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Emittance Reduction via Dynamic RF Frequency Shift at the SLC Damping Rings *

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The generation of small emittance beams is a key issue determining the luminosity at a future linear collider. Dedicated damping rings have been designed to produce such beams, but techniques to further reduce the design emittances would yield immediate improvements in terms of higher luminosity. At injection into the damping rings, the transverse beam emittances are large and the beam fills a large fraction of the dynamic aperture. At later times during the store, after the beam has radiation damped, the horizontal damping time and equilibrium emittance may be reduced by shifting the rf frequency, such that the particle orbit moves inwards. By passing off-center through the quadrupoles in regions of nonzero dispersion, the horizontal partition number J_x is changed. This reduces both the horizontal damping time and equilibrium emittance. In addition, to the extent that the vertical emittance is determined by betatron coupling, the reduction in horizontal emittance may be accompanied by a corresponding reduction in vertical emittance. We report experience with such a scheme at the Stanford Linear Collider damping rings.

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Abstract

The generation of small emittance beams is a key issue determining the luminosity at a future linear collider. Dedicated damping rings have been designed to produce such beams, but techniques to further reduce the design emittances would yield immediate improvements in terms of higher luminosity. At injection into the damping rings, the transverse beam emittances are large and the beam fills a large fraction of the dynamic aperture. At later times during the store, after the beam has radiation damped, the horizontal damping time and equilibrium emittance may be reduced by shifting the rf frequency, such that the particle orbit moves inwards. By passing off-center through the quadrupoles in regions of nonzero dispersion, the horizontal partition number J_x is changed. This reduces both the horizontal damping time and equilibrium emittance. In addition, to the extent that the vertical emittance is determined by betatron coupling, the reduction in horizontal emittance may be accompanied by a corresponding reduction in vertical emittance. We report experience with such a scheme at the Stanford Linear Collider damping rings.

1 INTRODUCTION

The horizontal damping time and beam emittance are both inversely proportional to the horizontal partition number $J_x = 1 - D$, where [1]

$$D = \frac{\int \eta G(G^2 + 2K_1)ds}{\int G^2 ds}. \tag{1}$$

Here η is the horizontal dispersion, G and K_1 describe properties of the magnetic guide field, and the integrals are evaluated around the ring circumference. For the non-combined function SLC damping ring dipole magnets, $GK_1 \approx 0$.

For an orbit offset Δx in the quadrupoles, the change in D is given approximately by

$$\frac{2{K_1}^2 \eta_q L_g N_q}{2\pi/\rho}\Delta x, \tag{2}$$

where $K_1 = \frac{ec}{E}(\frac{\partial B}{\partial x})$ with $e = 1.6 \times 10^{-19}$ C, $c = 3 \times 10^{10}$ m/s, $E = 1.19$ GeV, ρ is the local bending radius, η_q is the dispersion at the quadrupoles, and L_q and N_q are respectively the quadrupole length and number of quadrupoles.

The orbit may be offset in the quadrupoles by either changing the accelerating frequency or by physically displacing the magnet support girders. Emittance optimization using the accelerating frequency has been used in $e+/e-$ storage rings previously[2] and is used routinely at LEP[3]. The circumference adjustment is applicable provided that the transverse acceptance is not limited and that the injected beam energy spread is small compared to the energy acceptance. At the SLC, the electron damping ring was 'stretched'[4] in 1992 by 9 mm for a 15% increase in J_x. In doing so, the energy aperture at injection was reduced without any loss in transmitted beam current. For the case of the positron ring, the incoming beam fills the entire aperture and stretching the accelerator is not an option. For both rings, further gains can be made by changing the rf frequency during the store.

2 EMITTANCE PROJECTIONS

Shown in Fig. 1 is the calculated horizontal emittance $\gamma\epsilon_x$ as a function of time for 4 different frequency offsets. The beam is injected at the nominal rf frequency of 714 MHz with an initial emittance of 20×10^{-5} m-r. The accelerating frequency is increased after 1 ms (dashed line) for which the longitudinal emittance has damped by about a factor of 2.

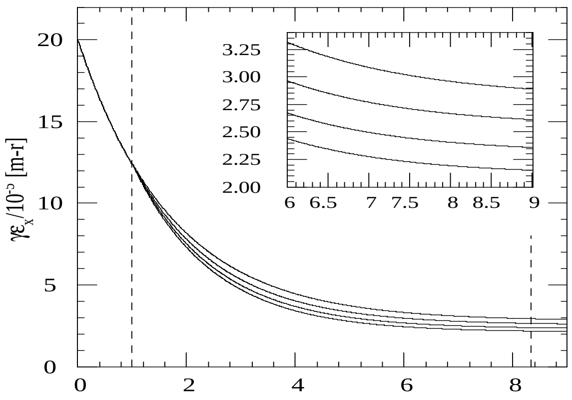

Figure 1: Normalized horizontal beam emittance as a function of store time for different frequency shifts. The full store time is shown with an expanded view near beam extraction at 8.33 ms shown in the insert. The curves, when viewed from top to bottom, correspond to frequency shifts of 0, 50, 100, and 150 kHz, respectively.

The simulations (using SAD[5]) with a trapezoidal approximation for the bending magnet fringe fields show a half unit reduction (i.e. 15-20%) in normalized emittance with a 100 kHz frequency change while the damping time reduces from 3.4 ms to 3.0 ms. In practice, the frequency must be ramped back to nominal just before extraction in order not to introduce any energy and/or phase errors in the downstream compressor and main linac. The time required

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to reset the frequency and relock the beam phase to the desired extraction phase was determined experimentally and found to be less than 200 μs.

3 FREQUENCY SHIFT

In these experiments an I-Q modulator was made to create a net phase rotation of the damping ring rf using two externally triggerable, digital function generators, mixers, and standard amplifiers and phase shifters. The rf phase was shifted by programming into the digital function generators smoothly varying, ramped sine (I) and cosine (Q) functions. To ensure proper regulation of the phase at extraction, the overall phase difference was adjusted to be an integral number of ring turns plus an offset to take into account the phase offset between injection and extraction from the damping rings. Any residual phase error was corrected, as usual, by the existing phase feedback loop. In standard operation, the reference input for this loop is changed slowly during the beam store time. In this application, the reference was changed quickly just before extraction.

With the change in accelerating frequency, the accelerating cavities are detuned by an amount characterized by the tuning angle ϕ_z which is given by

$$\phi_z = \tan^{-1}\left[2Q\left(\frac{f_0 - f_{\rm rf}}{f_0}\right)\right], \qquad (3)$$

where $Q = 6860$ is the loaded cavity quality factor, f_0 is the resonant frequency of the cavity, and f_{rf} is the frequency of the applied rf. With the cavity tuners *fixed*, the new tuning angle ${\phi_z}'$ corresponding to the new applied rf frequency ${f_{rf}}' = f_{rf} + \delta f_{rf}$ is given by

$$\tan {\phi_z}' = 2Q\left[1 - (1 - \frac{1}{2Q}\tan\phi_z)\frac{{f_{rf}}'}{f_{rf}}\right], \qquad (4)$$

which is shown in Fig. 2(a). Typically, the tuning angle is set for minimum reflected power:

$$\phi_z|_{\phi_l=0} = -\frac{I_b R}{V_c}\sin\phi_b, \qquad (5)$$

where $I_b = 0.2176$ A is twice the dc beam current, $R = 5$ MΩ is the total loaded impedance, $V_c = 800$ kV is the total cavity voltage, and $\phi_b \approx 80^\circ$ is the synchronous phase measured with respect to the crest of the accelerating rf. For example, from Fig. 2(a), with the parameters given above, the tuning angle at ${f_{rf}}' = f_{rf} + 100$ kHz is about -73° which is beyond the capabilities of the klystron in maintaining an 800 kV total cavity voltage during the frequency change.

The sustainable beam current for a fixed cavity voltage V_c is limited by the available generator power. The solid curve in Fig. 2(b) shows this limit [6] for a 60 kW klystron and $V_c = 600$ kV. Comparison with Fig. 2(a) shows that a 100 kHz frequency change can be made at the nominal current at this reduced cavity voltage with the cavity initially detuned; for example, from Fig. 2(a), the cavity tuning angle would be swept from -24° to -67° during the frequency change for 4×10^{10} particles per bunch (0.22 A). The klystron power required is less than 50 kW.

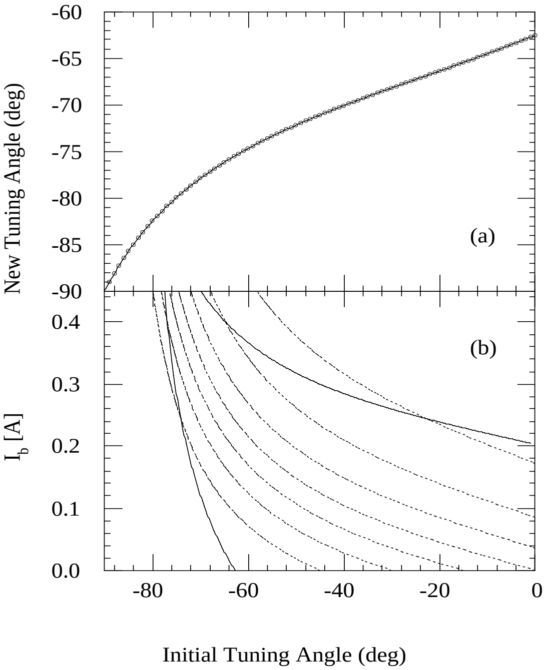

Figure 2: Cavity tuning considerations. The initial and final tuning angles at f_{rf} and ${f_{rf}}' = f_{rf} + 100$ kHz, respectively, are shown in Fig. 2(a). The stability boundary for cavity voltage regulation at 600 kV is given by the solid curve in Fig. 2(b). The dashed curves show the loading angle ϕ_l which is measured and regulated by the tuner feedback loops. At zero beam current, the loading angle is equal to the tuning angle.

4 EXPERIMENTAL RESULTS

Prior to implementation of the frequency shift, the energy aperture of the damping rings was measured. The frequency aperture may be limited by transverse betatron resonances, which can be encountered during the frequency ramp with nonzero chromaticity. The longitudinal aperture, measured by noting the extreme frequencies at which beam loss began to occur, was -70 to $+235$ kHz for the positron damping ring and -140 to $+160$ kHz for the (stretched) electron damping ring.

Measurements of the (positron) beam emittance both with and without the frequency ramp are given in Fig. 3. In this experiment, the downstream compressor was turned off in order to more cleanly detect the effect of the frequency shift on beam emittance. From Fig. 3, with a 62.5 kHz shift, the reduction in normalized emittance was from 3.30 ± 0.07 m-r to 2.66 ± 0.06 m-r. For the electron damping ring, the reduction with the frequency shift was from 3.22 ± 0.08 m-r to 2.93 ± 0.07 m-r.

The frequency shift scheme was installed and operational for over a week in the positron damping ring (SDR). No attempt was made to run routinely with the frequency shift in the electron damping ring (NDR) due to the explained power limitations. In the SDR, when the beam current was raised slightly, the beam became unstable due to insufficient klystron power during the frequency ramp; during the 1997/98 SLD run, one cavity in each damping ring was necessarily detuned (to avoid vacuum-related rf trips) by about $-20°$ which increased the power output demand since more power is reflected from a detuned cavity. The required detuning was unusual as compared to previous years. These problems are currently being addressed so that future operation with a mid-store frequency shift will not be limited cavity detuning.

5 LUMINOSITY PROJECTION

Using the 1997 interaction point parameters of $\theta_x, \theta_y = 450, 250$ μr angular divergence, and $\gamma\epsilon_x, \gamma\epsilon_y = (5.2, 1.1) \times 10^{-5}$ m-r normalized emittances measured in the final focus, the corresponding rms beam sizes are $\sigma_x, \sigma_y = 1.3, 0.5$ μm. With a 1 mm bunch length and 4×10^{10} particles per bunch, the luminosity is estimated from guinea-pig[7] to be 4.28×10^{32} m^{-2} per collision.

With the reduced emittances from the damping ring and fixed $\theta_{x,y}$, the estimated final focus emittance is $\gamma\epsilon_x = 4.4$ m-r which is computed assuming zero emittance growth in the linac and a 20% degradation in the final focus emittance. If, in addition, half of the anomalously large vertical damping ring emittance is due to betatron coupling so that the normalized vertical emittance is reduced by 0.1 m-r, and if half of this reduction is preserved to the interaction point, then $\gamma\epsilon_y = 1.0$ m-r. Then, from guinea-pig, the luminosity expected is 6.04×10^{32} m^{-2} per collision, which is an increase by over 40%. Additional gains may arise from a larger disruption enhancement.

Acknowledgements

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6 REFERENCES

[1] M. Sands, “The Physics of Electron Storage Rings”, SLAC-121 (1970).

[2] R.D. Kohaupt and G.A. Voss, 'Progress and Problems in Performance of $e+/e-$ Storage Rings', Ann. Rev. Nucl. and Part. Sci., **33**, (1983) 67.

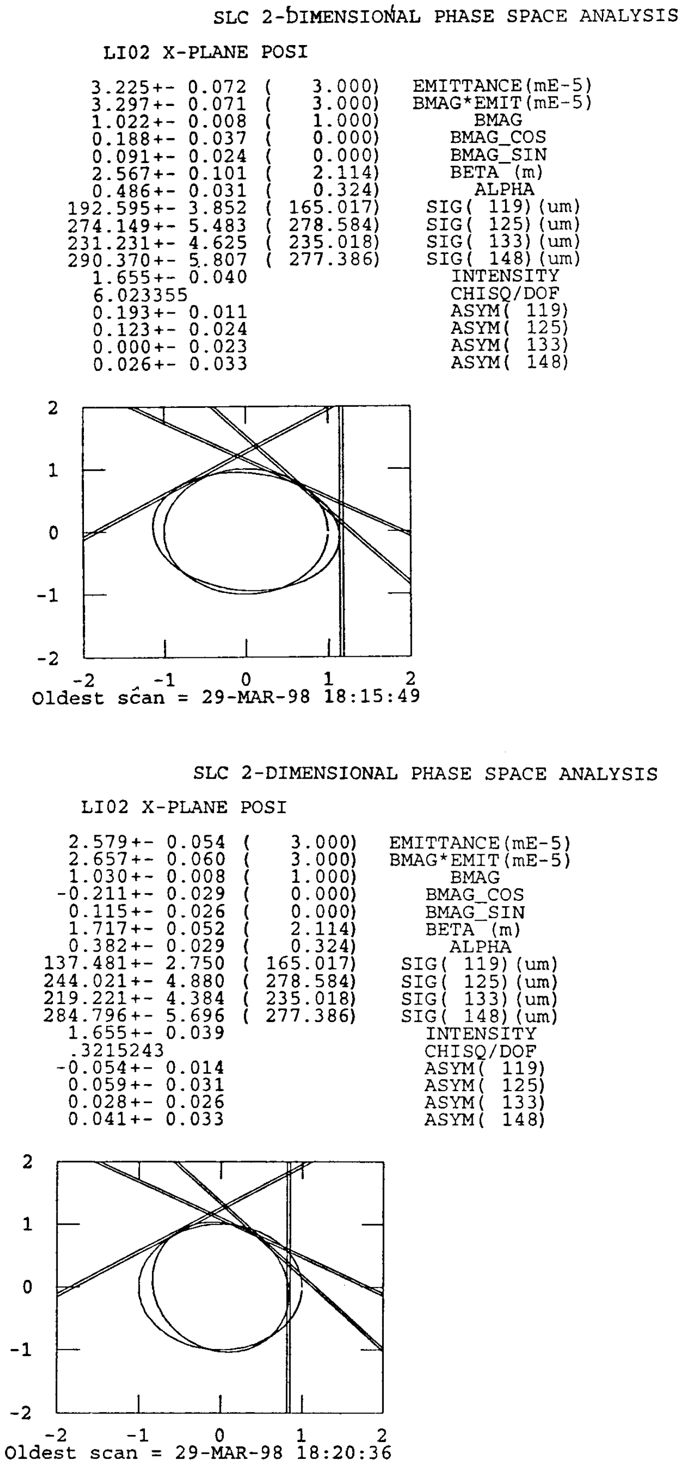
[3] I. Reichel, “Dynamic Aperture and Tail Scans”, Proc. 7th Wkshp. on LEP Performance (Charmonix, 1997).

[4] M.G. Minty *et al*, “Using a Fast-Gated Camera for Measurements of Transverse Beam Distributions and Damping Times”, AIP Conf. Proc., **281** J.A. Hinkson and G. Stover eds., Acc. Instr. Wkshp. (Berkeley, 1992) 158.

[5] SAD accelerator modeling code by K. Oide, unpublished.

[6] M.G. Minty and R.H. Siemann, “Heavy Beam Loading in Storage Ring Radio Frequency Systems”, Nucl. Instr. and Meth., A 376 (1996) 301.

[7] D. Schulte, “Study of Electromagnetic and Hadronic Background in the Interaction Region of the TESLA Collider”, Ph.D. thesis, University of Hamburg (1996).



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                    SLC 2-DIMENSIONAL PHASE SPACE ANALYSIS

   LI02 X-PLANE POSI

   3.225+- 0.072 (    3.000)  EMITTANCE(mE-5)
   3.297+- 0.071 (    3.000)  BMAG*EMIT(mE-5)
   1.022+- 0.008 (    1.000)      BMAG
   0.188+- 0.037 (    0.000)    BMAG_COS
   0.091+- 0.024 (    0.000)    BMAG_SIN
   2.567+- 0.101 (    2.114)    BETA (m)
   0.486+- 0.031 (    0.324)      ALPHA
 192.595+- 3.852 (  165.017)   SIG( 119)(um)
 274.149+- 5.483 (  278.584)   SIG( 125)(um)
 231.231+- 4.625 (  235.018)   SIG( 133)(um)
 290.370+- 5.807 (  277.386)   SIG( 148)(um)
   1.655+- 0.040                 INTENSITY
   6.023355                      CHISQ/DOF
   0.193+- 0.011                 ASYM( 119)
   0.123+- 0.024                 ASYM( 125)
   0.000+- 0.023                 ASYM( 133)
   0.026+- 0.033                 ASYM( 148)
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Oldest scan = 29-MAR-98 18:15:49
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                    SLC 2-DIMENSIONAL PHASE SPACE ANALYSIS

   LI02 X-PLANE POSI

   2.579+- 0.054 (    3.000)  EMITTANCE(mE-5)
   2.657+- 0.060 (    3.000)  BMAG*EMIT(mE-5)
   1.030+- 0.008 (    1.000)      BMAG
  -0.211+- 0.029 (    0.000)    BMAG_COS
   0.115+- 0.026 (    0.000)    BMAG_SIN
   1.717+- 0.052 (    2.114)    BETA (m)
   0.382+- 0.029 (    0.324)      ALPHA
 137.481+- 2.750 (  165.017)   SIG( 119)(um)
 244.021+- 4.880 (  278.584)   SIG( 125)(um)
 219.221+- 4.384 (  235.018)   SIG( 133)(um)
 284.796+- 5.696 (  277.386)   SIG( 148)(um)
   1.655+- 0.039                 INTENSITY
   .3215243                      CHISQ/DOF
  -0.054+- 0.014                 ASYM( 119)
   0.059+- 0.031                 ASYM( 125)
   0.028+- 0.026                 ASYM( 133)
   0.041+- 0.033                 ASYM( 148)
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Figure 3: Emittance measurements measured in the downstream linear accelerator with no frequency shift (top) and with a 62.5 kHz frequency shift (bottom). The normalized emittance was reduced from 3.30 ± 0.07 m-r to 2.66 ± 0.06 m-r.