ACCELERATOR PHYSICS CHALLENGES IN FUTURE LINEAR COLLIDERS*

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Abstract

At the present time, there are a number of future linear collider designs with a center-of-mass energy of 500 GeV or more that have luminosities in excess of $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. Many of these designs are very advanced, however, to attain the high luminosity, the colliders require very small beam emittances, strong focusing, and very good stability. In this paper, some of the outstanding issues related to the small spot sizes are discussed. Although the different designs are based very different rf technologies, many of these problems are common to all designs.

1 INTRODUCTION

Over the last decade, a number of linear collider designs have been developed to reach center-of-mass (cms) energies of 500 GeV or more [1]. These designs are the “next-generation” linear colliders and they incorporate extensively from the Stanford Linear Collider (SLC) which began operation in 1988. At present, there are four designs that are actively being pursued: TESLA [2], JLC-X [3], NLC [4], and CLIC [5]. The TESLA design is based on low frequency super-conducting rf technology while the others are normal-conducting designs. The JLC-X and the NLC designs are very similar; both utilize X-band (11.424 GHz) rf and are based on the same rf technology with identical beam parameters—for this reason, we will refer to the two designs as a single JLC/NLC design. Finally, the CLIC design is based on 30 GHz rf to allow higher acceleration gradients and the possibility of multi-TeV operation. Representative parameters for the designs are listed in Table 1.

All of the designs need to attain high luminosities:

$$\mathcal{L} = f_{rep}\frac{n_b N^2}{4\pi\sigma_x^\star\sigma_y^\star}H_D \tag{1}$$

where f_{rep} is the collider repetition rate, $\sigma_x^\star/\sigma_y^\star$ are the rms beam sizes at the interaction point (IP), N is the bunch charge, n_b is the number of bunches per rf pulse, and H_D is the luminosity enhancement which arises when the opposite charged bunches focus each other, increasing the beam densities. Unlike circular colliders, f_{rep} tends to be low and thus the luminosity must be attained through the bunch charge and spot sizes. Fortunately, the beam-beam tune shift is not a severe limitation and thus the beam sizes can be reduced. Typical beam sizes, listed in Table 1, are roughly a factor of 1000 smaller than in the LEP2 or PEP-II storage rings.

	TESLA	JLC/NLC	CLIC
Energy [TeV]	0.8	1	3
Lum. [10^{34}/cm^2/s]	5.0	1.3	10
Rf freq. [GHz]	1.3	11.4	30
Rep. Rate [Hz]	3	120	75
N [10^{10}]	1.4	0.95	0.4
Bunch Spacing [ns]	189	2.8	0.67
Ave. Current [A]	0.012	0.6	1.0
Pulse len. [μs]	850	0.27	0.10
$\gamma\epsilon_x^\star/\gamma\epsilon_y^\star$ [mm-mrad]	8/0.01	4.5/0.10	0.6/0.01
$\sigma_x^\star/\sigma_y^\star$ [nm]	391/2	234/3.9	40/0.6

Table 1: Representative parameters of future linear collider designs.

Thus, there are two classes of problems in a linear collider: those related to accelerating the beam, which depends on the rf technology, and issues associated with the very small spot sizes at the IP. To attain the small spot sizes, the colliders must operate with very small beam emittances, strong focusing, and very good stability. All of these designs are very advanced and have dealt with many or most of the technical issues, however, in the following, we will discuss some of the issues which are not yet adequately resolved related to producing and operating with the small spot sizes. In particular, we will discuss the topic of stability in the main linacs and damping rings, which is essential for tuning and operation of the collider, and then discuss the problem of beam collimation, which is difficult due to the very high beam densities and beam powers. These issues will be presented in reference to the JLC/NLC design although similar problems exist in the other designs.

2 DESIGN HIGHLIGHTS

Before discussing the issues in greater detail, it is worth discussing some of the principal features of the different collider designs [6]. All of the colliders consist of a polarized electron source and a positron source, damping rings to decrease the source emittances, bunch compressors to shorten the bunch lengths, main linacs to accelerate the beams to the full energy, collimation sections to remove tail particles that could contribute to backgrounds in the detectors, and final focus systems that demagnify the beams to the very small spot sizes at the IP. A schematic of the NLC design is illustrated in Fig. 1.

The TESLA design can achieve good rf efficiency at low beam currents and can operate with long pulse lengths because of the high-Q super-conducting rf cavities. At the low rf frequency, the wakefields, which dilute the beam emittances, are relatively weak and thus the dynamics in

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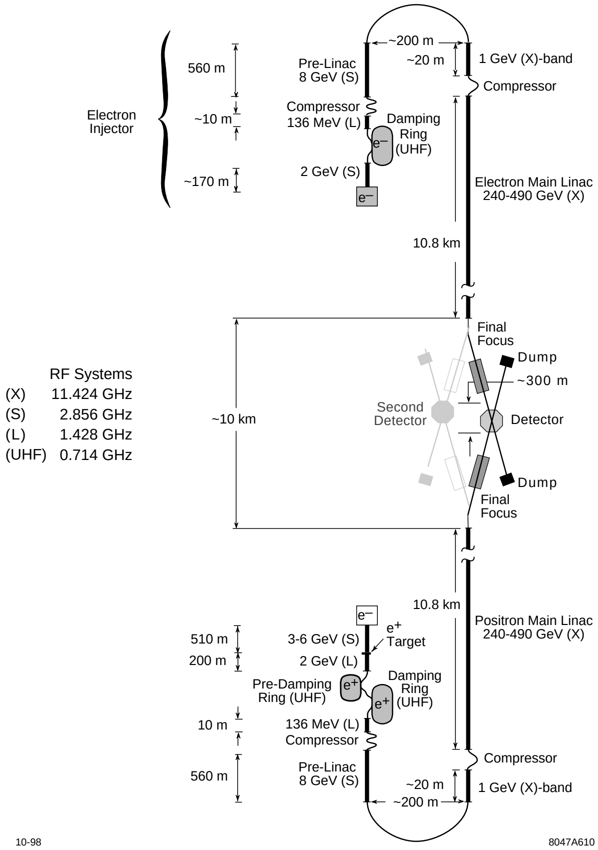

Figure 1: Schematic of the NLC from Ref. [4]

the linac is straightforward. In addition, because of the long bunch train, TESLA can use intra-train feedback to correct the effect of high frequency ground motion or other sources of train-to-train jitter. However, the long bunch train also has some liabilities: a novel damping ring with a 15 km circumference is required to store all of the bunches at once and one cannot design a conventional positron source that could produce the required bunch train.

The JLC/NLC design operates at an rf frequency which is four times that of the SLC linac. This allows for a higher loaded acceleration gradient of roughly 60 MV/m but it also implies stronger wakefields which were a significant limitation in the SLC operation. To deal with this problem, the JLC/NLC beam parameters have been chosen such that the effect of the wakefields on the beam dynamics is actually about four times less than in the SLC. Regardless, the design must rely on beam-based alignment techniques to attain the needed alignment tolerances. Furthermore, the shorter bunch train makes intra-train feedback a more difficult proposition and thus stability is very important. In addition, the higher rf frequency makes the rf sources significantly more difficult than in the SLC although research over the last decade has produced rf systems that meet the requirements.

Finally, the CLIC design operates at 30 GHz to allow for even higher acceleration gradients. However, at this frequency conventional rf sources are believed to be substantially more difficult and thus the CLIC design is based on a Two-Beam Accelerator (TBA) concept where the rf power is extracted from a drive beam, traveling adjacent to the primary beam, and transfered to the primary beam accelerator structures; although not as well tested as the more conventional rf systems, the TBA scheme extends to multi-TeV operation in a straightforward manner. At the higher rf frequency, the wakefields are still stronger (scaling as f_{rf}^3) than in the JLC/NLC design. However, for properly scaled beam parameters, the alignment tolerances only decrease inversely with the rf frequency [7] and thus the tolerances are comparable to those in the JLC/NLC design.

3 MAIN LINACS

In this section, we will discuss three issues which are related to stability in the main linacs: the Beam Break-Up (BBU) instability, diagnostic and magnetic field stability which is important for the beam-based alignment techniques, and beam-based feedback systems.

3.1 Higher-Order Modes & Beam Break-Up

In all designs, the main linacs operate with long trains of bunches to improve the rf efficiency. However, with the long bunch trains, the transverse wakefield must be carefully controlled to prevent the BBU instability. Beam break-up will amplify any incoming jitter and could easily make the linac inoperable.

In the NLC design, the 1.8-meter accelerator structures are constructed from 206 cavities, each of which is designed to have a different dipole mode frequency. This detuning causes a rapid decoherence of the long-range wakefield. In addition, as can be seen in Fig. 2, the transverse wakefield is weakly damped, to prevent the modes from re-cohering at a later time, by coupling the cavities to four manifolds that parallel the cavities [8]. However, in the present structure design it is difficult to couple the last few cavities at the end of the structure to the manifold and this results in a few modes that are not sufficiently damped, causing to a severe BBU instability [9]. Once it was identified, a number of methods have been found to solve this problem, however, it illustrates the sensitivity of the beam dynamics to the cavity design; a similar problem has been identified in the TESLA cavities [10].

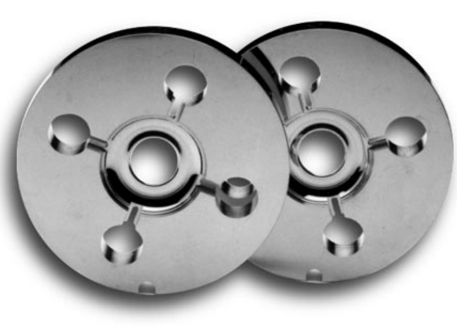

Figure 2: Photograph of two NLC Rounded Damped-Detuned Structure (RDDS) cavities.

3.2 Beam-Based Alignment

In the NLC and CLIC designs, the tolerances are sufficiently tight that the accelerator structures and focusing quadrupoles must be aligned using beam-based alignment techniques. The procedure envisioned for the NLC is similar to the technique used to align the Final Focus Test Beam (FFTB) facility at SLAC, namely:

1. Determine the position of the quadrupole magnetic center with respect to the Beam Position Monitor (BPM) mounted in the magnet by shunting the magnet and observing the downstream deflection

2. Move the quadrupoles to steer the beam through the magnetic center of the magnets

3. Align the accelerator structures to the trajectory using information derived from power measurements on the structure damping manifold [11]

The last two steps are iterated as component positions shift over time; more detail on the NLC scheme can be found in Ref. [12] and similar techniques are thought to be used in the CLIC facility [13, 14].

To facilitate the alignment, both the quadrupoles and the girders supporting the accelerator structures are mounted on remote movers. These techniques rely heavily on the diagnostic performance and on the accuracy of the mover systems. The NLC will use components similar to those developed for the FFTB, i.e. stripline BPMs with 1 μm resolution and movers with a 100 nm step. Depending of the time-scale of the misalignments, this alignment procedure would probably be implemented as a slow-feedback loop. However, there are still questions regarding the reproducibility of the magnetic center and the stability of the BPM electrical center over time. If the magnetic field center shifts significantly during the shunting procedure due to mechanical deformation of the magnet, thermal changes, or variations in the pole permeability, the alignment performance will be degraded [15]; experiments are underway at SLAC to measure the stability of the magnetic center. Similarly, if the electrical center of the BPMs shifts relative to the magnet center, the more time intensive 1^{st} step must be repeated.

3.3 Beam-Based Feedback

In future linear colliders, both train-to-train and intra-train beam-based feedback will be used to significantly ease tolerances that would be otherwise difficult to attain. Pulse-to-pulse beam-based feedback has been used extensively at the SLC to improve the operation of the collider. However, there were a number of difficulties using the feedbacks and the system gain was usually greatly reduced. Because of the importance of feedback in a future linear collider, we need to understand the performance limitations of the SLC systems.

The biggest limitations are believed to arise from the wakefields in the SLC linac at high current; actually, during low current tests in 1996, the feedback systems performed as expected. The wakefields have two primary effects [16]: they make the transport nonlinear along the linac length and they cause correlations along the beam that are not simply corrected by correcting the centroid as illustrated in Fig. 3. The former effect can be corrected by having the upstream feedback loops communicate with all downstream loops rather than the simpler linear cascade used in the SLC. The second limitation can be remedied by increasing the number of BPMs used by the feedback loops and minimizing the measured trajectory in an rms sense. Both of the these solutions require significant increases in the feedback processing rate and communication bandwidth.

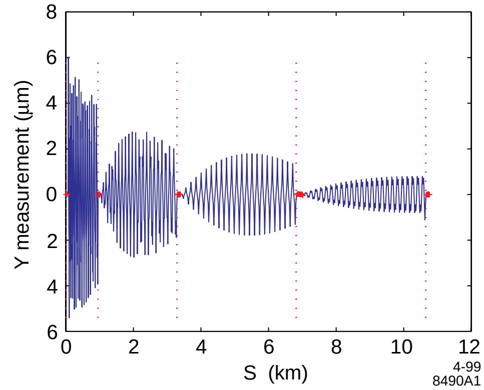

Figure 3: Simulation of SLC-style feedback in NLC linac; the dotted lines indicate the feedback locations.

Different limitations arise with the intra-train feedbacks. In particular, intra-train feedback will be very useful to relieve the tight jitter tolerances on the final focusing magnets. However, the system is complicated by the nonlinearity of the beam-beam deflection and the difficulty of separating angular separations from position offsets; an example of such a system is described in Ref. [17].

4 DAMPING RINGS

The damping rings for these colliders must produce very low emittance beams and they have all of the problems of the 3^{rd} generation synchrotron radiation sources, i.e. strong focusing optics with small dynamic aperture, heavily loaded rf systems, small impedance budgets, etc. For example, the NLC damping rings operate with an average beam current of roughly 1 A and need to produce beams with emittances of $\epsilon_{x,y} = 0.8$ nm-rad and 8 pm-rad [18].

In all the designs, the rings always operate in a transient regime where beams are injected and extracted at the collider repetition rate. This makes stability difficult but a very stable extracted beam phase space is extremely important for the operation of the rest of the collider; jitter of the beam will lead to emittance dilution and will make the beam-based tuning techniques extremely difficult. We will mention a few of the more difficult issues below.

4.1 Injection/Extraction Kickers

As stated, the rings operate with bunch trains injected and extracted at the collider repetition rate. In the JLC/NLC and CLIC rings, the full bunch train must be injected or extracted at once; these rings damp multiple trains of bunches at the same time and the trains are separated by a gap for the kicker to rise or fall (65 ns in the NLC rings). In the TESLA ring, the bunches are separated by roughly 10 ns and are extracted at a rate of one every few hundred nanoseconds to produce the TESLA bunch train. To avoid emittance dilution, the beams are injected and extracted on axis. This requires a large kick—typically the order of a few milliradians.

The required stability on the kicker is determined by the extracted horizontal emittance. In the NLC design, it is $\Delta\theta/\theta \lesssim 4 \times 10^{-4}$; this tolerance can be eased using a double kicker system [4] but is still a tight constraint for a pulsed device.

4.2 Instabilities

Another source of pulse-to-pulse or intra-train jitter are instabilities. First, to control the multi-bunch instabilities, the damping rings must use damped rf cavities and care must be taken in the design of all the vacuum components to avoid high-Q resonances. Furthermore, the rings require bunch-by-bunch feedback systems similar to those employed at the recently commissioned Φ-factory and the B-factories. The feedback gain requirements are determined by the chamber impedance, the expected injection errors, and the need to damp all transients by the time of extraction, however, one must be careful not to set the gain so high that noise from the feedback pickups or processing is amplified to point of being a significant source of jitter.

Second, to control the single bunch instabilities, the vacuum chamber must be designed to have a very low broadband impedance. For these rings, the longitudinal microwave instability usually has the lowest single bunch threshold. This microwave instability is frequently considered a 'benign' instability, however, bursting manifestations, like the 'sawtooth' instability observed in the SLC damping rings [19], are a limitation because of the sensitivity of the downstream systems to jitter sources. In the SLC, a 3% variation of the longitudinal distribution in the ring was clearly observable in the linacs [20]. Unfortunately, with further scrutiny, it appears that bursting modes of instability are prevalent in storage rings.

Finally, because of the low beam emittances and high densities, novel instabilities such as the fast beam-ion instability [21] or electron cloud instabilities [22] are potential limitations. At this time, there is insufficient experience with these effects to fully understand their implications however it is expected that they will impose severe constraints on the vacuum system design.

4.3 Transients

Other collective effects are directly related to the transient nature of the damping ring operation. Because beams are being injected and extracted at the collider repetition rate, one must be sure that all injection transients damp to levels small compared to the extracted beams by the time of extraction. This is complicated because most rings damp multiple bunch trains at once and the long-range wakefields can couple an oscillation from the most recently injected bunch train to drive a damped train to large amplitude even if the ring is 'stable' [23].

Another form of transient arises because of the gap between bunch trains which exists for the injection/extraction kickers in the NLC and CLIC rings and is created during the slow injection or extraction process in the TESLA ring. Here, the gap causes transient loading in the rf cavities which leads to a variation in rf phase along the bunch train; a similar effect in the transverse will cause a variation in position along the train.

4.4 Vibration and Slow Drifts

The final topic for the damping rings that we will mention is the effect of vibration or drifts. Fortunately, because of the high revolution rate, the effect of component vibration and drift on the trajectory can be treated using feedback in a manner similar to that used by the synchrotron light storage rings. However, it is also important to control the vertical equilibrium emittance which in the NLC rings is roughly 0.7% of the horizontal. This means controlling the coupling and the vertical dispersion which are more difficult to directly stabilize using feedback because the measurement is more complex; it is presently thought that accurate control of the trajectory will be sufficient although this needs verification.

In addition, the beam energy needs to be held fixed to a fraction of the natural energy spread. This arises because the bunch length is compressed by rotating the longitudinal phase space by roughly 90°. Thus, energy fluctuations from the ring turn into phase errors in the linacs which will cause energy errors at the IP and will shift the IP position.

To avoid shifts in the beam energy, the nominal-energy path length must be controlled. The path length can be varied due to orbit changes where the dispersion is non-zero or changes in the ring circumference. In the NLC damping rings, the variation of the circumference must be less than 18 μm to keep the beam energy changes to less than 0.01%. The observed changes in operating synchrotron radiation sources are over an order-of-magnitude larger; a method of controlling the path length is described in Ref. [24].

5 BEAM COLLIMATION AND MACHINE PROTECTION

Finally, the last problem we will mention is beam collimation and machine protection; this is a problem faced by all the linear collider designs. The collimation is needed because transverse particle tails get populated due to the transverse wakefields, beam-gas, beam-photon, and intrabeam scattering processes, and energy errors combined with chromatic effects. These large amplitude particles can generate backgrounds in the detector if they impact at small apertures in the final telescope or generate synchrotron radiation in the quadrupoles which impacts further downstream. In the NLC final focus design, the later effect limits the effective aperture to roughly $12\sigma_x \times 45\sigma_y$.

While $12\sigma_x \times 45\sigma_y$ may sound like large amplitude, the nominal linac beam sizes are $10 \times 1\,\mu$m. Thus, without increasing the beta functions significantly, the collimation would have to be performed at the $50 \sim 100\,\mu$m level. Unfortunately, the wakefields from these narrow gaps are very severe and could cause unacceptable emittance dilution or jitter amplification [25]. In addition, the very dense beams could destroy the collimators.

There are two primary ways in which the beams can damage the collimators: dE/dx heating when the beam passes through the collimators and ohmic heating by the image currents when a beam passes close to the collimator surface. The collimator could be damaged if the sudden thermal shock due to the beam causes stresses that exceed the tensile strength of the material. For Cu, this is expected to arise for $\Delta T \sim 200\,°$C, while for Ti or W, the limit is closer to $\Delta T \sim 800\,°$C. For comparison, the expected temperature rise in a thin Cu iris due to impact by the full bunch train at the end of the NLC linac is $\Delta T \sim 8 \times 10^5\,°$C.

The solution proposed in Ref. [4] is to increase the nominal beam size so that a spoiler system could withstand the passage of a full bunch train. This solution also acts as a partial component of the Machine Protection System (MPS) [26] which has a difficult task since the nominal beams can destroy the beamline components. However, this solution is also quite lengthy and uses very strong optics with large nonlinearities to generate the needed beta functions. The resulting tolerances and energy bandwidth are actually tighter than that in the final focus.

Our present concept is to reduce the passive survival constraint on the collimation system to only ensure survival for off-energy beams, a frequent occurrence in a linac, and use sacrificial devices to collimation the betatron phase space because large betatron errors without a corresponding energy error are infrequent. Further study on the material limitations, the collimator wakefields, and the optical solutions is still needed.

6 CONCLUSIONS

In this paper, we have discussed some of the remaining challenges in the designs of the next-generation linear colliders. These designs are all very advanced and have dealt with most of the technical problems. However, there are still a number of unresolved issues related to operation with the very small beams needed to achieve the high luminosities that are specified. These problems should be addressed over the next couple of years.

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