A R T I C L E

NOVEL FLAVOUR FACTORIES

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Abstract

The future study of quark flavours, including CP violation, requires new generations of colliding e^+e^- machines. The current proposed ϕ (charm, τ) and $\bar{B}B$ factories should reach luminosities of $10^{33} - 3 \times 10^{33}$ cm^{-2}s^{-1}. Future generations of machines must exceed 10^{34} cm^{-2}s^{-1} luminosity. We describe new collider concepts that have been put forward for these machines. Various ϕ factories and related tests are described as well as plans for test beds for some of these new concepts.

1. Introduction

Despite belief to the contrary, there are still great mysteries in Particle Physics. It is true that great advances in our knowledge have occurred in the last 20 years. However, the depth of that knowledge is sometimes unsatisfying when we must answer insightful questions. We are all troubled in one degree or another by a feeling of insufficiency in this regard.

Two such questions which, I feel strongly, need to be answered in greater depth involve the origin and meaning of quark flavour and the origin of CP violation. In the standard model these issues are linked together in the CKM matrix and to some this is answer enough. Nevertheless, we who have found ourselves *on the spot* to give precise answers concerning these issues, would like a deeper exploration of the origin of flavour and CP violation. Hence, the great interest in the community in *Flavour Factories*.

There are now five proposals (both formal and informal) for asymmetric B factories. These are designed for 3×10^{33} cm^{-2}s^{-1} luminosity.

Likewise, there are three ϕ factory projects which are in various states of proposal or approval. These are designed for projected luminosities from 10^{32} to 10^{33} cm^{-2}s^{-1}.

By in large, most of the machine designs for B and ϕ factories use a sort of "brute force" approach to achieve the luminosity desired. This approach is to increase the current and interaction rates in the storage ring by either increasing the number of bunches or decrease the revolution time. The former approach is being suggested for all of the B factories and one of the ϕ factories. The latter approach is being suggested for the other two ϕ factories [1].

Intense studies have been carried out since 1987 to identify the possible luminosities one could expect to achieve in both B and ϕ factories [1]. These studies have shown that such colliders are feasible at 3×10^{33} cm^{-2}s^{-1} luminosity for B factories and $\sim 3 \times 10^{32}$ cm^{-2}s^{-1} for ϕ factories.

As with all projects of this size, certain major goals have been described for B and ϕ factories. In both cases, the search for direct CP violation is of primary concern. In order to be able to carry out this search, certain luminosities have been projected as minimal. $\mathcal{L} \sim 10^{34}$ cm^{-2}s^{-1} is the needed luminosity for a very detailed study of CP violation in the B system. A luminosity of $\mathcal{L} \sim 10^{33}$ cm^{-2}s^{-1} is the expected requirement for a ϕ factory. We now discuss some of the physics motivations for these flavour factories.

1.1 The ϕ factories

The $K^0 - \bar{K}^0$ complex has been the most productive "interferometer" for elementary particle physics. With the advent of a ϕ factory with $\mathcal{L} \geq 10^{33}$ cm^{-2}s^{-1} we will enter another stage in the study of the system [2]. The sensitivity of this system to new physics can be judged by the possible level of search for direct CP violating effects which is

$$[\varepsilon'/\varepsilon]\times[\varepsilon]\times[\Delta M_{LS}] \sim 10^{-12} - 10^{-13}\ \text{eV} . \qquad (1)$$

No other system in nature has such a sensitivity. For this reason tests for fundamental principles, such as the CPT theorem, can be pushed to the limits of

$$\frac{M_{K^0} - M_{\bar{K}^0}}{M_{K^0}} \leq 10^{-19} , \qquad (2)$$

at a ϕ factory. In addition to the study of the $K^0 - \bar{K}^0$ system, new tests of CPT using semi-leptonic K^0 decays, and direct T violation tests will be available (fig. 1).

The advent of high luminosity ϕ factories will provide a new thrust in the search for violation of various symmetry principles. In addition, the measurement of CP violating parameters will be improved (i.e. ε'/ε to $\sim 10^{-4}$). Table 1 shows the extent to which symmetry principles for the various forces in nature have been tested. Table 2 lists some of the tests that can be carried out at a ϕ factory which will be described in this article.

The most pressing need for a ϕ factory is to help determine the value of ε'/ε in a manner that is complementary to studies

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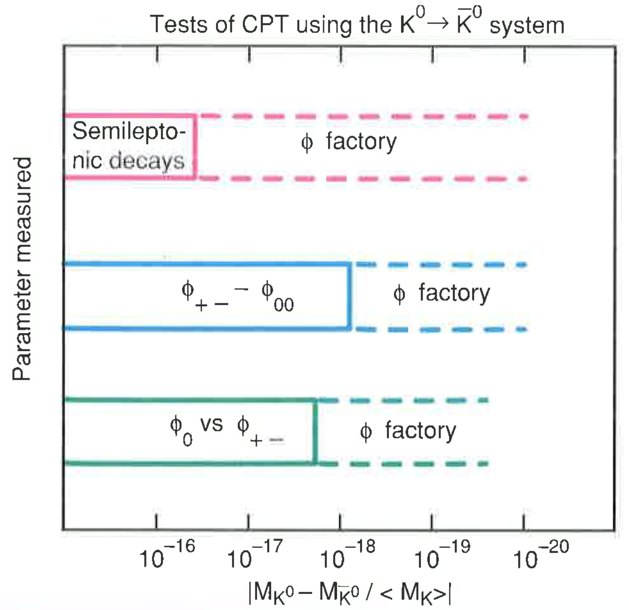

FIGURE 1

Limits to $\Delta M_K/M_K$ that may be reached using various types of measurement at a ϕ factory.

with $K^0/\bar{K}^0$ beams produced at fixed-target facilities such as CERN and FNAL. Determination of ε'/ε at a ϕ factory will likely involve different systematic errors from the fixed-target experiments and thus provides valuable additional conformation. We now review the work of R.C. Berg et al. [3].

Our main study centres on the process

$$\phi \to K^0\bar{K}^0 \to \pi^+\pi^- \ , \ \pi^0\pi^0 \ . \tag{3}$$

Our simulations correspond to operation at a ϕ factory with an integrated luminosity of 10^{40} cm^{-2} with a simple "reasonable detector, e.g. a vacuum region to 18 cm (30 τ_S, followed by good charged tracking with a magnetic field, good electromagnetic calorimetry, and a muon filter). This is equivalent to ~ 1.5×10^{10} $\phi \to K_S^0 K_L^0$, or 10^6 coherent $K^0\bar{K}^0 \to \pi^+\pi^-$, $\pi^0\pi^0$ decays, where both decays occur in the first 30 τ_S. As we demonstrate below, this should allow improvement in the measurements of Re$(\varepsilon'/\varepsilon)$ and $\Delta\phi$ (rad) $\equiv \phi_{00} - \phi_{\pm} \cong 3$ Im$(\varepsilon'/\varepsilon)$ by a factory of 3–5 over present measurements. We define the amplitudes η_1, η_2 for the various processes $K^0 \to (1)$ and $\bar{K}^0 \to (2)$ final states.

The probability density [4] can be written

$$\Gamma(t, \Delta t) \propto e^{-\gamma t} F(\Delta t) =$$

$$= e^{-\gamma t}\left[E\left|\sin\frac{\Delta\lambda\Delta t}{2}\right|^2 + F\left|\cos\frac{\Delta\lambda\Delta t}{2}\right|^2 + \right.$$

$$\left. + \ G\sin h\left(\frac{\Delta\gamma\Delta t}{2}\right) + H\sin(\Delta m\Delta t)\right] , \tag{4}$$

where E, F, G and H are functions of the amplitudes η_1 and η_2

$$E \equiv |\eta_2 + \eta_1|^2 \ , \quad F \equiv |\eta_2 + \eta_1|^2 \ ,$$

$$G \equiv |\eta_1|^2 - |\eta_2|^2 + \mathrm{Re}\left(\eta_1^*\eta_2 - \eta_1\eta_2^*\right) \ \text{and}$$

$$H \equiv -\mathrm{Im}\left(\eta_1^*\eta_2 - \eta_1\eta_2^*\right) \ .$$

A CP or CPT violating contribution alters the relative magnitudes of these four coefficients.

The statistical results of these studies for $\int \mathcal{L}dt = 10^{40}$ cm^{-2} and $\int \mathcal{L}dt = 10^{41}$ cm^{-2} (~ 2–3 years at 3×10^{33} cm^{-2}s^{-1}) indicate that $\varepsilon'/\varepsilon \sim 10^{-4}$ can be measured for 10^{41} cm^{-2}. This analysis shows the great power of a ϕ factory.

Another unique physics possibility for a ϕ factory is the unique test for T violation and measurement of ε_S. It is a little known fact that there is as yet no direct experimental evidence for

Table 1 Fundamental symmetry principles and forces.

Process tested	Forces tested/violation: Strong/EM	Forces tested/violation: Weak
Parity (P)	Extremely small	Maximal violation
Charge conjugation (C)	Extremely small	Maximal violation
Time reversal invariance (T)	Extremely small	Not directly tested yet
CP	Extremely small	$\varepsilon \sim 10^{-3}$
CPT	Extremely small	$[M_{K^0} - M_{\bar{K}^0}]/M_K < 10^{-16}$
Quantum mech./spin stats.	Excel. tests for ordin. QM procs.	Poorly tested

Table 2 Test of fundamental symmetry principles at a ϕ factory.

Symmetry principle	Forces: Strong/EM	Forces: Weak
C/G/parity	C violation decays of $\phi/\eta'\text{s}/\eta \to \pi^0 e^+ e^-$	Violated maximally
CP	CP violation of ϕ decays (i.e., $\phi \to K_L K_L$ and $\phi \to K_S K_S$) $\eta \to \pi\pi$ asymmetry in $\eta \to \pi^+\pi^-\pi^0$	Measure $\varepsilon'/\varepsilon \sim 10^{-4}$ CP violation in K^+/K^- other modes
T	Search for direct violation in ϕ decays $\phi \to K_L K_L$ or $\phi \to K_S K_S$	Direct search for violation in semi-leptonic K decays
CPT	$[(M_{K^0} - M_{\bar{K}^0})/M_K] < [10^{-17} - 10^{-19}]$	Measure δ, α parameters to limit $[M_{K^0} - M_{\bar{K}^0}]/M_K < 10^{-19}$
Quant. mech. spin stats. [(EPR) paradox] Isotropy of CPV proc.	Search for $\phi \to \gamma\gamma$; $\phi \to K_S K_S / K_L K_L$	(CP violation) study EPR correlations to the level of $u' = 10^5\,c$ for break down speed
Bell inequality	?	(CP violation) improve limits for procs. that also violate CP

T violation in the $K^0 - \bar{K}^0$ system. In order to understand this we write the K_S/K_L formulation

$$K_S \sim (1+\varepsilon_S)K^0 + (1+\varepsilon_S)\bar{K}^0$$

$$K_L \sim (1+\varepsilon_L)K^0 - (1-\varepsilon_L)\bar{K}^0 \ , \qquad (5)$$

where ε_S and ε_L refer to the CP violating parameters for the K_S^0 and K_L^0 systems respectively. So far no observation exists of CP violation in the K_S^0 system. A ϕ factory gives a unique source of K_S^0 mesons. The predictions of CPT and T invariance are

$$\text{CPT: } \varepsilon_L = \varepsilon_S \quad \text{and} \quad \text{T: } \mathrm{Re}(\varepsilon_L + \varepsilon_S) = 0 \ .$$

The relevant asymmetry in semi-leptonic decays can be measured with ~ 10^9 ϕ decays. If, on the other hand, T is not violated, the asymmetry could be zero and thus would imply a violation of CPT and CP but not T! It is possible to imagine cases where CP, T and CPT are all violated to some extent as well as, for example, if $\varepsilon_S = 1/2\ \varepsilon_L$; $\mathrm{Re}(\varepsilon_S + \varepsilon_L) \neq 0$ (T violation) and $\varepsilon_S \neq \varepsilon_L$ (CPT violation). Another type of experiment measures ε_S directly

$$\frac{\Gamma(K_S \to \pi^+ e^- \bar{\nu}) - \Gamma(K_S \to \pi^- e^+ \nu)}{\Gamma(K_S \to \pi^+ e^- \bar{\nu}) + \Gamma(K_S \to \pi^- e^+ \nu)} \cong 2\,\mathrm{Re}\,\varepsilon_S \ ,$$

and requires $\gtrsim 10^9$ tagged K_S for such an observation. With very high statistics it may be possible to search for small differences between ε_L and ε_S by using both techniques. These experiments are UNIQUE to a ϕ factory!

A recent study by Buchanan et al. [5], confirms these results and shows that it will be possible to search for non-zero values of δ, the mass matrix CPT violation parameter, using a combined analysis of both $\pi\pi$ and semi leptonic channels they find

$$|\mathrm{Re}\,\delta| < 6\times10^{-5},\ |\mathrm{Im}\,\delta| < 1.8\times10^{-3} \ \text{and}\ |\phi_{00} - \phi_{+-}| \le 0.2^0 \ .$$

This test of CPT will be extremely significant!

1.2 The *B* factories

The advent of the design of these machines occurred at about the same time as the initial observations of B^0 mixing by the ARGUS and UA1 Groups. By now there have been more than ten workshops devoted to *B* factories as well as the publication of many reports and design studies. The first concrete design came from K. Wille and his collaborators at Paul Scherrer Institute (PSI). There are two major physics motives for *B* factories:

(a) to search for CP violation in the *B* sector,
(b) to search for rare decay modes.

Both of these goals push the luminosity requirements into the $10^{33} - 10^{34}\ \mathrm{cm^{-2}s^{-1}}$ range (for e^+e^- colliders operating at the $\Upsilon(4S)$ resonance). The CP violation is perhaps the most restrictive since we have some idea of the level at which CP violation may be observable. It is now believed that the observation of CP violation will also require a new configuration of colliding beams with asymmetric energy. The asymmetric beams are needed to give the $\bar{B}B$ system a boost which makes the measurement of the CP violation at the γ(4S) possible. Other schemes would use higher energies above the γ(4S) to give the $\bar{B}B$ system a net momentum. It is important to understand that there may be many types of B meson factories, for example:

(a) hadron colliders: $S\bar{p}pS$, Tevatron I, SSC and LHC;
(b) fixed target collision at FNAL, UNK and the SSC;
(c) e^+e^- collisions at the Z^0;
(d) e^+e^- collisions at the Υ(4S) resonance.

While possibilities (a) and (b) are very important, they deserve more attention than can be given in this brief paper due to the complex questions of background and detector performance. Therefore, we have decided to concentrate on the e^+e^- options and emphasize the Υ(4S) resonance colliders in this note.

Suppose such colliders exist, what can they expect to produce? One of the key studies will be the search for rare decays of *charm* and τ leptons. While the optical study of *charm* and τ systems is likely carried out near threshold in a *charm*/τ factory. The search for CP violation in decay modes such as

$$B_d^0 \to K^0\psi$$
$$\to K\pi$$
$$B_d \to \pi\pi$$

are clearly of great interest and provide the major motivation for a $\bar{B}B$ factory. In the standard model approach to CP violation such processes are expected to display large CP violating effects. Since our only experience with CP violation so far is limited to the low rate process

$$K_L^0 \to \pi^+\pi^- ,$$

the observation of large CP violating effects will provide important new information. We emphasize that even though large effects are expected for the individual B decay channels, they are rare processes and the luminosity required to observe the CP violation effects is likely 10^{34} cm^{-2}s^{-1}. There is growing consensus now that the B factory should be asymmetric in energy to provide a boost for the B particles.

Another process that might be detected is C or B flavour changing weak neutral currents (a process searched for the past 25 years in K decays). In fig. 2 we attempt to summarize the processes that may be searched for, expected levels in the standard model and range of sensitivity in a τ, *charm* or $\bar{B}B$ factory. We also plot the sensitivity in other types of experiments such as fixed-target B studies at the Tevatron II or SSC in fig. 2.

It is clear that new collider principles will be required to "crack this barrier" and produce these higher intensities. Although we will not comment further on this, it should be mentioned here that one of the possible methods being considered is hadronic flavour beams. They are being studied seriously as a means to achieve this break-through and progress is being made.

If these predicted luminosity minimum are accurate in order to search for CP violation, then one of the first hurdles to be cleared is achieving them [2]. Even if the lower luminosity proves sufficient to provide a suitable method to observe direct CP violation, it is clear that the B and $K_L^0K_S^0$ systems have a rich structure and will take many years to unravel. For this reason we have no doubt that the next hurdle of flavour factories will be to achieve $\mathcal{L} > 10^{34}$ cm^{-2}s^{-1}.

2. Novel flavour factory concepts

In order to increase the luminosity of an e^+e^- collider it will be necessary to use one of two possible principles:

(a) reduction of the beam size at the IP for a Linac-based collider system,
(b) reduction of the beam size (and bunch length) or change the beam shape (round beam) in a circular collider.

The decision is not a trivial one. If one decides upon the first method we must use short bunches from a Linac and collide them with a ring or recirculator-based system. If the second method is

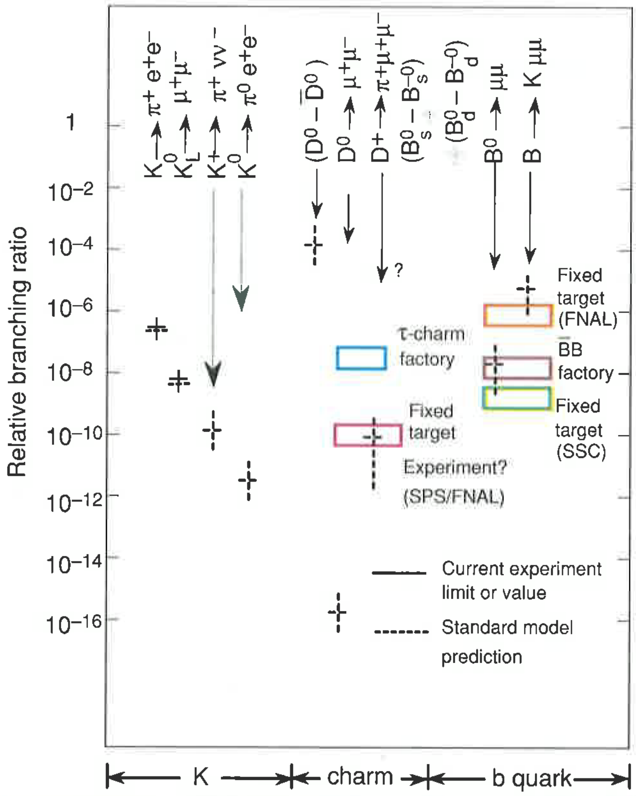

FIGURE 2

Search for flavour changing weak neutral currents.

chosen the beams in a storage ring must be formed with the desired characteristics. With either choice formidable obstacles are encountered. These obstacles are described further below. However, before doing so it is necessary to state that we believe that many of these obstacles can be overcome.

2.1 Linac–Linac collider

One of the first ideas for a novel-flavour factory was to use very high-repetition rate Linac–Linac colliders(*). The schemes used either conventional or superconducting Linacs. On paper it seemed that these ideas could give very high-luminosity colliders since, in principle, beam sizes could be reduced to 0.1 μm and the repetition rate could be large. However, there are two fundamental and fatal problems with these schemes:

(a) The very small spot size lead to large energy spread and the energy spread of the collider was no longer matched to the width of the $\Upsilon(4S)$.

(b) In order to remedy the energy spread problem it was necessary to use large spot size at the IP and regain luminosity by increasing the total number of positrons in the collisions. However, it was shown that the number of positrons needed exceeded that possible without destroying the e^+ production target on every pulse.

Thus, these schemes were abandoned.

2.2 The Linac ring collider

The next logical idea is to attempt to collide a Linac and a storage ring [6]. While this is an old idea, it has recently been revised for flavour factories [7]. The basic concept is shown in fig. 3. Reference [8] gives a set of parameters determined by the CERN group to achieve 10^{34} cm^{-2}s^{-1} for a $\bar{B}B$ factory. The fundamental issue with this scheme is the effect the Linac has on the stored beam of positrons. The results of the simulations of the build-up of noise in the storage ring, again done by the CERN group [9] show a potentially serious instability in this system. A CEBAF group is using this scheme to design a possible $\bar{B}B$ factory with the parameters given in table 3 [9,10].

2.3 The quasi linear collider

This scheme is for the construction of a high luminosity $L \approx 10^{34}$ cm^{-2}s^{-1} electron–positron collider, operating in the energy range of 10 to 15 GeV total centre-of-mass energy. The motivation for such a system is to study the physics of the $B\bar{B}$ system, in particular the rare decay modes and the CP violation [11].

This design is based on the following points (we follow ref. [10] here):

(a) unequal beam energies, to produce the B in motion in the laboratory frame;

(*) These schemes were studied mainly by U. Amaldi, G. Coignet and D. Cline.

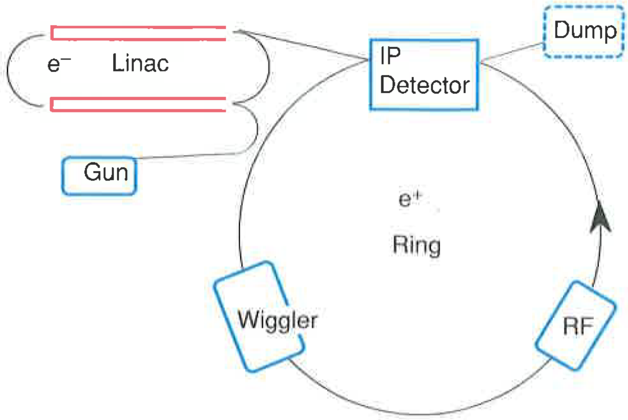

FIGURE 3

Linac ring collider overview.

Table 3
Conceivable parameters of a Linac ring $B\bar{B}$ factory, CEBAF [10].

Storage ring:	Collisions:
$E = 8.0$ GeV	$L = 10^{34}$ cm^{-2}s^{-1}
$I_{avg} = 1.94$ Å	$D_{ey} = 361.8$, $D_{pe} = 6.10^{-2}$
$N_\beta = 6.1 \times 10^{11}$	$\xi = 0.06$
$n_\beta = 30$	rep. rate 20 MHz
$S_\beta = 15$ m	$\beta^{*}e,y = \beta^{*}_{p,z} = 3.33$ mm
$P = 15.1$ MW	$\beta^{*}_{p,y} = 21.55$ mm
$n_{een} = 50$	
$E^\beta = 2.5$ MeV/cav.	
$C \cong 450$ m	
$R_p = 10$	
$\varepsilon_{p,n} = 5.75$ nm, $\varepsilon_{p,n} = 0.057$ nm	
$\alpha = 2.0 \times 10^{-3}$	
$\sigma_\delta = 2.45 \times 10^{-3}$	**Upgraded CEBAF Linac:**
$\sigma_\tau^F = 3.3$ mm	$N_e = 0.544 \times 10^9$
$(Z/n)_{tot} = 0.5$ Ω	$I_{avg} = 1.6$ mA
$P_{bend} = 45$ m	$f_{RF} = 1.5$ GHz
$\tau_x = 0.9$ ms	$\ell_z^e = 2.2$ ps
$\tau_y = 2.4$ ms	$\varepsilon_{e,y} = 5.66$ nm; $\varepsilon_{e,z} = 49.1$ nm
$\tau_z = 6.9$ ms	$P = 5.65$ MW
$L_{ceil} = 5$ m	power loss = 2.0 W/cav.
$\beta_x = 9.8$ m, $\beta_y = 1.4$ m, $D_\tau = 0.255$ m	rep. rate 20 MHz

(b) positron recovery and cooling;
(c) possibility of positioning the vertex detectors very near to the interaction point (IP);
(d) possibility of changing the centre-of-mass energy in the 10 GeV to 15 GeV range, maintaining a high luminosity, to be able to operate effectively at the $\Upsilon(4S)$ resonance or above;
(e) a small beam energy spread, < 0.1%, to be able to utilize effectively the $\Upsilon(4S)$ resonance.

To satisfy these conditions we propose a scheme utilizing:
(i) a 3–6 GeV high-gradient electron Linac, with a 5 kHz repetition rate, or an inverse free-electron laser;
(ii) one positron cooling and recovery ring (CRR), provided with a bypass, where the IP is located;
(iii) a positron converter, low-energy positron accumulator, booster synchrotron, to provide the positrons.

This scheme is illustrated in fig. 4 and described in table 4.

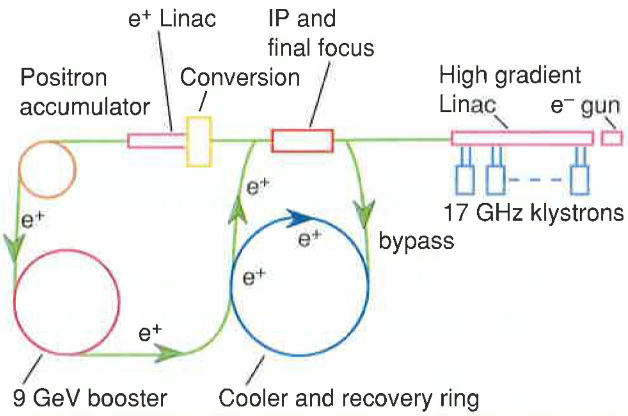

FIGURE 4

The proposed scheme for a quasi-linear collider $B\bar{B}$ factory.

The main advantage of this approach is to decouple the cooling and recovery function of the ring, from the IP, thus allowing an independent optimization of these different parts. For instance, one can reduce the vacuum beam pipe near the IP to a very small value without limiting the beam lifetime in the storage ring and increasing the background in the detector.

Using a bypass and utilizing each bunch only every few damping times, one can increase the beam–beam interaction parameter ξ (or equivalently the disruption parameter) to a value larger than that achievable in a storage ring collider, where a collision takes place at each revolution, and thus increase the luminosity per interaction.

The electron beam disruption can be made much larger than that of the positrons and we will utilize this possibility to reduce the electron–beam power for a given luminosity. To keep to a minimum the positron disruption it is convenient to have the positrons with an energy larger than that of the electrons. In this situation the characteristics of the two beams at the IP are completely asymmetric, with one beam having a large disruption (one thousand or more) and the other with a small or negligible disruption. This case has not yet been studied in the literature on beam–beam interactions, although it can make the collider design much more effective. To estimate what can happen we will use a simple model, with the positron bunch behaving to first approximation as a rigid bunch and the electrons being channelled by the positrons and executing many plasma oscillations within the positron bunch. Although one can reasonably expect that also in this situation the luminosity will be enhanced by the pinch effect, we will again assume for simplicity and to be conservative that there is no enhancement.

Table 4
Quasi-linear B factory collider parameters [11].

Energy (GeV)	positrons	9
	electrons	3
Positrons per bunch		1.6×10^{11}
Electrons per bunch		1.6×10^{10}
Normalized transverse emittance (cm per rad)	positrons	3×10^{-4}
	electrons	1×10^{-4}
Beta at IP (cm)		0.125
Bunch radius r.m.s. (cm)	positrons	4.6×10^{-5}
	electrons	4.6×10^{-5}
Bunch length (cm)	positrons	1.0
	electrons	0.01
Repetition frequency (s^{-1})		5×10^4
Beam power (MW)	positrons	11.5
	electrons	0.4
Luminosity ($cm^{-2}s^{-1}$)		4.8×10^{33}
Disruption parameter	positrons	1.2
	electrons	3580
Beamstrahlung parameter	positrons	1×10^{-3}
	electrons	3.3×10^{-4}
Centre-of-mass energy spread		6.6×10^{-4}

The collision frequency is mainly set by the Linac; if one uses a superconducting Linac it can be made very high, in the megahertz range, while for a room temperature Linac it is much smaller, in the 0.1 to 5 kHz range. We will partly compensate for this reduction by assuming that in each Linac pulse we can accelerate a train of ten bunches, to be collided with a similar train extracted from the storage ring. In this way we can obtain a collision frequency between 1 kHz and 50 kHz.

One can imagine a scaled-down version of this scheme for a ϕ factory (fig. 5) (Phase III of the UCLA ϕ factory Project) [12]. The major problem with this scheme is the complexity of the beam handling. However, at current $\bar{p}$ sources there is a similarly complicated beam handling problem that has been solved.

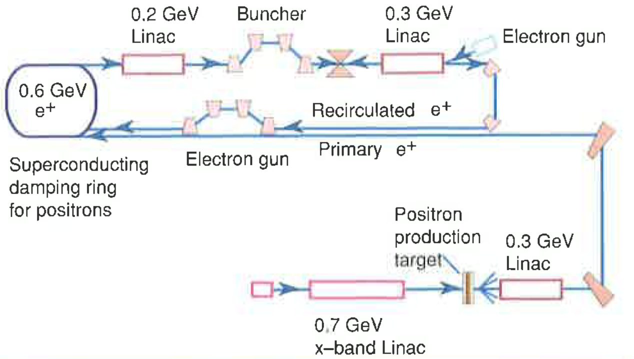

FIGURE 5

Asymmetric quasi-linear collider ϕ factory (schematic).

2.4 Circular colliders with beam structure manipulation

There are several techniques suggested to produce the required luminosity. Of these schemes, two are being seriously considered:

(a) to reduce the bunch length [13],
(b) to use round beams(*) [14].

The bunch length of the collider is usually set by the microwave instability and other parameters in the machine itself. At the present time there are two promising ideas for reducing the bunch length:

(i) the quasi-isochronous condition [11],
(ii) dielectric inserts to reduce the wake fields of the bunches [15].

The luminosity gain of round beams is rather controversial. There are, potentially, two factors to be considered:

(i) geometrical (~ 2),
(ii) increase in tune shift (~ 2?).

(a) Quasi-isochronous rings

We start by describing the quasi-isochronous ring concept being studied by C. Pellegrini at UCLA [13]. The basic idea is to reduce α to the smallest value and find a solution to the instability of the ring. The bunch length can be reduced like $\sqrt{\alpha}$ and the luminosity increased like $1/\sqrt{\alpha}$, in principle. Large damping is essential so this idea will likely work best in a compact storage ring. In practice, one must use the parameters α_1 and α_2 where α is the momentum compaction factor; α_1 and α_2 are the coefficients of the expansion that is linear in δ

$$\alpha = \alpha_1 + \alpha_2 \delta ,$$

where

$$\delta = \frac{E - E_s}{E_s} .$$

It is clear that large damping is required to reach adequate current and luminosity. This belief has been originally applied to a B factory and possible parameters are given in table 5.

Table 5
Quasi-isochronous B-factory parameters [13].

Circumference (m)	760
Energy E (GeV)	5
Luminosity $\mathcal{L}$ (cm^{-2}s^{-1})	10^{34}
Disruption fD	0.48
Tune shift ξ	0.05
Bunch length σ_L (mm)	1
Current I (mA)	194
Number of bunches	120
Current/bunch (mA)	1.6
Electrons/bunch	2.56×10^{10}
Energy loss/revolution U_0 (MeV)	3.5
Damping period τ_D (ms)	3.6
Synchrotron radiation power (MW)	0.68
Transverse emittance ε_T (m/rad)	2×10^{-2}
β^* (mm)	1.3
Bunch width σ^* (m)	1.1×10^{-5}
Momentum compaction (first order) σ_1	3×10^{-5}

(b) Round beam luminosity enhancement

We now turn to the issue of round beams advocated by the USSR-Novosibirsk Group [14,15]. We illustrate the possible effects of round beams for the Novosibirsk ϕ factory project in table 6. The claim is that a factor of 4 increase in luminosity will be gained using the round beam. The USSR Group has designed a solenoidal focusing system to achieve this gain (fig. 6). They also plan to use short bunches, however, recently this group has shown that there are severe problems with very short bunches [15] (a potential problem that must be addressed for the QIR as well).

(*) R. Seimans has long advocated using round beams (private communication).

Table 6 Basic parameters of the ϕ factory and beams, Novosibirsk [14].

Parameters		Units	ϕ factory	VEPP–2M
Circumference	c	M	≥ 32.6	17.88
Accelerating volt. feq.	f_0	MHz	700	200
Momentum compat. fact.	α	–	~ 0.04	0.167
Emittances	ε_{x0}	cm/rad	5×10^{-5}	4.6×10^{-5}
	ε_{z0}	cm/rad	5×10^{-5}	5.5×10^{-7}
Radiative energy loss/turn	ΔE_0	keV	33	9.1
Dimensionless damping	δ_x	–	1.3×10^{-5}	0.44×10^{-5}
Decrements bewtween	δ_z	–	1.3×10^{-5}	0.38×10^{-5}
Interaction points	δ_z	–	3.8×10^{-5}	0.94×10^{-5}
RMS energy spread at beam	$\sigma\Delta E/E$	–	7.7×10^{-4}	6×10^{-4}
Beta functions at IP	β_z	cm	~ 1	4.5
	β_x	cm	~ 1	48
RMS longitudinal bunch size	σ_s	cm	~ 0.7	3.5
Betatron tunes	υ_z	–	6.08	3.09
	υ_x	–	6.08	3.06
Number of particles in a bunch	n	e^+, e^-	$\lesssim 2 \times 10^{11}$	3.7×10^{10}
			(290 mA)	
Space charge parameters	ξ_z	–	≥ 0.1	0.05
	ξ_x	–	≥ 0.1	0.02
Luminosity in single-bunch mode	$\mathcal{L}_{max}$	$cm^{-2}s^{-1}$	$\geq 1 \times 10^{33}$	$\sim 1 \times 10^{31}$
Luminosity in triple-bunch mode	$\mathcal{L}_{max}$	$cm^{-2}s^{-1}$	$\geq 3 \times 10^{33}$	–

They note that σ_S = 0.8 cm is acceptable but for σ_S = 0.24 cm a severe increase in the tune shift dependence is observed [15].

Finally, on the subject of round beams, D. Möhl (and Al. Garren, private communication) has shown that the potential increase in luminosity [16] is off-set by the need to use quadrupoles for the final focus (fig. 7). For low-energy solenoid focusing can provide a correct solution to this problem as in the case of the Novosibirsk ϕ factory design (fig. 8).

3. The ϕ factories as test beds

In order to test the new principles inherent in the goals of novel flavour factories it is necessary to either use an existing Linac storage ring complex or to construct a new system entirely.

If we choose to use an existing complex, then one must accept certain built-in conditions which might prove limiting beyond acceptable limits. If we choose to construct a new system entirely then this system must be designed with sufficient flexibility to test the concepts as required. It is the latter choice which is being considered for the various ϕ factory projects. We give a brief comparison of ϕ factory designs around the world in table 7. The UCLA ϕ factory Project is proposed to follow a phased approach as given in table 8.

3.1 Conventional design

Two of the basic ideas behind the construction of ϕ factories is to construct a compact, high luminosity e^+e^- collider and to provide an environment that will serve as a base for an excellent educational program.

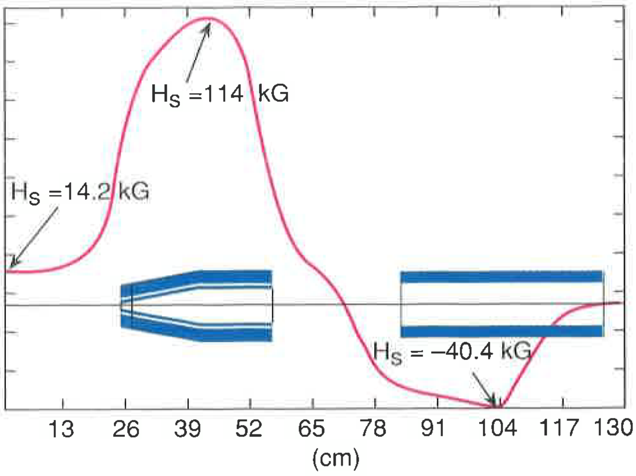

FIGURE 6

Interface region of the Novosibirsk ϕ factory design. The azimutal distribution of the longitudinal magnetic field on the solenoid axis in the experimental straight is plotted in this figure.

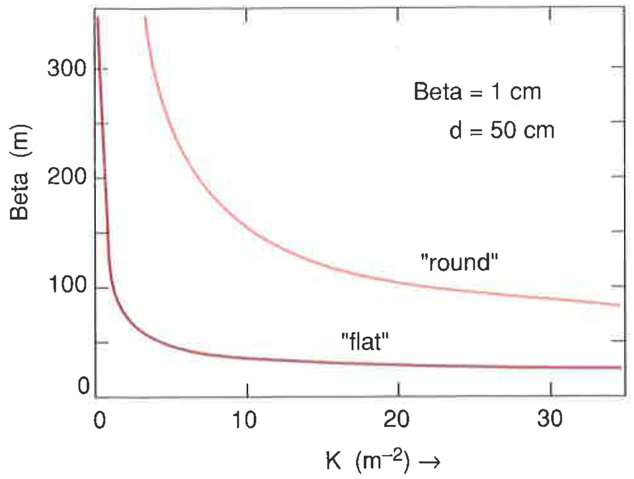

FIGURE 7

Maximum β vs quadrupole strength.

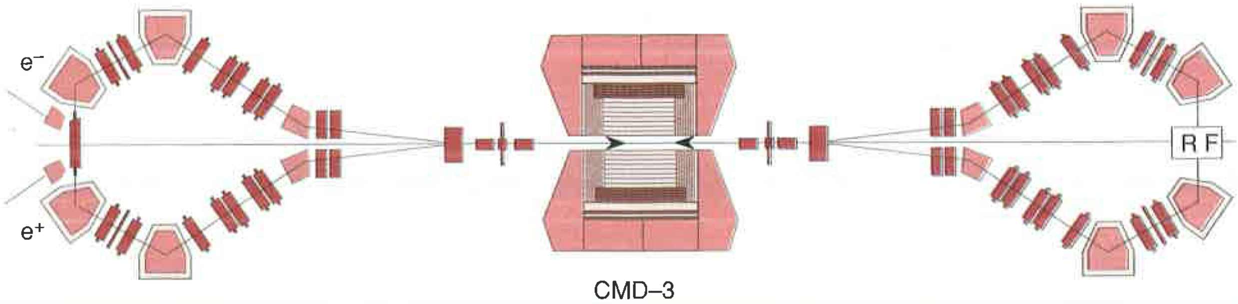

FIGURE 8

Novosibirsk ϕ factory design.

The compact nature of the machine increases the luminosity by obtaining a higher repetition rate. The compact structure is made possible by using high-field superconducting magnets similar to those being developed in Japan, West Germany, England and the USA for compact X-ray light sources. Thus, there is world-wide interest and expertise in this growing area of importance.

A schematic view of the Phase I (UCLA) ϕ factory complex is shown in figs 9(a) and 9(b). An initial set of parameters for the Phase I option is given in table 9 [17]. The UCLA ϕ factory Project will start with a quasi-isochronous design to be completed by 1996. The initial phase of the project (Phase I) is expected to reach 3×10^{32} cm^{-2}s^{-1} without the QIR condition. Phase II (shortly after 1996) is to reach $\mathcal{L} \sim 10^{33}$ cm^{-2}s^{-1} using the QIR condition. In order to go beyond 10^{33} the quasi-linear collider approach would be needed and may be planned around the year 2000! Note that the circumference in this design is 17.5 m [15]. The schedule for the construction of this complex is being worked on now but we hope it will be operational by the end of 1995.

3.2 Quasi-isochronous collider design

A study is underway at UCLA to design a 10^{33} cm^{-2}s^{-1} QIR ϕ factory; we expect this design to result in a slightly larger storage ring [16]. The principles were outlined in sect. 2.3. Very promising results have been obtained that will soon be presented in the point design proposal to the DOE.

Table 7
General characteristics of ϕ-factory proposals and projects.

Location	Circum.	Magnets/etc.	Luminosity $cm^{-2}s^{-1}$
Italy (Frascati)	~ 200 m	Normal many bunches Wigglers 2 rings	10^{32}
USSR (Novosibirsk)	~ 27 m	Superconducting Butterfly configuration round beam (to enhance lumin.) 1 ring	$\sim 2 \times 10^{33}$
USA (UCLA)	~ 21 m	Superconducting circular collider quasi-isochronous mode very short bunches considering round beam to enhance luminosity 1 ring	$\sim 2 \times 10^{32} - 10^{33}$
Japan (KEK)	~ 200 m	Normal many bunches flat beam 2 rings	$\sim 10^{33}$

Table 8
The UCLA ϕ factory Project.

Phase I	$\mathcal{L} \sim 2 \times 10^{32}$ $cm^{-2}s^{-1}$ *conventional* high current collider (like $\bar{B}B$ factories) (1 bunch e^+/1 bunch e^-)
Phase II	$\mathcal{L} \sim 10^{33}$ $cm^{-2}s^{-1}$ quasi-isochronus ring $B^* < 1$ cm $\alpha \sim 0$ ($\alpha \sim 1/\beta^* \sim 1/\sqrt{\alpha}$) or hybrid, multi-bunch + round beams[(a)]
Phase III	Asymmetric quasi linear Collider $\mathcal{L} > 3 \times 10^{33}$ $cm^{-2}s^{-1}$

(a) USSR/UCLA Collaboration study.

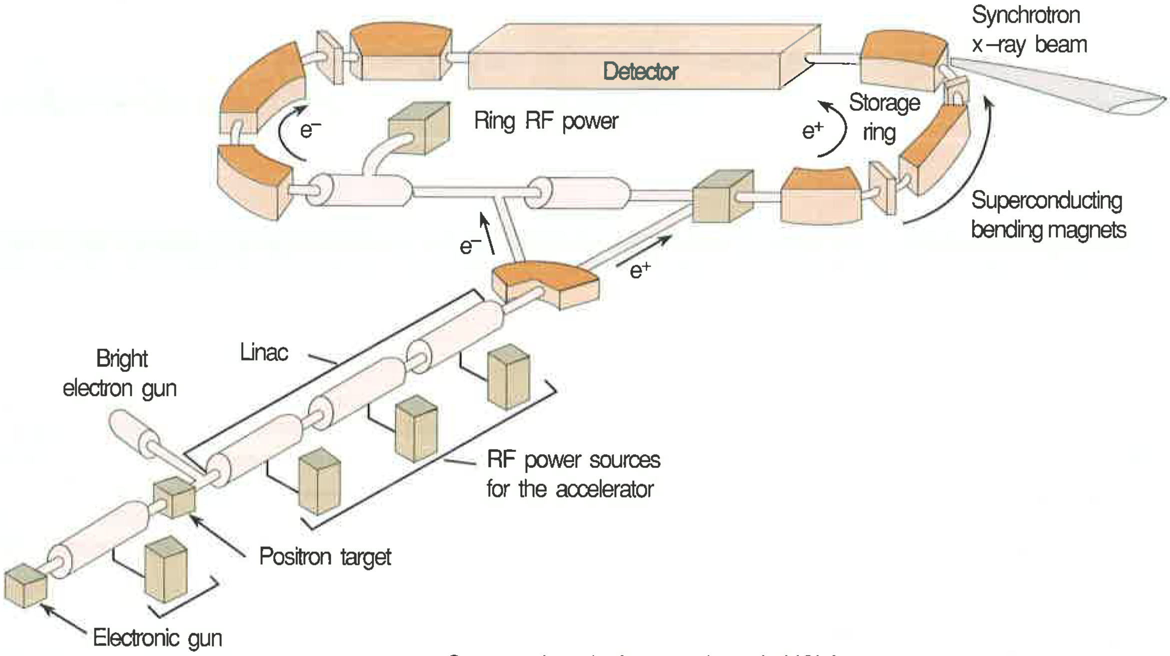

FIGURE 9(a)

Schematic of the UCLA ϕ factory.

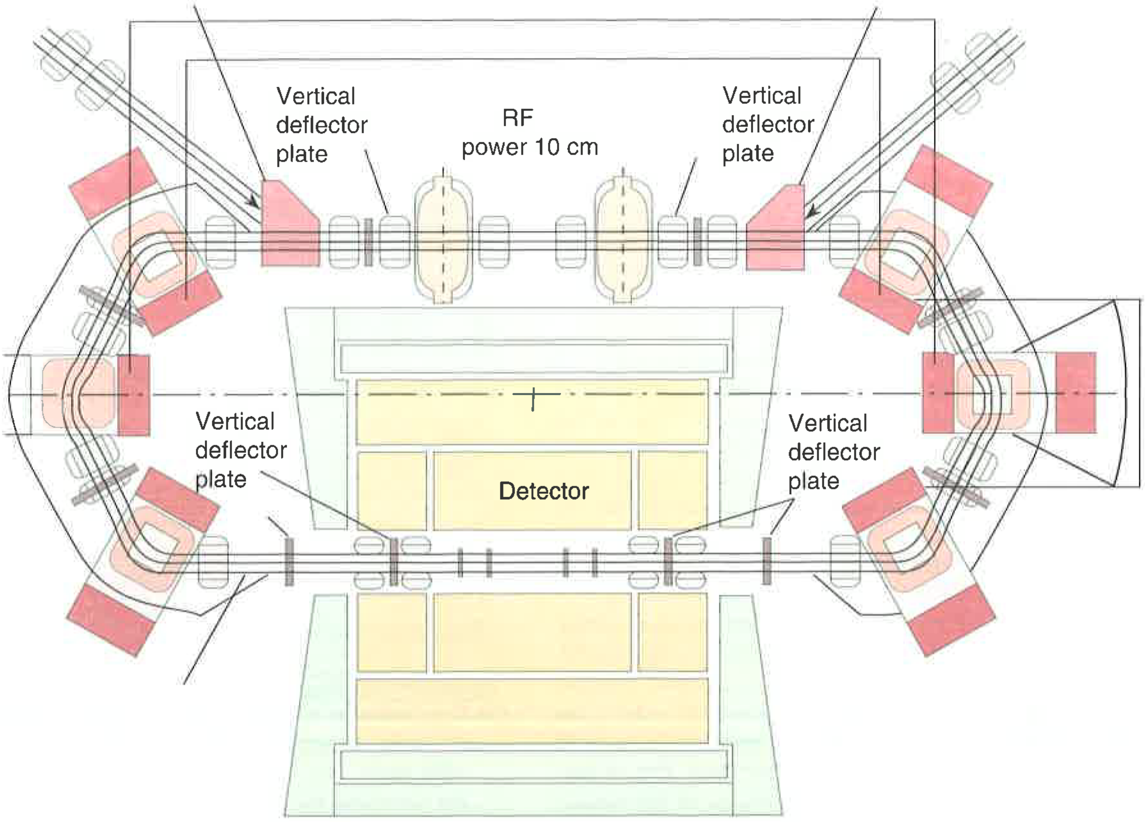

FIGURE 9(b)

Schematic of the Phase I UCLA ϕ Factory complex [17].

Table 9 Phase I ϕ factory [17].

Beam energy (MeV)	510	β_y at IP (cm)	3.9
Luminosity (cm^{-2}s^{-1})	2×10^{32}	σ_x at IP (mm)	1.1
Circumference (m)	17.4	σ_y at IP (mm)	0.2
Dipole bending radius (m)	0.425	$\delta\upsilon_x$	0.05
Betatron tunes, horizontal	2.1	$\delta\upsilon_y$	0.05
Betatron tunes, vertical	3.85	RF (MHz)	499
Momentum compaction	0.11	Harmonic number	15
Energy loss/turn. (keV)	14.1	RF voltage (kV)	400
Damping times, horizontal (ms)	4.6	Synchrotron tune	0.007
Damping time, vertical (ms)	4.2	Bunch length (cm)	3.0
Energy	2.2	Average current (A)	1.2
Natural emittance (mm/mrad)	3.2	Peak current (A)	270
Vertical/horizontal coupling	0.2	Z/n (Ω)	3
Number of particles/bunch	4×10^{11}	Lifetime, gas (10–9 Torr) (h)	1.8
Number of bunches/beam	1	Lifetime, Touschek (h)	2.5
Collision frequency (MHz)	17.2	β_x at IP (cm)	19

3.3 Round beam tests at Novosibirsk

The parameters of the Novosibirsk ϕ factory were given in sect. 2.3. We show the machine concept in fig. 8 for completeness. Note that this machine can, in principle, reach 3×10^{33} cm^{-2}s^{-1} if this concept works! Tests of the round beam enhancements will be carried out next year or so at Novosibirsk using VEPP–2M with modified beams. There will be an important test of some of these ideas at Novosibirsk in the next two years. The VEPP–2M machine (fig. 10) will be upgraded and operated with round beams. The luminosity is expected to be increased to ~ 10^{32} cm^{-2}s^{-1} (table 10) [18].

3.4 Compact detectors for compact ϕ factories

These compact storage rings require a detector for the ϕ physics that is designed as an integral and important part of the machine itself. Very careful integration of the detector into the collider is required [19]. However, the particle physics goals must not be compromised. In a recent study with M. Green of LBL we have identified the key problems and some possible solutions to the detector/machine interface [20] (figs 11 and 12 show schematic views of the USSR and UCLA detectors) which are:

(a) Measurement of ε'/ε to ~ 10^{-4}: the measurement of the direct component of CP violation in the K^0 system is among the most difficult measurements in particle physics. Current estimates give an expected value of ε'/ε ~ $(10^{-3} - 10^{-4})$. In order to measure this quantity we must measure the ratio of $K^0 \to \pi^0\pi^0/(K^0 \to \pi^+\pi^-)$ to incredible accuracy. Part of this measurement will entail a precise knowledge of the correction for *missed events.*

Table 10

Beam and optics parameters in round beam test experiment on the VEPP–2M collider in Wiggler-on operation mode [18].

Energy per beam	510 MeV
Circumference	17.88 M
Betatron tunes (in rotating frame)	3.1
Momentum compaction factor	0.18
Accelerator voltage frequency (q = 12)	200 MHz
RF voltage amplitude	70 kV
Radiative energy loss per turn	9.1 keV
RMS energy spread in the beam	6×10^{-4}
RMS emittances	2×10^{-5} cm/rad
Space charge parameter ζ	0.1
Number of particles per bunch	8.9×10^{10} cm^{-2}s^{-1}
Beam current	240 mA
Beam lifetime	1000 s
Luminosity	1.3×10^{32} cm^{-2}s^{-1}
β-function value in interaction point	4 cm

(b) Compensation technique: the current strategy adopted by all ϕ factory researchers is to maintain a 98% coverage of the solid angle. The reason for this precision is the need to keep the correction for *missed events* to ~ 2% and the uncertainty of the correction to an acceptable value of ~ 2.0%. If, for

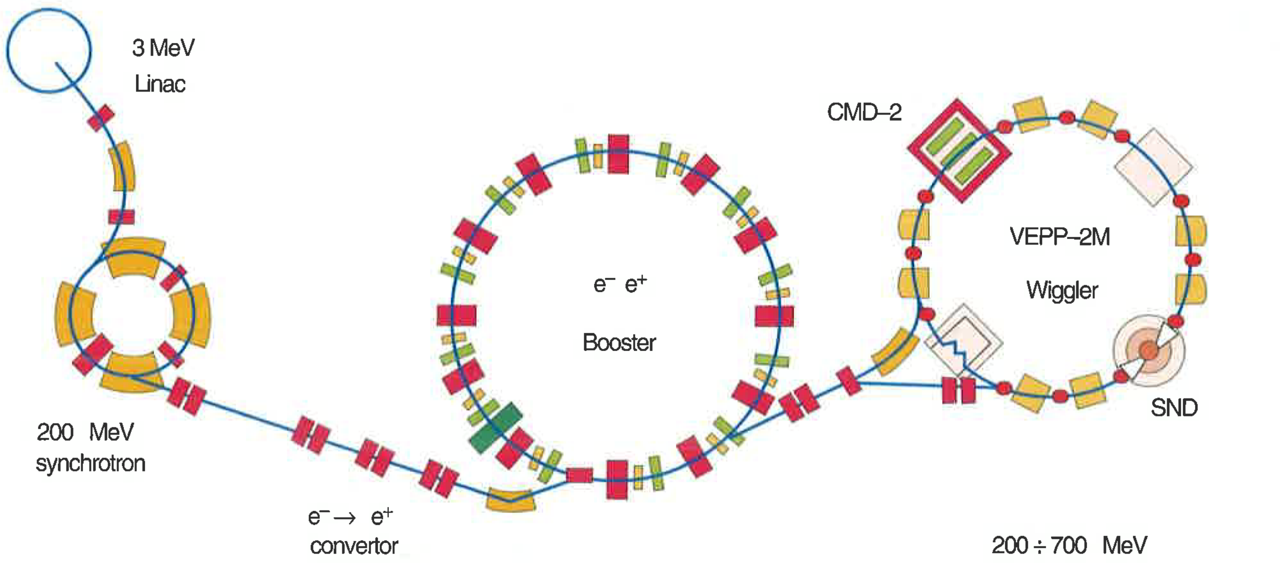

FIGURE 10

Layout of the VEPP–2M complex.

example, we lose 30% of the solid angle, the correction for *missing events* must be known to ~ 0.5% or better. At this time, such a precision is likely to be impossible.

(c) Final focus to obtain low β^*: as explained above, we must concentrate on keeping the solid angle to a minimum in order to control the correction for *missing events*. Therefore, we have a specific preference in regard to the final focus. We prefer the final focus to be $\gtrsim$ 50 cm from the IP.

(d) Background calculations in the detector: background calculations are crucial when the machine design is fixed. There have been extensive calculations for the Novosibirsk scheme and calculations are in progress at UCLA. The Novosibirsk calculations indicate that the background rates can be kept low provided various masking is carried out at different places in the machine [21]. However, the round beam tests of VEPP–2M discussed above will provide empirical information about this problem.

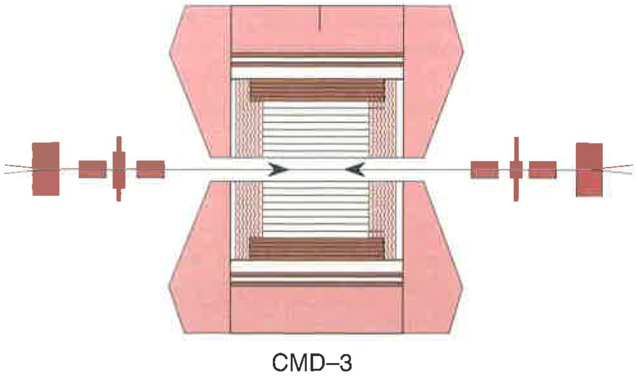

FIGURE 11

Novosibirsk ϕ factory detector.

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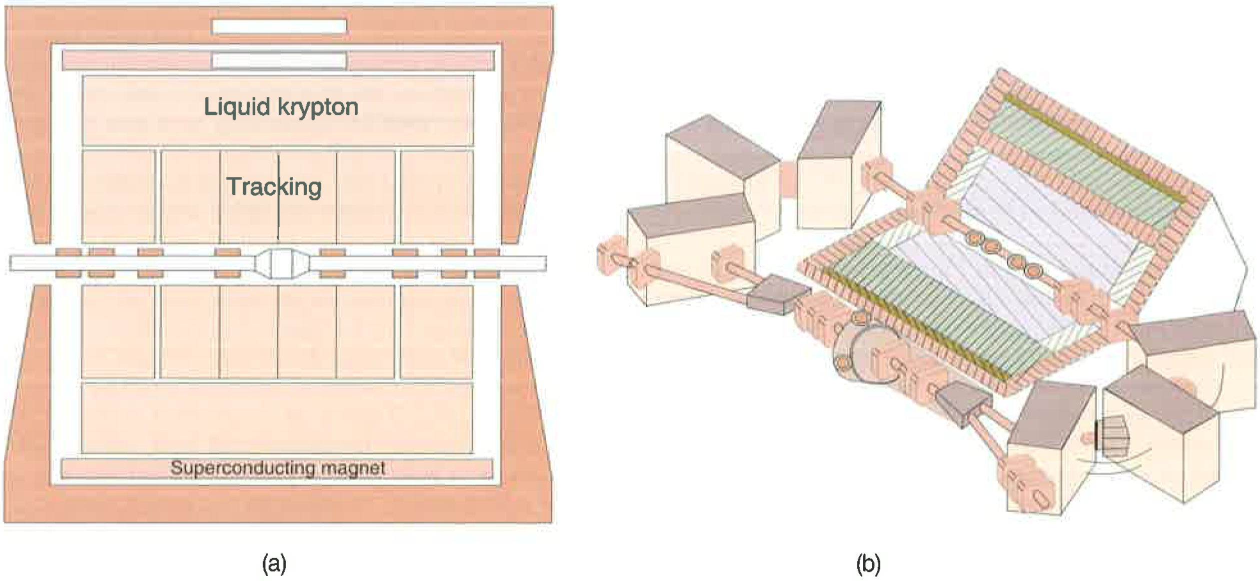

FIGURE 12

Schematics of the detector for the UCLA ϕ factory complex.

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