DEVELOPMENTS OF THE LEP LOW-β OPTICS CONFIGURATION

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Abstract In order to maximize the beam acceptance at injection, the envelope functions β^* at the interaction points are increased by a factor of 3 with respect to physics. Direct injection into the nominal low-β optics would speed-up the LEP fill and simplify the operation and data handling. An account is given of the experiments and achieved results.

The nominal β^*, i.e. $\beta_x^* = 1.75m$, $\beta_y^* = 0.07m$, were obtained from simulation work on the dynamic aperture. It is very tempting to reduce the envelope function as much as possible to gain luminosity. We give some theoretical justifications as well as the experimental results obtained so far.

Introduction

Although some aspects, like the dynamic aperture, remain to be clarified, the LEP optics seems sufficiently well understood that improvements beyond the nominal parameters are being tested. This paper reports on a further reduction of the β functions at the interaction points and on attempts to directly inject into the physics optics.

Nominal optics

At injection the β^*values are respectively 21 cm and 5.25 m in the vertical and horizontal planes at the interaction points. The drift space between the crossing point and the first low-β^*quadrupole is 3.7 m, causing a maximum β of 150 m, similar to its maximum arc value of 136 m.

This optics configuration is kept unchanged during acceleration. It was initially intended to change the β_x^* during acceleration so as to keep the beam-beam tune shifts constant. This refinement has not been implemented so far and does not seem necessary at least for the present beam intensity of 3 to 4 mA total.

The beams are put into collision at physics energy (i.e. presently between 45 and 47 GeV), and then the β^*values are decreased simultaneously to increase the luminosity. The nominal β^*values for physics are 7 cm and 1.75 m respectively in the vertical and horizontal planes. The reason for these values were both high-order chromaticity correction at high energy and quadrupole aperture [1]. The ratio of 25 between the two values is required to obtain the same beam-beam tune shift parameters in both planes for the design emittance ratio of 25. This β^*-ratio is always used.

Further reduction of the low-β function

Motivations

The LEP parameters were essentially optimized for the design energy of 55 GeV [1]. In fact, the optics components had equally to be studied and designed to allow the LEP energy upgrade. The present design of the low-β insertions and of their chromaticity correction should allow operation up to a little less than 100 GeV [1]. A sufficient flexibility was foreseen so that a further reduction of the β^* functions could be feasible.

The exploitation of LEP at the Z_0 energy of 45.6 GeV allows a reoptimization of the machine parameters. Indeed both emittances and rms energy spread are smaller, thus increasing the clearance with respect to the physical and dynamic apertures; The flexibility of the low-β insertion is such that a further reduction of the β^* functions is in fact feasible.

Quadrupole aperture

The residual closed orbit after correction does not increase with the maximum β-function. The reason is that the efficiency of the closed orbit correction is determined by the real beam position and not by the normalized one.

It is thus sufficient to consider the gain/loss in aperture due to the beam size only. The smallest physical aperture is in the insertion doublet when the machine is in the physics configuration of the optics.

The low-β quadrupoles were designed to be usable up to 67 GeV. The criterion used was that the clearance with respect to the good field region should be 10 rms transverse beam sizes :

$$10\sqrt{\beta_{max}\mathcal{E}} \leq r_{good}$$

This criterion is not affected when simultaneously the energy is decreased from 67 to 46 GeV and β^* from 7 cm to 3.2 cm (table 1).

Higher-order chromaticity

The amplitude detuning is weak in LEP due to the arc being arranged in second-order achromats. The non-linear chromaticity should be corrected to allow a stable motion for particles with the largest synchrotron amplitude accepted by the RF bucket i.e. $\pm 6.5\sigma_\epsilon$; σ_ϵ is the rms energy spread of the beam. This ensures that no 3^{rd}-order resonance is crossed during the synchrotron oscillation. The chromaticity correction is performed using six families of sextupoles.

The variation of the tunes with momentum for the nominal machine ($\beta_y^* = 7$ cm) are shown on figure 1. Figures 2 and 3 show the same information for two corrected machines with lower β_y^*:

- $\beta_y^* = 4.3$ cm, providing 60 % improvement in luminosity; the aim is to study this optics for normal operation,
- $\beta_y^* = 2.4$ cm, a target 'one inch machine'.

Given the value of the energy spread at 46 GeV, the criterion on resonance crossing at 6.5 σ_ϵ is fulfilled for all optics.

Implementation

Matched insertion gradients were prepared for β_y^*values as low as 1.8 cm. For this value, the matching of the β-functions starts deteriorating. It is the lower limit that may be reached with the present quadrupole arrangement. The lowest β_y^*value happens

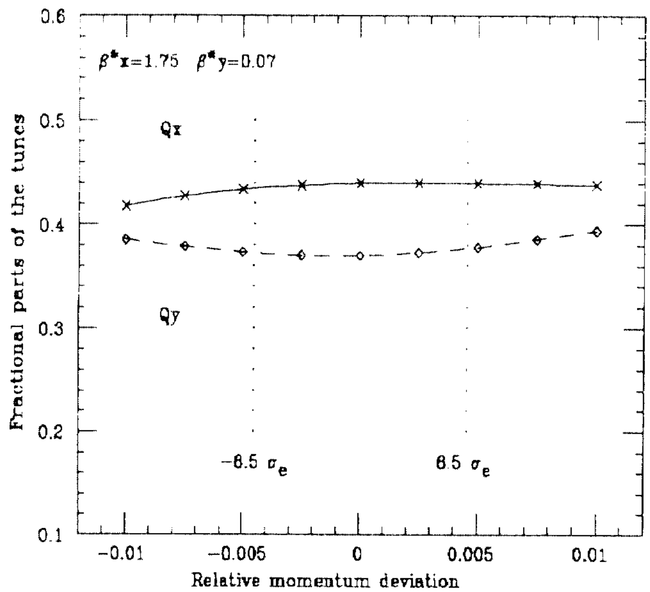

Figure 1: Dependence of the tunes on the energy error in the nominal optics

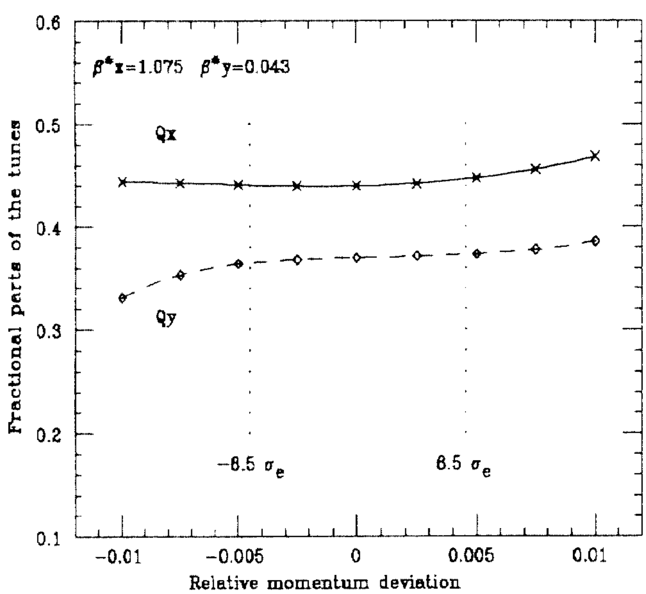

Figure 2: Dependence of the tunes on the energy error in the new 4.3 cm optics

to correspond to the natural bunch length at 45 GeV (1.7 cm). Decreasing β^*_y below this value would not improve the luminosity.

In LEP, the simultaneous change of magnet excitations is done by a time-linear ramp between the starting values and the target values. Therefore it is necessary to fraction any single significant optics change into several intermediate steps so that the machine optics remains acceptably matched during the time-linear ramp [2].

The criteria that were retained are: the tune shifts shall be smaller than 0.008, which is the maximum tune shift due to drifting power converters and magnets during physics; the chromaticity changes shall be smaller than 0.25, so as not to provoke a head-tail instability. The resulting intermediate steps are described in table 1:

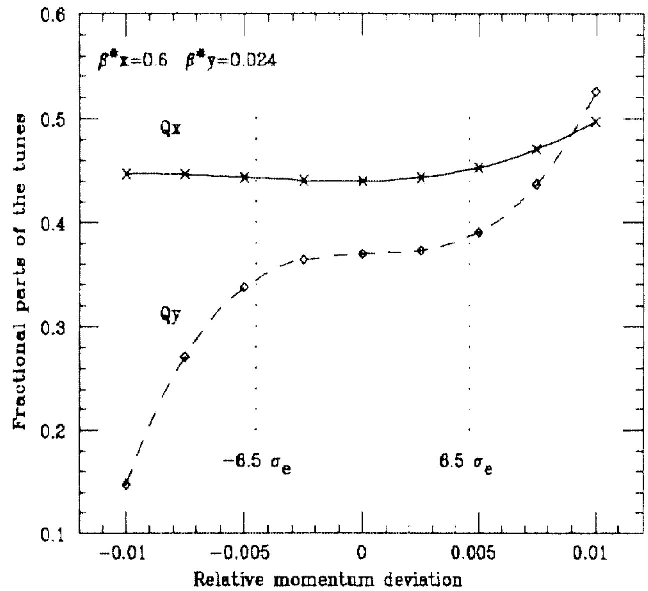

Figure 3: Dependence of the tunes on the energy error in the new 2.4 cm optics

β^*_y	ΔQ_x	ΔQ_y	$\Delta Q'_x$	$\Delta Q'_y$	$\hat{\beta}_x$	$\hat{\beta}_y$
cm					m	m
21-18	-0.0005	-0.0011	+0.02	+0.08	163.7	162.9
18-14	-0.0015	-0.0030	+0.06	+0.02	185.5	162.9
14-11	-0.0017	-0.0027	+0.07	+0.03	217.5	171.4
11-9	-0.0015	-0.0018	+0.06	+0.02	253.5	209.1
9-8	-0.0006	-0.0006	+0.02	+0.08	279.1	235.1
8-7	-0.0009	-0.0008	+0.03	+0.12	312.8	268.5
7-6	-0.0015	-0.0010	+0.05	+0.18	358.5	313.0
6-5	-0.0026	-0.0013	+0.08	+0.28	423.3	375.3
5-4.3	-0.0022	-0.0008	+0.06	+0.22	487.2	436.2
4.3-3.7	-0.0030	-0.0010	+0.07	+0.28	565.4	505.4
3.7-3.2	-0.0030	-0.0007	+0.06	+0.30	649.6	584.1
3.2-2.8	-0.0030	-0.0006	+0.05	+0.30	738.7	667.3
2.8-2.4	-0.0045	-0.0009	+0.06	+0.39	857.8	778.3
2.4-2.1	-0.0040	-0.0008	+0.02	+0.27	976.8	889.3
2.1-1.8	-0.0066	-0.0016	+0.04	+0.77	1135.7	1037.1

Table 1: Variations of the optical functions during the insertion tuning

Machine experiments

At first β^*_y was reduced to 4.3 cm (with β^*_x reduced to 1.075 m in order to keep the ratio of 25) in a machine development session. Very large unexpected tuneshifts occurred between 7 and 6 cm. Then the optics went to 4.3 cm after a closed orbit correction had been performed without too much loss, so that it was possible to measure and correct both tunes and observe the life-time. The latter was measured to be around 20 hours, which was considered as acceptable.

After the demonstration of feasibility, a second machine development session was dedicated to an improvement of the control of the tunes, chromaticity and closed orbits. The reasons for the observed tune and chromaticity deviations are not yet clear. The β^*_yvalue was checked in one experimental insertion by slightly changing the gradient of the strongest quadrupole and measuring the resulting tune shift. It was found insignificantly different from the optical model.

In order to explore the machine limits the validity of the dynamic aperture estimates and the safety margin for operation, a third machine development session was used to investigate a further reduction of the β^*'s. This was done with a medium intensity single beam. The β_y^* was reduced to 3.2 cm with a beam life-time of about 30 hours. A further reduction to 2.8 cm resulted in a beam life-time of the order of 300 s but the closed orbit distortion became large. Since then, no time could be invested in a further better controlled reduction of β_y^*.

The conclusion of these experiments was that the non-linearities do not limit the machine optics at least down to a β_y^* of 4.3 cm, if there is no significant blow-up of the emittances with beam current. The difficulties encountered were all related to linear optics, beam parameter measurement and software procedures.

Initial operational experience

After the second experiment, the end of a physics run which was done with β_y^*= 7 cm was used to check the 4.3 cm optics in operation. The current was about 1 mA total and the 'squeeze' of β^* went well. The luminosity increase was reported by two of the LEP detectors, ALEPH and DELPHI but not by OPAL and L3, although the quadrupole currents were checked to be identical in all four insertions.

Subsequent attempts to use this optics failed, until it was discovered that the tunes and the chromaticities had to be corrected again from 21 cm to 7 cm and 4.3 cm. This non-reproducibility of the magnetic optics is not yet understood. It is sufficiently small not to be too critical for the ramp and squeeze to 7 cm, but becomes more important when the machine sensitivity is increased.

The 4.3 cm optics was then used for a period to gain experience. The values of the specific luminosity are shown on figure 4 as obtained from the experiments. During this period, it was confirmed that two of the four detectors benefited from the expected luminosity increase. However, the two other experiments only observed an improvement by some 10 to 20 %. Measurements of the optical functions around these detectors have not yet allowed to find the source of the problem. A contribution of the parasitic vertical dispersion is presently being investigated.

Injection with tuned insertions

Motivation

A direct injection in the physics optics would drastically reduce the number of intermediate steps and thus reduce accordingly the number of large computer files and the operation time.

Machine experiment

This was tried so far in a single machine development session. After some difficulties to obtain injection, it was possible to accumulate 200 μA in the machine; the efficiency was about an order of magnitude smaller than with the nominal detuned injection optics. During this short experiment, all usual beam parameters were measured and corrected without a significant improvement. A further experiment is foreseen to study this apparent limitation.

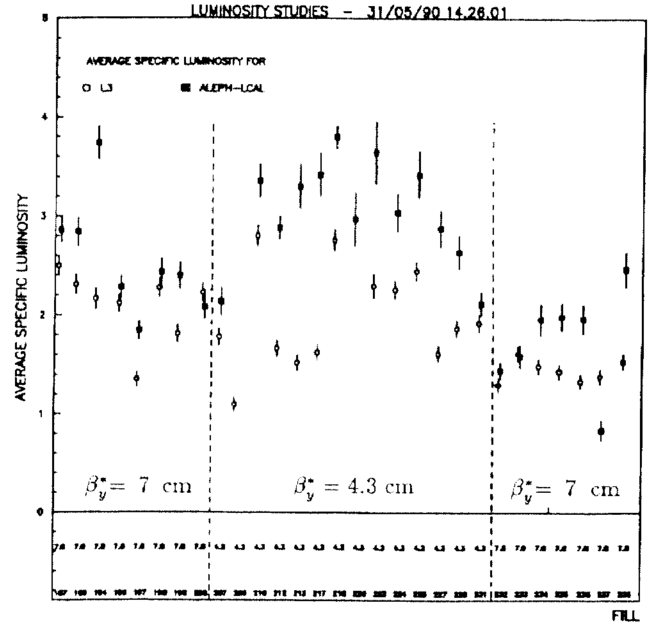

Figure 4: Specific luminosity

Conclusion

The attempts to further reduce the β_y^* have given encouraging results. Besides the puzzling behaviour of the luminosity at two of the four LEP detectors, it remains to be verified that this optics is not limited by the dynamic aperture in case of large emittance; emittance blow-up is indeed observed to vary from run to run. New experiments are foreseen to verify the above-mentioned points, before this stronger focusing becomes operational.

Acknowledgements

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References

[1] LEP Design Report Vol II, CERN-LEP/84-01 (1984).

[2] G. Guignard, J.P. Koutchouk, Y. Marti, F. Ruggiero, A. Verdier, 'LEP optical configurations for injection, acceleration and physics', this conference.