OVERVIEW OF LEP OPERATION IN 1998

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Abstract

After the installation of 32 additional RF cavities in the 1997-1998 shutdown LEP was operated at a beam energy of 94.5 GeV. The total integrated luminosity for the year 1998 clearly surpassed its target and reached 198 pb^{-1}. Vertical beam-beam tuneshifts of more than 0.07 were obtained. The performance did not seem to be beam-beam limited, but the total beam current was limited by power dissipation problems to around 6 mA.
A high phase advance optics (102°, 90°), with a smaller natural emittance, was used for regular operation in 1998. This contributed to the excellent performance of LEP, together with the further reduction of both the horizontal and vertical beta function at the interaction points. No dynamic aperture problems were encountered.

1 PERFORMANCE

The total integrated luminosity delivered by LEP to each of the experiment during 1998 was 198 pb^{-1}. This is significantly more than the performance of the previous years. Figure 1 gives a comparison of the LEP performance over the last six years with the corresponding beam energies. The beam energy increased over the years following 1995 because of the addition of superconducting cavities to the existing copper RF system. The operating beam energy for 1998 was 94.5 GeV, apart from 3.2 pb^{-1} at the Z^0 peak (45 GeV) used for detector calibration.

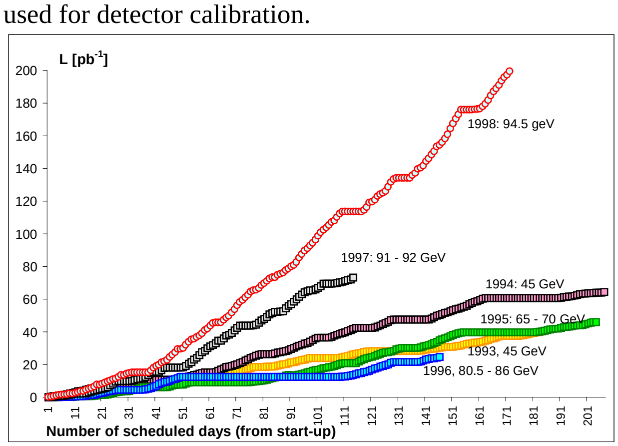

Figure 1: Comparison of the integrated luminosities for the years '93 to '98 with the corresponding beam energies.

The total beam current was limited to around 6.2 mA by the RF system (see section 2). Operation was with two beams of four bunches, except for the Z^0 running where two beams of eight bunches were used due to beam-beam limitations.

Vertical beam-beam tune shifts of more than 0.07 have been obtained on several occasions, with peak luminosities of about 10^{32} $cm^{-2}s^{-1}$. From figure 2 it is apparent that the beam-beam limit has not been reached. Beam size measurements do, however, show beam-beam blow-up when large beam currents are collided [1].

The improved performance, compared to 1997, can be attributed to the small beam size of the high phase advance optics, the further squeezing of the beta function at the interactions points, the larger beam currents (typically 6.0 mA in 1998 compared to 5.2 mA in 1997) and the good performance of the RF system.

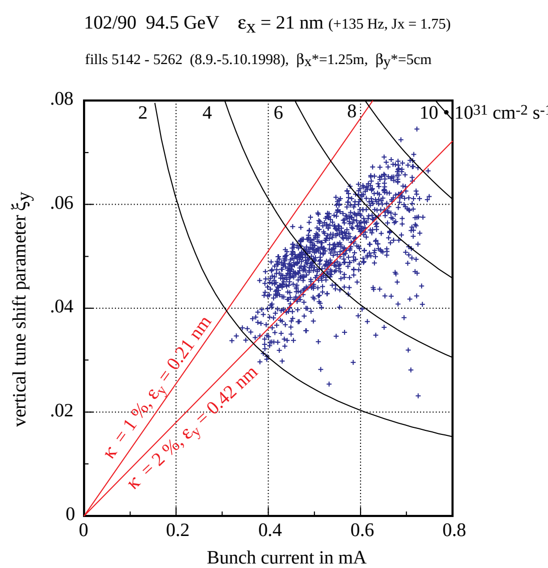

Figure 2: Vertical beam-beam tuneshift versus bunch current for the fills during the month of September.

2 THE RADIO FREQUENCY SYSTEM

The beam energy of 94.5 GeV could be obtained by the installation of 32 additional superconducting RF cavities. The RF system consisted of 272 superconducting cavities and 48 copper cavities. The maximum total voltage

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obtained was 2870 MV, while the required operating voltage to have sufficient quantum lifetime was 2720 MV (this allows operation with J_x = 1.75). This safety margin was generally sufficient: only about 10 % of the fills that were put in physics were lost due to the RF system. The good performance can for a large part be attributed to the new control facilities which included automatic switch on of tripped cavities, automatic field reduction in case of field oscillations and an automatic tuner set-point control to reduce the ponderomotive oscillations.

The total beam current that could be accelerated in LEP during 1998 was limited by the heating of the main antenna cables to around 6.2 mA. The antenna cables couple out a fraction of the higher order modes above 3 GHz. At high enough power levels the cables can be irreversibly damaged (burnt). As the signal from the main antenna cables are also used for the tuning of the cavities, the cavity becomes unusable if both main antenna cables are damaged.

The higher order modes above 3 GHz depend strongly on the bunch length. For this reason the bunch length was kept as long as possible during the ramp and generally above 10 mm. This involved careful control of the wigglers, RF voltage, frequency offset (to lengthen the bunch) and betatron tunes to avoid dangerous resonances. The gymnastics which were necessary is illustrated in figure 3. It shows the measured bunch length and the power measured at the exit of an antenna cable during the energy ramp.

A study estimated the maximum power level which could be tolerated by the antenna cable to be 8.0 W. A beam dump interlock was established at 8.5 W. Attempts to push the power limit higher towards the end of the year lead to a rapid increase in the number of broken cables. The total number of broken cables at the end of the running period was 31, resulting in 8 cavities being out of function.

During the 1998-1999 shutdown all main antenna cables will be replaced so they will not limit the beam current in 1999.

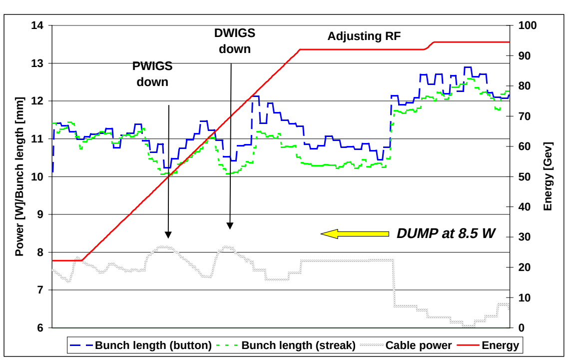

Figure 3: Bunch length and power measured at the exit of the RF antenna cable during the energy ramp.

3 OPTICS

Towards the end of the 1997 operational period a new high phase advance optics (102°, 90°) was commissioned [2, 3]. This optics was used for both the high energy running and the Z^0 calibration run in 1998. The main advantage of the (102°, 90°) optics relative to the previously used (90 °, 60 °) optics is the small natural emittance of 39.4 nm, at 94.5 GeV, compared with 50.8 nm for the (90 °, 60 °) optics. The high phase advance optics has a smaller momentum compaction factor which increases the energy that can be achieved for a given RF voltage.

No evidence of dynamic aperture problems were found, even not after further squeezing the horizontal and vertical beta functions at the interaction points during the year. Table 1 summarises the β^* values used over the year. The initial squeeze of the horizontal beta function had a clear positive effect on the luminosity. The following reductions of the beta functions probably contributed to the improved performance, but were hard to unravel from the other optimisations which took place continuously.

At injection and during the energy ramp the frequency offset was 115 Hz. This was necessary to lengthen the bunch during the ramp (see section 2). During physics the frequency shift was generally 135 Hz, resulting in a value of J_x of about 1.75. This reduced the horizontal emittance to 22.1 nm at 94.5 GeV. Assuming that the vertical emittance stays constant, this increased the luminosity by 33 %. The reduced beam size was also beneficial for the reduction of the background. However, the background was sensitive to small changes in especially the horizontal tune, resulting in background storms [4].

Table 1: The values of the horizontal and vertical beta functions at the interaction points during 1998.

Date	β_x^*	β_y^*
Startup: 6th May	2.0 m	5.0 cm
29th May	1.5 m	5.0 cm
8th September	1.25 m	5.0 cm
5th October	1.25 m	4.0 cm

4 PHASES OF OPERATION

4.1 Injection

Injection took place at the usual 22 GeV using synchrotron injection. The maximum bunch current was around 775 μA, resulting in a total beam current of 6.2 mA. The injection efficiency was often not very good and had a typical value of about 60 %. Almost all the RF cavities were kept on at injection, so the time lost waiting during the ramp for switching on cavities was minimised. The 520 MV demanded at the injection energy kept the RF cavities near the lower limit of their operational voltage.

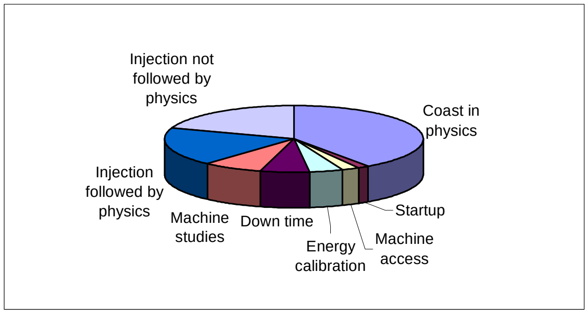

Figure 4: Distribution of the total time available for operation in 1998.

Figure 4 shows that 38 % of the total time available for operation was spent injecting particles. This was significantly larger than in other years.

4.2 Energy Ramp

Because of the limitation imposed on the bunch length and the working points at injection and full energy, the energy ramp was difficult and a lot of time was spent optimising the ramp, varying betatron and synchrotron tunes. This is reflected by figure 4, which shows that only about half of the total time which was spent injecting particles, was followed by a physics coast.

The development of the ramp was made a lot easier by the use of the Q-loop, a real time feedback of the measured betatron tunes to a pair of trim power supplies which act on the main quadrupoles. The fine control of the coherent betatron tunes would have been very difficult without it.

Once a good ramp was established excellent transmission rates (current at injection divided by the current in physics) were obtained, generally above 90 %.

Initially the squeeze of the beta functions took place near 45 GeV (the Z^0 energy). Small beam losses were observed in the ramp between 50 and 60 GeV, possibly caused by an insufficient momentum aperture of the squeezed (102^o, 90^o) optics. Squeezing the beta functions above 92 GeV proved to be a solution to get rid of these beam losses.

At 92 GeV a pause in the ramp was made to optimise the RF system if necessary. At this energy the RF was already ramped to the level needed at 94.5 GeV (2720 MV). Once the RF system was optimised, the continuation of the ramp to 94.5 GeV was generally without any problems.

4.3 Physics

As in the previous years a continuous optimisation of the horizontal and especially the vertical orbit took place to find the so-called 'golden orbit'. Even once this orbit was found it needed regular updating because of the continuously changing machine conditions. It is likely that the golden orbit is the result of an empirical search for the orbit with the lowest residual vertical dispersion for both beams. Typical values for the RMS vertical dispersion were around 3 cm. The coupling was well corrected. Dispersion free steering was also developed and will be available in 1999 [6].

4.4 Turn-around

The average turn-around, the time between dumping a fill which was in physics and restarting physics for the next fill, was 1 hour and 38 minutes, with a minimum of 42 minutes. Poor turn around was mostly related to poor injection or optimisation of the RF system.

The average time after which a physics coast was dumped was 3 hours and 42 minutes.

5 ENERGY CALIBRATION

Four percent of the operational machine time was used to measure the beam energy by resonant depolarisation. A dedicated (60^o, 60^o) optics was used for these measurements. For the first time polarisation was measured and the beam energy calibrated at an energy of 60 GeV. More details of the energy calibration results can be found in [7].

6 CONCLUSIONS

The year 1998 was a very successful year of LEP operation with a total integrated luminosity of 198 pb^{-1} at a beam energy of 94.5 GeV. The total beam current was limited to about 6 mA due to the heating of the RF antenna cables. The heating of the cables also imposed a limit on the bunch length during the energy ramp which resulted in a laborious development of different ramps.

The (102^o, 90^o) optics, developed in 1997, was used during the whole of 1998 for both the high energy run and the Z^0 run. The small emittance of this optics together with the additional squeeze of the beta functions at the interaction points and the operation with $J_x = 1.75$ largely contributed to the excellent machine performance.

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