

# RESOLVE AT CEBAF\*

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## Abstract

M. Lee's program RESOLVE[1] has recently been in extensive use at CEBAF to help identify and correct optics problems in recirculation arcs and in linac beamlines encountered during the commissioning of the 4-GeV accelerator. We describe the integration of the program with our machine applications software package. A significant vertical focusing error in one of the recirculation arcs, which is attributed to edge focusing of dipole magnets, was found from the analysis of difference orbit measurement data. A corrective measure has been successfully implemented. Optics checks in the spreader and recombiner regions are discussed along with linac optics and 60Hz jitter.

## I. INTRODUCTION

RESOLVE is a generic beam simulation code (up to second order in the transfer matrix) which can be used to find the possible causes of trajectory errors with multi-track data fitting capabilities. Usually, alignment errors and/or focusing errors of beam line magnets cause particle trajectories to deviate from the nominal path. Errors also show up when the beam energy is different from the design value. Finding and correcting sources of such errors quickly in the commissioning stage of a machine (CEBAF is currently commissioning a 4 GeV CW electron accelerator) is extremely helpful.

## II. PREPARATION OF RESOLVE DECKS

Most CEBAF accelerator beamlines are designed with the optics code DIMAD[2] and a layout of any beamline must agree exactly with a corresponding DIMAD deck. The accelerator is divided naturally into 18 beamline units (45 MeV injector, two linacs - North and South, nine arcs - Arc 1 to 9, five beam switch yard lines, three experimental hall lines - Hall A, B, and C). A conversion program from a DIMAD deck to a RESOLVE deck has been written to help preparing RESOLVE decks for these beamlines. For all beamline elements except a cavity, a straight forward translation of conventions and formats adopted in DIMAD to those of RESOLVE is required for the conversion. Currently, a cavity element in RESOLVE is supposed to simulate a traveling wave linear accelerator as in TRANSPORT with an energy gain proportional to the length of the element. However, we find that CEBAF cavity provides significant transverse focusing in both directions to low energy electron beam. This is especially true in the first two cavities of the 45 MeV injector where the beam energy changes from 500 keV to 5 MeV. A quite elaborate cavity handling routine[3] has been incorporated into the DIMAD being used at CEBAF in order to model transverse cavity focusing also into a cavity element. Consequently, the North

Linac model in RESOLVE is likely to predict a slightly different trajectory in the beginning section for the first pass beam compared to DIMAD. However, the modeling difference should be negligible in the North Linac at higher passes and in the South Linac at all passes. Our RESOLVE decks start from the 45 MeV beamline known as the Injector Chicane to minimize effects of cavity modeling presently available in the code.

## III. DATA TAKING AND READING

RESOLVE runs on a VAX system while machine control is by UNIX based computers at CEBAF. We have developed a fully interactive and easy to use RESOLVE data handling process integrated into CEBAF machine control system. The program is written in Tcl scripts since most high level optics control software such as orbit correction and energy and orbit locks programs are presently also written in Tcl[4] which is a very powerful scripting language based on a library of C procedures for developing GUI applications. From an operator console we can pull up an optics menu and initiate a data taking procedure. Fig. 1 shows the main window for a data taking. A click on SelectBeamline brings a menu of beamlines made of the 18 basic beamline units described in the previous section. One then assembles a beamline of interest concatenating several units selected from the menu.

```

                                Select Beamline
Your directory:      /usr/user2/mccops/tcl_apps/DataLog
                                Open Data File
Enter data file name      29MarArc1
Enter Reference Energy (MeV)      445
                                Make a note before taking each data
Note:      MBT1A01H
                                Take Data      1
                                Close Data File
                                View Data Info
                                Get Absolute Orbit from i-th Data Set
                                Get Difference Orbit from i-th and j-th Data Set
                                Clear data before opening another file
                                Clear Data
                                Quit
```

Figure. 1. A menu for data taking.

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Usually a corrector is chosen to provide a kick to the beam by a specified amount and then all beam position monitor(BPM) readings are recorded along with magnet settings and cavity gradients for future reference. After collecting all necessary data one can close a data file and quit or continue to prepare BPM input files required for the RESOLVE program with a click on either the GetDifference or GetAbsolute button. Data files taken previously are converted into .bpm files with a data read procedure written also in Tcl. Data analysis is performed with RESOLVE after transporting .bpm files to a VAX.

#### IV. OPTICS CHECK WITH RESOLVE

During the machine commissioning, we have systematically checked optics of beamline components with RESOLVE to ensure proper transport of the beam through the accelerator.

##### A. X-Y Coupling in Linacs

Data shown in Fig. 2 agree well with the linac model in the second(South) Linac, where the 1st pass beam with an initial energy of 445 MeV gains 400 MeV in energy. As expected, BPM data for the 1st pass beam in the first(North) Linac cannot be fitted with the model as a whole as a result of cavity focusing in the front end of the North Linac. An interesting feature seen in Fig. 2 is the existence of x-y coupling due to a skew quadrupole component of the fundamental accelerating mode of CEBAF superconducting cavity. A numerical calculation[5] predicts a total integrated gradient of the skew quad component, which is well localized at the location of higher order mode couplers, to be approximately 4 gauss when a single 5-cell cavity is powered at 5 MV/m gradient. Furthermore, it is shown that the skew quad component from each cavity of linacs (we have 180 cavities in each linac) adds when cavities are phased for acceleration. BPM data in Fig. 2 are for the beam motion initiated by kicking

the beam horizontally (top figure) at the entrance of the South Linac. The x-y coupling in cavities induces the motion in the vertical plane (bottom figure). The strength of skew quadrupoles used for the fit agrees with the numerically estimated value. We should also mention that an experiment to measure the skew quad component of a CEBAF cavity has been performed[6] at the first cryomodule of the North Linac and results qualitatively confirmed the theoretical estimate.

##### B. Arc Optics

Each arc is an isochronous 2nd order achromat, consisting of 3 distinct optical units called spreader, recombiner and arc proper. The nine arcs allow for 5 passes through the linacs.

In higher energy arcs starting from Arc 5 we find that difference orbit data at spreader/recombiner modules generally fit well with the models, while BPM data clearly deviate from the models at spreader/recombiner modules in the Arc 1 and 3. However, the agreement between the model and data is excellent in the spreader region of Arc 2 as shown in Fig. 3.

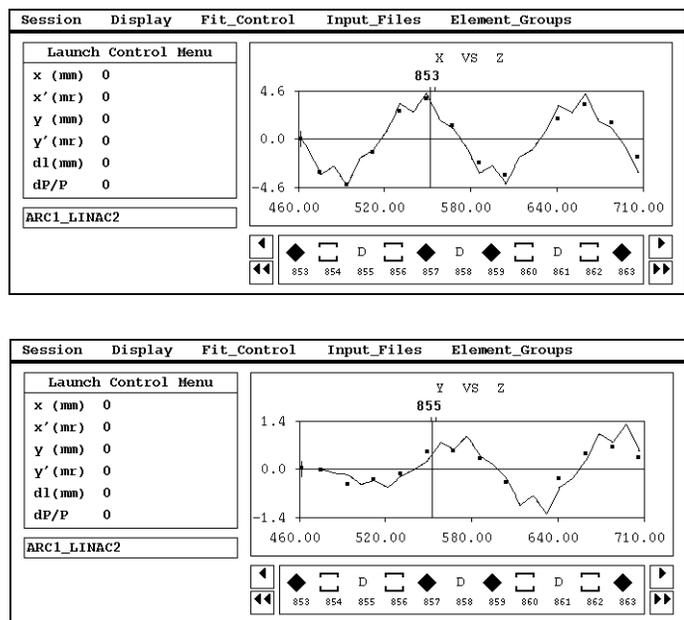


Figure 2. Fit of BPM data with model in S. Linac for the 1st pass beam. Phase advance per cell is set to 60 deg for this run.

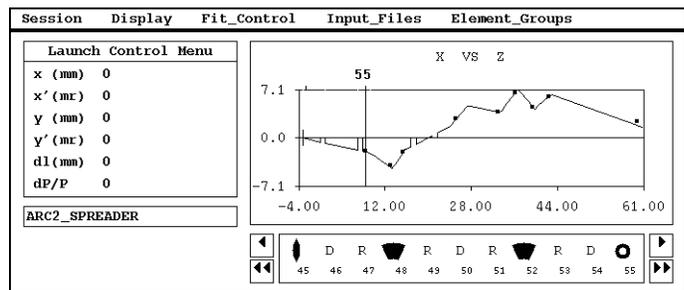


Figure 3. A difference orbit in 845 MeV Arc 2 spreader region.

BPM data in the Arc 1 shown in Fig. 4 clearly indicate that the vertical phase advance across the arc proper is more than the design value. RESOLVE finds that with a 2.7 % reduction in the strength of all 16 vertically focusing quadrupoles at the arc proper, the data agree well with our Arc 1 model as shown in the bottom figure of Fig. 4. Initially, we implemented this solution into the machine to correct arc optics and proceeded to the next Arc 2 expecting a similar optics problem. However, difference orbit data in Arc 2 proper agreed well with the Arc 2 model in both horizontal and vertical planes. This was a puzzle because Arc 2 appears optically almost identical to Arc 1. However, arc dipoles are not shimmed in general except in Arc 1. (All spreader and recombiner dipoles are shimmed.) In the 445 MeV Arc 1 beamline, an arc dipole is a 1-m long parallel faced magnet with a bending radius  $\rho = 5.10m$  and with a bending angle  $\theta = 11.25^\circ$ . With the nominal shimming, the angle of inclination  $\beta_1 = 5.625^\circ$  of the entrance face and the angle of inclination  $\beta_2 = 5.625^\circ$  of the exit face, the dipole is vertically focusing with an edge focal length  $f_y = 51.89m$ . As a result of shimming the beam following the reference trajectory now traverses the arc dipole with  $\beta_1 = \beta_2 = 7.165^\circ$ . An added edge focusing changes  $f_y$  to 40.65 m. One must compensate an extra phase advance introduced by reducing the strength of a vertically focusing quadrupole (with a nominal focal length  $f_q = 6.72m$ ) located next to the dipole. Consequently, we expect a change in  $f_q$  to 6.93 m which amounts to a 3.2% change, qualitatively explaining the discrepancy seen

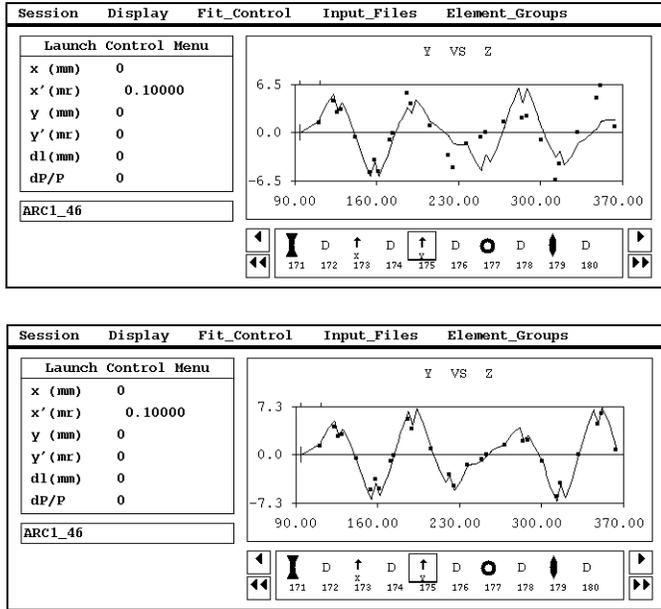


Figure 4. BPM data in Arc 1(top). The data fit nicely after vertical focusing correction(bottom).

between the model and data. The vertically focusing quadrupole family now has a strength in complete agreement with the value found with RESOLVE after DIMAD refitting Arc 1 optics with the shimmed dipoles.

### C. 60Hz Perturbations

When a pulsed beam was line synchronized, BPM data were collected through each section as a function of time delay from the AC zero crossing in order to identify distributed 60Hz perturbations[7]. To describe an algorithm employed to analyze data, we start by introducing the initial beam vector incoming to beamline  $R_0 = (x_0, x'_0, y_0, y'_0, \delta_0)$ , the BPM reading  $X = (x^{(1)}, x^{(2)}, \dots, x^{(m)})$  (We use only x readings for the simplicity of illustration.), and

$$M = \begin{pmatrix} M_{11}^{(1)} & M_{11}^{(2)} & \dots & M_{11}^{(m)} \\ M_{12}^{(1)} & M_{12}^{(2)} & \dots & M_{12}^{(m)} \\ \dots & \dots & \dots & \dots \\ M_{16}^{(1)} & M_{16}^{(2)} & \dots & M_{16}^{(m)} \end{pmatrix},$$

where  $x^{(i)}$  is the horizontal position at the  $i$ th monitor,  $M_{jk}^{(i)}$  is the transfer matrix from the start of the beamline to the  $i$ th monitor. These are related as  $X = R_0 M$ . A good fit requires terms upto the 3rd harmonic in the Fourier decomposition of 60Hz perturbed quantities. For example,

$$x(t) = x(0) + \sum_{n=1}^{n=3} [S_n \sin(2\pi n f_0 t) + C_n \cos(2\pi n f_0 t)],$$

where  $f_0 = 60\text{Hz}$ . Each element in the vectors  $X$  and  $R_0$  can be Fourier expanded yielding the vector coefficients  $S_{xn}$  and  $C_{xn}$  for the expansion of  $X$ , and  $S_{0n}$  and  $C_{0n}$  for the expansion of  $R_0$ . Assuming the transfer matrices are static, and using the orthogonality of sinusoidal functions, we get  $S_{xn} = S_{0n} M$ ,  $C_{xn} = C_{0n} M$

( $n=1,3$ ). This suggests that the propagation of the Fourier coefficients can also be treated by RESOLVE as difference orbits with respect to the time independent orbit (or the orbit averaging over time). Therefore, for each  $S_{xn}$  and  $C_{xn}$  ( $n=1,3$ ) a RESOLVE difference orbit can be obtained, and the incoming beam vector can be constructed by fitting  $S_{0n}$  and  $C_{0n}$ . A localized kick generated by a 60Hz field perturbation can be simulated as an additional  $\delta R = (0, \delta x', 0, \delta y', 0)$  at its location. One can decompose  $\delta R$  with coefficient vectors  $S_{\delta n}$  and  $C_{\delta n}$ . For a given  $n$ , the coefficients  $S_{\delta n}$  and  $C_{\delta n}$  behave just like kickers in the RESOLVE difference orbits for the corresponding  $S_{xn}$  and  $C_{xn}$ . As a consequence, we can quantify the distributed 60Hz kicks by resolving the difference orbits obtained from the coefficients of the frequency components of all the position monitors in the beamline.

As fully described in [7], a 60Hz kick of approximately 5 microradian in the path length adjusting “dogleg” region for the first pass was identified using RESOLVE. This is consistent with a measurement which shows that a malfunction in the dogleg magnet supplies generates ripple of approximately the same magnitude.

## V. ACKNOWLEDGEMENTS

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## References

- [1] M. Lee, “RESOLVE User’s Guide”.
- [2] R. Servranckx *et al.*, “Users Guide to the Program DIMAD,” SLAC report 285 (1985).
- [3] D. Douglas, private communication.
- [4] J. K. Ousterhout, *Tcl and the Tk Toolkit*, Addison Wesley Professional Computing Series (1994).
- [5] Z. Li, “Beam Dynamics in the CEBAF Superconducting Cavities,” Ph.D. thesis, The College of William and Mary, 1995.
- [6] M. G. Tiefenback, Z. Li, and B. C. Yunn, “Emittance Measurement and Transverse Cavity Transfer Matrix in the CEBAF Nuclear Physics Accelerator,” unpublished, 1993.
- [7] M. G. Tiefenback and R. Li, “Survey and Analysis of Line-Frequency Interference in the CEBAF Accelerator,” this conference.