CURRENT TOLERANCES FOR LEP MAGNET POWER CONVERTERS

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1. Summary

The excitation tolerances for the LEP power converters are important in the machine design. Three types of tolerances are discussed. The short term stability includes setting error, short-term current drift and current ripple. The long-term reproducibility corresponds to the overall error over a time scale of one week. Lastly, the field tracking error covers the current variation during energy ramping. The implications of excitation tolerances of the different types of LEP magnets on the machine performance are studied in order to establish the retained criteria, for instance on the tune and chromaticity variations. Possible means of control, such as field measurement systems, tune control loop and transverse feedback are considered to prevent the risk of defining too restrictive tolerances.

2. Introduction

The definition of current tolerances for the LEP magnet power converters (P.C.) is an important aspect of the machine design. Current tolerances are grouped into three families according to the underlying driving mechanism : short-term (hours) stability, including setting errors, short-term drifts and current ripple, field tracking error, which occur during energy ramping, and long-term (weeks) reproducibility which is dominated by temperature effects. Current tolerances are given in units of the P.C. maximum current at the LEP phase 1 energy of 60 GeV. As the current variation of power converters usually is independent of the actual excitation current, the relative current variation seen by the particles will be three times larger at injection energy as compared to the quoted tolerances at flat top level.

Criteria for tolerance requirements are derived according to the implications on the machine performance for the different power converters. Clearly long magnet chains like arc dipoles and quadrupoles or sextupole families play a dominant role, while individually powered magnets like injection dipoles, straight section quadrupoles or correction magnets are of less importance.

In order to arrive at practicable current tolerances possible means of current control have to be included in the arguments.

3. Criteria for tolerance requirements

Dipoles : The energy resolution of the physics detectors in LEP is of the order of 1 % of the width of the Z_o-peak, i.e. about ± 15 MeV. To keep the energy uncertainty of the $e^{\pm}$-beams below this value, the current tolerances of the arc dipole power converters must comply with

$$\frac{\Delta I}{I_{max}} \times \frac{60}{E_{Zo}} \leq \frac{15 \times 10^{-3}}{M_{Zo}}$$

at the Z_o beam energy of $E_{Zo} \approx 45$ GeV. This requires a current tolerance for dipole converters of

$$\left(\frac{\Delta I}{I_{max}}\right)_{dipoles} = 10^{-4} .$$

Quadrupoles : The main sources of tune variations driven by P.C. current variations are the two arc quadrupole chains plus the arc dipole chain which contributes via momentum variations. Compared to these sources the straight section quadrupoles, which are mostly powered in pairs, do not contribute much in a quadratic addition. The summation of the total effect assuming uncorrelated current variations of the same amount in the three main magnet chains gives a tune variation at energy E(GeV) [1]

$$\Delta Q \cong 140 \left(\frac{\Delta I}{I_{max}}\right)_{Q,D} \times \frac{60}{E} .$$

As P.C. drifts due to temperature variations will be at least partly correlated this value overestimates the effect.

For individually powered quadrupoles, i.e. low-β quadrupoles, the main criteria on current tolerance requirements stem from local optics pertubations rather than tune shifts.

In contrast to proton machines where many high-order resonances may be equally harmful, in electron machines usually well specified resonances surrounded by their satellite lines due to synchrotron motion are observed. A measure of the tolerable tune variation is therefore the synchrotron tune Q_s, giving the distance between the satellites. On the one side the experience gained on existing electron machines indicates that tune drifts of $\pm Q_s/10$ are harmful. On the other side, a tune shift (over one hour) of $Q_s/18$ has been observed at CESR [2] to be acceptable. Therefore, the proposed criterion for LEP at 60 GeV energy is

$$\Delta Q \lesssim \pm \frac{Q_s}{20} \simeq \pm 0.004$$

requiring arc quadrupole and dipole current tolerances of

$$\left(\frac{\Delta I}{I_{max}}\right)_{Q,D} = 0.3 \times 10^{-4}$$

Sextupoles : Assuming uncorrelated current variations of the same strength in all sextupole families, the induced chromaticity variations at energy E(GeV) are [1]

$$\delta\left[\frac{\Delta Q}{(\Delta p/p)}\right] = \delta Q' \leq 230 \left(\frac{\Delta I}{I_{max}}\right)_S \times \frac{60}{E} .$$

In this case momentum variations due to dipole current fluctuations can be neglected, as they contribute much less than the direct sextupole effects. A measure of the tolerable chromaticity variation δQ' is the head-tail instability at injection energy. δQ' must be positive for damping the lowest mode. For positive chromaticities, however, higher single bunch headtail modes can become unstable. Following studies of this effect [3] it has been estimated that for the LEP nominal parameters higher modes should be damped, as long as the chromaticity variations stay below $\delta Q' < 0.8$ neglecting the frequency spread in the bunch. Therefore, a good control of $\delta Q'$ is desirable. The proposed tolerance is

$$\delta \left[\frac{\Delta Q}{(\Delta p/p)}\right] = \pm 0.1,$$

and consequently a tolerance on sextupole current variations

$$\left(\frac{\Delta I}{I_{max}}\right)_{sextupole} = 1.5 \times 10^{-4} .$$

is required.

Orbit correction dipoles : The contributions to closed orbit distortions from current variations in the corrector magnets themselves should only present a fraction of the remaining closed orbit amplitudes after correction. Moreover, to control beam depolarization certain high harmonics of the vertical closed orbit should be corrected to values below the accuracy of the closed orbit measurement system. These harmonics can be created with small sets of correctors and the optimisation achieved by varying their strength while measuring the polarization. Small steps in the corrector strength are required. The criterion used on the corrector setting accuracy allows to control the polarization to within 1 % at 40 GeV. These arguments have led to the following corrector magnet current tolerance [1] :

$$\left(\frac{\Delta I}{I_{max}}\right)_{corrector} = 5 \times 10^{-4} .$$

4. Possible Means of Control

Reference magnets : The three arc magnet chains as well as the injection dipole chain contain reference magnets which are equipped with field measuring devices. The absolute precision of these systems is about 10^{-4} of the maximum field at 60 GeV, while the relative reproducibility is of the order of one in 10^5. The derived field information will be used to correct for systematic current variations along the cycle and long-term drifts by updating the reference current/ field tables (open loop).

The accuracy of this procedure is limited mainly by temperature differences between reference magnets in the surface buildings and ring magnets installed in the tunnel. Temperature coefficients for LEP magnets are 1.2×10^{-5} and 2.4×10^{-5} per degree for dipole fields and quadrupole gradients, respectively.

A more precise absolute knowledge on the beam energy, than the quoted one in 10^4, can be achieved by calibrating the beam energy using induced spin resonances [4]. The required current stability of 10^{-5} over depolarization times of one minute can be ensured with the help of the reference magnet system.

Tune control loop : A fast closed loop system feeding the measured coherent tune value back into one or several quadrupole chains is foreseen to correct for tune variations. Depending upon the required response time, setting accuracy and range of tune correction, as well as on the limit of admissable local optics pertubations different quadrupole chains can be used for this purpose. The envisaged setting accuracy is $\Delta Q = 0.002$ within a range of ± 0.4.

In colliding mode, however, this loop cannot be used, because the signals of the coherent dipole modes are not clean enough, in particular, when running close to the beam-beam limit.

5. Power Converter Tolerances

The required current tolerances for the different LEP power converter chains as derived from the previous arguments are summarized in Table 1 below.

Actual current variations should stay within a band of $\pm (\Delta I/I_{max})$, the tolerance values quoted in Table 1. Arguments used beside the main criteria listed in Chapter 3, in order to define all the values given in Table 1, are briefly summarized below.

Considering that drifts of dipole and quadrupole fields are partly correlated, the tolerances of the main power converters (dipoles, arc quadrupoles and sextupoles) satisfy the requirements of Chapter 3. Tolerances for the other magnetic elements like straight section quadrupoles are essentially

TABLE 1 Power Converter Current Tolerances

Magnet type	Current Tolerances ($\Delta I/I_{max}$)		
	short-term stability (hours)	long-term reproducibility (weeks)	tracking errors
Main dipoles	$0.5\ 10^{-4}$	$2.0\ 10^{-4}$	$0.5\ 10^{-4}$
Injection-region dipoles	$0.5\ 10^{-4}$	$2.0\ 10^{-4}$	$0.5\ 10^{-4}$
Arc quadrupoles	$0.5\ 10^{-4}$	$2.0\ 10^{-4}$	$0.5\ 10^{-4}$
Low-β quadrupoles QL1, QL2 QS1, QS2, QSC	$1.0\ 10^{-4}$	$2.0\ 10^{-4}$	$0.5\ 10^{-4}$
All other quadrupoles	$2.0\ 10^{-4}$	$5.0\ 10^{-4}$	$1.0\ 10^{-4}$
Sextupoles	$1.5\ 10^{-4}$	$3.0\ 10^{-4}$	$1.0\ 10^{-4}$
Correction magnets	$5.0\ 10^{-4}$	$1.0\ 10^{-3}$	$2.5\ 10^{-4}$

compatible with the first ones. Since the contribution to the tune shifts of the individual quadrupoles (outside the arcs) is weaker than the one of the arc quadrupoles, their current tolerance can be relaxed by a factor of four. This, however, does not apply to the low-β quadrupoles, which contribute relatively strongly to tune variations and are employed for special functions, like β*-measurement. Their tolerance is therefore relaxed by a factor of two only.

Long-term reproducibility tolerances have been relaxed generally with respect to short-term requirements as in this case one can rely on diagnostic means, like e.g. the field control system in the case of main magnet chains.

It has been checked, however, that on the one hand the retained value for the individual quadrupoles does not induce perturbations of the β-functions and the phase advances larger than those existing once the closed orbit has been corrected [5], on the other hand the dynamic aperture is not affected by the sextupole tolerance [6].

The tracking errors do not contain systematic effects, as these can be dealt with in form of corrections to the current/field tables. Tracking errors must not exceed the short-term tolerances. However, as they may in the worst case add to the latter, they have been reduced by a factor 2, where ever possible.

The current tolerances of Table 1 satisfy the requirements at 60 GeV flat top energy. However, at injection energy the induced tune variations stay about three times too large, and must be corrected with the help of the described control means. Since the control of chromaticity is not easy, the given short-term stability of the sextupole power converter satisfies the requirement at injection energy.

Current ripple, which normally ask for the most stringent tolerances, is of minor importance in LEP, because eddy currents in the LEP aluminium vacuum chamber strongly attenuate the corresponding field variations. According to measurements on prototype magnets [7] the attenuation starts already at very low ripple frequencies and reaches -20 db at 50 Hz.

The current tolerance values for injection-region dipoles ensure that closed orbit distortions due to field deviations of this magnets with respect to the main arc dipole fields are kept reasonably small.

References

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