LEP Status and Future Plans

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Abstract

At the end of 1992, LEP completed its fourth year of operation, producing more than 28 inverse picobarns of integrated luminosity in each of the four experiments and a total of three million hadronic Z^0s. For the first time the machine operated for physics with a new high-tune optics producing the smaller transverse emittance eventually needed for future operation at higher energy. As well as gaining valuable experience with this optics the luminosity lifetime could be improved by using wigglers to control the evolution of beam emittance during a run. In addition, the so-called 8-bunch "pretzel" scheme was commissioned, allowing the number of bunches per beam to be increased from four to eight towards the end of the year. Present performance limitations are discussed and future plans for increasing both the energy and luminosity are described. Many details of the topics mentioned here may be found in [1] and in contributed papers to this conference.

I. INTRODUCTION

In its fourth year of operation, the CERN Large Electron Positron (LEP) collider ran for 138 days for physics data taking, producing 28.6 inverse picobarns of integrated luminosity and a total of 3 million hadronic Z^0s summed over the 4 experiments (Figs. 1 and 2).

The peak luminosity achieved was 1.15 10^{31} cm^{-2} s^{-1}, about 15% higher than in 1991 and less than 20% below the design luminosity at 45 GeV. The average daily integrated luminosity of 206 inverse nanobarns was most 40% higher than achieved the previous year, mainly due to the very good luminosity lifetime. The limiting vertical beam-beam tune shift parameter was about 0.03 with 0.04 achieved under the very best conditions.

For most of the year, LEP ran as in the past with four counter-rotating bunches of electrons and positrons per beam. During the last month of operation the so-called "pretzel" scheme was commissioned. Electrostatic separators are used to horizontally separate the beams around most of the machine circumference in order to allow the number of bunches per beam to be doubled without exceeding the beam-beam limit.

A significant change compared with previous operation was the move to a new high-tune optics [2] (90° phase advance per cell compared with 60° in 1991). This change was made for three main reasons

• The 90° optics produces a smaller natural beam emittance allowing the possibility of controlled blow-up in order to remain at the beam-beam limit throughout a physics run, the luminosity thus decreasing proportional to the current and not to the square of the current

• The new optics was designed to cover machine development requirements, in particular the development of the 8-bunch pretzel scheme and energy calibration by resonant depolarization as well as normal operation. This made the use of machine development time much more efficient.

• The higher tune optics is necessary in order to achieve useful luminosity for future operation above the W-pair production threshold since the natural emittance increases like the square of the energy.

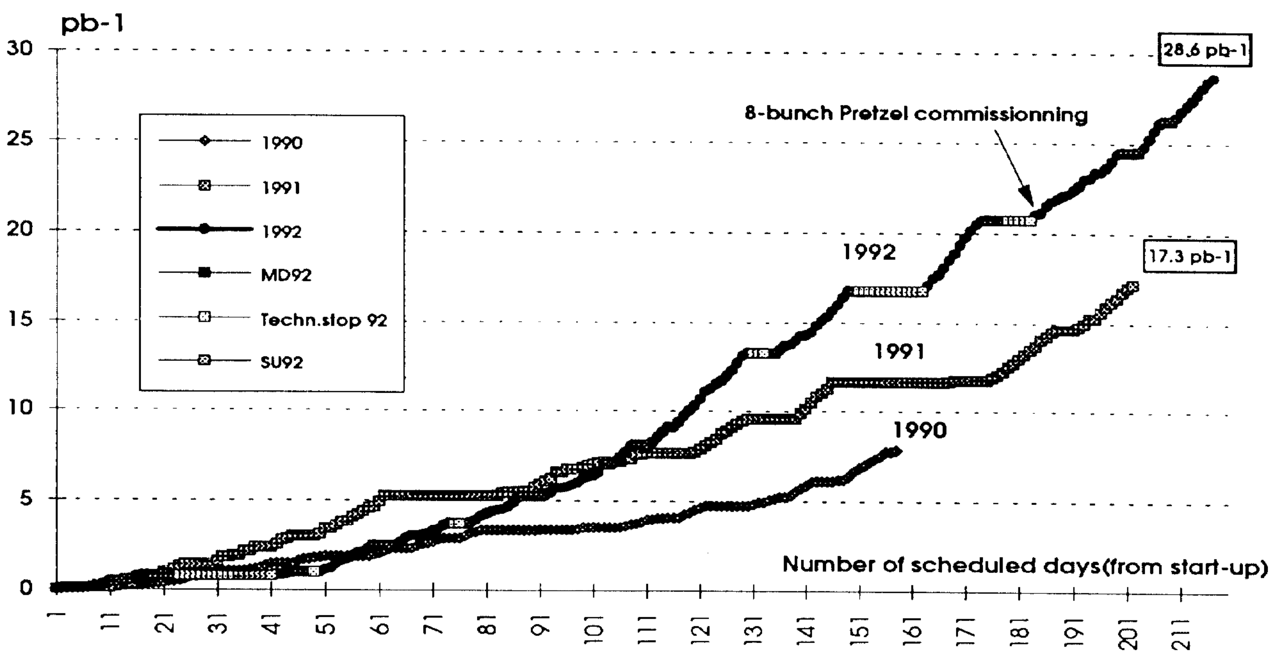

Fig. 1 Integrated luminosity per year 1991-1992

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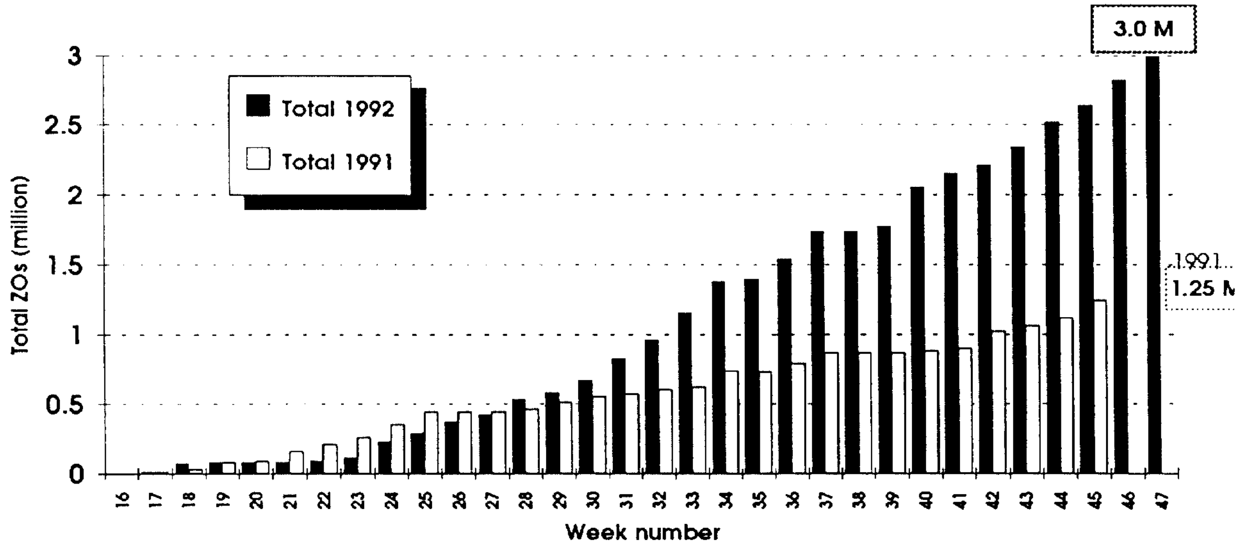

Fig. 2 Number of Z^0s detected in the four LEP experiments in 1991 and 1992

II. PERFORMANCE LIMITATIONS

The luminosity of an electron-positron collider is limited by three main parameters, the total circulating current, the maximum attainable beam-beam tune shift parameter and the minimum value of the vertical beta function at the interaction point.

2.1 The Beam Current

LEP suffers from both longitudinal and transverse instabilities. Turbulent bunch lengthening occurs but is of no consequence. Longitudinal dipole mode instabilities are damped by a 1 GHz feedback system [3] using cavities provided to CERN by the DESY laboratory.

LEP is the first machine in which higher head-tail modes can be observed directly using a novel streak camera to display the three-dimensional charge distributions of individual bunches on successive turns [4]. The chromaticity must be kept slightly positive in order to damp the classic mode m=0. However, for too strong chromaticity, mode m=1 is observed with a threshold behaviour when the growth rate exceeds the damping rate. The threshold depends in a complicated way on the bunch length. Moderately increasing the bunch length with wigglers couples the bunch spectrum to the machine impedance, dominated by the radio-frequency cavities, more efficiently and actually increases the growth rate. Above about 18 mm bunch length the growth rate once more decreases. The threshold also depends on the value of the chromaticity, which must be reduced to a small but positive value in order to keep mode m=0 stable as the current is increased. With Q' less than about 4 units, this instability does not limit the bunch current

The most fundamental limitation to the maximum single bunch current is as predicted many years ago, the fast head-tail or transverse mode-coupling instability (TMCI). The threshold for the onset of this instability is given by

$$I_b \approx \frac{2\pi Q_s E}{e\Sigma_i \beta_i k_i(\sigma_z)}$$

where Q_s is the synchrotron tune, E the beam energy, β_i is the betatron amplitude function at the location of the i^{th} transverse impedance driving the instability and k_i is the transverse loss factor of the impedance, which decreases with increasing bunch length.

The natural bunch length (σ_z) at the 20 GeV injection energy for the 90° lattice is less than 5 mm and the TMCI threshold is consequently much lower than with the 60° (σ_z = 20 mm) lattice. Lengthening the bunch increases the threshold of this instability as expected theoretically. Figure 3 shows the predicted threshold current [5] as a function of bunch length compared with a few measured points. The bunch lengthening was achieved using powerful wigglers. Single bunch currents of around 0.65 mA are presently achieved with a bunch length of about 20 mm and a synchrotron tune of 0.085. During machine studies the threshold has been increased to 0.8 mA by increasing Q_s to 0.13.

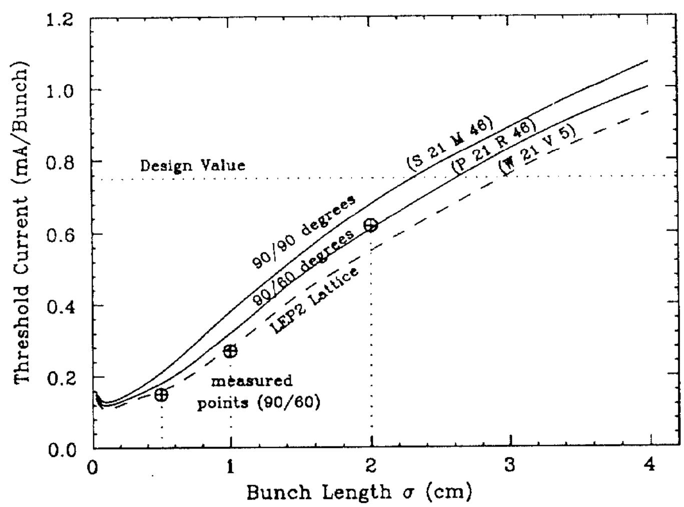

Fig. 3 Predicted TMCI threshold currents for various LEP lattices with some measured points. The slight dependence on lattice phase advance is due to the different β values in the RF cavities.

2.2 Beam-beam Limits

Although the bunch current can exceed 0.65 mA for a single beam under normal conditions, with two beams the current is limited to 0.55 mA. During injection and accumulation, the two beams are separated vertically at all eight collision points using electrostatic separators. This current limitation is most probably linked to the long range beam-beam interaction although the exact mechanism has not yet been clarified.

During collision, the maximum achievable beam-beam tune shift has been steadily increased since the early days of LEP commissioning by careful choice of integer and non-integer tune values and by the gradual correction of optical errors, phase advance between collision points, residual dispersion at the interaction points and residual separation between the two beams. With the small natural emittance (12 nm) of the 90° phase advance lattice, the beam sizes must be artificially increased with "emittance" wigglers before the beams are brought into collision otherwise they are lost. Achieving the highest possible tune shift is still an inexact science, requiring small empirical adjustments of critical parameters, particularly the closed orbit. The maximum tune shift still varies somewhat from run to run and shows some slight current dependence (Fig. 4) [6].

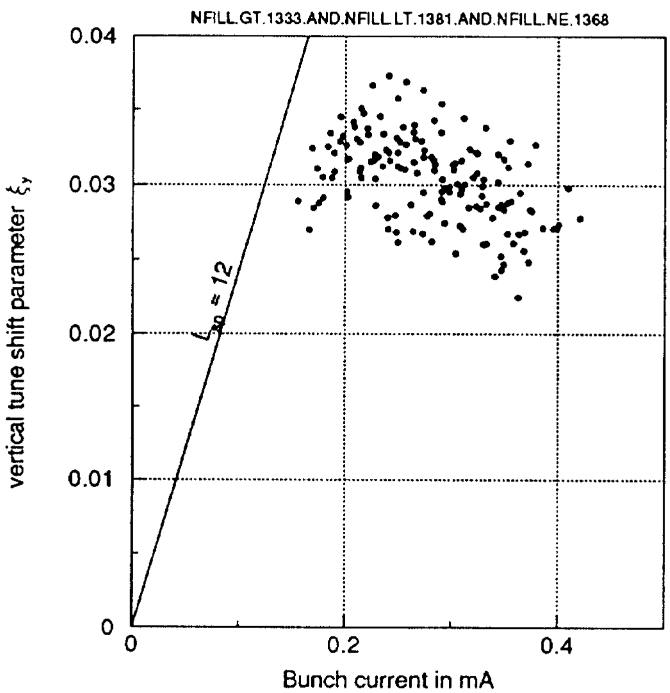

Fig. 4 ξ_y dependence on current over a number of physics runs.

A great advantage of the high tune lattice is that the beam size reduces with decreasing current so the tune shift can be kept close to the limit throughout the duration of a physics run, generally about 10 hours. Figure 5 shows an example [7] of a fill which was kept much longer than this due to trouble with the injectors. For the first half of the store the luminosity decreased approximately proportionally with beam current, indicating a more or less constant beam-beam tune shift. During the last hours the machine was no longer beam-beam limited so the luminosity decay was faster. This ability to stay at the beam beam limit means that the daily integrated luminosity is higher than expected from the original design even though the peak luminosity is slightly lower.

Although the two-beam current limit is 550 μA, the bunch intensity for physics runs is limited to below 450 μA in order to keep the background in the experiments under control. The horizontal aperture is collimated to about 45 nm for clean conditions.

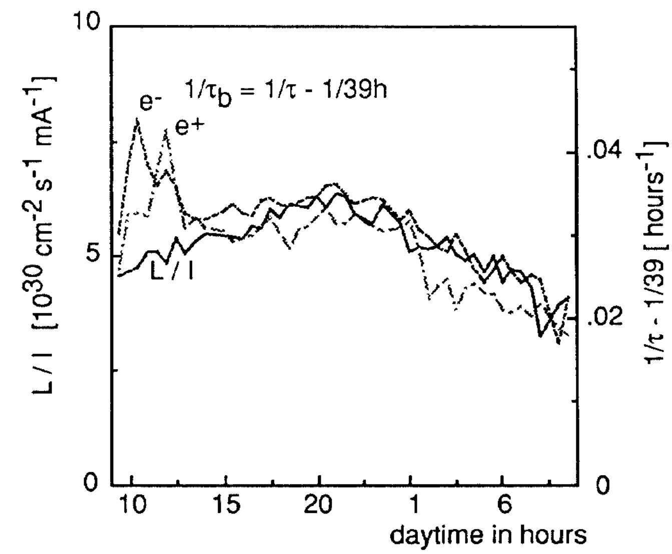

Fig. 5 L/I and inverse beam lifetime over a long run. For the first 10 hours, L/I is constant or slightly increasing. Later the beam-beam tune shift is no longer saturated and L/I decreases.

2.3 Beta Function at the IP

The minimum β^* at the IP is limited by the very high beta values in the insertion quadrupoles, producing large chromatic aberrations and closed orbit errors due to small displacement of these quadrupoles. In addition it has been shown [8] that a combination of spurious vertical dispersion and orbit errors in these quadrupoles can result in a rapid reduction in the vertical damping partition number. Up to now, LEP has run with β^*_H = 1.2 m, β^*_V = 0.05 m. Below this value the machine gets to be much too sensitive to the above mentioned effects.

The problem of keeping the background due to soft photons for large emittance beams can be alleviated by making a weaker horizontal focusing into the IP. At the end of the year a new optics with β^*_H = 2.5m was tried and should allow colliding beams with significantly more than 400 μA per bunch.

III. 8-BUNCH PRETZEL

Further substantial increase in luminosity at 45 Gev can only be achieved by increasing the number of bunches per beam. Going from 4 to 8 bunches means that the beams must be separated at all unwanted crossing points. In order to achieve this a scheme similar to those already used successfully at Cornell and at the CERN and FNAL proton-antiproton colliders has been implemented [9]. Electrostatic separators are used to make global horizontal orbit distortions in opposite directions for electrons and positrons between each experimental collision point (Fig 6).

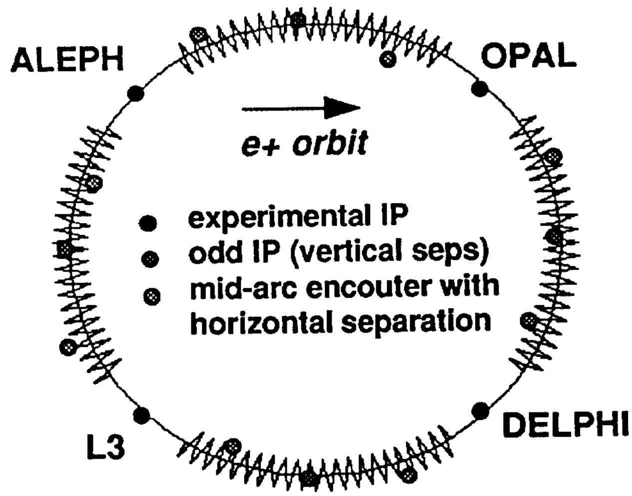

Fig. 6 Schematic representation of the orbits in the LEP pretzel scheme.

Early experience with horizontal separators in the high synchrotron radiation environment of LEP indicated a very high spark rate in the presence of the beams. Further investigation showed that the spark rate was strongly correlated with the polarity of the high voltage electrode [10]. For the normally used negative polarity, which avoids dark current in the high voltage circuit, the spark rate was found to be intolerably high whereas for positive polarity, it was reduced to an acceptable level. The exact mechanism has yet to be understood but it is felt that the positive polarity alleviates the problem of charging of the ceramic insulators by stray electrons.

During the January 1992 winter shutdown the full pretzel scheme consisting of 8 horizontal separators recuperated from the SPS proton-antiproton collider together with a number of sextupoles for independent tune control of the two beams was installed. Commissioning started in June 1992 and 8-bunch operation was implemented for physics during the last 5 weeks of the run. The main objective was to reach "break even", the same integrated luminosity with 8 bunches per beam as with 4, by the end of the year. This was achieved quite rapidly, the peak luminosity exceeding that achieved with 4 bunches by about 15%. This now provides a solid base on which to make further progress.

IV. POLARIZATION

The first observation of a small but significant level of transverse polarization was made in 1990. In 1991, polarization levels of between 10% and 20% were achieved. This level was perfectly adequate to allow precise energy calibration by resonant depolarization with a precision of better than 1 MeV at 45 GeV.

The high tune optics used in 1992 was designed to allow transverse polarization on the Z-pole under operational conditions in order to exploit more fully the possibility of systematic precision energy calibration during physics runs. However, three attempts to find polarization on this optics did not succeed. After extensive tests of the polarimeter it was concluded that the main reason was that the quality of the vertical orbit correction was insufficient, about 0.7 mm rms, due to the fact that the 90° optics allows four pickup measurements per betatron wavelength instead of six with the 60° optics of 1991, where 0.5 mm rms was routinely achieved.

During machine studies when the old optics was reloaded, polarization was quickly observed and calibration at two different beam energies was successfully performed [11]. However, transfer of calibrations between different optics is delicate so another hybrid optics which could eventually be used operationally was commissioned, with a phase advance of 90° in the horizontal plane in order to retain the small natural emittance but with the vertical phase advance reduced to 60° per period in order to optimize the orbit correction. Again, polarization was quickly observed and energy calibrations extensively performed. In addition, the depolarising effect of the ALEPH solenoid was compensated with dipole π-bumps in the arcs each side of the solenoid. This was an important step towards the final goal of energy calibration under full data taking conditions. Finally the pretzel was switched on and a useful amount of transverse polarization was still retained.

For a long time the extreme precision of energy calibration made available with polarized beams has revealed small but significant drifts in beam energy as a function of time. It had been postulated that these variations could be explained by small changes in the circumference of LEP due to the combined tidal effect of the sun and the moon deforming the earth's crust. An experiment was therefore performed to track the variation of the LEP energy over a 36 hour period coincident with strong tidal activity. A peak to peak energy variation of about 9 MeV, corresponding to a change in the 27 km circumference of about 1 mm, was indeed measured [12]. The cyclic nature of the phenomenon could be easily observed (Fig 7) and the measured results were found to be in good agreement with the theoretical prediction. This 18 MeV variation in the centre of mass energy is now the dominant factor in the determination of the Z^0 mass.

V. FUTURE PLANS

Over the next few years it is foreseen to increase both the energy and luminosity of the machine.

The energy upgrade will allow operation above the W-pair threshold for physics from the beginning of 1995. The cross section for W-pair production rises sharply above 82 GeV and a beam energy of at least 87 GeV is required in order to ensure a reasonable rate. At this energy, the synchrotron radiation loss per turn is 1.6 GeV and therefore a minimum circumferential RF voltage of 1900 MV is required. This will necessitate the installation of 192 superconducting cavities around the four even interaction points, 32 cavities each around points 2 and 6 where the copper cavities are presently installed and 64 cavities each at two new acceleration points 4 and 8. These cavities will be powered by twelve 1.3 MW klystrons, 16 cavities per klystron, operating at 352 MHz.

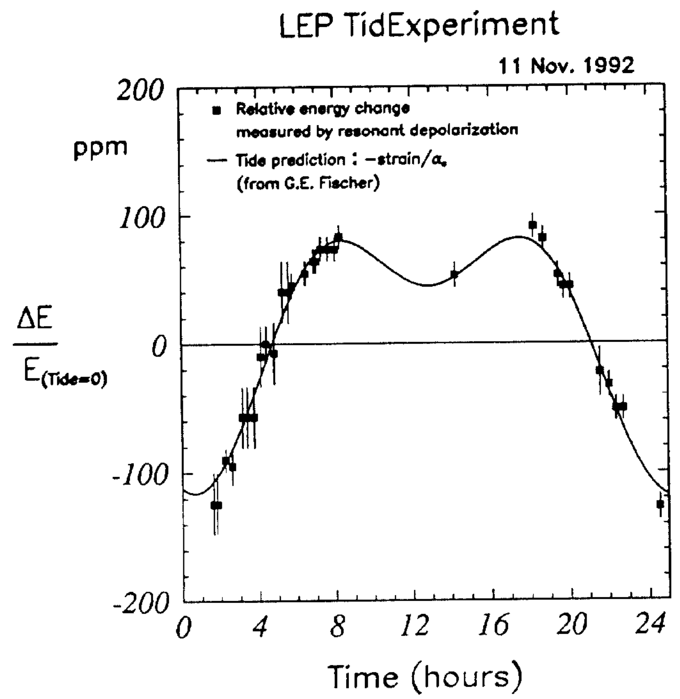

Fig. 7 Energy variation over a 24-hour period compared with the expectation.

The cooling of the cavities requires the installation of 4 cryoplants, each with a cooling capacity of 12 kW at 4.5 K.

The first set of 32 cavities at point 2 consists of 8 prototype Nb sputtered copper cavities made at CERN and 24 Nb sheet cavities, four prototypes and 20 industrially produced series units. All cavities have achieved or exceeded the specified gradient of 5 MV/m with a quality factor of 3 10^9.

LEP points 4, 6 and 8 will all be equipped with Nb sputtered copper cavities with a nominal gradient of 6 MV/m and a Q of 4 10^9. So far, 29 cavities fulfilling the above specification have arrived at CERN.

As well as the radio-frequency, major upgrades are needed on many other systems. A number of changes of the original lattice are needed because quadrupoles run out of focusing strength above 65 GeV and also because the length of the RF cells increases. The present superconducting quadrupoles need to be replaced by new ones with the gradient increased from 36 T/m to 55 T/m. The project also requires major modifications to vacuum, power converters and civil engineering. A more detailed presentation of the LEP2 project is given elsewhere in these proceedings [13].

At high energy, luminosity is of critical importance since the cross section for W-pair production is about three orders of magnitude lower than that at the Z-pole. In addition, the natural emittance at 90 GeV is a factor of 4 larger than at 45 GeV so the unperturbed tune shift for 0.5 mA per bunch is about 0.014, well below the saturation value.

Several measures are envisaged to increase the current per bunch. Firstly the injection energy into LEP will be raised from 20 GeV to around 22 GeV when a second superconducting cavity module is installed in the LEP injector (the SPS). This will raise the TMCI threshold by 10% as well as providing faster damping in LEP. Secondly it is envisaged to reduce the transverse impedance of LEP by removing the copper radiofrequency system, which is the main contributing element to the TMCI current limitation, and to compensate for the lost circumferential voltage by installing 32 additional superconducting cavities which, in view of their much larger iris diameter, have considerably lower impedance. Further bunch lengthening by varying damping partition numbers or with a higher harmonic cavity is under study as well as the possibility of operating at a higher synchrotron tune. It is predicted that these measures will allow the TMCI threshold to be raised to around 1 mA per bunch.

Studies have shown that background control in the experiments will become a serious problem in LEP2 because of the higher photon flux and the larger natural beam emittance. One option under serious consideration is to move to a low emittance lattice with a phase advance even higher than 90°, at the same time providing higher luminosity and better background control [14]. The fact that such flexibility exist says much for the quality of the original optical design of LEP.

In addition to the above measures, pretzel operation will be actively persued over the next two years, with 8-bunch operation at 1 mA per bunch at 90 GeV and an initial luminosity above 5 10^{31} cm^{-2} s^{-1} as an objective. RF power considerations and higher mode losses will then start to play an important role.

VI. CONCLUSIONS

LEP is now operating close to its design peak luminosity and with a better than expected luminosity lifetime. The main limitations to machine performance are now well understood and plans are underway to substantially improve the luminosity on several fronts. The LEP2 energy upgrade project is making progress and regular operation at energies above the W-pair production threshold is foreseen for 1995.

VII. ACKNOWLEDGEMENTS

This article is a brief review of the work done by many dedicated people in the accelerator and technical sector at CERN. More detailed contributions on specific items can be found elsewhere in these Proceedings.

VIII. REFERENCES

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