EMITTANCE DILUTION IN 1 AND 5 TeV 30 GHz LINEAR COLLIDERS

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Abstract

In this paper, we describe the single and multi-bunch sources of emittance dilution in the linacs of both 1 and 5 TeV center-of-mass energy linear colliders. The linacs operate at high rf accelerating gradients with a frequency around 30 GHz. At this high accelerating frequency, the wakefields are very strong and we discuss the BNS damping and correction procedures as well as the alignment and construction tolerances that are required to preserve the transverse emittance. Finally, because the collider must operate with long bunch trains, we consider the multi-bunch emittance dilution for a few cases where either the long-range transverse wakefield is damped or it is decreased by a combination of weak damping and detuning.

1 INTRODUCTION

In this paper, we discuss the emittance dilutions in linacs for linear colliders with center-of-mass energies (cms) between 1 and 5 TeV. The 5 TeV collider is based upon the design described in Refs. [1, 2] while the 1 TeV version is similar to the CERN Compact LInear Collider (CLIC)[3] although using slightly different parameters which have been optimized to reduce the effect of the transverse wakefields. The primary beam parameters for both cms energies are listed in Table 1.

Center-of-mass energy [TeV]	1	5
Luminosity [$10^{33} cm^{-2} s^{-1}$]	10	100
Part. per bunch (N) [10^{10}]	0.4	0.3
Bunches per train (n_b)	45	200
Bunch spacing (Δt) [ns]	0.5	0.5
Bunch length (σ_z) [μm]	50	35
Emit. from DR ($\gamma\epsilon_{x/y}$) [10^{-8}]	100 / 5	40 / 0.5
Emit. at FF ($\gamma\epsilon_{x/y}$) [10^{-8}]	125 / 10	50 / 1

Table 1: Beam parameters for 1 and 5 TeV colliders

In both cases, the accelerators are based on 30 GHz rf power. This relatively high rf frequency allows for much higher acceleration gradients *without* significantly more severe alignment tolerances[2, 4]. Even though the wakefields are much stronger in the high frequency structures, this scaling arises because the optimized charge and bunch length are much smaller and thus the *effect* of the wakefields and the required tolerances are comparable to those in lower frequency designs.

The primary sources of emittance dilution that we considered are due to misalignments, both static and time-varying, of the accelerator sections, quadrupoles, and BPMs. Simulations were performed using the codes LIAR[5] and MBTR[6] which differ slightly in the models utilized but give similar results. In the next sections, we first describe the linacs that were studied and then discuss the single bunch dilutions, the multi-bunch beam break-up and emittance dilution, and finally, the jitter and stability issues.

2 LINAC DESIGNS

The loaded accelerating gradient is 100 MV/m in the 1 TeV case while it is twice that in the 5 TeV design. Both designs have an injection energy of 10 GeV and the linacs are constructed from standard FODO arrays. In addition, the lattice cell lengths and beta functions, for the 1 and 5 TeV cases, scale roughly with the beam energy to the powers 0.4 and 0.5 and are arranged into 5 or 6 separate sectors, respectively. The linac parameters are listed in Table 2 and the vertical beta function in the 5 TeV design is shown in Fig. 1.

Center-of-mass energy [TeV]	1	5
Loaded acc. gradient (G) [MV/m]	100	200
Beam loading	15.7	12.3%
Total linac length [km]	8.1	15.8
Active/total length	65%	80%
Initial energy [GeV]	10	10
Init. cell length [m]	6.6	7.2
Approx. energy scaling	0.4	0.5
Average rf phase (ϕ_{rf})	$-13°$	$-5°$
Energy overhead for BNS	2%	1%

Table 2: Linac parameters for 1 and 5 TeV colliders

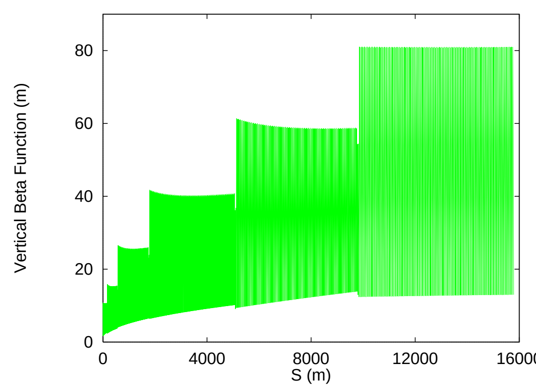

Figure 1: β_y in a linac of the 5 TeV collider.

In most sectors, the phase advance per cell starts at roughly 90° $\sim$100° and then slowly decreases, reducing the variation of the energy spread required for ‘autophasing’[7] which is used to control the single bunch beam break-up. In the 1 TeV case, this required energy spread is roughly 0.8% rms while it is about 0.4% rms in the 5 TeV case. Finally, the average rf phase required to achieve a final relative energy spread of 0.8% full width is -13° and -5° for the two cases while the energy overhead required to vary the rf phases and implement the autophasing is roughly 1$\sim$2%.

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3 SINGLE BUNCH DILUTIONS

The primary single bunch emittance dilutions are due to the transverse wakefields and the non-zero beam trajectory that arises from quadrupole and BPM misalignments. As listed in Table 3, we have assumed tolerances of 10 μm random misalignments of the accelerator structures and 2 μm alignment between the quadrupoles and the BPMs; the initial quadrupole alignment is not important. These values are similar to those used in the NLC design[8] and would be attained using beam-based alignment. Specifically, the accelerator structures could be aligned to the beam trajectory by measuring the beam induced dipole mode power and the quadrupole-to-BPM alignment could be determined by varying the quadrupole strengths; more details on the alignment techniques can be found in Ref. [8].

Center-of-mass Energy [TeV]	1	5
Tolerance on quadrupoles [μm]	100	100
Tolerance on rf struc. [μm]	10	10
Tol. on BPM-to-quad [μm]	2	2
Correction procedures	1-to-1	1-to-1 & ϵ-bumps
Single Bunch $\Delta\epsilon_y/\epsilon_y$	45%	33%
Full Train $\Delta\epsilon_y/\epsilon_y$	46%	37%
Emittance Budget	100%	100%

Table 3: Tolerances for 1 and 5 TeV colliders; the 1 TeV version only uses 1-to-1 trajectory correction while the 5 TeV collider also requires the use of emittance bumps similar in concept to those used in the SLC.

With these tolerances and correcting the trajectory with the simple 1-to-1 method, we find ~50% vertical emittance growth in the 1 TeV design and ~200% growth in the 5 TeV case. While with the 1 TeV parameters, the emittance dilution after the 1-to-1 trajectory correction is acceptable, this is not the case at 5 TeV and thus some additional form of emittance correction has to be considered.

3.1 Emittance Correction

There are a number of possible emittance correction techniques. In this paper, we describe a global correction technique where emittance tuning 'bumps' are varied to minimize the emittance at emittance diagnostic stations located along the linacs; a similar technique is routinely used at the Stanford Linear Collider (SLC) to reduce the vertical emittance dilution from roughly 1000% to about 100%[9]. In our case, the emittance tuning bumps are constructed from pairs of accelerator structures which are separated by 90° in betatron phase and are located upstream of the diagnostic stations. The results of simulations are shown in Fig. 2 where five sets of bumps reduce the emittance dilution from roughly 190% to about 35%. Finally, results using an alternate technique, where the phase advance along the linac is varied by small changes in the quadrupole strengths, are describe in Ref. [10]; here, a similar six-fold reduction was also found.

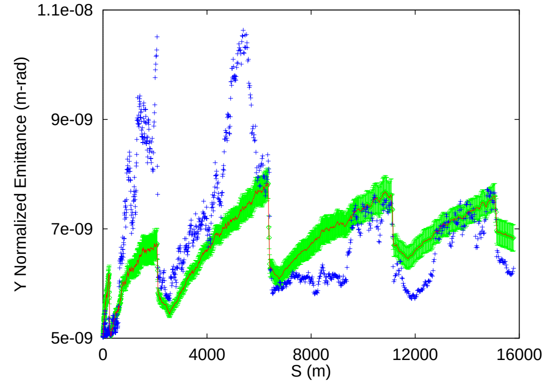

Figure 2: Simulation of emittance growth versus distance in 5 TeV linac after correction using 5 pairs of movable accelerator structures to minimize the emittance at the emittance diagnostic stations; the line is the average of 40 different error distributions with error bars to denote the variation while the crosses are the results from one of the 40 cases.

4 MULTI-BUNCH DILUTIONS

Multi-bunch beam break-up will limit the bunch-to-bunch spacing. In these high energy linacs, the amplitude of the long-range transverse wakefield is reduced by 'detuning' the dipoles modes so that there is a spread in mode frequency and/or by damping the wakefield directly. In either case, the wakefield decays rapidly with time. Thus, the threshold for multi-bunch instabilities, which is proportional to both the bunch charge and the wakefield, is extremely sensitive to the bunch separation.

We have calculated the emittance dilution that arises from an injection trajectory error versus the bunch separation assuming a wakefield calculated by scaling the NLC DDS accelerator structure[8] to 30 GHz. The dilution remains roughly equal to the single bunch dilution until the bunch separation is reduced to 10~12 rf buckets where the beam break-up becomes significant. Similar results are found using the wakefield for the CLIC damped structure[11] but the CLIC DDS accelerator structure[12] does not perform as well at the shorter bunch spacing because it was optimized for a bunch spacing of 30 buckets.

If the multi-bunch beam break-up is small, the multi-bunch emittance dilutions are also usually small when compared to the single bunch emittance dilutions. Assuming the tolerances described in the previous section, we find that this is true for both the 1 and 5 TeV cases; as listed in Table 3, the dilutions with a full bunch train are very similar to the single bunch dilutions.

5 JITTER AND STABILITY

One of the big liabilities in a large linear collider is the sensitivity to vibration and drifts. We can separate the motion into three regimes: motion due to ground waves which tends to be highly correlated, high-frequency motion which is essentially random from magnet-to-magnet (jitter), and slow drifts where the elements perform random-walk type movements.

5.1 Correlated Ground Motion

At low frequencies ($f \lesssim$10 Hz), where the wavelength is long compared to the betatron wavelength, the correlated ground motion has little effect on the beam; the beam simply follows the ground contour. In addition, the trajectory feedback systems further reduce the sensitivity to the low frequency motion. Calculations, based on measurements at SLAC[8], show that, in the worst case, the induced beam motion would be less than 5% of the beam size.

5.2 Jitter

The jitter tolerance, to limit the beam motion to 25% of the beam size due to uncorrelated magnet vibration, is 4.5 nm in the 1 TeV design and 1.2 nm in the 5 TeV design; the reduction is primarily due to the smaller beam sizes in the higher energy case. This imposes tight, although not unreasonable, tolerances on the man-made or 'cultural' vibration; measurements at the ALS in Berkeley and the FFTB at SLAC have observed roughly 1 nm difference between quiet conditions where the magnet motion is simply due to ground motion and noisy conditions where all systems where operational. If necessary, additional stabilization could be provided by using either active or passive damping.

5.3 Drifts

Slow drifts of the accelerator components are frequently described with the 'ATL' relation[13] which assumes that the magnet positions along the linac perform a random walk in both time and separation. In this case, the expected difference in transverse position between any two locations will vary as $\langle \Delta y^2 \rangle = A \star T \star L$ where T is the time between successive measurements, L is the distance separating the two locations, and A is a coefficient that depends on the geological conditions of the surrounding environment. For our calculations, we use a coefficient A=5$\times 10^{-7}\ \mu^2/s/m$. This is larger than values measured in the FFTB tunnel at Stanford Linear Accelerator[14] but is smaller than measurements at some other laboratories.

In the 1 TeV case, the emittance dilution increases by roughly 50% after 30 minutes which is similar (50% faster) to the NLC design. The dilution increases roughly 3 times faster in the 5 TeV case as is illustrated in Fig. 3. This suggests that, in the 5 TeV case, the beam trajectory should be re-steered (using 1-to-1 correction) every 5 minutes to constrain the time-averaged dilution to roughly 15%. Alternately, a similar correction procedure could be implemented as a slow steering feedback loop. In either case, there should be minimal luminosity impact.

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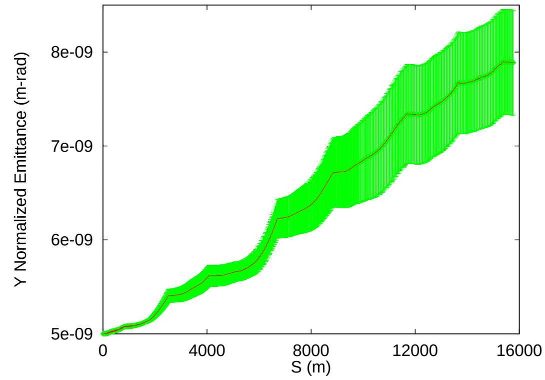

Figure 3: Simulation of emittance growth versus distance in the 5 TeV linac due to ATL motion after 10 minutes with coefficient $A = 5 \times 10^{-7}$; the simulation includes seven feedback stations that constrain the beam trajectory along the length of the linac and the results are the average of 40 different seeds with error bars denoting the variation.

7 REFERENCES

[1] P. Chen *et al.*, "A 5 TeV Linear Collider on the NLC Site", *Proc. of 1996 DPF/DPB Snowmass Meeting* (1996).

[2] J.P. Delahaye *et al.*, "A 30 GHz 5 TeV Linear Collider", *submitted to these proceedings*.

[3] CLIC is a 0.5∼1 TeV e^+e^- linear collider design using 30 GHz rf and operating as a Two-Beam Accelerator where a low energy 'drive' beam is used to generate the rf.

[4] J.P. Delahaye *et al.*, "Scaling Laws for e^+e^- Linear Colliders", Clic–Note–333 (1997).

[5] R. Assmann *et al.*, "LIAR—a simulation code for LInear Accelerator Research", *Proc. of the 1996 Linac Conf*, Geneva, Switzerland (1996).

[6] G. Guignard *et al.*, "Multibunch Emittance Preservation in CLIC", *Proc. of the 1996 Eur. Part. Acc. Conf.*, Sitges, Spain (1996).

[7] V. Balakin, *Proc. 1988 Workshop on Linear Colliders*, SLAC–report–355 (1989) p. 55.

[8] NLC ZDR Design Group, "A Zeroth Order Design Report for the Next Linear Collider", SLAC Report–474 (1996).

[9] J.T. Seeman, F.J. Decker, I. Hsu, "The Introduction of Trajectory Oscillations to Reduce Emittance Growth in the SLC Linac", *Proc. of 15th Int. Conf. High Energy Acc.*, Hamburg, Germany (1992) p. 879.

[10] G. Guignard *et al.*, "Beam Characteristics versus Cavity Models in CLIC", *submitted to these proceedings*.

[11] M. Dehler *et al.*, "CLIC Waveguide Damped Accelerator Structure Studies", *Proc. of the 1996 Linac Conf.*, Geneva, Switzerland (1996) p. 734.

[12] M. Dehler *et al.*, "Design of a 30 GHz Damped Detuned Accelerating Structure" *submitted to these proceedings*.

[13] V. Shiltsev, "Space-Time Ground Diffusion: the ATL Law for Accelerators," *Proc. of the 4th Int. Work. on Acc. Align.*, Tsukuba, Japan (1995).

[14] R. Assmann *et al.*, "Beamline Stability Measurements with a Stretched Wire System in the FFTB," *Proc. of the 1996 Linac Conf*, Geneva, Switzerland (1996).