SLC Positron Damping Ring Optics Design*

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Introduction

The basic SLAC Linear Collider operation scheme[1] assumes the use of two damping rings, one for the e^-, one for the e^+, in order to reduce the colliding beam normalized emittances to $\epsilon_x^* = \epsilon_y^* = 30\pi$ μradm hence raising the corresponding luminosity by a factor 170.

The e^- damping ring[2] optics, designed by H.Wiedemann[3], has been extensively studied and modelled[4] since it's completion at the end of 1982. The e^+ damping ring being built will be based on the same design except for some modifications resulting from the studies on the e^- damping ring which clearly pointed out two major weak points as far as the optics is concerned:

- the extracted normalized emittances are 30 to 60 % bigger than the design values (Table 1), which already left no margin for unavoidable blow-up between the damping rings and the SLC interaction point.
- the chromaticity correction based on distributed sextupole components provided by shaping the ends of the bending magnet poles was insufficient.

The present paper describes the basic modifications of the ring lattice and main equipment positions in order to improve the situation in the Positron Damping Ring.

Extracted Beam Emittance

The transient normalized emittance, ϵ_D^*, of a circulating beam after a time, t, from injection is given by:

$$\epsilon_D^* = \epsilon_I^* \exp(-\frac{2t}{\tau}) + \epsilon_0^*[1 - \exp(-\frac{2t}{\tau})]$$

where ϵ_I^* is the normalized emittance at injection, nominally:

$\epsilon_I^* =$ 300π μradm for electrons
$\epsilon_I^* =$ 10000π μradm for positrons

t is the storage time at 180 pps (120 pps)

$t =$ 5.56 (8.83) msec for electrons
$t =$ 11.11 (16.67) msec for positrons

ϵ_0^* is the normalized equilibrium beam emittance and τ is the transverse damping time; in the case of full coupling[5] $\tau = \tau_x = \tau_y$ and $\epsilon_0 = \epsilon_{0x} = \epsilon_{0y}$.

$$\tau = \frac{5.95\ 10^{24}\ R}{(2I_2 - I_4)\ E^3} \qquad \epsilon_0 = \frac{2.88\ 10^{-30}\ I_5\ E^3}{(2I_2 - I_4)}$$

with E (in eV) is the operating energy of the ring, R (in m) is the mean ring radius and I_n are the synchrotron integrals[6].

Table 1. Theoretical Performance (full coupling).

		Units	Design (CN 139)	Actual (e^- D.R.)	Proposed (e^+ D.R.)
Second synchrotron integral	I_2	m^{-1}	3.084	2.731	2.804
Fourth synchrotron integral	I_4	m^{-1}	0.0	0.261	0.0
Fifth synchrotron integral	I_5	m^{-1}	0.0264	0.0232	0.0177
Damping partition number	J_{x0}	—	1	0.904	1
Horizontal damping time	τ_{x0}	msec	3.06	3.82	3.36
Vertical damping time	τ_{y0}	msec	3.06	3.45	3.36
Transverse damping time	τ	msec	3.06	3.63	3.36
Horizontal tune	ν_x	—	7.20	7.15	8.17
Emittance (no coupling)	ϵ_{x0}^*	π μrad m	43.1	48.3	32.2
Emittance (full coupling)	ϵ_0^*	π μrad m	21.6	23.0	16.1
180 pps (120 pps) extracted electron emittance	ϵ_{D-}^*	π μrad m	28.9 (22.8)	35.9 (25.8)	26.5 (17.6)
180 pps (120 pps) extracted positron emittance	ϵ_{D+}^*	π μrad m	28.6 (21.7)	44.9 (24.0)	29.5 (16.6)

The operating energy, E = 1.21 Gev, of the damping rings has been carefully optimised during the design[3] for a minimum of the extracted beam emittance corresponding to a trade-off between the damping of the injected beam and the build-up of the equilibrium beam emittance (Fig. 1). The mean radius, R = 5.6134 m, of the damping rings corresponds to a cicumference just long enough to allow the rise and fall times of the injection/extraction kickers between the two circulating bunches. To further decrease the emittances of the extracted beam, three measures are proposed to optimize the only three parameters left which are the synchrotron integrals I_2, I_4 and I_5 (Table 1):

1. improve the field quality of the bending magnets by removing their specially shaped end pieces (holes and noses) that generate sextupole components but also lengthen the fringe field, thereby deteriorating the second synchrotron integral, I_2. Measurements of a prototype bending magnet[7] show a 3% gain in the second synchrotron integral which reduces the damping times in both transverse planes by the same amount;

2. replace the actual wedge magnets in the arcs by rectangular magnets with parallel faces which cancel the fourth synchrotron integral, I_4, thus reducing the horizontal damping time and equilibrium beam emittance by 10%;

3. increase the horizontal phase advance per cell in the arcs to the optimum of 135° which provides,[8] in the case of a FODO cell, the smallest fifth synchrotron integral, I_5. The corresponding equilibrium emittance should be reduced by another 25%.

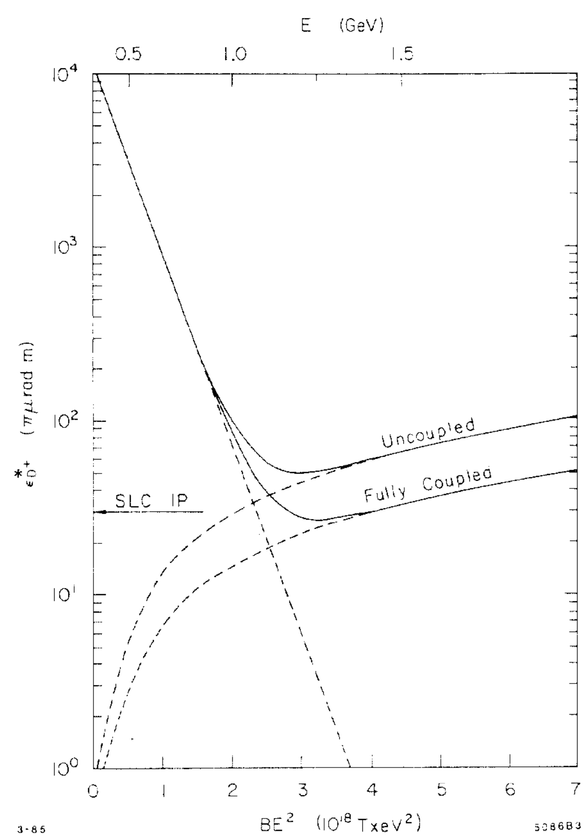

Fig. 1. Variation of Extracted Beam Emittance.

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Positron Damping Ring Lattice

In order to minimize the differences between the two damping rings, the Positron Damping Ring will be laid out like the Electron Damping Ring, with two arcs, each consisting of eight FODO cells, matched through dispersion suppressors to two straight sections used for injection and extraction. The only differences are:

– the arcs will be equipped with rectangular magnets, higher horizontal phase advance per FODO cell and distributed permanent sextupole magnets as proposed by J. Spencer[9] to correct the chromaticities.

– the dispersion suppressors will have the weak QDM quadrupole family removed in order to provide some room for additional trimming sextupoles on each side of the injection/extraction kickers and RF cavities. For this purpose, the cavities have been recentered in the available straight section to give a phase shift corresponding to $30\frac{1}{4}$ RF wavelengths between them. A slight shift (40 mm) of the QDI quadrupoles was nesessary after the removal of the QDM quadrupole family to maintain matching.

Lattice optimisation was carried out with the help of the optics programs COMFORT[10] and MAD.[11] The resulting main lattice characteristics are compared with the electron damping ring in the hard edge approximation:

1) The increased horizontal phase advance per cell lead to betatron tunes one unit higher in the horizontal plane with smaller maximum β functions in the straight sections. This allows a larger beam stay clear in the same vacuum chamber.

2) The natural chromaticities are increased by 30% in the horizontal plane but decreased by 5% in the vertical plane.

3) The perfect matching of the insertion to the arcs provides a horizontal phase advance per cell very near the optimum, resulting in a minimum equilibrium beam emittance 30% smaller than the design.

4) Thanks to the rectangular bending magnets, the horizontal damping partition number and the corresponding damping time are reduced by 13%, making them equal to the vertical plane. Shortening the bending magnet by half an inch reduces both transverse damping times by another 3%.

5) Finally, although the dispersion function is not strictly zero in the septa, the injection and extraction schemes, very similar to the design but 5% more efficient, do not necessitate any component change.

Chromaticity Correction and Dynamic Acceptance

The natural transverse chromaticities are both high and negative in the damping rings:

$$\xi_x = \frac{d\nu_x}{\Delta p/p} = -11.20 \qquad \xi_y = \frac{d\nu_y}{\Delta p/p} = -7.68$$

Two families of $N_{F,D}$ sextupoles with an integrated strength $S_{F,D}$ are normally sufficient to cancel the linear part of the chromaticities

$$S_F = \int \left(\frac{d^2 B_y}{dx^2}\right)_F ds = \frac{4\pi(B\rho)}{N_F D_{xF}} \left[\frac{\beta_{yD}\xi_x + \beta_{xD}\xi_y}{\beta_{xD}\beta_{yF} - \beta_{xF}\beta_{yD}}\right]$$

$$S_D = \int \left(\frac{d^2 B_y}{dx^2}\right)_D ds = \frac{4\pi(B\rho)}{N_D D_{xD}} \left[\frac{\beta_{yF}\xi_x + \beta_{xF}\xi_y}{\beta_{xD}\beta_{yF} - \beta_{xF}\beta_{yD}}\right]$$

where β_{xF}, β_{yF}, D_{xF}, β_{xD}, β_{yD}, D_{xD} are the usual Twiss parameters and dispersion functions in the F, D sextupoles.

But it is very well known[12–16] that the drawback of the sextupoles is to reduce the dynamic acceptance by the introduction of non-linearities responsible for geometric as well as chromatic aberrations. A harmonic analysis of the general equation of motion in the presence of sextupoles shows that:

– the geometric aberrations (independent of the particle momentum) excite the following betatron resonances[13]:

$\nu_x = p$	$2\nu_x = p$	
$3\nu_x = p$	$\nu_x + 2\nu_y = p$	$\nu_x - 2\nu_y = p$
$4\nu_{x,y} = p$	$2\nu_x + 2\nu_y = p$	$2\nu_x - 2\nu_y = p$

The two necessary conditions[15] in each transverse plane to be fulfilled are:

$$\int \beta^p S \exp^{\pm i\Psi} = 0 \qquad \int \beta^p S \exp^{\pm 3i\Psi} = 0$$

– the chromatic aberrations (dependent on momentum) affect the tune, dispersion and Twiss parameters[14–15] as a function of $\Delta p/p$.

In the case of the damping rings, these effects are particularly important for three reasons:

– the extremely low bending radius of the bending magnets ($\rho = 2m$) drives some more terms in the general equation of motion and complicate it's treatment.

– the necessity for full coupling the beam means working very close to the coupling resonance ($2\nu_x - 2\nu_y = 10$) which is excited by the sextupoles.

– the high chromaticities and small room available for the sextupoles impose a small number of strong sextupoles which drive low harmonic betatron resonances.

Sextupole Configuration

In order to be effective the sextupoles have to be placed in high dispersion regions with extreme $\beta_{x,y}$ to reduce the coupling between families. In the damping ring this is only possible in the arcs as the dispersion function is nearly cancelled in the rest of the machine. This is the reason why 80 sextupole components have been introduced in the Electron Damping Ring through holes and noses at both ends of the bending magnets. In the Positron Damping Ring, the necessary room for permanent sextupoles magnets[9] on both sides of the bending magnets has only been found with difficulty by D. Jeong after a careful redesign of the vacuum components.

Several possible sextupole arrangements employing one or two sextupoles per bending magnet were studied, the corresponding dynamic acceptance tracked with PATRICIA[15]. The betatron resonance driving terms as well as the chromatic aberrations can be minimized by the program HARMON[13] which adjusts the relative strength of different sextupole families. In the particular case of permanent sextupoles, this would lead to several sextupole designs which is not desirable. A particular configuration with 40 sextupoles based on one sextupole per magnet in the arcs in order not to perturb the exact cancellation of the geometric aberrations and one sextupole on both sides of the first bending magnet of the dispersion suppressor reduces considerably the chromatic aberrations. However the dynamic acceptance would be limited for a tune near the coupling resonance.

Finally, the 72 sextupoles configuration with one sextupole on each side of the bending magnets in the arcs, was adopted for (Fig. 2):

– very small variation of the tunes, dispersion function and Twiss parameters with particle momentum,

– smaller geometric and chromatic aberrations as well as reduced excitation of the coupling resonance,

– very stable particle tracking for any tune up to an emittance in both planes of 16 $\pi\mu$radm corresponding to the geometric ring acceptance and a factor four above the nominal positron beam emittance at injection.

The final number and integrated strength $S_{F,D}$ of the sextupoles necessary to adjust the chromaticities to $\xi_{x,y} = +1.0 \pm 0.2$ are

36 F sextupoles with $S_F = +\ 78\ \pm 1.1$ T/m

36 D sextupoles with $S_D = -110\ \pm 1.3$ T/m

The change of chromaticities resulting from a modification of the focusing and defocusing sextupoles strength, $\Delta S_F, \Delta S_D$, in the positions of the sextupoles as determined by D. Jeong are given by:

$$\Delta\xi_x = -0.176\Delta S_F + 0.014\Delta S_D$$
$$\Delta\xi_y = -0.106\Delta S_F + 0.154\Delta S_D$$

CONCLUSION

The SLC Positron Damping Ring has been kept very similar to the Electron Damping Ring in order to minimize the differences between the two rings. Nevertheless, some basic modifications have been introduced, as far as the optics is concerned, in order to improve the extracted beam characteristics:

– arcs equipped with rectangular shorter bending magnets and distributed permanent sextupole as proposed by J. Spencer[9].

– elimination of a weak quadrupole family to provide some room for additionnal trimming sextupoles.

– slight rearrangement of the insertion elements to optimize the characteristic functions as well as the injection/extraction schemes.

– new horizontal tune.

As a consequence (Table 1):

– the equilibrium transverse emittances are reduced to 25% below the design values

– the transverse damping times are 7.5% smaller than in the Electron Damping Ring

– the extracted beam emittances are then expected to be of the order of the SLC interaction point design values or about a factor two smaller if the SLC repetition rate is reduced from 180 to 120 pps.

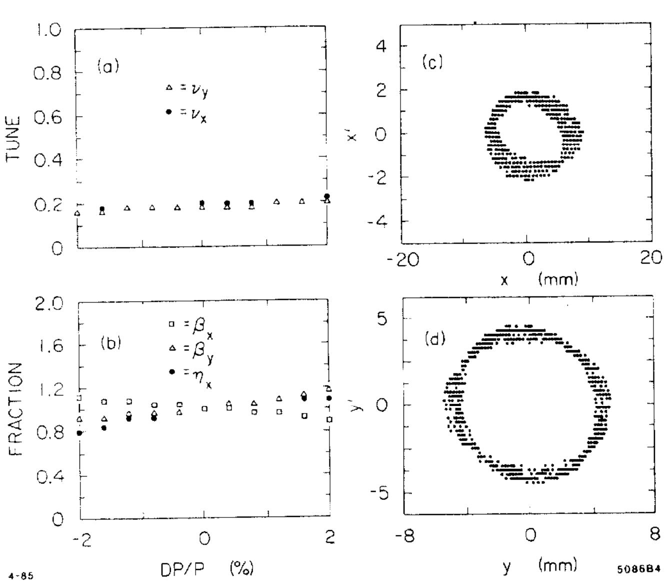

Fig. 2. PATRICIA Tracking for $\epsilon = 16\,\pi\mu$rad m, $\Delta p/p = \pm 1\%$.

Moreover, the chromaticity correction and adjustment have been improved keeping a comfortable dynamical acceptance more than four times bigger in both planes than the designed positron beam emittance at injection. The other basic elements (Quadrupoles, Septa, Kickers, RF cavities, vacuum chambers, injection/extraction schemes) can be kept identical to the Electron Damping Ring.

Finally, the proposed modifications of the Positron Damping Ring could easily be implemented in the Electron Damping Ring, making them identical which should facilitate in the future their operation and maintenance.

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