LINAC - RING - COLLIDER B-Factory

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1 Abstract

Parameters for an e^+e^- linac-ring-collider B-Factory with a luminosity of $10^{34}cm^{-2}s^{-1}$ are discussed. For the e^- linac the possibility to use the superconducting cavites developed for LEP is shown. The realization of a low emittance e^- source and a high current and low emittance e^+ ring is discussed. Simulations of the beam-beam effect in the case where the e^- beam is heavily disrupted by a stored e^+ beam are presented.

2 Introduction

An e^+e^- collider at the $Y(4s)$ resonance with asymmetric beam energies and a luminosity of $10^{34}cm^{-2}s^{-1}$ is considered to be an interesting laboratory for a study of CP-violation in B-meson decays. The luminosity requirement and the running mode with asymmetric beam energies are beyond present day experience with e^+e^- storage rings. Several detailed studies of ring-ring-colliders have been made[1]; some uncertainties remain if the desired high luminosities are to be achieved.

The main thrust of linac based e^+e^- colliders is towards higher collision energies. But the different nature of the beam-beam effect and the smaller beam currents could also make such schemes interesting options for a very high luminosity B-Factory. The luminosity of linac-linac-collider B-Factories is limited by the required high e^+ production rates[2]. The linac-ring-collider, which has been recently discussed also in connection with high energy colliders[3], avoids this problem by storing the e^+ beam, and there seems to be no principle obstacle to achieving very high luminosities in a B-Factory with asymmetric beam energies [4].

This contribution summarizes the findings of an informal study at CERN on the prospects for a B-Factory in the linac-ring scheme.

3 Parameters

Figure 1 shows a layout of a linac-ring-collider. An e^- beam is continuously renewed from a linac and dumped after the collision

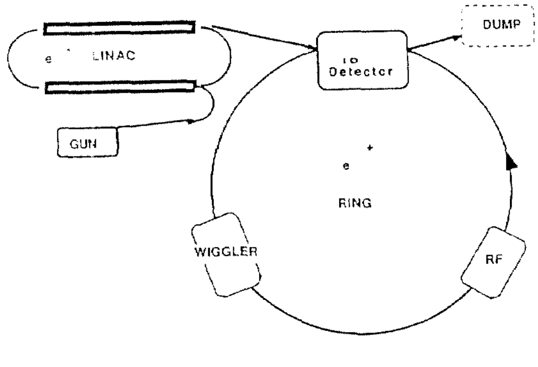

Figure 1: Linac-Ring-Collider Overview

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
$D^y_{e^-}$	660	350	610	130	230
$\xi^{y^e}_{e^+}$	0.018	0.05	0.05	0.05	0.05
$\delta_{bstr.}(10^{-1})$	1.9	0.7	0.4	2.6	1.0
$L(10^{34}cm^{-2}s^{-1})$	1.0	1.0	1.0	1.0	1.0

with an e^+ beam stored in a ring. The two beams are subject to very different constraints. Linac-ring-colliders are a new domain and generally accepted recipies for parameters do not yet exist. In Table 1 sets of possible parameters are given. In the following we discuss a few important limitations to the luminosity.

For a desired luminosity the power of the e^- beam (P_{e^-}) is given by the transverse density of the stored e^+ bunch.

$$P_{e^-} = 2.0MW \ \frac{10^{11}}{N_{e^+}} \cdot \frac{\sigma_x^{e^+} \sigma_y^{e^+}}{(\mu m)^2} \cdot \frac{1}{H_D} \cdot \frac{E_{e^-}}{GeV} \cdot \frac{L}{10^{34}cm^{-2}s^{-1}} \quad (1)$$

A low emittance high peak current e^+ beam is demanded to keep P_{e^-} in bounds. The e^- beam will be heavily disrupted by the required high e^+ charge density. The disruption parameter(D), which relates the bunch length (σ_z) to the effective focal length of the beam force, is inversely proportional to P_{e^-}.

$$D^y_{e^-} = 2.8 \cdot 10^5 \ \frac{MW}{P_{e^-}} \cdot \frac{2}{1 + \frac{\sigma_x}{\sigma_y}} \cdot \frac{\sigma_z^{e^+}}{cm} \cdot \frac{L}{10^{34}cm^{-2}s^{-1}} \quad (2)$$

Even a beam power of a few MW corresponds to a disruption parameter of several hundred and the electrons undergo several oscillations in the high density e^+ bunch.

At energies considered here the beamstrahlung losses ($\delta_{bstr.}$) cause no sizeable energy smearing of the e^- beam and the destabilizing effect on the e^+ beam seems to be the major concern. There is no simple criterion to judge the destabilizing effect from the magnitude of D (see chapter about beam-beam effect). We quantify the beam forçe by the linear tune shift(ξ_{e^+}) that the nominal linac beam causes to the e^+ beam, analogous to ring-ring-colliders. A lower limit for ξ_{e^+} requires an increase of the

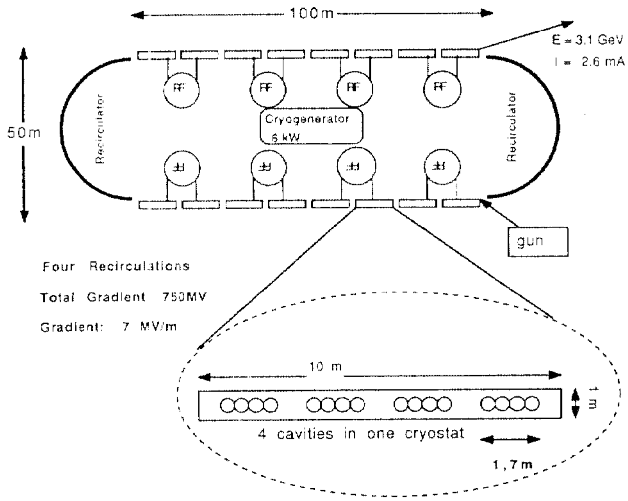

Figure 2: Recirculating LINAC based on LEP Cavities

e^+ current (I_{e^+}) and of the collision frequency (f_c) proportional to the betafunction ($\beta^y_{e^+}$) at the collision point.

$$I_{e^+} = 0.5A \cdot \frac{2}{1+\frac{\sigma_x}{\sigma_z}} \cdot \frac{\beta^y_{e^+}}{cm} \cdot \frac{0.05}{\xi_{e^+} H_D} \cdot \frac{9GeV}{E_{e^+}} \cdot \frac{L}{10^{34}cm^{-2}s^{-1}} \quad (3)$$

As a consequence of equation 3 higher beam energies imply smaller positron currents, but from synchrotron radiation power losses ($P_{e^+} \propto L \cdot E^5/\rho$) a lower E_{e^+} is preferred.

In Table 1 five sets of parameters each resulting in a luminosity of $10^{34}cm^{-2}s^{-1}$ are given. The first three cases are for a 3.1 GeV e^- beam and a 9 GeV storage ring beam; case D and E are for an 8 GeV e^- linac and a 3.5 GeV e^+ ring. For both energy choices round and flat beam examples are given. In case A a 1 Ampere e^+ beam and a 1 mA e^- beam are collided with a spot size of 1 μm; corresponding to the beam-beam simulations described later. In case B and C the essential input constraints are: $P_{e^-} = 8MW$, $\beta_{e^+} = 10mm$ and $\xi_{e^+} = 0.05$; in Case D and E :$P_{e^-} = 16MW$, $\beta_{e^-} = 7mm$ and $\xi_{e^+} = 0.05$.

4 Superconducting Linac

Superconducting radiofrequency cavities are by now applied in several projects[5]. Figure 2 outlines a recirculating linac using LEP cavities[6] as building blocks. In LEP, four 350 MHz cavities with four cells each are put into a common cryostat. The total length of such a unit is about 10m. Assuming four recirculations and a gradient of 7MV/m, 16 of those units(64 cavities) and 8 standard klystrons could accelerate a 2.6 mA beam up to 3GeV. The total amount of cavities and klystrons is comparable to about a quarter of what is planed for the energy upgrade of LEP.

For the envisaged low e^- beam current the higher order mode (HOM) couplers of the LEP cavities are adequate. With the long RF wavelength and the large iris holes of the superconducting cavities a degradation of the e^- beam quality (emittance growth, energy resolution) is not expected. In Table 2 the requirments for a B-Factory are compared with some basic parameter 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.

Table 2: Comparison of Superconducting RF Projects.

Project	LEP	HERA	KEK	CEBAF	B-Fact.
Total Gr. (GV)	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.

With $Q_0 = 5 \cdot 10^9$, which is not beyond reach at 7MV/m, the cryogenic losses due to residual RF resistance are less than 4kW at 4.2Kelvin. In additon static heat losses of about 1.5 kW are expected.

Gun: The high collision frequencies require a low emittance, short electron bunch directly from the cathode. Photocathodes irradiated by a laser and directly placed into a high gradient RF cavity have been developed for Free-Electron-Laser applications[7]. To overcome the large space-charge forces in nonrelativistic dense electron bunches, high acceleration gradients directly at the photocathode are demanded. Those photocathode laser guns are now being studied in several laboratories[8] including a CERN group for CLIC. In Table 3 projects in Los Alamos, Brookhaven (BNL) and a joint study for a gun with a superconducting RF cavity in Wuppertal,CEBAF and DESY(WCD) are compared to typical requirements for a B-Factory gun. The critical ratio of peak current to emittance

Table 3: Comparison of Laser RF Guns.

Project	Los A.	BNL	WCD	B-Fact.
$N_e \cdot (10^9/bunch)$	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

for a B-Factory is comparable to these projects. A high repetition rate could be achieved with a commercially available mode-locked laser.

5 Low Emittance High Current Ring

The requirements for the e^+ storage ring are comparable to these of very advanced synchrotron light sources or damping rings for future linear colliders. High peak and average currents together with the required low emittance challenge the beam stability and the alignment tolerances of such a ring.

Synchrotron radiation is 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 for this purpose. We studied the possibility of 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[9].

Due to the low emittance, small aperture quadrupoles can be used in the low β insertion and detector background problems from the high current ring should be small. Iontrapping problems inherent to e^- rings are avoided.

A more detailed feasibility study of the ring is needed.

6 Beam-Beam Effect

The beam-beam limit in storage rings is caused largely by the nonlinearities of the beam forces. A disrupted e^- beam with a drastically reshaped charge distribution might increase these nonlinearities. On the other hand the possibility to discard the beam after the collision opens new possiblities; also coherent phenomena and flip-flop effects are of less concern.

Simulations with two different programs have been performed using beam parameters corresponding to case A in Table 1; in addition the size of the e^- beam has been varied.

Figure 3a shows the 2σ contours of the e^+ beam with different e^- trajectories oscillating through the e^+ bunch. At the center of the collision area the e^- density is enhanced (pinch effect). In Figure 3b an e^- beam with $\sigma = 1\mu m$ is simulated. A luminosity enhancement appears, but the maximal tuneshift and the nonlinearities increase. In Figure 3c a much broader e^- beam distribution ($\sigma = 3\mu m$), but with a nominal e^+ bunch ($\sigma = 1\mu m$) is simulated; electrons are drawn in by the smaller e^+ bunch and the two bunches are better matched than in Figure 3b. Due to the intial phase space spread and the nonlinear forces of the Gaussian e^+ bunch no strong phase correlation between the electron trajectories exist.

In these simulations the positron field is taken from the unperturbed beam ('weak-strong'). In a second program developed for CLIC both beam forces are simulated simultanously ('strong-strong'). Figure 4 shows how the envelopes of the two beams evolve during the collision for different e^- bunch sizes. For the case of a broader electron distribution ($3\mu m$) the two bunches are overlapping at the collision time. Table 4 gives the luminosity with and without beam-beam forces for different e^- spot sizes normalized to an unperturbed collision size of 1 μm.

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

$\sigma^{e^+}(\mu m)$	$\sigma^{e^-}(\mu m)$	$H_D(noforce)$	$H_D(withforce)$
1.	1.5	0.53	1.56
1.	2.0	0.40	1.27
1.	3.0	0.20	0.94

The possibility to influence the nonlinear beam-beam forces by adjusting the electron beam initial condition looks encouraging.

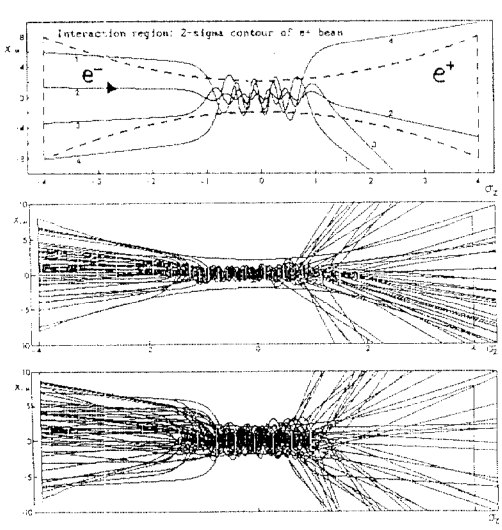

Figure 3: Electron Trajectories in Positron Bunch.

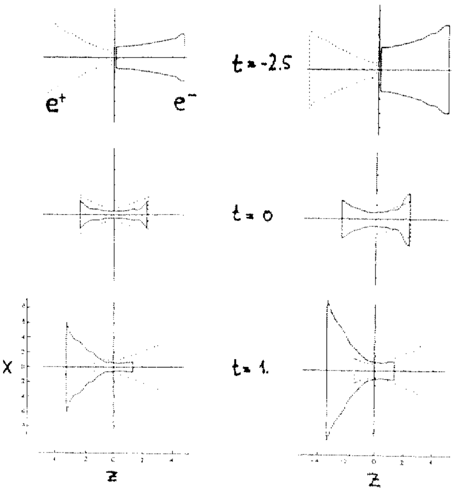

Figure 4: Beam Envelope during Collision.

To get a more quantitative picture for a possible limit of the linear tuneshift ξ_{e^+} a storage ring with nonlinearities and a low β insertion has to be simulated together with a large value of D. An experimental test of such a beam-beam interaction scenario would be helpful.

7 Conclusions

High luminosities seem possible in the linac-ring-collider scheme. The superconducting radiofrequency linac and the e^- gun could be built based on existing technology. The low emittance and high current e^+ ring could be designed 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 e^- ring and allows lower emittance beams. The fact that one beam is discarded after the collision opens new possibilities to improve the beam-beam limit. A linac-ring-collider appears attractive, but further studies are needed, to see how much of its potential could be realized.

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