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An optimised e-p interaction region for LEP and LHC

A. Verdier

Abstract

A very high energy hadron collider LHC, in project at CERN, is intended to be installed in the LEP tunnel. As there will be an overlap in the exploitation of LEP and LHC, it can be envisaged to make e-p collisions. It is shown here that for an electron energy of 60GeV and a proton energy of 7.7TeV, the luminosity reaches $2.8 \times 10^{32} cm^{-2} s^{-1}$. The full LEP RF power is used and electron beam-beam tune shifts are at their maximum. Limitations come from the parasitic mode losses in the superconducting cavities of LEP. The present optimisation process includes the detector design.

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An optimized e-p insertion for LEP and LHC

A. Verdier
CERN
CH-1211 Geneva 23

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1 Introduction

In order to obtain collisions with protons and electrons using LEP and LHC, the electron beam is steered towards the LHC plane and then deflected in order to make head-on collisions, the proton beam being kept in its plane. The topology of this arrangement is shown in fig. 1.

Fig. 1. Insertions layout

At the exit of the LEP arc, an upwards deflection directs the electron beam towards the LHC plane. A second deflection brings it into head-on collision with the proton beam in LHC. After collision, the electron beam is deflected downwards and then steered into the LEP plane. The dipole magnets which make deflections close to the interaction region are called separators because they separate the electron beam from the proton beam thanks to the large difference between their momenta.

A zoom of the central part of fig. 1 is shown on fig. 2. On this figure the aperture limitations due to the detector are shown.

2 Synchrotron radiations

The synchrotron radiation emitted by the electron beam when passing in the separators poses a serious problem because it may disturb the experiment. However it would be impractical to obtain collisions by deflecting the proton beam for two reasons. Firstly strong deflectors prevent from matching the vertical dispersion, secondly the crossing angle is too large and creates an unacceptable excitation of synchrotron resonances [2].

Fig. 2. Arrangement of the detector and the low- β quadrupoles.

It was admitted by the experimentalists that if the critical energy of the photons is below 50keV, most of the photons are easily absorbed. For instance, the vacuum chamber upstream of the experiment is sufficient to protect it against the radiations emitted by the upstream separator [3]. Therefore the separators consist of low field dipoles upstream and downstream of the insertion. A collimator placed upstream of the insertion, just before the insertion doublet, forces the hard radiations to be reflected twice before reaching the interaction point (details in ref [4]).

The present separator arrangement is possible thanks to the large free space between the crossing point and the LHC low- β quadrupoles. This large free space is related with the optimum values of the LHC β -function at the crossing point and the big β values admitted in the low- β quadrupoles for LHC [5].

3 Optimisation of the luminosity

The luminosity L is given by [6]:

$$L = \frac{f_{rev} k_b N_1 N_2}{2\pi\sigma_h\sigma_v} \quad (1)$$

f_{rev} is the revolution frequency, k_b the number of colliding bunches, N_e is the number of particles in the bunches of the electron beam, N_p is the number of particles in the bunches of the proton beam, σ_h and σ_v are the effective beam widths. From formula 1 it is clear that the maximisation of the luminosity requires that the intensities of the beams are made as large as possible. The emittances and the beta-functions at the crossing point should be made as small as possible, this being limited by the admissible beam-beam tune-shifts.

Intensity considerations

The intensity of the proton bunches has a limit of 3×10^{11} protons per bunch imposed both by the injectors and by stability considerations in the LHC. This limit is not influenced by the number of bunches in LHC.

The intensity of the electron beam is related to the maximum RF power in LEP which is assumed to be 32MW at the time LHC is in operation. This makes it possible to keep two beams of 5.15mA (or a single beam of 10.3mA) in LEP at 100GeV [7]. We will scale the beam intensity with the fourth power of its energy when the latter is changed. This is not simple in reality because the power supply of the RF cavities is then done at a low voltage and a high power, which is not the standard operation mode of LEP. For this sort of operation the coupling of the klystrons to the cavities has to be changed. This has not been studied yet. Furthermore there is a basic limitation to having a large intensity in LEP. The bunches passing in the RF cavities loose energy via excitation of parasitic modes of oscillation. This phenomenon is known as ' Higher Order Mode ' losses. According to a recent measurement with superconducting cavities installed in LEP [8], it is presently considered that 2kW could be taken away [9]. However it is not yet known whether some power is dissipated in critical cold elements of the RF cavities (load on the cryogenic system). Therefore the current of the electron beam is limited at a value corresponding to non resonant HOM losses of 1kW, i.e. a current of 154mA. With the above scaling law for the current versus energy, this can be obtained at 51.6GeV. Below this energy , the electron current is kept constant. It can be considered here that the HOM losses are non-resonant because the bunch frequency is about 6MHz .This makes it unlikely that the frequency of the dangerous parasitic modes is an exact multiple of the bunch frequency and it provides, on average, sufficient detuning that the resonant peak of energy dissipation is avoided.

Maximisation of the luminosity

From the intensity considerations, an upper limit of the numerator of formula 1 will be obtained by taking for N_b the maximum allowed value and for the product $k_b N_e$ the maximum value allowed by the RF power in LEP. Maximising the luminosity is then done by minimising the denominator of formula 1. There is a total of six variables to do it : the four β 's and the horizontal and vertical emittance of the electron beam. The lower limits to these variables originate from the following :

- the beam-beam tune-shifts parameters ξ must stay below the upper limits of 0.05 for electrons and 0.006 for protons (single e-p insertion).
- the aperture restrictions in the insertion, which are due to the detector, set lower limits to the β 's.
- the number of bunches must be smaller than 508 [10]
- the transverse size of the electron beam must be larger than or equal to that of the proton beam. It has been observed in the Sp $\bar{p}$ S collider that this is a condition for the relevance of the ξ -limit [12]
- The vertical electron emittance has a lower limit imposed by the separators.

Beam-beam tune-shift parameters

There are four beam-beam tune-shifts parameters : ξ_{xe} , ξ_{ye} , ξ_{xp} , ξ_{yp} [6]. The indices e and p refer to the particles, the indices x and y to the planes. The upper limits to the ξ 's makes four non linear inequalities between the six available variables.

For what concerns the disruption parameter [11] :

$$4\pi\xi\sigma_s/\beta^*$$

it has been checked that it is below the quoted limit [11].

Limits on the β 's due to the aperture restriction in the forward (plug) calorimeter

The arrangement of the forward calorimeter is shown on fig. 2. Due to the boost of the products of the collision in the direction of the proton beam, particles emitted at an angle of 10mrad to the proton beam have to be detected in order to obtain interesting physics results. Taking into account the width of the hadronic showers and the vacuum chamber, the experimentalists agreed that the forward calorimeter leaves a hole of radius 30mm at 5m from the interaction point for the beam.

This aperture limitation of radius r_{cal} introduced by the forward calorimeter will not intercept the halo of the beams if its acceptance is larger than that of the machine arc. Knowing the variation of β around the crossing point, this condition can be converted into another one for β^* :

$$\beta^* > \left[\frac{dr_{arc}}{r_{cal}} \right]^2 \frac{1}{\beta_{arc}}$$

where d is the distance at which r_{cal} is measured. Thus the only insertion parameter on which β^* depends is r_{cal}/d i.e. the angular acceptance of the bore in the forward calorimeter, which is relevant for physics. For a value of r_{cal} of 30mm, and a distance d of 5m, the limits to β^* are below 0.05m for LHC i.e. well below the minimum values acceptable in the LHC insertions. For LEP they are 0.25 and 0.86m in the vertical and horizontal plane respectively. Therefore the aperture restriction due to the forward calorimeter imposes a lower limit to the value of β^* for the electron beam but not for the proton beam.

Practical computation of the maximum luminosity

The numerator of formula 1 is set at its maximum as explained above. From the two formulae for ξ_{xe} and ξ_{ye} we can compute the β_x 's for both beams for given values of the β_y 's, because the proton emittances are given. As the lower limit of β_{ye} is given, the best procedure is then to set β_{ye} at this lower limit, and then to find the value of β_{yp} for which β_{xe} reaches its minimum. At this point all the optics functions involved in formula 1 are computed and the luminosity can be evaluated, with the emittances of the electron beam being set at their minimum values (phase advance in the cells of the LEP arc of 90° and transverse damping partition numbers to their maximum).

It can be checked numerically that the maximum luminosity is always obtained if this procedure is applied.

At this point it has to be checked that the transverse sizes of the electron beam are both larger than or equal to those of the proton beam. If it is not the case, the emittances of the electron beam are increased accordingly.

Then ξ_{xp} and ξ_{yp} are merely used to compute the minimum number of bunches so that they are both below their admitted limits, the electron current being distributed among this minimum number of bunches. If the number of bunches computed this way is larger than 508, the relevant emittance of the electron beam is increased to make it smaller. Increasing the emittance of the electron beam can be done until the dynamic aperture is reached. With the present beam parameters, this occurs only at around 25GeV and hence does not introduce any limitation to the e-p performance.

4 Conclusion

The luminosity for e-p collisions has been computed for an energy of the electron beam comprised between 20 and 100GeV. Is is shown on fig. 3. It must be remembered that the design of the insertion is strictly valid only for an electron energy around 60GeV or below. Above this energy the luminosity given on fig. 3 is an upper limit.

The luminosity curve given in fig. 3 is valid for a proton energy comprised between 2 and 7.7TeV. This is possible because the β^* can be made small enough to compensate for the increase of the emittance of the proton beam when its energy is decreased. In fact, whether small values of

these β^* (see table 2) can be achieved, depends on the design of the quadrupoles for the low-beta insertion, which has not yet been done.

Fig. 3. Luminosity in e-p collisions versus electron energy

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