A Candidate Low Emittance Lattice for LEP at its Highest Energies

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Abstract

Several low emittance lattices have been proposed for LEP at its highest energies in order to reduce the horizontal beam size and bring the beam-beam limit within reach. However, optics with high phase advance per cell tend to have strong tune dependence on amplitude that can reduce the dynamic aperture and the beam lifetime, possibly limiting the maximum beam energy or creating operational difficulties. Recently an optics with a phase advance of 17π/30 in the horizontal and π/2 in the vertical plane was developed. This optics has a significantly smaller detuning with amplitude. The results of experiments on this optics are compared with expectations and some details of the first operational experience with this lattice are presented. The potential performance at maximum energy is discussed.

1 INTRODUCTION

At high energy reducing the horizontal emittance (ε_x) can be used as a way of increasing the luminosity. This is done routinely in LEP by increasing the horizontal damping partition number (J_x). However, higher horizontal phase advance (μ_x) in the arc FODO cells has the additional advantage of a smaller momentum compaction (α_c) thereby increasing the maximum energy attainable with a given RF voltage. Various lattices with 90° $\leq \mu_x \leq$ 135° have been tested [1, 2, 3]. The vertical phase advance per cell used was either $\mu_y = 60°$ or 90°.

Of concern in the development of the candidate low emittance lattices was the dynamic aperture which was the subject of many tracking studies, the results of which agreed well with measurements. In practice, however, operation with optics where $\mu_x = 108°$ was hampered by the presence of strong tails (even with a single beam in the machine) [4] which could affect performance.

Low emittance lattices require stronger sextupoles for chromatic correction, increasing the non-linearity of particle dynamics at large amplitudes; the $\mu_x = 108°$ optics show a strong detuning with amplitude and it was demonstrated that this detuning can bring particles onto non-linear resonances, for example $3Q_x$. Transport processes associated with resonances can enhance the tails of the beam distribution and reduce lifetime when ε_x is made large artificially [5]. The objective was therefore to develop an optics with a reduced horizontal detuning [6].

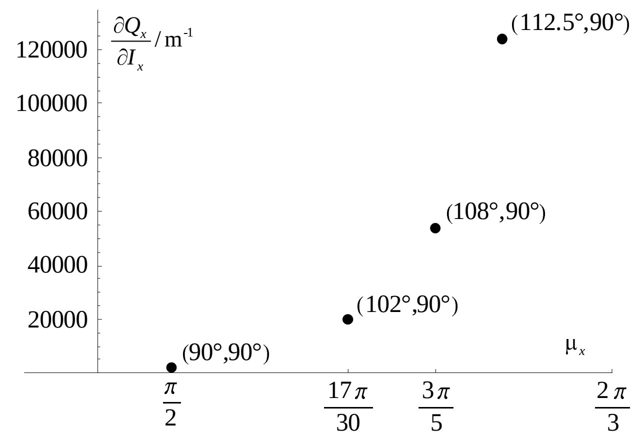

Figure 1: Horizontal detuning with amplitude (for one octant) as a function of μ_x with $\mu_y = 90$.

2 THE $(102°, 90°)$ OPTICS

2.1 Design

In reducing μ_x from 108° to 102°, the horizontal detuning decreases by more than a factor 2 (see Fig. 1). The move to 102° decreases the horizontal tune Q_x by 4 units thus satisfying the usual LEP constraints without modifying the insertions. Furthermore ε_x is increased by only 13% in comparison with the $(108°, 90°)$ lattice.

Although $\mu_x = 102° = 17\pi/30$ is not a simple fraction of π:

- The excitation term of the systematic 3rd order resonance is smaller than for the $(90°, 60°)$ lattice [6].
- The horizontal non-linear chromaticity is corrected by grouping the horizontally focusing sextupoles (SF) into several families [7].

Because the non-linear chromaticity in the horizontal plane is not too strong, the sextupole grouping is not critical for values of $\beta_x{}^*$ down to 1.5 m, the minimum compatible with acceptable background. The grouping of the SF families was optimised as follows: the two main families are constructed so that the correction of the horizontal non-linear chromaticity reduces the horizontal detuning without increasing either the vertical or the cross-detuning $(\partial Q_y/\partial I_x)$ terms. Besides this, two sextupoles per octant are powered independently to allow the optimisation of the horizontal detuning. The final sextupole scheme for the

	1 SF family			3 SF families			
	Mean	Median	σ	Mean	Median	σ	Unit
Horizontal dynamic aperture, $\sqrt{A_x}$	2.39	2.41	0.15	3.38	3.42	0.25	$\sqrt{\mu\mathrm{m}}$
Vertical dynamic aperture, $\sqrt{A_y}$	1.18	1.18	0.09	1.19	1.18	0.08	$\sqrt{\mu\mathrm{m}}$

Table 1: Predicted dynamic apertures determined from the optics evaluation procedure. The dynamic aperture is related to the maximum stable initial action by $A_x = 2I_x^{\max}$ with units such that the phase space average $\langle I_x \rangle = \varepsilon_x = 40.3\,\mathrm{nm}$.

whole machine has a total of three SF families and two SD families. The two SD families correct the vertical non-linear chromaticity.

The cross-detuning of the $(102^\circ, 90^\circ)$ lattice is smaller than that of the $(90^\circ, 60^\circ)$ lattice by a factor 2, thereby increasing its dynamic aperture. As a result of the sextupole optimisation, the horizontal detuning of the 102° optics can be made a factor 20 lower than that of the 108° optics.

2.2 Evaluation

The optics has been rigorously tested following an established Monte-Carlo procedure that has produced good statistical agreement with measurements on previous optics. An ensemble of 30 imperfect machines is generated with realistic random field errors, tilts and misalignments in all magnetic elements. The closed orbit, coupling from experimental solenoids, interaction point optics and tunes are corrected. The orbit and optics of e^+ and e^- are very different because of the effects of strong synchrotron radiation and the distribution of RF cavities. So they are computed separately.

Four-dimensional (3 action variables and the synchrotron phase) scans [2] are carried out to determine the distribution of dynamic apertures. This tracking is done with the deterministic part of the synchrotron radiation to generate damping. Finally, the beam core distribution in 6D phase space is found by tracking with quantum fluctuations. This includes the effect of higher-order synchro-betatron resonances [8] on the vertical emittance, ε_y^q. The usual linear calculation, ε_y^0, includes only the first-order couplings.

These studies show that the $(102^\circ, 90^\circ)$ optics is qualitatively and quantitatively similar to other optics that have performed well in LEP. The predicted dynamic apertures are quoted in Tab. 1. Values are quoted for two sextupoles schemes, one of which uses one SF family, the other three sextupole families. The horizontal dynamic aperture is significantly larger in the second case. Part of the reason for this is that with one SF family a resonance structure at large amplitude modifies the radial transport mechanisms, enhancing the beam tail when ε_x is blown-up. The three-SF scheme moves the resonance outside the dynamic aperture, now determined by cross-detuning and radiative beta-synchrotron coupling [2], suppressing the tail-enhancement.

These results agree well with measurements of dynamic aperture in 1997 [4], by the standard collimator method, which gave $(\sqrt{A_x}, \sqrt{A_y}) \simeq (2.6, 1.4)\,\sqrt{\mu\mathrm{m}}$ (at 90 GeV, one SF family), to be compared with predicted means of $(2.74, 1.47)\,\sqrt{\mu\mathrm{m}}$ for the $(102^\circ, 90^\circ)$ optics tested then.

3 FIRST EXPERIENCE IN 1997

The presence of strong tails with the 108° optics implied the need for tests with the proposed $(102^\circ, 90^\circ)$ lattice before using this optics operationally. However, the sextupole configuration available at that time did not allow for a proper correction of the non-linear chromaticity. Thus a single family of sextupoles was used in the horizontal plane. During these tests, the horizontal detuning of the $(102^\circ, 90^\circ)$ optics was varied by trimming the strengths of the available sextupoles. The horizontal detuning ($\partial Q_x/\partial I_x$) was varied between 1.2 10^4 and 6.0 10^4 m^{-1}, the upper value corresponding to the value of the $(108^\circ, 90^\circ)$ optics used in 1996. A measurement of the acceptable maximum horizontal emittance was made by artificially increasing ϵ_x (by means of a negative RF frequency shift) to the point where the lifetime dropped to about one hour. These measurements confirmed that the maximum possible horizontal emittance is reduced when the horizontal detuning is increased [9]. The overall behaviour of the $(102^\circ, 90^\circ)$ optics was as expected.

Based on these encouraging results, a re-cabling of the sextupole families was performed towards the end of 1997, to allow a realistic test which included performance with colliding beams. With the new sextupole configuration, a $(102^\circ, 90^\circ)$ optics was tested for one week in November 1997. The maximum single-bunch intensity was $610\,\mu\mathrm{A}$, comparable to that previously achieved with the $(90^\circ, 60^\circ)$ optics. After some time spent improving the beam-beam tune shift and the luminosity, 4 fills were put into collision with high intensities (4.1–5.1 mA in two beams). The beam-beam tune shift reached 0.053 with a good lifetime. Low chromaticity ($\simeq$ 2) was necessary to avoid low lifetime and beam losses in the vertical plane. High chromaticity increases tune-shifts and leads to particle losses on resonances. It was also demonstrated that high chromaticity enhances the population of particles in the beam tails leading to losses if the acceptance is too small or if the collimator settings are too tight.

Comparison between the performance with $(90^\circ, 60^\circ)$ and $(102^\circ, 90^\circ)$ is shown in Tab. 2. It can be seen that the $(102^\circ, 90^\circ)$ performance for the same energy was as good as the best achieved with an already proven optics.

Photon and off-energy background at 92 GeV were very acceptable, except for the off-energy background in the OPAL experiment. This was probably due to abnormally high vacuum pressures. Photon background rates per mA of beam current, with comparable emittances, were generally smaller by 30% to 50% with the $(102°, 90°)$ optics as compared to the $(90°, 60°)$. Off-energy rates were about the same [10].

optics	J_x	Itot [mA]	ε_y [nm]	ξ_y	L [10^{30} cm^{-2} s^{-1}]
$(102°, 90°)$	1.56	4.8	0.29	0.053	44
$(90°, 60°)$	1.6	4.5	0.23	0.055	50

Table 2: Best fills in 1997.

4 INITIAL EXPERIENCE IN 1998

The $(102°, 90°)$ optics developed for 1998 differs from that tested in 1997. It has a different sextupole configuration (see section 2) and allows the horizontal detuning ($\partial Q_x/\partial I_x$) to be varied over the range 0.28 to 1.4 10^4 m^{-1}. The second major modification is that a reduction of β_x^* from 2.0 m to 1.5 m has been implemented.

The new $(102°, 90°)$ optics has been successfully commissioned. The calibration of the LEP detectors at 46 GeV has been performed with this lattice at relatively low intensities (to minimise beam-beam effects linked to the low emittance). Presently, the $(102°, 90°)$ optics is operated at 94.5 GeV. The total intensities brought into collisions have been increased in steps (presently 4.5 mA) in order to cope with RF and cryogenics limitations. The horizontal β-squeeze has been commissioned without any difficulties. At present the $(102°, 90°)$ optics is performing according to expectations and the record performance obtained in 1997 should be reproduced as soon as the total current reaches 5 mA.

5 FUTURE PERFORMANCE

Until the end of 1997, the move to a low emittance lattice like the $(102°, 90°)$ optics would not have been easily justified by performance considerations: for the same values of β^* functions, a $(102°, 90°)$ optics with a J_x=1.2 yields the same performance as a $(90°, 60°)$ optics with a J_x=1.5. The improvement would be the increase of J_x for the $(102°, 90°)$ optics to the value of 1.5. Although not negligible, this potential gain of 25 % has to be compared with the possible additional difficulties when moving from a well established optics $(90°, 60°)$ to a inherently more difficult optics in terms of beam-beam effects and reduced dynamic aperture.

The advantage of a low emittance optics emerges when the performance of the machine at very high energies is considered. In this case, the available cryogenics power becomes the relevant, limiting, parameter. The lower momentum compaction factor of a low emittance lattice then becomes important, and at 100 GeV [11] the $(102°, 90°)$ optics has a potential performance exceeding that of the $(90°, 60°)$ optics.

6 CONCLUSIONS

A low emittance optics with a phase advance of 102° per cell in the horizontal and 90° in the vertical plane has been developed and commissioned. This optics has significantly smaller detuning with amplitude, a large detuning having proved to be the source of operational problems with low emittance lattices with higher horizontal phase advance. The measured dynamic aperture is as expected, the importance of the detuning was demonstrated and measurements show acceptable transverse tails. Tests and subsequent operation have demonstrated that the achievable maximum bunch intensity and the luminosity performance are comparable to the well established operational optics. The $(102°, 90°)$ optics gives a slightly higher energy for a given total RF voltage and has a potentially higher performance at the highest energy achievable by LEP.

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