LESSONS LEARNED FROM LEP

M. Lamont, R. Assmann and B. Goddard CERN, Geneva, Switzerland

Abstract

LEP was commissioned in 1989 and closed down in November 2000. During this time it has operated in many different modes, with many different optics and at many different energies. Some of the lessons learnt that might be of general applicability are elucidated.

1 INTRODUCTION

The LEP accelerator was commissioned in 1989 and de-commissioned at the end of 2000. During the intervening years it provided collisions at and around the Z^0 resonance and subsequently, in conjunction with a staged installation of superconducting RF, above the W pair threshold up to a maximum beam energy of 104.5 GeV. Over 4 million Z bosons and around 10,000 W pairs were collected by each of the four experiments. This, together with a painstaking beam energy calibration program, allowed tests of the standard model to be made with unprecedented high precision.

Operations spanned many different regimes and this paper attempts to identify lessons arising that might have general applicability.

2 OPERATIONS

Although the commissioning in 1989 went smoothly, subsequently LEP operations during the first years were difficult. This was due to a lack of basic high-level controls facilities and poor data management. Although the existential beam instrumentation hardware was in place, signals in the controls room were lacking and acquisition systems were slow and unreliable. A learning phase is inevitable, but progressing up the curve is a lot easier and faster with appropriate tools, diagnostics control & instrumentation. Surprisingly some basic optics measurements and corrections, which later became standard, were not made, reflecting perhaps a lack of communication between the accelerator physicists and day-to-day operations.

Efficient turn-around clearly can save a lot of time and over the years this area was targeted and significant improvements were made. They could have been made sooner. Among things that helped were the definition of a clear sequence, and use of a semi-automatic sequencer, the use of which reduced considerably the room for unforced errors and omission. Reproducibility was vital, both in settings and cycling of the machine. In addition, sufficient lead-time was essential for changes of operational mode and, in particular, of optics.

3 BEAM-BEAM

LEP operated in two regimes: the first, on the Z^0 resonance at around 46 GeV was well into the soft beam-beam limit and approaching the hard limit, the second was at high energy where strong damping lifted the beam-beam limit and LEP was not beam-beam limited.

There was unique experience with ultra-strong damping at LEP with high energy providing a very good working regime. Extremely strong transverse damping (60 turns at 104 GeV) means that the second beam-beam limit was avoided as the beam-beam limit was pushed upwards. Operationally, LEP profited from smaller vertical emittances and higher currents. The 1/3 resonance could be jumped to a more favourable working point, and it was possible to ramp the beams in collision with collimators closed.

By looking at the functional dependence of beam-beam parameter on bunch current, attempts were made to infer the beam-beam limit at high energy. Although the beam-beam limit was not reached, some beam blow up was observed. Performing a two parameter fit to extract the dependency of ξ_y on beam current gives a beam-beam limit of about 0.115 at 101 GeV. Given the data at different energies a scaling law relating the damping decrement with the beam-beam limit could be obtained.

4 OPTIMISATION

One needs appropriate control of all basic parameters at all stages, since playing fast and loose with basics like chromaticity, dispersion, coupling, beta beating and orbit inevitably lead to problems. At LEP these stages included injection, the ramp and squeeze as well as physics conditions. Good diagnostics and easy-to-perform measurement procedures were vital. In addition periodic checks, particularly after interventions or change of optics, were soon discovered to be essential.

Working in the soft beam limit at 45 GeV meant that optimisation was somewhat arbitrary, with reproducibility (including re-establishing tune values and reloading golden orbits) being the main line of attack. However, at high energy the vertical beam size was targeted rigorously. Of importance was correction of global and local coupling (measured using the closest tune approach). Correction of the latter was mainly to compensate the effect of the experiments' solenoids. The β-function at interaction point was measured and corrected by adjustment to the superconducting low beta quadrupoles. This correction also reduced the beta beating in the machine, which was measured in parallel.

Of particular importance was correction of the vertical orbit to get the smallest RMS dispersion. For many years

0-7803-7191-7/01/$10.00 ©2001 IEEE.

the "Golden orbit" strategy for optimisation was followed, essentially an empirical approach wherein the orbit was saved and corrector settings reloaded when good conditions were found. This strategy was later complemented with Dispersion-free steering (DFS) where both the orbit and dispersion were measured and a correction calculated simultaneously to optimise both.

5 TRANSVERSE SPIN

Unique at LEP was the large range of energies, from 22 GeV to104.5 GeV, with polarization studies performed from 41 GeV to 98.5 GeV. Transverse spin polarization were crucial for precision measurements of the W and Z properties (energy calibration) and required the exploration of spin dynamics in a unique regime. It allowed benchmarking of theoretical predictions. New varieties of Harmonic Spin matching gave up to 57% polarization.

Transverse spin polarization at these high-energies was measured well above the previously addressed regime, providing the first measurement in the regime of uncorrelated spin resonance crossing. No sign of transverse polarization above 61 GeV was seen, in good agreement with theory and simulations.

6 CONTROLS AND DATA MANAGEMENT

The eventual efficiency with which LEP could be operated, even in the final years at the performance limits of the hardware systems, was in large part due to the integration of a well designed control system using commercial databases. This provided the essential coherency, integration and data management, which together provided the necessary high-level tools to operate the machine. An appropriate level of control was an important aspect of the LEP system, and incorporated such features as fixed displays for important raw and derived parameters, communications channels with the LEP experiments, and an easy uniform way of accessing and correlating essential operational data.

In contrast, the early years of LEP operation suffered from the absence of such an integrated controls system. The conclusions are twofold: first, it should not be imagined that the tools used for commissioning will suffice for regular operation. Secondly, issues and problems that are foreseeable should be solved and tested and implemented in advance. It is unforgivable that valuable commissioning time be devoted to the solving the problems of ill thought out software or controls implementation. There will be enough unforeseen problems to go around.

The use of databases was pioneered and provided the backdrop to effective settings management allowing proper parameter maintenance in the ramp and squeeze, reproducibility of physics conditions and the provision of such facilities as rollback, important in recovering good conditions.

7 BEAM INSTRUMENTAION

The lack of usable beam instrumentation (BI) system was the second major factor in the difficulties associated with the first years of operation. The BI equipment was not properly commissioned with the rest of the machine, and as a result the performance of suffered greatly. The BI systems also suffered from a lack of integration, with hardware seriously compromised by poor acquisition performance and a lack of top-end facilities.

Over the closing period of LEP operation the BI systems were much more mature and contributed significantly to the ease of operation. Examples are the fast display of lifetimes and beams sizes, tune feedback in the ramp, slow orbit feedback and the bunch current equaliser for managing injection.

Of particular note was the implementation of tune feedback in the ramp. When finally implemented some 8 years after the start of LEP this proved invaluable and losses in the ramp due to tune excursions became a distant nightmare.

8 INTENSITY LIMITATIONS

The bunch currents that could be collided at 45 GeV were limited by beam-beam, however the experienced increase in the beam-beam limit at high energy was anticipated and a lot of effort was made to push the bunch limit at injection. In the end the bunch current was limited by the RF, in the meantime the bunch limit had been taken to the TMCI limit during machine development. The threshold for the TMCI has been increased: the injection energy was increased from 20 to 22 GeV, transverse impedance was reduced with the removal of copper RF cavities, the synchrotron tune was increased from 0.08 (design value) to 0.13. The decrease in bunch length that accompanies the latter was nullified by the use of wigglers. With these improvements the bunch current limit was around 1 mA per bunch.

9 INJECTION

In 1995 synchrotron injection was commissioned with the injected beam injected with a momentum offset parallel to, and offset with respect to the circulating beam. The injected beam then performs energy oscillations with respect to the circulating beam before damping onto it. This method was capable of very efficient injection, even into a partially beta squeezed optics, avoiding as it does betatron oscillations in the low beta insertions.

10 ALIGNMENT

A major realignment of the machine was performed in the shutdown between 1992 and 1993. The result was vastly improved performance with, for example, residual dispersion being significantly reduced. The success of the realignment meant the implementation of a program of survey and fine-tuning of the alignment of the machine every shutdown.

11 HARDWARE LIMITS

The hardware sub-systems in LEP were generally extremely reliable and reproducible, and thus contributed greatly to the machine availability. The main accelerator sub-systems were the huge superconducting RF installation, the arc and insertion magnets and their power supplies, the vacuum system, the beam injection and dump, the beam separation system, the beam instrumentation and the access system. Deficiencies in the latter were probably the only weakness that persisted through the life of LEP.

A very important factor in the continued good performance of these systems was the make up of the teams building and running this equipment. These teams had clear goals and excellent motivation resulting from the close interaction with the whole machine and the experiments. Much of this can be attributed to the presence of a common control room, which served as a focus for information exchange, problem solving and short-term coordination. LEP also certainly benefited from a productive cross-fertilization from other labs.

Other issues deserving of mention are the importance of continued in-house expertise in the above equipment fields which enabled improvement, upgrade, invention and innovation when called upon from an overall machine point of view, and also the importance of rugged initial design with adequate safety margin, which left enough capacity in hand to cope with the unexpected.

12 SOCIOLOGY

The sociological aspects of the LEP years provide instructive insights. Key factors contributing to the motivation, flexibility and the efficiency of the various LEP teams included the open and effective liaison between equipment groups, accelerator physicists and operations, with the operations as a focus. Regular informal contact at all levels contributed to fast feedback concerning problems, developments, successes and short-term goals, while comprehensive annual workshops (the “Chamonix” workshops) served as an efficient forum for formalising the overall progress, difficulties and aspirations. Objectives were identified and shared, and allowed a common approach for their realisation. Involvement of the physics community in these communications channels served to regularly situate accelerator-based objectives (luminosity, energy, background) in a wider context, resulting in a deep and productive empathy between the experimental and the accelerator communities.

General and wide-ranging involvement of the LEP teams was a natural and positive result of the above approach. A significant exception was the Accelerator Physics experts who were not sufficiently involved in day-to-day operational issues. This remove was generally problematic and several times resulted in problems where possibilities for diagnosis and optimisation were missed, or misunderstandings were propagated.

Another issue was the importance of first-person observation or measurement. Reliance on hearsay on occasion resulted in a build-up of ungrounded “facts”, and these perceived truths sometimes hampered accurate diagnosis, problems solving and decision making. This type of occurrence was sometimes exacerbated by insufficient rigour in the use of statistics and analysis. Fortunately for LEP, the annual Chamonix workshops served to enforce a minimum rigour and to expose areas in which the underlying arguments were weak. For this to be an effective process, the interactive and participative nature of these workshops was of paramount importance.

The ongoing shift (or evolution) in operational and machine objectives provided a continual pressure on the LEP team, providing an important motivational factor. This pressure was invariably self-applied in a positive manner with well-stated and attainable objectives, resulting in some outstanding machine performances. A dynamic and healthy balance was achieved between fresh ideas and well-developed, well-understood procedures. Room was left for creative thought and invention, and LEP benefited significantly from this culture where new ideas were encouraged. Nevertheless, this balance between order and invention had to be actively maintained in order to avoid falling into either unproductive chaos or uninteresting sterility (there should not be fear of new things, but they should be well separated and tried one at a time in a staged way). In this respect, as for other areas, experience was very, very important in LEP, with enough qualified people being made available from day to day.

13 CONCLUSIONS

In the final overall analysis, LEP was undoubtedly a major success. The delivery of a large amount of data on and around the Z^0 resonance and above the W pair threshold made a monumental contribution to the verification of the standard model. However, LEP started slowly, and the importance of good diagnostics, together with a well-designed, well-implemented control system, cannot be overstressed. Strong commitment from well-qualified equipment specialists was extremely important in providing availability. Rugged equipment design also allowed the accelerator to be exploited over an unforeseen range of energies. Day-to-day liaison with accelerator physicists could have been better managed, as it is clear that LEP benefited elsewhere from have appropriate expertise present in the control room. Finally, LEP also suffered from not having enough time or resources to complete fully its physics program.

14 REFERENCES

A comprehensive list of publications concerned with the operation of LEP have been collated at:
http://lamontm.home.cern.ch/lamontm/lep/lep_pubs.htm