

Energy Recovery Linac in the Wilson Tunnel

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ABSTRACT

This is a brief discussion of two out of the many modifications that will be needed to retrofit the Wilson laboratory as an energy recovery linac (ERL). The two issues are: fitting the facility within the existing site boundaries; and designing the approximately isochronous yet adjustable arcs needed to transport ultrashort bunches.

1. Introduction

Loosely speaking, the “quality” of synchrotron radiation produced from an electron beam is proportional to its three dimensional phase space density and, at fixed beam current, this is inversely proportional to the beam emittances. Small transverse emittance yields X-ray beams of high brilliance, small longitudinal emittance yields the ultrashort bursts of X-rays needed for real-time “pump probe” studies. The electron beam, when first injected from a linear accelerator into a circular ring, has inherited the ultra-small emittances characteristic of linacs. But the phase space density is greatly diluted in the subsequent thousands of turns around the storage ring. By using the electrons during their first turn the high phase space density of the just-injected linac beam could be exploited. Unfortunately it is not economically feasible to waste the linac-provided energy by dumping the electrons after a single turn. The purpose of “energy recovery” in an ERL is to recover a sufficiently high fraction of this energy to make it economically feasible to use only single turn electrons.

As elementary particle physics research at Wilson laboratory winds down (on a time scale of about five years) it is anticipated that the laboratory’s mission as a synchrotron radiation facility will expand. The thrust of this note is how to best make use of the existing facilities during this evolution.

In an ERL each electron makes “one and a half” passes around the ring—two passes through the linac, one pass around the rest. The main complication this introduces is that the transverse focusing optics through the linac sections has to be appropriate for two beams of vastly different energies. One way of handling this is to break the linac into sections and to separate the accelerating and decelerating beams between sections so the optics can be appropriate for both. By including deflection in the separated-beam sectors the overall “linac” can be made to follow a curve. This makes the apparatus conform more closely to a pre-existing ring (such as the Wilson tunnel) than might have been expected for something going by the name “linac”.

2. Fitting Onto the Site

The existing CESR RF system can provide a few MeV energy increase per turn, but what is now required is at least 5 GeV in a single pass. This acceleration can only be provided by a linac and only superconducting linacs can operate CW. The length of the linac depends on the achievable gradient (15-20 MeV/m at present, perhaps as much as 25 MeV/m in future) and the required energy (certainly at least 3 GeV, probably 5 GeV and ideally up to 7 GeV). Furthermore these gradients do not account for inevitable insertions that reduce the fill factor to perhaps 0.9. These figures require a linac length of $3000/0.9/15 = 220$ m for conservative 3 GeV operation. With achievable accelerating gradients increasing all the time, it perhaps makes sense for initial operation at an energy somewhat below 5 GeV with provision to later raise the energy above 5 GeV.

The Wilson tunnel is more or less circular with a circumference of 780 m. It might be barely possible to scrunch up the magnets to make room for 220 m worth of linac, broken into short enough lengths to fit into the tunnel. But this would necessitate multiple separation sections that would take up space and this would require the magnetic field strengths to be even higher. Furthermore it would make it impossible to achieve the electron energies above 5 GeV that would be needed to compete (on the high X-ray energy front) with existing facilities such as APS and ESRF.

It is therefore necessary to expand beyond the bounds of the Wilson tunnel. The proposed expansion is illustrated in Fig. 2.1, which shows both the existing ring and its proposed ERL extension. The general idea is to preserve the south half of the facility, including the experimental halls and building, and to allow the north half to bulge out to the site boundary (which is Tower Road). The total length of the linac sections is 300 m which is comfortably, but not extravagantly, greater than the 220 m minimum given in the previous paragraph.

It appears that the optimal number of linac sections is four. A design with just two linac sections (making the ring look like “home plate” with the tip toward Tower road) was investigated. This design has the advantage that no beam separation is required since the energies of accelerating and decelerating beams are equal in the region between the two linacs, so they can share the same focusing optics. But the maximum linac length

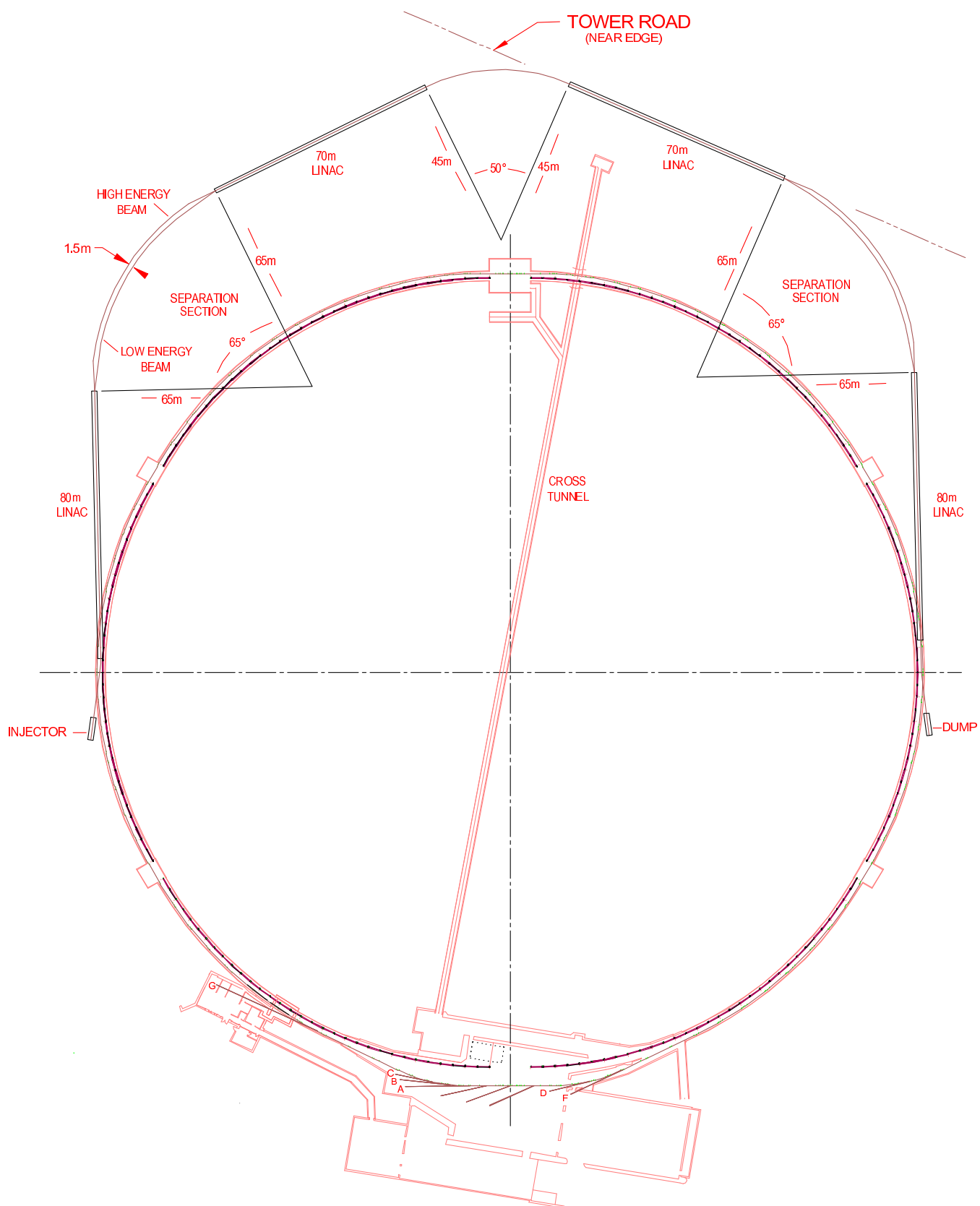


Figure 2.1: ERL “within” the Wilson tunnel formed by inserting four linac sections in CESR.

in the two-linac option is about 200 m, which is inadequate. With more than four linac sections the potential increase in linac length is not very great, especially accounting for circumference taken up by separation elements and for the “weak bends” needed to shield the linacs from X-rays. Furthermore the extra flexibility in transverse optics allowed by the presence of more regions in which the beams are separated appears to be superfluous. A complete lattice design has not yet been performed for the proposed four-linac design shown in Fig. 2.1. But the optics of an earlier design (of Ivan Bazarov) with just a single linac section was acceptable for the core of the beam, though problematical as regards beam halo and sensitivity to jitter in the electron source. The possibility of separate optics in three sectors seems to be more than enough to make a satisfactory lattice design possible.

3. Isochronous Arc Design

One of the main selling points for the ERL is that the beam bunches can be short enough to study real time dynamical evolution of molecular structures on ultrashort time scales. For bunches circulating in CESR at present the r.m.s. bunch lengths are about 2 cm (about 70 picoseconds in time units). If one bunch is to shock excite a localized structure the time scale of subsequent dynamics studies cannot be less than about 100 picoseconds. One would like to reduce this time by two orders of magnitude or more. But producing and handling such short bunches is not easy.

Let T (typical value $1 \mu\text{s}$, which is about a half turn around the Wilson tunnel) be the time spent by electrons of momentum p_0 as they traverse an arbitrary arc of the ring. A momentum spread Δp (typical value $10^{-3}p_0$) will result in a flight time spread ΔT given by

$$\frac{\Delta T}{T} = \left(\alpha - \frac{1}{\gamma^2} \right) \frac{\Delta p}{p_0} \approx \alpha \frac{\Delta p}{p_0}, \quad (3.1)$$

where $\gamma \approx 10^4$ is the usual relativistic factor and α is the so-called “momentum compaction factor”. (Though α is conventionally regarded as a parameter of an entire ring we are generalizing its definition here to apply to partial sectors of the ring.) For present purposes the final, approximate version of Eq. (3.1) is adequate since, for a ring with tune Q dominated by FODO arcs, $\alpha_{\text{typ.}} = 1/Q^2 \approx 0.01 \gg 1/\gamma^2$. Inserting the typical numerical values given

so far yields

$$\Delta T \sim 0.01 \times 10^{-3} \times 10^{-6} = 10 \text{ ps.} \quad (3.2)$$

This shows that the length of a zero length bunch will grow to 10 ps in a half turn of the Wilson tunnel. It follows that, even if the bunches are arbitrarily short as they leave the linac, they will become unacceptably long (for high speed experiments) after traversing any appreciable FODO arc.

At this time it is not clear how many beamlines will need ultrashort bunches or where they will be located, nor how the bunch length will be adjusted around the rest of the ring. Once the difficulty of conveying short bunches is fully appreciated it seems likely to me that the ultrashort bunch region will be restricted to a relatively short sector, presumably at the center of the south experimental hall. Over most of the ring the bunch length will be considerably longer. In order to achieve such manipulation it seems appropriate to design the arcs to be approximately isochronous ($\alpha = 0$), but with provision for adjusting the local values of α .

In planning the evolution from colliding beam physics to X-ray physics it seems desirable to minimize the disruption of Wilson lab to the extent possible. Certainly the entire north half of the facility needs to be rebuilt, but it is desirable to minimize the disruption of the south half. From these considerations the question arises: is it possible to modify the arcs in the south half of the Wilson ring to be isochronous with variable α ? Ideally the tunnel would need no modifications and the CESR magnets would be used. Accomplishing this will be considered next.

The equation for α applicable to an arc of length C is

$$\alpha = \frac{1}{C} \int_C \frac{D(s)}{\rho(s)} ds, \quad (3.3)$$

where the “dispersion” $D(s)$ satisfies the equation

$$\frac{d^2 D}{ds^2} + K_x(s) D(s) = \frac{1}{\rho}. \quad (3.4)$$

Here $1/\rho$, the curvature (inverse radius of curvature) acts as a “source” of dispersion, and K_x is the coefficient of the force that “focuses” $D(s)$ in such a way that D ’s propagation in bend-free regions is the same as a particle trajectory. Because ρ is normally positive the value of $D(s)$ tends to be positive, with the result, from Eq. (3.3), that α is positive.

There are two ways to overcome this tendency. One is to use reverse bends so that $\rho < 0$. This is rather unattractive however, since the major function of the arcs is to turn the electrons through 360 degrees. The more favorable possibility is to adjust the horizontal focusing in such a way as to make D_s negative in some sectors of the ring. Since this has the concomitant effect of increasing $D(s)$ in other sectors of the ring it is necessary to concentrate the bending in regions where $D(s)$ is negative. There have been several papers investigating this approach.¹⁻³

A natural approach, possibly due to Guignard¹, is to design a triplet of FODO cells, symmetric about the center cell, with negative dispersion in the central cell and positive dispersion in the outer cells. Then one increases the steering in the negative dispersion region and decreases it in the positive dispersion region. This reduces the momentum compaction. Since the beta functions are reasonably insensitive to the distribution of steering, these steering changes have little effect on the lattice optics.

The effect of concentrating the bends is to make the closed orbit less round and hence less in conformity with the existing tunnel. For the southeast and southwest arcs (the sections we wish to preserve) there are straight sections at L1 and L5 (present originally for the synchrotron RF). Though probably not obligatory, it seems worthwhile to match the flat sections of the arcs to those points as shown in Fig. 3.1. This design uses dipole and quadrupole magnets from CESR to build the lines. It can be seen that the beamlines fit reasonably comfortably in the existing tunnels. With the beam flush up against the outer wall at the points of maximum bending, the flat sections miss the inner wall by more than half a meter. Whether this is enough to retain a passageway requires more careful study. At worst human traffic could “duck under” the ring at two points in each arc, as in the present transfer line regions.

To study geometry in which accuracy has to be preserved on a fine scale (with the apparatus spread over a large scale) it is necessary to use a CAD program. In order to make adjustments it is convenient if the program also supports programming structures so that entire sectors can be parameterized in terms of the small number of (adjustable) parameters of building blocks such as half cells and triplets. I have found the code SmartSketch ideal. Produced by Intergraph Corporation (an outfit that used to be big in the CAD world with Microstation). SmartSketch is inexpensive and is said to be easier to learn than

AutoCAD. (It took me several weeks.) SmartSketch can import and export AutodCAD or Microstation files, both digital and bit-mapped, and it supports programming structures, as well as linking to spreadsheets and other database structures.

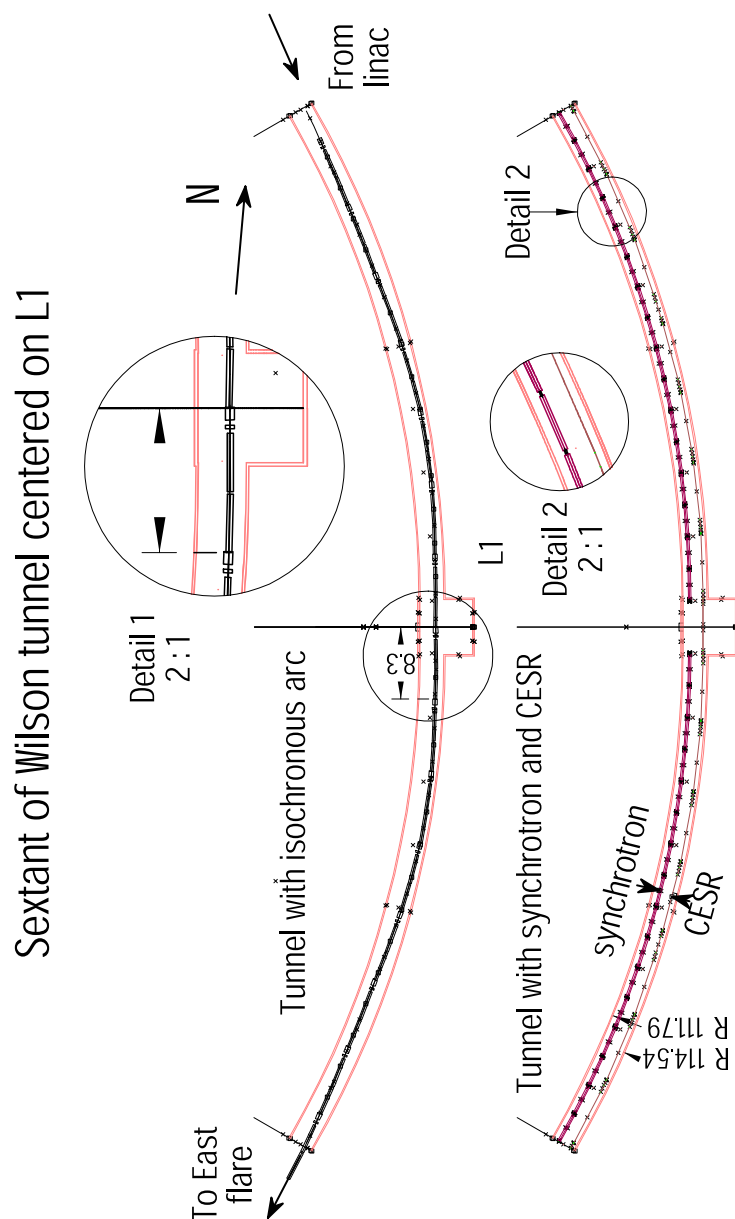


Figure 3.1: The left figure shows the (southeast) isochronous arc conveying beam from end of the final ERL linac section to the Wilson experimental hall. For comparison purposes the right figure shows the present tunnel layout. The southwest arc is similar.

4. Tuning the Isochronicity

Starting from FODO half cells (half-cell length 8.0 m) with quadrupole strengths $q1 = 0.07549/\text{m}$ and $q2 = -0.07581/\text{m}$ close to those of the present CESR, a triplet geometry close to that suggested by Trbojevich and Courant was next found; the values

$$\begin{aligned} q1w &= q1 * (1 + 0.55\chi), \\ q1s &= q1 * (1 + 0.35\chi), \\ q2w &= q2 * (1 - 0.8\chi), \\ q2s &= q2 * (1 - 0.8\chi), \end{aligned} \tag{4.1}$$

(with tunability parameter χ set to 1.0) were found to give the lattice functions shown in Fig. 4.1 and Fig. 4.2. Accepting the quadrupole strengths given by Eqs. (4.1), the weak and the strong dipole bends were then adjusted according to

$$\Delta\Theta_w = \Delta\Theta_0 (1 - \delta), \quad \Delta\Theta_s = \Delta\Theta_0 (1 + \delta), \tag{4.2}$$

where $\Delta\Theta_0 = 4.4$ degrees is an average bend per half cell appropriate for staying within the tunnel. Scanning the value of δ (still with $\chi = 1$), zero momentum compaction was obtained for $\delta = 0.76$. In this condition the strong bends have been almost doubled and the weak bend strengths reduced by a factor of about four.

To “tune” the momentum compaction it would be impractical to vary the closed orbit geometry. But it is easy to adjust the quadrupole optics. This was the purpose of including the parameter χ in Eq. (4.1). The effect of adjusting χ is exhibited in Fig. 4.3. The optics is “delicate” in the sense that the momentum compaction has barely made it below zero when instability sets in. There may be a solution with greater “stability margin” but I have not looked for it.

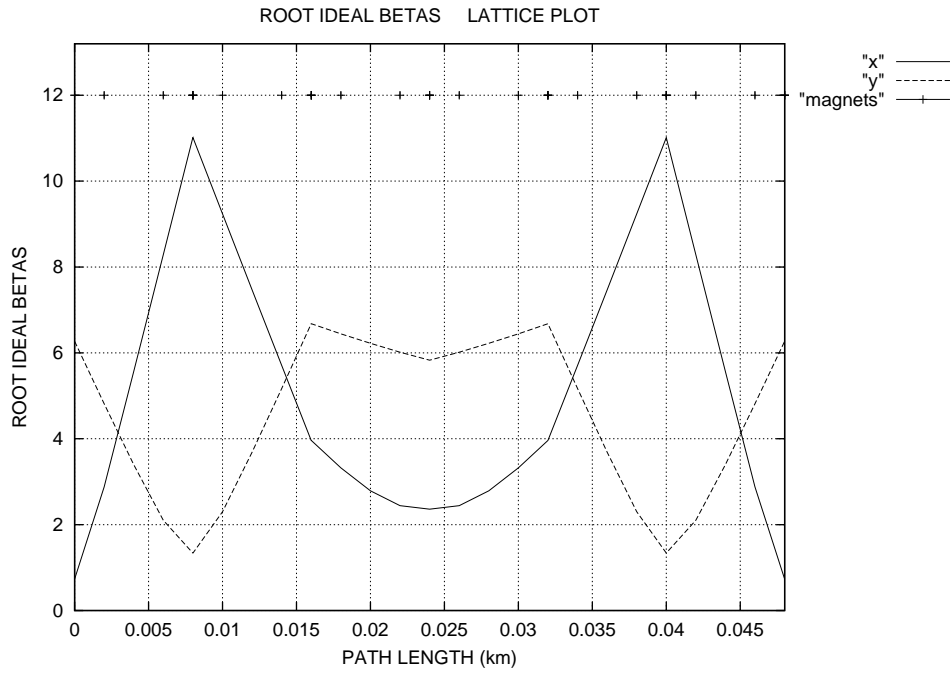


Figure 4.1: Lattice β -functions through isochronous arc (one triplet, $2\pi/16$ bend angle) centered on the L1 straight section.

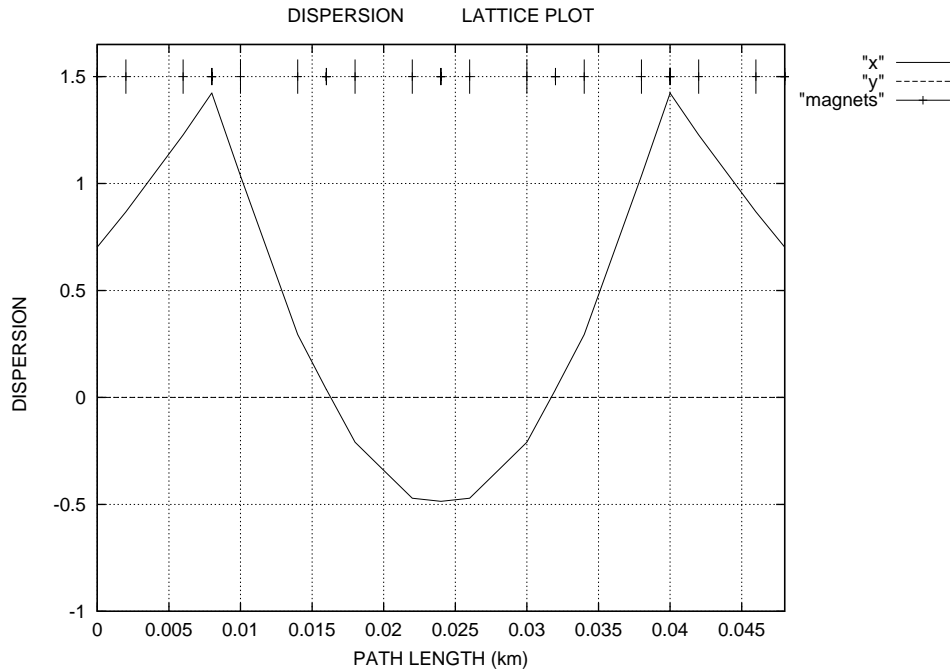


Figure 4.2: Horizontal dispersion function for isochronous arc centered on the L1 straight section.

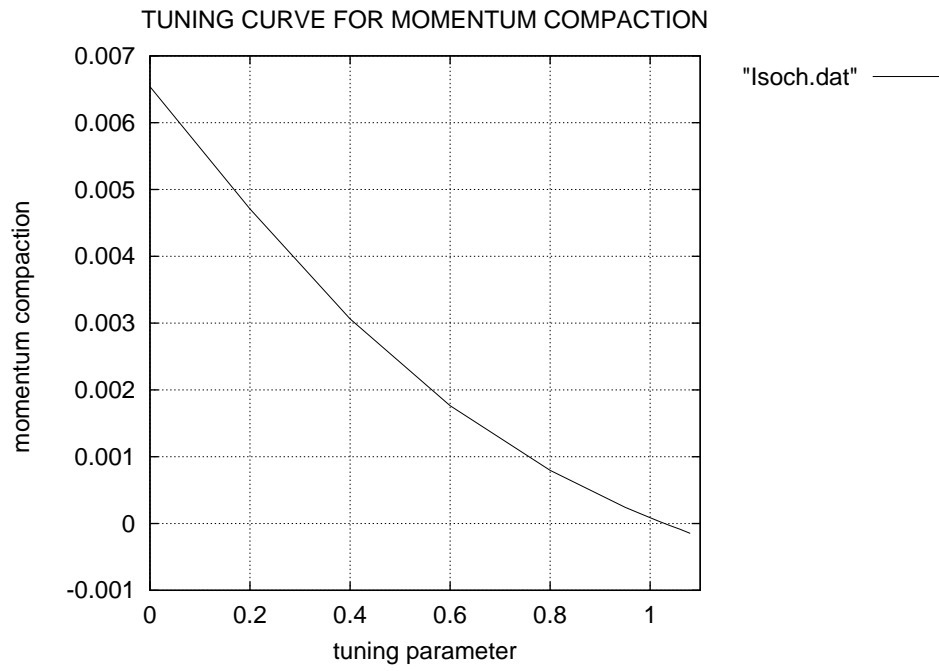


Figure 4.3: Tuning curve for momentum compaction of arc (with fixed steering) centered on the L1 straight section.

References

1. G. Guinard, *A Lattice With No Transition and Largest Aperture*, Proc. IEEE Part. Acc. Conf., 1989, p. 915.
2. D. Trbojevic and E. Courant, *A Standard FODO Lattice With Adjustable Momentum Compaction*, Brookhaven report, 1994?.
3. S. Lee, K. Ng, and D. Trbojevic, *Minimizing Dispersion in Flexible Momentum Compaction Lattices*, Phys. Rev. E, **48**, p. 3040 (1993).