SIMULATION OF THE ELECTRON CLOUD FOR VARIOUS CONFIGURATIONS OF A DAMPING RING FOR THE ILC

M. Pivi , T. Raubenheimer, L. Wang, SLAC, Menlo Park, CA 94025, USA.
K. Ohmi, KEK, Japan.
R. Wanzenberg, DESY, Germany.
A. Wolski, University of Liverpool and the Cockcroft Institute, UK.
F. Zimmermann, CERN, Geneva, Switzerland.

Abstract

In the beam pipe of the positron damping ring of the International Linear Collider (ILC), an electron cloud may be first produced by photoelectrons and ionization of residual gases and then increased by the secondary emission process [1].

This paper reports the assessment of electron cloud effects in a number of configuration options for the ILC baseline configuration. Careful estimates were made of the secondary electron yield threshold for electron cloud build-up, and the related single- and coupled-bunch instabilities, as a function of beam current and surface properties for a variety of optics designs. When the configuration for the ILC damping rings was chosen at the end of 2005, the results from these studies were important considerations. On the basis of the theoretical and experimental work, the baseline configuration currently specifies a pair of 6 km damping rings for the positron beam, to mitigate the effects of the electron cloud that could present difficulties in a single 6 km ring.

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INTRODUCTION

The TESLA TDR specified a "dog-bone" damping ring with 17 km circumference. The ILC collaboration invested considerable effort studying alternative damping ring configurations in order to reduce the circumference, increase the dynamic aperture, and reduce space charge effects. However, the build-up of the electron cloud is strongly dependent on the bunch separation, which decreases with the damping ring circumference.

Reduction in the circumference could make electron cloud effects more severe. Coupling between electrons in the cloud and the circulating beam can cause coupled-bunch instabilities, coherent single-bunch instabilities or incoherent tune spreads that may lead to increased emittance, beam blow-up and ultimately to beam losses. All these effects would directly affect the collider luminosity, and therefore it is important to suppress the electron cloud in the positron damping ring. In this paper, we summarize the simulation results for the electron cloud build-up and the related single-bunch instabilities. These results were obtained by an international collaborative study [2] of eight different damping ring lattice designs, including the original TESLA design. The main parameters of these lattices are listed in Table 1. The nomenclature (PPA, OTW etc.) is designed to provide a means of referring to the lattices that is objective, and not colored by any associations.

SIMULATION CAMPAIGN

The electron cloud effects are prominent among the criteria to be considered when choosing the damping ring circumference and setting the specifications for the vacuum system. To provide operational flexibility, the damping rings should also be capable of accommodating a range of bunch charges; to provide a given luminosity, reducing the bunch charge means increasing the number of bunches, and decreasing the bunch separation.

Damping rings with circumferences significantly below 6 km would require performance specifications on the

Table 1: Parameters for possible ILC positron damping rings.

| Lattice	PPA	OTW	BRU	OCS	2×OCS	MCH	DAS	TESLA
Circumference [m]	2824	3223	6333	6114	12228	15935	17014	17000
Energy [GeV]	5.0	5.0	3.74	5.066	5.066	5.0	5.0	5.0
Bunch charge [10^{10}]	2.4	2.2	2.0	2.0	2.0	2.0	2.0	2.0
Bunch Spacing [ns]	4.0	4.2	6.154	6.154	14.4	15.38	20.0	20.12
Momentum compaction [10^{-4}]	2.83	3.62	11.9	1.62	1.62	4.09	1.14	1.22
Bunch length [mm]	6.0	6.0	9.0	6.0	6.0	9.0	6.0	6.0
Energy spread [10^{-3}]	1.27	1.36	0.97	1.29	1.29	1.3	1.3	1.29
Synchrotron Tune [10^{-2}]	2.69	4.18	12.0	3.37	3.37	15.0	6.6	7.1
Mean horiz. beta function [m]	13.1	58	57.6	25.6	25.6	109	106	120
Mean vert. beta function [m]	12.5	63.8	55	31	31	108	106	121
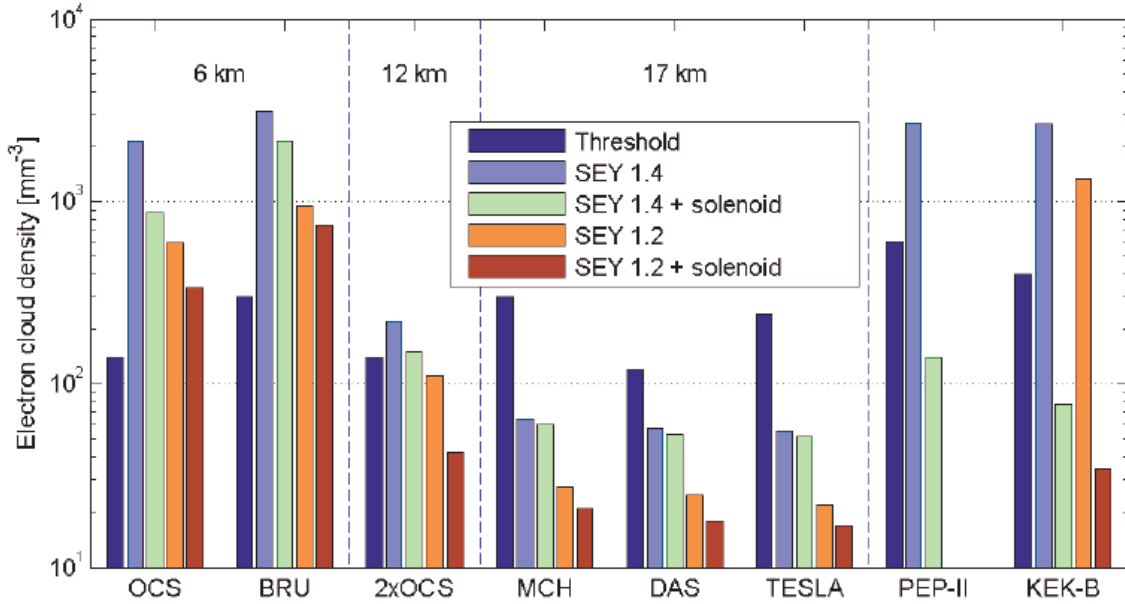
Figure 1: Instability thresholds and cloud densities for various SEY and solenoid combinations in the different damping ring configurations and the B factories. A wiggler vertical full aperture of 18mm is assumed in these simulations.

injection and extraction kickers that are presently considered too demanding. We therefore focused our studies on rings with circumferences of 6 km and larger.

As far as possible, the different reference lattices were analysed with the same techniques and assumptions applied to each. The methodology was as follows:

- Pertinent parameters were compiled, including beam sizes in arcs, wiggler, and straights, bunch spacing, tunes, beta functions, chamber dimensions, and lengths of regions with magnetic fields.
- Electron cloud build-up was simulated for the different regions (arcs, wigglers, straights) in the rings, considering actual sets of beam parameters and for two different secondary emission yields.
- A common secondary emission yield model [2] was used for benchmarking the simulation codes. Predictions of electron cloud build-up in the damping rings using different simulation codes were compared.
- For simulations in the wigglers, the field was modelled at various levels of sophistication, and the importance of refined models was explored.
- Single-bunch wake fields and the thresholds of the fast head-tail TMCI-like instability were estimated both by simulations and analytically.
- Multi-bunch wake fields and growth rates were inferred from build-up and multi-bunch simulation codes.
- Tune shifts induced by the electron cloud were calculated and compared.

Codes used in these studies for simulations of the build-up of electron cloud in these studies were POSINST (LBNL/SLAC), ECLOUD (CERN) and CLOUDLAND (SLAC). Instability simulation codes used were PEHTS (KEK) and HEAD-TAIL (CERN) for single-bunch instabilities, and PEI-M (KEK) for multi-bunch instabilities [3].

As part of these studies, we performed simulations for the PEP-II and KEKB positron rings, and compared the electron cloud build-up and instability characteristics with the different DR configuration options. Studies to benchmark the simulation codes against experimental data are ongoing at the CERN SPS, DAΦNE, LANL PSR, PEP-II and KEKB; so far, the results of the simulation codes are generally supported by experimental data.

SINGLE-BUNCH INSTABILITY

The single-bunch instability due to electron cloud is assumed to be determined by the average electron density along the ring,

$$\langle \rho_e \rangle = \frac{1}{C} \oint \rho_e(s)ds \qquad (1)$$

where C and ρ_e are the ring circumference and the electron density at ring location s, respectively. The build-up of the electron cloud is strongly dependent on the bunch separation, which scales with the damping ring circumference. Longer rings with larger bunch spacing are preferable to mitigate the development of the electron cloud.

According to the broad-band resonator model [4, 5], the threshold of the instability is approximately given by:

$$\rho_{e,th} = \frac{2\gamma \nu_s \omega_e \sigma_z / c}{\sqrt{3}KQr_e\beta C} \qquad (2)$$

where β is the average vertical beta function, ν_s is the synchrotron tune, r_e is the classical electron radius, γ is the relativistic factor, σ_z is the bunch length, ω_e is the resonant electron frequency, Q characterizes the quality-factor of the resonator and K is an enhancement factor due to the cloud size.

A smaller circumference, larger synchrotron tune and/or larger momentum compaction are helpful to mitigate the head-tail instability. The critical issue is that

the cloud build-up increase rapidly with short bunch spacing while the single-bunch instability has a much weaker dependence on the ratio between the synchrotron tune and the circumference. Thus, a larger ring circumference is preferable. Incoherent effects may be also a concern if electrons are accumulated.

SIMULATION RESULTS

Figure 1 shows the electron cloud single-bunch instability thresholds and integrated simulated density over all the magnets and drift spaces for each of the eight lattices considered. Cloud densities are shown for peak secondary emission yields δ_{max}=1.2 and 1.4; these values are likely to be achieved in an accelerator environment after conditioning (electron bombardment) of copper chambers or for chambers coated with thin film like TiN or TiZrV. It is not yet clear whether conditioning reduces the SEY below ~1.2 in an accelerator environment. Experimental studies are ongoing to resolve this issue. At present, it is a challenge to reduce the SEY below 1.2 in accelerator vacuum chambers under operational conditions.

The SEY limits are tighter and the instability threshold is more likely to be exceeded in smaller rings. Note that for the MCH ring, simulations were performed with maximum available bunch spacing of 18.8 ns (rather than 15.4ns).

We also considered the alternative configuration of two 6 km positron damping rings sharing the same tunnel; for simplicity we refer to this configuration as 2xOCS. This effectively provides a 12 km damping ring configuration with maximum bunch spacing of 14.4 ns, and considerably reduces the build-up of the electron cloud compared to the single 6 km ring.

RECOMMENDATIONS

The advantages of a 6 km damping ring with a high degree of lattice symmetry are a significantly increased dynamic aperture, reduced space charge effects and improved machine availability and reliability with lower costs. However, shorter rings have a closer bunch spacing, which greatly enhances the build-up of the electron cloud. The electron cloud can be difficult to suppress in the dipole and wiggler regions where it is expected to be most severe, and the instabilities associated with the electron cloud could significantly affect the performance of the damping rings.

KEKB and PEP-II B-factories have adopted external solenoid fields to mitigate the electron cloud in field-free regions, which constitute a large fraction of those rings. The ILC damping rings typically do not have long field free regions. In much of the ring, the beam pipe is surrounded by magnets, such as wigglers and dipoles, where large electron cloud densities may develop. In magnetic field regions, external solenoid fields are not effective at suppressing the build-up of the electron cloud. Notably, the electron cloud effect in KEKB remains a major obstacle to shorter bunch spacing and higher luminosity, even with solenoid windings [6].

A large bunch spacing is desirable to limit the build-up of the electron cloud. A large synchrotron tune raises the threshold for the electron cloud driven instability.

The damping ring configuration option lattices may be listed in order of preference from the point of view of electron cloud, as (see Figure 1): MCH, TESLA, DAS, 2xOCS, BRU, OCS. MCH and BRU are preferable in their respective circumference ranges because of their large synchrotron tune and/or momentum compaction.

As a general consideration, simulations show that in the ILC damping rings, larger chamber sizes are beneficial to reduce the electron cloud. In particular, increasing the wiggler full aperture beyond the nominal 18 mm assumed in these simulations could further reduce the cloud density in the 2xOCS to a margin safely below the threshold for instability. With larger wiggler apertures, the 2xOCS ring can accommodate rather large values of SEY, yet to be determined by simulations.

If the secondary electron yield can be reduced to δ_{max}=1 in magnet regions then one single 6 km ring for the positrons may be feasible.

Based on the above considerations, the recommendation for the baseline configuration [5] was that the positron damping ring should consist of two (roughly circular) rings of approximately 6 km circumference in a single tunnel. Electron-cloud effects make a single ring of circumference 6 km or lower unattractive, unless significant progress can be made with mitigation techniques.

Possible cures in wiggler and dipole regions include grooves cut into the vacuum chamber, and the use of clearing electrodes [7, 8, 9]. Although very promising, these techniques need further studies and a full demonstration.

ACKNOWLEDGMENTS

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