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LATTICE OF THE NAL PROTON SYNCHROTRON

Alper A. Garren

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The proton synchrotron of the National Accelerator Laboratory has been designed to have a 1000 meter radius, separated-function lattice. This report presents the parameters of this lattice as of February 1969, which have been modified in non-fundamental ways from those described by Wilson[1] at the Cambridge Conference and from those given in the NAL Design Report.[2] These parameters are summarized in Table I and Fig. 1. The last part of the paper will present a brief description of some alternative designs that were considered for this accelerator.

Present Design of the Synchrotron

General Description

The synchrotron is initially to accelerate protons to 200 GeV. However, it is envisioned that after some period of operation, the machine will be modified to permit acceleration to 400 GeV or higher. During the initial, 200-GeV operation, the bending magnets will be excited to a peak field of 9 kG, and the quadrupole gradient will be 1.25 kG/cm. Conversion to 400 GeV involves primarily increasing magnet power and cooling to raise the peak field to 18 kG, and the peak quadrupole gradient to 2.5 kG/cm.

Superperiods

The synchrotron lattice (see Fig. 1) is divided into six identical superperiods, S. Each superperiod contains sixteen cells of three types C, CM, and CL arranged in the sequence $CL \cdot C^2 \cdot CM \cdot C^{12}$. A normal cell C contains one radially focusing quadrupole QF, one radially defocusing quadrupole QD, and eight dipole bending magnets B, four in each of the half-cells, FD and DF. Each quadrupole is followed by a 2-meter drift space for trimming elements and beam-sensing devices. With this simple FODO type separated function cell structure one achieves the greatest focusing effect for the least total quadrupole length.

The special cell CM is like a normal cell except that the two bending magnets downstream from the focusing quadrupole are missing, creating a straight section (called a medium straight section) about 15 meters long for beam scrapers.

The other special cell, CL, contains three extra straight sections, the 51-meter long straight L, and the 9- and 3-meter straights L1 and L2 (see Fig. 1). One of these six special cells is used for beam injection and extraction, one for RF acceleration cavities, one for a possible internal target area, one for feeding a future storage ring. The other two could be used for such purposes as additional external beams, more RF cavities, or a beam bypass. It is desirable to have a sufficient number of superperiods to avoid the strongest structure-induced resonances.

Cell with Long Straight Section, CL

This cell may be described as follows: One imagines a normal cell, extending from the center of a focusing quadrupole to the center of the next focusing quadrupole. The first half of this cell, FD, is then replaced by a special structure of quadrupoles, bending magnets, and drift spaces -- including L, the long straight. This half-cell replacement, FLD, is matched to the normal cell; i.e., its effect on the matched beam ellipses is the same as that of the normal half-cell FD which it replaces. The second half of CL is like a normal half-cell DF. If the half-cell replacement FLD is divided into two halves, the second half is the mirror reflection of the first half except that focusing and defocusing quadrupoles are interchanged and there are unequal numbers of bending magnets in the end spaces.

As originally designed (cf. Ref. 2) the long straight section L was flanked on either end by two quadrupoles of unequal length, both longer than the cell quadrupoles. In addition, quadrupoles a little more than half as long as cell quadrupoles were placed at either end of the half-cell replacement. Thus the synchrotron would have quadrupoles with four different lengths, two of them long enough to cause complications in fabrication and cooling.

This part of the lattice has recently been modified to the form shown in Fig. 1, so that the synchrotron now contains only two types of quadrupoles: normal cell quadrupoles QF and QD about 2.1 meters long, and short quadrupoles QF' and QD' about 1.3 meters long. All of these lenses have the same gradient (in magnitude).

The structure described above has the following advantages:

i) The amplitude in the long straight quadrupoles is not much larger than in the normal cells.

ii) The increase in the excursion of off-momentum particles is not large.

iii) The arrangement of drift spaces and the focusing properties of the structure are favorable to the planned beam-extraction system.

Orbit Characteristics*

The cell quadrupole strength was chosen to minimize the amplitude of the betatron oscillations. When this is done the phase advance per cell is about 70°. The beam could be more strongly focused by reducing the length of each cell, but the required circumference would then increase to accommodate the larger number of longer quadrupoles. The cell with the long straight section is not perfectly matched for the closed orbits of off-momentum particles. However, the maximum displacement per unit momentum error $\Delta p/p$ is only 5.22 m compared with 3.70 m in a ring made up entirely of normal cells. The amplitude of betatron oscillations reaches a maximum value in the long straight section 11% greater than in the normal cells.

*Calculation of orbit properties, design of matching straight sections, etc. involved application of the computer programs SYNCH[3] and TRANSPORT.[4]

The chosen design of long straight section is favorable for the contemplated slow extraction system--which involves building up coherent radial oscillations, partly because the radial phase advance between the electrostatic septum to the second magnetic septum in the long straight drift space is not too large. Curves of the square root of the amplitude function β and of the displacement of the off-momentum closed orbit per $\Delta p/p$, x_p, are shown in Figs. 2, 3, and 4.

In case it should ever prove desirable to run the synchrotron at different ν values, by changing the relationship between the quadrupole gradient and the magnetic field, we see in Table II that the increase in β_{max} is tolerable over a considerable range. This property may be useful when the accelerator is pushed to maximize the proton energy. The increase in β_{max} is introduced by the mismatch of the special half-cells FLD that occurs when all of the quadrupoles are not set at the design value. This mismatch would be avoided or at least minimized if the ten quadrupoles of the half-cell were independently controlled.

Discussion of Alternative Designs

Combined Function 200-GeV Synchrotron

The synchrotron described in the 200-BeV design study[5] is a conventional combined function lattice. The principal variations considered for the lattice of this design pertained to the long straight sections.[5,6]

Expanditrons

In 1967 it was suggested[7] that a synchrotron might be built to operate originally at say 200 GeV and subsequently be converted to operate at higher energy by addition of more magnets. A number of lattices were designed to illustrate this possibility, including combined function, separated function, and mixed types. At the summer study in 1967 at the National Accelerator Laboratory the two-energy-step idea was adopted, but as explained previously, it was decided to have all the magnets in place originally so as to reduce the conversion shutdown time.

Separated and Combined Function Lattices

It was also decided at the summer study to adopt a separated function lattice. Space does not permit discussion of the separated vs combined function question here; we will merely remark that it does seem that separated function lattices often have less circumference than comparable combined function lattices, and the tuning range is greater. The case for separated function lattices has been strongly urged by Danby et al.[8] During the summer study the lattice was designed, substantially in its present form.

Alternative 400-GeV Lattices

During the fall of 1967 it was thought advisable to design a few lattices significantly different from the provisionally adopted one, as a final effort to avoid missing some important advantage. While these lattices have not been as carefully worked out as the adopted design, they are useful for comparison.

'Doublet' separated function lattice. (See Fig. 5). Focusing is provided by equally spaced quadrupole doublets, two doublets in each of the 54 cells. Eight bending magnets are placed in each half-cell. The long straight sections are made by removing bending magnets from normal cells.

This lattice is attractive because of its simplicity and large tuning range due to the very weak superperiod structure. However, it has 50% more quadrupole length than the adopted FODO lattice, and the transition energy is rather close to the injection energy.

'Triplet' separated function lattice. (See Fig. 6). The ring is made up of 54 equally spaced quadrupole triplets. As in the doublet lattice, bending magnets are simply removed from normal cells to provide space for the long and medium straights. As with the 'doublet' lattice, simplicity and a weak superperiod structure are present. If the quadrupoles in each triplet are tied to the same rigid support, the closed orbit distortion will be relatively small. This lattice requires about 40% more quadrupole length than does the adopted FODO lattice, and the beam is large vertically in the QD quadrupoles.

Separated function FODO lattices with different long straight sections.

a) Symmetric type. The structure $\ell \cdot QF \cdot QD \cdot L \cdot QD \cdot QF \cdot \ell$ can be inserted at the center of a cell F-quadrupole.

b) Empty cell type. This is a lattice made up only of identical FODO-type cells. The long straights are provided by removing the bending magnets from two successive half-cells. Neither a) nor b) seemed well suited for extraction, and b) might pose difficulties for internal targeting experiments.

Combined function lattice. The cells, about 60 m long, have the structure (FF)O(FF)(DD)O(DD), where F and D represent 6.5 m length, gradient magnets with 16.5 kG at 400 GeV, and with $k = B'/B = 2\ m^{-1}$. The lattice as worked out had six 46-meter long straight sections L and six 22-meter medium straight sections LM, both provided by Collins-type insertions. The short straight sections LS are 2.75 m long and the synchrotron radius R is 1006 m. The straight section lengths could be changed to 51, 14, and 2 m respectively, as in the adopted lattice, with a corresponding machine radius of close to 1000 m. Militating against this design is the belief that the separated function dipole magnets can ultimately be pushed to relatively higher-fields than can the gradient magnets. Also this lattice would have more magnet types than the adopted design.

This study suggests that while there are reasonable alternatives to the design adopted, none have any obvious superiority to that presented in Table I and Fig. 1. It is believed that this lattice well fulfills the requirements of the accelerator, with simplicity and economy.

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7. A. A. Garren, G. R. Lambertson, E. J. Lofgren, and L. Smith, Extendible Energy Synchrotrons, Nucl. Instr. Methods 54, 223-228 (1967).

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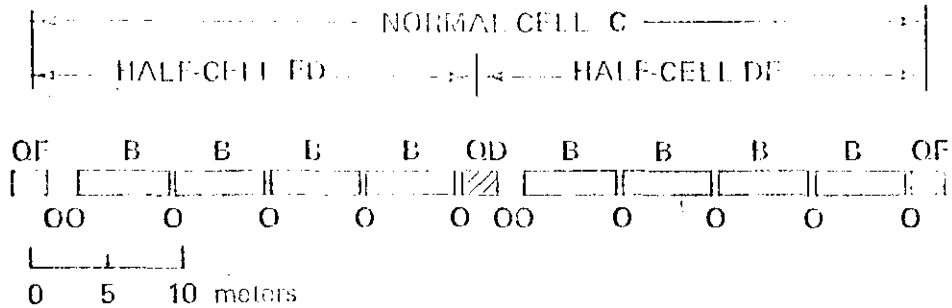
Table I. Parameters of the NAL Synchrotron.

Kinetic energy	400 GeV
Radius (circumference/2π)	1000 m
Magnetic radius	747.8 m
Magnetic field	17.88 kG
Quadrupole gradient	2.505 kG/cm
Betatron oscillation frequency, ν	20.25
Transition kinetic energy	17.5 GeV
Number of superperiods	6
Number of long straights	6
Number of medium straights	6
Number of cells (including 12 special half-cells)	96
Number bending magnets	774
Number standard cell quadrupoles	192
Number short quadrupoles	48
Cell length	59.49 m
Length of half-cell replacement FLD	125.15 m
Total quadrupole length	473 m
Total bending magnet length	4698.6 m
Lengths of magnets and straights-- See Fig. 1	
Orbit functions -- See Figs. 2,3, and 4	

Table II. Quadrupole gradients at 400 GeV and orbit parameters for various ν values. Short and long quadrupoles are at the same gradients. Values of β_x, β_y and x_p are the maxima in normal cells.

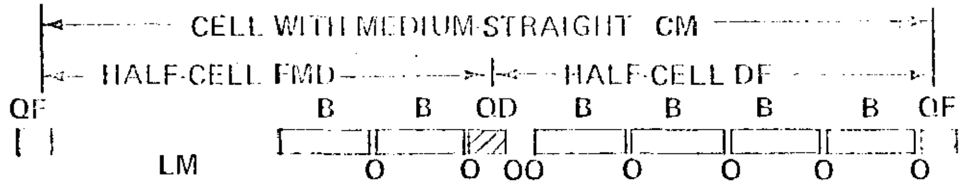
ν_x	ν_y	B'_F (kG/cm)	B'_D (kG/cm)	β_x (m)	β_y (m)	x_p (m)
17.25	17.25	2.17	-2.17	112	112	7.07
18.75	18.75	2.34	-2.34	107	109	7.48
19.25	19.25	2.39	-2.39	103	104	6.17
19.75	19.75	2.45	-2.45	101	101	5.55
20.25	20.25	2.50	-2.50	99	99	5.24
20.75	20.75	2.55	-2.55	106	104	5.08
21.25	21.25	2.61	-2.61	115	113	5.04
22.25	22.25	2.71	-2.71	107	107	5.48
23.25	23.25	2.81	-2.81	118	117	8.76
19.75	18.75	2.42	-2.37	100	115	5.71
20.25	19.25	2.47	-2.42	102	109	5.38
20.75	19.75	2.53	-2.47	117	106	5.21
21.25	20.25	2.58	-2.53	126	105	5.17
18.75	19.75	2.37	-2.42	115	99	7.08
19.25	20.25	2.42	-2.47	108	101	5.87
19.75	20.75	2.47	-2.53	105	115	5.36
20.25	21.25	2.53	-2.58	104	124	5.08



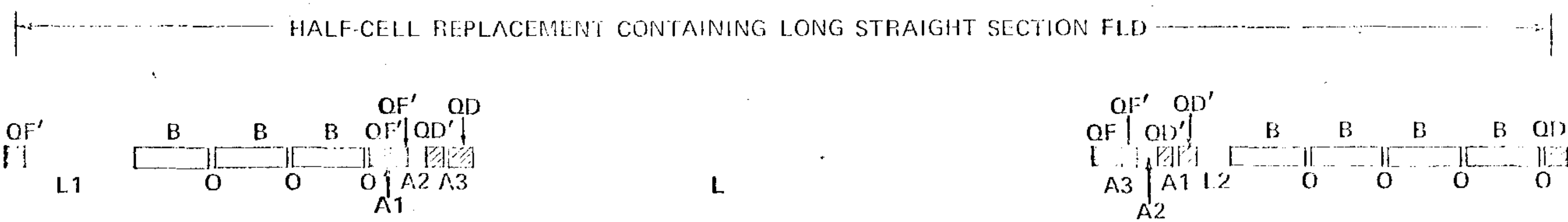
B	6.0706 m	19 ft 11 in	OO	2.1082 m	6 ft 11 in
QF, QD	2.1336 m	7 ft	O	0.3048 m	1 ft

Magnetic field at 400 GeV = 17.88 kG

Quadrupole gradient = 2.505 kG/cm



LM 14.859 m 48 ft 9 in



B	6.0706 m	19 ft 11 in	L2	2.9223 m	9 ft 7.05 in
QF, QD	2.1336 m	7 ft	O	0.3048 m	1 ft
QF′, QD′	1.3195 m	4 ft 3.95 in	A1	0.3462 m	1 ft 1.63 in
L1	9.2977 m	30 ft 6.05 in	A2	1.7729 m	5 ft 9.8 in
L	50.8343 m	166 ft 9.35 in	A3	0.2710 m	10.67 in

Fig. 1. Illustration of lattice of the NAL 200-GeV Synchrotron. Each of the six superperiods has the structure $S = CL \cdot C^2 \cdot CM \cdot C^{12}$. The three different cell-types in turn are composed as follows: $C = FD \cdot DF$, $CL = FLD \cdot DF$, $CM = FMD \cdot DF$.

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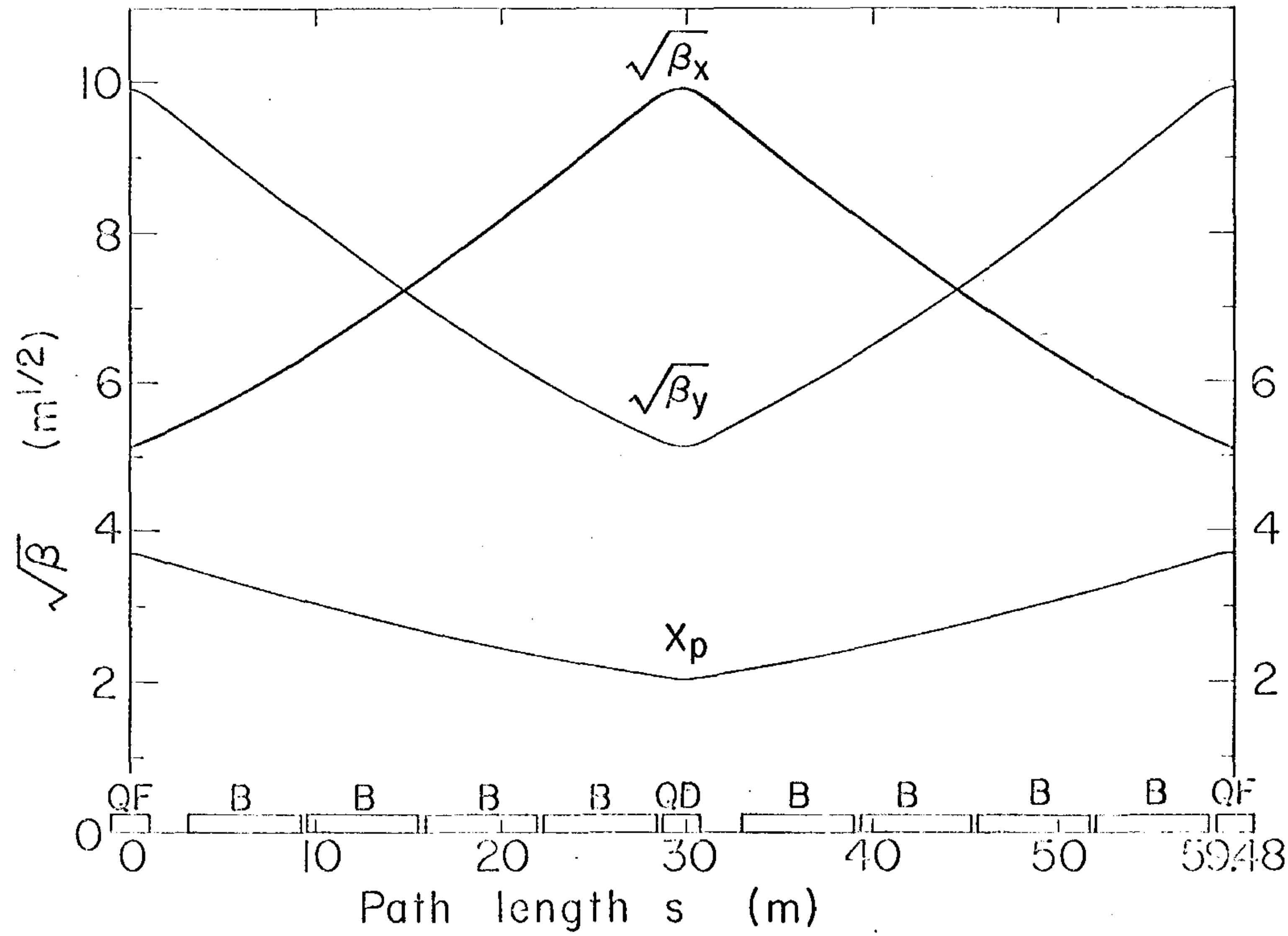

Fig. 2. Orbit functions in a normal cell C of the NAL Synchrotron. β_x and β_y are values of the Courant-Snyder amplitude function in the horizontal and vertical planes, x_p is the radial displacement of the closed orbit per unit momentum error $\Delta p/p$.

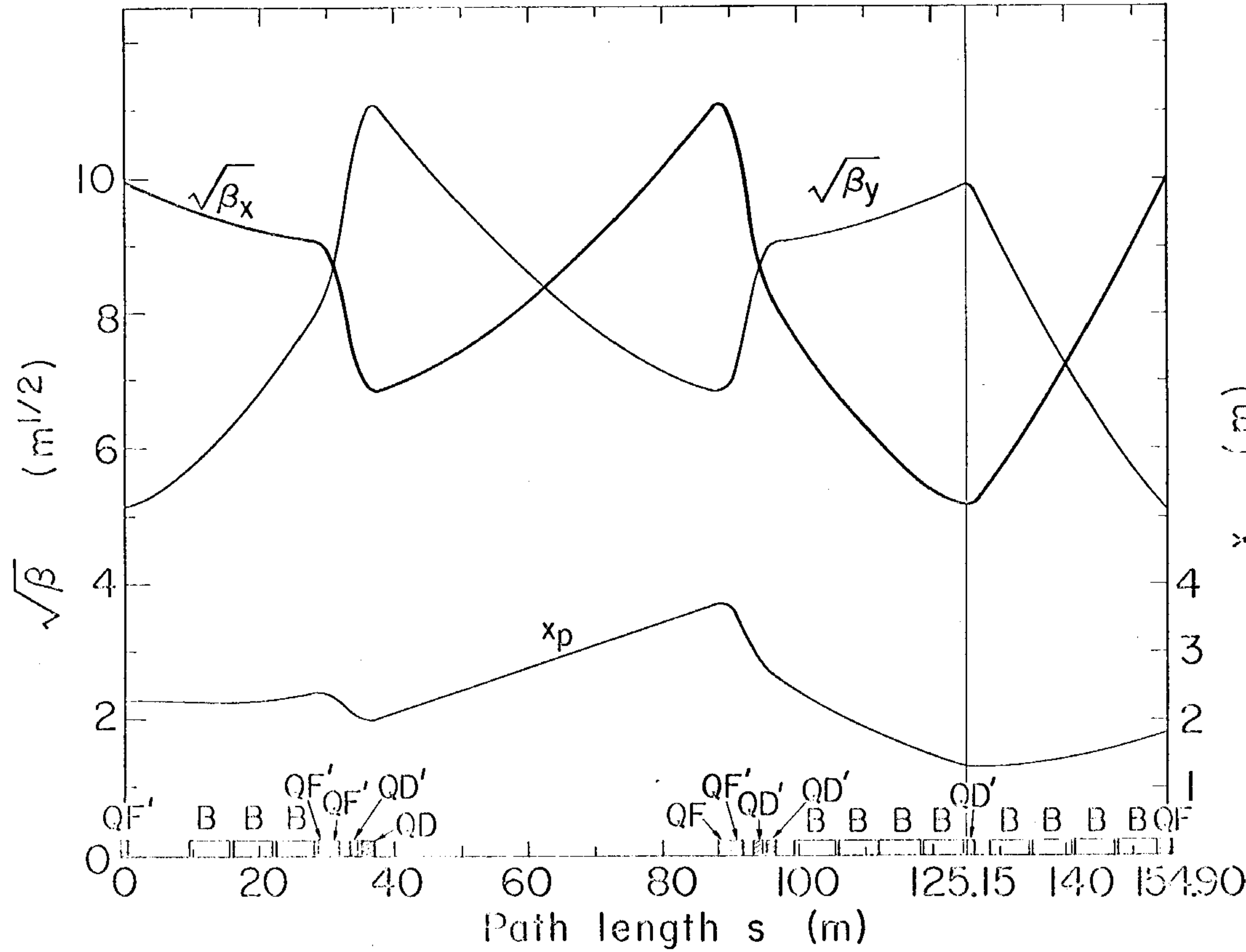

Fig. 3. Orbit functions in the cell CL that contains the long straight section.

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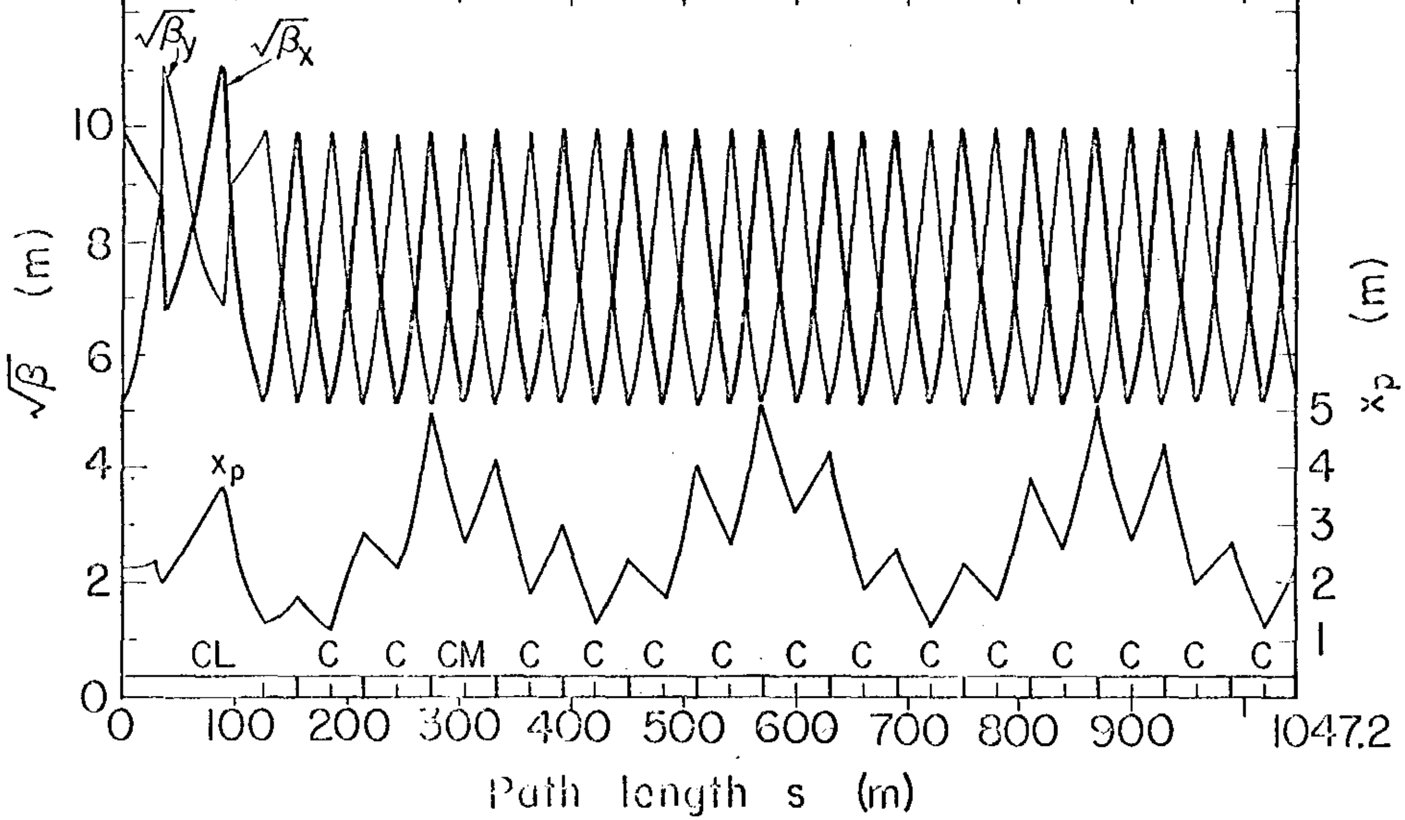

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Fig. 4. Orbit functions through one superperiod of the NAL Synchrotron.

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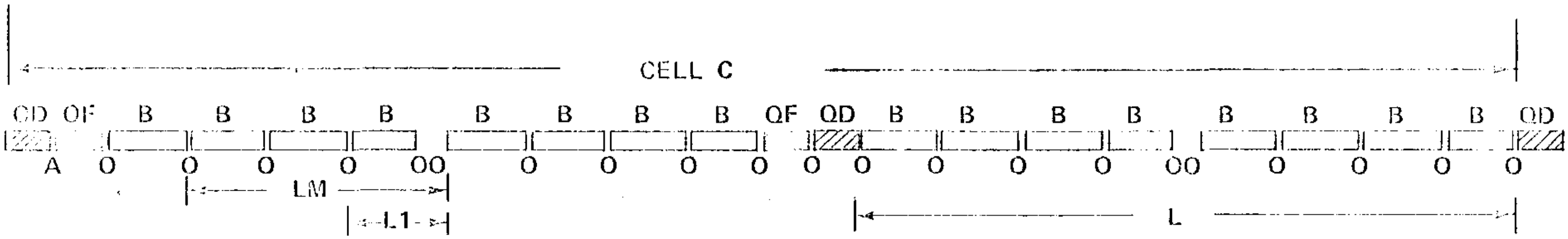


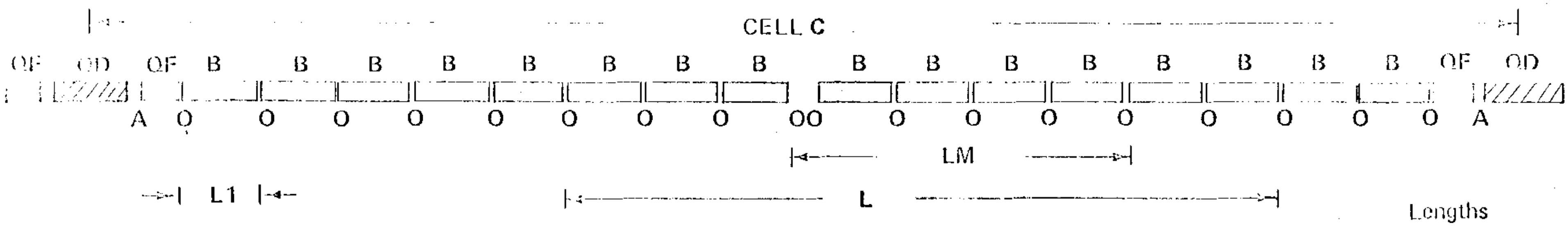
Radius	999.5 m
Magnetic field	18.2 kG
Quadrupole gradient	2.58 kG/cm
Betatron frequency	14¼
Transition kinetic energy	11.9 GeV
Number super-periods	6
Number long straights L	6
Number medium straights LM	6
Number of cells	54
Number bending magnets B	798
Number quadrupoles QF,QD	216
Amplitude function β_{max}	104 m
Closed orbit disp. per $\Delta p/p$	8.47 m

	Lengths
B	5.8166 m
QF,QD	3.3528 m
O	0.3048 m
OO	2.1336 m
A	0.3353 m
LM	20.4978 m
L1	8.255 m
L	51.1048 m
Cell C	116.3 14 m
Total quadrupole	724 m
Total bending	4642 m

Cell CL with long straight section: cell with magnets B4, B9--B16 removed.
Cell CM with medium straight section: cell with magnets B2, B3, B4 removed.

Superperiod structure: CL · C^7 · CM.

Fig. 5. 400-GeV separated function synchrotron with quadrupole doublet focusing.



Radius	1000.3 m
Magnetic field	18.0 kG
Gradient in QF quadrupoles	2.60 kG/cm
Gradient in QD quadrupoles	−2.51 kG/cm
Betatron frequency	14¼
Transition kinetic energy	12.3 GeV
Number of super periods	6
Number long straights L	6
Number medium straights LM	6
Number of cells	54
Number bending magnets	780
Number quadrupoles QF	108
Number quadrupoles QD	54

Amplitude function β_x, β_y	
--QF	103, 129 m
--QD	82, 173 m
B	102, 102 m
Closed orbit displ. per Δp/p	8.13 m

Lengths		
B	5.9436	m
QF	3.0	m
QD	6.0	m
O	0.3048	m
CO	2.3809	m
A	1.0	m
LM	27.3744	m
L1	6.5532	m
L	52.3681	m
Cell C	116.4	m
Total quad.	648	m
Total bending	4636	m

Cell CL: Magnets B1, B6-B14 removed
Cell CM: Magnets B8–B12 removed

Superperiod: CL · C^6 · CM · C

Fig. 6. 400-GeV separated function synchrotron with quadrupole triplet focusing.

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