SLAC-PUB-10556
July 2004

EMITTANCE DILUTION SIMULATIONS FOR NORMAL CONDUCTING AND SUPERCONDUCTING LINEAR COLLIDERS *

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Abstract

An electron (or positron) multi-bunch train traversing several thousand accelerator structures can be distorted by the long-range wakefields left behind accelerated bunches. These wakefields can at the very least, give rise to a dilution in the emittance of the beam and, at worst can lead to a beam break up instability. We investigate the emittance dilution that occurs for various frequency errors (corresponding to small errors made in the design or fabrication of the structure) for the GLC/NLC (Global Linear Collider/Next Linear Collider) and for TESLA (TeV Energy Superconducting Linear Accelerator). Resonant effects, which can be particularly damaging, are studied for X-band and L-band linacs.

Paper presented at the 2004 9th European Particle Accelerator Conference (EPAC 2004)
Lucerne, Switzerland
5th - 9th July 2004

This work is supported by Department of Energy grant number DE-AC03-76SF00515*

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An electron (or positron) multi-bunch train traversing several thousand accelerator structures can be distorted by the long-range wakefields left behind accelerated bunches. These wakefields can at the very least, give rise to a dilution in the emittance of the beam and, at worst can lead to a beam break up instability. We investigate the emittance dilution that occurs for various frequency errors (corresponding to small errors made in the design or fabrication of the structure) for the GLC/NLC (Global Linear Collider/Next Linear Collider) and for TESLA (TeV Energy Superconducting Linear Accelerator). Resonant effects, which can be particularly damaging, are studied for X-band and L-band linacs.

INTRODUCTION

We investigate the emittance dilution that occurs from the long-range wakefield left behind accelerated bunches in the main linacs of two linear colliders. RF parameters for each collider are given in table 1.

The GLC/NLC collider [1] is designed to operate at room temperature and at a frequency 4 times that of the present SLAC collider using travelling wave linacs. The 500 GeV centre-of-mass collider is comprised of 17,856 accelerator X-band structures in total. The Q of the accelerating mode of each structure is ~ 7000 and this gives rise to an 'e-folding', length that prescribes an RF structure filling time of ~100 ns. The Q limits the number of bunches to 192. The average iris size sets the intra-bunch wakefield, as it is proportional to $a^{-3.8}$ (in units of λ_{RF}). We chose a ~ 0.17 in order to attain manageable beam-based structure alignment and BNS [2] damping of short range wakefields. The long-range wakefields can dilute the emittance of the beam and can give rise to a BBU instability [3]. To avoid the deleterious effects of these wakes we force the individual modes of the wakefield to add de-constructively by detuning the dipole frequencies of the cells in precise manner. As there are, of course, a finite number of cells then eventually the wake re-coheres. To minimize the remaining wake we provide 4 damping manifolds per structure to couple out a portion of the remaining wake.

For the TESLA design [1,4], as the cavities are superconducting, then the losses are minimal and the fill time and the length of the train of particle bunches can be very long. For this reason 2820 bunches are in the charged particle train, which is 950 μs long. Each cavity consists of 9 cells, operating in the standing wave mode and with a π phase advance per cell. There are close to 21,000 cavities in the collider. Errors in fabricating the cells and indeed in simulating the structure dimensions can reduce the effectiveness of the damping markedly for the GLC/NLC and, under appropriate conditions, can reduce the emittance dilution for TESLA. Here we consider, frequency errors that are repeated from cell-to-cell and from structure-to-structure.

Quantity	Symbol	X	L
Accelerating freq. (GHz.)	f_{acc}	11.424	1.300
Loaded gradient (MV/m)	G_{acc}	50	23.4
Bunch train length (T_{fill})	T_b	2.3	2.3
Bunch spacing (T_{RF})	T_{bb}	16	438
Charge per bunch (10^{10})	N_e	0.75	2
Structure Iris radius (λ_{RF})	a	0.17	0.15
Bunch length (μm)	σ_z	110	300
Pulse rate	f_{rep}	120 150	5

Table 1: Parameters for the X-band and L-band linacs of each collider

The paper is organized in two main sections. The following section describes the implications of systematic frequency errors on the GLC/NLC collider including the effect of random frequency errors. In the last main section we investigate frequency errors for the TESLA collider. In all simulations we assume all cells and cavities are perfectly aligned.

GLC/NLC X-BAND LINACS

The long-range transverse wakefield in each of the accelerating structures that comprise the X-band linacs, is forced to decohere by carefully changing the iris and cavity dimensions such they have an error function profile. Additional damping is provided by 4 manifolds and 4-fold interleaving of neighboring structures [5]. This results in quality factors for the dipole modes of the accelerating structure of the order of 500. We utilize LIAR[6] to track the beam down the linac under influence of long-range wakefields with an injection offset of the beam of 1μm and an initial normalized emittance of 20 nm.rads. The results of these simulations are illustrated in Fig 1 where the structures have been subjected to various frequency errors. For the case of no random errors, indicated in Fig. 1 (A), no appreciable emittance dilution occurs over a very wide band $\Delta s_b/s_b$. The largest emittance dilution occurs at $\Delta s_b/s_b$~0.88% and the corresponding phase space at this bunch spacing, shown in Fig. 1 (F), reveals that the bunches are well-contained in normalized phase space. The next simulation, Fig. 1 (B), is performed under identical conditions as Fig. 1. (A) except that random frequency

* Supported by the Department of Energy, grant number DE-AC03-76SF00515

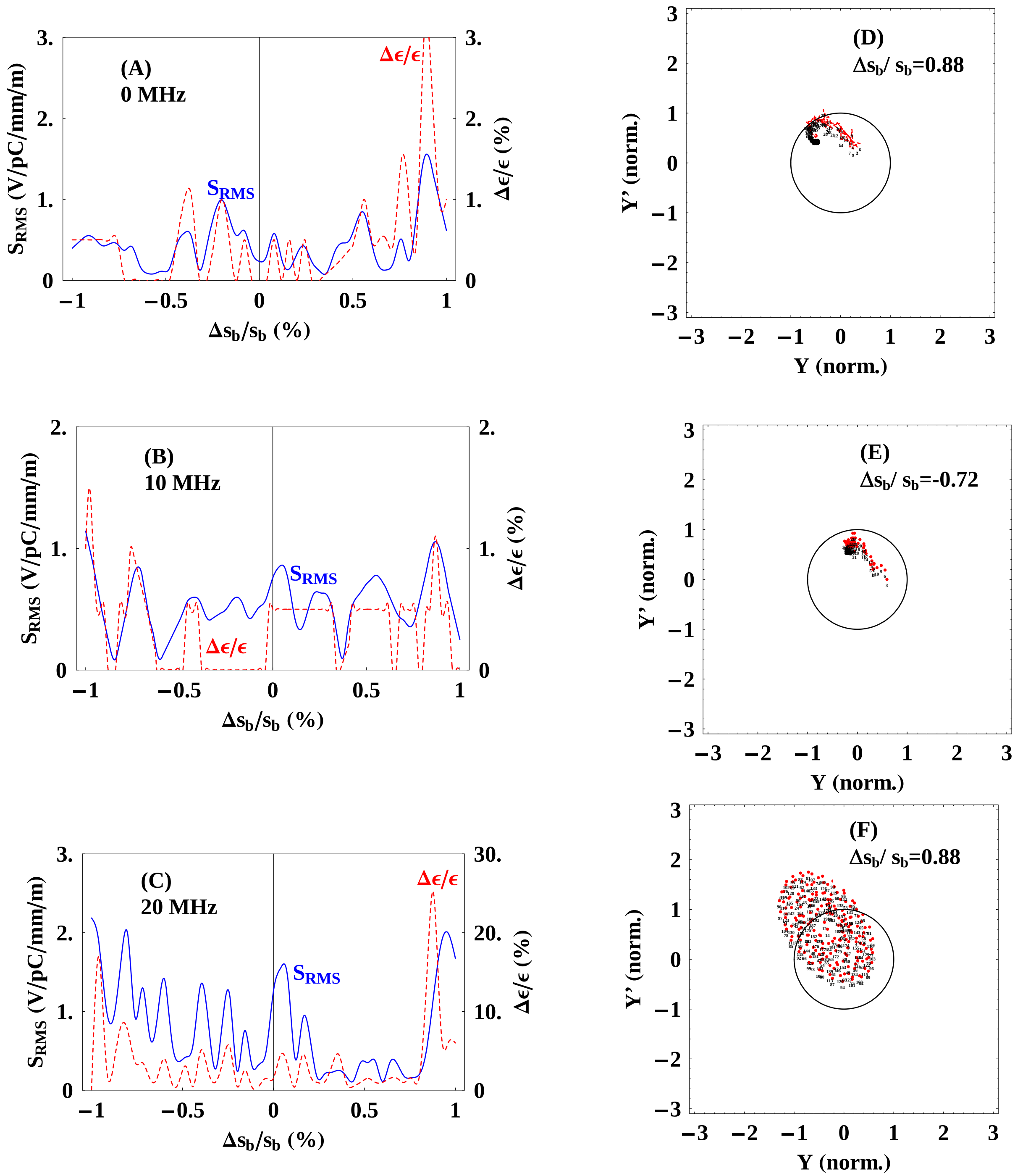

Fig. 1: The percentage emittance dilution that occurs at the end of the NLC X-band linac together with the RMS of the random frequency errors is shown in A to C. The abscissa corresponds to a fractional deviation in the bunch spacing expressed as a percentage of the nominal bunch spacing of 42 cm A small shift in the spacing between bunches leads to a similar effect as would occur from changing all of the cell frequencies by a systematic amount. In all simulations the beam is injected into the linac with an initial offset of 1 μm from the axis of the linac (along the y-axis). The emittance dilution is expressed as a percentage of the injected normalized emittance of 20 nm.rads (along the y-axis). Also shown, in D to F, is the normalized phase space at the points of maximum emittance dilution which are given in regions A to C.

errors, with an RMS value of 10 MHz from cell-to-cell are included in the simulation. It is interesting to note that in this case the overall emittance dilution is.reduced. This remains the case, provided the RMS value of the frequency errors is small compared to the minimum frequency separation of the dipole modes in a single structure, which is ~15 MHz. When the frequency errors are larger than the mode minimum mode spacing in a single structure then the benefits of precise machining are lost. For example, the larger RMS frequency error of 20MHz gives rise to an emittance dilution of ~28% at $\Delta s_b/s_b$ =0.88%. However, in practice frequency errors are likely to occur randomly from structure-to-structure as as well as from cell-to-cell. Recent simulations indicate that 4% emittance dilution occurs under these conditions. Thus the frequency tolerances, and hence machining tolerances on X-band linacs, are rather loose from the perspective of BBU. However, adding tolerances on the alignment of groups of cells gives rise to more stringent frequency tolerances [7].

TESLA L-BAND LINACS

For the TESLA cavities, there are no more than a few modes that interact strongly with the beam in the first three pass-bands. Using HOM couplers attached to the beam pipe at either side of each cavity the Q of these modes is reduced from the ~ 10^9 to below 10^5. Measurements made in the majority of cavities built to date indicate this damping level is achieved. Fig. 2 shows the envelope of the wakefield, together with the Qs and kick factors [8] of the dipole modes. The frequencies and quality factors given here are results from measurements in the single-cavity test setup in 36 cavities [9]

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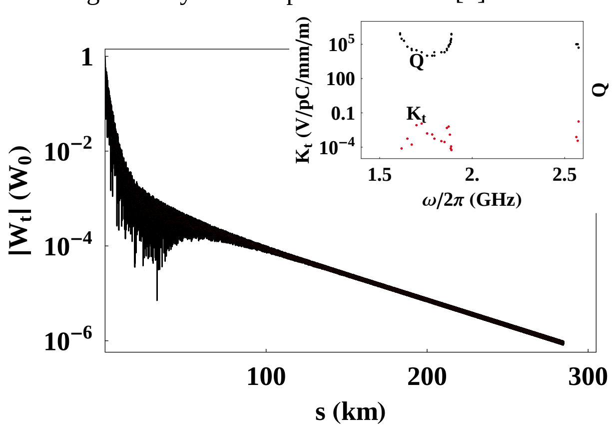

Fig. 2: Envelope of TESLA transverse wakefield. The abscissa runs over the distance of the complete bunch train. The ordinate has been normalised with respect to W_0, (0.11V/pC/mm/m). The kick factors and Q values are shown in the inset.

We inject the beam 4 μm from the axis of the cavities to study the emittance dilution that results from the long-range wakefield. The beam is injected with an initial normalized emittance of 20 nm.rads. There are a limited number of modes with high kick factors to disturb the progress of the beam down the linac. Nonetheless, in our tracking simulations, performed with MAFIA-L [10], we use all modes indicated in Fig 2. The result of this tracking simulation, for two separate cases is shown in Fig 3. At first we track the beam down the complete linac with identical cavities and this we refer to as one class of cavities. In this situation there is significant emittance dilution –in many cases of the order of 1000%. We also display the RMS of the sum wakefield and to some extent there is a correlation between the RMS of the sum wake and the emittance. However, in the BBU region we do not expect the RMS to be well- correlated

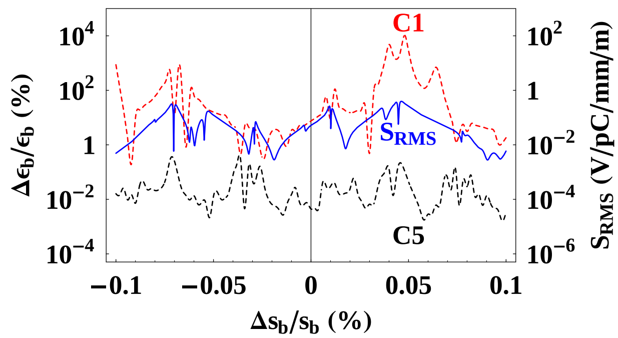

Fig. 3: Emittance dilution, $\Delta\varepsilon/\varepsilon$, for a single class of cavities (C1 shown in red) and for five classes of cavities (C5 shown in black). The RMS of the sum wakefield, S_{RMS}, is also illustrated for a single class of cavities (shown in blue)

with the emittance dilution and, over much of the range in the abscissa the linac is in the regime of BBU. In order to randomize the overall transverse kick the beam receives we add a small linear frequency shift over 5 cavities. We adopt a 1% (~20 MHz) span in frequencies over 5 cavities. This is referred to as five cavity classes (C5) and the results of this simulation indicate that there is a drastic reduction in the emittance dilution as it is now below unity for the complete range in bunch spacings. Further simulations including an RMS error of 0.1% (~2 MHz) indicates that the emittance dilution with 5 classes is reduced even further –the maximum in this case being four orders of magnitude below unity. Thus, for TESLA random errors reduce the emittance dilution significantly and are beneficial to the operation of the linac. Cavity misalignments also dilutes the emittance of the beam and this will be dealt with in a future publication [11].

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