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A Linac-on-Ring Collider B-Factory Study

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ABSTRACT

A preliminary survey of the machine parameters required to achieve a luminosity of $10^{34} cm^{-2} s^{-1}$ at the $\Upsilon(4S)$ resonance in a linac-on-ring collider has been made. The low emittance electron source and recirculating superconducting linac based on LEP cavities appears to be within the scope of present technologies. The high-current, low-emittance positron storage ring with it's low-beta collision point can be broadly specified but a more detailed feasibility study is needed. Simulation of the beam-beam effect indicates that the beam-beam limit may be higher than in equivalent ring-on-ring colliders. The heavily disrupted electron beam poses no obvious problem.

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1 Abstract

A preliminary survey of the machine parameters required to achieve a luminosity of $10^{31}cm^{-2}s^{-1}$ at the $\Upsilon(4S)$ resonance in a linac-on-ring collider has been made. The low emittance electron source and recirculating superconducting linac based on LEP cavities appears to be within the scope of present technologies. The high-current, low-emittance positron storage ring with it's low-beta collision point can be broadly specified but a more detailed feasibility study is needed. Simulation of the beam-beam effect indicates that the beam-beam limit may be higher than in equivalent ring-on-ring colliders. The heavily disrupted electron beam poses no obvious problem.

2 Introduction

An e^+e^- collider at the $\Upsilon(4S)$ resonance with asymmetric beam energies and a luminosity of $10^{31}cm^{-2}s^{-1}$ is now actively sought for detailed studies of B-meson decays, and in particular CP-violation. The experimental requirement of very high integrated luminosity implies continuous operation at or near peak performance over months or even years and this sets an extraordinarily challenging goal for accelerator designers - a goal that entices new designs since it lies beyond the readily available performance of conventional colliders. Several feasibility studies of ring-on-ring colliders are under way or completed[1]. The very high performance requirements justify the study of alternative schemes such as the linac-on-ring collider

The main thrust of linac-on-ring collider studies has been towards higher collision energies[3], but additionaly, the different nature of the beam-beam effect and the smaller beam currents could be key elements in extending the luminosity limit beyond that presently attainable in low-energy colliders. The obstacle in the linac-linac B-Factories of achieving sufficiently high positron production rates[2] is avoided by storing the positron beam. Some preliminary studies have been made with encouraging results[4] and this contribution summarises the findings of an informal study at CERN on the long-term prospects for a linac-on-ring B-Factory.

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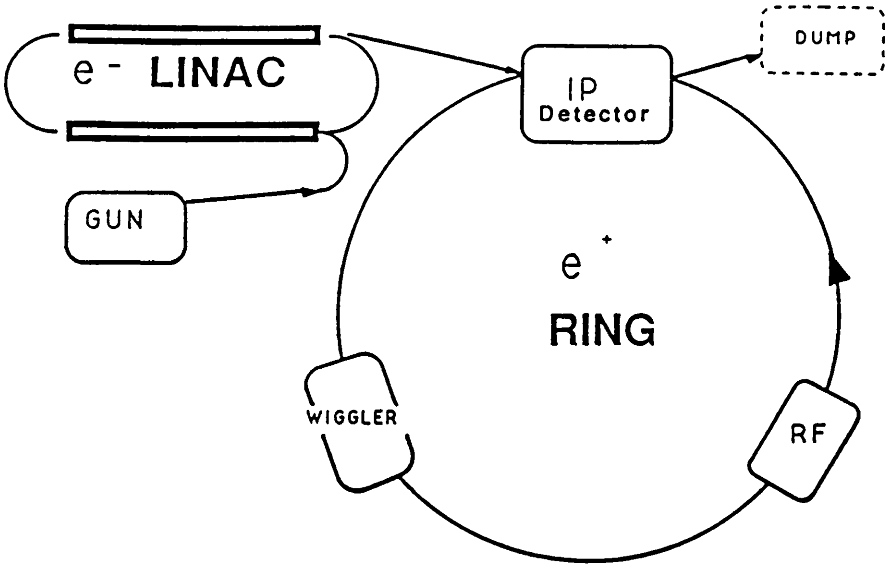


Figure 1: Linac-Ring-Collider overview

3 Design Constraints and Parameter

Figure 1 shows a layout of a linac-ring-collider. A positron beam has to be stored over long periods without significant emittance blow up and an electron beam has to be continuously renewed from a linac and dumped after the collision.

Linac-ring-colliders are a new concept and recipies for parameter lists based on experience do not yet exist. Both beams have different constraints and one expects the intensity of the two beams to be very different. Possible set of parameters are given in Table 1 . In the following we discuss how a few important parameters limit the luminosity; the most important goal for a B-factory. For a given power of the electron beam (P_{e^-}) the luminosity is determined by the transverse density of the stored positron bunch.

$$L = 10^{31} cm^{-2} s^{-1} \cdot \frac{P_{e}^{-}}{2.0MW} \cdot \frac{N_{e^+}}{10^{11}} \cdot \frac{(\mu m)^2}{\sigma_x^{e^+} \sigma_y^{e^+}} \cdot H_D \cdot \frac{GeV}{E_{e^-}} \qquad (1)$$

Where H_D is an enhancement factor due to the pinch effect in the beam-beam interaction. If one wants to achieve a luminosity of $10^{31} cm^{-2} s^{-1}$, an electron beam power of a few MW and a low emittance high peak current positron beam are needed. The electromagnetic forces, that accompany the positron bunch, act like a strong focusing lens on the electrons.

The disruption parameter(D), which relates the bunch length (σ_z) to the effective focal length of the beam force, is used to quantify the pinch effect of the beam-beam interaction in linear colliders.

Table 1: Linac Ring Collider Parameters.

Case	A	B	C	D	E
$E_{e^-}(GeV)$	3.1	3.1	3.1	8.0	8.0
$E_{e^+}(GeV)$	9.0	9.0	9.0	3.5	3.5
$I_{e^-}(mA)$	1	2.6	2.6	2	2
$I_{e^+}(A)$	1	0.5	0.9	0.9	1.6
$P_{e^-}(MW)$	3.1	8.0	8.0	16.0	16.0
$\rho_{e^+}(m)$	100	100	100	60	60
$P_{e^+}(MW)$	5.8	2.9	5.2	0.2	0.4
$f_c(MHz)$	30	10	18	28	50
$N_{e^-}(10^9)$	0.2	1.6	0.9	0.4	0.3
$N_{e^+}(10^{11})$	2	3	3	2	2
$\sigma_x(\mu m)$	1.0	2.0	5.0	1.4	4.0
$\sigma_y(\mu m)$	1.0	2.0	0.8	1.4	0.5
σ_z (mm)	7	10	10	7	7
$\beta_y^{e^+}$ (mm)	7	10	10	7	7
$D_{e^-}^y$	660	350	610	130	230
D_{e^+}	0.22	0.6	0.6	0.6	.6
$\xi_{e^+}^y$	0.018	0.05	0.05	0.05	0.05
$\delta_{bstr.}(10^{-4})$	1.9	0.7	0.4	2.6	1.0
H_D	1.0	1.0	1.0	1.0	1.0
$L(10^{31}cm^{-2}s^{-1})$	1.0	1.0	1.0	1.0	1.0

$$D_{e^-}^y = 2.8 \cdot 10^3 \, \frac{MW}{P_{e^-}} \cdot \frac{2}{1+\frac{\sigma_y}{\sigma_x}} \cdot \frac{\sigma_z^{e^+}}{cm} \cdot \frac{L}{10^{31}cm^{-2}s^{-1}} \tag{2}$$

The disruption parameter is inversely proportional to the electron beam power. For a luminosity of $10^{31}cm^{-2}s^{-1}$, a beam power of a few MW corresponds to a disruption parameter of several hundred. For such large values the electrons are strongly overfocused and undergo several oscillations through the high density positron bunch.

During the disruption process the electrons emit synchrotron radiation, so called beamstrahlung. At energies relevant for a B-factory the beamstrahlung losses ($\delta_{bstr.}$) are at the level of 10^{-4} and the energy smearing of the electron beam is of no concern.

The destabilizing effect that such a highly disrupted beam has on the storage ring beam cannot be simply quantified by the magnitude of D; in particular it is not obvious if fewer oscillations are less harmful to the stability of the ring beam (see chapter about beam-beam effect for further discussion).

Another important factor is obviously the intensity of the electron bunch, in Table 1 we therefore quantify the beam force by the linear tune shift(ξ_{e^+}) that the nominal linac beam causes to the positron beam. In ring-ring-colliders ξ is used to characterize the strength of the non-linear forces. A lower limit for ξ_{e^+} requires an increase of the positron current (I_{e^+}) and of the collision frequency (f_c) proportional to the beta function ($\beta^y_{e^+}$) at the collision point.

$$I_{e^+} = 0.5A \cdot \frac{2}{1+\frac{\sigma_y}{\sigma_x}} \cdot \frac{\beta^y_{e^+}}{cm} \cdot \frac{0.05}{\xi_{e^+} H_D} \cdot \frac{9GeV}{E_{e^+}} \cdot \frac{L}{10^{31} cm^{-2} s^{-1}} \tag{3}$$

As a consequence of equation (3) higher positron beam energies imply smaller positron currents, but from synchrotron radiation power losses ($P_{e^+} \propto L \cdot E^3/\rho$) a lower E_{e^+} is preferred.

In Table 1 five sets of parameters each resulting in a luminosity of $10^{31} cm^{-2} s^{-1}$ are given. The first three cases(A,B,C) are for a 3.1 GeV electron beam and a 9 GeV storage ring beam; cases D and E are for an 8 GeV electron linac and a 3.5 GeV positron ring. For both energy choices round and flat beam examples are given.

In case A a one Ampere positron beam and a one mA electron beam are collided with a nominal collision spot size of 1 μm. This case corresponds to the beam-beam simulations described later. In cases B and C the essential input constraints are the electron beam power ($P_{e^-} = 8MW$), the betafunction of the positron beam at the collision point ($\beta^y_{e^+} = 10mm$), and the linear tuneshift caused by the nominal electron beam onto the positron beam ($\xi_{e^+} = 0.05$).

In cases D and E, where the linac beam is the high energy beam, we allow for a larger linac beam power ($P_{e^-} = 16MW$), reduce the betafunction of the lower energy ring ($\beta_{e^+} = 7mm$) and keep the same tune shift parameter($\xi_{e^+} = 0.05$).

4 Superconducting Electron Linac

Superconducting radiofrequency cavities offer the possibilty for a high current and high frequency electron beam with very efficient conversion of wall plug power into beam power. Those cavity designs have matured over the last years and are now applied in several projects[5] involving electron storage rings, nuclear physics linear accelerators and free electron laser applications. Figure 2 shows a standard LEP unit of four 350 MHz cavities with four cells each put into a common cryostat. The total length of such a subunit is about 10m; electrons are accelerated by 50 MeV with a gradient of 7 MV/m and a packing factor of 2/3. Such a unit has been tested successfully in LEP this year and for LEP200 it is forseen to install up to 64 units[6].

Based on the LEP units we outline in Figure 3 a recirculating linac. Assuming four recirculations and a gradient of 7MV/m, 16 of those units(64 cavities) and 8 standard LEP klystrons could accelerate a 2.6 mA beam up to 3GeV. The total amount of cavities and klystrons would be comparable to about a quarter

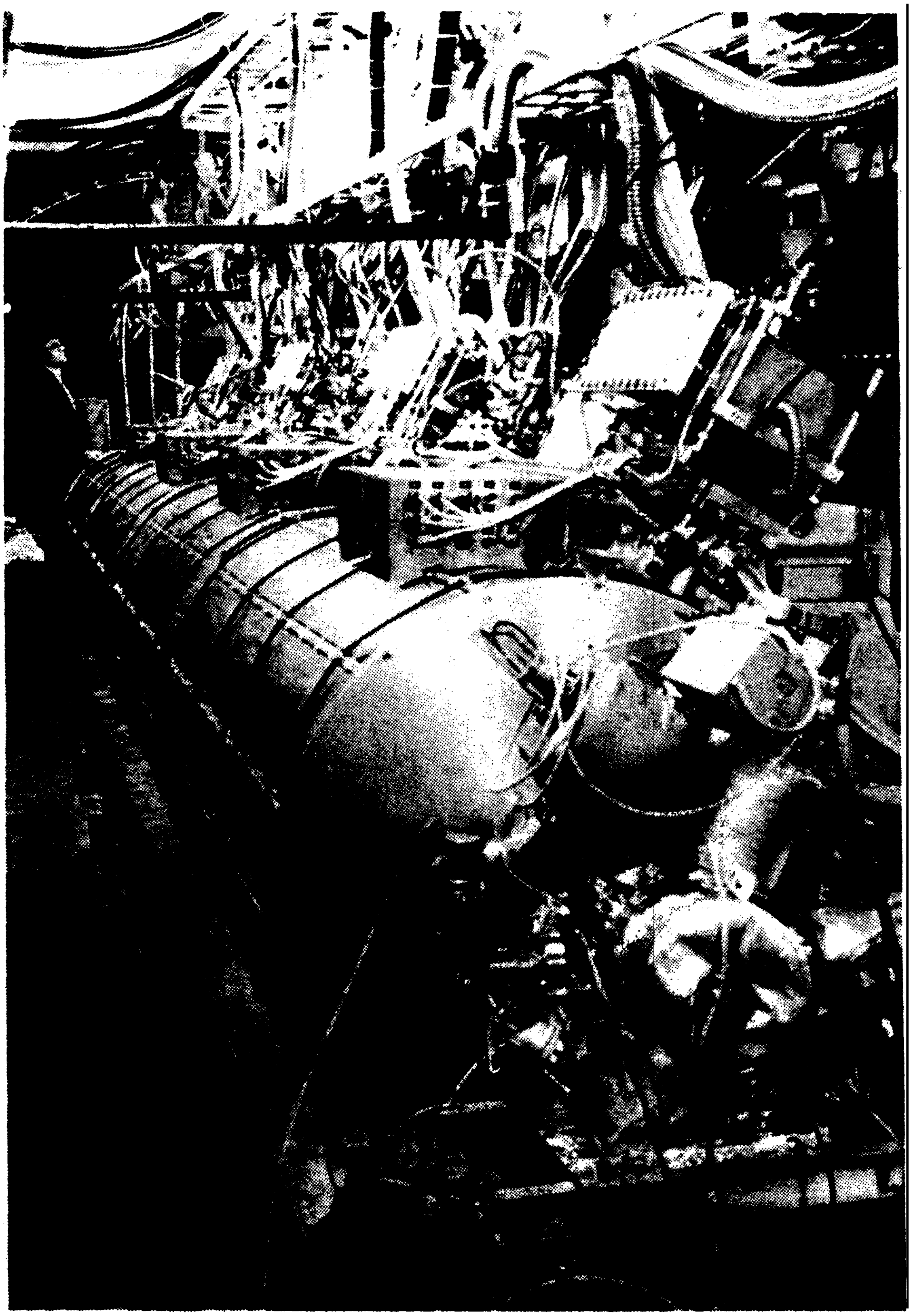


Figure 2: Four LEP cavities in one cryostat

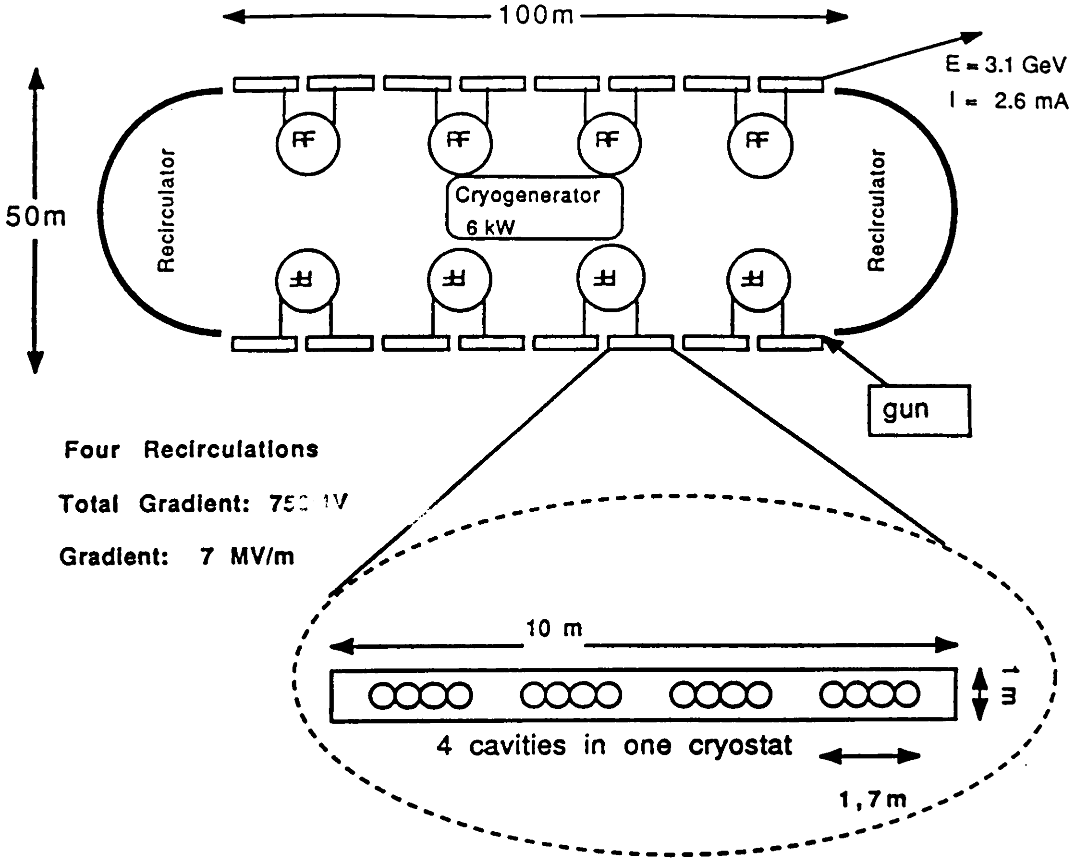


Figure 3: Recirculating linac based on LEP cavities

of what is planned for LEP200. The use of an existing production line allows a relatively reliable estimate of the complexity of such a linac and its industrial production costs.

In superconducting cavities a degradation of the beam quality due to transverse wakefields (emittance growth) or due to beam loading (energy resolution) is not expected, because of the possibility of large RF wavelength and large iris holes.

The higher order mode (HOM) couplers developed for the LEP cavities are adequate for the average and the peak currents envisaged in the recirculating linac. In Table 2 the requirments for a B-Factory are compared to some basic parameters of superconducting RF projects at LEP, HERA, TRISTAN and CEBAF. None of the quantities like total gradient, peak or average current are more demanding than those typically required in these projects.

In order to estimate the cryogenic losses we assume a $Q_0 = 5 \cdot 10^9$ at 4.2Kelvin, which is not beyond reach at a gradient of 7MV/m. Cryogenic losses due to residual RF resistance of less than 1kW at 4.2Kelvin are expected. In additon static heat losses of about 1.5 kW have to be envisaged. The expected cryogenic

Table 2: Comparison of Superconducting RF Projects.

Project	LEP	HERA	KEK	CEBAF	B-Fact.
Energy (GeV)	3.	0.3	0.2	0.8	0.8
rep. freq.(MHz)	0.04	10.	0.2	1500.	30
$N_{bunch}(10^{10})$	41.	2.	32.	.0003	.16
σ_z (mm)	16	8	12	1	7
$I_{peak}(KA)$	1.2	0.1	1.2	.0005	.01
$I_{average}(mA)$	6.	30.	20.	1.	10.
$f_{RF}(MHz)$	350	500	500	1500	350
$P_{RF}(MW)$	16.	9.	5.	.8	8.

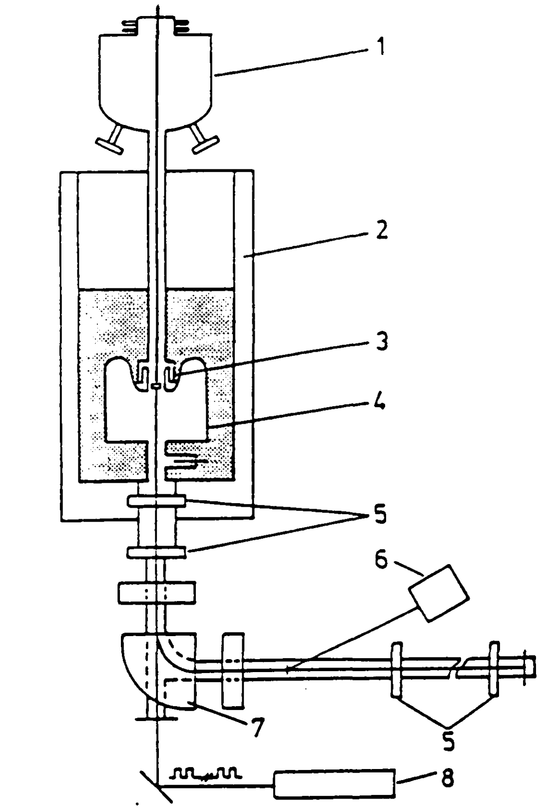
load of less than 6 KW at 4.2Kelvin corresponds to about one third of the cryogenic power installed for the superconducting magnets at HERA.

An electron linac with 8 GeV beam energy and a beam power of 16 MW, as demanded for case D and E in Table 1, could be realized with twice the number of cavities and klystrons shown in Figure 3 and five recirculations.

Optics for the recirculators have been worked out for CEBAF [7] and for a similar project under study in SACLAY[8]. At the energies considered the required low level of energy smearing and emittance can be conserved in the recirculating arcs with sufficient bending radius and a low dispersion optics.

5 Electron Gun

A low emittance short electron bunch with a high repetition rate is demanded. The high repetition rates exclude the use of damping rings and low emittance electron beams directly from a cathode have to be used. For Free-Electron-Laser applications[9] electron guns with the required specifications have been developed. To avoid emittance blow up by the large space-charge forces in nonrelativistic dense electron bunches, high acceleration gradients at the photocathode are essential; photocathodes irradiated by a laser are directly placed into a high gradient RF cavity to overcome the space charge forces. In several laboratories[10] those electron guns are developed. Figure 4 shows the design for a gun with a superconducting RF cavity as proposed by Wuppertal,CEBAF and DESY(WCD) [11]. In Table 3 projects in Los Alamos, Brookhaven (BNL) and the design from Figure 4 are compared to typical requirements for a B-Factory gun. In these projects the peak currents and emittances are comparable to the requirements of a B-Factory. The BNL and the Los Alamos projects have repetition rate of a few Hz, because they are essentially developed for study reasons. As discussed in the Wuppertal-CEBAF-DESY RF gun design, a high repetition rate could be achieved with a commercially available mode-locked laser.



1: photocathode preparation chamber,
2: bath cryostat, 3: photocathode, 4: reentrant cavity,
5: wire scanner monitor, 6: streak camera,
7: spectrometer, 8: Nd:YAG laser

Figure 4: Electron gun; from ref. 11

Table 3: Comparison of Laser RF Guns.

Project	Los A.	BNL	WCD	B-Fact.
N_e-($10^9/bunch$)	60.	6.	1.	1
$\sigma_z(mm)$	9	.6	2.6	7
$I_{peak}(A)$	130	100	7.3	2.7
$\epsilon_n(mm - mrad)$	18	7.3	45	10
$f_{RF}(MHz)$	1300	2850	1300	–
rep. freq. (MHz)	few Hz	few Hz	125	30

6 Low Emittance High Current Positron Ring

The emittance requirements for the storage ring are comparable to those of damping rings for future linear colliders or advanced synchrotron light sources.

Synchrotron radiation provides a fast cooling mechanism, but to avoid beam heating, radiation losses in regions with large dispersion have to be avoided. Various lattice types have been considered including a high tune FODO lattice with wigglers in dispersion free zones. This type of ring has for example been studied for a CLIC damping ring in the SPS-tunnel[12] and a conversion of the PEP ring into a synchrotron radiation facility[13]. Tight alignment tolerances are required for those low emittance lattices.

Due to the low emittance, small aperture and high gradient quadrupoles can be used in the low β insertion and detector background problems from the ring are expected to be small. Since the electron beam is discarded after the interaction, chromaticity introduced by the low-beta insertion is of little concern for the electrons and is more easily minimized for the positron ring.

High peak and average currents are required like in the ring on ring scheme with the resulting challenge for beam stability. However ion trapping problems inherent to electron rings are avoided since only a positron ring is needed.

A more detailed feasibility study of the ring is indicated.

7 Beam-Beam Effect

The beam-beam limit in storage rings is caused largely by the tune-spread resulting from the non-linearity of the beam forces. A disrupted electron beam with a drastically reshaped charge distribution increases these non-linearities. On the other hand the fact that one beam is discarded after the collision opens up new possibilities: one can arrange for the discarded beam to have the lower energy thereby assigning the tune spread to the stiffer (less easily perturbed) beam, also coherent phenomena and flip-flop effects are of less concern.

Two different simulation programs have been used to study the set of beam parameters corresponding to case A in Table 1; in addition the size of the electron beam has been varied.

Figure 5a shows the 2σ contours of the positron beam with different electron trajectories oscillating through the positron bunch. At the center of the collision region the electron density is enhanced (pinch effect). The simulation presented in Figure 5b shows the trajectories of electrons within a beam with $\sigma_x = 1\mu m$; luminosity enhancement appears, but the maximum tuneshift and non-linearities increase. In Figure 5c a much broader electron beam distribution ($\sigma_x = 3\mu m$), but with nominal positron bunch ($\sigma_x = 1\mu m$) is represented; electrons are drawn in by the smaller e^+ bunch and the two bunches are better matched than in the former case (Fig. 5b). Due to the non-linear forces of the gaussian positron bunch there is no strong phase correlation between the electron trajectories.

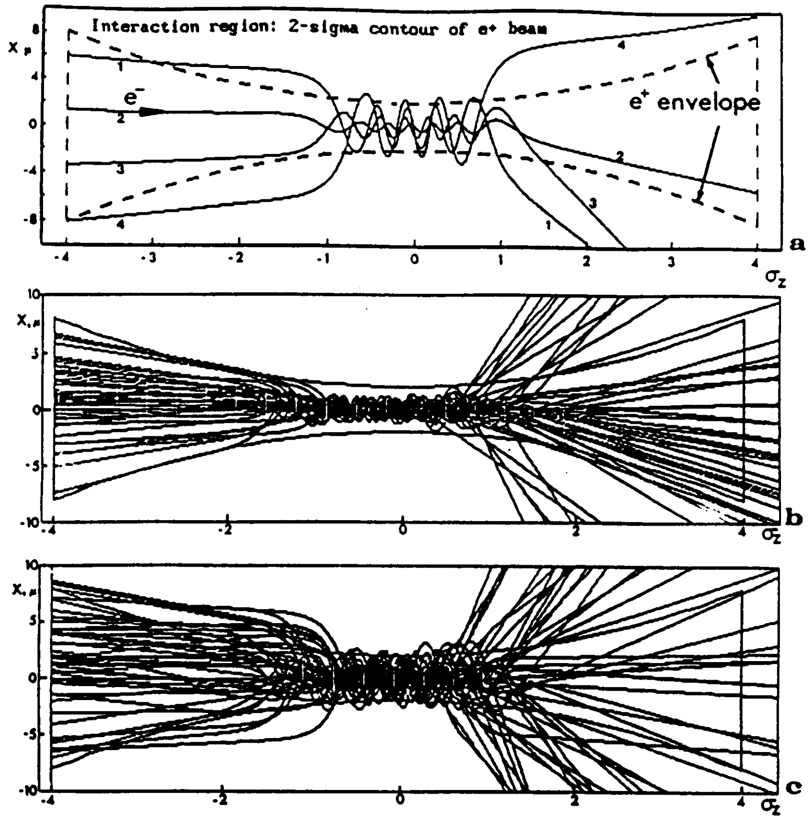


Figure 5: Electron trajectories in positron bunch.

In these simulations the positron field is generated for an unperturbed positron bunch ('weak-strong'). In a second program developed for the CLIC studies, both beam forces are simulated during the bunch crossing ('strong-strong').

Figure 6 shows how the envelopes of the two beams evolve during the collision for two different electron bunch widths. For the case of the broader electron distribution ($3\mu m$) the two bunches are well matched at the collision time (Fig. 6b,t=0.0). Table 4 gives the luminosity with and without the mutual pinch (forces on and off) for different e^- spot sizes normalised to an unperturbed collision size of $1\mu m$. The possibility to influence the nonlinear beam-beam forces by

Table 4: Luminosity Enhancement($H_D = \frac{L}{L^0}$)

$\sigma^{e^+}(\mu m)$	$\sigma^{e^-}(\mu m)$	$H_D(no force)$	$H_D(with force)$
1.	1.5	0.53	1.56
1.	2.0	0.40	1.27
1.	3.0	0.20	0.94

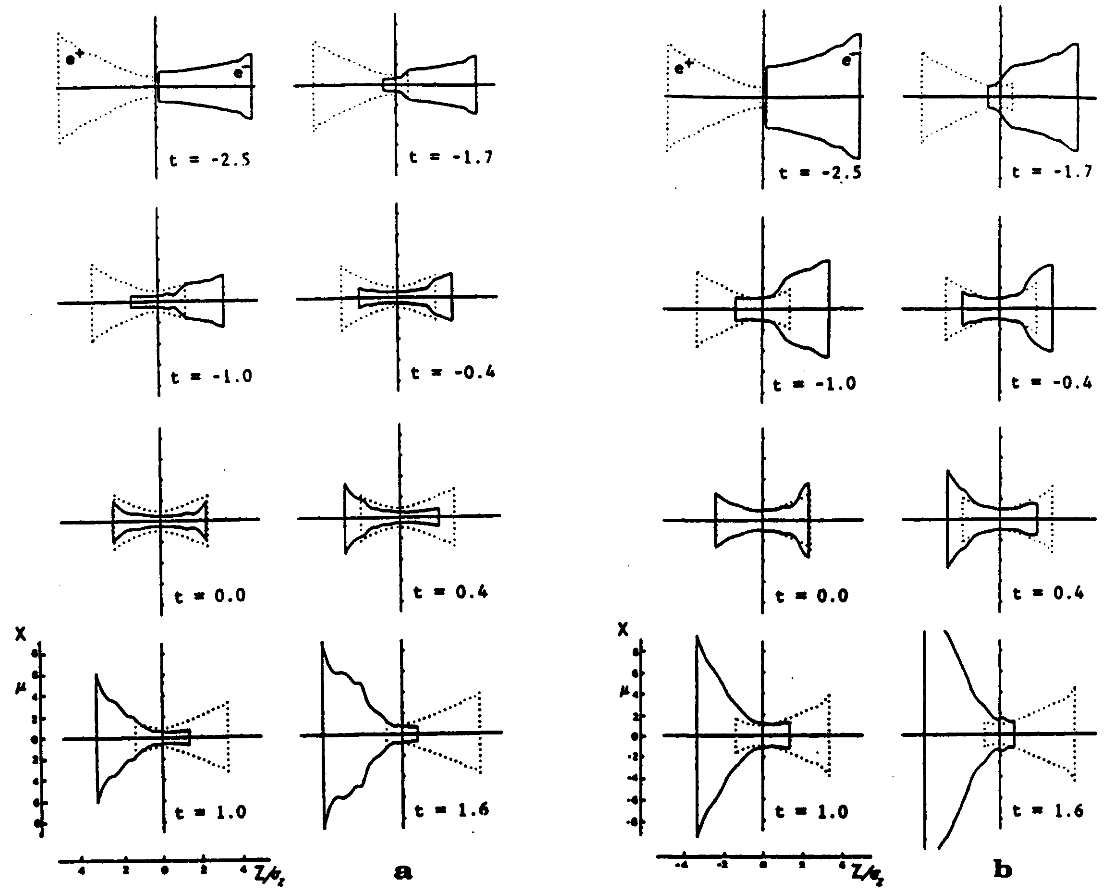


Figure 6: Beam envelope during collision.

adjusting the electron beam initial conditions is interesting and could give operational advantages; also the strong pinch renders the design relatively insensitive to linac beam quality.

A fairly extreme case with $\sigma_x = 1\mu m$ for both beams (other parameters as for case A in Table 1) results in an electron pinch down to $\sigma_x = 0.42\mu m$. The longitudinal form of the pinch is shown in Figure 7. The resulting distribution of the integral forces experienced by the opposing positrons (integrated over $\pm 3\sigma_z$) are illustrated in Figure 8. Because of the electron pinch the tuneshift of the positrons is correlated to their synchrotron amplitudes. Some preliminary studies of the consequences of this correlation and the behaviour with respect to bunch length have begun using a 'weak-strong' tracking program. This work is described briefly elsewhere in these proceedings[11]. To obtain a fully quantitative estimate of the acceptable limits of the linear tuneshift ξ_{e^+} and the bunch lengths, a storage ring with nonlinear elements and a low-β insertion must be

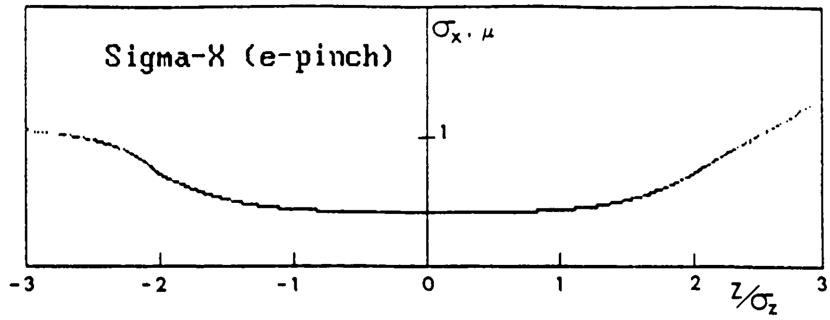


Figure 7: Longitudinal form of the pinched e^- beam.

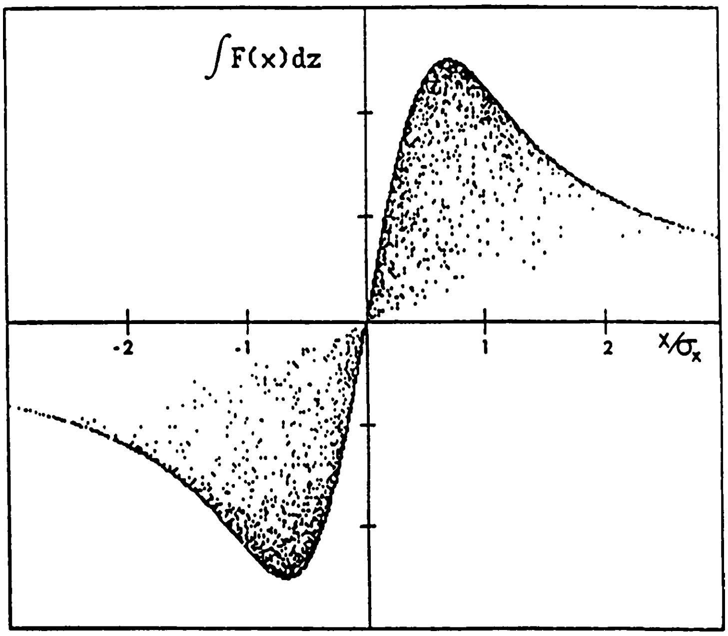


Figure 8: Integrated forces on the e^+ due to the pinched e^- beam

simulated. An experimental test of the linac-on-ring beam-beam interaction strategies would of course be invaluable.

8 Conclusions

A B-factory with a luminosity of $10^{34} cm^{-2} s^{-1}$ seems possible in the linac-ring-collider scheme. The superconducting radiofrequency electron linac together with a low emittance gun could be built based on existing technology. A design for the low emittance and high current positron ring looks possible along the lines of advanced synchrotron light sources or damping rings for future linear colliders. Compared to a ring-ring-collider the linac-ring-collider avoids a high current electron ring and allows lower emittance beams. New possibilities to improve the beam-beam limit might be given since the electron beam is discarded after the collision. Further studies have to be done , to see how much of the potential of a linac-ring collider could be realized to make it an attractive alternative for a low energy,high luminosity collider.

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