LEP-II

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ABSTRACT

The Large Electron Positron ring LEP is presently being built at CERN. It will provide colliding beams of energies between 15 and 100 GeV each, a range chosen to connect to the physics done at PETRA, PEP and TRISTAN and to cover Z_0 and W production. It has a circumference of ab ›ut 27 km and uses existing CERN machines as injectors. The difficulties given by the large size of this machine require special efforts in civil engineering, the fabrication of large quantities of components and the planing and installation, while the basic accelerator physics is not much different from other existing storage rings. In this report however we concentrate on this last point and show how the underlying accelerator physics led to the choice of certain parameters and hardware solutions such as concrete magnets and storage cavities. We also investigate some special effects and their importance for the operation of LEP at high energies.

1 INTRODUCTION

The name LEP stands for the Large Electron Positron Ring which is presently being constructed at CERN. It will provide colliding electron and positron beams with energies of about 15 to 100 GeV each, the lower limit being chosen to connect to experiments carried out at the existing rings PETRA, PEP and TRISTAN while the upper one covers the production of the charged intermediate vector bosons through the reaction $e^- + e^+ \rightarrow W^- + W^+$. In the middle of the energy range covered by LEP lies the resonance of the neutral vector boson produced by the reaction $e^- + e^+ \rightarrow Z^0$ at about 47 GeV per beam. The LEP ring will have four interaction regions and is expected to reach a maximum luminosity of about $L \sim 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at an energy around 80 GeV. The circumference of LEP is $C = 26.66$ km and it is located partly in France and partly in Switzerland. Its tunnel lies between 43 and 138 m beneath the surface. For the larger part it traverses molasse rock which is a good material for tunneling, whereas a smaller section under the Jura mountain goes through limestone which is more difficult. The storage ring has eight long straight sections four of which are used at the beginning for particle physics experiments; Fig.1. These four experiments are called L3, ALEPH, OPAL and DELPHI and are located in the interaction regions 2, 4, 6, and 8. For the injection of electrons and positrons into LEP the existing CERN machines PS (Proton Synchrotron) and SPS (Super Proton Synchrotron) are used. In addition a 600 MeV LEP Injector Linac (LIL) and a 600 MeV Electron Positron Accumulator (EPA) were built. From the latter the particles are injected into the PS and accelerated to 3.5 GeV. Then, they are transferred to the SPS to be accelerated to 20 GeV before being injected into LEP.

One of the most interesting reactions to be studied with LEP is the production of the neutral intermediate vector boson, $e^- + e^+ \rightarrow Z^0$ which requires an energy of about 47 GeV per beam. This energy lies in the middle of the energy range covered by LEP. Since the top part of this range can profit from superconducting cavities still under development it was decided to build LEP in two steps:

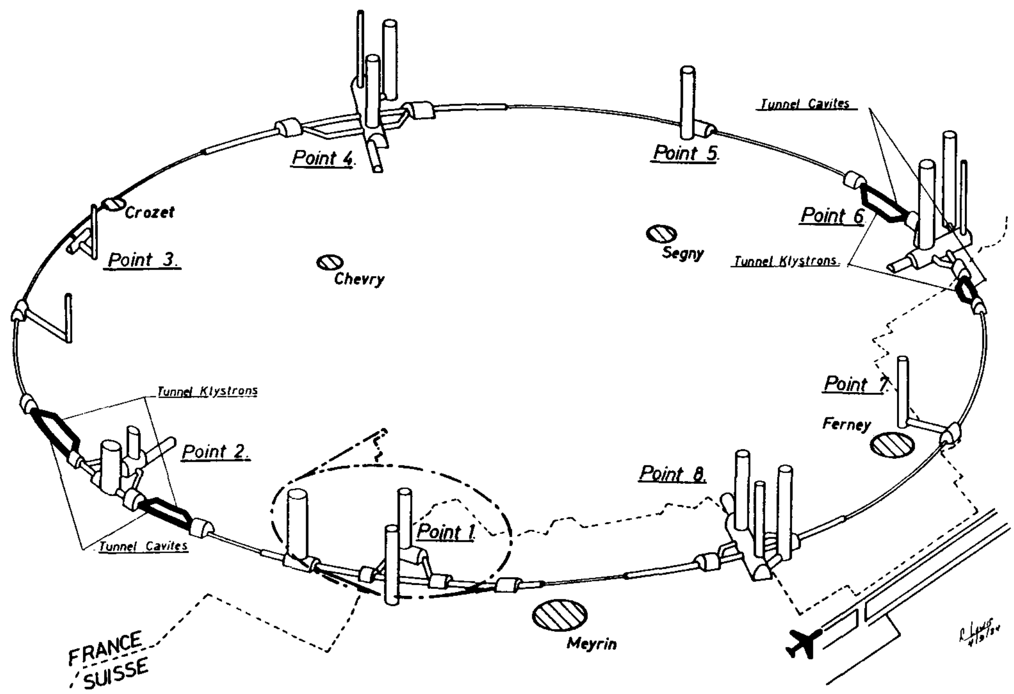

Figure 1: General Situation of LEP; (from R. Lewis)

Step 1, $E \sim 15 - 55\,\mathrm{GeV}$, which was approved by the CERN Council at the end of 1981. It covers the Z^0-production and uses two RF stations with a total of 128 copper cavities which are powered by sixteen 1-MW klystrons. The luminosity will reach approximately $L \sim 2 \cdot 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The first beams are expected for summer 1989.
Step 2, $E \sim 15 - 100\,\mathrm{GeV}$ which has recently been approved. It covers W-production and uses superconducting cavities and is expected to reach a luminosity of about $L \sim 10^{32} cm^{-2} s^{-1}$. It is this second step which is known as LEP-II.

If LEP is compared to other electron storage rings such as PETRA, PEP or TRISTAN it is the size which is considerably different. This large size demands a special effort in civil engineering, fabrication and control of many components, installation and overall planning. On the other hand the accelerator physics involved is qualitatively the same although there are some quantitative differences in many effects. In this report we will not give a general description of LEP [1] but concentrate on these differences and see how they affect the choice of the machine parameters [2]. We will also investigate some special effects and judge their importance for the high energy operation of LEP.

2 LEP PARAMETERS DETERMINED BY ACCELERATOR PHYSICS

2.1 General behavior

The basic parts of the storage ring can be seen in Fig.2 which gives a simplified view of one sixteenth of the machine. It consists of an interaction region where the two beams collide. To obtain a high luminosity and a correspondingly high interaction rate the beams are strongly focused to have a small

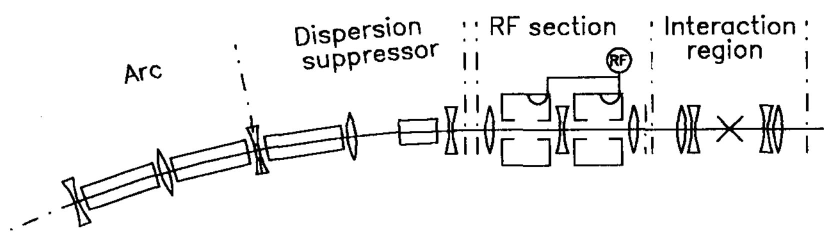

Figure 2: The principle parts of LEP

cross section at the collision point. This part is usually called the 'low-beta insertion' [3,4] and contains not only the actual low-beta quadrupoles which provide the strong focusing but also a set of additional lenses which optically match the insertion to the rest of the machine.

Next is the section containing the RF cavities which replace the energy lost by the particles through synchrotron radiation and other effects and provide phase focusing. This section is followed by the dispersion suppressor which matches the dispersion to zero in the RF section and in the low-beta insertion. As a consequence particles with different energies will have the same orbits in these latter sections. A finite energy spread will therefore not increase the beam size in the interaction point, so avoiding a reduction of the luminosity. Finally we come to the arc which consists of a regular array of dipole and quadrupole magnets which bend the beam in a circle and focus it at the same time. As we will see, most of the beam parameters are determined by the arc.

The focusing and bending properties of the beam optics have two effects. First, a particle having the nominal energy but an error Δx in position or an error $\Delta x'$ in angle will be focused towards the nominal orbit and will oscillate around it. This oscillation is called betatron oscillation and has the form

$$x(s) = a\sqrt{\beta(s)}\cos(\phi(s) + \phi_0).$$

The function $\beta(s)$ has the same periodic structure as the lattice and its square root gives the envelope of a betatron oscillation over many turns. The betatron phase advance $\phi(s)$ is related to the beta function by

$$\phi(s) = \int_0^s \frac{1}{\beta(s)} ds.$$

The value of the β function is large in a focusing quadrupole and small in a defocusing one. The excursion $x(s)$ of an oscillating particle varies around the ring but the area this oscillation covers in the phase space x, x' $(x' = dx/ds)$ is a constant. At locations where the beta function has a maximum or minimum this area is simply

$$\pi x(s) \cdot x'(s) = \pi \frac{x^2(s)}{\beta(s)} = x'^2(s)\beta(s) = \text{constant}.$$

An electron beam consists of many particles oscillating with different amplitudes. One defines the emittance as the average area covered by the phase space trajectories

$$E_x = \pi\langle \frac{x^2(s)}{\beta(s)} \rangle;$$

(often the factor π is omitted when giving the emittance). At other places where the beta function does not have a maximum or minimum the phase space trajectory has the form of a skew ellipse and the expressions are slightly more complicated. The local properties of the focusing provided by the beam optics is expressed by the beta functions while the overall strength of the focusing is given by the number Q_x of betatron oscillations per revolution. To avoid resonant excitation of betatron oscillations this number Q_x should not be an integer or a simple rational. Such focusing properties given above for the horizontal x-plane also exist correspondingly for the vertical y-plane.

Further properties of the focusing and bending provided concern particles which have an energy (or momentum) deviation ΔE from the nominal energy E. Particles with an excess energy suffer less bending in the dipole magnets but go off-center through the quadrupole and are subjected to extra bending. As a result the closed orbit of an off-energy particle has a horizontal displacement $\Delta x_p(s)$ with respect to the nominal orbit

$$\Delta x_p(s) = D_x(s)\frac{\Delta p}{p} \approx D_x(s)\frac{\Delta E}{E}.$$

The factor $D_x(s)$ is called dispersion. It depends on the longitudinal position s and is typically large at the horizontally focusing quadrupoles and small at the defocusing ones. By using the proper transition to the arc, called a dispersion suppressor; it can be arranged that the dispersion vanishes in the straight section. In LEP this is done for all the long straight sections. The finite energy spread will therefore not contribute to the beam size at the interaction point. Furthermore, having vanishing dispersion at the RF cavities avoids the excitation of certain synchro-betatron resonances. In the arcs, where there is bending, the dispersion is finite. This leads to a change of the circumference path length C with energy deviation. It is expressed by the momentum compaction α

$$\frac{\Delta C}{C} = \alpha\frac{\Delta p}{p} \approx \alpha\frac{\Delta E}{E}.$$

This circumference change with energy together with the slope of the RF voltage leads to phase focusing; Fig.3. A particle with the nominal energy and the correct arrival time in the cavity will see there an RF voltage U_0/e, where U_0 is the energy loss per turn due to synchrotron radiation. Another particle with an excess energy ΔE has a longer path length and will arrive later when the voltage is smaller. It receives less acceleration and suffers an overall energy loss. This corrective action leads to a phase or synchrotron oscillation around the nominal phase and at the same time to an energy oscillation around the nominal energy.

The energy loss due the synchrotron radiation and its replacement by the RF system leads to damping of the synchrotron and betatron oscillation. On the other hand the fact that this energy is radiated in quanta leads to noise excitation of these oscillations. The interplay of these two effects leads to a Gaussian equilibrium distribution of the particle in energy and longitudinal position, and also in horizontal position and angle. The vertical distribution is usually given by its coupling to the horizontal one.

2.2 Luminosity

The luminosity of a colliding beam facility is defined as the interaction rate per unit reaction cross sections. For two beams having Gaussian transverse distributions with rms values σ_x^* and σ_y^*, a number N of particles in k bunches and with revolution frequency f_0 this luminosity is [5]

$$L = \frac{N^2 f_0}{4\pi k \sigma_x^* \sigma_y^*}. \quad (1)$$

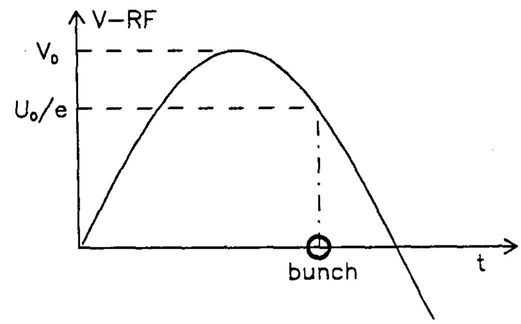

Figure 3: RF acceleration and phase focusing

This simple expression indicates how the beam parameters can be changed to optimize the luminosity. However there is an important limitation imposed by the beam-beam effect which is due to the non-linear electromagnetic forces between the two crossing beams. This force has a linear part which leads to a change of the betatron frequency and is called the beam-beam tune shift. It is, for the assumption $\sigma_y^* \ll \sigma_x^*$ [5],

$$\Delta Q_x = \frac{N r_e \beta_x^*}{2\pi k \gamma \sigma_x^{*2}}\ , \quad \Delta Q_y = \frac{N r_e \beta_y^*}{2\pi k \gamma \sigma_x^* \sigma_y^*}\ , \tag{2}$$

where r_e is the classical electron radius and β_x^*, β_y^* are the horizontal and vertical beta functions at the interaction point. This tune shift is a good measure of the non-linear part of the beam-beam force. It turns out that for most colliding-beam storage rings this tune shift per crossing is about

$$\Delta Q_{x,y} \leq \delta Q \sim 0.03\ -\ 0.06.$$

To optimize the luminosity we start by choosing the tune shift as large as possible and take $\Delta Q_x = \Delta Q_y = \delta Q$. By substituting Eq. (2) in Eq. (1) we get

$$L = \frac{N f_0 \gamma \delta Q}{2 r_e \beta_y^*}\ , \quad \frac{\beta_y^*}{\beta_x^*} = \frac{E_y}{E_x}\ ,$$

where E_x and E_y are the horizontal and vertical emittances. The horizontal emittance is given by the quantum excitation due to synchrotron radiation and the ratio between the two emittances is given by coupling. For LEP running at 55 GeV theses values are

$$E_x = 51.6\,\pi\, nm\, rad \quad \beta_x^* = 1.75\, m$$
$$E_y = \ 2.1\,\pi\, nm\, rad \quad \beta_y^* = 0.07\, m$$

Clearly, the luminosity can be improved by reducing the values of the beta functions β_y^* and β_x^* at the interaction point [3,4] by using low-beta insertions. There are some limits to the minimum value one can obtain for the beta function. If β^* is the value at the interaction point $\beta(s)$ will increase as the distance s from the interaction point increases according to the relation

$$\beta(s) = \beta^*(1 + (s/\beta^*)^2).$$

Since the bunch has a finite rms length σ_s, the beta function has to be larger than σ_s otherwise the transverse beam dimensions change over the bunch length which may again reduce the luminosity. It can also make the beam-beam effect worse. A further limitation comes from the fact that the low-beta quadrupoles have to be located at a certain distance from the interaction point to make room for the high energy physics experiment. This requires rather strong quadrupoles with large apertures. Apart from technical difficulties such strong quadrupoles produce chromatic effects which have to be corrected with sextupoles.

To optimize the luminosity further we have to distinguish between two cases determined by another limitation. We first consider the situation where the current per bunch is not limited. In order to increase the luminosity without exceeding the beam-beam limit the emittance could be increased leading to a larger beam size for a given beta value at the interaction point. This seems at first to decrease the luminosity. But now the beam current can be increased until the beam-beam limit is reached resulting in an overall increase of the luminosity. The emittance can be changed by making the focusing in the arcs weaker, with wiggler magnets, or by changing the distribution of the radiation damping among the three modes of oscillations as will be shown later. The increase of the emittance is limited by the available aperture of either the vacuum chamber or the dynamic acceptance of the beam optics. In the other case the current is limited by instabilities or maximum RF power such that the beam-beam tune shift is below the limit. Reducing the emittance until the beam-beam limit is reached can regain some of the luminosity in this situation. Increasing the focusing in the arcs and changing damping partitions are the means to do this.

2.3 Energy loss due to synchrotron radiation

The choice of the electron ring parameters is greatly influenced by the energy loss due to synchrotron radiation. This loss per turn is given by [6]

$$U_s = \frac{4\pi}{3}\frac{r_e m_0 c^2 \gamma^4}{\rho}, \tag{3}$$

where ρ is the bending radius in the arc which is 3096 m in LEP. The resulting energy loss is 140 MeV and 2330 MeV for the LEP operating energies of 47 GeV and 95 GeV and has to be replaced by the RF system. To minimize the cost of a large electron ring we derive a scaling law for the size of the machine. The circumference is approximately proportional to its bending radius. We distinguish now between components whose cost is about proportional to the size of the machine (the tunnel, the vacuum system, the infrastructure and, to some extent, also the magnets) and the RF system with a cost being about proportional to the energy loss $U_s \propto \gamma^4/\rho$ of Eq. (3). Assuming the division of the costs between the two groups of components has been optimized at one energy we can derive how the bending radius ρ has to scale with energy to keep this optimum division. One finds easily that [5,7]

$$\rho \propto \gamma^2 \ , \ U_s \propto \gamma^2 \ , \ cost \propto \gamma^2. \tag{4}$$

Looking at different machines we find that the size increases a little slower than the square of the energy. Optimizing the individual components has helped to improve on this simple scaling law.

For the bending magnets one finds that the field scales as $B \propto 1/\gamma$ and this leads to rather low fields for LEP namely 0.05 T and 0.10 T for the operating energies 47 GeV and 95 GeV respectively. Such low field magnets do not need much iron. The LEP dipole magnets consist of widely spaced iron laminations with concrete in between [8,9] , as shown in Fig.4. These magnets are not only cheaper but lighter and stiffer which simplifies their transportation, support and installation. The low bending magnet field makes the use of distributed ion pumps for the vacuum system less efficient. For LEP another solution has been chosen consisting of Non-Evaporable Getter (NEG) pumps [10].

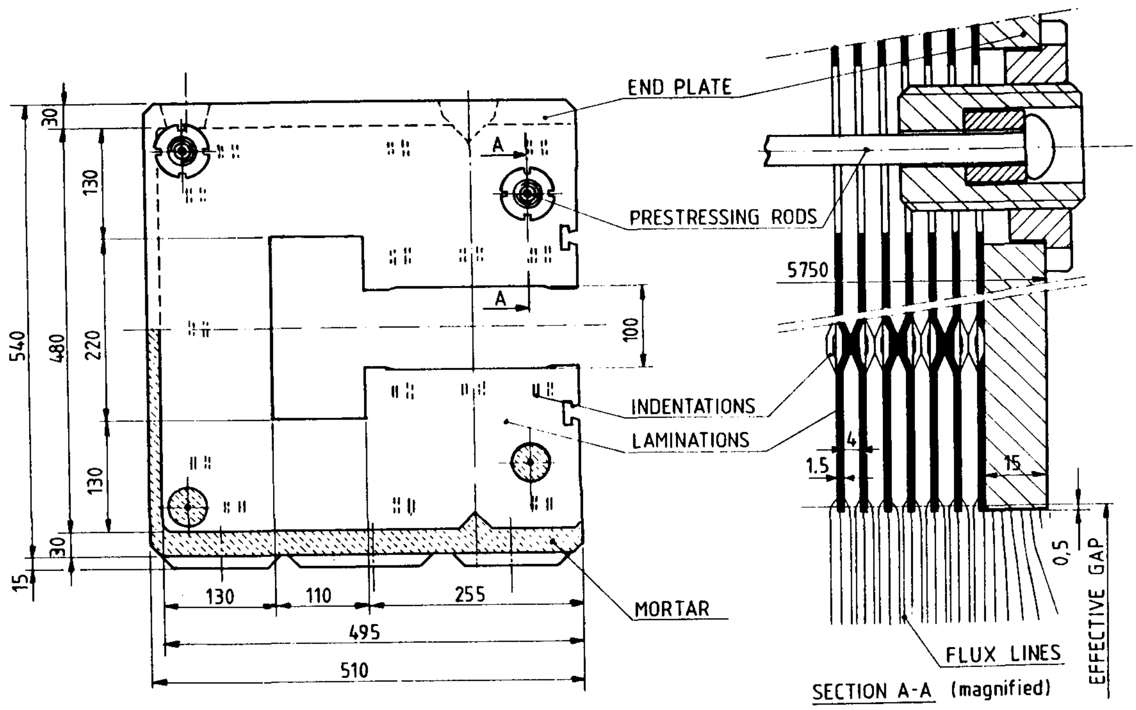

Figure 4: Concrete magnets

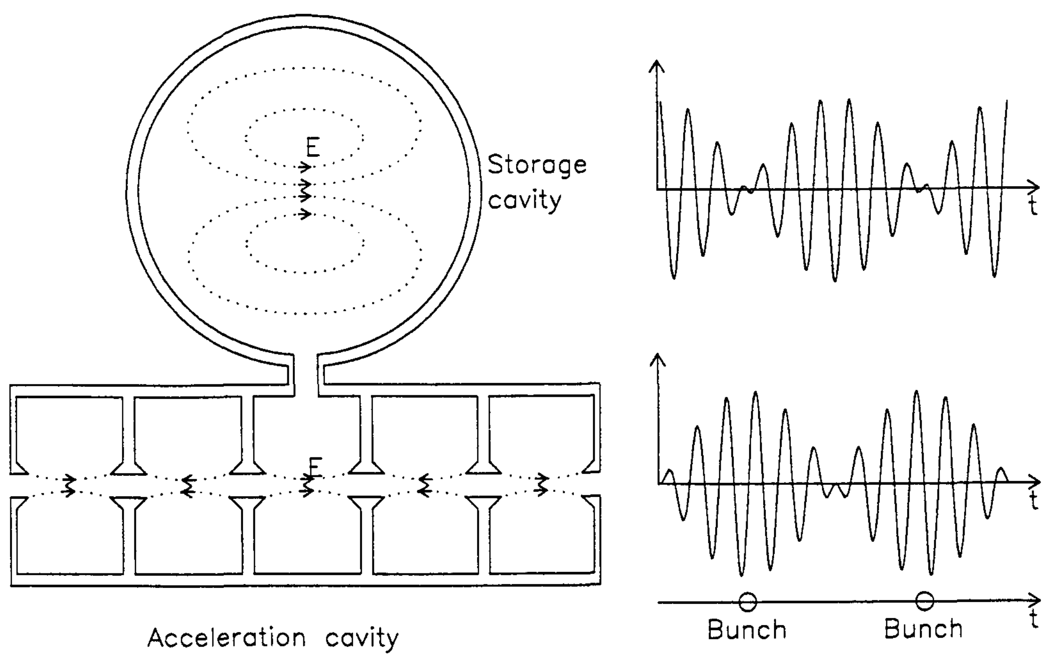

Figure 5: Storage and accelerating cavity

An important optimization can be achieved for the RF system which has to replace the synchrotron radiation power emitted by the two beams. Additional power is lost in the cavities due to the finite conductivity of their walls. This latter effect can be quantized by the shunt impedance R_s of the cavities. The total RF power becomes

$$P_{RF} \sim 2I(U_s/e) + \frac{(U_s/e)^2}{2R_s} \sim P_{radiation} + P_{cavity},$$

where I is the total current per beam. For a machine which is properly scaled according to Eq. (4) the synchrotron radiation loss U_s increases as the square of the energy. It is less clear how the current I will scale. From the luminosity equation we could assume that it decreases proportionally to energy if the beta functions are kept constant. In reality it tends to decrease somewhat more slowly. Using this we find that the first term in the above expression scales between the first and the second power of the energy while the second term goes with the fourth power

$$P_{radiation} \propto \gamma^1 - \gamma^2 , \quad P_{cavity} \propto \gamma^4.$$

For very high energy rings the power dissipated in the cavity dominates the situation more and more and should be improved. To describe the different methods of improvement we write the cavity shunt impedance we wish to maximize in the form

$$R_s = \frac{R_s}{Q} \cdot Q$$

where Q is the quality factor. Under the assumption that we compare cavities oscillating with similar modes we can say that the first term R_s/Q depends mainly on the form of the cavity while the second factor is mainly determined by the conductivity of the cavity walls. The first factor has already been increased by adding 'noses' at the cavity beam ports of the last generation of rings and could not be improved much further for LEP. An improvement in the power lost in the walls was made by coupling the accelerating cavity to a storage cavity as indicated in Fig.5. This cavity oscillates with a mode which has relatively weak fields at the wall and therefore small losses and is tuned to a slightly different frequency. The system behaves like a coupled pendulum and energy moves back and forth between the accelerating cavity and the storage cavity. LEP operates with four bunches and has a revolution frequency of $f_0 = 11.25\,kHz$. The time between bunch passages through the cavities is therefore $22.2\,\mu s$. The detuning between the two cavities is chosen such that the RF energy is in the accelerating cavity when the bunches pass by and goes to the low loss storage cavity in between. This leads to an improvement of about 40% in effective quality factor [11,12]. To go to energies higher than 55 GeV for the second step of LEP, superconducting cavities will be used. The wall losses are in this case extremely small leading to quality factors of the order of $Q \sim 10^9$. This is so large that one can relax on the factor R_s/Q and use a very smooth cavity form with a large beam port. The smooth form is actually necessary to avoid multi-pactoring in the cavity. This form, together with the large aperture, reduces the parasitic impedance due to higher modes and improves considerably the stability of high intensity bunches. The use of superconducting cavities gives a very large saving in power for given voltage. In addition, and most important, these cavities also give a much larger acceleration voltage gradient.

The energy loss due to synchrotron radiation and its replacement by the RF system has a beneficial effect. It provides damping of horizontal and vertical betatron oscillations and of synchrotron oscillations. The sum of these three damping rates is a constant given by

$$\frac{1}{\tau} = \frac{2P_s}{E} = \frac{1}{\tau_x} + \frac{1}{\tau_y} + \frac{1}{\tau_E} = \frac{P_s}{2E}(J_x + J_y + J_E) = \frac{2P_s}{E}, \qquad (5)$$

where P_s is the power radiated by a particle and E the particle energy. The numbers $J_x, J_y and J_E$ are called damping partitions. Their sum is always four but within this sum rule they can be changed individually. This is usually done by changing the RF frequency by a small amount which gives the beam an energy deviation and forces it to go off-center through the quadrupoles located at points of finite dispersion. This procedure exchanges damping between the horizontal betatron oscillation and the energy oscillation and can be used to adjust the emittance for the beam-beam effect optimization.

2.4 Synchrotron radiation spectrum - quantum excitation

The synchrotron radiation has a wide spectrum which is characterized by the critical photon energy ϵ_c

$$\epsilon_c = \frac{3}{2}\frac{\lambda_{Comp.} m_0 c^2 \gamma^3}{2\pi\rho}, \tag{6}$$

where $\lambda_{Comp.} = h/m_0 c$ is the Compton wavelength and h is Planck's constant. For LEP this critical photon energy is 76 keV and 0.62 MeV for 47 GeV and 95 GeV operating energy respectively. The fact that the radiated energy is emitted in photons leads to a sudden loss of the electron energy which excites energy oscillations. The interplay between this quantum excitation and damping leads to an equilibrium distribution which is Gaussian and has an rms width given by [13]

$$(\frac{\sigma_E}{E})^2 = \frac{55}{64\pi\sqrt{3}}\frac{h}{m_0 c}\frac{\gamma^2}{J_E \rho} \tag{7}$$

for a uniform ring. For LEP this relative rms energy spread σ_E/E is 0.0007 and 0.0015 for 47 GeV and 95 GeV electron energy respectively. It is interesting to note that a machine as large as LEP based only on macroscopic engineering has global parameters which depend so critically on Planck's constant. If in the above equation we use the scaling of the bending radius $\rho \propto \gamma^2$ we find that the relative energy spread is independent of the energy for which the machine is optimized. In other words, the relative energy spread in LEP is about the same as in PETRA assuming both operate at their optimum energy. The absolute energy spread, however, scales approximately with energy. If the emission of a photon happens at a location where the dispersion is finite the electron has suddenly a lower energy and its new equilibrium orbit lies further inwards. It will start a betatron oscillation around its new orbit. This quantum excitation of betatron oscillations together with the damping leads to a Gaussian equilibrium distribution. For a regular lattice with betatron tune Q_x the resulting horizontal emittance is given by

$$\frac{\sigma_{x\beta}^2}{\beta_x} \sim \frac{\alpha R J_E}{Q_x J_x}(\frac{\sigma_E}{E})^2, \tag{8}$$

where R is the average radius and α the momentum compaction. The vertical beam emittance is given by coupling which is controlled with rotated quadrupoles. The above expression gives the energy spread and horizontal emittance for a uniform machine with bending magnets of equal strength. Wiggler magnets which are located in regions with large dispersion and have strong fields can be used to control the quantum excitation and emittance.

In order to optimize the luminosity LEP has provision to control the horizontal emittances by powering wigglers, by changing damping partitions through a small change in RF frequency or by changing the tune Q_x using different focusing strength in the arcs. The vertical emittance can be controlled by changing coupling with rotated quadrupoles.

3 OTHER EFFECTS

3.1 Polarization

The synchrotron radiation also leads to a transverse polarization of the electrons and positrons. It is most interesting at the energy of about 47 MeV for Z_0 production. However at this energy the polarization time is rather long, about four hours. It can be reduced to less than an hour by using asymmetric wigglers which have strong and short fields bending in one direction and long and weak fields bending in the other direction. However these wigglers also increase the energy spread. Small machine imperfections lead to depolarizing resonances. The strongest ones are spaced by 440 MeV. At high operating energies the absolute value of the energy spread in LEP is large compared to other machines and it is difficult to place the energy distribution between two such resonances. At the more interesting lower energy however, a modest amount of transverse polarization is expected to be achievable. For particle physics experiments longitudinal polarization is necessary. With a combination of vertical and horizontal bends the polarization can be rotated. In LEP the amount of transverse polarization will be measured with a polarimeter using laser back scattering. Several experiments can be carried out to measure the strength of some depolarizing resonances and their reduction with a careful orbit correction. The basic resonances, which are spaced by 440 MeV, can be used foı an absolute energy calibration. Rotators to obtain longitudinal polarization might be installed later.

3.2 Energy variation around the ring

When LEP is operated at high energy the relative energy loss per turn is rather large such that a non-negligible fraction is lost between the two RF stations. As a result the energies of the electrons and positrons vary around the ring and can be different from each other. The particle just coming out of the cavity has an excess energy compared to the particle going into it. In places with finite dispersion the orbits of electrons and positrons can be horizontally separated. This not harmful by itself but if it is combined with vertically deflecting field errors it can lead to a slight vertical beam separation in the interaction points.

3.3 Quantum correction to the synchrotron radiation spectrum

The classical synchrotron radiation spectrum used for all storage ring calculation has a high energy tail which decays exponentially but goes basically to infinite energies. This cannot be quite correct since the photon energy must be smaller than the energy of the electron itself. To take this effect into account a quantum correction is applied. It leads to some modification of the high energy end of the spectrum and to a slight reduction of the classical energy loss U_s per turn [14]

$$U_s = U_{s-clas.}(1 - \frac{55}{8\sqrt{3}}\frac{\epsilon_c}{E}). \tag{9}$$

For LEP operating at 95 GeV this correction is only about 2.6 10^{-5} and therefore negligible.

3.4 Coherent synchrotron radiation

In all the investigations the synchrotron radiation was calculated for a single particle and the radiation emitted by the whole beam was obtained by summing the power contributions of the individual particles. At the very low end of the spectrum where the radiated wavelength becomes comparable to the bunch length, the individual particles radiate in phase and the radiation becomes coherent. Now the individual field contributions have to be summed and then squared to obtain the total power. This would lead to an increase of the power radiated at very low frequency. A simple-minded calculation gives for LEP operating at about 55 GeV an increase in total radiated power of nearly 2% which means that the necessary RF voltage increases by about this amount and the RF power by about 4%. However, the presence of the conducting vacuum chamber close to the beam suppresses most of this coherent radiation. There are two ways to understand this at least qualitatively. First, the vacuum chamber has inner dimensions which are comparable to the bunch length. The cut-off frequency below which wave propagation is impossible inside the chamber has a wavelength which is also of the same order as the bunch length. Most frequencies contained in the expected coherent spectrum cannot propagate and are suppressed. Another way to look at this problem involves image charges. For the frequencies in question the vacuum chamber is still a good conductor and the boundary conditions for the electric field of the bunch can be fulfilled by placing an image charge of opposite polarity behind the wall. The fields emitted by these fictitious charges just about cancel the radiation emitted by the bunch itself for wavelengths comparable to the distance between the beam and the chamber wall. As a result the coherent radiation becomes negligible in LEP.

3.5 Instabilities

Coupled bunch instabilities are not very strong in LEP due to the large bunch spacing. However, the single-bunch transverse mode coupling instability is expected to limit the current per bunch to about 0.75 mA at injection. All luminosity calculations and optimizations are based on this value. As a reserve there is a reactive feed-back system which should increase this current according to calculations and an experiment carried out at PEP. Once the copper cavities are replaced with the superconducting ones, which have a lower transverse impedance, this transverse instability should only occur at about 1.25 mA.

3.6 Life time

The life time due to beam-gas bremsstrahlung is expected to be about 20 hours for a pressure of 3×10^{-9}Torr. The strongest effect is the beam-beam bremsstrahlung which leads to a life-time of about 11 hours. An interesting effect, pointed out by V.I. Telnov [15], is the Compton scattering between the electrons and the photons of the black body radiation of the vacuum chamber which could result in a life time of about 40 hours at 100 GeV operating energy. This vacuum chamber wall is at a temperature of about 300^0 K and emits black body radiation with a typical photon energy of about 0.07 eV. The Compton scattering with the 100 GeV electrons can give these photons a rather large energy, sufficient to result in a loss of the electron. Although the resulting life time of about 40 hours at 100 GeV is well above the one due to other effects, it is interesting to look at the kinematics of this scattering. We consider an electron with energy $m_0c^2\gamma$ going in the z-direction. A photon with energy ϵ going at an angle θ with respect to the z-direction collides with the electron. After the collision the electron and the photon have the energies $m_0c^2\gamma'$ and ϵ' respectively and move in directions with angles α' and θ'. From conservation of energy we get

$$m_0c^2\gamma + \epsilon = m_0c^2\gamma' + \epsilon'.$$

The conservation of momentum in the z-direction gives

$$m_0 c\beta\gamma + \frac{\epsilon}{c}\cos\theta = m_0 c\beta'\gamma'\cos\alpha' + \frac{\epsilon'}{c}\cos\theta'$$

and perpendicular to it

$$\frac{\epsilon}{c}\sin\theta = m_0 c\beta'\gamma'\sin\alpha' + \frac{\epsilon'}{c}\sin\theta'.$$

We can eliminate the angle α' by squaring the two momentum equations after multiplying them with c

$$(m_0 c^2\beta'\gamma')^2 = (m_0 c^2\beta\gamma)^2 + \epsilon^2 + \epsilon'^2 + 2m_0 c^2\beta\gamma(\epsilon\cos\theta - \epsilon'\cos\theta') + 2\epsilon\epsilon'\cos(\theta - \theta').$$

Using the relation $\beta^2\gamma^2 = \gamma^2 - 1$ and expressing the left hand side with the energy equation gives for the energy of the scattered photon

$$\epsilon' = \epsilon\frac{m_0 c^2(\gamma - \sqrt{\gamma^2 - 1}\cos\theta)}{m_0^2(\gamma - \sqrt{\gamma^2 - 1}\cos\theta') + \epsilon(1 + \cos(\theta - \theta')}. \tag{10}$$

We look first at the case of head-on collision $\theta = \pi$ where the photon receives the maximum energy. Since the momentum of the electron is much larger than that of the photon we expect that the scattered photon moves at a very small angle with respect to the z-axis, $\theta' \ll 1$. Further we consider only the ultra-relativistic case $\gamma \gg 1$ and get from Eq. (10)

$$\epsilon'(\theta = \pi) = \epsilon\frac{4\gamma^2}{1 + \gamma^2\theta^2 + \frac{4\epsilon\gamma}{m_0 c^2}}.$$

Taking the case $m_0 c^2\gamma = 100$ GeV and $\epsilon = 0.07$ eV we find for the energy of a photon scattered in the forward direction $\epsilon'(\theta = \pi, \theta' = 0) \sim 9.7$ GeV which will lead to a loss of the electron involved. For a photon moving perpendicular to the z-direction $\theta' = \pi/2$ we find

$$\epsilon'(\theta = \pi/2) = \epsilon\frac{2\gamma^2}{1 + \gamma^2\theta^2 + \frac{4\epsilon\gamma}{m_0 c^2}}$$

which is only half of the head-on case but still sufficient to lead to a loss of the electron. To obtain the resulting life time the number and energy distribution of the black body photons have to be calculated and the cross section integrated over the angles [15].

4 PRESENT STATUS AND PLANS

As of October 1987 the following milestones have been achieved. The injector chain has already been operated. The linac LIL, the accumulation ring EPA and the PS have accelerated electrons and positrons well above the design intensity. Positron beams well above the design intensity have been injected into the SPS where not all of the necessary cavities are installed yet but acceleration up to 18 GeV has been achieved. Electrons were also injected. The LEP tunnel in the molasse rock is finished and installation of components is going on. In the geologically difficult Jura region the tunneling through the most critical part is complete and the rest should be finished in January 1988. An injection test into one octant is planned for July 1988 in order to check the different types of component and their operation through the control system. Injection into the final machine is foreseen for summer 1989. In the mean time work on the superconducting cavities is progressing well. Acceleration gradients of 7 MV/m have been achieved which is considerably higher than the 1.5 MV/m obtained with the copper cavities and should allow the goals set for the second step of LEP to be reached. Different scenarios can be considered for achieving these higher energies, involving different number of cavities and klystrons. Examples and parameter lists have been presented in reports [16,17], but will not be given here.

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REFERENCES

[1] LEP Design Report; CERN-LEP/84-01, 1984.

[2] A. Hofmann, Proc. of the Int. Symposium on Lepton and Photon Interactions at High Energies, Nucl. Phys. B (Proc. Suppl.) 3 (1988) 511.

[3] K. Robinson and G.A. Voss; CEA-TM-149, 1965.

[4] K. Robinson and G.A. Voss; Proceedings of the Intern. Symposium on e^+, e^- Storage Rings, Saclay, September 1966; Presses Universitaire de France, p III.4.

[5] E. Keil, Proc. 9th Int. Conf. on High Energy Accelerators, Stanford 1974; CONF 740522, USAEC, Washington, p. 660.

[6] A.H. Lienard, L'Eclairage Electr. 16 (1898) 5.

[7] B. Richter, Nucl. Instrum. Methods 136 (1976) 47.

[8] J.P. Gourber et al.; LEP Note 360, 1982.

[9] J.P. Gourber et al.; IEEE Trans. Nucl. Sci. NS-30; No. 4 (1983) 3514.

[10] C. Benvenuti, J.C. Décroux; Proc. 7th Int. Vacuum Congr., Vienna 1977; IVC-ICSS 1977, p. 85.

[11] W. Schnell, CERN ISR-LTD/76-8, 1976.

[12] P. Brown et al., IEEE Trans. Nucl. Sci. NS-28; No. 3 (1981) 2707.

[13] M. Sands, Phys. Rev. 97 (1955) 470.

[14] A.A. Sokolov, N.P. Kleipikov and I.M. Ternov, JETF 23 (1972) 632.

[15] V.I. Telnov, Part. Phys. Inst. Novosibirsk Preprint 86-175, 1986.

[16] P. Bernard, H. Lengeler, E. Picasso, CERN LEP-DI/86-29, 1986.

[17] E. Keil, CERN LEP-TH/87-02, 1987.