POLARIZED AND UNPOLARIZED POSITRON SOURCES FOR LINEAR COLLIDERS

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Abstract

A common feature of all linear collider projects currently under investigation is the requirement of a high intensity positron source. Beside improvements of conventional sources, positron sources based on wiggler or undulator radiation are proposed which allow also the production of polarized positrons. An overview of the sources of various linear collider projects will be given and parameters and strategies will be compared. Results concerning polarized positron sources will be discussed.

Introduction

Future lepton colliders have to reach center-of-mass energies above 300 GeV, where the relation of construction cost to maximum energy favours linear colliders.

Various linear collider designs are under investigation in high energy laboratories throughout the world. Tab. 1 summarizes some important parameters.

A common feature of all linear colliders is the requirement of a huge number of particles which have to fit into the acceptance of the damping ring. Even if a portion of the particles can be collected and recycled after the collision [1, 2], the requirements are still beyond the current SLC source at SLAC which is, up to now, the positron source with the highest intensity. In addition the acceptance of the damping rings is in some cases smaller than at the SLC.

Linear colliders have to work in a pulsed mode with a repetition frequency between 10 Hz and 1.7 kHz. Up to 800 positron bunches would be accelerated during one rf-pulse. Therefore a high number of bunches has to be produced at the repetition frequency.

A fundamental intensity limit for positron sources is given by thermal stress which is built up in the conversion target due to the energy deposition of the primary beam. Only if the bunch spacing is above several hundreds of nanoseconds can the pulsed thermal stress be reduced by means of a rotating target [3], which is a very effective method in the case of sources for B-factories [4]. In the case of linear colliders only the superconducting TESLA and CLIC can take full advantage of a rotating target while in the case of the other machines only the mean thermal stress can be reduced.

The present design considerations of high intensity sources for linear colliders concentrate on two different source types (Fig. 1): an improved SLC-type source in combination with a pre-damping ring and sources based on wiggler or undulator radiation which also offer the unique possibility of polarized positron beams.

Proposals based on channeling radiation [5], pair creation in a strong laser field [6] or sophisticated target geometries [7] are under discussion.

The SLC-type positron source

Fig. 1 shows the principle layout of a SLC-type positron source.

A high power electron beam generates the positrons in a conversion target of 3 to 6 radiation length (X_0) thickness. The conversion efficiency can be approximated by [8]:

$$\frac{Ne^+}{E\,Ne^-} = 0.402 - 0.0399 \cdot \ln(E) \qquad (1)$$

E = Electron beam energy in GeV
valid for 0.3 GeV < E < 30 GeV

Thus at a given beam power a higher yield is obtained with high current, low energy beams. However, an upper current limit is given by beam loading effects and hence the beam energy has to be as high as 10 GeV.

Typically 30% of the power of the primary electron beam is deposited in the conversion target. In order to reduce the peak temperature to below ~500°C the spot size of the incoming electron beam has to be 3 to 7 mm^2. On the other hand the phase-space density of the positrons emerging from the target is reduced by an increased spot size.

To reach the luminosity goals of linear colliders ($L > 10^{33}$ cm^{-2} s^{-1}), beams with very small emittances have to be focused to tiny spot sizes at the interaction point. The vertical emittance of the positron beam from the source is reduced by 4 to 6 orders of magnitude in a damping ring.

The optics of a damping ring is designed to reach the required equilibrium emittance of $\gamma\varepsilon = (5.0 - 100) \cdot 10^{-8}\,\pi$ m within the time limits given by the repetition frequency of the linear collider. To this end damping wigglers and chromatic corrections are required which in turn reduce the dynamic acceptance of the ring to values below $\gamma A \sim 0.01\,\pi$ m, which is too small for a positron source with an increased spot size.

In order to relax the conditions at the positron source, pre-damping rings are proposed.

They are characterized by a large dynamic aperture, a short damping time and an intermediate equilibrium emittance. The positrons are injected into the pre-damping ring where the beam emittance is reduced so that the beam fits into the acceptance of the damping ring. In this scheme the total time for emittance damping is also doubled.

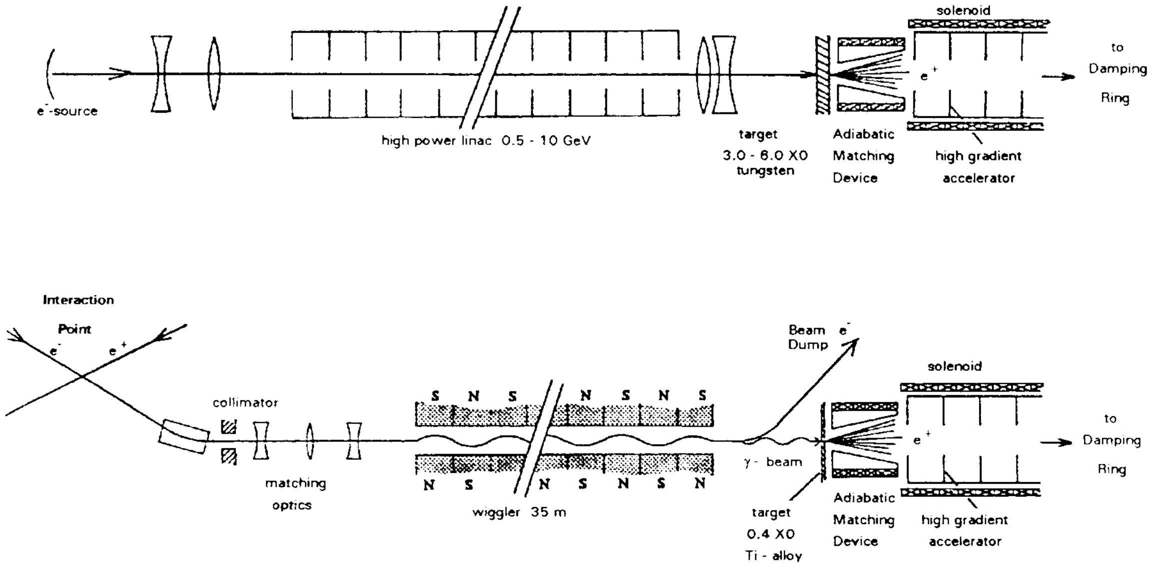

Fig. 1 Schematic layout of a SLC-type positron source and a source based on wiggler radiation.

	SLC	JLC	NLC	CLIC	VLEPP	DESY/ THD	TESLA
Ne+ per pulse [10^{10}]	5	80	63	0.6	20	360	4000
number of bunches per pulse	1	70	90	1	1	172	800
bunch spacing [ns]	-	2.8	1.4	-	-	12	1000
repetition frequency [Hz]	120	150	180	1700	150	50	10
γA of the damping ring [π m]	0.01	0.0045	0.015	$8.0 \cdot 10^{-5}$	0.1	0.012	0.012
γA of the pre-damping ring [π m]	—	0.027	0.04	> 0.6	—	—	—
positron source type		SLC-type			wiggler/undulator based		

Tab. 1 Parameters of various linear collider projects. SLC parameters are given as reference. (γA = normalized acceptance)

The capture optics

A key component of all positron sources is the capture optics behind the conversion target.

The positrons produced in the target have a broad distribution of transverse and longitudinal momentum components.

Hence they have to be accelerated in a high gradient section embedded in a solenoid field of 0.5 - 1.0 T.

The acceptance of a solenoid is characterized by a large spot size and small angles while for the positrons emerging from the target a small spot size and large angles are characteristic. To match the positron beam to the acceptance of the solenoid an Adiabatic Matching Device (AMD) is used. It consists of a tapered solenoid field, which starts with a high initial field and tapers down adiabatically to the constant end field. The optimum field distribution follows the law [9]:

$$B(z) = \frac{B_i}{1 + g \cdot z} \qquad (2)$$

z = longitudinal co-ordinate
B_i = initial solenoid field
g = taper parameter m^{-1}

with g = 30 - 60 m^{-1}. Initial fields up to 8 T can been obtained by means of a pulsed flux concentrator added to a DC-field [10].

The condition of adiabaticity for a field following eq. 2 is given by:

$$\frac{g \cdot P}{e \cdot B_i} << 1 \qquad (3)$$

which depends on the particle momentum P. Thus particles with energies above ~10 MeV suffer an emittance increase in the non-adiabatic field and might reach the acceptance limit.

Further particle losses occur as a consequence of a bunch lengthening due to path length differences and velocity differences in the AMD and in the subsequent high gradient section.

Fig. 2 shows the spectrum of positrons emerging from the target and the fraction which fits into the acceptance of the damping ring. Losses due to the non-adiabaticity of the field and due to bunch lengthening are indicated. Fig. 3 shows the longitudinal particle distribution after the capture optics. A long tail due to bunch lengthening is visible.

The capture optics represents a bottleneck with respect to acceptance if a pre-damping ring with large dynamic acceptance is considered. Increased solenoid fields and larger iris radii of the rf-sections are proposed to overcome this problem. Even higher acceptances can be reached if L-band sections are used instead of the standard S-band sections. This implies, however, problems concerning large aperture focusing elements and the availability of high power klystrons.

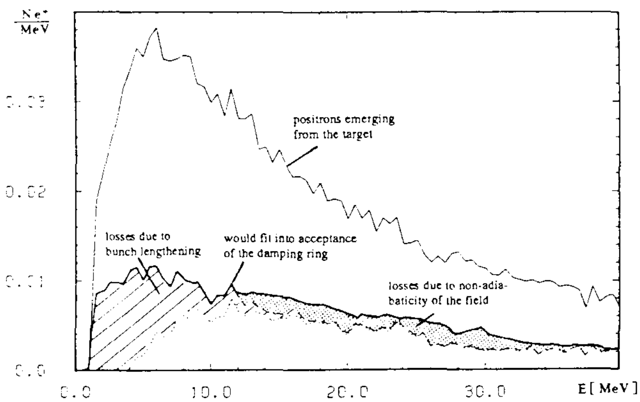

Fig. 2 Particle losses in the capture optics due to non-adiabatic fields and due to bunch lengthening. All curves are normalized to one positron emerging out of the target.

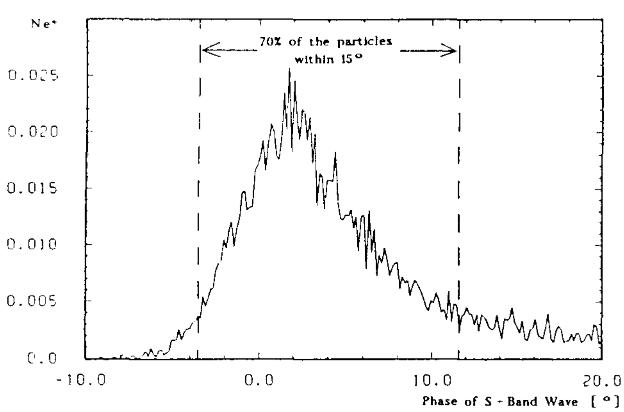

Fig. 3 Longitudinal beam profile after the matching device. Bunch length of the primary beam $\sigma s = 2.5°$. Broken lines indicate the energy acceptance of the damping ring.

High intensity sources based on wiggler radiation

High intensity positron sources based on wiggler radiation have been proposed for the DESY/THD S-band study [11], for TESLA [12] and recently for NLC [13]. These concepts modify an idea of V. E. Balakin and A. A. Mikhailichenko [14] (see also [15]). Fig. 1 shows a schematic layout of the scheme.

The 250 GeV beam is used after collision as a primary beam. Due to the strong beam-beam force intense γ-radiation, called beam-strahlung, is generated during the collision process. This results in a considerable energy spread within each bunch after collision. However, typically, 70% of the particles are still within a bandwidth of ±3%. After travelling through a special matching optics, the beam emittance is still small enough to pass the subsequent wiggler section of ~35 m length. Here photons with a mean energy of 22 MeV are emitted in a narrow cone. The minimum attainable spot size on the target is about 0.5 mm. The photons will be converted into electron positron pairs inside a thin target of titanium alloy while the primary electrons are deflected by a dipole magnet.

In sources based on photon conversion very thin targets ($< 1X_0$) can be used. Thermal load problems are reduced due to two effects [3]:

* A conventional target requires many radiation lengths for full development of the electromagnetic shower. Positrons which are produced in the first steps of the cascade will not emerge from the target due to ionisation losses inside the material. The ionisation loss per radiation length depends on the material and is lower for high Z materials. Thus, in order to achieve a high yield, one *has* to use high Z materials in conventional sources.

  In thin targets, however, the conversion efficiency is in first order independent of the material. Hence it is possible to use low Z materials which in general have a higher heat capacity (Dulong-Petit-rule). In Fig. 4 the positron yield for a 1 m long wiggler is plotted for different materials. From the point of view of yield titanium is only about 16% worse than tungsten if a target of 0.4 X_0 is considered.

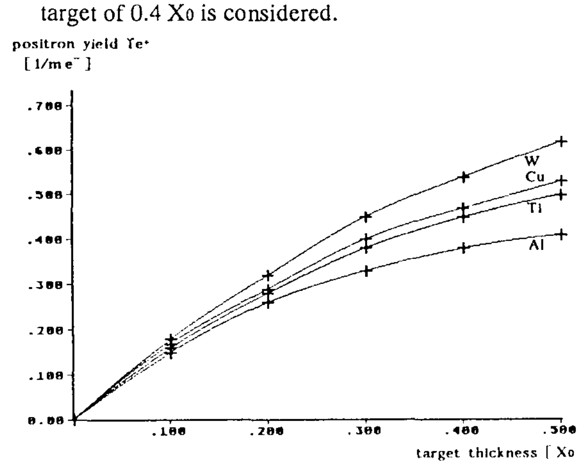

Fig. 4 Positron yield for different materials obtained with wiggler photons (B=1.7 T; S=1m; E=250 GeV) versus target thickness in units of radiation length X_0.

The maximum allowable particle density inside the target is, however, up to an order of magnitude higher for a titanium alloy than for a tungsten alloy.

* The second advantage of a thin target is the reduction of multiple-scattering inside the target. Fig. 5 shows a comparison of the transverse momentum distributions of a SLC-type source (30 GeV on a 6 X_0 target) and a source based on wiggler radiation (0.4 X_0). The results were calculated by means of the Monte-Carlo program EGS4 [16].

As a result of the narrower transverse momentum distribution the phase-space density is higher in the case of a thin target source and the capture efficiency is increased by a factor of ~5 compared to a SLC-type source with the same acceptance of the capture optics.

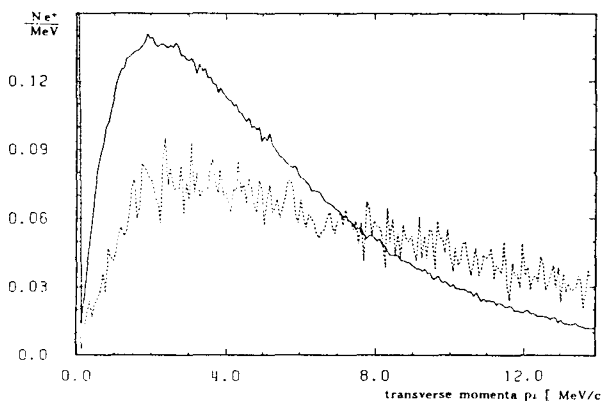

Fig. 5 Comparison of the transverse moments of a SLC-type source (6X_0, W, dotted line) and a thin target driven by wiggler photons (0.4X_0, Ti, solid line).

No pre-damping ring is required for TESLA or the DESY/THD S-band study due to the better source performance and due to the bigger acceptance of the damping rings compared to other designs.

The mean power deposition and the neutron production is also reduced in a source based on wiggler radiation. Further improvements of these parameters can be achieved if the target thickness is reduced which , however, is only possible if the wiggler length is increased [13].

The capture optics of a source based on wiggler radiation follows the same principles as for the SLC-type source. Special techniques are proposed for TESLA in order to meet the requirements of the long bunch train. A multi-bunch SLED-system will be used to produce a short rf-pulse for each bunch in a bunch train which will be fed into short S-band sections. Thus the accelerating gradient is increased by a factor of 1.5 while the heatload is reduced by a factor of ~2.6. For details see ref. 12.

Polarized Positron Sources

Measurements of asymmetries under spin helicity reversal provide a powerful tool for the investigation of high energy physics problems. For asymmetries based on polarization effects we find the error ΔA_{LR} of an asymmetry measurement A_{LR} by [17]:

$$\Delta A_{LR} = \left[A_{LR}^2 \left(\frac{\Delta P_g}{P_g}\right)^2 + \frac{1}{P_g^2 \cdot N} \right]^{1/2} \qquad (4)$$

N = number of events

P_g is a generalized polarization defined by:

$$P_g = \frac{Pe^- + Pe^+}{1 + Pe^- \cdot Pe^+} \qquad (5)$$

Pe^- = electron polarization

Pe^+ = positron polarization

It can be shown that the integrated luminosity which is necessary to measure A_{LR} within given statistical limits can be reduced by a factor 2 to 4 if the positron beam is polarized in addition to the electron beam. The error ΔP_g in the measurement of the generalized polarization is also reduced and tends to zero if both beams are polarized 100%.

Hence, polarized positron beams offer a great physical potential even if the electron beam is already polarized.

The basic idea of a polarized positron source was proposed by V. E. Balakin and A. A. Mikhailichenko in 1979 [14, 18]. Instead of a planar wiggler a helical undulator has to be used to produce circularly polarized photons which are converted into longitudinally polarized positrons in the target. A polarization of up to 70% can be achieved.

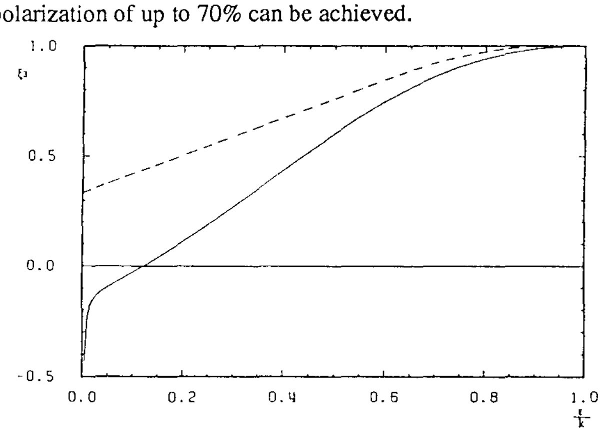

Fig. 6 Circular polarization of the positrons produced in a pair production process (solid line) and after bremsstrahlung (broken line) as function of the fractional energy.

Fig. 6 shows the longitudinal polarization of positrons as produced in a pair production process versus the fractional energy. The incoming photon has an energy of 20 MeV and is circularly polarized. The high energy positrons carry the polarization of the incoming photons while the low energy positrons have a negative polarization. However, most of the low energy positrons will be stopped in the target due to ionisation losses. The low energy parts of the spectrum will be repopulated via bremsstrahlung processes. The polarization spectrum of the positron source is hence dominated by the bremsstrahlung process which is also shown in Fig. 6.

In order to take care of all processes in the shower, polarization states have been included into EGS4 [3].

In Fig. 7 the polarization is plotted as function of a normalized scraper angle for various undulator parameters K. Since only the radiation near the optical axis of the undulator is completely circularly polarized a scraper is used to collimate the photon beam. The undulator parameter is defined as:

$$K = 0.943 \cdot B \cdot \lambda \tag{6}$$

B = max. magnetic field in T

λ = period length of the undulator in cm

λ has to be of the order of 1 cm in order to produce photons with an energy of ~20 MeV with an electron beam of 250 GeV. At high magnetic fields more photons are emitted per undulator length but the fraction of off-axis radiation increases more than proportionally for high K-values. Nevertheless represent high K-values in combination with a scraper an effective parameter set for a polarized positron source. For K~1 the length of the undulator has to be of the order of 150m if a polarization of 70% is envisaged. The technical feasibility of a helical undulator with these parameters has to be proven.

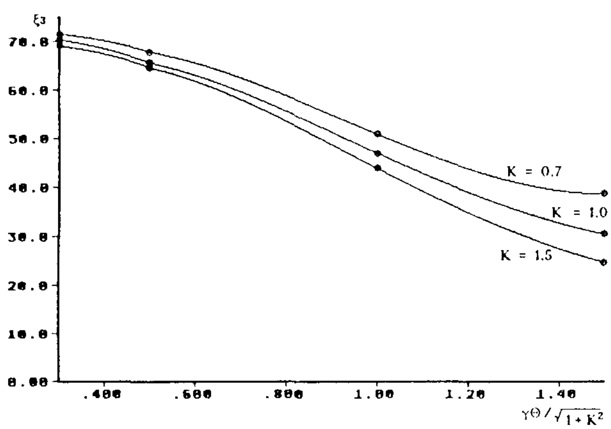

Fig. 7 Polarization versus scraper angle for various undulator parameters K.

Conclusions

Positron yields of up to $8 \cdot 10^{11}$ positrons per pulse can be reached with improved SLC-type sources. Higher yields are available with sources based on the conversion of wiggler photons. These sources also provide the interesting possibility of polarized positrons which, however, demand strong technological efforts.

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