LEP OPTICAL CONFIGURATIONS FOR INJECTION, ACCELERATION AND PHYSICS

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Abstract A LEP run, from injection to physics, is defined by ~ 10 intermediate states called optics. Each of them is characterized by a cell phase advance, the betatron tunes, the β^*'s , a chromaticity correction ,...

These states have been chosen to allow linear interpolation between them. At injection, the low-β insertions are detuned by a factor of 3 to minimize the sensitivity of the machine.

The acceleration from 20 to 45.6 GeV is made at constant detuned low-β optics. However, as there are spurious field components which are energy independent, the quadrupole and sextupole strings are readjusted and the dispersion suppressors rematched at intermediate energies. At top energy, the low-β insertions are tuned progressively. This operation requires 6 matched intermediate steps to limit the mismatch due to the linear interpolation.

The whole process was conveniently simulated with MAD7 to determine the required number of intermediate steps. The actual optics was found reasonably close to the model.

Introduction

The LEP ring is made of a sequence of optical modules which are specialized in their functionality [1]:

- the arcs, for beam transport, tune and chromaticity control,
- the dispersion suppressors, which match the arc to the RF straight-sections,
- the RF straight-section, providing FODO cells with a minimum of the average β,
- the insertions, with two configurations (conventional or superconducting final focus) and variable β^* at constant phase advance. The betatron phase advance may be varied to change the integer part of the tunes.

This paper describes how these optical modules are controlled during a LEP cycle.

The LEP cycle

The LEP cycle, of a duration of 4 to 8 hours, is made of a sequence of four operations:

1. injection and accumulation at 20 GeV,
2. acceleration to 45.6 GeV (called ramping),
3. insertion tuning and preparation for the physics,
4. physics data taking.

Optical modifications or manipulations are carried out in the three first steps. The set of magnet/lens excitations defines a LEP optical configuration, called an optics for short.

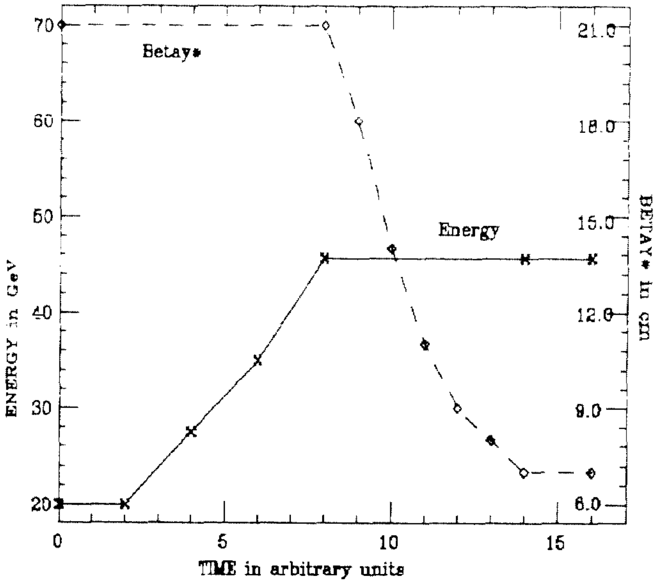

Figure 1: The LEP cycle

Injection

Design Parameters

The betatron phase advance of the arc FODO cell has for long [1] be set to 60°. This choice provides, using six interleaved families of sextupoles, a large dynamic acceptance at injection. By further increasing β^* by a factor of 3, the maximum of the β function in the insertions is reduced to its arc value. It increases the machine acceptance for orbit imperfections and betatron oscillations resulting from the injection process as well as the dynamic acceptance.

The betatron phase advance is kept constant in the insertions, irrespective of their tuning. The tunes were initially chosen to be:

$$Q_x = 70.42 \qquad Q_y = 78.35 \qquad Q_s = 0.07$$

If the lattice were perfect, the injection optics would only differ from the physics optics by the tuning of the insertions and the corresponding adjustment of the arc sextupoles.

However, imperfections in the LEP lattice, identified partly in an injection test carried out one year before the commissioning and during the commissioning proper led us to modify some optics parameters.

Modifications following the injection test

During the LEP injection test [2], betatron phase advance measurements carried out over one octant [3] revealed a small deviation ($\mu_x = 58.5°$, $\mu_y = 61.8°$) with respect to the expected 60°. Left uncorrected, this deviation would have caused a tune split of 2! Field measurements showed that the dipole field was slightly distorted by a very thin magnetized layer of Ni, deposited on the vacuum chamber in the process of welding the lead shield. They further showed that other field components were present (mainly sextupoles).

The early detection of the parasitic fields allowed to partially compensate the higher-order component by shimming the dipoles.

The quadrupole component measured after this shimming was taken into account when rematching the standard cell to obtain a phase advance of exactly 60° in both planes. The dispersion suppressors were rematched accordingly to the new cell.

In the injection insertions, shorter and stronger dipoles are installed to allow for some space for the septa and kicker magnets. The parasitic integrated quadrupole is thus weaker in the injection cells. The resulting mismatch was compensated by a proper excitation of the two nearby dispersion suppressors.

The sextupole component was compensated using the SF's and SD's configured in two families. It was checked that no significant higher-order effects were thus introduced.

Modifications following the commissioning

The injection test, limited to one LEP arc (about 10 PU's) did not allow a sufficient sensitivity to identify another spurious field component which revealed itself during the commissioning. In addition to the right multipoles, skew multipoles were observed to excite the coupling resonance [4]. Given their distribution which is largely 8-fold symmetric (i.e. the symmetry of the dipoles), the closest difference resonance, $|Q_x - Q_y| = 8$, was so strongly excited that it was difficult to distinguish the horizontal and vertical modes. The resonance strength is indeed estimated to be $|C| \approx 0.5$.

Several iterations, based on simulations and experiments, were necessary to select another tune split and the best technique to achieve it. In its present version, the tunes are:

$$Q_x = 71.38 \qquad Q_y = 77.28 \qquad Q_s = 0.085$$

The cell phase advance was kept at exactly 60°. The parasitic vertical dispersion

$$D_y(s) = \frac{\sqrt{\beta_y(s)}}{2\sin\pi Q_y} \int \sqrt{\beta_y(\sigma)} K_{skew}(\sigma) x(\sigma) \cos\left[\pi Q_y - |\mu(s) - \mu(\sigma)|\right] d\sigma$$

largely cancels for this phase advance. The linear coupling resonance $|Q_x - Q_y| = 6$, was compensated by means of the solenoid skew quadrupole compensation scheme [5].

The change of tunes by one unit was achieved by changing the focusing in the non-experimental low-β insertions. This solution minimized the number of modifications to the previously used optics. It was however not possible to maintain the ratio β_x/β_y equal to the emittance ratio:

Optics	β_x m	β_y m	β_x/β_y	Emittance ratio
Design	19.50	0.78	25	25
New	20.00	1.4	14.3	25

The beams are however separated at these positions and this change would only have a consequence in case of a break-down of the separators.

The fractional parts of the tunes have been chosen by 'the machine', to maximize the accumulated current.

Acceleration from 20 to 46 GeV

The design acceleration scheme assumed that the machine performance would be limited by the beam-beam effect. In this case, an optimal acceleration should keep constant the strongest beam-beam effect. For separated beams, the strongest disturbence is the horizontal beam-beam detuning, which can be kept constant if $\gamma\beta_x^* =$ constant. This is equivalent to a gradual tuning of the insertions in the horizontal plane, while accelerating. The vertical tuning was planned to be initially carried out at the end of the acceleration to decrease the sensitivity of the optics.

For commissioning purposes, it is important to reduce the complexity of operation as far as possible. Following the reasonable assumption that the performance would not be rapidly limited by the beam-beam effect, the acceleration was prepared at *constant optics* and constant synchrotron tune.

An acceleration is specified by a sequence of intermediate states. Each state is defined by an energy, an optics (specified in normalized strength), an RF voltage and a time interval to reach the next state. Between states, all controllable quantities are *linearly* interpolated.

If all magnetic fields would scale with energy, there would be no need of intermediate states, but for the RF voltage. However, the field imperfections in the dipoles do not scale with energy (fig. 2).

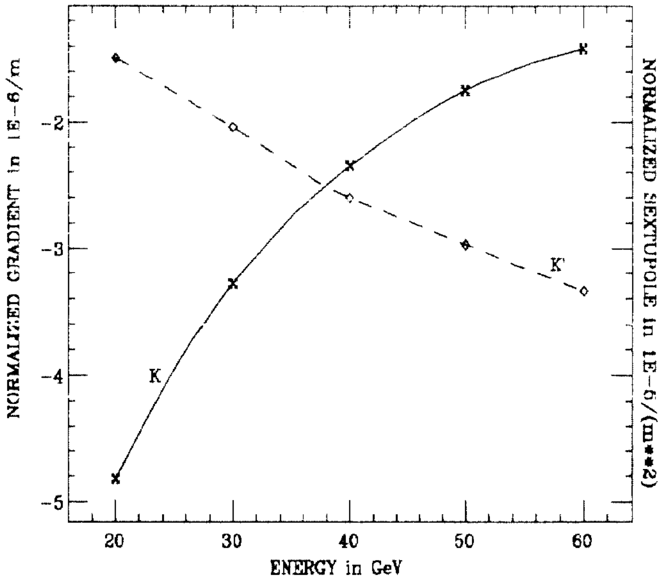

Figure 2: Energy dependence of field imperfections

A direct interpolation from 20 to 50 GeV would have given a large detuning and chromatic error (fig 3), as well as some β mismatch. The number of intermediate states (2) was chosen as small as possible to save memory space, while limiting the detuning to $\Delta Q < 0.008$ and the chromaticity error to less than 0.25 units. The tune tolerance of 0.008 had been defined as the maximum tune drift acceptable for physics. The chromaticity tolerance of 0.25, around its design value of 0.5, allows to keep the chromaticity positive while not exciting higher-order head-tail. The most sensitive parameter, the tunes, are shown on fig 3 before and after matching. The chromaticity error and β-beating are insignificant after matching. The dispersion suppressors where matched for each intermediate step to avoid any β beating.

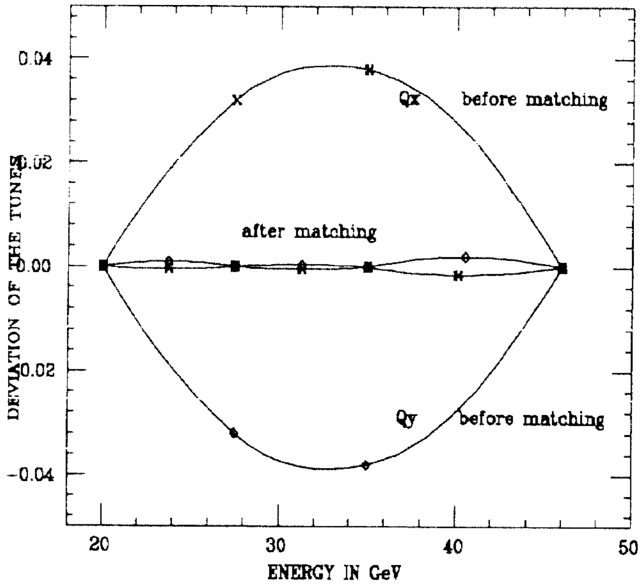

Figure 3: Mismatch during the acceleration

Insertion tuning

The tuning of the experimental insertions is done at constant energy. However, the path between $\beta_y^* = 21$ cm and $\beta_y^* = 7$ cm is not a linear function of the gradients and still requires a number of matched intermediate states.

The most sensitive quantities are the tunes and even more the chromaticities. By introducing 5 intermediate states approximately equidistant in $1/\beta_y^*$, it was possible to maintain the required tolerances. The tunes and chromaticities are shown on figures 4 and 5 before and after matching the intermediate states.

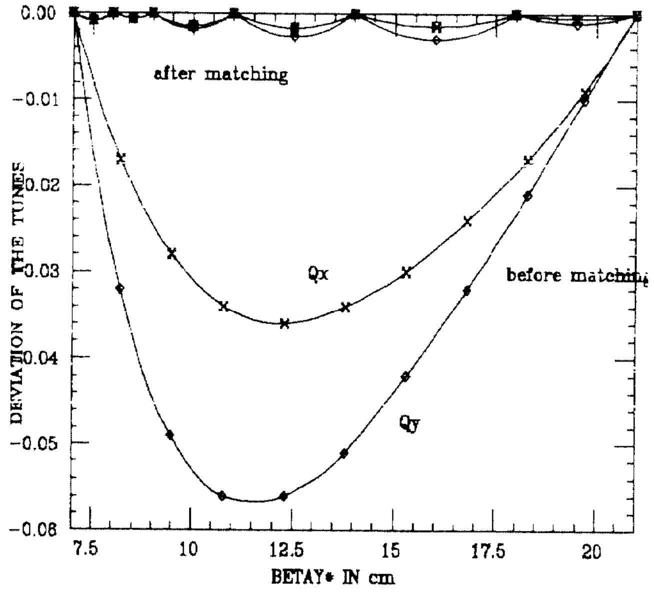

Figure 4: Mismatch during the insertion tuning: tunes

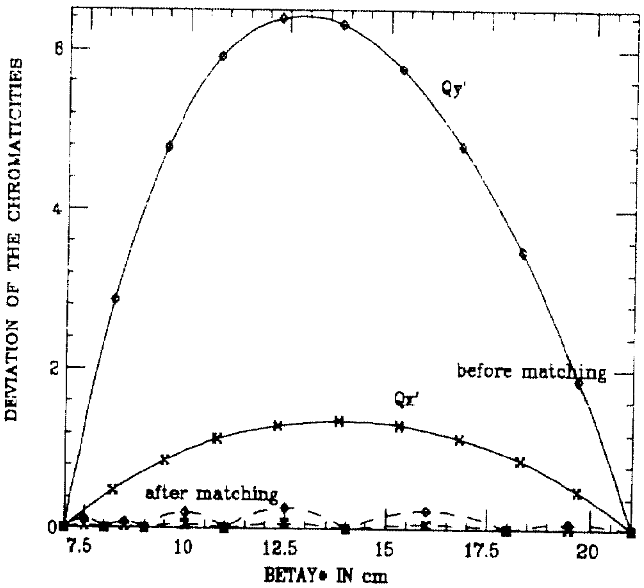

Figure 5: Mismatch during the insertion tuning: chromaticities

Conclusion

The optical properties of the real LEP are very close to the prediction of the optical models. The imperfections which have been discovered could rapidly be overcome before and during the commissioning. This is largely due to the basic LEP design; its modularity allowed a simple and rapid answer to unexpected situations. The power of the optical program MAD [6] was put in full use, especially to match the intermediate steps and linearly interpolate between them. With the two possible configurations of the insertions and the intermediate optics, the LEP optics library already includes some 140 operational possibilities.

Acknowledgements

The magnetic measurements of figure 2 were carried out by J. Billan.

References

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