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**DAMPING RINGS FOR ACHIEVING
ULTRA-SMALL ELECTRON BEAM EMITTANCE**

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1. Introduction: Emittance Requirements for TeV e⁺/e⁻ colliders

In order to produce an e⁺/e⁻ linear collider operating at TeV energies with adequate luminosity the emittance of the beam after acceleration must be extremely small. Since beam emittance (normalized) grows during acceleration the emittance at injection must be even smaller. This requirement of extremely low emittance has been widely recognized as an essential constraint and may prove to be a major impediment to successful construction of a TeV collider.

More quantitatively, by manipulation of the usual formulas¹ for the luminosity, disruption and beam power we can obtain the following rather intriguing relationships, which are given below in practical units for round gaussian beams

($\sigma_x = \sigma_y$),

$$(a) \text{ Luminosity/single beam power} \approx \hat{L} = 3.45 \times 10^{34} \text{ D}/\sigma_z [\text{cm}^{-2}\text{sec}^{-1}/\text{megawatt}]$$

(D is the dimensionless disruption parameter. We have ignored any luminosity enhancement from focussing effects during the bunch collision. In computer simulations, this typically gives about a factor of 3 increase in luminosity for D>2). σ_z is the bunch length in microns. This result holds for any beam energy, an arbitrary repetition rate, and does not depend on the parameters of the final focus.

(b) At the final focus the focal length β^* needed to achieve this luminosity can be written

$$\beta^* = br_o \left(\frac{\sigma_z}{D} \right)$$

$$b \equiv N/\gamma c$$

$$N = \# \text{ electrons in bunch}$$

$$\gamma = E_o/mc^2$$

$$c = \text{beam emittance}$$

$$r_o = \text{classical electron radius}$$

The constraint $\beta^* > \sigma_z$ is seen to imply a relation between the disruption parameter and the beam emittance:

$$br_o > D$$

This gives an upper bound on the useful beam emittance for a given disruption parameter.

Numerically, br_o is about 1-2 for the beam injected into the SLC². For a higher energy linear collider with (for example) $\hat{L} = 3.5 \times 10^{32} \text{ cm}^{-2}\text{sec}^{-1}/\text{Mw}$, $\sigma_z/D = 0.1 \text{ nm}$ and the emittances obtained with the SLAC damping ring, $\beta^* < 0.1 - 0.2 \text{ mm}$, a small value which seems totally beyond reach with presently known beam focussing techniques. Also D<2 is implied by the requirement that the bunch length

be shorter than β^* , so it would be impossible to optimize the enhancement due to disruption. Clearly a smaller beam emittance is needed, i.e. a larger value of ϵ_r . We will ignore the perhaps even more difficult problem of how to preserve low beam emittance during acceleration and concentrate on how to produce low emittance at injection.

2. High Tune Damping rings as Sources of Low Emittance Electron Beams

The advent of practical superconducting quadrupoles used at proton storage rings with gradients of order 1 Tesla/cm leads us to ask whether lower beam emittance might be achieved if these high gradients could be used in electron storage rings. We assume here that the engineering problems associated with synchrotron radiation can be solved. In what follows we present results of a simulation using the tracking program "XSIM" for machines of radius 100 meters and 1000 meters. Of course even larger machines are possible. For example, Amaldi suggested³ using the LEP tunnel as the damping ring for a linear collider.

The results of this simulation can be used to set design goals for both the accelerator and the final focus of a future TeV linear collider.

3. Details of Machine Lattices Used in Simulation

Two machines were studied using the simulation program. Since we are interested only in a general understanding rather than a specific engineering design, it was assumed that the machines are circular with no straight sections. A simple FODO cell, repeated in the form FODOF, was used. The phase advance was chosen to give minimum emittance. Of course a real machine will differ from this design in several respects:

- (1) there will be straight sections for injection and beam extraction, with a consequent need for matching the lattice into the straight sections.
- (2) the dispersion, although very small in a machine with a tune this large, needs to be suppressed at the rf to prevent synchrotron resonances. No attempt was made to incorporate any of these features at this very preliminary stage and the synchrotron resonances can be clearly seen in the simulation. The primary constraint on the design was that the quadrupole gradient be approximately 80 Tesla/Meter at the design energy. The latter was chosen as a guess for a nominal design current. Once the phase advance and quad gradient are fixed, only the length of the unit cell needs to be specified. This must be long enough so that the quad length is not unphysically longer than the cell itself.

The two machines were assumed to have radii of 100 and 1000 meters. The unit cell lengths were 2 meters and 4 meters respectively. These produce nominal horizontal and vertical tune values of about 55 and 275. In this report we consider only the case where horizontal and vertical tunes are nearly equal. This is because there may be some advantage to obtaining round beams for injection into the linear accelerator. However, in the simulation the results presented in this report do have considerable horizontal/vertical asymmetry, because we did not have enough time to investigate the more symmetrical case.

Table I gives the detailed list of lattice characteristics for both the "100 meter" and "1000 meter" machines.

TABLE I
LATTICE CHARACTERISTICS

	100 m.	1000 m.
phase advance/ unit cell	62 degrees	62 degrees
length of unit cell	2 m	4 m
nominal tune	55	275
no. unit cells	314	1570
nominal energy	5 GeV	25 GeV
dimensions:		
quad length	.218 m	.545 m
drift length	.782 m	1.455 m
bending radius	62.5 m	581.5 m
bending field	.267 T	.143 T
quad gradient	86.6 T/m	88.5 T/m
momentum		
compaction	3.6×10^{-4}	1.4×10^{-5}
natural (arc)		
chromaticity	-1.114	-1.114
Twiss parameters:		
alpha (H,V)	0. 0.	0. 0.
beta(H,V)	3.35 m 1.09 m	6.67 m 2.19 m
dispersion	0.046 m	0.018 m

4. The Program

The program XSIM takes into account the following physical effects, listed roughly in order of increasing complexity: First order beam transport; damping from energy loss due to synchrotron radiation; excitation from the quantum nature of the radiation; beam excitation due to the presence of gas molecules in the beam pipe; the effect of magnet errors; beam growth due to intrabeam (electron-electron) scattering; and the effect of wakefields induced in the rf cavity. In addition, a separate program allows us to study the effects of higher order optics on the dynamical aperture (we don't include the higher order optics in the main program, since they slow the program down by an order of magnitude.)

The first order optics and the effects of synchrotron radiation are modeled after a program developed by R. Siemann,⁴ and are simple, well understood effects. The effects of magnet errors, which cause a coupling between horizontal and vertical motion that would otherwise be absent, are handled by introducing a 45 degree skew quadrupole magnet, the strength of which is set in an ad hoc manner to give reasonable coupling (of course, any treatment of magnet errors must contain some amount of guesswork; we simply set the strength of the skew quad to give the same ratio of horizontal to vertical emittance as is observed at CESR). A vertical dispersion, also due to magnet errors, was assumed to be 1% of the horizontal dispersion.

The effects of non-zero chromaticity were included in the program, but due to time constraints, were not studied in detail. As is well known, the addition of sextupoles can cancel the effects of non zero chromaticity, at the expense of dynamical aperture. Future work will study these effects in more detail.

The code also contains the possibility of a fine tuning quadrupole which can be used to vary the ratio of vertical to horizontal tunes. If set to the proper value, the tunes become equal and the beam becomes round. In addition, there are provisions for higher order multipole moments of the magnets, which can simulate the fact that the quadrupoles and bending dipoles are not perfect.

We investigated two approaches to intrabeam scattering: Piwinski's,⁵ and Bjorken and Mtingwa's.⁶ Although the two approaches involve slightly different approximations, and indeed are quite different in the mathematical steps taken and in the final formulae, we found that they gave essentially identical results. However, the computer implementation of Bjorken and Mtingwa's method involves integrating the inverse of a 4x4 matrix, whereas Piwinski's treatment could be reduced to a simple, one dimensional integral. Consequently, Piwinski's method was found to be significantly faster, and this is what was used in the code.

For the wake field effects, we are indebted to R. Siemann.⁷ The general treatment of wake fields is extremely difficult, and indeed is one of the major problems facing modern tracking programs. Since our purpose was not to do the detailed design of a damping ring, it sufficed to take the wake fields for an arbitrary (but realistic) rf cavity provided to us by R. Siemann. Using these wake fields, together with a hermite polynomial decomposition of the beam distributions, we were able to model the wakefields in a realistic way. Future work will be directed toward studying the wakefield instabilities in more detail.

A more complete description of the program, including the formulas used, will be published elsewhere.

5. The Runs

As mentioned, we used XSIM to study two different damping rings (see table I). For each machine, we made several runs at different energies for a range of beam currents. Due to intrabeam scattering, there is an energy for which the emittance is minimized for each current, as seen in figures 1-3. In addition, wakefield effects impose a maximum current before instabilities arise. By increasing the current, one can minimize the invariant emittance per particle. As explained in the introduction above, the reciprocal of this quantity forms an excellent figure of merit for the injected beam. The ultimate limit is set by single beam instabilities at currents somewhat higher than shown in the graphs. As the impedance of the vacuum chamber is not included in the calculation, the true thresholds may lie somewhat lower than the present calculations indicate.

6. Conclusions

Using XSIM, we have seen that high tune machines of the form considered here appear to be feasible, with emittances several orders of magnitude smaller than presently observed in existing machines. Intrabeam scattering, negligible under normal conditions, becomes the dominant process affecting the beam emittance. Due to this effect, the curve of emittance versus beam energy at fixed current has a minimum value. The energy at which this minimum occurs increases with increasing current, until single beam instabilities are encountered.

We estimate that, for the 100 m. radius machine, emittances as low as 10^{-9} m-radians can be obtained with currents of order 10 mA. For the 1000 m. radius machine, emittances of almost one order of magnitude lower, or about 10^{-10} m-radians, are possible with currents of several mA.

If we use $Nr_0/\gamma c$ as a figure of merit as explained above, the 100 m. machine can give up to 80 or so, as compared to 1 or 2 for the present SLC injected beam. The 1000 m. machine will yield up to 1000 or more for this parameter. (One cautionary note: at the higher currents the impedance of the vacuum chamber, which we have ignored, may play a significant role).

With gains in the figure of merit of 1000, β^* values at the final focus can be of the order of 10 to 20 centimeters, as compared to 0.1 to 0.2 mm dictated by presently available beams. This conclusion, if borne out by more detailed subsequent calculations, allows for the first time the design of realistic final focus optics for a TeV e^+/e^- linear collider. Of course the problem of maintaining the low emittance during acceleration remains unsolved.

Table II

100 m. Machine at 10 GeV

Machine Parameters

Beam energy	10.00 GeV
Machine average radius	99.949 meters
Magnet fill factor	.628
Beam revolution period	2.095 microseconds

Synchrotron Radiation Parameters:

Energy loss/turn	14.100 MeV
Radiation damping times: energy	1.49 milliseconds
horiz	2.97 "
vert	2.97 "

Rf Parameters:

Peak rf voltage	20.000 MeV
Rf frequency	1498.950 MHz
Synchrotron tune	.0136
Harmonic number	3140
Overvoltage factor	1.418
Stable rf phase	2.359 radians
Half-width(rel.energy) of stable rf bucket	1.308 %

Lattice Parameters:

Betatron tunes(Q_x, Q_z)		54.269	45.252
Damping partition numbers	.999	1.000	2.001

Stochastic Beam Parameters: (without intrabeam scattering)

Betatron emittance: horizontal	19.57 angstrom-radians
vertical	1.48 "
Beam size: horizontal	.089 mm
vertical	.013 "
Bunch length	9.63 psec
"	2.89 mm
Energy spread	.108 %

1000 m Machine, 25 GeV

Machine Parameters

Beam energy	25.00 GeV
Machine average radius	999.493 meters
Magnet fill factor	.582
Beam revolution period	20.948 microseconds

Synchrotron Radiation Parameters:

Energy loss/turn	59.388 MeV
Radiation damping times: energy	8.82 milliseconds
horiz	17.64 "
vert	17.64 "

Rf Parameters:

Peak rf voltage	100.000 MeV
Rf frequency	1498.950 MHz
Synchrotron tune	.0104
Harmonic number	31400
Overvoltage factor	1.684
Stable rf phase	2.506 radians
Half-width(rel.energy) of stable rf bucket	3.771 %

Lattice Parameters:

Betatron tunes(Qx,Qz)	274.754	274.750
Damping partition numbers	1.000	1.000
		2.009

Stochastic Beam Parameters (without intrabeam scattering):

Betatron emittance: horizontal	1.02 angstrom-radians
vertical	1.34 "
Beam size: horizontal	.028 mm
vertical	.017 "
Bunch length	4.05 psec
"	1.21 mm
Energy spread	.089 %

References

1. See, for example, the article by L.N. Hand and J.R. Rees in "The Generation of High Fields for Particle Acceleration to Very High Energies", page 230 ff., ECFA 85/91 and CERN 85-07.
2. For $N = 10^{10}$ electrons and $\gamma\epsilon = 3 \times 10^{-5}$ m-radians, $br_0 = 1$. This corresponds (approximately) to the presently achieved injection beam emittance at the Stanford SLC.
3. U. Amaldi, "TeV Electron-Positron Collisions with Luminosities of 10^{34} cm^{-2} sec^{-1} Using the CERN Tunnels for the Damping Rings", CERN EP/85-102, June 1985.
4. R. Siemann, "Computer Models of Instabilities in Electron Storage Rings", AIP Conference Proceedings No. 127, Physics of High Energy Accelerators, BNL/SUNY summer school 1983, page 368 ff.
5. A. Piwinski, Proceedings of the 9th International Conference on High Energy Accelerators, 1974, pg 405. We thank Dr. J.R. Evans for discussions about practical computations with Piwinski's formulas.
6. J.D. Bjorken and S.K. Mtingwa, "Intrabeam Scattering", Particle Accelerators, 13, 115 (1983)
7. Wake fields were calculated by R. Siemann for a 1500 MHz. cavity similar to those used in PEP. The longitudinal wake was calculated for a gaussian beam of rms length 0.6 mm and the transverse wake with rms bunch length 1.5 mm. For our purposes, we used these wake fields instead of (unavailable) point charge wakes. Instability thresholds would be somewhat lower if the correct wake fields were used. The number of rf cavities was 200 (20 meters total length) for the small machine, and 1000 (100 meters total length) for the large machine. An rf gradient of 1 MeV/meter was assumed. We would like to thank Professor Siemann for making his calculations available to us.

Figure Captions

Figure 1

Horizontal emittance is plotted vs beam energy for the 100 meter ring. Without intrabeam scattering the emittance grows proportional to (energy)², as expected. Wakefield effects are absent here.

Figures 2, 3

Horizontal emittance vs energy for the 100 meter and 1000 meter machines. Wakefields and intrabeam scattering are included, but gas scattering is omitted. Zero chromaticity is assumed. Single beam instabilities occur at energies just below where these curves are cut off by the upper end of the graph shown. Note difference in both emittance and energy scales between figure 2 and figure 3.

Figure 4

Minimum emittance vs current for the two machines. The energy is varied with the current to maintain conditions at the minimum emittance.

Figure 5, 6

Run history of various quantities vs turn number for two cases. Figure 5 shows the behavior far from an instability, i.e. at low current. Figure 6 shows the onset of a single beam instability at high current, near to the maximum possible current. The energy is 6 GeV and currents are 10 mA and 100 mA. The machine is the "100 meter" radius machine.

Figures 7, 8

These figures are the power spectrum obtained by Fourier analysis of the average horizontal and vertical positions, bunch longitudinal position relative to the stable phase at zero current, and average displacement of the energy from the nominal value. The conditions are the same as in Figures 5 and 6. The effects of wakefields can be seen in the presence of higher harmonics of the synchrotron frequency, frequency spread in the synchrotron oscillations. The relative absence of synchrotron sidebands in the betatron oscillator power spectrum indicates that the instability limiting the current is a longitudinal instability.

Figure 9

Shows the same conditions in figure 8 but on a log scale for the power spectrum.

Figure-1

Figure-2

Figure-3

Figure-4

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Figure-5

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Figure-6

Figure-7

Figure-8

Figure-9