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Computational Needs for the ILC*

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Abstract

The ILC requires detailed studies of the beam transport and of individual components of the transport system. The main challenges are the generation and preservation of the low emittance beams, the protection of the machine from excessive beam loss and the provision of good experimental conditions. The studies of these effects lead to specifications for the different accelerator components and hence can significantly impact the cost.

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INTRODUCTION

The ILC is a study of a linear electron-positron collider with a centre-of-mass energy of 500 GeV. A schematic layout is shown in Fig. 1.

The work is coordinated by an international collaboration, the Global Design Effort (GDE) headed by Barry Barish [1]. This collaboration is currently evaluating the cost of such a collider with the aim to achieve a reliable estimate by the end of 2006. The baseline design has been documented in the BCD [2] (baseline configuration document) and put under the control of a committee which has to approve changes. The work on the different parts of the machine is organised in a number of working groups. They either address a particular subsystem, e.g. the main linac, or area of expertise, e.g. vacuum. One of these working groups is focused on beam physics.

Computations are needed in many places for the ILC. Very substantial effort needs to go into the damping ring, the low emittance transport (LET) and the calculation of the RF properties of beamline elements. In this paper the emphasis will be on the LET, with only some short remarks on the damping ring. While the RF simulations deliver vital input for the beam dynamics studies they are not treated here.

In the following we will give a short introduction into the beam physics studies that currently are or should be on the way for ILC. The work is progressing very rapidly, and the tight schedule of the ILC makes it hard to document all the results immediately in reports. The main aim is to prepare the RDR—the Reference Design Report—that should be published in 2007. We will thus not attempt to give a review of the status of the work but rather explain the motivation of the ongoing effort. The references in this paper will remain incomplete and many point to presentations or web sites. The reader who wants to be better informed should ask to be added to the ILC accelerator physics mailing list [3].

MACHINE PARAMETERS

A generic layout of the machine is shown in Fig. 1. The polarised electron beam is produced in a source that consists of a photo cathode gun, an RF buncher and an injector linac. It's emittance is then reduced in a damping ring. After extraction from the damping ring, the beam is sent through a turn-around into the bunch compressor where it is longitudinally compressed. After a first stage of acceleration in the main linac it is sent through a helical undulator in order to produce photons that are needed for the positron source. After a second acceleration stage the beam tails are removed in the collimation system and the beam is focused to a very small size in the final focus system. After the collision the beam is extracted and guided to a beam dump. The positron beam system is comparable.

The luminosity goal for the ILC is very demanding. Since the beams collide only once, in contrast to a ring-based collider, the transverse beam size needs to be very small at collision. This gives rise to very strong beam-beam effects. The small beam size also requires very small transverse beam emittances, which need to be generated and transported to the interaction point.

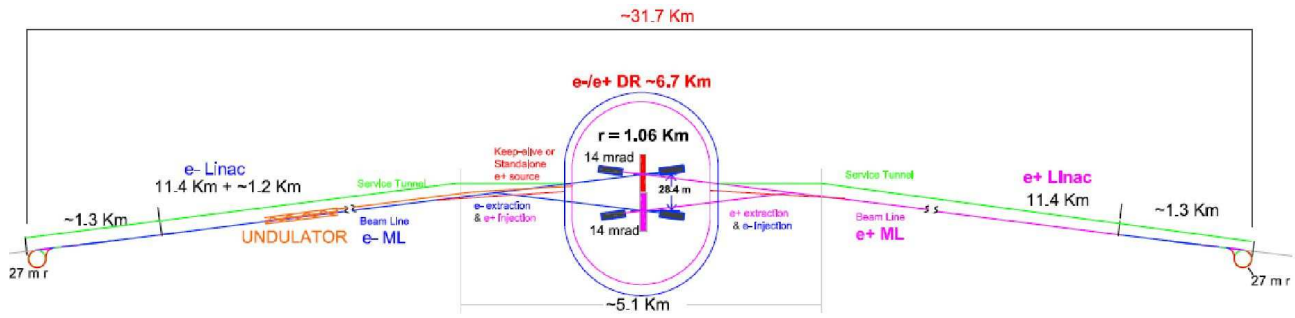
A number of parameter sets for ILC have been suggested in reference [2], see table 1. The reason not to pick a single parameter set was to be able to investigate the flexibility of these parameters.

GOALS OF THE SIMULATION STUDIES

It is generally considered that the ILC is basically feasible and that all relevant beam dynamics problems can be overcome. However, it has not yet been fully established that the machine can achieve it's performance goals, in particular that the full luminosity can be reached in spite of dynamic and static imperfections, even if this seems very likely. In addition, studies are needed in order to specify the tolerances for different imperfections and to specify the required instrumentation. These have an impact on the cost.

Benchmarking of the simulation tools is essential to achieve reliable predictions. The damping ring simulations can to some extent be benchmarked at ATF, CESER, KEKB or others. Currently ATF2 [5], a model of the final focus system, is being constructed where first beam will be available in 2008.

Not all aspects of the machine performance can be tested by experiment before the construction of the ILC. We will thus have to rely on simulations in order to predict the performance. It is therefore important to ensure the correct-



Schematic Layout of the 500 GeV Machine

Figure 1: Layout of the ILC.

ness of the simulations. Potential sources of error are

1. incomplete models for the dynamic and static imperfections
2. incorrect models for the instrumentation performance
3. errors in the tracking simulations
4. or errors in the simulation of the correction, tuning and feedback procedures.

In order to address these issues we need to

1. use realistic models for the pre-alignment, for ground motion, element vibrations, RF errors and other error sources
2. use realistic modelling of the instrumentation, in particular complex instruments such as laser wires or the fast luminosity measurement
3. benchmark the tracking codes against each other
4. have each alignment, tuning or feedback result be derived by two independent studies.

In order to fully verify the impact of the different effects, integrated simulations are needed that cover different time-scales and sub-systems of the machine. Studies of individual systems are still an essential step on this way. They are also helpful to cope with limited computing resources.

LET STUDIES

The low emittance transport system is quite different from a circular machine since one is essentially permanently injecting beam. The single pass mode eases some problems but makes others worse. Particularly special is the interaction point. Since the beams collide only once, one can allow for very large beam-beam effects. In the following we will first introduce the beam-beam interaction and then focus on the LET. Finally we will add some comments on the damping rings.

Beam-Beam Effects

The high luminosity requirement leads to the need of very small transverse beam size at the interaction point.

The high concentration of charge gives rise to a very strong electron-magnetic field that focuses the oncoming bunch. The strength of this effect is conveniently expressed by the disruption parameter $D_{x,y}$. For small values of D the beam acts as a thin lens, but for large values the particles of one beam start significant transverse motion in the field of the other beam. For the nominal parameter set the values are $D_x \approx 0.15$ and $D_y \approx 18$; the beam acts as a thin lens in the horizontal and a thick lens in the vertical plane. Since the forces are focusing this leads to a reduction of the effective beam size and consequently to an increase of the luminosity. The ratio of actual luminosity to the one that one would obtain without the beam-beam force is expressed by the luminosity enhancement factor H_D , which typically is in the range of 1–2.

The fact that the beam particles travel on curved trajectories leads to the emission of beamstrahlung. This process is similar to synchrotron radiation. The typical number of photons a beam particle emits during the collision is of the order of one and the typical energy of the photons is of the order of some percent of the beam energy. As a result, the luminosity is not described by narrow peak around the nominal centre-of-mass energy but has a tail toward smaller energies, see Fig. 2. It is obvious that this degradation of the luminosity spectrum affects the physics experiments. However, another effect exists that will modify the spectrum; initial state radiation is a radiative correction to the physics cross sections. A particle that interacts with a particle from the other beam can emit a photon during this collision. The effective luminosity spectrum due to this process is similar to the effect of beamstrahlung, see Fig. 2.

The interaction of the beams is simulated by use of dedicated codes, CAIN and GUINEA-PIG [6, 7], that represent the beam by macro-particles. These are distributed over grids to determine the beam fields which are then applied to the beams. The codes also contain the emission of beamstrahlung and monitor the collision of beam particles and beamstrahlung photons to simulate the production of the most common secondaries, low energy electron-positron pairs.

Table 1: The main beam parameters for different ILC configurations taken from reference [2]. The beam dimensions are given at the interaction point, the luminosities and backgrounds have been calculated using beam-beam simulations [4].

		Nominal	Low Q	Large Y	Low P	High L
E_0	[GeV]	250	250	250	250	250
\mathcal{L}	[$10^{34} \text{cm}^{-2} \text{s}^{-1}$]	2.12	2.00	1.78	2.01	5.16
N	[10^{10}]	2	1	2	2	2
n_b		2820	5640	2820	1330	2820
f_{rep}	[Hz]	5	5	5	5	5
Δz	[ns]	308	154	308	462	308
ϵ_x/ϵ_y	[μm]	10 / 0.04	10 / 0.03	12 / 0.08	10 / 0.035	10 / 0.03
β_x/β_y	[mm]	21 / 0.4	12 / 0.2	10 / 0.4	10 / 0.2	10 / 0.2
σ_x/σ_y	[nm]	655.2 / 5.7	495.3 / 3.5	495.3 / 8.1	452.1 / 3.8	452.1 / 3.5
σ_z	[μm]	300	150	500	200	150

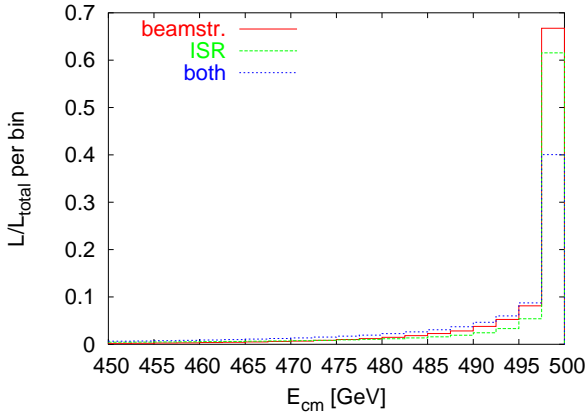


Figure 2: The luminosity spectrum for the nominal ILC parameters.

Beam Transport

During the transport, the beam is affected by the magnets and by wakefields mainly from the accelerating cavities, the collimators and special transversely deflecting cavities. The emittance preservation is strongly affected by the static imperfections, e.g. the position error with which the quadrupoles are placed in the beam lines. Depending on the actual misalignments, the machine performance can be quite different. The goal for the alignment and tuning procedures is therefore to ensure that with a likelihood of 90%, the emittance growth is below the target. In addition dynamic imperfections can degrade the luminosity. In particular to keep the beams in collision at the interaction point is challenging. these effects are mitigated using feedback.

Several codes exist to study the beam transport [8–14]. They represent the beam with a number of macro-particles. In the bunch compressor, helical undulator and beam delivery system, a large number of point-like particles is used, since non-linear fields longitudinal particle motion and energy loss play an important role. In the main linac, one can either also use point-like particles or one can represent the beam by a small number of slices that have a transverse extension and do not move longitudinally. This is possi-

ble since non-linear fields are usually negligible and the particles do not move longitudinally since they are ultra-relativistic and have only small angles with respect to the nominal beam line. The codes allow to include the different imperfections.

Computing Time

Systematic studies [15] of the beam-beam effects have been performed for TESLA to determine the number of particles that are needed to achieve convergence of the luminosity. Typically 5×10^4 – 10^5 particles are sufficient. Hence, a comparable number of particles should be used in the whole of the LET system for full consistency; exploratory studies can be done with fewer.

To give a rough feel for the computing time involved in the ILC beam dynamics simulations a few numbers should be given. They were obtained by running PLACET on a 3GHz pentium IV. Since the numbers should only be indicative no effort was made to compare to other codes but one would expect them to be in the same ball-park. In all cases 10^5 particles are tracked. The results are 150s for the bunch compressor, 120s for the main linac, and 40s for the beam delivery system. If slices are used in the main linac the tracking time is reduced to less than 1s. The beam-beam simulations take from 30s to several minutes depending on the level of detail, in particular whether the background generation and tracking is included.

The simulation of a single collision requires some minutes, simulating the collision of two bunch trains (containing ≈ 3000 bunches each) takes many days. If one wants to simulate a number of consecutive pulses months would be needed. Consequently one tries to find convenient short cuts. An important example is that essentially all alignment simulations are based on single bunch studies, assuming that the multi-bunch effect is small. In particular, in presence of dynamic imperfections multi-bunch effects can be potentially severe [16, 17].

The LET studies require that a number of machines is simulated each with a different seed for the random number generator. The cheapest way to provide the required computing power is by a large number of independent PC

based on commodity hardware that run one seed each.

The development of the feedback, correction and tuning algorithms however profits from the ability to have a fast turn-around for a small number of seeds. Since modern PCs are usually already equipped with gigabit Ethernet simple parallel clusters can easily be built. The development of parallel codes that can exploit such Beowulf systems seems thus advantageous.

The needs for the simulations of the RF components each element needs to be simulated only once. This normally performed by placing a grid over the element and solving the field equations repeatedly on this grid. To obtain high resolution, a large number of grid points is required leading to high requirements for memory and computing time. Hence, these codes are more strongly demanding parallel computer systems.

Static Beam-Based Alignment and Tuning

The beam-based alignment and tuning procedures in the different sub-systems of the LET proceed in a similar manner. The elements are positioned by the survey, simple steering is used to make the beam pass the sub-system followed by complex beam-based alignment, in which different measurements of the beam in the BPMs are used to optimise the trajectory. In a further step beam-based tuning is used in order to minimise the final beam emittance. This step relies on beam size or ultimately even on luminosity measurements.

The main emphasis of the tuning studies has been on the main linac [20–23]. Different alignment methods have been proposed but currently the focus is on only one of them, the dispersion free steering. In this method beams of different energy are made to follow the same trajectory, thus suppressing dispersion. A particular question that needed to be addressed for the main linac has been whether the tunnel could follow the curvature of the earth. While this is clearly less good for beam dynamics, it is advantageous for other systems. It has been shown that the impact of following the earth curvature on beam dynamics is acceptable, provided that the BPMs are well calibrated.

The main linac studies showed that dispersion free steering alone is not sufficient to achieve the target performance but that the above mentioned tuning bumps are also required.

Alignment studies for the ring to main linac transport have not been completed yet. For the part up to the first bunch compressor that has been studied further improvement of the procedures is required [24–26].

Further studies are being performed for the beam delivery system. Currently the procedures yield a performance that is not to far from the goal but not quite satisfactory [27].

Banana Effect

An example of the importance of the integration of different sub-systems is the so-called banana effect [29]. This

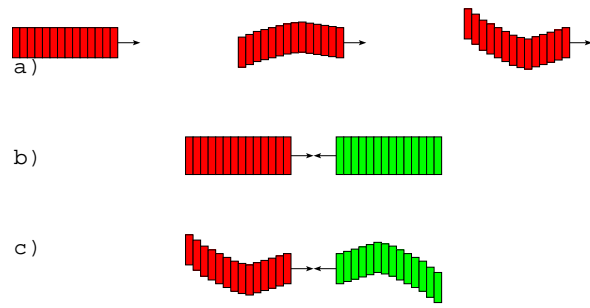


Figure 3: Sketch of the emittance growth in the main linac due to wakefields and dispersion and the possible translations into beam shapes at the IP.

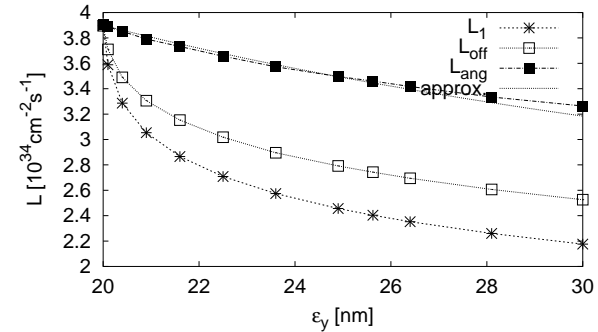


Figure 4: Luminosity as a function of the emittance in the case of TESLA.

effect has initially been studied for TESLA but is also important for ILC. In early studies the of the emittance growth in the main linac were separated from the beam-beam simulations. Wakefield effects in the main linac introduced correlated offsets in the beam, see a) Fig. 3. The projected emittance has then been used as input for the beam-beam simulations (b), while simulations with full correlation should have been used (c). Systematic studies showed that the luminosity drops much faster with increasing beam emittance if the correlations are used in simulations than anticipated from the projected emittances [19]. This is due to the fact that the collision is unstable due to the high disruption. The effect can be avoided if full luminosity optimisation is performed at the interaction point by varying the beam-beam offset and angle. This procedure however takes time and will be discussed in the feedback section.

Different time-scales need to be integrated into a common simulation in order to ensure that dynamic imperfections do not impact the correction of the static ones. In addition fast and slow feedback system can interfere.

Beam-Beam Feedback

In ILC different feedback systems will be essential to achieve the target luminosity. Due to the long pulse length it is possible to use intra-pulse feedback in addition to pulse-to-pulse feedback. The most important intra-pulse feedback is a beam-beam feedback at the collision point

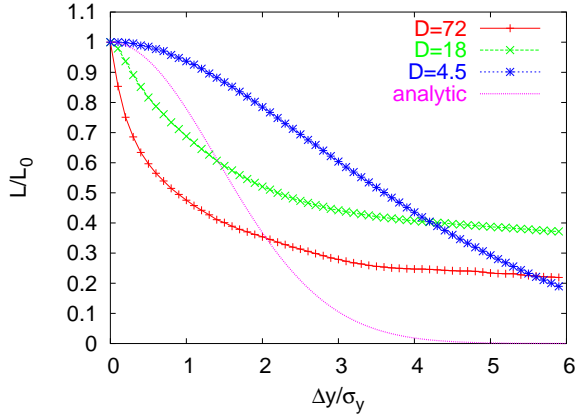


Figure 5: The relative luminosity as a function of the beam-beam offset.

that ensures that the two beams are in collision [28].

Very small relative offsets—in the range of nanometers—of the two beams lead to significant luminosity loss. An important example of a noise source that can lead to these offsets are transverse jitters of the quadrupoles of the final doublet of the final focus system. The bunch offset leads to a large deflection in the order of micro-radians. Measurement of their offset after the collision can therefore be used to correct the beam-beam offset with a feedback. Due to the long distance between bunches this is even possible on a bunch-to-bunch basis.

Different options exist to optimise the collision. In the simplest case only the beam position is used as a signal for the feedback. This can recover all the luminosity loss due to the beam offset. Other dynamic effects can lead to a deformation of the bunch shape, the resulting loss can be large due to the banana effect. This can be mitigated scanning the beam offset and angle in order to optimise the luminosity [19]. It seems possible to perform this scan during the first part of a single pulse [30].

The importance of the dynamic effects is illustrated by results that have been obtained for the TRC [34]. It compares the achieved luminosity to the target. For a noisy site the following has been found

- Uncorrected ground motion can reduce the luminosity to 40%, even in the presence of pulse-to-pulse feedback.
- Stabilisation of the final doublets helps little in this case.
- Correcting the beam-beam offset with an intra-pulse trajectory feedback can allow to achieve 85% of the luminosity.
- Intra-pulse luminosity optimisation achieves 95%.

Code Benchmarking

Significant effort is being put into benchmarking the tracking codes with each other. A previous study compared three codes [32, 33] simulating a beam oscillation in a per-

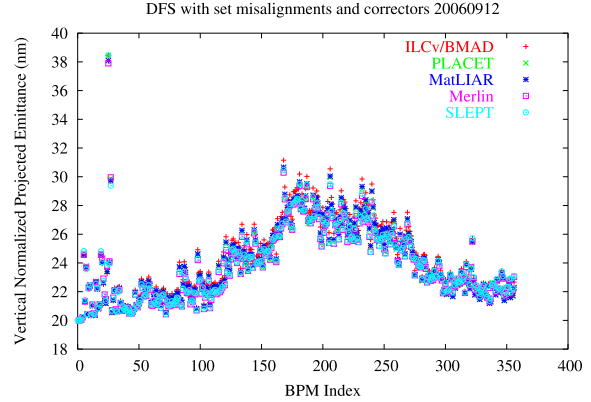


Figure 6: The plot shows the emittance in one corrected main linac as compiled by J. Smith based on results [35] of K. Kubo, P. Lebrun, K. Ranjan, D. Schulte and N. Walker.

fect machine. It has been extended to include more codes and to also cover the alignment algorithm in a systematic fashion. Figure 6 shows the emittance along a single machine for several codes. A realistic machine has been generated in one code; the corrector dipoles have then been used to correct the beam line. The agreement between the different codes is very good.

Further studies compared the performance of dispersion free steering in the main linac. Each code simulated 100 machines with errors derived from normal distributions with a given width. After adjusting the alignment algorithms, the agreement has been found to be very good. However, the performance of the original alignment procedures differed slightly due to details of the procedures. It should be noted that during this benchmarking at least one significant bug has been found and fixed.

DAMPING RINGS

The damping ring also needs significant computational effort. The layout is documented in the [2, 39]. Some important topics are

- The dynamic aperture is tight and simulations with realistic field errors are required.
- During beam extraction a significant variation of the beam loading occurs. This transient effect needs to be studied.
- The electron cloud is a concern in the positron damping ring.
- The fast beam-ion instability is a concern in the electron damping ring [36, 37].
- The alignment and tuning of the ring is critical.
- Careful evaluation of the impedance of all elements is necessary to ensure that the impedance budget can be met.

A problem of particular concern in the ILC damping ring is the electron cloud effect in the positron damping

ring. Electrons will be set free by synchrotron radiation and beam-gas ionisation. Accelerated by the beam fields they will hit the surface of the vacuum chamber where they can produce a number of secondary electrons, which are also accelerated by the beam. This can lead to an exponential rise of the density of electrons in the vacuum chamber that will be only limited by the self force of the generated electrons. A beam that passes through such an electron cloud can be rendered unstable.

In the first iteration of the baseline design it has been foreseen to build two stacked positron damping rings in order to increase the bunch distance by a factor two in order to avoid the instability. Recent studies indicate that different countermeasures against the electron cloud may be sufficient, e.g. the use of weak solenoids in field free regions, or the use of grooved surfaces [40]. Hence, one has been able to accept a cheaper option that uses only one positron damping ring.

CONCLUSION

A large effort in simulation studies is required for the ILC. In particular the simulation of RF components, instrumentation, the damping ring, the low emittance transport and the background are important. For the low emittance transport fully integrated simulations are finally need that combine the different sub-systems and time-scales into a single study. However the required computing power is substantial and consequently simplifications of the problems will still remain a valuable tool. The beam dynamics studies will be documented in 2007 in the RDR.

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