ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAF021

START TO END SIMULATION OF THE CBETA ENERGY RECOVERY LINAC*

W. Lou, A. Bartnik, J. A. Crittenden, C. Gulliford, G. H. Hoffstaetter, D. Sagan
Cornell University, Ithaca NY, 14853
J. S. Berg, S. Brooks, F. Meot, D. Trbojevic, N. Tsoupas
Brookhaven National Laboratory, Upton NY, 11967

Abstract

CBETA is an energy recovery linac accelerating from 6 MeV to 150 MeV in four linac passes, using a single return line accepting all energies from 42 MeV to 150 MeV. We simulate a 6-dimensional particle distribution from the injector through the end of the dump line. Space charge forces are taken into account at the low energy stages. We compare results using field maps to those using simpler magnet models. We introduce random and systematic magnet errors to the lattice, apply orbit correction algorithm, and study the impact on the beam distribution.

INTRODUCTION

The Cornell Brookhaven Energy Recovery Linac Test Accelerator (CBETA) [1] is currently under construction at the Cornell Wilson Laboratory. CBETA will be the first Energy Recovery Linac (ERL) using Fixed Field Alternating Gradient (FFAG) magnets. The accelerator consists of a 1.3 GHz 80 MeV Linear accelerator and one recirculating beam line. Fig. 1 shows the layout of the CBETA with various labelled sections, including the Injector (IN), Linear accelerator (LA), Splitters (SX, RX), FFAG recirculating beamline (FA, TA, ZA, ZB, TB, FB) and the Beam Stop section (BS).

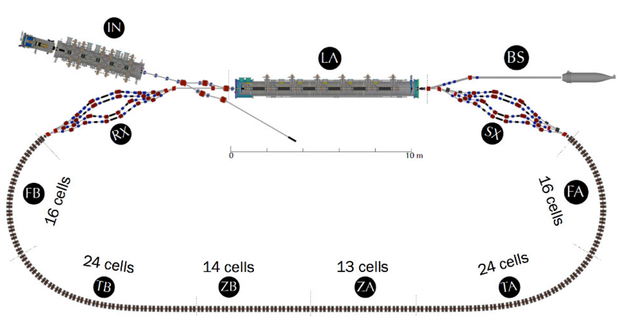

Figure 1: Layout of the CBETA accelerator. The section labeled (LA) is the ERL, The sections labeled (FA), (TA), (ZA), (ZB), (TB), and (FB) are the FFAG sections which will accommodate four recirculating orbits with an energy range from 42 MeV to 150 MeV.

The current design of CBETA aims to achieve maximum electron beam energy at 150 MeV. This will be accomplished by injecting 6 MeV bunches into the LINAC and accelerating each bunch by 36 MeV each time they pass through the ERL via the single recirculating FFAG beamline. After the bunches reach the top energy of 150 MeV, they are recirculated back into the LINAC, each time delivering 36 MeV of energy back to the LINAC until they reach the 6 MeV energy and be dumped at the beam stop.

The start to end simulation aims to study the 6D beam distribution through the CBETA design lattice. The main simulation program used to model CBETA is Bmad [2], developed by Cornell CLASSE. Bmad is an open source library for relativistic simulation of charged particles, allowing customized lattice design and optimization. Optics matching and orbit correction tolerance study are also carried out in Bmad. For the injector section, Bmad does not well simulate the space charge effect which dominates at low energy. Consequently, 3D space charge simulation code GPT (General Particle Tracker) is used to track particles up to 42 MeV. The beam distribution is then passed to Bmad and tracked throughout the entire 4-pass lattice. For this paper we will compare the GPT tracking results with the actual measurement of the beam distribution. Then we will show the tracked distribution at different stages of the lattice, and explain how optics are optimized for an acceptable distribution. Lastly we will show the result of orbit correction which indicates the lattice's tolerance under various random errors.

BEAM TRACKING WITH GPT

Like all the particle tracking programs, GPT requires an initial 6-dimensional beam distribution. The distribution in the X-Y position space can be directly measured at the beam source (Fig. 2). The temporal profile of a bunch pulse (charge v.s time) can also be measured. The distributions in the momentum space are assumed to be Gaussian, with the characteristic spreads known from the beam source specification. We assume no extra coupling between the phase space coordinates, and the 6D distribution is transported to GPT and ready to be tracked. Since the space charge effects dominates at low energy, we make GPT track the beam not only through the injector section (0 MeV to 6 MeV), but also up to the end of the LINAC (6 MeV to 42 MeV). Fig. 3 compares the tracked beam profiles with the actual measurement at the end of LINAC. The agreement is decent. Some might wonder why GPT tracking is necessary if we could just measure the beam profile at 42 MeV instead. The truth is that, we could only measure the projection of the

* This work was performed with the support of NYSERDA (New York State Energy Research and Development Agency).

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2018). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAF021

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2018). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

6D distribution onto certain planes (the ones in Fig. 3 for instance). Without tracking we could not know the many coupling terms between phase space coordinated. On the other hand, GPT tracking allows us to check the validity of the design lattice against the actual layout of CBETA.

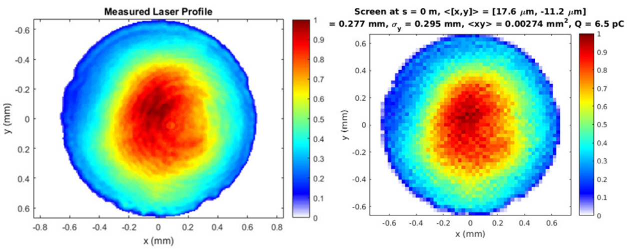

Figure 2: The left image is the measured beam profile in the X-Y position space at the beam source. The right image shows the corresponding transported beam profile in GPT ready to be tracked, with 20k macro-particles.

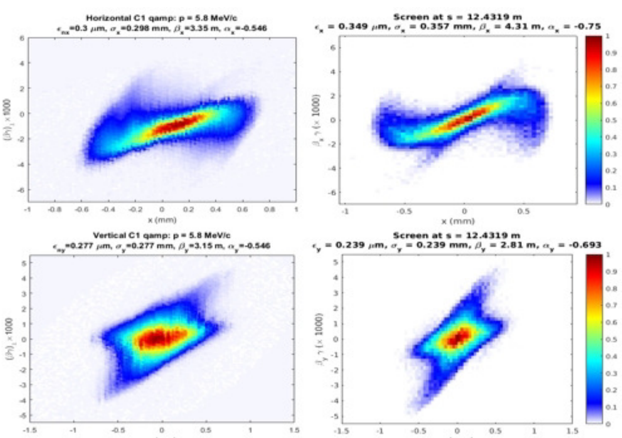

Figure 3: The left column shows the measured beam profiles (X-Y, X-PX, and Y-PY from top to bottom) at the end of the LINAC (42 MeV). The right column shows the corresponding results of GPT tracking, which well agree.

BEAM TRACKING WITH BMAD

The entire CBETA lattice has been developed using Bmad, and is still under minor modifications. The beam distribution tracked by GPT up to 42 MeV is passed to Bmad for further tracking. The optics and beam sizes of the CBETA 4-pass lattice are shown in Fig. 4. In the FFAG arc, both beta functions and dispersion are very small (typically below 2 m and 0.1 m respectively), and the transverse beam sizes remain small too, on the order of 0.1 mm. In the splitter sections, the beta functions and dispersion can go up to 50 m and 1 m respectively, and x beam size can reach 1 mm at the lower energy passes. The bunch length in the longitudinal direction remains mostly constant between 4 ps to 5 ps. To achieve isochronous acceleration, effort has been put into making the r_{56} contribution zero over each recirculation pass. This can be done by adjusting the quadrupole magnets at the splitter sections (SX and RX). However, these magnets are also used to match the optics into and out of the FFAG beamline, so finding a numerical solution can be difficult for certain passes. Fig. 5 shows longitudinal phase space of the tracked beam at the end of the LINAC at different recirculation passes. As shown in Fig. 4, the bunch length σ_z remains relatively constant. If the r_{56} values were not tuned to zero or sufficiently small values, σ_z would likely increase, and the distribution would become sheared and distorted. The relative spread in energy σ_δ remains approximately 0.003 until the distribution becomes distorted at end of the final (decelerating) pass. The distortion is acceptable since the beam will be dumped shortly after, no longer used to energy recovery.

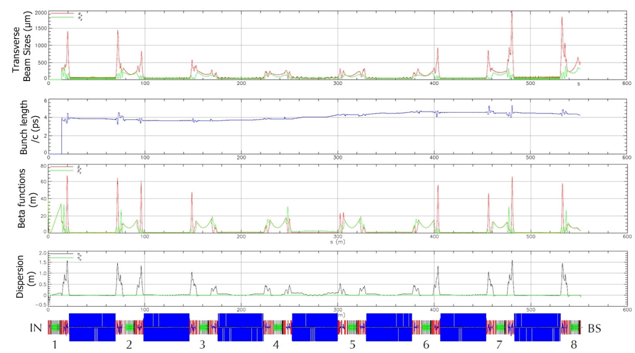

Figure 4: The beam sizes and optics of the CBETA 4-pass lattice. The five plots from top to bottom are: transverse beam sizes, longitudinal bunch length, transverse beta functions, dispersion, and the layout of the elements seen by the bunches. The green elements in the layout are the LINAC of different pass, indicated by the integers below. The blue elements are the FFAG beamline.

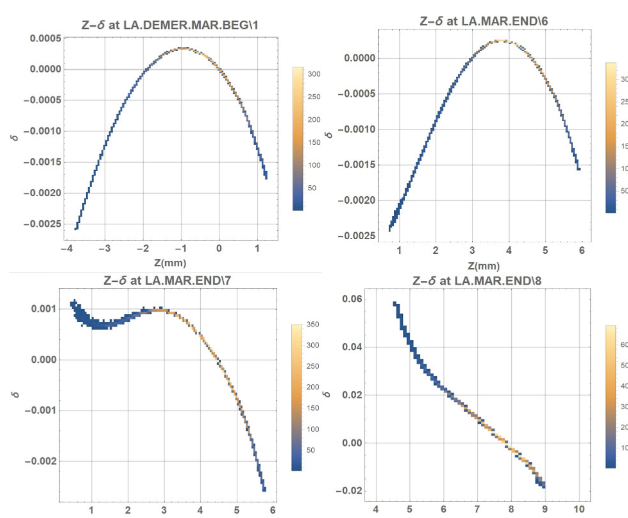

Figure 5: The longitudinal phase space distribution of the Bmad-tracked beam at the end of 1st (top left), 6th (top right), 7th (bottom left), and 8th (bottom right) LINAC pass. The images from 2nd to 5th pass look very similar to the 1st and 6th pass, and are not included for space constraint.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAF021

ORBIT CORRECTION AND FFAG TOLERANCE STUDY

All the tracking we have done so far assumes that the lattice parameters are ideal. In reality, random and systematic errors exist, and the most concerning ones are the positioning and field errors in the magnets. Orbit correction is therefore required to fix the particle trajectory (orbit) when errors are present. The goal of the tolerance study is to find at which magnitude of the error(s) the orbit correction can no longer recover the desired orbit or the beam profile. Unlike conventional accelerators which have one single orbit, CBETA has 4 coexisting design orbits in the FFAG beamline. This means any errors in the FFAG magnets would affect all four orbits, and any correction scheme must aim to fix them simultaneously. Fig. 6 shows how Bmad applies orbit correction on the first half of the FFAG beamline (FA, TA, ZA) to fix all 4 orbits subjected to random quadrupole gradient errors in the FFAG magnets.

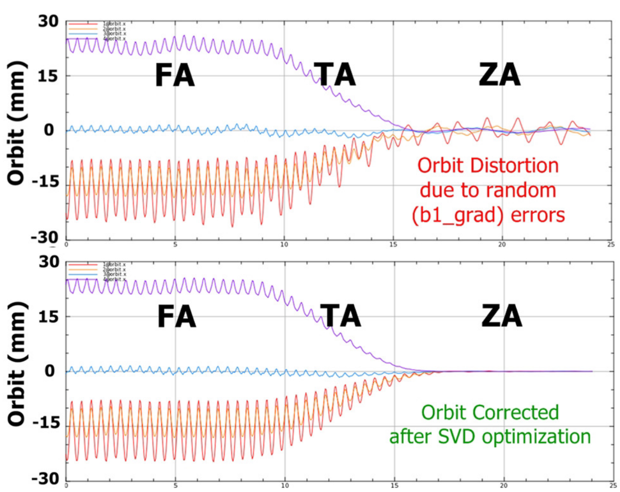

Figure 6: With random quadrupole errors introduced to the magnets, the four orbits in the first half of the FFAG beamline before (top) and after (bottom) orbit correction in Bmad. Clearly all four orbits are affected by the random errors and the correctors. The correction is successful since the design orbits are periodic at FA and zero at ZA.

Since FFAG is also the dominant beamline of CBETA, for now we perform tolerance study on the FFAG beamline only. Assuming all the magnets have a single type of random error, at what error magnitude would the transverse beam size or emittance of the tracked beam increase unacceptably after orbit correction is applied? The criterion we choose for "unacceptable" increase is when there is more than 10% growth in the 1σ value of either the transverse beam size or emittance at the end of the lattice (in this case, end of FB). We also define this limiting magnitude as the "individual limit" of this error. Fig. 7 shows how tolerance study is carried out in Bmad. For each random error type we run at least 100 simulations for the calculated limit to be statistically representative. Table 1 summarizes the individual limit of the main error types. In reality we need to include multiple

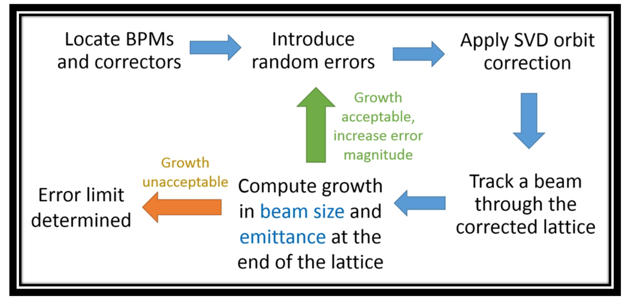

Figure 7: A schematic diagram showing how the individual limit of an random error type is determined in a tolerance study using Bmad.

Table 1: Individual Limit of the Primary Error Types in the FFAG Beamline

Gradient Error (Magnets)	0.27%
Multipole Errors (Magnets)	Available in [1]
X offset (Magnets)	0.5 mm
Y offset (Magnets)	> 0.5 mm
Tilt (Magnets)	6.5 mrad
X Reading Error (BPMs)	0.2 mm

error sources together and determine a physical "combined limit". This has been done for at least the multipole field errors in the FFAG magnets (up to 20-pole) [1]. Fortunately all the proposed CBETA parameters so far are within or capable of being inside these computed limits.

One important assumption of the tolerance study on the FFAG beamline only is that orbit distortions do not propagate from pass to pass. In other words, we have assumed that correctors in the splitter sections can individually fix each orbit before they enter the FFAG beamline. In reality this might not be achieved. More realistic tolerance simulations which include not just the FFAG beamline, but the entire CBETA 4-pass lattice, is currently in progress.

SUMMARY

The start to end simulation of CBETA aims to track a 6D particle distribution through the entire design lattice. To account for space charge effect at low energy, GPT is used to track the bunch up to 42 MeV, then Bmad is used to track until the end. Tracking is successful with no particle loss, and the beam sizes and bunch length stay within reasonable ranges. Tolerance study with multipass orbit correction has been performed on the FFAG beamline, and the individual limits of the primary error sources have been found reasonably above the actual specifications. Future simulations will include other physical effects, including micro-bunching, CSR, and wakefields.

REFERENCES

[1] G.H. Hoffstaetter, D Trbojevic *et al.*, *CBETA Design Report*, `https://arxiv.org/abs/1706.04245`

[2] D. Sagan, *Bmad Simulation Software* `https://www.classe.cornell.edu/bmad/`

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2018). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.