

# **A Simulation Program to Study Longitudinal Phase Space Dynamics in CEBAF-ER/CD**

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## **Abstract**

An interactive and user-friendly simulation program has been developed to study longitudinal phase space dynamics in CEBAF. The program was created specifically to address the effects of the energy recovery and current doubling experiments on longitudinal dynamics. This note serves to document the program and introduce its main features. With a developed simulation program, expectations are that a more thorough analysis of the longitudinal dynamics will be presented in the near future.

## **Introduction**

With the recent approval by the Program Advisory Committee (PAC) to test energy recovery and current doubling in CEBAF, a simulation was developed to understand the dynamics of longitudinal phase space and address potential problems and/or areas of concern. The simulation was created in Igor Pro version 4. Igor Pro is a powerful data analysis software package with tremendous graphics capabilities. It also allows for implementation of a user-friendly interface for the manipulation and presentation of data.

This simulation is based on past programs used to model longitudinal phase space dynamics in the FEL driver. These simulations were based in Excel and are documented elsewhere [1].

## **Overview of the Simulation**

The way the simulation program works is quite simple. Based on the initial conditions supplied by the user (maximum energy spread  $\Delta E$ , bunch length  $\delta l$ , and bunch tilt  $r_{12}$ ), twelve points are calculated and used to create the initial or injected phase ellipse. This phase ellipse is then propagated through the various elements in CEBAF by transforming each point according to the type of element it is traversing. Since we are dealing with longitudinal dynamics only, we model CEBAF as a series of drifts, bends and impulsive energy kicks, while disregarding any focusing elements (dipole fringe fields, quadrupoles, higher-order poles, etc...). The simulation then provides phase space plots at various points of interest around the accelerator.

Igor Pro has the added advantage in that it has its own programming language. Therefore, unlike previous simulations based on spreadsheet manipulations, this simulation runs via a compiled code. This allows for greater flexibility and robustness in modeling an accelerator. For example, once the routines have been written for a drift, linac and bend, one only has to call the appropriate combination to model different machines or different conditions of the same machine. That is, it is a simple matter to go from modeling acceleration in the north linac and deceleration in the south linac (1-pass) to modeling energy recovery with 1-pass up/1-pass down (2-pass) or current doubling (3-passes).

## Details of the Simulation

The details of the simulation, such as specifics about the user-interface, algorithms, and graphical outputs follow. A screen shot of the most current version of the simulation is show in Figure 1. Please refer to this when reading the following sections. For those readers with the Igor Pro software, a copy of the Igor experiment can be opened from: <http://www.jlab.org/~tenant/CEBAF-ER/>

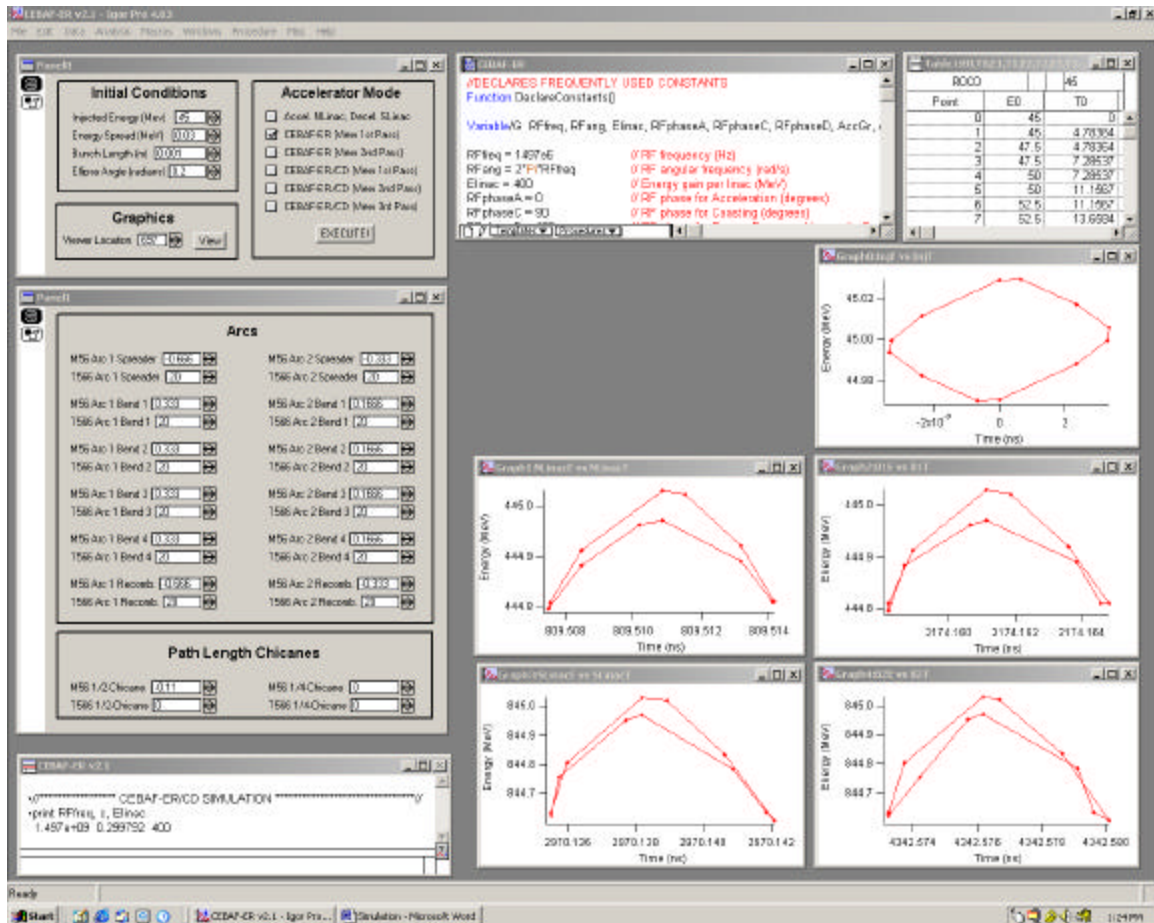


Figure 1: Screen shot of CEBAF-ER/CD simulation.

## I. Inputs and User-Interfaces

As was mentioned previously, Igor Pro provides for the use of a user-friendly interface to manipulate data. The user has control over the following list of parameters.

1. Initial/Injected Phase Space Ellipse:  
Using the control panel in the top, left corner entitled “Initial Conditions”, the user may specify appropriate values for the maximum change in energy  $\Delta E$ , bunch length  $\delta l$ , phase ellipse tilt  $r_{12}$ , and injected energy  $E_{inj}$ . Twelve points, which define the phase ellipse, are then computed. These points are subsequently propagated through the lattice. See Figure 2 for a visual interpretation of the points defining the phase ellipse.
2. M56 and T566 for Arc 1 and Arc 2  
For all the proposed phases of the CEBAF-ER/CD experiment, beam will only be traversing Arcs 1 and 2 [2]. Each arc was divided into six sections: a spreader region, four identical super-periods, and a recombiner region. Like the real machine, the M56 and T566 elements can be changed independently in each region. Although probably not a concern for energy recovery experiments, it may prove useful for future simulation studies to have independent control of these matrix elements for each region. This interface is the large, leftmost control panel labeled “Arcs”. (Note: when the user changes the value of any parameter in the control panels, all calculations, and consequently the graphics, are updated automatically to reflect the change).
3. M56 and T566 for Path Length Chicanes  
The simulation also allows the user to specify the M56 and T566 elements of the  $\lambda_{RF}/2$ - and  $\lambda_{RF}/4$ -path length chicane (depending on what experiment you are modeling – energy recovery or current doubling, respectively).
4. Accelerator Running Mode  
This convenient control panel is located in the top, leftmost corner of the window and labeled “Accelerator Mode.” By “checking” various checkboxes, the appropriate phase space plots for the selected experiment are calculated.
5. Command Window  
Although not an input interface, for those readers familiar with Igor, the command window is located on the bottom left of the screen. This window allows you to execute functions while bypassing Igor dialog boxes.

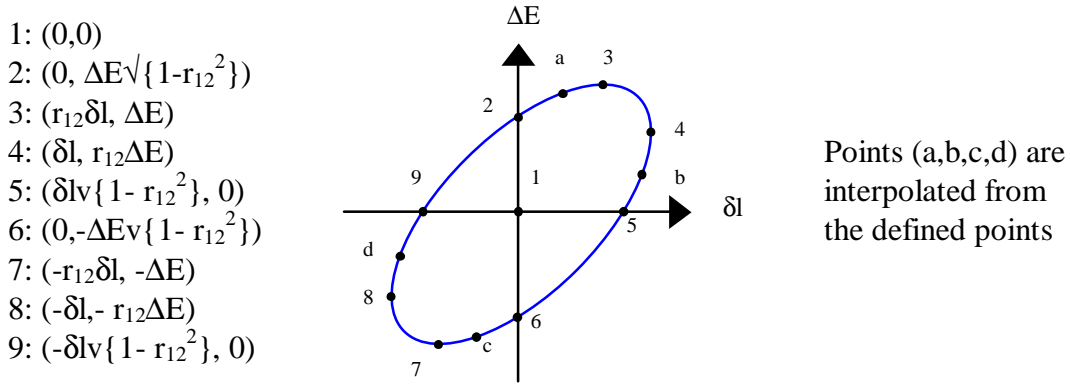


Figure 2: Initial phase ellipse defined by twelve points calculated from user input values

## II. Algorithms

To model CEBAF for the energy recovery and current doubling experiments, one needs to simulate the effects on phase space of traveling through the North Linac, Arc 1, the South Linac and Arc 2. Since we are interested in longitudinal dynamics, each of these subsections of CEBAF is created using a series of bends and drifts or accelerating kicks and drifts.

### 1. North Linac

The north linac provides a total of 25 slots for cryomodules, 20 of which are filled. A single cryomodule is 9.6m long measured from the center of the quadrupoles and is shown schematically in Figure 3. Within each cryomodule there are 8 accelerating cavities, each with a gradient of 2.5 MeV. Furthermore, each cavity consists of 5 cells. But for the sake of simplicity each cavity is modeled by a short drift, an impulsive (zero-length) energy kick, and followed by another short drift. This means that a synchronous particle gets accelerated (20x8) cavities/linac x 2.5MeV = 400 MeV per linac.

With knowledge of how a particle transforms in a drift and under the influence of an impulsive kick, the linac can be modeled quite accurately. The transform for a drift of length  $L_{drift}$ , is:

$$\begin{aligned} t^* &= t + L_{drift}/c \\ E^* &= E \end{aligned}$$

where  $(E,t)$  are the energy and time of the particle at the entrance of the drift and  $(E^*,t^*)$  are the energy and time at the exit of the drift. The electrons are assumed to be ultra-relativistic so that their velocity is the speed of light,  $c$ . An impulsive energy kick due to a cavity is given by:

$$t^* = t$$

$$E^* = E + E_{linac} \cos(\mathbf{w}_{RF}t + \mathbf{f}_{RF})$$

The amplitude  $E_{linac}$  is the full energy gain of a synchronous particle across the cavity with the nominal value of 2.5 MeV. For normal operation of CEBAF, particles are accelerated on crest and  $\phi_{RF}$  is 0. In CEBAF-ER mode, the second pass will have an RF phase of 180 degrees, while in the CEBAF-ER/CD mode the second pass beam will be coasting and will have an RF phase of 90 degrees. The RF phase is not a user-controlled variable, but rather a parameter that is passed in the function call for the north linac.

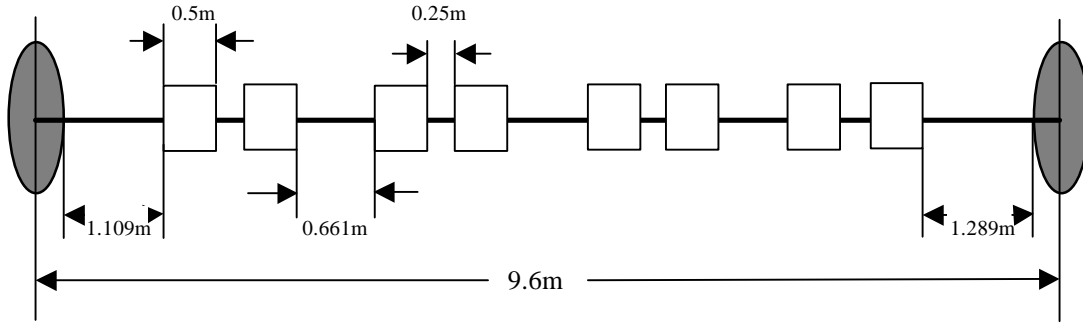


Figure 3: Schematic of a single cryomodule. (Based on an Optim file for north linac)

2. Arc 1

Arc 1 is subdivided into six separate bends to allow for the independent control of the compaction values in each region. The arc is divided into a spreader region, four super-periods and a recombiner region. An Optim file was used to get the correct path length for each bend, which is a parameter that must be specified in the code. The particle transformation for a bend of length  $L_{bend}$  is given as:

$$t^* = t + 1/c(L_{bend} + M_{56}d + T_{566}d^2)$$

$$E^* = E$$

where  $\delta$  is defined as the fractional energy,  $\Delta E/E$ . The user has complete control over the M56 and T566 values, although for CEBAF running in the ER and CD modes, the values will most likely be fixed to the design values due to the constraints of the optics.

3. South Linac

The south linac is modeled in almost the same manner as the north linac. But unlike the north linac whose accelerating modules are followed by a drift, the south linac contains the appropriate path length chicane ( $\lambda_{RF}/2$  or  $\lambda_{RF}/4$ ) and dump chicane in two of the vacant cryomodules following acceleration. The dump chicane will be used to remove the 45 MeV, energy recovered beam as quickly as possible after deceleration in the south linac and will be located in the 2L22 region. The effect of the dump chicane on the 845 MeV beam - whose phase space is under investigation - is negligible and is omitted in the simulation code. The path length chicane on the other hand, is modeled by using a bend of length  $\lambda_{RF}/2$  or  $\lambda_{RF}/4$  depending on whether CEBAF is in the ER or ER/CD mode, respectively. This “twin chicane” will be located in the 2L23 region [3]. As was mentioned earlier, the user has the ability to change the compaction values M56 and T566 of the path length chicanes.

4. Arc 2

Arc 2 is modeled in the same way as Arc 1. The only changes are the differences in the path lengths for each bending section, as can be verified by inspection of the appropriate Optim file.

### III. Outputs

As its output, the simulation produces five phase space plots at observation points for one pass through the accelerator. In addition, a spreadsheet containing the results of the element by element particle transformations is displayed.

1. Phase Space Plots

The five observation points at which phase space plots are displayed are: at injection, and at the exits of the north linac, arc 1, the south linac and arc 2. For those experiments requiring more than 1 pass in the accelerator, the phase space for each pass can be viewed separately using the “Accelerator Mode” control panel.

2. Spreadsheet Display

The spreadsheet containing all the transformation results is also displayed although it is used primarily for debugging rather than having any practical use for the user.

3. Graphics Interface

The control panel labeled “Graphics”, located in the top, left corner, is used to view the phase space at a location other than those locations already displayed by Igor. The value of “Viewer Location” is the row index of the spreadsheet.

## **Conclusions**

A simulation was developed to study the longitudinal phase space dynamics in the approaching CEBAF-ER and CEBAF-ER/CD experiments. This note serves as an introduction to, and documentation of, the program. The simulation has reached the point where it can effectively be used as an analysis tool and investigations into specific phases of the energy recovery and current doubling experiments will be forthcoming.

## References

- [1] D. Douglas, “Modeling of Longitudinal Phase Space Dynamics in Energy-Recovering FEL Drivers”, JLAB-TN-99-002
- [2] Bogacz, A., Benesch, J., Butler C., Chao Y., Chattopadhyay S., Dickson R., Douglas D., Guerra A., Hutton, A., Krafft G., Lauze R., May R., Meringa L., Neil G., Oren W., Spata M., Tennant C., Tiefenback M., White K., “CEBAF Energy Recovery Experiment”, PAC22 Proposal, 2002
- [3] *ibid*