LEP note 120
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DESCRIPTION OF LEP VERSION 8

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In two previous notes[1),2)], a procedure was presented for choosing the main parameters of a large electron storage ring of just under 5 km radius, referred to as LEP Version 8. It was assumed that 96 klystrons were to be installed to enable just over 80 GeV to be reached with conventional cavities (see Table 1). However, it was hoped that storage cavities presently under intensive study[3),4),5)] would enable 85 GeV to be obtained with the same installed power. In this paper, a lattice layout is developed which uses conventional RF cavities and gives the nominal luminosity at 80.5 GeV at the nominal tune shift of 0.06. This lattice would also be suitable for higher energy operation by varying the lattice phase advance[6),7)] or the coupling[8)] but this has not yet been worked out in detail. Similarly, the low energy performance using variable lattice phase advance or wigglers[9),10),11)] has been provided for but not evaluated in detail.

In designing the lattice, some choices can be made on well-established grounds, and where it seemed useful the theories are explained. Other choices must be made rather arbitrarily at this stage of our knowledge and these are clearly indicated including the preconceptions affecting the choice. The lattice studies which will be pursued over the coming months will be aimed primarily at replacing the preconceptions by more soundly based theories.

1. General Layout

The machine is a direct descendant of the previous CERN studies of large electron storage rings[12),13)] and incorporates many of the general features. The RF sections are placed either side of the eight insertions in a dispersion-free zone. The dispersion suppressors which join these straight sections to the arcs are however modified[14)] to maximize the bending radius and also to enable a range of lattice phase advances to be accommodated. One consequence of this is that the length of a half-period in the RF sections can be adjusted to fit snugly around eight five-cell cavities which are fed from a single klystron.

The concept oftwo different insertion types for LEP has gained wide acceptance and is therefore adopted for the present design. The four short insertions offer a nominal luminosity[15] of 10^{32} $cm^{-2}s^{-1}$ with ±5 m free space and a vertical amplitude function β_y^* of 0.1 m. The four long insertions provide half the luminosity with twice the free space and β_y^* of 0.2.

The regular arcs determine the emittance of the beams which must be optimized so that the nominal luminosity can be obtained without exceeding the canonical value of the linear tune-shift $\Delta Q \leq 0.06$. This is described in the next section.

3. Beam Emittance

It is instructive to derive the expressions even though they are incorporated in the DESIGN[16] program written by E. Keil and are well known among the experts[6].

The luminosity for head-on collisions is given by[17]

$$\mathcal{L} = \frac{N^2 f}{4\pi\, k_b\, \sigma_x^*\, \sigma_y^*} \tag{1}$$

where N is the total number of particles per beam, f is the revolution frequency, k_b is the number of bunches per beam and σ_x^* and σ_y^* are the horizontal and vertical beam radii at the interaction point. The beam-beam tune shifts in the two planes are given by[17]

$$\Delta Q_x = \frac{N\, r_e\, \beta_x^*}{2\pi\, k_b (\sigma_x^* + \sigma_y^*)\sigma_x} \tag{2}$$

$$\Delta Q_y = \frac{N\, r_e\, \beta_y^*}{2\pi\, k_b (\sigma_x^* + \sigma_y^*)\sigma_y^*} \quad . \tag{3}$$

Equating the two tune shifts gives the well-known result

$$\frac{\sigma_y^*}{\sigma_x^*} = \frac{\beta_y^*}{\beta_x^*} \tag{4}$$

and

$$\Delta Q_x = \Delta Q_y = Q = \frac{N\, r_e}{2\pi\, k_b\, \gamma}\ \frac{\beta_x^*}{\sigma_x^*\ (1 + \beta_y^*/\beta_x^*)} \quad . \tag{5}$$

In an electron machine the uncoupled horizontal emittance E_{xo} is the important quantity and always equals the sum of the coupled emittances in the two planes. It is defined as

$$E_{xo} = \frac{\sigma^*_{xo}}{\beta^*_x} = \frac{\sigma^{*2}_x}{\beta^*_x} + \frac{\sigma^{*2}_y}{\beta^*_y} \tag{6}$$

in the case of zero dispersion at the crossing point. Substituting equation (4) into equation (6) gives

$$E_{xo} = \frac{\sigma^*_x}{\beta^*_x}\left(1 + \frac{\beta^*_y}{\beta^*_x}\right) \tag{7}$$

and putting this into equation (5) leads to the simple expression

$$\Delta Q = \frac{N\, r_e}{2\pi\, k_b\, \gamma\, E_{xo}} \quad . \tag{8}$$

This implies that for a given number of particles, energy and ΔQ the required uncoupled emittance is independent of the coupling[18]. Substituting equation (7) into equation (1) gives

$$L = \frac{N^2 f}{4\pi\, k_b\, E_{xo}} \left[\frac{1}{\beta^*_x} + \frac{1}{\beta^*_y}\right] \tag{9}$$

and eliminating N between equations (8) and (9) gives the required uncoupled emittance in terms of the design parameters

$$E_{xo} = \frac{L\, r_e^2}{\pi\, k_b\, f\, \gamma^2\, \Delta Q^2} \left[\frac{1}{\beta^*_x} + \frac{1}{\beta^*_y}\right]^{-1} \quad . \tag{10}$$

Note that if the machine circumference is scaled approximately as γ^2 all other parameters remaining the same, then the uncoupled emittances are similar and the aperture is only changed if the amplitude functions are different.

For LEP Version 8 $E_{xo} = 6.88\times10^{-8}\ \pi$ m compared with $6.78\times10^{-8}\ \pi$ m in the Blue Book[13].

4. Lattice Periods and Tune

The uncoupled emittance is related to the machine tune in the regular arcs Q_A and approximately[17)]

$$E_{xo} \approx C_q \frac{R}{\rho} \frac{\gamma^2}{Q_A{}^3} \tag{11}$$

where $C_q = 3.84\times10^{-13}$ m and R is the average machine radius in the arcs. In a large machine like LEP the ratio of the bending radius ρ to R is about 0.85. Substituting the emittance from equation (10) into equation (11) gives an upper limit to Q_A of 55.38.

It will be assumed that the phase advance per period $\mu = \pi/3$ as in the Blue Book so the number of periods should be less than $6Q_A$, i.e. ≤ 326. Since the machine has eightfold symmetry the number of periods is taken as 320. The period length is now defined from the average radius in the arcs as $L_p = 78.68$ m compared with the Blue Book value of 53.0 m.

The quadrupole strength can now be calculated from simple thin lens formulae[19)]

$$\delta = KL_Q = \frac{4}{L_p} \sin \frac{\mu}{2} \tag{12}$$

Choosing the length of the quadrupole to be about the same as in the Blue Book gives a gradient of about two thirds the Blue Book value. This should give adequate margin to reach the higher energies required in LEP Version 8.

The bending length per period is about 0.85 L_p, i.e. 66.9 m. The most plausible distribution is to have three double-core magnets per half period, each $\sim$11.2 m long.

Sextupoles will be required next to each quadrupole as in the Blue Book. However, in order to ensure that the lattice is correctable at the top energy they should be somewhat longer. Since the high energy optics have not yet been studied, the sextupole length is chosen arbitrarily and may require modification later.

5) Dispersion Suppressors

It has been demonstrated that dispersion suppressors can be designed with no unnecessary straight sections and no additional aperture requirements[14). The trick is to reduce the period length in this region compared to the regular lattice. In the present case, an obvious first choice is to assume six half-periods, each with only two double-core magnets (with the same field as in the lattice) and with the quadrupole strengths individually variable. A short straight section is introduced for the wiggler magnets. It is situated next to the D (horizontally defocussing) quadrupole nearest to the regular lattice where the dispersion is still large. The reasons for this choice are the same as given in the Blue Book. It was quickly verified with the AGS[20) program that this arrangement provided an effective suppressor and was therefore adopted.

The lattice arcs are now more or less determined: 36 regular lattice periods each with six double-core dipoles and on either end three dispersion suppressor cells each with four double-core dipoles (the total length and bending is then equivalent to 40 lattice periods). Finally, a half period is added either end with two weak (10% field) double-core magnets to reduce the synchrotron radiation background reaching the detectors in the insertion.

Since the insertions are about 4 km apart it is not economic to carry the excitation current for the special quadrupoles through the tunnel. The preferred arrangement is to have the power supplies for each insertion (and dispersion suppressor) in the auxiliary building near each access shaft and control them remotely by computer. This allows the quadrupoles in each insertion to be excited differently with practically no additional complexity. Use will be made of this feature in the machine optics.

6. Straight Sections

The period length in the RF straight section has already been fixed as $2 \times 28\lambda = 47.50667$ m. Using the dispersion suppressor to match from the regular lattice into this section gave an approximate phase advance per period of 55°. The betatron envelope functions and hence the beam size are therefore smaller than in the arcs and indeed are rather similar to the Blue Book values. The RF cavity design therefore requires no change except a trivial scaling to the new frequency (353.39 MHz).

The quadrupole strengths in this region are stronger than in the lattice in the standard configuration. However, the phase advance per cell in the straight section is not required to change at high energies (unlike the lattice in the arcs) and the same quadrupoles (physically) may be suitable.

The insertions were matched to this lattice with little difficulty. For reasons explained below (section 8) the matching of the long insertion was altered (outside the ±10 m free space) so that it resembled the 5 m insertion - indeed only the low beta quadrupoles are changed in position.

An important feature is that the outermost 25 m of the insertion have identical envelope functions to the immediately adjacent RF straight section (since the last quadrupole has the standard strength the beam does not 'know' that it is not in the lattice until it finds the next quadrupole missing). This space is therefore to be used as the reserve straight section space. Extra RF cavities (and their associated klystrons) could be mounted here if storage cavities do not prove feasible. Alternatively, superconducting cavities could also be installed here to give a flying start to the superconducting improvement program. The position, far from the synchrotron radiation in the arcs, would be a distinct advantage in the latter case.

7. Machine Tune[21)]

It is assumed that LEP has essentially eightfold symmetry (the difference between the two insertion types will perturb this slightly). The structure resonances of a machine with eight superperiods are shown schematically in Fig. 1. There are six regions of width at least ± ¼ which are completely free of resonances up to sixth order.

A)	$8n$	$<$	Q	$<$	$8n + 1.33$
B)	$8n + 2$	$<$	Q	$<$	$8n + 2.66$
C)	$8n + 3.2$	$<$	Q	$<$	$8n + 4$
D)	$8n + 4$	$<$	Q	$<$	$8n + 4.8$
E)	$8n + 5.33$	$<$	Q	$<$	$8n + 6$
F)	$8n + 6.66$	$<$	Q	$<$	$8(n + 1)$

There are half integral stop bands caused by the beam-beam tune shift just below tunes $Q = 4n$. Its width is given by[22)]

$$\delta Q = \frac{S}{\pi} \tan^{-1} (2\pi\Delta Q) \qquad (13)$$

where $S = 8$ is the number of superperiods. For $\Delta Q = 0.06$, as assumed, the permissible working range is

$$4n < Q < 4n + 3.08$$

which excludes regions C and F.

Regions A and D are rather close to strong resonances of low order and for this reason were avoided in the previous LEP versions. However, there is theoretical[22)] and experimental[23),24),25)] evidence that higher luminosity can be obtained if the phase shift per insertion is just above a multiple of a half integer, i.e.

$$Q = 4n + \delta \tag{14}$$

with δ small. This would tend to favour regions A and D.

There are other effects which are influenced by the choice of the tune. Coherent beam break-up due to the dipole component of beam-beam effect[26)] would be minimized in regions A and D. On the other hand, the excitation of synchro-betatron resonances by (accidental) dispersion in the cavities[27)] is weakest in regions C and F. It is hoped that a detailed examination of lattices with different Q values but otherwise similar characteristics will help to establish a clear preference between the possible regions.

8. Phase Advances

The lattice octant comprises three separate regions: the short insertion including the adjacent RF straight section and dispersion suppressor; the regular arc consisting of 36 cells and 72 sextupoles; the long insertion including the adjacent RF straight section and dispersion suppressor. The flexibility of the lattice allows the phase advances across these three sections to be independently variable subject to the constraint imposed by the machine tune.

The degree to which the chromatic defects of a storage ring can be corrected must be strongly influenced by the design of the linear lattice. Unfortunately no coherent recipe has yet been proposed which ensures that the lattice is well and easily correctable. Since the lattice of LEP Version 8 is so flexible it seems an ideal test-bed for trying out various configurations in the hope of establishing some basic rules. A priori, a rather arbitrary series of assumptions must be made to obtain what will be called the nominal configuration. Over the coming months other lattices will be prepared which violate one (and ideally only one) of each of the assumptions. It is hoped that this methodical procedure will result in a clearer understanding of the factors affecting the 'correctability' of a lattice and a reliable procedure for choosing a 'good' lattice.

The assumptions made for the 'nominal' lattice are as follows:

(a) It is assumed that the vertical and horizontal phases across half the insertion should differ by $\pi/2$. This arises out of some unpublished work by Montague and Zyngier. They tracked chromatic defects from the centre of an insertion to the regular lattice and found that if the phases in the two planes differed by $\pi/2$ at the first sextupole it would have a beneficial effect on both planes. The total sextupole strength should then be much reduced since sextupoles are not 'fighting' each other. It is for this reason that the old long insertion (phase difference $\sim\pi$[13]) was rematched so it resembles the short insertion (phase difference $\sim\pi/2$).

A consequence of this is that the total tune split is about 4 (with equal vertical and horizontal phase advances in the arcs) so that the tunes will either be in regions A and D or B and E.

(b) It is assumed that the phase advance per cell should be an exact rational fraction of π - in the optics for the design energy it is $\pi/3$. This contrasts with the Blue Book where in the vertical plane the phase advance was 62°.

(c) It is assumed that every sextupole has an equivalent sextupole (both in strength and local beta value) at exactly an odd number of half wavelengths away[28]. This compensation should avoid resonance excitation. In the nominal lattice this is achieved with six families of sextupoles assigned sequentially along the lattice. Local correction near the insertion would not necessarily be excluded by this assumption however.

(d) It is assumed that the arcs are symmetrically placed between insertions in phase as well as geometrically. Since the insertions themselves are not identical this means that the quadrupoles strengths in the RF straight sections and the dispersion suppressors will not be identical in the two insertions.

9. Detailed Layout and Betatron Matching

All the elements are now available to put the ring together and match the betatron functions[20]. All the lengths are adjusted to give the correct circumference and particularly in the insertions the quadrupole positions are carefully chosen to ensure that the minimum beta values at the crossing point can be varied over a reasonable range.

The final layout of the lattice periods and dispersion suppressors is shown in Fig. 2. The total length of the lattice period is 79 m and the bending length per period 69.48 m giving a filling factor of 0.88. Most distances between magnetic elements are identical to the Blue Book; the most notable exception is a reduction from 50 cm to 30 cm between the double-core dipoles following a detailed study of the vacuum requirements in this region[29]. There are no spaces left for sextupoles in the suppressor region but the use of multipoles there has not been ruled out.

The layout in the RF region is shown in Fig. 3. It is anticipated that some of the waveguide distribution network will be in the klystron tunnel rather than the accelerator tunnel; Fig. 3 shows one possible layout[30]. The arrangement of the vacuum components in this region is still the subject of a detailed study[29]. There is the possibility of a correction magnet in each half cell and there is a synchrotron radiation collimator in the space adjacent to it.

The insertions are ±102.99333 m long so that the first cavity in the RF straight section is 124 wavelengths from the crossing point. Both insertions can be detuned by a factor of at least 3 maintaining the same ratio of β_y^* to β_x^*. The smooth variation of all parameters, i.e. the lack of discontinuities, is shown in Figs. 4, 5 and 6.

The tune values adopted for the nominal lattice are $Q_x = 72.3$, $Q_y = 76.2$. The betatron matching of the long and short insertions is shown in Figs. 7 and 8; the similarity between the two is obvious.

10. Flexibility

It is perhaps worth enumerating the features of the lattice which can be varied easily:

(a) the beta values in the crossing points in both insertions,

(b) the phase advance from the centre of the insertion to the regular arcs - both planes independent in both insertions,

(c) the phase advance per cell in the regular arcs in both planes.

The last point is important for the high energy optics but at present a detailed lattice arrangement has not been worked out since it is not yet clear what constitutes a 'good' phase advance.

11. Conclusions

A lattice is presented which confirms the expected performance[2]. It is very flexible and will enable a systematic study of the influence of the linear lattice on chromatic correction to be carried out. A detailed parameter list of the lattice has been prepared as a companion note[31].

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TABLE 1

MAIN PARAMETERS OF LEP VERSION 8

	32 MW	64 MW	96 MW	
Klystrons per station	2	4	6	
Total klystrons	32	64	96	
RF cavity length	542.93	1085.87	1628.8	m
Circumference	30607.32	30607.32	30607.32	m
Fundamental RF cells	760.11	1520.22	2280.32	m
3rd harmonic cells	760.11	760.11	760.11	m
Empty reserve cells	1900.27	1140.16	380.5	m
Insertions	1628.80	1628.80	1628.80	m
Weak bends	380.05	380.05	380.05	m
Normal arcs	25177.98	25177.98	25177.98	m
Bending radius	3406.12	3406.12	3406.12	m
Parasitic imped. RF	6.5	13.0	19.5	GΩ
Parasitic imped. chamber	8.9	8.9	8.9	GΩ
Parasitic imped. total	15.4	21.9	28.4	GΩ
Energy at max. luminosity	59.02	72.35	80.82/85*	GeV
Current at max. luminosity	9.13	9.13	9.13	mA
Max. luminosity	0.73×10^{32}	0.90×10^{32}	1.0×10^{32}	$cm^{-2}s^{-1}$
Synchrotron radiation	5.76	13.00	20.24	MW
Higher mode losses	2.57	3.65	4.73	MW
Cavity dissipation	21.26	42.54	63.81	MW
Cavity input power	29.59	59.19	88.78	MW

STAGE II

Max. energy at 3 MeV/m	116.45	GeV
Luminosity at max. energy	1.0×10^{32}	$cm^{-2}s^{-1}$
Max. energy at RF power limit	130	GeV
Gradient at RF power limit	5	MeV/m

* with storage cavities (or else 16 MW extra RF power)

FIGURE CAPTIONS

1) Structure resonances for a machine with eight superperiods

2) Detailed mechanical layout of the lattice period and dispersion suppressor period

3) Layout of half a period in the RF straight section

4) Variation of quadrupole strengths in the long insertion during detuning

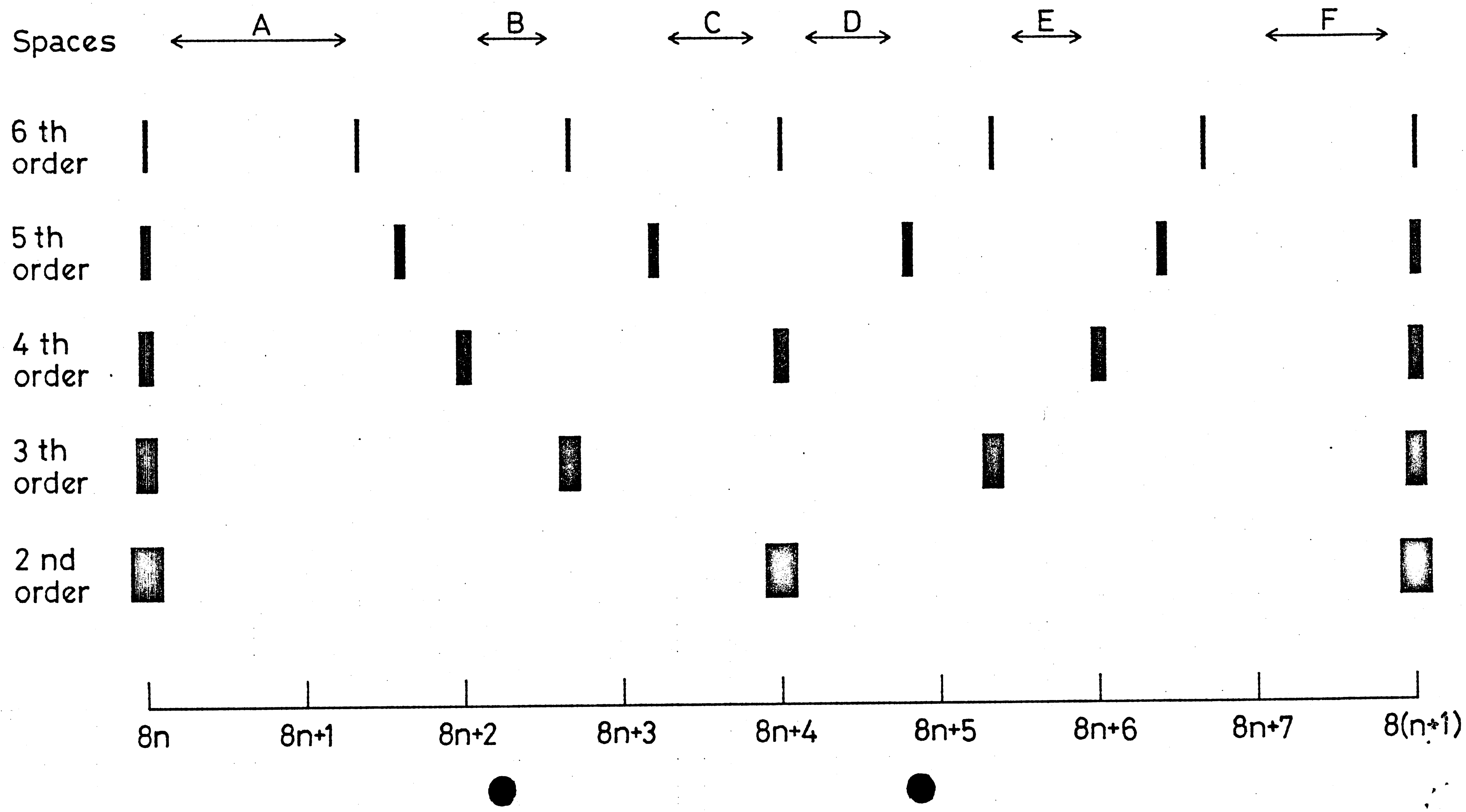
5) Variation of quadrupole strengths in the short insertion during detuning

6) Variation of the phase shift across insertions during detuning

7) Betatron functions in the long insertion and dispersion suppressor

8) Betatron functions in the short insertion and dispersion suppressor

FIG. 1 : STRUCTURE RESONANCES FOR A MACHINE WITH 8 SUPERPERIODS



LEP, Version 8: RF System

PLAN VIEW OF TUNNELS.

Figure 3.

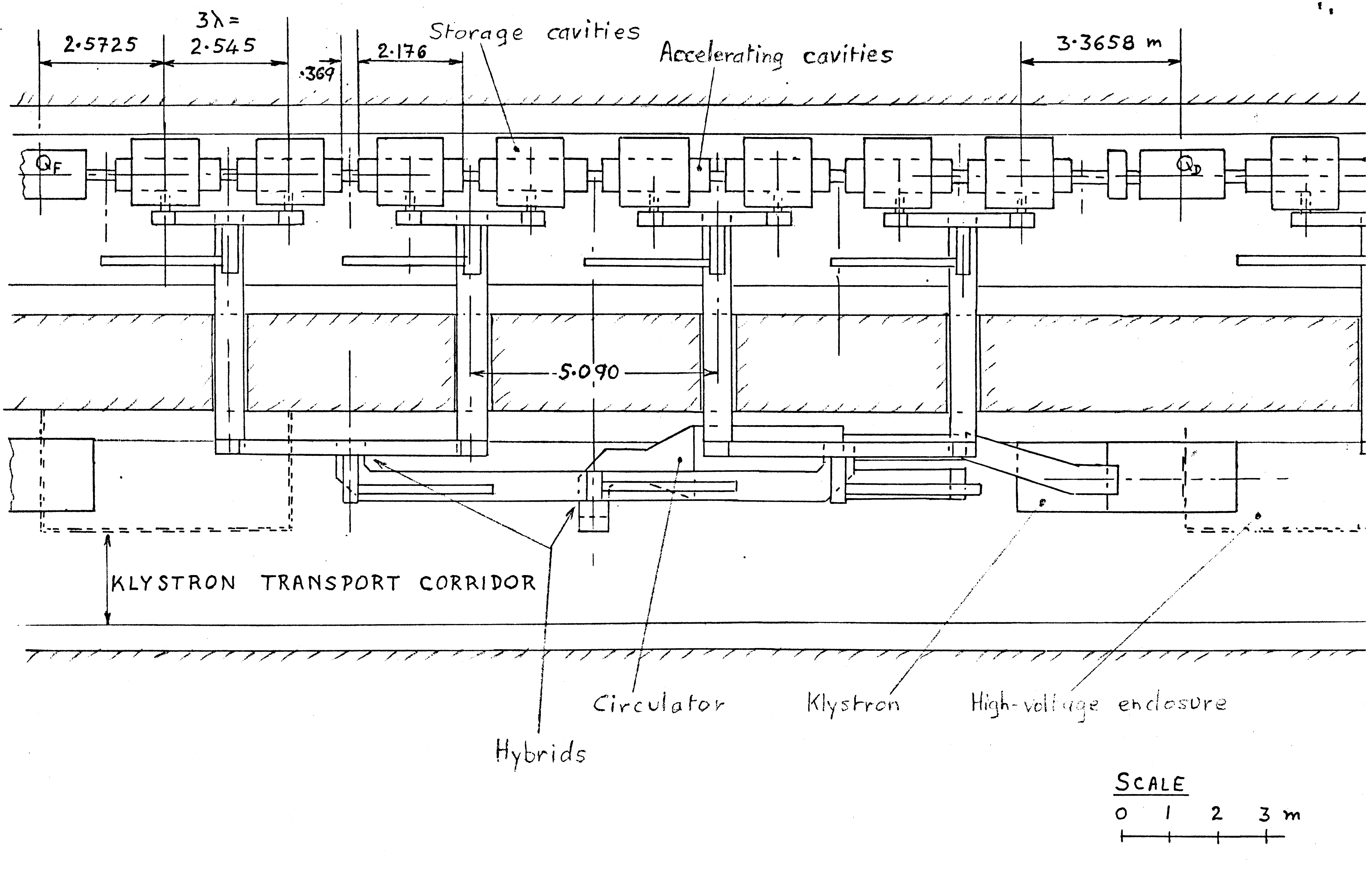


Fig.4 LONG INSERTION

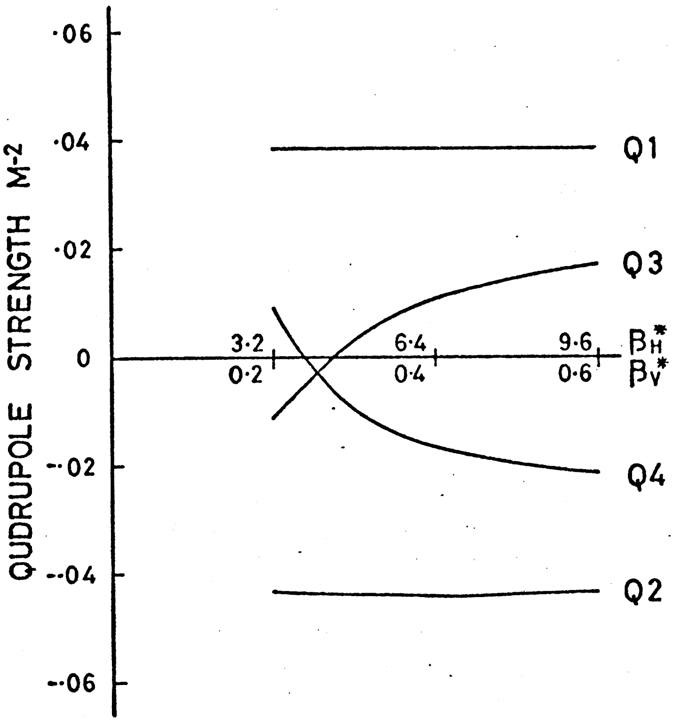
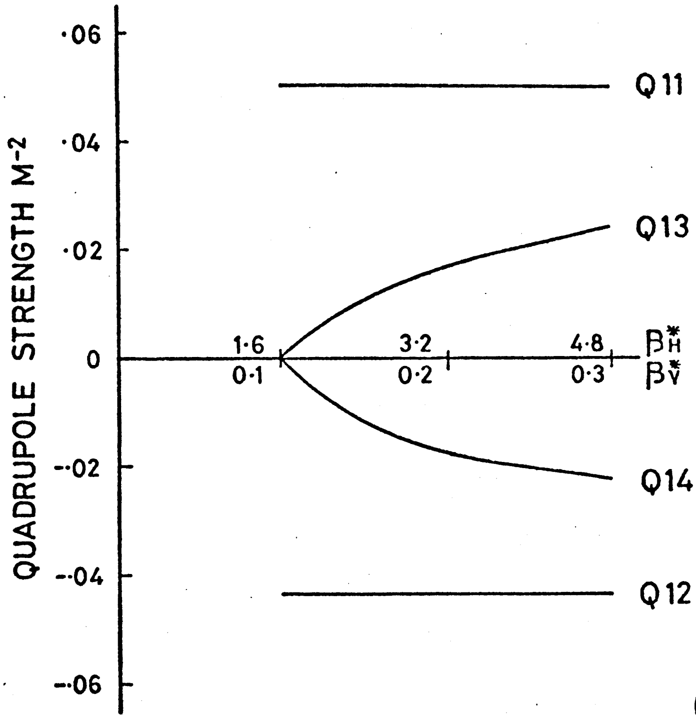
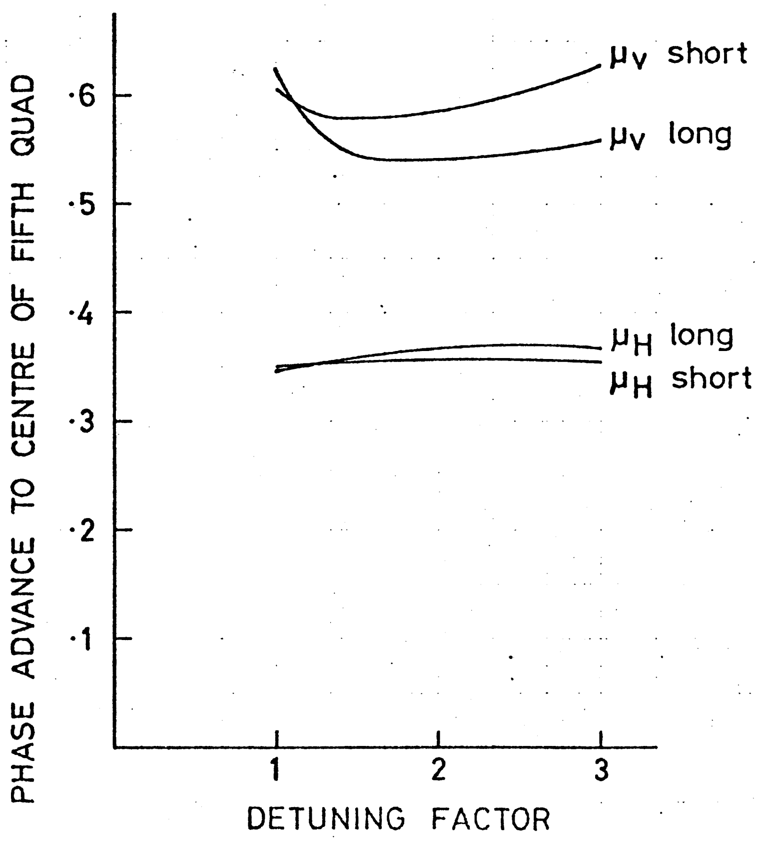


Fig. 5 SHORT INSERTION



VARIATION OF THE QUADRUPOLE STRENGTHS DURING DETUNING

FIG. 6 : VARIATION OF THE PHASE SHIFT ACCROSS INSERTIONS DURING DETUNING



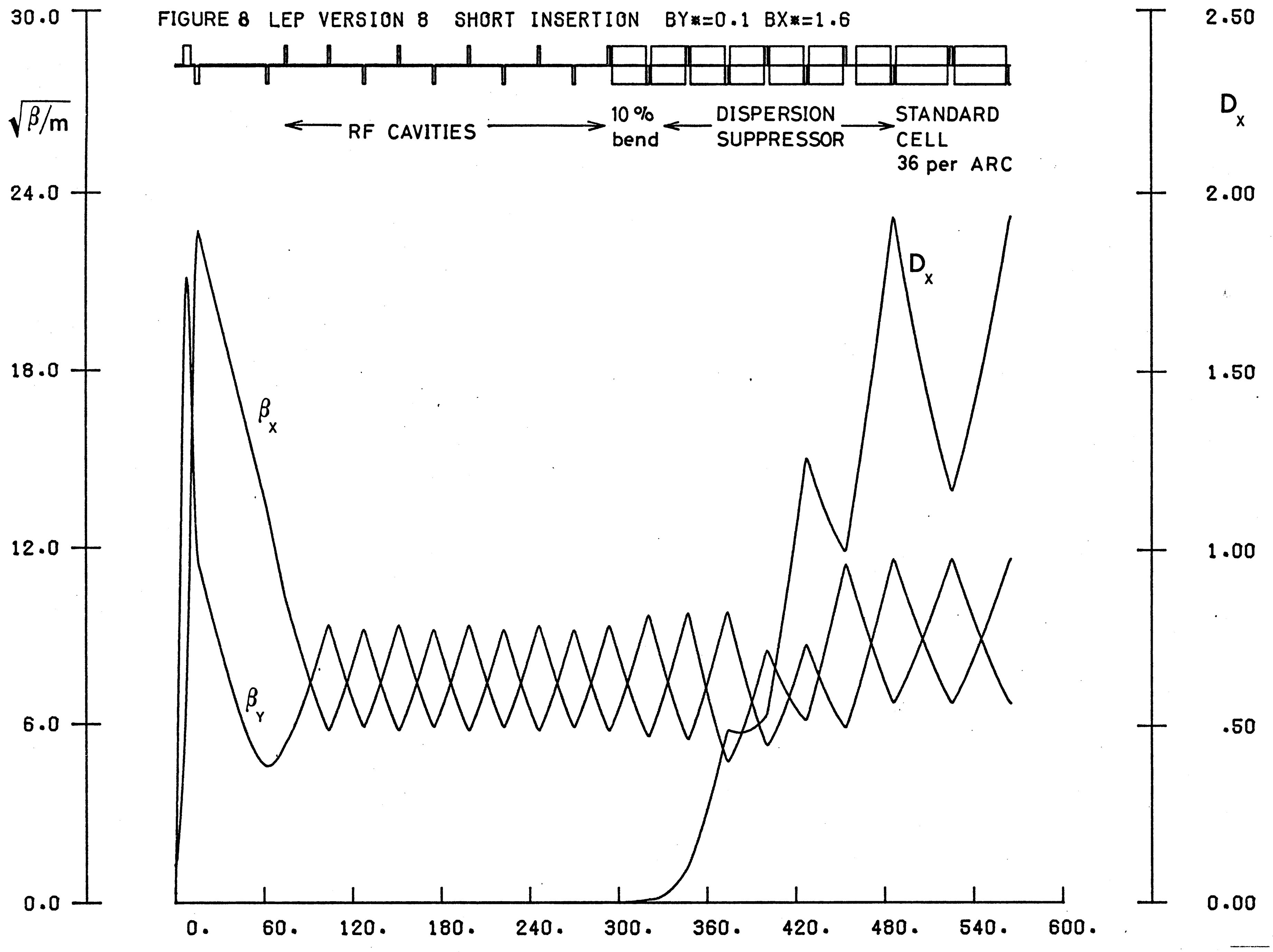
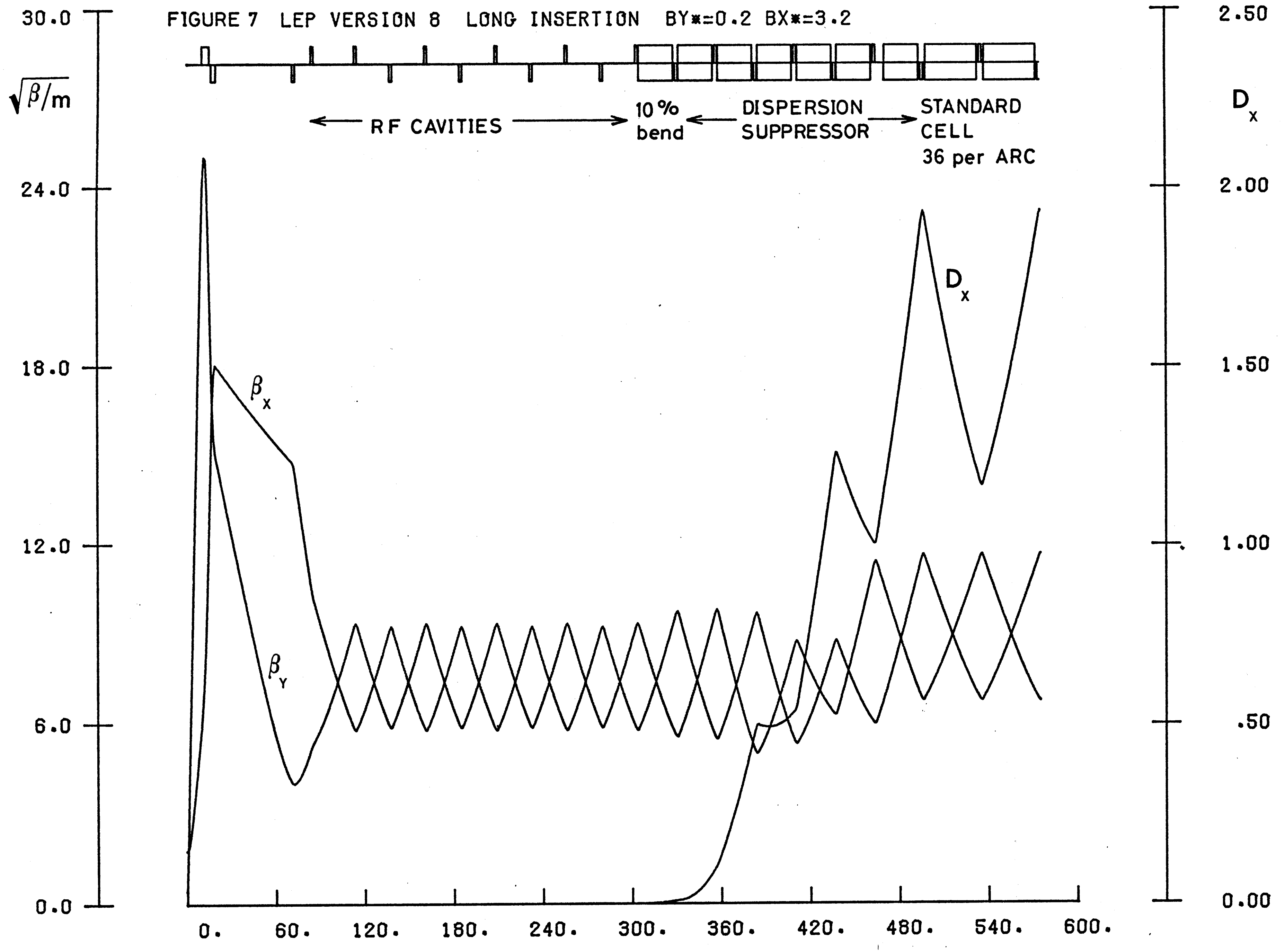
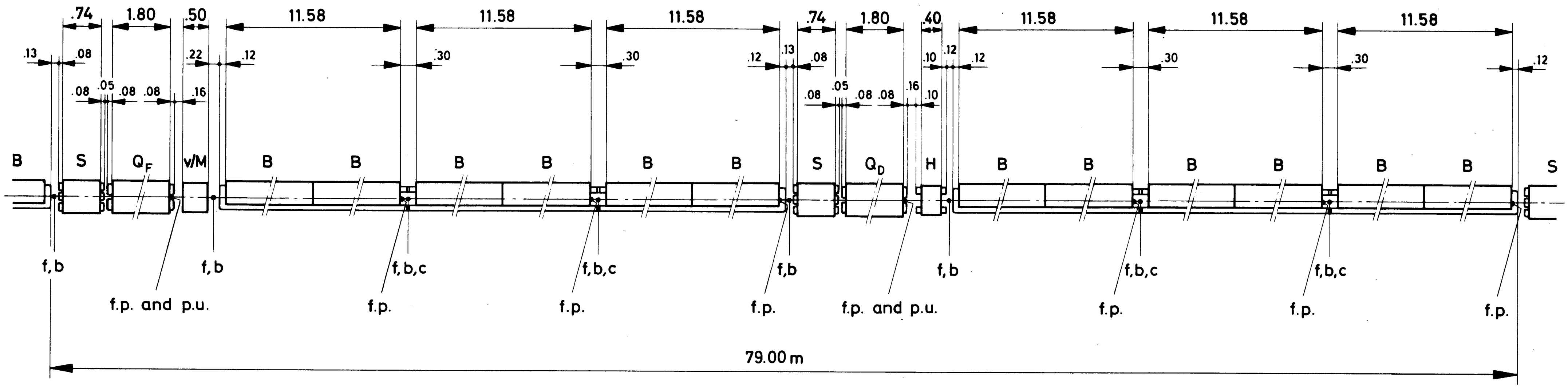


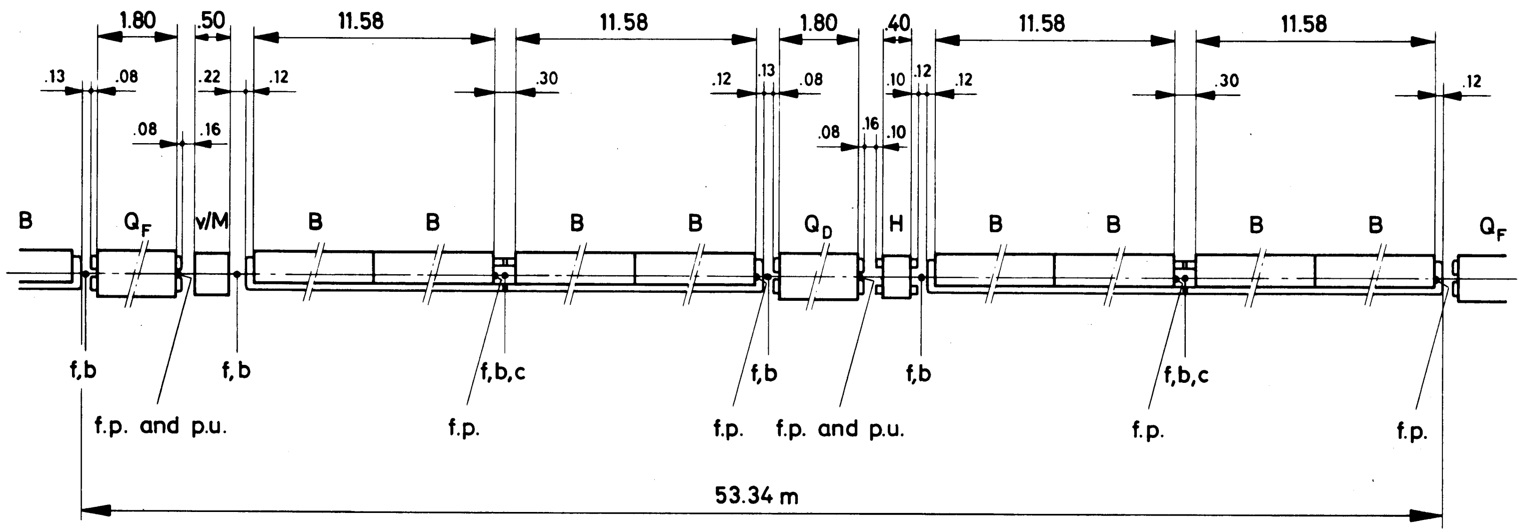
FIGURE 8 LEP VERSION 8 SHORT INSERTION BY*=0.1 BX*=1.6
30.0
24.0
18.0
12.0
6.0
0.0
$\sqrt{\beta/m}$
RF CAVITIES
10 %
bend
DISPERSION
SUPPRESSOR
STANDARD
CELL
36 per ARC
β_x
β_y
D_x
0.
60.
120.
180.
240.
300.
360.
420.
480.
540.
600.
2.50
2.00
1.50
1.00
.50
0.00

FIGURE 7 LEP VERSION 8 LONG INSERTION BY*=0.2 BX*=3.2





STANDARD CELL



DISPERSION SUPPRESSOR CELL

B - bending magnet
Q_F, Q_D - quadrupoles
S - sextupole
H - horizontal-field dipole
M - multipole

f - flange
b - bellows
c - connections
f.p. - fixed point
p.u. - pick-up
v - valve

LEP VERSION 8

16.11.1978 / Fi.