OVERVIEW OF COLLECTIVE EFFECTS IN THE NLC MAIN DAMPING RINGS*

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Abstract

The present design for the NLC Main Damping Rings (MDRs) meets the specifications for acceptance and extracted emittance, in the limit of zero current. However, the relatively large bunch charge and moderate energy mean that a variety of collective effects can impact the beam dynamics, leading to loss of stability or increase of equilibrium emittance. These effects include intra-beam scattering, impedance from numerous sources, fast-ion instability, and (in the positron ring) electron cloud. In this note, we survey the expected impact on damping ring performance from each of a number of collective effects, and discuss the priorities for future studies in this area.

1 NLC DAMPING RINGS

The Next Linear Collider is a proposed electron-positron linear collider, with baseline parameters of 500 GeV center of mass energy and peak luminosity of 2.5×10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The high luminosity requires small beam emittances and high beam power. This leads to challenging requirements for the damping rings, which must be capable of rapidly damping high current beams to very low emittances. The present lattice design [1] has a circumference of 300 m, and a racetrack layout, with the arcs based on low equilibrium emittance TME cells. One of the straights contains 50 m of damping wiggler, and the other contains various systems and components, including the RF cavities and the injection and extraction systems.

The moderate energy of 1.98 GeV has been chosen to allow small equilibrium emittance in a relatively small circumference. Although the fast radiation damping will help control some of the instabilities, the high current and moderate energy mean that a range of collective effects are potentially significant. We have performed initial estimates, and report the results here. Our aim at this stage is just to indicate the likely significance of different effects; this will be helpful in planning and prioritizing more rigorous studies.

Some relevant parameters are shown in Table 1. Note that we consider only the Main Damping Rings; the positron Pre-Damping Ring is expected to suffer less from collective instabilities, in part because of the larger beam sizes and vacuum chamber aperture.

2 COUPLED-BUNCH INSTABILITIES

Long-range wake fields driving coupled-bunch instabilities arise from RF cavity and vacuum chamber impedances, and also from electron cloud (positron ring) or ions (electron ring). In this section, we consider the impedance sources; electron cloud and ion effects are discussed below.

Table 1: Relevant Parameters for the NLC MDRs

Energy	E	1.98 GeV
Circumference	C	299.792 m
Betatron tunes	ν_x, ν_y	27.26, 11.14
Synchrotron tune	ν_s	0.0035
Mean beta functions	$<\beta_{x,y}>$	3.6 m, 7.1 m
Momentum compaction	α	2.95×10^{-4}
Natural energy spread	σ_δ	0.0909 %
Bunch length	σ_z	3.60 mm
RF acceptance (1.07 MV)	$\varepsilon_{\mathrm{RF}}$	1.5 %
Particles per bunch	N_b	7.5×10^{9}
Bunch separation	s_b/c	1.4 ns
Fill pattern (trains×bunches)		3 × 192
RF frequency	f_{RF}	714 MHz
Energy loss per turn	U_0	792 keV
Radiation damping time	τ_y	5.00 ms
Equilibrium emittance	$\gamma\varepsilon_{x,y}$	2.2, 0.013 µm
Mean horizontal *H* function	$<H>$	1.91 mm
Vacuum chamber material		Aluminum
Beam pipe radius (standard, wiggler)	b	0.016 mm, 0.008 mm

For an arbitrary fill function, calculation of the longitudinal and transverse coupled-bunch growth rates can be cumbersome, since modulation coupling and Landau damping have to be taken into account. In our case, where we are dealing with three trains of equally charged, uniformly separated bunches, we can derive useful information about the upper boundaries of the growth rates by studying uniform fills.

Given the impedance, it is straightforward to calculate the coupled bunch growth rates [2]. The vertical coupled-bunch growth rates are shown in Figure 1; the horizontal growth rates are similar. The line is obtained by analyzing a uniform fill with the same current per bunch as the actual three-train fill. The filled areas are obtained from an analysis of a uniform fill with same total current. The horizontal broken line indicates the radiation damping rate. The resistive wall impedance dominates, and there would be little advantage of developing the cavity design to damp further the higher order modes. The range of modes with growth rates faster than the radiation damping rate indicates that a feedback system will be required, with bandwidth of the order 350 MHz, and sufficient gain to damp modes with growth times of the order 100 µs. In the longitudinal plane, there is a single mode, arising from the accelerating mode detuning, above the radiation damping threshold.

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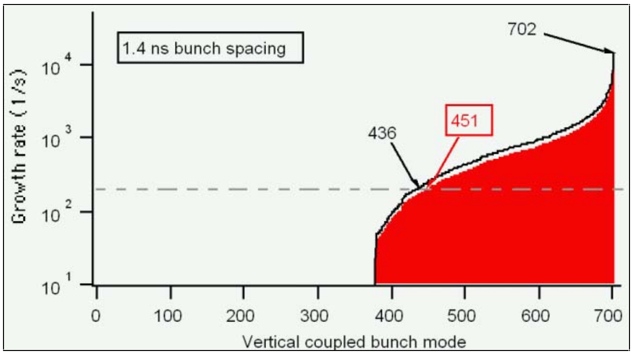

Figure 1: Vertical coupled bunch growth rates in the NLC MDRs.

3 SHORT-RANGE WAKE FIELDS

An impedance model has been produced [3]; the total short-range longitudinal wake potential from a variety of components (including RF cavities, resistive wall, BPMs, bellows masks etc.) is shown in Figure 2. The solid line shows the potential generated by a bunch with shape given by the broken line. The impedance is principally resistive, with Z/n = 25 mΩ.

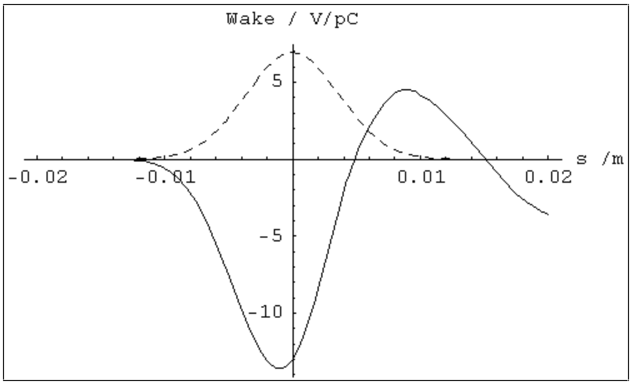

Figure 2: Short-range longitudinal wake potential.

The effects of potential well distortion are found by solving the Haissinski equation; a small bunch lengthening of the order 5% is expected. The microwave threshold may be estimated from the Boussard criterion, which suggests that the threshold lies at a peak current of 120 A, about three times larger than the nominal operating peak current. More rigorous tracking studies will be needed to verify this margin.

4 TOUSCHEK LIFETIME

Touschek scattering is often the main lifetime limitation in low emittance electron storage rings. An estimate of the lifetime, assuming Gaussian bunch profiles, is readily obtained using standard expressions [4]. An important parameter is the momentum acceptance, which depends on the RF voltage and the dynamics in the lattice. The RF voltage is specified to give an acceptance of 1.5%, and it is hoped that the dynamic momentum acceptance will be above 1% [1]. With an acceptance of 1.5%, the lifetime with the nominal parameters is a little more than 200 s. This is not a limitation on operation, since any bunch is stored in the ring for only 25 ms, and the combined power load from Touschek losses is less than 10 W. However, the short lifetime will make commissioning and tuning the lattice difficult. For these purposes, it should be possible to improve the lifetime either by coupling the beam, or operating with lower bunch charge. Both these strategies have other implications, however, and it is desirable to improve the momentum acceptance of the ring.

5 INTRA-BEAM SCATTERING

Intra-beam scattering (IBS) is a well-studied process in hadron machines, where the small-angle scattering of particles within a bunch leads to measurable growth rates in the bunch dimensions. In electron machines, the radiation damping usually dominates the effect, and only at low energies and very small beam sizes is IBS apparent. Observations have been made at the KEK ATF [5], and at the ALS [6]. Work is in progress to verify the agreement between theory and observations; experimental study is difficult, since significant growth is observed only with extremely small vertical beam sizes, such as will be found in the damping rings.

Estimates of the emittance growth from IBS may be made using simple formulae [7], that approximate the more rigorous treatment of Bjorken and Mtingwa [8]. It is important to consider the evolution of the emittances during the damping cycle, since the beam is extracted some time before equilibrium. It is also important to consider the relative contributions to the vertical emittance from the vertical dispersion and the betatron coupling. In practice, one expects the contribution from vertical dispersion to dominate, and the relative growth in the vertical emittance in this case is less than the relative growth in the horizontal from IBS.

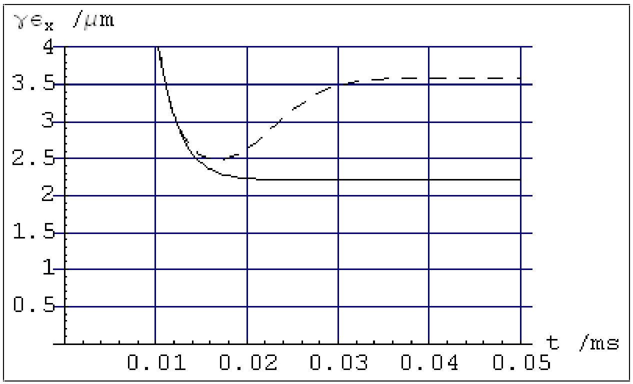

Figure 3: Damping of horizontal emittance without IBS (solid line) and with IBS (broken line).

Figure 3 shows the horizontal emittance as a function of time, up to 50 ms after injection. In operation, the beam will be extracted 25 ms after injection. The solid line shows the damping with radiation only; the broken line shows the effect of including IBS emittance growth. It appears that IBS could lead to an increase of the extracted horizontal emittance, above the specified 3 μm-rad. The effect is less severe in the vertical, although it could again be difficult to achieve the specified limit of 0.02 μm-rad.

There are several possibilities for overcoming the emittance growth from IBS. These include bunch lengthening (e.g. by higher harmonic cavities), and increasing the energy of the ring. None the options appears particularly attractive, and work is continuing to validate the present estimates, so that a cure with minimal impact on other properties of the ring may be found.

6 PHASE TRANSIENTS

Beam loading of the RF cavities together with gaps between the bunch trains in a storage ring lead to a variation in the synchronous phase along the bunch trains. This effect has been studied using a tracking code based on difference equations used to model the longitudinal motion of each individual bunch; we find that a close to linear variation of 100 mrad occurs along each train. This is a little larger than the specified limit for the bunch compressors, although the linearity of the variation means that it may be possible to compensate in the bunch compressors themselves. Alternative approaches would be to adjust the damping ring generator voltage as a function of time, or use lower harmonic cavities.

7 ELECTRON CLOUD

Electrons generated by a variety of processes may be trapped in the potential well of the beam in a proton or positron storage ring. Under appropriate conditions, the electron cloud can drive instabilities in the beam, and such effects have been observed in a number of storage rings. We have reported in more detail elsewhere [7] the models we have used (following on the work of Ohmi et al [8] and others) to estimate the effects in the NLC Main Damping Rings. Here, we briefly state the results.

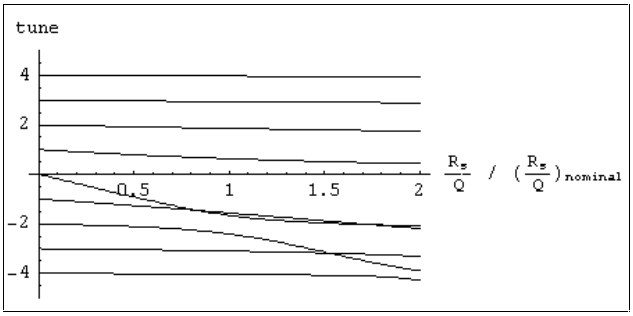

Figure 4: Synchrotron sideband tunes as a function of nominal electron cloud impedance.

We assume that the equilibrium average density of the cloud is given by the neutralization condition, and that the short-range and long-range wake fields may be modeled by a broad-band resonator with appropriate parameters. We estimate the fast head-tail threshold using the standard mode-coupling theory, and find that the nominal operating parameters are close to the threshold (Figure 4). We are also concerned that the incoherent tune shift induced by the cloud could be as large as 0.3. The shortest growth times for the coupled-bunch modes are of the order 20 μs (Figure 5). Together, these results indicate that electron cloud could be a serious limitation on operational performance of the damping rings. It is known that coating the vacuum chamber with a material with low secondary electron yield, or using weak solenoid fields to trap secondary electrons near the wall can be effective in preventing the build-up of electron cloud. More detailed studies and simulations of electron cloud effects, and investigations to find the most appropriate cures for the damping rings, are planned.

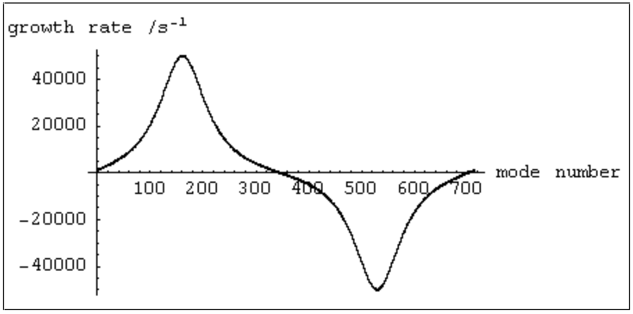

Figure 5: Coupled-bunch growth rates resulting from the electron cloud long-range wake.

8 FAST ION INSTABILITY

Under certain conditions, ionization of the residual gas can give rise to a fast instability, which is not controlled by gaps in the bunch train. The fast ion instability has been analyzed by Raubenheimer and Zimmermann [9], and has been observed in a number of machines [10]. Although the growth is not strictly exponential, we estimate rise times of the order 0.2 μs with a partial pressure of 1 nTorr CO. Further studies are planned to verify the theory, produce more careful estimates, and investigate possible cures.

9 REFERENCES

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