LEP Performance Limits re-visited

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Abstract

A first estimate of the LEP performance in 1999 - 2000 has been presented in Ref. [1]. Based on new data collected during the 1998 run, some of the basic parameters entering the calculation have been updated. This note presents the expected implications on the performance of the machine.

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1 Introduction

A rather detailed evaluation of the effects which will limit the performance of LEP in 1999 and 2000 has been presented in Ref. [1]. Although most of the arguments developed in that note remain valid, the data collected during the 1998 run allows a refined estimation for some of the parameters involved. In order to clarify the approach of the present note, the same structure as that used in [1] will be maintained. For each section, it will be mentioned whether modifications have been considered, and where applicable, the new set of parameters will be discussed. This note should therefore be considered as an update of Ref.[1].

2 Formulae and scaling laws

This section presents a collection of the different scaling laws which can be applied throughout the report. It is not affected by any modification.

3 Optics, required voltage and gradient

This is one of the few sections where the experience accumulated in 1998 allows to reduce the number of options which had been considered so far.

3.1 Optics

The 102°/90° optics proved to work remarkably well and it is therefore assumed that this optics will be used for the future operation. The performance of the machine will still be optimised by varying the horizontal damping partition number $J_x$. As far as the available RF voltage allows, it is likely that the machine will be operated with a $J_x$ around 1.5. On the other hand, when attempting to reach the highest possible energy, then $J_x$ will be reduced up to the point where the corresponding horizontal emittance reaches a value around 50 nm, which, from the measurements performed on different optics, is presently considered as the largest value tolerable from aperture considerations (more accurate estimations should become available in 1999). Above 100 GeV, an emittance of 50 nm corresponds to a $J_x$ between 0.95 and 1.0. For the present study, we shall therefore consider the two extreme cases $J_x = 1.5$ and $J_x = 1.0$, assuming that all other scenarios will fall between these two options. The new values for the beta functions successfully used in 1998, i.e. $\beta_x^* = 1.25$ m and $\beta_y^* = 0.04$ m have also been included in the present model.

3.2 RF voltage and gradient

From 1999 onwards, the RF installed in the machine will be composed of 272 Nb-Cu cavities, 16 Nb cavities and 48 conventional Cu cavities which are expected to
Table 1: Available RF voltage with nominal gradients, 96 % efficiency and 1 klystron off.

<table>
<thead>
<tr>
<th>Grad. (MV/m)</th>
<th>Volts (MV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>272 Nb-Cu cav.</td>
<td>6</td>
</tr>
<tr>
<td>16 Nb cav.</td>
<td>5</td>
</tr>
<tr>
<td>From Cu-system</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
</tr>
<tr>
<td>96 % efficiency</td>
<td></td>
</tr>
<tr>
<td>1 klystron off</td>
<td></td>
</tr>
<tr>
<td>Avail. for beams</td>
<td></td>
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</tbody>
</table>

 deliver about 120 additional MV to the voltage of the superconducting system. For the operational margin, we shall now assume that 96 % of the RF system is available and that one klystron (8 cavities) is needed in reserve. Table 1 illustrates the available RF voltage in case the nominal gradients are assumed.

With an effective voltage of 2833 MV and the 102°/90° optics ($J_x=1.0$), a maximum energy of 97 GeV could be achieved in 1999. Since the objective is to reach higher energies, it implies that the accelerating gradient of the cavities has to be increased above its nominal value of 6 MV/m. The energy remaining a free parameter, Fig. 1 illustrates the required gradient as a function of the energy for the 102°/90° optics and the two values of $J_x$ retained. It shows that values close to 7 MV/m are required to reach 100 GeV.

4 Individual limits

4.1 Aperture

Measurements performed during 1998 with the 102°/90° optics at 94.5 GeV did not exhibit the kind of tails previously observed on other low emittances lattices. Aperture measurements in collision with high intensities did show some tails (expected from beam-beam effects) whose magnitudes remain small enough to allow for an operation at 100 GeV [2]. Our present understanding is therefore that a 102°/90° optics with a $J_x$ of 1.0 should not be a problem at high energy in terms of aperture.

4.2 Power supplies, magnets and water cooling

The requirements on power supplies and water cooling of magnetic elements as well as issues related to the deterioration of the magnetic field quality by saturation are treated in the LEP2 design report [3]. A recent study has shown
that after a re-distribution of some of the power converters (to be done in the 98-99 shutdown), both the available power supplies and the magnets, would allow to operate LEP up to 103 GeV with the 102°/90° optics. It thus follows that the hardware available for the start-up in 1999 is fully compatible with the performance presented in this report.

4.3 Limit by RF power

To first order, the maximum possible current in the machine is limited by the available RF power:

\[ P_{RF} \approx 2I_0U_0 \]

For 1999, we shall have 35 klystrons (since 1 is assumed in reserve) providing 0.96 MW each (96 % efficiency of the waveguide distribution system). Adding about 0.5 MW from the conventional Cu-system, it follows that 34.1 MW will be available. The corresponding maximum beam currents (and luminosities) depend on the energy considered, however, the corresponding limits turn out to be above 10 mA (total currents) and shall therefore not be considered here.

4.4 Synchrotron radiation

This section remains unchanged.

4.5 Robinson instability

No modification with respect to [1].

4.6 Beam lifetime

The same assumptions as those presented in Ref. [1] have been included in the present study.

4.7 Limit by cryogenic cooling power

The arguments presented in Ref. [1] are still valid. However the numerical evaluation of the corresponding limits is changed by the modification of two parameters entering the equation for the dynamic load at 4.5 K per RF module containing 4 SC cavities:

\[ P_{cm} = \frac{4V_c^2(E_a)}{(R/Q)Q(E_a)} + \frac{R_m(\sigma_s)}{2k_b}(2I_0)^2 \]

where \( V_c \) is the RF voltage delivered by one cavity (obviously a function of the accelerating gradient \( E_a \)), \( R/Q \) is the normalised shunt impedance of the
cavity, $k_b$ the number of bunches per beam, $I_0$ the intensity in one beam, $Q(E_a)$ the quality factor of the cavity and $R_m(\sigma_s)$ the (bunch length dependent) loss impedance. The actual modifications apply to the last two quoted parameters i.e. $Q(E_a)$ and $R_m(\sigma_s)$. The changes directly follow from the experience accumulated in 1998.

4.7.1 The quality factor $Q(E_a)$

In Ref. [1], a linear dependence of $Q$ as a function of the accelerating gradient was assumed such that $Q=3.2 \times 10^9$ at 6 MV/m down to $Q=2.3 \times 10^9$ at 7 MV/m. Recent measurements on the cavities indicate that this assumption may have been pessimistic. For this reason, it has been agreed to consider a second model, namely that developed for the definition of the specifications for the cavities [3, 4]:

$$Q(E_A) = 10^{(9.806-5.017e^{-2*E_a(MV/m)})}$$

According to this model, the quality factor becomes $Q=3.2 \times 10^9$ at 6 MV/m and $Q=2.85 \times 10^9$ at 7 MV/m. The main property of this new model is thus to exhibit larger Q-values at high gradients. Consequently, the cryogenics requirements will be reduced (see the first term in the equation for $P_{cm}$) and this will allow to operate either at a slightly higher energy and/or with an increased total current in the machine. In order to emphasise the effect of this modification, performance estimates will be presented for both the old and the new model.

4.7.2 The loss impedance $R_m(\sigma_s)$

Measurements performed in 1996-1997 allowed to determine a value of $R_m=16$ MΩ for bunches of about 9 mm in length. Independently of the cryogenics aspect, operation in 1998 has shown that when the higher order mode (HOM) power in the field probe cables (two per cavity) exceeded 8 W, these cables were overheating and eventually burned. At least one of these cables being essential for the control of the cavity, the observed behaviour imposed an intensity limitation for the operation of the machine during the whole running period. During a shutdown, a test to check whether it would be possible to replace these cables “in-situ” was successful. Subsequently, measurements of the requirements of the cooling power were performed on the module equipped with the new cables. It was found that the old cables were contributing significantly to the loss impedance, since the value obtained for the modified module reduced to $R_m=10$ MΩ. As can be seen from the equation of the dynamic load, this reduction substantially changes the maximum possible current which can be considered for the cryogenics budget. As will be shown in the final section presenting the performance estimate as a function of the energy, both the modification on the quality factor $Q$ and...
the installation of new field probe cables, will modify the estimates presented in Ref. [1].

4.8 Limit at higher-order mode power

This section is unaffected by the new set of parameters. It remains true that the HOM power limit is above other thresholds and can thus be ignored in this note, given that the field probe cables will be replaced in the RF modules during the 98/99 shutdown.

4.9 Beam-beam limit

The vertical beam-beam parameter $\xi_y$ achieved in physics this year largely exceeded any previous expectation. A value of $\xi_y = 0.075$ was reached and there was no indication that the beam-beam limit had been reached. A revised estimate has to be made for the future operation. A slightly refined model will be used to compute the actual beam-beam parameter and therefore the performance of the machine. The luminosity is evaluated according to:

$$L = \frac{k_b N f_0 \gamma \xi_y}{2 r_e \beta_y^*}$$

with the beam-beam parameter $\xi_y$ defined as

$$\xi_y = \frac{N r_e \beta_y^*}{2 \pi \gamma \sigma_x^* \sigma_y^*}$$

where $r_e$ is the classical electron radius, $N$ the number of particles per bunch, $\gamma$ is the relativistic factor, $k_b$ the number of bunches per beam, $f_0$ is the revolution frequency, $\sigma_x^*$, $\sigma_y^*$ and $\beta_y^*$ are the beam sizes and the beta-function at the interaction points. The simplest model is to assume that $\xi_y$ grows linearly with intensity up to the point where the beam-beam limit $\xi_y^{max}$ is reached. After this point, the vertical beam size increases linearly with current so that $\xi_y$ remains constant (conventional approach). Measurements of the luminosity show that, in practice, the beam-beam parameter does not change abruptly from a linear growth to a constant value. In fact, when approaching the beam-beam limit, one should rather use a modified beam-beam parameter $\xi_y^r$ which can be parametrised by the following expression:

$$\xi_y^r = \xi_y^{max} (1 - \exp \left( -\frac{A \xi_y}{\xi_y^{max}} \right))$$

The Figure 2 illustrates the model used for the present approach, which follows from both experimental observations collected at 46 GeV and from simulation
results [5]. Up to a beam-beam value of 0.05, the conventional approach is used. Above this value, the modified value \( \xi_y^* \) is used for the evaluation of the luminosity (\( A=1.54 \) in the above exponential). Furthermore, a maximum value of \( \xi_y^{max}=0.08 \) has been retained for the present estimation. As can be seen from the plot, at high \( \xi_y \) values, the conventional model (dashed line) would yield an overestimated luminosity. As far as the horizontal beam-beam parameter \( \xi_x \) is concerned, we approached a value of \( \xi_x=0.05 \) without problems. We shall assume that it is justified to consider only the vertical beam-beam effect in the present study.

4.10 Transverse Mode Coupling Instability (TMCI)

As far as the TMCI threshold is concerned, it is still expected that the limit should be reached with a current of about 1 mA per bunch. In case the total current available would exceed 8 mA, then an option with more than 4 bunches per beam would have to be considered.

5 Numerical results

All the different limits can be independently evaluated and plotted in a luminosity vs. energy diagram. In order to allow a comparison with the results presented in Ref. [1], Table 2 summarises the main modifications between the two studies.

<table>
<thead>
<tr>
<th></th>
<th>Values used in Ref. [1]</th>
<th>Modified values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avail. RF voltage [MV]</td>
<td>2870</td>
<td>2833</td>
</tr>
<tr>
<td>( R_m(\sigma_s) )</td>
<td>16 M( \Omega )</td>
<td>10 M( \Omega )</td>
</tr>
<tr>
<td>Q(6 MV/m) [10(^9)]</td>
<td>3.2</td>
<td>3.2</td>
</tr>
<tr>
<td>Q(7 MV/m) [10(^9)]</td>
<td>2.3</td>
<td>2.85</td>
</tr>
<tr>
<td>( \beta_x^* [m] )</td>
<td>2.0</td>
<td>1.25</td>
</tr>
<tr>
<td>( \beta_y^* [m] )</td>
<td>0.05</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Table 2: Parameters which have been modified with respect to Ref. [1].

The corresponding performance is presented in Fig. 3. It illustrates the limits expected for the 102°/90° optics, \( J_x=1.5 \) and 4 bunches per beam and the previous model for the quality factor of the cavities (linear decrease from \( 3.2\times10^9 \) to \( 2.3\times10^9 \) when going from 6 MV/m to 7 MV/m). The line labelled 12 kW gives the expected limit after the upgrading of the LEP cryoplants implemented in the winter shutdown 98/99. The figure corresponds to the dynamic load capacity at 4.5 K of each of the four LEP cryoplants. The line labelled 6.2 kW gives the dynamic load capacity available in 1998 for comparison, showing the importance of this upgrading. Fig. 4 shows the same behaviour but with the new model for
the quality factor (logarithmic behaviour). Based on these representations, it is possible to highlight the effects of the modifications presented in Table 2:

- The introduction of new boundary conditions for the available voltage (96\% efficiency and one klystron off instead of two klystrons off [1]) results in a somewhat smaller voltage (see Table 2) and thus to a slightly lower maximum energy which will depend on the value of $J_x$ actually used in operation.
- The reduced loss impedance $R_m(\sigma_s)$ implies that, for a given gradient (energy), it is possible to have a little bit more total current in the machine and thus a higher luminosity.
- The reduction of the beta functions at the even interaction points has been successfully implemented during 1998. It yields a higher luminosity.
- The major effect is certainly the assumed modification of the quality factor $Q(E_a)$. As can be seen from comparing Figs. 3 and 4, the latter allows for a significant gain in both energy and luminosity. This sheds some light on the importance this parameter will have on the future performance of the machine.

Independently of these aspects, it remains true that the upgrade of the LEP cryoplants to 12 kW is mandatory for energies around 100 GeV.

Figures 5 and 6 illustrate the expected performance of the machine where $J_x$ has been reduced to $J_x=1.0$ for the two different models of the quality factor. As expected under such conditions, it is possible to achieve a slightly higher energy (less RF voltage required to reach a given energy). However, the essential issue is highlighted by the lines indicating the performance achieved with 6 mA and 8 mA respectively. The effect of the increased emittances is clearly visible on the corresponding luminosity, which is significantly lower than in the case $J_x=1.5$.

5.1 Maximum intensities

Apart from the TMCI limit, the other limits considered in this approach would allow for total currents of the order of 10 mA. The fact that the performance has been presented for 6 and 8 mA in the previous figures is because, as long as the machine is limited in total current, it should be operated with 4 bunches per beam. On top of this, it should be recalled that, so far, a total current of around 6.5 mA has never been exceeded for physics at high energy. It therefore remains to be demonstrated that total currents up to 8 mA can indeed be brought into collisions. However, in the case where higher total currents are possible, then it would be possible to switch to an operation with 6 bunches per beam. For completeness, such a case is illustrated in Fig. 7. It should be emphasised that such a scheme would only come into consideration once the TMCI limit has been reached.
5.2 Interpretation of the figures

In order to avoid some possible confusion, it is briefly recalled how the presented figures should be interpreted:

1. The RF conditions define the average gradient which is available from the RF system.
2. From Fig. 1 it is possible to extract the maximum energy corresponding to this gradient.
3. Depending on the optics conditions ($J_x$ and model for the quality factor) it is possible to read the expected performance corresponding to this energy from Fig. 3 to 6 as a function of the total current.

5.3 Performance estimate

The number of free parameters is too large to allow for a well defined performance prediction. However, the procedure to be applied is rather straightforward, once the peak luminosity $L_0$ has been estimated (from the plots). The integrated luminosity $L_{int}$ can be approximated by

$$L_{int} = L_0 \cdot \eta \cdot T$$

where $\eta$ is a factor describing the global efficiency of the machine (typically between 0.15 and 0.2 from the previous periods of LEP operation) and $T$ is the total time of operation.

6 Conclusions

This report presents an updated version of the performance estimate described in Ref. [1]. The present update introduces the latest values obtained during 1998 into the performance estimate. The main modifications can be summarised as follows:

- New boundary conditions have been introduced for the available RF voltage. The latter slightly reduce the total voltage available for operation.
- The final optics used is the $102^\circ/90^\circ$ optics. The latest values for the beta functions at the even interaction points have been introduced.
- The replacement of the field probes cables in the modules is expected to reduce the loss impedance $R_m(\sigma_s)$. The revised estimate of $R_m(\sigma_s) = 10$ MΩ (for a bunch length of 10 mm) has been introduced.
- The latest estimations of the quality factor Q of the cavities as a function of the gradient have been included. The latter turn out to be very important for the future performance of the machine, since they significantly influence both the maximum energy and the instantaneous peak luminosity.
• As can be seen from the different figures, the cryogenics limit only becomes relevant at energies implying gradients well above 7 MV/m (see vertical dashed line indicating the 7 MV/m limit). It seems therefore reasonable to conclude that the major consequence of all the modifications presented in this note is that the real limitation for the future performance of the machine will be the achievable gradient in the SC cavities.

The arguments presented in this note show that the combined global effect of these modifications is to increase the expected performance of the machine. It thus confirms that, provided a gradient around 7 MV/m is achievable, an integrated luminosity of the order of 1 pb$^{-1}$ per day at an energy slightly above 100 GeV should be within range.

7 Acknowledgements

We are deeply grateful to K. Hübner who strongly encouraged us to write this report. We also thank G. Geschonke and J. Tückmantel for very useful discussions concerning the model to be used for the quality factor $Q$ of the SC cavities.

References


[2] G. von Holtey; *private communication*


[4] G. Geschonke; *private communication*

Figure 1: Required gradient as a function of the energy - 102°/90° optics with the boundary conditions defined in Table 1
Model for the beam-beam parameter $\xi_y$

For $\xi_y < 0.05$: linear model

$$\xi_y = \xi_y^r$$

For $\xi_y > 0.05$: $\xi_y = \xi_y^r (1 - \exp(A \cdot \xi_y - \xi_y^r))$

$$\xi_y^r = 0.08$$

$$A = 1.54$$

Figure 2: Model used for the computation of the beam-beam parameter $\xi_y^r$
Figure 3: LEP luminosity limits for the $102^\circ/90^\circ$ optics - $J_x=1.5$ - 4 bunches/beam - old Q-model
Performance Limits (102\textdegree /90\textdegree optics - J_x = 1.5 - 4 bunches)

\[ Q(E_a) = 10^{(9.806 - 5.017e^{-2} E_a \text{ (MV/m)})} \]

Figure 4: LEP luminosity limits for the 102\textdegree /90\textdegree optics - J_x = 1.5 - 4 bunches/beam - new Q-model
Figure 5: LEP luminosity limits for the 102°/90° optics - $J_x=1.0$ - 4 bunches/beam - old Q-model
Figure 6: LEP luminosity limits for the 102º/90º optics - J_x = 1.0 - 4 bunches/beam - new Q-model
Figure 7: LEP luminosity limits for the $102^\circ/90^\circ$ optics - $J_x=1.5$ - 6 bunches/beam - new Q-model