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DAMPING RING TO INTERACTION POINT BEAM TRANSPORT ISSUES

N. Walker, DESY, Hamburg, Germany,
D. Schulte, CERN, Geneva, Switzerland,
A. Wolski, LBNL, Berkeley, CA 94720, USA
P. Tenenbaum, A. Seryi, M. Woodley, SLAC, Stanford, CA 94309, USA

Abstract

One of the major challenges facing the proposed high-energy linear e^+e^- colliders is the preservation of the extremely small vertical emittance from the damping rings to the interaction point (IP). This emittance must be transported through bunch compression sections, the main linac and finally through the beam delivery system to the IP. Historically, the beam dynamics issues of each sub-system have been studied quasi-independently, with the beam conditions and tolerances being specified at the boundaries. As part of the recent International Linear Collider Technical Review Committee [1], new simulation tools have been developed to simulate the beam transport through the integrated system, including static and dynamic errors, stabilization systems, and tuning algorithms.

INTRODUCTION

Two major factors in achieving the ambitious luminosity goal of a few 10^{34} cm^{-2}s^{-1} in a future e^+e^- linear collider are maintaining the small vertical normalised emittance, and keeping the nanometer-sized beams in collision at the IP. While the damping rings are responsible for producing these unprecedented normalised vertical emittances (~10^{-8} m), the beam transport from the damping ring to the IP – which includes the main linac – must preserve them to within tolerable levels.

The low emittance transport (LET) system generically refers to:

- the damping ring to main linac transport line, including bunch compression (BC) and pre-acceleration;
- the main linac;
- the beam delivery system (BDS).

Table 1 summarises the relevant parameters for the LET systems of the TESLA, JLC/NLC and CLIC designs. The beam parameters are specified at the main sub-system boundaries. To some extent, the BC and BDS sub-systems of the LET systems are interchangeable between the machines. The primary performance differences are driven by the choice of linac technology.

Table 1: Important design parameters for the LET sub-systems for TESLA, JLC/NLC and CLIC (taken from [1]).

			TESLA		**JLC/NLC**		**CLIC**		***Comments***
c.o.m. energy		GeV	500	800	500	1000	500	3000	*important for (all sections):*
particles / bunch		$\times 10^{10}$	2	1.4	0.75		0.4		*wakefields, beam-beam*
bunches / train			2820	4886	192		154		*long-range wakefields,*
bunch separation		ns	337	176	1.4		0.67		*intra-train feedback*
repetition rate		Hz	5	4	120$^{i)}$		200	100	*vibration suppression (orbit feedback)*
initial conditions (damping ring)	E_{beam}	GeV	5		1.98		2.42		
	$\gamma\varepsilon_y$	nm	20	10	20		5		*important for (all sections):*
	σ_δ	%	0.13		0.09		0.13		*chromatic effects*
	σ_z	mm	6		4		1.3		*wakefield effects, beam-beam*
after bunch compressor	E_{beam}	GeV	4.6		8		9		*TESLA uses single-stage compression. CLIC and NLC/JLC use two stage compression.*
	$\gamma\varepsilon_y$	nm	20	10	22		5		
	σ_δ	%	3		1.5		1.36		
	σ_z	mm	0.3		0.11		0.035		
IP (linac exit)	E_{beam}	GeV	250	400	250	500	250	1500	
	$\gamma\varepsilon_y{}^{ii)}$	nm	30	15	40		10		
	σ_δ	%	0.08$^{iii)}$		0.25		0.25		
	σ_z	mm	0.3		0.11		0.035		
	σ^*_y	nm	5	2.8	3	2.1	1.5	0.7	*drives vibration tolerances*
	L	$\times 10^{34}$ cm^{-2}s^{-1}	3	5	2	3	2	8	*including beam-beam enhancement*

i) NLC/JLC also has options for 150 Hz and 100 Hz operation at 500 GeV and 1 TeV respectively.
ii) Includes emittance dilution budget
iii) Represents the energy spread at the exit of the main linac. At the IP, the electrons have an additional contribution from the positron source undulator which increases the energy spread to ~0.15% at E_{beam} = 250 GeV.

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The International Linear Collider Technical Review Committee (ILC-TRC) published its findings earlier this year [1]. As part of that process, new simulations of the performance of the LET systems were performed. Several codes were developed and bench marked against each other. As a by-product of the review, the available simulation tools have become more sophisticated. In this report, we will first briefly overview the important issues pertaining to LET system performance, and then discuss the status of the simulation tools that are used to study them.

BEAM DYNAMICS ISSUES

One of the major challenges facing the LET system is achieving and maintaining the tight alignment tolerances. Although there are certainly other concerns in the LET systems[*], we will concentrate on the alignment issues.

Before specifically discussing component alignment and beam-based tuning, we will first briefly discuss each LET sub-system in turn and highlight the main beam dynamics mechanisms that are important.

Bunch Compression

The bunch length must be compressed from the several millimetre lengths in the damping rings to the sub-millimetre lengths required at the IP, before injection into the main linac. Bunch compression is achieved by an effective $\pi/2$ rotation of the longitudinal phase space. In JLC/NLC this is achieved in two stages using an L-band compressor at 1.98 GeV and a X-band compressor at 8 GeV. The current TESLA design has a single-stage L-band compressor at 5 GeV. One direct consequence of bunch compression is the relatively large energy spread at the exit of the compressor, which can cause substantial emittance growth from dispersive effects arising from component misalignment. This is particularly true for the single stage TESLA system, where the ~3% energy spread after compression is responsible for a large fraction of the emittance growth budget over the first sections of the linac (~50% of the total linac emittance growth is over the first ~8% of the linac). The two-stage JLC/NLC design mitigates these effects to a large extent since the energy spread from the initial compression is first adiabatically reduced by accelerating the beam up to 8 GeV before the second stage is applied[†].

Other important beam dynamics issues in the bunch compressors are:

- nonlinear optical effects – especially the nonlinear path-length terms – must be included in the simulations;
- wakefield effects and cavity misalignments (particularly tilts) for the longer bunches need to be considered.;
- the tolerances on both amplitude and phase of the RF tend to be very tight.

For the ILC-TRC the bunch compressor systems were only marginally included during the LET simulation studies, but this is being addressed in the current ongoing effort.

Main Linac

The dynamics of the main linac are generally divided into multi-bunch and single-bunch effects; the former is the study of long-range wakefields (higher-order modes, or HOMs), which can lead to multi-bunch beam break up (MBBU). Singe-bunch dynamics are concerned with the effects of short-range wakefields. Much engineering effort has been invested on mitigating the HOM effects by the use of detuned structures and HOM couplers. Assuming that these measures successfully damp the HOMs to the required levels, it is the single-bunch effects (short range wakes) that require the most attention: nearly all of the studies for the ILC-TRC were concerned with single-bunch dynamics.

Emittance dilution mechanisms can be loosely categorised into transverse wakefield effects and chromatic (dispersive) effects, although the two are related via beam loading and its compensation. Both effects are driven by the alignment of the components and the bunch trajectory (orbit). All of the linac beam-based tuning algorithms are ultimately concerned with achieving a ‘gold orbit’ which minimises the emittance dilution. The tolerances on both RF structure and quadrupole alignment are governed by several factors:

- structure alignment is dominated by the strength of the transverse wakefields which scale roughly as the 3rd power of the RF frequency, and are therefore much stronger in the X-band machines than in TESLA;
- the X-band designs compensate the stronger wakefields by use of shorter bunches, stronger focusing and longitudinally correlated energy spread (so-called BNS damping [2]), all of which lead to tighter (but still achievable) alignment tolerances;
- the intense beam-beam interaction in TESLA significantly increases the luminosity loss for a given (longitudinally correlated) emittance growth[‡];
- the quadrupole alignment tolerance is a function of the energy spread in the beam, and the strength of the focusing, both of which change along the linac (especially in the presence of strong BNS damping);

Beam Delivery System (BDS)

The BDS is responsible for providing:

- the required strong demagnification of the beam to produce nanometre spot sizes at the IP;

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[*] The reader is referred to (for example) the ILC-TRC report [1] for a more comprehensive discussion of all the issues pertaining to the beam dynamics of the LET systems.

[†] The final energy spread for JLC/NLC is comparable to the coherent energy spread introduced in the linac for BNS damping.

[‡] See section on Beam-Beam effects.

- post-linac beam-halo collimation to shield the physics detector from background.

The strong demagnification is primarily achieved by the short focal length quadrupole doublet close to the IP. The resulting high chromaticity of this 'final lens' must be compensated using strong sextupole magnets in dispersive regions. The design of such optical systems requires a careful balance of nonlinear optical terms, and this ultimately leads to very tight tolerances on both field strength and alignment of the magnets. The worst case is the final doublet itself, where vibration stabilisation[§] to the ~nanometer RMS level is required.

All BDS designs contain a dedicated collimation section. The wakefields induced by the collimator gaps are a significant source of emittance dilution [3]. The collimator wakefields amplify the transverse beam jitter and increase the transverse emittance. The ILC-TRC has identified collimator wakefields as a concern for all the current proposed designs.

Beam-Beam Effects

The dynamics of the beam-beam interaction can be loosely characterised by the *disruption parameter*:

$$D_y \propto \frac{N_e \sigma_z}{\sigma_x \sigma_y}; \qquad \sigma_x >> \sigma_y \tag{1}$$

where N_e is the charge per bunch, and $\sigma_{x,y}$ are the RMS horizontal, vertical beam extents and σ_z is the RMS bunch length (all at the IP). TESLA has the highest value of disruption parameter at ~25 (for E_{cm} = 500 GeV), while JLC/NLC and CLIC have values of 13 and 8 respectively.

The large value for TESLA has a marked impact on the luminosity performance due to the so-called kink instability, where the collision effectively becomes unstable [4]. The luminosity becomes very sensitive to relatively small variations in the bunch charge distribution, particularly in terms of beam-beam offset: for TESLA, a $1\sigma_y$ vertical offset (5 nm) causes ~60% reduction in luminosity, compared to typically less than 10% for the lower disruption machines [1].

The sensitivity to beam-beam offset can for the most part be mitigated by the use of the fast intra-train beam-beam feedback system [5]. Unfortunately the high disruption parameter also makes the collision sensitive to the so-called 'banana' effect [4], or longitudinally correlated emittance growth of the type driven by wakefield effects. Up to 30% reduction in nominal luminosity has been simulated for TESLA due to this effect. Simulations have also shown that the loss can be regained by scanning the collision angle and offset at the IP, an optimisation that can potentially be performed during a single bunch-train [6].

Figures of Merit for Performance

In past studies, the RMS emittance has generally been adopted as the figure of merit for performance for linac studies, while the RMS transverse beam sizes at the IP were used for the BDS. While both of these quantities are certainly useful and important, care must be taken in interpreting such results when considering luminosity. For TESLA, it would be misleading to quote only RMS emittance and beam size performance due to the strong disruption effects. Conversely, RMS values can in some cases overestimate the impact on luminosity degradation: RMS values are sensitive to long tails on distributions which are often driven by nonlinear optics effects and wakefields, while the core of the distribution – responsible for the luminosity – remains unperturbed. In both cases, it is desirable to use the luminosity as simulated by a beam-beam code such as GUINEAPIG [7] to give a better estimate of performance. Many of the LET studies for the TRC (and since) have used simulation in which GUINEAPIG forms an integrated part.

STATIC AND DYNAMIC ALIGNMENT ERRORS

Table 2 lists the goal alignment tolerances for design luminosity, and the modelled installation accuracies. Irrespective of which technology is being discussed, the required tolerances needed to achieve the luminosity performance are not attainable with current state-of-the-art mechanical alignment and survey techniques, and beam-based tuning and alignment methods are required. At this point the beam diagnostics – and particularly beam position monitors (BPMs) – begin to play a very significant role. In general the achievable performance of these machines is limited by the resolution of the BPMs.

Static Alignment Errors

For the main linacs, two related methods of beam-based alignment have been considered in detail:

Dispersion Free Steering (DFS): as its name implies, the goal of this method is to find an orbit (trajectory) which does not generate dispersion. The beam-lattice energy match is varied (through a combination of beam energy and magnet optics changes[**]) and the resulting difference orbit recorded. From these measurements and knowledge of the optics an orbit is found which minimises the difference when the energy is changed. DFS suffers from several problems, not least that in the presence of BPM errors the orbit solutions tend to have very large amplitudes, and this tendency must be compensated by applying an additional constraint on the absolute orbit. The method is also sensitive to upstream beam jitter, which must be fitted out or averaged away to avoid confusing the algorithm. DFS has been extensively simulated for all linac designs with varying degrees of success, and has been experimentally demonstrated at the SLC [9] and at LEP [10].

[§] Both in terms of mechanical stabilisation and beam-based feedback systems.

[**] For TESLA it is important to change the initial beam energy to correctly measure the dispersive kicks from tilted cavities [8].

Table 2: Component tolerances for the main linacs. The Luminosity Tolerances are those random RMS values which result on average in the budgeted emittance growth after a 1-to-1 linac steering. The numbers should be taken as an *indication* of the alignment which the various beam-based methods must achieve. Units are μm and μrad.

		TESLA	JLC/NLC	CLIC
Luminosity Tolerances				
BPM offsets		25	5	0.7
structure	offsets	500	13	8
	tilts	300	100	8
Modelled Installation Accuracy				
quadrupole offsets		300	50	100
structure	offsets	300	25	20
	tilts	300	33	20
BPM	offsets	200	100	10
	res.	10	0.4	0.1
struct. BPM	res.	n/a	5	10
girder	offsets	200	50	-
	tilts	-	15	-

Notes: quadrupole, structure and BPM offsets are defined with respect to the girder alignment, with the exception of the BPM CLIC number, which is relative to a stretched wire system. The girder alignment is with respect to the accelerator reference line. A dash indicates an unknown (or not modelled) number.

Ballistic Alignment (BA): with this method, a reference line is established by turning all the magnets and RF[††] off and allowing the beam to coast through the section. The BPM readings are then used to define a straight reference line[‡‡], to which the orbit is steered when the nominal settings for the section are restored. Because a single ballistic shot is all that is required to establish the 'straight line' (to within the BPM resolution), the method is not so sensitive to beam jitter. The main disadvantage with BA is controlling the beam during the ballistic measurement, given that it will have a large β-beat and large coherent amplitude in the downstream linac sections.

Both of these methods address the quadrupole alignment and the related emittance dilution due to dispersive effects (they also implicitly address the issue of BPM offsets). The achievable results are ultimately given by the resolution of the BPMs.

The methods do not address the control of the structure alignment and the associated transverse wakefield effects. Here there is a clear difference between TESLA and the X-band machines, since the strength of the wakefields are much larger in the latter. For TESLA no additional alignment over that achieved during construction of the cryomodule and installation is foreseen. For both JLC/NLC and CLIC, the significantly tighter tolerance must again be achieved using beam-based techniques. Each structure will have a 'structure BPM' which will effectively measure the transverse dipole mode excited by an off-axis beam. Several adjacent structures will be mounted on a single remotely translatable girder allowing the average offset and tilt of the structures to be corrected to the μm- and μrad-level respectively.

Dynamic Alignment Errors (vibration)

Unfortunately dealing with the static errors is not the end of the story. Due to ground motion and other vibration sources, the accelerator components move away from their beam-based aligned positions over time. The most sensitive elements are the magnets in the Final Focus System, where vibration tolerances are in the ~1 to 100 nm range (the strong final doublet being the worst case). Fast quadrupole vibration leads to beam jitter which will:

- cause the beams to move out of collision at the IP; and
- increase the beam size at the IP due to emittance dilution.

Of these two mechanisms the first is generally the more critical. To compensate the effects of component vibration, three approaches are generally adopted (with varying degrees of emphasis):

- use of beam-based orbit feedback, particularly at the IP to maintain the beams in collision;
- mechanical stabilisation of components using either passive damping or active feedback;
- prudent choice of a 'quiet' site.

In all cases – and particularly when considering beam-based feedback – the frequency spectrum of the 'noise' and the spatial correlation must be considered. Three ground motion models have been developed [12] corresponding to measured quiet, medium and noisy sites. The models are now extensively used to simulate ground motion effects in the LET systems, examples of which can be found in [13].

For beam-based feedback, the beam repetition rate is critical. The high rates of the X-band machines allow suppression of beam motion (jitter) below ~10Hz; typical ground motion spectra above this frequency show motion at the nanometer level. For TESLA, the collisions at the IP are maintained within the long bunch train, which effectively removes all train-to-train jitter [5]. The effect on the emittance of the upstream jitter can be significant however, where the cut-off for the rep. rate limited orbit correction is typically 0.1 Hz. Orbit-based feedbacks at this rate are however sufficient for dealing with slow diffusive ground motion as described by the so-called *ATL* law [14].

SIMULATION TOOLS

The tools used to simulate the performance of the LET must support the necessary (important) beam dynamics and in addition allow the correct modelling of the various tuning algorithms outlined in the previous sections. Specifically they should:

[††] It is particularly important to turn off the RF for TESLA due to the transverse kicks from the tilted cavities [11]. For JLC/NLC and CLIC this is less of a problem since the cavity tilts are expected to be compensated during the structure girder alignment process.

[‡‡] The effects of transverse wakefields and other external fields will define how straight the ballistic line is.

- Correctly model the beam transport (i.e. transverse optics); for the BC and BDS sections this must also include nonlinear geometric and chromatic effects.
- Include acceleration (including the RF curvature).
- Include transverse and longitudinal wakefield effects.
- Support general three-dimensional component alignment errors (transverse offsets, tilts and rolls etc.).
- Allow several grouped components to move together simulating the action of girders and mechanical movers.
- Provide quasi-realistic models of diagnostics and corrector magnets.
- Allow modelling of the various tuning algorithms (DFS, BA, feedback systems etc.)
- Support ground motion models, specifically the frequency spectrum and the spatial correlation (particularly across the IP).

Several tools now exist for performing extensive and complex simulations of all aspects of the LET, although there is still room for improvement. For the more recent studies (specifically the TRC), the following tools were used, either separately, or *chained* together:

LIAR [15]: developed at SLAC to model both the SLC and NLC linacs; extensively used for NLC simulations.

PLACET [16]: developed to study both the CLIC main linac and drive beam dynamics. One particular noteworthy aspect of PLACET is its speed.

MERLIN [17]: developed at DESY for tuning and ground motion studies for the TESLA BDS, and extended to include the main linac and bunch compressor dynamics.

GUINEAPIG [7]: used extensively for modelling the beam-beam interaction.

DIMAD [18]: ray tracing optics code which includes synchrotron radiation effects, used for BDS and BC studies.

MADacc [19]: A SLAC version of the MAD code which includes acceleration and wakefields.

ELEGANT [20]: ray tracing code which includes acceleration, wakefields and both incoherent and coherent synchrotron radiation.

Each of these codes can be used with various degrees of successes for specific sub-systems of the LET, and several of them have been successfully benchmarked against each other [21].

SIMULATION AND THE REAL WORLD

The expected luminosity performance of all the linear collider designs is essentially based on simulation. The types of simulations briefly reviewed in this report have shown that the LET systems can for the most part perform to the design goals *providing* the initial conditions and hardware performance of the systems simulated are achieved. Specifically:

- the component installation alignment tolerances (table 2) are achieved;
- the BPMs and other diagnostics perform to the desired resolution and do not excessively drift;
- the mechanical magnet and girder movers (several hundreds for JLC/NLC and CLIC) perform to specification;
- fast feedback kickers and other corrector magnets perform within tolerances;
- the time required for static tuning is short compared to the characteristic time for the natural component drift.

The simulations are only as good as the information that goes into them. The next step is to include the impact of ground motion (vibration) on the static tuning algorithms[§§], a task that has already begun [22]. The effects of component failures and 'flyers' (*i.e.* a few % of components whose alignment are at several standard deviations of the distribution) also need to be quantified. Modelling of the alignment and survey techniques rather than just using random uncorrelated errors is another potential topic of study.

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