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INSERTION DESIGN FOR e^+e^- STORAGE RINGS

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Introduction

The insertion design of an e^+e^- storage ring determines not only the physics potential of the facility but also the basic machine parameters, and considerable economies can be made by suitably tailoring the insertions to the detector requirements. This paper shows how the use of specialized insertions can improve the machine characteristics and discusses the solution adopted for LEP[1], the large e^+e^- storage ring currently under study at CERN.

Limitations on the Insertion

The luminosity in an e^+e^- storage ring can be written

$$\mathcal{L} \approx \frac{\Delta Q}{2er_e} \frac{I\gamma}{\beta_V^*} \qquad (1)$$

where ΔQ is the maximum permitted value of the linear beam-beam tune shift (a value of 0.06 is usually assumed), I is the current in each beam (assumed equal), γ is the beam energy in units of the rest mass of the electron, e is the electronic charge, r_e is the classical radius of the electron and β_V^* is the vertical amplitude function at the interaction point. This equation implies that the vertical and horizontal emittances have been suitably adjusted so that the maximum permitted ΔQ is reached in both planes simultaneously and that the beam size at the crossing point is much smaller vertically than horizontally. Additionally, it is assumed that the bunch length is short compared to β_V^* so that the beam dimensions do not vary significantly along the collision region. This imposes a lower limit on β_V^*. From equation (1) it can be seen that the current required to reach the nominal luminosity $\mathcal{L}$ at the design energy γ is directly proportional to β_V^*.

The lower limit of β_V^* is not only determined by the bunch length but also by the associated high beta values in the adjacent strong insertion quadrupoles. The beta values rise quadratically in the free space in the insertion and the maximum value is related to L^2/β_V^* where $\pm L$ is the free space between insertion quadrupoles. Both the position tolerances of these quadrupoles and the chromatic aberrations which they cause are approximately proportional to L/β_V^* and these quadrupoles are the most critical components in the ring[1]. Thus in any insertion design for LEP there is a maximum value of L/β^* of about 50 imposed by beam dynamics while the minimum value of β_V^* is about 0.1 m. So an insertion of ±5 m free space could have $\beta_V^* = 0.1$ m while in an insertion of ±10 m free space β_V^* cannot be less than 0.2 m.

Experimental Requirements

Let us now consider the experiments that are to be performed at LEP or, more precisely, the detectors that will be required. Figure 1 shows the floor space occupied by detectors in a wide variety of storage ring experiments either existing or proposed[2]. Roughly speaking the experiments can be divided into two categories. Wide angle detectors are usually relatively short in the beam direction but require the highest possible luminosity since the cross-sections are small. However, some forward tagging or luminosity measurement is normally required which increases the total length of the detector. Small angle experiments need much more free space in the beam direction but, since cross-sections are somewhat larger, do not demand the highest luminosity. From Fig. 1 it is clear that all experiments will fit into a free space of ±10 m. However, a large number, mostly wide-angle experiments, would also fit into ±5 m free space.

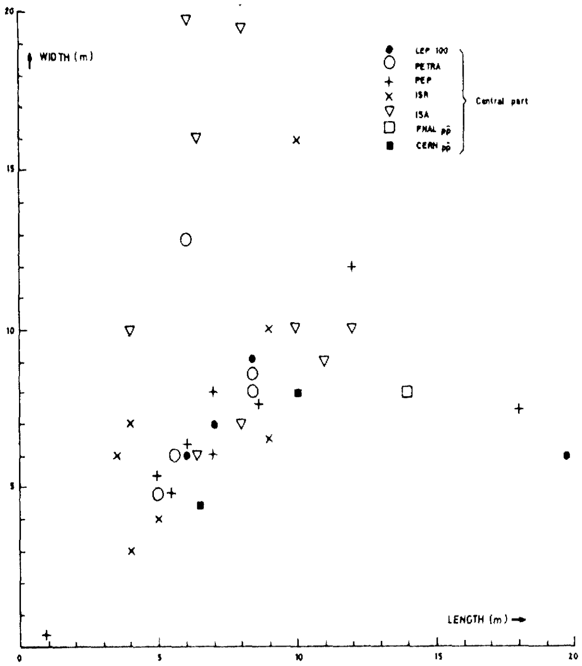

Fig. 1. Floor space occupied by different storage ring experiments

Insertion Characteristics

For LEP, two specialized insertion types are proposed: four short insertions with ±5 m free space, $\beta_V^* = 0.1$ m and a luminosity of $10^{32}\text{cm}^{-2}\text{s}^{-1}$ and four long insertions with ±10 m free space, $\beta_V^* = 0.2$ m and a luminosity of $0.5\times10^{32}\text{cm}^{-2}\text{s}^{-1}$. There are four bunches per beam which collide naturally in the eight insertions.

To demonstrate the advantages of this approach the machine is compared with an identical ring equipped with eight long insertions with ±10 m free space, $\beta_V^* = 0.2$ m and a luminosity of $10^{32}\text{cm}^{-2}\text{s}^{-1}$. To reach this luminosity requires twice the current per beam which can be achieved in two ways: either the number of bunches can be doubled with the same charge per bunch or the charge per bunch can be doubled with the same number of bunches. A machine of each type will be considered. In the first case, separation of the beams at eight unwanted crossings is necessary. At present, it seems that the separators will also affect collisions in the insertions due to imperfect cancellation of the beam bumps. Calculations indicate that extremely tight tolerances are placed on all components in the region of the separating plates[3]. In the second case, doubling the bunch charge increases the space charge forces and makes the machine more sensitive[1]. It will be assumed that these technical problems can be overcome but this will certainly add to the hardware costs. The parameters of the three machines referred to later as A, B and C are given in Table 1, together with the relevant parameters of LEP.

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Table 1. Characteristics of Machines Compared

Machines	'A'		'B'	'C'	
Vertical beta at insertion β_V^*	0.1	0.2	0.2	0.2	m
Free space 2L	±5	±10	±10	±10	m
Luminosity	10^{32}	0.5×10^{32}	10^{32}	10^{32}	$cm^{-2}s^{-1}$
Number of insertions	4 + 4		8	8	
Number of bunches k_b	4		8	4	
Separation required	NO		YES	NO	
Current per beam I	10.54		21.08	21.08	mA

General

Design energy	E	70	GeV
Radius of curvature	σ	2.344	km
RF cavity shunt impedance	Z_{CAV}	3.23×10^7	M
Stable phase angle	ϕ_s	120	degrees
RF waveguide losses		7½	%
RF power operation efficiency		57	%

RF Power

The total RF power is the sum of three main contributions: synchrotron radiation P_B, parasitic mode losses P_{PM} and cavity dissipation P_D. The power lost by both beams due to synchrotron radiation is given by

$$P_B = 2\times8.85\times10^{-5}\,\frac{E^4(\mathrm{GeV})\;I(\mathrm{A})}{\sigma(\mathrm{km})}\quad\mathrm{MW}\qquad(2)$$

The power lost by both beams into parasitic modes is given by

$$P_{PM} = 2\times I^2(\mathrm{A})\times Z_{PM}\,(\mathrm{M\Omega})\quad\mathrm{MW}\qquad(3)$$

where Z_{PM}, the parasitic mode impedance of LEP is[1]

$$Z_{PM} = \frac{6.6\times10^4}{k_b}\quad\mathrm{M\Omega}\qquad(4)$$

The number of bunches k_b enters into this expression since the voltage induced is proportional to the bunch charge not the total charge. The exact formula for the cavity dissipation is rather complicated[4] but for the present purposes it is more instructive to use a simple approximate formula which shows the relative importance of the contributing factors more clearly.
The error introduced by this approximation is only a few percent.

$$P_D \approx \frac{1}{Z_c(\mathrm{M\Omega})\,\sin^2\phi_s}\left\{8.85\times10^5\,\frac{E^4(\mathrm{GeV})}{\sigma(\mathrm{km})} + I(\mathrm{A})Z_{PM}(\mathrm{M\Omega})\right\}^2\quad\mathrm{MW}\qquad(5)$$

The second term in the brackets is the voltage required to replace the energy lost to parasitic modes. This increases the dissipation in the cavity by an amount which greatly exceeds the power lost directly into parasitic modes. The RF power balance for the three machines is given in Table 2. Both machines with equal insertions (B and C) require more power than the machine with specialized insertions (A), 25 MW and 50 MW additional RF power respectively for B and C. With typical power conversion efficiencies this implies an increase in the mains power consumption of 43 MW or 89 MW - the latter figure is equivalent to the total power available for the CERN SPS including all of the experimental areas.

Table 2. RF Power of Machines

Machine	'A'	'B'	'C'	
Synchrotron radiation P_b	19.11	38.22	38.22	MW
Parasitic mode losses P_{PM}	3.67	7.33	14.66	MW
Cavity dissipation P_D	48.25	48.25	65.04	MW
RF power required at cavities	71.0	93.8	117.9	MW
RF generator power	76.8	101.4	127.5	MW
Mains power for RF	135	178	224	MW

Other Components

The machine implications are not limited to the RF system, however. The synchrotron radiation emitted by the beam strikes the vacuum chamber, heating it and producing outgassing. The additional synchrotron radiation power in machines B and C implies additional cooling and shielding for the vacuum chamber and, possibly, additional pumping around the entire circumference.
In addition, the direct power loss to parasitic modes can be important in some specific places - notably in the intersection region where the vacuum chamber is considerably less smooth and uniform than elsewhere.
The increased parasitic mode losses in machines B and C (by a factor 2 or 4 respectively) clearly aggravate this problem.

If eight bunches are used then separating plates must be installed in the eight unwanted crossings.
Apart from the theoretical problems discussed above, additional aperture must be provided in the region of the beam bumps. This implies special vacuum chambers, special magnets etc. quite apart from the separating plates themselves.

Costs

In evaluating the differences in cost between the three machines it is not sufficient to consider the construction cost alone. The substantial differences in the mains power required mean that the running costs must also be taken into consideration. Comparing the sum of the construction cost and the ten-year running costs by using the prices from reference 1, the machines with equal insertions (B and C) are more expensive than the machine with specialized insertions (A) by about 8% and 16% respectively. This difference is associated purely with the RF system although it must be remembered that only the machine with specialized insertions is 'cost optimized'[5]. Evaluating the additional cost of the other components cannot be done precisely without a detailed study. However, provision of eight long insertions would add a minimum of 10% (or 20%) to the total construction and ten-year running costs.

Improvements to the Short Insertion

From Fig. 1 it is clear that a free space of ±5 m is by no means generous compared with existing electron storage rings. Careful design of the machine components in the insertion region can ensure that the experiments are able to make full use of the space. An important point is that most detectors have solenoidal fields which generally have compensating solenoids to avoid coupling of the vertical and horizontal emittances. It is also possible to use skew quadrupoles placed outside the insertion region free space. Such a scheme has been operating on the ISR for some years[6] and calculations show that it can be used for LEP[7].

The study of 2γ physics is best done in ±10 m insertions. However, these processes are considered as background in other experiments and most detectors require some kind of discrimination against 2γ processes, the level of accuracy depending on the particular experiment. This is usually done by observation of one (or both) of the electrons produced in the final state using a 'tagging' system, the efficiency of which depends strongly on the minimum angle at which particles can be detected. With no compensating solenoid, it is the first insertion quadrupole which limits the acceptance. The use of slim superconducting quadrupoles would be a considerable improvement and this is currently under study. An alternative is to 'tag' through the first quadrupole and this possibility is also under study.

Beam Lifetime

A fundamental limitation in e^+e^- storage rings is given by the bremsstrahlung lifetime, defined as

$$\tau_{bb} = \frac{N}{\sigma_{bb} \sum \mathcal{L}} \qquad (6)$$

where N is the total number of particles per beam, σ_{bb} is the cross-section for the process ($\sim 3\times10^{-25}\mathrm{cm}^{-2}$) and $\sum\mathcal{L}$ is the total luminosity summed over all interaction regions. The smaller current in the machine with specialized insertions means that the beam lifetime is shorter - 6.6 h instead of 8.8 h for the machines with long insertions. This can be somewhat alleviated by reducing the vertical beam size during a physics run[8], but even so refills must be performed frequently and rapidly if the average luminosity is not to fall too far below the peak luminosity.

Number of Each Insertion Type

For LEP, four short and four long insertions are proposed. This is the result of a compromise between high luminosity with a small beam current and a reasonable beam lifetime. Thus, if all eight insertions had the maximum luminosity with ±5 m free space, the beam-beam lifetime would be only 4.4 h. In the early stages of machine operation it appears to be an advantage to maintain a high superperiodicity. In principle, however, the number and length of the insertions could be tailored exactly to the requirements of the individual experiments. There are two basic factors to be borne in mind. Firstly, the luminosity will be inversely proportional to the free space. Secondly, the beam lifetime will be inversely proportional to the total luminosity summed over all insertions. The effect of a shorter beam lifetime is to reduce the ratio of average to peak luminosity in all insertions.

Conclusion

It is proposed that LEP be equipped with four short high-luminosity insertions and four long insertions with a lower luminosity. This results in considerable savings compared with a machine with eight long high-luminosity insertions. Practically every aspect of the machine is improved and there is a considerable reduction in the total power requirements. The restrictions imposed by the insertions on the detector design were examined at the Les Houches Summer Study on LEP[9] where it was concluded that the physics programme would not be significantly affected. This concept will be applied to future versions of LEP[10] although the exact length of the insertions may undergo minor modifications.

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