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CAPRI: AN ASYMMETRIC ϕ FACTORY TO TEST CPT AND QUANTUM MECHANICS†

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ABSTRACT

We describe the scientific motivation for a novel ϕ factory: the California Asymmetric Phi-Factory or CAPRI. The goals include a detailed test of CPT and $\Delta S = \Delta Q$ violation, as well as unique test of Quantum Mechanics. We study two classes of asymmetric ϕ factories with either high energy or low energy e^+ storage rings. We show that a high energy linac low energy e^+ collider offers the best chance for success.

1 INTRODUCTION

The enormous success of the Standard Model (SM) of elementary particles leads us to look into physical phenomena that may go far beyond the current energy range of the SM. One hope was the observation of proton decay that could probe the Grand Unification Theory (GUT) energy scale of $\sim 10^{15}$ GeV. The current limits on proton decay are close to the limits of observability on earth.* A tiny neutrino mass might hint at a very high mass scale through the see-saw mechanism. However, the current evidence for a non-zero neutrino mass is far from compelling. CP violation not only remains a puzzling symmetry violation but may provide a window into an even higher mass scale: the Planck Mass. Because of the existence of CP violation, it is possible to search for very tiny violation of the CPT symmetry and perhaps even Quantum Mechanics (QM) in the $K_S^0 K_L^0$ system[1,2,3].

Over the past 10 years there have been repeated suggestions, starting from S. Hawking, that CPT symmetry may not be entirely sacred[2]. Recently, some strong interation particle theorists and black hole advocates have joined the discussion. (See the recent CERN report from J. Ellis, D. Nanopolous, etc.)

How can we probe CPT and QM breakdown[1,2,3]? It has recently been proposed by M. Kobayashi and A. Sanda that B factories might be used for this purpose[1]. While this is a possibility, we believe that different types of ϕ factories are likely to provide the greatest sensitivity in the foreseeable future[2,3].

Symmetric ϕ factories have been studied extensively at Novosibirsk, UCLA, KEK, and Frascati[2,3]. At Frascati they now have the good fortune to be funded to construct DAPHNE[3]. In the US, at present, foresight seems lacking by the Witherall panel and the US DOE seems shortsighted, as they have disapproved the UCLA symmetric ϕ factory project. While we believe

† Invited talk at the Frascati Conference on DAPHNE and Other Physics, held Nov. 1992 and to be published in World Scientific, "γ and Neutrino Cosmology and Physics from the Planck Scale", 1993.

* The current proton decay limits for $p \to K^+ \bar{\nu}_\mu$ decay are also close to the limits of observability on earth. Recent extrapolation to the unification energy gives an expected lifetime for $p \to e^+ \pi^0$ of $\sim 10^{36} - 10^{38}$ years.

this to be a serious 'lack of vision', there is little that a University based Consortium can do to change the direction of a large federal bureaucracy and its minions once in motion.

In retrospect it seems fair to say that a similar 'lack of vision' occurred when the decision was made to let CERN carry out a rapid construction of the $\bar{p}p$ collider, [as suggested by C. Rubbia and P. McIntyre (both then of Harvard) and myself]. The result was that the W and Z were discovered in Europe. And yet another example of limited foresight could be sited in the case of the Gallium experiments. Gallex was started in the US. Failing to obtain support funding, the experiment was moved to Europe.

Fortunately for the US scientific effort, other ideas exist when the problem of short-sightedness hits the scientific funding agencies in this country. One such idea is an Asymmetric ϕ Factory concept. We believe it can play a unique role in the search for CPT and QM behavior and are pursuing funding in order to make this idea a reality.

2 TESTS OF CPT AND QUANTUM MECHANICS AT AN ASYMMETRIC ϕ FACTORY

Tests of CPT and QM* rely on precise measurement of K_S^0 decays and the ϵ_S parameter in the K_S^0, K_L^0 system. Any deviation from $\epsilon_S = \epsilon_L$ would signal a breakdown. Such a breakdown could occur in the semi-leptonic or non-lepton channels.

The ultimate problem of measuring ϵ_S at a symmetric ϕ factory is the level of systematic errors due to the very small decay length. An asymmetric ϕ factory, therefore, offers the potential of a superior measurement of ϵ_S and of CPT tests. Our goal will be to test CPT, in model independent fashion, to the level of

$$\frac{M_{K^0} - M_{\bar{K}^0}}{\langle M_K \rangle} \leq 10^{-19}$$

which is in the same range as

$$\frac{M_{\text{Quark}}}{M_{\text{Planck}}} \sim 10^{-18} - 10^{-19}$$

At this level it is quite possible that CPT could be violated.

A. *Concepts for Testing CPT*

1) $\phi \to K^0 \bar{K}^0$

This concept allows unique and direct comparison of the properties of K^0 and $\bar{K}^0$. No other system is as clean, i.e. $\bar{p}p$, or has the potential rate of events.

2) CPT Test

These tests require some tag of the flavor of the state, since $K^0 - \bar{K}^0$ comparisons must be made. They can be made in several ways:

a) Assume $\Delta S = \Delta Q$ Rule, then

$$K^0 \to \pi^+ \ell^- \bar{\nu}_e$$
$$\bar{K}^0 \to \pi^- \ell^+ \nu_e$$

However, $\Delta S = \Delta Q$ could fail at the same level as CPT and CP

b) Flavor Tag

The flavor tag in this case would be

$$\bar{K}^0 + p \to \vee + \pi^+$$

* The following is but a brief review. To learn more see Refs. 2,3,5,6,7

c) Regeneration
Amplitudes for KN and $\bar{K}N$ are very different, for example, $\bar{f} > f$ at low energies.

d) Allowing both CPT and $\Delta S = \Delta Q$ to be violated provides a very complex analysis situation.

How large could CPT violation be? In Fig. 1 we show the constraints in CPT from the 2π, K^0 decay. We also note that, for CPT violation, the unknown direct amplitude and mass matrix terms could even cancel. Thus, if they cancel, this would allow a significantly larger violation than is currently assumed. This possibility is worth pursuing. We believe both a symmetric and an asymmetric ϕ factory can contribute to unravelling this possibility[7].

B. *Concepts for Testing QM*

Testing QM requires measurements that include putting regulators in the "K_S^0 beam". Decay processes don't play the same role (see Refs. 5 and 6).

A clever method to test for locality in QM has been devised by P. Eberhard[5,6]. In Fig. 2 this method is shown. Since regenerators have to be inserted into the "K_S^0 beam", this test requires an asymmetric ϕ factory[6].

3 KINEMATICS OF ϕ FACTORIES

The goals of ϕ factories are: (1) Measurement of $[\epsilon'/\epsilon]$ to $\sim 10^{-4}$, (2) Search for CP violation in other decays (such as $K_S^0 \rightarrow \pi^0\pi^0\pi^0$), and (3) Search for possible CPT violation at a very sensitive level (such as $(M_{K^0} - M_{\bar{K}^0})/M_K < 10^{-18}$). In this section we compare the kinematics of symmetric and asymmetric ϕ factories and show how the experimental precision can be increased and the detector simplified for the latter case.

We consider the ϕ factory configuration in which a 2 GeV/c e^- linac beam collides with a stored 120 MeV/c e^+ beam. A scintillating fiber Pb detector covering the angular region of ± 60o is assumed for the purpose of reference. This will lead to a sharply reduced detector cost compared to a symmetric ϕ factory.

The major problem of studying K_S^0's at a symmetric ϕ factory is the very short decay length compared with the experimental resolution of final states, such as

$$K_S^0 \rightarrow \pi^0\,\pi^0 \tag{1}$$

$$K_S^0 \rightarrow \pi^0\,\pi^0\,\pi^0 \tag{2}$$

Shown in Figs. 3a and 3b are comparisons of the decay length distribution for the two cases. In Table 1 we give a figure of merit of the two cases, showing the considerable advantage of the asymmetric ϕ factory. In addition, all new tests of quantum mechanics at ϕ factories require the insertion of some material into the beam in order to perform the measurement. An asymmetric ϕ factory allows inserts of $(1-2)$ cm of material, thus providing the only way to test QM.

Another comparison to be made concerns the energy distribution of the photons from reaction (1). We expect reaction (2) to give similar results.

The second major problem of a symmetric ϕ factory is the very low energy tail of the photon distribution. It is difficult to detect photons with energy below 100 MeV with high efficiency. This difficulty is exacerbated for photons below 50 MeV. The photon energy spectra for the symmetric and asymmetric cases is compared in Figs. 4a and 4b.

The combination of extended decay length and harder photon spectrum considerably increases the advantage of an asymmetric ϕ factory. Superimposed in cross-hatch on Fig. 4 is the energy distribution for photons as angles less than 60° with respect to the high energy beam direction.

This spectrum, shown in Fig. 4b, is fairly hard and allows a relatively simple and inexpensive detector. We estimate the cost of the detector will be $\sim$ 10% of the cost of the 4π detector previously proposed for the UCLA symmetric ϕ factory concept. In Table 2 we give some general arguments in favor of an asymmetric ϕ factory.

4 ASYMMETRIC ϕ FACTORIES

The types of asymmetric ϕ factories and some pros and cons for these machines are listed in Table 3. There have been other discussions of asymmetric ϕ factories[8]. We will consider type 1 (as presented in Table 3) here and will return to a comparison in a later section. Two specific methods to produce an asymmetric ϕ factory are considered here.

A. *Method 1:*

Let us consider a method employing two approximately collinear beams of e^+ and e^- with energies E_1 and E_2. The center of mass energy is given by

$$E_{cm} = \sqrt{2E_1E_2\,(1 - \beta_1\beta_2\,\cos\theta} \tag{3}$$

where θ is the angle between the beam (0^0 for collinear). In order to obtain a center of mass energy of the ϕ resonance and well below $\sqrt{2E_1E_2}$, we will require that the beam cross at a small angle such that $(1 - \beta_1\beta_2\cos\theta)$ is small. The net momentum of the ϕ is given by $(\bar{P}_1 + \bar{P}_2)$. In the case we study here we choose that $E_1^{e^-}$ be 2 GeV and $E_2^{e^+}$ be 1 GeV. Thus, the net momentum of the ϕ is $\sim$ 3 GeV/c and the momenta of the K_S, K_L will be $\sim$ 1.5 GeV/c. The mean K_s decay length will then be $\sim$ 2 cm and the K_S, K_L will be produced at an angle of $\sim 4°$. The $K_S \to \pi\pi$ mean angle of the π's will then be $\sim 16°$. The energy of the π^0 and γ from the decays will be similarly boosted. This will greatly simplify the detector for the ϕ physics. However, we note that the net ϕ energy should not be too great or the detector problems will again increase due to the small angles of the decay products.

What we proposed here, in method 1, is to colider a very intense low emittance e^- beam, produced by a compact linac with a high current stored e^+ beam, in a compact superconducting storage ring. This scheme is shown schematically in Fig. 5. The beams are made to cross at the appropriate angle to produce the ϕ mass in the e^+e^- rest frame. To insure maximum overlap beam density and luminosity, a crab crossing scheme may be useful. We also explore the possibility of increasing the interaction probability of increasing the interaction probability by having the e^+ and e^- beams cross at several points in the interaction region in an oscillatory fashion. In principle, there could be many such beam crossings and the luminosity could be considerably enhanced.

The luminosity of the collider, assuming cross angles comparable to the physical crossing angles and large energy asymmetry, is given by

$$\mathcal{L} = \frac{f N_{e^+}\, N_{e^-}\, H}{4\pi\sigma_x\sigma_y}\,\ell\sin^2\theta \tag{4}$$

where f is the interaction frequency, N_{e^+} is the number of positrons in each bunch, N_{e^-} is the number of electrons in each linac bunch, σ_x and σ_y are transverse beam sizes, H is the pinch enhancement, and ℓ is the number of different interactions the beams make in the interaction area. We take the following parameters for illustration:

$$H = 1, \quad f = 2\times 10^4\,\mathrm{sec}^{-1}, \quad N_{e^+} = 2\times 10^{11},$$
$$N_{e^-} = 5\times 10^{10}, \quad \sigma_x = \sigma_y = 10^{-4}\,\mathrm{cm},$$
$$\ell = 4, \quad \text{and} \quad \sin^2\theta = 1/4.$$

The resulting luminosity is

$$\mathcal{L} \simeq 1.6\times 10^{33}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1} \tag{5}$$

Note that these beams are not expected to be seriously disrupted due to the collinear nature of the collision. There will, however, be some electrostatic pinch for these collinear beams. We expect that the storage ring will need to be refilled every 4 – 5 hours under any extent. Since the revolution frequency of the storage ring is 14 MHz and the collision rate is 10^4 Hz, the positrons generally have 10^3 revolutions between collisions to partially damp out the effects of the interaction. Several bunch operations of the collider will also be envisioned.

The e^- linac should be a very compact device modeled on the 1 GeV X-band test linac presently being constructed at SLAC. The e^- beam is driven by a bright RF gun/photocathode source. The e^+ storage ring is expected to follow the initial design of the UCLA symmetric ϕ factory storage ring with a modified lattice proposed by A. Garren and W. Gabella[9,10]. The storage ring will be 18 m in circumference. The positron source also follows the UCLA symmetric ϕ factory design[10]. It is not clear, however, that full energy injection is required in the present case since it was originally proposed for the e^+e^- beam colliding in the same storage ring for the UCLA symmetric ϕ factory. It may be possible to accelerate the storage ring to the desired energy and obtain the desired high current operation. These options will be studied in the forthcoming report.

B. Method 2:

A second method to produce an asymmetric ϕ factory is to achieve head on collision between the 2 GeV/c^2 e^- beam and a stored e^+ beam of energy 120 MeV/c^2. This method is illustrated in Fig. 5. The positron storage ring can be constructed with normal magnets and the positron source can be generated using the spent e^- beam after the collision. The e^+ beam would have to be matched to the e^- beam in order to obtain the highest possible luminosity ($\sim 10^{33}$ cm^{-2}sc^{-1}). The advantage of this method is that the storage ring is very modest and much less expensive. The disadvantage is the low energy beam dynamics. In the future a small team at UCLA will study this option. This concept is similar to the quasi-linear collider scheme for $\bar{B}B$ factories[11]. And another option to be studied is a 1 GeV e^- linac and a 250 MeV e^+ storage ring.

5 ASYMMETRIC ϕ FACTORY WORKSHOP

A mini-workshop on the design of an asymmetric ϕ factory was held at UCLA on October 28, 1992[12]. The following is a brief summary of this meeting.

i) A strong scientific motivation for an asymmetric ϕ factory was made by D. Nanopoulos (Texas A & M), A. Kostelecky (Indiana) and P. Eberhard (LBL). Fig. 6 shows the analysis of Ellis, the possibility of large CPT violation in the $K^0 - \bar{K}^0$ system concerning ..?..

ii) There was discussion of the 1st and 2nd types of ϕ factories (see Table 3). S. Chattopadhyay (LBL) presented designs of low energy linacs colliding with high energy e^+ rings.

iii) I presented a concept related to the UCLA Asymmetric ϕ Factory (AϕF) model 1. A comparison of the parameter for schemes 1 and 2 (Table 3) is given in Table 4 (Fig. 5).

iv) A design of a small compact storage ring was provided by W. Gabella (UCLA); see Figs. 7a and 7b[15].

v) Consideration on the effects of beam-beam interactions in model 2 are shown in Fig. 8 (from C. Johnson, CERN). Note that beam-beam interaction rapidly destroys the emittance of the storage ring[16].

vi) Previous CERN calculations of the beam-beam pinch effects were shown and are presented in Fig. 9[16].

vii) T. Levine reported on the progress on the development of X-band Klystron high gradient linacs at SLAC (Fig. 10)[17].

viii) C. Pellegrini gave an overview of the constraints on asymmetric ϕ factories that does not exclude reaching a luminosity of $\sim 10^{33}$ cm^{-2}sec^{-1}, in principle!

6 AN ASYMMETRIC ϕ FACTORY AT UCLA

The UCLA Center for Advanced Accelerators is carrying out preliminary design work for an asymmetric ϕ factory. The design is intended for the construction of a machine to be placed in

the new Science and Technology Building at UCLA (see Fig. 11). We have also chosen a name for this machine: CAPRI [California Asymmetric Phi Factory].

7 REFERENCES

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TABLE 1

FIGURE OF MERIT OF AN ASYMMETRIC ϕ FACTORY TO A SYMMETRIC ϕ FACTORY

$$R^{-1} = \left(\frac{\Delta t}{t}\right) = \left(\frac{\delta x}{\langle x \rangle}\right) \quad \text{for position measurement}$$

$$(\delta x)_{\text{Symmetric}} \; (\pi^0\pi^0) \sim (2 - 3) \text{ mm}$$ (UCLA Study for Krypton Detector)

$$(\delta x)_{\text{Asymmetric}} \; (\pi^0\pi^0) \sim (1 - 2) \text{ mm}$$ (due to higher energy photons)

$\langle x \rangle$ Scales with Asymmetry $\langle x \rangle_{\text{S}} \sim 6\,\text{mm}$

$\langle x \rangle_{\text{A}} \sim 2\,\text{cm}$

$$R_{\text{S}} \sim (2 - 3)$$
$$R_{\text{A}} \sim (10 - 20)$$

An Asymmetric ϕ Factory gives a
Much Better Resolution for the Crucial

$$(K_S - K_L) \rightarrow \pi^0\pi^0$$

Interference Pattern

TABLE 2

ADVANTAGES OF AN ASYMMETRIC ϕ FACTORY

1) **K_S^0 is Boosted** $\rightleftharpoons$ (High Resolution time)
["K_S^0 Beam"]

Energy of $\pi^0\pi^0$ (π^0) increased • Easier Detection of Photon

Events folded Forward • Simpler • Smaller Detector

2) **Experiments with Regenerators Possible**

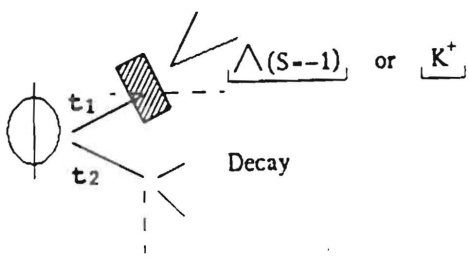
a) New Tests of Quantum Mechanics — P. Eberhard

b) New Tests of CPT — C. Cline

3) **New Experiments Possible** where K^0 or $\bar{K}^0$ is Directly Tagged to "Separate Variables" in CPT Tests

(i.e., Sanda ... include $\Delta S = -\Delta Q$ + CP + CPT $\cdots$)

[Low Energy K^0, K^0 Cross Sections Large]



from $t_2 > t_1$ (2) Particle starts out as a a K^0 or $\bar{K}^0$

These are similar to CP LEAR but much cleaner Experiments.

TABLE 3

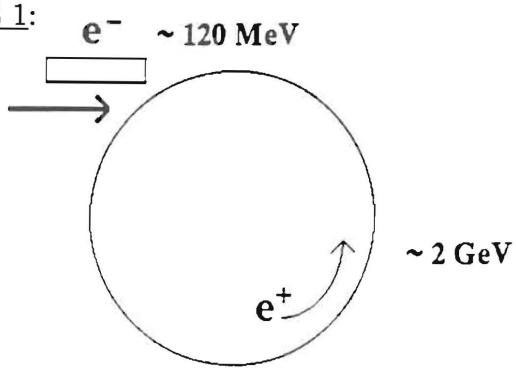
TYPES OF ASYMMETRIC ϕ FACTORIES

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

TABLE 4

TWO GENERAL SCHEMES DISCUSSED AT UCLA MEETING

SCHEME 1:



$$\mathcal{L} = \frac{f N_{e^-} - N_{e^+} H}{4\pi\sigma_x\sigma_y}$$

$f \rightarrow$ Large
$N_{e^-} << N_{e^+}$
Weak – Strong
Beam – Beam

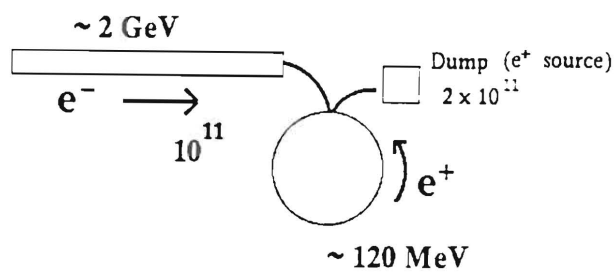
Example from Chattopadhyay Talk (at 1st Asymmetric ϕ Factory Workshop)*

$f = 100\,\mathrm{MHz}$ $\quad \sigma_x \times \sigma_y = (30 \times 40\,\mu^2)$ $\quad H = 1$

$N_{e^+} = 3 \times 10^{10}$ $\quad \mathcal{L} = \mathbf{1.5 \times 10^{31}\,cm^{-2}sec^{-1}}$

$N_{e^-} = 7.2 \times 10^8$ $\quad$ Electron Current: **11 mA** $\quad$ P = 1.5 **mW**

SCHEME 2:



Example from Cline Talk*

$f = 200\,\mathrm{Hz}$ $\quad H \sim 3$ $\quad fr = 3 \times 10^7\,\mathrm{Hz}$

$\sigma_x\sigma_y = (1 \times 1\,\mu^2)$ $\quad \mathcal{L} \sim \mathbf{10^{32}\,cm^{-2}sec^{-1}}$ $\quad$ Coll. Freq. $10^5 = 200\,\mathrm{Hz/Hz}$ ..?..

$N_{e^-} = 10^{11}$ $\quad$ **Semi-strong × Strong Beam Interation**

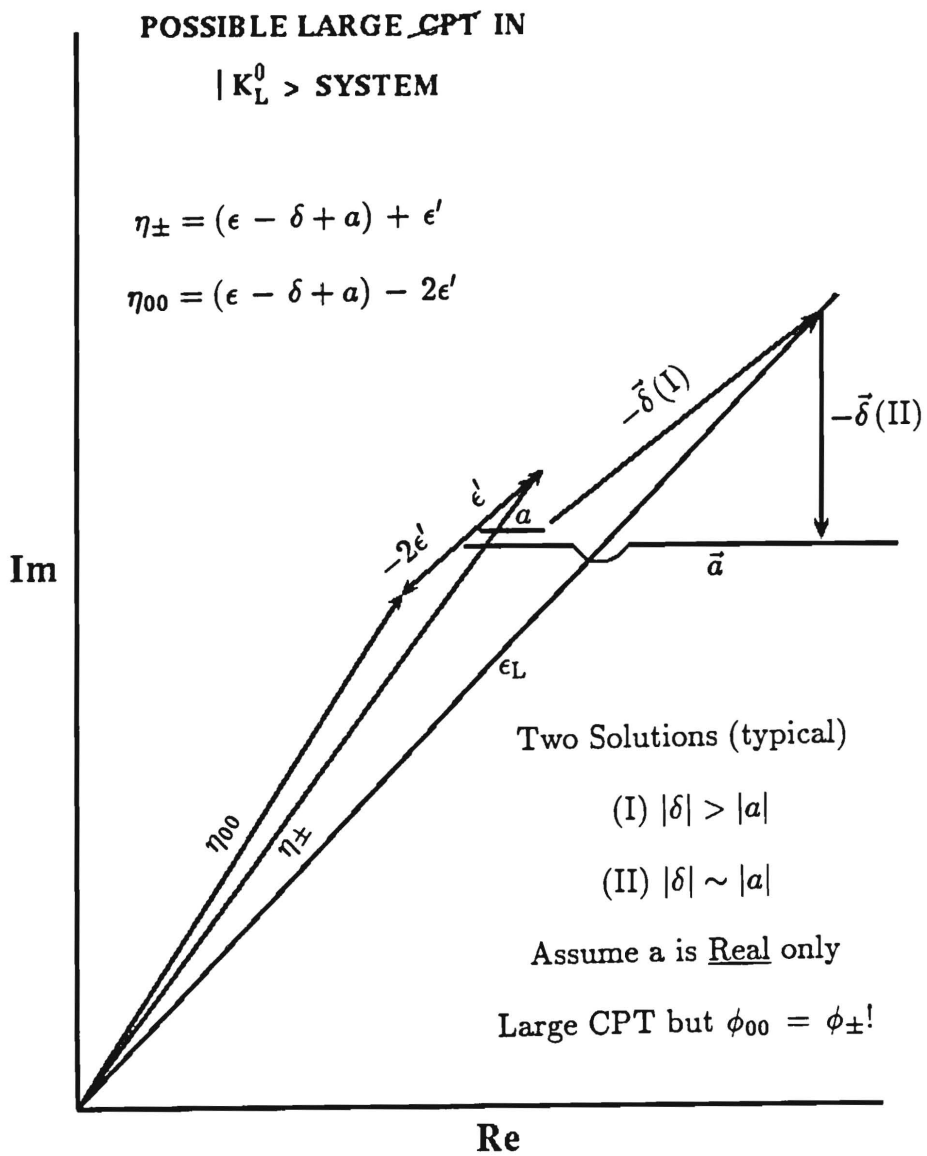

POSSIBLE LARGE CPT IN
$|K_L^0>$ SYSTEM
$\eta_\pm = (\epsilon - \delta + a) + \epsilon'$
$\eta_{00} = (\epsilon - \delta + a) - 2\epsilon'$
$-\vec{\delta}(I)$
$-\vec{\delta}(II)$
ϵ'
a
$-2\epsilon'$
$\vec{a}$
Im
ϵ_L
Two Solutions (typical)
(I) $|\delta| > |a|$
(II) $|\delta| \sim |a|$
Assume a is Real only
Large CPT but $\phi_{00} = \phi_\pm$!
η_{00}
$\eta_\pm$
Re

FIG. 1

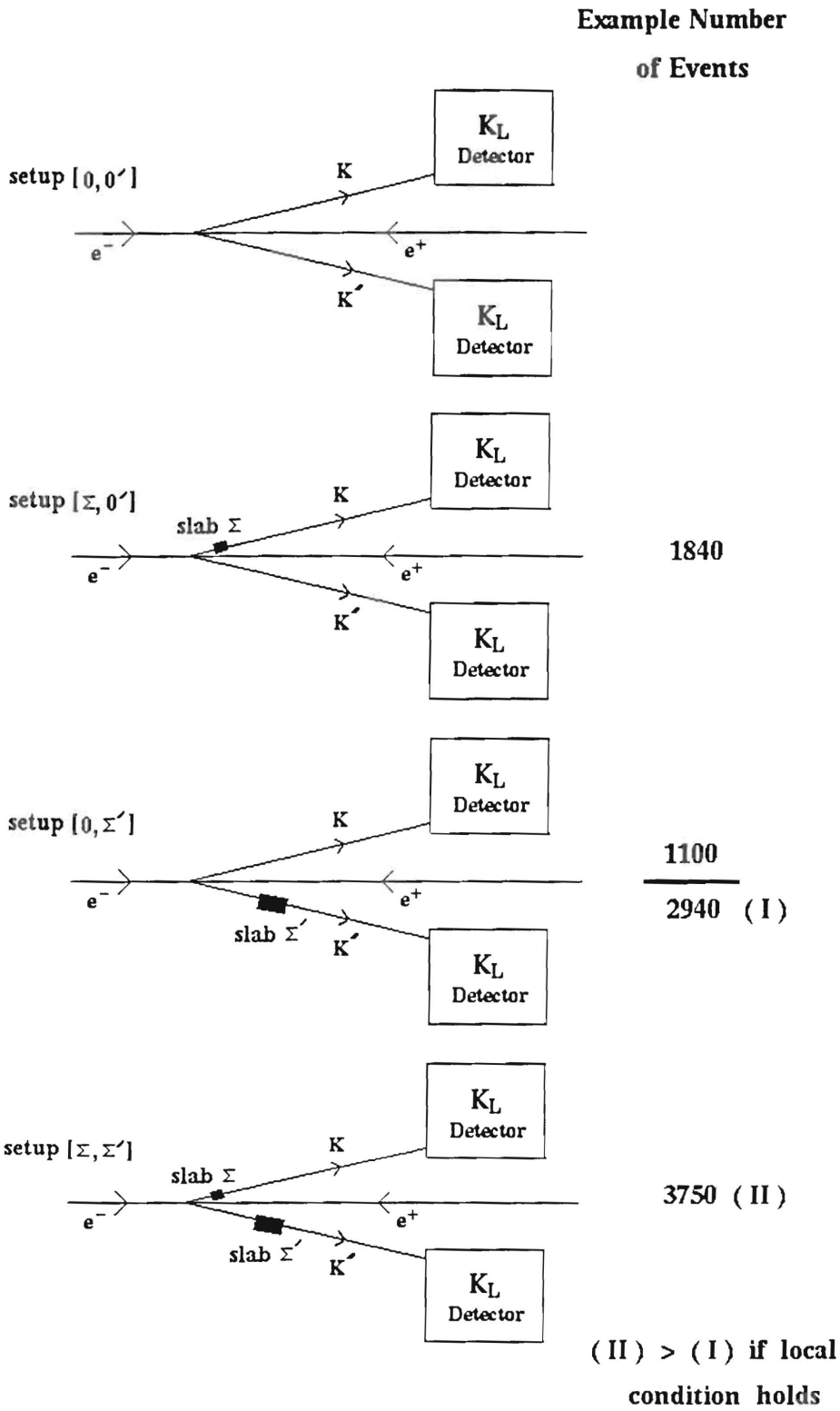
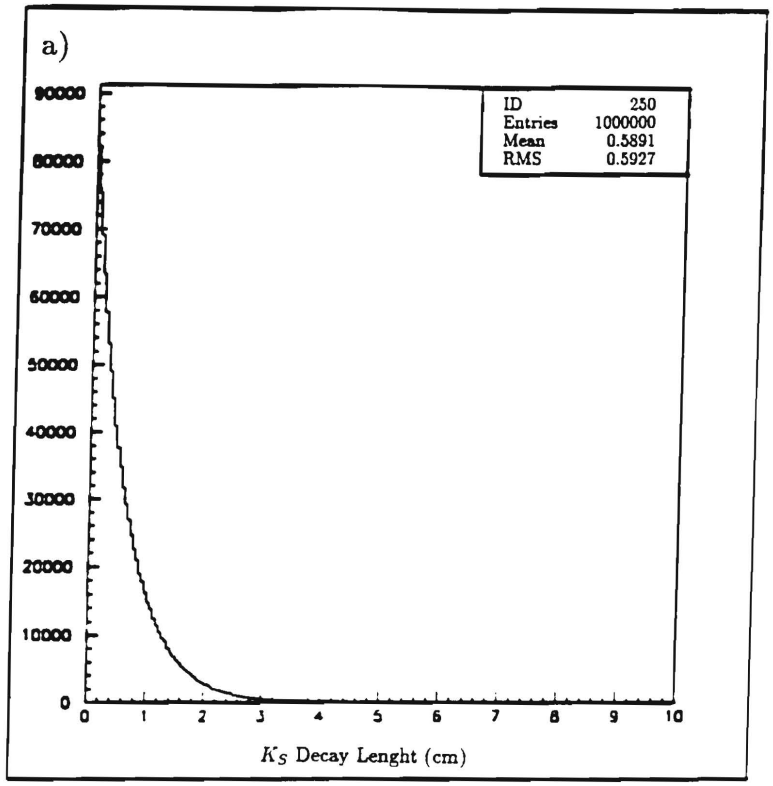


FIG. 2: The four experimental setups.



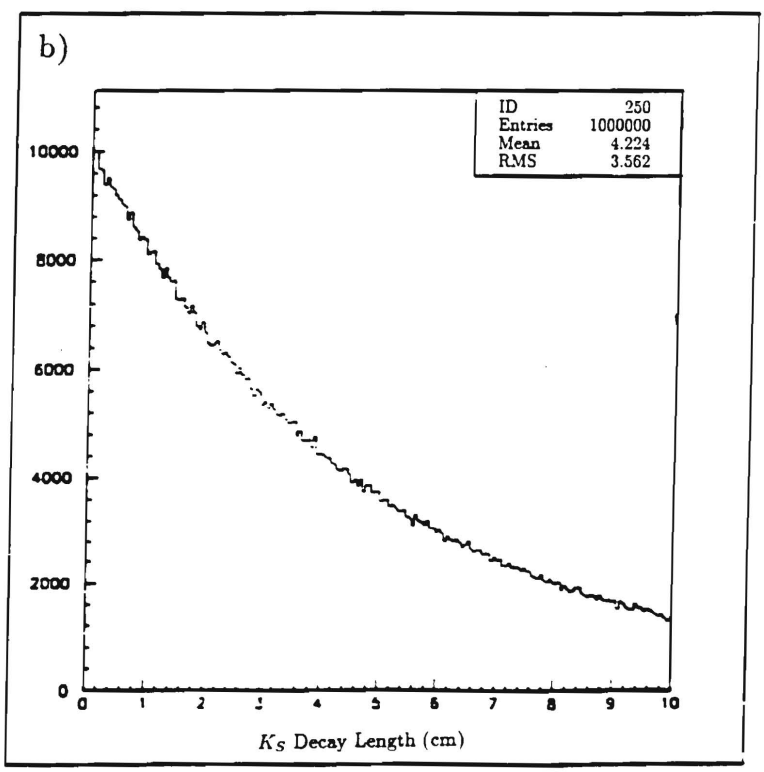
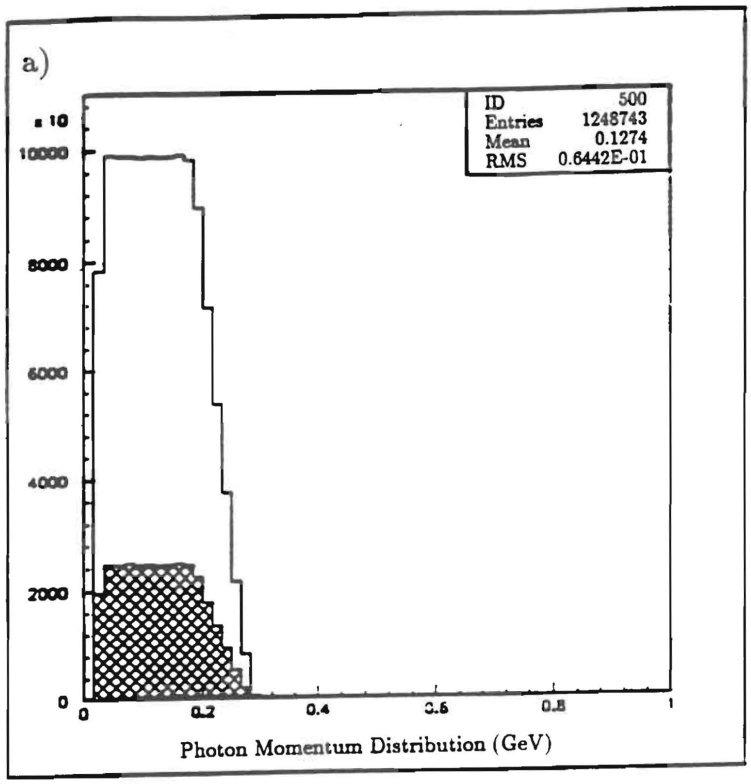


FIG 3: a) K_S decay length (cm) for a symmetric ϕ factory; b) K_S decay length (cm) for an asymmetric ϕ factory.



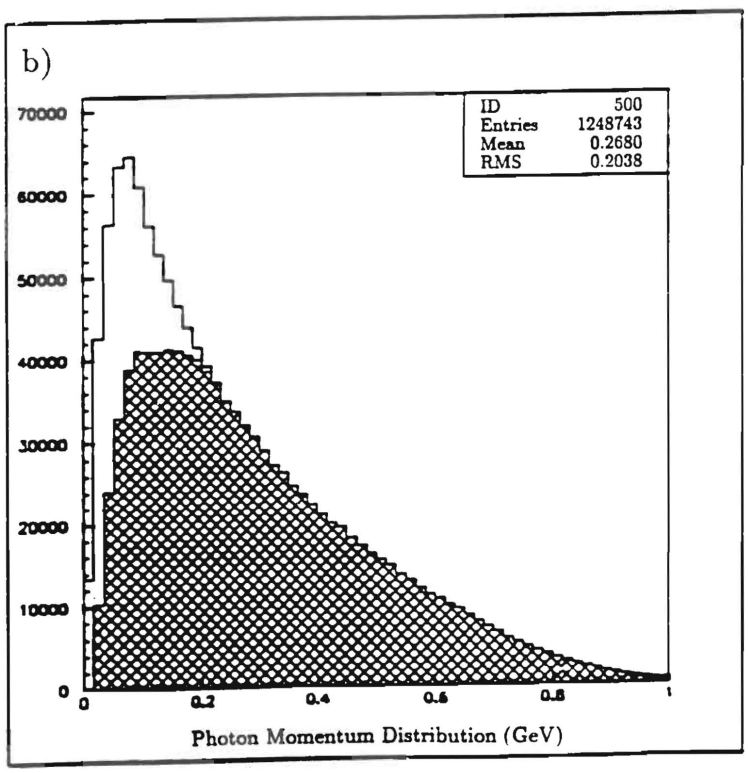


FIG. 4: a) Photon momentum distribution (GeV) for a symmetric ϕ factory; b) Photon momentum distribution (GeV) for an asymmetric ϕ factory. Superimposed in cross-hatch is the distributions for photons that are within the reference calorimeter acceptance.

ASYMMETRIC ϕ FACTORY

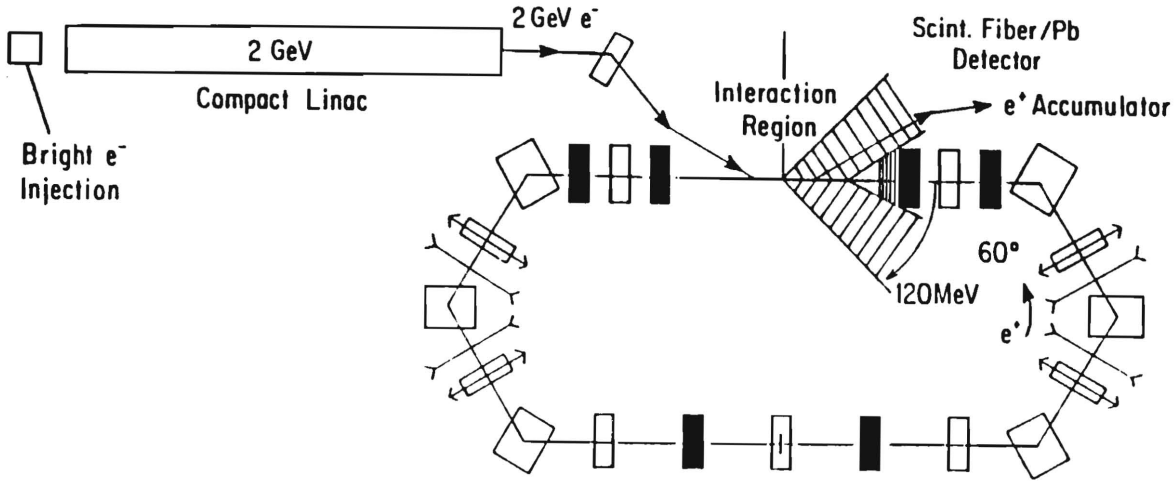


FIG. 5

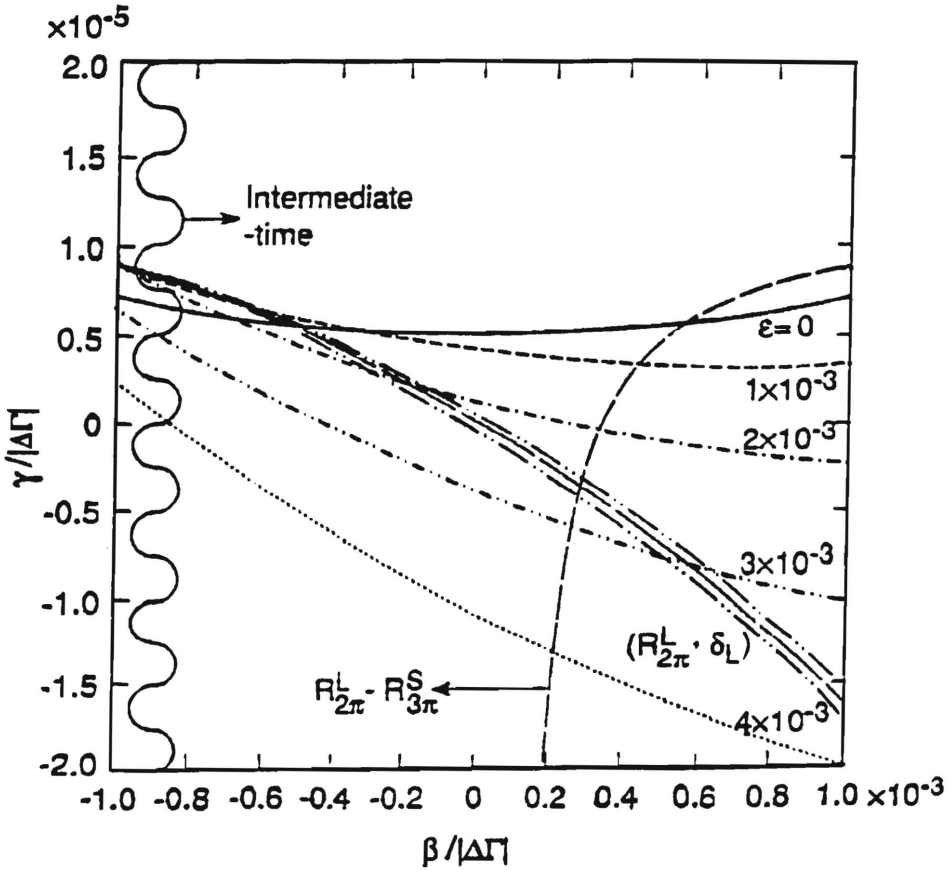


FIG. 6

A COMPACT STORAGE RING THAT COULD BE USED
FOR A e^+ TARGET FOR AN ASYMMETRIC ϕ FACTORY

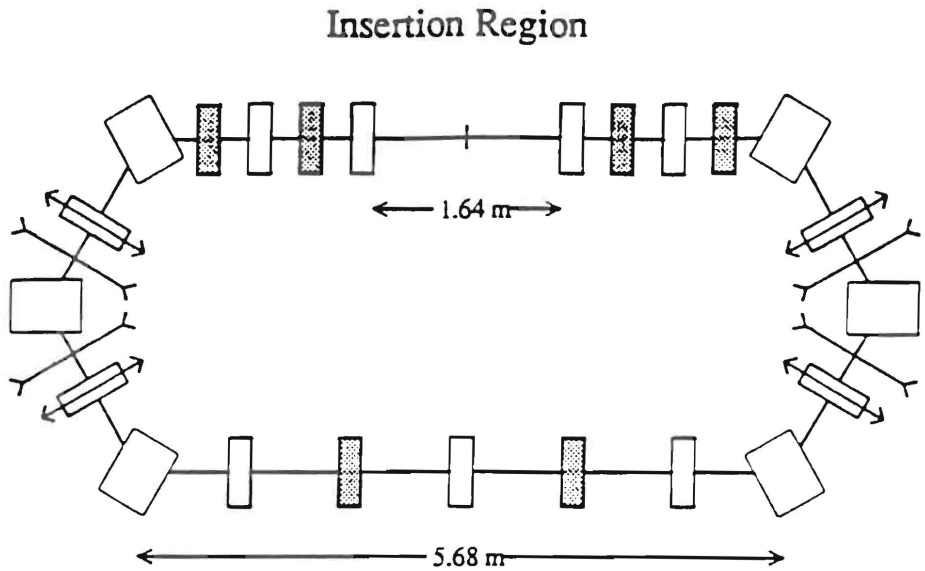


FIG. 7a: Schematic layout of the light source. The bend magnets are shown as large boxes at each angle in the central orbit. The quadrupoles are shown as thinner rectangles and the sextupoles as lines terminated with arrows or inverted arrows.

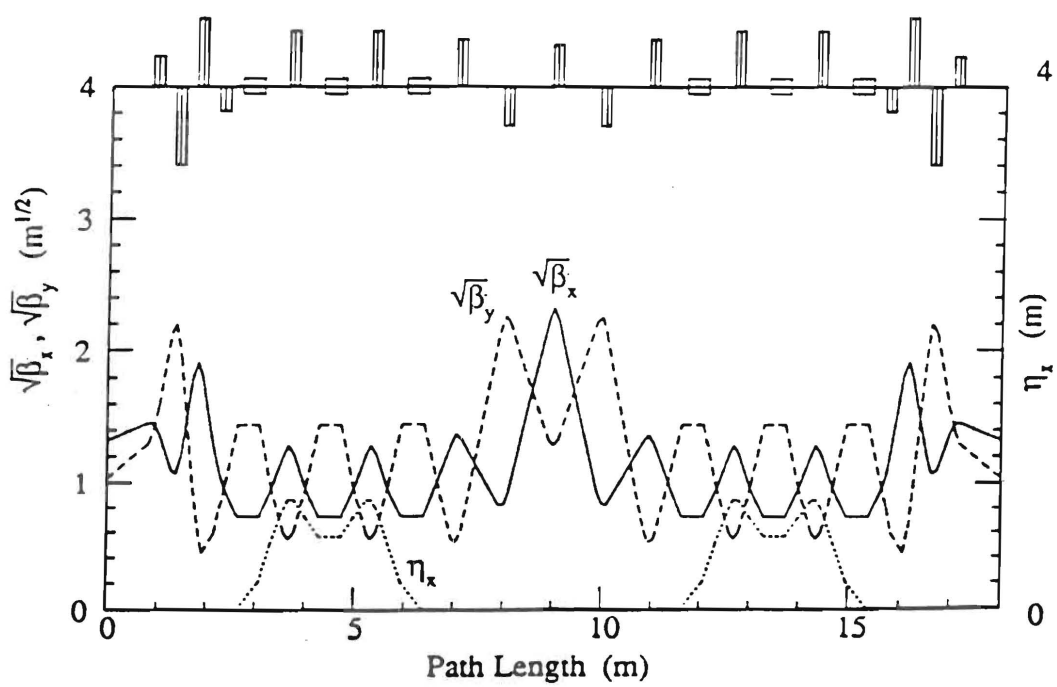


FIG. 7b: Lattice parameters for the light source. The insertion device region is in the center of the straight section shown at the ends of the figure; the injection system is in the straight section shown in the center of the figure.

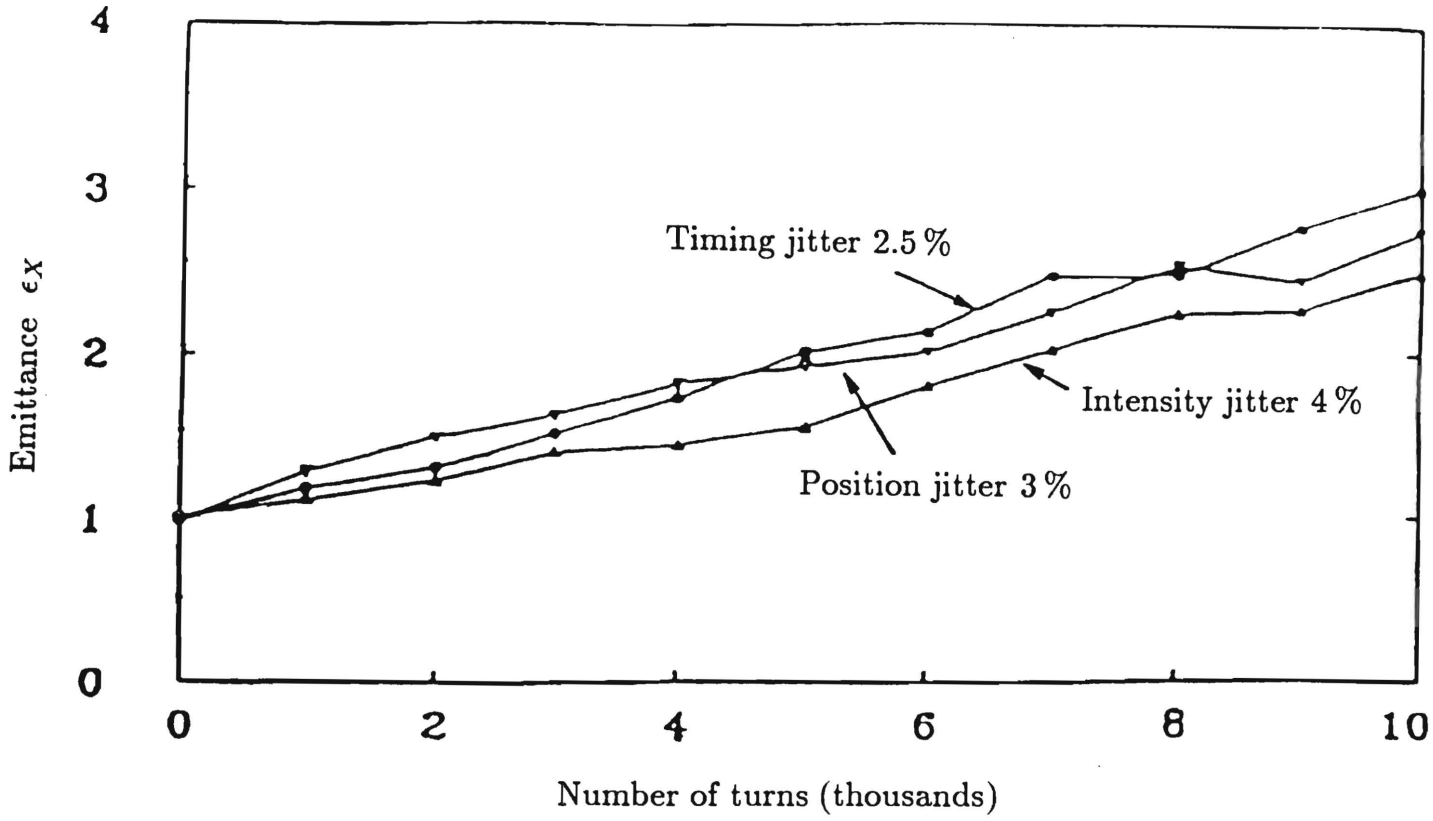
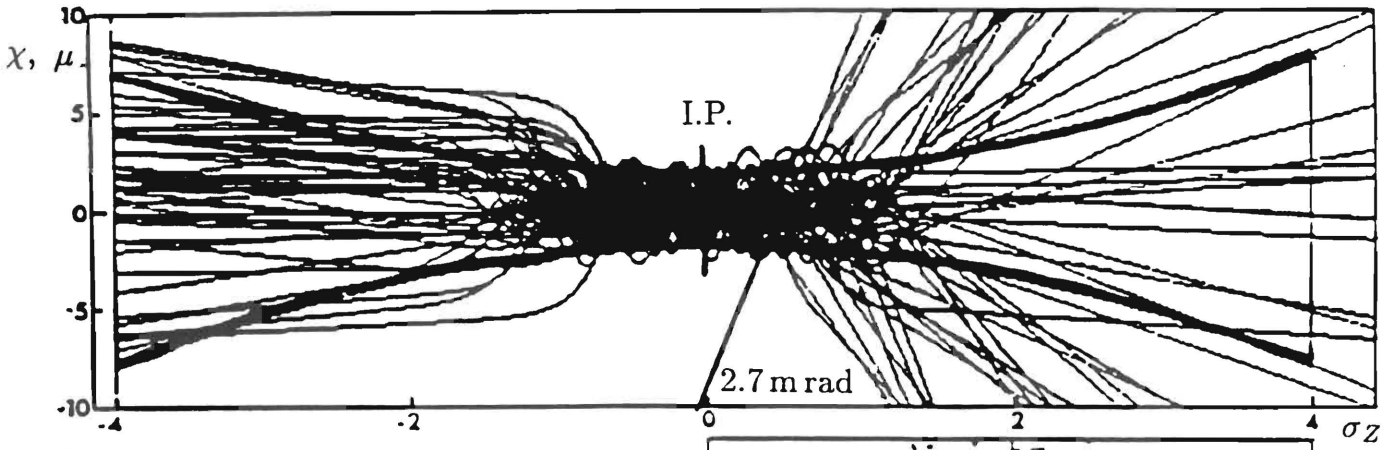


FIG. 8: Fluctuations in intensity timing and position-effect on groups of 100 positrons over 10^4 turns.



Interaction point : 2σ contour

BEAM-BEAM : Linear on SR 11-08-89

Positrons 2×10^{11}

$\sigma\chi e$: $3.0\,\mu$

σ_Z : 7 mm

β^* : 20 mm

Emittance e^- : 4.5×10^{-10} m rad

Longitudinal cut : 1σ

χ RMS : 0.848

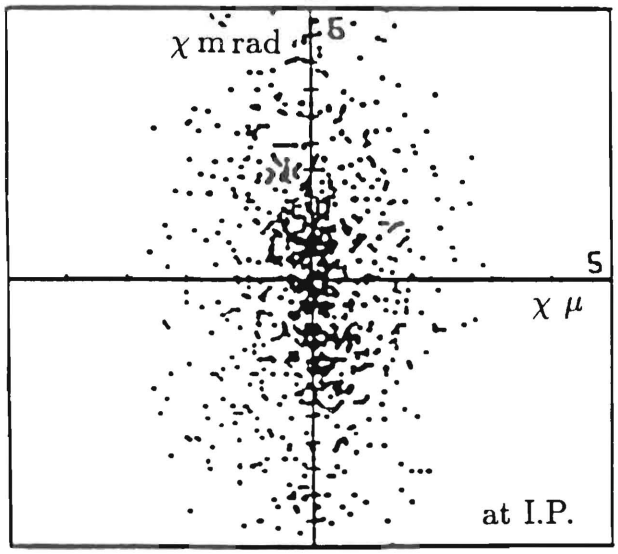


FIG. 9

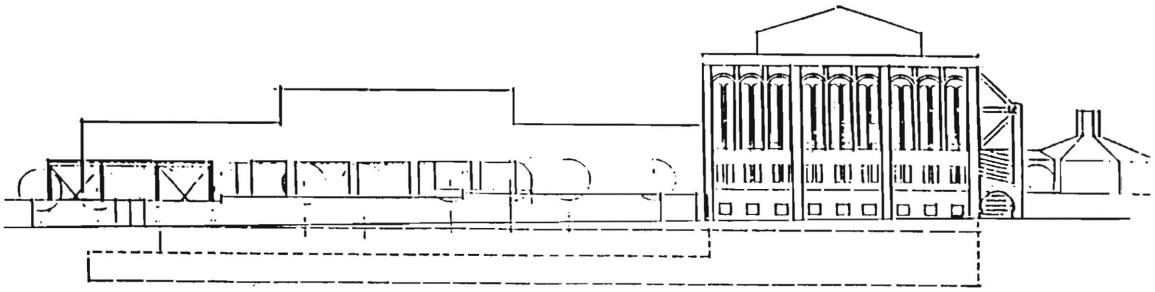


FIG. 10

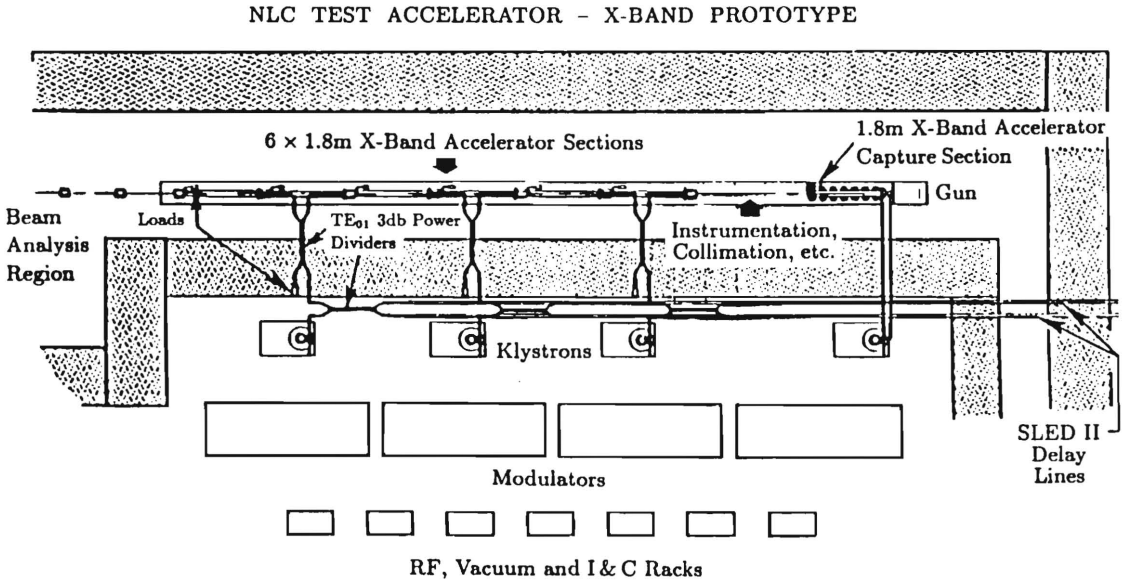

NLC TEST ACCELERATOR - X-BAND PROTOTYPE
6 × 1.8m X-Band Accelerator Sections
1.8m X-Band Accelerator
Capture Section
Gun
Beam
Analysis
Region
Loads
TE01 3db Power
Dividers
Instrumentation,
Collimation, etc.
Klystrons
SLED II
Delay
Lines
Modulators
RF, Vacuum and I & C Racks

FIG. 11