor is plotted with solid lines. The theoretical response is obtained from equation (2) by replacing V^+/V^- with the theoretical expression for M^+/M^-. The curves are seen to be quite close to each other and, as predicted by equation (3) for a=1, have normalized slopes of 2 and 2cos 45° for small displacements. Figure 3 is an un-normalized plot of $V_{\rm DC}$ versus y position in mm. The irregularity at the positive extreme in position for both Figures 2 and 3 is attributed to the wire bumping into the loop pickup. The last wire measurements performed (Figure 4) demonstrate the insensitivity of the position monitor to different magnitudes of beam current. Here, $V_{\rm DC}$ is plotted against beam current for several different wire positions.

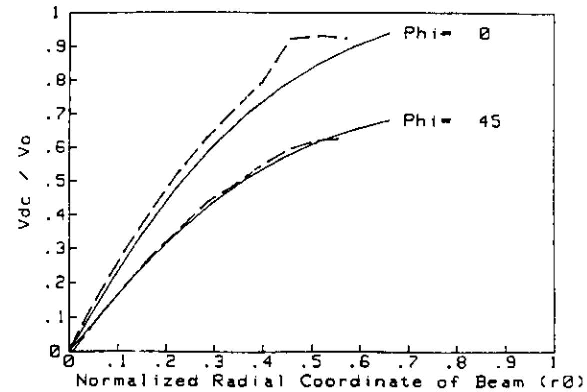

Figure 2: Normalized Position Sensitivity of Loop Monitor

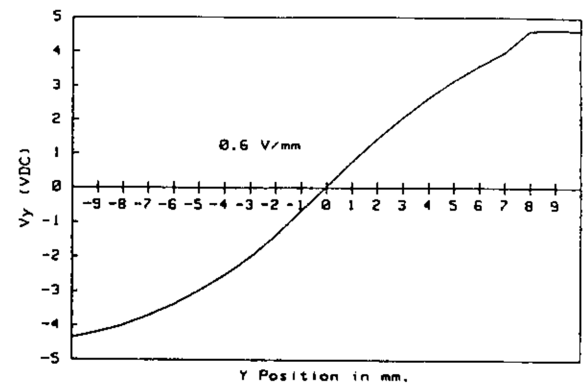

Figure 3: Un-normalized Position Sensitivity of Loop Monitor

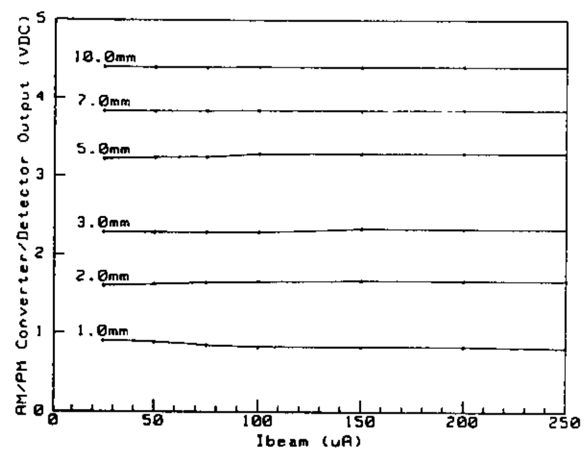

Figure 4: Beam Position Monitor Current Independence

In addition to wire measurements, the inductive loop position monitor was tested with the 100 KeV electron beam from the CEBAF injector. In order to modulate the DC injector beam, a simple 10 MHz chopping scheme was used. The chopper consisted of a pair of plates inside the beamline resonated at 5 MHz and 400 V peak to peak to wave the beam transversely in front of an aperture downstream. The deflected beam, passing the aperture twice per 5 MHz cycle, resulted in a 10 MHz amplitude modulated current.

The prototype monitor with two AM/PM circuits, one for each axis, was installed downstream of the chopper system. The DC outputs of the AM/PM circuits were connected to an oscilloscope operating in $x-y$ mode. In this manner, beam position could be determined directly by observing the location of the spot on the oscilloscope screen. For comparison purposes, beam position was also observed with an intercepting foil and TV camera located downstream of the position monitor. For these tests, the gains of the four monitor channels were calibrated using a beam that was visually centered on the foil viewer. In practice, however, gain calibrations as well as position sensitivity calibrations are performed on the wire test stand before installation in the beamline. In the final system, there will be a provision for recalibrating the pickup gains with the monitor in place in the beamline.

Typical results from the injector measurements are given in Figures 5a-5f. Figures 5a and 5b show a centered, 2 μA peak to peak beam as seen with the foil viewer (5a) and measured with the monitor (5b). As indicated, the diameter of the oscilloscope spot, representing noise is 0.3 V. Figures 5c and 5d show the same 2 μA beam displaced 4.2 mm in the $+x$ direction as measured on the foil viewer. Figure 5d indicates an x voltage of 2.2 V. Applying the 0.6 V/mm sensitivity figure from Figure 3 yields a measured position of 3.7 mm. The difference between the foil and monitor measurements is to be expected because the transverse effect of beam steering upstream of the monitor is greater at the foil which is located somewhat downstream from the monitor.

Figure 5a

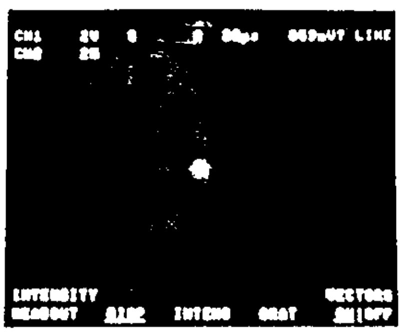

Figure 5b

Figure 5c

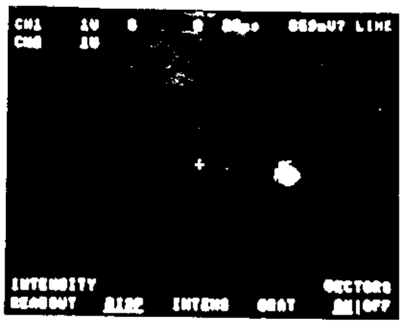

Figure 5d

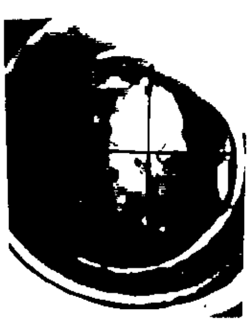

Figure 5e

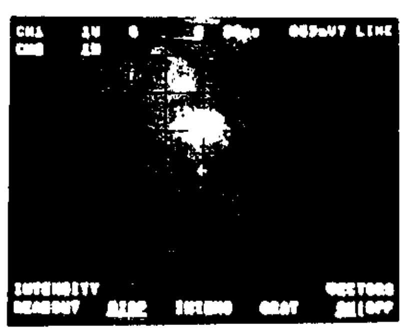

Figure 5f

Figures 5e and 5f show a 1 μA peak to peak beam displaced 2.5mm in the $+y$ direction. The same comments as above apply to this measurement. It should be noted that the noise has doubled to 0.6 V because of the lower current. In terms of position uncertainty (the radius of the spot in mm) the 1 μA beam can be measured to within 0.5 mm. In order to decrease the uncertainty to 0.1 mm, the present specification, simple averaging with 25 samples may be used. From this, a lower bound on the measurement time for a 1 μA beam with 0.1 mm accuracy can be determined:

$$T_{\min} = (4.2\ \mu\text{sec}) \times (5\ \text{passes}) \times (25\ \text{samples}) = 525\ \mu\text{sec} \quad (4)$$

Data Acquisition and Beam Position Monitor Camac Module

As stated in the introduction, the inductive loop monitors will operate with 4 μsec bursts of 10 MHz modulation so as to track the position of a single beam in the linacs throughout its five passes. In addition, approximately 25 sets of five pass measurements need to be taken and averaged in order to increase signal to noise to the 0.1 mm at 1 μA level of resolution. A conceptual diagram of a data acquisition system for performing these tasks appears in Figure 6.

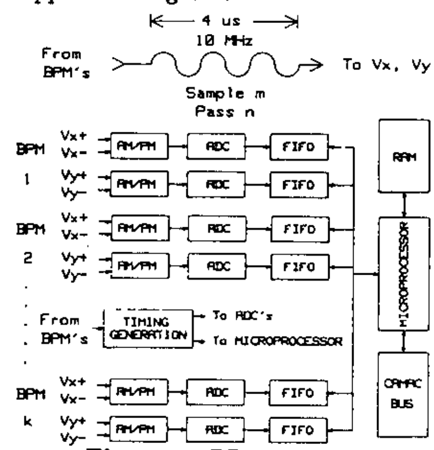

Figure 6: BPM Module

From a given monitor, the $x^{\pm}$ and $y^{\pm}$ pulses containing position information for the mth sample of the n^{th} pass are fed into x and y channel AM/PM converter/detectors. The information is immediately digitized and sent to a first in-first out (FIFO) buffer. An on-board microprocessor then reads the FIFO buffers and stores the data in RAM according to monitor, pass and sample number. The microprocessor also averages the samples, applies necessary calibration data, and puts the data in a format necessary for acquisition by the accelerator control computer. As indicated in Figure 6, timing for gating the measurements and counting samples and passes is derived from the leading edge of the pulses at each monitor. Additional circuitry, not shown in Figure 6, provides for de-Q-ing the resonant pickups between pulses.

At present, it is envisioned that four beam position monitors will be incorporated into one double wide CAMAC module. It is also expected that other data acquisition schemes involving multiplexing a fewer number of ADCs will be evaluated on an economic basis.

References:

[1] W. Barry, "Inductive Megahertz Beam Position Monitors for CEBAF," CEBAF-PR-89-003.

* This work was supported by the U.S. Department of Energy under contract DE-ACO5-84ER 40150.