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MACHINE PARAMETERS AND CHARACTERISTIC FEATURES

by

J. Le Duff
Orsay

Copies available upon request from Ch. Redman, CERN/ISR
LEP Summer Study Secretariat

1. Introduction

A study carried out in 1976 on a large electron-positron storage ring, which included a top luminosity of 10^{32} cm^{-2} s^{-1} at a nominal energy of 100 GeV, did not conclude with sufficient confidence regarding its feasibility (this was the main conclusion of the extended ECFA meeting held at DESY in May 1977). A new study, less ambitious since it assumed 10^{32} at 70 GeV, began in June 1977 and ended a year later with the so-called "Blue Book" ("Design Study of a 15 to 100 GeV e^+e^- Colliding Beam Machine LEP" - CERN/ISR-LEP/78-17). Included in this new design was however the possibility to reach 100 GeV with less luminosity by assuming that conventional RF cavities could be replaced at a later stage by superconducting ones. This optimism certainly follows the very recent interest expressed in this field.

The "les Houches" meeting followed the publication of the "Blue Book". It should be mentioned that very rapidly the non-conventional part of the design (70 to 100 GeV) became known as SLEP, which stands for SUPER LEP. The activity of the machine experts during this meeting mainly concentrated on the existing design in order to make a careful assessment of its feasibility, and also on the general constraints which are related to very large e^+e^- storage rings for both conventional and non-conventional techniques.

2. A Brief Description of the Present LEP Design

The basic assumptions included in the design were:

- 70 GeV nominal energy (conventional first stage);
- luminosity of 10^{32} cm^{-2} s^{-1} at nominal energy;
- 8 interaction regions; to avoid bad effects from beam separation a natural choice of 4 bunches was made (half the number of crossing points).

The ring size, for a 70 GeV top energy, was determined by using the B. Richter approach for cost minimization assuming pure conventional elements (magnets, RF). Unit costs included in that scaling mostly refer to SPS and PETRA constructions.

From the previous approach, one gets separate laws for the bending radius and the total cavity length:

$$\rho \propto E^2$$
$$L_c \propto \frac{1}{\rho} \sqrt{\frac{1}{Z}}$$

where Z is the shunt impedance per metre of RF structure. This parameter is directly connected to the RF power dissipated in the cavity walls:

$$P_d = \frac{V^2}{R\,L_c} \qquad \text{(V = total peak accelerating voltage).}$$

The factors entering in the proportions involve unit prices, as previously mentioned, which are mainly the costs per metre of the ring, per metre of RF cavities and per Watt of RF power, including ten years of operational cost.

Table 1 gives the corresponding basic parameters of the ring

bending radius		$\rho = 2.344$ Km
cavity length	$\begin{cases} Z = 24\ \mathrm{M\Omega/m} \\ f_{R.F.} = 357\ \mathrm{MHz} \end{cases}$	$L_c = 1.344$ Km

Table 1

The radius being defined, it remains to discuss the beam characteristics, and hence the optics, to fit the required performance. The luminosity, which represents the rate of events for a process which has a unit total cross-section, is purely a machine parameter:

$$L = f_r \frac{N^+N^-}{b.S}$$

where:
f_r = revolution frequency $(= \frac{c}{2\pi R})$
$N^{\pm}$ = total number of particles in each beam
b = number of bunches per beam
S = effective interaction cross-section $(S = 4\pi\sigma_x\sigma_z)$.

Clearly, the luminosity depends on the transverse particle density and the number of circulating bunches. However, the beam-beam interaction (space-charge effect) set a limit on the number of particles that can be stored and then on the maximum luminosity that can be reached. That limit also depends on the transverse particle density, but in such a complex way that finally it leads to the paradoxical fact that more luminosity is obtained for larger transverse beam sizes.

The corresponding number of particles can be minimized by using "low-β insertions" which turn out to be very strong focussing (at least in one transverse plane) straight sections. This number of particles, or the corresponding beam intensity, is very important as it determines the amount of beam power that must be provided by the RF accelerating system:

$$P_b = 2\ I.U_o \qquad (I^{\pm} = N^{\pm}\ e\ f_r)$$

where U_o is the accelerating voltage seen by the particles which compensate for the energy lost per turn, mainly due to the synchrotron radiation:

$$U_{o\,(GeV)} = 88.454\cdot 10^{-6} \frac{E^4_{(GeV)}}{\rho_{(m)}}$$

Notice that there are other sources of energy losses in large electron-positron storage rings which depend on the peak current so that finally the right optimization can only be reached by a series of trials.

Table 2 gives the main beam characteristics and the corresponding optic parameters which comply with the assumed performance.

Nominal energy		70 GeV
Number of interaction regions		8
Number of bunches per beam		4
Ring circumference		22.208 Km
Mean radius of the ring		3.535 Km
Circulating current per beam		10.5 mA
Number of particles per beam		$4.9\cdot 10^{12}$
Relative energy spread (σ_E/E)		$1.24\cdot 10^{-3}$
Natural bunch length (σ)		12.7 mm
Beam-beam bremsstrahlung lifetime		6.6 hours
Luminosity	10^{32}	$0.5\cdot 10^{32}$ cm^2 s^{-1}
Amplitude function at crossings (β^*)	10	20 cm
Dispersion function " (D^*)	0	0
Transverse beam size at crossing σ^*_H	0.32	0.45 mm
Transverse beam size at crossing σ^*_V	0.02	0.028 mm
Free space for detectors	10	20 m
R.F. frequency		357 MH_z
Energy loss per turn (S.R.)		906 MeV
Beam power (S.R.)		19 MW
Cavity power dissipation		51 MW
Peak R.F. voltage		1243 MV
Cavity length		1344 m
Total R.F. power (including parasitic losses)		74 MW

Table 2

Let us emphasize a few points.

- The beam lifetime due to beam-beam bremsstrahlung is relatively low. This is partly due to the large number of crossing points as they all add to the corresponding rate of events, but it is also a compromise with beam power as it turns out that beam-beam lifetime becomes shorter if a given luminosity is obtained with smaller current:

$$\tau_{bb} \propto \frac{I}{L_{total}}$$

- In order to satisfy detector requirements the straight sections have been split into two types: 4 short sections with ± 5 metres free space and 4 long sections with ± 10 metres free space. The latter have only half the maximum luminosity because it is more difficult to get a low-β function in long straight sections without entering into optic problems (aperture, chromaticities).

- The additional beam power which comes from parasitic losses is down to a satisfactory low level assuming that it will be possible to lengthen the bunch with the use of a harmonic RF system (notice that natural bunch lengthening may occur but scaling laws are still unreliable).

Below 70 GeV, where the space-charge effect limits the stored current, the natural variation for the luminosity is expected to scale like E^4 (Fig. 1), assuming fixed optics for which the beam transverse cross-section varies by E^2. The corresponding stored current will scale to E^3.

The luminosity at 15 GeV (injection energy which permits to link up with PETRA energies) is then down by more than two orders of magnitude (factor ~ 1/500) and probably useless for good physics apart from resonances. Obviously, it has to be improved quite a lot. In the present LEP design, this is done by using sets of "wigglers" (three poles short bending magnets) correctly located in the ring lattice. The main effect of the wigglers is to increase the average radiated power and a direct consequence is an increase of the relative energy spread of the beam* (σ_E/E). The beam transverse dimensions being proportional to the relative energy spread, it is now clear that they can be controlled by powering the wiggler magnets. It is expected from wiggler operation to maintain constant beam sizes over the whole energy range up to 70 GeV, and that corresponds to a luminosity variation of E^2 (and beam current of E). The luminosity at 15 GeV is now roughly $0.4 \cdot 10^{30}$ cm^{-2} s^{-1} (Fig. 1: nominal performance).

The increase in beam power does not matter at energies below the nominal one as long as the stored current there does not exceed the stored current at

* Large energy spread is certainly undesirable for studying narrow resonances, but in this case less luminosity is tolerable so that wigglers can be turned off.

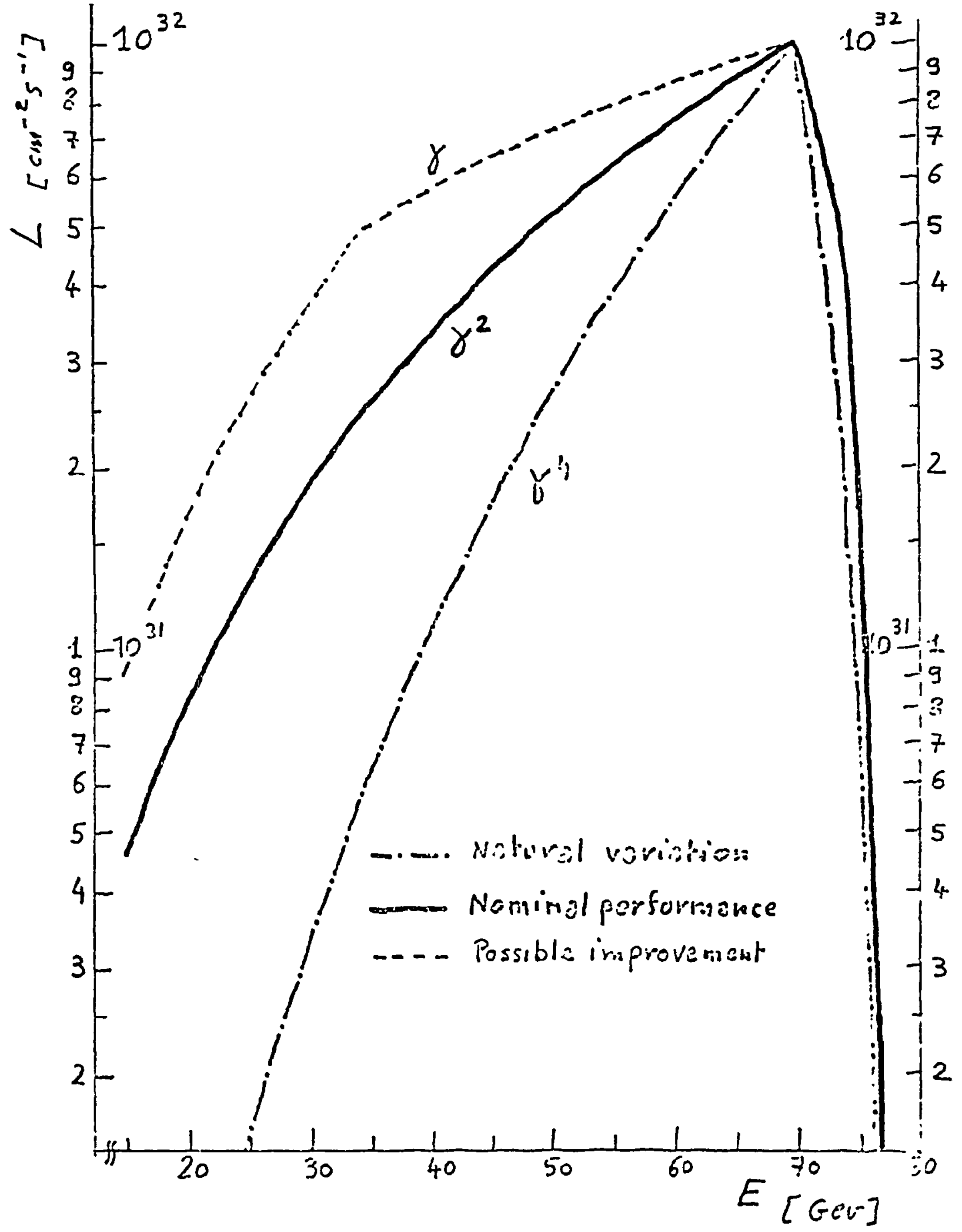

Figure 1 : LEP Performance (Stage I)

top energy; then one always stays below the beam power limit.

In fact the present LEP design includes some more hope in the low energy range. Provision has been made for large closed-orbit distortions that may happen at the very beginning of machine operation. As soon as the closed orbits are brought to a proper correction level, the corresponding aperture gain can be used to increase (further) the transverse beam dimensions at low energies. This possible improvement is also shown in Fig. 1; however the increase in beam dimension, going down in energy, has to stop when the aperture limit is reached. This is expected to happen around 35 GeV and then, for energies below, the beam size at the best must stay constant again. Such a procedure may permit a luminosity variation such as γ (constant stored current) between 35 and 70 GeV, while below 35 GeV it will scale again to γ^2.

Up to now the discussion centred on the conventional part of the LEP design (Stage I). A second stage corresponding to a future improvement has been looked at, where all the copper cavities are replaced by superconducting cavities (such an improvement has already been considered for PETRA). It is likely that the frequency of 357 MHz will remain the same so that the klystrons and much of the RF hardware can be retained. The expected performance above 70 GeV shown in Fig. 2 call for the following comments:

- The beam power is kept constant at a value of 25 MW which presently corresponds to the maximum power the vacuum chamber can dissipate. The slight increase in beam power from 19 to 25 MW explains why the maximum luminosity is slightly increased above 10^{32} cm^{-2} s^{-1} and occurs above 70 GeV. This increase in beam power is dissipated in the superconducting cavity walls. If the vacuum chamber could dissipate more power better performances could be reached, otherwise the missing dissipation in the cavity can be considered as operation economy.

- The fact that beam power must be limited imposes a reduction in beam size when going to higher energies. This is done by two methods: variable tune and variable coupling. Assuming that these two methods together permit reaching the space-charge limit, the luminosity will scale to E^{-3}, otherwise it would drop rapidly to E^{-10} and even faster.

- The high shunt impedance which characterizes superconducting cavities satisfies accelerating voltage requirements at higher energies. However, due to surface effects, the accelerating field will be limited around 3 MV m^{-1} and then the maximum energy will be limited too, very close to 100 GeV.

In concluding this section, let us point out that the present design assumes that the machine is to be constructed near the present CERN site, following in that way an ECFA recommendation. The machine is to be built underground (60 metres average depth) and makes use of SPS techniques. The main problems will certainly consist in the existence of very large underground experimental halls, but it seems that appropriate solutions can be found.

The capital cost for construction can be summarized as follows:

Ring	470 MSF
R.F.	200 "
Injector	90 "
Tunnel & Buildings	280
Total	1,040 MSF

while operation costs are estimated to be 90 MSF per year. Construction time according to present calculations will be approximately 6 years.

Superconducting Cavities

Assume : - constant beam power
- variable tune
- variable coupling

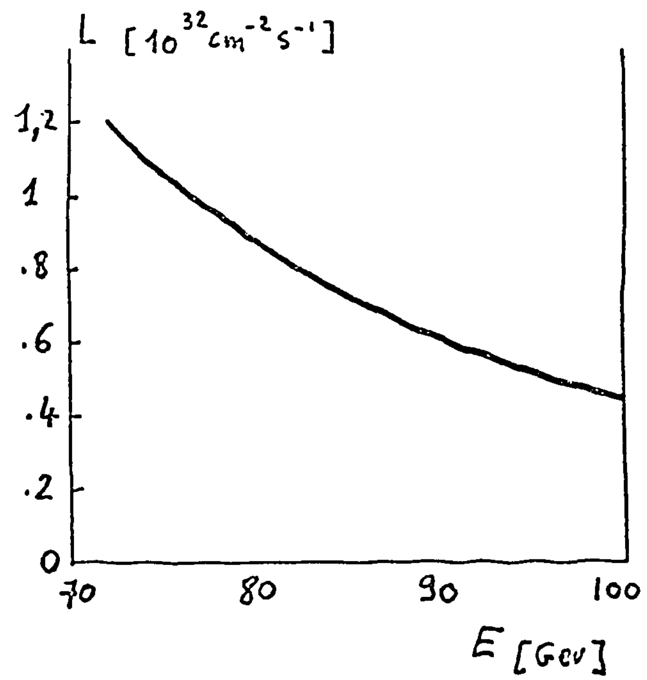

Figure 2 : LEP (Stage II)

3. The LEP Summer Study: Discussions and Conclusions

The main topics discussed in the "machine parameter" group*, which were brought into discussions many times with the other participants, were

- design philosophy,
- performance in the space-charge limit domain,
- injection improvements,
- optimization of storage rings with and without superconducting cavities,
- constraints related to very large e^+e^- storage rings.

Part of the work consisted also in presenting and explaining the present LEP design as described in the "blue book" and summarized in the first part of this report.

3.1 Design Philosophy

The design philosophy of a large electron positron storage ring such as LEP is similar to that adopted for PETRA and PEP. It is mainly dictated by the SPEAR performance which in turn confirmed in many ways results obtained earlier with smaller rings. New ideas which have never been checked on existing machines, but which may provide more hope, can either be considered as future improvements or directly included in the project, depending on the amount of difficulty expected from them or on the corresponding development stage.

An interesting fact which has been established at SPEAR is the simplicity of operating guide fields made of FODO channels with in addition low-β insertions which turn out to give high performance, at least with single circulating bunches per beam. SPEAR results may be roughly summarized as follows:

- at low energies the luminosity scales as E^4 (Fig. 3.a));
- for a fixed energy there was no more gain in luminosity when lowering too far the amplitude function β at the crossing points. In practice β = 20 cm or 10 cm gave the same luminosity (Fig. 3.b));
- additional energy losses corresponding to the excitation of high-frequency modes in the vacuum pipe and the cavities were found to be in very good agreement with theoretical models. Of course, these losses came in addition to the synchrotron radiation loss. At high energies these additional losses limited the current because of vacuum chamber heating problems (Fig. 3.a));
- making use of electrostatic fields to separate the two beams at one crossing point led to less performance for the remaining crossing point.

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* The Working Group at Les Houches consisted of W. Bauer, M. Bassetti, E. Keil, J. Le Duff, J. Maidment, M. Month, G. Saxon, W. Schnell, M. Sommer, S. Tazzari, H. Wiedemann and H. Zyngier

So finally what did we learn from SPEAR results? To go further it is necessary to introduce a few formulae which describe the beam-beam interaction in a very simple way.

The luminosity defined in the previous section may be written as follows:

$$L = \frac{\pi f_r}{r_e^2} \; b \, \gamma^2 \, \frac{\varepsilon_{xo}}{\beta_z^*} \, \xi^2$$

with r_e = classical electron radius

f_r = revolution frequency

γ = E/E_{rest}

β_z^* = vertical amplitude function at crossing point

ε_{xo} = horizontal emittance for zero transverse coupling

$$\varepsilon_{xo} = \sigma_{xo}^2/\beta_x \text{ is invariant,}$$

and where ξ is a parameter related to the beam current:

$$N = \frac{2\pi}{r_e} \; b \, \gamma \, \varepsilon_{xo} \, \xi$$

very often called the space-charge strength. If the tuning of the machine is not too close to an integer, this parameter ξ is equal to the linear tune shift ΔQ caused by the additional thin quadrupole lens which to first order represents the electromagnetic interaction of the two beams colliding. Let's remind the experts that the previous formulae include optimum coupling or in other words equal ΔQ for both transverse planes.

Knowing that for a fixed optic the natural variation of the emittance goes like $\varepsilon_x \propto E^2$ it becomes clear that $L \propto E^4$ implies a constant ξ value (or ΔQ).

SPEAR performances described in terms of ΔQ (per crossing) become:

$\beta^* = 20$ cm $\quad \Delta Q_{max} = 0.06$

$\beta^* = 10$ cm $\quad \Delta Q_{max} = 0.04$

At this point one should notice that SPEAR has a maximum of two crossing points and there is still some doubt about getting the same maximum ΔQ value if the number of crossing points is increased by having more bunches per beam. This kind of problem emerged after the observation of ACO and ADONE, where it was emphasized that the maximum ΔQ per crossing was lower when increasing the number of crossings (roughly $\propto 1/\sqrt{b}$). However ADONE, with 6 crossings (3 bunches per beam), and operating very close to an integer, has been able to reach a maximum ΔQ per crossing of 0.04 which in that case corresponded to a ξ value of 0.06.

The result of this discussion was certainly that LEP is not too conservative as it uses the following numbers: 8 crossings, $\beta^* = 10$ cm, $\Delta Q_{max} \simeq \xi_{max} = 0.06$. PETRA and PEP used practically the same hopes at the design level, so it now remains to see the operation on these machines before eventually correcting the LEP performance.

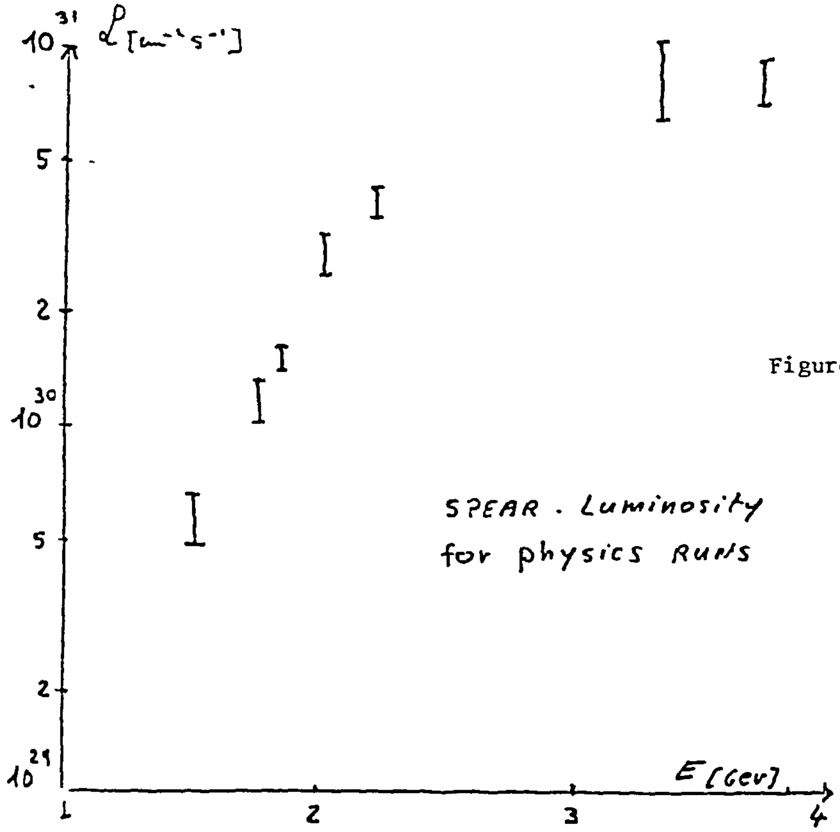

Figure 3.a)

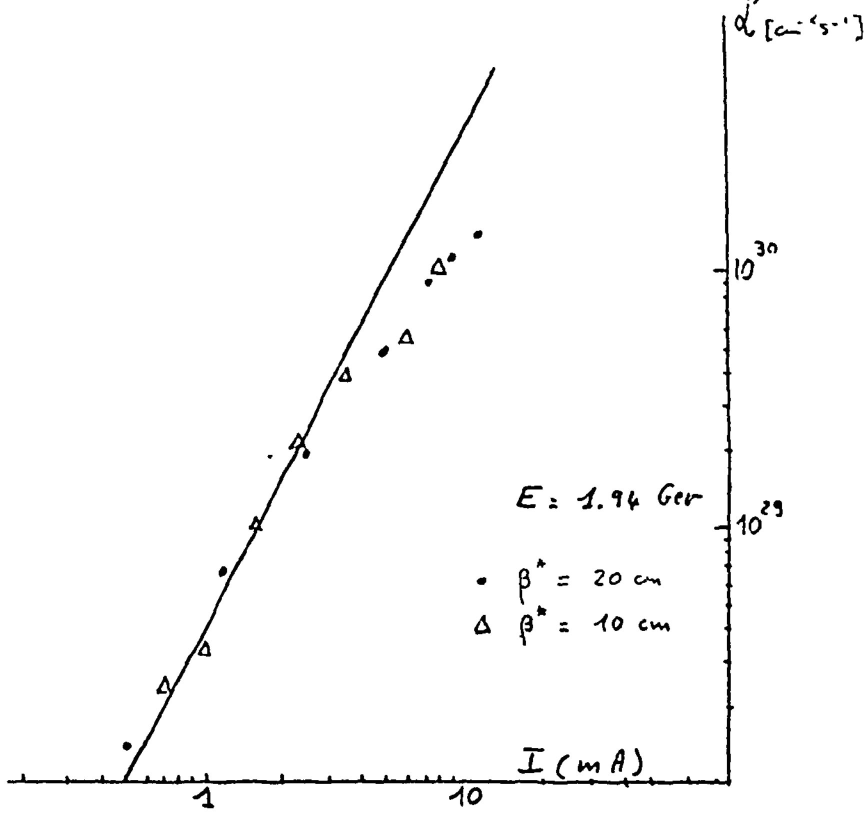

Figure 3.b)

3.1 Performance Close to the Space Charge Limit

This corresponds to the low energy range from 15 to 70 GeV, or Stage I of LEP. Nominal performances for LEP assume a constant emittance which should lead to an E^2 variation for the luminosity. During the meeting at Les Houches the different emittance control methods were examined, and Table 3 summarizes the advantages and disadvantages of each method.

Emittance Control Methods	Advantages	Disadvantages
variable tune	No change in the energy spread (σ_E)	Catalogue of operating points
wigglers	lower damping times	increase in energy spread
mismatch dispersion	no change in the energy spread	chromaticity corrections did work at SPEAR but never used for operation
non-zero dispersion	no change in the energy spread	non-operational results on existing machines (synchro-betatron coupling)
stochastic kicking		never worked on existing machines

Table 3

The wiggler method has been used in the LEP design although it has never been tried on existing machines. A wiggler consists of additional short bending magnets suitably located in the lattice and certainly the corresponding free space is much easier to find in very large machines in comparison with the existing small rings. No surprises are expected from bending magnet operation and no criticism was expressed of the LEP choice. However, during the discussions it was stressed that a second approach should be studied in addition. This corresponds to the variable tune method (presently used at PETRA) and has the disadvantage of requiring the computing of a catalogue of operating points which must satisfy both injection and chromaticity corrections. It may also require more aperture and this has still to be investigated. However, this second method has the advantage of not producing additional energy spread which looks better for resonance studies.

The use of larger emittance at lower energy is included in the design in order to improve the luminosity ($L \propto E$) later on. The aim is to regain, after a while, the aperture provision left for closed orbit distorsion. The corresponding increase in emittance should permit an E variation for the luminosity (constant current) between 35 and 70 GeV. It was pointed out at the meeting that an even larger increase in emittance could be obtained by increasing the aperture in the large insertion quadrupole to have it fit with the arc aperture. This could help to lower the variation of the luminosity to E at very low energies. It should be mentioned however that an increase in the aperture of these big quadrupoles may later require superconducting quadrupoles when one reaches the second stage using superconducting cavities with beam energy up to 100 GeV.

If electrostatic beam separation at a few discrete crossing points was proved to work in the future, it could be used to increase the number of bunches (keeping the same number of interaction points) at low energy to improve the luminosity. An improvement in the E law will need more stored particles however, and it then becomes mainly an injection problem. The method could only be used to reach the E law with less aperture. No promises could emerge from discussion as to that method, although simple methods of obtaining beam separation in the arcs were brought to our attention by H. Wiedemann.

It was agreed that the top luminosity occurring at 70 GeV could be improved upon at the expense of a larger number of stored particles, and probably some further provision for aperture requirements with, as a direct consequence, a need for more beam power. An increase in the number of particles per bunch would increase energy losses into higher modes of the cavities. This would be in addition to the radiation energy losses and would enhance the required generator power and wall heating. Such an improvement in the luminosity at the design energy (first stage) is therefore strongly correlated to the overall cost. One has however to keep in mind that any change in ΔQ_{max} will result in a change in luminosity proportional to $(\Delta Q_{max})^2$.

3.2 Injection Improvements

The LEP filling time for maximum current, which may correspond either to the normal design energy (L_{max}) or to all energies up to 70 GeV, should not exceed 15 minutes. This is necessary in order to maintain a good average luminosity. Experience with existing storage rings caused some problems (for example 4-turn injection, average filling time) and new safety factors were sought which could be included in the present design without bringing about any fundamental change. It was concluded that:

i) the positron rates can be raised by at least a factor of 2 using high loaded cavities for the Linac. This was proved to work with NINA;

ii) an energy compression process for positrons at the end of the Linac will reduce the energy spread of the Linac pulse and favour the capture into the first injection ring. Such a scheme uses an achromatic guide field followed by an accelerating cavity; particles with different energies have a different path length so that they will see a different accelerating voltage. The method does not much disturb the pulse shape.

In addition to this, it was agreed that any attempt to raise the injection energy would be welcome.

3.3 Optimization of Storage Rings With and Without Superconducting Cavities

Discussions on these problems were triggered by a talk given by W. Bauer during a plenary session.

The usual cost optimization as performed by B. Richter for conventional large storage rings fails to a certain extent when superconducting cavities are considered. The fact is that superconducting cavities lead to an improvement factor of 10^5 for the shunt impedance per meter, at least in the frequency region of 357 MH_Z. As a result, the optimized total cavity length would be very short, which is completely unrealistic just because superconducting cavities are limited by the maximum tolerable accelerating field gradient (around 3 MVm^{-1} for the frequency considered). This limitation corresponds to the surface effects. Then, this new parameter has to be taken into account in the optimization procedure.

Table 4 shows comparative optimization with and without superconducting cavities. The result is:

i) the first column practically corresponds to the present LEP version, stage I;

ii) the second column shows that an optimized 70 GeV storage ring with superconducting cavities is smaller in size by a factor 0.64 as compared to an optimized conventional 70 GeV ring. Moreover, the reduction in the cost is expected to be also a factor 0.6;

iii) optimization at 100 GeV with superconducting cavities has to be made on the assumption of a maximum beam power of 25 MW. It appears then that the second stage of LEP is quite close to an optimized 100 GeV machine with superconducting cavities when including a maximum available beam power of 25 MW.

It appeared that more experience with superconducting cavities is needed, in particular when discussing unit prices, reliability and maximum field gradient (extrapolation to low RF frequencies), before one can reasonably include them in a realistic design. The optimized 70 GeV with superconducting cavities, which at first looks very exciting, doesnot permit the extension of the energy range at a later date. Now, if such a non-conventional machine was really proved to work, there is no doubt that LEP stage II could reach energies much beyond 70 GeV when replacing the cavities. Higher beam power should help to obtain better performance in the high energy range, but this needs more investigation on vacuum chamber heating limitations.

Ring Parameters	70 GeV Normal Cavities	70 GeV Superconducting Cavities	100 GeV Superconducting Cavities
ρ (m)	2469	1576	2355
L_c (M)	1491	629	1753
P_b (MW)	18.9	29.6	25
P_D (MW)	40.5	0.005	0.013
P_{TOTAL} (MW)	59.4	29.6	25
$\mathcal{L}$ ($cm^{-2}s^{-1}$)	10^{32}	10^{32}	$4x10^{31}$

Table 4

As previously mentioned, LEP Stage II assumes no change in the RF frequency (357 MH_z). However, it appears that experts in the superconducting field would prefer higher frequencies (an optimum is set around 700 MH_z). Table 5 shows the expected advantages and disadvantages of higher frequencies.

Advantages of High Frequencies	Disadvantages of High Frequencies
- maximum accelerating field gradient is higher	- high synchrotron frequencies (synchro-betatron coupling)
- cavity easier to build	- smaller bunch length (higher mode losses)
- better stability	- klystron more expensive
- smaller cryostat (less helium)	- more expensive to go from Stage I to Stage II
- lower price (?) → at least for materials	- harmonic RF system more difficult to design

Table 5

It was agreed that additional cost related to the cavity replacement (LEP Stage I → LEP Stage II) needed more investigation.

3.4 Constraints Related to Very Large e^+e^- Storage Rings

The second scheme which could be used to reach higher energies with conventional elements requires a larger ring and cost optimization gives a radius increasing as E^2. We are then back to the difficulties encountered with the initial LEP 100 design study, namely:

i) sensitivity to closed orbit distortions,

ii) low bending field at injection energy,

iii) high beam loading.

Since the time the initial report on LEP 100 was published, better under-understanding of closed-orbit distortion effects reduces the problems, though it is still expected that operating a larger storage ring will bring more difficulty. Scaling laws are not very useful here and the remaining difficulties can only be determined, for a practical case, by computer simulation of particle behaviour.

The low injection field related to very large storage rings imposes some serious constraints on the vacuum requirements. Distributed pumps must be replaced by something for which new ideas have still to germinate. New types of bending magnets may also be necessary. These constraints appear finally as more of a technical development and cost problem than as real limitations.

In a larger storage ring, to maintain a design luminosity of 10^{32} cm^{-2} s^{-1}, the number of stored particles has to increase because the revolution frequency is lower. If a large number of particles is distributed in a small number of bunches the corresponding bunch spacing becomes important and gives rise to heavy transient beam loading on the fundamental mode of the RF cavities. At each bunch passage a considerable amount of stored energy is taken from the cavities which have to be refilled before the next bunch passes. This results in a voltage modulation and corresponding reflected power to the generator. In addition to this effect comes the beam loading on the higher modes of the cavities (or any other boxes along the ring circumference) which causes particle energy losses. Finally the efficiency in transforming power from the RF generator to the beams is reduced.

The first effect becomes very important when the bunch spacing is of the same order of magnitude as the cavity filling time. The second effect depends strongly on the longitudinal bunch distribution and is useful for smaller bunch lengths because higher and higher order modes can interact with the beam.

The total generator power should be written:

$$P_g = P_b + P_{b\ h.m.} + P_D \left(1 + \frac{U_{h.m.}}{U_o}\right)^2 + P_{ref}$$

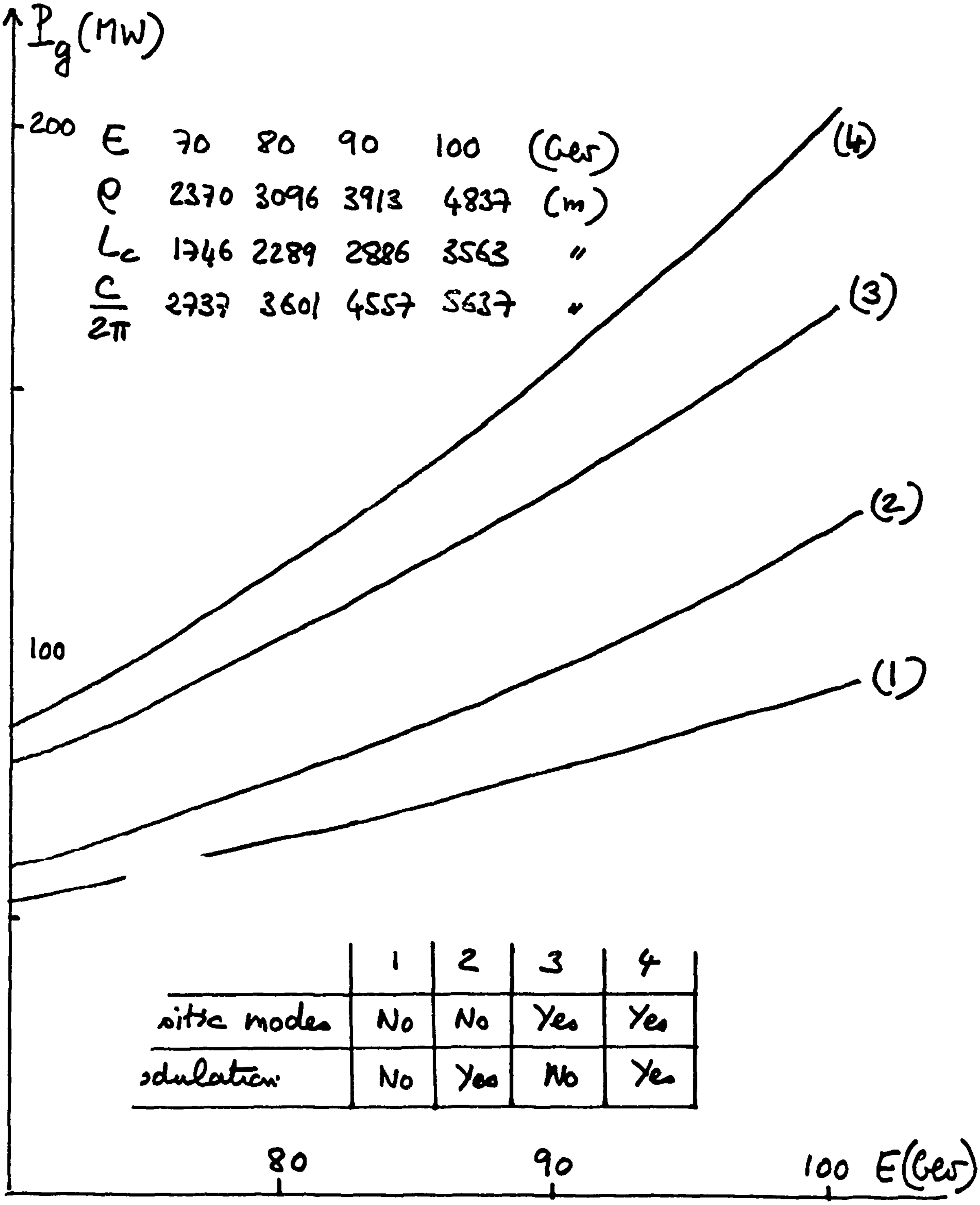
P_g (MW)
200
100
E 70 80 90 100 (GeV)
ρ 2370 3096 3913 4837 (m)
L_c 1746 2289 2886 3563 "
$\frac{C}{2\pi}$ 2737 3601 4557 5637 "
(4)
(3)
(2)
(1)
1 2 3 4
itic modes No No Yes Yes
odulation No Yes No Yes
80
90
100 E(GeV)

Figure 4

where

U_o = synchrotron radiation loss

$U_{h.m.}$ = higher order mode losses

P_b = synchrotron radiation beam power

$P_{b\ h.m.}$ = higher order mode beam power

P_D = cavity dissipation in the absence of higher order modes

P_{ref} = reflected power.

Figure 4 shows that the slope of the power generator drastically changes at higher energies as the radius becomes larger. These curves were computed by E. Keil on the assumption of different optimized rings for different energies from 70 to 100 GeV with conventional cavities, and four bunches per beam.

The amount of reflected power can be reduced by increasing the number of bunches. For the same luminosity the number of particles per bunch is then reduced and the higher order mode losses too. This was the reason for having 32 bunches in the initial LEP 100 design. As a severe consequence the beams must be electrostatically separated at all useless crossing points, a method which still gives cause for thought.

However, these effects do not give a fundamental limitation, apart from the cost, if the number of bunches is kept small enough to fit the number of interaction regions.

3.5 Conclusions

These may be briefly summarized as follows:

i) The present LEP design is quite feasible;

ii) Improvements in luminosity are strongly related to cost;

iii) Corrections to the present design may emerge very shortly, as further insight is gained from PETRA and PEP operation;

iv) Improving the energy requires far more knowledge of a theoretical and technical nature before a realistic design may be settled upon. DORIS operation with a single cell superconducting cavity may soon help in that way. A comparative design of a conventional 5 Km radius storage ring will help too.