WAKE-FIELDS AND BEAM DYNAMICS SIMULATIONS FOR ILC ACD ACCELERATING CAVITIES

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Abstract

The ILC aims at colliding bunches of electrons and positrons at a centre of mass energy of 0.5 TeV and in a proposed upgrade to 1 TeV. These bunches of charged particles are accelerated in superconducting linacs. The baseline design for the ILC relies on the relatively mature TESLA-style cavities, with a proposed gradient of more than 30 MV/m and is known as the baseline configuration document (BCD). However, here we investigate the electromagnetic fields in superconducting cavities with the potential to reach accelerating gradients in excess of 50 MV/m; these are the subject of the alternative configuration document (ACD). We analyse the necessary damping requirement of the wake-fields in two design configurations: Cornell's Reentrant cavity and KEK's Ichiro cavity. The emittance dilution arising from beams subjected to injection offsets and from cavity misalignments are studied in beam dynamics simulations.

INTRODUCTION

The main superconducting (SC) linacs of the ILC will accelerate electron / positron beams from energies of a few GeV to a center of mass energy of 500 GeV at collision. Efficient operation of the machine demands high luminosity collisions which are achieved by accelerating a train of 2625 bunches of low emittance particle beams. This low emittance must of course be preserved in transport through the main linacs and beam delivery system to the interaction point.

Here we consider the main linacs where the beam quality can be degraded and the emittance can be diluted due to a number of factors including energy spread, phase jitter in cavities, beam position feedback errors, quadrupole magnet misalignments and wakefield effects. Here we focus on the dilution in the transverse emittance due to transverse wakefields and in particular on long range wakefields due to higher order modes in the accelerating cavities [1]. These wakefields have the potential to not only dilute the emittance, but can also cause a beam beak up instability (BBU)[2].

The ILC will employ superconducting cavities operating at gradients above 30 MV/m. It is envisaged that the cavity design will be the TESLA type which has been developed at DESY over a long period [3]. The TESLA is a relatively mature design, however there are still significant concerns regarding the limited yield and reproducibility of high gradient cavities.

There is also a concerted international effort focussed on increasing the gradient of the SC cavities. Reshaping the cavity has allowed the accelerating gradient to be increased without pushing the magnetic field past the quenching limit ($\sim$ 180 mT) on the walls of the cavity [4]. This has allowed cavity designs which in theory will sustain accelerating gradients in excess of 50 MV/m.

In practise only single cell cavities have reached these gradients, at Cornell University [5] with the Reentrant design and at KEK with the Ichiro design [6]. Complete 9-cell cavities are in the process of being fabricated and tested for both designs with a view to achieving similar gradients.

Notwithstanding the fact that both operate at 1.3 GHz, as does the TESLA design, the differing contours of the new cavities necessarily produce a repartioning of the higher order modes that will change the wakefield. These wakefield and beam dynamics issues are the focus of this paper. The transverse long range wakefield experienced by the bunch train is given by:

$$W_T\left(t\right) = \sum_p K_p \sin(\omega_p t) e^{-\frac{\omega_p t}{2Q_p}} \quad (1)$$

where $\omega_p/2\pi$, K_p and Q_p are the modal frequencies, kick factors[1] and damping Qs respectively for the dipole mode p.

These modes have been simulated in detail using parallel finite difference and finite element codes [7, 8] and this data has been used as input for beam dynamics simulations, using the code LIAR [9], which tracks multi-bunch beams through the lattice of the main linac. The envelope of the transverse long range wakefield is displayed in Fig. 1 with a damping Q imposed on all modes of 10^5 for the Ichiro cavity. Here it is evident that after 500 bunches ($\sim$ 50 km) the wake has decayed by 6 orders of magnitude. Thus, in all beam dynamics simulations 500 bunches is sufficient to account for the interaction between the wakefield and the multi-bunch train. We report on the results of these simulations in the next section.

BEAM DYNAMICS SIMULATIONS

A fictious linac made up of identical cavities with identical modal frequencies would impart the same kick coherently from cavity-to-cavity to the accelerated beam. This clearly would resonantly drive BBU and lead to severe emittance dilution. In constructing the ILC linacs approximately 16,000 cavities will be required. During industrial fabrication of these cavities small manufacturing errors will inevitably occur. These will cause each cavity to exhibit slightly different modal frequencies and effectively interleave the resonances. Thus, errors in the frequencies of the modes will occur as a natural consequence of fabricating

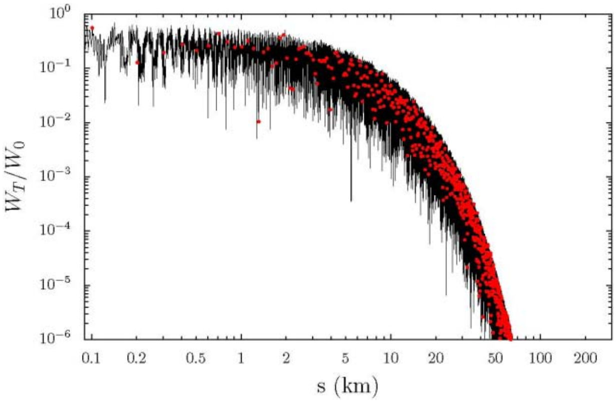

Figure 1: Envelope of the long range transverse wakefield for the Ichiro cavity with $Q = 10^5$, $W_0 = 0.1472$ V/pC/mm/m. Points show the location of the bunches.

these cavities and will allow BBU and severe emittance dilution to be avoided. Indeed, it is expected there will be a Gaussian spread of the order 0.1 MHz [10].

Nonetheless, there will still be emittance dilution and we investigate this by subjecting the beam to an initial injection offset of $\sim \sigma_y/3$ and tracking it down the complete linac.

The simulations detailed here incorporated the manufacturing errors by calculating 50 wakefields based on randomly detuned modal frequencies with an RMS spread of 1 MHz, 3 MHz or 10 MHz and with, initially, a uniform damping Q of 10^6. These 50 wakefields are then randomly distributed through the length of the linac, *i.e.* between the cavities, by LIAR before beam tracking occurs. The results presented here are the average of 100 machines formed with different random number seeds. The complete ILC beam consists of 2625 bunches and we utilised the USCold lattice [11]. The projected emittance for the whole beam was recorded at the end of the tracking procedure.

As shown in Eq. 1 the amplitude of the wakefield depends on $\sin(\omega_p t)$. Random and systematic fabrication errors will alter the mode frequencies as described earlier. The time t is determined by the bunch spacing. Should any modes lie such that ωt is close to $\pi/2 + 2n\pi$ or $3\pi/2 + 2n\pi$ $(n = 0, 1, 2, ...)$ then resonant BBU could occur. By varying the bunch spacing by a small fractional amount $(\pm 0.1\%)$ we can investigate the sensitivity of the long range wakefield to systematic errors in the bunch spacing. This is equivalent to systematic errors in the frequencies of the modes.

Fig. 2 contrasts the resulting emittance dilutions for linacs made up of Reentrant and Ichiro cavities and provided with uniform damping of 10^6 and random frequency spread of 1 MHz. The abscissa in all cases is fractional deviation in the bunch spacing from the nominal design value of 369 ns. In order to assess the dependence of emttance dilution on the spread in frequency errors we increased the RMS random detuning of the higher order modes to 3 MHz and 10 MHz respectively. These results are displayed in Figs. 3 and 4. In all cases we see little dependence on the specific value of the RMS introduced, as expected.

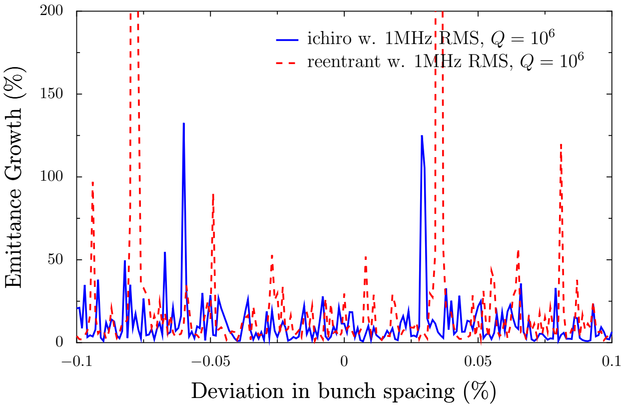

Figure 2: Emitt. dilution, $Q = 10^6$, 1 MHZ RMS spread.

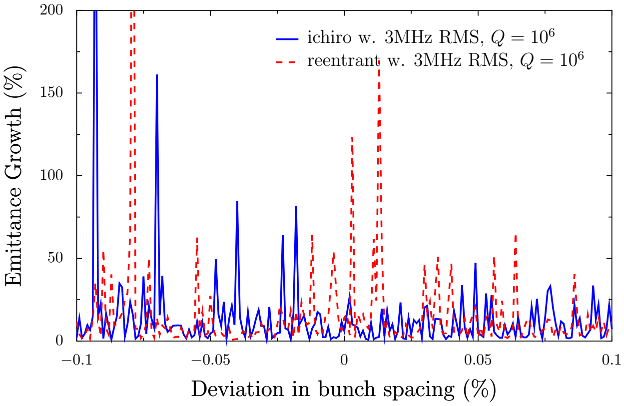

Figure 3: Emitt. dilution, $Q = 10^6$, 3 MHZ RMS spread.

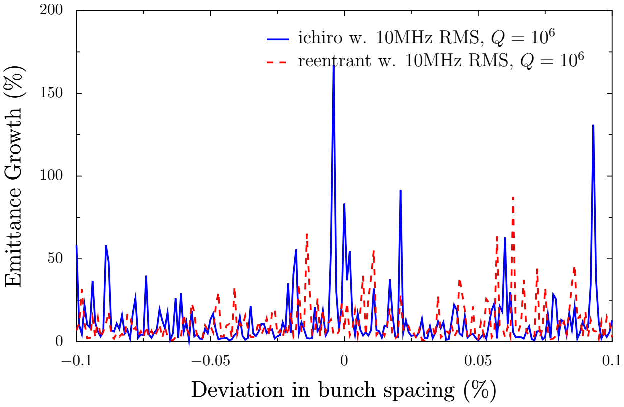

Figure 4: Emitt. dilution, $Q = 10^6$, 10 MHZ RMS spread.

Damping of the Higher Order Modes will be provided by damping couplers which, with careful design, should allow damping to a Q of 10^5 [12]. Figs. 5 and 6 show the emittance dilution resulting in the case of 1 MHz and 3 MHz RMS spread and a uniform damping $Q = 10^5$ for all modes. It is interesting to consider the case in which opti-

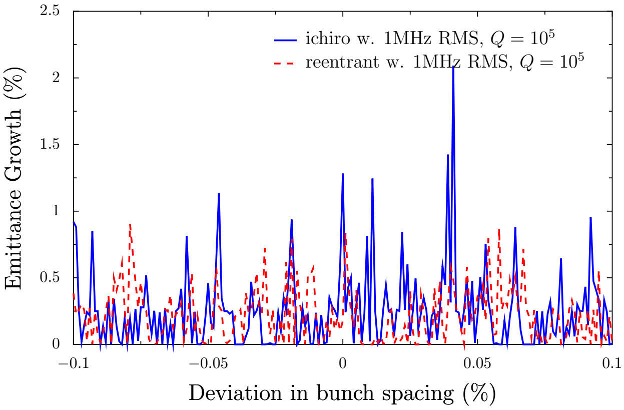

Figure 5: Emitt. dilution, $Q = 10^5$, 1 MHZ RMS spread.

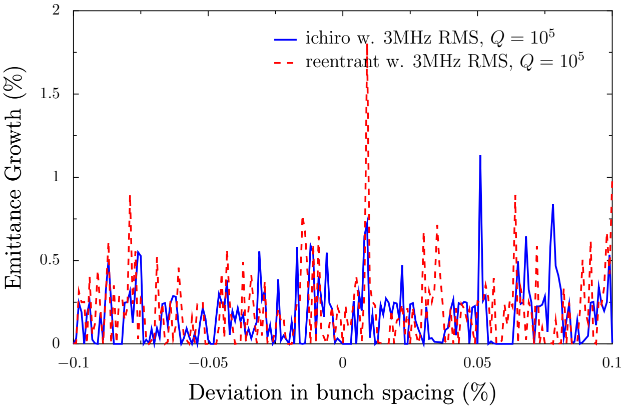

Figure 6: Emitt. dilution, $Q = 10^5$, 3 MHZ RMS spread.

mal damping of all modes has not been achieved and while some are well damped, a limited number of modes remain poorly damped. Such modes are often trapped away from the higher order mode couplers and end cells. In Fig. 7 the case of sub-optimal damping is considered. Here $Q = 10^5$ has only been achieved for the five modes with largest kick factors, which are the most destructive to the beam, the rest of the modes considered were simulated using $Q = 10^6$. This we refer to as targeted damping of the modes as we focus on damping a limited number of modes properly. We investigate the implications on emittance dilution of allowing the remaining modes to be non-optimally damped. This simulation reveals that provided the modes with the highest kick factors are well-damped the emittance dilution is well-contained it is below 10% in all cases.

CONCLUSIONS

Beam dynamics simulations have shown that targeted damping of the most strongly deflecting dipole modes in the Ichiro and Reentrant cavities can suppress emittance growth to below 10% in the main linacs.

Further, the simulations suggest that the emittance growth and long range wakefield do not show much sensitivity to the degree of higher order mode detuning due to manufacturing errors or deliberate frequency detuning as expected.

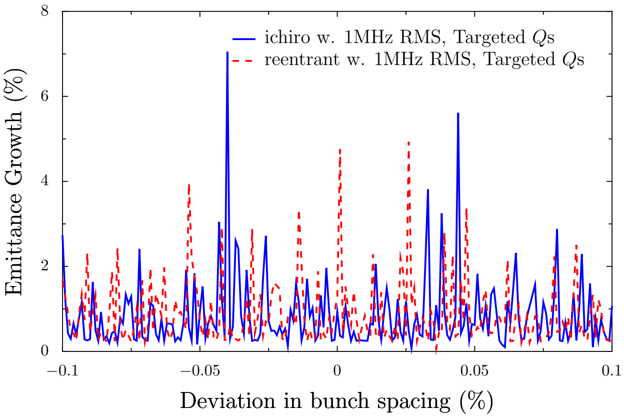

Figure 7: Emitt. dilution, Targeted Damping, 1 MHZ RMS spread.

We note that mode trapping could have a serious effect on beam quality and the cavity cell shapes and coupler positioning must be arranged appropriately to eliminate this possibility.

Continuing work comprises simulations of emittance dilution issues using Lucretia [13] and including short range wakefield effects, realistic component misalignments and long range wakefields.

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