Longitudinal Polarization at LEP
-A Feasibility Study-

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Abstract

This document has been prepared at the request of the LEPC by members
of the Polarization Working Group of the LEPC and by a Study Group of the
Accelerator Divisions.

After an overview of the achievements and prospects of transverse polarization at
LEP, the technical feasibility of providing longitudinally polarized beams at all
four experimental interaction points is established. The consequences on machine
performance and layout are discussed as well as the consequences for the four LEP
detectors. Implications on the planning of the LEP operation and compatibilities
with the other LEP upgrades are discussed. An estimate of the cost and manpower
for achieving longitudinally polarized beams at LEP is provided.

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SUMMARY

The discovery of some 9% of transverse polarization in LEP in 1990 and the subsequent confirmation in 1991 have been a considerable encouragement to pursuing the polarization studies. The recent improvement of the polarization level to 16%, the successful calibration of the beam energy to high accuracy and the overall consistency of the predictions and measurements firm up the conviction that a high degree of polarization, more than 50%, is achievable in LEP.

Providing longitudinally polarized beams to the experiments requires spin rotators, a modification to the magnetic optics of the insertions, ancillary equipment to protect the experiments and machine components from the synchrotron radiation, and tilting the detectors by 15 mrad (except L3). The technical conclusions from this feasibility study are as follows:

- The improvement of the transverse polarization level in LEP is not straightforward but the steps needed are identified, and some of them are already being undertaken.
- The design of the spin rotators is such as to allow the required longitudinal polarization level and luminosity.
- The background from high energy particles can be reduced to tolerable values. Although no satisfactory scheme has yet been finalized, ideas exist on how to control the synchrotron radiation background emitted in the spin rotator dipoles.
- Adapting the LEP experiments to the slope of the LEP orbit imposed by the spin rotators and improving their luminosity measuring systems are both feasible.
- The L3 detector does not need to be tilted.
- The engineering of the spin rotators does not present any great technical difficulty.

As no such rotators has ever been tried in a real machine, it is therefore considered that a necessary first step is to build a demonstration spin rotator in a non-experimental insertion. The uncertainties to be resolved range from the modeling of spin dynamics to the efficiency of the shielding against synchrotron radiation. If approved, the full programme would be carried out in three phases:

- Improvement of the transverse polarization level and polarization rise-time over the coming years.
- Design, construction, installation and testing of a demonstration spin rotator in a non-experimental insertion of LEP. Its installation could take place in the 1993/94 shutdown. It would need to be movable for compatibility with the LEP 200 programme.
- Design, construction, installation, and commissioning of spin rotators in the experimental insertions of LEP to be installed after the completion of the LEP-200 physics programme.

The resources necessary to carry out the programme have been estimated as follows:

- The cost of this programme would be about 6 MSF for the demonstration spin rotator and an additional 19 MSF for the ensemble of spin rotators for the experiments.
- The manpower required would be about 30 man-years for the demonstration rotator, including polarization studies, and 40 man-years for design, construction and installation of the rotators.
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1 INTRODUCTION

In October 1986, at the request of the LEPC, a Polarization Working Group was set up to review the physics case and the experimental possibilities of carrying out experiments with longitudinally polarized beams in LEP. A workshop on this topic was held at CERN about one year later in November 1987 after which five study groups, convened by various members of the Polarization Working Group, were set up to pursue specific topics in detail. A final report covering the work done by these working groups was published in September 1988 [1].

The Polarization Working Group has continued to meet since that time in order to keep the topic under review and to examine and discuss relevant data from machine studies and from the experiments after LEP came into operation in 1989. The physics case was rediscussed by the LEPC at its review meeting in Cogne in September 1990. By this time, transverse polarization at the level of about 9% had been observed in LEP opening the possibility of determining the energy of LEP to better than 5 MeV and giving cause for optimism for obtaining the higher levels of polarization that would be needed for a viable programme of physics with longitudinally polarized beams.

In the conclusions of the Cogne meeting, which were subsequently endorsed by the Research Board, highest priority was given to bringing LEP 200 into operation by 1994 and to developing in parallel a scheme which would allow 8 x 8 bunch operation at LEP 200 energies. The importance of a physics programme with longitudinally polarized beams was also recognized and, although not given the same degree of priority as LEP 200 and 8 x 8 bunch operation, it was agreed that further work should be done on the various unresolved problems including backgrounds at the detectors. In addition, it was agreed that dedicated wigglers aimed at reducing the polarization time should be installed in the 1990/1991 shutdown and that machine studies to optimize transverse polarization should continue with special emphasis given to developing a resonant depolarization scheme for measuring the LEP energy.

The purpose of this report, which has been prepared at the request of the LEPC, is to describe the results of this recent work which is concerned primarily with resolving as far as possible the problems which were still outstanding at the time of the Cogne meeting. It also attempts to provide the LEPC with as much information as possible to enable recommendations to be made to the Research Board on how to proceed in the future. As discussed in subsequent sections of the report, the results of the polarization studies obtained are very promising, a feasible design for the spin rotators has been developed and background problems seem to be manageable. The physics that is possible with longitudinal polarized beams is not addressed in this report. It is fully discussed in Ref. [1] where the case for precision experiments with polarized beams is explored in detail.

2 TRANSVERSE POLARIZATION

The LEP physics programme with longitudinally polarized beams requires that the beam be polarized at a level higher than 50%. It furthermore assumes that the machine is operated with polarized beams without a significant loss in efficiency and luminosity. The transverse polarization programme which is under way aims at calibrating the $Z^0$ energy with the highest accuracy and at meeting these two targets.
2.1 Potential for transverse polarization

Whereas the possibility and interest of polarized beams at LEP have been recognized from early in the studies of the machine [2], there has been continuous debate as to whether the strong depolarizing mechanisms expected in LEP would allow spontaneous polarization. The possibility was however maintained by avoiding any known source of depolarization, by designing the wigglers for damping and emittance control in a way such as to decrease the build-up time of the polarization [3] and by investing in a polarimeter. The first quantitative studies made for the Workshop on Polarization in LEP (1987) [4] showed that a polarization level of about 20 % should be observed if the LEP orbit is well corrected, taking into account only the linear depolarizing effects. It was further shown that this level could be increased to about 60 % by controlling the orbit harmonics beating with the spin precession frequency. However, given the long rise-time of the polarization in LEP, this maximization of the polarization level would have taken 10 to 16 hours.

To decrease drastically this time, dedicated asymmetric wigglers were proposed [5] and installed in the machine in the 1990/1991 winter shut-down. They reduce the polarization rise time from 300 to 36 minutes at the Z^0 energy and make it possible to carry out polarization maximization in a reasonable time. A further advantage is that they reduce the strength of the betatron spin resonances produced by sources such as the beam-beam effect or the spin rotators. Their drawback is to enhance the energy spread and thus the synchrotron satellites of the spin resonances in a way that, so far, no analytical theory could successfully predict. Although dealing with a simplified model, computer simulations [6] showed that the enhancement was close to a factor of two. The natural polarization level should thus be about 10 % with wigglers. It was nevertheless possible to compensate for this enhancement of the depolarization by a refined harmonic spin matching. The polarization level then reaches 50 to 60 % between higher-order spin resonances.

A practical consequence is that the polarization should be first searched without wigglers. The higher-order depolarizing mechanisms are then much weaker and the expected polarization level is close to the prediction of the linear model.

It was further found that the strength of the different families of spin resonances is modulated depending on the bending symmetry and betatron tunes [7]. As a result, the level of polarization to be expected at the Z^0 peak with the standard LEP optics (Q_x ≈ 71, Q_y ≈ 77) is much reduced and the polarization was searched at the much more favourable energy of 46.5 GeV (ν = 105.5). In 1991, the LEP optics was changed to both increase the luminosity prospects and make it possible to avoid the systematic spin resonances at the Z^0 energy.

The LEP commissioning put into evidence two unexpected phenomena: the beam dynamics is perturbed by a strong betatron coupling due to a thin Ni layer on the vacuum chamber, and the vertical dispersion function is 2 to 3 times larger than calculated from expected field tolerances. Calculations show that the polarization disappears in these conditions. Temporary remedies to these problems were found in a drastic change of the fractional part of the horizontal betatron tune to avoid a strong spin resonance driven by the coupling and a much better orbit correction to reduce the dispersion. With these provisions, a natural polarization level of some 10 to 20 % was predicted [8], which could be increased to 40 to 50 % after harmonic spin matching.
2.2 Polarimetry

The LEP polarimeter [9], based on spin-dependent Compton scattering of circularly polarized photons from polarized particles [10], monitors the transverse polarization of the electron beam. A frequency-doubled Nd-YAG laser situated in an Optical Laboratory close to the LEP tunnel generates 50 mJ, 12 as long pulses at ~30 Hz repetition rate. As shown in Fig. 1, the 532 nm wavelength light is guided over a distance of 115 m to the Laser Interaction Region (LIR) in a roughly evacuated transport line including three lenses and five dielectric mirrors. Final steering onto the electron beam under an interaction angle of 2 to 3 mrad is provided by (Ag + Mg F2)-coated Cu mirrors in the LIR section of the LEP vacuum chamber.

From the Compton interaction between an e− bunch and a relatively intense laser pulse (multi-photon operation mode), about 10^8 photons within an energy range of 0-28 GeV are backscattered in a cone of half aperture 1/γ and their transverse profiles are recorded in a silicon strip detector 247 m downstream the LIR [11]. A typical vertical γ-profile shows an r.m.s. width of ~5 mm (Fig. 2).

The spin-dependent Compton scattering cross section depends both on the light and the electron polarization states. The measurement of transverse polarization consists in detecting the centre-of-gravity shift ∆(Y) of the vertical γ-profiles when reversing the handedness of the circular laser light from −ξ to +ξ:

\[ \Delta(Y) = \kappa \xi P_{\perp} \]  

where \( \kappa \) is the analyzing power of the polarimeter and \( P_{\perp} \) the electron transverse polarization. Simulations of our polarimeter give \( \kappa = 500 \pm 30 \mu \text{m} \) at 46.5 GeV.

A 10% beam polarization yields a ~ 50 μm mean-shift for 100% circular light polarization.

For linearly polarized light the Compton scattering cross section does not depend on the beam polarization: reversing the handedness leads to a change in the shape of the γ-distributions with no mean-shift. This feature was extensively exploited to tune the polarimeter independently of the amplitude of the polarization level of the circulating beam.

A flexible control of the light polarization is provided by the setup described in [11]. A rotating half-wavelength retardation plate provides a continuous handedness reversal of the incoming linear light at a pulse to pulse rate, while a quarter-wavelength retardation plate provides any elliptical light state via an adjustable time delay on the laser trigger system. Depolarizing effects (reflections, birefringence etc.) from the optical elements in the light path can in this way be compensated and the amount of circular light state at the LIR optimized. The electron beam is then illuminated by a sequence of pulse-to-pulse alternating-handedness circular or linear light states, to average out systematic uncertainties.

The considerable evolution experienced by the instrument after the initial observations in 1990 is summarized in the following.

The control of the helicity states of the incident photons at the LIR has been implemented. The light beam can be extracted towards two optical boxes before entering the vacuum chamber with a Cu-mirror identical to that under vacuum. The relative amounts of linear and circular light as well as the light spot at the focus can in this way be monitored in condition reproducing the situation at the interaction point since the light path and the optical elements in the external beam are the same as under vacuum. A more precise compensation of the light depolarizing effects from optical elements in the line is then possible.
together with the tuning of the light spot, otherwise hidden in the LIR section. The light transmission along the optical line has been improved and the luminosity of the interaction increased, yielding a larger number of backscattered photons per interaction.

The Si-detector preamplifiers have been modified and noise from motor drivers has been properly filtered out to improve the quality of the measurements. Together with the data acquisition system, now based on a Motorola DSP56001 Digital Signal Processor allowing data collection and processing at each laser shot, the overall acquisition rate has improved by a factor 5 to 10.

On-line data analysis software provides background subtraction and computation of the mean shift of the vertical distributions with different algorithms. It is now available in the LEP control room (Fig. 3) from where the evolution of the polarization signal can be followed during the several manipulations carried out in the experiments.

2.3 Results of Polarization Experiments

It took approximately 70 hours of dedicated machine time to implement an optics compatible with the 10% polarization level and to commission the polarimeter. A clear polarization signal was detected at the very end of the 1990 running period, as shown in Fig. 4. The level measured was $9.1\% \pm 0.3_{\text{stat}} \pm 1.8_{\text{syst}}$ [8], a little less than the predictions. The validity of the signal was assessed in three different ways:

1. The polarity of the signal was inverted by inserting a $\lambda/2$ plate on the path of the circularly polarized laser beam.
2. The polarization signal was suppressed by controlled excitation of the spin resonance $\nu = 106$. This is done by creating specific harmonics of the closed orbit. The calculated and measured decay time of the polarization due to this resonance were furthermore in good agreement.
3. The polarization rise time was measured after controlled depolarization. It was found reasonably consistent with the asymptotic level of polarization which is independently computed from the asymmetry of the back-scattered photons. The two quantities are related by:

$$P_\infty = \frac{92.3\%}{\tau_p/\tau}$$

where $\tau_p \approx 300$ minutes is the Sokolov-Ternov polarization rise time and $\tau$ the observed rise time.

In 1991, the same result, i.e. a level around 10% of polarization, was reproduced in each of two consecutive experiments. The polarimeter and data processing had then been improved, resulting in higher statistics and faster response, as may be seen in Fig. 5.

In a third experiment, no clear polarization signal could be measured.

In a fourth experiment, a very clean signal of 5% was obtained and checked successfully for consistency. The lower polarization level is consistent with a closed orbit which could not be corrected as well as before. An improvement of the Beam Orbit Measurement (BOM) system would have required a long access to the machine.

In the fifth experiment, the BOM System had been improved and a polarization signal of some 10% was observed. The first successful depolarization by an artificial spin resonance
was carried out, leading even to spin flip. This artificial depolarization makes it possible to measure the beam energy to very high accuracy.

In the sixth experiment, the polarization level was increased to 16 % after a successful orbit correction. The asymptotic level was not reached. From the rise-time, it can be calculated to be 20 % ± 2 %. The artificial depolarization was proven to be related to the beam energy. The beam energy could be calibrated to about 1 MeV.

In all the above experiments, no efforts were yet invested in increasing the polarization level by dedicated means nor to shorten the rise-time with the polarization wigglers.

2.4 Conclusion and Prospects

Given the uncertainties on the achievable polarization level in LEP, the observation of a 16 % signal can be considered as a significant success. Its reproducibility is an important achievement in the direction of operation with polarized beams. The fact that the observed polarization level is consistent with the predictions gives more confidence that the high level of polarization predicted for the LEP beam is possible.

The most important requirements for further progress are:

- A very precise measurement of the closed orbit. An improvement programme of the hardware is under way and is of the highest priority for the success of the polarization programme.
- Powerful algorithms to disentangle beam monitor measurement errors from the effect of field imperfections.
- A very precise measurement of the dispersion and dispersion correction algorithms. An important step forward has just been achieved and is very promising [12].
- A reduction of the effect of the parasitic coupling fields. An in-situ demagnetization is already in progress.
- Studies for the understanding and maximization of the machine stability and reproducibility levels which are presently insufficient but are being improved.
- Studies of beam dynamics in presence of wiggler magnets.

An important goal is to improve the magnetic optics and hence the polarization level using observables other than the polarization level itself, such as the closed orbits, the dispersion functions, the beam emittances. Much time can be gained in this way. All these steps are liable to increase significantly the level of performance of LEP for the Z⁰ physics in the coming years and are therefore of general interest.

To be completed, the programme must tackle the polarization maximization, assess the compatibility with physics conditions (solenoids, high currents, beam-beam effect, physics optics), and introduce the polarization wigglers which may require spin matching. The evaluation of the effort in terms of manpower and machine time is given in Chapter 11.

3 ACCELERATOR PHYSICS OF SPIN ROTATORS

Several spin rotator designs are possible in principle. The conceptually simplest one is the Richter-Schwitters [13] scheme which is inserted into the straight sections surrounding the
experimental interaction points (IP). It rotates the spin from the direction perpendicular to the median plane into the direction along the beam axis with dipole magnets which bend the beam only in the "vertical" plane, i.e. the direction perpendicular to the median plane. The Richter-Schwitters spin rotators for LEP differ from the original proposal where the dipole magnets are installed in the field-free region surrounding the interaction point [13] by having quadrupoles interspersed with the dipole magnets. This added complication implies that the effects of these quadrupoles on the spin must be taken care of by "spin-matching", first achieved in 1988 [14]. The spin rotator insertion could then be shortened [15, 16]. The spin rotators proposed here are described in [17].

All spin rotators which bend the beam only in the "vertical" plane have the property that the beam axis at the interaction points is tilted by the angle required to rotate the spin by 90°. At the Z° energy of 45.6 GeV, this angle is about 15 mrad. This drawback would be avoided by compact spin rotators [18, 19] which are installed on either side of the experimental insertions and use a combination of horizontal and vertical dipole magnets. These rotators can be matched into the LEP lattice optically. However, they have the severe drawback that it is impossible to simultaneously achieve a small ratio between the vertical and horizontal beam emittances needed for a good luminosity and a high degree of polarization.

3.1 The Principle of Richter-Schwitters Rotators

The spin rotators proposed here were designed in June 1991. Their design is based on the hypothesis that they will be installed after completion of the LEP-200 programme. Their layout was obtained by modifying Version 2 of the LEP-200 lattice [20] which was available at that time. Since then, Version 3 of the LEP-200 lattice has been developed with many minor modifications which should not affect the conclusions of this feasibility study. This lattice is not four-fold symmetric due to different arrangements of the RF cavity straight sections in IP2/6 and IP4/8.

A schematic layout of half of the spin rotator near IP2 and IP6 is shown in Fig. 6. The other half is antisymmetric with respect to the interaction point. The string of bending magnets B1-B2-B2 between the quadrupoles QS2 and QS3 bends the beam vertically down by 21.2453 mrad, and the bending magnet B3 between the quadrupoles QS9 and QS10 bends the beam vertically up by −6.0602 mrad. The sum of the bending angles is 15.1792 mrad, such that the spin is rotated from the vertical direction into the longitudinal one at the Z° energy of 45.6 GeV. For energies slightly off the Z° energy the spin will not be exactly longitudinal at the interaction points but the antisymmetry of the rotator ensures that the spin is again vertical at the far end of the rotator. The maximum vertical displacement of the design orbit with the spin rotator in the standard LEP configuration occurs in the B2 dipoles and amounts to ±629 mm. The layout of the quadrupoles near IP2 and IP6 is identical to that in the LEP-200 lattice with the following exceptions: One of the existing quadrupoles, QS2.2, is not excited, and two quadrupoles, QS5A.2 and QS6A.2, have been added. The strengths of the quadrupoles are discussed in Section 9.2.2.

The spin rotator layout near IP4 and IP8 is very similar, only the numbers change slightly. The B1-B2-B2 dipole chain bends the beam by 22.6271 mrad, while the B3 dipole bends the beam by 7.4479 mrad. The maximum vertical offset is ±655 mm. The layout of the
quadrupoles near IP4 and IP8 is identical to that in the LEP-200 lattice with the following exceptions: One of the existing quadrupoles, QS2.4, is not excited, and two quadrupoles, QS4A.2 and QS5A.2, have been added. The strengths of the quadrupoles are discussed in Section 9.2.2.

Because of the vertical slope of the design orbit, each spin rotator increases the LEP circumference by a few millimetres. This effect has no consequences on the exact positions of the bunch collisions along the beam axis, provided that diametrically opposite spin rotators are identical, as is the case in this feasibility study. Neighbouring spin rotators need not be identical, and are different in this feasibility study.

3.2 Control of the Depolarization by the Rotator

Because the spin rotator replaces a section of the standard LEP lattice, it has to be optically matched to it. In addition, the spin rotator has to satisfy spin-matching conditions. A detailed description of the optical and spin matching conditions, and the procedure used for finding the proposed spin rotators for LEP may be found in [17]. Fig. 7 and Fig. 8 show the optical functions in one half of the straight sections near IP2 and IP6, and near IP4 and IP8, respectively, and demonstrate that the optical matching conditions are indeed satisfied.

One of the design principles for LEP spin rotators is keeping the vertical dispersion $D_y$ low in the B1-B2-B2 dipole. This minimizes the quantum excitation of the vertical emittance which is used as a criterion. When the polarization and emittance wigglers are excited, the emittances with spin rotators in all four experimental insertions are:

$$E_x = 23.01 \text{ nm} \quad \text{and} \quad E_y = 0.48 \text{ nm}$$

(3)

The vertical emittance $E_y$ is larger than in other spin rotator designs for LEP, indicating that there is room for improvement. However, it is already smaller than that needed for operating LEP at design current and at the design value of the beam-beam strength parameter $\xi_y$.

So far, no effort has been made to achieve the correct tunes $Q_x$ and $Q_y$ for LEP with spin rotators, to correct the chromaticities $Q'_x$ and $Q'_y$, and to compute the dynamic aperture. The phase advances in the arcs were simply adjusted to achieve about the same fractional tunes as in LEP-200. A comparison of the phase advances $\mu_x$ and $\mu_y$, the tunes $Q_x$ and $Q_y$ and the chromaticities $Q'_x$ and $Q'_y$ between Version 2 of the LEP-200 lattice and LEP with spin rotators is shown in Tab. 1. With spin rotators, the tunes are about four units higher. At the $Z^0$ energy, the spin tune is $\nu \approx 103.5$. Hence, the present horizontal tune $Q_x$ falls close to the systematic spin resonance $Q_x = \nu - 8$ and will need to be decreased. A straightforward solution is to operate LEP with spin rotators at tunes $Q_x = 94$ and $Q_y = 100$ which are three units higher than in LEP-200, and 24 units higher than the present tunes. The actual values of the tunes will depend on the operational experience gained when the machine is operated in the LEP 200 configuration. For the beam-beam effect tunes different by four units are equivalent. A change of tune by one unit is simple, and can be done in the non-experimental insertions. It remains to be seen whether more drastic changes of the tunes are also possible. The chromaticities are a few units too low and can also be corrected easily, by slightly increasing the sextupole strengths. The dynamic aperture of LEP with spin rotators will be close to that of LEP-200 without them, since the sextupole strengths are similar, while the changes in the layout affect only the straight sections where only linear elements are modified, i.e. dipoles and quadrupoles.
Table 1: Phase advances $\mu$ between interaction points, tunes and chromaticities

<table>
<thead>
<tr>
<th></th>
<th>without rotators $\mu_x/2\pi$</th>
<th>with rotators $\mu_x/2\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$IP2 - IP4$</td>
<td>22.847</td>
<td>23.846</td>
</tr>
<tr>
<td>$IP4 - IP6$</td>
<td>22.847</td>
<td>23.846</td>
</tr>
<tr>
<td>$IP6 - IP8$</td>
<td>22.847</td>
<td>23.846</td>
</tr>
<tr>
<td>$IP8 - IP2$</td>
<td>22.848</td>
<td>23.845</td>
</tr>
<tr>
<td>$Q'$</td>
<td>91.389</td>
<td>95.383</td>
</tr>
<tr>
<td>$Q$</td>
<td>5.607</td>
<td>-4.353</td>
</tr>
</tbody>
</table>

The polarization computed with the first-order algorithms in SITF [21] is shown in Fig. 9. The polarization wigglers are excited to achieve a polarization time of 32 minutes. The emittance wigglers are excited to increase the horizontal emittance.

3.3 Control of the Depolarization by the Solenoids

In a first approach, the compensation by skew quadrupoles is switched off. The four experimental solenoids are all excited, with polarities such that L3 and OPAL, and ALEPH and DELPHI, respectively, compensate each other approximately. To achieve these polarities ALEPH would have to reverse its polarity. The emittances are larger than without solenoids, shown in Eq. (3), in particular the vertical one:

$$E_x = 23.73 \text{ nm} \quad \text{and} \quad E_y = 0.78 \text{ nm}$$ (4)

The finite polarization achieved between the spin resonances is a starting point for improvements by various correction methods.

A complete and flexible compensation of the betatron coupling due to the solenoids requires four skew quadrupoles on each side of the solenoid. There is however no space for such a scheme between the spin rotator dipoles. If the positions of the quadrupoles are used as parameters in a fixed optics, it is possible to reduce the number of quadrupoles by a factor of two. In reality the freedom to choose the positions is limited and the correction is only partial. A satisfactory solution was found, given in Tab. 2. It can be implemented with the existing skew quadrupoles. The beam transverse emittances are:

$$E_x = 23.67 \text{ nm} \quad \text{and} \quad E_y = 0.69 \text{ nm}$$ (5)

The polarization level is not totally restored (Fig. 10). A full compensation should be possible by an additional rotation of the polarization using standard orbit bumps.

3.4 LEP Performance

The consequences of the beam-beam effect on the degree of polarization have been measured at PETRA [22, 23] where a drop of the polarization with increasing bunch current was observed. The generally accepted interpretation of these data is that there is no loss in polarization as long as the vertical beam size is not blown up by the beam-beam forces.
Table 2: Compensation of the experimental solenoids with two pairs of antisymmetric skew quadrupoles per even interaction point. The strengths of the corresponding skew quadrupoles on the right hand side of the interaction points have opposite signs.

<table>
<thead>
<tr>
<th>Element</th>
<th>Position</th>
<th>$B_s I$ in Tm or $K_s$ in m$^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>L3-SOL.2</td>
<td>3325.566966</td>
<td>-3.756771E-03</td>
</tr>
<tr>
<td>QTS1.L2</td>
<td>3314.707466</td>
<td>5.064478E-04</td>
</tr>
<tr>
<td>QTS2.L2</td>
<td>9989.556183</td>
<td>-5.595987E-03</td>
</tr>
<tr>
<td>QTS4.L4</td>
<td>9977.527183</td>
<td>-5.640886E-04</td>
</tr>
</tbody>
</table>

Since the change of the LEP working point earlier this year, no such blow up has been observed up to the maximum beam currents reached so far. Hence, the performance estimate can be based on the nominal LEP beam sizes at 45.6 GeV since they are not too different from those for which the polarization shown in Fig. 9 was obtained. With a bunch current of 0.75 mA, the canonical limit of the beam-beam strength parameters $\xi_\ast = \xi_\nu = 0.03$ is reached at 45.6 GeV with emittances $E_\ast = 67$ nm and $E_\nu = 2.7$ nm, resulting in rms beam radii at the even interaction points of $\sigma_\ast = 0.34$ mm and $\sigma_\nu = 13.7 \mu$m, and a luminosity of $L = 13 \times 10^{30}$ cm$^{-2}$s$^{-1}$ with four bunches in each beam, and correspondingly higher with more bunches.

4 CONTROL OF SYNCHROTRON RADIATION AND PARTICLE BACKGROUNDS

Due to the complexity of the background problem and the limited manpower that was available for the study, definitive answers cannot yet be given to all questions described in this chapter. In particular, the problem of synchrotron radiation emitted in the rotator dipoles needs more dedicated effort in order to work out a consistent and practicable solution. Work has so far concentrated on insertions 2 and 6 and part of it has to be repeated for insertions 4 and 8 as the layout for the two types of insertions is different.

4.1 Photon Background

The strong dipole field of the spin rotator magnets which are located some 30 m away from the interaction point (IP) presents a very important source of synchrotron radiation (SR) background to the LEP detectors [24]. The group of three spin rotator dipoles B1-B2-B2 on
either side of the IP radiate about $6 \times 10^{12}$ photons per bunch crossing and per mA beam current. Half of this radiation is directed towards the IP, and about $4 \times 10^{10}$ photons shine directly onto the thin vacuum pipe inside the physics detector ($\pm 2.5$ m length and 106 mm diameter). The critical energy of these photons is 263 keV. Most of the other half, directed away from the IP, is intercepted by the vacuum system within 60 m from the interaction point, and can contribute to the background at the IP after one or more scatterings.

The maximum tolerable synchrotron radiation photon rate at various LEP detectors is estimated in Chapters 5 to 8. The currently observed background rates for 3 mA of total current circulating in LEP are generally rather low, and it has been estimated that an increase of up to a factor of ten should be tolerable. The limit is due to accumulated dose and current drawn by drift chambers rather than occupancy. This leaves room for a factor of 5 only for the possible increase of background rates assuming a doubling of the LEP currents at the time of running of the polarization programme.

The calculated rate of synchrotron radiation photons that hit the 106 mm diameter IP-pipe with present optics conditions is about 15 photons/mA/crossing [25]. According to the above arguments, this rate should not exceed 75 photons/mA/crossing. It follows that any collimator protection system must reduce the synchrotron radiation photon flux emitted by the spin rotator magnets by factors of well above $10^6$. This reaches the limit of what can be calculated with the available computer simulation code [26]. Order of magnitude estimates, however, can be obtained with solid angle and simple photon albedo calculations. They allow to identify the critical parts of the system and are in fact used in a first stage of the design of a protection system.

The direct synchrotron radiation photon flux onto the IP-pipe can be easily intercepted by vertical collimators, e.g. 15 m away from the experiment (see Fig. 12). However, the number of photons that scatter off the inner collimator surface and its edge and will reach the LEP detectors is still much too high ($10^4$/mA/crossing [27]). This scattered flux can be reduced by about one order of magnitude by tilting the collimator surface out of the direction of the direct photon cone (see Fig. 13). However, this is not sufficient, and the only way to decrease the rate by a further two orders of magnitude is by reducing the field strength of the rotator dipole that radiates onto the collimator edge. Therefore, in order to keep the contribution of this unavoidable photon background source below tolerable limits, a weak field dipole of 7 m length and 15% of the main rotator field strength had to be introduced.

The probability of photons in the synchrotron radiation energy range to be reflected from the vacuum chamber walls or collimator surfaces is about 1/sr for small forward scattering angles (few mrad) and about two orders of magnitude smaller for backward scattered photons. With incident photon rates of $10^{11}$/mA/crossing per metre of vacuum chamber, single scattered photons must be stopped as much as possible from reaching the IP-pipe.

A collimator system protects the physics detectors from all direct and most of the single scattered photons radiated in the spin rotator dipoles and beam line quadrupoles. Preliminary photon background simulations under these conditions yield rates of photons incident onto the IP-pipe of about 40 photons/mA/crossing. Half of this rate is due to backward scattered photons from quadrupole or dipole radiation. The other half originates from collimator edge scattering. The collimator system (Fig. 12) consists of 6 vertical and 6 horizontal collimators per experiment each with two movable jaws made out of tungsten. For four of the vertical collimator jaws the angle with respect to the beam direction must be adjustable.
This collimator system is very complicated in the sense that nearly all jaw settings are closely interlinked, which will make the optimization of background rates and the operation of such a system rather complicated.

The above solution, however, is not complete because it neglects multi-scattered photons. Due to the very high density of incident photons onto the vacuum chambers of the rotator dipoles, the contribution of double scattered photons to the photon background cannot be neglected. The complete simulation of this family has not yet been successful. Estimates indicate that doubly scattered photons might become the dominating background source. To stop multiply scattered photons from reaching the detectors by introducing further collimators does not seem to be a practical solution.

A remedy proposed by D. Treille proceeds in two directions: (i) to absorb photons, that would reach the IP-pipe after two forward scatterings, by introducing special vertically enlarged vacuum chambers in the rotator dipoles B1-B2-B2, and (ii) to add local masks and, if needed, a high-Z material layer around the vacuum chamber in the detectors.

A sketch of a possible local mask is shown in Fig. 14. The cylindrical mask located at 2.1 m from the IP has an inner diameter of about 75 mm. It will protect the IP-pipe from photons up to 7.5 mrad incidence (to the mid-point) and not interfere with the future small angle detectors (SAT) above 25 mrad. The 75 mm bore leaves sufficient acceptance for the LEP beams. A layout for enlarged vacuum chambers in the rotator dipoles including a photon dump is being studied and looks feasible.

Although this scheme needs further study, it appears to be a very promising solution to the photon background problem, as long as local masks are acceptable for the LEP experiments.

4.2 Electron Background

Off-momentum electrons and positrons produced by bremsstrahlung of beam particles with rest-gas molecules are the dominating source of the high energy electron background at the LEP detectors [28]. This background can be simulated with good accuracy. The measured rate with present LEP conditions is about $5 \times 10^{-3}$ electrons and positrons per mA and bunch crossing [25].

Most of the off-momentum particle background at the detector is created within the last 500 m upstream of the experiment. The rotator dipoles will decrease this considerably by directing off-momentum particles into the vacuum chambers far from the experiment or onto vertical collimators around the IP's. Simulations for the spin rotator optics result in off-momentum particle background rates of $\lesssim 5 \times 10^{-4}$/mA/crossing.

The only point of concern, still to be studied, is a relatively high flux of off-momentum electrons (about $10^8$ Hz/mA in total) that is impinging onto the upper or lower jaw of collimators at 15 m and 36 m from the IP. Although most of these particles will be cleanly absorbed in the 30 radiation lengths of tungsten jaws, there is a certain fraction of shower energy that will escape through the collimator edge and could add to the background at LEP detectors.

4.3 Protection of LEP Equipment

Superconducting RF cavities in points 4 and 8 and vertical electrostatic separators around all four interaction points must be protected against direct synchrotron radiation emitted in
the spin rotator dipoles.

The electrostatic separator plates at about 23 m from the IP, just upstream of the weak field rotator dipoles B1, are in the shadow of the 36 m collimators assuming a separator gap of 120 mm. As in the present layout, they need protection from synchrotron radiation emitted in the low-β quadrupoles by a vertical collimator placed immediately upstream of the separator (23 m collimator of Fig. 12). A vertical collimator is needed to protect the electrostatic separator placed at 67 m from the IP against the synchrotron radiation of the large vertical dipoles B2. The already existing vertical collimators near quadrupole QS5 will protect these separators from the opposite side against SR from the rotator dipoles B3.

In points 4 and 8 superconducting RF cavities will be left in place between quadrupoles QS10 and QS8. These cavities must be protected from the synchrotron radiation emitted by the B3 rotator magnets with vertical collimators or masks next to QS8. Further horizontal collimators next to quadrupoles QS10 will protect the cavities from synchrotron radiation out of the arc. These horizontal collimators are already included in the LEP-200 programme.

5 IMPLICATIONS FOR ALEPH

The ALEPH collaboration expressed interest in experiments with longitudinally polarized beams very early [29] and, provided there is enough evidence that the programme can be carried out successfully, certainly supports it strongly. This short contribution discusses some of the practical implications, which are three:

- Rotation of the detector by 15 mrad;
- Capacity of the detector to handle additional synchrotron radiation exposure;
- Improved luminosity detector.

5.1 Rotation of the Detector

The ALEPH detector is situated in point 4, where the slope of the beam is 3.6 mrad in the usual configuration. It is proposed to proceed to the 15.2 mrad rotation, corresponding to a 90° spin rotation, in the opposite direction. The detector is then tilted by -11.6 mrad with respect to the horizontal position.

This rotation can be accommodated by the hydraulic jacks supporting the detector. However, in order to keep the detector centered at the interaction point, a longitudinal translation of 80 mm has to be foreseen. Even though the liquid helium dewar will be in somewhat less favorable situation than presently, the tilt should be acceptable.

The modifications to be performed in order to tilt and translate the detector have been studied carefully. These modifications are relatively small, and should cost one to two months of work, which can be prepared well in advance. The actual rotation of the experiment should take between two weeks and one month. The total cost is estimated to be less than 500 kSF, including manpower.

5.2 Handling of Synchrotron Radiation

The maximum tolerable photon flux to ALEPH was determined during a collimator experiment done on 24 May 1991. The 8.5m horizontal collimator, which protects the experiment
from local and scattered photons, was opened partially until the ALEPH tracking chambers were both running at 90-95% of the trip-off current. Experience from 1990 running shows that the chambers may be damaged by running for a continued period at this level.

The photon background is quantified by counting the hits seen in the TPC and ITC that are not associated with charged tracks. The average number of these unassociated hits per crossing during normal conditions in 1991 is approximately 6 in the TPC and 4 in the ITC. When the 8.5m collimator was opened, the average number of unassociated clusters seen in the TPC was approximately 50 and in the ITC 35. Since this background corresponds to what we consider the maximum tolerable in the TPC, we conclude that a factor of 7-8 is the maximum tolerable increase in photon flux.

Several caveats are in order. Only higher energy photons will make visible clusters in the tracking chambers. It is hard to know what the change of spectrum was when the collimators were opened, and whether the flux uniformly increased by a factor of 7, or simply more high energy photons were able to impact the chamber. More work is needed to understand the response of the chambers to different photon energies to give a more precise estimate of the increase which the detectors can withstand.

5.3 Luminosity Measurement

As pointed out in earlier reports [30], making the best use of the availability of longitudinal polarization requires a luminosity monitor which provides: i) statistics of low angle Bhabha scattering events well in excess of that of hadronic Z decays at the peak of the Z resonance; and ii) bunch-to-bunch normalization systematics well below $10^{-3}$.

ALEPH is presently upgrading its luminosity measurement with SICAL [31], a compact tungsten-silicon calorimeter extending the present acceptance of the luminosity measurement [32] from around 50 mrad down to 28 mrad. The accepted Bhabha cross-section is 102 nb, a factor 3.5 times the Z peak cross section. The contribution to the statistical error is therefore negligible.

The SICAL design has profited from the experience gained in ALEPH on precision measurement of absolute luminosity [32], in such a way as to improve it further. A breakdown of the systematic errors on absolute luminosity with the present set-up shows that only the following sources of errors could affect the relative bunch-to-bunch normalization: i)background estimate, 0.03%; ii)Trigger efficiency, nil; iii)Beam parameters: 0.02%. The situation for a bunch-to-bunch normalization should be even more favorable, but this convincingly demonstrates that bunch-to-bunch systematics should be well below $0.5 \times 10^{-3}$.

The SICAL is expected to operate already in 1992.

5.4 Conclusions

Tilting ALEPH requires preparation work amounting to one to two month and a cost of less than 500 kSF, including manpower. The actual tilting operation would take of the order of two to four weeks.

Synchrotron radiation exposure can be withstood if it does not exceed a factor of (7-8) more than the present LEP operation.

Luminosity measurement is being upgraded with SICAL and should not limit the precision measurement of $A_{LR}$. 
6 IMPLICATIONS FOR DELPHI

The DELPHI Collaboration is extremely interested in the possibility of pursuing $Z^0$ physics with longitudinally polarized beams after the LEP 200 program. This interest has been demonstrated by the part taken since long by DELPHI members both in the study of synchrotron radiation shielding and in the construction and use of instruments for the measurement of beam polarization. The use of longitudinally polarized beams will necessitate, in particular, to rotate the DELPHI detector, to handle the higher level of synchrotron radiation, and to measure the luminosities with enough accuracy. These issues are addressed in the following.

6.1 Tilting DELPHI for polarization

Due to the inclination of the LEP ring DELPHI is already tilted by 3.6 mr with respect to the floor. The tilt for the polarized beams is of the order of 15 mr which could be either way. During construction of the DELPHI Barrel RICH the 3.6 mr tilt was taken into account, in designing the liquid radiator system. Consequently a counter-tilt of DELPHI would only be possible by modifying a large number of connections (the access of which is difficult). Therefore DELPHI should be tilted further, i.e. in total by 18.6 mr. This seems to be possible but necessitates quite a number of modifications:

- lowering the support of at least 8 under-carriage systems
- acquisition of 8 jacks with longer and shorter stroke
- dismantling of the driving elements for the end-caps
- dismantling of the stabilizer wheel
- reinforcement of the horizontal drive for end-caps (has to w uphill)
- construction of 2 conical shielding pieces to fill the gap between DELPHI and the movable shielding blocks
- modification of cryogenics connections
- modification of supports for the vacuum pumps
- modification of the cooling water connections to the barrel
- compensation of barrel centre.
- improvement of some detector supports.
- alignment of barrel detectors.

We assume that DELPHI and/or the end-caps will not be moved into garage position during the year of polarized beams - otherwise we would have to modify further parts which could be simply dismantled.

At the end of the polarization period everything has to be brought back into the original shape.

The cost is estimated to be 300 kSF.
6.2 Synchrotron radiation from rotator magnets

Three detectors have been looked at to study the amount of radiation which can be safely handled by DELPHI.

- **Microvertex detector:** Beam backgrounds are not a problem for the extraction of track hits from the DELPHI vertex detector. Our concern is the accompanying radiation dose which can harm the readout electronics. We monitor this dose in two different ways. First, we have installed TLD monitors to integrate the dose over whole years of running. During the 1989 - 1990 running we accumulated 24 rads. These results are not yet available for the 1991 running, but will be at the end of the year. For 1991 we have also installed real-time background monitors. Unfortunately, these devices have not integrated the whole year's dose. However, studies of their output, in combination with background levels in our vertex detector, lead us to estimate the 1991 dose at 100 - 200 rads. This is consistent with the 1990 result and the expected increase due to the smaller LEP beam pipe. The detector readout electronics will fail if it receives more than 15 krad, and its hit resolution will worsen noticeably for doses above 5 - 8 krad.

- **Inner detector:** From the mean free path of photons in argon we estimate an average of 10-2 conversion probability in the detector gas. The present level of radiation is not noticeable. A factor of more than 10 above the present level would be tolerable and would not cause problems to the pattern recognition. Another point however is the ageing of the detector. From the most pessimistic estimate found in the literature, the lifetime of the detector at 200 photons / crossing would be about 10 years. This is likely to be an upper limit on the tolerable synchrotron radiation level.

- **TPC:** From present experience with the operation of the TPC, the increase of synchrotron radiation would have no influence on pattern recognition and data size could be handled. The main uncertainty is on space charge effects and on currents drawn by the MWPC end plates. It is safe to consider that an increase of a factor of 10 or less above the present level is tolerable. Beyond that, the accuracy of the TPC and its lifetime would have to be assessed.

6.3 Luminosity

Luminosity measurements in DELPHI were carefully reviewed in CERN 88-06, Vol. 2, p. 107, and the necessary accuracy is reachable.

7 IMPLICATIONS FOR L3

7.1 Tilt of the Beam-pipe

The L3 magnet cannot be tilted by 15 mrad, since it is embedded in concrete, and more importantly, the magnet is not constructed to withstand the stresses generated by such a tilt. The proposal is to tilt only the beampipe, together with the luminosity monitors and the nearby quadrupoles. This can be carried out without affecting other parts of the L3 detector, except for the Silicon Microvertex Detector, which would have to be removed (this could be avoided if the beam pipe radius were reduced by about 1 cm).
7.2 Orbit Correction in L3

The nominal LEP orbit passes through the solenoid at a vertical angle of about 15 mrad at 45.6 GeV. The solenoid field thus has a vertical component and causes a horizontal orbit deflection. A simplified model [35] was studied for the spin rotator [15], and used again for the present spin rotators:

- The L3 solenoid is represented by a solenoid which replaces a drift space of 6.752 m length between the QS0 quadropoles. Its strength is adjusted such that the integrated longitudinal field is correct. This approximation avoids the problems associated with superimposed solenoid and quadropole fields.
- The whole solenoid is divided into 10 slices with tilts and displacements such that the whole solenoid is correctly tilted around the interaction point near IP2 as a rigid body.

An orbit which starts at the interaction point in IP2 with initial conditions \( x_{P2} = 0 \) and \( z_{P2} = 0 \) leaves the outboard QS1 quadropole with a position \( z_{QS1} = 3.079 \) mm and a slope \( z'_{QS1} = 0.033 \) mrad. A pair of horizontal orbit correctors is necessary and sufficient to correct both \( z \) and \( z' \). One corrector should be installed as close to the outboard QS1 quadropole as possible, i.e. at a distance \( s_{QS1} \geq 13.7 \) m. The other corrector should be installed as close as possible to the inboard face of the weak spin rotator dipole B1, i.e. at a distance \( s_{B1} \leq 28.576 \) m. Taking the equal signs in both distances \( s \), one finds for the kick \( \phi_{B1} \) near the vertical dipole B1 and for the kick \( \phi_{QS1} \) near QS1:

\[
\phi_{B1} = \frac{x_{QS1}}{s_{B1} - s_{QS1}} = -0.207 \text{ mrad} \quad \phi_{QS1} = z'_{QS1} - \phi_{B1} = 0.174 \text{ mrad} \tag{6}
\]

Kicks of this size are within the rating of the MCHA correctors. The arrangement on the other side of IP2 is symmetrical. A graph of the horizontal orbit from the interaction point near IP2 to the entrance face of the large spin rotator dipole is shown in Fig. 11.

The horizontal orbit distortions are confined to a distance \( s = \pm 28.576 \) m falling in between the large vertical dipoles which rotate the spin into the beam direction. The sum of all horizontal deflections in corrector magnets, quadropoles and the L3 solenoid vanishes. Hence, this arrangement is spin transparent.

7.3 Luminosity Measurement

The present Luminosity detector, consists of a segmented BGO array to measure precisely the energy and the impact coordinates of the scattered particles. The detector covers the angular region from 30 to 62 mrad, corresponding to an effective Bhabha cross section of \( \sigma \approx 100 \) nb, i.e. 3.5 times larger than the Z production cross section. This is adequate [34] to perform a precise \( (10^{-3}) \) \( A_{LR} \) measurement with about \( 10^6 Z^0 \) decays assuming that \( P_C \approx 50\% \) and the bunch-to-bunch normalization errors can be maintained at the \( 10^{-3} \) level.

The performances already achieved are summarized in Table 3.

From the encouraging results already obtained it seems that a bunch-to-bunch normalization systematics below \( 10^{-3} \) will be achievable, and will then not limit the precision measurement of \( A_{LR} \).

In 1992 the L3 luminosity Detector will be upgraded by replacing the present proportional chambers in front of the BGO array with Si detectors which will allow a better scattering angle determination.
Table 3: Summary of experimental systematic errors in the present absolute luminosity measurement in L3 [33].

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<table>
<thead>
<tr>
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<th></th>
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</thead>
<tbody>
<tr>
<td>Luminosity Trigger</td>
<td>0.1%</td>
</tr>
<tr>
<td>Geometry of the calorimeters</td>
<td>0.4%</td>
</tr>
<tr>
<td>Bhabha event selection</td>
<td>0.5%</td>
</tr>
<tr>
<td>Background subtraction</td>
<td>0.1%</td>
</tr>
<tr>
<td>Total experimental uncertainty</td>
<td>0.7%</td>
</tr>
</tbody>
</table>

7.4 Synchrotron Radiation

The synchrotron radiation background due to the spin rotator will be the same as for the other experiments, with in addition the synchrotron radiation due to the horizontal orbit correctors. With correctors of standard length (0.51 m) they will add a field of 0.062 T at the exit of the last rotator magnet (25 m from the IP) and a field of 0.052 T near the outboard of QS1 (15 m from the IP). The magnetic field bending the electrons in the horizontal plane can be compared with the field values of the weak vertical bend of B1 (spin rotator) which is 0.027 T. Thus with this setup the resultant synchrotron radiation would be in total 5 times that without the correctors.

We are not yet in a position to predict the effect of the extra synchrotron radiation. However, since other studies indicate that the situation is already very difficult with just the spin rotators, we can expect that the correctors will introduce a serious complication to the synchrotron radiation problem at L3. If non-standard correctors (longer than 0.51 m) could be used, the problem would be alleviated.

Clearly the backgrounds from synchrotron radiation could affect the new Luminosity trackers, the SMD (were it still in place) the central detector (TEC) and the trigger rates. These effects have not been studied in detail and require more attention to be able to give a final statement.

7.5 Conclusions

The use of longitudinally polarized beams in L3 necessitates tilting of the beamline. This has the consequence that an important part of the detector, the SMD, must be dismounted.

In order to compensate for the effect of the L3 solenoid, a spin matched solution has been developed entailing the use of extra bending magnets between 15 and 25 m on either side of the interaction point. This increases the synchrotron radiation background in L3 by approximately a factor of 5 with respect to the other IP's. We have not yet been able to study the implications of this background.
8 IMPLICATIONS FOR OPAL

8.1 Modifications to OPAL

8.1.1 Introduction

This section deals with the practical installation implications of a longitudinal polarization physics programme on OPAL. Two aspects are considered:

- Rotation of OPAL to the new beam direction.
- Improving the luminosity measurement.

8.1.2 Rotation of the Detector

In the present configuration, the slope of the beam at OPAL is 13.9 mrad. We propose to effect the 15.2 mrad rotation required for a 90° spin rotation by tilting the detector in the opposite direction, resulting in a net rotation relative to the vertical of -1.3 mrad. In order to keep the detector centered at the beam interaction point, a longitudinal translation of 80 mm has also to be foreseen.

OPAL’s tilting system was only foreseen to accommodate a 20 mm horizontal displacement. Modifications of the jacks will allow the necessary 8 cm displacement to be achieved. However, in this new position, the weight of the magnet assembly will be taken up mainly by one set of wheels on the double rails. Although the details have not been fully studied, it appears that this extra force can be supported by the present transport mechanism.

Physical Interference:

The main clearance problems will occur close to the beam line at each end of the magnet. The patch chambers of the end cap muon detectors (ME) will interfere with the existing shielding box which was added to provide adequate radiation protection. On one side (RHS) of the magnet, the shielding box can be modified relatively easily to provide compatibility. On the other side (LHS) however, the interference to ME is more serious and also involves the piping for the cooling water. The difficulties involved in removing this interference may oblige OPAL to consider modifying the ME patch chambers on this side.

There remains the problem of providing a sufficiently hermetic radiation shield, given that the existing mobile shielding has been designed for a 13.9 mrad slope. However, as this shielding region has to be redesigned to accommodate the rotator, the necessary modifications to match it to the new position of OPAL will be incorporated in this redesign.

A last point concerns the reinforced concrete beams on which the OPAL pole tip supports weight is taken. There are 2 such beams on each side of the OPAL magnet which are used when opening up OPAL in the beam position, and the 140 t weight of the pole tip assembly has to be fairly evenly distributed on both beams. The 8 cm horizontal displacement causes the support point on the LHS to fall completely on one beam. A means of redistributing the weight onto both beams has to be found.

A first estimate of the total costs involved is 100 kSF, excluding the modifications to the mobile shielding.
8.1.3 Improved Luminosity Measurement

In order to take full advantage of the availability of longitudinally polarized beams, the luminosity monitor should have:

- an accepted Bhabha cross section significantly larger than that of hadronic \( Z \) decays.
- a bunch-to-bunch normalization error below \( 10^{-3} \).

OPAL has prepared a proposal for a new smaller angle luminosity detector which is compatible with the two above requirements. It is planned to present the proposal to the November 1991 LEPC meeting.

8.2 Limits on Synchrotron Radiation Background in OPAL.

8.2.1 Introduction

The installation of spin rotators around OPAL is expected to increase the synchrotron radiation background levels in the detector. Since it appears that the radiation spectrum with rotators is very similar to the present background spectrum, we are able to put limits on the background intensity by scaling. For the different OPAL detectors which are near the beam pipe, we have made rough estimates of how much more photon background they can tolerate.

Note that all the numbers below are relative to the present background levels and therefore correspond to total circulating currents of about 3 mA, corresponding to .375 mA/bunch. By the time the polarization programme is running, the total circulating current should have reached its nominal .75 mA/bunch. Furthermore the number of bunches should also have increased. These factors should be taken into account in evaluating the background predictions.

8.2.2 Silicon Microvertex Detector

The limit quoted here is that given by an extrapolation of the present radiation dose. Presently the annual dose is in the region of 100 Rad. Since significant radiation damage in the readout electronics of the microvertex detector will occur when the total integrated dose approaches 10 kRad or more, the increase in synchrotron radiation should not exceed a factor of 100.

A large part of the dose comes from "catastrophic events" such as beam loss or from very bad beam steering. We have assumed that these doses also scale with the general photon background levels.

8.2.3 Vertex Chamber

Increased LEP backgrounds will affect vertex chamber performance by accelerating the rate of wire ageing and by degrading the spatial resolution. The tracking efficiency is not affected by the present noise rates and would not be seriously compromised by background increases up to a factor of 100 times the present rate.

Ageing has been studied by monitoring the average ADC pulse heights over the first two years of LEP running, as well as by monitoring the spectra of Fe\(^{56}\) sources located at the
ends of some wires in the chamber. These studies indicate that the useful lifetime of the vertex chamber will extend just beyond the end of LEP I, taking into account the fourfold increase of rates expected next year from the switch to $8 \times 8$ running. A factor of 10 increase in background rates would be unacceptable.

8.2.4 Jet Chamber

Present background situation

The average anode background currents per group of 16 wires measured during clean physics runs are of the order of a few nA. The innermost groups, however, draw currents of about 10 nA. Under bad beam conditions the background currents sometimes increase by a factor 5 (to 50 nA) in the innermost groups of wires.

The average number of additional hits due to synchrotron radiation background is measured to be of the order of 10 hits (0.4 per sector) per event. This number has to be compared with the average number of hits within a multi hadronic event of about 3000 hits and can be neglected.

Effect of background increases

We have studied the effects of increasing the background currents by factors of 10 and 100. In the former case, the background currents would be roughly as experienced during the pilot run, and are therefore acceptable, and the 3% additional hits should be no problem for the pattern recognition. The reduction in gas gain should on average be less than 0.5% and not require special treatment.

An increase of 100 in the background would result in anode and potential currents which are much too close to the high voltage trip limits. The chamber life would also be reduced significantly. The additional 30% background hits would require a re-tuning of the pattern recognition parameters. Nonetheless, the pattern recognition efficiency would drop significantly and the failure rate increase. Both the $z$ and $dE/dx$ measurements would be affected by the more dense hit environment and the $dE/dx$ measurement would suffer from a background dependent gas gain drop of about 10% or more.

Conclusions.

A background increase of 10 in the OPAL jet chamber seems not to influence significantly the data quality. An increase by a factor of 100, however, would seriously deteriorate the data quality and would reduce the high voltage safety margin. A factor of 30 increase in the background level might be acceptable.

9 Engineering of spin rotators

As mentioned earlier, it is assumed that spin rotators will not be installed in the LEP experimental points until after the completion of the LEP energy upgrade [36]. Hence, the layout of the spin rotators was obtained by modifying Version 2 of the LEP-200 lattice [20] available at the time of the design.
9.1 Layout and Civil Engineering

It is assumed that the spin rotators have their slopes oriented such as to minimize the slope of the beam trajectory through the experiments. In the sectors affected, the height of the beam above the floor is presently 0.8 m. On the side of the experiment where spin rotator takes the beam line up, blocks will be provided, on the other side it will be necessary to dig a trench between QS5A and the separator at 23 m from the interaction point. By modifying the way of supporting the quadrupoles it should be possible to limit the depth of the trench to a maximum of 25 cm, with a total of 8 m$^3$ of material to be excavated at each point. At point 5 the present beam height is 65 cm, so that a demonstration spin rotator (see Chapter 10.1) would require a correspondingly deeper trench, with a total quantity of about 20 m$^3$ to be excavated.

In the vicinity of the experiments, the girders supporting the quadrupoles will be displaced and rotated to their new positions. At points 4, 6 and 8 this operation will be done simultaneously with the rotation of the experiments. It should not be necessary to modify significantly the mobile shielding, apart from the addition of a wedge-shaped piece at the junction with the end cap. Recesses will be machined in situ in the lower girder to house the jacks supporting the mobile girder on the side to be lowered. Modifications will be required to be made to the shielding walls protecting the experiment from radiation coming along the machine tunnel. The salient features of the layout up to QS4 are visualized in Fig. 15.

9.2 Spin Rotator Components

We assume that the components must provide the possibility of running the machine up to an energy of about 48 GeV, in order to study adequately both sides of the $Z^0$ peak. The choice of a higher top energy would influence the utilization of the quadrupoles described below.

9.2.1 Vertical Dipoles

<table>
<thead>
<tr>
<th>Name</th>
<th>Distance from IP [m]</th>
<th>Length [m]</th>
<th>Angle [mrad]</th>
<th>Field [T]</th>
<th>Crit.energy [keV]</th>
<th>Rad.power [W/mA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1.2</td>
<td>28.576</td>
<td>7.000</td>
<td>1.242561</td>
<td>0.027000</td>
<td>37.337</td>
<td>13.427</td>
</tr>
<tr>
<td>B2.2</td>
<td>36.776</td>
<td>8.000</td>
<td>10.001388</td>
<td>0.190158</td>
<td>262.958</td>
<td>761.149</td>
</tr>
<tr>
<td>B2.2</td>
<td>45.976</td>
<td>8.000</td>
<td>10.001388</td>
<td>0.190158</td>
<td>262.958</td>
<td>761.149</td>
</tr>
<tr>
<td>B3.2</td>
<td>151.297</td>
<td>9.789</td>
<td>6.066186</td>
<td>0.094263</td>
<td>130.351</td>
<td>228.950</td>
</tr>
<tr>
<td>B1.4</td>
<td>30.086</td>
<td>7.000</td>
<td>1.242561</td>
<td>0.027000</td>
<td>37.337</td>
<td>13.427</td>
</tr>
<tr>
<td>B2.4</td>
<td>38.786</td>
<td>8.000</td>
<td>10.692248</td>
<td>0.203293</td>
<td>281.122</td>
<td>869.936</td>
</tr>
<tr>
<td>B2.4</td>
<td>47.986</td>
<td>8.000</td>
<td>10.692248</td>
<td>0.203293</td>
<td>281.122</td>
<td>869.936</td>
</tr>
<tr>
<td>B3.4</td>
<td>136.059</td>
<td>11.195</td>
<td>7.447908</td>
<td>0.101198</td>
<td>139.941</td>
<td>301.650</td>
</tr>
</tbody>
</table>

Three types of vertical bending magnets will be required: B1, B2, and B3. Their properties as used for the calculations of the spin rotators are listed in Tab. 4. The values of the
magnetic field $B$, of the critical energy $E_c$ and of the synchrotron radiation power per dipole and per mA of total circulating current in both beams apply to a beam energy of 45.6 GeV.

These vertical bending magnets would be constructed as follows. To allow for the installation of a 120 mm diameter vacuum chamber, equipped with water cooling and bake-out equipment, a gap width of 150 mm has been chosen. To minimize cost, components have been standardized to a maximum. It is envisaged to make the B2 and B3 magnets using the same 5.1 m long yokes and modular coils with the main, water-cooled winding of the three B2 units having twice the number of turns of those of the two B3 units. The difference between this arrangement and that taken for the spin matching calculations is negligible.

These magnets can be excited in series; the B3 coils will include correction windings to give the precise deflection. The magnetic length of each unit will be 5.25 m, and the precise value of field adjusted accordingly. The very weak bend B1 will consist of three narrow yokes aligned on a girder and excited by a single indirectly cooled low current coil. Its magnetic length will be 7 m. Tentative cross-sections of the three magnets are shown in Fig. 15.

9.2.2 Quadrupoles

A tentative assignment of quadrupole types to the quadrupoles around the interaction points is shown in Tab. 5. The underlying principle in the quadrupole assignment is to replace the strongest MQA quadrupoles QS4.4 and QS5.4 by pairs of MQ quadrupoles which are available because the QS2 quadrupoles are not necessary. In the experimental insertions, there are eight more quadrupoles with spin rotators than in both LEP-1 and LEP-200. We have labelled them MQB. The quadrupole type MQA can be used for these quadrupoles up to an energy of 47.7 GeV. If MQA quadrupoles are operated beyond their nominal rating or if new quadrupoles MQB are somewhat stronger the maximum operating energy would be increased accordingly.

9.2.3 Orbit Correcting Dipoles

At most 12 horizontal and 8 vertical orbit correcting dipoles of the MCHA and MCVA types will have to be provided.

9.2.4 Power Converters and Cables

The new magnets are designed to use standard LEP type power supplies. Twelve 360 A and sixteen 50 A circuits will be required for the vertical bends and quadrupoles; the orbit correcting dipoles use 5 A bipolar supplies. Suitable cables must be laid.

9.3 Modifications to the RF Systems

The final spin rotators will be installed in the experimental insertions at locations occupied by Cu and superconducting (s.c.) RF cavities. To allow for the civil engineering work (section 9.1), it appears reasonable to assume that all equipment will be removed from the tunnel. Most of the RF cavities will not be re-installed in their previous locations, occupied by the extra dipoles and quadrupoles of the spin rotators. Because it is undesirable to use RF cavities installed in regions where the dispersions do not vanish, it is assumed in the following
that all RF cavities between the B3 dipoles are removed. Tab. 6 shows a comparison of the numbers of RF cavities which will be in LEP-200 and for which space will remain available in LEP with spin rotators. Three case are considered, namely:

- The RF cavities are re-installed in their previous locations in all experimental insertions wherever this is possible.
- In points 4 and 8, the s.c. rf cavities are also installed in the slots available for that purpose outside the spin rotators.
- Points 2 and 6 are converted to the style of points 4 and 8; the Cu RF cavities are completely removed.

It should be remembered that the modules consisting of four superconducting cavities are equipped with sector valves and designed and installed such that any module can be removed in an orderly fashion. In the first two cases, the circumferential RF voltage is barely enough for the full pretzel scheme with 36 bunches of 0.75 mA in each beam [39]. In the last case a LEP layout is obtained with almost fourfold symmetry, 160 evenly distributed s.c. and a sufficient RF power which is very well suited not only for the longitudinal spin physics programme at high luminosity but also for e-p physics between LEP and LHC.

<table>
<thead>
<tr>
<th>Name</th>
<th>LEP-1</th>
<th>LEP-2</th>
<th>LEP with spin rotators</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8 MQC</td>
<td>8 MQC</td>
<td>8 MQC</td>
</tr>
<tr>
<td>QS0</td>
<td>16 MQA</td>
<td>16 MQA</td>
<td>16 MQA</td>
</tr>
<tr>
<td>QS1</td>
<td>16 MQA</td>
<td>8 MQA</td>
<td>8 MQA</td>
</tr>
<tr>
<td>QS2</td>
<td>16 MQ</td>
<td>8 MQ</td>
<td>8 MQA</td>
</tr>
<tr>
<td>QS3</td>
<td>8 MQA</td>
<td>8 MQA</td>
<td>8 MQA</td>
</tr>
<tr>
<td>QS4</td>
<td>8 MQA</td>
<td>8 MQA</td>
<td>4 MQA + 8 MQ</td>
</tr>
<tr>
<td>QS4A</td>
<td></td>
<td></td>
<td>4 MQA</td>
</tr>
<tr>
<td>QS5</td>
<td>8 MQA</td>
<td>8 MQA</td>
<td>4 MQB + 8 MQ</td>
</tr>
<tr>
<td>QS5A</td>
<td></td>
<td></td>
<td>4 MQA</td>
</tr>
<tr>
<td>QS6</td>
<td>8 MQA</td>
<td>8 MQA</td>
<td>8 MQA</td>
</tr>
<tr>
<td>QS6A</td>
<td></td>
<td></td>
<td>4 MQA</td>
</tr>
<tr>
<td>QS7</td>
<td>8 MQA</td>
<td>8 MQA</td>
<td>8 MQA</td>
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<tr>
<td>QS8</td>
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<td>8 MQA</td>
<td>8 MQA</td>
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<tr>
<td>QS9</td>
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<td>8 MQA</td>
<td>8 MQA</td>
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<tr>
<td>QS10</td>
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<td>8 MQA</td>
<td>8 MQA</td>
</tr>
<tr>
<td>Total MQ</td>
<td>16</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>Total MQA</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Total MQB</td>
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<td>0</td>
<td>8</td>
</tr>
<tr>
<td>Total MQC</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>
Table 6: Numbers of Cu and s.c. RF Cavities

<table>
<thead>
<tr>
<th>Rotators</th>
<th>P2 Cu</th>
<th>P2 s.c.</th>
<th>P4 Cu</th>
<th>P4 s.c.</th>
<th>P6 Cu</th>
<th>P6 s.c.</th>
<th>P8 Cu</th>
<th>P8 s.c.</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>60</td>
<td>32</td>
<td>64</td>
<td>32</td>
<td>60</td>
<td>32</td>
<td>64</td>
<td>32</td>
</tr>
<tr>
<td>Yes(Case 1)</td>
<td>52</td>
<td>-</td>
<td>16</td>
<td>52</td>
<td>-</td>
<td>16</td>
<td>-</td>
<td>16</td>
</tr>
<tr>
<td>Yes(Case 2)</td>
<td>52</td>
<td>-</td>
<td>40</td>
<td>52</td>
<td>-</td>
<td>40</td>
<td>-</td>
<td>40</td>
</tr>
<tr>
<td>Yes(Case 3)</td>
<td>-</td>
<td>40</td>
<td>40</td>
<td>-</td>
<td>40</td>
<td>-</td>
<td>40</td>
<td>-</td>
</tr>
</tbody>
</table>

9.4 Modifications to the Electrostatic Separation

As in the present version of LEP, there are two vertical electrostatic separators on each side of the experimental interaction points, fewer than will be installed in LEP-200. However, they are installed at the same distances from the interaction points. The separators are close to the vertical dipoles B1-B2-B2. As discussed in Section 4.3, collimators are installed around the separators and dipoles such that the vertical fan of synchrotron radiation does not hit the separator plates. The electric fields in the separators listed in Tab. 7 are within their maximum range. The ongoing crash pretzel programme [37] provides much valuable information about the interaction between synchrotron radiation and electrostatic separators, and about appropriate counter measures.

Table 7: Electrostatic Separator Positions and Fields

<table>
<thead>
<tr>
<th>Name</th>
<th>Distance from IP</th>
<th>Electric Field [MV/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZL2.2</td>
<td>27.565</td>
<td>2.392</td>
</tr>
<tr>
<td>ZL4.2</td>
<td>71.156</td>
<td>-0.590</td>
</tr>
<tr>
<td>ZL2.4</td>
<td>26.365</td>
<td>2.314</td>
</tr>
<tr>
<td>ZL4.4</td>
<td>71.156</td>
<td>-0.609</td>
</tr>
</tbody>
</table>

9.5 Modifications to the Vacuum System

Modifications to the LEP vacuum system consist mainly of:

- mounting new vacuum chambers in the vertical dipoles,
- dismounting the vacuum system over 300 m (450 m for the demonstration rotator) in order to change the magnet and chamber supports and allow access for civil engineering work,
- remounting vacuum system and installing new collimators and new chambers with increased cooling on both sides of the vertical dipoles.

The bending magnet chambers, the adjacent quadrupole chambers and the new collimators will have to absorb the synchrotron radiation emitted by the beams. Scaling from the
synchrotron radiation power shown in Tab. 4 at a bunch current of 0.75 mA, the synchrotron radiation power emitted in the dipole chain B1-B2-B2 may reach 95 kW with 36 bunches in each beam at a beam momentum of 45.6 GeV. For this reason, the vacuum chambers must be water-cooled.

As an aluminium extrusion of some 300 m of a special profile for the new chambers seems excluded, it is proposed to use stainless steel tubes with cooling pipes wrapped around the outside and vacuum brazed. Water-cooled internal absorber blocks may be needed in order to protect the flanges and bellows against synchrotron radiation. The pumping will be provided by ion and sublimation pumps located on each side of the magnets. The collimators will have their own pumping systems. The vacuum system must be baked in order to reduce the outgassing due to synchrotron radiation.

9.6 Instrumentation and Control

Eight extra beam position monitors are needed because of the extra quadrupoles installed in the experimental insertions. The insertion beam monitors may require a shield against the direct photons. A transverse polarimeter for the positron beam is also needed.

Modifications to existing databases and programs are necessary to cope with the increased number of dipoles and quadrupoles. Specific new software is necessary to handle polarization.

10 SCENARIO, PLANNING, COMPATIBILITY

10.1 Demonstration Spin Rotator

In the course of this feasibility study, the major difficulties have been identified and solutions are either devised or in sight. It remains that no high-energy accelerator has ever been operated with longitudinally polarized beams. No experience is available to confirm that e.g. higher-order depolarization by a rotator is indeed negligible, or that shielding against synchrotron radiation is as efficient as expected.

It is therefore considered that the installation of a demonstration spin rotator is a necessary precursor to a full programme of longitudinal polarization. A basic design, as close as possible to that of the final rotator, has been made [38] for the non-experimental interaction point 5. The aims would be:

- Verifying the concepts upon which our feasibility study is based
- Looking for unexpected phenomena beyond what can reasonably be predicted by theory and simulation
- Measuring the synchrotron radiation and particle background and developing minimization techniques
- Developing the know-how in the accelerator physics of polarized beams in LEP.

Some of the components of the demonstration spin rotator could be recuperated to build one of the final rotators. To prevent any conflict with the ongoing LEP 200 programme, the set up should be movable by motorized jacks.
10.2 Scenario

The aim of this scenario is to simulate how a longitudinal polarization programme would fit in the global LEP programme, which includes other upgrades and various constraints.

10.2.1 LEP Polarization Programme

Such a polarization program is naturally split in four phases:

1. LEP energy calibration with polarized beams

2. Development of procedures for reaching a higher degree of polarization than that achieved so far [8], as discussed in chapter 2.

3. Installation and testing of a demonstration spin rotator in a non-experimental insertion.

4. Installation of spin rotators in all experimental insertions in LEP, re-commissioning of LEP followed by a programme of precision particle physics near the $Z^0$ peak using longitudinally polarized beams.

The first phase will be soon completed, as far as machine studies are concerned; the second one is being prepared. These phases follow each other naturally, the results of one phase being the basis for a decision to go ahead with the next one. However they still conserve their usefulness if the ideal consequential chain cannot be implemented.

10.2.2 Framework for LEP Longitudinal Spin Physics Programme

The programme of polarized beams in LEP will have to be undertaken in parallel with the two other LEP upgrade programmes:

1. The LEP energy upgrade [36] will enable beam energies beyond the W pair production threshold to be reached after the 93/94 LEP shutdown.

2. The LEP luminosity increase [39] will allow storing up to 36 bunches in each beam at the $Z^0$ energy once the LEP energy upgrade is completed.

The feasibility study is based on the LEP-200 configuration [20]. The installation of the spin rotators in the experimental insertions can only be done after the physics programme associated with the energy upgrade is completed. The completion of the luminosity upgrade is not required, though desirable. After installation of the spin rotators, it is excluded to operate LEP at energies above the $Z^0$ peak, with or without polarization. The components are designed accordingly.

10.3 Planning

The planning of a longitudinal spin programme in LEP is summarized in Tab. 8. It reflects the four phases of the LEP polarization programme discussed in Section 10.2. The end of the year LEP shutdowns are the only opportunities for installation work in the LEP tunnel. Therefore, the installation of the demonstration spin rotator is foreseen in the 93/94 shutdown and that of the four definitive spin rotators not before the 95/96 shutdown. The periods of LEP operation between the shutdowns are foreseen for experimental work, e.g.
Table 8: Milestones, Activities and Installation Schedule

<table>
<thead>
<tr>
<th>Year</th>
<th>Shutdown</th>
<th>Installation time (weeks)</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>91</td>
<td></td>
<td>LEP energy calibration</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Launch demonstration rotator programme</td>
<td></td>
</tr>
<tr>
<td>92/93</td>
<td></td>
<td>LEP energy calibration operational</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Improve transverse polarization</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Procurement of demonstration rotator</td>
<td></td>
</tr>
<tr>
<td>93/94</td>
<td>18</td>
<td>Install demonstration spin rotator</td>
<td></td>
</tr>
<tr>
<td>$Y - 2$</td>
<td></td>
<td>Decision on physics programme</td>
<td></td>
</tr>
<tr>
<td>$Y - 1/Y$</td>
<td>23</td>
<td>Installation of spin rotators</td>
<td></td>
</tr>
<tr>
<td>$Y$</td>
<td></td>
<td>Start physics with polarized beams</td>
<td></td>
</tr>
</tbody>
</table>

improving the polarization level, testing the demonstration spin rotator, etc. This planning and the manpower estimates in Section 11.2 are tightly related.

If the programme is to be approved, decisions are needed preferably before the end of 1991 to go ahead with the demonstration spin rotator programme, and two years before the installation of spin rotators in the experimental insertions. This estimate assumes continuity in the effort. It should be revised if this aim cannot be reached.

10.3.1 Installation Schedule

The time required to install the rotator components and ancillary systems are given in Tab. 8. Much of the work would be done in parallel with other shutdown activities. Nevertheless somewhat longer shutdowns than have been the case so far will be needed for the installation of the spin rotators. Depending on the nature of these other activities, it should possible to limit this lengthening to less than six weeks in the case of the demonstration rotator and eight weeks for the complete system.

10.3.2 Commissioning and Machine studies

- **Demonstration spin rotator:** The present demonstration rotator design is based on the 60° lattice. When the LEP 200 optics is finalized, the rotator insertion will be redesigned. The optics commissioning is reduced to testing a different but adapted insertion. Based on our experience, this should take at most 24 hours. The same amount of time would be needed to commission the spin matched optics.

Background studies, search and maximization of the polarization level should take about 250 hours. About 2/3 of the overall machine studies could be done during regular MD sessions, leaving an extra 100 hours to be taken from physics, if the study programme is carried out over one year.

- **Spin rotators in experimental insertions:** Assuming the success of phases 2 and 3 of the polarization programme, the commissioning of a dedicated polarization optics
Table 9: Cost Estimate in kSF

<table>
<thead>
<tr>
<th></th>
<th>demonstration rotator</th>
<th>+ four rotators for experiments</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnets</td>
<td>1’200</td>
<td>4’900</td>
<td>6’100</td>
</tr>
<tr>
<td>Magnet infrastructure and civil engineering</td>
<td>1’800</td>
<td>500</td>
<td>2’300</td>
</tr>
<tr>
<td>Power converters + cables</td>
<td>600</td>
<td>1’200</td>
<td>1’800</td>
</tr>
<tr>
<td>Vacuum</td>
<td>1’300</td>
<td>5’000</td>
<td>6’300</td>
</tr>
<tr>
<td>Collimators</td>
<td>400</td>
<td>2’800</td>
<td>3’200</td>
</tr>
<tr>
<td>Polarimeter + beam observation</td>
<td>100</td>
<td>500</td>
<td>600</td>
</tr>
<tr>
<td>Experiment rotation</td>
<td></td>
<td>1’200</td>
<td>1’200</td>
</tr>
<tr>
<td>Dismantling cavities</td>
<td></td>
<td>1’000</td>
<td>1’000</td>
</tr>
<tr>
<td>Contingency</td>
<td>600</td>
<td>1’900</td>
<td>2’500</td>
</tr>
<tr>
<td>Totals</td>
<td>6’000</td>
<td>19’000</td>
<td>25’000</td>
</tr>
</tbody>
</table>

...and machine should last a few weeks at most. Reaching a performance comparable to the one arrived at before the LEP-200 physics programme will be much slower, given the fact that LEP will not have been operated at the $Z^0$ energy for several years.

10.4 Compatibility with other LEP Upgrades

The layout of LEP with spin rotators is compatible with the layout for high-luminosity operation because the horizontal electrostatic separators needed to excite the pretzel orbits are outside the spin rotators, and far enough from the nearest vertical dipoles to allow shielding them against synchrotron radiation emitted there. It remains to be demonstrated that an optical configuration can be found which satisfies the matching conditions for both pretzel orbits and spin rotators. The prospects for achieving this aim are good because the pretzel orbits and spin rotators impose conditions on the odd and even straight sections, respectively. There is only a slight risk of ending up with undesirable tunes.

The compatibility problems between LEP-200 without and with spin rotators arises mainly from the fact that a large fraction of the straight sections surrounding the experimental interaction points will be occupied by Cu and superconducting (s.c.) RF cavities. This fundamental incompatibility will not vanish however much ingenuity is applied to solving it. A few approaches are discussed in Section 9.3.

The upwards displacement of the LEP orbit in the spin rotators is incompatible with the installation of the LHC in those regions. The longitudinal spin physics programme in LEP is therefore foreseen to be terminated and the spin rotators removed before the LHC installation is completed in the experimental insertions of LEP.

11 MANPOWER AND COST ESTIMATE

11.1 Cost Estimate

The cost estimate for equipping LEP with spin rotators is given in Tab. 9. The estimates
Table 10: Manpower Estimates in man-years

<table>
<thead>
<tr>
<th></th>
<th>Increase Pol. level</th>
<th>demonstration rotator</th>
<th>four rotators for experiments</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnets</td>
<td></td>
<td></td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>Magnet infrastructure</td>
<td></td>
<td>2</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>and civil engineering</td>
<td></td>
<td>3</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>Power converters + cables</td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Dismantling cavities</td>
<td></td>
<td></td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Vacuum</td>
<td></td>
<td>3</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>Experiment rotation</td>
<td></td>
<td></td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Collimators</td>
<td></td>
<td>2</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Polarimeter + beam observation</td>
<td>2</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Acc. Physics: Spin dynamics</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>Acc. Physics: Experiments</td>
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<td>43</td>
<td>70</td>
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given in the table assume that some equipment provided for the test rotator is re-used in the final set-up.

11.2 Manpower Estimate

The estimate of CERN manpower required for equipping LEP with spin rotators is given in Tab. 10. The estimates given in the table assume that the experience gained through the test rotator is useful for the final set-up. The numbers assume that most effort would be provided on a part-time basis, in normal CERN fashion, which implies that a significantly larger number of people than enumerated in the table would be involved in the project. While the global figures should give a fairly good idea of staff required, the individual entries in the table should be taken as a rough indication.

In addition, we assume that the contributions of the Ecole Polytechnique, IN2P3 and Max-Planck-Institute Munich continue at the same level.

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References

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   J. Badier et al., ALEPH 87-17 note 87-05 (1987);
   G. Alexander et al., Working Group Report CERN/LEPC/87-6 LEPC/M81 (1987);
   ALEPH Collaboration, CERN/LEPC 88-12, LEPC/M 87, 14 october 1988.

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Figure 1: Layout of the Laser Interaction Region (LIR).

Figure 2: Measured vertical $\gamma$-distribution at the detector.
Figure 3: Acquisition software display.
Figure 4: First Evidence of polarization in LEP: the excitation of an integer spin resonance causes the polarization to decay; when the resonance excitation is suppressed, the polarization reappears. Dotted line: prediction; full line: fit to the data. The large negative values are due to a controlled inversion of the laser beam helicity. The approximate scaling is 50 µm for 10 % polarization.

Figure 5: While the first depolarization was due to the excitation of an integer spin resonance, the following ones were produced by a varying transverse magnetic field. Its frequency provides the beam energy. A significant amount of spin flip occurs.
Figure 6: Layout of the Richter-Schwitters Spin Rotator in IP2 and IP6
Figure 7: Optical Functions of the Spin Rotator in IP2 and IP6
Figure 8: Optical Functions of the Spin Rotator in IP4 and IP8
Figure 9: Polarization with Spin Rotators
Figure 10: Polarization with Solenoids
Figure 11: Horizontal Orbit Distortion Near IP2
Figure 12: Synchrotron Radiation from Spin Rotator Dipoles
Figure 13: SR Photons Scattered onto ± 2.5 m IP Pipe from 10 cm W collimator at 8.5 m
Figure 14: Sketch of Local Mask
Figure 15: Layout in the region of an interaction point