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Vertical Arc for ILC Low Emittance Transport

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1 Introduction

A 1 TeV CM ILC which relies upon 30 MV/m accelerating cavities with a packing fraction of 65% will require almost 48 km of main linac, which suggests that the total site length including BDS and bunch compressors will be on the order of 53 km. If built in a laser-straight tunnel with the low-energy ends near the surface, and assuming a perfectly spherical "cue ball" planetary surface with radius 6370 km, the collider halls will necessarily be 55 meters below grade, as shown in the top plot of Figure 1. Such depths would demand extensive use of deep tunneling, which would potentially drive up the cost and difficulty of ILC construction.

An alternate solution is to use discrete vertical arcs at a few locations to allow a "piecewise straight" construction in which the depth of the tunnel below grade does not vary by more than a few meters. This approach is shown schematically in the bottom plot of Figure 1. In this Note we consider the issues for a design with one such vertical arc at the 250 GeV/c point (ie, midway down the linac for 1 TeV CM), and a second arc at the entrance to the BDS (ie, the entire BDS lies in one plane, with vertical arcs at each end).

2 Saggita of the Proposed Solution

Figure 2 shows the depth below grade for a 53 km long ILC in which the accelerator has vertical bends at the approximate center of each linac and outboard of the BDS on each side. In this configuration, the maximum depth variation of any segment is less than 3.5 m, and the depth variation of the BDS is approximately 0.18 m. This is a far more sensible solution than the straight tunnel solution, in which the maximum variation is over 55 meters.

3 Optics of the Vertical Arc

Figure 3 shows the optical functions of a vertical arc consisting of five (5) 90-degree FODO cells interleaved with bend magnets. The optics achieves a zero dispersion at entrance and exit by using the dispersion matching scheme of Keil [1]. The system as shown is designed to achieve a 1.309 mrad total bend angle, which corresponds to the required bend between the second half of the linac and the BDS, assuming system lengths of 11.9 km for the former and 2.37 km for the latter. System total length is 160 meters. Table 1 shows the key parameters for the magnets in the system.

As shown in Figure 3, the vertical arc does not incorporate any dispersion correction quadrupoles. The vertical dispersion can be corrected by adjusting the strengths of some of the main FODO quads in $-I$ pairs (ie, change a quad at a given point and perform an equal-and-opposite change of another quad which is exactly 2 cells away). Because the optics contains 5 cells, it is possible to correct dispersion in both betatron phases without interleaving corrections. Correction of horizontal dispersion would require insertion of skew quadrupoles, which can easily be accomplished at the cost of a slight increase in system length. Given that the horizontal dispersion must be coupled out of the vertical plane by bend or quad rotation errors, that the horizontal emittance is much larger than the vertical, and that the energy spread will be relatively small, it may be practical to simply forego horizontal dispersion correction entirely.

Table 1: Parameters of magnets in the 1.3 mrad vertical arc between the end of the linac and the BDS.

Name	Type	Length [m]	Pole Field [T]	Aperture Radius [mm]	Count
VQF	Quad	1.0	0.85	20	20
VQD	Quad	1.0	0.85	20	20
VB1	Bend	2.0	0.023	20	16
VB2	Bend	2.0	0.023	20	16
VB	Bend	2.0	0.045	20	8

4 Synchrotron Radiation Issues

The energy loss per particle from synchrotron radiation is given by [2]:

$$\Delta E = \frac{2}{3}\frac{r_e E^4}{(m_e c^2)^3} I_2, \tag{1}$$

where r_e is the classical electron radius of 2.8×10^{-15} meters and I_2 is the second synchrotron radiation integral, $I_2 \equiv \int ds/\rho^2$. For the system shown in Figure 3, $I_2 = 2.38 \times 10^{-7}$ m^{-1}, yielding an energy loss per electron of 208 MeV for 500 GeV/c beams. For 500 GeV/c beams with 22.6 MW beam power, the power dissipated in the vertical arc is 9.4 kW.

The growth in normalized emittance from synchrotron radiation is given by:

$$\Delta\gamma\epsilon = 40.43 \text{ nm} E^6[\text{GeV}^6] I_5[\text{m}^{-1}], \tag{2}$$

where I_5 is the fifth synchrotron radiation integral, $I_5 \equiv \int ds(\gamma\eta^2 + 2\alpha\eta\eta' + \beta\eta'^2)/|\rho|^3$. For the system shown in Figure 3, $I_5 = 7.85 \times 10^{-19}$ m^{-1}, yielding a normalized vertical emittance growth at 500 GeV/c beam energy of 0.50 nm, which is 2.5% of the damping ring extracted emittance specification of 20 nm.

5 Energy Scaling

In the previous Section we considered the energy loss and emittance growth for 500 GeV/c beams passing through the 1.3 mrad vertical arc from the main linac into the BDS. The vertical arc required at the 250 GeV/c point in the linac has a larger total bend angle of approximately 2.1 mrad. This is compensated by the much lower beam energy. Since mean energy loss scales as $E^4\theta^2$, and normalized emittance growth scales as $E^6\theta^5$, we conclude that we can use the same optics with scaled-up bend strengths at the 250 GeV/c point and expect negligible energy loss and emittance growth.

More problematic is the case of energy upgrade, for example to 3 TeV CM (or equivalently 1.5 TeV/c final beam energy). The arc at the end of the linac would generate 16 GeV energy loss and normalized emittance growth of 364 nm. The emittance growth is certainly unacceptable, especially if the normalized emittance is to be reduced to 5 nm as part of the energy upgrade, as some parameter sets propose; the energy loss of 1% is likely also unacceptable, as it would certainly entail dumping on the order of 100 kW in the arcs.

In the case of upgrades to such high energies, we note that the current packing fraction of bend magnets in the arc is only about 50%. One possible scenario for upgrade is to replace the arc design presented here with an arc which uses a dense array of combined function bend magnets (essentially quadrupole magnets with mm-scale intentional offsets with respect to the survey line), and possibly to slightly extend the length of the arc into the linac and BDS. Given the rapid scaling of synchrotron radiation effects with bend radius and focusing, an acceptable solution for 3 TeV CM should be achievable.

References

[1] E. Keil, CERN 77-13 (1977).

[2] R. H. Helm, M. J. Lee, P.L. Morton, “Evaluation of Synchrotron Radiation Integrals” (1973).

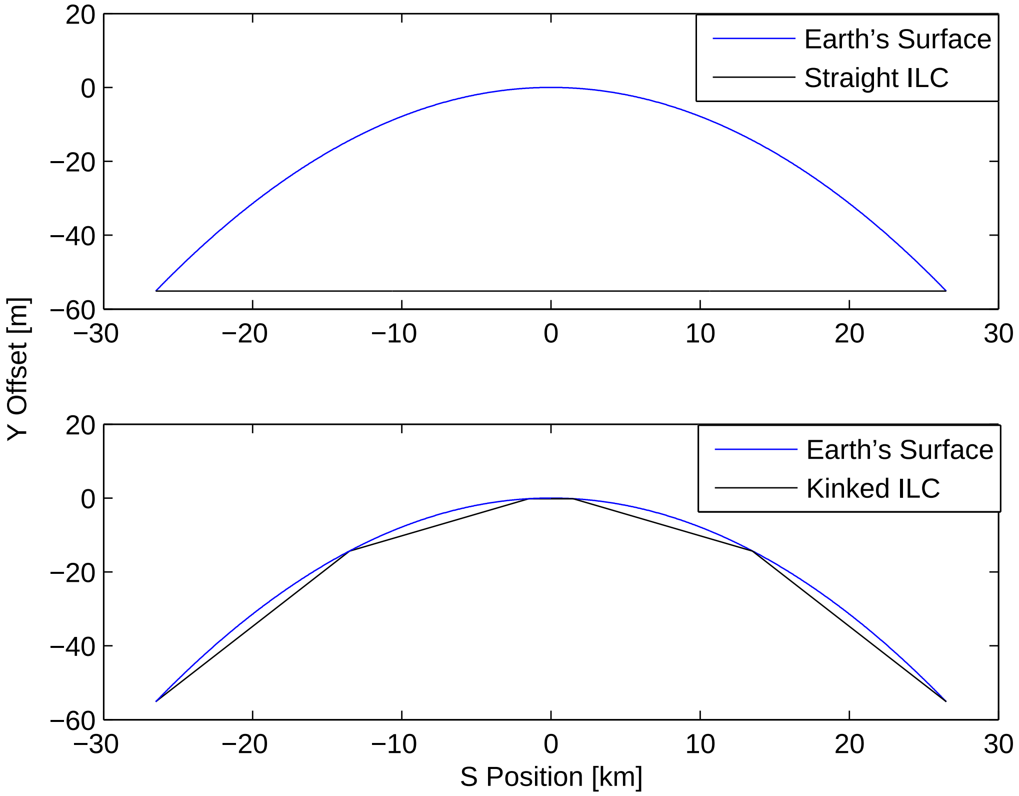

Figure 1: Two possible configurations for a 53 km ILC site. Top: a perfectly straight tunnel running under the curved surface of the Earth. Bottom: A piecewise straight configuration as described in the text.

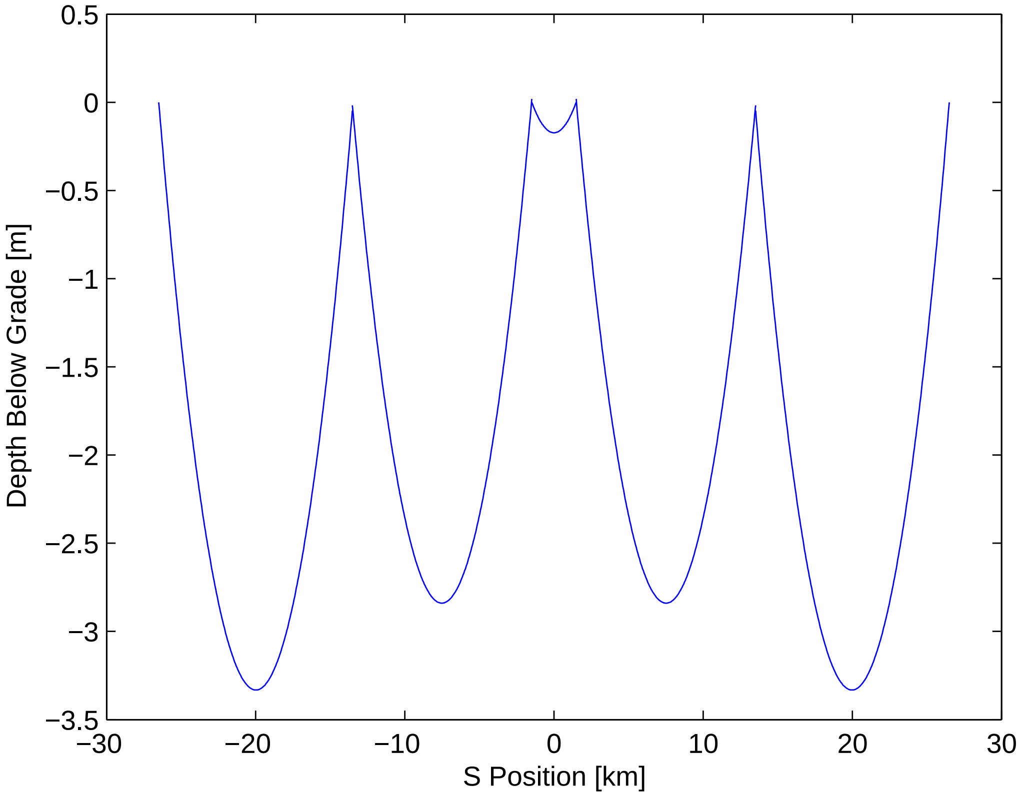

Figure 2: Depth variation for the piecewise-straight ILC as described in the text.

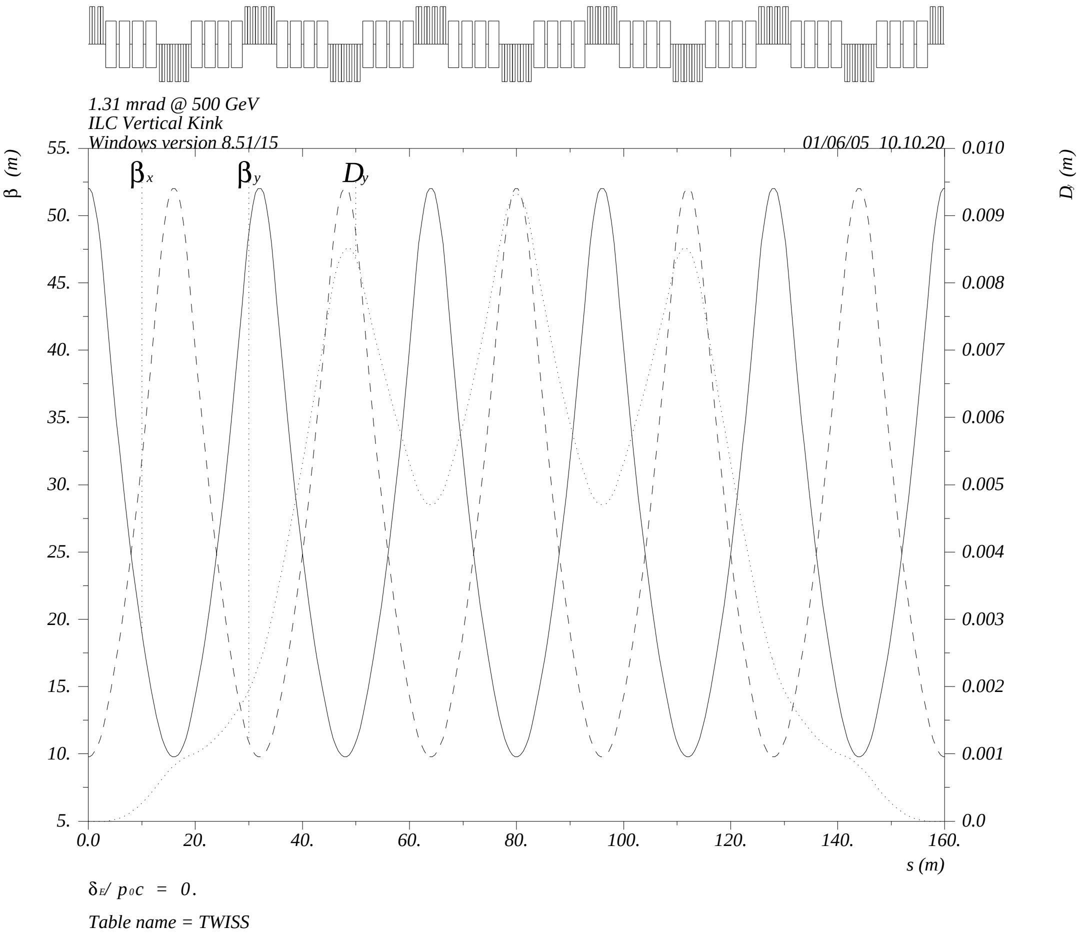

Figure 3: Optics function of the 1.3 mrad vertical arc required between the end of the linac and the entry to the BDS.