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COMPARATIVE ASSESSMENT OF SIMULATION TOOLS FOR BEAM DELIVERY SYSTEMS OF LINEAR COLLIDERS

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Abstract

In this paper, simulation codes for Beam Delivery Systems in linear colliders are discussed. Several tracking codes are available for particle tracking. They do not normally include precise calculation of the beam-beam effect, with accounting for pinch, hour-glass, pair production. They provide instead the particle distributions at the interaction point, after tracking through the different components of the linear collider. Other simulation programs must be used to compute precisely the beam-beam interaction. The traditional approach is to use the output bunches from the tracking codes as input for the beam-beam programs. Several tools suitable for advanced luminosity studies are presented. The use of these codes is put into perspective, treating in detail the example of the Compact LInear Collider (CLIC) beam delivery system (3 TeV option).

1 INTRODUCTION

All projects of future linear collider aim at high luminosity, from $0.5\times10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ to $1.0\times10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, for beam energies from 0.25 TeV to 1.5 TeV. Very small beam sizes are required to achieve such luminosity performance. In particular, the aimed vertical RMS spot sizes must be in the 1 nm to 5 nm range. As no test facility is presently available to prove experimentally the feasibility of these parameters, realistic predictions of the machine performance must fully rely on measured component stability and on advanced simulation codes for particle tracking and luminosity calculation. The comparison of different codes is useful to assess the confidence in the simulation results.

In this paper, several tools available for luminosity studies for linear colliders are presented and compared. As a case study, the beam delivery system of the Compact LInear Collider (CLIC) is treated in detail. This work continues and completes the results presented in [1]. In Section 2, an overview of the considered codes is given. In Section 3 the parameters of the CLIC lattice are listed and the simulation set up is described. Section 4 shows some examples of the tracking results, in terms of particle distribution at the IP. In Section 5 and Section 6, a detailed comparison of beam sizes and luminosity performance as calculated with the various codes is given. Then, in Section 7 some conclusions are drawn.

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2 SIMULATION CODES

Four codes for particle tracking through Beam Delivery Systems (BDS) of linear colliders have been considered: `MAD` [3], `DIMAD` [4], `Merlin` [5], `Placet` [6].

- `MAD` is a general all purpose simulation code developed at CERN [3]. The version 8 was used. Tracking is performed using the *Transport formalism* [7].
- The program `DIMAD` [4] tracks trajectories of the particles according to a second order matrix formalism similar to *Transport*. `DIMAD` can simulate synchrotron like `MAD`. Release 2.8, available from the SLAC website [8], has been used.
- `Merlin` is a `C++` class library for performing charged particle accelerator simulations [5]. It was developed at DESY for the simulations of linear collider beam dynamics but is also used for simulation of storage ring physics. `Merlin` performs tracking using first- and second-order transport matrices for quadrupoles and sextupoles. Higher order multipoles are treated as thin lenses (kick applied in the middle of the magnet).
- `Placet` is a tracking program originally conceived for linac simulations [6]. Recently it has been upgraded to include high order multipoles and synchrotron radiation and was used for the simulations of a whole linac and beam delivery system. It can handle both a ray and a macroparticle description of the beam; see also [9].

All the above programs provide six-dimensional particle distributions at the IP, but do not perform detailed beam-beam calculations. In order to include the relevant effects of the beam-beam interaction, such as hour-glass, pinch, beamstrahlung and e^+e^- production, the tracking programs have been interfaced with `GuineaPig` [10]. This programs provides a full simulation of the two beam interaction at the IP, including all the mentioned effects. The interface between the tracking codes and `GuineaPig` has been done off line. The only exception is `Merlin` (`Linux` version), which can invoke directly `GuineaPig` via a series of scripts. (Similar simulations have also been setup at SLAC [11]).

Even though in this paper the attention has been focused on beam delivery systems only, it should be mentioned that the above programs can be used also for linac simulation. Some results on the code comparison for full linac simulations can be found in [16]. Synchrotron radiation was not

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included in this comparison. DIMAD has been nicely interfaced with LIAR, a program for the linac tracking [12], and GuineaPig for IP simulations. All codes have been implemented into the commercial program MatLab [13, 14]. A similar interface has also be done for Merlin (see, for instance, [15]). The obtained programs are called MatLIAR and MatMerlin, respectively, and are particularly useful for simulations with feedback systems, implemented with built-in packages of MatLab. Placet is fully integrated in the TCL language and is potentially suitable for similar implementations. These features have not been used in the work presented in this paper.

3 CLIC BEAM DELIVERY SYSTEM AND SIMULATION SETUP

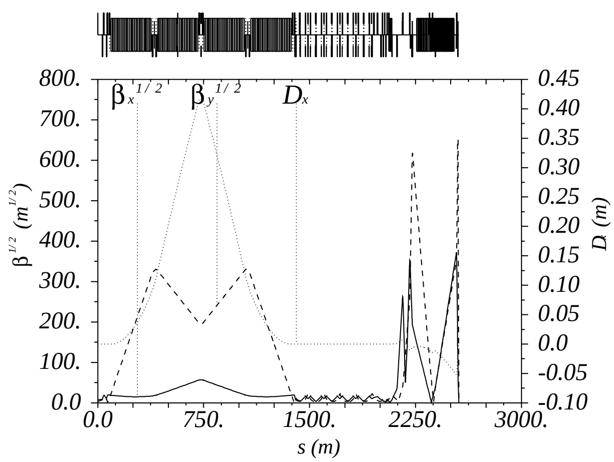

Figure 1: Layout of the present design of the CLIC beam delivery system. See [19, 20] for more details.

The beam line used for luminosity calculations and for comparing the simulations codes is shown in Fig. 1. The latest design of the CLIC beam delivery system has been considered. This is a Raimondi-like compact design [24] and was first presented at LC02 [18]. More details about it can be found in [19] and in these proceedings [20]. This lattice contains both the final focus telescope and the collimation system. It has about 60 quadrupoles, 11 sextupoles and two octupoles. The main parameters of the beam at the BDS entrance are listed in Table 1.

The main differences with respect to the old design, previously used for comparing tracking codes [1], are the following: (1) The system is considerably shorter, 2.55 km instead of 6.2 km. This improvement was obtained mainly with a reduction of the collimation system. The final focus section is instead unchanged. (2) The vertical normalized emittance at the entrance of the beam line is 10 nm instead of 20 nm. (3) The beta functions at the IP calculated from the linear optics are smaller than before. The new values are β_x=6 mm and β_y=0.07 mm instead of 8 mm and 0.15 mm, respectively.

Particle distributions respecting the nominal beam parameters of Table 1 were tracked through the CLIC BDS with each code. The output bunches were then used for computing the luminosity with GuineaPig. The various programs require different input formats. In order to obtain a homogeneous set of data to be compared, exactly the same sets of particle distributions and initial coordinates were used for each code.

Table 1: Some beam parameters at the entrance and at the IP of the CLIC BDS of Fig. 1. The energy spread is a square distribution with a 1% full width. The given beam sizes at the IP are the theoretical values calculated as $\sqrt{\epsilon_i \beta_i^*}$.

	BDS entrance	
Beam energy	E	1500 GeV
Energy spread	$\Delta E/E$	1 % (FW sq. dist.)
Hor. beta functions	β_x	64.171 m
	α_x	-1.95 m
Ver. beta functions	β_y	18.000 m
	α_y	0.61 m
Normal. emittances	ϵ_x	680 nm
	ϵ_y	10 nm
Bunch length	σ_z	35 μm
	Interaction Point	
Beta functions	β_x^*	6 mm
	β_y^*	0.07 mm
Theoretical beam sizes	σ_x	37.28 nm
	σ_y	0.49 nm

Five sets of 50000 particles were tracked. In order to obtain reliable luminosity results with GuineaPig. For each particle set, the beam sizes and the luminosity were calculated. In the following, the average of all sets will be considered. An estimate of the error on beam sizes and luminosity was obtained as the standard deviation of the five sets divided by $\sqrt{N-1}$=2, where N=5 is the number of sets. The cases of perfect bunches and of bunches with an energy spread were considered. For the latter synchrotron radiation emission in dipoles, quadrupoles and sextupoles was optionally included in the simulations.

The considered programs use different models for the synchrotron radiation. MAD uses the model of [21] and accounts for energy losses due to photon emission by artificially re-accelerating the beam after each element. So the beam maintains the nominal mean energy and is always matched with the downstream lattice. DIMAD features several options for the synchrotron radiation. The so-called “option 11” was used. It implements the routine described in [23] and does not account for the beam energy losses. Both Merlin and Placet use the Monte Carlo generator of [22]. Merlin allows a rescaling of the magnet strength according to the actual beam momentum. Placet can simulate both beam re-acceleration and magnet rescaling. The comparison between these models will be discussed later.

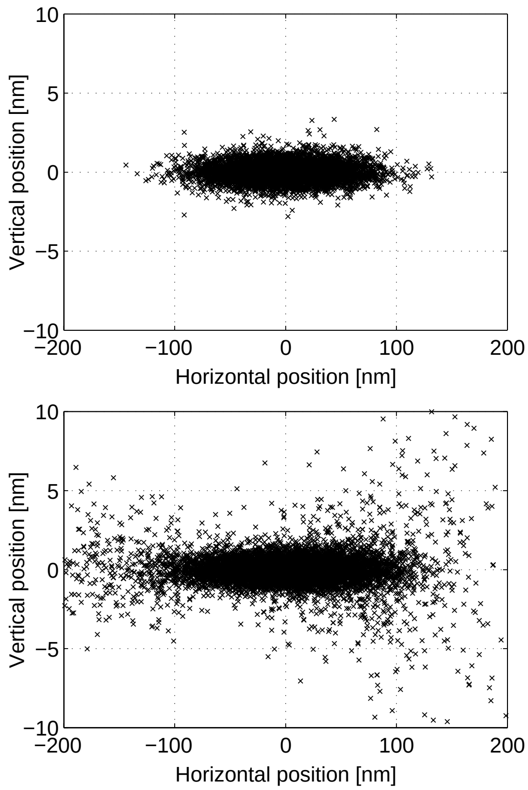

Figure 2: Transverse beam profile at the IP for a bunch with (bottom) and without (top) energy spread. Results are obtained with `Merlin`.

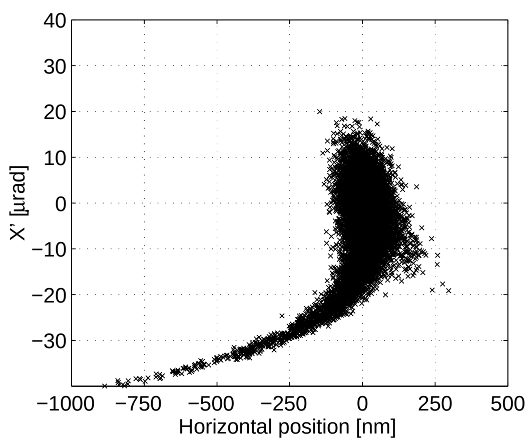

Figure 3: Horizontal phase-space particle distribution at the IP as calculated with `Merlin` for a bunch with the nominal energy spread.

4 RESULTS OF THE SIMULATIONS

Here, some results obtained with `Merlin` are presented. The other codes are in qualitative agreement. A detailed quantitative comparison will be left for the following section. In Fig. 2 the beam transverse profile at the IP is shown for the cases with and without energy spread and no synchrotron radiation. If energy spread is taken into account,

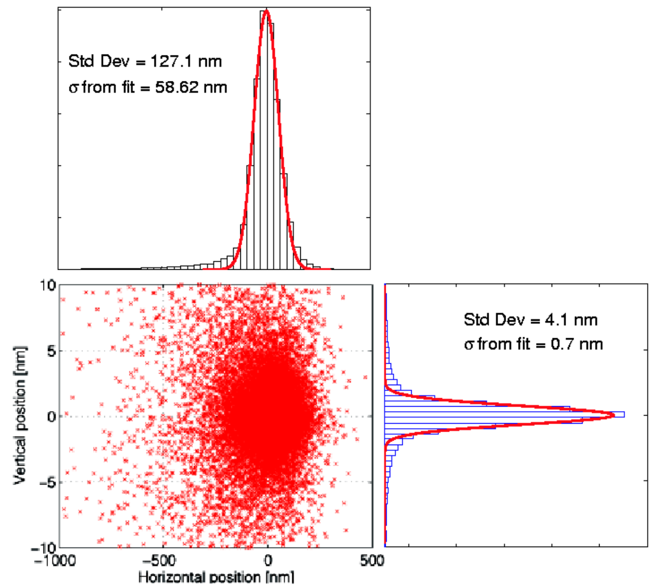

Figure 4: Transverse beam profile at the IP as calculated with `Merlin`. The synchrotron radiation in dipoles, quadrupoles and sextupoles is included. Gaussian fits to the projected particle distributions is also shown.

Table 2: Halo population at the IP according to the `Merlin` tracking. The percent number of particles with amplitudes larger than 3 and 6 σ is shown. The σ is calculated with a Gaussian fit to the particle positions.

		ΔE	ΔE + SR
Horizontal	Ampl.$> 3\sigma$	6.8%	6.7%
	Ampl.$> 6\sigma$	2.6%	2.3%
Vertical	Ampl.$> 3\sigma$	8.6%	15.2%
	Ampl.$> 6\sigma$	3.8%	7.7%

beam halos appear at amplitudes much larger than in the ideal case. This is also shown in Fig.3, where the horizontal x-x' distribution is given for a larger x axis. Particles are found even at amplitudes larger than 1 μm, while the horizontal beam size is about 40 nm. In Table 2 the number of particles with amplitudes larger than 3 and 6 sigmas is shown, for a bunch with energy spread, with and without synchrotron radiation. According to `Merlin` calculations, in the vertical direction, 15 % of the initial particles have amplitude larger than 3 σ and 7.7 % larger than 6 σ. On the other hand, for an ideal bunch without energy spread, the particles at amplitude larger than 3 σ are no more than 1 %, as expected from statistical fluctuations. The large population of the bunch tails is peculiar for this design of the final focus and was not found in the previous design [1].

In Fig. 4 the transverse beam profile is shown for the most realistic simulated case, i.e. for a bunch with energy spread and with synchrotron radiation. The histograms of the horizontal and vertical particle distributions are also shown. These histograms have been fitted with Gaussian distributions. The fit shows that the distributions are not Gaussian and that there are long particles tails at amplitudes of several sigmas. The plots also show that the width of the fitted Gaussian distribution is considerably smaller than the standard deviation of the particle positions. The effective beam size obtained from the Gaussian fits is still quite small. For instance, in the vertical plane the standard deviation of the particle position is 4.1 nm, but the effective beam size is 0.7 nm. More details on this aspect are discussed in the next Section.

5 COMPARISON OF THE TRACKING RESULTS

For Gaussian-like particle distributions, the beam size can be simply estimated with the standard deviation of the particle positions. Indeed, this parameter has been previously used to compare the tracking results from different codes [1]. In Table 3 the results obtained with the various codes for the lattice of Fig. 1 are summarized. The beam sizes at the IP are listed for the cases of a perfect bunch, for a bunch with energy spread and for the case with synchrotron radiation. Regardless of what was found for the previous CLIC BDS design, in this case considerable differences between the various codes are found. For instance, for a bunch with energy spread, `MAD` gives smaller beam sizes than the other codes. When synchrotron radiation is considered, `Merlin` seems instead to disagree from the others. Discrepancies up to 30 % are found.

The standard deviation of the particle positions does not give a good estimate of the beam size for non Gaussian beams, like the ones that are obtained at the end of the CLIC BDS. It has been shown in Section 4 that the beam tails are populated by about 10 % of the total bunch particles. The value of the standard deviation is much affected by few large amplitude particles, for which the code prediction is more difficult. Therefore, it is better to estimate the beam size with a Gaussian fit. The width of the fitted Gaussian provides a better estimate of the beam core, which actually matters for the luminosity performance. The beam sizes calculated with a Gaussian fit after tracking with the considered programs are given in Table 4.

The beam sizes obtained from the fit are much smaller than before. For the realistic case of energy spread and synchrotron radiation, the beam size is about 55 nm $\times$ 0.7 nm (horizontal $\times$ vertical). These values are in good agreement with the effective beam sizes that determine the luminosity, as calculated in [25]. This justifies the previous statement that the Gaussian fit gives a good estimate of the beam size for non Gaussian particle distributions.

In Fig. 5 and 6 the data of Table 4 are summarized in a graphical way. For the considered cases (three columns of Table 4), the average beam sizes are plotted for each code. The errors are small with respect to the considered scale and are omitted. These plots show the differences and, in addition, show the increase of the beam sizes due to energy spread and synchrotron radiation. The vertical beam sizes calculated with `MAD` for the case without synchrotron radiation show larger discrepancies with respect to the results from the other codes. The source of these discrepancies has not been understood yet. For the other cases, the agreement between the codes is quite good. There are not significant differences for the simulations with energy spread but without synchrotron radiation. With synchrotron radiation discrepancies of up to 6% and 17% are found for the horizontal and for the vertical planes, respectively. These differences, which are still relatively small, might be explained by the different implementation of modeling the photon emission. This is treated in more detail in the next session.

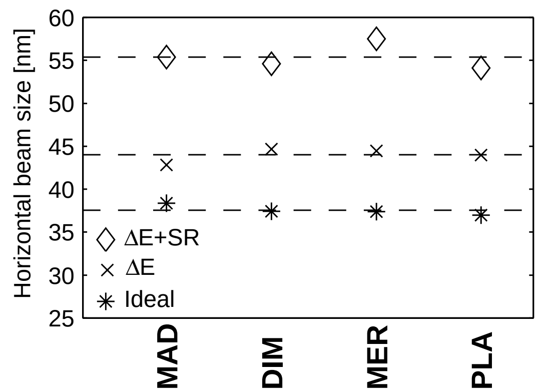

Figure 5: Comparison of the horizontal beam sizes calculated with a Gaussian fit. On the x axis there are the four considered codes and on the y axis the horizontal beam size. The points are the average of the data of Table 4. On this scale the error bars due to statistical fluctuations are negligible and have been omitted.

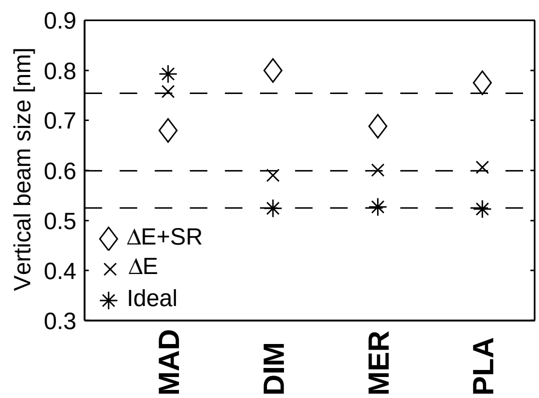

Figure 6: Same plot as Fig. 5 for the vertical beam sizes.

6 COMPARISON OF THE PREDICTED LUMINOSITY PERFORMANCE

Here, the results of the luminosity calculation obtained with `GuineaPig` are given. `GuineaPig` was interfaced with all the above tracking codes and used the output bunch

Table 3: Horizontal and vertical beam sizes at the IP after tracking with MAD, DIMAD, Merlin and Placet. Here, the beam sizes are calculated as standard deviation of the particle distributions. The average of five sets of 50000 particles is shown. The error is calculated as the standard deviation of the five mean values divided by $\sqrt{N_{set}-1}$.

	No ΔE - No SR	ΔE/E=1% - No SR	ΔE/E=1% - SR
Horizontal beam sizes			
MAD	38.87 nm±0.06 nm	74.91 nm±1.09 nm	96.28 nm±0.73 nm
DIMAD	37.60 nm±0.05 nm	106.32 nm±1.38 nm	99.04 nm±1.42 nm
Merlin	37.53 nm±0.05 nm	103.33 nm±1.37 nm	129.65 nm±1.51 nm
Placet	37.09 nm±0.05 nm	108.99 nm±1.47 nm	99.33,nm±1.31 nm
Vertical beam sizes			
MAD	0.937 nm±0.002 nm	1.432 nm±0.013 nm	3.050 nm±0.036 nm
DIMAD	0.562 nm±0.001 nm	1.824 nm±0.012 nm	3.349 nm±0.056 nm
Merlin	0.569 nm±0.001 nm	1.814 nm±0.012 nm	4.038 nm±0.033 nm
Placet	0.571 nm±0.001 nm	1.904 nm±0.013 nm	3.416 nm±0.026 nm

Table 4: Horizontal and vertical beam sizes at the IP after tracking with MAD, DIMAD, Merlin and Placet. Beam sizes are calculated as width of a fitted Gaussian distribution. The average of five sets of 50000 particles is shown. The error is calculated as the standard deviation of the five mean values divided by $\sqrt{N_{set}-1}$.

	No ΔE - No SR	ΔE/E=1% - No SR	ΔE/E=1% - SR
Horizontal beam sizes			
MAD	38.35 nm±0.14 nm	42.83 nm±0.08 nm	55.39 nm±0.07 nm
DIMAD	37.45 nm±0.12 nm	44.67 nm±0.08 nm	54.59 nm±0.17 nm
Merlin	37.38 nm±0.13 nm	44.48 nm±0.07 nm	57.49 nm±0.13 nm
Placet	36.96 nm±0.12 nm	43.99 nm±0.08 nm	54.12 nm±0.17 nm
Vertical beam sizes			
MAD	0.793 nm±0.001 nm	0.758 nm±0.003 nm	0.680 nm±0.001 nm
DIMAD	0.524 nm±0.001 nm	0.590 nm±0.001 nm	0.800 nm±0.002 nm
Merlin	0.527 nm±0.001 nm	0.601 nm±0.001 nm	0.688 nm±0.002 nm
Placet	0.523 nm±0.001 nm	0.606 nm±0.001 nm	0.775 nm±0.002 nm

at the IP as input for the luminosity calculation. Pinch, hour-glass and e^+e^- pair production were all included in the simulations. In Table 5 the results are summarized. The luminosity is shown only for the cases with energy spread and synchrotron radiation. The average of five sets of 50000 particles is shown.

MAD, DIMAD and Merlin implements different models for the synchrotron radiation, as mentioned in Section 2. In addition, they treat the compensation for energy losses due to photon emission differently, and this leads to slightly different lattice configurations. MAD re-accelerates the beam to maintain its mean energy, Merlin rescales the magnet strength according to the actual beam energy and DIMAD does not do any compensation. Placet was adapted to simulate all the above compensation schemes of the beam energy losses. Therefore its corresponding results are compared with the ones from the other codes, respectively.

Table 5 suggests that the differences between the various codes are mainly induced by the different kind of compensation for the energy losses due to photon emission. Differences up to 16 % are found, corresponding to a luminosity difference of about $0.11 \times 10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, which seems reasonably small. On the other hand, if the same model is used, differences of only a few percent are found instead.

Table 5: Luminosity in $10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ calculated for the case with energy spread and synchrotron radiation. The average of 5 bunches of 50000 particles is given. MAD, DIMAD and Merlin used different models for the synchrotron radiation implementation. Placet reproduces all different models and its results are compared with the other programs.

		Placet
MAD	0.817±0.003	0.820±0.003
DIMAD	0.747±0.005	0.755±0.005
Merlin	0.704±0.002	0.679±0.003

The model based on the magnet rescaling is supposed to better simulate the tuning of a real machine. It is the one that results in the smallest value of the luminosity. For CLIC, the value $0.7 \times 10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ was found. However, the lattice has been designed using MAD; so the MAD result should be regarded as the reference design value since the lattice was optimized for this case.

7 CONCLUSIONS

In this paper, several codes for luminosity studies have been presented. Detailed calculations have been performed for the case study of the CLIC beam delivery system. Different tracking codes were used to obtain the particle distributions at the IP, which were then used as input for a program of luminosity calculation.

The analysis of the particle distributions after tracking has revealed considerable differences in the prediction of the tail population for the tracking codes considered. Generation and transport of beam tails can be important for collimation and background issues. They do not seem to be treated sufficiently well by the codes presently available, even when synchrotron radiation is not taken into account.

On the other hand, the luminosity predictions from various codes are in a much better agreement. If the same model for the synchrotron radiation is used, differences are within a few percent. This depends on the fact that the ultimate luminosity is not affected much by the few tail particles. Luminosity is in fact mainly determined by the bunch core, the effective size of which is well represented by a Gaussian fit of the particle distribution. The standard deviation of particle positions, often used as estimate of the beam size, has proven not to characterize properly bunches with long tails. The different models for synchrotron radiation show discrepancies as big as $0.11 \times 10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (up to $16\,\%$ of the absolute value).

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9 REFERENCES

[1] S. Redaelli *et al.*, "Comparison of Simulation Tools for Beam Delivery Systems of Linear Colliders", *EPAC2002*, Paris (2002).

[2] R. Aßmann *et al.*, "Overview of the CLIC Collimation Design", *PAC2001*, Chicago (2001).

[3] `http://mad.home.cern.ch/mad/`

[4] R. Servranckx, K. Brown, L. Schachinger, D. Douglas, "Users Guide to the Program DIMAD", SLAC-0285 (1990).

[5] `http://www.desy.de/~merlin/`

[6] D. Schulte, *et al.*, "Simulation Package based on PLACET", *PAC2001*, Chicago (2001).

[7] K.L. Brown, *et al.*, "TRANSPORT - A Computer Program for Designing Charged Particle Beam Transport Systems", *CERN-80-04*, Geneva (1980).

[8] `http://www-project.slac.stanford.edu/lc/NLC-tech.html`

[9] D. Schulte, *et al.*, "CLIC Simulations from the Start of the Linac to the Interaction Point", *EPAC2002*, Paris (2002).

[10] D. Schulte, "Beam-Beam Simulations with GUINEA-PIG," *ICAP98*, Monterey, CA., USA (1998).

[11] A. Seryi and L. Hendrickson, private communication.

[12] R. Aßmann *et al.*, "The Computer Program LIAR for the Simulation and Modeling of High Performance Linacs," *PAC97*,Vancouver, Canada (1997).

[13] `http://www.slac.stanford.edu/accel/nlc/local/AccelPhysics/codes/liar/web/liar_matlab.htm`

[14] `http://www.mathworks.com/`

[15] G.R. White, "Feedback on Nano-Second Timescale: Fast Feedback Simulations," these proceedings.

[16] D. Schulte, P. Tenenbaum, N. Walker, A. Wolski, M. Woodley, "Tests of 3 Linear Colliders Beam Dynamics Simulation Programs," *LCC-0091*, also as *Tesla-2002-08*, also as *CLIC-513*, (2002).

[17] R. Aßmann *et al.*, "The CLIC Study of Magnet Stability and Time-Dependent Luminosity Performance",*PAC2001*, Chicago (2001).

[18] `http://www-conf.slac.stanford.edu/lc02/`

[19] F. Zimmermann *et al.*, "Design Status of the CLIC Beam Delivery System", *EPAC2002*, Paris (2002).

[20] F. Zimmermann *et al.*, "The CLIC Beam Delivery System", these proceedings.

[21] F. Barbarin, F. C. Iselin and J. M. Jowett, "Particle dynamics in LEP at very high-energy," *EPAC 94*, London, England.

[22] H. Burkhardt, "Monte Carlo Generator for Synchrotron Radiation", *LEP Note* **632**, Geneva, 1990.

[23] G.J. Roy, Nucl. Instrum. Meth. A **298**, 128 (1990).

[24] P. Raimondi, A. Seryi, "Novel Final Focus Design for Future Linear Colliders," Phys. Rev. Letters **86**, 17 (2000) p. 3779.

[25] D. Schulte *et al.*, "Luminosity Limitations at the Multi-TeV Linear Collider Energy Frontier," *EPAC2002*, Paris (2002).