Operational Experience with the LEP Low-Beta Superconducting Quadrupoles

P. Lebrun, O. Pagano, T.M. Taylor, L. Walckiers, CERN
CH-1211 Geneva 23

Abstract

It was initially foreseen that the first phase of LEP should operate with room-temperature magnets only, and that the so-called mini-beta scheme using superconducting quadrupoles would be introduced as an upgrade. The potential benefit with regard to luminosity, however, generated overwhelming support from the users for introducing the superconducting scheme from the outset. As budget and personnel were already allocated, the decision to follow this approach despite the added complication called for particular ingenuity in the conception and realization of the quadrupoles and their associated equipment. This decision was nevertheless rewarded with the result of substantial luminosity at LEP after just a few months of operation. Since it was commissioned in September 1989, the mini-beta scheme has been in regular use, and indeed been pushed to give smaller values of beta at the crossing point than originally foreseen. In this paper, we describe the experience with the magnets, and their cryogenics, surveillance and alignment systems, over the first two and a half years of operation of the LEP machine.

1 INTRODUCTION

In LEP, the Large Electron Positron collider now operating at CERN, the luminosity is enhanced using mini-beta insertions incorporating superconducting quadrupole magnets. These insertions provide an increase in luminosity by a factor of about five times that obtainable with the back-up insertion, in which the superconducting quadrupoles are not excited [1]. Because of the luminosity payoff, a high priority was put on getting the mini-beta insertions into a reliably operating state, and apart from the initial two months of the commissioning of LEP, the back-up has been rarely used.

Besides having to provide high gradients, the quadrupoles closest to the interaction point are embedded into the detectors and are thus both inaccessible and subject to the rigours of the local environment (which include that of the solenoidal field) [2]. Closest of all are the superconducting magnets, which are installed on either side of the four experiments, and are operated as eight independent units cooled by four independent cryogenic systems; at the two sites which house experiments with superconducting spectrometer solenoids, the same cryogenic plant cools solenoid and quadrupoles. The design and results of the performance in test conditions of the superconducting magnet and its cryostat have been previously reported [3, 4, 5], as has the principle of the cryogenic system [6], so in this paper we confine ourselves to providing complementary information on monitoring, and to an appraisal of experience with the installed systems.

2 MACHINE OPERATING CONDITIONS

Prior to using the superconducting quadrupoles they are cycled to 1500 A and back to 180 A (or at most 350 A) before being set at about 500 A required for 20 GeV operation. This procedure sets reproducibly the remanent field due to persistent currents, and ensures the validity of the calibration tables in the database. Injection is made with the low-beta insertions detuned, i.e. with the vertical betatron amplitude at the interaction point, $\beta_v^* = 20$ cm, to which corresponds a peak value of $\beta_v = 100$ m in the closest quadrupole (compared with 135 m in the arcs). In this configuration as the aperture is not limited in the insertions, it is very unlikely that beam loss will occur there. The β_v^* is squeezed to its working value of about 5 cm towards or at the end of the ramp up to the normal working energy of 46 GeV. The squeezing path is obtained by varying settings of the first six quadrupoles on either side of the crossing point as determined by matching. Most of the effect is produced by the third and fourth magnets, the settings of the superconducting quadrupoles remaining practically fixed during this operation. In order to ensure that the aperture limit never occurs near an interaction point, it is necessary to simultaneously insert aperture limiting collimators which are installed in an arc far from the experiments. If this is not done , there is a risk of large beam loss or radiation in the region which may damage experimental apparatus and/or cause a superconducting quadrupole to quench.

3 MONITORING

At each interaction point there are monitoring systems which survey the functioning of the two local superconducting quadrupoles, provide the cryogenic system with essential control information and generate interlock and alarm signals.

3.1 *Surveillance of Operating Conditions*

A local system makes available the status of all surveyed parameters via the LEP control system and the CERN networks. This system, which is VME-based, incorporates a circular buffer logging changes in the various parameters which is regularly downloaded and archived for reference purposes. A self-adapting sample rate allows for a minimum of one week of local autonomy; the recording of critical changes is performed at a rate of up to one event every 10 seconds. The system controls up to 60 analog channels and 40 digital values per interaction point (two magnets and associated cryogenics). The parameters surveyed include temperature at various points of the magnet, helium liquid level, pressure in the helium vessel and in the vacuum vessel, voltages across the each of the four coils, voltages and temperatures associated with the current leads, excitation current, and the status of various valves and pumps.

The system has proved to be very useful to trace the reasons for failures due to temporary malfunctioning which did not persist until the arrival of the specialist. Examples of such problems are as follows: quenching due to the accumulation of gas in the transfer line; increase in the pressure drop in the return gas flow of a transfer line due to icing; and a small leak in a vacuum enclosure which showed up as an increase in pressure when a cryostat warmed due to a cryoplant failure.

The same VME system also generates alarms which are transmitted to the control room, such as low helium level in the cryostat or the intermediate dewar, or temperature increasing on a current lead, which warn the operators to take appropriate action before the hardwired interlocks cause the power converter to trip and beam to be lost.

Interlock chains derived from temperature differences over the magnet are used to control a valve limiting the cooldown rate should the gradient exceed 50 K/m.

The cooldown, filling and helium level control are fully automatic; the only intervention required being the (remote) start-up of the pumping system of the insulating vacuum enclosure.

3.2 *Quench Recorder*

An independent G64-based 16-channel event recorder is used to sample and store quench-relevant information in a circular buffer having a time resolution of 10 mS. Should a transition from superconducting to normal state occur, as detected by the appearance of a voltage difference across different quadrants, the quench recorder is triggered. The information is subsequently downloaded via the control system into an archive and the system reset. The data recorded by this system includes the voltages across the four pole windings, and the current, from which can be derived the maximum voltage and hotspot temperature at quench. The temperature of small copper calorimeters, recessed into the end flanges of the stainless steel helium vessel are also monitored. Operating in a vacuum at liquid helium temperature, these latter devices provide a estimate of the temperature rise which can be expected in the coil in the event of beam-related energy deposition [7].

The quench recorders have been essential for identifying the origin of quenches.

4 RELIABILITY

The systems have been operational for a total of about 9000 hours, and magnets have experienced an average of 5 cooldown/warmup cycles, and about 2000 excitation cycles. No retraining has been observed. Quenches have occurred but these have in all cases been explained either by accidental loss of cooling (nine times), or by beam induced losses as identified by heating of the calorimeters (four times).

4.1 *Cryogenics*

In the second year of operation trouble with the solenoids interfered with the cooling regime of the quadrupoles and on several occasions the intermediate buffer dewar emptied, following which relatively warm gas was transferred to the quadrupoles; it was found that in this case even if the quadrupole helium vessel is nearly full, the magnet can quench. A change in the logic controlling the opening of the relevant valve cured this problem. The susceptibility of the system to external failures, e.g. water-cooling of the compressors, influenced the global reliability especially in the second year, because of the mean time of intervention due to the size of LEP. The different systems have since become more reliable, and due to this and a judicious increase in the quantity of liquid stored in the intermediate dewar, this type of failure has been virtually eliminated. It is important to avoid quenches due to lack of cooling when the magnets are running at 1150 A, corresponding to the normal LEP phase I operating energy of 46 GeV, because the quench is slow to propagate through the winding, which leads to high values of hotspot temperature (about 280 K). The stresses could harm the magnet in the long term. In this repect the beam-induced quenches, in which the temperature does not exceed 80 K because of the relativly even distribution of the heating, are less cause for concern. These losses are nevertheless very important for the experiments, and the calorimeters may be used in the future to provide a beam interlock signal.

It should however be said that very little time was lost due to these problems, as they were provoked in most cases by the failure of other systems, the consequences of which masked the non-availability of the quadrupoles. Loss of beam time due to these cryogenic difficulties was only about 2 percent of running time in the first and second years, and this fell to less than 1 percent in the last year.

4.2 *Longitudinal Alignment*

Machine performance has however been affected by other problems associated with the low-beta insertions. When β_v^* was reduced from the nominal 7 cm to 5 cm the expected increase in luminosity was not observed, and differences appeared from one experiment to the other of 10 to 20 percent. After a significant time spent on machine studies, the cause of this was traced to longitudinal displacements of the magnets with respect to their nominal positions. At the beginning of the long 1990/1991 shutdown it was discovered that some of the quadrupoles had moved by up to 15 mm due to the failure of the longitudinal positioning column, a tubular glassfibre/epoxy component defining the axial position of the helium vessel inside the vacuum vessel. The component was replaced by a stainless steel version on all magnets during the shutdown and this cured the problem, at the expense of an extra watt of heat inleak at 4.2 K.

4.3 *Transverse Alignment*

There being no line of sight through the experiment, the relative transverse position of the magnets on either side is difficult to survey. This is of particular concern in the vertical plane when the insertions are tuned to give small β^*, because the large peak value of β_v at the quadrupole amplifies the effect on the closed orbit. When $\beta^* = 5$ cm a relative displacement of 10 microns can cause the vertical closed orbit distortion to increase by 0.5 mm. The static offset is compensated using orbit correcting dipoles; when the combination of corrections correlates with a significant displacement, a physical correction is made. This intervention takes about an hour. It is more difficult to deal with dynamic effects; temperature variations of a degree, and temperature gradients of some tenths of a degree across parts of the cantilever support structure cannot be avoided, and these produce movements at the 10 micron level. While an equal movement on each side produces a small π bump at the crossing point and does not affect the closed orbit, differences do affect it. These are not perceptible when the machine runs at the nominal β^* of 7 cm, but become increasingly worrisome as β^* is squeezed to lower values.

The insertion associated with the L3 experiment is particularly vulnerable to this problem, as the girders which support the quadrupoles are in turn supported via the 32 m long tube which holds the experiment [2]. For this reason it was planned from the outset to equip the large tube with motorized jacks controllable by a level monitoring system. This VME-based system was brought into service in July 1991 and has had a very beneficial effect on operating conditions when β^* is squeezed to below 7 cm.

In order to improve the stability of the closed orbit at very small β^*, a procedure will be introduced during the next running period in which the orbit will be sampled regularly and discrete correcting kicks applied by the local correcting dipoles on an automatic basis.

5 CONCLUSIONS

The performance of the mini-beta insertions has surpassed expectations. The reliability of the systems which was found to be good from the outset, has steadily improved. The problems which are now being addressed are brought on by the desire to push the performance beyond that which was originally planned; their solution can be based on the consolidated experience which is now available.

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