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Synchrotron Tune Adjustment by Longitudinal Motion of Quadrupoles

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Synchrotron Tune Adjustment by Longitudinal Motion of Quadrupoles

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Abstract

Adjustment of the tune of a synchrotron is generally accomplished by globally varying the strength of quadrupoles, either in the main quadrupole bus or in a set of dedicated trim quadrupoles distributed around the ring. An alternate scheme for tune control involves varying the strengths of quadrupoles only within a local insert, thereby adjusting the phase advance across this insert to create a "phase trombone."

In a synchrotron built of permanent magnets, such as the proposed Fermilab Recycler Ring, tune adjustment may also be accomplished by constructing a phase trombone in which the longitudinal position rather than the strength of a number of quadrupoles is adjusted. Design philosophies and performance for such phase trombones will be presented.

Introduction

The design of a storage ring based on permanent magnets introduces a number of unusual challenges, and suggests reconsideration of a number of standard design approaches. One of the fundamental areas in which questions arise is tune adjustment. While one can fabricate permanent magnet quadrupoles with mechanically-adjustable strength (1), this is somewhat difficult. One can also counter-rotate two quadrupoles which are located adjacent to one another, as is presently planned for the Recycler Ring (2). While this should work well, it may be difficult to eliminate skew quadrupole components introduced due to mechanical tolerances in the rotation, or high-order errors which may be introduced by the slight difference in β functions at the two quadrupoles (3). It would be desirable to investigate other options and to have a back-up scheme for adjusting tune which does not rely on powered quadrupoles.

In early discussions of the design of a permanent magnet storage ring at Fermilab, it was suggested by Klaus Halbach to investigate tuning by longitudinal motion of quadrupoles, as is the standard tuning approach in photon optics where adjustable-strength lenses are also difficult to make. The "phase trombone", a local lattice insertion with fixed lattice functions at the ends and a variable phase advance, is a convenient way to accomplish this, since it requires that only a small number of quadrupoles be movable.

Phase trombones may be designed to vary both the *x* and *y* phase advances together or to vary them separately, and may be designed with or without dispersion. A phase trombone may be most easily designed as an insertion with mirror symmetry (4).

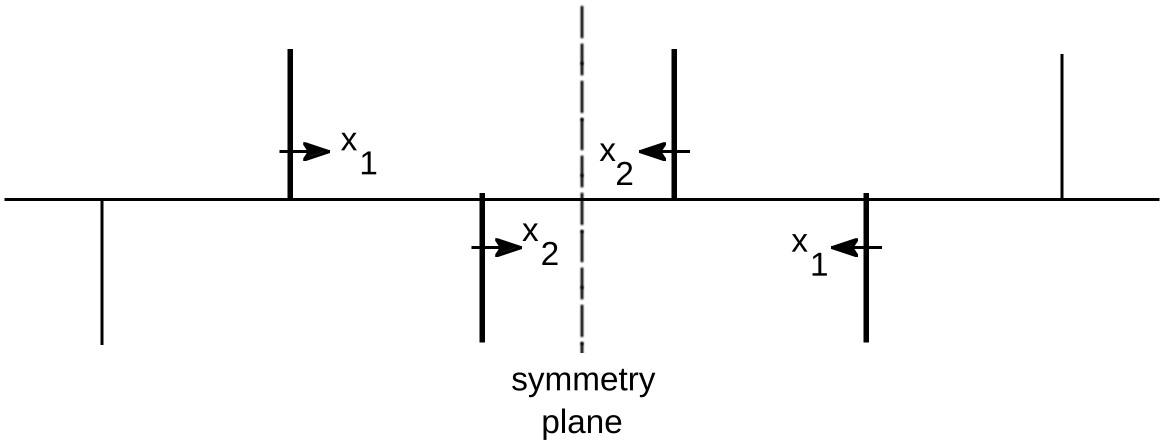
If the *x* and *y* phases are to be varied together, the phase trombone may be designed to replace an *odd* number of half-cells. The insertion should be anti-symmetric about its midpoint, such that the y-plane looking backward through the insert is identical to the *x*-plane looking forward. For the given initial α_x and β_x, it is then necessary to set three parameters to match the final α_x, β_x, and ψ_x. By virtue of the mirror symmetry of the lattice functions, the β_y, α_y, and ψ_y will automatically be correct. Thus, three independent "knobs" are needed; because of the mirror symmetry, this requires that six quadrupoles have adjustable positions.

If the *x* and *y* phases are to be varied independently, the phase trombone may be designed to replace an *even* number of half-cells. The insertion should be symmetric about its midpoint. For the given initial α_x, α_y, β_x, and β_y, it is necessary to set four parameters to force α_x=α_y=0 at the midpoint of the insertion, and to set the desired ψ_x and ψ_y. The mirror symmetry will then force the final $\alpha_{x,y}$ and $\beta_{x,y}$ to match their initial values. This requires that eight quadrupoles have adjustable positions.

In this paper we will assume that a dispersion-free straight section exists in which the phase trombone may be realized, so the effects of dispersion will be ignored. It will be convenient to think of the phase trombone as beginning and ending at a point where α is zero, i.e. at the center of a quadrupole in the original lattice. It will also be assumed that the standard lattice cell has a 90° phase advance, since this is the case for the proposed Recycler Ring. In addition, we will consider quadrupoles of about 0.5m length and half-cells of about 17m length, which are the parameters for the proposed Recycler Ring, and will try to restrict quadrupole travel to less than 2m, or about 0.12 half cell lengths.

Simulations

The most straightforward design approach is to simply move quadrupoles in a section of the original FODO lattice. Including the quadrupoles at the ends of this section, a five-half-cell section is necessary to provide six movable quadrupoles. However, with 90° phase advance per cell, the four adjustable quadrupoles in 3 half-cells are sufficient to give a nearly perfect match (fig. 1). This provides a tuning range of slightly more than 30° (about 0.08 tune unit), but requires large displacements for two of the four quadrupoles. (In addition, the β functions become large for these large displacements.) While these large displacements are not practical for normal tuning of the Fermilab Recycler Ring, it may be useful to note that the tunes may be shifted by nearly 30° by repositioning only two quadrupoles.



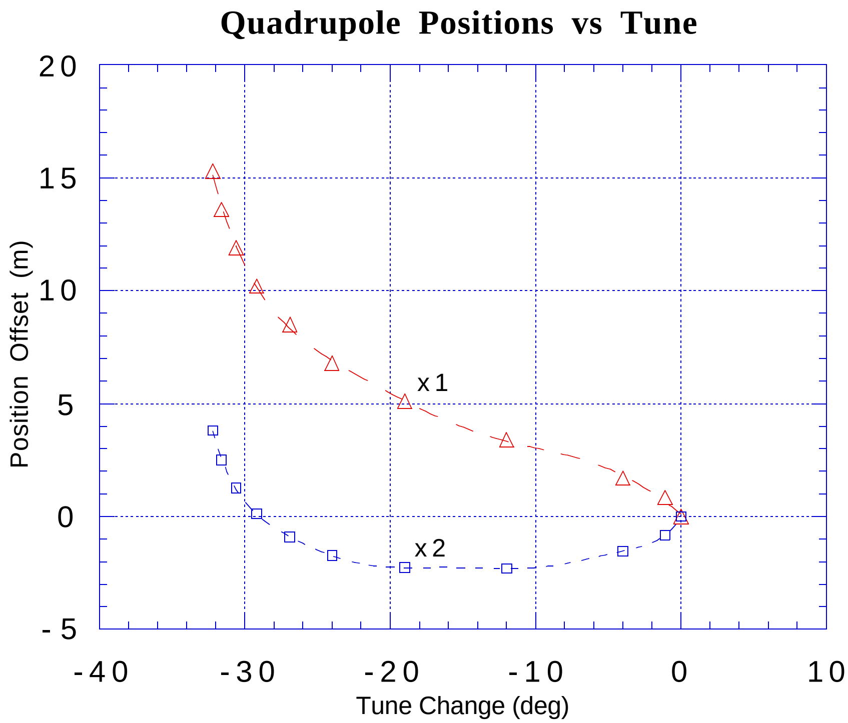


Fig. 1. a) Motion of quadrupoles in original lattice. Note that the entire quadrupole at the end of the insertion is moved, not merely half of it. b) Phase advances due to these motions.

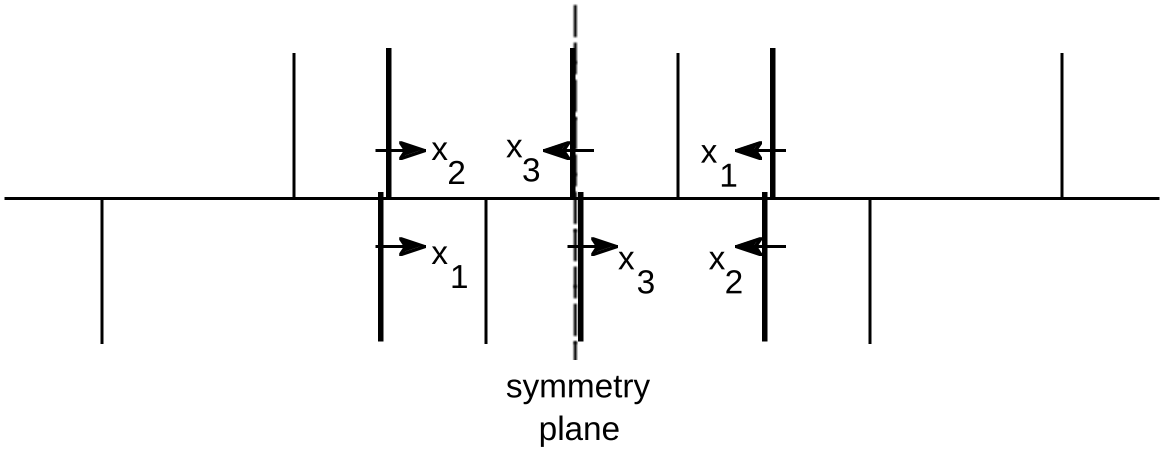
The fundamental cause of these large displacements is that a FODO lattice is relatively insensitive to quadrupole displacement, due to the uniform spacing between quadrupoles. It is necessary to find an insertion which has higher sensitivity to quadrupole displacement. Taking a hint from photon optical focusing systems, where standard practice is to use focusing and defocusing lenses which are very close together, we will investigate insertions with focusing and defocusing quadrupoles which are very close together.

One way to accomplish this is to insert quadrupole doublets in the standard lattice, with a variable gap between the quadrupoles in each doublet. There are two natural places to position such a doublet; either between two standard quadrupoles, or adjacent to one of the standard quadrupoles, forming a triplet. For simplicity, we will consider that the quadrupoles in these doublets are identical in strength and length to the standard quadrupoles.

An example of an insertion for equal x and y tune shifts is shown in fig. 2. Although three independent parameters are available (x_1, x_2, and x_3), again variation of only two parameters (x_1 and x_2) gives a good match for the case of 90° cells, and the central quadrupole doublet may be omitted. Here the tune is more sensitive to quadrupole motion and the motion is quite linear. However, for reasonable quadrupole excursions (about 2m total travel, worst case) the total tuning range is only about 10° (0.03 tune units). This may be adequate for operational adjustments of tune, but is probably not adequate for commissioning of the ring.

One of the problems with this approach is that inserting the quadrupole doublets is not very "natural"; it disturbs the original lattice and tends to overfocus for large separations or large quadrupole strengths. In addition, it only allows adjustment of the natural tune in one direction. Increasing the strength of the quadrupole doublets does not help significantly, because this implies an increase in quadrupole length and in minimum spacing, and exhibits a greater tendency to overfocus. Geometries with the doublets placed adjacent to the standard quadrupoles, forming quadrupole triplets, also do not seem to improve the situation.

It would be preferable to find a mirror-symmetric insertion in which quadrupoles naturally occur in focusing-defocusing pairs. This suggests a FOFDOD lattice insertion. Again we will restrict ourselves to using quadrupoles which are identical in strength to the standard quadrupoles.



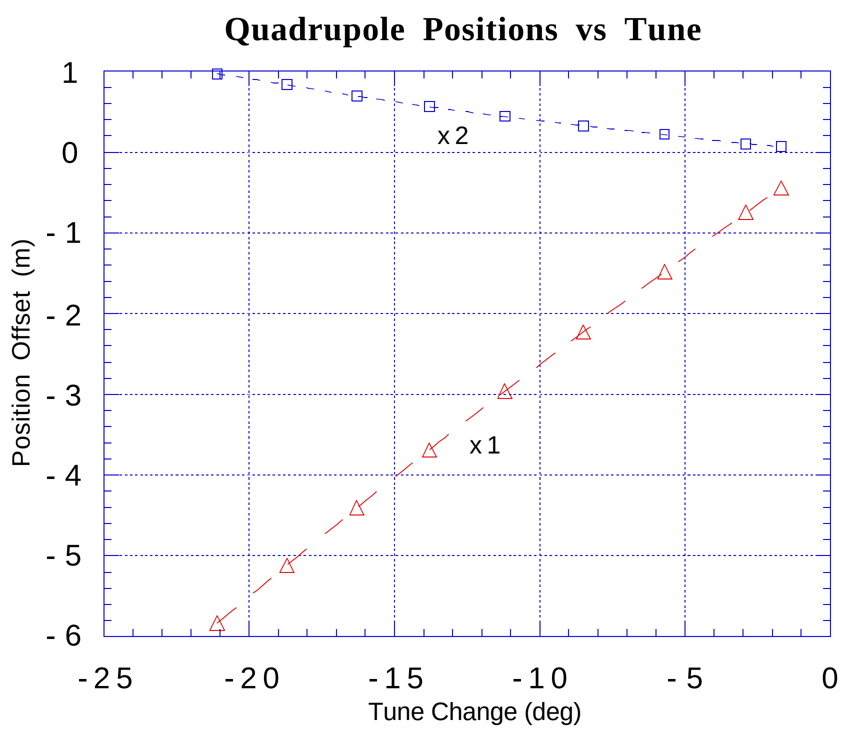


Fig. 2. a) Motion of quadrupole doublets which have been added to the FODO lattice. b) Phase advances due to these motions (where $x_3 = 0$).

A FOFDOD lattice will have different natural β functions than a FODO lattice, so can not be arbitrarily substituted for it. However, if a section of FOFDOD lattice has a phase advance which is a multiple of 180°, it will reproduce the input β's at the output, whether or not they are matched to the lattice of the FOFDOD insertion. Thus we may, for example, replace 2 90° FODO cells with 3 60° or 4 45° FOFDOD cells, without disturbing the rest of the lattice. This produces an insertion which naturally has focusing and defocusing quadrupoles close together, and should offer greater sensitivity to quadrupole motion.

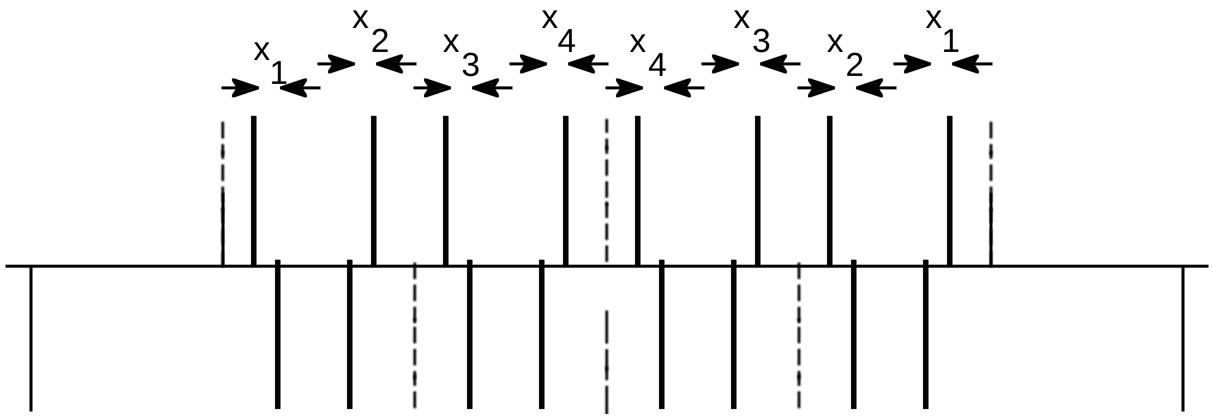
Simulations with such insertions show that tuning is fairly sensitive to differential motion between the quadrupoles in focusing-defocusing pairs, but is relatively insensitive to their motion together. Thus, although a mirror-symmetric insert of 4 45° FOFDOD cells has 8 independent tuning parameters, 4 of these are quite weak.

Fig. 3 shows an insertion composed of 4 45° FOFDOD cells. Note that the quadrupoles at the ends of the insertion are half-strength. In this simulation, the quadrupoles in each focusing-defocusing pair were moved differentially, with the midpoint of each pair remaining fixed. It would probably be simpler in practice to move only one quadrupole of each pair, while retaining the overall mirror-symmetry of the insertion. While this will slightly change the performance of the insertion, it should not do so markedly.

For a reasonable range of motion (±1m), this insertion gives a reasonable range of common-mode tune adjustment (±25°). However, it does not allow tunes to be split very far (about 10°), and only allows this in one direction. While this range is not as great as one would like, it may be practical for operational adjustment of tunes.

Conclusions

The longitudinal motion of quadrupoles has potential as a tune adjustment scheme for synchrotrons. While the tuning range tends to be limited, it may be adequate for operational adjustments of tune. It may also be practical to implement multiple insertions to achieve a larger tuning range. Of the schemes which we investigated, a 180° FOFDOD lattice insertion seems to offer the most promise, as it gives the greatest tuning range for a given mechanical travel. It may also be useful to note that the motion of two pairs of quadrupole doublets results in a quite linear tune adjustment over a small range, and that the relocation of only two quadrupoles in the original lattice can jump the tunes by about 30°.



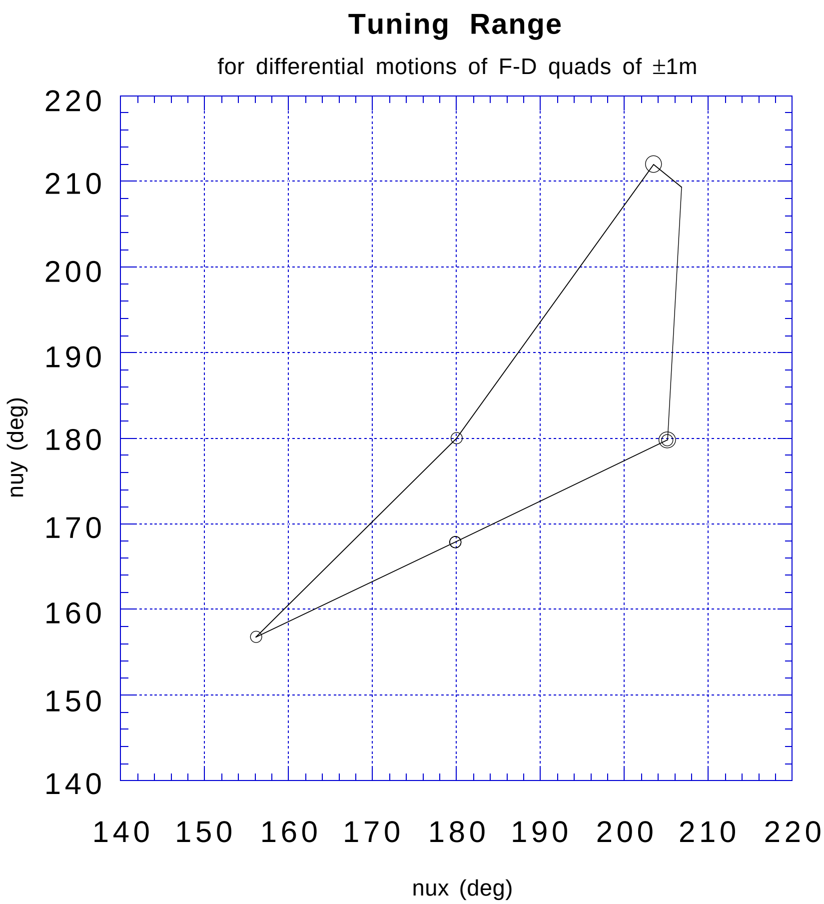


Fig. 3. a) FOFDOD insertion. Dotted lines represent quadrupoles removed from the original FODO lattice. b) Phase advances due to these motions.

References

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