A Scheme to Improve the Low Energy
Luminosity in LEP¹

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INTRODUCTION

In the design of large electron positron colliding beam facilities, it has become customary to use a certain optimization procedure^(2,3) to establish desired beam performance. The results of this procedure are the minimum requirements in terms of RF-power, bending radius and focusing - e.g. distance of quadrupoles in the arcs - to achieve a desired luminosity, usually $10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$, at a given energy.

This procedure, however, neglects the optimization of the storage ring performance below and above that design energy. Below the design energy the luminosity is optimized by lowering the tune^(2,4) or by use of wiggler magnets⁽⁵⁾. Both methods result in a luminosity scaling like $\mathcal{L} \sim E^2$.

To improve the luminosity expectation above the design energy, the optimized lattice design⁽²³⁾ has to be changed as has been done in the design of PETRA and PEP.^(6,7) In these designs the cell length was chosen to be only half as long as the optimized cell which requires twice as many quadrupoles. With the reduced cell length it is possible to increase the tune of the storage ring by a much larger amount than it would be possible with a larger lattice cell.

1. LEP-Design-Study, CERN/ISR-LEP/78-17.
2. J.R.Rees, B.Richter, PEP Note 69.
3. B.Richter, CERN/ISR-LTD/76-9.
4. H.Wiedemann, PEP Note 58.
5. J.Paterson, J.R.Rees, H.Wiedemann, PEP Note 125.
6. H.Wiedemann, Proc. of 9th Inter. Conf. on High Energy Accel, Stanford, CA 1974.
7. H.Wiedemann, PEP Note 117.

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This increase in tune reduces the beam emittance and increases the luminosity above the design energy where the storage ring performance is limited by the available RF power. With this reduction of the lattice cell lengths the maximum energy capability from the point of view of the lattice design was raised in PETRA and PEP from about 16 to 17 GeV to over 30 GeV⁽⁷⁾ with the luminosity scaling like $\mathcal{L} \propto E^{-3}$. This scaling assumes a constant synchrotron radiation power.

These arrangements for shorter cell length are also valid for the LEP design. In addition, shorter cells in LEP give the possibility of improving the design luminosity below 70 GeV by as much as an order of magnitude. This seems to be an important factor in the design of LEP in view of the many worries about the low luminosity expectations expressed by particle theorists and experimentalists during the LEP Summer Study 1978.

2. Optimization of the Low Energy Luminosity in LEP

Before we discuss the optimization of the low energy luminosity in LEP let us recall the limitations. The luminosity is given by

$$\mathcal{L} = \frac{N}{AB} N f_{\text{rev}} \quad (1)$$

with $N = N^+ = N^-$ the number of particles per beam, $A = 4\pi \sigma_x^* \sigma_y^*$ the beam cross section at the interaction point, B the number of bunches per beam and, f_{rev} the revolution frequency.

The beam intensity is limited by the beam beam limit

$$\Delta Q_y = \frac{2r_e}{\gamma} \frac{N \beta_y^*}{BA} \leq .06 \quad (2)$$

with γ the beam energy, β_y^* the vertical beta function at the interaction point and r_e the classical electron radius. We assume the coupling K is adjusted such that $\Delta Q_x = \Delta Q_y$ which gives $K = \sqrt{\beta_y^* / \beta_x^*}$.

If we now insert Eq.(2) into Eq.(1) and set $A = 4\pi \sigma_x^* \sigma_y^* = 4\pi K/(1+k^2)$.
 $\epsilon_{x0} \sqrt{\beta_x^* \beta_y^*}$ we get

$$\mathcal{L} = \frac{\pi \Delta Q^2 f_{rev}}{r_e^2 \beta_y^* (1+k^2)} \gamma^2 B \epsilon_{x0} \quad (3)$$

Eq.(3) shows us how to maximize the luminosity as long as there is no rf-power limit.

- : β_y^* should be as small as the chromaticity correction system allows it to be. We assume it cannot be made smaller than in the LEP design.
- : B the number of bunches could be increased. This, however, would require separation of the bunches between interaction points and is, therefore, and because of other reasons not popular.
- : ϵ_{x0} the natural beam emittance could be increased. For every factor of 4 increase of ϵ_{x0} , however, the beam size and therefore the magnet apertures would have to be increased by a factor of 2 which is very costly.

The last argument, however, is true only if we stay with the optimized lattice design which usually results in large values of the beta function (in LEP: $\beta_{max} \approx 100m$). For a shorter cell length the maximum beta function can be reduced and for the same aperture the beam emittance and with it the luminosity can be proportionately increased.

We will see that the luminosity can be increased by up to an order of magnitude if we make proper use of the magnet apertures. There will be a problem in the interaction region quadrupoles since here we cannot decrease the betatron function. A solution will be discussed in Section 4.

3. Short Lattice Cell Design for LEP

To design a new lattice for LEP capable of going up to 100 GeV I will use the parameters of the PEP quadrupoles and of the PEP vacuum chamber cross section.

We will use a cell length of 25m as shown in Fig. 1. Shorter cells will very quickly increase the rf-power requirements without giving much benefit in luminosity. The physical dimensions correspond to those in PEP.

Magnetic Length:	Bending Magnet	$L_B = 4.93m$
	Quadrupole	$L_Q = 1.60m$
	Sextupole	$L_S = 0.25m$

$\frac{1}{2}$ CELL LATTICE

Fig. 1

The new bending radius is

$$\rho = 2200m \quad (\text{was } \rho = 2344m)^{(1)},$$

the bending magnet filling factor

$$\eta = 79\% \quad (\text{was } \eta = 85\%)^{(1)},$$

and the energy loss per turn at 70 GeV

$$U = 966 \text{ MeV} \quad (\text{was } U = 906 \text{ MeV})^{(1)}.$$

The inside width of the vacuum chamber is assumed to be $W = 110\text{mm}$. Since the aperture of the quadrupoles is only 100mm $\emptyset$ we have a good field region of $\pm 50\text{mm}$. We will assume that all of this good field region can be occupied by the beam and orbit distortions of more than about $\pm 1\text{mm}$ be corrected before the beams are brought into collision.

Before we discuss the low energy performance we have to make sure we do not jeopardize the high energy performance.

To get the desired luminosity of $\mathcal{L} = 1 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$ at 70 GeV we need a beam emittance of $\epsilon_{x0} = 6.4 \times 10^{-8} \text{ rad m}$.⁽¹⁾ Using the scaling laws for FODO-lattices⁽⁸⁾ we find a quadrupole strength of $K = .023 \text{ m}^{-2}$ or $g = 5.4 \text{ Tesla/m}$ and a maximum beta function of $\hat{\beta}_{\text{cell}} = 68\text{m}$. Both parameters are no problem.

At 100 GeV we would like to get the smallest beam emittance possible. Keeping the synchrotron radiation power between 70 GeV and 100 GeV constant at 20 MW for both beams we reach the beam beam limit at 100 GeV for a beam current of 2.6 mA and an emittance of $\epsilon_{x0} = 1.1 \times 10^{-8} \text{ rad m}$. The luminosity in this case is $\mathcal{L} = 0.36 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$. The quadrupole strength necessary to get this small beam emittance is $g = 17.3 \text{ Tesla/m}$ at 100 GeV and the maximum cell betatron function is $\hat{\beta}_{\text{cell}} \approx 43 \text{ m}$. The field quality of the PEP quadrupoles has been found to be sufficiently good over the whole aperture up to a gradient of $g_{\text{max}} = 18.5 \text{ Tesla/m}$.

We conclude the shorter lattice cells do not jeopardize the luminosity expectations between 70 GeV and 100 GeV.

4. Low Energy Performance

We assume that we need an aperture of $\pm 10 \sigma_{\text{xtot}}$ where $\sigma_{\text{xtot}}^2 = \epsilon_{x0} \hat{\beta}_{\text{xcell}} + \hat{D}_{\text{cell}}^2 \left(\frac{\sigma_E}{E} \right)^2$, $\hat{D}$ the dispersion function and σ_E/E the relative energy spread.

With an aperture of $A = \pm 50$ mm we have for the maximum possible beam emittance

$$\epsilon_{xo \max} = \frac{\left(\frac{A}{10}\right)^2 - \hat{D}_{\text{cell}}^2 \left(\frac{\sigma_E}{E}\right)^2}{\hat{\beta}_{x \text{ cell}}} \approx \frac{A^2}{100 \cdot \hat{\beta}_{x \text{ cell}}} \approx \frac{25 \cdot 10^{-6}}{\hat{\beta}_{x \text{ cell}}} \quad (4)$$

For the lattice discussed here we always have $100 \cdot \hat{D}^2 (\sigma_E/E)^2 \ll A^2$.

The value of the maximum beta function in a FODO lattice reaches a minimum for a betatron phase advance of 76° and is in the chosen lattice $\hat{\beta}_x = 41.6$ m.

This gives a maximum possible beam emittance of

$$\epsilon_{xo \max} = 0.6 \cdot 10^{-6} \pi \text{ rad m}.$$

Since the luminosity according to Eq.(3) is proportional to the beam emittance we can increase the luminosity by a factor of up to

$$\frac{\mathcal{L}}{\mathcal{L}_0} \leq \frac{\epsilon_{xo \max}}{\epsilon_{xo}} = \frac{0.6}{0.064} = 9.4 \quad (5)$$

We will, however, not be able to realize this improvement factor at all energies below 70 GeV. Just below 70 GeV the increase of luminosity is limited by the available rf-power and by the cavity loading which should not exceed the value of the LEP design⁽¹⁾ at 70 GeV. This means we keep the beam power P_B and the ratio P_B/P_{cy} constant (P_{cy} = cavity losses). The maximum current then is given by:

$$i_{\max}(\text{mA}) = i_{70}(\text{mA}) \left(\frac{E(\text{GeV})}{70} \right)^4 = 4.6 \cdot 10^{-7} \cdot E^4(\text{GeV}^4). \quad (6)$$

The maximum current due to the beam beam limit or aperture limit is given according to Eq.(2) by

$$i_{\max}(\text{mA}) = \frac{\epsilon_{xo \max}}{\epsilon_{xo}} \left(\frac{E(\text{GeV})}{70} \right) i_{70} = 1.5 \cdot E(\text{GeV}). \quad (7)$$

There is another limit mentioned earlier. If we increase the beam emittance we also have to increase the aperture of the interaction region quadrupoles since the betatron function cannot be changed. This poses a problem since the present design of the LEP interaction region quadrupoles already are at their magnetic limit at 100 GeV and the aperture, therefore, cannot be increased.

In this paper two possible solutions are proposed:

- 1.) Have three sets of interaction region quadrupoles -
 one for $15 \text{ GeV} < E < 35 \text{ GeV}$ with a bore of 380 mm ϕ
 one for $35 \text{ GeV} < E < 70 \text{ GeV}$ with a bore of 210 mm ϕ and
 one for $70 \text{ GeV} < E < 100 \text{ GeV}$ with a bore of 145 mm ϕ (LEP design).
 The required strengths could be met in each energy region by linear scaling of the LEP design quadrupole.
- 2.) Use large bore (380 mm ϕ) superconducting quadrupoles which would cover the whole energy regime.

With a maximum betatron function in these interaction quadrupoles of $600 \text{ m}^{(1)}$ we arrive at the following maximum beam emittances:

Conventional Quadrupoles:

$E \leq 35 \text{ GeV}$	380 mm ϕ	$\epsilon_{\text{max}} = 0.6 \times 10^{-6} \pi \text{ rad. m}$
$E \leq 70 \text{ GeV}$	210 mm ϕ	$\epsilon_{\text{max}} = 0.18 \times 10^{-6} \pi \text{ rad. m}$
$E \leq 100 \text{ GeV}$	145 mm ϕ	$\epsilon_{\text{max}} = 0.09 \times 10^{-6} \pi \text{ rad. m}$

Superconducting Quadrupoles:

$E \leq 100 \text{ GeV}$	380 mm ϕ	$\epsilon_{\text{max}} = 0.6 \times 10^{-6} \pi \text{ rad. m}$
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The maximum beam currents under these conditions as a function of energy as well as the luminosity are plotted in Fig. 2.

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Beam Current & Luminosity

Fig. 2

Since the luminosity increase is proportional to the current increase the beam beam bremsstrahlung lifetime is not decreased below the value at 70 GeV which is 6.7 hours. (1)

5. Increase of the Beam Emittance

An effective way to increase the beam emittance is to enhance the synchrotron radiation and with it the quantum fluctuations of the betatron oscillations by means of wiggler magnets. (5) The increase in the beam emittance is given by

$$\frac{\epsilon}{\epsilon_0} = \frac{1 + \frac{L_W}{L} \frac{H_W}{H} \left(\frac{\rho}{\rho_W}\right)^3}{1 + \frac{L_W}{L} \left(\frac{\rho}{\rho_W}\right)^2} \quad (8)$$

where L is the circumference of the machine, ρ the bending radius of the main bending magnets, L_W the total length of the wiggler magnets and ρ_W the bending radius in the wiggler magnets.

$$H = \frac{1}{L} \int_0^L \frac{1}{\beta_x} \left[D_x^2 + \left(D_x' \beta_x - \frac{1}{2} \beta_x' D_x \right)^2 \right] ds \quad (9)$$

and

$$H_W = \frac{1}{L_W} \int_0^{L_W} \frac{1}{\beta_x} \left[D_x^2 + \left(D_x' \beta_x - \frac{1}{2} \beta_x' D_x \right)^2 \right] ds. \quad (10)$$

Together with the increase in the beam emittance goes an increase in the energy spread.

$$\frac{\sigma_\epsilon}{\sigma_{\epsilon 0}} = \frac{1 + \frac{L_W}{L} \left(\frac{\rho}{\rho_W}\right)^3}{1 + \frac{L_W}{L} \left(\frac{\rho}{\rho_W}\right)^2} \quad (11)$$

From the experimenters point of view this is an unfortunate side effect. By designing special wiggler sections, e.g., in the middle of the arcs, we can minimize this effect. From Eqs.(8) and (11) we find that the ratio H_W/H has to be made very large. It is conceivable to design a wiggler section such that in this area, for example, $D_x \approx 2m$ and $\beta_x \approx 4m$. In this case we have $H_W \approx 1$ and the ratio $H_W/H \approx 1100$ for $E < 35$ GeV.

The necessary wiggler parameters turn out to be $L_W = 0.66m$, $\rho_W = 88m$ and the maximum wiggler field $B_W \approx 1.3$ Tesla. Since the wiggler is very short and the additional energy loss is small compared to the energy loss elsewhere in the ring ($\approx 3\%$) it is conceivable to use only one wiggler triplet in the ring.

The resulting energy spread for the necessary emittance blow up is plotted in Fig. 3 as a function of energy. We see that the energy spread everywhere is smaller than that at 70 GeV unlike the present LEP design where $\sigma_E/E = 1.28 \times 10^{-3}$ for all energies below 70 GeV.

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Energy Spread

Fig. 3

6. Concluding Remarks

A scheme has been described to increase the luminosity capability of LEP at energies below and above 70 GeV by reducing the distance between quadrupoles in the arcs. The new lattice allows the beam emittance to be increased beyond the present design value. Correspondingly the beam currents and the luminosity are increased. While we wish to increase the luminosity such as to keep $\mathcal{L}/i$ constant because of the beam beam bremsstrahlung lifetime the increase in beam current brings some problems. The major problem with the larger beam current are the increased higher-order-mode losses.

The total higher-order-mode losses per revolution has to be compensated by the rf system. Since these losses are serious only at low energies where plenty of rf power is available anyway we need not worry.

There is, however, another aspect to the higher-order-mode losses. Losses in individual vacuum chamber components can heat them up and lead to failure. The higher-order-mode power into an individual component is proportional to the product of the peak current per bunch and the average total current. In SPEAR⁽⁹⁾ this product can be as large as 10 amp^2 without dangerous heating. In LEP where the same bunch length is expected ($\sigma \approx 3$ to 4 cm) this product is about the same, namely 10.5 amp^2 for an average beam current of 11 mA . Being aware of this heating the vacuum components in new storage rings are all carefully designed for minimum losses much below those in SPEAR components. The improvement has to be determined by experimental design but can be expected for the most critical components like bellows and flanges to be at least an order of magnitude better than in SPEAR. This, however, is enough for all currents contemplated in this report.

Last but not least, the shorter lattice cells which enable us to go to

9. J. M. Paterson - private communication.

larger beam emittances serve as a kind of insurance against possible reductions of luminosity due to a smaller than assumed beam beam limit.

It has become customary in design of e^+e^- storage rings to assume a maximum beam beam limit of $\Delta Q \leq .06$ independent of energy, damping time, value of the vertical betatron function at the interaction point β_y^* or the number of interactions per turn. If any of these quantities has to be changed to more conservative values one would lose in luminosity proportional to the square of the realistic $\Delta Q_{\max}$ if the beam emittance cannot be enlarged.