First experience with a low emittance lattice for the LEP energy upgrade programme

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Abstract The operation of LEP in its second phase with higher energies requires a low emittance lattice. To achieve this, a new lattice with a phase advance of 90° per arc cell was developped which should give a horizontal emittance as low as 2 nm rad at injection. First operational experience with this new lattice is presented. The momentum compaction factor α is smaller than for the nominal lattice used for the operation of LEP and as a result, the r.m.s. bunch length is 3 mm, i.e. only half the usual value. Consequently, the high frequency range of the impedance becomes important and introduces some unexpected phenomena like transverse instabilities. Qualitative descriptions of the observed instabilities and the possible cures are presented. Novel methods used for the beam observation were a great help to understand the underlying mechanisms.

1 Introduction

In 1994, it is planned to operate LEP at energies around 90 GeV to allow for the production of W^+W^- pairs. This new mode of operation requires a smaller horizontal emittance to reach the required luminosities at the higher energy. This can be achieved by a stronger focusing so a lattice with 90° phase advance per arc cell in both planes has been developed [1].

This paper summarizes both the accumulated experience and the main results obtained during the commissioning of this new optics. The actual aim of these studies can be summarized as follows:

- Demonstrate that machine and beam parameters (emittances, dispersion and bunchlength) correspond to the expectations.
- Identify possible problems and cure them.
- Prove that the lattice can be made operational under reasonable physics conditions.

It was not obvious that the latter could be achieved because the dedicated machine experiment sessions had to take place between normal 60° physics runs. As a consequence, some of the available hardware did not correspond to what is foreseen for the future operation of LEP. In particular, problems could be expected with the following systems:

- Tilted quadrupoles in the arcs for coupling compensation.
- Collimation around experimental areas.
- Sextupole arrangement with six families for chromaticity correction.

The consequences of these constraints are discussed and the solutions are presented.

2 Experimental procedure

All studies were performed between normal physics runs and any modification made had to be reversible.

Injection

The SPS provides electrons and positrons for LEP and in order to obtain a good injection efficiency, the parameters of the transfer line have to be matched to the main ring parameters. This was done by changing the transfer lines from the SPS into LEP to a phase advance of 90° per cell and by adjusting injection region in the LEP main ring to optimise the accumulation rate. This manipulation can easily be performed and reversed whenever it is needed.

RF requirements

The experience gained during normal operation showed that it is preferable to work with a relatively high synchrotron tune (i.e. $Q_s \approx 0.085$ at injection) and to keep it constant during the ramp. With the smaller dispersion of the 90° lattice, more RF voltage is required to fulfill this request. At the top energy of 46 GeV a total RF power of 360 MV was necessary.

Ramping and squeezing

During the normal operation of LEP the energy is ramped and the beta functions at the even interaction points are reduced simultaneously to keep the beam-beam effect small during ramping. This procedure works well for the 60° lattice and we decided to use the same strategy for our experiments. One of the problems is that it is increasingly difficult to identify whether deviations from the expected behaviour (e.g. closed orbit) are due to the energy change or the change of the optics in the interaction region. For the commissioning of our optics we have slowly stepped through the different parts of the ramp and squeeze and carefully corrected the closed orbit, tune values and chromaticity. Details about the procedure can be found in [3].

Orbit correction

With an increased phase advance, the correction of the closed orbit might have turned out to be more difficult. With 90° phase advance (instead of 60°), the orbit is undersampled and this could make an adequate correction more delicate. Such a problem is particularly important for the LEP energy calibration with polarization, where the requirements for a good orbit are very strong. During our MD sessions, we used the standard orbit algorithms available for the normal operation of LEP. It was no problem to correct the orbits in both planes to a precision of about 1.0 - 1.2 mm r.m.s. No attempt was made to improve beyond these values.

Beam instrumentation

For measuring the beam parameters we have used the usual LEP beam instrumentation. An exception is the measurement of the bunch length which is of great importance for the 90° lattice. For this measurement we have used a fast optical device known as a streak camera [4]. This also allows the observation of instabilities and the logging of the measurements.

Beam separation

The beams were separated using the normal electrostatic separators. At the top energy the separation bumps around the interaction points were not perfectly closed (with an r.m.s. $\approx$ 0.3 - 0.4 mm) and the luminosity had to be optimised by scanning the two beams against each other.

3 Expected and measured machine parameters

Transverse beam dimensions

The main effects of a 90° phase advance are the stronger focusing and a smaller dispersion function which together result in a reduced horizontal beam size. The value expected for the horizontal emittance is $\epsilon_x = 12.3$ nm at the present maximum energy of 46 GeV. All beam sizes were measured with the synchrotron light monitors at different positions in the ring with different betatronic functions and dispersion. After a correction for a diffraction effect was applied, we obtained a horizontal emittance of $\epsilon_x = 13$ nm, in excellent agreement with the expectations. The vertical emittance was measured to be $\epsilon_y \approx 0.7$ nm indicating an emittance ratio of about 6%. However, the correction for the diffraction effect is of same order of magnitude as the emittance and these numbers have consequently a rather large uncertainty.

Residual dispersion

The dispersion was measured using the closed orbit measurement system and the residual vertical dispersion in the arc was found to be about 10 cm, whereas it was about 4 cm in the straight sections [5].

Bunchlength

One of the most obvious changes due to the new optics is the bunchlength. The theoretical value at injection is as low as $\sigma_s = 3$ mm. Even at low intensity, the streak camera indicated values around 5-6 mm. The difference is thought to be related to some noise in the RF system producing the observed lengthening.

Non-linearities

Detailed scans of the tunes as a function of momentum have been performed. The measurements can be reproduced very accurately by including an octupolar component of 0.1 % and a decapolar component of 0.3 % ($\Delta B/B$ at 59 mm), into the model. However, the magnitude of these components are between one and two orders of magnitudes larger than those measured on LEP magnets. Nevertheless, assuming these components are justified, we could explain the observed larger momentum acceptance of the 90° optics compared to that with 60° phase advance. The dispersion of the 60° optics is two times larger and consequently the tuneshifts of off momentum particles are larger since they scale with the second (octupole) and third (decapole) power of the dispersion.

Beam-beam and luminosity

During our last MD, eight bunches of about 90 μA/bunch were brought into collision. After only partial compensation of the machine coupling, the three LEP experiments running at that time indicated a specific luminosity (luminosity divided by the bunch currents) around 10 (in units of $10^{30}\text{cm}^{-2}\text{s}^{-1}\text{mA}^{-2}$). After a scan of $\pm$ 5 μm, of the two beams against each other in one of the interactions points, it increased to 13 which corresponds to a luminosity of about $1.6 \cdot 10^{30}\text{cm}^{-2}\text{s}^{-1}$. For comparison, the specific luminosities achieved with the 60° optics range from 4 to 6. From this luminosity, one can evaluate the corresponding vertical beam-beam tuneshift and one obtains $\xi_y = 0.027$. Considering that this value obtained with only 90 μA/bunch is already quite large, any extrapolation for achievable luminosities at higher currents is rather difficult. With the pessimistic assumption that one is already in a beam-beam limited regime, one sees that luminosities at least comparable to those achieved with the 60° optics can be envisaged. Artificially increasing the emittance (e.g. with emittance wigglers) and controlling it during the run might give an improved integrated luminosity.

Background conditions in experimental areas

The particle background was measured in physics conditions during one of our experiments. Problems due to the unfavorable phase advances for the collimator positions were expected. Except in one of the experiments (bad local closed orbit) the background rates were however very similar to those obtained during normal running if the measurements are scaled to the nominal current of 3 mA.

It can be expected that these rates can be further improved by a proper phase advance for the collimators and a careful fine adjustment of the collimator jaws around the closed orbit.

Chromaticity correction

A collider with low-β insertions and integer tunes near a multiple of the superperiodicity of the machine requires many sextupole families per plane for the chromaticity correction. Fortunately, with the selected integer tunes (91,97) a chromaticity correction with only two families could be envisaged. With such a simplified correction scheme, the beam is not expected to cross any low order resonance for synchrotron oscillations with amplitudes up to 6 σ_E at 46 GeV, which should guarantee a good luminosity lifetime. This behaviour is confirmed by experimental observation.

Coupling

The coupling observed between the two planes was rather high and it is well known that the coupling in LEP is very sensitive to the closed orbit and the settings of the tilted quadrupoles. The coupling was measured qualitatively by observing the beam dimensions on the synchrotron light monitor. We first tried to reduce the coupling by global and local orbit corrections and a reduction of the closed orbit to a vertical r.m.s. of about 0.9 mm reduced the vertical beam size by about a factor two. A second improvement was achieved by using two sets of orthogonal skew quadrupoles powered such as to compensate either the real or the imaginary part of the C^- coefficient [6]. Machine coupling was very efficiently reduced by compensating the imaginary component.

4 Instabilities

With the much shorter bunchlengths inherent to the 90° optics, lower thresholds for instabilities could be expected. Indeed, in the first series of experiments (no wigglers, measured σ_s=6 mm), a very fast and strong instability prevented us from accumulating more than about 150 μA/bunch. By lengthening the bunches with both damping wigglers (resulting σ_s=10 mm) and polarization wigglers (σ_s=18 mm) we could accumulate up to 450 μA and 600 μA respectively. At the highest intensity, we then hit again a fast and strong transverse instability, which we believe is a manifestation of the transverse mode coupling instability (TMCI). However, the most striking effect observed during our bunchlength manipulations was the onset of a transverse m=1 head-tail instability predicted by theory but never observed experimentally so far. By carefully adjusting both the bunchlength and the chromaticity, the adverse effect of the head-tail instability could be overcome. It should be stressed that the availability of the streak camera proved to be an essential ingredient in both the identification and the cure of this instability.

5 Conclusion

The commissioning of a new 90° optics during dedicated MD sessions has been extremely successful. All the objectives have been reached, namely:

- Previously observed intensity limitations at low current have been understood and cured.
- A complete ramp with simultaneous squeeze has been established.
- Machine and beam parameters agree with the expectations.
- Specific luminosity achieved is two times larger than the maximum value obtained with the 60° optics.
- Background conditions (scaled to high intensities) proved to be comparable to those usually achieved with the 60° optics.

All these considerations clearly indicate that the 90° optics could be made operational much earlier than foreseen. Even in the case where the operation would be beam-beam limited there is a good indication that one could gain in terms of integrated luminosity. For these reasons, one could envisage with a reasonable optimism that such an optics could be advantageously used for LEP as early as the 1992 running period.

References

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