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Comparison of Different Tracking Codes for Beam Delivery Systems of Linear Colliders

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COMPARISON OF DIFFERENT TRACKING CODES FOR BEAM DELIVERY SYSTEMS OF LINEAR COLLIDERS

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Abstract

The vertical RMS spot sizes at the interaction point of linear colliders are in the 1 nm to 5 nm range at beam energies from 0.25 TeV to 1.5 TeV. Numerical tracking of particles through the magnetic focusing systems is used for the design and the performance prediction of the magnetic systems. In view of the small spot sizes and the high beam energies, it is important that the numerical codes include a careful treatment of the chromatic magnet properties and an accurate modelling of synchrotron radiation. Significant differences in the results of various codes have been observed and some fixes have been applied. In order to establish a basis for future simulations, the results of various tracking and modelling codes are compared for identical input.

1 INTRODUCTION

Future linear colliders are designed to focus electron and positron beams down to the nanometer scale in order to achieve high luminosity. For the projects presently under study, the vertical beam sizes at the Interaction Point (IP) range between 1 nm and 5 nm at energies from 0.25 TeV to 1.5 TeV. There is currently no high-energy facility suitable to test the ultimate luminosity performance of the future linear collider. Therefore, the study of the machine performance must rely on the simulations of tracking codes. Several simulation codes for linear colliders have been developed in different laboratories throughout the world. Here, the results of the comparison of five codes is presented. The code comparison is intended to give confidence on the simulation results and a basis for future studies and design work. The work has been done with the joint effort of CERN, DESY and SLAC.

As a case study, the beam delivery system (BDS) of the Compact LInear Collider (CLIC) is considered [1]. The same particle distributions are tracked through the BDS with the different programs. Horizontal and vertical beam sizes at the interaction point are used as parameters to compare the simulation results. The case of a perfect machine (no misalignments of the magnets) has been considered. Bunches with and without energy spread and synchrotron radiation have been tracked.

2 SIMULATION CODES

Five tracking codes have been compared: `MAD` [2], `DIMAD` [3], `Merlin` [4], `Placet` [5] and `BDSIM` [6].

- `MAD` [2] is a general all purpose simulation code. Tracking is performed using the transport formalism [7].
- The program `DIMAD` [3] tracks trajectories of the particles according to the second order matrix formalism. `DIMAD` does not provide synchrotron motion analysis but can simulate it. Release 2.8, available from the NLC web-site [8], has been used.
- `Merlin` is a `C++` class library for performing charged particle accelerator simulations [4]. It was originally developed at DESY for the simulations of linear collider beam dynamics and then extended to include storage rings physics.
- `Placet` is a tracking program originally conceived for the linac simulations [5]. Recently it has been upgraded to included high order multipoles and synchrotron radiation and used for the simulations of a whole linac and beam delivery systems. See also [9].
- `BDSIM` is a new accelerator tracking code based on Geant4, that combines fast accelerator-style tracking in the beam pipe with traditional Geant-style tracking in materials. More detail can be found in [6].

3 THE CLIC BEAM DELIVERY SYSTEM

The beam line used for the code comparison is shown in Fig. 1. This is the design of the CLIC Beam Delivery System first presented in [1]. It contains both the collimation system and the final focus, for a total length of about 6.2 km. This beam line contains about 80 quadrupoles and 16 sextupoles. It has been optimised for a 1.5 TeV energy beam. Horizontal and vertical beta functions at the IP are of 8 mm and 0.15 mm, resulting in an ideal beam size of 43 nm $\times 1$ nm. Note that the optics used for the code comparison is not the final design proposed for CLIC. A shorter beam delivery system is presented in the companion paper [11].

4 SIMULATION SETUP

The properties of the bunches to be tracked though the CLIC BDS are listed in Table 1 (see [9] for the most recent

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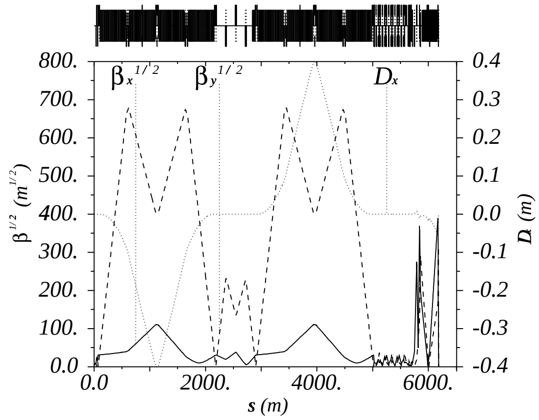

Figure 1: Layout of the CLIC beam Delivery System used for the code comparison. A shorter BDS design for CLIC is presented in [11].

results on the CLIC linac simulations). The bunches were generated with Matlab routines in formats suitable for the different programs. The same seeds for the random number generators were used in the various cases in order to track exactly the same particle distributions with all programs. Two values of the normalised vertical emittance have been considered, *i.e.* $10\,\mathrm{nm}$ and $20\,\mathrm{nm}$. The energy spread is a square distribution with a 1% full width.

Table 1: Beam parameters at the entrance of the beam line used to generated the particle distributions to be tracked. The particle energy is a square distribution with a full width of $1\,\%$.

Parameter	Symbol	Value
Energy	E	$1500\,\mathrm{GeV}$
Energy spread (full width)	$\Delta E/E$	$1\,\%$
Hor. beta functions	β_x	$65\,\mathrm{m}$
	α_x	0
Vert. beta functions	β_y	$18\,\mathrm{m}$
	α_y	0
Hor. norm. emittance	$\gamma\epsilon_x$	$680\,\mathrm{nm}$
Vert. norm. emittance	$\gamma\epsilon_y$	$10/20\,\mathrm{nm}$
Bunch length	σ_z	$30\,\mu m$

Horizontal and vertical beam sizes at the interaction point are the parameters used to compare the codes. They are calculated as the RMS values of the particle distributions. Five bunches of 20000 particles with the properties of Table 1 have been tracked. The average beam sizes are then calculated and the errors estimated as the standard deviation of the $N = 5$ available values multiplied by $1/\sqrt{N-1} = 0.5$. Simulations have been done for a perfect machine (no misalignment of the beam line magnets). For two values of $\gamma\epsilon_y$, the cases with and without energy spread were considered. For the latter case, synchrotron radiation in all the elements of the beam line (dipoles, quadrupoles and sextupoles) has also been included in the simulations.

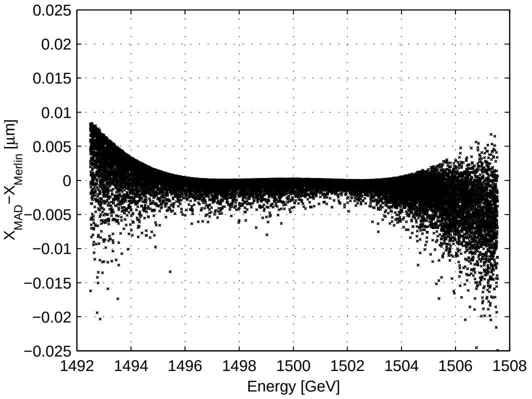

Figure 2: Difference of the horizontal particle position at the end of the BDS versus particle energy, as calculated by `Merlin` and `MAD`.

5 RESULTS OF THE SIMULATIONS

The tracking results are summarised in Tables 2 and 3 for the cases of $\gamma\epsilon_y = 10\,\mathrm{nm}$ and $\gamma\epsilon_y = 20\,\mathrm{nm}$, respectively. A good agreement between the results of the different codes is found when the synchrotron radiation emission is not considered (first and second columns). The differences of the beam sizes are within the error bars (three sigmas). The largest discrepancies are found for the horizontal beam size for bunches with energy spread. In particular, with `MAD` slightly larger values for σ_x are found. The absolute differences do not exceed $0.4\,\mathrm{nm}$ (horizontal plane). Fig. 2 gives the difference of the horizontal particle positions at the IP as calculated with `MAD` and `Merlin`. Maximum differences up to about $30\,\mathrm{nm}$ are found for particles with large energy offset. The data standard deviation is $3\,\mathrm{nm}$. On the other hand, if `DIMAD` and `Merlin` are compared, differences up to $16\,\mathrm{nm}$ and a standard deviation of $1\,\mathrm{nm}$ are found.

When the synchrotron radiation is considered, differences up to $2.3\,\mathrm{nm}$ and $0.4\,\mathrm{nm}$ are found for the horizontal and vertical beam sizes, respectively. The codes considered use different models for synchrotron radiation simulations. The implementation in `MAD` is described in [12]. To account for energy losses due to photon emission, the beam is re-accelerated after each element such that it keeps the nominal mean energy and is matched with the downstream lattice. On the other hand, `Placet`, `Merlin` and `BDSIM` implement the Monte Carlo generator of [13] and re-scale magnet strengths to match the actual beam momentum, as in a real machine. `DIMAD` simulations have been performed using the “option 11” [3], which includes synchrotron radiation in all the elements of the beam line for each beam particle, according to the model of [14]. This option does not include compensation for the energy losses.

From the above, it is therefore not possible to compare directly the results obtained with the different programs. Differences of the beam sizes up to 4% in the horizontal direction and up to 20% in the vertical direction are found. `Merlin` and `Placet`, which implement the same model for the synchrotron radiation simulations, show indeed a better agreement than with the other programs. The larger dif-

Table 2: Horizontal and vertical beam sizes at the end of the beam line of Fig.1 as calculated with `MAD`, `DIMAD`, `Merlin` `Placet` and `BDSIM` for the case $\gamma\epsilon_x = 680\,\mathrm{nm}$, $\gamma\epsilon_y = 10\,\mathrm{nm}$.

Horizontal beam sizes			
	No ΔE - No SR	ΔE/E=1% - No SR	ΔE/E=1% - SR
`MAD`	42.96 nm±0.09 nm	48.34 nm±0.07 nm	60.24 nm±0.27 nm
`DIMAD`	42.96 nm±0.09 nm	48.10 nm±0.05 nm	61.23 nm±1.98 nm
`Merlin`	42.93 nm±0.09 nm	47.98 nm±0.06 nm	59.20 nm±0.25 nm
`Placet`	42.93 nm±0.07 nm	47.97 nm±0.05 nm	58.92 nm±0.15 nm
`BDSIM`	42.96 nm±0.10 nm	48.06 nm±0.11 nm	59.33 nm±0.13 nm
Vertical beam sizes			
`MAD`	0.715 nm±0.001 nm	0.90 nm±0.01 nm	1.57 nm±0.03 nm
`DIMAD`	0.715 nm±0.001 nm	0.91 nm±0.01 nm	1.78 nm±0.02 nm
`Merlin`	0.715 nm±0.001 nm	0.92 nm±0.01 nm	1.49 nm±0.06 nm
`Placet`	0.715 nm±0.001 nm	0.91 nm±0.01 nm	1.51 nm±0.02 nm
`BDSIM`	0.716 nm±0.002 nm	0.93 nm±0.02 nm	1.75 nm±0.03 nm

Table 3: Vertical beam sizes at the end of the beam line of Fig.1 as calculated with `MAD`, `DIMAD`, `Merlin` `Placet` and `BDSIM` for the case $\gamma\epsilon_x = 680\,\mathrm{nm}$, $\gamma\epsilon_y = 20\,\mathrm{nm}$.

Vertical beam sizes			
	No ΔE - No SR	ΔE/E=1% - No SR	ΔE/E=1% - SR
`MAD`	1.012 nm±0.001 nm	1.28 nm±0.02 nm	2.30 nm±0.04 nm
`DIMAD`	1.012 nm±0.001 nm	1.30 nm±0.02 nm	2.64 nm±0.09 nm
`Merlin`	1.012 nm±0.001 nm	1.30 nm±0.02 nm	2.20 nm±0.07 nm
`Placet`	1.012 nm±0.001 nm	1.30 nm±0.02 nm	2.25 nm±0.05 nm
`BDSIM`	1.013 nm±0.003 nm	1.33 nm±0.03 nm	2.44 nm±0.03 nm

ferences found with `BDSIM` are under investigation. Larger values are also found with `DIMAD`, maybe because the used option does not compensate for the energy losses and as a consequence the beam-lattice match is lost. Note that the beam sizes calculated as RMS of particle distributions are very sensitive to the position of the few tail particles. Comparisons of true luminosity performances are expected to agree better.

6 CONCLUSIONS

The results of the joint effort of CERN, DESY and SLAC to compare tracking codes for linear collider simulations have been reported. `MAD`, `DIMAD`, `Merlin`, `Placet` and `BDSIM` have been compared using the CLIC beam delivery system. The programs are in good agreement for the simulations of a perfect machine without synchrotron radiation. Minor differences appear when the energy spread is taken into account. Differences of the beam sizes as calculated with synchrotron radiation are up to 4% in the horizontal plane and up to 20% in the few nanometer vertical size (*e.g.*, $1.5 \pm 0.3\,\mathrm{nm}$). The small differences are attributed to the different models used.

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