EFFECT OF FILL PATTERNS ON EXTRACTION JITTER IN DAMPING RINGS*

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Abstract

Injection of fresh bunches into a storage ring can induce jitter on stored bunches, as a result of wake field coupling. This transient effect can lead to an undesirable increase in the emittance of stored bunches; in the case of linear collider damping rings, there can also be jitter in the extracted bunches, which can adversely affect performance. We consider how the wake field coupling in a storage ring depends on the fill pattern, and, for the damping rings of the international linear collider (ILC), present the results of simulations of the transverse dynamics with a resistive wall wake field for two different fill patterns. For constant current in the damping rings, it appears that the extraction jitter is only very weakly dependent on the fill pattern.

INTRODUCTION

The performance of a linear collider will depend critically on the emittance and stability of bunches arriving at the interaction point. Electron and positron sources are not capable of producing beams of the necessary quality and stability for planned linear colliders; so the beams will be stored in damping rings between machine pulses, where radiation effects and feedback systems reduce the emittance and coherent oscillations (jitter) of the bunches. However, in some schemes (such as that proposed for the ILC [1]) fresh bunches from the sources begin to be injected into the damping rings before all the damped bunches are extracted. During this process, jitter on the incoming bunches can be coupled to the damped bunches through long-range wake fields. It will be difficult to correct this jitter, since it will be random and uncorrelated. Therefore, it is therefore important to characterise the jitter, and to minimise wake field effects by specifying limits on the injected beam jitter, and on the design of the damping rings themselves.

In this paper, we present the results of a simulation study of transverse jitter induced on bunches extracted from the ILC damping rings, resulting from coupling to the injected bunches through resistive wall wake fields. While other sources of long-range wake fields (such as higher-order modes in the rf cavities) are expected to play some role, initial estimates suggest that the resistive wall wake fields are likely to dominate. Other wake fields can easily be included in our simulations once they have been sufficiently well characterised. Our aim at present is to obtain an idea of the magnitude of the effects that may be expected, and to understand how they relate to design and operational features such as the fill pattern, vacuum chamber, feedback system performance, etc. We focus on effects in the vertical plane: since linear colliders require beams with extremely low vertical emittance (of order 20 nm normalised), their performance will be particularly sensitive to any vertical jitter.

In the following sections, we first describe (in rather general terms) the fill patterns presently specified for the ILC damping rings, before proceeding to discuss the methods used for the simulation studies of bunch jitter coupling through wake fields. Finally, we present results illustrating the impact of injection jitter on the stability of extracted bunches with two different fill patterns, and discuss the implications for the ILC specifications and design.

DAMPING RING FILL PATTERNS

There are a number of strong constraints on the fill patterns that can be used during operation of the damping rings of a linear collider [2,3]. Some of these constraints come from other systems in the collider, such as the positron source. Other constraints come from the need to avoid dangerous effects in the damping rings themselves; so, for example, it is necessary to include regular gaps in the fill to mitigate electron cloud effects or fast ion instability. The present configuration of the ILC damping rings specifies a circumference of 6476 m that allows a number of different fill patterns to be adopted, to provide flexibility in parameters such as the bunch charge and bunch spacing in the linac.

A typical fill pattern consists of a sequence of trains of 45 bunches, separated by gaps of between 30 and 126 rf buckets. Within a train, the bunches are separated by two rf buckets, or about 3.1 ns. The bunch population varies from roughly 10^{10} at the smallest inter-train gap, to about 2×10^{10} at the largest inter-train gap, so that the average current in the ring stays constant at around 400 mA. Injection and extraction will happen on a bunch-by-bunch basis, using fast kickers on opposite sides of the ring. An extraction/injection cycle happens over the course of one machine pulse (approximately 1 ms for the ILC), with bunches stored in the damping rings for the time (approximately 200 ms) between machine pulses.

To avoid jitter on the injected bunches coupling to damped bunches awaiting extraction, it would be necessary to empty the ring completely before injecting the fresh bunches. However, this would not be possible for the positron bunches (where the injection jitter is expected to be large) since the fresh positron bunches are created using the electron bunches in the main linac over

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the course of a machine pulse. Furthermore, the large variation in beam loading while reducing the current in the ring to zero would itself cause problems for beam stability. Therefore, to mitigate the effects of wake field coupling, the fill patterns are designed so that extraction and re-injection start from the rear of each bunch train, and move forward bunch by bunch. This maximises the distance between each freshly injected bunch and the nearest following damped bunch.

WAKE FIELD COUPLING SIMULATIONS

Simulation of bunch movement is carried out in the time domain, and is based on the method described in [4]. Each bunch is treated as a single particle. It experiences two types of transverse forces: one is the force from the magnets, and the other is the force from the wake fields, which we shall call the "wake force". The effect of the magnets is modelled using lattice functions computed by the MAD8 accelerator design software. The dynamical state of each bunch can be described using Cartesian variables or action-angle variables. Working in action-angle variables is convenient for modelling the effects of the magnetic lattice, since evolving the variables over a single time step simply involves increasing the value of the angle variable by the phase advance between the two appropriate points in the lattice. To include the effect of the wake force, we first convert from action-angle to Cartesian variables using the appropriate Twiss parameters, add a "kick" to the transverse momentum, then convert back to action-angle variables. The kick is obtained by summing up the wake forces from all previous bunches, and multiplying by the time step. To calculate this kick, the coordinates of bunches over a number of earlier time steps must be used. The need to store and use this history turns out to be the most time-consuming step of the computation.

We assume that the dominant contribution to the wake fields comes from the resistive wall of the beam pipe. There are contributions from many other sources, such as rf cavity, beam position monitors, antechambers, etc. In [4], we have estimated that the effect of the rf cavities is comparatively small. We hope to study the effects of the other contributions in our future work. The wake force is usually expressed in terms of the product of a wake function and the displacement. The wake function is a function of the distance, z, between bunches. It depends on the structure and materials of the environment of the beam. In the case of transverse wake forces, the wake function is denoted by $W_1(z)$; for resistive wall wake forces, $W_1(z)$ depends on the beam pipe radius and wall resistivity. In [4], we used a conventional formula for the resistive wall transverse wake field, in which $W_1(z)$ varies as $1/\sqrt{z}$. This formula is based on the assumptions that the walls of the pipe are infinitely thick, and that the skin depth is much shorter than the radius of the pipe. Neither assumption is true in general, with the result that, in the parameter regime of the ILC damping rings, the conventional formula gives values for the transverse wake function that are somewhat too small. In order to obtain accurate values, we use the method in [5]. The results are significantly different from the thick wall approximation. We have developed the algorithm to cover the case of a wall constructed from layers of different materials: this would be of interest where coatings, such as titanium nitride or NEG, are used to mitigate electron cloud effects or to improve the vacuum quality. We assume that the cross-section of the vacuum chamber will be circular, although it is possible that an antechamber will be used in much of the ring, to reduce the number of photons in the main part of the chamber.

Time domain simulations involve summing the wake force contributions from bunches over many turns around the ring. A large number of turns can be required for convergence, because the wake force is long range and decreases very slowly with distance. Using a "direct" method to perform the summation, a typical simulation would take 3 months on a 3.6 GHz Pentium 4 computer. In order to overcome this problem, we adopted a method that uses Fourier convolution [6]. In this method, the wake forces are separated into contributions from bunches in different turns in history. The wake force from each bunch is essentially a product of the transverse wake function $W_1(z)$ and the transverse displacement, up to a constant factor. Within each turn, the sum is therefore a discrete convolution of an array of displacement values, and an array of wake function values. For the parameters of the ILC damping rings, using the Fourier convolution method rather than performing the summation directly results in an increase in computation speed by two orders of magnitude.

RESULTS

Our simulation is based on the DCO2 lattice [7], which is the current baseline design for the ILC damping ring. The machine parameters we used are shown in Table 1. Note that our simulations also included a bunch-by-bunch feedback system, which was assumed to reduce the amplitude of coherent oscillations of each bunch with a damping time of 20 turns. The fill patterns used are shown in Table 2.

Table 1: Parameters used in simulation studies.

Harmonic no. (circumference)	14042 (6476 m)
Beam energy	5 GeV
Beam pipe material (conductivity)	Al (3.2×10^{17} s^{-1})
Beam pipe radius	3 cm
Wall thickness	2 mm

Table 2: Fill patterns used in simulation studies.

	Pattern I	Pattern II
Bunches per train	45	45
Bunch spacing (rf buckets)	2	2
Bunch population ($\times10^{10}$)	1.0	1.9
Inter-train gap (rf buckets)	30	126

The simulation is carried out in the vertical plane, where the emittance requirement is most stringent. A random distribution of initial displacement offsets is generated for the injected bunches. The initial history is zero, since there is no wake field from the injected bunches before they are injected, and all stored bunches are assumed to be on the axis of the beam pipe. The system is evolved until all bunches have been extracted; the total length of time required for extraction is equal to the revolution period times the number of bunches per train.

Using a test case with non-zero, random initial history, we found that 50 turns of history must be included before the wake sum converges. The history size is also determined by the number of bunches and by the time step, which must be small enough to sample the variations in the lattice functions around the ring. We found that a time step corresponding to the bunch spacing (3.08 ns) was sufficient. Using double precision, 20 GB of memory space is needed to store 50 turns of history. By summing over only non-zero history, the simulation could be completed in 20 hours.

Bunch jitter can be given as an absolute value, corresponding to the betatron amplitude $2\gamma J$, where γ is the relativistic factor, and J the betatron action of a particle at the centroid of the bunch. This is convenient for specification of the jitter on the injected beam. For the extracted beam, however, we generally specify the jitter in terms of the displacement as a fraction of the specified beam size. The displacement can be written as $y = \surd(2\beta J)$ where β is the beta function; and the beam size is given by $\sigma = \surd(\beta\varepsilon)$, where ε is the specified emittance (2 pm for the ILC damping rings). Hence, the relative jitter is given by $y/\sigma = \surd(2J/\varepsilon)$. Whether specified as an absolute or relative value, the jitter is independent of position around the ring.

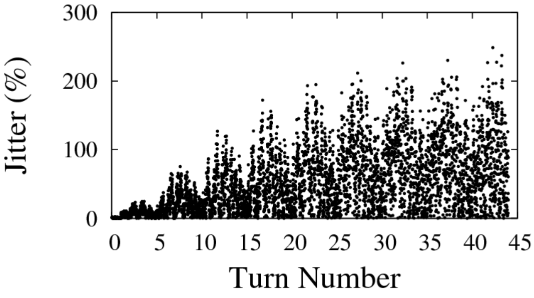

Figure 1: Extraction jitter in simulation for Fill Pattern I (45 bunches per train; gap between trains 30 rf buckets).

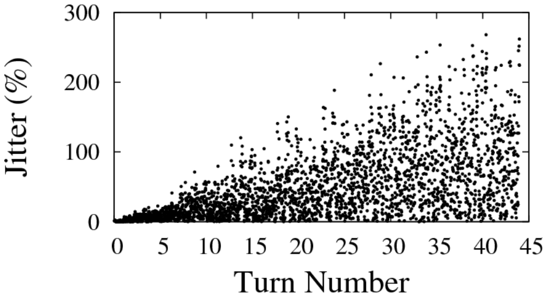

Figure 2: Extraction jitter in simulation for Fill Pattern II. (45 bunches per train; gap between trains 126 rf buckets).

Figs. 1 and 2 show the relative jitter found in simulations for Fill Patterns I and II, respectively. For both cases, the coordinate jitter on the injected bunches had a Gaussian distribution, with standard deviation corresponding to a betatron amplitude of 1.7 mm·rad. This value was chosen as a pessimistic estimate of the jitter that may occur on the injected positron beam, and corresponds to an rms coordinate jitter that is 10% of the specified beam envelope – of the injected beam.

DISCUSSION

Despite the fact that the gap between bunch trains is very different for the two cases considered here, the jitter in the extracted beam is almost the same in each case. This is because a higher bunch charge cancels the advantage from a larger gap, which provides a larger time for the wake field to decay. We may expect similar results from the other possible fill patterns, which span the range between the two patterns considered here.

The size of the jitter observed in the simulations is a concern. Nominally, to preserve luminosity in ILC, the jitter y/σ in the vertical plane should not exceed 10%; whereas with an assumed injection jitter of 1.7 mm·rad, the extracted jitter observed in both figs. 1 and 2 is about 50% (averaged over all bunches). Since the jitter varies as the square root of the betatron amplitude, this suggests that the injection jitter should be kept below 70 μm·rad. At 5 GeV and a (typical) beta function of 10 m, this corresponds to a coordinate jitter of roughly 0.2 mm (rms). It may be possible to relax this specification, if a feed-forward system can be used to reduce the bunch-to-bunch jitter on the extracted bunch trains, in the turn-around between the damping ring and the main linac.

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