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P. Grosse Wiesmann,
CERN, 1211 Geneva 23, Switzerland

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The collision of a linear accelerator electron beam with a particle beam stored in a ring allows center of mass energies and luminosities beyond those achievable in pure storage ring colliders. The constraints of such a collider scheme and the unusual beam-beam interaction scenario with a highly disrupted electron beam are discussed. Machine parameters for a high luminosity B factory are given. The possibilities to use the LEP type superconducting acceleration cavities for the linac and a low emittance and high current positron ring analogous to advanced synchrotron light sources are outlined. The option for parallel use of the electron beam for linac-ring collisions and fixed target operation is mentioned.

1 Introduction

Colliders using the storage ring approach have been very successful in establishing our present understanding of particle physics. For electron colliders the rapid increase of synchrotron radiation with beam energy and the disturbing beam-beam forces during the collision severely limit an extension in the center of mass energy and luminosity of storage ring based colliders. The collision of an electron linac beam with a particle beam stored in a ring aims at overcoming those limitations, while at the same time try to keep as much as possible of the economy of the successful storage ring concept.

Figure 1 outlines the basic components of a linac-ring collider. An electron linac beam produced at a low emittance gun is collided in a single pass with a continuously stored positron or hadron beam. Linac and ring beams are relatively decoupled: basic beam parameters like energy and intensity can be independently chosen and the impact from the beam-beam interaction will be very different for both beams.

Possible future projects of the linac-ring collider concept are [1]:

- several hundred GeV e^+e^- collider
- several TeV e^-P collider
- high luminosity e^+e^- particle factories

For the high energy applications very demanding electron linacs with an energy of at least a few hundred GeV are needed. Nevertheless the combination of a linac with the LEP ring[2] or a proton rings[3] in construction have been considered.

During the last years in particular linac-ring B factories with an asymmetric beam energy and a luminosity of $10^{34}cm^{-2}sec^{-1}$ have been studied[4],[5],[6]. While the main goal of linac-ring colliders is towards higher collision energies, the different nature of the beam-beam effect and the low current and small emittance beams could push the luminosity limit beyond the present performance with low energy storage ring colliders.

Figure 1: Linac-Ring Collider Overview

A high luminosity particle factory would allow to establish the concept without building a few hundred GeV electron linac. The possibilities to use a continuous high power electron beam in parallel for fixed target operation and to use the low emittance high current positron ring for research with synchrotron radiation could be valuable byproducts.

2 Constraints on Linac Ring Collider

One of the major luminosity limitation of any linac based single pass collider will be the magnitude of the linac beam power. For a given energy the luminosity of such a collider is proportional to the beam power and the transverse density of the stored particle bunch.

$$L = 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \cdot \frac{P_{e^-}}{\text{MWatt}} \cdot \frac{N_s}{2 \cdot 10^{11}} \cdot \frac{(\mu\text{m})^2}{\sigma_x^* \sigma_y^*} \cdot H_D \cdot \frac{\text{GeV}}{E_{e^-}} \quad (1)$$

Here N_s and σ^* are the number of particles and the transverse dimensions of the storage ring bunch. The linac-ring collider asks for a low emittance and high peak current storage ring beam. The requirements for positron storage rings are comparable to advanced synchrotron light sources; in proton storage rings the beam dimensions shrink by relativistic contraction and the concept is expected to work best at very high beam energies.

Even for micron size bunches several MWatt of beam power are demanded for a high luminosity operation, and an accelerator with an efficient conversion of wall plug power into beam power is needed. The optimal choice would be a superconducting linac, but although a conventional pulsed linac with multibunch operation could be considered.

Figure 2: Beam-Beam Simulations

The electromagnetic forces of particle bunches act like focusing lenses during the beam-beam collision. Dense particle bunches as considered for the linac ring collider correspond to an unusual beam-beam interaction scenario. The strength of the beam-beam interaction can be quantified by the disruption parameter, which relates the focal length of the beam lens to the particle bunch length. For high luminosity and a reasonable beam power the focal length of the storage ring bunch for the electron trajectories will be much smaller than the bunch length and the disruption parameter for the linac beam will be of the order of a few hundred. The electron beam current can be kept small in order to cause only a small perturbation of the ring beam. As an approximately correct picture one can consider the ring bunch as being inertial during the collision and the electrons oscillating several times around the positron beam axis. Monte Carlo simulations have been performed to investigate such a scenario [6],[7],[8],[9]. Figure 2 shows such overfocused electron trajectories oscillating through the strong electromagnetic forces of a ring bunch.

One of the major concern is the stability of the ring beam. To quantify the destabilizing

effect, which a highly disrupted electron beam will have onto the storage ring beam, the magnitude of the disruption parameter or the number of electron oscillations are not a particular meaningful number. It is more adequate to quantify the beam forces by the linear tune shift, the positron beam will get during the collision. The luminosity of the collider is then although determined by the following storage ring parameter: the total current, the tune shift value and the beta function at the collision point.

$$I_{e^+} = \text{Ampere} \cdot \frac{\beta_{e^+}^y}{\text{cm}} \cdot \frac{0.05}{\xi_{e^+} H_D} \cdot \frac{9 \text{GeV}}{E_{e^+}} \cdot \frac{L}{10^{31} \text{cm}^{-2} \text{s}^{-1}} \quad (2)$$

The instability of the ring beam is largely caused by the tune spread resulting from the non linear part of the beam-beam interaction. The fact that the linac beam will be discarded after the collision might open new possibilities to improve the luminosity limitations caused by the beam-beam interaction. For example the initial conditions of the linac beam can be chosen to favorably shape the charge distribution and therefore the forces the ring beam sees during the collision. This is being studied in the above mentioned Monte Carlo simulations. A test for such a beam-beam scenario would be highly desirable as discussed by O. Napoly in a contribution to this workshop [10].

3 B Factory Examples

The study of CP violation in B-meson decays is an important test of the standard model of particle physics. The Cabibbo-Kobayashi-Maskawa (CKM) approach of parameterizing quark mixing can describe the observed CP violation in Kaon decays. The CKM model makes definite predictions about CP violation in B-meson decays. Large asymmetries are expected, but unfortunately only for decay modes with small branching ratios. In order to test the CKM model in e^+e^- collisions, luminosities beyond the available performance of conventional colliders are demanded[11]. An e^+e^- collider at the $\Upsilon(4s)$ resonance with asymmetric beam energies or a collider at the Z^0 with polarized beams - both with unprecedented high luminosity - are crucial missing tools to perform such an experimental study of the CKM model. Any of those colliders - if ever realized - would accumulate the largest number of heavy quark and lepton pairs in the clean environment of e^+e^- collisions.

A B factory at the $\Upsilon(4s)$ seems to be the more readily available example to start with, essentially due to the low beam energies involved. Therefore we outline in the rest of this chapter the feasibility of a linac-ring B factory at the $\Upsilon(4s)$.

Figure 3 shows a layout of a linac-ring collider B factory. A linac beam fed by a low emittance gun will be realized with superconducting cavities and a recirculation scheme. The positron beam will be continuously stored in a low emittance and high current ring with the size of typically the ISR or the PETRA tunnel. The linac could be used in parallel for a fixed target program as indicated in figure 3; this aspect is discussed in more detail in the next chapter.

In Table 1 four sets of possible parameters for linac-ring collider B factories are shown[6]. The case A and B assume a 3.1 GeV electron beam and a 9 GeV positron ring. In the case C and D the electron beam is the high energy beam and we assume 8 on

Figure 3: Layout of a B Factory

Table 1: Linac Ring Collider Parameters.

		A	B	C	D
Beam Energy	$E_{e^-} (GeV)$	3.1	3.1	8.0	8.0
Beam Energy	$E_{e^+} (GeV)$	9.0	9.0	3.5	3.5
Beam Current	$I_{e^-} (mA)$	2.6	2.6	2	2
Beam Current	$I_{e^+} (A)$	0.5	0.9	0.9	1.6
Beam Power	$P_{e^-} (MW)$	8.0	8.0	16.0	16.0
Ring Bending Radius	$\rho_{e^+} (m)$	100	100	60	60
Beam Power	$P_{e^+} (MW)$	2.9	5.2	0.2	0.4
Collision Frequency	$f_c (MHz)$	10	18	28	50
Particles per Bunch	$N_{e^-} (10^9)$	1.6	0.9	0.4	0.3
Particles per Bunch	$N_{e^+} (10^{11})$	3	3	2	2
Collision Spot Size	$\sigma_x (\mu m)$	2.0	5.0	1.4	4.0
Collision Spot Size	$\sigma_y (\mu m)$	2.0	0.8	1.4	0.5
Bunch Length	$\sigma_z (mm)$	10	10	7	7
Beta Function	$\beta_y^{e^+} (mm)$	10	10	7	7
Disruption Parameter	$D_{e^-}^y$	350	610	130	230
Tune Shift	$\xi_{e^+}^y$	0.05	0.05	0.05	0.05
Beamstrahlung Loss	$\delta_{bstr.} (10^{-4})$	0.7	0.4	2.6	1.0
Luminosity	$L (10^{34} cm^{-2} s^{-1})$	1.0	1.0	1.0	1.0

Figure 4: A Recirculating Linac with LEP Cavities

Table 2: Comparison of Superconducting RF Projects.

	LEP	CEBAF	3.0 GeV	8.0 GeV
Acceleration Voltage (GeV)	3.	0.8	0.8	1.6
Number of Recirculations	—	5	4	5
Bunch Frequency (MHz)	0.04	1500.	120	150
Particle per Bunch (10^{10})	41.	.0003	.06	.04
Peak Current (KA)	1.2	.0005	.01	.01
Average Current (mA)	6.	1.	10.	10.
RF Power (MWatt)	16.	.8	8.	16.

3.5 GeV collisions. From the linac-ring collider constraints there seems to be no unique advantage for the choices between linac and ring energy, although the beam-beam limit has a slight preference for a high energy ring. The cases A and C differ from B and D by the aspect ratio at the collision point. Although here the choices are not final; the beam-beam effect favors round beams, but flat beams seem to be more easy to handle.

All four examples are constructed to achieve a luminosity of $10^{34} \text{cm}^{-2} \text{s}^{-1}$. Essential input constraints to achieve $10^{34} \text{cm}^{-2} \text{s}^{-1}$ are the beta function at the collision point, the linear tunes shift onto the ring beam and the linac beam power. At this stage of the studies, the parameters are just examples to indicate possible ranges; more detailed studies and a practical experience would certainly see trade-offs between parameters, and there is no principal obstacle why a luminosity of several times $10^{34} \text{cm}^{-2} \text{s}^{-1}$ could not be reached.

3.1 Superconducting Linac for a B Factory

Superconducting radiofrequency cavities offer the possibility for a high current and high frequency electron beam with very efficient conversion of wall plug power into beam power. The technology has been matured over the last decade and is now applied in several projects[12] involving electron storage rings, nuclear physics linear accelerators and free electron laser applications. LEP200 and CEBAF are two major ongoing projects with an industrial production line. A comparison with those projects allows a reliable estimation of the complexity and cost involved in the construction of a the linac needed for a B factory. In Table 2 the requirements for a B-Factory are compared to some basic parameters of those superconducting RF projects. All quantities like acceleration voltage, peak or average current are comparable to those typically required there.

Figure 4 outlines a linac based on LEP type cavities with five recirculation and a final energy of 8 GeV. In an expanded view the details of a basic subunit are shown. Four 350 MHz cavities with four cells each are assembled in a common cryostat. Two such assemblies could be fed by a standard LEP klystron with one MWatt RF power. With a gradient of 7 MV/m and a total acceleration voltage of 100 MVolt electrons are accelerated by 100 MeV. Of course structures with a different frequency and assembly are possible. The LEP units have been tested successfully with beams[13] and for LEP200

it is foreseen to install up to 32 units, twice the amount shown in Figure 4. The newly developed technology of sputtering Nb on Cu cavities[14] reduces the costs and improves the operational reliability. The industrial production costs for a subunit with eight cavities and a one MWatt klystron - as shown in the expanded view of Figure 4 - are about 5 million Swiss Franc; assuming final testing and assembling at the acceleration laboratory[15].

Beside the efficient conversion of power, superconducting cavities offer superior beam qualities. With the comparably long RF wavelength and the large iris holes the expected degradation of the electron beam emittance or energy resolution is negligible.

With a RF quality factor, $Q_0 = 5 \cdot 10^9$ cryogenic losses due to residual RF resistance of less than 8 KWatt at 4.2Kelvin are expected. In addition static heat losses of about two KWatt have to be envisaged. The expected cryogenic load of less than 12 KWatt at 4.2Kelvin corresponds to about two third of the cryogenic power installed for the superconducting magnets at HERA[16].

An electron linac with 3 GeV beam energy and a beam power of 8 MWatt, as demanded for case A and B in Table 1, could be realized with half the number of cavities and klystrons shown in Figure 4 and four recirculation.

Optics for the recirculator have been worked out for CEBAF [17] and for a similar project under study in SACLAY[18]. The possibility of a recirculating beam optic in analogy to the microtron has although been recently studied[19]. 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.

The possibility to use a single pass linac without recirculation has although been considered [20]. For LEP type cavities the structure costs and the cryogenic losses make such a choice uneconomical compared to the recirculation option. But in connection with development work for a future high energy collider this might become a valuable alternative for superconducting RF cavities with a higher frequency, a larger gradient and an improved Q value.

3.2 Electron Gun for a B Factory

The required high repetition frequency for a linac-ring B factory excludes the use of damping rings and a low emittance electron beam directly from a cathode has to be used. For Free-Electron-Laser applications[21] 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 those electron guns with tight specification towards emittance and pulse to pulse stability are developed. In Table 3 a project in Los Alamos[21] and the design for an RF gun in a superconducting cavity, which has been done at Wuppertal, CEBAF and DESY[22], are compared to typical requirements for a B-Factory gun. The peak currents and emittances are comparable to the requirements of a B-Factory. The Los Alamos project has a repetition rate of a few Hz, because it has been built to study the principles of such laser RF guns. In the superconducting RF gun design a continuous operation with repetition rate up to several hundred MHz is anticipated with a commercially available mode-locked laser.

Table 3: Comparison of Laser RF Guns.

	Los Alamos	Superconducting	B-Factory
Particle per Bunch (10^9)	60.	1.	1.
Bunch Length (mm)	9	2.6	7
Peak Current (A)	130	7.3	2.7
Normalized Emittance (mm-mrad)	18	45	10
rep. freq. (MHz)	few Hz	125	30

3.3 Positron Ring for a B Factory

For the positron storage ring of a linac-ring B factory the emittance requirements are comparable to those of advanced synchrotron light sources.

Synchrotron radiation provides a fast cooling mechanism, but in order to get a balance between cooling and quantum heating at a low emittance level, radiation losses in regions with large dispersion have to be avoided. The equilibrium emittance is inversely proportional to the cube of the number of lattice cells and a ring with many focusing elements is demanded. A high tune FODO lattice with wigglers in dispersion free zones has for example been studied for a damping ring in the SPS-tunnel[23] and a conversion of the PEP ring into a synchrotron radiation facility[24]. The dynamic aperture in those high tune lattices is critical and tight alignment tolerances are demanded. The longitudinal stability requires a low impedance design of all beamline components.

Low emittance beams offer considerable advantages: small aperture quadrupoles with very high gradients can be used in the low β insertion and detector background problems from synchrotron radiation of the high current 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. This is of particular importance since two beams with unequal energies have to be focused to the same interaction point. Ion trapping problems inherent to electron rings, as proposed for double storage ring colliders, are avoided since only a positron ring is needed.

4 Fixed Target Options

In Figure 1 the electron beam is dumped after the collision with the ring beam. The envisaged large beam power requires a well shielded and carefully designed beam dump in order to minimize the impact to the environment.

A more attractive possibility would be to use the electron beam for further experiments. In Figure 3 we outline a possible parallel operation of a linac for a linac-ring B factory and a fixed target program with electron, photon and kaon beams.

A dedicated high duty electron beam with an intensity of 0.1 nA could be accelerated in parallel in the same superconducting acceleration structure and separated afterwards. A subsequent acceleration into the energy region beyond 10 GeV could be done in a dedicated

Figure 5: Timing Structure for two parallel Beams

accelerator. The operation of such a beam would be relatively decoupled from the linac-ring collider, and parameters like energy and intensity could be selected independently.

Figure 5 shows a possible timing structure for both beams, where every second RF bucket would be used for a dedicated low intensity electron beam. A linac based on 350 MHz cavities with five recirculation could deliver a 35 MHz beam with 2 mA intensity and in parallel a second 175 MHz and 0.1mA beam, both with about 8 GeV energy.

For a dedicated electron hadron scattering experiment the beam current will be limited by target heating at the level of 50 to 100 μ A. An electron beam with a power of about 10 MWatt and a sharp timing structure opens new possibilities for dedicated beam dump experiments and attractive secondary beams.

The low ratio of neutrons to kaons in electron compared to hadron production together with the precise timing structure offers unique kaon beams[25]. For K_L^0 the momentum could be determined by time of flight measurements to better than one percent. The beam power would guaranty sufficiently large kaon fluxes to study several 10^6 kaon decays per second, and K_L^0 decay modes with a branching ratio at the level of 10^{-13} might be accessible. Although energy and flavor tagged neutrino beams from K_L^0 decays are possible.

5 Conclusions

Linac-ring collider offer unique possibilities to improve the center of mass energy and luminosity limitations of e^+e^- and eP collider. High energy colliders and high luminosity particle factories have been considered.

A crucial question for such a scheme is the beam-beam interaction with a highly disrupted electron beam and the stability requirement for the ring beam. New possibilities to improve the beam-beam limit might be given since the electron beam is discarded after the collision, but more Monte Carlo studies and eventually a test are envisaged.

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. Compared to a ring-ring-collider the linac-ring-collider avoids a high current electron ring, allows lower emittance beams and might improve the beam-beam limit.

The electron linac could be used in parallel for a fixed target operation with electron, photon and kaon beams.

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