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ABSTRACT

Synchrotron guide-field arrangements have been developed that provide for a convenient and economical later increase in energy by the addition of components omitted in the initial construction. Criteria for the design of such an accelerator include new considerations such as emphasis on small circumference to reduce initial costs and on magnet configurations for both stages that have similar orbit behavior and that require little realignment or replacement of the original magnets in the conversion.

Space added for future components might also be useful to improve the accelerator in other directions. Thus, at modest cost, the initial layout would afford, in addition to specific provision for conversion to higher energy, a more general flexibility for response to future needs and exploitation of future technology.

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1. INTRODUCTION

Most large proton synchrotrons have been modified during their lifetime in order to increase their productivity by increases in intensity or expansions in experimental facilities. The possibility of increasing peak proton energy has generally been ruled out because of limitations imposed by the accelerator circumference and the saturation properties of the magnets. This paper describes guide-field configurations that allow, at moderate initial cost, a subsequent large increase in peak proton energy by insertion of additional magnets and other components. It should be understood that the insertions specified are only examples of what might be done; the actual conversion to higher energy would come after some years of operation and would take advantage of accumulated experience and advances in technology. Thus the accelerator in its final form might bear little resemblance to a machine designed today for that final energy, and might indeed be superior in function for less ultimate cost.

Although the principle of extendible energy is applicable to an accelerator of any initial energy, we have chosen to consider guide-field configurations providing an initial energy of 200 GeV, in order to be able to compare them with the 200-GeV accelerator now under consideration in the United States¹). Examples of synchrotrons extendible to 300, 400, and 500 GeV by conventional means are presented, including rough cost comparisons between the two 300-GeV designs and the reference case.

Any decision to incorporate such a feature in a new accelerator must of course take into consideration many nontechnical factors beyond the scope of this feasibility study.

To define the study, we have adopted the following guide lines:

- a. As initially constructed (Stage I), the synchrotron must incorporate provisions for a later increase in peak energy (Stage II), such as additional circumference to permit the insertion of new components.
- b. Stage I must meet the standards of the reference 200-GeV accelerator with regard to reliability and assurance of immediate usefulness as a research tool.
- c. Since the feature of extendibility is regarded as an option for future development, greater emphasis should be placed on initial cost than on ultimate cost. For example, the components needed in Stage I should not be overdesigned in anticipation of their use in Stage II.
- d. The tentative design for Stage II should be adequate in overall performance by present standards, but may be less conservative than for Stage I, since the eventual design would draw on knowledge unavailable to us now.

2. DESIGN CONSIDERATIONS

2.1 Utilization of Original Units

One should plan to use most of the initial components at or close to full capacity both before and after conversion. To simplify conversion, the Stage-I magnets should remain on the same supports displaced only slightly to match the closed orbit in Stage II. The displacements are of the order of 1 cm or less in the examples presented.

2.2 Preservation of Orbit Properties

It is important that the orbit properties in Stage II closely

resemble those of Stage I, so that operational experience will be relevant. The converted machine might then be built with less generous safety factors in aperture and with higher magnetic fields than would be chosen for a completely new accelerator. The examples presented retain the same v value in both stages and exhibit reasonably small changes in the amplitude function β and the excursion of off-momentum particles.

2.3 Distribution of New Bending and Focusing Magnets

In order to use the same tunnel, same magnet-support system, and most of the original magnets at or near their original positions in the converted accelerator, the space allowed for new bending-magnet units should be distributed as uniformly as possible. Similarly, new focusing units should be installed at frequent intervals in each cell to prevent excessive changes in orbit properties. Since focusing quadrupoles are considerably less expensive than bending units one may consider replacing the quadrupoles rather than increasing their excitation or adding a new class of quadrupoles. This option is illustrated in the examples.

2.4 Aperture vs Circumference

The relative weight given to these parameters should be different than for a one-stage project. An increase in focusing strength permits a decrease in aperture, but leads to shorter cells and shorter magnets. However, this choice increases the circumference because of the increased number of straight sections and because the permissible peak field decreases with increasing gradient. Aperture and circumference are also coupled by the assumption we make that emittance in each

plane is proportional to the injected current. Thus, for a fixed number of protons per pulse, the aperture required decreases with increasing circumference.

Since the ratio of tunnel-related costs to magnet costs in Stage I is higher than for a one-stage synchrotron of the same energy, the optimum is shifted toward small circumference at the expense of aperture.

2.5 Long Straight Sections vs Aperture

Freedom to balance aperture against circumference is limited by a relation between the attainable drift length in the long straight sections and the maximum value of the betatron amplitude function, $\beta_{\max}$, which determines beam size. Since the drift spaces must be long enough for Stage II operation, the design value of $\beta_{\max}$ must not be too low.

Recently developed techniques in straight-section design²⁾ have led to ratios of field-free length to $\beta_{\max}$ higher than the value 0.6 specified in the 200-BeV Accelerator Design Study¹⁾. This ratio is 0.65 in the four-quadrupole insertion of the 400-GeV example and 0.8 in the four-quadrupole replacement of half a cell used in the 500-GeV example. As a result, the increase in $\beta_{\max}$ required for an adequate drift length is sufficiently modest that the apertures required in the example synchrotrons should be similar to those required for a conventional 200-GeV accelerator. Furthermore, the relative increase in β in these straight sections is considerably less than in two-quadrupole configurations. Further improvements seem possible and are being explored.

2.6 Magnetic Fields and Gradients

Magnetic-field levels are assumed to be about 10% higher in Stage II than in Stage I. The available good-field aperture would decrease, but experience with the Stage-I machine could well lead to a more efficient use of available aperture than would be possible to predict for a completely new accelerator. The final decision on field level and energy would in fact be a compromise based on operating experience and the prevailing emphasis on energy, intensity, and operational flexibility.

3. EXAMPLES OF EXTENDIBLE-ENERGY SYNCHROTRONS

Magnet configurations and principal parameters of four extendible-energy synchrotrons are given in Figs. 1 through 4. All are designed for initial operation at 200 GeV, and the examples respectively illustrate conversion capability to 300, 300, 400, and 500 GeV.

These examples are not the result of optimization, but only illustrate that reasonable designs can be made consistent with the foregoing criteria. Since the practicability of building extendible-energy synchrotrons was not obvious to us at the outset, we first considered examples giving a modest increase of a factor of 1.5 in energy. The cases providing greater increase were considered later and have been less thoroughly studied.

3.1 200 → 300-GeV Synchrotrons

3.1.1 Separated-function synchrotron

A separated-function lattice is attractive in that it probably provides maximum flexibility for choice in the conversion. In the

example shown in Fig. 1, space is left in each half-cell for the addition of one new bending magnet. Quadrupoles would be replaced by stronger ones on conversion, and the orbit properties would be almost unchanged. The radius of this $200 \rightarrow 300$ -GeV example (the arrow denotes extendibility to the higher energy) is only 27% greater than that of the 200-GeV reference design because of the high fields and low circumference factor assumed for the Stage-II design. A four-quadrupole matched insertion at a junction between a focusing (F) and a defocusing (D) region (F-D point) is used for the long straight section to achieve a greater drift length than is possible with a conventional two-quadrupole insertion in such a FODO lattice.

3.1.2 "Hybrid" synchrotron

In the example shown in Fig. 2, the cells are FOFDOD type in Stage I, with F-D and D-F straight sections lengthened sufficiently to permit later addition of bending magnets. Quadrupoles would be added in the F-F and D-D straight sections in Stage II. The name "hybrid" synchrotron refers to the addition of separated-function elements to a combined-function accelerator.

The long straight-section drift length is achieved in this lattice with an insertion consisting of two quadrupoles and two short gradient magnets at an F-D point, as in the Design Study Synchrotron.

If one compares the two 300-GeV examples, $\beta_{\max}$ and the excursion of off-momentum particles in Stage I are less in the hybrid than in the separated-function machine; the orbit properties change more upon conversion, though still not significantly. The radius is slightly larger in the hybrid example.

The aperture estimates for the 200 $\rightarrow$ 300-GeV examples are consistent with preliminary calculations made by Dr. L. J. Laslett of the closed-orbit error. He finds that for foundations appropriate to a hard-rock site, closed-orbit displacements would be comparable to those of the 200-GeV Design Study synchrotron.

3.2 200 $\rightarrow$ 400-GeV Synchrotron

To provide the 2:1 energy ratio of the 200- to 400-GeV synchrotron (Fig. 3), the cells are constructed of magnet pairs consisting of one old and one new unit. The lattice in both stages is of the combined function type, in contrast to the hybrid 300-GeV example. The value of the profile parameter $k = (dB/dR)/B$ required in the new gradient magnets is so low that their field level can be nearly as high as in zero-gradient magnets. The long straight-section drift length is obtained easily with four-quadrupole insertions at F-D points because of the high slope of β at these positions.

3.3 200 $\rightarrow$ 500-GeV Synchrotron

Figure 4 shows a synchrotron with energy extendible from 200 to 500 GeV. The normal cells in Stage II are derivable from those of the 200 $\rightarrow$ 400-GeV example by the addition of a zero-gradient magnet in each F-D space. Rather than let the length of the cell straight sections continue to increase, with corresponding growth of $\beta_{\max}$ and circumference, we have held these lengths to 3 meters and provided two-quadrupole Collins-type insertions, some with 11-meter and others with 25-meter drift lengths; however the suggested number, distribution, and drift lengths of these insertions are not based on detailed evaluation of space requirements. A feasible and possibly economical

variation of these Collins straight sections consists of replacing the quadrupoles with gradient magnets. The long 73-meter drift lengths are provided by four-quadrupole, antisymmetric, long straight sections that replace half of a cell, and whose transfer matrix is matched to the cell betatron functions of an FF point at one end and of a DD point at the other. The ratio of drift length to $\beta_{\max}$ is very good (0.8), and the displacement of off-momentum particles is substantially reduced by the use of bending magnets in the outer ends of the array.*

At present, calculation of the strength and location of the quadrupoles in Stage II to preserve matching, while keeping ν and the straight-section lengths unaltered, has not been completed. The multiplicity of straight-section types and the change in cell structure at conversion increase the complexity of this example. A separated-function synchrotron might be conceptually simpler in view of the large energy ratio.

4. CONSTRUCTION COSTS

Approximate costs of the 200 $\rightarrow$ 300-GeV extendible examples have been estimated for comparison with the 200-GeV Design Study accelerator. These estimates apply for conditions at the hard-rock site used in that study. Cost differences in Table 1 include allowances for engineering and contingency, and are additive to the reference-design costs of about 200 M\$ for accelerator construction. Only

*The array resembles the momentum-compensated π straight section²⁾ but requires less quadrupole length and aperture.

major contributions to cost differences have been considered; for example, possible modifications to the injection system have not been estimated. Experimental areas and equipment are not included in the 200 \$M accelerator costs; additional expenditures would surely be required in these categories for Stage II.

The results illustrate that the main increase in initial cost arises from enclosure and supports, estimated at about \$3000 per ft, and increased rf voltage required to maintain a fixed acceleration time. A more costly magnet and power supply in the separated-function example appears to outweigh the related reduction in circumference, compared to the hybrid case. The initial investment of 20 M\$ seems moderate for an option to increase energy by 50%. The total additional 70 M\$ indicates that one may obtain a 300-GeV facility in this way without cost penalty, and possibly with savings due to the experience factor. On the other hand, the ultimate capability of such a facility might be less than that of a more conservative, one-stage design.

To extend cost comparisons to higher-energy examples introduces more uncertainty. While one would expect the major cost items to be the same as those shown in the 300-GeV cases, a more complete analysis of the entire system is needed as one departs further from the reference 200-GeV design.

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Table 1
Major differentials in construction costs
of 200 → 300-GeV examples (in M\$)

	Reference 200-GeV costs	Differentials			
		Separated function		Hybrid	
		Initial	Conversion	Initial	Conversion
Magnet	42	1.3	20	-2.2	15
Power supply	19	4.2	18	0.9	18
Rf system	14	3.8	9	4.5	9
Enclosure and support structure	44	11.6		14.4	
Controls, injector, etc.	86				
Total accelerator*	≈ 200	≈ 21	≈ 47	≈ 18	≈ 42
Sum of differentials		≈ 70		≈ 60	

* Accelerator costs exclude experimental areas and support facilities, the cost of which would bring the total facility to ≈ 290 M\$.

Figure Legends

Fig. 1. 200 $\rightarrow$ 300-GeV separated-function synchrotron.

Fig. 2. 200 $\rightarrow$ 300-GeV "hybrid" synchrotron.

Fig. 3. 200 $\rightarrow$ 400-GeV combined-function synchrotron.

Fig. 4. Exploratory 200 $\rightarrow$ 500-GeV synchrotron.

10 Meters

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STAGE I (200 GEV)

STAGE II (300 GEV)

RADIUS, (meters)
RADIUS / REFERENCE RADIUS
BETATRON OSCILLATION NUMBER
NUMBER OF SUPERPERIODS
NUMBER OF CELLS

R 911
1.32
 ν 19.25
 N_s 12
N 108

PEAK MAGNETIC FIELD
INITIAL MAGNETS
STAGE II
PROFILE PARAMETER
FIELD GRADIENTS
CELL QUADRUPOLES
STR. SECT.
APERTURES - APPROX.
GRADIENT MAGNETS
BENDING MAGNETS
CELL QUADRUPOLES
STR. SECT.

B
k
 B'_0
wxh

STAGE I	STAGE II	
16	17.5	k G
—	20	"
2.19	2.19	m ⁻¹
—	222	kG/m
180	222	"
12 x 5	12 x 5	cm x cm
—	10 x 4.5	"
—	11 x 5	"
12 x 6	12 x 6	"

BETATRON AMPLITUDE FUNCTION
GRADIENT MAGNETS
BENDING MAGNETS
CELL QUADRUPOLES
STR. SECT. QUADRUPOLES
CLOSED ORBIT DISPL. PER $\Delta p/p$

β_{max}

 X_{pmax}

STAGE I	STAGE II	
74	81	meters
—	63	"
—	82	"
99	98	"
6.0	5.8	"

MAGNET AND STRAIGHT SECTION LENGTHS IN METERS ARE INDICATED ON DIAGRAM.

SCALE 10 Meters

Fig. 2

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XBL 673-1316

		STAGE I		STAGE II				APERTURES - APPROX.		wxh	
RADIUS, (meters)	R	1373	PEAK MAGNETIC FIELD	B							
RADIUS/ REFERENCE RADIUS		1.99	INITIAL GRADIENT MAGNETS	16.25	18.06	kG	GRADIENT MAGNETS		14 x 6	cm x cm	
BETATRON OSCILLATION NUMBER	ν	23.75	STAGE II " "	—	18.50	"	BENDING MAGNETS		14 x 6.5	"	
NUMBER OF SUPERPERIODS	N_s	10	INITIAL BENDING MAGNETS	18.0	20.0	"	LONG STR. SECT. QUADS.		14 x 7	"	
NUMBER OF CELLS	N	100	STAGE II " "	—	20.0	"	BETATRON AMPLITUDE FUNCTION	β_{max}			
SUPERPERIOD COMPOSITION:			PROFILE PARAMETER	k			GRADIENT MAGNETS		91	meters	
CELLS		10	INITIAL GRADIENT MAGNETS	2.03	2.03	m ⁻¹	BENDING MAGNETS		97	"	
SHORT STR. SECT.		3	STAGE II " "	—	2.20	"	LONG STR. SECT. QUAD'S		114	"	
MEDIUM STR. SECT.		1	QUADRUPOLE GRADIENTS :	B'_0			CLOSED ORBIT DISPL. PER $\Delta p/p$	$X_{p,max}$	5.4	"	
LONG STR. SECT.		1	LONG STR. SECT., OUTER	184		kG/m					
			" " " , INNER	178							
			MEDIUM STR. SECT.	201							
			SHORT STR. SECT.	214							
NOT CALCULATED											
MAGNET AND STRAIGHT SECTION LENGTHS IN METERS ARE INDICATED ON DIAGRAM.											
SCALE 10 METERS											

SCALE 10 METERS

Fig. 4

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