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COMPARISON OF ALIGNMENT TOLERANCES IN THE LINEAR COLLIDER DAMPING WITH THOSE IN OPERATING RINGS*

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Abstract

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COMPARISON OF ALIGNMENT TOLERANCES IN THE LINEAR COLLIDER DAMPING RINGS WITH THOSE IN OPERATING RINGS*

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Abstract

The next generation linear colliders require damping rings to generate beam with very small transverse emittances to attain the desired luminosity. The required emittances are smaller than that of most operating synchrotron radiation sources. In this paper, the alignment tolerances needed to attain these small emittances are compared with those of the operating synchrotron radiation facilities and a prototype damping ring, the ATF at KEK. The concept of this study originated at the Nanobeams workshop during a discussion in the Storage Rings Working Group although the results were not discussed at that meeting.

INTRODUCTION

The next generation linear colliders require very small spot sizes to attain the desired luminosity. To focus the beams to these small spots sizes, the transverse beam emittances must also be very small. Damping rings are used to generate electron and positron beams with the desired phase space properties. These storage rings must generate very low emittance beams that are stable from pulse-to-pulse and must operate as 'factories,' routinely extracting beams with very high beam availability. Achieving the small emittances requires tight component alignment and jitter specifications and, attaining these goals routinely, means that the alignment and tuning of the rings cannot be too difficult or invasive.

Synchrotron radiation faculties also strive for relatively low emittance beams and must operate as user facilities with very high beam availability. To get an idea of the difficulty of operating the damping rings, it is useful to compare the alignment tolerances with tolerances in the operating synchrotron radiation facilities and with tolerances in the operating Advanced Test Facility damping ring prototype at KEK.

To understand the performance requirements on the damping rings, it is useful to estimate the sensitivity of the ring to random misalignments. In a storage ring, the equilibrium vertical emittance is determined by the residual vertical dispersion and betatron coupling in the bending magnets (including the wigglers) where the beam emits synchrotron radiation. Usually the betatron coupling and vertical dispersion are generated by errors distributed around the ring. There are three main driving terms: closed orbit offsets, quadrupole rotations, and vertical sextupole misalignments. It is straightforward to estimate the contributions to the vertical equilibrium emittance from random quadrupole rotations and sextupole misalignments. The effect of the closed orbit offsets is more difficult to calculate because it depends on detailed correlations from point-to-point however the sensitivity also tends to be much weaker than either of the other effects.

TOLERANCE CALCULATIONS

In this note, we compare four quantities. First, the primary errors that generate the vertical emittance are vertical sextupole misalignments and rotational quadrupole misalignments. Thus, we list the random vertical sextupole and random rotational quadrupole alignment tolerances that would generate an expected emittance equal to either the desired equilibrium emittance in the damping rings or the measured equilibrium emittance in the operating rings. Second, the primary source of vertical beam motion is the vertical motions of the quadrupoles and thus we calculate the random vertical quadrupole jitter that would cause the beam centroid to move by an amount equal to the beam size. Finally, we list the random quadrupole strength fluctuations that would cause a tune shift of 0.001 in the horizontal or vertical planes since this can be an important effect that limits the dynamic aperture in these strong focusing rings.

All of the 'tolerances' are calculated assuming purely uncorrelated errors and thus they should not be taken as tolerances. Real misalignments have correlations that can enhance the effects but usually reduce the sensitivities and thus the actual misalignment tolerances are larger than our numbers. For this reason, the values listed should be interpreted as measures of the sensitivity and only used as a comparative basis.

The tolerance values are calculated using expressions that are valid for uncorrelated errors in uncoupled e+/e- storage rings [1]. These are listed below:

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Table 1. Alignment and jitter sensitivities in operating low emittance rings and the linear collider damping ring designs

	ALS	APS	SLS	ATF	NLC DR	TESLA DR
Energy [GeV]	1.9	7	2.4	1.3	2	5
Circumference [m]	200	1000	288	140	300	17,000
$\gamma\varepsilon_x$ [mm-mrad]	24	34	23	2.8	3	8
$\gamma\varepsilon_y$ [nm-rad]	500	140	70	28	13	14
Sext. vertical alignment [µm]	135	74	71	87	31	11
Quad. roll alignment [µrad]	860	240	374	1475	322	38
Quad. vertical jitter [nm]	850	280	230	320	75	76
ΔK/K [0.01%]	1.5	1.4	1.5	2.1	1.8	1.1

$$e_y \approx \sum \left(K_2 l_s y_s\right)^2 \left[\frac{J_x(1-\cos 2pn_x \cos 2pn_y)}{J_y 4(\cos 2pn_x - \cos 2pn_y)^2} b_y b_x e_x + \frac{2J_e s_e^2}{8\sin^2 pn_y} h_x^2 b_y \right] \quad (1)$$

$$e_y \approx \sum 4\left(K_1 l_q q_q\right)^2 \left[\frac{J_x(1-\cos 2pn_x \cos 2pn_y)}{J_y 4(\cos 2pn_x - \cos 2pn_y)^2} b_y b_x e_x + \frac{2J_e s_e^2}{8\sin^2 pn_y} h_x^2 b_y \right] \quad (2)$$

$$s_y^2 \approx \sum \left(K_1 l_q y_q\right)^2 \left[\frac{b_y}{8\sin^2 pn_y} \right] \quad (3)$$

$$\left(\Delta u_{x,y}\right)^2 \approx \frac{1}{16p^2} \sum \left(\Delta K_1 l_q b_{x,y}\right)^2 \quad (4)$$

where K_1 and K_2 are the normalized quadrupole and sextupole fields, l_q and l_s are the magnet lengths, and y_q, t_q, and y_s are the misalignments. In addition, Je and se are the longitudinal damping partition and the longitudinal energy spread respectively. In Eqs. (1) and (2), the first term is due the betatron coupling from the linear sum and difference resonances while the second term is due to the vertical dispersion.

The calculations use the lattice functions of the operating or design rings and the decks from which the lattice functions were calculated are described in the references. The emittance and beam size values used in the calculations are based on published or recent email exchanges and again the values are likewise described. The calculations were performed with the computer code CTRAN [2]. It should be noted that the coupling bumps in the TESLA damping ring straight sections were not included in the calculations. These will reduce the vertical sensitivity to vertical motion however it causes a vertical sensitivity to horizontal motion, which is not necessarily easier to deal with!

RESULTS

The final results are listed in Table 1 for three synchrotron light sources, the ALS at Berkeley [3], the APS at Argonne [4], and the SLS in Zurich [5], as well as the ATF at KEK [6] and the NLC [7] and TESLA [8] damping ring designs. In general, all of the synchrotron light sources operate with much larger normalized emittances and only the ATF has attained emittances close to those desired. The synchrotron radiation sources and the ATF all operate with significantly looser tolerance sensitivities – the vertical alignment in the operating rings is typically 2 ~ 3 times larger than the requirement in the NLC damping ring and 6 ~ 9 times larger than the requirement in the TESLA ring while the roll tolerances are comparable to those needed in the NLC ring but a factor of 10 timers larger than the requirement in the TESLA ring. Both of these tolerances comparisons imply that the linear collider damping rings will be more difficult to operate and align than the radiation sources or the ATF prototype ring. Similarly, the jitter sensitivity is roughly 4 ~ 5 times looser in the synchrotron radiation sources and the ATF than in the linear collider damping ring designs, again, implying that the new rings will be more difficult to operate with stable beams. Finally, the tune shift sensitivities are comparable in all the designs suggesting that the power supplies are not going to have more stringent requirements.

DISCUSSION

The alignment and jitter sensitivities indicate that the operation and emittance tuning of the linear collider damping rings should not be vastly different than in the operating synchrotron radiation facilities and, in this sense, the damping ring operation should be possible. However, while not vastly different, the damping rings will require more effort to control and stabilize the beam than is typically achieved. Of course, the light sources generally do not strive for very low vertical emittance, since this adversely affects the beam lifetime. Although low coupling has been achieved in a number of light sources, it is quite possible that much lower vertical emittance could be demonstrated if there were strong operational motivations. Regardless, since the radiation facilities already devote significant effort to achieving excellent beam stability, the required improvement over those results could be significant and may impact the design of the diagnostic systems and controls, the vacuum system, the component supports, and the conventional facilities. All of these are likely to increase the facility cost.

REFERENCES

[1] T.O. Raubenheimer, "Tolerances to limit the vertical emittance in future storage rings," **Part.Accel. 36:75-120,** SLAC-PUB-4937 (1991).

[2] T.O. Raubenheimer, "A Formalism And Computer Program For Coupled Lattices," PAC'89, SLAC-PUB-4913 (1989).

[3] Advanced Light Source (commissioned 1993): http://www-als.lbl.gov/. The ALS deck (alsbswigskew.mad) was received from Christoph Steier 10/31/02. In addition, Christoph noted that typical operation was at 1.9 GeV with natural horizontal and vertical emittances of 6.3 nm-rad and 0.13 ~ 0.15 nm-rad which is about a 2% coupling ratio. More recently, additional skew quadrupole power supplies were installed and the vertical emittance was further decreased.

[4] Advanced Photon Source (commissioned 1995): http://www.aps.anl.gov/aps/frame_home.html. The APS deck was provided by Louis Emery on 10/31/02. Louis noted that the APS operates at 7 GeV and the natural horizontal emittance had been decreased to 2.5 nm-rad and the minimum coupling ratio was 0.4%. Louis also noted that roughly one year ago coupling ratios of 0.22% had been attained with a corresponding horizontal emittance of 3.5 mn-rad but they have not been able to achieve this result recently possibly due to the ring alignment.

[5] Swiss Light Source (commissioned 2002): http://www.psi.ch/index_e_sls.shtml. The SLS deck (sls_ri_d2rj_20. 42_8.17.mad) was provided by Michael Boege on 10/30/02. The beam energy has been 2.4 GeV during most of the running. The horizontal emittance was measured to be 5 nm-rad. The emittance ratio is estimated to be 0.3% based on the vertical dispersion and coupling measurements and this is supported by Touschek lifetime measurements. However, direct pin hole measurements yield a value of 1.5%. For this study, I assumed a value of 0.3% which gives the smaller tolerance numbers – the tolerances scale with the square root of the emittance.

[6] Advance Test Facility (commissioned 1997): http://lcdev.kek.jp/ATF/. Kyoshi Kubo provided the ATF deck. The normalized horizontal and vertical emittances have been measured to be 2.8 mm-mrad and 28 nm-rad (a 1% emittance ratio) at low current.

[7] NLC Main Damping Ring (commissioning 2012??): http://awolski.lbl.gov/NLCDRLattice/default.htm. The NLC main damping deck was taken from Andy Wolski's web site. The design horizontal and vertical normalized equilibrium emittances are 3.0 mm-mrad and 13 nm-rad. No measurements have yet been made.

[8] TESLA Positron damping Ring (commissioning 2012 ??): http://www.desy.de/~wdecking/dog/dogbone.html. The TESLA damping ring (dog6.4.1.lat.mad) was provided by Andy Wolski on 7/5/02 who received the lattice from Winfried Decking a bit earlier. The design normalized equilibrium emittances for the TESLA damping ring are: 8 mm-mrad and 14 nm-rad however the deck supplied has a horizontal emittance of 5 mm-mrad. I assumed this is due to variation in the lattice functions in the wiggler regions and used a normalized horizontal emittance 8 mm-mrad for this study.