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LATTICE DESIGN STUDIES FOR THE CERN PROTON DRIVER ACCUMULATOR AND COMPRESSOR

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Abstract. The CERN baseline scenario for a Neutrino Factory comprises accumulation and compression of the beam delivered by a 2.2 GeV kinetic energy H^- linac, to provide the time structure needed on the target. Originally, accumulation and bunch compression in one single ring was envisaged. To limit the RF voltage necessary for bunch rotation, quasi-isochronous lattices were studied. The low transition energy together with the long circumference, either leads to large dispersion or necessitates the addition of bending magnets with negative deflection angle. Several solutions for quasi-isochronous lattices were investigated. Finally, the quasi-isochronous lattices were abandoned, and a solution has been chosen with two separate rings, one for accumulation and the other for bunch-compression, and conventional lattices working far below transition.

INTRODUCTION

For a Neutrino Factory, a proton beam with sufficient intensity has to be delivered onto a target with a time structure appropriate for ionisation cooling of the secondary muon beam.

The CERN scenario [1] consists of acceleration in a Superconducting Proton Linac (SPL) [2], a 2.2 GeV kinetic energy H^- linac, followed by accumulation and bunch compression for a total beam power of 4 MW. The aim is to convert the long (about 2 ms) linac pulse into a sequence of very short bunches with a spacing appropriate for the pion/muon cooling channel, and a total length smaller than the muon decay ring.

QUASI-ISOCHRONOUS LATTICES

Originally, a solution consisting of one single ring for accumulation and bunch compression has been envisaged [3].

At that time it was felt advantageous to work with a very small momentum slip factor η, i.e. a machine close to transition. Then, neglecting direct space charge forces and potential deformations, modest RF voltages are sufficient to keep the beam bunched during the charge exchange injection and for the bunch rotation.

Furthermore, the circumference of the accumulator ring should be large, in order to limit the number of foil traversals during the charge exchange injection, but short enough that the secondary muon beam fits into the decay ring.

A ring of an appropriate circumference could be located in the existing Intersecting Storage Rings (ISR) tunnel. Thus, lattices should have a geometry which fits into this tunnel, i.e. with a mean radius of 150 m and a width of about 15 m.

Basic Limitations For Isochronicity

The main difficulty [3, 4] encountered during the search for quasi-isochronous lattices is to avoid an unacceptably large dispersion leading, in conjunction with the large relative momentum spread during bunch compression, to large horizontal beam sizes.

This can be analysed by considering the standard expression for the momentum compaction factor:

$$\alpha = \frac{1}{C} \int_0^C ds \frac{D(s)}{\rho(s)} = \frac{1}{\gamma_{tr}^2} \qquad (1)$$

with C the machine circumference, $D(s)$ and $\rho(s)$ the dispersion and the curvature radius at the longitudinal location s respectively. In case of a quasi-isochronous lattice, γ_{tr} must be close to the relativistic γ of the beam, which is $\gamma = 3.45$ in our case. Equation (1) can be rewritten, assuming a constant radius of curvature inside one bending magnet (different magnets may have different curvature radii)

$$\alpha = \frac{1}{C} \sum \overline{D}_i \ \theta_i \qquad (2)$$

with i an index running over all bending magnets, $\overline{D}_i$ and θ_i the average dispersion and the deflection angle of the i-th magnet respectively. Requiring isochronicity and assuming only positive deflections, one can deduce a lower bound for the maximal average dispersion $\max(\overline{D}_i) \geq C/(2\pi\gamma_{tr}^2)$, in the case under discussion $\max(\overline{D}_i) \geq 12.6$ m. The only way to achieve the necessary small γ_{tr}, with the given long circumference and reasonable values of dispersion, is to combine dipoles with both positive and negative deflection and, hopefully, positive and negative dispersion. These considerations are the motivation for the lattices presented in the following.

LEAR-like Lattice

The lattice described in this section is similar to that of the old Low Energy Accumulator Ring (LEAR) [5], in the sense that focusing is mainly performed by doublets on either side of a bending section. However, one more horizontally defocusing quadrupole is added at the centre of the bending sections. The phase advance between centres of bending sections is somewhat larger than π as in LEAR. Whereas this led to a negative dispersion at the bendings (and thus a negative α) in LEAR, this leads to the appropriate behaviour of the dispersion for our application, since the bending sections have alternatively positive and negative deflection angle.

The geometry and the lattice functions along two periods are shown in Fig. 1. The total positive bending angle is 4π, while the total negative bending angle is 2π (to restore the necessary 2π overall deflection). The maximal dispersion is reduced to about 5 m. This type of lattice leads to relatively long straight sections without magnets, leaving space for equipment.

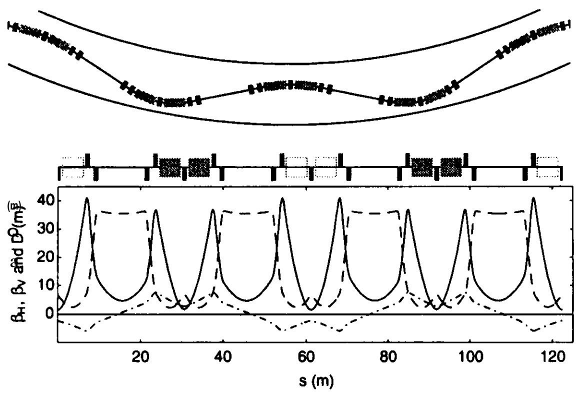

FIGURE 1. Geometry and Twiss functions for the LEAR-like isochronous lattice (β_H solid, β_V dashed, and D_H dot-dashed).

Modified FODO Lattice

The lattice presented in this section is similar to the one described above in the sense that the phase advance between sections with positive deflections and sections with negative deflections is somewhat larger than π. The focusing is done by a rather regular FODO channel with the bending magnets inserted at appropriate locations. Then, the gradients of the quadrupoles are only slightly readjusted to locate the transition exactly at $\gamma_{tr} = 3.54$.

The result is shown in Fig. 2. Again, the total positive and negative deflection is 4π and 2π respectively, and the maximum dispersion is about 5 m. The focusing is smooth and the betatron functions remain generally small.

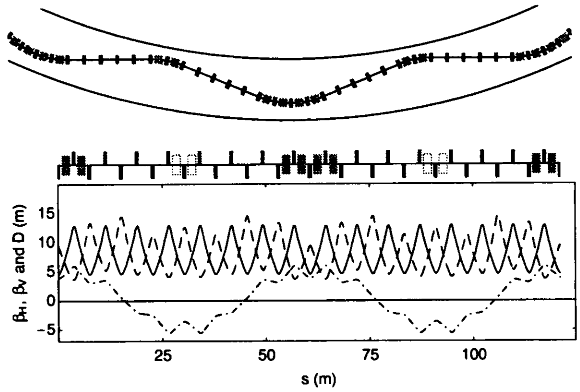

FIGURE 2. Geometry and Twiss functions for the modified FODO lattice (β_H solid, β_V dashed, and D_H dot-dashed).

Lattice With Wigglers

The design philosophy of the lattice with *wigglers* differs from the lattices presented above. One starts from a piece of a regular FODO lattice (called arc in the following) and adds FODO cells with positive and negative bending angles, such that the optics in the arc is not affected by these wigglers [4]. Focusing is provided by a regular FODO lattice and, since this machine is modelled in thin element approximation, the dipoles do not affect the Twiss functions. The regular arc consists of one single FODO cell, extending from the centre of one defocusing quadrupole to the next (see Fig. 3) with two bendings in the centre between quadrupoles. One wiggler consists of three FODO periods with dipoles in between. The first attempt, placing the dipoles at the centres between quadrupoles, did not allow to satisfy all requirements. Thus additional bendings were placed at both ends of the wiggler structure, thus implying combined function elements, $3/2$ periods from the beginning and the end, and at the centre of the structure. Finally, four such modules were placed between regular arc cells. For a given focal length, the three bending angles are used as parameters to adjust the geometry (total deflection of wiggler vanishes), the dispersion in arcs (not affected by wigglers) and α. In thin lens approximation, this can be done analytically [4]. It turns out that the focal length of the lenses has to be rather short w.r.t. the distance between quadrupoles to find real solutions. This leads to large variations of the betatron functions and, thus, to rather large chromatic effects.

Lattice With Dispersion Suppressors And Low-β Insertions

Such a lattice is built by combining different modules in thin lens approximation. The optical properties are, as far as possible, expressed by analytic formulae. The

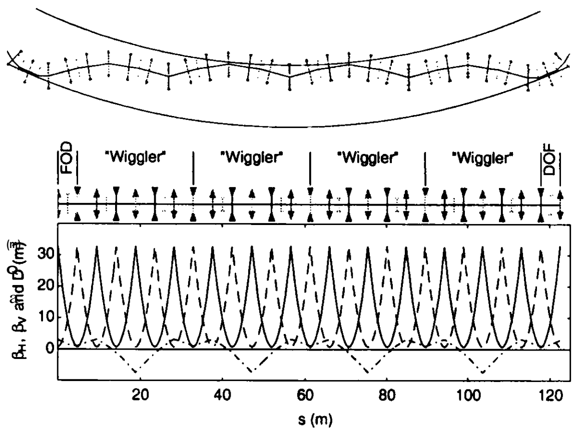

FIGURE 3. Geometry and Twiss functions for the lattice with wigglers (β_H solid, β_V dashed, and D_H dot-dashed).

modules (see also symbolic representation in Fig. 4) are:

- regular arc (made of 3 FODO cells),
- dispersion suppressors (made of 1 FODO on both sides of arc with 2 bendings between quadrupoles),
- matching section (doublet) and
- low-β insertion made of 3 FODO cells.

For a given focal length of the quadrupoles, three parameters (the deflection angles of both the arc dipoles and the two dipoles in the arc) allow to adjust the geometry, the dispersion (zero inside the insertion) and the momentum compaction α. Also in this case the focal length must be small to obtain real solutions for the deflection angles. Two solutions are found, one with a positive and one with a negative deflection angle in the arc. Only the latter is shown in Fig. 4, the first being similar apart from the geometry.

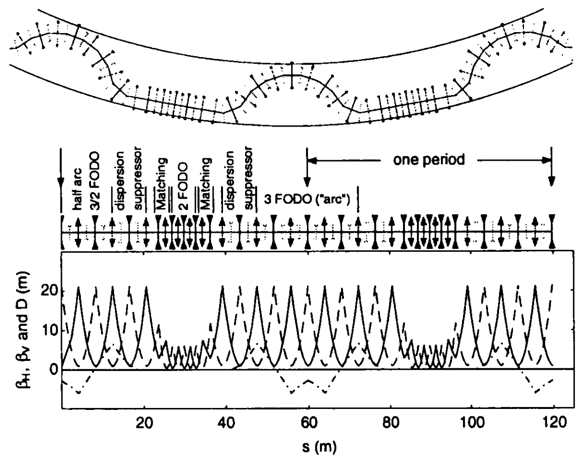

FIGURE 4. Geometry and Twiss function for the lattice with dispersion suppressors and low-β insertions (β_H solid, β_V dashed, and D_H dot-dashed).

CONCLUSIONS

In this paper, a number of ring lattices have been presented, having a large circumference combined with a low transition energy and rather small maximum value of the dispersion function. This has been achieved by using different schemes with various combinations of alternating sign dipoles. All these properties make the optical structures discussed in previous sections good candidates for a lattice of a single ring where both accumulation and bunch rotation take place.

However, plain optics considerations are not the only arguments to be considered in the choice of the final ring layout. In fact, the analysis performed in the framework of a Neutrino Factory study at CERN, showed that the very different physical conditions of the beam during accumulation and compression make it not feasible to perform both actions in the same ring.

The main problem is the beam loading in the high voltage RF system needed to perform the bunch compression. Therefore, the envisaged solution consists of two rings [6]: in the first one a low voltage RF system (about 0.5 MV needed to compensate the longitudinal space charge forces) runs during the 2 ms accumulation stage, while in the second ring the high voltage RF system (about 8 MV), performs the fast compression stage during a few machine revolutions.

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