Polarized Positrons for Future Linear Colliders

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Abstract. The high luminosity requirements and the option of a polarized beam present a great challenge for the design of the positron source for future linear colliders. This contribution provides an overview of the proposed designs for the polarized positron sources of the International Linear Collider (ILC) and the Compact Linear Collider (CLIC).

1. Introduction
Experiments at future linear electron-positron colliders running at high energies of few hundred GeV up to few TeV will allow to test the Standard Model and physics beyond. In contrast to hadron machines, the initial state parameters are known: the particle type is defined, and energy and beam polarization can be measured with high precision. Since weak interactions violate parity, beam polarization is important to differentiate weak processes and to search for new physics scenarios. The choice of beam polarization allows to enhance or suppress Standard Model processes and to disentangle new processes. Providing a high luminosity, precision measurements at high energies can be performed and will give us a deeper insight into the underlying symmetries and the nature of electroweak symmetry breaking. Although the physics potential can be substantially increased if both beams are polarized [1], up to now linear colliders have been operated with unpolarized positrons. It is a challenge to create the intense polarized positron beam for future $e^+e^−$ machines as ILC and CLIC. However, already a low degree of positron polarization, $P_{e^+} > 30\%$, improves the physics performance. In this contribution the possibilities to produce polarized positrons for future linear colliders are discussed and the main components of the positron source are presented.

2. Generation of polarized positrons
Longitudinally polarized positrons can be produced via the pair-production process initiated by circularly polarized photons [2]. Two methods are under consideration to produce the polarized photons for future linear colliders: the undulator scheme and laser backscattering. In the first scheme proposed by Balakin and Mikhailichenko [3] a multi-GeV electron beam is passed through a helical undulator to generate the multi-MeV circular polarized photon beam. In the second, circularly polarized laser light is backscattered off an electron beam [4, 5].

2.1. Polarized positrons from helical undulator
A helical undulator consists of a wire (often engineered as ribbon-wire) wound in a double helix to generate a rotating dipole field in the transverse planes along the beam axis. The electrons follow a helical path and emit photons. The photon spectra and photon radiation cone depend
on the undulator parameters strength $K$ and period $\lambda$, and on the electron energy. The desired photon yield determines the length of the undulator. Also the photon polarization spectrum depends on the undulator parameters; the direction of the helical field windings defines the sign of the polarization. The undulator method was tested in the proof-of-principle experiment E166 at the Final Focus Test Beam of the Stanford Linear Accelerator Center (SLAC).

2.1.1. Proof-of-principle experiment E166 The 46.6 GeV electron beam passed a 1-m-long helical undulator with period $\lambda = 2.25$ mm, $K = 0.17$ and aperture 0.9 mm. The circularly polarized photon beam of peak energy $\approx 8$ MeV impinged on a 0.2-radiation-length tungsten target to produce positrons and electrons which were separated and measured using a Compton transmission polarimeter. In agreement with the expectations, the longitudinal polarization of positrons was above 80% for positrons at 6 MeV. A more detailed discussion of the experiment and its results can be found in references [6, 7].

2.2. The Compton scheme

Compton backscattering of circularly polarized photons off an electron beam results in longitudinally polarized electron-positron pairs. The sign of the averaged positron polarization is given by the sign of the photon polarization. The method was tested in an experiment at the Accelerator Test Facility (ATF) at KEK [5].

2.2.1. Test experiment at KEK A circularly polarized laser beam of 532 nm was scattered off a high-quality, 1.28 GeV electron beam to produce photons with maximum energy of 56 MeV. A special apparatus (Compton chamber) was constructed to realize head-on electron-photon collisions. The magnitude of positron polarization was measured with a Compton transmission polarimeter for different states of laser polarization; $|P_{e+}| = 73 \pm 15$(stat) $\pm 19$(sys)% was achieved. For linearly polarized laser light the positron polarization was zero. It is an advantage of Compton scheme that the reversal of positron helicity can be done easily by reversing the polarization of laser light.

2.3. Polarized positrons for future linear colliders

The methods described above allow to produce longitudinally polarized positrons from circularly polarized photons with an efficiency at the level of a few percent. Hence, a high power photon beam is needed to create the required amount of positrons. To keep the heat load at the positron production target within reasonable limits and to avoid damage, the target has to be rotated. Nevertheless, thermal problems in the target or the photon collimator demand special care in the design. Serious thermal problems also arise with a conventional unpolarized positron source where an electron beam hits a relatively thick target to produce electrons and positrons via the bremsstrahlungs process. It is possible to spread the heat load over a large area or several targets by deflecting the electron beam, but the thick target yields widely spread positrons resulting in a low capture efficiency. Therefore the energy deposition in the target and the capture section is very high, even higher than in photon-based positron sources.

3. The International Linear Collider (ILC)

The Reference Design Report (RDR) [8] for the ILC project was presented in 2007. The ILC energy should be adjustable from 200-500 GeV and upgradeable to 1 TeV, the luminosity amounts $2 \times 10^{34}$ m$^{-2}$s$^{-1}$ to collect 500 fb$^{-1}$ within the first four years. The electron beam will be polarized with a degree of at least 80%, positron polarization of about 60% is foreseen as an upgrade option. The energy stability and precision should be better than 0.1% to reach all physics goals. The layout is sketched in Fig. 1. The ILC includes the polarized electron source, the undulator-based
The positron source and the 5 GeV damping rings for electrons and positrons housed in a common tunnel at the center of the ILC. Each beam passes subsequently a bunch compressor system prior the injection into the 11 km long main linacs which are utilizing 1.3 GHz superconducting RF cavities operating at an average gradient of 31.5 MV/m. The RF pulse length is 1.6 ms, the pulse repetition rate is 5 Hz. The total power consumption is 230 MW. The ILC comprises one interaction region for measurements with two push-pull detectors.

The RDR design is revised for improvements and cost savings, currently the Strawman Baseline 2009 Design Proposal (SB2009) [9] is under consideration. The goal is to reduce the overall costs, to optimize the facilities and to improve the performance of the ILC. Main features are the change from the double-tunnel system to a single tunnel, the relocation of the positron source and a reduced power operation. The Technical Design Report will be released end 2012.

3.1. The ILC positron source

The positron source as described in the reference design [8] is based on a superconducting helical undulator located at the 150-GeV-point in electron linac. The undulator period is $\lambda = 1.15 \text{ cm}$, the B-field on axis is 0.86 T corresponding to $K = 0.92$, and the aperture is 5.85 mm. The length of the undulator is 147 m to finally achieve the yield of 1.5 positrons per electron passing the undulator. The photons (10 MeV cut-off energy of the first harmonic) hit a 1.4 cm thick Ti-alloy target 500 m downstream the undulator. The positrons are captured using a pulsed flux concentrator (FC) as optical matching device and accelerated to 125 MeV using normal-conducting structures embedded in a solenoid with 0.5 T. The electrons and the photon beam are dumped, the positrons are accelerated to 5 GeV and injected into the damping ring. A 4 m ILC undulator prototype has been constructed and tested at Cockroft Institute [10]. The overall scheme of the ILC positron source is sketched in Fig. 2. This baseline design provides a
Figure 2. Schematic layout of the ILC positron source (not to scale).

A positron beam with 34% polarization which can be further increased by implementing a photon collimator upstream the target [11]. To utilize the positron polarization for physics, it has to be brought to the interaction point, i.e. spin rotators are also needed for the positron beam line, and it must be possible to reverse the helicity of positrons rapidly to control systematic effects. Two proposals exist to change the helicity of positrons of energy 400 MeV or of 5 GeV [12]. A detailed spin tracking has still to be performed to finally decide the best option.

The SB2009 design suggests to place the positron source at the end of the main linac. This allows to use the same machine protection elements for both the undulator and the directly downstream beam delivery system, saving technical elements and tunnel space. However, this effects substantially the positron polarization: since the electron energy determines the opening angle of the undulator radiation, a 250 GeV-electron beam yields a positron polarization of only 22% (see also references [13, 14]). The physics gain of this low positron polarization is not sufficient taking into account the effort to keep it to the interaction point and to measure it precisely. So, the positron polarization should be increased, e.g. assembling a photon collimator or changing the undulator parameters. Alternatively, an unpolarized positron beam could be used; either by destroying the positron polarization or implementing a planar undulator to create linearly polarized photons. If they hit the target and undergo the pair-production process, unpolarized positrons and electrons are generated. But the photon yield in a helical undulator is about 1.5–2 times higher than that in a planar undulator for the $K$ values of interest, not to mention that it is impossible to take advantage of polarized positrons for physics.

3.1.1. Positron target and capture The positron target is located about 500 m downstream the undulator and consists of a Titanium alloy wheel (2 m diameter) of thickness 1.4 cm and is designed as rim stabilized by five spokes. The incident photon beam spot size depends on the opening angle of the photon beam, it is of $O(\mu m)$. The total power deposition in the target is 10.4 kW for the RDR and up to 8 kW for the SB2009 design. To reduce local thermal effects and also radiation damage, the target wheel has to be rotated with 2000 rpm. The positron yield depends on the capture optics (optical matching device) behind the target. Assuming an Adiabatic Matching Device (AMD) with a B field tapered from 5 T at the target to 0.5 T at 20 cm downstream, the capture efficiency is 30%. However, eddy currents increase substantially the heat load in a rotating target immersed in a high magnetic field. The influence of eddy currents and the mechanical stability of the target wheel design were tested with a prototype (without cooling channels) built and operated at Cockroft Institute [15]. The torque associated with eddy current production in the target was measured depending on the immersion depth and the magnetic flux densities. The extrapolation of the results indicates that an additional power of 8 kW will be deposited in a target immersed in fields of approximately...
1 T at revolution rates of 2000 rpm. Hence, the B field on the positron production target should be low to avoid eddy currents and the corresponding heat load. However, this implies a lower capture efficiency.

To minimize the risk, the SB2009 design suggests a quarter wave transformer (QWT) instead of the flux concentrator (FC) to collect the positrons exiting the target. This decreases the positron capture efficiency to 15%. A longer undulator (231 m) compensates this reduction. Using a QWT would make the positron polarization upgrade to 60% almost impossible. The undulator length has to be increased to an extent that the energy loss of electrons as well as the photon power loss in the undulator become worrying. A pulsed flux concentrator with low B field at the target affords a capture efficiency of 22% but requires still design work and the test of a prototype. It is under study at LLNL [16]. More details about the ILC positron source can be found in references [14, 17, 18].

4. The Compact Linear Collider (CLIC)

The Compact Linear Collider CLIC [19] is based on two-beam acceleration; the technology affords operation at 500 GeV, up to the multi-TeV range. The luminosity will be in the range $10^{34} \text{cm}^{-2}\text{s}^{-1}$. Energy and luminosity will be finally reviewed depending on the LHC physics results. The CLIC electron source will be polarized, polarized positrons are planned as an upgrade option.

The CLIC scheme uses high-frequency normal conducting accelerating structures with a main linac radiofrequency of 12 GHz and an accelerating field of 100 MV/m. The total power consumption should be below 500 MW.

The overall CLIC scheme is displayed in Fig. 3. The central injector complex includes sources,
is transferred by Power Extraction and Transfer Structures (PETS) to the low current (1.2 A) main beam for acceleration.

4.1. Polarized positrons for CLIC using the Compton scheme
The baseline positron source is unpolarized, polarization is planned as an upgrade option and needs substantial effort. The preferred design for the polarized positron source is based on the Laser-Compton method which can be implemented at any time without modifications of the CLIC complex. The problems concerning the positron production target and the capture section are similar to that studied for the ILC; the main differences concern the time structure and bunch charge. Hence, a close collaboration between the ILC and CLIC source communities exists.

Due to the relatively low Compton cross section high intensities for the electron and the laser beam are required which are presently not available. Several methods to produce the polarized positron beam with the CLIC time structure are under consideration, details can be found, e.g., in references [20, 21]:

- **CLIC positron injector with Compton ring** In this option a Compton ring with circulating electrons is used in conjunction with a high-finesse optical cavity powered by a YAG laser. Simulations show, that the size of the ring, the number of electrons per bunch and the length of the laser pulse can be synchronized such that sufficient 200-MeV-photons can be created to produce polarized positrons with the right pulse structure for CLIC.
- **CLIC Compton ERL** Instead of the Compton ring an Energy Recovering Linac can be used. This scheme provides a large number low-charge bunches with high-repetition frequency. The CLIC time structure is generated by a positron stacking procedure.
- **CLIC Compton linac** Here, the photons are created by Compton backscattering of photons from a CO\(_2\) laser an electron beam from a linac. The CO\(_2\) laser provides 10 times more photons per Joule than a YAG laser. The production of one photon per electron has been demonstrated at BNL [22]. To realize this scheme for CLIC, ten consecutive Compton IPs are needed to accumulate the required photon flux.

4.2. CLIC undulator scheme
The undulator option can also be applied at CLIC. But the integration of the undulator into the CLIC scheme has to be taken into account from the beginning, otherwise it is difficult to implement the undulator into the CLIC main linac and the positron injection part. The performance of the undulator, target and capture section are similar to that at the ILC, more details can be found in reference [21].

5. Polarimetry at the positron source
It requires some effort to measure the polarization at the positron source. Since the beam size is large upstream the damping ring, \(O(\text{cm})\) a Compton polarimeter will not work due to the tremendous laser power needed. It has been studied in simulations, that a Bhabha polarimeter would be a good option to measure the longitudinal polarization of positrons with energies of few hundred MeV [23]. Once the positrons passed a damping ring, a Compton polarimeter can be used. However, after passing the DR the spins are oriented to the transverse direction. The measurement of the asymmetries in the Compton scattering process with transversely polarized leptons depends on the energy and on the spatial distribution, and needs more effort than that of the Compton process with longitudinally polarized leptons. Since at CLIC the beams pass few damping rings in the injection complex, one should simulate the full spin tracking from the creation of positrons to the injection to the main linac to study possible sources of depolarization and to find out the best method and position for the polarimeter at the source.
**6. Summary**

Physics measurements at future high energy linear colliders will benefit from polarized beams. A positron source based on a helical undulator provides polarized positrons from the beginning, the degree of polarization can be increased by upgrades later on. Since later upgrades to a polarized source influence the source layout as well as the design of the whole accelerator, positron polarization must be regarded already in the baseline design.

The ILC design is already in a very progressive stage. Some problems are still under consideration; for the positron source these are in particular the thermal stress and the vacuum seals at the rotating positron production target as well as functionality of a flux concentrator to achieve a high positron yield. Currently the ILC layout is revised to develop the baseline design for the ILC TDR which will be released end 2012. The conceptual design of CLIC is under way and will be submitted in 2011. In parallel with the design work also a realistic spin tracking from start to end is being performed to figure out possible sources of depolarization and to guarantee a high and stable degree of positron polarization. Although not mentioned in this contribution, the precise measurement of the positron polarization at the interaction point is very important [24]. In particular, depolarization could occur in the strong field of beam-beam interaction during bunch crossing and has to be known with high accuracy. The success of a future LC depends substantially on making available polarized beams and the precise measurements at the IP.

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