DEVELOPMENT OF AN ASYMMETRIC ϕ FACTORY FOR PRECISION CPT TESTS*

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ABSTRACT

We describe the concept of a high-luminosity asymmetric ϕ factory and show how high-intensity, strangeness-tagged $K^0/\overline{K}^0$ particles can be obtained for CPT tests. We also describe the concept of an asymmetric ϕ factory using linac storage rings. Finally, we describe the study of a powerful linac storage-ring collider that could give an asymmetric-ϕ-factory luminosity of 10^{34} cm^{-2} s^{-1}, making for the ultimate CPT tests.

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1. INTRODUCTION

The final frontier of particle physics may occur at the Planck scale (~ 10^{19} GeV). In as much as there is no known method to produce such energies, two tests have been proposed to study this region:

1. If proton decay is observed, and if it proceeds through the exchange of an X particle of mass of ~ 10^{16} GeV, there could be interference effects due to the Planck mass exchange.
2. CPT could be violated at the Planck scale if locality of the fields is broken.[1]

Both of these types of measurements are extremely hard to do. We discuss here the search for CPT violation using a special type of ϕ factory called an "asymmetric ϕ factory ."[2,3]

In Fig. 1, we trace the road to ϕ factories (this is from work we did in the late 1980s).[1] Note that it has taken nearly 30 years to actually build a ϕ factory (DAϕNE), which should operate in 1997. Unfortunately, the UCLA symmetric ϕ factory (which used an entirely different approach) was not approved by the US Department of Energy in 1991.

The test for CPT violation that uses $K^0/\overline{K}^0$ beams attempts to measure the CPT violating parameters shown in Fig. 2. Since there is no real theory of CPT violation, it is hard to "predict" the nature of a signal for this violation. However, we know that present limits are not all that far from the possible Planck-scale violation effects.

2. SYMMETRIC VS ASYMMETRIC ϕ FACTORIES

Many virtues of a symmetric ϕ factory were emphasized in a 1990 workshop at UCLA and published in the proceedings.[1] The concept of an asymmetric ϕ factory arose in 1992 at another workshop at UCLA;[2] there was also a workshop on symmetric ϕ factories in 1993 at UCLA. Figure 3 gives a comparison of the K_s^0 decay length for the two (symmetric and asymmetric ϕ factories), showing the large difference. This is the key parameter to be able to tag $K^0/\overline{K}^0$ in a model-independent way.

A second useful aspect of an asymmetric ϕ factory is the possibility of tagging the strangeness of the beam by the strong interaction of the K^0 or $\overline{K}^0$, e.g.,

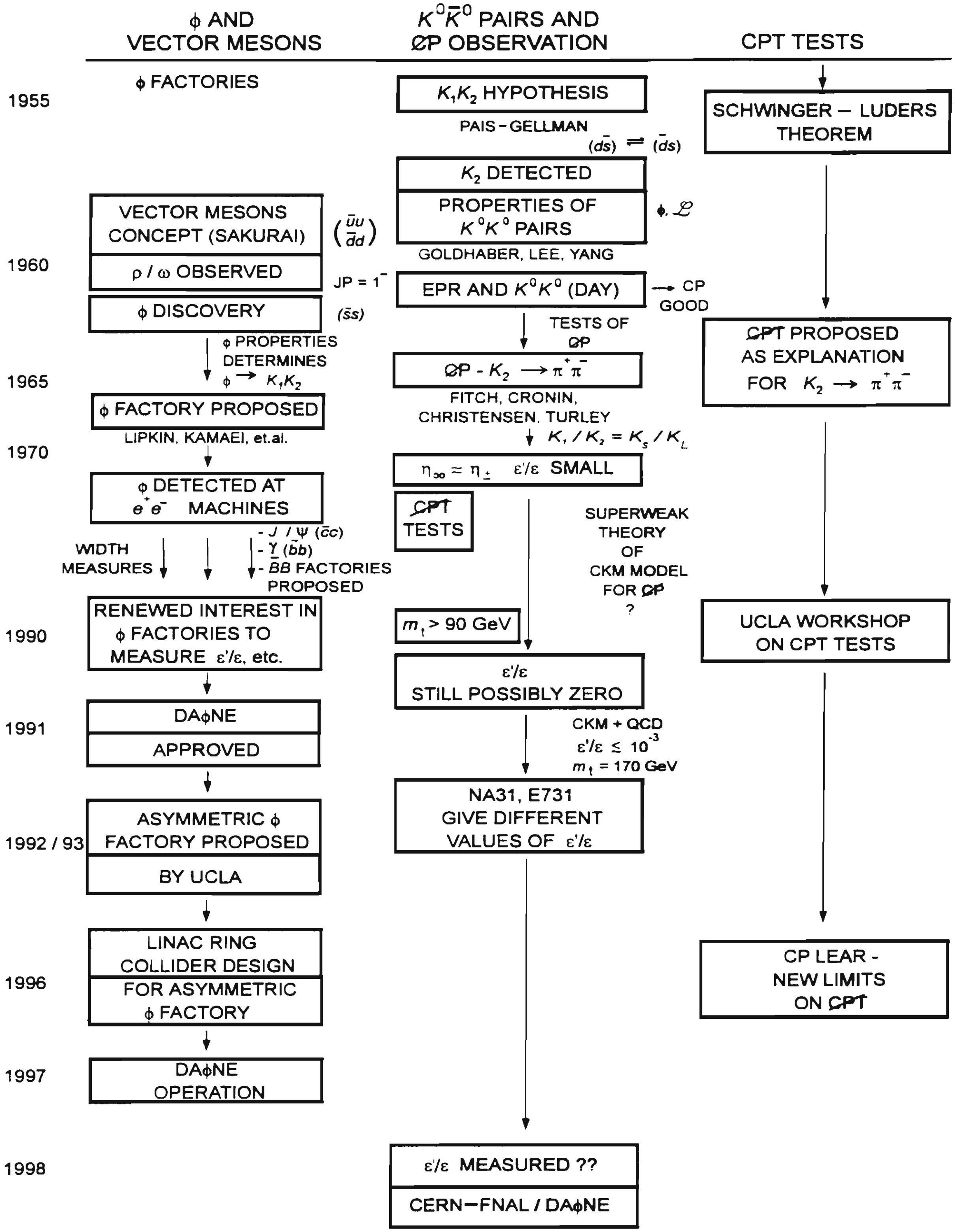

Fig. 1. Road to ϕ factories and CPT tests.

$$|K_s^0> \frac{1}{\sqrt{2(1+|\epsilon+\delta|^2)}}\{[1+(\epsilon+\delta)]\,|K^0>+[1-(\epsilon+\delta)]\,|\bar{K}^0>\} \;,$$

$$|K_L^0> \frac{1}{\sqrt{2(1-|\epsilon+\delta|^2)}}\{[1+(\epsilon-\delta)]\,|K^0>-[1-(\epsilon-\delta)]\,|\bar{K}^0>\} \;,$$

$$\eta_{\pm} = \epsilon_0 + \epsilon' \;, \qquad \epsilon_0 = \epsilon - \delta - \lambda_0 \;, \qquad \lambda_0 = \frac{(\bar{A}_0 - A_0)}{(\bar{A}_0 + A_0)} \;,$$

where δ = CPT in mass matrix. and λ_0 = CPT in direct amplitude.

Fig. 2. K_s^0/K_L^0 formulation with CPT violating parameters indicated.

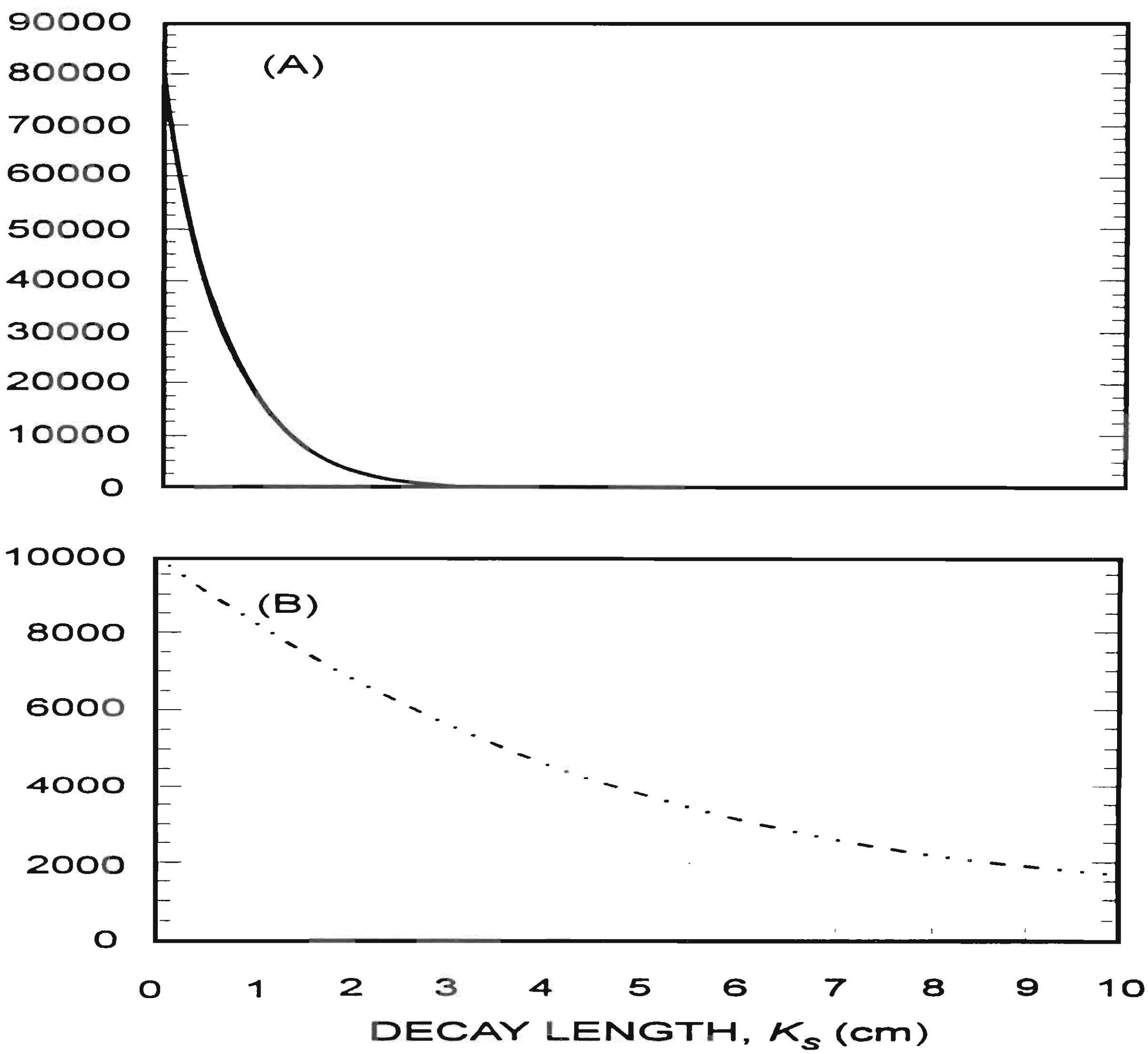

Fig. 3. K_s decay length for (A) symmetric and (B) asymmetric ϕ factories.

$$\phi \to K^0/\overline{K}^0 \quad , \quad \overline{K}^0 + p \to n + \overline{N}^+ \quad ,$$

$$\phi \to K^0/\overline{K}^0 \quad , \quad K^0 + p \to K^+ + n \quad .$$

If the $K^0/\overline{K}^0$ is tagged at $t = t_a$, the other particle in the ϕ decay must be the antiparticle at that time, thus giving a particle/antiparticle-identified beam.[3] A detailed comparison of tagged $K^0/\overline{K}^0$ beams leads to extremely precise CPT tests, some of which are listed in Table 1. We emphasize that this tag does not rely on the use of the $\Delta S = \Delta Q$ rule.

A third feature of an asymmetric ϕ factory is the possible realization of very high luminosity in a linac storage-ring collider, which we will now discuss.

Table 2 lists the various types of asymmetric ϕ factories with some pros and cons for the different schemes.[2] In this paper, we only discuss the linac collider option with a high-energy e^+-beam storage ring and a low-energy e^--beam.

The basic idea to enhance the luminosity of a linac ring collider is shown in Fig. 4(A) and (B). A high-current, high-energy stored e^- beam interacts with a lower-current, lower-energy e^- beam and, in the process, the e^- beam is pinched into the e^+ beam, giving a high-density e^+e^- beam, with the resulting e^- beam fully disrupted, as shown in Fig. 4(B). This process occurs at high frequency, giving rise to a possible high luminosity. Care must be taken that the low-current e^- beam does not cause other types of damage (e.g., a displacement, etc.) to the e^- beam. We believe these and many other problems can be overcome if the high-energy e^+ storage ring has a very fast damping time to erase such displacements and other problems. Other schemes for asymmetric ϕ factories have been proposed.[4] A key issue is the dynamics of the beam–beam interaction, which has been studied elsewhere.[5,6]

3. A POSSIBLE, POWERFUL LINAC STORAGE-RING ASYMMETRIC ϕ FACTORY

The linac ring scheme that is being studied at UCLA is shown in Fig. 5. A powerful compact storage ring that uses 7-T superconducting bending magnets is used for the positron beam. Table 3 gives some parameters for the storage ring. Note that the damping times are 200–400 μs! An advanced linac such as Tesla, which is shown schematically in Fig. 5,[6] is used for the e^- beam. Table 4 gives the required parameters of the linac and the overall parameters required to reach a luminosity of 10^{34} cm^{-2}s^{-1}.

Table 1. Methods to Tag the K^0 Strangeness with an Asymmetric ϕ Factory

If ϕ » $\overline{K}^0_i K^0_j$ $(t_i = t_j)$,

(i) $\overline{K}^0_{i,j} + p \rightarrow \Lambda + \pi^-$ for flavor ID in a connector (do not need $\Delta S = \Delta Q$ rule for test)

(ii)

- $\overline{K}^0_i \rightarrow \pi^+ e^- \overline{\nu}$, — $\Delta S = \Delta Q$ rule assumed $t_i = t_j$
- $\overline{K}^0_j + p \rightarrow \Lambda + \pi^-$, — Flavor ID

(iii)

- $\pi^+ e^- \overline{\nu}_e$
- $\pi^- e^+ \nu_e$

$\Delta S = \Delta Q$ rule assumed $t_i = t_j$; unique e^- ID using forward C counters and magnetic spectrometer

(iv) ϕ » $K_i K_j$ — Symmetric or asymmetric ϕ factory

↓ ↓

$\pi^+\pi^-$ — $(t_i = t_j)$; possible serious background from $\phi \rightarrow K_S K_S \gamma$

Table 2. Types of Asymmetric ϕ Factories

Type	Advantages	Disadvantages
1. Low-energy e^- storage ring or accumulator and high-energy e^- linac	(A) Rapid damping time e^+ means reduced instabilities (B) Easy to produce low-energy e^- storage ring	(A) Need high rep rate e^- linac (B) High-energy linac expensive
2. Low-energy e^- linac and high-energy e^- storage ring	(A) Low-energy super-conducting linac (B) e^- trapped in e^+ bunch	(A) Expensive e^- source (B) Damping time of e^+ ring may allow build-up of instabilities
3. e^- linac or e^+ linac	Requires novel e^+ source for e^+ linac	
4. e^- storage ring on e^+ storage ring	More difficult than a symmetric e^-e^- collider	

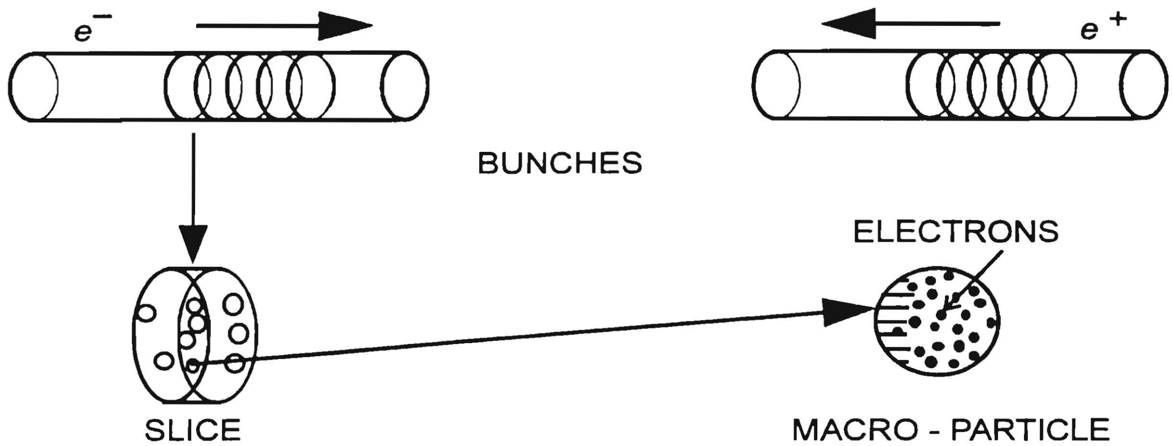

Fig. 4. (A) Collision model where colliding bunches are divided into slices, with each slice populated with a random distribution of macroparticles containing the charged particles. The overall behavior of the particles in the bunches is approximated by the behavior of the macroparticles.

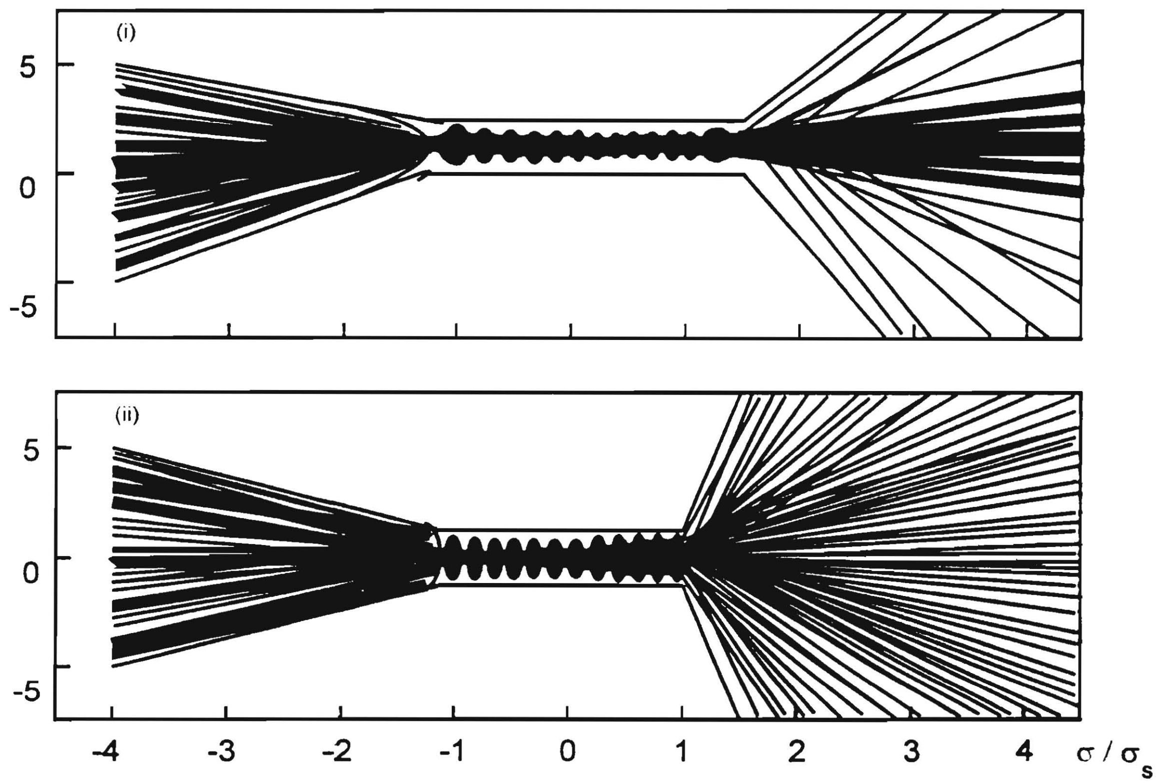

Fig. 4. (B) Electron trajectories at the collision point (2σ contour) viewed in the test frame of the positron bunch with (i) Gaussian and (ii) parabolic longitudinal distributions.

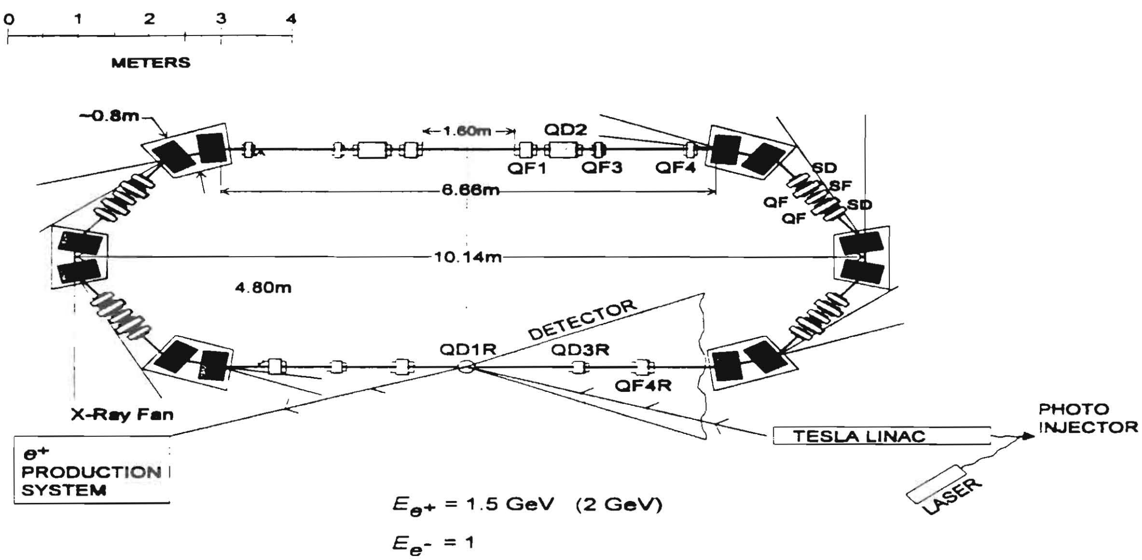

Fig. 5. UCLA ultra-compact light source and asymmetric ϕ factory.

4. TESTS OF QUANTUM MECHANICS

The asymmetric ϕ factory concept provides for novel tests of quantum mechanics. One possibility, which was devised by P. Eberhard is shown in Fig. 6.[7] The rates in the various configurations should show clearly the effects of quantum interference, which has never been measured for a $K^0/\overline{K}^0$ correlated pair.[7]

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Table 3. Lattice Parameters for the Compact Storage Ring

Maximum stored-beam energy (GeV)	1.5
Projected injection-beam energy (GeV)	0.1
Projected beam current (mA)	-200
Circumference (m)	26
Bend radius (m)	0.7257
Dipole bend angle (deg)	30
Integrated dipole induction* (T m)	2.6197
Dipole central induction (T)	6.894
Dipole magnetic length along the bend (m)	0.38
Critical energy (keV)	10.3
Horizontal natural emittance* (μm)	2.34
Vertical coupled emittance* (μm)	1.17
Vertical operating emittance* (μm)	0.0234
Horizontal tune	3.17
Vertical tune	2.57
Horizontal chromaticity	-2.22
Vertical chromaticity	-5.24
Maximum horizontal beta function (m)	3.09
Maximum vertical beta function (m)	6.66
Maximum dispersion (m)	1.29
Energy loss per turn* (MeV)	0.617
RF voltage (MV)	2.5
RF frequency (MHz)	499
Energy spread (parts in 1000)	1.52
Bunch length rms* (mm)	30
Horizontal damping time* (ms)	0.412
Vertical camping time* (ms)	0.422
Energy damping time* (ms)	0.213
Quantum lifetime (s)	2.2×10^8

*At the maximum beam-energy design.

Table 4. Asymmetric ϕ-Factory Linac Calculations

No. of electrons	$N_e = 10^{10}$
Electron avg repetition rate	$f_e = 5 \times 10^5$
No. of positrons	$N_p = 10^{11}$
Positron period	$T_p = 87 \times 10^{-9}$
Positron avg repetition rate*	$f_p = T_p^{-1}$
Electron current	$I_e = 8 \times 10^{-4}$ ($I_e = N_e \times 1.6 \times 10^{-19} \times f_e$)
Duty cycle of electrons	$\eta = 0.044$ ($\eta = f_e/f_p$, $4 \times$ Tesla test facility)
Accelerating gradient in Tesla linac	$E_{acc} = 1.5 \times 10^7$
Electron beam energy (eV)	$E_e = 1.8 \times 10^8$
Active length of linac	$L_{acc} = 12$ m ($L_{acc} = E_e/E_{acc}$)
Normalized emittance of electrons	$\epsilon_e = 2 \times 10^{-6}$
Physical electron emittance	$\epsilon = 5.678 \times 10^{-9}$ ($\epsilon = \epsilon_e/\gamma$, where $\gamma = E_e/5.11 \times 10^5$)
Positron energy (eV)	$E_p = 1.5 \times 10^9$
Luminosity ($cm^{-2}\ s^{-1}$)	$\mathcal{L} = 10^{34}$

*Same as electron avg repetition rate during linac pulse.

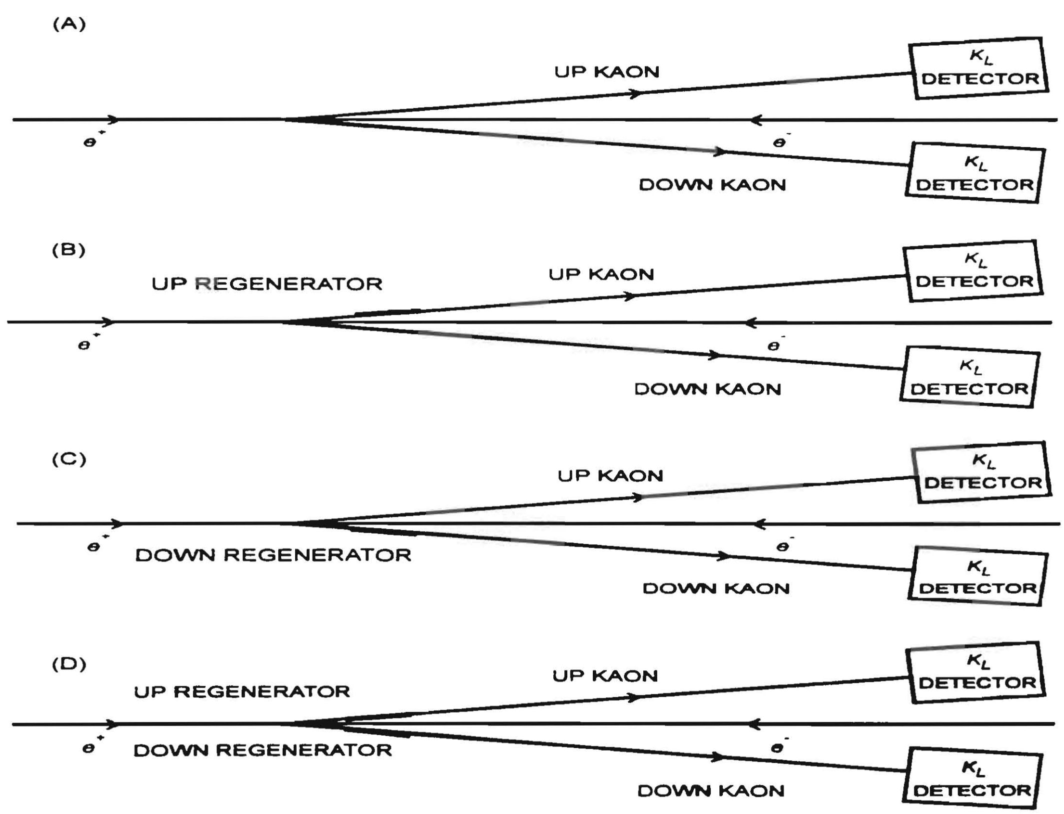

Fig. 6. Setups for the destructive interference test.