FEASIBILITY STUDY FOR A B-MESON FACTORY
IN THE CERN ISR TUNNEL

T. Nakada (Editor)
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ABSTRACT

A feasibility study has been made for a $B$-meson factory, using the ISR tunnel and the LEP injector at CERN. An electron-positron collider operated with asymmetric beam energies of 8 and 3.5 GeV at a luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ will permit decisive answers on the question of CP violation within the framework of the Standard Model. This report outlines the physics motivation and detector requirements and gives a description of the machine design. It is proposed that the design goal is reached in two stages, with a collider with two rings of equal size. In the first stage a luminosity of $10^{33} \text{ cm}^{-2}\text{s}^{-1}$ may be achieved, allowing a rich programme of charm, beauty and $\tau$-lepton physics. A further tenfold increase of the luminosity would require additional R&D on various machine aspects.
Feasibility Study for a B-Meson Factory in the CERN-ISR Tunnel

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Summary

The origin of CP violation is one of the most intriguing puzzles in elementary particle physics. The observation of CP violation outside the Kaon system would provide vital information as to whether the effect can be described in the framework of the Standard Model. The study of $B$-mesons is particularly promising in this respect. It requires, however, the production of large numbers of $B$-mesons under clean experimental conditions. This would be best achieved by a high-luminosity $e^+e^-$ collider with the centre of mass energy tuned to the $\Upsilon(4S)$.

We have carried out a feasibility study for an asymmetric electron-positron collider in the CERN-ISR tunnel with a centre of mass energy around 10 GeV and with a luminosity $L = 10^{34}$ cm$^{-2}$s$^{-1}$. On the basis of a previous study in the PSI proposal, a machine design has been worked out with an initial luminosity of $L = 10^{33}$ cm$^{-2}$s$^{-1}$ but with all the known features built in to reach the ultimate goal of $L = 10^{34}$ cm$^{-2}$s$^{-1}$, implying in particular a large magnet aperture and, in view of the high synchrotron radiation power, a copper vacuum chamber. An asymmetry of 8 vs. 3.5 GeV is optimal for CP violation studies from the combined requirements of machine and detector. The machine is, however, flexible enough to allow larger asymmetries up to 10 vs. 3 GeV, though at lower luminosity. The possibility to operate the machine in a symmetric mode is also included in the design.

The collider is a double storage ring with two equal size rings and two interaction regions. The beam separation in case of asymmetric operation is done with a tilted detector solenoid field. The stage one machine uses copper cavities with mode damping antennas. The ultimate machine needs very short bunches and has to be equipped with superconducting cavities. The filling times for the ultimate machine are short enough to ensure a good average luminosity. The machine, although using the existing CERN LEAR electron-positron injector complex, would run without any noticeable interference with the rest of the CERN program.

The first stage machine is estimated to cost 160 MSF including external labour contracts and using the available ISR tunnel and the CERN injection system, but without contingency. After commissioning the machine, the integrated luminosity required to start the search for CP violation can be reached rather quickly. The ultimate goal of $L = 10^{34}$ cm$^{-2}$s$^{-1}$ requires a few years of R&D and improvements to the RF system.

The scientific program covers, apart from CP violation, a broad spectrum of topics in heavy flavour physics. These include $B_s\overline{B}_s$ oscillations, rare $B$- and $D$-meson decays, a rich $\tau$-physics program and QCD studies in weak $D$- and $B$-decays. The stage one machine produces already $8 \cdot 10^9 \tau^+\tau^-$, $10^7 c\bar{c}$, $2 \cdot 10^7 B$-mesons at the $\Upsilon(4S)$, and $2 \cdot 10^6 B_s$-mesons at the $\Upsilon(5S)$ in one year. The stage two machine aims at ten times more.

An upgraded LEP with $L = 1.5 \cdot 10^{32}$ cm$^{-2}$s$^{-1}$ could produce the same number of $b$, $c$, and $t$ as our first stage machine with $L = 10^{33}$ cm$^{-2}$s$^{-1}$, but the $B$-tagging efficiency and invariant mass resolution is more than an order of magnitude better at our proposed collider. The question of CP violation can only be answered with a machine optimized and dedicated for this purpose.
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Appendix I

Appendix II
1 Introduction and Machine Requirements

The present situation in particle physics is characterized by the overwhelming success of the Standard Model. It provides a clear and simple picture of the fundamental particles and forces and gives rules for calculations which are testable with precision experiments. The correct prediction of the masses and properties of the $W$ and $Z$ particles was certainly its most astounding success, but almost equally remarkable is its ability to account for practically all phenomena so far observed in particle physics, both at low and high energies.

Nevertheless, the model leaves many fundamental questions unanswered, indicating that it has to be part of a more extended theory and pointing to physics beyond the Standard Model. In particular, the theory does not give an explanation for the origin of the symmetry between the three generations of fundamental fermions, their mixing properties in weak interaction processes, and the observed violation of CP invariance in the $K^0$-system. Reliable techniques for calculating strong interaction phenomena, in particular in the confinement region, are still at a very early stage. In order to make further progress in our understanding of the Standard Model and find indications for deviations revealing new physics beyond it, two complementary experimental directions should be followed. Experiments at the highest energies probe the short distance scale by the study of particle interactions at very high $Q^2$. These experiments should, however, be complemented by very high precision experiments at lower energies to test the consistency of the Standard Model, to measure all properties of quarks and leptons, especially in the third family, to further explore the CP violation puzzle and to look for non-standard model physics in rare decay processes.

In particular $B$-meson factories, $e^+e^-$ colliders with a centre-of-mass energy around $E_{cm}=10$ GeV and with luminosities a factor of 10-100 higher than those of present machines in this energy range, can make decisive contributions to

- understanding CP violation, by observing its occurrence in $B$-meson decays,
- determining with high precision parameters of the Standard Model,
- better understanding the dynamics of the strong interaction at energies of a few GeV, and
- looking for the boundaries of the Standard Model by observing rare decays of $B$- and $D$-mesons and $\tau$-leptons.

CP violation is certainly the most compelling physics argument for a $B$-meson factory. It therefore defines the guideline for the optimization of such a machine.

At present there exist three $e^+e^-$ colliders which cover the energy range around $E_{cm}=10$ GeV: CESR, DORIS II and VEPP-IV. All these are colliders in which electrons and positrons are stored in a single ring. The average luminosity for experiments has reached values around 100 pb/y at DORIS and 500 pb/y at CESR. As will be shown in section 2.1, the goal for CP violation studies in $B$-meson decays should be set at around $10^5$ pb/y, while a luminosity of about $10^4$ pb/y would
already open a wide field of new heavy flavour studies, with even the possibility of
the first evidence for CP-violation in B-meson decays.

There is a worldwide interest in the possible construction of B-meson factories
[1]. Design studies have been made at PSI [2], Frascati [3], Novosibirsk [4], Cornell
[5], SLAC [6, 7], DESY [8] and KEK [9] for both circular and linear machines. Some
of these studies (Cornell, SLAC, Novosibirsk) have already been at a very detailed
level and proposals for funding are being prepared. These latter studies, including
the one discussed in this report, converge to a similar design concept: a double ring
collider, both rings having the same circumference and allowing the possibility to
operate the machine with different beam energies in the two rings.

This report summarizes the results of a feasibility study carried out at the joint
initiative of CERN and the Paul Scherrer Institute (PSI) to explore the possibility
of building a B-meson factory in the ISR tunnel at CERN, using the PSI proposal

There is general agreement that an asymmetric energy collider offers the best
chances for observing CP-violation effects. However, no experience exists in running
machines in an asymmetric mode and the possible influences on the ultimate
luminosity are therefore uncertain. On the other hand, asymmetric energies allow
an effective magnetostatic beam separation with a short separation length between
bunches which leads to higher luminosity. The asymmetry should not be too small
allowing an effective magnetostatic separation and not too large because of the rapid
increase of synchrotron radiation power. The choice of the optimum is also influ-
enced by the necessary time resolution for observing CP violation in B-meson decays
from moving \( \Upsilon(4S) \) mesons. Using present experience with silicon vertex
detectors, the studies in section 2.1 and 4.1 show that the minimum machine asymmetry for
that purpose is around 7 vs. 4 GeV. To allow some safety margin, an asymmetry of
8 vs. 3.5 GeV should be taken as a starting point for the machine optimization.

In case the asymmetric operation shows unexpected luminosity limitations, one
should have a possibility to run the machine with symmetric beam energies. CP vi-
olation is also observable in this case using \( B^+ B^- \) pairs produced at an energy slightly
above the \( \Upsilon(4S) \) resonance. This method, however, requires roughly four times
higher luminosity than with boosted \( \Upsilon(4S) \) mesons. In symmetric machines, several
arrangements have been proposed to achieve beam separation: small angle crossing
with or without crab crossing or, for head-on collisions, separation by electrostatic
or RF-magnetic fields.

The ISR tunnel with a circumference of 1 km is well suited for a double storage
ring of the required energy range. It would allow to operate the machine both in
a symmetric mode in a centre-of-mass energy range from 7 to 14 GeV and in an
asymmetric mode with energy asymmetries around 8 vs. 3.5 GeV. Beam separation
for bunch distances down to 3 m might in this case be achieved magnetostatically
by a slight tilt of the solenoidal detector magnet. There is good confidence that
with present experience and technology a luminosity of a few times \( 10^{33} \text{ cm}^{-2}\text{s}^{-1} \),
corresponding to a few \( 10^4 \text{ /pb/y} \) can be obtained.

It is felt that a further increase in luminosity to about \( 10^5 \text{ /pb/y} \) is not beyond
reach, but requires intensive R&D efforts at an existing high luminosity machine.
This should therefore be considered the second stage of the project. The first stage
machine with a design luminosity of $10^{39}$ cm$^{-2}$s$^{-1}$ is called the "reference machine" in chapter 5. This machine, assuming a yearly running time of $10^7$ s, would produce $10^4$ events /pb/y, corresponding to

$$8 \cdot 10^6 \, \tau^+\tau^- \text{ pairs,}$$
$$2.5 \cdot 10^7 \text{ multihadron events,}$$
$$\text{including } 1 \cdot 10^7 \, c\bar{c} \text{- quark events,}$$
$$2 \cdot 10^7 \, B \text{ mesons if operating on the } \Upsilon(4S) \text{ resonance, and}$$
$$\sim 2 \cdot 10^8 \, B_s \text{ mesons if running on the } \Upsilon(5S)$$

per year and would already allow an extremely rich program in beauty, charm and \(\tau\)-lepton physics.

Table 1.1: Approximate \(B\)-meson production rates at existing and planned machines in comparison to the studied machine, here called BFI-I for the reference machine and BFI-II for stage two. \(\sigma_b\) is the production cross section, \(\dot{N}_b\) is the rate, and the last column gives the fraction of \(b\)-quark events in all hadronic events.

<table>
<thead>
<tr>
<th></th>
<th>(E_{CM}) [GeV]</th>
<th>(\mathcal{L}_{peak}) [cm$^{-2}$s$^{-1}$]</th>
<th>(\mathcal{L}_{av.}) [pb$^{-1}$y$^{-1}$]</th>
<th>(\sigma_{bb}) [nb]</th>
<th>(\dot{N}_{bb}) [y$^{-1}$]</th>
<th>(N_{bb}/N_{had})</th>
</tr>
</thead>
<tbody>
<tr>
<td>DORIS-II</td>
<td>(e^+e^-)</td>
<td>10.6</td>
<td>(3 \cdot 10^{31})</td>
<td>100</td>
<td>0.9 nb</td>
<td>(10^5)</td>
</tr>
<tr>
<td>CESR</td>
<td>(e^+e^-)</td>
<td>10.6</td>
<td>(10^{32})</td>
<td>500</td>
<td>1.1 nb</td>
<td>(5 \cdot 10^5)</td>
</tr>
<tr>
<td>BFI-I</td>
<td>(e^+e^-)</td>
<td>10.6</td>
<td>(10^{33})</td>
<td>(10^4)</td>
<td>1.1 nb</td>
<td>(10^7)</td>
</tr>
<tr>
<td>BFI-II</td>
<td>(e^+e^-)</td>
<td>10.6</td>
<td>(10^{34})</td>
<td>(10^5)</td>
<td>1.1 nb</td>
<td>(10^8)</td>
</tr>
<tr>
<td>LEP</td>
<td>(e^+e^-)</td>
<td>91.1</td>
<td>(1.5 \cdot 10^{31})</td>
<td>100</td>
<td>6 nb</td>
<td>(6 \cdot 10^5)</td>
</tr>
<tr>
<td>LEP upgr.</td>
<td>(e^+e^-)</td>
<td>91.1</td>
<td>(1.5 \cdot 10^{32})</td>
<td>1000</td>
<td>6 nb</td>
<td>(6 \cdot 10^6)</td>
</tr>
<tr>
<td>HERA</td>
<td>(ep)</td>
<td>300</td>
<td>(10^{31})</td>
<td>100</td>
<td>4 nb</td>
<td>(4 \cdot 10^5)</td>
</tr>
<tr>
<td>TEV-II</td>
<td>(pW) (\sim 50)</td>
<td>(\sim 10^{31})</td>
<td>(\sim 100)</td>
<td>(\sim 1 \mu b)</td>
<td>(\sim 10^8)</td>
<td>10$^{-6}$</td>
</tr>
<tr>
<td>TEV-I</td>
<td>(\bar{p}\bar{p})</td>
<td>2000</td>
<td>(10^{30})</td>
<td>10</td>
<td>15 (\mu b)</td>
<td>(1.5 \cdot 10^8)</td>
</tr>
<tr>
<td>TEV-I upgr.</td>
<td>(\bar{p}\bar{p})</td>
<td>2000</td>
<td>(5 \cdot 10^{31})</td>
<td>500</td>
<td>15 (\mu b)</td>
<td>(8 \cdot 10^9)</td>
</tr>
<tr>
<td>LHC</td>
<td>(pp)</td>
<td>16000</td>
<td>(10^{34})</td>
<td>(10^5)</td>
<td>200 (\mu b)</td>
<td>(2 \cdot 10^{13})</td>
</tr>
<tr>
<td>SSC</td>
<td>(pp)</td>
<td>40000</td>
<td>(10^{33})</td>
<td>(10^4)</td>
<td>500 (\mu b)</td>
<td>(5 \cdot 10^{12})</td>
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</table>

The competitiveness of \(B\)-meson factories with other existing or planned machines is shown in table 1.1. Whereas \(Z^0\)-production at LEP and \(ep\) collisions at HERA will not be competitive in the number of \(B\)-mesons produced, hadron colliders are superior in this respect to a \(B\)-meson factory. Production rates of \(10^8\) or more \(B\)-mesons per year seem feasible at today's \(\bar{p}\bar{p}\) colliders. However, only a tiny fraction of the events produced, \(3 \cdot 10^{-4}\) at TEV-I, contains a \(B\)-meson. Therefore sophisticated triggering schemes are needed to filter out the \(B\)-meson events, either requiring a specific highly characteristic decay channel with a small decay fraction or a very complicated trigger setup, both resulting in a significant reduction of the sensitivity. In the case of LHC and SSC the fraction of \(B\)-meson events reaches
values of 0.3 to 0.5% of the total event rate. Together with the high luminosity expected for these colliders a competitive number of $B$-meson decays may be collected. However, the trigger problems encountered there are far from being solved.

The $B$-meson rates at the reference machine are an order of magnitude higher than at LEP with its design luminosity. The $B$-meson factory with $10^5$ \$/pb$/y is again an order of magnitude better than an upgraded multibunch LEP with a few $10^{32}$ \$cm^{-2}$$s^{-1}$. Other advantages at a $B$-meson factory in comparison to LEP are summarized in section 4.4.

There is a clear incentive in view of the physics reach and its uniqueness to consider the construction of a $B$-meson factory in Europe. The machine studied in this document has two intersection regions. It therefore offers room for two experiments matching the wide physics interest throughout Europe or even worldwide.

The contents of this document are organized as follows: Chapter 2 contains nine selected topics on the physics motivation. Chapter 3 summarizes detector requirements, and chapter 4 presents some recent simulation studies on "pilot reactions" in $B$-meson decays together with a comparison to the LEP capabilities. Chapter 5 describes the machine designs for both $\mathcal{L} = 10^4$ and $10^5$ \$/pb$/y including the injection system and other infrastructure available at CERN.
2 Physics Motivation

The following sections describe a selection of nine physics topics which strongly motivate the construction of a $B$-meson factory. This selection is by far not a complete list, for more see ref. 2 and the proceedings of recent symposia on heavy flavour physics [10].

2.1 The CKM Matrix and CP Violation

With the important observation that there are only three families of fermions [11], the standard charged weak interaction between $u, c, t$ and $d, s, b$ quarks is completely described by its V-A structure, the Fermi coupling constant $G_F$, and the Cabibbo-Kobayashi-Maskawa (CKM) matrix [12], a convenient approximation of which is due to Wolfenstein [13]:

$$V_{CKM} = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} \approx \begin{pmatrix}
1 & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} . \quad (2.1)
$$

The four parameters $\lambda$, $A$, $\rho$, and $\eta$ are related to $\vartheta_{12}$, $\vartheta_{13}$, $\vartheta_{23}$, and $\delta$ of the PDG parametrization [14] by

$$\lambda = \sin \vartheta_{12}, \quad A = \sin \vartheta_{23}/\lambda^2, \quad \rho = \sin \vartheta_{13} \cdot \cos \delta/(A \cdot \lambda^3), \quad \eta = \sin \vartheta_{13} \cdot \sin \delta/(A \cdot \lambda^3) .$$

The standard model does not predict the values of the four parameters, they have to be obtained from experiment. Present results are:

$$\lambda = 0.220 \pm 0.002 \text{ (from } K \text{ and hyperon decays [15, 16])} ,$$

$$A = 0.97 \pm 0.10 \text{ (from the rate of semileptonic } B \text{ decays [17])} ,$$

$$\sqrt{\rho^2 + \eta^2} = 0.4 - 0.9 \text{ (from leptons with high momentum in } B \text{ decays [18])} .$$

If CP violation in $K^0\bar{K}^0$ oscillations ($\epsilon$), the possibly observed direct CP violation in $K^0 \rightarrow \pi\pi$ decays ($\epsilon'$), and $B^0\bar{B}^0$ oscillations ($x_0$) are due to the standard weak interaction, we have three additional constraints on $\rho$ and $\eta$:

$$|\epsilon| = \eta \cdot B_K \cdot f_1(m_t, \rho) , \quad |\epsilon'| = \eta \cdot f_2(m_s, m_t) , \quad |x_0| = f_B^2 \cdot B_B \cdot f_3(m_t) \cdot [(1 - \rho)^2 + \eta^2] .$$

Using the known functions $f_1$, $f_2$, $f_3$ [19, 20], the experimental mean values $|\epsilon| = (2.26 \pm 0.02) \cdot 10^{-3}$ [14], $|\epsilon'| = (4.7 \pm 2.0) \cdot 10^{-6}$ [21, 22], and $|x_0| = 0.72 \pm 0.13$ [17], the limit $m_t > 77$ GeV from the direct $t$-quark search at CDF [23], the range $m_t = (130 \pm 35)$ GeV from radiative corrections to the relation between $m(Z^0)$ and $\sin^2 \vartheta_W$ [24], and assuming $f_{B^0}/B_B = (160 \pm 40)$ MeV, $B_K = 0.75 \pm 0.15$, $m_s = (150 \pm 50)$ MeV, a least-square fit results in the best estimate $(\rho, \eta) = (-0.4, +0.2)$ and one- and two-sigma contours as shown in fig. 2.1 [25]. The fit quality is good, i.e. all used observations and assumptions are perfectly consistent with each other and with the standard model.
Figure 2.1: Result of a least square fit on the CKM matrix parameters $\rho$ and $\eta$, defined in eq. 2.1. The fit inputs are described in the text. The angle $\beta$ of the “CP triangle” determines the amount of CP violation in $B^o \rightarrow J/\psi K^o_s$ decays in the standard model.

Further and more stringent consistency checks as well as more precise determinations of the standard model parameters $\rho$, $\eta$, and $A$ (resp. $\theta_{13}$, $\theta_{23}$, and $\delta$) are of greatest importance for understanding the origin of CP violation. $B$-meson decays play an outstanding role in these two respects. More precise measurements of $V_{cb}$ and $V_{ub}$ from exclusive semileptonic $B$ decays and of $B^o\bar{B}^o$ and $B_s\bar{B}_s$ oscillations will increase the information on $\rho$ and $\eta$. The observation (or absence) of CP-violating hadronic $B$ decays will then show if the CKM matrix and therefore the standard model in its present form can fully describe the phenomenon of CP violation.

We do not want to list here all possible CP-violating $B$ decay channels [26], but rather focus on a single channel $J/\psi + K^o_s$. This channel has three advantages:

1. The order of magnitude of the decay fraction is known; the four observed events [27] correspond to $|B(B^o \rightarrow J/\psi K^o_s) + B(\bar{B}^o \rightarrow J/\psi K^o_s)|/2 \approx 4 \cdot 10^{-4}$.

2. The observable CP asymmetry in this decay,

$$A_{obs} = \frac{N(\psi K^o_s; \bar{T}) - N(\psi K^o_s; T)}{N(\psi K^o_s; \bar{T}) + N(\psi K^o_s; T)} = A_0 \cdot \sin[\Delta m \cdot (t_1 \pm t_2)]  \ , \quad (2.2)$$

is completely determined by standard model parameters and is free from hadronic uncertainties. The parameter $t_1$ is the time between $B^o\bar{B}^o$ production and the $\psi K^o_s$ decay, $t_2$ between production and the tagging decay into mode $T$ or $\bar{T}$. Mode $\bar{T}$ is a $\bar{B}^o$ decay, e. g. into a negative lepton and anything, $T$ a $B^o$ decay, e. g. into a positive lepton. The plus sign between $t_1$ and $t_2$ is for a two particle state with $C = P = +1$, the minus sign for $C = P = -1$, e. g. for a $B^o\bar{B}^o$ pair from the $\Upsilon(4S)$. $A_0$ is equal to $\sin 2\beta$ if CP violation has its origin completely in the standard weak interaction, where $\beta$ is one of the angles in the CP triangle defined in fig. 2.1, and $\Delta m$ denotes the mass difference between the two weak eigenstates of the $B$-meson.

3. No other decay channel discussed so far has a lower estimate for the necessary number of $B\bar{B}$ pairs for observing CP violation in $B$-meson decays.
Integrating over all decay times \( t_1 \) and \( t_2 \), we obtain

\[
A_{\text{obs, int}} = \frac{N_{\text{int}}(\psi K_s; \overline{T}) - N_{\text{int}}(\psi K_s; T)}{N_{\text{int}}(\psi K_s; \overline{T}) + N_{\text{int}}(\psi K_s; T)} = \begin{cases} 
0 & \text{for } C = -1, \\
r \cdot A_0 & \text{for } C = +1,
\end{cases}
\]

where \( r = 2x_0/(1 + x_0^2)^2 = 0.62 \) for \( x_0 = \Delta m(B^o)/\Gamma(B^o) = 0.72 \). Therefore, a time-integrating method leads only to an observable asymmetry for \( C = +1 \). This requires \( B^*B \) pairs produced at an energy slightly above the \( \Upsilon(4S) \) and the cross section for their production is about \( 1/4 \) of that for \( \Upsilon(4S) \). Further details can be found in ref. 28.

Because of the dependence on \( \Delta m \cdot (t_1 - t_2) \) for \( B \)-meson pairs produced from \( \Upsilon(4S) \) decays with \( C = -1 \) (see eq. 2.2), detection of both decay vertices from an \( \Upsilon(4S) \) at rest still leads to zero observable CP asymmetry since the production vertex is not known with sufficient precision. For boosted \( \Upsilon(4S) \), however, the difference \( (t_1 - t_2) \) becomes measurable and the CP asymmetry can be observed [29]. A boost of \( \beta \gamma \) leads to a decay vertex separation of \( l_1 - l_2 \approx c \beta \gamma (t_1 - t_2) \) independent of the location of the production vertex. The necessary boost depends on the resolution for \( l_1 - l_2 \). In section 4.1 we demonstrate that \( \beta \gamma = |p(e^+) - p(e^-)|/[m(\Upsilon4S) \cdot c] \approx 0.4 \) is a reasonable choice. Too small boosts do not provide enough resolution and too large boosts become rapidly uneconomic because of the \( E^4 \) increase of synchrotron radiation and the necessity for a detector with larger acceptance.

The maximum information on the CP violation parameter \( A_0 \) is obtained from a maximum-likelihood fit to the observed CP asymmetry as a function of \( t_1 - t_2 \). For an observation of \( A_0 \) with a significance of \( S \) standard deviations, \( S = A_0/\sigma(A_0) \), we have to produce the following number of boosted \( \Upsilon(4S) \) mesons:

\[
N(\Upsilon4S) = \frac{S^2}{2 \cdot I_o \cdot A_0^2 \cdot B_1 \cdot B_2 \cdot B_3 \cdot B_4 \cdot \eta_{\text{rec}} \cdot \eta_{\text{tag}} \cdot (1 - 2w)^2},
\]

where \( B_1 = B(\Upsilon4S \to B^o \overline{B^o}) \), \( B_2 = [B(B^o \to J/\psi K_s^o) + B(\overline{B^o} \to J/\psi K_s^o)]/2 \), \( B_3 = B(J/\psi \to l^+l^-) \), and \( B_4 = B(K_s^0 \to \pi^+\pi^-) \), \( \eta_{\text{rec}} \) is the reconstruction efficiency for \( B^o \to J/\psi K_s^o \), \( \eta_{\text{tag}} \) is the reconstruction efficiency for the tag channels \( T \) and \( \overline{T} \), and \( w \) is the fraction of wrong flavour tags. The statistical factor \( I_o \), the information per reconstructed event, depends on the boost and the assumed vertex resolution. With \( \beta \gamma = 0.4 \) and the vertex resolution obtained from the simulation study in section 4.1, we have \( I_o = 0.30 \) [30].

The present standard model expectation for \( A_0 = \sin 2\beta \) is \( 0.30 \pm 0.09 \) as obtained from the fit in fig. 2.1. The estimated 95% confidence range is 0.12 to 0.48. With \( B_1 = 0.50 \), \( B_2 = 4 \cdot 10^{-4} \), \( B_3 = 2 \cdot 0.07 \), \( \eta_{\text{rec}} = 0.62 \), \( \eta_{\text{tag}} = 0.32 \), and \( w = 0.07 \) we obtain \( N(\Upsilon4S) = 3 \cdot 10^7 \) for observing CP violation in \( B^o \to J/\psi K_s^o \) decays with a significance of 3 standard deviations if \( A_o = 0.3 \). The efficiencies depend on the detector properties; the values chosen here are from the pilot reaction study in section 4.1. With an \( \Upsilon(4S) \) production cross section of 1.1 nb, the required integrated luminosity corresponds to \( 3 \cdot 10^4 \) /pb. The uncertainty range of \( A_o \) between 0.12 and 0.48 as mentioned above translates into integrated luminosities between \( 1 \cdot 10^4 \) and \( 2 \cdot 10^5 \) /pb, the optimistic value corresponding to a one year’s program of the “reference machine” and the upper value to a few years with the envisaged extension.
Once CP violation is seen in $B \rightarrow J/\psi K_s^0$ decays, a wide research program on CP violation will open up. The next channels to be investigated are probably $\pi^+\pi^-$ and $K^+\pi^+$ (see ref. 26).

Understanding the origin of CP violation needs more effort than the discovery of CP violating decay modes of the $B^0$ meson. Of equal importance is a high precision in the determination of the standard model parameters $\theta_{13}$ and $\delta$ in the CKM matrix. Much more statistics than presently available is required for a determination of $|V_{ub}| = \sin \theta_{13}$. Inclusive semileptonic $B$ decays from $\Upsilon(4S)$ decays at rest have given model-dependent results for $|V_{ub}/V_{ts}|$ between 0.08 and 0.20 [18]. The model dependence can be considerably reduced when a large number of exclusive semileptonic $B$ decays is observed. A pilot reaction study of $B^+ \rightarrow \rho^0 l^+\nu$ and $\omega l^+\nu$, summarized in section 4.3, has shown that $10^5 \Upsilon(4S)$ mesons will be sufficient for a determination of $|V_{ub}|$ with a precision in the order of 10%. A measurement of these exclusive decays is therefore a very important and realistic program point for the initial luminosity range of the proposed machine.

### 2.2 $\bar{B}B$ Oscillations

With $e^+e^-$ annihilation on the $\Upsilon(4S)$ resonance, ARGUS and CLEO have observed $B^0\bar{B}^0$ oscillations ($B^0 = \bar{b}d$) and have determined $x_s = \Delta m(B^0)/\Gamma(B^0) = 0.72 \pm 0.13$. With $p\bar{p}$ annihilation at $\sqrt{s} \approx 500$ GeV, UA1 has observed a combination of $B^0\bar{B}^0$ and $B_s\bar{B}_s$ oscillations ($B_s = \bar{b}s$) suggesting that $x_s = \Delta m(B_s)/\Gamma(B_s)$ is large. An even rough determination of $x_s$ is highly important and still missing.

The oscillation parameter $x_s$ is proportional to $m_t^2|V_{td}|^2$, $x_s$ to $m_t^2|V_{ts}|^2$. Using unitarity of the CKM matrix in the standard model, $V_{ts} = -A \cdot \lambda^2$ is well known, but $V_{td} = A \cdot \lambda^3 \cdot (1 - \rho - i\eta)$ only with the precision shown in fig. 2.1. If $m_t$ will be measured in the future, we obtain better information on $(\rho, \eta)$ from $x_s$ alone. The ratio $x_s/x_\gamma$ gives the same information independent of $m_t$ (or even more information since the ratio of decay constants $f_{B_s}/f_{B_s}$ is theoretically less uncertain than $f_{B_s}$ alone).

A $B$-meson factory allows the study of $B_s\bar{B}_s$ oscillations by $e^+e^-$ annihilation on the $\Upsilon(5S)$ resonance which has a formation cross section of $\sim 0.3$ nb. About one third of the $\Upsilon(5S)$ mesons decay into $B_s$-mesons and the decomposition into $B_s\bar{B}_s$, $B_s^*\bar{B}_s + B_s\bar{B}_s^*$, and $B_s^*\bar{B}_s^*$ is unknown. Since the $B_s^*$ decays only into $B_s\gamma$, the decomposition can be determined by measuring the fraction of identified $B_s$ mesons which are accompanied by 0, 1, and 2 photons.

$B_s$ decays are selected by their semileptonic decays, $B_s \rightarrow D_s \ell \nu X$. Around 5% of the $D_s$ can be fully reconstructed in $K\bar{K}$, $K^*\bar{K}$, $\phi\pi$ and $\phi 3\pi$. A first measurement of $B_s\bar{B}_s$ oscillations will be possible from the time-integrated oscillation parameter $\chi_s$,

$$\chi_s = \frac{N_\ell(\ell^+\ell^-) + N_\ell(\ell^-\ell^+)}{N_\ell(\ell^+\ell^-) + N_\ell(\ell^+\ell^+) + N_\ell(\ell^-\ell^-)},$$

which is equal to $x_s^2/(2+2x_s^2)$ for $B_s\bar{B}_s$ pairs with $C=-1$ from $\Upsilon(5S) \rightarrow B_s\bar{B}_s$, or $B_s^*\bar{B}_s^*$ and $(3x_s^2 + x_s^4)/(2(1 + x_s^2)^2)$ for $B_s\bar{B}_s$ pairs with $C=+1$ from $\Upsilon(5S) \rightarrow B_s^*\bar{B}_s + B_s\bar{B}_s^*$. A rough estimate of rates and reconstruction efficiencies leads to the conclusion
that an integrated luminosity of $10^4$ /pb, i.e. one year of running with the reference machine, leads to a determination of $x_s$ if $x_s \lesssim 3$ and to a lower limit of $x_s > 3$ (90% CL) if $x_s$ is larger.

The standard model with the parameters in fig. 2.1 expects $x_s$ to be around 7. A measurement of such a large value is not possible with the time-integrated method even with large statistics and no $C=+1$ vs. $C=-1$ uncertainty. A study of the time dependence of both $B_s$ decays is then required. Integrating over all $t_1 + t_2$ for a given $\Delta t = t_1 - t_2$, the rate of $B_s\overline{B}_s$ decays (e.g. $D_s\ell^+\ell^-X$) is given by [31]

$$N_{\pm} \propto \begin{cases} e^{-r\cdot\Delta t} [1 + \cos(\Delta m \cdot \Delta t)] & C = -1 \\ e^{-r\cdot\Delta t} \left[ 1 + \frac{1}{1 + x_s^2} \cos(\Delta m \cdot \Delta t) - \frac{x_s}{1 + x_s^2} \sin(\Delta m \cdot |\Delta t|) \right] & C = +1 \end{cases}$$

and the rate of $B_sB_s$ and $\overline{B}_s\overline{B}_s$ decays (e.g. $D_s\ell^+\ell^+X$) by

$$N_{\pm\pm} \propto \begin{cases} e^{-r\cdot\Delta t} [1 - \cos(\Delta m \cdot \Delta t)] & C = -1 \\ e^{-r\cdot\Delta t} \left[ 1 - \frac{1}{1 + x_s^2} \cos(\Delta m \cdot \Delta t) + \frac{x_s}{1 + x_s^2} \sin(\Delta m \cdot |\Delta t|) \right] & C = +1 \end{cases}$$

Fig. 2.2 shows the like sign rates $N_{\pm\pm}$ for $C=+1$ and $C=-1$. In the case of $C=+1$, the oscillation is strongly damped. Our study in section 4.2 assumes dominance of $C=-1$, suggested by the coupled channel analysis in ref. 32. The study shows that $x_s$ values up to $\sim 6.5$ can be measured on the $\Upsilon(5S)$ with $10^4$ /pb, i.e. one year with the reference machine. This assumes an energy asymmetry of 8.4 vs. 3.5 GeV. Larger $x_s$ values become measurable with more statistics or with a larger beam energy asymmetry. The latter possibility underlines the value of a flexible machine.
design. The present machine study suggests good luminosity up to 10 vs. 2.9 GeV, which allows the measurement of \( x \), up to \( \sim 8.5 \) with \( 10^4 \) /pb.

2.3 \( B \) and \( D \) Meson Decays

The investigation of weak and rare decays of heavy mesons contributes to three areas of progress: the determination of standard model parameters, the understanding of the strong interaction, and the search for new physics.

A better determination of the standard model parameters \( \theta_{13} \) and \( \theta_{23} \) will be achieved from exclusive semileptonic decays like \( B \rightarrow \pi \ell \nu, \rho \ell \nu \) and \( B \rightarrow D \ell \nu, D^* \ell \nu \). Some \( 10^4 \) /pb will be needed to improve the precisions on \( \theta_{23} \) and \( \theta_{13} \) by one order of magnitude; at present they are \( \pm 10\% \) and \( \pm 40\% \) respectively.

Nonleptonic decays like \( B \rightarrow D^* \pi \) and \( B \rightarrow \psi K \) are the simplest laboratory for studying strong interaction dynamics: a two-quark state evolves into a four-quark state under the influence of the well known weak interaction. Present decay fractions are uncertain by a factor of 2. A luminosity increase by a factor of 100 will allow important contributions to QCD \cite{33}.

The search for rare \( D \) and \( B \) decays opens a window for new physics. Examples are \( D \bar{D} \) oscillations, \( B^0 \) and \( D^0 \) decays into \( e^+e^- \), \( \mu^+\mu^- \), and \( \mu^+\pi^- \) where standard model predictions are zero or so small that new physics may have a chance to dominate \cite{34}.

The \( B \) and \( D \) decay program can be studied at an \( e^+e^- \) collider with small asymmetry (\( \beta \gamma \approx 0.4 \)) as perfectly as at a symmetric one; a few explicit simulation results are presented in chapter 3.

2.4 Measurement of \( B \)-meson Mean Lives

The Lorentz boost of \( B\bar{B} \) pairs from \( \Upsilon(4S) \) mesons at an asymmetric collider opens up the possibility of measuring the mean lives of neutral and charged \( B \)-mesons. At an \( 8 + 3.5 \) GeV machine with a boost \( \beta \gamma = 0.42 \), the \( B \) decay length is of the order 150 \( \mu \)m and thus becomes measurable with state-of-the-art silicon micro-strip vertex detectors. The distribution of the decay time difference between the two \( B \)-mesons produced from the \( \Upsilon(4S) \) decay is identical to the decay time distribution of the \( B \)-meson itself. As shown in section 2.1, the decay time difference can be determined from the decay vertices of the two \( B \)-mesons.

In order to distinguish between neutral and charged \( B \)-mesons, one \( B \) must be fully reconstructed. The most straightforward choice of event topologies are low-multiplicity exclusive decays with only charged tracks in the final state. In a first step, one may want to exclude decay chains involving a \( D \)-meson to avoid \( B^0 \)-\( B^+ \) confusion due to low momentum particles. Under these restrictions, the most suitable \( B \) decays are \cite{35}

\[
\begin{align*}
B^0 & \rightarrow J/\psi K^0 \\
\bar{B}^0 & \rightarrow J/\psi K^+\pi^- \\
B^+ & \rightarrow J/\psi K^+
\end{align*}
\]
and charge conjugate states. The effective branching ratios for these channels to decay into final state topologies $\ell^+\ell^-K^\pm$, $\ell^+\ell^-\pi^+\pi^-$, $\ell^+\ell^-K^{\pm}\pi^\mp$ or $\ell^+\ell^-K^{\pm}\pi^\mp\pi^\mp$, where $\ell^+\ell^-$ is a lepton pair from the $J/\psi$ decay, are $4 \cdot 10^{-4}$ for the $B^0$ and $3 \cdot 10^{-4}$ for the $B^+$. The reconstruction efficiency for such states is assumed to be $\sim 0.5$.

The other $B$ decay vertex can be reconstructed in the same way as described in section 4.1 and we conclude that a vertex reconstruction efficiency of $\sim 0.6$ with a time difference resolution of $\sigma_{\Delta t} \approx 0.5$ ps can be achieved.

Assuming an integrated luminosity of $\int L dt = 10^4$ pb, i.e. one year running with the reference machine, we obtain useful event samples of 600 for neutral and 450 for charged $B$-mesons. The precision on the mean life achievable with these samples is

$$\sigma_t = \sqrt{\frac{\tau_B^2 + \sigma_{\Delta t}^2}{N}},$$

i.e. 0.05 ps and 0.06 ps respectively with $\tau_B = 1.2$ ps. This shows that a measurement of the lifetime difference between neutral and charged $B$-mesons at the level of a few percent is possible with few years of running with the reference machine.

2.5 Spectroscopy and Decays of $b\bar{q}$, $c\bar{q}$, and $cqq$ States

The majority of charmed mesons has been discovered in $e^+e^-$ annihilation near 10 GeV, namely the $D_s$, $D_s^*$, $D_1(2420)$, $D_2(2460)$, $D_3(2770)$, and $D_{s1}(2536)$ states. Even the $\ell = 1$ $c\bar{q}$ multiplet is not yet complete, spin-parity analyses are missing or need confirmation, and higher excited states have still to be found. Their masses and decay fractions will be valuable contributions for bound state QCD calculations.

Excited $B$-mesons have not yet been reconstructed at all. The only indirect evidence for $B^{*+}$, $B^{*-}$, and $B^*_s$ comes from the observation of monochromatic photons on the $\Upsilon(5S)$ and from their Doppler broadening. Higher luminosity on the $\Upsilon(5S)$ and at center of mass energies around 14 GeV will open a new field of spectroscopy.

Of special interest for QCD are also the weak decays of the charmed baryons $\Lambda_c$, $\Xi_c^+$, $\Xi_c^0$, and $\Omega_c$ [36]. Their study, as well as all studies on excited $cqq$ states and those on excited $c\bar{q}$ states mentioned above, can take place at any energy near 10 GeV, e.g. on the $\Upsilon(4S)$ where a $B$-meson factory would run predominantly because of the CP violation interest. All the charm program can be run as well on an asymmetric machine with $\beta_\gamma \approx 0.4$ as on a symmetric machine.

2.6 Spectroscopy of $b\bar{b}$ States

Because of the larger mass of the $b$-quark, the $b\bar{b}$-system has a much richer spectrum of bound states below flavour threshold than the $c\bar{c}$-system. Because of the presumably too large $t$-quark mass and the absence of more fermion families, the
$b\bar{b}$ system will be the heaviest hadron system for systematic studies of hadron wave functions and of photonic and gluonic transitions.

Nine bound $b\bar{b}$ states below threshold are known. Out of the missing ones, the states $\eta_b(1S,2S,3S)$, $h_b(1P,2P)$, and $T_J(1D)$ with $J=1,2,3$ are the most interesting ones. The 1D states are especially sensitive to the long range part of the $b\bar{b}$ potential and therefore to the confinement mechanism. Around $10^7 \, \Upsilon(3S)$ decays will be sufficient for the observation of 100 events with a photon cascade involving 1D states [37]. As shown in chapter 3, these studies can also be performed with asymmetric beam energies.

2.7 $\tau$ Decays

A $B$-meson factory is an intensive source of $\tau^+\tau^-$ pairs in an energy range which is optimal for the reconstruction of $\tau$ decays. With a rate of about $10^7 \, \tau$ pairs produced per year very sensitive tests of the standard model can be performed. Due to the large $\tau$ mass, $\tau$ decays are more sensitive to new physics on a large mass scale than $\mu$ decays. In addition, the large $\tau$ mass offers the possibility to study in a rather clean way hadronic currents.

Many of the arguments why we expect $b$ quark interactions to probe physics beyond the standard model are similarly applicable to the leptons $\tau$ and $\nu_\tau$ of the third fermion family. Thus we can consider the $\tau$ physics program as another strong justification for the construction of a high luminosity machine.

At a $B$-meson factory major progress can be expected from the following experiments:

- $\tau$-mean life: It is important to have a precise value for the mean life because it links the measured branching ratios to the theoretically relevant partial widths. With the proposed high-resolution micro strip vertex detectors the vertex resolution will be, in contrast to previous experiments, much smaller than the $\tau$ decay length. Hence both the statistical and systematic uncertainty in the lifetime measurements will decrease.

- Lorentz structure of leptonic $\tau$ decays: In ref. 38 a complete set of measurements is suggested to fix the V-A structure of $\tau$ decays. Any deviation from the expected structure signals the onset of new physics (new intermediate bosons, charged Higgs, etc.). The measurements require the analysis of momentum and angular correlations in the decays of $\tau$ pairs, which was up to now not possible because of lack in statistics.

- Hadronic $\tau$ decays: With the $\tau$ being the only lepton heavy enough to decay into hadrons it offers the unique possibility to study the weak hadronic currents and test the underlying picture of quark and lepton interactions. Lepton universality can be tested in $\tau$ decays into single mesons ($\pi$, $K$), which are related to the corresponding leptonic decays of these mesons. The CVC and PCAC hypotheses and the existence of second class currents can be investigated at relatively high $Q^2$ values where no stringent tests from other experiments are
available. The $\tau$ decays also provide information on the breaking of flavour SU(3) symmetry and are an ideal field for spectroscopy of light mesons.

- Rare $\tau$ decays: The investigation of muon decays with intense muon sources has confirmed to a very high level of confidence that the standard model holds for these decays. Similar studies must be carried out for the $\tau$ leptons which are more sensitive to new physics on a large mass scale. For example, Higgs boson couplings grow with the particle mass and effects from supersymmetry or compositeness are also generally enhanced for heavier fermions. An important class of rare decays involves lepton number violation. Such decays, as far as they have no neutrinos in the final state, are relatively easy to recognize by kinematical reconstruction.

### 2.8 The $\tau$-neutrino Mass

The mass of the $\tau$-neutrino is consistent with zero and has an upper limit of 35 MeV. Sensitivity for lower mass values is an important goal for future $e^+e^-$ colliders both at "$B$ energies" and at "$c$-$\tau$ energies". A study for the PSI proposal [39] has shown that $10^4 /$pb, i.e. one year's running with the presently discussed reference machine, will lead to a sensitivity of $\pm 3$ MeV on $m(\nu_\tau)$ from the $5\pi$ mass spectrum in $\tau \rightarrow (5\pi)\nu_\tau$ decays. This corresponds to an upper limit of 6 MeV if $m(\nu_\tau) = 0$. The same conclusion is reached in the study for the SLAC $B$-meson factory [40]. An integral of $3 \cdot 10^5 /$pb will lead to $m(\nu_\tau) < 1.7$ MeV (95% CL) if $m(\nu_\tau) = 0$. This requires, however, that the $\tau$-mass, now only known within $\pm 3$ MeV, has an according precision.

As for rare $D$ and $\tau$ decays and all $c\bar{q}$ and $cqq$ studies, the $\tau$-neutrino mass program will be a side program at any energy of the $B$-meson factory and will therefore profit from its total integrated luminosity. Asymmetric operation with $\beta\gamma \approx 0.4$ will be as good as energy-symmetric operation.

### 2.9 Two-photon Physics

In the following we shortly summarize the discussion of a two-photon physics program at a $B$-meson factory as given in the PSI proposal [41].

At a $B$-meson factory the kinematical range with sufficient $\gamma\gamma$ flux extends at least up to the charmonium region (e.g., $1.7 \cdot 10^5$ $\eta_c$-mesons will be produced with an integrated luminosity of $10^4 /$pb). In this region the main physics issues are the studies of two photon couplings to resonances, two-photon production of specific non-resonant states and the total hadronic cross section of two photons.

By virtue of the expected high luminosity, two-photon experiments at a $B$-meson factory will not merely improve the results obtained at other machines but almost certainly will provide new physics insight. In particular, we can expect a major step forward in our understanding of the classification of light hadrons, which is crucial for the fundamental question about the existence of non-$q\bar{q}$ states, such as glueballs or four-quark mesons.
A large part of resonance physics can be done without "tagging", i.e. without the detection of the scattered electrons and positrons. In this case the detector requirements for $\gamma\gamma$ physics are similar to those for the analysis of $B$ decays (good acceptance, high efficiencies for charged and neutral particles, good particle identification). Particularly important for $\gamma\gamma$ physics is the acceptance in beam direction and the trigger efficiencies for low momenta and low multiplicities.

The acceptance for $\gamma\gamma$ events is not affected by asymmetric beam energies. The additional boost from the beams just shifts the boost distribution of the $\gamma\gamma$ system which is flat in the relevant acceptance region.

In order to be able to tag the photons for kinematical reconstruction of the $\gamma\gamma$ system ($Q^2, W_{\gamma\gamma}$) the scattered electrons have to be detected. Small angle tagging devices could be installed in front of the mini-$\beta$ quadrupoles. A 0°-tagging detector is desirable, in particular for total cross section measurements, but may be difficult to realize with the very high beam currents we are aiming for.
3 Detectors

The wide physics interest fully justifies the machine to be designed with two intersections. One of them should be reserved for a "Universal Detector" which is particularly optimized for studies of $B$ and $\tau$ decays. In this chapter, we discuss the requirements on such a Universal Detector.

3.1 Requirements

An increase of the reconstruction efficiencies for $B$-mesons by at least one order of magnitude from its current value of about $10^{-3}$ requires a detector of which the performance over a large solid angle is determined by:

- excellent momentum resolution and high efficiencies for the reconstruction of charged particles down to momenta as low as 30 to 50 MeV/c,

- vertex reconstruction with a resolution of a few tens of $\mu$m,

- detection of photons and electrons with excellent energy and spatial resolution down to energies below 50 MeV,

- good particle identification for electrons, muons, pions, kaons and protons at least up to the highest momenta occurring in $B$-decays (2-3 GeV/c).

The CLEO II detector [42] can be regarded at the present as the best detector for $B$ physics. However a next generation detector should be improved in two respects; charged particle identification and vertex detection. In both cases, intensive R&D is required and has already been started in several institutes in connection with the $B$-meson factory proposal at PSI.

An example for a Universal Detector has been studied in the PSI proposal [2]. The main components of this detector as shown in fig. 3.1 are:

1. a silicon vertex detector around a narrow beam pipe,

2. a precision tracking chamber (PTC),

3. a main drift chamber (MTC),

4. a ring imaging Cherenkov detector (RICH),

5. a CsI calorimeter,

6. a superconducting solenoid coil (1.5 T),

7. muon detectors.

The performance of the detector can roughly be characterized by the following properties:
Figure 3.1: The Universal Detector studied in the PSI proposal.

- Impact parameter resolution from the vertex detector ($P_t$ in GeV/c):
  \[ \sigma_\delta^2 = (8.3 \mu m/\beta p_t)^2 + (8 \mu m)^2, \]

- Momentum resolution for charged particles, where $p$ is in GeV/c:
  \[ (\sigma_p/p)^2 = (0.0019 \cdot p)^2 + (0.0048)^2, \]

- Particle identification:
  - Drift chamber: $\sigma(dE/dx) \approx 7\%$, K/$\pi$ separation about 2 s.d. at 1.5 GeV/c.
  - RICH: K/$\pi$ (K/$p$) separation about 3 (12) s.d. at 2.5 GeV/c.

- Calorimetry with $E$ in GeV:
  \[ (\sigma_E/E)^2 = 0.01^2/E + 0.01^2 \]
  \[ \sigma_\theta(E) = (3 \text{ mrad}/\sqrt{E} + 1 \text{ mrad}) \sin \theta \]
  \[ \sigma_\phi(E) = 3 \text{ mrad}/\sqrt{E} + 1 \text{ mrad}. \]

The PSI detector has originally been designed for operation at a symmetric machine with bunch crossing frequencies up to about 10 MHz. The most relevant differences in the running conditions of a $B$-meson factory in the ISR tunnel would be:

- asymmetric energies (8 GeV against 3.5 GeV),
- luminosities up to $10^{34} \text{ cm}^{-2}\text{s}^{-1}$,
• beam crossing frequencies up to 100 MHz.

We have studied the performance of the PSI detector under these new conditions and conclude that this detector would meet most of the requirements. However, when a $B$-meson factory in the ISR tunnel will be approved, further design studies will be necessary.

### 3.2 Acceptance and Resolution for Asymmetric Beam Energies

In an asymmetric machine, the particles are boosted along the beam direction. We have studied the effect of such a boost on the acceptance and resolution of the PSI detector. In particular, we have evaluated the mass resolution for $D$-mesons, the energy and vertex resolution for $B$-mesons and the energy resolution of photons.

**Mass resolution for $D$-mesons:** The mass resolution of neutral $D$-mesons produced in $\Upsilon(4S)$ decays was determined for the decay modes

$$D^o \to K^+\pi^- \text{ and } D^o \to K^+\pi^-\pi^+\pi^-.$$

Table 3.1 [43] summarizes the results on the $D$ mass resolution and the acceptance for inclusive $D$-mesons. For the symmetric and the 8 vs. 3.5 GeV configuration the differences in both the acceptance and resolution are small, while the acceptance loss becomes large for the 12 vs. 2.3 GeV configuration. Also the mass resolution becomes in the latter case noticeably worse.

**Energy and vertex resolution in the decay $B \to J/\psi K^0_s$:** The reaction $B \to J/\psi K^0_s$ is studied in detail in section 4.1. It is found that the detector resolution is sufficient to separate it from the final state $B \to J/\psi K^0_s\pi^0$ which has the opposite CP eigenvalue. The vertex resolution necessary for the determination of the CP asymmetry was evaluated for 170 to 200 $\mu$m thick silicon strip detectors with double-sided readout. For beam pipe radii below 25 mm, the vertex resolution is found to be sufficient. Thinner detectors with new noise-reducing readout schemes [44] should further improve the vertex resolution.

<table>
<thead>
<tr>
<th>$\sigma(m_{K\pi})$ [MeV]</th>
<th>$\eta(D^o \to K^-\pi^+\pi^-)$</th>
<th>$\sigma(m_{K^3\pi})$ [MeV]</th>
<th>$\eta(D^o \to K^-\pi^+\pi^+\pi^-)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>symm.</td>
<td>8 vs. 3.5 GeV</td>
<td>12 vs. 2.3 GeV</td>
<td></td>
</tr>
<tr>
<td>6.1</td>
<td>0.87</td>
<td>0.85</td>
<td></td>
</tr>
<tr>
<td>6.3</td>
<td>0.85</td>
<td>0.74</td>
<td></td>
</tr>
<tr>
<td>3.9</td>
<td>0.73</td>
<td>0.68</td>
<td></td>
</tr>
<tr>
<td>4.0</td>
<td>0.68</td>
<td>0.51</td>
<td></td>
</tr>
</tbody>
</table>
Figure 3.2: The simulated response of CsI crystals in the Crystal Barrel Detector for 100 MeV photons in the $e^+e^-$ rest frame for; a) a symmetric collider and b) an 8 vs. 3.5 GeV asymmetric collider.

**Energy resolution of monochromatic photons:** In order to study decays such as $B^+ \to B\gamma$ and $\Upsilon(3S) \to \chi_{bJ}(2P)\gamma \to \Upsilon_J(1D)\gamma\gamma \to \chi_{bJ}(1P)\gamma\gamma\gamma \to \Upsilon(1S)\gamma\gamma\gamma$, an excellent photon energy resolution is required. In an asymmetric machine, these photons are no longer monochromatic. Both angular and energy resolution of the photon detector determine how well the photon energy can be reconstructed in the $e^+e^-$ rest frame. The simulation program of the Crystal Barrel Detector [45] was used to study this question for photons of 100 MeV in the $e^+e^-$ rest frame. Fig. 3.2 shows the response of the CsI crystals to 100 MeV photons which are isotropically emitted in the $e^+e^-$ rest frame. In fig. 3.2a, the detector is placed at a symmetric machine. The r.m.s. width of the Gaussian part of the peak is $\sigma = 3.7$ MeV. The peak contains 80% of all generated photons within $\pm 3\sigma$. Fig. 3.2b shows the reconstructed photon energy in the $e^+e^-$ rest frame for an asymmetric collider with $\beta\gamma = 0.42$. The efficiency is reduced to 77% and the r.m.s. of the Gaussian is 3.5 MeV. The same negligible changes are expected with the CsI calorimeter of the Universal Detector.

### 3.3 Detector Improvements

Although the Universal Detector described in the PSI proposal appears to satisfy most of the requirements for running at the proposed machine, certain adjustments may be considered. For asymmetric energy operation, there may be a slight advantage to give up on detector symmetry to improve the acceptance and the detector performance in the boost direction.

Bunch crossing frequencies of up to 100 MHz require a reconsideration of the trigger concept. A first look into this problem shows the following: The general trigger concept of ref. 2, which includes a deadtimeless first level decision by using
data and trigger pipelines, does not have to be changed. It is possible to run the trigger pipeline at a lower frequency, e.g. 10 MHz, than the crossing frequency. In this case the trigger decision integrates over several crossings. Because of the low event rate, this does not lead to a loss of information.

The first level trigger must have a time resolution of the order of 50 ns for e.g. gating the CsI read-out. This should be achievable with the fast components of the detector, such as PTC and RICH.

The data acquisition system for a $B$-meson factory with a peak luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$ is a challenge. On the $\Upsilon(4S)$, the rate of multi-hadronic events from one-photon reactions will be about 40 Hz. With a low-bias trigger, a multiple of this rate is expected from QED and two-photon reactions. Fast preprocessors must reduce this event rate to about 100 Hz. With an event length of 20 kbytes, this requires a recording capability of 2 Mbytes/s. Such a data flow looks manageable.

Because of the high currents in the machine, it is necessary to improve the radiation hardness of the detector components. In particular, the CsI crystals in the end caps may suffer radiation damage [46]. The resistivity against radiation is known to depend on the doping of the crystals. Pure CsI is more radiation resistant than Tl-doped crystals, but has also a much lower light output. To achieve the same signal-to-noise ratio, lower noise photodiodes have to be developed. All subdetectors will probably use highly integrated front-end electronics. We expect that current developments on radiation-hard electronics can be exploited.

### 3.4 The Detector in a Tilted Solenoid Field

High luminosity requires a large number of bunches and therefore the bunch distance is short. This demands a fast beam separation at the interaction region. For asymmetric beams, this can be accomplished by a magnetic dipole field. However, from the experimental point of view a detector dipole field is not attractive.

A solenoid field of 1.5 Tesla tilted with respect to the beam in the horizontal plane by about 5°, yields a field component which is sufficient to separate the beams vertically. A possible machine optics around the interaction region for this scheme is described in section 5.2.11. Here, we want to discuss the influence of this scheme on the detector design. We have considered two possible detector arrangements: (a) tilt of the whole detector and (b) tilt of the coil and the iron yoke only.

(a) If the whole detector is tilted (see fig. 3.3), the inner drift chambers have to be cut out to leave room for the beam pipe (PTC) or the mini-$\beta$ quadrupoles (MTC). The vertex detector should remain aligned along the beam pipe. The inner tubes of the drift chambers may get an oval shape cross section. The disadvantage is that one loses about 1.5% acceptance in the boost direction. On the other hand, the advantage of this setup is that the B field is parallel to the drift chamber wires.

(b) Tilting only the detector components outside the calorimeter (i.e. the coil, the iron yoke and the muon chambers) avoids acceptance losses. Also, the chamber design does not have to be matched from the beginning to the tilt
angle, which could be changed later if necessary. In the considered detector
design, essentially no increase of the outer detector dimensions is necessary for
tilts below 10°. The disadvantage of this solution is clearly that the B field is
not parallel to the drift chamber wires, in particular the Lorentz angle changes
with the azimuth. Although such a situation is in principle not prohibitive,
the chamber calibration will certainly become more tedious.

We conclude that a tilted solenoid appears compatible with the requirements on
the detector. Which of the two solutions is preferable has to be found out in a more
detailed study.
4 Pilot Reactions and Comparisons with LEP

In this chapter, we first present results from simulation studies on three selected topics, CP violation in $B \rightarrow \psi K^0_s$, $B_s \rightarrow \pi^0 \pi^0$, oscillations, and $B \rightarrow \rho \ell \nu$ and $\omega \ell \nu$. We then compare the potential of LEP with that of the $B$-meson factory for a few important $B$ physics program points.

![Figure 4.1: Vertex detector layout](image)

Event generation and detector simulation are done with the same program as used for the PSI proposal [2, 47]. The basic characteristics of the detector are summarized in section 3.1. We assume a 500 $\mu$m thick beryllium beam pipe with a radius of 25 mm. The set-up of the vertex detector system is shown in fig. 4.1. The vertex detector system consists of two layers of silicon with double-sided strips with a read-out pitch of 50 $\mu$m at radii of 28 mm and 60 mm, and with thicknesses $t$ of 170 $\mu$m and 200 $\mu$m, respectively.

![Figure 4.2: The $z$ resolution of the vertex detector used in the simulation study as a function of the polar angle of the track. The parameter $t$ is the thickness of the silicon layer and $d$ is the read-out pitch.](image)

The spatial resolution of the vertex detector in the $\phi$ direction is 5 $\mu$m. The spatial resolution along the $z$ direction, $\sigma_z$, is expected to be 5 $\mu$m for a track perpendicular to the Si layer and to deteriorate for tracks with smaller crossing
angles. Fig 4.2 shows $\sigma_z$ as a function of polar angle of the track used in our simulation.

It should be noted that this polar angle dependence of $\sigma_z$ leads to a deterioration of the vertex resolution along the $z$ direction for a very high boost, since more tracks go into the forward direction where $\sigma_z$ is worse.

The rest of the detector performance such as the momentum resolution for the charged tracks is identical to that described in ref. 2.

### 4.1 CP Violation in $B \to J/\psi K_s^0$

In the simulation of this decay, the $\Upsilon(4S)$ is produced by colliding $e^-$ and $e^+$ beams with 8 and 3.5 GeV respectively. The $\beta\gamma$ of the $\Upsilon(4S)$ for this configuration is 0.42.

The $B$ decay vertex for $B \to J/\psi K_s^0$ is reconstructed with two leptons from the $J/\psi \to \ell^+\ell^-$ decay. Our study shows that 62% of the $B \to J/\psi K_s^0$ decay can be reconstructed with a decay vertex resolution in the boost direction of $\sigma_{z_{\text{vertex}}} \sim 25 \mu m$. The energy resolution of the detector is sufficient to distinguish $B \to J/\psi K_s^0$ or $B \to J/\psi K_s^0\pi^0$ from $B \to J/\psi K_s^0$ decays [43].

The semileptonic decay provides a clean flavour tag for the other $B$-meson. A positively charged lepton comes from the $B^0$ decay, while a negatively charged lepton comes from the $B^0$ decay. In order to avoid confusion from a lepton of the semileptonic $D$-meson decay simulating a wrong $b$-flavour tag, we use only leptons with large momenta, $p > 1.3$ GeV. The tagging efficiency with this method is $\sim 10\%$.

A drastic increase in the tagging efficiency can be obtained by also using charged kaons [48]. In order to reduce wrong tags coming from the $B \to D\bar{D}$ decays, only events with one kaon are accepted. The combined information from the RICH counter and the dE/dx measurement from the drift chamber is sufficient for this purpose. Our simulation study shows that a combination of the two methods leads to a flavour tagging efficiency of $\sim 44\%$. About 7% of these are wrong flavour tags.

The reconstruction of the decay vertex of the tagging $B$ is done in the following way: One vertex is reconstructed using all charged tracks with exception of those from the $J/\psi K_s^0$ decays. Since the majority of the $B$-mesons decays into a $D$-meson, the reconstructed vertex mostly lays between the $B$ and $D$ vertices. In order to exclude events where the $B$ and $D$ vertices are far apart, a $\chi^2$ cut is applied to the vertex fit. After the cut, $\sim 55\%$ of the events remain with a resolution for the $z$ component of the reconstructed vertex of $\sim 36 \mu m$. Since there are more $D$-mesons going into the boosted direction, there is an average systematic shift of $\sim 9 \mu m$ which has to be corrected.

When an event does not pass this $\chi^2$ cut, we check whether the event contains a lepton with a momentum larger than 1.3 GeV. If there is such a lepton, a vertex is reconstructed using that lepton and a line which is parallel to the $z$ axis and goes through the reconstructed $J/\psi$ vertex. This gives an additional 18% contribution to the vertex reconstruction efficiency. The resolution for the $z$ component of the reconstructed vertices with this technique is $\sim 58 \mu m$. Combining the two methods, an efficiency of 73% for reconstructing the vertex of the tagging $B$-meson can be
Figure 4.3: Difference between the generated and reconstructed decay time difference between the two $B$-mesons. The dashed curve is obtained by fitting a Gauss function.

achieved. The total efficiency on the tagging side is therefore $\eta_{\text{tag}} = 32\%$.

From the difference between the $z$ components of the two $B$-meson decay vertices and the boost factor $\beta \gamma$, we obtain the decay time difference

$$\Delta \tau \equiv (t_1 - t_2) = \frac{z(J/\psi) - z(\text{tag})}{\beta \gamma c}.$$  

Fig. 4.3 shows the difference between the generated and reconstructed decay time difference. The dashed curve is obtained by fitting a Gauss function to the distribution with $\sigma_{\Delta \tau} = 0.48 \text{ ps} \approx 0.4 \tau_B$.

As described in section 2.1, the CP asymmetry $A_\omega$ is obtained by fitting the distributions of the decay time differences for $J/\psi K_s^* + T$ events and $J/\psi K_s^* + \bar{T}$ events. The error obtained on $A_\omega$ can be expressed as [30]

$$\sigma^2_{A_\omega} = \frac{1}{N \cdot I_o},$$

where $N$ is the number of events used in the fit and the information $I_o$ is defined as

$$I_o = \int_{-\infty}^{+\infty} \frac{(\partial g(\Delta \tau)/\partial A_\omega)^2}{g(\Delta \tau)} \cdot d\Delta \tau.$$  

The function $g(\Delta \tau)$ is the probability density function for $\Delta \tau$ folded by a Gauss function describing the finite resolution of the $\Delta \tau$ measurement,

$$g(\Delta \tau) = \frac{1}{2\sqrt{2\pi} \sigma_{\Delta \tau}} \int_{-\infty}^{+\infty} \exp \left[-\frac{(\Delta \tau - \Delta \tau')^2}{2\sigma_{\Delta \tau}^2}\right] \cdot [1 + A_\omega \sin(\Delta m \cdot \Delta \tau')] \cdot d\Delta \tau'.$$
Table 4.1: Effect of the beam energy asymmetry on the necessary number of events for the observation of CP violation in $B \to J/\psi K_s^0$. The parameters $\eta_{\text{rec}}$ and $\eta_{\text{tag}}$ are the efficiencies to reconstruct the $J/\psi K_s^0$ and the tagging $B_s$, $\sigma_{\Delta \tau}$ is the resolution of the decay time difference and $I_o$ is the information as explained in the text. The necessary number of events is normalized to the $8$ GeV case.

<table>
<thead>
<tr>
<th>$E_{\text{high}}$ [GeV]</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_{\text{rec}} \cdot \eta_{\text{tag}}$</td>
<td>0.23</td>
<td>0.21</td>
<td>0.20</td>
<td>0.18</td>
<td>0.16</td>
</tr>
<tr>
<td>$\sigma_{\Delta \tau}$ [ps]</td>
<td>1.47</td>
<td>0.63</td>
<td>0.48</td>
<td>0.36</td>
<td>0.29</td>
</tr>
<tr>
<td>$I_o$</td>
<td>0.14</td>
<td>0.28</td>
<td>0.30</td>
<td>0.32</td>
<td>0.33</td>
</tr>
<tr>
<td>$N_{\text{events}} / N_{\text{events}} (8 \text{ GeV})$</td>
<td>1.86</td>
<td>1.02</td>
<td>1.00</td>
<td>1.04</td>
<td>1.14</td>
</tr>
</tbody>
</table>

We obtain $I_o = 0.30$ for $A_o = 0.3$. With these results, the necessary number of $\Upsilon(4S)$ mesons for the observation of CP violation can be determined from eq. 2.3 in section 2.1.

Table 4.1 summarizes the results for various beam energy asymmetries with our detector. The event reconstruction efficiency drops with increasing asymmetry, primarily due to the loss of the geometrical acceptance. Since there is no large change in the vertex resolution, the resolution of the decay time difference becomes better for larger boosts. However, $I_o$ does not further increase, once the time difference resolution becomes better than $\sim 0.5$ ps. We conclude that $8$ vs. $3.5$ GeV is a good choice for the study of CP violation in the $B \to J/\psi K_s^0$ decay with our detector.

To summarize, CP violation in the decay $B \to J/\psi K_s^0$ can be observed with a three standard deviation effect after a few years of running with the reference machine if the CP asymmetry parameter $A_o = 0.3$. If $A_o$ is $0.12$, which is the smallest value in the allowed range within the standard model, the "ultimate machine" is needed.

### 4.2 Measurements of $B_s \overline{B_s}$ Oscillations

In this simulation, the masses for $\Upsilon(5S)$, $B_s^*$ and $B_s$ are assumed to be $10.865$, $5.420$, and $5.370$ GeV/c$^2$ respectively. The beam energy configuration is $8.4$ vs. $3.5$ GeV. The considered decay chain is shown in fig. 4.4. In the discussion, we imply the charge conjugate states as well.

Only events containing two leptons with momenta larger than $1.3$ GeV are considered. After recalculting the momenta of $K^+$ and $K^-$ using the $\phi$ mass constraint, the $D_s^-$ decay vertex is reconstructed. The $D_s$ momentum is recalculated with the $D_s$ mass constraint. Then, the $B_s$ decay vertex is determined by combining the reconstructed $D_s^-$ track and the $\ell^+$. The resolution for the reconstructed $B_s$ decay vertex is $\sim 30$ µm.

The vertex for the $\overline{B_s}$ is obtained from the remaining $\ell^-$ and the line which is parallel to the $z$ axis and goes through the reconstructed $B_s$ vertex. The resolution for the reconstructed $\overline{B_s}$ decay vertex, and consequently the difference between the two $B_s$-meson decay times, can no longer be expressed with a single Gauss function.
\[ \gamma(5S) \longrightarrow B_s^* \overline{B_s}^* \]
\[ \longrightarrow B_s^* + \gamma \]
\[ \longrightarrow B_s + \gamma \]
\[ \longrightarrow l^- + X \]
\[ \longrightarrow D_s^{*-} + l^+ + \nu \]
\[ \longrightarrow D_s^- + \gamma \]
\[ \longrightarrow \phi + \pi^- \]
\[ \longrightarrow K^+ + K^- \]

Figure 4.4: The decay chain considered for the study of $B_s \overline{B_s}$ oscillations.

A sum of two Gauss functions with different widths and heights is used in order to describe the resolution. Fig. 4.5 shows the difference between the generated and reconstructed decay time difference between two $B_s$-mesons, and the broken line indicates the fit result. The width of the narrower Gauss function which mainly determines the $\tau_s$ resolution is 0.52 ps. The efficiency of this method is 30%.

![Figure 4.5: Difference between the generated and reconstructed decay time difference between the two $B_s$-mesons. The dashed curve is obtained by fitting two Gauss functions.](image)

Oscillations lead to $\ell^+\ell^+$ events. Therefore, we can no longer decide which lepton must be combined with the $D_s^-$. For such a situation, two squared missing mass values are calculated by combining the $D_s^-$ with each of the leptons. The squared missing mass obtained by combining the $D_s^-$ with the correct $\ell^+$ is expected to be close to zero. Therefore, we always take the combination which gives the smaller absolute value of the squared missing mass. The simulation study shows that this choice is the correct one for 85% of all cases.
Figure 4.6: Fitted $x_s$ as a function of generated $x_s$. The error bars indicate one standard deviation.

The fitted curve in fig. 4.5 is used to study how well we can determine $x_s$ by simultaneously fitting the $\Delta \tau$ distribution for $\ell^+\ell^-D_s^-$ and $\ell^+\ell^-D_s^+$ events. Assuming that $C = -1$ pairs are dominant, fig. 4.6 shows the fit results as a function of $x_s$ for an integrated luminosity of $10^4$/pb, i.e. from 2000 reconstructed events. We assumed that $\sim 8\%$ of the $D_s$-mesons can be fully reconstructed from charged particles only. It shows that in one year with the reference machine, $x_s$ can be determined for values up to $\sim 6.5$.

If we increase the beam energy asymmetry to 10 vs. 3 GeV ($\beta\gamma = 0.65$), the resolution of the decay time difference becomes better. The fit of the distribution for the difference between the generated and reconstructed $\Delta \tau$ to two Gauss functions gives a $\sigma$ of 0.35 ps for the narrow Gauss function. In this case, $x_s$ can be measured up to a value of $\sim 8.5$ after one year of running with a machine of luminosity $10^{33}$ cm$^{-2}$s$^{-1}$.

### 4.3 $B \rightarrow \rho \ell \nu$ and $B \rightarrow \omega \ell \nu$

In current experiments, the large combinatorial background limits the observation of $B \rightarrow \rho \ell \nu$ and $\rightarrow \omega \ell \nu$ decays [49]. Various studies [8, 50] have shown that the vertex information obtained with an asymmetric collider efficiently reduces this background. Here, we demonstrate that the background can be reduced equally well with the help of the full-energy tagging method described below.

The $Y(4S)$ resonance decays always into two $B$ mesons, and the energy of the initial $B$-meson is well defined. When one $B$ is fully reconstructed, all the remaining particles in the event belong to the second $B$-meson. If all remaining charged and neutral particles are observed in the detector, their sums of energy, momentum and charge must be consistent with those of the remaining $B$-meson. In order to use this
Figure 4.7: Missing mass distribution for $B \rightarrow \omega \ell \nu$ including background from $2 \cdot 10^7 \Upsilon(4S)$ decays and $6.6 \cdot 10^7$ continuum events, assuming $B(B \rightarrow \omega \ell \nu) = 10^{-4}$.

constraint, almost perfect particle identification and a very good electromagnetic calorimeter are required.

After selecting events with a lepton momentum of $p > 1.3$ GeV in the center of mass system, candidates for the semileptonic decays $B \rightarrow \rho \ell \nu$ and $\omega \ell \nu$ are selected by calculating the missing mass [51]. At this stage, the $B$ momentum is set to zero, hence the distribution of the squared missing mass is very broad, $\sigma \approx 1$ GeV$^2$/c$^4$.

Table 4.2: Simulation results for $B^+ \rightarrow \rho^0$, $\omega \ell^+ \nu$ decays. $N_{\text{rec}}$ and $N_{\text{bg}}$ are the reconstructed number of signal events and the number of background events respectively. The parameter $\sigma_B/B$ is the relative statistical error on the obtained decay fraction.

<table>
<thead>
<tr>
<th>decay fraction</th>
<th>$4 \cdot 10^{-4}$</th>
<th>$2 \cdot 10^{-4}$</th>
<th>$1 \cdot 10^{-4}$</th>
<th>$4 \cdot 10^{-5}$</th>
<th>$2 \cdot 10^{-5}$</th>
<th>$N_{\text{bg}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho \ell \nu$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N_{\text{rec}}$</td>
<td>1008</td>
<td>504</td>
<td>252</td>
<td>101</td>
<td>50</td>
<td>192</td>
</tr>
<tr>
<td>$\sigma_B/B$</td>
<td>3.4%</td>
<td>5.2%</td>
<td>8.3%</td>
<td>17%</td>
<td>31%</td>
<td></td>
</tr>
<tr>
<td>$\omega \ell \nu$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N_{\text{rec}}$</td>
<td>713</td>
<td>359</td>
<td>180</td>
<td>74</td>
<td>37</td>
<td>59</td>
</tr>
<tr>
<td>$\sigma_B/B$</td>
<td>3.9%</td>
<td>5.7%</td>
<td>8.6%</td>
<td>16%</td>
<td>26%</td>
<td></td>
</tr>
</tbody>
</table>

For the candidate events, the total energy and charge of the remaining charged and neutral particles are calculated. Only those events with total energy and charge being compatible with a $B$-meson are selected and the total momentum vector is determined. The efficiency of this full-energy tagging method is about 10%. The $B$
momentum vector is used for a new squared missing mass determination which is then improved by a factor of ten.

In order to estimate the background, $2 \cdot 10^7 \ U(4S)$ and $6.6 \cdot 10^7$ continuum events are generated. Fig. 4.7 shows the squared missing mass distribution for $B \to \omega \ell\nu$ candidates obtained with the total-energy tagging method assuming a branching fraction of $10^{-4}$. Table 4.2 summarizes the results of this study for various assumptions on the decay fraction. Combining $\rho\ell\nu$ and $\omega\ell\nu$ gives a significance of six standard deviations and a relative error of 20% on the decay fraction for $B = 2 \cdot 10^{-5}$.

In the absence of theoretical uncertainties, this would allow us to determine $|V_{ub}|$ with an error of 10% for $|V_{ub}|$ as small as 0.001. With a value around 0.005 [18] which is presently preferred, a statistical error around 2% on $|V_{ub}|$ is obtained. Theoretical uncertainties are now at the $\pm 40\%$ level [52]. Studies on angular and $q^2$ distributions with hundreds of $B \to \rho$, $\omega\ell\nu$ events will reduce the theoretical uncertainties.

The results given above are obtained for a symmetric $B$-meson factory. The changes which occur for running with various asymmetric beam energies are studied for the decay $B^- \to \rho^0 l^-\bar{\nu}$ and summarized in Table 4.3. The efficiency is reduced by 30% for a beam energy asymmetry of 8 vs. 3.5 GeV with roughly the same background level. Therefore, the effect of a moderate asymmetry on the reconstruction of the semileptonic decay $B^- \to \rho^0 l^-\bar{\nu}$ is quite negligible. The background level can further be reduced by using additional information from the $B$ vertex. This might also allow to relax some cuts used in the energy symmetric case and to increase the efficiency without increasing the background.

Table 4.3: The effect of different beam energy asymmetries on the reconstruction of $B^- \to \rho^0 l^-\bar{\nu}$.

<table>
<thead>
<tr>
<th>asymmetry</th>
<th>tagging efficiency [%]</th>
<th>missing mass resolution [GeV$^2$/c$^4$]</th>
<th>total efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.29 x 5.29</td>
<td>13.5%</td>
<td>0.110</td>
<td>7.9</td>
</tr>
<tr>
<td>7 x 4</td>
<td>11.9%</td>
<td>0.113</td>
<td>6.7</td>
</tr>
<tr>
<td>8 x 3.5</td>
<td>10.1%</td>
<td>0.123</td>
<td>5.3</td>
</tr>
</tbody>
</table>

### 4.4 Comparison with LEP

The $Z^0$ decays into $b\bar{b}$, $c\bar{c}$ and $\tau^+\tau^-$ pairs with branching ratios of 15%, 12% and 3%, respectively. LEP is therefore a place to study beauty, charm and $\tau$ decays. With the design luminosity of $1.5 \cdot 10^{31}$ cm$^{-2}$s$^{-1}$, the yearly rates are given in Table 4.4 (assuming as everywhere in this document $10^7$s/year). It has been proposed to upgrade LEP with a so-called pretzel scheme [53] which allows to store more bunches than at present, leading to a luminosity ten times higher than the original design luminosity. Besides LEP-200 and polarization on the $Z^0$, this proposal offers a third
possibility of future LEP operation. The expected rates for this upgraded LEP are also shown in table 4.4 together with the “reference machine” and the “ultimate” $B$-meson factory. It shows that only the upgraded LEP will have competitive rates for $b$, $c$, and $\tau$-decay studies. We therefore consider only the upgraded LEP in the following.

Table 4.4: Yearly rates for LEP, upgraded LEP, stage-I and stage-II $B$-meson factory in the ISR tunnel.

<table>
<thead>
<tr>
<th></th>
<th>$\mathcal{L} , [\text{cm}^{-2}\text{s}^{-1}]$</th>
<th>$\dot{N}_{Z^0} , [\text{y}^{-1}]$</th>
<th>$\dot{N}_{\bar{b}b} , [\text{y}^{-1}]$</th>
<th>$\dot{N}_{\bar{c}c} , [\text{y}^{-1}]$</th>
<th>$\dot{N}_{\tau^+\tau^-} , [\text{y}^{-1}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEP</td>
<td>$1.5 \cdot 10^{31}$</td>
<td>$4 \cdot 10^5$</td>
<td>$6 \cdot 10^5$</td>
<td>$5 \cdot 10^5$</td>
<td>$10^5$</td>
</tr>
<tr>
<td>LEP_upgr.</td>
<td>$1.5 \cdot 10^{32}$</td>
<td>$4 \cdot 10^7$</td>
<td>$6 \cdot 10^6$</td>
<td>$5 \cdot 10^6$</td>
<td>$10^6$</td>
</tr>
<tr>
<td>BFI-I</td>
<td>$10^{33}$</td>
<td>-</td>
<td>$10^7$</td>
<td>$10^7$</td>
<td>$8 \cdot 10^6$</td>
</tr>
<tr>
<td>BFI-II</td>
<td>$10^{34}$</td>
<td>-</td>
<td>$10^8$</td>
<td>$10^8$</td>
<td>$8 \cdot 10^7$</td>
</tr>
</tbody>
</table>

The $B$-meson factory operating at the $\Upsilon(4S)$ resonance produces $B^+B^-$, $B^0\bar{B}^0$, $c\bar{c}$ and $\tau^+\tau^-$ pairs simultaneously. For studies of $B_s$ mesons, $bqq$ and excited $b\bar{q}$ states, one has to operate the storage ring at higher center of mass energies. LEP working at the $Z^0$ energy produces all these states simultaneously, which is an advantage for the study of $B_s$ and excited $b\bar{q}$-mesons and $bqq$-baryons.

For the reconstruction of inclusive and exclusive final states, the mass and decay time resolutions are important. This is true especially for the determination of $m(\nu_{\tau})$ and rare $\tau$ and $B$ decays. On the $\Upsilon(4S)$, $B^+B^-$ and $B^0\bar{B}^0$ pairs are produced without any extra particles. This allows the very efficient use of the energy constraint in the $B$-meson reconstruction resulting in an excellent $B$ mass resolution of $\sim 3$ MeV with the PSI universal detector [2]. The resolution is mainly determined by the beam energy spread. A further advantage on the $\Upsilon(4S)$ is that the charge of the second $B$ can be obtained if one $B$ is fully reconstructed. The reconstruction of inclusively produced $D$-mesons has to be done without the help of the energy constraint. The mass resolutions for $D^0 \rightarrow K^-\pi^+$ and $\rightarrow K^-\pi^+\pi^-\pi^+$ with the PSI type detector are $\sim 6$ MeV and $\sim 4$ MeV, respectively (see section 3.2).

On the $Z^0$, the $b$-quark fragmentation properties allow only a rough estimate of the $B$-meson energy and the charge of a $B$-meson cannot be determined from the charge of the other reconstructed $b$-hadron. The simulation result on $D^0$ mass resolutions for $D^0 \rightarrow K^-\pi^+$ and $\rightarrow K^-\pi^+\pi^-\pi^+$ in the DELPHI detector are $\sim 25$ and $\sim 20$ MeV, respectively [54]. The same study shows that the $B$-meson mass resolution of all charged final states is $50 \sim 70$ MeV.

$B$-mesons from the $Z^0$ have $\beta\gamma$ around 7 and those from moving $\Upsilon(4S)$ mesons in an asymmetric $B$-meson factory with 8 vs. 3.5 GeV have $\beta\gamma = 0.42$. For any detector, the decay vertex resolution stays approximately constant with the boost of the decaying particle from $\beta\gamma = 0$ to $\beta\gamma \approx 1$. Therefore, the improvement on the decay time resolution is proportional to $\beta\gamma$. However with higher boosts, the decay vertex resolution becomes worse since the opening angles between the decay
products become smaller. Hence, the decay time resolution no longer improves for \( \beta\gamma \gg 1 \).

For the determination of the decay time, the momentum of the decaying particle must be measured. As discussed previously, \( B \)-mesons from the \( \Upsilon(4S) \) have known momentum even without being fully reconstructed. On the \( Z^0 \), the \( B \)-meson momentum can be estimated with a resolution of 15% or better [55, 56] for partially reconstructed \( B \)-mesons decaying semileptonically. This allows to utilize partially reconstructed \( B \)-mesons in \( Z^0 \) decays.

As shown in sections 4.1 and 4.2, the decay time difference between one fully and one partially reconstructed \( B \)-meson from the boosted \( \Upsilon(4S) \) with \( \beta\gamma = 0.42 \) can be determined with a resolution of \( \sim 0.5 \text{ ps} \approx 0.4 \tau_B \). At LEP, the decay time of a single \( B \)-meson can be determined with a precision of \( \sim 0.2 \tau_B \) using the reconstructed production and decay vertices. This may be reduced by a factor of two in the future.

In the mean life measurements of neutral and charged \( B \)-mesons as discussed in section 2.4, the precision of the life time obtained with a decay time resolution of 0.1 \( \tau_B \) is not significantly different from that obtained with 0.4 \( \tau_B \) (see eq. 2.4). Therefore, the number of events is the essential factor and stage-I \( B \)-meson factory and upgraded LEP are comparable. An analysis presented in ref. 56 concludes that by reconstructing \( B \)-mesons from their semileptonic decay modes, the mean life can be measured with a statistical error of \( \sim 3\% \) with even \( 10^7 \) \( Z^0 \) which may be achieved by 1992. To measure the mean life difference between neutral and charged \( B \)-mesons, a careful analysis is needed in order to ensure that no slow charged particles fake the charge of the reconstructed \( B \)-meson. The energy constraint on the \( \Upsilon(4S) \) guarantees the absence of this "feed through" in the fully reconstructed \( B \)-mesons. LEP has the advantage to be able to measure the mean life of \( \Lambda_b \) which is not produced on the \( \Upsilon(4S) \).

A rate estimate for the observation of CP violation in the \( B \to J/\psi K^\pm \) decay with a \( Z^0 \) machine is first discussed in ref. 57. They conclude that for unpolarized \( Z^0 \) a luminosity similar to an asymmetric \( B \)-meson factory is needed in order to achieve the same sensitivity. Therefore, the first stage machine is already superior to the upgraded LEP. It should also be noted that the final state \( J/\psi K^\pm \pi^\mp \) must be rejected since it carries the opposite CP eigenvalue. For an asymmetric \( B \)-meson factory, the excellent \( B \) mass resolution is sufficient to reject an extra \( \pi^0 \) in the final state. On the \( Z^0 \), some additional cuts, e.g. transverse momentum balance, may become necessary. The observation of CP violation with the upgraded LEP may only be possible if the parameter \( A_0 \) is maximal within the presently allowed range determined by the standard model.

\( B_s \)-meson production is incoherent at the \( Z^0 \) and its decay time evolution follows

\[
P(B_s \to \bar{B_s}; t) \propto e^{-\Gamma t} \left[ 1 - \cos(x_s \cdot \Gamma \cdot t) \right]
\]

Simulation studies for \( B_s\bar{B_s} \) oscillations at LEP are done using partially reconstructed \( B_s \) decays, e.g. \( B_s \to \ell D_s X \) [55, 58]. With this method, a decay time resolution of 10% can be achieved provided a beam pipe with a small radius of \( \sim 5 \) cm is installed in the interaction region together with a high resolution vertex detector with double-sided read-out. Ref. 56 concludes that with \( 10^7 \) \( Z^0 \), 120 flavour tagged \( B_s \)-mesons with decay vertices will be reconstructed. The flavour tag is done
by the sign of the lepton in the jet which does not contain the reconstructed $B_s$.
This number of reconstructed $B_s$-mesons with the flavour tag may be increased by a
factor of two or more by including more decay channels in the $B_s$ reconstruction and
using improved tagging techniques. The oscillation parameter $x_s$ may then be de-
termined up to values of $\sim 15$ [58] after one year of running with the upgraded LEP.
This estimate, however, does not take the wrong tag contributions into account.

In conclusion, the first stage of the $B$-meson factory proposed here and the high
luminosity LEP upgraded with a pretzel scheme are roughly equivalent as far as
rates are concerned. The kinematic conditions under which $B$-meson decays can be
studied are very different at the two machines and thus they should be considered as
complementary. For the CP violation study in the $B \rightarrow J/\psi K_s$ decay, already the
first stage $B$-meson factory has an advantage. However, the exploration of the full
parameter space presently allowed by the standard model requires the "ultimate"
asymmetric $B$-meson factory with a luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$. 
5 Machine Design

5.1 Introduction

This chapter presents the results of a study made by a CERN-PSI collaboration of the feasibility of constructing and installing a B-meson factory in the ISR tunnel. The terms of reference of this feasibility study (Appendix I) also specified that after proper project definition and preliminary cost estimate a detailed design study could be launched at a later date.

The approach adopted has been to study a machine which can start with a luminosity of $10^{33}$ cm$^{-2}$s$^{-1}$, but choosing major components such that it would have the potential to go to $10^{34}$ cm$^{-2}$s$^{-1}$. The cost estimate has been made on this basis. The procedure has been as follows:

1. A tentative parameter list for a collider providing a luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$ is worked out based on present day knowledge of such machines. An asymmetric machine is chosen. It is called "The stage II Machine" or "The Ultimate Machine" (see Appendix II, table 6.1).

2. The possibility of conversion to a symmetric machine is introduced in the design because of the lack of experimental data about the physics of the beam-beam interaction in asymmetric machines. This requires the study of a parameter list of a high luminosity symmetric machine (see Appendix II, table 6.1).

3. A parameter list for a $10^{33}$ cm$^{-2}$s$^{-1}$ asymmetric machine is produced, based on technology which exists, or can easily be developed. The essential features allowing an evolution towards the high luminosity asymmetric machine or conversion to the symmetric machine are introduced in the design. This machine is called in the text "The Stage I Machine" or "The Reference Machine" (see table 5.1).

A preliminary design of the reference machine has been made in order to estimate the cost. This raised several problems which are discussed in the text, and required some choices between the various options, even though some issues are still open: for example we have selected head-on collisions rather than small angle crossing and flat beams rather than round beams.

In the course of this study no major difficulties were encountered. On the contrary, it appears possible, thanks to the flexibility of the CERN injector complex, to use the LEP injector with practically no interference with the CERN programme.

General Layout

The ISR was installed in a circular tunnel of 15 m width and 300 m diameter as shown in fig. 5.1. Two transfer tunnels TT1 and TT2 provided the link to the PS used as proton injector. The tunnel TT6 was added later to allow for injecting antiprotons into the ISR from the PS.
Figure 5.1: Layout of the ISR and transfer tunnels.
Figure 5.2: Layout of the B-factory in the ISR tunnel and the old interaction regions labelled 1-8.

It is proposed to use the tunnel TT2 to inject into the B-factory 3.5 GeV positrons accelerated in the PS. The injection of 8 GeV electrons will require successive acceleration to 3.5 GeV in the PS and 8 GeV in the SPS using the LEP electron channels. The injection of the electrons will then be done from the SPS using as a transfer line TT10, TT2, the PS ring, then TT6 and TT1. No new civil engineering work is required.

The ISR beams collided in 8 interaction areas numbered I1 to I8 (fig. 5.2). It is proposed to install two interaction areas for the beauty factory in I4 and I8. The RF straight sections would be placed in I2 and I6. Four short straight sections in I3, I7 and I1, I5 would be used for injection and for the installation of wigglers respectively. The new ring installed in the ISR tunnel is also shown in fig. 5.2. No modification of the ISR tunnel is required.
5.2 Storage Rings

The reference machine will work with a luminosity of $10^{33}$ cm$^{-2}$s$^{-1}$, and will be an asymmetric machine with head-on collision of flat beams. The reasons for these last choices are developed in section 5.4 (Variants). Lattice, magnets and vacuum chambers, which are the basic elements, must be compatible with an ultimate design for asymmetric and symmetric machines.

Using these specifications the parameter lists of these three machines have been worked out. The parameter list of the reference machine is given in table 5.1, the parameter lists of the two ultimate machines in Appendix II. In this section we describe the procedure used to obtain a parameter list and then analyse the consequence of our choice.

5.2.1 Parameters

It can be demonstrated that the optimum luminosity is obtained when the bunches of the two machines have the same dimensions $\sigma_H$, $\sigma_V$, $\sigma_s$ at the crossing point and the same bunch frequency $f_b$ [59, 60]. The five basic equations giving the definition of the luminosity and of the horizontal and vertical beam-beam tune shift in each ring must then be considered. The search for the optimum luminosity can be described using the following equations:

$$\mathcal{L} = \frac{1}{2} e \cdot r_e \left( \frac{1}{\beta_V^*} + \frac{1}{\beta_H^*} \right) \cdot \xi \cdot I_i \cdot \gamma_i, \ i = 1, 2$$ (5.2.1)

$$\mathcal{L} = \frac{\pi}{r_e^2} \gamma_1 \cdot \gamma_2 \xi^2 \left( \frac{1}{\beta_V^*} + \frac{1}{\beta_H^*} \right) \varepsilon_0 \cdot f_b,$$ (5.2.2)

where $e$ and $r_e$ are the charge and classical radius of the electron, $I_i$ the average current in ring $i$, $\varepsilon_0$ the equilibrium emittance in the absence of coupling, $\beta_V^*$ and $\beta_H^*$ the vertical and horizontal beta functions at the interaction point and $\gamma_i$ the relativistic factor $\gamma_i = E_i/m_e c^2$ of beam $i$. These equations are only valid if the four beam-beam tune shift parameters $\xi$ have been chosen equal (which minimizes the horizontal emittances), and if the same vertical beta functions are selected for the two beams (which minimizes the currents). Equation (5.2.2) is independent of the degree of the asymmetry, since $\gamma_1 \cdot \gamma_2$ is a constant for the operation of the machine at the $\Upsilon(4S)$ resonance.

Since flat beams are selected the quantity in brackets reduces to $1/\beta_V^*$ because $\beta_H^* \gg \beta_V^*$.

The Ultimate Machines

The minimum value of $\beta_V^*$ of the ultimate machines can be deduced from the lattice and low beta study. We have selected somewhat arbitrarily 1 cm for both the symmetric and asymmetric machines. A more precise number will result from the detailed study of a low beta insertion and from lattice optimization.

The design of the interaction areas restricts the maximum number of bunches in the ultimate machines to 320 for the asymmetric and 48 for the symmetric machine, thus defining the quantity $f_b$. 

Table 5.1: Parameter list of the reference machine with a luminosity of $10^{33}$ cm$^{-2}$s$^{-1}$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ring 1</th>
<th>Ring 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particles</td>
<td>$e^+$</td>
<td>$e^-$</td>
</tr>
<tr>
<td>Energy E</td>
<td>[GeV]</td>
<td>3.5</td>
</tr>
<tr>
<td>Circumference L</td>
<td>[m]</td>
<td>963.430</td>
</tr>
<tr>
<td>Bending radius $\rho$</td>
<td>[m]</td>
<td>65</td>
</tr>
<tr>
<td>Number of bunches $n_b$</td>
<td></td>
<td>80</td>
</tr>
<tr>
<td>Harmonic number</td>
<td></td>
<td>1600</td>
</tr>
<tr>
<td>RF frequency</td>
<td>[MHz]</td>
<td>497.9</td>
</tr>
<tr>
<td>Momentum compaction factor $\alpha$</td>
<td></td>
<td>0.0086</td>
</tr>
<tr>
<td>Horizontal tune $Q_H$</td>
<td></td>
<td>14.3</td>
</tr>
<tr>
<td>Vertical tune $Q_V$</td>
<td></td>
<td>16.4</td>
</tr>
<tr>
<td>Aspect ratio $\sigma_V/\sigma_H$</td>
<td></td>
<td>0.03</td>
</tr>
<tr>
<td>Vertical tune shift $\xi_V$</td>
<td></td>
<td>0.03</td>
</tr>
<tr>
<td>Horizontal tune shift $\xi_H$</td>
<td></td>
<td>0.03</td>
</tr>
<tr>
<td>Vertical beta at interaction point $\beta_V^*$</td>
<td>[m]</td>
<td>0.03</td>
</tr>
<tr>
<td>Horizontal beta at interaction point $\beta_H^*$</td>
<td>[m]</td>
<td>1.0</td>
</tr>
<tr>
<td>Vertical emittance $\epsilon_V = \sigma_V^2/\beta_V^*$</td>
<td>[$10^{-6}$m]</td>
<td>0.009</td>
</tr>
<tr>
<td>Horizontal emittance $\epsilon_H = \sigma_H^2/\beta_H^*$</td>
<td>[$10^{-6}$m]</td>
<td>0.30</td>
</tr>
<tr>
<td>Disruption parameter $D$</td>
<td></td>
<td>0.25</td>
</tr>
<tr>
<td>Bunch length $\sigma_s$</td>
<td>[m]</td>
<td>0.02</td>
</tr>
<tr>
<td>Energy spread $\sigma_e/E$</td>
<td>[$10^{-3}$]</td>
<td>0.52</td>
</tr>
<tr>
<td>Longitudinal damping time</td>
<td>[ms]</td>
<td>37</td>
</tr>
<tr>
<td>Total current $I$</td>
<td>[A]</td>
<td>1.28</td>
</tr>
<tr>
<td>Current per bunch $I_b$</td>
<td>[A]</td>
<td>0.016</td>
</tr>
<tr>
<td>Particles per bunch $10^{11}$</td>
<td></td>
<td>3.21</td>
</tr>
<tr>
<td>Radiation loss per turn $U_o$</td>
<td>[MeV]</td>
<td>0.3</td>
</tr>
<tr>
<td>Synchrotron radiation power</td>
<td>[MW]</td>
<td>0.39</td>
</tr>
<tr>
<td>Radiation loss per meter in bending magnets</td>
<td>[kW/m]</td>
<td>0.64</td>
</tr>
<tr>
<td>Peak RF voltage $V_{RF}$</td>
<td>[MV]</td>
<td>2.0</td>
</tr>
<tr>
<td>Total RF power $P_{RF}$</td>
<td>[MW]</td>
<td>0.70</td>
</tr>
<tr>
<td>Number of 1 MW klystrons</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Number of cavities</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Beam power loss $P_{beam}$</td>
<td>[MW]</td>
<td>0.6</td>
</tr>
<tr>
<td>Dissipated power per cavity $P_{diss}$</td>
<td>[kW]</td>
<td>34</td>
</tr>
<tr>
<td>Higher order mode losses per cavity $P_{HOM}$</td>
<td>[kW]</td>
<td>8.2</td>
</tr>
<tr>
<td>HOM power in vacuum chamber $P_{VAC}$</td>
<td>[kW]</td>
<td>140</td>
</tr>
<tr>
<td>Total input power per cavity</td>
<td>[kW]</td>
<td>175</td>
</tr>
<tr>
<td>Accelerating field</td>
<td>[MV/m]</td>
<td>1.6</td>
</tr>
</tbody>
</table>
For the ultimate machines we considered, that beam-beam tune shifts of $\xi=0.05$ could be achieved after a long period of machine improvement. This is a reasonable estimate for the symmetric machine, but assumes that no new phenomena limit this value in asymmetric machines (see section 5.4).

The vacuum chamber and magnet aperture is fixed using equation (5.2.2) which determines the emittance. Because the number of bunches is much smaller, it is the symmetric machine which determines the magnet gap with an emittance four times larger than the asymmetric machine (0.4 mm mrad against 0.1 mm mrad) even though the luminosity is reduced from $10^{34}$ to $6 \cdot 10^{33}$ cm$^{-2}$s$^{-1}$.

From equation (5.2.1) the maximum currents and the resulting synchrotron radiation power are deduced. This determines the choice of copper for the vacuum chamber material (see section 5.2.4)

The bunch length $\sigma_\ell$ must be determined before the RF and stability requirements can be studied. For that we use the disruption limitation (see section 5.2.3). For the ultimate machines we have fixed somewhat arbitrarily the disruption $\mathcal{D}_V=0.3$. This gives a bunch length which determines the RF system, and as a consequence the length of the straight sections required to install the RF cavities.

The Reference Machine
The straight section lengths, vacuum chamber aperture and therefore magnet gap of the reference machine have been specified by the ultimate machines.

To define the parameters of the reference machine a safer choice of beam-beam tune shift $\xi=0.03$ and disruption $\mathcal{D}_V=0.25$ is made. The number of bunches can be reduced to 80 since the vacuum chamber is large enough to accept an emittance of 0.3 mm mrad and this eases the design of the active dampers.

### 5.2.2 Lattice

The principles underlying the PSI lattice proposal have been used in this study [61]. Geometrical constraints on the lattice coming from the existing shape and dimensions of the ISR tunnel result in the following modifications to the original lattice proposed for the PSI project:

- The straight sections of the original racetrack design were too long to fit in the circular ISR tunnel. They have been shortened to 50 m, still compatible with the separation schemes for the symmetric option. Magnetic separation employing a tilt of the detector solenoid is used in the asymmetric cases, as described in section 5.2.11. The first four quadrupoles on either side of the interaction point are common to both beams.

- The dispersion suppressors using the missing magnet scheme were replaced with ones that use only quadrupoles, making it possible to increase the bending radius of the machine to 65 m.

- The asymmetry of 3.5 on 8 GeV requires more straight section space with zero dispersion for the installation of RF cavities.
- The existing injection lines from the PS require additional straight sections for injection into the ring at specific locations in the tunnel.

It was quickly realized that a study of the use of ISR magnets in a lattice requiring a high degree of flexibility was incompatible with the limited time available. The difficulty of installing ISR magnets one on top of the other or side by side, combined with severe requirements on the bending radius makes it difficult to adopt this scheme without a detailed mechanical and optical analysis.

The circumference of the ISR tunnel (about 1000 m) is probably close to the optimum for a beauty factory. A smaller circumference would require a smaller bending radius and therefore would exceed the limit of power deposition by synchrotron radiation on the vacuum chamber. A larger circumference would cost more; it would increase the number of particles required and hence the load on the injectors.

![Dispersion function](image1)

![Vertical beta function](image2)

![Horizontal beta function](image3)

Figure 5.3: Dispersion, vertical and horizontal beta functions of one quadrant.

A new lattice has been designed [62], providing 100 m of straight sections for the RF, as well as 100 m of space for injection and other special inserts. The optics of the new dispersion suppressors provides a wide variety of lattice functions, both with zero and with large dispersion for the emittance control with wigglers. A classical FODO cell structure is used in the arcs, the cell length being 12.7 m. The phase advance per cell is variable over a wide range of more than a factor of two, providing variation in emittance of at least a factor of ten and a factor of more than
Table 5.2. Parameters of the wigglers magnets and impact on the lattice.

<table>
<thead>
<tr>
<th></th>
<th>$\mathcal{L}=10^{33}$ cm$^{-2}$s$^{-1}$</th>
<th>$\mathcal{L}=10^{34}$ cm$^{-2}$s$^{-1}$</th>
<th>$\mathcal{L}=6 \cdot 10^{33}$ cm$^{-2}$s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Energy</td>
<td>High Energy</td>
<td>Low Energy</td>
</tr>
<tr>
<td>Natural emittance $\varepsilon_H = \sigma_H^2/\beta_H^*$</td>
<td>$[10^{-6}$ m]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase advance per cell</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Momentum compaction $\alpha$</td>
<td>50°</td>
<td>50°</td>
<td>50°</td>
</tr>
<tr>
<td>Radiation loss per turn $U_\circ$</td>
<td>$[\text{MeV}]$</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Energy spread $\sigma_{\varepsilon}/E$</td>
<td>$[10^{-3}]$</td>
<td>0.37</td>
<td>0.37</td>
</tr>
</tbody>
</table>

Wigglers on

<table>
<thead>
<tr>
<th></th>
<th>$\mathcal{L}=10^{33}$ cm$^{-2}$s$^{-1}$</th>
<th>$\mathcal{L}=10^{34}$ cm$^{-2}$s$^{-1}$</th>
<th>$\mathcal{L}=6 \cdot 10^{33}$ cm$^{-2}$s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Energy</td>
<td>High Energy</td>
<td>Low Energy</td>
</tr>
<tr>
<td>Emittance with wigglers $\varepsilon_H = \sigma_H^2/\beta_H^*$</td>
<td>$[10^{-6}$ m]</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>$\mathcal{H}$ in the Wiggler$^1$</td>
<td>$[\text{m}]$</td>
<td>0.7</td>
<td>0</td>
</tr>
<tr>
<td>Wiggler field strength</td>
<td>$[\text{T}]$</td>
<td>0.9</td>
<td>0</td>
</tr>
<tr>
<td>Wiggler length</td>
<td>$[\text{m}]$</td>
<td>4.2</td>
<td>0</td>
</tr>
<tr>
<td>Radiation loss per turn $U_\circ$</td>
<td>$[\text{MeV}]$</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Energy spread $\sigma_{\varepsilon}/E$</td>
<td>$[10^{-3}]$</td>
<td>0.52</td>
<td>0.37</td>
</tr>
</tbody>
</table>

Note 1: $\mathcal{H}$ is defined as $\mathcal{H} = \gamma D^2 + 2\alpha DD' + \beta D^2$

Note 2: The emittance in the symmetric machine is adjusted with the phase advance in the arcs
five in the momentum compaction factor. Results of tracking studies for an ideal machine showed a stability region greater than the vacuum chamber dimensions for a chromaticity correction scheme using only two sextupole families.

The lattice functions for the reference machine are shown in fig. 5.3 for a phase advance per cell of 50 degrees in the horizontal and 60 degrees in the vertical planes. The corresponding values of the lattice parameters are summarized in tables 5.1 and 5.2. The interaction region optics is described in section 5.2.11. The vertical dispersion function has not been matched and is not displayed. This matching together with the compensation of coupling should be the next iteration on the lattice studies.

The emittance in the low energy ring is adjusted using wiggler magnets. The magnets, totaling 4.2 m in length and providing maximum magnetic field of 1.5 T, affect not only the emittance but also the energy spread and the length of the bunch as well as the radiation loss per turn and the damping times. The present solution for wiggler insertion optics minimizes their impact on the RF system requirements. The main parameters affected by wigglers are summarized in table 5.2.

### 5.2.3 Disruption

In the course of this study it became evident that collisions in high luminosity circular colliders with large beam-beam tune shifts and \( \sigma_s \) to \( \beta^* \) ratios approaching or becoming larger than one were nearing conditions found in linear colliders. These conditions are met when the betatron wavelength through the “thick” beam lens becomes comparable to the bunch length or, stated alternatively, when the average transverse displacement of a particle due to the beam-beam interaction over the length of the opposing bunch becomes comparable to the transverse rms beam size. In a circular collider, because of repeated beam-beam collisions and the particle’s synchrotron motion, the single particle dynamics are affected differently than what one would expect if the bunches were very short compared to \( \beta^* \). In particular, the beam-beam interaction can now couple the longitudinal and transverse motions of the particle. The effect can be characterized by a parameter called the disruption \( D \) [63]. The disruption parameter of a storage ring is related to the tune shift parameter by

\[
D_V = 4 \pi \xi \sigma_s \frac{\beta^*}{\beta_V} .
\]  

(5.2.3)

An examination of experimental results drawn from various machines, and in particular from a machine study performed at Cornell [64], indicates that there is a limit on the maximum achievable disruption. This limit is in the range 0.25-0.3. To obtain high luminosity in circular colliders low values of \( \beta^* \) are required; consequently, if one chooses, as we do, to abide by the above stated experimentally observed limit, then very short bunch lengths must be used. This new limit increases significantly the load on the RF system.
5.2.4 Vacuum System

The machine aperture has been defined on the following criteria:

\[
\begin{align*}
\text{horizontal aperture} & \quad a_H = 10 \sqrt{\sigma_H^2 + \left(D_H \frac{\sigma_e}{E}\right)^2} + a_{c.o.} \\
\text{vertical aperture} & \quad a_V = 10 \cdot \sigma_V + a_{c.o.}
\end{align*}
\]

The closed orbit amplitude \(a_{c.o.}\) has been assumed to be \(\pm 3\) mm. The horizontal emittance without coupling \(\varepsilon_H = \varepsilon_o\) and the vertical emittance with full coupling \(\varepsilon_V = \varepsilon_o/2\) of the symmetric machine (Appendix II) define the beam size. The limiting values of emittance and \(\sigma_e/E\) can be found in the parameter tables, namely with some safety margin, \(\varepsilon_o = 0.4\) mm mrad and \(\sigma_e/E = 10^{-3}\). The lattice parameters – including some margin for tuning – are \(\beta_{\text{max}} = 35\) m and \(D_{H_{\text{max}}} = 3\) m and therefore one finds

\[
a_H = \pm 50\text{ mm}; \quad a_V = \pm 30\text{ mm.}
\]

The vacuum system design is based on LEP experience, with the exception of the vacuum chamber which follows HERA using copper. This is imposed by the large power deposited by the synchrotron radiation along the outer wall of the chamber. The characteristics of the synchrotron radiation are given in Table 5.3 for the various machines considered.

<table>
<thead>
<tr>
<th>Luminosity</th>
<th>(\text{[cm}^{-2}\text{s}^{-1}])</th>
<th>(10^{33})</th>
<th>(10^{34})</th>
<th>(6 \cdot 10^{33})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>(\text{[GeV]})</td>
<td>3.5</td>
<td>8.0</td>
<td>3.5</td>
</tr>
<tr>
<td>Current</td>
<td>(\text{[A]})</td>
<td>1.3</td>
<td>.56</td>
<td>2.6</td>
</tr>
<tr>
<td>Linear power density</td>
<td>(\text{[kW/m]})</td>
<td>0.64</td>
<td>7.6</td>
<td>1.3</td>
</tr>
<tr>
<td>Photon flux</td>
<td>(10^{18} \text{ m}^{-1}\text{s}^{-1})</td>
<td>8.9</td>
<td>8.7</td>
<td>17.8</td>
</tr>
<tr>
<td>Critical energy</td>
<td>(\text{[keV]})</td>
<td>1.5</td>
<td>18</td>
<td>1.5</td>
</tr>
</tbody>
</table>

The performance of the vacuum system is expressed (amongst other aspects) by the beam-gas lifetime which measures the rate of decay of the beam due to interactions with the residual gas. The desorption of molecules by the walls under the impact of synchrotron radiation increases the pressure. This pressure increase is measured by a coefficient: the specific pressure rise. This coefficient decreases after the walls have been cleaned by the photon bombardment. Table 5.4 gives these values after various levels of dose accumulation.

The vacuum chambers will be made of copper in order to cope with the very high power deposition by synchrotron radiation and by higher order modes. A thermal and stress analysis of the chamber under irradiation has been made [65] which demonstrates that the present design could evacuate up to 20 kW/m at least. Such a performance is excluded for an aluminium chamber. The two rings will have
Table 5.4: Dynamic pressure at the nominal current $I_{nom}$ after dose accumulation

<table>
<thead>
<tr>
<th>Luminosity Energy</th>
<th>10$^{33}$</th>
<th>10$^{34}$</th>
<th>6-10$^{33}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[cm$^{-2}$s$^{-1}$]</td>
<td>[GeV]</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>At startup</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>static pressure (approx.) [10$^{-10}$ Torr]</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>After a dose of 1 A·h</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific pressure rise [10$^{-9}$ Torr/A]</td>
<td>5.6</td>
<td>7.7</td>
<td>5.6</td>
</tr>
<tr>
<td>Dynamic pressure at $I_{nom}$ [10$^{-9}$ Torr]</td>
<td>7.3</td>
<td>4.3</td>
<td>14.5</td>
</tr>
<tr>
<td>Beam current for 4h lifetime [A]</td>
<td>0.8</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td><strong>After a dose of 10 A·h</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific pressure rise [10$^{-9}$ Torr/A]</td>
<td>1.7</td>
<td>1.0</td>
<td>3.5</td>
</tr>
<tr>
<td>Dynamic pressure at $I_{nom}$ [10$^{-9}$ Torr]</td>
<td>2.2</td>
<td>0.56</td>
<td>9.1</td>
</tr>
<tr>
<td>Beam lifetime at $I_{nom}$ [h]</td>
<td>9.9</td>
<td>18</td>
<td>4.9</td>
</tr>
</tbody>
</table>

the same chamber for standardization and in order to avoid a special cooling circuit for aluminium. Moreover no lead shield is required with the copper chamber because of the large photon absorption coefficient [66]. Finally copper has a low desorption coefficient under photon bombardment. This explains that after only 10 A·h the machine will be operable at nominal intensity (table 5.4).

![Figure 5.4: Copper vacuum chamber in dipole magnet.](image)

The pumping system follows the LEP design. One ion pump (30 $\ell$/s) is installed per drift chamber (or dipole) and two NEG ribbons are mounted in a separate pumping channel of the vacuum enclosure. This provides an average pumping speed of 500 $\ell$/s/m. A model of cross section of the magnet-vacuum chamber assembly is presented in fig. 5.4. The layout of equipement in a cell has been sketched in fig. 5.5.
At high luminosity the power deposited by parasitic mode losses in the vacuum chamber is considerable, 600 kW in the low energy ring of the asymmetric machines and 850 kW in each ring of the symmetric version. A special effort is required in order to develop bellows capable of coping with the high HOM power. This heat load must be added to the synchrotron radiation heat deposition. At full luminosity each vacuum chamber has to be cooled individually, at lower intensities they can be connected in series.

5.2.5 Magnet System

The lattice study results in the characteristics and the number of the magnetic elements as given in table 5.5. It is proposed to install in the first stage machine all the elements needed for the high luminosity machine. However, only 50% of the closed orbit correctors will be connected to a power supply and the sextupoles will be connected to form two families for the \( \mathcal{L} = 10^{33} \text{ cm}^{-2} \text{s}^{-1} \) luminosity machine.

<table>
<thead>
<tr>
<th>Element</th>
<th>Number</th>
<th>Magnetic length</th>
<th>Overall length</th>
<th>Integ. strength</th>
<th>Number of power supplies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipoles</td>
<td>104</td>
<td>3.93 m</td>
<td>4.25 m</td>
<td>2.1 T-m</td>
<td>2</td>
</tr>
<tr>
<td>Main quads</td>
<td>78</td>
<td>0.47 m</td>
<td>0.70 m</td>
<td>5.6 T</td>
<td>2</td>
</tr>
<tr>
<td>Match. quads</td>
<td>76</td>
<td>0.47 m</td>
<td>0.70 m</td>
<td>5.6 T</td>
<td>24</td>
</tr>
<tr>
<td>Sextupoles</td>
<td>104</td>
<td>0.16 m</td>
<td>0.45 m</td>
<td>29 T/m</td>
<td>2</td>
</tr>
<tr>
<td>C.O. correctors</td>
<td>104</td>
<td>...</td>
<td>...</td>
<td>0.035 T-m</td>
<td>52</td>
</tr>
</tbody>
</table>

The strength of the elements has been specified for a beam energy of 10 GeV in both rings in agreement with the physics requirements of 10 GeV (see section
4.2) and the need of standardization. The power supplies have been defined for the reference machine.

The aperture of the dipole magnet has been calculated from the vacuum chamber dimensions as detailed in table 5.6. Similar calculations have been used to evaluate the inside radius of the quadrupoles and sextupoles [67].

The dipoles have a C-shaped cross section with the yoke placed toward the outside of the ring in order to leave accessible the pumping side of the vacuum chamber (see fig. 5.4). It is proposed to stack two dipoles on top of each other on a single support, to align this assembly in the laboratory and then to install it in the ring with one of the 30 t cranes of the ISR. A similar technique can be used for the instrumentation, sextupole plus quadrupole assembly (fig. 5.6). A portion of the ring is represented in fig. 5.7.

<table>
<thead>
<tr>
<th>Table 5.6: Magnet gap definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam half aperture vertical</td>
</tr>
<tr>
<td>Copper vacuum chamber thickness</td>
</tr>
<tr>
<td>Magnet longitudinal shims</td>
</tr>
<tr>
<td>Tolerances</td>
</tr>
<tr>
<td>Half magnet gap</td>
</tr>
</tbody>
</table>

Figure 5.6: Arrangement of two quadrupoles and two sextupoles on top of each other.
Figure 5.7: Layout of the two rings in the ISR tunnel.
5.2.6 The RF System

The RF system has been designed [68] for the reference machine; nevertheless the possible extension towards the ultimate luminosity influenced the selection of the RF frequency and the straight section length reserved for the cavities.

Frequency
The final choice of the RF frequency $f_{RF}$ will need a more detailed study. In particular double frequency accelerating systems (a lower frequency part providing for the power loss compensation and a higher harmonic part providing for the longitudinal focusing) could be advantageous in the ultimate machines. In this study, in order to take advantage of existing technologies, we have restricted the choice to the two standard frequencies (350 MHz and 500 MHz), compatible with the length of the injected bunches. The RF-voltage $V_{RF}$ is mainly determined by the longitudinal focusing needed to get short bunches:

$$V_{RF} \propto \frac{\alpha}{f_{RF} \sigma_s^2}$$

(5.2.5)

where $\alpha$ is the momentum compaction factor. This favors the 500 MHz system which requires about 30% lower voltage (and therefore less straight section space) than the 350 MHz system.

Power
The RF voltage determines the part of the RF power dissipated inside the cavity walls; if superconducting cavities are used, this dissipation becomes negligible. The power lost by the beam, to be restored by the RF system, is the sum of the radiation losses, and the HOM losses in the various discontinuities of the vacuum chamber.

Higher order mode losses
The higher order mode losses in a cavity are given by

$$P_{HOM}^{\text{cav}} = k(\sigma_s) \frac{I_b^2}{f_b}$$

(5.2.6)

where $k(\sigma_s)$ is the loss factor for a cavity, (roughly inversely proportional to the bunch length in the region of interest), and has been calculated for the selected cavity model [69] (see below). To this value (multiplied by the number of cavities) the higher order mode losses in the vacuum chamber must be added. The corresponding loss factor has been estimated from the values measured at CESR in Cornell [70] and the results are presented in tables 5.7 and 5.9. For the symmetric machine a larger loss factor has been used in order to take into account the effect of separators.

The Reference Machine
The RF requirements of the reference machine are compatible with the use of a normal conducting system. Monocell type cavities have been selected for easier attenuation of parasitic resonances and coupling of high power into each cell. A shape characterized by a smooth accelerating gap region and a large pipe diameter is proposed instead of the conventional “nose cone shape”. It allows to achieve
higher accelerating fields, to reduce the parasitic transverse impedances and to lower the propagation cutoff frequency at the expense of a relatively low increase in total power consumption. Passive HOM dampers installed on each cavity [71] and a complementary active system (section 5.2.8) will ensure the beam stability against coupled bunch instabilities [72, 73]. A model cavity designed according to these guidelines [69] is being tested at PSI. It is represented in fig. 5.8, and its computed characteristics are listed in table 5.7; the parameters of the RF system are found in table 5.1.

The choice of six sets of 1 MW klystrons powering four cavities each (one set in the low energy ring, five sets in the high energy ring) leads to a performance comparable to presently operating systems (see table 5.8). All the cavities can be installed in one of the two long straight sections reserved for the RF.

A gallery is foreseen on top of the ISR tunnel in I2 or I6 [74] for housing the klystrons and their associated equipment (HV cages, protecting crowbar circuits, circulators as well as all electronics for RF controls, interlocks, diagnostics, etc.). The regulation cubicles will be installed inside the hall I1 and transformers and rectifier cubicles outside in the vicinity of this hall.

Table 5.7: Computed characteristics of the model RF cavity

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>500 MHz</td>
</tr>
<tr>
<td>R/Q</td>
<td>73 electr. Ω</td>
</tr>
<tr>
<td>Q0</td>
<td>50 000</td>
</tr>
<tr>
<td>Shunt impedance $R_s$</td>
<td>3.65 MΩ</td>
</tr>
<tr>
<td>$E_{max}/E_{acc}$</td>
<td>2.1</td>
</tr>
<tr>
<td>HOM loss factor ($\sigma_s = 2$ cm)</td>
<td>0.125 V/pC</td>
</tr>
<tr>
<td>transverse cut-off frequency</td>
<td>1.3 GHz</td>
</tr>
<tr>
<td>longitudinal cut-off frequency</td>
<td>1.6 GHz</td>
</tr>
</tbody>
</table>
Ultimate machines
The RF parameters presented in Appendix II are based on the use of a superconducting system (500 MHz, monocell cavities); a maximum accelerating field of 10 MV/m is assumed (see table 5.8).

Table 5.8: Required performance of the normal conducting ($L=10^{33}$ cm$^{-2}$s$^{-1}$) and superconducting cavities

<table>
<thead>
<tr>
<th></th>
<th>n.c.</th>
<th>s.c.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerating voltage $V_{acc}$ [MV]</td>
<td>0.75</td>
<td>3.0</td>
</tr>
<tr>
<td>Accelerating gradient [MV/m]</td>
<td>2.5</td>
<td>10.0</td>
</tr>
<tr>
<td>Power dissipation in the walls [kW]</td>
<td>80</td>
<td>-</td>
</tr>
<tr>
<td>Input power [kW]</td>
<td>250</td>
<td>200</td>
</tr>
<tr>
<td>HOM power [kW]</td>
<td>10</td>
<td>40</td>
</tr>
</tbody>
</table>

The high energy ring of the asymmetric machine requires a very high voltage (120 MV). The use of a superconducting system is imposed by space constraints. The voltage can be provided by 64 superconducting cavities (the maximum number that can be installed in the 16 half cell straight sections reserved for the RF) for a total RF power of about 7 MW. The HOM power to be extracted per cavity is about 7 kW.

The low energy ring requires less voltage (20 MV, 8 superconducting cavities) but the current is higher, leading to 5 times more HOM power per cavity. A normal conducting system could fit within the available straight sections. It is probably easier than with a superconducting system to provide the damping of the higher order modes and to extract 35 kW of power per cavity. However, it requires 40 cavities, leading to large expected impedance values. We therefore propose a superconducting system.

In the symmetric high luminosity machine the required RF voltage is 115 MV. This voltage can be supplied with 40 superconducting cavities, the total RF power being 3.3 MW. The HOM power deposited per cavity again reaches 35 kW.

Critical issues
The HOM damping devices currently in use in the superconducting cavities [75] are not effective enough for our application. The capability to extract HOM power has to be increased and the currently achieved quality factors decreased by nearly two orders of magnitude with respect to presently operating systems. Experts in the field consider these requirements as a reasonable aim for a vigorous R&D program [76].

The environment for the superconducting cavities in the B-factory will be extremely harsh due to high beam currents and high synchrotron radiation power. The question of the system's performance under these conditions has not been addressed in this study and will have to be answered in further design studies.
5.2.7 Beam Instabilities

The single bunch longitudinal instabilities are driven by broad band impedances. To avoid the lengthening of the bunch with its attendant loss in luminosity, strict limits must be placed on the longitudinal broad band impedance of the machine. The limiting values of the impedance coming from the turbulent bunch lengthening threshold are computed [77] using the Chao-Gareyte correction factor for short bunches [78]. The expected impedances are computed from the estimated loss factors, using the broad band resonator model [72, 79]. The results, usually more critical for the low energy ring, are given in table 5.9.

With these values of longitudinal impedance the potential well bunch lengthening has been estimated to be small [77].

The transverse broad band impedance requirements for transverse mode coupling stability are less severe than the corresponding longitudinal requirements.

Ions will be trapped in the $e^-$-beams unless specific measures are taken [80]. The installation of an efficient system of clearing electrodes appears to be very difficult. It is proposed to clear the ions by the technique of missing bunches. In addition we propose to store the electrons in the high energy machine in which the more rigid beam is less sensitive to ion induced effects.

Multibunch instabilities are mostly driven by parasitic resonances in the RF cavities. The parasitic modes in the 500 MHz cavities, equipped with passive dampers, have been studied in detail [71] and the corresponding growth rates calculated [69, 72]. The growth rate is in the worst case about 150 turns or 0.5 ms. In all cases the growth rate is faster than the natural damping rate, indicating the need for an active damping system described in the next section.

Intrabeam scattering is negligible, even in the low energy rings [81].

<table>
<thead>
<tr>
<th>Table 5.9: Loss factors and longitudinal broad band impedances</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Current I [A]</td>
</tr>
<tr>
<td>Total number of bunches</td>
</tr>
<tr>
<td>Energy spread $\sigma_e/E$ [$10^{-3}$]</td>
</tr>
<tr>
<td>Bunch length $\sigma_z$ [m]</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Number of cavities</td>
</tr>
<tr>
<td>Vacuum chamber loss factor [V/pC]</td>
</tr>
<tr>
<td>Loss factor per cavity [V/pC]</td>
</tr>
<tr>
<td>HOM losses in vacuum chamber [kW]</td>
</tr>
<tr>
<td>HOM losses per cavity [kW]</td>
</tr>
<tr>
<td>Vacuum chamber contrib. to $(Z/n)_0$ [Ω]</td>
</tr>
<tr>
<td>Total cavity contrib. to $(Z/n)_0$ [Ω]</td>
</tr>
<tr>
<td>$(Z/n)_0$ expected [Ω]</td>
</tr>
<tr>
<td>$(Z/n)_0$ threshold [Ω]</td>
</tr>
</tbody>
</table>
5.2.8 Active Dampers

An active damping system has to be installed to control the multibunch instabilities. The most demanding period for the damping system will typically occur during injection. Here the contributing factors to the growth of the instabilities include: imperfect closure of the injection bumps, the fraction of the design charge injected per pulse, differences between the injected bunch phase and energy compared to that of the stored bunch, spacing between the injected bunch and the stored bunch at the septum, path length differences, and random noise.

The voltage required per turn to stabilize the beam can be estimated from injection error considerations and the expected rise times of the instabilities. For errors of $1\sigma$, in either the longitudinal or transverse directions, it is estimated that a longitudinal kick (expressed in volts) of 45 kV and a transverse kick (also expressed in volts) of 6 kV are needed.

The bandwidth of the damping system must be large enough to provide damping of all possible modes. For the case of 80 bunches in the machine a bandwidth of 12.5 MHz is required.

The longitudinal damping system will use mode detection electronics modelled after those developed for the CERN PS booster and subsequently employed in many other machines. RF cavities will be used in the longitudinal direction to provide the necessary damping voltage. Two cavities, with overlapping bandwidths of 8 MHz each, are sufficient to cover the entire 12.5 MHz range. These will be operated at approximately 800 MHz and will have loaded $Q$'s on the order of 100 and shunt impedances of approximate 20 kΩ. The peak power required is then on the order of 50 kW. This is available using commercially available standard UHF TV klystrons.

The transverse damping system will be similar in design to that presently in use in the NSLS booster. The transverse kicker plates will be approximately 1 m in length with a gap of approximately 40 mm. Proper design gives an input impedance of 50 Ω, thus the peak power required will be approximately 1 kW. More details are given in [73].

5.2.9 Control and Instrumentation

The ISR equipment buildings will house the power supplies and the electronics associated with hardware and beam diagnostic equipment connected to the machine. They will be the source of approximately 4000 control channels and 500 analog signals per ring. When necessary these buildings will be equipped with local workstations connected to the network for tests and fault finding. A list of beam instrumentation per ring used for cost evaluation is given in table 5.10.

All signals will be connected to a local control room by a local area network and an analog signal multiplexing system. The local control room will be equipped with the scopes, spectrum analysers, FFT devices, digitisers etc. for running-in or tests and workstations for local operation of the machine. This local control room will be linked to the centralized control room of the PS complex. During physics runs the operation will be done from this latter control room, in order to reduce the number of operating teams. The transmission of signals will be done after digitalisation, since
Table 5.10: Beam instrumentation (per ring)

| 140 | Beam position electrodes (button type)      |
| 2   | Wide band pick-ups (stripline) and drivers |
| 2   | Beam transformers (fast and slow)           |
| 4   | Luminescent screens (for injection observation and beam dumping) |
| 2   | Synchrotron radiation monitors ($\beta_{\text{max}}, D_{\text{H_{max}}}$) complete with optical equipment for transport and analysis of signals |
| 1   | Luminosity measurement system per interaction area |
| 12  | Scrapers, collimators for beam measurement and protection of detectors |

Modern instruments are equipped for remote operation and display. The control's structure, operating systems and protocols will be the CERN recommended ones; standard software tools (display, log, archive, etc.) will be available from the PS software library.

The ring and the experimental area will be included into a single access control zone. There will be 20 doors interlocked and three doors for normal access controlled from the main control room. The system will be completed by switching magnets and the associated beam dumps, safety circuits and control equipment. More details are given in ref. 82 and ref. 83.

5.2.10 General Services

The adaptation of the existing equipment of the ISR to the B-factory requirements has been analysed in some detail [74, 84].

The civil engineering work required to install the B-factory in the ISR tunnel is mainly concerned with the overhaul of the existing building (leveling of floors, overhaul of cranes, repairs of walls) and with the installation of klystron galleries on top of one of the two long straight sections reserved for the RF described in the RF section.

The water cooling capacity installed close to the ISR tunnel and presently not used is sufficient for the needs of the beauty factory. However, a complete overhaul of the 4 cooling towers, of the circulation pumps and of the heat exchangers is required. Three separate circuits will be installed: one for the main machine components at 6 bar to fit the present piping characteristics, one for the cooling of the experimental equipment and electronics to ensure independence during machine shutdowns and a 15 bar circuit for the forced cooling of septa.

The ventilation and air conditioning equipment of the ISR building is still operational. It is sufficient for the needs of the B-factory. The adoption of a copper vacuum chamber has the side advantage to reduce the formation of ozone to an acceptable level by stopping the synchrotron radiation power at the source.

The 18 kV AC distribution is sufficient for the B-factory needs. The 380 V distribution must be made operational and adapted to the B-factory. A certain number of equipments redeployed in LEP will need replacement.
5.2.11 Interaction Region

5.2.11.1 Design of the Interaction Region

It is the advantage of asymmetric machines that the beam separation may be achieved by magnetostatic fields. It is proposed in this study that the required vertical separation between beams of $5 \cdot \sigma_H$ for a distance between bunch crossing points of 3 m is produced by the horizontal field component resulting from a $5^\circ$ rotation of the detector solenoid [85]. This provides for operation with up to 160 bunches per ring. The separation between beams is already $2 \cdot \sigma_H$ at 1.5 m from the interaction point and with optimization it should be possible, by increasing the rotation of the detector to less than the maximum acceptable value of about 10 $^\circ$, to obtain sufficient bunch separation for 320 bunch operation in the ultimate asymmetric machine. It must be mentioned, that the tilted solenoid fields in this study have been modeled in a very simplified way; in particular the edge effects, which reduce the exit angle of the trajectory by a factor of two, have not been taken into account.

The general layout is shown in fig. 5.9. The concept described by K. Wille [61] to focus simultaneously beams of unequal energy has been extended to apply to beams of 3.5 and 8 GeV. The first four quadrupoles are shared by the two beams, and are centered on the 3.5 GeV beam. The rest of the quadrupoles in the straight sections are used for matching into the dispersion suppressors. In order to minimize the peak values of the beta functions in the final focus quadrupoles and their chromaticity contribution, the first quadrupole is placed very close to the interaction point. A free space of ±0.7 m is available between the flanges of the cryostats encasing the superconducting quadrupoles Q1 and Q2.

![Diagram](image)

Figure 5.9: Magnetic separation of the 3.5 and 8 GeV beams. VB1 is a magnetic septum. (angles in mrad)

The values of 0.03 m and 1 m for $\beta_V$ and $\beta_H$ respectively in the reference machine can be achieved without difficulty [86]. Preliminary optics solutions with 0.01 m for $\beta_V$ required in the ultimate machine have been worked out, but neither the separation schemes nor the dynamic aperture or the masking solution could be studied in the short time available.
Table 5.11: Parameters of the superconducting mini-beta quadrupoles

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>nominal gradient</td>
<td>50 T/m</td>
</tr>
<tr>
<td>magnetic length</td>
<td>0.6 m</td>
</tr>
<tr>
<td>warm bore radius</td>
<td>60 mm</td>
</tr>
<tr>
<td>coil inside radius</td>
<td>80 mm</td>
</tr>
<tr>
<td>cryostat outside radius</td>
<td>200 mm</td>
</tr>
<tr>
<td>nominal current</td>
<td>1000 A</td>
</tr>
</tbody>
</table>

The superconducting quadrupoles Q1 and Q2 [87] are helium bath cooled, iron-free magnets of similar design to that of the LEP low-$\beta$ quadrupoles. The major characteristics of these magnets are given in table 5.11.

The generous aperture allows for clearance between vacuum pipe and warm bore, so that the magnets can be retracted to permit access to the inner detector. Higher peak values of $\beta$ associated with lower values of $\beta^*$, necessary to achieve higher luminosities, can also be accommodated.

A 3 m long magnetic septum VB1 centered at 8 m from the interaction point serves to kick the beams to their nominal separation of 0.8 m. In order to minimize the photon background from the septa, these are arranged to give only 5 (28) mrad kicks to the incoming 8 (3.5) GeV beams, which leads to the 30 mrad tilt of the beam axes (and the experiment) at the interaction point as shown in fig. 5.9. In order to have equal path length in the interaction region, the interaction point is located some 10 cm below the mid-plane of the two rings. Dedicated vertical bending magnets VB2 are required to bring the trajectories parallel.

The symmetric mode option relies on RF dipole separators of the type employed at CERN [88], placed immediately after the Q1, Q2 doublet; the normal quadrupoles are rearranged for this optics. For 48 bunch operation each such device requires an input power of 300 kW [89]; it will, however, add less impedance than an electrostatic separator, and its operation will be far less sensitive to radiation. Two RF dipoles are needed for each experiment.

5.2.11.2 Background Considerations

An important criterion in the design of a high performance collider and detector for B-physics is a small diameter beam pipe around the interaction point and a low rate of synchrotron radiation photons and off momentum electrons hitting the beam pipe or absorber masks. We have investigated these two questions for the reference machine for a beam pipe of 25 mm radius and four absorber masks for synchrotron radiation at $\pm 30$ cm and at $\pm 80$ cm from the beam crossing point. The layout of the interaction region with beam pipe, masks and quadrupoles is shown in fig. 5.10.

Synchrotron Radiation

The main source of synchrotron radiation in the interaction region originates from the final focus quadrupoles $Q1 - Q4$. The $\beta$-function, and therefore the beam size, is largest in these quadrupoles and particles in the halo of the beam are bent
Figure 5.10: Layout of the interaction region.

strongly. The radiation due to the tilted detector solenoid can be neglected.

A strong source of photons scattered into the detector are the collimators. They are made from 8 mm of copper coated with 2 mm of tungsten, and should shield the direct radiation from the quadrupoles, but should not be hit by particles in the 10 σ tail of the bunch. A preliminary study using a modified version of the program of ref. 90 has shown that circular collimators at z = ±30 cm with a vertical opening of ±15 mm (3.5 GeV) and ±20 mm (8 GeV) are necessary to shield radiation in the vertical plane. Radiation in the horizontal plane is shielded in addition by elliptical collimators at z = ±80 cm with horizontal openings of ±16 mm. The number of direct and of backsattered photons from these masks into the detector (z=±8 cm) as a function of the beam pipe radius is shown in fig. 5.11. A beam pipe radius of 25 mm is seen to be reasonable.

The spectrum of the photons scattered into the detector from the 8 GeV beam after passing through the beryllium beam pipe of 500 μm thickness is shown in
Figure 5.11: Number of photons hitting the beam pipe as a function of the beam pipe radius.

Figure 5.12: Photon spectrum of backscattered synchrotron radiation from the masks into the detector.
fig. 5.12. The peak around 8 keV is from the Cu X-rays. The integral above \( E_\gamma = 10 \) keV is of order \( 10^7 \) photons s\(^{-1}\)A\(^{-1}\).

Another problem with the intense synchrotron radiation is the photodesorption in the beam pipe. For this, low energy photons (\( E_\gamma \lesssim 10 \) eV) are important. The absorber masks are hit by \( 10^{16} \) photons/s with \( E_\gamma > 10 \) eV and in order to ensure a good vacuum (\( 10^{-9} \) Torr) at the interaction point during storage ring operation, it is necessary to install pumps with a capacity of at least 300 \( \ell/s \) close to the absorber masks. It has been estimated that a partial pressure of \( 10^{-9} \) Torr of CO or \( \text{H}_2 \) can be maintained after \( 10 - 100 \) A-h of beam operation.

**Beam Pipe Heating**

A possible problem is the resistive wall heating of the beam pipe due to the image current of the beam. With an equal bunch population in the storage ring, the lowest frequency in the problem is given by the bunch spacing and is 25 MHz in our proposal with 80 bunches. The amplitude \( a_n \) of the \( n \)-th harmonic of the beam current is \( a_n = \exp(-n^2 \frac{2\pi^2}{\sigma_s^2/T^2}) \) with \( \sigma_s = \) bunch length and \( T = \) distance between bunches; \( a_n \) drops to \( 1/e \) at \( n = T/(\sqrt{2}\pi\sigma_s) \) which is 180 for \( \sigma_s = 2.0 \) cm. Therefore frequencies up to \( \sim 5 \) GHz are important. We calculate a heat production of \( \sim 8.8 \) W/m for the reference machine and \( r_{b,p} = 2.5 \) cm (Be) which gives for a 16 cm long beryllium pipe a heat production of 1.32 W from the two beams. This is increased by a factor of three if the number of bunches is reduced to 48 keeping the same average current. Smaller beam pipe diameters, shorter bunches, or more current would also increase the heating. For the ultimate asymmetric machine the heat load increases from 1.3 W to 11 W. If no care is taken, the HOM losses could even be larger.

**Off Momentum Particles**

A source of background in the detector are off-momentum particles which hit the beam pipe wall in the vicinity of the interaction point. We have estimated this effect for a uniform vacuum pressure of \( 2.3 \cdot 10^{-9} \) Torr around the rings which corresponds to the dynamic pressure at \( I_{\text{nom}} \) from table 5.4. At each point \( s \) around the storage ring, and for a series of values of \( dE \), we have calculated the transfer function for a particle with energy \( E_0 - dE \) to the interaction point. \( E_0 \) is the nominal energy and the range of \( dE \) is given by \( 0 \leq dE/E_0 \leq 10\% \). A contour map of such a transfer function depending on the location \( s \) of the collision point and on the energy loss \( dE \) is presented in fig. 5.13.

It can be seen that only some small sections of the circumference contribute to the particle loss in the interaction region; these are located in the dispersion suppressors. The most important zones are located roughly 40 m and 70 m from the I.P. These electrons and positrons should be removed by scrapers before they hit the region close to the detector. The most effective location for a scraper is at a betatron phase of \( 180^\circ \) from the I.P. With such a scraper the number of particles hitting the synchrotron radiation collimator can be reduced to less than \( 10^4 \) s\(^{-1}\).

The transfer function shown in fig. 5.13 corresponds to particles hitting the outer, horizontally narrow synchrotron radiation collimator of the 3.5 GeV storage ring. For both rings the inner synchrotron radiation collimators are within the shadow...
Figure 5.13: Contour map of the transfer function of particles which hit the beam pipe at the I.P. as a function of $dE/E$ and the origin $s$ of the energy loss.

of the outer ones as far as off-momentum particles are concerned. For the outer synchrotron radiation collimator of the 8 GeV ring the situation is quite similar to the 3.5 GeV case.
5.3 Injection

5.3.1 General Description

The luminosity lifetime in the B-factory in the ISR tunnel (BFI) is relatively short (section 5.3.2). In order to obtain a high average luminosity, energy ramping must be avoided and injection at operating energy is mandatory. In order to minimize ion-induced emittance blow-up and instabilities, it is preferred to have the electrons at 8 GeV. Electrons of this energy can only be provided by the SPS; the 3.5 GeV positrons are produced by the PS which works also as electron injector for the SPS at 3.5 GeV as for LEP. Having made these choices, the path the particles have to take is determined after examination of the present use of the transfer lines and the disposition of the tunnels [74].

![Diagram](image)

Figure 5.14: Transfer of electrons (a) and transfer of positrons (b).

Fig. 5.14 shows the general layout. The electrons are transferred from the SPS to BFI via TT10 through the PS, used as a transfer line, and via TT6 and TT1; the latter two tunnels have to be re-equipped because their beam lines serving the ISR have been removed [91]. The positrons are transferred directly from the PS to BFI through TT2 which is still equipped apart from the piece between the branching-off of TT10 and the injection point.

The electron injection point is close to the old I3 interaction point of the ISR, 74 m downstream of the junction of the transfer tunnel TT1 with the ISR tunnel. The positron injection point is close to the old I7 interaction point, 85 m downstream of the junction of TT2 with the tunnel [91].

The electrons and positrons for the PS are produced by the LEP Pre-injector (LPI) which consists of the LEP Injector Linac (LIL) and the Electron-Positron Accumulation ring (EPA); both would operate at 0.65 GeV. LIL is the only accelerator which needs substantial upgrading for BFI.

All circular machines operate with 8 bunches as foreseen for LEP [92]. The transfer scheme [93] is based on equidistant bunches which are handled individually by the injection and ejection equipment as for LEP. The transfer scheme uniquely determines a set of possible BFI circumferences from which the value of 963.430 m has been chosen on the basis of geometry and lattice considerations. Since the
maximum number of bunches is 320, the harmonic number must contain 320 as factor. The number of bunches injected must be a multiple of 8 or better a multiple of 16 in order to keep open the option of operation with 16 electron bunches (see 5.3.4). The injection system does not set an upper limit on the number of bunches in BFI.

The design of the two BFI injection systems [94] follows the classical approach of using a fast bump produced by three kicker magnets per ring. The bump periodically moves the stored bunch to be added towards the septum. However, the particles received in the same acceleration cycle in other collecting buckets must not be moved to the septum because they are not yet damped. In order to respect this constraint, the kickers have a rise and fall time shorter than the revolution time divided by the number of bunches injected per cycle, i.e. 400 ns since PS and SPS operate with eight bunches.

5.3.2 Injector Performance and Average Luminosity

The work done on this point was guided by the desire to have a sufficient stacking rate so that the rings can be refilled in a reasonably short time after a beam loss and that the beams can be topped up quickly, providing a good average luminosity. On the other hand, the constraints on intensity and cycle time in the injectors had to be respected avoiding expensive modifications.

It should be understood that the schemes presented in the following are particular examples which can be considered as reference cases. Further study of alternative solutions and cost optimization may very well lead to different choices for the final system.

5.3.2.1 Operating Modes and Injector Performance

Table 5.12 gives the number of particles per bunch $N_b$ and the total number of particles $N$ in the individual machines. The number of positrons is limited by the maximum $N_b$ in the PS [95] and the number of electrons is determined by $N_b$ in the SPS which is limited to $1.6 \cdot 10^{10}$ in order to avoid crossing the threshold of a longitudinal instability [96]. A bunch compression in the SPS will be required, the natural bunch length being too long to fit into the BFI buckets [97]. The available RF voltage in the SPS is sufficient to do this. We assume transfer efficiencies $\eta$ given in table 5.13, which are based on experience with present machines at CERN, taking into account that the bunch intensities used for BFI will exceed the $N_b$ used for LEP. In order to have complete freedom in the arrangement of electron and positron cycles it is assumed that EPA can accumulate the positrons in 1.2 s which implies a LPI performance upgrade by a factor of 6.5.

Dedicated Mode

This mode will only be used in case fast refilling of $e^+$ or $e^-$ or both is required. In this mode the injectors are reserved for a few minutes for either refilling or topping-up. Fig. 5.15a shows the PS and SPS cycles schematically. The PS cycle includes a flat top at 8 GeV for electron transfer from SPS to BFI. The PS cycle is the same for positrons to simplify operation. It might be desirable to build up both
beams quasi-simultaneously in BFI. Then, one would alternate between long trains of positron and electron cycles with the length of the trains properly adjusted.

Given the length of the cycle, 1.2 s, the number of particles per bunch, the number of bunches and the transfer efficiencies, the stacking rate in BFI and the required stacking rate in EPA are uniquely determined. The refilling times $F_{\gamma}$ for each of the rings and the total refilling time $F_{r}$, the sum $F_{r1} + F_{r2}$ is also given in table 5.12. The refilling time of 11 min is deemed to be acceptable.

### Table 5.12: Complete refilling times and injector performance

<table>
<thead>
<tr>
<th>Operations Mode Particle</th>
<th>Dedicated $e^+$</th>
<th>$e^-$</th>
<th>Interleaved $e^+$</th>
<th>$e^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BFI $E$ [GeV]</td>
<td>3.5</td>
<td>8.0</td>
<td>3.5</td>
<td>8.0</td>
</tr>
<tr>
<td>$N_b/10^{13}$</td>
<td>2.57</td>
<td>1.12</td>
<td>2.57</td>
<td>1.12</td>
</tr>
<tr>
<td>$\dot{N}/10^{10}$ [s$^{-1}$]</td>
<td>9.0</td>
<td>2.8</td>
<td>3.0</td>
<td>0.93</td>
</tr>
<tr>
<td>$I$ [A]</td>
<td>1.28</td>
<td>0.56</td>
<td>1.28</td>
<td>0.56</td>
</tr>
<tr>
<td>$\dot{I}$ [A/min]</td>
<td>0.27</td>
<td>0.086</td>
<td>0.090</td>
<td>0.029</td>
</tr>
<tr>
<td>$F_{\gamma}$ [min]</td>
<td>4.8</td>
<td>6.5</td>
<td>14.4</td>
<td>19.5</td>
</tr>
<tr>
<td>$F_r$ [min]</td>
<td>11.3</td>
<td>34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SPS $E$ [GeV]</td>
<td>–</td>
<td>8.0</td>
<td>–</td>
<td>8.0</td>
</tr>
<tr>
<td>$N_b/10^{10}$</td>
<td>–</td>
<td>1.6</td>
<td>–</td>
<td>1.6</td>
</tr>
<tr>
<td>PS $E$ [GeV]</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>$N_b/10^{10}$</td>
<td>5.0</td>
<td>2.0</td>
<td>5.0</td>
<td>2.0</td>
</tr>
<tr>
<td>EPA $E$ [GeV]</td>
<td>0.65</td>
<td>0.65</td>
<td>0.65</td>
<td>0.65</td>
</tr>
<tr>
<td>$N_b/10^{10}$</td>
<td>6.3</td>
<td>2.5</td>
<td>6.3</td>
<td>2.5</td>
</tr>
<tr>
<td>$\dot{N}_b/10^{11}$ [s$^{-1}$]</td>
<td>0.52</td>
<td>0.2</td>
<td>0.52</td>
<td>0.21</td>
</tr>
</tbody>
</table>

### Table 5.13: Transfer efficiencies

<table>
<thead>
<tr>
<th>EPA to PS</th>
<th>PS or SPS to BFI</th>
<th>Stacking in BFI</th>
</tr>
</thead>
<tbody>
<tr>
<td>80%</td>
<td>90%</td>
<td>30%</td>
</tr>
</tbody>
</table>

**Interleaved Mode**

The main operating mode will be the interleaved mode as used for LEP filling [92]. The positrons and electrons are accumulated at the same rate as in the dedicated mode. The cycle pattern is sketched in fig. 5.15b for the electrons. The 4e-cycles are fitted between the proton cycles so that the SPS fixed target and eventually LHC [98] are completely unaffected. LEP will share the injector with the B-factory. As explained in the next section proper scheduling can avoid any conflict between LEP and BFI.

It is pointed out that collecting the positrons during the proton cycles, as it
Figure 5.15: (a) Dedicated operation during BFI filling; schematic PS and SPS magnetic cycles. (b) Interleaved mode with four e-cycles; pattern repeats with a 14.4 s period.
is done for LEP, and operating with a sequence $e^+e^-e^+e^-$ would provide the same average stacking rates over a filling and would require an upgrading of LPI by a factor of 1.5 only. However, this would render the dedicated mode much less attractive and filling of the positron ring alone would take 29 min in the interleaved mode but would allow for considerable saving. Since it would reduce the overall performance, this solution is not considered further in this report. But is was felt that this option should be mentioned.

5.3.2.2 Filling Modes and Average Luminosity

Refilling will be used after an accidental beam loss and during machine development which will be an important activity in the quest for highest luminosity. However, the most important filling mode for the physics runs is topping-up. Since injection is performed at operating energy, the beams do not have to be dumped at the end of a physics run but the remaining particles stay in BFI for the next run. The injectors have to add only those particles which have been lost, resulting in a considerable saving in injection time. This is successfully done in PEP and DORIS and is called "topping-up".

The average to peak luminosity for a given machine depends on the length of the physics run $T$ and the total dead time $F_{\text{tot}}$, which is the sum of the injection time and of the time required to switch the detector off and on. The latter includes some time for beam steering to optimize luminosity and to minimize background. It is assumed that 2 min have to be added to the plain injection time to get the total dead time $F_{\text{tot}}$. Fig. 5.16 shows a sketch of the luminosity versus time. Fig. 5.17 gives the luminosity and the currents in the two rings as a function of time. The following mechanisms for particle loss are taken into account: beam-beam bremsstrahlung, beam-gas bremsstrahlung, beam loss by Touschek effect and quantum effects. Table 5.14 gives the initial beam lifetimes (inverse decay rates) for the first three effects; the last one is negligible. The resulting beam lifetime $\tau$ due to all three effects is also given. The beam-gas life time is obtained from table 5.4 for a synchrotron radiation dose accumulated after 10 A-h.

Now we turn to the examination of average luminosity for the different filling

![Figure 5.16: Luminosity as a function of time; $F=$deadtime, $T=$duration of physics run.](image-url)
Table 5.14: Initial beam lifetimes and beam decay

<table>
<thead>
<tr>
<th>Particles</th>
<th>$e^+$</th>
<th>$e^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>E [GeV]</td>
<td>3.5</td>
<td>8.0</td>
</tr>
<tr>
<td>$\tau_{fb}$ [h]</td>
<td>11.8</td>
<td>5.2</td>
</tr>
<tr>
<td>$\tau_{gas}$ [h]</td>
<td>9.9</td>
<td>18.0</td>
</tr>
<tr>
<td>$\tau_{T_o}$ [h]</td>
<td>18</td>
<td>514</td>
</tr>
<tr>
<td>$\tau$ [h]</td>
<td>4.1</td>
<td>4.0</td>
</tr>
<tr>
<td>$I$ [A]</td>
<td>1.3</td>
<td>0.6</td>
</tr>
<tr>
<td>$\dot{I}$ [mA/min]</td>
<td>-5.2</td>
<td>-2.3</td>
</tr>
</tbody>
</table>

times. The relevant diagram for refilling is shown in fig. 5.18. Average to peak luminosity is plotted against $T$ with the total dead time as parameter. To determine the average to peak luminosity one selects a run time $T$ and reads from fig. 5.17 the amount of electrons $\Delta I^-$ and positrons $\Delta I^+$ required to "top up" to full current and therefore to full luminosity. For example, for $T=2$ hours the relative loss is $\Delta I^+/I^+ = 31\%$ and $\Delta I^-/I^- = 39\%$; the required time to restore the peak luminosity in interleaved mode is obtained using table 5.12: namely $4.5$ min for positrons and $7.6$ min for electrons. The corresponding average to peak luminosity of $60\%$ is deduced from fig. 5.18. Fig. 5.19 gives the average to peak luminosity calculated in this way for a range of running times. It also gives the corresponding dead time for topping-up time.

![DECAY OF PARTICLES AND LUMINOSITY](image)

Figure 5.17: Luminosity and beam currents as function of time.

Table 5.15 summarizes the conclusions for the topping-up with interleaved mode (1.2 s long cycle), with the assumption that LPI would be improved by a factor of seven. The first three lines give the values at maximum average luminosity. The total BFI dead time $F_{tot}$ is equal to the duration of the injection proper plus 2 min according to our working hypothesis. The optimum running time of 0.3 hours seems
Figure 5.18: Average to peak luminosity as a function of $T$ with $F$ as parameter.

Figure 5.19: Average to peak luminosity (full line) and deadtime $F$ of BFI (dashed line) as a function of $T$ for topping-up.
Table 5.15: Dead time, average to peak luminosity and length of physics run for the reference machine ($\mathcal{L}=10^{33}$ cm$^{-2}$s$^{-1}$).

<table>
<thead>
<tr>
<th>Filling mode</th>
<th>Topping-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T^{\text{opt}}$</td>
<td>0.3 h</td>
</tr>
<tr>
<td>$(\bar{L}/\dot{L})^{\text{opt}}$</td>
<td>0.75</td>
</tr>
<tr>
<td>$F_{\text{tot}}$</td>
<td>5 min</td>
</tr>
<tr>
<td>$T$</td>
<td>2.0 h</td>
</tr>
<tr>
<td>$\bar{L}/\dot{L}$</td>
<td>0.59</td>
</tr>
<tr>
<td>$F_{\text{tot}}$</td>
<td>14 min</td>
</tr>
</tbody>
</table>

impractical. With a running time of two hours an average to peak luminosity of 59% can be achieved.

In this example the injection into BFI will take 12 minutes every two hours. In the worst case LEP needs 20 min every three hours. If refilling of LEP would be required at the same time as a topping-up of the B-factory, the run of the B-factory could be prolonged by the time spent on LEP filling, which results in a small loss in average luminosity.

In the "continuous" filling mode one would frequently inject small quantities of particles in order to keep the beams near their maximum intensity. The period would have to be much shorter than the beam lifetime at peak luminosity given in table 5.14. Comparison of the stacking rates shown in table 5.12 and the beam decay in table 5.14 indicates that the best operating mode for this purpose, the interleaved mode, provides the required stacking rate. There are, however, reasons why continuous injection cannot be considered at present for the filling of BFI, though this might be possible in the future after further study. Since injection with beams in collision that are close to the beam-beam limit is hardly conceivable, the beams would have to be separated in the interaction points in a time short compared to the injection interval and brought into collision again very quickly and precisely after injection. Whether this periodic separation, the moving of the beams towards the septa, and the accumulation of new particles, can be done with tolerable background so that the detector does not get damaged remains to be demonstrated. It is also doubtful whether the beam-beam limit and the high beam intensities can be reached with this periodic perturbation of the beams. Moreover, this filling mode could only be used in between two LEP fills.

5.3.3 Subsystems

This point deals mainly with the hardware modifications and additions to the present LEP injection system required to make it suitable as an injector for the reference machine with a luminosity of $\mathcal{L}=10^{33}$ cm$^{-2}$s$^{-1}$.

The high luminosity asymmetric and symmetric machines need a better performance of some subsystems. This influences the hardware requirements which are discussed together with the overall injector performance for these BFI variants in
section 5.3.4.

5.3.3.1 Upgrading of LPI

The LEP Pre-Injector (LPI) provides either positrons or electrons in eight bunches to the PS. It consists of the Electron-Positron Accumulation ring (EPA) and the LEP Injector Linacs (LIL). The principle of operation would be similar to that used for LEP [92].

The present peak accumulation rate per bunch for the electrons is $1.4 \times 10^{11} \text{s}^{-1}$ which is more than sufficient as comparison with table 5.12 shows; the accumulation rate for positrons ($8 \times 10^9 \text{s}^{-1}$) is a factor of 6.5 below the required rate. This factor could be obtained by increasing the primary beam power by a factor of 4.3 and by raising the repetition frequency from 100 to 150 Hz, as suggested in a first study [99].

![Diagram of LIL layout](image)

**Figure 5.20: Old and new LIL layout.**

Fig. 5.20 gives the old and new linac configurations. Three klystron stations have been added and all RF networks are equipped with SLED type RF pulse compressors called LIPS at CERN. The average accelerating gradient in the accelerating section becomes 18 MV/m, still below SLED II gradients in SLAC, with a modest klystron power of 25 MW over a 4.5 μs long pulse. The primary beam energy becomes 630 MeV instead of 220 MeV. Since the stored energy per section is high, the number of primary electrons per pulse can be increased from $3 \times 10^{11}$ to $4 \times 10^{11}$ without increasing the energy spread which is mainly given by beam loading. Hence, the energy per pulse is increased by a factor 4 including some margin.

The converter target has to withstand ~7 times higher beam power, and the shielding around the converter has to be redesigned for the higher dose rate. Finally, the EPA injection kickers will be modified to allow for a repetition frequency of 150 Hz. A first check shows that all these modifications are possible [99]. However,
a more detailed study is needed to find out how long it would take to displace the converter, though it is likely that the time of a LEP shutdown is sufficient. All other modifications can be implemented gradually.

### 5.3.3.2 The Synchrotrons

**PS [95]**

The PS accelerates both types of particles in 8 bunches as for LEP. Careful scrutiny showed that the PS can fulfill these tasks as it is but it will have to work with positron currents close to the maximum obtained. Machine experiments could be performed later to find out where the instability thresholds are, in order to get a better judgment of the available safety margin. The electron current required is much lower than the current obtained. The cycle with ejection at 3.5 GeV and flat top at 8 GeV for electron transfer to BFI is feasible. The positron beam parameters are shown in table 5.16.

**Table 5.16: Parameters of beam injected into BFI**

<table>
<thead>
<tr>
<th>Particles</th>
<th>e⁺</th>
<th>e⁻</th>
</tr>
</thead>
<tbody>
<tr>
<td>E [GeV]</td>
<td>3.5</td>
<td>8</td>
</tr>
<tr>
<td>(\sigma_t [\text{ns}])</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>((\sigma_{x}/E) \cdot 10^3)</td>
<td>0.6</td>
<td>1.0</td>
</tr>
<tr>
<td>(\sigma_{x}/\beta_M [\mu\text{m}])</td>
<td>0.1</td>
<td>0.05</td>
</tr>
<tr>
<td>(\sigma_{y}/\beta_r [\mu\text{m}])</td>
<td>0.1</td>
<td>0.03</td>
</tr>
<tr>
<td>(N_b/10^{10})</td>
<td>(\leq 4.5)</td>
<td>(\leq 1.4)</td>
</tr>
</tbody>
</table>

**SPS [96]**

The SPS has to accelerate the 8 electron bunches from 3.5 to 8 GeV which is well below the energy of 20 GeV available for LEP injection. In order to facilitate BFI injection it is proposed to arrange the bunches in the SPS equidistantly, which implies an acceptable change in harmonic number from 4620 to 4624 compared to the LEP operation [93]. Since the beam is only accelerated by 4.5 GeV, the cycle can be very short compared to 1.2 s so that the beam can be ejected when the PS magnetic field has reached 8 GeV (see fig. 5.15a). The injection kickers will operate as for LEP. The ejection kicker, which is identical to the positron injection kicker (MKP) used for LEP, can handle 2 bunches without recharging. It will be recharged within 30 ms three times by a new charging circuit whilst BFI and SPS stay synchronized during reloading.

Observation shows that the number of particles \(N_b\) per bunch is limited by a longitudinal instability. If the threshold is exceeded, the bunch blows up and no longer fits into the BFI bucket [97]. In order to be safe, \(N_b\) should not exceed \(1.6 \cdot 10^{10}\) for \(\sigma_x = 8\ \text{cm}\) as shown in table 5.12. The parameters of the ejected beam are given in table 5.16.
5.3.3.3 Beam Transfer Lines

Upgrading of Existing Beam Lines [95]
The beam line FA58, which will be the common part of the electron lines in TT70 at 3.5 GeV and in TT6 at 8 GeV, has to switch between these two levels in much less than 1.2 s (see fig. 5.15), and the switching dipole at its end has even to change polarity and level in this short time. At the moment, this line is only equipped for d.c. operation. The beam line in TT70 used for 3.5 GeV electron transfer does not need any switching and can be used as it is.

The beam line in TT10 through which the 8 GeV electrons return to the PS, has also to transport the 14 GeV protons in the interleaved mode. Since the available switching time is long, the present equipment is adequate.

The beam line in TT2 has to be set to 3.5 GeV during positron transfer from PS to BFI and to 8 GeV during transfer of the electrons from the SPS to the PS. This is feasible with the present equipment as the time elapsing between these two operations is fairly long (see fig. 5.15). Some upgrading is needed if the following operations in the interleaved mode are desired: i) antiproton transfer for LEAR after an antiproton production cycle; ii) an antiproton production cycle before the first positron cycle for BFI.

![Diagram of beam transfer lines](image)

Figure 5.21: Layout of injection elements in one BFI ring.

New Transfer Lines [91]
Fig. 5.14 shows that two transfer tunnels have to be re-equipped as their beam lines were removed after the decommissioning of the ISR. A new 560 m long 8 GeV electron beam line in TT6/TT1 and a 230 m long 3.5 GeV positron line in TT2
for the 3.5 GeV positrons have to be built. The electron beam line consists of 16 FODO cells each 25 m long, two matching regions and the injection region. The positron line has 5 FODO cells and the same number of supplementary regions as the electron line. In total, 65 main dipoles (0.11 T/GeV, 1.3 m long) and 42 lattice quadrupoles are foreseen plus 21 matching quadrupoles and 18 steering dipoles. The vacuum pipe has 50 mm internal diameter leaving a good margin for beam position drifts, which is welcome for operational reasons.

**BFI Injection System** [94]

Fig. 5.21 shows the layout of one injection system in BFI based on the classical scheme as used in other electron rings. The fast bump moving the bunch to be added towards the septum is generated by three fast kickers having a rise and fall time of less than 400 ns. Three kickers are used to make this half wave length bump since this provides flexibility to cope with variations in phase advance in the lattice. The conceptual design is made for an injected beam emittance corresponding to 5.3 GeV beams to be injected for the symmetric BFI option, leading to a required admittance for injection of 50π mm-mrad in BFI. Since the machine admittance is larger than 50π mm-mrad, a closed orbit bump contributes to the total bump in order to save kicker power. It is created by three small pulsed dipoles shown in fig. 5.21. This slow bump is on during the whole injection time.

### 5.3.4 Injection System for BFI Variants

Detailed solutions for the other two BFI variants have been worked out [83, 100, 101]. A brief summary is given below.

#### 5.3.4.1 High Luminosity Asymmetric BFI

In the asymmetric $L=10^{34}$ cm$^{-2}$s$^{-1}$ BFI version the luminosity decay is even more rapid and the beam intensity is higher. The luminosity is only one third after 50 min and is about 10% after 2 h. The optimum run time of 12 min shown in table 5.17 is impractical, but with longer run times the average luminosity is substantially reduced; the latter is 40% of the peak luminosity for $T = 60$ min and it becomes 29% of the peak luminosity for 2 h long runs (cf. table 5.17). Continuous filling would give a better performance, but first it must be demonstrated that it is really a viable proposition.

The stacking rates assumed are twice the ones shown in table 5.12. In both synchrotrons the e-cycle should be shortened to 0.6 s. The positron production rate of LIL would have to be improved by a factor of 14 compared to the present performance. This could be done by a further increase of primary beam power, by raising the linac frequency to 200 Hz and by redesigning the positron collection system [99].

In order to minimize cost, the positron stacking rate could be traded against increased electron rate obtained by operating with 16 bunches in the SPS but these studies are left for a design proposal.
Table 5.17: Dead time, average to peak luminosity and length of physics run for the ultimate asymmetric machine ($\mathcal{L}=10^{34}$ cm$^{-2}$s$^{-1}$ interleaved mode with 0.6 s e-cycles).

<table>
<thead>
<tr>
<th>Filling Mode</th>
<th>Topping-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{opt}$</td>
<td>0.2 h</td>
</tr>
<tr>
<td>$(\bar{L}/\bar{L})_{opt}$</td>
<td>0.53</td>
</tr>
<tr>
<td>$F_{tot}$</td>
<td>7 min</td>
</tr>
</tbody>
</table>

5.3.4.2 Symmetric BFI

In the symmetric variant, both BFI beams would be at 5.3 GeV and are provided by the PS which can cope with the enhanced synchrotron radiation. Since the bunches are short, only one additional 114 MHz RF cavity needs to be installed and the wigglers for damping control are just powerful enough in the PS [95]. Table 5.18 gives the results for the $\mathcal{L}=4\cdot10^{33}$ cm$^{-2}$s$^{-1}$ version and 1.2 s long PS e-cycles with LPI performance improved by a factor of three compared to the present situation.

Table 5.18: Dead time, average to peak luminosity and length of physics run for the ultimate symmetric machine ($\mathcal{L}=4\cdot10^{33}$ cm$^{-2}$s$^{-1}$ interleaved mode with 1.2 s e-cycles).

<table>
<thead>
<tr>
<th>Filling Mode</th>
<th>Topping-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{opt}$</td>
<td>0.2 h</td>
</tr>
<tr>
<td>$(\bar{L}/\bar{L})_{opt}$</td>
<td>0.64</td>
</tr>
<tr>
<td>$F_{tot}$</td>
<td>5 min</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Filling Mode</th>
<th>Topping-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$</td>
<td>2.0 h</td>
</tr>
<tr>
<td>$\bar{L}/\bar{L}$</td>
<td>0.36</td>
</tr>
<tr>
<td>$F_{tot}$</td>
<td>14 min</td>
</tr>
</tbody>
</table>
5.4 Variants and Further Studies

5.4.1 Critical Issues with the Asymmetric Machines

The biggest uncertainty in the design of asymmetric machines is their performance limitations coming from the beam-beam interaction.

Already in the existing symmetric single-ring colliders the currents of the two beams are equalized in order to avoid blowing up the transverse dimensions of the weak beam by the strong beam due to the beam-beam interaction, with a corresponding loss in luminosity. Often an additional requirement of equal vertical and horizontal tune shift parameters is imposed in an attempt to optimize the luminosity.

In order to match the beam-beam interaction of two unequal energy beams, several attempts have been made to put down a set of constraints on the parameters of the two beams [102]. In our study [60] we have adopted a subset of these rules. We require:

a) complete overlap of the beams at the interaction point, i.e. equal transverse beam sizes, equal bunch lengths, equal beta functions and equal emittances of the two beams, and

b) equal tune shift parameters in both planes and for both beams.

The lack of experimental data on this subject has stimulated intense simulation and theoretical studies, as well as a series of experiments to be done in the near future on the existing machines [103]. We have tried to maintain a great deal of flexibility in our lattice design in order to be able to match new requirements on the machine introduced by new effects in the beam-beam interaction.

Given this set of rules, the product of the beam current and the beam energy is equal for the two rings.

The current in the low energy ring of an asymmetric machine will be higher than in a symmetric machine by the ratio of the energy (50% higher for the 3.5 GeV ring as compared to the 5.3 GeV ring of the symmetric machine). This places stricter requirements on the impedance of the low energy ring to keep the beam instabilities under control.

Furthermore, the peak synchrotron radiation power loss in the high energy ring will be 3.5 times higher than in the symmetric case (it varies as $E^3$ at constant luminosity), placing severe constraints on the design of the vacuum system in that ring.

5.4.2 Critical Issues with the Symmetric Machines

Beam separation in the symmetric machine cannot be made by static magnetic deflection as in the asymmetric case because the two beams have the same energy.

The beam separation must be made using either electrostatic or, preferably, RF magnetic deflectors [88, 89, 104]. This still results in a much smaller number of bunches per ring. The alternative would be a finite crossing angle solution in the horizontal plane with or without crab crossing (see below).
Fewer bunches in the machine means higher current per bunch and requires a higher emittance for a given value of the tune shift parameter, or a lower value of the beta function at the interaction point, compared to the asymmetric option. In the "low" luminosity range ($\mathcal{L} \approx 10^{33}$ cm$^{-2}$s$^{-1}$) the emittance required by equation (5.2.2) is still compatible with a standard magnet size, but for higher luminosity configurations of a symmetric machine ($\mathcal{L} \approx 10^{34}$ cm$^{-2}$s$^{-1}$) the magnet cost becomes important. Another serious drawback of a small number of bunches will come from the higher order mode losses in the RF cavities and in the rest of the vacuum chamber. The situation will be improved, if the development of RF magnetic separators allows a higher number of bunches.

5.4.3 Coherent Synchrotron Radiation Emitted by Short Bunches

The synchrotron radiation is usually treated as incoherent in time since for most of the spectrum there is no phase correlation between the photons emitted by different electrons. To get the total power emitted by the beam, the power contributions of the individual electrons are summed up. For the radiation emitted at wave lengths longer than the bunch length, $\lambda > \sigma_s$, this is not correct, since there is now a phase relation between the radiation from different particles on a scale of the bunch length [105]. In the extreme case $\lambda \gg \sigma_s$, all the $N_b$ electrons in a bunch can be considered as a single particle with charge $N_b e$. Since the contributions of the individual electrons are now in phase, the field of the radiation is $\mathbf{E} = N_b \mathbf{E}_1$, where $\mathbf{E}_1$ is the field due to one electron. The total emitted power at these long wave lengths is proportional to the square of the field $P_{\text{tot}} \propto E^2 \propto N_b^2 P_1$, where $P_1$ is the power which would be emitted by a single electron. The power emitted per electron is $N_b$ times larger in the coherent case than in the incoherent one.

This effect could increase the radiated power in many machines if it were not partially suppressed by the presence of the conducting vacuum chamber. The ratio of the coherent radiation power to the incoherent one is approximately [105, 106]

$$\frac{P_{\text{coh}}}{P_{\text{incoh}}} \sim 0.5 \left( \frac{a}{\sigma_s} \right)^2 \left( \frac{\rho}{\sigma_s} \right)^{2/3} \frac{N_b}{\gamma^4},$$

where $a$ is the half height of the vacuum chamber and $\rho$ is the bending radius. Since the incoherent power itself is proportional to $\gamma^4$ the above expression indicates that the coherent power is independent of the energy as expected for the low frequency part of the synchrotron radiation spectrum. For some of the high luminosity parameters, the coherent radiation could lead to a sizable increase of the RF power necessary in the beauty factory. The RF parameters given in Appendix II, table 6.1 do not include the additional power requirements due to this effect. However, the above expression is rather approximate and the coherent power can be reduced relatively fast by increasing the bunch length.
5.4.4 Head-on Collisions Versus Small Angle Crossing

In existing machines, head-on collisions have led to higher luminosity than small angle crossing. We have therefore chosen head-on collisions. There is, however, a series of studies which could modify this choice. This is in particular true for the "crab crossing" proposal [107].

The idea is to separate completely the machines by installing a small angle at the crossing point. The angle must be large enough to allow the installation of separate low-beta quadrupoles in the two rings. In order to obtain head-on collisions in the center of mass the longitudinal axes of the two bunches are placed at an angle with respect to their respective trajectories (crab crossing). This way one can combine the advantage of head-on collisions, which allow larger beam-beam tune shifts and separate low-beta quadrupoles; the latter eases the design of the insertion and allows to store a large number of bunches.

The scheme presents several difficulties: the separation has to be large enough for the installation of the low beta quadrupoles and small enough to reduce the requirements on the crab crossing deflectors. A first investigation of this technique for a B-factory in the ISR tunnel has been made [108]. The angular rotation of the bunch must be produced by RF cavities excited on a deflecting mode. They must work at high frequency because the required effect is not simply a deflection but a variation of deflection along the bunch. A set of two superconducting high frequency cells per deflector is required. The main problem here is again the extraction of powerful higher order modes from small size cavities. The second difficulty is in the design of low-beta sections using quadrupoles with small transverse dimensions. The present idea is to use permanent magnet quadrupoles as the first elements. No detailed layout is yet available. These studies should be actively pursued before a design proposal is made.

The machine layout is entirely different since the magnets are installed side by side instead of on top of each other so that a conversion from head-on collision with separation in the vertical plane to small angle crossing seems impractical.

5.4.5 Round versus Flat Beams

The luminosity equations 5.2.1 and 5.2.2 contain a factor

\[ \frac{1}{\beta_V} + \frac{1}{\beta_H}, \]  

(5.4.7)

and for round beams, where \( \beta_V \approx \beta_H^* \), the same luminosity as for flat beams could be achieved with larger values of \( \beta^* \). Since small values of \( \beta^* \), due to the disruption limit (see section 5.2.3) lead to a short bunch length, the use of round beams could potentially result in less severe requirements on the RF system. The interaction region optics designs for round beams and their impact on the rest of the machine parameters are under investigation.

The dynamics of the beam-beam interaction for round beams has recently received a lot of attention[103, 109, 110], but the results so far have been inconclusive.
5.4.6 The Various Machines

The search for optimum parameters is illustrated in table 5.19, where the limiting parameters of different machines have been listed. The machines with a luminosity of $L=10^{33} \text{cm}^{-2}\text{s}^{-1}$ have been defined with $\xi=0.03$ and $D=0.25$, the others with $\xi=0.05$, and $D=0.3$.

- Machine 1 is our reference machine, used for the cost estimate. The detailed parameter list of this machine is given in table 5.1. We propose it as an example of a first stage machine.

- Machines 2 and 3 show that the ultimate luminosity imposes more demanding requirements. Some of these can be alleviated by increasing the number of bunches. The study of the insertions with the tilted detector shows, that 160 bunches are feasible and that 320 bunches are not excluded. The detailed list of parameters of machine 3 is given in the appendix.

- Machine 4 shows the possible advantages of round beams.

- Machine 5 is a stage I symmetric machine. Machine 6 is like machine 3 limited by higher order mode losses. The detailed list of parameters of this machine is given in Appendix II as an example of an ultimate symmetric machine.

- Machine 7 shows the beneficial effect of increasing the number of bunches in a conventional design.

- Machine 8, a crab crossing symmetric machine with 800 bunches demonstrates the possibilities of this technique. This case has been computed with $\xi=0.03$ and $D=0.3$.

5.4.7 Summary of Further Studies

This feasibility study has, of necessity, left aside all problems which take more than a few months to treat (e.g. vertical dispersion matching and coupling compensation). A longer term program of work would have to cover theoretical and experimental studies. Hardware prototypes should also be built. A tentative list of studies and prototype work is given in table 5.20.

As explained in section 5.4.1, a major uncertainty concerns the beam-beam effect in the collision of beams of different energies. More simulation work is required in order to understand better the constraints; a large amount of work has already been done [103] but the conclusions are not yet final.

The respective possibilities of round and flat beams must be resolved.

The limitation due to disruption presented here has a considerable influence on the design (e.g. a larger beam-beam tune shift will only be useful if one can have a smaller bunch length or a larger $\beta$-function). The validity of this limitation should be checked by simulations in the case of the beauty factory.

The "crab crossing" alternative should be investigated with great attention because it does not appear to be compatible with a pair of rings vertically stacked and therefore requires a decision at an early stage. Prototypes of the deflecting cavities should be considered.
Table 5.19. The limitations of various machines. The index 1 is for the low energy, the index 2 for the high energy beam. The RF parameters for the machines 1, 4, 5, and 8 are for n.c. cavities, the rest for s.c. cavities. The momentum compaction factor in the low energy rings is $\alpha_1=0.0086$ for all cases.

<table>
<thead>
<tr>
<th>Machine number</th>
<th>$L$ [10$^{33}$ cm$^{-2}$s$^{-1}$]</th>
<th>$n_b$</th>
<th>$\beta_V$ [mm]</th>
<th>$\sigma_s$ [mm]</th>
<th>$I_1$ [A]</th>
<th>$P_1$ [MW]</th>
<th>HOM$_1$ [kW]</th>
<th>$\varepsilon_0$ [10$^{-6}$m]</th>
<th>$\alpha_2$</th>
<th>$P_2$ [MW]</th>
<th>$(V_{rf})_2$ [MV]</th>
<th>$P_{syn/m}$ [kW/m]</th>
</tr>
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<tbody>
<tr>
<td>reference</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Asymmetric 3.5x8 GeV</td>
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<td></td>
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<td></td>
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<td>1</td>
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<tr>
<td>2</td>
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<td>160</td>
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<td>round beams</td>
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<td>Symmetric 5.3x5.3 GeV</td>
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<td>10</td>
<td>0.1</td>
<td>0.007</td>
<td>4.7</td>
<td>17.1</td>
<td>7.5</td>
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</table>
Table 5.20: R & D program.

<table>
<thead>
<tr>
<th>Theoretical studies:</th>
</tr>
</thead>
<tbody>
<tr>
<td>- I.R. optimisation (vert. dispersion, coupling, backgrounds ...)</td>
</tr>
<tr>
<td>- Shielding of superconducting cavities</td>
</tr>
<tr>
<td>- Feedback systems</td>
</tr>
<tr>
<td>- Crossing with an angle</td>
</tr>
<tr>
<td>- Beam-beam simulation (asymmetry, disruption ...)</td>
</tr>
<tr>
<td>- Short intense bunches (coherent radiation, impedance)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Experimental studies</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Beam-beam effects (symmetric, asymmetric, disruption)</td>
</tr>
<tr>
<td>- Short intense bunches</td>
</tr>
<tr>
<td>- Crab crossing experiments</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Prototypes</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Copper vacuum chambers with extreme cooling requirements</td>
</tr>
<tr>
<td>- Low HOM RF cavities (including HOM dampers and couplers)</td>
</tr>
<tr>
<td>- Low impedance bellows, kickers, septa etc.</td>
</tr>
<tr>
<td>- Separators for symmetric machines</td>
</tr>
<tr>
<td>- Crab crossing cavities</td>
</tr>
</tbody>
</table>

Prototypes of RF magnetic deflectors should be developed, possibly in collaboration with other laboratories, in order to test the symmetric option.

The race for luminosity implies an increase in circulating currents. The requirement for short bunches combined with high intensities raises the problem of higher order mode excitation in all equipment interacting with the beam: RF cavities, bellows, kickers, septa, deflectors, detectors etc. Considerable progress has already been made in reducing the impedance of the modern machines. More is required if the luminosity of $\mathcal{L}=10^{34}$ cm$^{-2}$s$^{-1}$ is to be reached. The first priority is the development of prototypes of RF cavities with powerful higher order mode couplers, especially for the superconducting cavities.

Finally, the continuous refill mode of operation of these high luminosity colliders should be investigated. In this scheme each 15 or 30 seconds a new injection takes place after the detector electronics has been gated for a few damping times, but the high voltages maintained. The average luminosity then becomes equal to the maximum luminosity, and the injector can still feed other machines in interleaved operation.
5.5 Cost Estimate

The cost evaluation of the reference machine has been made in detail [111]. A summary is presented in table 5.21. Contingency or provision for spare parts are not included.

We decided fairly early in this study to set aside for later analysis the possible reuse of the ISR magnets and of the LEP normal conducting cavities. Both seem unlikely in a machine with very advanced performance requirements but one can only be conclusive after a detailed study for which no time was available.

Table 5.21: Summary of cost estimate in MSFr.

<table>
<thead>
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<th></th>
<th>Total</th>
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<th>Labour Contracts</th>
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</thead>
<tbody>
<tr>
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</tr>
<tr>
<td>2. Interaction region</td>
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<td>11.30</td>
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</tr>
<tr>
<td>3. Vacuum System</td>
<td>21.00</td>
<td>18.00</td>
<td>3.00</td>
</tr>
<tr>
<td>4. RF System</td>
<td>26.50</td>
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<td>4.30</td>
</tr>
<tr>
<td>5. Active Dampers</td>
<td>3.00</td>
<td>2.50</td>
<td>0.50</td>
</tr>
<tr>
<td>6. Injection &amp; Beam Transfer</td>
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<tr>
<td>7. Instrumentation &amp; Controls</td>
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</tr>
<tr>
<td>8. General Services</td>
<td>16.00</td>
<td>14.80</td>
<td>1.20</td>
</tr>
<tr>
<td>Total</td>
<td>163.50</td>
<td>143.00</td>
<td>20.50</td>
</tr>
</tbody>
</table>
6 Conclusions

To further our understanding of the structure of matter a new generation of powerful accelerators is required to become operational by the second half of this decade. The high energy frontier will be formed by multi-TeV hadron colliders like the LHC and the SSC. However, these machines should be complemented by high luminosity electron-positron colliders at moderate energies. They will approach the fundamental questions posed by today’s experiments from a different complementary perspective.

$B$-meson factories, in particular, offer the potential of far reaching experimental observations through high precision studies of the properties of heavy quarks and leptons. The most significant result such $B$-meson factories may achieve is the observation of CP-violation in the $B$-meson system. For that, their luminosity should reach values of $10^{33}$-$10^{34}$ cm$^{-2}$s$^{-1}$, a factor of 10 to 100 larger than realized so far.

The great and broad scientific interest of a $B$-meson factory obliges the European community of particle physicists to seriously consider the construction of such a machine in Europe.

In this report results are given of a feasibility study carried out on the initiative of CERN and PSI to assess the possibility of using the ISR tunnel and other CERN infrastructure to build a $10^{34}$ cm$^{-2}$s$^{-1}$ $B$-meson factory. Physics arguments are presented and a few pilot reactions are discussed which confirm the conclusion that such a machine would be able to meet the challenge of the physics questions.

The work carried out by CERN and PSI accelerator physicists leads to the conclusion that the ISR tunnel perfectly matches the requirements for an $e^+e^-$ collider with a center of mass energy of about 10 GeV and a luminosity in the range $10^{33}$-$10^{34}$ cm$^{-2}$s$^{-1}$. A double ring collider with asymmetric beam energies (8 vs. 3.5 GeV) seems at the present to offer the best promises for reaching the ultimate luminosity. This would also be the preferred mode of operation from the physics point of view, in particular for observing CP-violation in the $B$-meson system. However, the design should be sufficiently flexible to allow also operation with symmetric beam energies, if asymmetric operation runs into unforeseen problems. A luminosity goal of $10^{34}$ cm$^{-2}$s$^{-1}$ is a non-trivial challenge for the accelerator builders and presumably can only be approached in two stages. In the first stage a luminosity of $10^{33}$ is aimed for, while in the second stage the luminosity might be further increased depending on progress made in an extensive accelerator R&D programme.

A decision to further proceed with the preparations of a $B$-meson factory project would imply an extensive R&D programme including in particular the following accelerator topics:

- Theoretical analysis of intersection optics and corresponding simulation studies.

- Experiments with existing machines to study the effect of energy asymmetry.

- Construction and tests of prototypes, in particular copper vacuum chambers with extreme cooling requirements, superconductive RF cavities, higher order
mode couplers, low impedance vacuum chamber equipment, and separators for a symmetric machine.

Although most of the technology for the detectors is available, some R&D is required, in particular in the areas of data acquisition and radiation resistance of detector components and front-end electronics.

The great physics interest of a $B$-meson factory justifies the construction of such a machine in Europe. Its design is a major challenge from the point of view of accelerator technology. The construction costs, however, would remain relatively modest, in particular when existing infrastructure can be used. This, together with the need for a team of highly qualified accelerator experts to design and construct the machine, strongly argue for its construction at an outstanding existing accelerator laboratory. CERN certainly satisfies these requirements. A $B$-meson factory in the ISR tunnel would add an exciting and promising program of particle physics to the activities of CERN and could be operated without any interference with the running program of the laboratory.
Acknowledgement

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Appendix I

Terms of reference for the CERN-PSI collaboration on the design of a B-factory located in the ISR tunnel:

- work out a plausible set of parameters for a B-factory in the ISR tunnel
- examine the existing injection system and any necessary additions
- examine the use of the ISR buildings and the available infrastructure
- evaluate the project cost with respect to the existing cost estimate for the facility at PSI.

The facility must have an initial luminosity of several \(10^{33} \text{ cm}^{-2}\text{s}^{-1}\) and have the visible potential to go up to \(10^{34} \text{ cm}^{-2}\text{s}^{-1}\), and accommodate two experimental areas. The options of symmetric and asymmetric beam energies must be examined, the top energy being 8 GeV.

After proper project definition, a detailed design study and a study of the integration of this programme in the laboratory would be launched at a later date.

Appendix II

A possible parameter list of the "ultimate" asymmetric machine with \(\mathcal{L}=10^{34} \text{ cm}^{-2}\text{s}^{-1}\) and the "ultimate" symmetric machine with \(\mathcal{L}=6 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}\) is presented in Table 6.1. This parameter list has been used to define the magnet aperture, the design of the vacuum chamber, and the space requirements for the accelerating RF-cavities.
<table>
<thead>
<tr>
<th>Type</th>
<th>Asymmetric 10^{34}</th>
<th>Symmetric 6·10^{33}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity [cm^{-2}s^{-1}]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Particles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy [GeV]</td>
<td>3.5</td>
<td>8</td>
</tr>
<tr>
<td>Circumference L [m]</td>
<td>963.43</td>
<td>963.43</td>
</tr>
<tr>
<td>Bending radius ( \rho ) [m]</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>Number of bunches ( n_b )</td>
<td>320</td>
<td>320</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>1600</td>
<td>1600</td>
</tr>
<tr>
<td>RF frequency [MHz]</td>
<td>497.9</td>
<td>497.9</td>
</tr>
<tr>
<td>Momentum compaction factor ( \alpha )</td>
<td>0.0086</td>
<td>0.005</td>
</tr>
<tr>
<td>Horizontal tune ( Q_H )</td>
<td>14.3</td>
<td>18.3</td>
</tr>
<tr>
<td>Vertical tune ( Q_V )</td>
<td>16.4</td>
<td>16.4</td>
</tr>
<tr>
<td>Aspect ratio ( \sigma_V/\sigma_H )</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Vertical tune shift ( \xi_V )</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Horizontal tune shift ( \xi_H )</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Vertical beta at interaction point ( \beta_V^* ) [m]</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Horizontal beta at interaction point ( \beta_H^* ) [m]</td>
<td>0.33</td>
<td>0.33</td>
</tr>
<tr>
<td>Vertical emittance ( \epsilon_V=\sigma_V^2/\beta_V^* ) [10^{-6} m]</td>
<td>0.003</td>
<td>0.003</td>
</tr>
<tr>
<td>Horizontal emittance ( \epsilon_H=\sigma_H^2/\beta_H^* ) [10^{-6} m]</td>
<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>Disruption parameter ( D )</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
<td>Bunch length ( \sigma_s ) [m]</td>
<td>0.0048</td>
<td>0.0048</td>
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<tr>
<td>Energy spread ( \sigma_E/E ) [10^{-3}]</td>
<td>0.41</td>
<td>0.85</td>
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<tr>
<td>Longitudinal damping time [ns]</td>
<td>50</td>
<td>4.6</td>
</tr>
<tr>
<td>Total current [A]</td>
<td>2.56</td>
<td>1.12</td>
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<tr>
<td>Current per bunch ( I_b ) [mA]</td>
<td>8</td>
<td>3.5</td>
</tr>
<tr>
<td>Particles per bunch [10^{11}]</td>
<td>1.6</td>
<td>0.70</td>
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<tr>
<td>Radiation loss per turn [MeV]</td>
<td>0.22</td>
<td>5.6</td>
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<tr>
<td>Synchrotron radiation power [MW]</td>
<td>0.56</td>
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<td>Peak radiation loss in bending magnets [kW/m]</td>
<td>1.28</td>
<td>15.3</td>
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<tr>
<td>Peak RF voltage ( \mathcal{V}_{RF} ) [MV]</td>
<td>20.5</td>
<td>120</td>
</tr>
<tr>
<td>Total RF power ( P_{RF} ) [MW]</td>
<td>1.4</td>
<td>6.8</td>
</tr>
<tr>
<td>Number of 1 MWatt klystrons</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>Number of cavities</td>
<td>8</td>
<td>64</td>
</tr>
<tr>
<td>Beam power loss ( P_{beam} ) [MW]</td>
<td>1.4</td>
<td>6.8</td>
</tr>
<tr>
<td>Dissipated power per cavity ( P_{diss} ) [kW]</td>
<td>s.c.</td>
<td>s.c.</td>
</tr>
<tr>
<td>HOM losses per cavity ( P_{HOM} ) [kW]</td>
<td>34</td>
<td>6.5</td>
</tr>
<tr>
<td>HOM power in vacuum chamber ( P_{VAC} ) [kW]</td>
<td>590</td>
<td>110</td>
</tr>
<tr>
<td>Total input power per cavity [kW]</td>
<td>180</td>
<td>110</td>
</tr>
<tr>
<td>Accelerating field [MV/m]</td>
<td>8.5</td>
<td>6.3</td>
</tr>
</tbody>
</table>