The TESLA 5 GeV Damping Ring

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Abstract

This paper describes a project completed for the 2002 LEPP REU at Cornell University. The purpose of the project is to investigate various properties of the TESLA 5 GeV damping ring using computer simulation programs developed at Cornell. Twiss parameters (beta functions, dispersion, tunes) and emittance are calculated and compared with previous results. The performance of the ring is examined after imposing a gaussian distribution of ring errors.

Introduction

TESLA is an acronym for **T**era electron Volt **E**nergy **S**uperconducting **L**inear **A**ccelerator. This refers to a proposed design for a 33 km long electron-positron linear collider to be built in Germany. The TESLA collider will use superconducting radiofrequency cavities to accelerate the particle beam to an energy of 500 GeV. As shown in Figure 1 [1], the collider consists of two linear accelerators, one for electrons and one for positrons. The positrons and electrons are accelerated toward each other from the far ends of the collider, and then meet in the middle. It is expected that, among other things, TESLA will measure the mass and lifetime of the Higgs particle, and provide insight into the theory of supersymmetry.

The luminosity of a particle beam is the number of particles per second per unit area, and is related to the frequency of particle collisions. This design for a linear collider requires an especially small beam size for optimum luminosity. More precisely, we define the beam emittance as the area of the particle beam when plotted in phase space, and require that this quantity is small. However, the particle sources alone (particularly the positron source) will not produce a beam with a sufficiently small emittance. Therefore, the design for the TESLA linear collider provides a method of reducing the size of the beam prior to acceleration. This is the purpose of the damping rings, which are the dog-bone shaped structures labeled in Figure 1.

Design of the Damping Ring

A more detailed picture of the TESLA damping ring is shown in Figure 2 [2]. The ring consists of two return arcs, two long straight sections, and two wiggler sections. This particular shape was chosen because of the ring's large circumference. The type of superconducting accelerating cavities that TESLA employs requires a certain spacing of the particle bunches. This spacing along with the number of bunches determines the circumference of the ring. The bunches can be compressed in order to reduce this length; the spacing cannot be too close, however, or the action of a kicker ejecting a bunch from the ring will affect other nearby bunches. The combination of these factors yields a damping ring circumference of 17 km. Digging a tunnel for a circular ring with such a large circumference would be difficult, and furthermore the substantial number of bend magnets needed would be very expensive. The

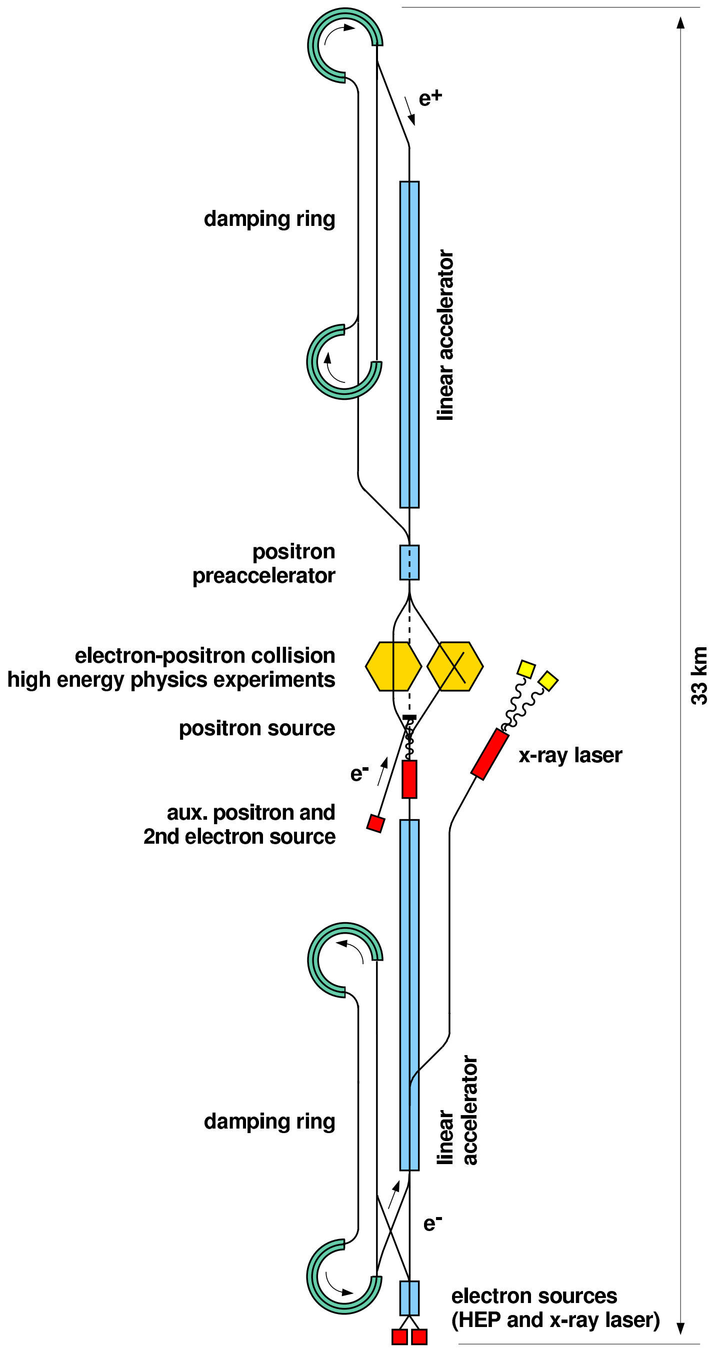

FIGURE 1. The TESLA linear collider

TABLE 1. Selected parameters for the TESLA damping ring

Energy	5 GeV
Circumference	17 km
Number of Bunches	2820
Bunch Spacing	20×10^{-9} s
Injected Electron Emittance	10^{-9} m
Injected Postitron Emittance	10^{-6} m
Energy Loss/turn (positrons)	21 MeV
Horizontal Extracted Emittance	8×10^{-10} m
Vertical Extracted Emittance	2×10^{-12} m

dog-bone shape allows the majority of the ring's circumference to be straight sections that are installed in the linac tunnel, which will already exist. Briefly, the damping ring works as follows. After being produced at the source, the particles are accelerated to 5 GeV, at which point they enter the damping ring. Particles in the damping ring experience acceleration that causes energy loss through synchrotron radiation. This "damps" out the transverse velocities and lowers the transverse beam emittance to the appropriate values (the RF cavity provides only a longitudinal acceleration to keep the particles in the ring). Then the particles are injected into the linac. The majority of the energy loss per turn occurs in the wiggler sections, but there is also some energy loss in the arcs. The damping is exponential, and the final extracted emittance is given by

$$\epsilon_f = \epsilon_{eq} + (\epsilon_i - \epsilon_{eq})\, e^{-2t/\tau_D} \tag{1}$$

where ϵ_{eq} is the equilibrium emittance, ϵ_i is the initial injected emittance, τ_D is the damping time, and t is the storage time. Some important damping ring parameters are summarized in Table 1 [2].

Methods

Our primary tool for performing computer simulations of the TELSA damping ring is

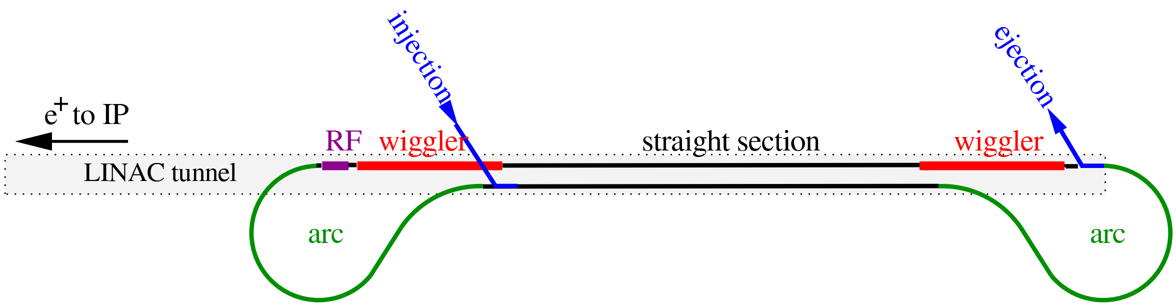

FIGURE 2. The design of the TESLA damping ring

TABLE 2. A simple ring lattice file

```
beam, energy = 1.98
NUMBER_CELLS := 20
BEND_MAGNET: SBEND, L=5.0, ANGLE=PI/NUMBER_CELLS
QUAD_FOC_HALF: QUADRUPOLE, L=.25, K1= .12
QUAD_DEFOC_HALF: QUADRUPOLE, L=.25, K1= -.33
FODO_CELL: LINE=(QUAD_FOC_HALF, BEND_MAGNET, 2*QUAD_DEFOC_HALF,&
BEND_MAGNET, QUAD_FOC_HALF)
IP_L0:  MARKER
END: MARKER
RING: LINE=(20*FODO_CELL)
THIS_LATTICE: LINE=(IP_L0, RING, END)
use, this_lattice
```

a particle tracking program called BMAD [3]. In this program, the ring is represented by something called a ring lattice file. The lattice file specifies the beam energy and defines all the individual ring elements (such as quadrupoles, bend magnets, ...etc). The individual elements are combined into cells or sections, and then the sections are combined to form the ring. For example, consider the simple ring lattice file shown in Table 2. First, the beam energy is set to 1.98 GeV. Then the three types of magnets making up a FODO cell are defined with their appropriate parameters. The ring itself is composed of 20 FODO cells, which form a complete circle. The lattice file for the TESLA damping ring is of course much more lengthy and complex. The ring itself consists of about 12,000 elements.

BMAD can take a given lattice file and compute important quantities characterizing the ring:

- horizontal and vertical orbits of a particle as it travels through the ring
- horizontal and vertical beta functions, which describe the magnitude of particle oscillations about the ideal orbit
- horizontal and vertical dispersion, which describe the deflection of an off-energy particle from the ideal orbit
- horizontal and vertical tunes, which describe the number of oscillation periods a particle undergoes in one turn of the ring
- horizontal and vertical emittance

The emittance of the TESLA damping ring as computed by BMAD for two different versions of the ring lattice is shown in Table 3. These results can be compared to the extracted emittance values stated in Table 1. BMAD was used to examine the twiss parameters in different regions of the ring. For example, Figure 3 is a plot that appeared in a paper by W. Decking, showing the beta functions and the horizontal dispersion for an arc bending cell [2]. Figure 4 shows my attempt to reproduce this plot with output from `stay_clear`,

TABLE 3. Beam emittance of the TESLA damping ring as computed by BMAD

Lattice file	Horizontal Emittance (m)	Vertical Emittance (m)
`dog_test.lat`	5.30×10^{-10}	0
`dog6_1_1_rot.lat`	5.16×10^{-10}	1.22×10^{-15}

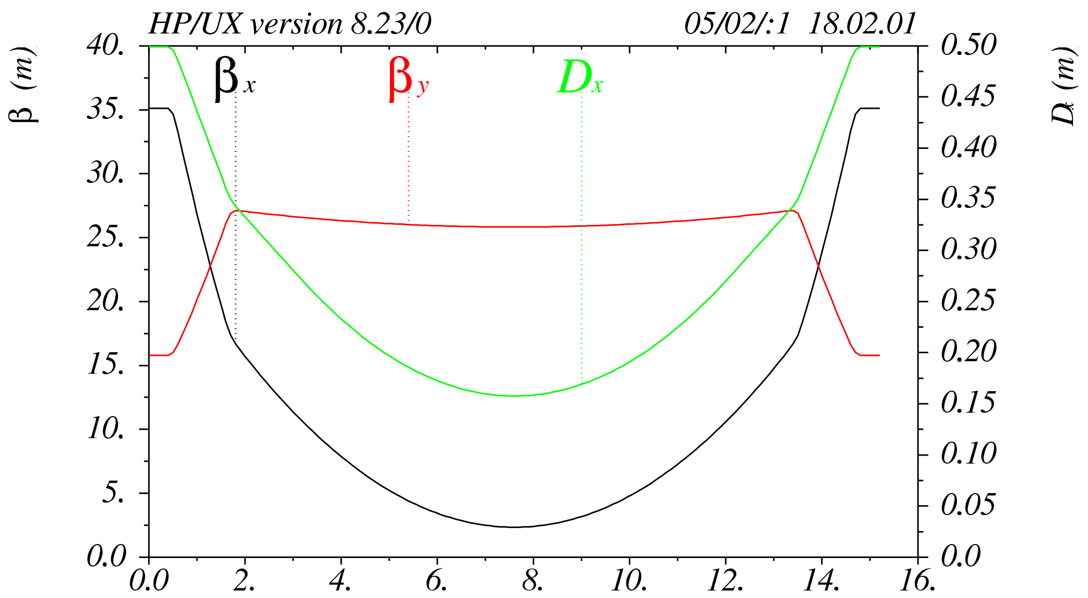

FIGURE 3. A plot of an arc bending cell by W. Decking

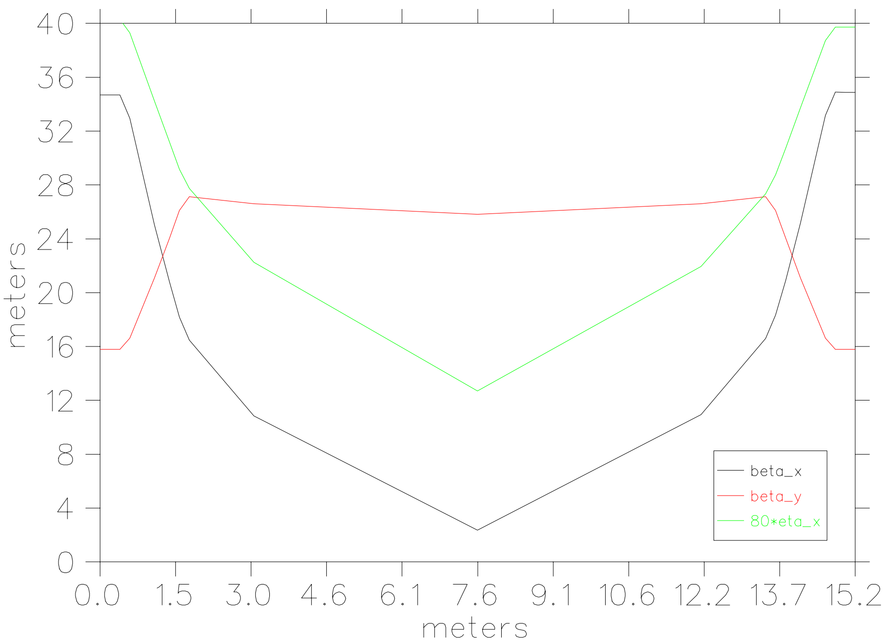

FIGURE 4. A plot of an arc bending cell using output from BMAD

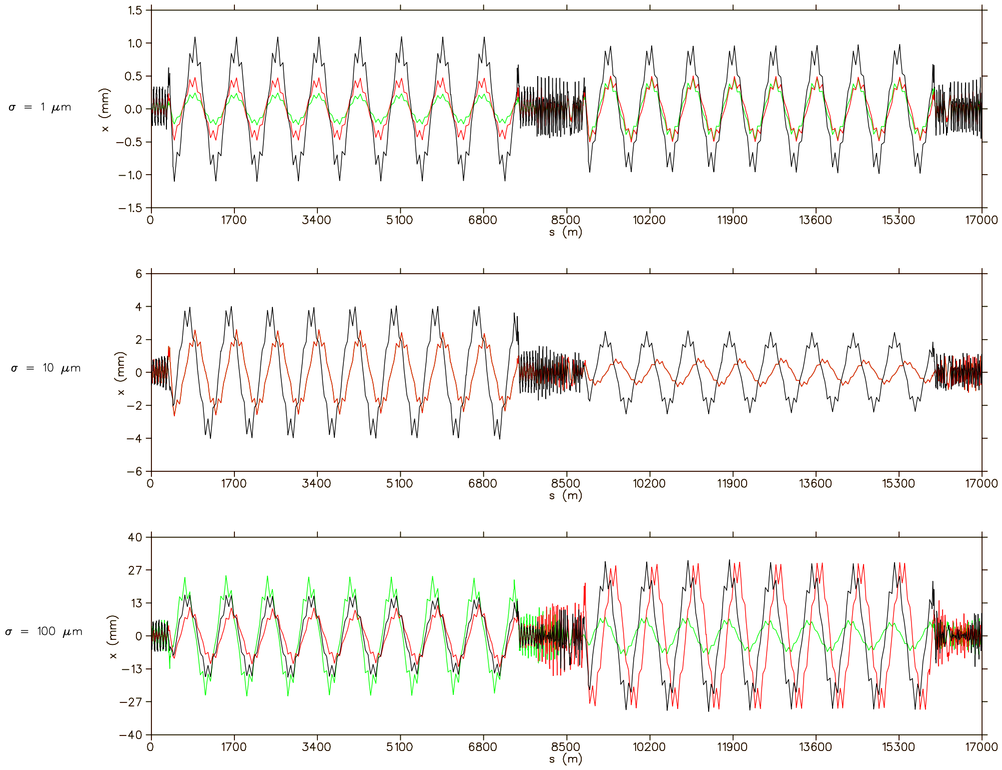

FIGURE 5. Variation of the x-orbit due to random errors

a program consisting of BMAD subroutines. It is encouraging that the two plots are quite similar. Results for other ring sections were also comparable to those in [2], but in some cases there were slight discrepancies in the length of a cell or the magnitude of the oscillations. This may be due to alterations of the ring lattice since the time of Decking's calculations.

Ring Errors

The ring magnets must be positioned very precisely for the damping ring to function properly. However, the magnets will inevitably be subject to small random alignment errors. Therefore, it is necessary to ensure that such errors will not affect the performance of the ring. Associated with each magnet defined in the lattice file is a set of misalignment parameters, such as offsets, pitches, and tilts. Offsets displace an element by a specified distance with respect to the beam coordinate system. A horizontal(x) pitch is a rotation about the y-axis, and a vertical(y) pitch is a rotation about the x-axis. A tilt is a rotation about the beam path axis that introduces coupling of transverse motion. A misaligned quadrupole can also be approximated by a kicker element, which deflects particles by a given angle. These types of errors can be introduced simply by modifying the element definition in the ring lattice file.

First, individual errors were inserted into the ring in order to observe how this affected the emittance. For example, consider the quadrupole located in the straight section at s = 12,353 m (in the lattice file `dog_test.lat`). After giving this element a vertical offset of .1 mm, the horizontal emittance is 5.30×10^{-10} m and the vertical emittance is 2.83×10^{-13} m. The ring now has nonzero vertical dispersion and emittance. As another

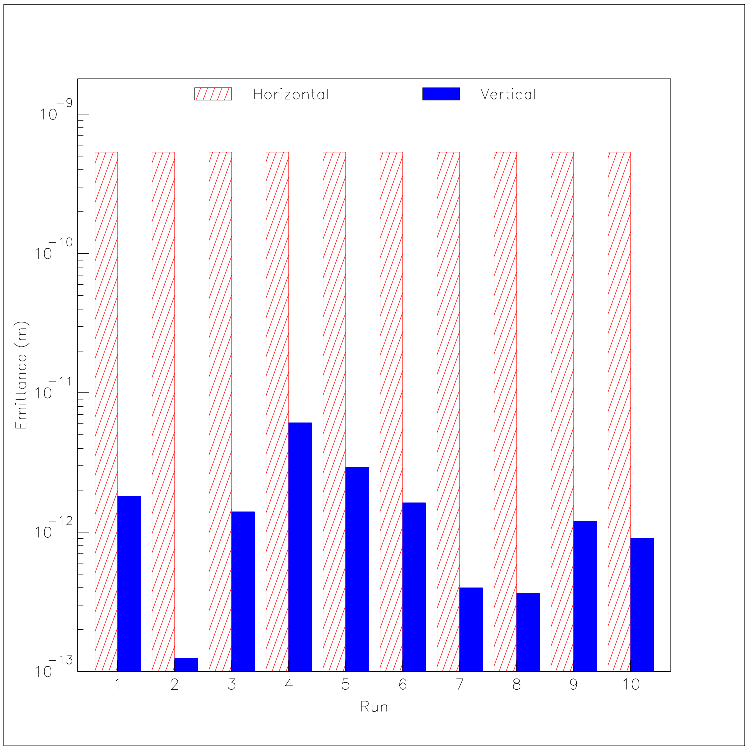

FIGURE 6. Emittance values for 10 runs of random tilts given to quadrupoles with a standard deviation of .000066 radians

example, it is interesting to consider how ring errors relate to the coupling insertion in the damping ring. The lattice file `dog6_1_1_rot.lat` has skewed quadrupoles at the beginning and end of the straight sections that introduce (and then remove) coupling of transverse motion. The coupling enlarges the beam size slightly, making the beam less dense (during the straight section only). This is beneficial because it reduces the effects of interactions between particles within a bunch. The amount of coupling is indicated by the $\overline{\mathbf{C}}$ matrix elements, which come from a similarity transform of the transfer matrix [4]. When there is no coupling, the matrix elements are zero. A quadrupole located at s = 8,194 m (a region without coupling) was given a tilt of .2 miliradians. This error had little effect on the $\overline{\mathbf{C}}$ matrix elements and the vertical dispersion. This method of investigating ring errors has limited benefits though; realistically the ring will contain a large number of errors and it might be expected that the magnitude of these errors are governed by some probability distribution. A modified version of `stay_clear` written by graduate student Richard Helms assigns random errors to elements in the lattice file such that the magnitudes of the errors form a gaussian distribution. The user decides what types of elements receive errors and what kind of errors each element type receives (offsets, pitches, tilts,. . . etc).The user can also adjust the standard deviation of the error distribution for each kind of error. The maximum error possible is set to be 3 standard deviations from the mean. Figure 5 shows variation in the x-orbit for three different standard deviations: 1 μm, 10 μm, and 100 μm. For each standard deviation, the program has been run three times. Note that as the size of the error increases, the magnitude of the oscillations and the variation between different runs increases as well. To look at how the emittance varies, the quadrupoles in the ring were given

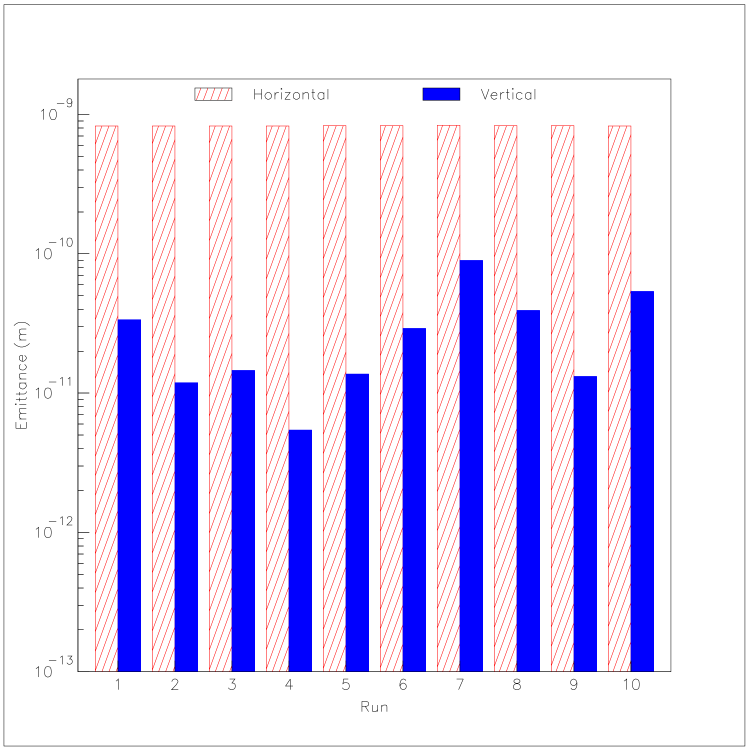

FIGURE 7. Emittance values for 10 runs of random y_offsets given to quadrupoles, with a standard deviation of 3.3 μm

a guassian distribution of tilts so that the maximum possible tilt (3 standard deviations) is .2 milliradians. The horizontal and vertical emittance values from ten runs are shown in Figure 6. A similar chart for vertical offsets is shown in Figure 7.

Conclusions

Research into the TESLA damping ring at Wilson Laboratory is in its preliminary stages, so clearly no final judgements are warranted at this time. In the future, damping ring parameters will be studied in more detail. Further investigation into the effects of ring errors are necessary to confirm that the ring is functional under real life limitations. If necessary, modifications to the ring design may be proposed to correct problems. Finally, experiments with CESR may be performed to provide hard evidence that the ring design is valid.

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Footnotes and References

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