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COLLECTIVE EFFECTS IN THE NLC DAMPING RING DESIGNS*

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I. Introduction

In this paper, we give an overview of collective effects and related issues in the damping rings for the NLC[1]. The main damping ring will have a maximum average current of 1 A in four bunch trains which are separated by 60-80 ns, allowing the fast kickers to inject and extract individual trains. Each bunch train consists of 75-90 bunches, separated by 1.4 ns, with a maximum bunch population of 1.5×10^{10}. Because of the large average current, coupled bunch instabilities are a potential problem; these can be driven by the ring impedance or by a collective beam-ion instability. In addition, because the ring has a very small momentum compaction and synchrotron tune, potential well distortion and the microwave instability could be important. Finally, because of the very small beam emittances, the intrabeam scattering is significant.

In the next sections, we will describe the present state of our calculations. We begin by describing the vacuum chamber design and RF cavities. We then discuss the longitudinal and transverse coupled bunch instabilities, the potential well distortion and the microwave instability, and finally, mode-coupling, ion effects, and intrabeam scattering.

II. Vacuum System

The vacuum system is designed for an average operating pressure of 1 nTorr; see discussion of ion trapping. This pressure must be maintained under conditions of very intense synchrotron photon bombardment which produces a large gas load. For example, 2600L/s of pumping per bend magnet is required in the arcs to maintain the desired pressure.

The dynamic gas load and the aperture of the beam channel (25mm) are such that the required pressure can only be attained by pumping via an ante-chamber. The beam and ante-chambers are interconnected by a 5mm high slot; this height is determined from consideration of both the bunch length and the radiation spot size including allowances for mis-steering of the beam and misalignments of the vacuum chamber.

Discrete photon absorbers are located in the ante-chamber to intercept the synchrotron photons. Most of the gas load to the system is released from these absorbers. The most efficient pumping of the system is thus obtained by locating the pumps in close proximity to the absorbers. The absorbing surface will be inclined at a grazing incidence angle to the incoming photons to reduce the power density to a manageable level. A high strength copper alloy, such as Glidcop, will be required to resist thermal stresses.

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Upon consideration of the pressure profile it was found desirable to evenly distribute the thermal load (and thus the gas load) between each absorber. By using an ante-chamber, the required average operating pressure was obtained with only a small rise in pressure between pumps. The static pressure without beam was calculated to be an order of magnitude below the dynamic pressure.

To minimize the ring impedance, close attention is being given to eliminating mechanical discontinuities in the beam channel design. The ante-chamber and coupling slot are not interrupted through each of the two arcs. The magnet poles are designed to fit around the ante-chamber in a manner similar to that used in the Advanced Light Source at Berkeley. The expansion bellows between vacuum chamber modules is being modeled on those proposed for the SLAC B-factory LER [2].

III. RF Cavities

The narrow-band impedance of the storage ring is dominated by the radio-frequency cavities. In order to minimize this impedance, we choose to use a "monochromatic" cavity, which uses waveguides mounted on the cavity body to suppress the cavity higher order modes (HOM's). In addition, we incorporate a tapered beam pipe near the cavity, which substantially reduces the transverse impedance. The basic cavity shape is a re-entrant structure with nose cones and is based on the PEP-II cavity design. The beam pipe has a 3.1 cm radius at the cavity and is then tapered down to the main chamber radius of 1.25 cm over 15 cm length. Absorbing material will be needed to absorb the propagating HOM's.

Three waveguides are attached to the cavity body for the purpose of damping the higher order modes. These waveguides are dimensioned to have a cut-off frequency above the frequency of the accelerating mode of the cavity, but below the frequency of the lowest HOM. Thus the HOM power may couple through the apertures in the cavity wall to the waveguides, where it is absorbed in a lossy material. The location of the absorptive material is at a sufficient distance from the cavity aperture to minimize dissipation of the fundamental mode power from an evanescent waveguide mode. Experience with the PEP-II cavities shows that Q values of the HOM's can be damped to the order of a few 100's in most cases [3].

We have scaled the dimensions of the PEP-II cavities to achieve a resonant frequency of 714 MHz. The addition of the damping waveguides can be expected to reduce the fundamental shunt impedance and unloaded Q value by roughly 30%. We then calculate a shunt impedance of R_s = 3.3 MΩ, Q_0 = 24500, and R/Q = 135 Ω for the NLC damping ring RF cavities.

The total loss parameter for each cavity is computed to be $k_l = 1.7$ V/pC for a bunch length of 3.3 mm, of which the fundamental mode contributes 0.26 V/pC and modes below cut-off contribute 1.1 V/pC. The transverse kick factor is 39.4 V/pC/m. Tables 1 and 2 list the strongest monopole and dipole mode frequencies and R/Q's.

The determination of the number of cavities required involves a compromise between their power handling capabilities and the beam impedance presented by the cavities. We expect that two cavities per ring will be sufficient to attain the required 1 MV RF voltage [1].

Table 1. Strongest monopole HOM's.

Frequency (MHz)	R/Q (Ω)
1932	7.3
2362	4.9
3150	4.8
4673	3.2

Table 2. Strongest dipole HOM's.

Frequency (MHz)	(R/Q)/(kr)**2 (Ω)
1194	17
1995	4.2
2312	0.9
2404	0.8
2509	6.7

IV. Coupled Bunch Instabilities and Feedback

A. *Longitudinal* $m = 0$

In the case of longitudinal beam oscillations, the RF cavities provide the only sources of impedance strong enough to drive coupled bunch (CB) instabilities. As described above, we are using the measured parameters of the HOM's of the 476 MHz PEP-II RF cavity scaled to 714 MHz to estimate the growth rates in the NLC damping ring. For calculations of the CB growth rates, we have assumed that all HOM's have been damped to Q's of 200.

In this case, we find that all CB growth rates fall below the radiation damping rate of 400/sec except for a few CB modes which are driven by the HOM at 3150 MHz and have growth rates of 450/sec. Because the bandwidth of the HOM's is large compared to the revolution frequency, we do not expect any change in the growth rate from frequency variations of the HOM's. All growth rates for higher mode CB ($m > 0$ modes) oscillations fall well below the radiation damping threshold.

Because the fastest growth rates are only slightly above the radiation damping threshold, we are not planning for a longitudinal CB feedback although the situation must be reevaluated once an actual RF cavity is available. Also, although most CB modes are stable, it is possible that their transient response following injection has unacceptably large amplitudes, resulting in an emittance increase or beam loss. This is especially important because of the relatively short time the beam is in the damping ring. We are currently evaluating this problem.

B. *Transverse* $m = 0$

In the transverse plane, the principal impedances for driving CB oscillations are the dipole HOM's of the RF cavities and the resistive wall impedance. For the expected aluminum beam pipe with a radius of 1.25 cm, the real part of the resistive wall impedance is estimated to be $Z_{rw} = 0.47\ M\Omega/m$. As for the monopole HOM's, we assume the dipole HOM's are damped to Q's of 200.

We find the fastest growth rates of ~1400/sec to be driven by the resistive wall impedance. This is about ten times the radiation damping rate of 216/sec in the vertical plane. The CB modes driven by cavity HOM's all have growth rates less than the radiation damping rate except for a mode at 1194 MHz which is roughly three times higher.

A transverse CB feedback system or a large transverse bunch-to-bunch tune variation is needed to stabilize the fast CB growth rates. Because the CB growth is dominated by the resistive wall impedance, it may be possible to design a lower bandwidth system (~50 MHz) to deal only with those CB modes rather than a broadband system (357 MHz) which would cover all possible CB modes.

C. *Transverse* $m = 1$

The method described in [4] and [5] was used to compute $m = 1$ (head-tail) coupled bunch growth rates. The $m = 1$ modes are especially important since they are very hard to damp with a feedback system. If the cavity Q's are less than 300, the $m = 1$ growth rates are negligible. If instead we assume cavity Q's of 3000, there is one cavity mode (2509 MHz) which drives an $m = 1$ mode above the radiation damping rate at a beam current of roughly 1.3 A. This is probably not a significant limitation.

V. Impedance and Microwave Instability

Usually the microwave instability is considered to be a benign instability, leading an increased bunch length and energy spread. But, there is some concern that the instability can exhibit a bursting behavior [6]. This can be a severe limitation in a damping ring since the extracted beam energy and phase fluctuates pulse-to-pulse.

To calculate the potential well distortion and the threshold for the microwave instability, we need to know the details of the vacuum chamber geometry. As was the case for the SLC damping rings, small changes in vacuum chamber cross-section can dominate in their contribution to the ring impedance over larger objects such as the rf cavities[7]. In the SLC rings, we were able to model the important elements and construct an accurate wake function; using this wake function the calculated bunch shape and basic properties of the microwave instability generally agreed well with measurements [8][9].

At this time, we are assembling detailed designs of the BPMs, bellows, masks, *etc.*, so that we can perform a similar calculation for the NLC rings. Although this task is not yet complete, as a zeroth order approximation, we have assumed that the impedance is dominated by RF cavities. Using the wakefield of these cavities, and solving the

Haïssinski equation[10] we find that the potential well distortion is small, hardly perturbing the distribution from the nominal, gaussian shape. Next, using the perturbation approach of [11] to solve the linearized, time independent Vlasov equation, which includes the potential well distortion as a zeroth order effect, we find a microwave threshold at roughly 3.5 times the nominal current. While these results are encouraging, they are obviously incomplete and we need to calculate the full wakefield to perform more realistic estimates.

VI. Other Issues

A. Mode-coupling

We use the method described in [4] and [5] to compute the single bunch mode-coupling threshold. For the transverse impedance, we use the model described in in [12] which consists of the transverse HOM's, the resistive wall, and a high frequency tail due to the cavities. The effect is most severe in the vertical plane where we find a threshold at roughly 28 mA; this is about an order of magnitude above the actual single bunch current.

B. Ion Effects

Because of the high beam current and the small beam emittances, ion effects can be significant. Although the 60 ns gap separating the bunch trains clears the ions between trains and prevents 'ion trapping', ions generated within the passage of a single bunch train will affect the dynamics. There are two primary issues: tune shifts due to the focusing from the ions and a fast beam-ion collective instability that can arise in both the electron and positron rings and grows as $\exp(\sqrt{t/\tau_c})$ [13].

At a vacuum pressure of 10^{-9} Torr, the ions will produce a variation in betatron tune of $\Delta\nu_y \approx 0.002$ across the electron bunch train; although this is small, it can have an appreciable effect and may even stabilize some of the transverse coupled bunch instabilities. At this same vacuum pressure, the predicted characteristic times τ_c for the collective instability are 500 ns in the electron ring and 120 μs in the positron ring; the characteristic times are inversely proportional to the vacuum pressure and decrease by an order of magnitude at a pressure of 10^{-8} Torr. Methods of alleviating this instability are discussed in Ref. [13].

C. Intrabeam Scattering and Touschek Lifetime

Because of the small emittances, intrabeam scattering and Touschek effects are significant. With a single bunch population of 1.54×10^{10}, intrabeam scattering increases the equilibrium horizontal emittance of the beam core by about 25% and the equilibrium vertical emittance by about 5%; the scattering has a much smaller effect on the vertical emittance, which is mainly determined by the vertical dispersion because $\langle\mathcal{H}_y\rangle/\langle\mathcal{H}_x\rangle \ll \epsilon_y/\epsilon_x$, where $\mathcal{H}_{x,y}$ is the Courant-Snyder dispersion invariant [14]. In addition, the scattering populates large amplitude tails in the particle distribution that need to be collimated before the IP [15].

Similarly, the Touschek lifetime is only 100 seconds. Although this is very short, it is long compared to the store time of 22 ms. If stored beam is desired for commissioning or diagnostic purposes, the Touschek lifetime can be lengthened by introducing vertical dispersion in the wigglers and increasing the equilibrium vertical emittance.

D. Beam-Gas Scattering

With vacuum $\leq 10^{-8}$ Torr, beam-gas scattering has no significant effect on the emittances. It only contributes to large amplitude tails in the particle distribution [16], [17]. These tails must be collimated before the IP to prevent backgrounds in the detector.

VII. Summary and future work

Baseline designs for the vacuum chamber and RF cavities are given for the NLC damping ring, from which instability estimates were made. We find that coupled bunch instabilities can be handled by reasonable feedback systems. Preliminary estimates indicate that the beam is below the microwave instability threshold, but more detailed calculations need to add in numerous small contributions. Simulations indicate that ion effects could put stringent requirements on the vacuum; here experimental verification is desirable.

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