On-Line Measurement and Tuning of Multi-Pass Recirculation Time in the CEBAF Linacs*

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Abstract

CEBAF is a CW, recirculating electron accelerator, using on-crest RF acceleration and isochronous recirculation arcs. Previously installed diagnostics [1] allow us to monitor the phase difference between the first-pass beam and the linac RF. The error signal is used for feedback correction of residual drifts in the RF timing system. We also experience drift in the path length (recirculation time) for the recirculated beam resulting in beam energy drift of several times 10^{-4} for some acceleration passes, even when one beam energy is held fixed by adjusting the RF gradient. We have extended the beam-based RF phase diagnostic system [1] to the recirculating beam, and can monitor and correct the path length at the 50 micron level (timing to 200 femtoseconds). The previous procedure for measuring and tuning the path length was coarser in resolution and required suspension of beam delivery.

1 INTRODUCTION

The layout of the accelerator is shown in Figure 1. Within certain limits, beam can be delivered to the three independent experiments from any of the five acceleration passes. Changes in linac accelerating gradient or slippage of the beam arrival time relative to the RF phase will naturally change the beam energy on target. This paper deals with detection and correction of drifts in the beam path length which cause the beam to drift off-crest with respect to the accelerating fields.

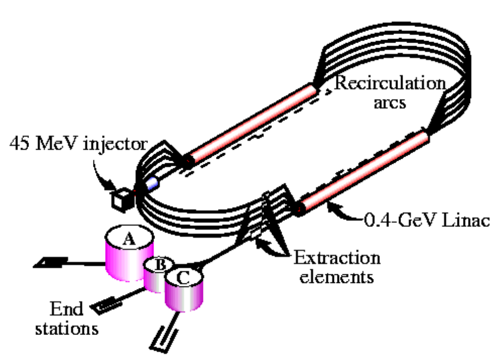

Figure 1: Layout of CEBAF Accelerator. The North Linac is at the upper left, immediately following the injector. The diagnostic reported here is about 80% of the way clockwise around recirculation arcs at the top right.

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Some nuclear physics experiments fielded at CEBAF require the beam energy to remain in a window as narrow as 10^{-4}. We have had simultaneous experiments requiring such stability at different beam energies. A major consideration for energy stability is control of the recirculating beam transit time to maintain uniform energy gain for each recirculation pass. The system described here provides the ability to monitor the path length during beam delivery. This enables tuning of the path length to maintain the beam energy for each pass with no need to interrupt beam. Multi-pass path length regulation is complementary to gradient-based beam stabilization tools, including the Fast FeedBack (FFB) [2] system and its predecessor slow energy lock system [3].

2 PROBLEM

The path length of the system is adjusted using symmetric three-magnet chicanes, one placed near the entry of each of the nine recirculation arcs. These chicanes compensate for as-built variations in the beam circulation time and for orbit dependencies in the path. As a result of setup tolerances and post-setup path length drifts for the recirculating beam, the relative energies of the various passes do not remain constant. Stabilization of phase-driven energy variation for any single pass is possible by adjusting the accelerating gradient, but does not provide equivalent long-term stability for the other passes. Gradient based feedback regulation referenced to an experimental hall provides short-term levels of stabilization (at the few times 10^{-5} level). With control of path length errors, the beam energy for all users can be fixed at this level essentially indefinitely.

2.1 Gradient Drifts

Variations in the beam energy and orbit are detected in the recirculation arcs and in the experimental halls using Beam Position Monitors (BPMs) in dispersive regions. The FFB system obtains the beam energy from BPM data sampled at 2 kHz in one of two appropriately instrumented experimental halls. It adjusts the accelerating gradient of a group of cavities in the South Linac to hold the beam energy constant in the selected hall. This system maintains beam energy within a band currently estimated at the 10^{-5} level. In addition to stabilizing beam injection steering into the hall, the FFB system provides Fourier amplitudes for the residual energy and orbit errors. The energy data provide a useful supplement to the system described below.

2.2 Path Length and Phase Drifts

Imperfect temperature compensation of the RF Master Oscillator (MO) reference results in phase variation of the accelerating fields of each linac on the scale of a few degrees of the 1497 MHz fundamental accelerating cavity frequency, as well as a small loss in acceleration due to a slight loss of coherence. Timing errors commonly result at the 0.5 degree scale for the higher passes from our standard setup and tuning procedures, and are sufficient to drive 10^{-4} scale relative energy variations with phase drifts as small as one degree.

3 SOLUTION

The first-pass phase measurement system reported in [1] provides an error signal to use for feedback control of the linac phases. It was installed to supplement gradient regulation with control of the first-pass linac phases and reduce the effect of recirculation path length errors. The regulation band of approximately 0.2 degrees is small enough to maintain the beam energy within 10^{-4} on the time scales associated with the RF reference drifts, but the beam energy is still vulnerable to path length changes in the accelerator induced by ground motion, temperature change, or by other failures in hardware or configuration control.

This system is commonly called the “MOMod” system. A 0.1 degree peak-to-peak phase modulation is imposed on the MO at a different frequency in each linac, thus modulating the linac RF phase. The global RF phase relative to the beam is proportional to the beam energy modulation synchronous with the phase modulation.

The system reported here extends the first-pass system to the recirculating beam, measuring the cumulative effect on the beam of this phase modulation. It is part of the effort at CEBAF to minimize dedicated beam time required for accelerator tuning. The path length drift we have experienced is dominantly an annual cycle, but the drift rate can vary substantially over short times, such as during startup after maintenance. With a continuous monitor, we can consider automating feedback control of the path length. This will remove one more distraction from accelerator operations, and help maintain the specified beam parameters.

The path length diagnostic previously used [4, 5] measures the arrival phase relative to the RF reference for multiple passes of the same beam pulse at a single location. It requires pulses shorter than the $4\ \mu$sec recirculation time. The beam-induced 1497 MHz RF signal from a (normal-conducting) cavity on the beam line is mixed to DC against the MO reference. With the RF inputs in quadrature, differences in the output signal from pass to pass measure the variation in arrival phase of each pass. This satisfied the initial requirements, and still works well for beam setup, but does not allow monitoring of the path length during CW beam delivery.

3.1 Hardware Layout

The MOMod system is shown schematically in Fig. 2. As outined in [1], each linac has an independent phase modulation. The resulting beam energy variation is detected using a BPM in a dispersive region. The beam steering caused by linac phase modulation is negligible, and the signal is dominated by the energy modulation. The pickups must be at locations with sufficient dispersion to produce detectable beam motion. The dispersion at the first-pass pickup is 1.4 m, and the design dispersion at the multi-pass pickups is 2.5 m. Dispersion leakage in the higher passes is considerably less than 0.5 m, and because the signal calibration is directly proportional to the dispersion at the pickup location, the multi-pass phase signal calibration should vary by less than 20% due to beam optics errors.

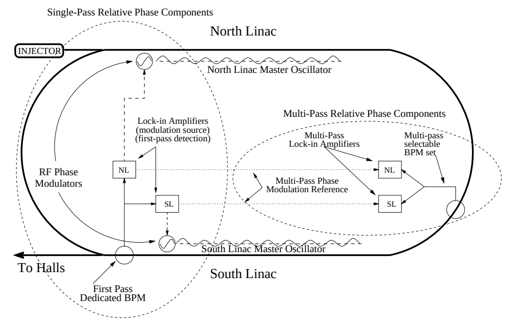

Figure 2: First-pass system (left-hand ellipse) and the multi-pass extension (right-hand ellipse) for measuring relative phase of beam and RF. Independent phase modulation signals are generated for the two linacs. The pickups for the multi-pass system are referenced to those remote signals and require no additional perturbation of the beam.

The multi-pass system also provides redundant first-pass data as a consistency check. Simultaneous higher-pass measurements are not possible, as the pickups are multiplexed through a single set of signal processing hardware (as shown in Fig. 3). The path length error signal is the difference between first-pass and multi-pass measurements, which must be made simultaneously in order to exploit the instrumental precision. The time required to measure

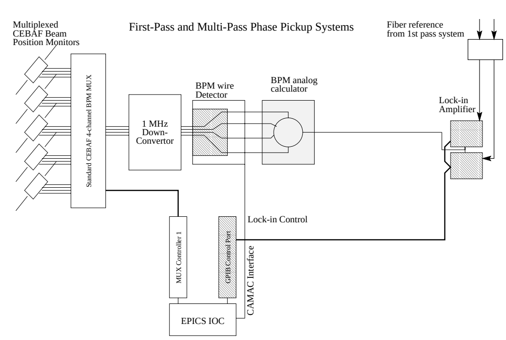

Figure 3: BPM and signal processing schematic for the recirculated beam.

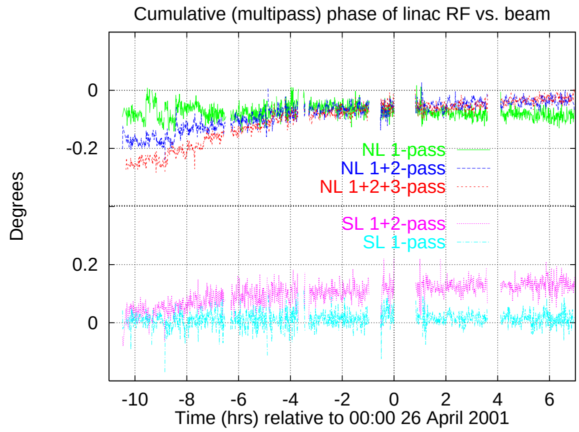

Figure 4: Example data for 100 μA of beam delivered on third pass to an experiment in Hall A. Gaps in the plots are during times when beam was interrupted. The traces appear from top to bottom as in the legend. No path length correction was attempted during this time span.

the beam phase relative to linac RF is about 10 seconds, and over such a time the RF phase can easily change by tenths of a degree. The BPM signals remain available for the Beam Position Monitor system, although the multiplexing rate is slowed greatly when path length measurements are being made.

The multi-pass pickups cover all passes through the linacs except for the final pass through the South Linac for the highest energy beam in use. Fortunately, the highest pass South Linac phase can be tuned using the FFB Fourier component measurements for the relevant experimental hall. The FFB system does not provide the sign of the phase error, but the sign may be discovered by inspection or by trial and error, and the phase error may be minimized by zeroing the Fourier amplitude at that frequency.

3.2 Calibration and Resolution

The overall system calibration can easily be measured by changing the linac RF phases and measuring the signal from the beam-based monitor. Some system calibrations have drifted by a factor of three. The causes are not clear, but current dependence in the analog beam position signal processing is a suspected cause. It is planned to upgrade the unmonitored phase modulation hardware with units which can be readily dismounted from the system for maintenance activities, and which are self-monitoring and addressable through the control system.

The resolution of the system is quite adequate for our purposes, as seen from Fig. 4, showing data taken in late April while delivering 100μA of beam to Hall A (three acceleration passes). The vertical scale in the graph is the difference between the measured phase for the continuously available first-pass system and from multi-pass pickups. The apparent noise level is under 0.1 degrees, and is about twice as large for the South Linac as for the North Linac. The first-pass traces are stable at zero for the South Linac and -0.1 degree for the North Linac. This probably indicates a calibration scale error for one of the two North Linac systems. The data indicate a 0.2 degree contraction in the first and second pass circulation times during the first 8 hours of the graph, then stabilizing. The change in the second-pass traces is the average of a 0.2 degree early arrival of the second-pass beam with respect to the stable first-pass reference. The diagnostic output is the average of these two values. The shift in third-pass data for the North Linac is the average of 0, 0.2, and 0.4 degrees, because the first- and second-pass delays accumulate.

4 OUTLOOK

High-level controls for the path length monitor are not yet in place. The low-level controls available for manual operation can be used for path length monitoring and adjustment, but continuous monitoring of the recirculated beam has not been routine. All mechanisms necessary for routine on-line adjustment have been tested successfully, but are not yet incorporated into operational procedures. Routine procedures for calibration and signal validation will be necessary before path length feedback control can be considered.

Path length adjustment is done by changing the magnetic field in the chicanes mentioned earlier. Residual calibration errors in the large opposing fields of the dipoles in each chicane, as well as hysteretic effects, result in significant beam steering effects when correcting the path length. In order to minimize disturbing the beam position on experimental targets, it may be useful to empirically adjust the chicane magnet calibrations. Other changes may be desirable, such as incorporating the controls for part of the chicane into the beam orbit feedback. The path length and orbit correction systems overlap in the accelerator, and linking the two in this way would reduce the liklihood of their opposing each other and being driven out of regulation range.

5 REFERENCES

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