BEAM OPTICS REQUIREMENTS AND POSSIBLE PARAMETERS FOR OPERATING LEP

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1. Summary

For LEP Phase 1, the beam optics requirements are derived for injection, energy ramping, and flat-top. The requirements for tuning the insertions, controlling the orbits and betatron parameters, and for the use of wiggler magnets at lower energies are described. For the simple ramping scheme using a constant synchrotron tune, self-consistent sets of parameters have been calculated for injection and flat-top energies. At flat-top, the parameters are derived for the non-collision and collision cases. Recent estimates of the LEP transverse impedance and of the longitudinal loss factor have been used to re-evaluate the threshold intensity for the Transverse Mode Coupling Instability (TMCI) and the needed total RF power, respectively. Finally the parameters related to various schemes aimed at maximizing the threshold for the TMCI and the luminosity at flat-top energies are presented and discussed.

2. Basic assumptions for the calculations

The self-consistent sets of LEP parameters presented below are based on a certain number of assumptions which are briefly summarized. One important point is that the machine is supposed to be perfect, in the sense that the effects of non-vanishing orbit distortions and of multipole components, except the designed sextupoles, are not taken into account. It was verified that the simulated dynamic aperture is sufficient for the proposed parameters [1,2]. Another point is that possible performance enhancement with transverse reactive feedback is not considered and kept in reserve. Finally, the absence of bunch lengthening by collective effects is taken into account.

The longitudinal impedances and the related loss factors k_{hm} were revised for the copper cavities and for the vacuum elements like bellows, vacuum chambers, valves, collimators and sliding contacts. The higher mode impedances are related to the loss factors by the time T_B separating the bunches

$$Z_{hm}(\sigma_z) = k_{hm}(\sigma_z)\, T_B \quad , \qquad (1)$$

and depend on the bunch length σ_z. Assuming LEP running with 4 bunches, Table 1 summarizes the values retained for $Z_{hm}(\sigma_z)$. For the actual calculations, a margin of about 10% was taken w.r.t. these values.

Table 1 - Higher mode impedances

σ_z (mm)	10	15	20	30	40
k_{hm} (V/pC)	330	245	193	130	92
Z_{hm} (GΩ)	7.3	5.4	4.3	2.9	2.05

In order to take into account the actual beam blow-up due to beam-beam collisions, it has already been suggested to use an effective beam-beam tune shift ΔQ, which is different but depends on the unperturbed beam-beam tune shift ΔQ_0. Simulation and phenomenology provide the means to calculate ΔQ from ΔQ_0 [3] :

$$\Delta Q = A\{1 - \exp\left[-\frac{\min(\Delta Q_s, \Delta Q_0)}{A}\right]\left(1 - \frac{B_0}{B}\right)\} \qquad (2)$$

where B is the damping increment, i.e. the amount of radiation damping between beam-beam collisions. Taking into account that the beams are separated in the non experimental crossing points, the parameters in Eq. (2) can be chosen for LEP as $A = 0.064$, $\Delta Q_s = 0.06$, $B_0 = 3.2\ 10^{-2}$. The simple function (2) is valid for $B > 1.48\ 10^{-4}$, i.e. for damping times smaller than ~ 150 ms, which is satisfied in the cases considered. For ΔQ_0 between 0.045 and 0.06, $\Delta Q \approx \Delta Q_0/1.5$.

The LEP beam current is limited by the transverse mode coupling instability and the well-known simplified criterion for the threshold current can be written [4] :

$$I_{th} = C\,\frac{E\,Q_s}{\langle\beta\rangle k_\perp(\sigma_z)} \qquad (3)$$

C is a constant, $\langle\beta\rangle$ is a weighted average of the β-function where the impedances are and $k_\perp(\sigma_z)$ is the transverse loss factor which also depends on the bunch length. Calculations of $k_\perp$ were done recently for LEP and the threshold current was calculated as a function of the bunch length for particular LEP parameters [5]. Using numerical simulations, it was checked that the proportionality to E and Q_s in Eq. (3) remains valid within ~ 5% for the range of LEP parameters considered. Hence, it was possible to use Eq. (3) in order to compute the product of energy and synchrotron tune E Q_s necessary for reaching 3 and 5 mA with 4 bunches at different σ_z (Fig. 1).

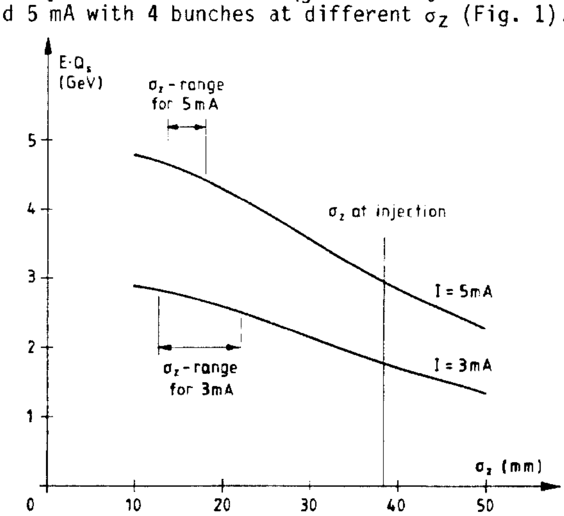

Fig.1 - Threshold values of E Q_s as a function of σ_z (TMCI)

There are also two practical limits which have to be satisfied for LEP Phase 1. The first one concerns the RF power at cavity window which cannot exceed 14 MW, to compensate for radiation and higher mode losses. The second one is related to the beam lifetime. If the overall lifetime has to exceed 5 hours for runs of the order of 3.5 h, the quantum lifetime should not be smaller than 24 hours.

3. Beam parameters at injection

Let us start with the so-called nominal conditions which were defined by a beam current of 3 mA and a synchrotron tune equal to the one found for flat top conditions, i.e. $Q_s = 0.09$. The curve of Fig. 1 indicates that for an injection energy of 20 GeV and a current of 3 mA, the bunch length must be at least equal to 38 mm. In order to reach this value of σ_z,

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all the wiggler magnets [6] (4 emittance wigglers at $D_x \neq 0$ and 4 damping wigglers at $D_x = 0$) are excited to their maximum field of 1 T. In this way, the damping times are decreased and the wigglers contribute as much as possible to bunch lengthening. To lengthen bunches further, the value of the longitudinal damping partition number has to be $J_e = 0.8$ (see Table 2).

Let us then study possibilities to have higher beam currents at injection energy. Fig. 1 shows that the threshold current increases when the bunch length and/or Q_s rise. Furthermore, keeping all wigglers at maximum field, the partition number J_e can be decreased to vary the energy spread σ_e and act on σ_z. Two adjustment possibilities using J_e can be considered. The first one, consisting of decreasing J_e while keeping Q_s constant, is ruled out since both σ_e and σ_z increase and consequently the quantum lifetime τ_Q decreases exponentially to reach too low values. The second one uses the fact that Q_s can be increased while J_e is reduced, in such a way that the bunch length remains constant and equal to the nominal value of 38 mm mentioned above. In this case, σ_e and Q_s increase, implying an increase of the bucket size and as a consequence of τ_Q. The results obtained are shown in Fig. 2 and τ_Q is not a limitation anymore.

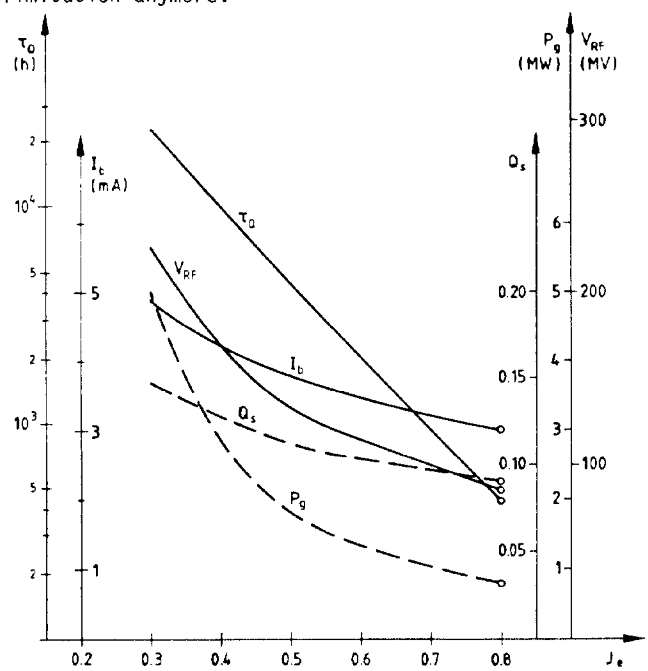

Fig.2 - Injection parameters for increasing beam current

No limitations come from RF voltage and power using the impedances of Table 1. The only possible limitations could come from longitudinal instabilities, but σ_z is relatively large, and by the physical aperture which defines the largest tolerable σ_e. The estimated limit is close to $J_e \approx 0.3$ which corresponds to an approximate beam current of 5 mA (see Figs. 1 and 2). Some of the beam parameters associated with the two extreme cases $J_e = 0.8$ and 0.3 are given in Table 2.

Table 2 - Possible parameters at injection (20 GeV)

Beam current (mA)	3	5
Long. partition number	0.8	0.3
Long. damping time (ms)	506	1350
Horiz. damping time (ms)	184	150
Bunch length (mm)	38	38
Wiggler field (T)	1	1
Synchrotron tune	0.09	0.147

The idea of keeping σ_z constant but at a lower value like 20 mm is also ruled out by the fact that Q_s becomes then larger than 0.2 and the RF power exceeds rapidly the 14 MW available. Hence, the solutions shown in Table 2 and given in Fig. 2 are the best obtained, respecting all conditions.

4. Beam parameters at flat-top energies

Let us start again with the nominal conditions which were defined by a beam current of 3 mA, an emittance ratio of 4% and an effective beam-beam tune shift of about 0.03. This means that the unperturbed tune shift must be ~ 0.045. With these data, it is interesting to look for the maximum energy satisfying the basic assumptions (Section 2). The horizontal partition number J_x must be adjusted for the given ΔQ_0, the bucket size must be such that τ_Q = 24 hours and the energy can be increased until the necessary RF power reaches 14 MW with the higher mode impedances given in Table 1. Such a consistent set of parameters (with a minor deviation for ΔQ) was found at an energy of 55 GeV and the estimated luminosity for the perfect machine is 1.7 $10^{31}cm^{-2}s^{-1}$. These parameters and those at injection for 3 mA beams are published in the revised LEP parameter list [7].

The possible performance in an energy range between 30 GeV and 57 GeV (zero-luminosity maximum energy) was investigated for a beam current not exceeding 3 mA, a Q_s value of 0.09 and an unperturbed ΔQ_0 not larger than 0.06. The adjustable parameters are the RF voltage (bucket size) and the wiggler strength (bunch length) at lower energies. The values of Table 1 have to be used, the formula (2) and the criterion for transverse stability (Fig. 1) must be satisfied. Consistent sets of parameters have been found and are drawn in Fig. 3 together with the estimated luminosity. The nominal parameters are marked and the obligation to decrease the beam current above 55 GeV due to RF limitation is shown. The range of σ_z-values is indicated in Fig. 1, and σ_z exceeds 20 mm only for E = 30 GeV.

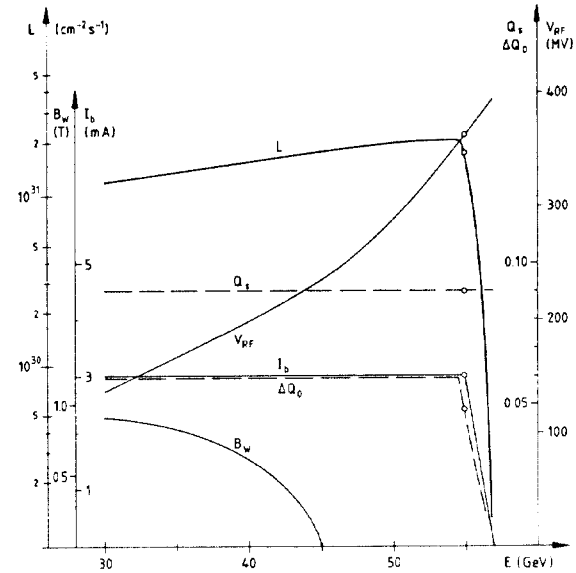

Fig.3 - Flat-top parameters for constant Q_s and 3 mA beams

The same investigation was pursued for the maximum current expected at injection without reactive feedback, i.e. 5 mA. The synchrotron tune Q_s is now added to the parameters which can be adjusted in order to satisfy all conditions, including the TMCI threshold (Fig. 1). Consistent sets of parameters have been found and are drawn in Fig. 4 together with the estimated luminosity. The wigglers are now used up to ~ 50 GeV

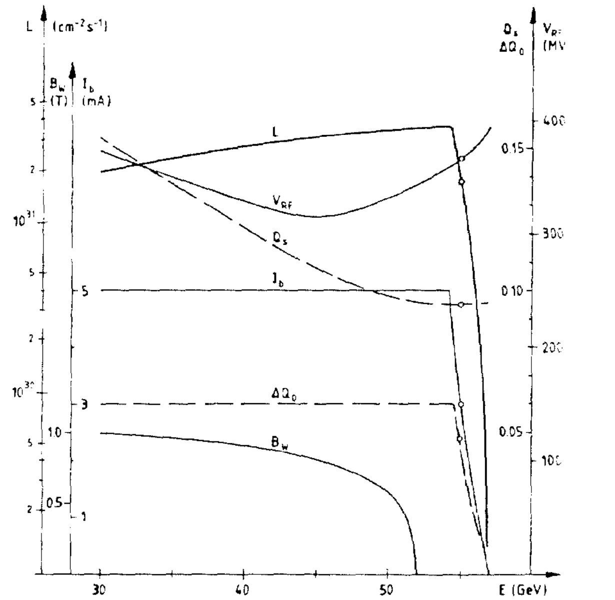

Fig.4 - Flat-top parameters maximizing TMCI threshold and luminosity.

and Q_s reaches about 0.15. These estimates are somewhat optimistic, mainly for energies below 40 GeV where ΔQ_0 = 0.06 was still applied. The range of σ_z-values is indicated in Fig. 1. Values of some of the parameters at 45 (Z_0-peak) and 55 GeV are given in Table 3.

Table 3 - Possible parameters at flat-top energies[1]

Beam energy (GeV)	45	45	55
Beam current (mA)	5	3	3
$\Delta Q/\Delta Q_0$	0.04/0.06	0.04/0.06	0.032/0.048
Energy spread ($^0/_{00}$)	1.06	0.7	0.98
Bunch length (mm)	16.1	12.8	17.9
Synchrotron tune	0.108	0.09	0.09
Vert.emittance (nm)	3.38/2.25	2.03/1.36	2.1/1.4
Hor.beam size at IP (r.m.s. in μm)	< 384/313	< 298/244	< 300/245

[1] Where there are two values they correspond to colliding and separated beams, respectively.

5. Beam optics requirements

Optics requirements associated with the schemes described before are briefly summarized. At injection energy, one particular requirement comes from the needs of sufficient aperture in the interaction regions for betatron accumulation and of reduced sensitivity to vertical misalignments. Therefore, the experimental insertions are adjusted at 20 GeV to 3 times their nominal β-values. Of course, during energy ramping the β-values must be reduced again, while the beams are separated. Simultaneously, the residual beam-beam tune shifts ΔQ_r must be kept under control so that the beam-beam tune spread remains smaller than $Q_s/2$. Starting from (y standing for x or z) :

$$\Delta Q_r \propto \frac{\beta_y^*\gamma}{(E\ell)^2\beta_z^*\beta_{zE\ell}} \quad , \qquad (4)$$

the integrated field of the electrostatic separators is set to satisfy the condition mentioned at flat-top energy. In order to satisfy the condition at all energies, the product $\beta_y^*\gamma$ must be kept constant during ramping, mainly in the horizontal plane which is more critical. Hence, β^*_x must be reduced by a factor 3 when going up in energy from 20 to ~ 60 GeV. The β^*z-value is kept larger during the whole ramping to limit the risk of orbit distortions and can be reduced only when the flat-top is reached. Going from 20 GeV to any flat-top energy considered in Section 4 (Figs. 3 and 4), it is also necessary to control the tunes Q_x and Q_z to avoid synchro-betatron resonances. When Q_s is kept constant (Fig. 3), it is sufficient to have a fixed working point distant from these resonances. However, when Q_s is varied to increase the beam current at injection (Fig. 2) and to maximize the TMCI threshold (Fig. 4), the working point must be moved during ramping. It may even be necessary to cross synchro-betatron resonances (Fig. 5) which should be possible without beam losses as shown in recent numerical simulations [8]. Finally, the chromaticity has to be maintained between 0 and about 0.8 in order to avoid head-tail instabilities and the wiggler field must vary according to the values of Figs. 3 and 4.

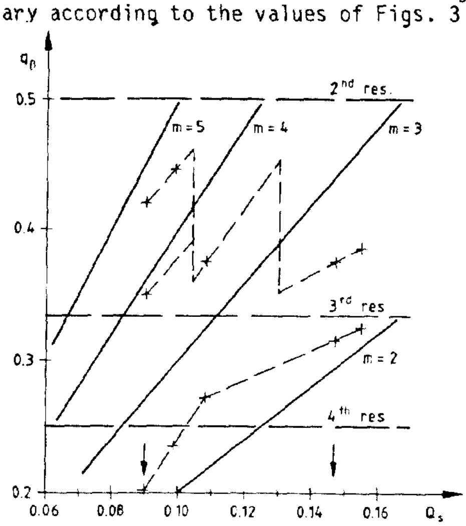

Fig.5 - Possible tune paths during energy ramping.

During ramping and on the flat-top, the orbit distortions and the perturbations of the betatron functions must be kept under control [9,10]. When beams collide, the luminosity has to be optimized to compensate for current losses either by increasing J_x if there is sufficient RF power or by decreasing the coupling from its nominal value of 4% to the expected minimum of ~ 1% due to residual vertical dispersion.

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