IMPROVEMENTS TO THE LEP LATTICE DESIGN

by

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Presented at 12th International Conference on High-Energy Accelerators
Fermi National Accelerator Laboratory, Batavia, IL, August 11-16, 1983

Geneva, Switzerland
August 1983
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Summary
The design principles of the latest layout of the LEP lattice are presented. The 4 experimental insertions have \( 3.5 \) m free space, \( a^* = 7 \) cm and the most quadrupole on either side is superconducting. \( a^* \) is chosen to be 1.75 m (25 \( \beta^* \)) to minimize the aperture of the insertion quadrupoles and to reduce the chromatic aberrations. Back-up quadrupoles are provided for the machine to be operated if the superconducting quadrupoles in an insertion are not available; this back-up solution has a similar layout to that of the 4 non-experimental insertions. A new arrangement in the dispersion suppressor region gives greater flexibility in the choice of working point for the two nominal values of the phase advance per period, in the bending arcs (60° and 90°). Another advantage is that the beta functions in the RF cavities are reduced by this compared to the previous version, increasing the threshold for the transverse mode-coupling instability.

Introduction
Since the publication of the last design study\(^1\), extensive modifications have been made to the experimental insertions and the dispersion suppressors. This paper describes the reasons for these changes and the principles underlying the new layout. This version of LEP is the first to incorporate superconducting low-beta quadrupoles. An improved performance insertion was first requested at the ECF conference \(^2\) at Villars, the basic idea being to reduce the free space. This meant that the horizontal beta function at the interaction point \( \beta^* \) proportionally. The mutual interference between innermost quadrupoles and the experimental detectors, together with the necessary increase in integrated gradient, led inevitably to the adoption of iron-free superconducting magnets. Having confined\(^3\) that the choice of \( 3.5 \) m free space was indeed a reasonable compromise, it was noticed that the horizontal beta function at the crossing point \( \beta^* \) has an important influence on the insertion characteristics, and that a modest increase could lead both to an improvement in performance, by reducing horizontal chromaticity, and a reduction in cost due to smaller apertures.

The insertion studies led to a re-evaluation of the dispersion suppressor. The initial LEP proposals\(^4\) incorporated dispersion suppressors based on the missing magnet principle. But this layout only works for one fixed machine tune, and for subsequent versions of LEP it was modified by decreasing the quadrupole spacing in the dispersion suppressor regions, and by varying the quadrupole strengths\(^5\). More recently, however, the length of the dispersion suppressor was reduced from seven to five half-cells, with a corresponding decrease in the number of variables, in order to make space for more sextupoles to try to improve the chromaticity correction associated with the favoured high-tune machine \( (90^\circ \) phase advance per period in main arcs). It was found that for a machine having 60° phase advance this scheme was not sufficiently flexible in that the tune could only be varied by about \( \pm 1 \) unit, instead of a desirable \( \pm 2 \) units. The problem was traced to the dispersion suppressor, which had to be extended into the main arc.

Several complete lattices have been matched to tune values similar to those of the previous versions, and it has been demonstrated that the chromatic aberrations of this new lattice are well correctable.

Brief Description of the Lattice
LEP uses a separated function F000 lattice. Eight arcs are joined by dispersion suppressors, straight (RF) sections, and matched insertions, reflected about the eight crossing points. Machine operation with a phase advance of 60° or 90° per period in the arcs is foreseen and following this study there are 31 periods, each of length 79 m, per arc. The arc cells have not been changed, and the approximate values of the structure constants are given in Table I.

<table>
<thead>
<tr>
<th>Phase advance</th>
<th>60°</th>
<th>90°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadrupole</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \beta_\mu/m )</td>
<td>135</td>
<td>135</td>
</tr>
<tr>
<td>( \beta_\rho/m )</td>
<td>46</td>
<td>46</td>
</tr>
<tr>
<td>( \delta_\rho/m )</td>
<td>2.2</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Physically the arc quadrupoles are all of the same type (MQ). The quadrupoles in the straight sections and the dispersion suppressors are stronger than those of the main arcs but they are also all of the same type (MQA), as established previously. In phase 1 LEP will be operated up to about 60 GeV.

Insertions
In the first LEP proposal\(^5\) all eight insertions were identical and had a free space of \( \pm 10 \) m. In order to better satisfy the user requirements, the later versions of LEP\(^1\) provided two different insertion types: \( \pm 5 \) m free space with \( \beta^* = 0.1 \) m and \( \pm 10 \) m free space with \( \beta^* = 0.2 \) m. Because of the sensitivity of the closed orbit to the positioning of the insertion quadrupoles, the insertions are designed to allow continuous detuning, increasing the values of \( \beta^* \) by up to a factor of three to reduce the peak values of \( \beta \) in the quadrupoles, maintaining the phase across the insertion constant.

Both insertion types have since been modified. It was decided for funding reasons to equip only 4 experimental areas, and the long experimental insertions were therefore replaced by relatively high-beta long non-experimental insertions\(^6\) using standard machine quadrupoles. This type of insertion is maintained but the free space is slightly modified.

Following the request from the users\(^2\) for better performance low-beta insertions for the 4 experimental areas, a detailed study was made on how the insertion parameters depend on the free space, taking into account the limitations of proven magnet technology. In the case of LEP phase 1 it was found that whereas the lower limit for the free space was about \( \pm 2.5 \) m, the improvement in machine performance in going from \( \pm 3.5 \) m to \( \pm 2.5 \) m was marginal, and the interference with the experiments increased rapidly. It was therefore decided to adopt the value of \( \pm 3.5 \) m with a corresponding value of \( \beta^* = 0.07 \) m.

For all previous insertions the ratio of beta values at the crossing point was chosen to be 16. This ratio gave roughly equal maximum values of the beta function in the two planes. However, the naturally circular aperture of the superconducting quadrupole can be used to best advantage if the beta ratio is chosen such that horizontal and vertical aperture requirements are made equal. The vertical aperture is calculated to match the vertical acceptance of the arcs, while the horizontal aperture is determined by synchrotron
radiation background, itself a function of the horizontal emittance. The ideal beta ratio lies between 25 and 35 depending on the horizontal emittance assumed.

If the machine is operated at the same beam-beam limit in both planes, the maximum luminosity is obtained when the ratio of the horizontal to vertical emittance is equal to the ratio of horizontal to vertical beta function at the crossing point. Simulation of the closed orbit correction system on previous versions of LEP showed that an emittance ratio of 16 was almost always possible but was near the limit. After further study it was however agreed that one could adopt the beta ratio of 25 as the standard value, giving a horizontal beta value of 1.75 m.

The last requirement was to ensure that a valid low-beta scheme (the back-up insertion) can be provided when the superconducting quadrupoles are not active. This requirement was also considered in the parameter study and resolved by adding conventional quadrupoles on either side of the insertions. In the back-up configuration the second quadrupole of the mini-beta doublet is reversed in polarity and the third quadrupole provides horizontal focusing.

For the purposes of matching, which was done using the AGS program, the distance from the crossing point to the magnetic end of the superconducting quadrupole was taken to be 3.7 m (3.5 m physical free space + 0.2 m for the cryostat end), and leaving 9.2 m to the face of the second quadrupole to permit opening of the end-caps of the machine without having to dismantle machine components. As aperture requirements using the new beta ratio were similar to those offered by the standard lattice quadrupoles, it was decided to evaluate an insertion using these quadrupoles and, in addition, to make the physical layout of the back-up scheme and the long insertion identical, as shown in Fig. 1. The essential parameters of the insertions thus obtained are summarized in Table 1.

![Image of Fig. 1](image-url)

**Fig. 1: Insertion layout**

**Table 1: Preliminary insertion parameters**

<table>
<thead>
<tr>
<th>Insertion</th>
<th>$\beta$ range at I.P.</th>
<th>Quad.</th>
<th>QSC</th>
<th>QS2</th>
<th>QSBU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low beta</td>
<td>$\beta_z/m$ min 0.07</td>
<td>0.162</td>
<td>-0.035</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\beta_z/m$ max 0.21</td>
<td>289</td>
<td>131</td>
<td>62</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\beta_x/m$ min 1.75</td>
<td>33</td>
<td>310</td>
<td>297</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\beta_x/m$ max 5.25</td>
<td>11</td>
<td>103</td>
<td>99</td>
<td></td>
</tr>
<tr>
<td>Back-up</td>
<td>$\beta_v/m$ min 0.2</td>
<td>163</td>
<td>530</td>
<td>291</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\beta_v/m$ max 0.6</td>
<td>54</td>
<td>177</td>
<td>97</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\beta_s/m$ min 5.0</td>
<td>14</td>
<td>92</td>
<td>239</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\beta_s/m$ max 15.0</td>
<td>4</td>
<td>17</td>
<td>77</td>
<td></td>
</tr>
<tr>
<td>Long</td>
<td>$\beta_v/m$ 0.7</td>
<td>(0.12)</td>
<td>154</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\beta_s/m$ 17.5</td>
<td>56</td>
<td>145</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The Dispersion Suppressor

The conditions that are imposed on the dispersion suppressor are rather stringent. Starting from the main arcs where the lattice functions ($\beta_y, \beta_z, \delta_y$) repeat regularly with the lattice periodicity, the dispersion and the dispersion slope must be brought to zero (two constraints), and the vertical and horizontal beta functions and their slopes must be matched to the values in the straight section (four constraints). Thus a minimum of six variable quadrupoles are required to satisfy the constraints. If the dispersion suppressor is to work over a range of phase advances in the arcs and phase advances in the RF straight sections then six variables may not suffice. In the initial study, seven variable quadrupoles were used to cover lattice phase advances of 60°, 72°, 90°, 105° and 119° for a fixed 49° phase advance in the straight section. The layout described in the Pink Book closely followed this design (see Fig. 2) but for 60° in the arcs only 6 variable quadrupoles were employed.

![Image of Fig. 2](image-url)

**Fig. 2: Evolution of dispersion suppressor layout**

Following the acceptance of the high tune proposal’s layout was sought which was optimized for 60° phase advance, and this was maintained in Version II (the first LEP with a circumference of 26.6 km). The chromaticity correction was considered as the major problem to be resolved with this lattice, and the dispersion suppressor was shortened from 7 to 5 half-cells in order to minimize the number of sextupole locations. This layout, which is shown in Fig. 2(II) only permits a maximum of six variable quadrupoles, and though flexible for the 90° lattice was much less satisfactory when the arcs were tuned to 60° phase advance. Moreover, because of difficulties with the chromaticity correction of the 90° lattice, it was proposed to use 60° for LEP phase I.

Symptomatic of the problem of the 60° lattice when used with the 5 half-cell dispersion suppressor was a high local peak value of $\beta_y$ (~160 m), and high peak values of $\beta_y$ (~125 m compared to ~80 m for the 90° lattice) in the RF cavity region. Considerable insight into the focusing conditions in the straight section can be gained by examining the Courant and Snyder necktie diagram as shown in Fig. 3. With the five half-cell dispersion suppressor the focusing conditions of the 90° lattice are represented by a point at the centre of the necktie, but the point corresponding to the 60° lattice falls into the narrow part. This means any attempt to make small changes to the focusing conditions results in beta values which are even larger than in the nominal condition. Thus the region which should act as the phase 'trombone' to provide changes in machine tune is effectively blocked.

When it was found to be impossible to move the working point in the straight section towards the centre of the necktie, a new dispersion suppressor was sought. The problem was highly constrained: no major
The Courant and Snyder necktie diagram

Fig. 3 The Courant and Snyder necktie diagram

geometry change (e.g. machine radius changes greater than 1 m) could be tolerated, and the number of dipoles was fixed. It was therefore decided to increase the length of the dispersion suppressor at the expense of the regular arcs in order to increase the number of variable quadrupoles. The layout which was found is shown in Fig. 2(ii).

The basic idea is to split up a standard half-period consisting of three pairs of dipole cores and to insert one quadrupole. The addition of this quadrupole into the FODO lattice causes a problem with the polarity. Either the polarity of the quadrupoles in the arc must be changed or the polarity in the straight sections inverted[1]. Since the polarity of the insertion doublet cannot be changed there must in the latter case be a pair of adjacent quadrupoles with the same polarity in the region Q3, Q4. Examination of both possible polarities and both 60° and 90° lattices showed that the deficiencies of the previous layout had been corrected. This was done by considering six points spread out over the stable part of the necktie diagram and matching the lattices to each point. It was also verified that the insertions could be matched to each point. The final choice of maintaining the polarities in the arcs was made to satisfy hardware problems. Optimization of the positions of Q3 and Q4 continues[1].

Chromaticity Corrections

Chromaticity corrections have been made using the HARMON program[1] in order to evaluate the strengths of the sextupoles which could fill the 63 available positions in the non-zero dispersion region of each arc. The sextupoles were grouped into 6 families for the 60° lattice and 4 families for the 90° lattice. The dependence of the tunes and of the beta functions in the short and long straight sections on the relative momentum deviation was optimised through a systematic use of weights used in the HARMON program to minimise the chromatic functions[9]. The effect of the corrections was checked using the AGS program[10] with the 60° option for tracking for energy deviations of ±1.8%. The code PATRICIA[10] was then used to define the dynamic acceptance of the corrected lattices. Typical results from AGS tracking are shown in Fig. 4, and are better than all previous versions of LEP.

Fig. 4 Example of chromaticity correction

Conclusions

New insertions have been designed, improving the background conditions, reducing chromaticity and providing a better performance/cost ratio. It has been demonstrated that the new dispersion suppressor gives the full flexibility required. Chromatic errors in the new machine can be well corrected.

References