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Colliding a Linear Electron Beam with a Storage Ring Beam*

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ABSTRACT

We investigate the possibility of colliding a linear accelerator electron beam with a particle beam stored in a circular storage ring. Such a scheme allows e^+e^- colliders with a center-of-mass energy of a few hundred GeV and eP colliders with a center-of-mass energy of several TeV. High luminosities are possible for both colliders.

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1. Introduction

In order to get a better understanding of the standard model of particle physics, higher energies and higher luminosities in particle collisions are desirable. It is generally recognized that particle collisions involving leptons have a considerable advantage for experimental studies over purely hadronic interactions. The initial state is better defined and cleaner event samples are achieved. Unfortunately, the center-of-mass energy and the luminosity achievable in an electron storage ring are limited. The energy losses from synchrotron radiation increase rapidly with the beam energy. Even with the largest storage rings under construction or under discussion the beam energy cannot be extended far beyond 100 GeV [1]. In addition, the luminosity in a storage ring is strongly limited by the beam-beam interaction. Event rates desirable to investigate the known particles are not even available at existing storage rings.

One way out of this problem is the linear collider scheme [2,3]. Here, synchrotron radiation losses are avoided and the beam-beam interaction limits are much weaker. In order to get the desired high luminosity, very tiny beam sizes at the collision point have to be achieved. So far, experience with linear colliders is very limited [4]. Although high energy, high luminosity linear colliders are under discussion [4,5], a technically detailed proposal does not yet exist.

Here we discuss a scheme, in which the electron beam from a linear accelerator (linac) is collided with a beam stored in a ring [6]. Such a concept allows the economy of a storage ring to be used, but at the same time can potentially avoid its energy and luminosity limitations.

A high intensity proton or positron beam can be stored at an energy independent of the electron beam. The proton beam can be stored at a very high energy using superconducting bending magnets. For positrons, in contrast to the linear collider concept, a high intensity positron source and the adjunct cooling rings are unnecessary.

The particle density of the stored beam at the collision point is not limited by the usual tune shift induced by the opposite beam, since the electron beam is not recycled. The electron beam has to be of relatively low current, so that the storage ring beam is not disrupted. Linac and storage ring beams are relatively decoupled. This gives more freedom to choose parameters and, in addition, the linac beam can be instantaneously adjusted to the parameter of the storage ring beam.

A very important advantage of such a scheme is that a low emittance electron beam can be directly produced by a suitable source [7], so that cooling rings are not necessary, and polarized electron beams can be achieved by using a special cathode and polarized laser light [8].

To see if such a scheme is practical we have to study the achievable luminosity. The luminosity in a collider, assuming a Gaussian particle density distribution, is

$$L = f \cdot \frac{N_e N_p}{4\pi\sigma_x\sigma_y} \cdot H_D \quad , \tag{1}$$

where f is the collision frequency, N_e is the number of electrons, N_p is the number of stored particles, σ_x and σ_y are the horizontal and vertical beam size at the collision point and H_D is the luminosity enhancement due to beam-beam focusing.

In principle, the luminosity can be increased by increasing fN_eN_p or by decreasing the beam spot size. Unfortunately, technical and financial limits tightly constrain these options.

In this paper we first discuss the various constraints of such a collider scheme. We then apply these constraints to four different configurations: a high luminosity b-factory, a high luminosity Z^0-factory, a few hundred GeV e^+e^- collider and a few TeV eP collider.

2. Constraints Affecting the Machine Parameter Choices

2.1 Power Consumption for the Beams

One of the major limitations for any high energy electron machine is the overall power consumption. The power consumption for a linac is

$$P_e = 1.6 \cdot \frac{N_e}{10^{10}} \cdot \frac{f}{\text{KHz}} \cdot \frac{E}{\text{TeV}} \cdot \frac{1.}{\eta_{la}} (\text{MW}) \quad , \tag{2}$$

where E is the beam energy and η_{la} is the acceleration efficiency for the linear accelerator. η_{la} for conventional disk loaded linac structures is at most a few percent [9,10]. Superconducting cavities can potentially achieve efficiencies of $\sim 50\%$, but are rather expensive [11].

The power needed to restore energy lost by the stored positrons due to synchrotron radiation is

$$P_s = 2.6 \cdot \frac{N_p n_b}{10^{13}} \cdot \left(\frac{E}{25\ \text{GeV}}\right)^4 \cdot \left(\frac{\text{km}}{\rho}\right)^2 \cdot \frac{1.}{\eta_{sa}} (\text{MW}) \quad , \tag{3}$$

where n_b is the number of stored bunches, ρ is the bending radius and η_{sa} is the efficiency to restore the synchrotron radiation losses. n_b is related to f and ρ by $n_b = \frac{f 2\pi\rho}{c}$. Here, a superconducting accelerator structure with high efficiency is the appropriate choice.

2.2 Current Limitations for the Linac Beam

The number of electrons per bunch in the linac beam is limited by its effect on the storage ring beam. This is traditionally expressed in terms of the tune shift limit ΔQ [12]:

$$N_e = 4.36 \cdot \frac{E_p}{\text{GeV}} \cdot \frac{\sigma_y(\sigma_x + \sigma_y)}{(\mu\text{m})^2} \cdot \frac{\text{cm}}{\beta_y} \cdot \Delta Q_y \cdot 10^8 \quad . \tag{4}$$

β_y is the vertical β function at the collision point. Based on experimental experience, $\Delta Q \leq 0.06$ for electron storage rings and $\Delta Q \leq 0.003$ for proton storage rings are considered to be possible [13]. This limit will demand low intensity beams in the linac.

2.3 Current Limitations for the Storage Ring

Assuming fN_e fixed by power considerations, the ratio $\frac{N_p}{\sigma_x \sigma_y}$ determines the achievable luminosity. Therefore, one would like to get as many particles per storage ring bunch as possible and tiny spot sizes at the collision point.

Besides power considerations, single beam instabilities, beamstrahlung by the electron beam and intrabeam scattering limit the maximum number of particles in the storage ring.

The peak currents which can be kept stable in a storage ring are determined by the transverse impedance of the accelerator. The transverse impedance depends on the detailed structure of the accelerator. In existing and planned storage rings, $\sim 10^{12}$ particles are achieved or planned.

The intense electric and magnetic field of the storage ring beam causes the electrons of the linac beam to radiate photons ('beamstrahlung'). Specifying a certain tolerable beamstrahlung loss constrains the number of particles and the bunch size of the storage ring beam. The storage ring beam acts like a lens on the electron beam and causes it to oscillate around the beam axis. In contrast to a pure linear collider, where the focusing effect happens in both beams and can cause instabilities due to plasma oscillations, here only the linac beam is affected. The focusing effect for the storage ring beam is small and is quantified in the tune shift limit discussed above. An oscillation of the electron beam around the center of the storage ring beam increases the luminosity by ~ 1.5. This beam focus effect also removes the constraints that β be greater than σ_z at the collision point. The focus of the electron beam has only to ensure that the particles are caught by the storage ring bunch. The fractional energy loss of the electrons can be calculated [14]. The result is

$$\delta = \left(\frac{N_p}{10^{12}}\right)^2 \cdot \frac{\text{cm}}{\sigma_z} \cdot \frac{(\mu\text{m})^2}{\sigma_x \sigma_y} \cdot \frac{E_e}{\text{TeV}} \cdot H_D \cdot H_\Upsilon \quad , \tag{5}$$

where H_D corrects for the pinch effect and H_Υ is the quantum correction factor.

The maximum amount of beamstrahlung is expected around one σ away from the axis. Therefore, we expect a small decrease of beamstrahlung due to the focusing of the electron beam. Quantum corrections reduce beamstrahlung at very high energy [14]. In our examples we are essentially in the classical region and the quantum reduction is small enough that we can assume, for our numerical calculations, $H_D = 1$ and $H_\Upsilon = 1$.

In a storage ring with very high particle densities, scattering of particles within the beam increases the emittance. This effect is called intrabeam scattering. Emittance growth rates can be calculated as a function of the current, the beam energy and various lattice parameters [15,16]. Emittance blow-up due to intrabeam scattering is most severe at low energies. In our positron storage ring examples, the energy is high enough and the cooling rates are fast enough so that intrabeam scattering can be limited by suitable optics. For proton storage rings, even at energies of a few tens of TeV, intrabeam scattering has to be taken into account. In our examples we explicitly calculate the beamstrahlung losses and we neglect effects from transverse impedance and intrabeam scattering (for protons this requires additional cooling).

2.4 Small Spot Sizes

To get high luminosities the collision area has to be made sufficiently small, while keeping positrons and protons stored at high energies.

The beam size at the interaction point of a storage ring is determined by the β amplitude and the emittance ϵ; $\sigma = (\beta\epsilon)^{1/2}$. Using a low β insertion scheme, β can be made relatively small at the collision point [17]. To avoid chromaticity problems in the adjacent quadrupoles a small β implies quadrupole magnets close to the interaction point. In addition, one only gains in luminosity if β is larger than the bunch length (σ_z). In existing storage rings, β values of a few centimeters are used. In our numerical examples, we assume β values at the interaction point of 1 cm for positron and 25 cm for proton storage rings if not otherwise specified. Because of the beam focusing effect, the β-value of the linac beam can be made smaller without reducing the luminosity gain.

The emittance has to be kept sufficiently small at high energy and for high current storage rings. This is contrary to the usual desire in e^+e^- storage rings, where one tries artificially to increase the emittance in order to get the maximum luminosity in the tune shift limit. Low emittance positron storage rings are desired by synchrotron users and several of these rings are under construction. In a storage ring the emittance is reduced by synchrotron radiation cooling. Cooling times depend on the magnetic field (B), the energy and mass of the stored particle ($\tau_{cool} \propto \frac{1}{B^2\gamma}$) and the storage ring optics. Electrons of several GeV are cooled in milliseconds. For protons of a few tens of a TeV and magnetic fields of a few Tesla, cooling times of one hour can be achieved. Quantum fluctuations increase the horizontal emittance (ϵ_x) in bending areas with large dispersion. The vertical emittance (ϵ_y) is determined by coupling to the horizontal emittance and can be kept smaller. Finally, an equilibrium emittance between synchrotron radiation cooling and the quantum fluctuations is achieved. The equilibrium value depends on the optical details of the storage ring and the beam energy. In the most practical storage ring lattice (FODO) the equilibrium emittance is [16,18]

$$\epsilon_x = \frac{55}{32 \cdot \sqrt{3}} \lambda_c \frac{\gamma^2}{Q^3} \frac{1}{J_x} \frac{R}{\rho} \quad , \tag{6}$$

where J_x is the horizontal partition function and $\frac{R}{\rho}$ is the ratio of the ring radius to the bending radius. Assuming $\frac{1}{J_x}\frac{R}{\rho} = 1$ for positrons gives the following relation:

$$\epsilon_x = 3.8 \cdot 10^{-13} \frac{\gamma^2}{Q^3} (\mathrm{m}) \quad . \tag{7}$$

In order to get ϵ_x small, the horizontal betatron tune (Q_x) has to be large.

The possibility of reducing the emittance by other methods, as applied to recent synchrotron light source storage rings, is not pursued further in this article. By using suitable wigglers one can expect roughly an order of magnitude decrease in the emittance compared to a simple FODO lattice [19].

For proton storage rings low emittance can be achieved by a cool proton source. Very high energies shrink the transverse dimensions of the beam. For example, the two large proton colliders under discussion (SSC, LHC) [20,21] are planning on spot sizes of a few μm. In principle, hadron storage rings at sufficiently high energies could achieve cooling times of less than an hour. SSC and LHC are in a transition region and intend to use both methods to get and keep the transverse emittance small. The emittance in a proton ring is limited by intrabeam scattering [15]. Intrabeam scattering increases the emittance proportional to the square root of the number of particles. Growth rates strongly decrease with the beam energy, in contrast to the synchrotron cooling rates, which strongly increase. In the energy range of the LHC or SSC an active cooling mechanism would be necessary. Electron cooling [22] is a possibility for cooling high energy and low emittance proton bunches [23]. Taking cooling rates, quantum fluctuation in synchrotron radiation and intrabeam scattering into account, the energy, radius and lattice of a proton storage ring with a certain equilibrium emittance can be designed.

2.5 Low Emittance Electron Accelerator

To get a linac electron beam with the spot size of a μm requires the acceleration of low emittance electrons. It is believed that an invariant emittance of $\sim 10^{-6}$ m for bunches with 10^{10} electrons can be achieved by a laser driven cathode source [7]. In order to achieve micron spot sizes for an energy of 2.5 GeV, a β function of 5 mm is necessary. A cool electron source in the linear accelerator can deliver a high frequency beam without damping rings. In addition, longitudinally polarized electrons can be obtained by using a circularly polarized laser beam.

In this paper we do not want to emphasize a detailed acceleration scheme. But from the constraint on the tune shift it is clear that the scheme prefers a low intensity electron beam with a high repetition frequency. Superconducting cavities with a high gradient field would be optimal. A disk loaded acceleration structure with a lower repetition rate could be used by accelerating several bunches on the same pulse and/or by allowing a higher tune shift per collision and a longer cooling time in between collisions.

3. Examples

Taking the discussion about the positron and proton storage rings and the electron beam as a basis, we present a few numerical examples to illustrate the scope of such a collider scheme. None of the parameter lists is meant to be complete, but are an illustration of what is feasible given the constraints discussed above.

The overall goal is the construction of a collider with a maximum luminosity and/or high center-of-mass energy for the minimum costs. With smaller spot sizes, lower power consumptions and, therefore, smaller operational costs can be achieved. But small spot sizes require greater technical complexity and, therefore, higher construction costs. Given the many unknowns in such a cost optimization, we do not try to find an optimal solution but rather arbitrarily take a few parameters as input parameters and derive other quantities using the equations derived above.

As input parameters we chose the energy of the two beams, the collision rate, the bunch dimensions and β function at the collision point, the radius of the storage ring and number of particles per stored bunch. The spot size and the β at the collision point determine the horizontal tune Q_x of the storage ring.

The number of electrons in the linear accelerator is determined by the assumed tune shift limit. Reducing the spot size at the interaction point would require a reduction in the number of electrons in order to meet the tune shift requirement. Therefore, a further reduction of the spot size would effectively reduce the power consumption of the electron beam, but would leave the luminosity unchanged. Given the storage ring beam parameter and the linac beam energy, the beamstrahlung of the electron beam can be calculated. A reduction of the beam size increases the beamstrahlung and would require a reduction in the number of stored particles if one aims for a certain beamsstrahlung loss.

As mentioned above, we apply the concept to four different cases. The first two cases are a b-factory (Table 1) and a Z^0-factory(Table 2). Here, the goal is to achieve a very high luminosity. For the b-factory examples, the unequal beam energies would make lifetime information at the $\Upsilon(4s)$ available, which is crucial to establish CP violation in the B-meson system. At the Z^0-resonance polarized beams could be realized in a simple way.

The third case is e^+e^- colliders with few hundred GeV center-of-mass energies (Table 3). An e^+e^- collider with a luminosity of a few times 10^{32} cm/sec and a center-of-mass energy of 300 GeV would be sensitive to neutral Higgs particles up to a mass of $2M_{Z^0}$. In addition, the pair production of vector bosons above threshold could be investigated.

The last examples are eP colliders with center-of-mass energies of several TeV (Table 4). Within this scheme, eP colliders offer the possibility of going into the TeV energy regime.

4. Summary

The collision of an electron beam from a linear accelerator with a storage ring beam allows high energy and high luminosity e^+e^- and eP collisions.

For an e^+e^- collider, such a scheme has several advantages compared to a purely circular machine or a purely linear collider. In contrast to the traditional storage ring, the center-of-mass energy and the luminosity are not so tightly constrained. Compared to a linear collider, the scheme avoids a high flux positron source and a large damping ring complex. In addition, the spot size requirements are less demanding. However, unlike the linear collider, the scheme cannot achieve TeV center-of-mass energies for e^+e^- collisions. For high luminosity b-factories or Z^0-factories, the scheme offers new possibilities. In eP collisions, much higher center-of-mass energies and luminosities can be achieved compared to the purely circular approach.

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Table 1. Parameters for a *b*–factory.

Particles	e^-	e^+	e^-	e^+	e^-	e^+
Energy (GeV)	2.5	10.0	2.5	10.0	2.5	10.0
E_{cm} (GeV)	10.0		10.0		10.0	
Circumf. (km)	–	2.0	–	2.0	–	2.0
Coll. Rate (MHz)	1		5		20	
N particle (10^{10})	0.4	100	0.2	50	0.1	30
Power (MW)	1.7	0.4	4.2	1.1	8.4	2.6
σ_x (μm)	4.0	4.0	2.0	2.0	1.0	1.0
σ_y (μm)	4.0	4.0	2.0	2.0	1.0	1.0
σ_z (cm)	–	1.0	–	0.5	–	0.3
β^* (cm)	–	2.0	–	1.0	–	0.5
ϵ_x (m)	–	$8.0 \cdot 10^{-10}$	–	$4.0 \cdot 10^{-10}$	–	$2.0 \cdot 10^{-10}$
Q_x	–	58	–	74	–	93
$\delta_{bstr.}$	0.0002	0.000	0.0003	0.000	0.0008	0.000
Luminosity (cm^2)	$3.1 \cdot 10^{33}$		$1.6 \cdot 10^{34}$		$7.5 \cdot 10^{34}$	

Table 2. Parameters for Z^0-factories.

Particles	e^-	e^+	e^-	e^+	e^-	e^+
Energy (GeV)	46.0	46.0	30.0	70.0	70.0	30.0
Circumf. (km)	–	20.0	–	20.0	–	4.0
Coll. Rate (KHz)	1000		500		1000	
N particle (10^{10})	0.09	30	0.14	30	0.06	30
Power (MW)	6.6	5.9	3.3	15.8	6.6	5.3
σ_x (μm)	1.0	1.0	1.0	1.0	1.0	1.0
σ_y (μm)	0.5	0.5	0.5	0.5	0.5	0.5
σ_z (cm)	–	0.4	–	0.4	–	0.4
β^* (cm)	–	1.0	–	1.0	–	1.0
Q_x	–	324	–	428	–	243
$\delta_{bstr.}$	0.018	0.000	0.012	0.000	0.028	0.000
Luminosity (cm^2)	$6.5 \cdot 10^{33}$		$4.9 \cdot 10^{33}$		$4.2 \cdot 10^{33}$	

Table 3. Parameters for e^+e^- colliders of 300 and 500 GeV.

Particles	e^-	e^+	e^-	e^+
Energy (GeV)	300.0	75.0	500.0	125.0
$E_{\rm cm}$ (GeV)	300.0		500.0	
Circumf. (km)	–	20.0	–	70.0
Coll. Rate (KHz)	500		200	
N particle (10^{10})	0.05	20	0.08	20
Power (MW)	11.3	13.9	12.6	12.2
σ_x (μm)	1.0	1.0	1.0	1.0
σ_y (μm)	0.2	0.2	0.2	0.2
σ_z (cm)	–	0.4	–	0.4
Q_x	–	448	–	630
$\delta_{bstr.}$	0.08	0.000	0.14	0.000
Luminosity (cm^2)	$2.8 \cdot 10^{33}$		$2.0 \cdot 10^{33}$	

Table 4. Parameters for eP colliders.

Particles	e^-	P^+	e^-	P^+
Energy (TeV)	0.3	7.5	0.8	20.0
E_{cm} (TeV)	3.0		8.0	
Coll. Rate (KHz)	500		500	
N particle (10^{10})	0.08	100	0.05	100
Power (MW)	18.8		33.5	
σ_x (μm)	1.0	1.0	0.5	0.5
σ_y (μm)	1.0	1.0	0.5	0.5
σ_z (cm)	–	10.0	–	10.0
$\delta_{bstr.}$	0.03	0.000	0.32	0.000
Luminosity (cm^2)	$4.7 \cdot 10^{33}$		$1.3 \cdot 10^{34}$	