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INSERTIONS FOR COLLIDING-BEAM STORAGE RINGS

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Abstract

A new approach is presented for the design of the beam-collision straight sections of high-energy colliding-beam storage rings. Interchangeable special function lattice insertions are used to obtain local beam characteristics at the collision point to meet the requirements of individual experiments. Other insertions are used to adjust the phase advance and the orbit-length dispersion to optimize the performance of the rings. These insertions are modularized in length and matched to one another in optics and dispersion functions so that they can be inserted or joined together with maximum flexibility. Examples are given for 1000 GeV-1000 GeV superconducting magnet proton storage rings.

Introduction

The magnet rings of colliding-beam storage rings can be considered as being composed of two types of sections serving different functions. These can roughly be identified as the inactive curved sections and the active straight sections. In straight sections beams are injected and made to collide, and experiments are performed. Curved sections serve only to transport the beams from one straight section to the next. The design of the inactive curved sections is based only on beam stability and economy, and is generally the concern of the accelerator builders alone; whereas the design of the active straight sections is crucial to both the builders and the users.

The conventional procedure for designing the straight sections is to first assemble the builders and the users in study sessions. Plans of all conceivable colliding-beam experiments are made. Each straight section is designed for one or a group of these hypothetical experiments. These straight sections are then incorporated as integral parts of the magnet lattice of the storage rings. In contrast, for conventional experiments using the external beam from an accelerator, because of the flexibility in the interposing beam lines the design of specific experiments have much less influence on the design of the magnet lattice. We suggest here a parallel interpretation of colliding-beam experiments which restores to some degree the decoupling between the machine and the experiments and leads to a different approach for design of the straight sections in storage rings.

When the beam in a storage rings exits from a curved section it can be considered as having been extracted from the machine. A tailor-made line is provided to transport the "external" beam to the experimental target (the collision point) for the specific

experiment. After going through the very thin target (the other beam) the beam unaffected by the target is transported "back" by another tailor-made beam line to be reinjected and recirculated in the following curved section. The design approach suggested by this interpretation consists in modularizing and specializing segments (insertions) of the straight-section ("external") beam lines of storage rings in such a way that all segments are mutually matched and hence mutually interchangeable. Specific modules are joined together to transport the beams to the collision point with the characteristics appropriate to the specific experiment. Other appropriate modules joined together then transport the beam onward to the next curved section properly matched for recirculation. In this manner the flexibility in the external beam lines of an accelerator could, to a large extent, be retained for the straight-section beam lines of storage rings. The parallelism is broken only by the needs of recirculation which impose the following additional constraints on the straight-section beam lines for storage rings:

(a) For an accelerator the length of the external beam line is to some extent flexible. For storage rings the length of the straight-section beam line constrained between curved sections is fixed.

(b) The phase advance in the transport line which is of little consequence for the external beam of an accelerator must be considered for the straight-section beam lines of storage rings.

(c) We need a standard recirculating line which simply transports the beam across a straight section and properly matched for recirculation without "targeting" for experiments.

(d) Since the target is the other beam the same consideration of matching and recirculation applies also to the "target" beam.

Examples

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To demonstrate the practicality of this approach we will use as an example two 1000-GeV proton colliding-beam storage rings using superconducting magnets. In each ring the curved sections are composed of 100 curved separated-function FODO cells each 60 m long and having a phase advance of 90°. The parameters of such a cell are given in Fig. 1. The curved sections of the two rings are assumed to be stacked one above the other with a vertical separation of 0.3 m between beams. In or near the beam-collision point it is likely that some quadrupoles will be used in common by both beams. These quadrupoles will have opposite focal actions on the two beams traveling in opposite directions. Thus, the

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simplest lattice arrangement is such that all adjacent quadrupoles between the two rings have opposite focal actions on the two beams, hence the same field-gradient polarity.

As initial steps in the development of this approach we assume:

(a) The simplest standard recirculating line would consist of straight cells formed by leaving out the dipoles in the curved FODO cells. A series of a multiple of 4 of these straight cells would have unity transfer matrices in both the horizontal and the vertical planes and would hence match both optics and dispersion. The straight-section length could therefore be 240 m, 480 m, etc.

(b) The lengths of the modular insertions should be multiples of the half-cell length of 30 m. Since the length of the straight sections is fixed insertions should be kept as short as possible.

(c) As standard transport elements for the straight-section beam lines we will use 1.1 m quadrupoles and 6.2 m dipoles. These turn out to be convenient choices of lengths. The currents in these magnets are adjusted to give the required strengths in the same manner as for transport elements in external beam lines of accelerators.

(d) Although not demanded in principle, matching for recirculation would be greatly simplified if the phase advances in the horizontal and the vertical planes are identical in all insertions. This is automatically guaranteed by making all insertions antisymmetric such that the two planes are longitudinal reflections of each other.

We now give a few examples of specific insertions. Optics and dispersion matching is obtained by first using the "thin" version of the computer program MAGIC¹ in which all magnet elements are assumed to be of zero length. The results are then used as trial input to the "thick" version of the program to give the final physical parameters. For simplicity, when several standard transport elements must be strung together to give the required strength we have not included the short drift spaces between the elements necessary to accommodate the end structures and connections.

A. Dispersion Modifying Insertion

As examples we give here two zero-dispersion insertions (dispersion function $= \eta = 0$) which reduce the horizontal dispersions at the ends of curved sections to zero. If the curved section ends in an F quadrupole where the dispersion is large the insertion would have to be 2 cells in length and look like that shown in Fig. 2. Four 24.67 mrad dipoles introduced into the normal straight cells produce a local horizontal orbit displacement of 0.740 m and a horizontal dispersion to cancel that from the curved section. There does not seem to be any advantage in modifying the optics by rearranging the quadrupoles. If the curved section ends in a D quadrupole where the dispersion is small the insertion could be reduced to 1½

cell long by first modifying the optics in the insertion (still matched to that of normal cells at the ends) and then introducing four 12.44 mrad dipoles. The local orbit displacement is reduced to 0.228 m. This insertion is shown in Fig. 3. Identical insertions would be used in reverse at the downstream end of the straight sections to re-match dispersion for recirculation.

Conventionally, zero dispersion in the straight section is obtained by modifying the ends of the curved sections as an integral part of the ring lattice. These insertions illustrate the basic departure of the present approach. They can be inserted or withdrawn freely without affecting the operation of the ring.

B. Beam-Size Modifying Insertion

As an example we show in Fig. 4 a low- β insertion (β = amplitude function). This insertion is conventional except that it is antisymmetric, matched to the normal cell optics at the ends, and has a length modularized to 2½ cell lengths. The β -value β^* at the central collision point is 1 m in both planes. The total free drift space on either side of low- β point is 25 m long. The free drift-space length could be substantially increased for higher low- β values. For extremely long drift spaces the insertion would be 3½ cells in length. Presumably several insertions with different β^* values (including high- β values) would be needed.

C. Phase Adjusting Insertion

To make it possible to freely interchange insertions having different phase advances we need an insertion with a phase advance which is adjustable over a wide range. Evidently this insertion would be used to adjust the betatron tune of the ring. In other cases one may also use it to adjust the phase advance across a single straight section to a desired value. An example of this insertion which is antisymmetric and matched to the normal cell optics is shown in Fig. 5. The phase advance is adjustable from 100° to 300°. The field-gradient settings of the quadrupoles are plotted against the phase advance. It should be possible to program these curves into the control computer so that the phase advance can be adjusted by turning a single knob.

D. Orbit-Length Dispersion Adjusting Insertion

This is an obvious companion to the phase adjusting insertion. To be useful the insertion should be rather long. The simplest would be a 4-cell long antisymmetric insertion with 360° phase advance. By varying the field-gradients of the quadrupoles but keeping the phase advance at 360°, one can vary the orbit-length dispersion $\frac{\Delta L}{\Delta p}$ without affecting the optics and dispersion matching at the ends. No example is given for this simple insertion. The utility of this insertion is less obvious than that of the phase adjusting insertion, but clearly it could be used to adjust the transition energy of the ring.

E. Beam Crossing ("Targeting") Insertion

The beams traveling in opposite directions in the two rings stacked one on top of the other are separated by 0.3 m. These two beams can be displaced vertically to come together to collide head on in a half-cell by three vertical dipoles as shown in Fig. 6. These dipoles must have a vertical good field aperture of more than 50 mm. It is likely that the standard transport dipoles turned vertical would have an adequate aperture. Several remarks should be made for this insertion.

(1) This insertion is generally followed by a beam size modifying insertion. The vertical dipoles in this insertion should be trimmed to give the appropriate small beam separation and angle at the entrance to the following insertion such that the beams would cross each other at the proper location (e.g. the low- β point) and at the desired small angle. Furthermore, the vertical dipoles could easily have an adequate trimming range to accommodate either the cross-over geometry (the upper beam becomes the lower beam in the following curved section) or the no-cross-over geometry.

(2) The small vertical dispersion introduced by the vertical bends will make the distance over which the beams collide longer hence extending further away from the low- β point. The resulting reduction in luminosity is generally quite small, especially if the horizontal dispersion is made zero in the collision region.

(3) This short insertion occupying only a drift space is not a true insertion in the dispersion-optical sense. In some cases it can be merged into the ends of other insertion, i.e. the vertical dipoles can be placed in a drift space of adequate length in any insertion.

With the sample insertions given above we can now put together an example of a complete straight-section beam line. To get the maximum luminosity we would want zero-dispersion

and low- β at the beam-collision ("targeting") point. This could be obtained from the string of insertions shown in Fig. 7. The total length is $7\frac{1}{2}$ cells or 450 m.

Similar exercises in putting together other complete straight-section beam lines indicate that a straight-section length of 4 cells or 240 m (in 1000-GeV storage rings) is too short for full exploitation of the flexibility inherent in this scheme. A straight-section length of 6 cells (480 m) or greater would be more appropriate. This study also shows that the straight-section length should be measured in terms of the betatron oscillation wave length in the curved section which is in turn governed by the available dipole and quadrupole strengths for the specified beam energy. One wave length is too short, two or more wave lengths would be adequate.

An obvious criticism for this design approach is that the flexibility is bought at the expense of longer straight sections. However, comparison with conclusions of design studies for Isabelle and PEP indicates that, in fact, the additional length required is rather small. Recalling the parallelism invoked in the introduction we observe further that even with the slightly longer length these straight-section beam lines are much shorter than the conventional external beam lines of an accelerator at the same energy. This parallelism also provides a basis for the choice of the number of straight sections. Accelerator facilities in which experiments are performed mainly in external beams typically have 4-6 external beam lines. A similar number of straight sections in a colliding-beam storage ring facility is thus appropriate.

References

1. M.J. Lee, W.W. Lee and L.C. Teng, "Magnet Insertion Code (MAGIC)", Note-61, 1973 PEP Summer Study Report (1973).

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Figure 1. Normal curved cell

Figure 2. Zero-dispersion insertion (P type)

Figure 3. Zero-dispersion insertion (D type)

Figure 4. Low- β insertion

Figure 5. Phase adjusting insertion

Figure 6. Beam crossing insertion

Figure 7. High luminosity straight section