LINEAR ACCELERATOR SIMULATIONS WITH Bmad *

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Abstract

Bmad is a subroutine library for modeling relativistic charged-particle dynamics. It has been used extensively as a diagnostic tool at the Cornell Electron Storage Ring (CESR). The Bmad libraries have recently been extended to include modeling of the dynamics of linear accelerators. Calculations of emittance dilution due to orbit offsets and misalignments have been compared with LIAR, Merlin and PLACET. Good agreement is found with both particle and macroparticle tracking through the NLC and TESLA lattices for the bunch compressor, main linac and final focus regions.

INTRODUCTION

Bmad is a simulation tool originally developed for study of the Cornell Electron Storage Ring (CESR) [1]. Capable of simulating a wide variety of accelerator structures, the Bmad library provides a flexible and powerful platform for code development. It has been used for design of CESR optics and analysis of beam-based measurements in CESR [2]. The library has recently been expanded to enable linear collider simulations. Additions include implementation of macroparticle tracking, accelerating cavities, and longitudinal and transverse wakefields.

A variety of tests have been performed benchmarking Bmad with LIAR, the linac simulation tool used at SLAC [3]. Our comparison was motivated by a need to cross-check Bmad and was modeled on a similar comparison of results of the simulation codes LIAR, MERLIN, and MAD [4].

Two lattices — A TESLA and a NLC [5] lattice — were used for the comparisons. The TESLA lattice came from the TESLA TDR and is the same as was used in Ref. [4]. The NLC lattice was a newer version than used in Ref. [4] so the NLC results given cannot be directly compared with the results of Ref. [4]. Other lattice properties such as wakefields, initial beam parameters, etc., were the same as were used in Ref. [4].

DETAILS OF THE CALCULATIONS

To speed up the simulation, particles are lumped together into macroparticles. In Bmad, macroparticles are Gaussian in shape and are represented by a centroid position and a 6 x 6 σ matrix [1]. The macroparticle studies were performed with one bunch evenly divided in longitudinal position into 51 slices and each slice was evenly divided in energy into 11 equal charge macroparticles. The emittance of a beam of macroparticles is then calculated using the spread of the macroparticles about the beam centroid including the 6-D size of the macroparticles themselves.

In LIAR, longitudinal dynamics are ignored for speed and macroparticles are represented by a centroid position and a 4 x 4 σ matrix. When longitudinal dynamics are relevant, in the bunch compressor and beam delivery system, LIAR is used with the DIMAD [6] tracking option which converts the macroparticles into a collection of rays.

ACCELERATING CAVITY STUDY

To compare the treatment of transverse wakefields by Bmad and LIAR, the smallest unit of the acceleration system was studied: a single cavity. A single cavity was offset and a beam tracked through to examine the longitudinal position dependent deflection that the particles within the bunch receive due to the bunch's transverse wakefield. The NLC cavity used had a length of 0.9075 m and was offset by 1 mm transversely. The tracked beam had an energy of 7.87 GeV, a length of 110 μm and a charge of $0.75 \times 10^{10} e$. The resulting angle of deflection of the macroparticles as a function of their longitudinal position within the bunch is shown in Fig. 1, which indicates good agreement between Bmad and LIAR.

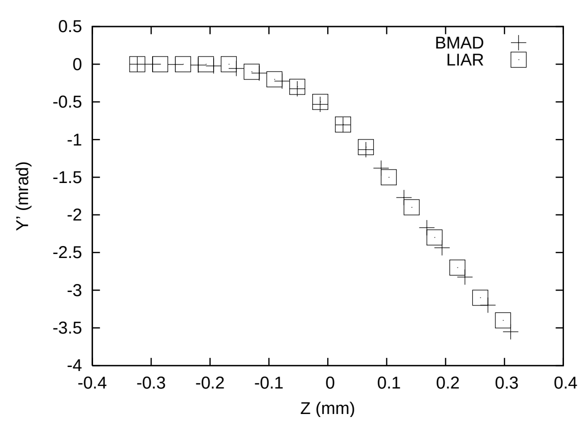

Figure 1: Macroparticle deflection along a bunch resulting from an offset NLC cavity with transverse wakefields.

BUNCH COMPRESSOR STUDY

We also compared Bmad and LIAR using the NLC and TESLA bunch compressors. The initial beam parameters used for the simulations are given in Table 1. The NLC bunch compressor was simulated with longitudinal and

* Work supported by the United States Department of Energy and the United States National Science Foundation.

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Table 1: Initial Bunch Compressor Beam Parameters

Parameter	Unit	NLC	TESLA
σ_z	mm	5.00	6.00
σ_δ	%	0.10	0.13
Energy	GeV	1.98	5.00

Table 2: Results of Bunch Compressor Simulations

NLC			
Parameter	**Unit**	**Bmad**	**LIAR**
σ_z	mm	0.126	0.102
σ_δ	%	1.350	1.420
Energy	GeV	7.779	7.884
TESLA			
Parameter	**Unit**	**Bmad**	**LIAR**
σ_z	mm	0.291	0.284
σ_δ	%	3.070	3.180
Energy	GeV	4.595	4.596

transverse wakefields and the TESLA bunch compressor was simulated with no wakefields after it was determined they had negligible effect on the final beam parameters.

The results for bunch length, energy spread, and energy at the end of the bunch compressor are shown in Table 2 and indicate good agreement between the longitudinal dynamics models used in Bmad and LIAR with DIMAD.

MAIN LINAC STUDY

Several simulations were performed tracking a beam with the initial conditions described in Table 3 through the NLC and TESLA main linacs. An initially on-axis beam was tracked from start to end of the main linac and Bmad and LIAR results for final energy, energy spread, and horizontal and vertical beam sizes are shown in Table 4.

This simulation was repeated with the beam offset in the vertical direction by an amount equal to the initial vertical beam size as given in Table 3 to study the emittance dilution from short-range transverse wakefields in the main linac. The vertical normalized emittance growth due to this offset is plotted over the length of the NLC main linac in Figure 2 and the TESLA main linac in Figure 3, and the value at the end of the main linacs is shown in Table 4.

Table 3: Initial Main Linac Beam Parameters

Parameter	Unit	NLC	TESLA
Energy	GeV	7.87	4.60
σ_δ	%	1.28	3.00
σ_z	mm	0.110	0.300
Charge	$10^{10}e$	0.75	2.0
$\gamma\epsilon_x$	μm	3.0	8.0
$\gamma\epsilon_y$	nm	20.0	20.0
$1 \times \sigma_y$ offset	μm	1.9	10.2
dP_z/d_z	m^{-1}	-67.27	0.00

Table 4: Results of Main Linac Simulations

NLC			
Parameter	**Unit**	**Bmad**	**LIAR**
Energy	GeV	250.2	250.1
σ_δ	%	0.250	0.263
σ_x	μm	18.6	19.3
σ_y	μm	0.73	0.70
$\delta\gamma\epsilon_y$, $1 \times \sigma_y$ offset	nm	19.0	19.9
TESLA			
Parameter	**Unit**	**Bmad**	**LIAR**
Energy	GeV	251.302	251.282
σ_δ	%	0.078	0.076
$\delta\gamma\epsilon_y$, $1 \times \sigma_y$ offset	nm	4.24	4.44

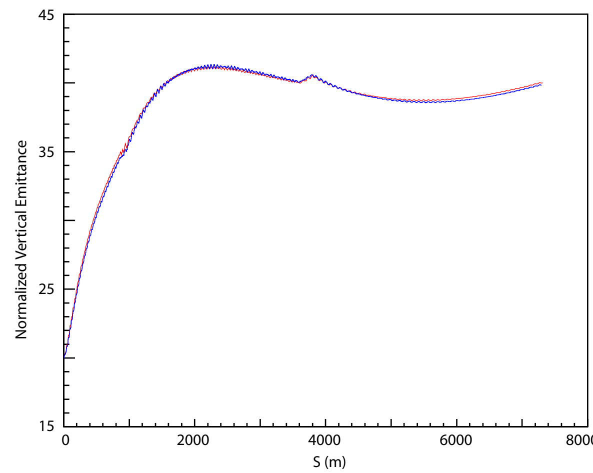

Figure 2: Vertical normalized emittance growth in the NLC main linac resulting from an initial vertical beam offset equal to the injected beam size.

Another set of main linac simulations was conducted following the beam to the interaction point. The final beam size, centroid position and emittance growth of an initially on axis beam are shown in Table 5. The emittance growth and beam size for a bunch initially offset in the vertical direction are also shown in this table. Agreement is seen in results from Bmad and LIAR/DIMAD which validates the codes' handling of the wakefields in the main linac as well as the longitudinal dynamics in the beam delivery system.

Additionally, the final beam energy as a function of the bunch charge was determined by tracking through the main linac to the interaction point for the NLC, and good agreement was found thus confirming the longitudinal wakefield simulations of Bmad and LIAR.

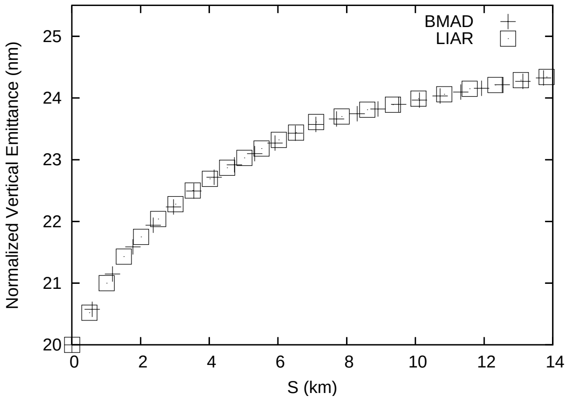

Figure 3: Vertical normalized emittance growth in the TESLA main linac resulting from an initial vertical beam offset equal to the injected beam size.

Table 5: Results of Main Linac to IP Simulations

Parameter	Unit	Bmad	LIAR
NLC			
σ_x^*	nm	215	225
σ_y^*	nm	1.87	1.90
x^*	nm	-15.8	-19.8
y^*	pm	0.0	-7.6
$\delta\gamma\epsilon_x$	μm	0.1	1.13
$\delta\gamma\epsilon_y$	nm	0.21	0.70
σ_y^*, $1 \times \sigma_y$ offset	nm	2.51	2.51
$\delta\gamma\epsilon_y$, $1 \times \sigma_y$ offset	nm	16.0	16.3
TESLA			
Parameter	**Unit**	**Bmad**	**LIAR**
σ_x^*	nm	499	504
σ_y^*	nm	4.24	4.21
x^*	nm	-4.2	30.4
y^*	pm	-0.1	-5.4
$\delta\gamma\epsilon_x$	μm	0.14	0.21
$\delta\gamma\epsilon_y$	nm	0.21	0.20
σ_y^*, $1 \times \sigma_y$ offset	nm	4.71	4.68
$\delta\gamma\epsilon_y$, $1 \times \sigma_y$ offset	nm	7.68	7.80

BEAM DELIVERY SYSTEM STUDY

A final comparison between Bmad and LIAR (with DIMAD) was made by measuring the bandwidth of the NLC Beam Delivery System (BDS). A bandwidth study uses a monochromatic beam to examine the compensation of nonlinear properties of the BDS and answer the question "How far off-energy does a particle have to be before it starts sampling the nonlinear behavior of the BDS?"[7] The goal of this study was to compare Bmad and LIAR/DIMAD's handling of the nonlinear behavior of the BDS.

Using a beam (initial conditions specified in Ref. [4]) with an extremely small 0.0001% energy spread, the beam energy was varied between 247.5 and 252.5 GeV, and the

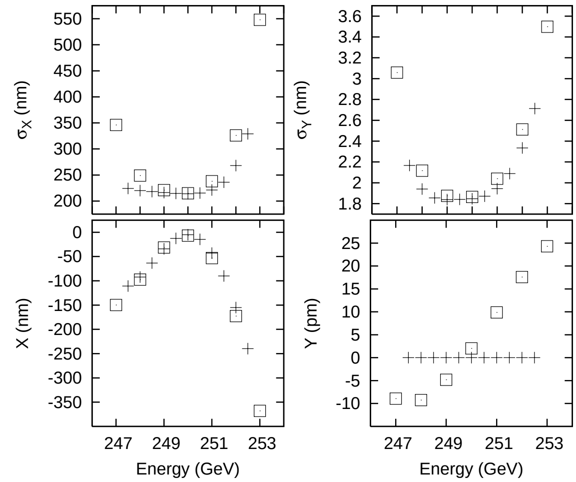

Figure 4: Impact of NLC BDS nonlinearities on off-energy beam parameters. Cross = Bmad, Box = LIAR/DIMAD.

final beam sizes and position were studied. The Bmad and LIAR/DIMAD results are shown in Figure 4 and agree well. Note that the discrepancies in the plot of centroid y position are at the level of tens of picometers and thus negligibly small.

CONCLUSION

We have demonstrated that the Bmad model of linear accelerating structures and guide fields includes all of the essential physics. These results can be compared with those produced by Schulte *et al.* to show good agreement between all four simulation codes: Bmad, LIAR, MERLIN, and MAD. Following the work presented here, linear acclerator simulations with Bmad have been used to investigate beam-based alignment algorithms for the ILC [8].

REFERENCES

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