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B-Meson Factories: Physics, Machines and Detectors *†

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Abstract

This report gives a short survey of the present status of B-meson factory plans and discussions at different laboratories. The physics motivation for an e^+e^- machine running with the highest possible luminosity in the $\Upsilon(4S)$ energy region is outlined emphasizing the possibility to observe CP violation in the B-meson system. The technical concepts for such machines together with the basic luminosity limitations are discussed. Finally, the requirements on a detector which is able to cover the rich physics program are presented.

1 Introduction

There is a general agreement amongst high energy physicists that detailed studies of the properties of the third family fermions (b, t, τ, ν_τ) provide most sensitive tests of the Standard Model and may bring us closer to an understanding of the origin of masses, flavour mixing and CP violation. In fact, the observation of CP violation in the B-meson system would stringently test the unitary of the Cabibbo-Kobayashi-Maskawa (CKM) matrix which, according to the latest LEP results, should hold for three generations.

The observation of CP violation as well as of other rare processes requires high production rates of b quarks, at least 10^7 to 10^8 per year depending on detection efficiencies. A comparison of b quark production rates for various existing and planned machines is given in Table 1. Regarding B-physics one can distinguish between three machine types:

- e^+e^- colliders running at the $\Upsilon(4S)$ resonance, i.e. close to threshold for $B\overline{B}$ production;
- e^+e^- colliders running on the Z^0 peak where $b\bar{b}$ production is relatively larger than in the continuum;
- hadron colliders in the TeV range with a huge $b\bar{b}$ cross section but even larger backgrounds.

Table 1: Potential for b-physics at different machines. BFI refers to the study of a B-factory in the ISR tunnel. From [2].

		E_{CM} [GeV]	$\mathcal{L}_{peak}$ [$cm^{-2}s^{-1}$]	$\mathcal{L}_{av.}$ [$pb^{-1}y^{-1}$]	$\sigma_{b\bar{b}}$	$\dot{N}_{b\bar{b}}$ [y^{-1}]	$N_{b\bar{b}}/N_{had}$
DORIS-II	e^+e^-	10.6	$3 \cdot 10^{31}$	100	0.9 nb	10^5	0.19
CESR	e^+e^-	10.6	10^{32}	500	1.1 nb	$5 \cdot 10^5$	0.23
BFI-I	e^+e^-	10.6	10^{33}	10^4	1.1 nb	10^7	0.23
BFI-II	e^+e^-	10.6	10^{34}	10^5	1.1 nb	10^8	0.23
LEP	e^+e^-	91.1	$1.5 \cdot 10^{31}$	100	6 nb	$6 \cdot 10^5$	0.22
LEP$_{upgr.}$	e^+e^-	91.1	$1.5 \cdot 10^{32}$	1000	6 nb	$6 \cdot 10^6$	0.22
HERA	ep	300	10^{31}	100	4 nb	$4 \cdot 10^5$	10^{-3}
TEV-II	pW	~ 50	$\sim 10^{31}$	~ 100	$\sim 1\ \mu b$	$\sim 10^8$	10^{-6}
TEV-I	$\bar{p}p$	2000	10^{30}	10	15 μb	$1.5 \cdot 10^8$	$3 \cdot 10^{-4}$
TEV-I$_{upgr.}$	$\bar{p}p$	2000	$5 \cdot 10^{31}$	500	15 μb	$8 \cdot 10^9$	$3 \cdot 10^{-4}$
LHC	pp	16000	10^{34}	10^5	200 μb	$2 \cdot 10^{13}$	$3 \cdot 10^{-3}$
SSC	pp	40000	10^{33}	10^4	500 μb	$5 \cdot 10^{12}$	$5 \cdot 10^{-3}$

The vast majority of B-physics results comes from the threshold machines DORIS II and CESR running on the $\Upsilon(4S)$ resonance, where $B\overline{B}$ pairs are produced in a well defined quantum state with a relatively large cross section and small background. The current experiments CLEO and ARGUS combined have collected about a million $B\overline{B}$ pairs and branching ratios down to 10^{-4} to 10^{-5} are accessible. To go further and in particular to reach the most important goal of observing CP violation, one or two orders of magnitude larger luminosities are required.

The luminosity of LEP will probably not become sufficient for an investigation of CP violation, though important contributions to other topics in B-physics are expected (e.g., oscillations in the strange B-meson system) [1]. Hadron colliders have high b-quark production rates but also enormous backgrounds. First results from the $p\bar{p}$ colliders indicate that there is a good chance that these experiments will become competitive in measuring rare B decays with low multiplicities, in particular if they contain large momentum leptons which can be detected at the trigger level. Certainly these machines will not cover the broad spectrum of B-physics accessible at threshold e^+e^- machines where the complete reconstruction of the final states, which have also well defined quantum numbers, is possible. In particular, hadron collider experiments will have large difficulties to determine the flavour quantum

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numbers of bottom hadrons as required for the observation of CP violation.

In the following we want to call B-meson factories e^+e^- colliders in the energy range of the Υ resonances with luminosities

$$L = 10^{33} \; to \; 10^{34} \; cm^{-2}s^{-1}.$$

Such machines are currently studied in Europe (CERN/PSI [2], DESY [3]), in the USA (SLAC [4], Cornell [5]) and in Asia (KEK [6], Novosibirsk [7]). The proposal for a B-factory at the Paul Scherrer Institute (PSI) [8] has not been approved. Therefore PSI and CERN initiated a feasibility study for a B-factory in the ISR tunnel [2].

2 Physics Program of a B-Meson Factory

2.1 Physics Topics

The primary goal of a B-factory, the observation of CP violation in the $B\overline{B}$ system sets the scale for the luminosity requirements: ultimately one would like to reach a peak luminosity of 10^{34} cm^{-2}s^{-1} corresponding to about $10^8 \; nb^{-1}$ per year (with π as the usual efficiency factor). Such a machine produces not only a huge number of B mesons but also orders of magnitude more τ, charm and two-photon events than are available today. Typical rates per year are:

$2 \cdot 10^8$ B mesons,
$6 \cdot 10^7$ τ pairs,
$7 \cdot 10^7$ $c\bar{c}$ pairs,
$2 \cdot 10^8$ light quark pairs.

Such high statistics data samples promise major progress in many areas of particle physics as we will shortly summarize below (more detailed discussions can be found in the design studies for B-factories, e.g. [2,8,9,10,11]).

2.1.1 B-Physics

Precision measurements and tests of the unitarity of the CKM matrix are the main reasons for the construction of a B-factory. These measurements include $b \to c$ and $b \to u$ transitions as well as mixing and CP violation in the $B\overline{B}$ systems. The study of rare B decays (as well as D and τ decays) may open a window for new physics. For example, current experiments are not yet sensitive to Higgs contributions to B decays via penguin processes.

Because of its importance we will discuss below in more detail the theoretical predictions and experimental requirements for the observation of CP violation in the $B\overline{B}$ system.

2.1.2 τ-Physics

A B-meson factory is an intensive source of τ pairs in an enery range which is optimal for the reconstruction of τ decays. Due to the large τ mass, τ decays are more sensitive to new physics on a large mass scale than are μ decays. Many of the arguments why we expect b quark interactions to probe physics beyond the standard model are similarly applicable to the leptons τ and ν_τ of the third fermion family. Thus we consider the τ physics program as another strong justification for the construction of a high luminosity machine:

- Measurements of the τ lifetime can be substantially improved by exploiting the proposed micro-strip vertex detectors.
- Determination of the Lorentz structure of τ decays will reach a precision which may reveal the onset of new physics (new intermediate bosons, charged Higgs, etc).
- With the τ being the only lepton heavy enough to decay into hadrons, hadronic τ decays offer the unique possibility to study the weak hadronic currents and the underlying picture of quark and lepton interactions.
- The search for rare τ decays, such as lepton number violating decays, is a promising approach to new physics.
- With the envisaged high luminosity the sensitivity on the τ neutrino mass from kinematical reconstruction of τ decays will come into the range of ±3 MeV. In some models a ν_τ mass limit in this range would be more stringent than the current limits on the electron and muon neutrino masses.

2.1.3 Heavy Flavour Spectroscopy

On the $\Upsilon(4S)$ resonance charmed meson and baryon spectroscopy can be done simultaneously with the other program. Also the $b\bar{b}$ spectroscopy can be pursuit but would require special running on the lower Υ resonances.

2.1.4 Two-Photon Physics

By virtue of the expected high luminosity, two-photon experiments at a B-meson factory will not merely improve existing results but almost certainly will provide new physics inside. 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.

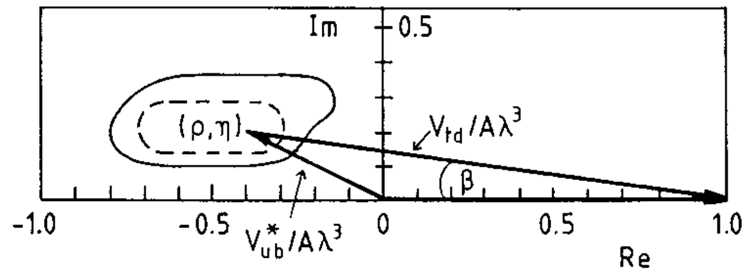

Figure 1: Unitarity triangle containing the result of a fit for the CKM matrix parameters ρ and η as described in [2]. The angle β determines the amount of CP violation in the decay $B^0 \to J/\psi K_s$ in the Standard Model.

2.2 CP Violation

2.2.1 The Phase in the CKM Matrix

The predictions for CP violation in the $B\overline{B}$ system are based on an analysis of the unitarity constraints for the CKM matrix:

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

The approximation on the right hand side is given in the Wolfenstein notation [12] with $\lambda = \sin\Theta_c$ (Θ_c is the Cabbibo angle); A is determined from $b \to c$ transitions and $\sqrt{\rho^2+\eta^2}$ from $b \to u$ transitions.

Applying the unitarity constraint to the first and last column

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

one obtains in this approximation

$$V_{ub}^* - \lambda V_{cb}^* + V_{td} = 0$$

which defines a triangle in the complex plane with all sides having a length of order λ^3. Normalizing to $\lambda V_{cb}^* = A\lambda^3$ one obtains the triangle shown in Fig.1. The coordinates (ρ,η) of the upper corner are constraint by the measurements of CP violation in the kaon system, the limits on the top mass, $B^0 - \overline{B^0}$ mixing and the $b \to u$ transitions. A fit [2] yields

$$(\rho,\eta) = (-0.4, +0.2)$$

with one- and two-sigma contours as shown in Fig.1.

All measurements constraining the triangle, are up to now consistent with each other. A stringent test would be possible by a measurement of CP violation in B decays which depends, according to the Standard Model, on the angles in the triangle.

In principle, CP violation is established if one finds that the decay of a B into a final state f has a rate different from the decay of $\overline{B}$ into the charged conjugate state $\overline{f}$:

$$\Gamma(B \to f) \neq \Gamma(\overline{B} \to \overline{f})$$

If $f \neq \overline{f}$, like in $B^0 \to K^+\pi^-$ and $\overline{B^0} \to K^-\pi^+$, the final state determines the B flavour. However, there seems to be no such decay mode with high enough rates and asymmetries to make CP violation observable. More promising is the case where f is a CP eigenstate ($f{=}\overline{f}$), like in $B^0, \overline{B^0} \to J/\psi K_s$ (or $\pi^+\pi^-$). Of course, this is only possible for neutral B mesons. In this case the flavour of the decaying B has to be inferred from the production process. This 'flavour tagging' can be done by reconstructing the associated beauty hadron or by detecting the charge of associated leptons or kaons as a flavour signature.

2.2.2 The Pilot Reaction $B^0, \overline{B^0} \to J/\psi K_s$

The decay

$$B^0, \overline{B^0} \to J/\psi K_s \to l^+l^-\pi^+\pi^-$$

is considered to be the most promising candidate for observing CP violation in the B system. Therefore, in the design studies for B-meson factories this decay is used as a pilot reaction for tuning the machine and detector parameters. The decay has been observed both by ARGUS and CLEO with a branching ratio of about $4 \cdot 10^{-4}$. The time dependence for this decay is:

$$\begin{aligned} N(B^0 \to J/\psi K_s) &\sim e^{-\Gamma t}(1 - A_0 \sin\Delta m t) \\ N(\overline{B^0} \to J/\psi K_s) &\sim e^{-\Gamma t}(1 + A_0 \sin\Delta m t) \end{aligned}$$

The Standard Model predicts $A_0 = \sin 2\beta = 0.30 \pm 0.09$ where β is the angle indicated in Fig.1.

To determine the asymmetry A_0 the flavour of the decaying B has to be tagged. On the $\Upsilon(4S)$ resonance the charge of a lepton or kaon correlated with the $J/\psi K_s$ decay determines with good efficiency the flavour of the other B at the time when it decayed.

To take proper account for the oscillations one has to note that the $\Upsilon(4S)$ decays into a coherent P-wave $B^0\overline{B^0}$ state. Because of Bose symmetry this P-wave state cannot oscillate into identical bosons, like B^0B^0 or $\overline{B^0B^0}$. Thus we know that the first B decay occurs from a $B^0\overline{B^0}$ state and the other B only then starts to oscillate with a phase depending on the time difference to the first decay. Since the CP asymmetry arises from an interference between the amplitudes to decay either as a

B^0 or as a $\overline{B^0}$ the asymmetry will also depend only on the time difference between both decays. Explicitly, for events of the type

$$e^+e^- \to \Upsilon(4s) \to B^0\overline{B^0} \to J/\psi \ + \ tag \ + \ anything$$

one finds the asymmetry:

$$A_{obs} \ = \ \frac{N\left[\psi K_s(t_1),\ tag(t_2)\right] \ - \ N\left[\psi K_s(t_1),\ \overline{tag}(t_2)\right]}{N\left[\psi K_s(t_1),\ tag(t_2)\right] \ + \ N\left[\psi K_s(t_1),\ \overline{tag}(t_2)\right]} \ = \ A_0 \sin \Delta m(t_1 - t_2)$$

At the time t_1 a B decayed into $J/\psi K_s$ and at the time t_2 the other B decayed, tagged as a B^0 by a negative lepton or kaon (tag) or as a $\overline{B^0}$ by a positive lepton or kaon ($\overline{tag}$).

The cases $t_1 < t_2$ and $t_1 > t_2$ have to be treated independently since the asymmetry changes sign and the average of both is zero. Thus a determination of the asymmetry requires a measurement of the time order of the two B decays. This requirement is a consequence of the CP asymmetry arising in this case from $B^0 - \overline{B^0}$ mixing combined with the fact that the $B^0\overline{B^0}$ pair produced at the $\Upsilon(4S)$ is in an odd wave.

An alternative approach is to run close to the BB^* threshold and look for

$$e^+e^- \to B^0\overline{B^{0*}} \to B^0\overline{B^0} + \gamma \ (or\ c.c.).$$

In this case the $B^0\overline{B^0}$ state is in an S-wave. The resulting asymmetry is proportional to $\sin \Delta m(t_1 + t_2)$, i.e. the time integrated asymmetry does not vanish. This possibility has been studied in detail, e.g. in [11], but in general was found to be less attractive than running on the $\Upsilon(4S)$.

2.2.3 Measuring the Time Order of B Decays

The measurement of the time order of the B decays on the $\Upsilon(4S)$ is everything else but trivial. Since the $\Upsilon(4S)$ is close to the $B\overline{B}$ threshold the B mesons have small momenta in the $\Upsilon(4S)$ CM-system which coincides with the laboratory if the e^+ and e^- beams have equal energies. In this case the B's fly in opposite directions and decay after about 25 μm. Even if these decay lengths could be well enough measured the much less accurate knowledge of the production vertex in an e^+e^- machine forbids the determination of the time difference.

Following a suggestion by P. Oddone the $\Upsilon(4S)$ can be boosted along the beam direction by using different beam energies E_1, E_2 with the constraint $4E_1E_2 = M^2_{\Upsilon(4s)}$. E.g., a boost factor of $\beta\gamma = 1$ yields a mean decay length for the B mesons $\lambda = c\tau \approx 350 \mu m$. Since both B's are essentially boosted in the same direction the decay length difference, which has the same mean of 350 μm can be directly measured and converted to a time difference (Fig.2).

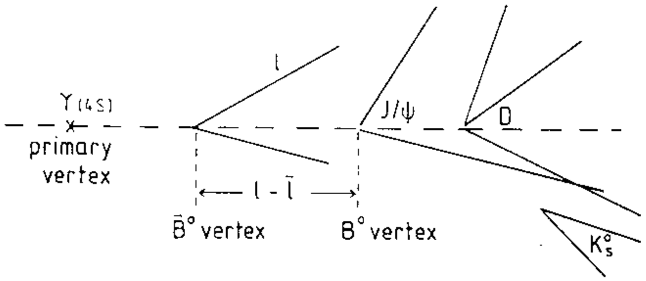

Figure 2: Vertex pattern for the CP violating decay mode discussed in the text as it could be observed in an asymmetric machine.

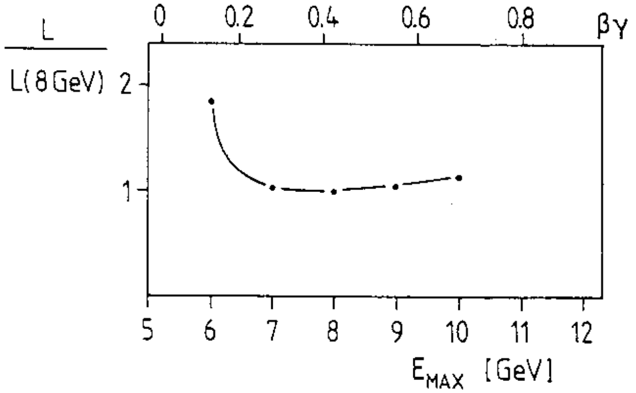

Figure 3: Relative luminosity required for different boosts if CP violation in $B^0 \to J/\psi K_s$ is to be measured with the same precision.

2.2.4 Optimization of the Machine Asymmetry

The optimal asymmetry of a machine is a compromise between the different requirements from:

- physics,
- machine (available facilities, machine performance),
- detector performance (vertex detection etc.),
- acceptance (reduction by boost).

As an example we show in Fig.3 the results of Monte Carlo similations for the CERN/ISR study [2]. Plotted is the relative luminosity required to reach a certain precision in the determination of the CP asymmetry in the $J/\psi K_s$ pilot reaction. The curve reaches around $\beta\gamma = 0.4$ a shallow minimum and is relatively flat above.

In this case the optimum boost is found at $\beta\gamma = 0.42$ ($E_1 = 8\,GeV,\ E_2 = 3.5\,GeV$), a choice which is certainly not quite independent of the constraint that the machine should fit into the ISR tunnel. Other groups find similar results though the position of the minimum can be somewhat shifted, e.g. by introducing an asymmetric rather than a symmetric detector as assumed in the CERN/ISR study.

To be more quantitative: The measurement of a 3σ effect on the asymmetry parameter A_0 requires 1 year of running with L= 10^{33} cm^{-2}s^{-1} if A_0 is close to the best Standard Model estimate $A_0 \approx 0.3$. If A_0 is closer to the lower limit, $A_0 \approx 0.12$, one needs 2 years of running with the ultimate luminosity L= 10^{34} cm^{-2}s^{-1}.

More demanding with respect to the machine asymmetry could be a measurement of $B_s - \overline{B_s}$ oscillations. A B_s meson is expected to oscillate much more often during its lifetime than a B_d meson. The oscillation parameter x_s is expected to be at least 5 times larger than x_d, while the lifetimes are similar. Since fast oscillations wash out time integrated mixing effects one has to resolve the time dependence of the oscillations. In the CERN/ISR study (3.5 GeV against 8 GeV), it was found that x_s values up to about 6 can be resolved, while in a DESY study for 2.8 GeV against 10 GeV x_s values up to about 15 could be resolved [13].

The measurement of x_s contributes another important constraint to the CKM matrix ($x_s \sim |V_{ts}|^2$). However, it would require extra running time at the $\Upsilon(5s)$ resonance, probably more than a year. Since on the other hand $B_s - \overline{B_s}$ oscillations may be measurable at other machines (e.g. LEP), there may be good reasons to give priority to the CP violation program with less demanding boost requirements.

3 B-Meson Factory Machines

3.1 Introduction

There are two requirements which make the design and construction of a B-meson factory a challenging enterprise:

- high luminosity up to 10^{33} to 10^{34} cm^{-2}s^{-1},
- asymmetric beam energies.

This cannot be achieved in conventional single ring colliders. The current design studies at CERN, DESY, SLAC, Cornell, Novosibirsk and KEK are based on:

- double-ring machines
- with many bunches.

Solutions with linear colliders or linac-ring colliders (see e.g. [14]) are no longer in the main stream, mainly because such machines probably need longer development times.

3.2 Asymmetry of Beam Energies

In the different design studies boosts between $\beta\gamma \approx 0.4$ and 0.9 are considered. As we have seen in the previons section the measurement of CP violation defines the lower value, while the upper value would be optimal to study $B_s - \overline{B_s}$ oscillations. Experimentally a lower boost is preferable because of decreasing detector acceptance.

The design of an asymmetric machine confronts machine physicists with many unknowns, in particular concerning the beam-beam dynamics in the interaction region. On the other hand an asymmetric machine may even lead to a higher luminosity because it allows a fast beam separation with static magnetic fields and thus shorter bunch distances. The asymmetry is however limited by the increasing power consumption and synchroton radiation of the high energy beam.

3.3 Luminosity

In a machine with different beam energies one has to worry about instabilities due to the beam-beam interactions leading to asymmetric beam blowup. Simulation studies indicate that the effects of the beams on each other could be symmetrized by obeying the following rules [15]:

- complete transverse overlap at the interaction point (IP)
($\sigma^*_{V1} = \sigma^*_{V2},\ \sigma^*_{H1} = \sigma^*_{H2}$);
- all four tune shifts should be equal
($\Delta\nu_{V1} = \Delta\nu_{V2},\ \Delta\nu_{H1} = \Delta\nu_{H2} = \xi$).

These rules lead to fixed relations between the β-functions at the IP, the emittences, the energies and the currents so that the luminosity can be expressed in terms of the parameters of one beam only (i =1 or 2):

$$L \;=\; 2.17\cdot 10^{34}\,\xi\,(1+r)\left(\frac{I_i\,[A]\cdot E_i\,[GeV]}{\beta^*_{Vi}\,[cm]}\right)\;cm^{-2}s^{-1}.$$

In this formula E_i and I_i are the energies and currents of the beams, β^*_{Vi} the vertical β values in the IP, ξ the tune shift parameter and $r = \sigma^*_V/\sigma^*_H$ the aspect ratio. These parameters cannot be chosen freely but are subject to limitations as discussed in the following. Table 2 lists examples for parameter choices from different machine design studies.

Currents: High currents lead to coupled bunch instabilities due to higher order mode losses in the RF and vacuum system. The necessary currents of 1 Ampere and more can only be reached with strong feed back systems. A very carefull design of the vacuum system is necessary in order to avoid vacuum breakdown due to synchrotron radiation.

Table 2: Choices of luminosity parameters in different studies for asymmetric B-factories.

Machine	L [cm^{-2}s^{-1}]	E [GeV]	I [A]	β^* [cm]	σ_l [cm]	ξ	r	f$_b$ [MHz]
SLAC	$3\cdot 10^{33}$	3.1	2.23	3.0	1.0	0.03	1.0	177
		9.0	1.54	6.0	1.0	0.03	1.0	177
CERN (reference)	10^{33}	3.5	1.28	3.0	2.0	0.03	0.03	25
		8.0	0.56	3.0	2.0	0.03	0.03	25
CERN (ultimate)	10^{34}	3.5	2.56	1.0	0.5	0.05	0.03	100
		8.0	1.12	1.0	0.5	0.05	0.03	100
DESY	$3\cdot 10^{33}$	2.8	2.20	2.0	1.4	0.04	0.1	63
		10.0	1.20	4.0	1.65	0.04	0.1	63
KEK	$1.02\cdot 10^{33}$	2.33	1.32	2.0	2.0	0.03	0.02	64
		12.0	0.51	4.0	2.00	0.03	0.02	64

In addition to the total current limitations the single bunch current is limited by the beam-beam interaction. An increase of the total current above this limit is only possible by increasing the number of bunches. To avoid spurious bunch crossings this requires a fast separation scheme. Here asymmetric beam energies have the advantage that a separation with static magnetic fields is possible, avoiding the technical difficulties connected to the use of electrostatic separators or RF magnets. E.g., in the CERN/ISR study one finds that in an asymmetric machine crossing frequencies up to about 100 MHz are possible while it would be only 15 MHz in a similar symmetric machine.

β-function in the interaction point: Near the IP the β-function depends quadratically on the distance s from the IP:

$$\beta(s) = \beta^* + \frac{s^2}{\beta^*}.$$

Making β^* small, as required for a high luminosity makes the β function rising very fast to both sides. Two limitations have to be taken into account: Firstly, the betatron amplitude in the first focussing quadropole has to be limited to avoid chromatic errors. Therefore, the mini-β quadrupoles have to be close to the IP to get small β^*. Secondly, the β-function should not vary too much over the length of the luminous region which corresponds to the bunch length σ_l. Emperically one finds the constraint $1.5\sigma_l \leq \beta^*$. Note that shorter bunches can only be achieved with additional RF power.

Tune shift: Nonlinearities in the beam-beam interaction lead to a spread around the working point in the tune diagram. The tune shift parameter ξ is limited by resonances in the tune diagram, empirically one finds $\xi < 0.03...0.07$. A conservative assumption is, e.g., $\xi = 0.03$.

Aspect ratio: In current e^+e^- machines the aspect ratio r is small (flat beams). Up to a factor of 2 in luminosity could be gained by making the beams round ($r = 1$). However, there is no experience yet if this would have a bad impact on the tune spread. Furthermore, the SLAC study indicates that for round beams the synchrotron radiation in the IP is more difficult to shield [4].

3.4 Critical Machine Issues

With a carefull machine design, incorporating all available wisdom, an initial luminosity of 10^{33} cm^{-2}s^{-1} should not be too difficult to reach. This would be an order of magnitude improvement over the currently highest luminosity reached at CESR. However, it is also clear that the ultimate goal of a luminosity of 10^{34} cm^{-2}s^{-1} can only be reached by substantial research and development work on the interaction region design, the RF and vacuum systems and other components.

3.4.1 Interaction Region

The interaction region, being the interface between machine and experiment, has to fulfill quite contradictory requirements. The high luminosity can only be reached with optical elements for strong focussing (low β^*) and for fast separation (large bunch number) as close to the interaction point as possible. These optical elements will limit the acceptance near the beam pipe and at the same time generate large synchrotron radiation backgrounds.

Beam collisions under a small angle yield much less radiation than head-on collisions which require strong bending close to the IP. However, from the fate of the original DORIS machine we know that finite angle crossing leads to beam blowup due to transverse-longitudinal coupling of the bunch oscillations. This instability may be avoided with the socalled "crab crossing" scheme which is currently favoured at Cornell [5]. In this scheme the bunches are tilted before and after the IP by RF kicks so that they are parallel during the intersection. Since crab crossing has not yet been used in a machine, we don't know if it really works as expected.

Most machine designs are conservatively based on head-on collisions. Various schemes of how to get the separating dipole field close to the IP have been suggested, e.g., the dipole field may be produced by an off-axis quadropole. A special solution

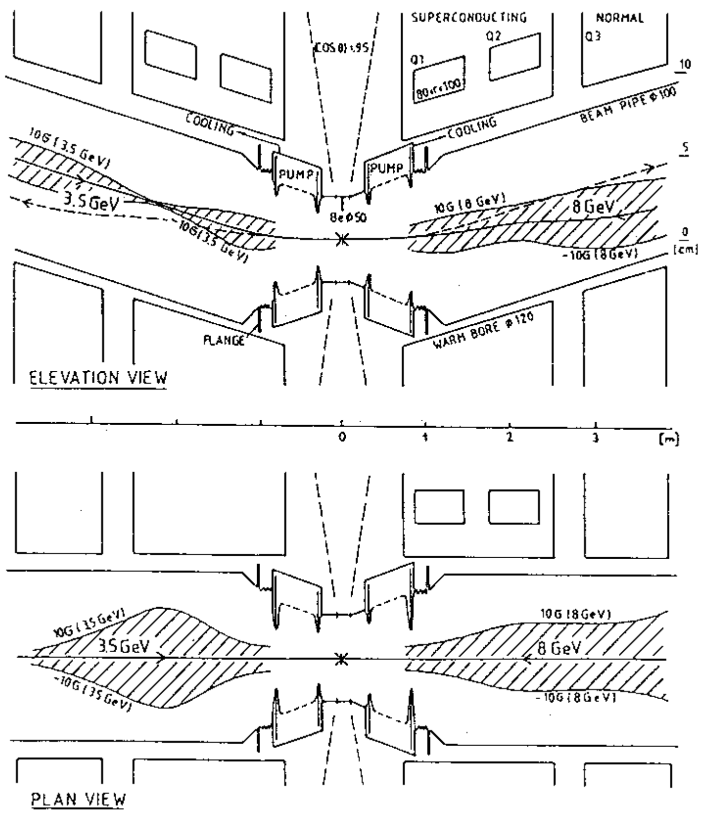

Figure 4: Layout of the interaction region for the B-factory in the ISR tunnel.

has been suggested in the CERN/ISR study [2]: the detector solenoid field could be tilted with respect to the beam by about 4°, yielding a dipole component strong enough to separate the beams.

The radiation background is a particularly critical point since the physics program strongly asks for a very narrow beam pipe in the interaction region ($r \approx 15...25\ mm$). The chosen beam pipe radius has to fulfill the criterium that less than one photon in the several keV range hits the detector during one beam crossing. For example, in the CERN/ISR study an arrangement of quadropoles and shielding masks was found which allows for a 25 mm beam pipe radius (Fig.4).

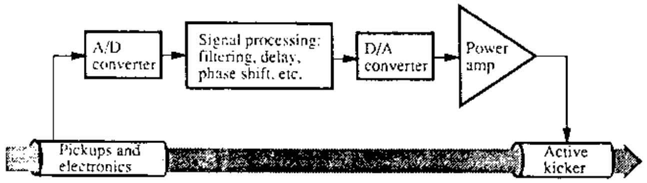

Figure 5: Principle of an RF feedback system.

3.4.2 The RF and Feedback Systems

The parameter list for a "10^{33}-machine" contains quite conventional values for the parameters except for the currents which have to be of the order of 1 Ampere (see Table 2). For such high currents the ring performance is strongly affected by coupled bunch instabilities due to higher order mode losses in the cavities and the vacuum system (RF fields generated by one bunch due to inhomogeneities disturb the following bunches).

The strategy to beat these instabilities relies on a proper cavity and vacuum system design as well as on the implementation of an active feedback system. Design criteria for the cavities include: low impedance (like superconducting cavities even if they are normal conducting) and effective damping of all but the wanted mode.

The scheme of a feedback system for damping the coupled bunch instabilities is shown in Fig.5: a signal with information about the bunch is processed and fed with a proper phase to a RF kicker. A feedback system with a bandwidth of 10 MHz has been developed and successfully tested for HERA. For B-factories higher bunch densities may be achieved and accordingly bandwidths of up to 100 MHz are required which have still to be developed.

3.4.3 Vacuum System

With the high currents the vacuum system has to dissipate some 10 to 15 kW/m power from synchrotron radiation and RF losses. The heating leads to gas desorption which shortens the beam lifetime and leads to background from off-momentum particles. The design criteria for the vacuum system, including good thermal conductivity, low outgassing rate und distributed pumping, can probably be fulfilled by a copper pipe system as developed for HERA.

3.4.4 Injection

It is the average and not the peak luminosity which finally counts. The average luminosity depends on the beam lifetime and the deadtime caused by refilling etc. For higher luminosity the lifetime becomes shorter because radiative Bhabha scattering, being proportional to the luminosity, becomes increasingly important. Since this cannot be avoided the success of a B-factory will crucially depend on the efficiency of the injection system.

For example, the study of a B-factory in the ISR tunnel shows that at the "ultimate" luminosity of 10^{34} cm^{-2}s^{-1} the optimal cycle would be 12 minutes running followed by 7 minutes deadtime yielding an efficiency of only 53% [2]. Such short cycles may not be possible and more practical solutions yield efficiencies of about 30%.

Short filling times can only be reached if the particles are injected at their final energy (no energy ramping) and if only the lost intensity has to be refilled (topping-off mode). For short cycles and effective filling the additional deadtime generated by switching on and off detector components (e.g. chamber high voltages) becomes important. In current systems these switching times seem to be given by detector capacities. In the design of B-factory detectors one should also consider these aspects.

4 B-Factory Detectors

4.1 Detector Requirements

The gain in luminosity has to be accompanied by improvements in the detector capabilities. Aiming at an increase of the reconstruction efficiency for B mesons from currently about 10^{-3} to about 10^{-2} the following detector properties are particularly important:

- charged track reconstruction with good momentum resolution and high efficiencies down to low transverse momenta;
- vertex detection with resolutions in the 10 μm range;
- γ and electron detection with good resolution and high efficiencies down to small energies;
- particle identification for electrons, muons, pions, kaons and protons up to the highest momenta occuring in B decays.

How these requirements could be achieved is demonstrated in Fig.6 by the model detector assumed for the study of B-factory physics at SLAC [9]. Despite the tight package of the separating dipoles and the final focus quadropoles near the IP, the acceptance for charged and neutral particles covers 95% of the solid angle. The major components are a solid state vertex detector (here a pixel device), a more or less conventional drift chamber, a ring imaging Cerenkov counter (CRID or RICH), a highly segmented CsI calorimeter, a superconducting coil and a hadron filter. In particular the vertex reconstruction and particle identification employ novel ideas and demand a lot of research and development.

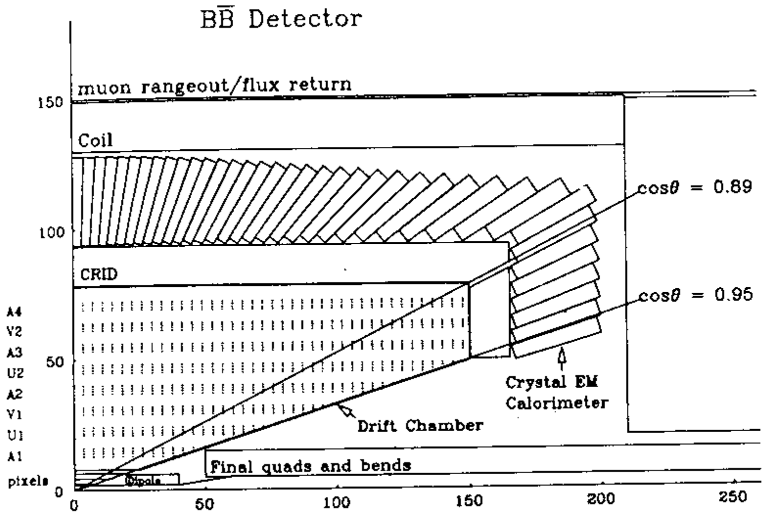

Figure 6: Detector for a B-factory.

4.2 Vertex Detectors

As we have discussed in Sect.2.2 the observation of CP violation on the $\Upsilon(4S)$ requires good vertex resolutions making the vertex detector one of the most important detector components. B and D mesons and τ leptons are weakly decaying with lifetimes of order 10^{-12} s corresponding to decay lengths of order 100 μm in the Υ energy range. With a vertex resolution of some 10 μm one can precisely measure these lifetimes. Even more important is the possibility to tag B, D and τ decays which can enormously reduce the combinatorial background. The requirements on the vertex detector are:

- good spatial resolution in all three dimensions,
- short lever arm to the beam, i.e. small beam pipe radius,
- low mass of both the detector and the beam pipe to reduce multiple scattering.

The best spatial resolution is obtained by silicon detectors, either with strips or pixels. Strip detectors have been mainly developed for high energy fixed target experiments. B-physics experiments are in two respects more demanding: Firstly, the resolution should be good for a wide angular range of track incidences on the silicon. The resolution deteriorates with the length of the projection of the ionisation path unto the strip plane. Improvements could come from thinner detectors (standard is 300 μm) and more sophisticated electronics which is able to determine entrance

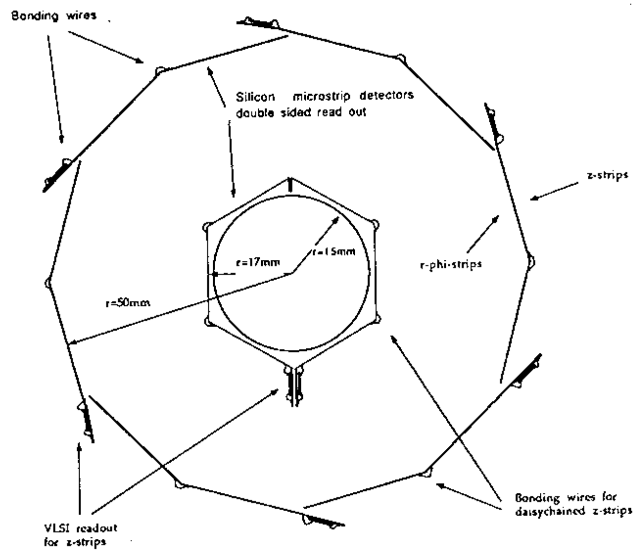

Figure 7: Example for a silicon strip vertex detector for a B-factory.

and exit point of the track. Secondly, since the average momentum in $\Upsilon(4S)$ decays is about 0.5 GeV/c multiple scattering is a major problem. A study for the new ARGUS micro vertex driftchamber [16] showed that a gaseous detector is superior to a silicon detector with the standard thickness of 300 μm and only one readout side. Meanwhile progress has been made in the development of thinner detectors (e.g. 170 μm) and double-sided readout for both coordinates. Such an detector arrangement (Fig.7) is described in the PSI proposal [8] which yields an estimated impact parameter resolution of

$$\sigma_\delta \;=\; \sqrt{8^2 \,+\, \left(\frac{8.3}{\beta\, p_T\,[GeV]}\right)^2}\;\mu m.$$

The intrinsic structure of pixel devices (two-dimensional, thin) suggests that they are better suited for B-physics. However, there are still a lot of technical problems to be solved, like the readout speed, cooling, mechanical support.

4.3 Charged Particle Tracking

The charged particle tracking will be done with a driftchamber providing good momentum resolution and high reconstruction efficiencies as well as trigger and

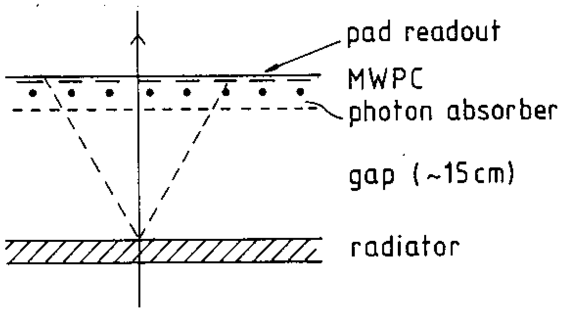

Figure 8: Possible geometry for a RICH counter in a B-detector.

dE/dx informations. Important are the resolution and reconstruction efficiency for low momenta; high efficiencies down to 30 MeV/c are desireable.

Since B mesons predominantly decay via charmed mesons and a large fraction of it via D^*'s, the performance of different detectors can be judged by comparing resolutions and efficiencies for exclusive D and D* spectra. Most sensitive to the low momentum efficiency is the transition $D^* \rightarrow D\pi$ which has a very small Q-value. In this case the efficiency is around 90% for a momentum cut-off at 50 MeV/c and drops to about 70% for a cut-off at 100 MeV/c.

4.4 Particle Identification

In the current detectors for B-physics measurements of specific ionisation, time-of-flight, electromagnetic showers and hadron absorption provide particle identification with $\pi - K - p$ separation up to about 1 GeV. Here a significant improvement is possible using ring imaging Cerenkov counters (RICH), which would allow to achieve $\pi - K - p$ separation up to about 3 GeV covering the whole momentum range in B decays. The performance of the RICH should be sufficient to allow particle identification in such decays as $B^0 \rightarrow \pi^+\pi^-$ or π^-K^+ (to be distinguished from π^+K^-) and $\tau^\pm \rightarrow K^\pm X$.

Being placed in front of the calorimeter the RICH detector should be very compact and thin in terms of radiation lengths. The principle geometry suitable for a B-detector is shown in Fig.8; the radiator is followed by a gap, which allows the radiation ring to develop and the photons are absorbed in a MWPC which produces signals on a fast pad readout ($\sigma \approx 5mm/\sqrt{12}$). In the PSI proposal [8] a NaF radiator was combined with photon absorption in tri-ethyl-amine (TEA). New measurements show that the refractive index of NaF in the absorption band of TEA has a larger value and a larger dispersion than expected. The resulting change in total reflection and in the chromatic errors make this combination less attractive than expected. Currently several groups (e.g. [17]) investigate if this problem can be overcome by using as absorbers CsI cathodes evaporated on the MWPC pads [18].

4.5 Electromagnetic Calorimetry

In most design studies for detectors at B-factories CsI(TL) is chosen as calorimeter material. The advantages are:

- short radiation length, as compared, e.g., to scintillating glass;
- hight light yield which allows for a photodiode readout;
- easy to handle.

The disadvantages are:

- long signal decay time ($\sim 1\mu s$),
- less radiation hard than e.g. scintillating glass.

In the PSI proposal the resolutions for a calorimeter with about 12000 crystals has been calculated to be:

$$\begin{aligned} \left(\frac{\sigma_E}{E}\right)^2 &= \left(0.01 + \frac{0.01}{\sqrt{E}}\right)^2 + \left(\frac{0.001}{E}\right)^2 \\ \sigma_\Theta &= \frac{4\,mrad \cdot \cos\Theta}{\sqrt{E}} \\ \sigma_\Phi &= \frac{4\,mrad}{\sqrt{E}} \end{aligned}$$

The three terms in the energy resolution formula are due to leakage, photon statistics and electronic noise, respectively. The resolutions for electromagnetic showers translate to a π^0 mass resolution of 2% at 1 GeV. The combined calorimeter, dE/dx and RICH measurements yield an electron-hadron separation of 1000:1. The granularity assures that in about 80% of the $\Upsilon(4S)$ events all showers are completely separated.

4.6 Rates, Triggers and Data Acquisition

Triggering and data acquisition in a B-factory experiment is a challenge, at least at the planned "ultimate luminosity" of 10^{34} cm^{-2}s^{-1}. On the $\Upsilon(4S)$ resonance the rate of hadronic annihilation events is about 40 Hz. QED and two-photon event rates are orders of magnitude larger. If the QED rates are prescaled and proper thresholds for two-photon events are chosen the physics rate could come down to 100-200 Hz, corresponding to an estimated data flow of 2-4 Mbyte/s.

It is clear that under these conditions a very effective online filtering of the events is necessary. This can be achieved by a multi-level trigger system, with increasing sophistication and decreasing rate on each level. Given the high crossing and event rates, deadtimeless triggering is only possible if during the time needed for the first level decision ($\sim 2\mu s$) all information is chronologically stored in a pipeline. On the following levels less events are stored in buffers but the decision times increase.

The trigger scheme would be similar to those developed for the HERA experiments but further development is needed to handle the much higher rates.

5 Summary

The rich physics program of a B-meson factory in the Υ energy region allows to probe physics beyond the Standard Model by studying with high statistics decays involving the third family fermions b, t, τ, ν_τ. Of course, the most important motivation for a B-factory is the possibility to observe CP violation in the B system. If $B^0 - \overline{B^0}$ mixing is the dominant source for CP violation, its determination at the $\Upsilon(4S)$ requires a measurement of the time dependence of the B decays. This is only possible in asymmetric machines where the $\Upsilon(4S)$ is boosted.

Asymmetric e^+e^- ring colliders have been studied in many laboratories. There is a general agreement that luminosities of about 10^{33} cm^{-2}s^{-1} can be reached with todays technologies. No principal reasons have been found which would forbid reaching also the "ultimate" luminosity of 10^{34} cm^{-2}s^{-1}, but more research and development is necessary.

Detectors for B-factories should be tuned to high reconstruction efficiencies for B decays. This requires besides good charged particle tracking and high resolution calorimetry in particular improved particle identification up to about 3 GeV/c (probably with RICH) and high precision vertex detection.

The physics program and the technical concepts for B-meson factories are well defined and not controversial. The B-factory enthusiasts are now waiting for political decisions.

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