AUTOMATED PATH LENGTH AND M_{56} MEASUREMENTS AT JEFFERSON LAB

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Abstract

Accurate measurement of path length and path length changes versus momentum (M_{56}) are critical for maintaining minimum beam energy spread in the CEBAF (Continuous Electron Beam Accelerator Facility) accelerator at the Thomas Jefferson National Accelerator Facility (Jefferson Lab). The relative path length for each circuit of the beam (1256m) must be equal within 1.5 degrees [1] of 1497 MHz RF phase. A relative path length measurement is made by measuring the relative phases of RF signals from a cavity that is separately excited for each pass of a 4.2 μs pulsed beam. This method distinguishes the path length to less than 0.5 degrees of RF (<280 μm) and gives the direction of the path length error. The development of a VME based automated measurement system for path length and M_{56} has contributed to faster machine setup time and has the potential for use as a feedback parameter for automated control.

1 INTRODUCTION

CEBAF is a 4 GeV electron accelerator producing CW beams for nuclear physics research. The accelerator consists of a 45 MeV injector and two parallel 400 MeV linacs. The linacs each contain 20 cryomodules each of which have 8 superconducting cavities. The beam is circulated a total of five times to achieve 4 GeV of total acceleration. The cavity phases are set to provide maximum acceleration using first pass beam. To keep higher passes on crest, the path length of each pass must be adjusted to less than 1.5 degrees. When performed locally in the service buildings measurements of path length and M_{56} can be imprecise and are time consuming. This paper describes the implementation of the hardware and software used to perform and automate the path length and M_{56} measurements using the EPICS (Experimental Physics and Industrial Control System) at Jefferson Lab.

2 MEASUREMENT METHODS

2.1 Description of Path Length and M_{56} Measurements

At CEBAF the beam is relativistic after the first superconducting cavity so the path length is a time of flight measurement of the whole electron bunch. The distance for each pass of the machine is measured in an integral number of 20 cm RF periods. The path length measurement method finds the length that each pass deviates within 1 RF period. M_{56} is a measurement of the degree that the path length changes for a given momentum change (ΔP)

$$M_{56} = \Delta \text{path length} \frac{\Delta p}{p}$$

The path length and M_{56} of the arcs are found using a precision phase detector [3] to measure the time of arrival of the electron bunches at a 1497 MHz cavity monitor [1] (M_{56} cavity). Because the beam induced voltage in the cavity is in phase with the bunch current, a measurement of the phase of the RF from the cavity is a direct measurement of the time of arrival of the electron bunches. An M_{56} cavity is located at the end of each linac, thus all five passes of the beam propagate through the cavity. A macro pulse with a duration less than the circulation time (4.2 μsec) is established at a 60 Hz rep rate. This pulse separately excites the cavity each time it completes one circulation. A difference in path length between passes is measured as a phase difference between the RF from each pass.

2.2 Path Length Theory of Operation

The phase of RF coming from the pickup cavity is adjustable relative to a 1497 MHz reference with a programmable phase shifter. The signal is then mixed with the RF reference where the voltage output (V_{out}) of the mixer is:

$$V_{out} = \text{cavity RF} \times \text{Reference Signal}$$

$$V_{out} = A_1 \sin(\omega t + \phi_1) A_2 \sin(\omega t + \phi_2)$$

The high frequency components are removed by a low pass filter. V_{out} is now dependent only upon the beam current and the phase difference between the RF from the cavity and the RF reference.

$$V_{out} = A_1 A_2 / 2 \ \sin(\phi_1 - \phi_2)$$

To perform a path length measurement the phase shifter is adjusted so that $(\phi_1 - \phi_2)$ is near 0, and using the small angle approximation

$$V_{out} \cong A_1 A_2 / 2 \ (\phi_1 - \phi_2)$$

The reference phase ϕ_2 is a constant, therefore any indicated phase change is due to a change in ϕ_1 from the cavity. The macro pulse separately excites the cavity for each pass and a separate measurement for V_{out} for each pass results. A change in phase of the cavity RF (ϕ_1) for any pass will result in a change in V_{out} for that pass (Figure1).

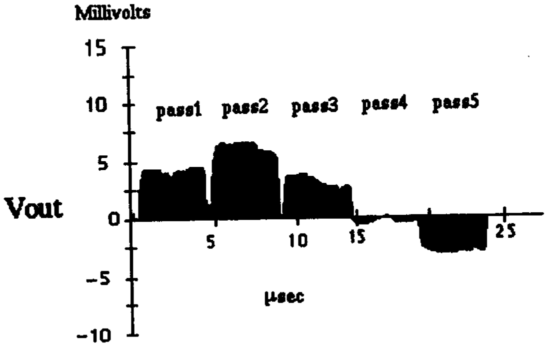


Figure 1 Relative Phase Measurement Between Passes

The cavity is calibrated by using the phase shifter to adjust ϕ_2 through a range of phases in the near-linear region of the output of the phase detector where $\sin(\phi_1-\phi_2)$ is close to 0. The slope of V_{out} as a function of $\Delta(\phi_1-\phi_2)$ in mV/degree is found. During a measurement this constant is used to find the path length difference for any change in V_{out} between passes.

3 PATH LENGTH MEASUREMENT SYSTEM

3.1 Path Length / M_{56} Measurement Hardware

The cavity is a simple pill box cavity, resonating the TM_{010} mode at 1497 MHz. Constructed of stainless steel in order to minimize drifts due to temperature, Q_0 is approximately 3000 and the geometric shunt impedance is 180 Ω [2]. The signal from the cavity is sent to the isochronous measurement chassis as shown in Figure 2.

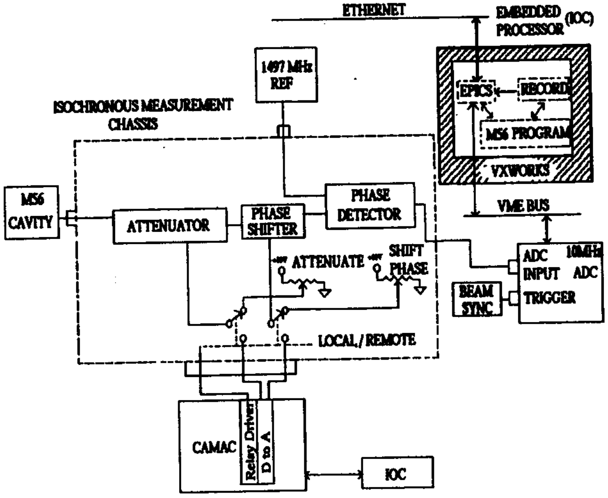


Figure 2 Schematic of Path Length Measurement System

The EPICS controls system is used to control an RF switch, a phase shifter, attenuator, and a 10 MHz ADC. The output signal from the phase detector is sent to the ADC which digitizes the M_{56} wave form when triggered by the 60 Hz beam sync signal.

3.2 Path Length / M_{56} Measurement Software

The path length program performs a selected number of averages on the digitized waveform and stores the averaged waveform in a EPICS wave form database record. The record is then parsed into segments for each pass, and the average of each parsed segment is found and a single value representing the cavity voltage for each pass is obtained. Three calibration factors are needed and stored for path length measurements. The first is the phase shifter setting found when pass1 is adjusted to 0 phase. The second is the attenuator setting for minimum attenuation. The third is a calibration of the phase detector with beam in the cavity with $A_1A_2/2 \sin(\phi_1-\phi_2)$ in the near-linear region. With the output of the detector adjusted to 0 phase for pass 1, a relative path length measurement is made from one pass to the next. The cavity voltage for each pass is multiplied by the calibration factor in degrees/mV. The display screen shown in Figure 3 is used to initiate a path length measurement and display the result.

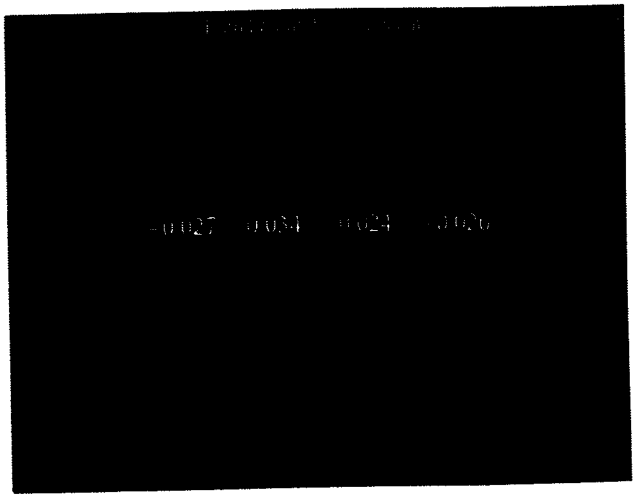
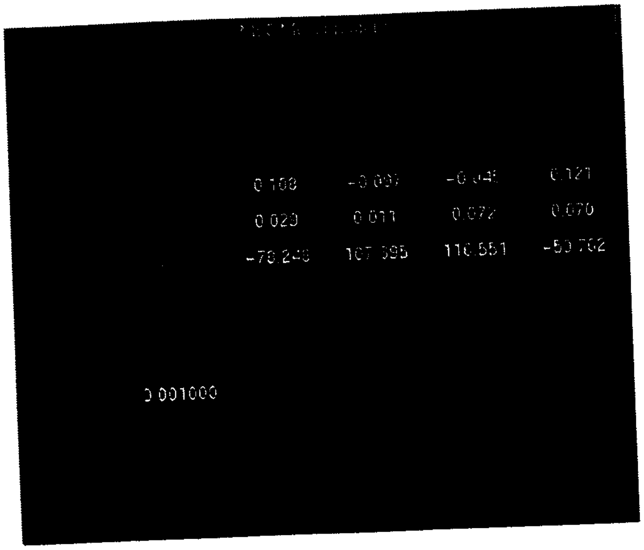


Figure 3 Path Length Measurement Screen

The relative path length between passes is measured in degrees. The update rate depends upon the number of averages selected on the M_{56} expert page, with 50 averages selected an update rate of approximately 2 seconds has been observed.

M_{56} measurements are made using the display screen shown in Figure 4. M_{56} is measured by performing one path length measurement at the nominal operating energy and another with a small energy offset ($\Delta P/P$).

The program calculates the M_{56} for each pass and displays the results.



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0.108     -0.009     -0.045     0.121
0.023      0.011      0.072     0.070
-78.248   107.595    110.551   -50.762

0.001000
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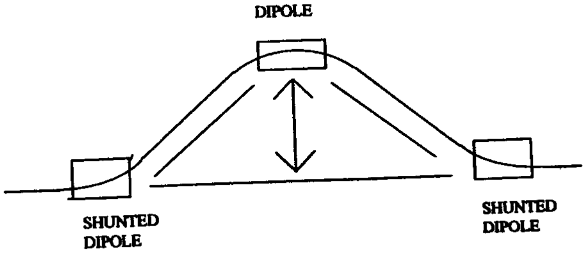
Figure 4 M_{56} measurement screen

4 PATH LENGTH MEASUREMENT RESULTS

In each arc at CEBAF there is a dogleg magnet system that is used to adjust the path length to set the energy cresting for the next linac. The dogleg control bus consists of a dipole and two shunts that allow the path length to be adjusted by up to 8 degrees in either direction from the designed orbit (Figure5).



Path Length adjusted in either direction from Designed orbit by changing bend angle

Figure 5 Dogleg System

To test the accuracy of path length measurements, a range of path lengths from from +4 to -3 degrees in 0.5 degree increments was introduced into the dogleg of the second arc. The corresponding path length measured was as shown in figure 6. The accuracy of the measurement (as indicated by one standard deviation of no greater than .12 degrees) allows the system to diagnose path length error well below the design requirements of 1.5 degrees.

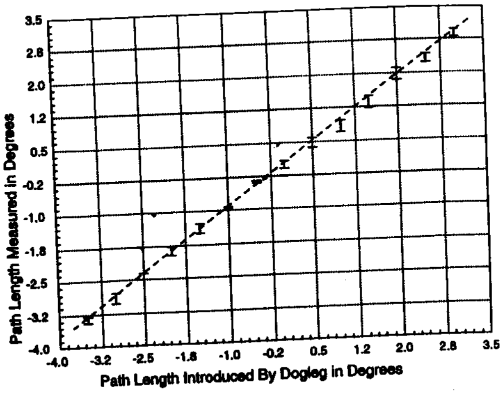


Figure 6 Path Length Introduced vs Measured

5 CONCLUSIONS

The novel use of relative phase measurements to perform path length and M_{56} and measurements results in a system that performs path length measurement in less than 3 seconds and gives a 2σ measurement error of <.25 degrees (< 140 µm). Presently an M_{56} measurement requires an operator to make the energy change. In the future the path length program will work at 30 Hz allowing M_{56} measurements to have the same speed performance as the path length program. Another feature of the system is that it gives the direction of the measured path length. This allows for quick calculation of needed corrections to the optics. Future developments may include automatic correction of path length and M_{56}

REFERENCES

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[2] R. Ursic, K. Mahoney, C. Hovater, A. Hutton, C. Sinclair, "CEBAF Beam Loss Accounting", TN#95-034

[3] G. A. Krafft, M. Crofford, D. R. Douglas, S. L. Harwood, R. Kazimi, R. Legg, W. Oren, K. Trembay, and D. Wang, Proc. 1995 Particle Accelerator Conf., pp 2429-2431