# SIMULTANEOUS MULTIPLE PASS STEERING AT JEFFERSON LAB*

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*Abstract*

The CEBAF recirculator at Jefferson Lab includes two linear accelerators, each 200 meters in length. Due to varying betatron phase advance for different recirculation passes, misalignment, and other steering effects, orbit correction in the CEBAF linacs presents a complicated problem defying pass-by-pass solutions. Utilization of information from the beam position measurements at all recirculation passes allows us not only to perform multi-pass steering minimizing beam displacements inside the linacs, but also to determine displacements of linac BPM's and focusing quadrupoles from an ideal axis. This paper describes a steering algorithm and presents the experience in multi-pass orbit correction.

## 1 THE PROBLEM

Jefferson Lab operates its CEBAF accelerator, with which it is often synonymous, as a nuclear physics research facility currently delivering CW electron beam to three fixed-target experiments with energy up to 5 GeV. CEBAF consists of injector, multi-pass linacs, recirculating arcs, beam separation (spreader) and recombination (recombiner) structures, and extraction lines to experiments. These are shown in Figure 1. The linacs consist of FODO structures providing constant focal length for the first pass beam at 120 degrees betatron phase per period. Orbit correctors are active only at the focusing elements in each plane. This has proven effective in avoiding excessive correction for the first pass orbit.

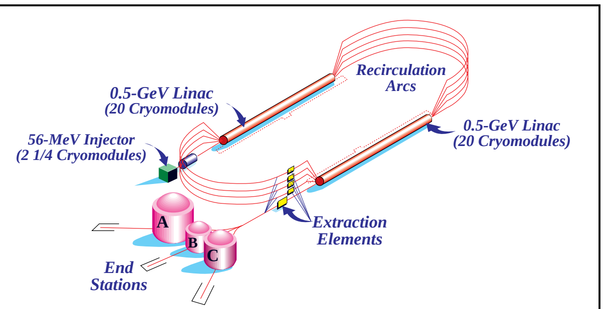

Figure 1: CEBAF conceptual layout

In early 1998, despite successful steering to orbit within 1 mm in the first pass linacs, large and persistent orbit patterns in higher passes were seen to develop. In higher passes orbit deviation could exceed 4 mm in the x plane in both linacs, while the typical operational requirement for absolute orbit was 1 mm. It was hypothesized that misaligned quadrupoles and BPM's, and other unaccounted disturbances to the beam were mainly responsible. Significant difference in betatron phase advances between different passes and absence of correctors exactly coinciding with all potential errors left higher pass orbits at the mercy of first pass corrections. This was exacerbated by unknown systematic offsets in the multi-pass BPM's [1] which monitor the orbit for all passes.

## 2 INTERPRETING THE ORBIT

An analysis on the multiple pass orbit was performed to interpret the observed anomaly. Table 1 gives a parameter count relevant to this analysis in the South Linac. The free parameters were unknown kicks and monitor offsets shared by all 5 passes, and injection errors distinct for each pass. The constraint came from the orbit readbacks at 27 linac BPM's for all 5 passes. An unknown kick was assigned to each quadrupole location, which was sufficient to represent the effect of all misalignment-related errors. The assumption that each monitor offset was the same for all passes was reaffirmed by the outcome of the analysis showing negligible pass-to-pass variation in the fit residual at all BPM's except one. This highly constrained system promised a redundancy important in ensuring the reliability of the analysis.

| Element | Per pass | Total |
|---|---|---|
| Orbit reading | 27 | 135 |
| Total constraints | | 135 |
| Injection position | 1 | 5 |
| Injection angle | 1 | 5 |
| Unknown kick | 27 | 27 |
| Monitor error | 27 | 27 |
| Total free parameters | | 64 |

Table 1: Parameter counts

The analysis was done through least square fitting using the parameters and constraints of Table 1. All input data were generated by a machine snapshot program FOPT which, in addition to recording the orbit and magnet information at a given operating point, generated estimates of individual BPM resolution for the data set of interest. Input orbit data were weighted according to these estimates. A BPM known to display anomalous behavior was deleted from the input. Figure 2 shows the offset in quadrupoles and BPM's as calculated by the fit, where the fitted unknown kicks were converted to

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equivalent offsets of quadrupoles. The baseline in Figure 2 has been adjusted to minimize overall RMS of the quadrupole offsets. Error analysis was performed using the BPM resolution estimated by FOPT. The RMS errors on most of the fitted quadrupole and BPM offsets were on the order of 0.1-0.3 mm. The quadrupole next to the malfunctioning BPM displayed the largest RMS error in offset of 0.8 mm. The fit residuals at 135 locations were consistently below 0.2 mm in both planes, with the exception of the malfunctioning BPM displaying variable residuals from pass to pass with magnitudes of several millimeters. Figure 2 also demonstrates corroborating offset patterns between quadrupoles and BPM's, lending further credibility to the analysis[♣]. The persistent orbit in higher pass linacs was understood, after this analysis, as the cumulative effect of kicks caused by long range quadrupole offset pattern with respect to the ideal straight line[‡]. This effect has been imperfectly cancelled in the first pass by correctors only in the focusing zones under the 120-degree optics. In higher passes the remnant of the first pass correction built up considerably over several zones due to much slower phase advance.

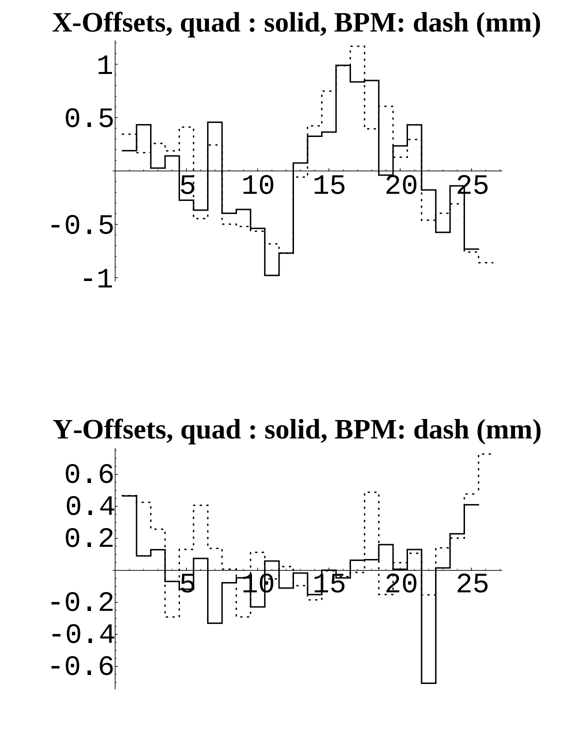


Figure 2: Quadrupole and BPM offsets in mm

[♣] This also confirms the effort of beam-based BPM alignment with respect to the nearest quadrupole carried out at CEBAF.

[‡] There is no independent confirmation as to whether this pattern reflects real distortion in the baseline, thus quadrupole offsets can also be viewed as representative of all unaccounted kicks.

## 3 MULTI-PASS STEERING

It was realized, after the above analysis, that using all the correctors inside the linac, which affects all passes differentially, as well as injection fixes from individual upstream recombiners, we could reduce the orbit in all passes significantly. Simulation of this process was encouraging. There was the option of whether to set the target of steering to the ideal straight line between the ends of the linac, or to set it to the centers of the working BPM's. The latter option was adopted in view of the possibility that the offset pattern of Figure 2 may indicate actual beam line distortion. In other words, apparent BPM centers may conform to the actual deformed baseline, and steering to an absolute straight line, instead of the apparent BPM centers, may in fact compromise aperture.

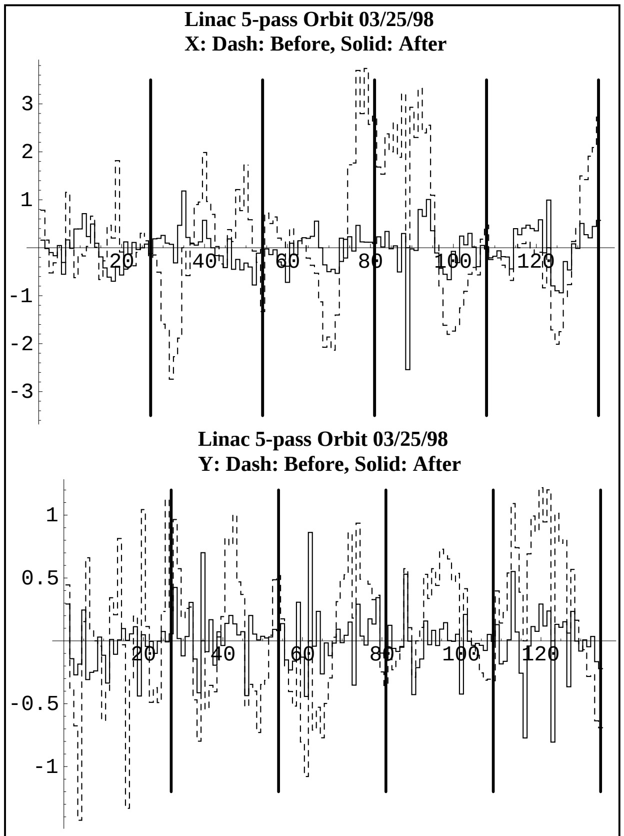


Figure 3: Multi-pass linac orbit before and after correction in mm

Corrector strengths needed for simultaneously steering all 5 passes in the South Linac were calculated using PROSAC, a locally developed steering algorithm with a strong emphasis on fully exploiting hard corrector limits while strictly conforming to them[¶]. This proved critical to muti-pass steering. This procedure was applied to the South Linac. The highly over-constrained nature of the

[¶] Expecting correctors reaching design limits, we did not use SVD-based steering with its intrinsically pathological limit-handling scheme.

problem forced several correctors to their limits as expected, but simultaneous orbit reduction was achieved. Figure 3 shows the BPM readings in mm before and after the correction, with all 5 pass orbits displayed in tandem for each plane. The solid line in x-plane is an order of magnitude smaller in RMS than the dashed line[↑]. A total of 12 horizontal and 13 vertical correctors inside the South Linac and 10 correctors in each plane in the upstream recombiners were used to achieve this orbit reduction at 135 locations in each plane. Simulation also showed promise for multi-pass steering in the North Linac, where higher passes displayed persistent orbit similar in magnitude to the South Linac. However this was not implemented because orbit analysis indicated, at the time of test, that several BPM's displayed behavior anomalous enough to compromise the offset interpretation and the effectiveness of steering.

## 4 CONCLUSION

We have successfully demonstrated simultaneous multi-pass steering in the CEBAF linac. Algorithm was developed to extract information on unknown kicks and monitor offsets, which were in turn translated into information on potential baseline misalignments. Multi-pass steering was done by an effective algorithm using common correctors in the linac and injection adjustments upstream. Implementation of this algorithm as a routine online program is included in the next phase of high level application plan at CEBAF.

## REFERENCES

[1]. T. Powers and S. Schafner, these proceedings.

[↑] Some solid spikes correspond to malfunctioning BPM's.