Future Sources of Polarised Positrons

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Abstract

Polarised positrons have a range of applications in modern physics: from surface science measurements requiring energies as low as a few eV, to studies of the proton structure function and of the fundamental interactions of elementary particles at energies approaching the TeV scale. The common challenge for all of these studies is to generate sufficient numbers of positrons. A discussion of this topic is pertinent to these proceedings as it has been suggested that anti-protons can be efficiently polarised through a hyperfine spin-flip interaction with polarised positrons. In this paper I review the current state of high-intensity sources of polarised positrons. Emphasis is placed on those sources being developed to meet the requirements of future e^+e^- colliders.

1 Introduction

Despite the large range of applications for polarised positron beams [1], including the possibility of polarising anti-protons [2], there are relatively few schemes by which such beams can be created efficiently. The two main methods are:

1. Moderation of positrons emitted by radio-isotopes.

2. e^+e^- pair-production of circularly polarised gamma rays.

In the following section I briefly review the first of these methods, which is primarily used for the production of so-called slow positrons with energies up to a few tens of keV. In the subsequent section I discuss the pair-conversion method, with emphasis on its role in providing polarised positrons for future high-energy particle colliders.

Positrons produced at other intense sources, such as reactor-based facilities [3], or electron beam facilities [4],[5],[6], are typically unpolarised and are consequently outside the scope of this review.

2 Radio-Isotope Positron Sources

Positrons emitted in the β^+ decay of radioactive isotopes are preferentially produced in a longitudinally polarised state due to the chiral coupling of the W boson to fermions. Remarkably, much of the polarisation has been shown to survive moderation [7]; hence positrons produced in this way can be formed into intense slow, polarised beams. The favoured isotope for many applications is ^{22}Na which has a half-life of approximately two years and an end point energy close to 1 MeV which maximises the degree of polarisation of the positrons produced [7]. Short-lived β^+ emitters can also be exploited as useful sources of polarised positrons by beam-based facilities employing reactions such as ^{11}B(p,n)^{11}C [8].

Typical rates for contemporary radio-isotope polarised positron sources are of the order of 10^5 positrons per second with some sources reaching rates of 10^7 or more [1]. As the polarisation of the positrons is energy-dependent, the overall polarisation of the beam can be enhanced by selectively absorbing positrons of low energy. Consequently, sources that are not optimised for delivering high-polarisation can operate at rates one or two orders of magnitude higher than their polarised counterparts. Refinements to the moderator and capture optic designs of such sources have been proposed which may allow an increase in the positron production rate by a further order of magnitude [9]. Although it may be technically feasible to achieve even higher rates in the future by increasing the quantities of radio-isotope used, costs and safety regulations may inhibit this development [10].

3 Requirements of Future Linear Colliders

There is a broad consensus within the particle physics community that the next high-energy collider facility to be built following the completion of the Large Hadron Collider (LHC) at CERN should be a linear e^+e^- collider. At present there are two concepts being explored by the international accelerator physics community, the International Linear Collider (ILC) which has a centre-of-mass energy of 500 GeV and for which a comparatively mature design already exists [11], and the Compact LInear Collider (CLIC) which holds the promise of a centre-of-mass energy of several TeV, but relies on novel dual-beam accelerating technology which is still under evaluation [12].

To reach their design luminosity, the nominal design parameters for CLIC require approximately 6.2×10^{13} positrons per second at the interaction point, whilst those for the ILC require approximately 2.6×10^{14} positrons per second. Good design practice suggests that in order to meet these goals, the sources should be designed to inject positrons into their respective damping rings at rates at least twice those expected at their interaction points. Although the average rates at which positrons are required to be produced are similar between the ILC and CLIC, the different time structures of their beams may lead to different technology choices for their sources. In both cases it is highly-desirable that the positron beam as well as the electron beam should be polarised to maximise the physics reach of the machines [13]. For example, at the ILC, the effective luminosity of e^+e^- collisions is predicted to be approximately 50% greater when using an electron beam with a longitudinal polarisation of 80% colliding with a positron beam with a longitudinal polarisation of 60% compared to colliding the same electron beam with an unpolarised positron beam. A summary of the beam characteristics in the current designs of these two accelerator concepts is given in table 1. Following a recent change in the specification of the CLIC r.f. accelerator gradient from 150 MeV/m to 100 MeV/m, the beam parameters for CLIC are subject to revision.

It is clear that the radio-isotope sources of positrons discussed in the previous section will be unable to meet the intensity requirements of future high-energy colliders. At the SLC, the (unpolarised) positrons were produced by the application of an electron beam to a tungsten conversion target producing 6×10^{12} positrons per second [14]. In principle, this technique could be adapted for the production of polarised positrons by using a polarised electron beam [15]. Bremsstrahlung photons radiated by longitudinally po-

		CLIC 3 TeV	ILC 500 GeV
Energy	GeV	9	15
Bunch population	10^9	4.1	20
Bunches per train	-	311	2625
Bunch spacing	ns	0.667	369
Train length	ns	207	968625
Normalised emittances	nm.rad	600,10	8400,24
RMS bunch length	μm	43-45	300
RMS energy spread	%	1.5-2	1.5
Repetition frequency	Hz	50	5
Beam power	kW	91	630

Table 1: Comparison of beam parameters for ILC and CLIC at the entrance of the main linac.

larised electrons incident on the target would have a high degree of circular polarisation. When these photons themselves travelled the remainder of the distance through the target some would undergo pair-conversion, generating longitudinally polarised positrons. Whether polarised or otherwise, the intensities of all such conventional positron sources (i.e. those which use an electron beam and a conversion target) are constrained by the need to limit the stresses and radiation damage in the conversion target itself. Therefore, to meet the intensity requirements of future colliders, positrons from conventional sources may have to be accumulated in a storage ring or else multiple sources may have to be operated in parallel, greatly complicating the design. As the CLIC beams have five times less bunch charge and eight times less bunches per pulse than the ILC beams, the stresses on the conversion target of its positron source will be lower, and the use of an unpolarised conventional positron source without the need to accumulate positrons may be possible using a sufficiently robust target [16]. However, given the desirability of producing polarised positrons, there has been a substantial effort over the last couple of decades to develop novel sources in which an intense beam of circularly-polarised photons is formed and directed at a thin conversion target. This presents two major challenges: the formation of the photon beam itself, and the design of a suitable target.

The positron source incorporated in the baseline design of the ILC addresses the first of these challenges using a long helical undulator insertion device operating in the main electron beamline, producing an intense beam of circularly-polarised photons with energies of a few tens of MeV.

An alternative method of photon beam production for both the ILC and CLIC positron sources is to use the Compton scattering of a circularly-polarised laser beam pulse by an electron drive beam of relatively modest energies (a few GeV) to produce a similar photon beam to that from a helical undulator, but with fewer harmonic peaks in the energy spectrum. The undulator and Compton sources are both discussed in more detail in the following sections along with some aspects of the ILC baseline target design.

3.1 Helical Undulator-Based Positron Sources

The idea of using helical undulator radiation to produce intense polarised positron beams from a target has been studied for several decades [17],[18]. In recent years a proof-of-principle experiment, E166, operating at SLAC has successfully demonstrated the viability of this technique [19]. The experiment used a 1 m long helical undulator to perturb the trajectories of the 46.6 GeV SLAC Final Focus Test Beam (FFTB) electron beam, and a 0.25 radiation length tungsten conversion target to produce approximately 10^7 positrons per electron bunch of 10^{10} electrons. The longitudinal polarisation of the positron bunches was measured to be greater than 80%, and the average energy of the bunches was measured to be approximately 6.1 MeV.

For the ILC design, it is intended to divert the high-energy (150 GeV) electron beam from the electron linac through a beamline containing a helical undulator insertion device 147 m in length with a period of 1.15 cm, to generate gamma rays with an average energy close to 10 MeV. This will require an on-axis magnetic field strength of approximately 0.86 T causing electrons travelling along the central axis of the undulator to describe a helical trajectory with a radius of approximately 5 nm. Both super-conducting and permanent magnet designs for the undulator have been considered, where the super-conducting designs have been shown to be more appropriate for this application [20]. It is envisaged that the undulator lattice will consist of a series of cryostats each containing two undulators approximately 2 m in length, with collimators and orbit correction magnets located in the room temperature sections between the cryostats. Each undulator is to be constructed from an iron former around which will be wrapped a bifilar helix of NbTi [21] or NbSn [22] wire. A prototype module with parameters close to those specified for the ILC is currently being constructed by the HeLiCal collaboration [23].

The average integrated power of the photon beam generated by the ILC undulator will be approximately 131 kW, with each bunch of photons carrying a total energy of approximately 10 J and consisting of order 10^{13} photons. The beam will be incident on the rim of a Ti 6%Al 4%V target wheel 0.4 radiation lengths thick. The proposed target wheel comprises a circular rim connected to a central drive shaft by five equally-spaced radial struts. The wheel will be oriented with the photon beam parallel to the drive shaft, such that photons will strike the rim, which will have a radial width of 30 mm. The target will be positioned at least 500 m downstream of the centre of the undulator, giving a photon beam spot with a rms radius of at least 2 mm.

Particle tracking simulations [24] predict that approximately 8% of the power of the photon beam will be dissipated in the target. The total energy deposition from each photon pulse is therefore expected to be approximately 22 J/g for a rim speed of 100 ms^{-1}, compared with 900 J/g for a static target. As the target wheel will be housed in a vacuum vessel at a pressure of 10^{-7} Torr or less, the wheel will be water-cooled. The water will flow through the hollow drive shaft via a rotating union and through an internal channel contained inside the target rim.

Positrons emitted from the target wheel are to be focused in a pulsed flux concentrator device before being accelerated first to 400 MeV by normally-conducting r.f. cavities, and subsequently to 5 GeV by a superconducting booster linac before finally being injected into a damping ring with longitudinal and transverse acceptances of ($\pm$3.4 cm) $\times$ ($\pm$25 MeV) and 0.09 m.rad respectively.

It is predicted that this configuration will generate a positron beam with 30% longitudinal polarisation. A more highly-polarised beam can be generated by extending the undulator length and collimating the resulting photon beam to remove photons emitted at large angles. If the target is partially immersed in the magnetic field of the capture optics then the capture efficiency tends to be greater, but parasitical eddy currents will be generated in the wheel rim. The size of these eddy current effects is currently being studied through the construction of a prototype target wheel at Daresbury Laboratory [25]. Liquid metal targets and alternative configurations of the capture optics are under consideration, but the survival of beam windows associated with such designs has not yet been demonstrated [26].

A similar undulator design to that described above has been proposed as a possible positron source for CLIC, but detailed studies have yet to be carried out [27].

A related concept envisages the use of a plasma wiggler [28] to replace the superconducting undulator, but it is not clear whether the gamma rays emitted by such a device would have sufficient circular-polarisation to generate a highly-polarised positron beam.

3.2 Compton-Based Positron Sources

A proof-of-principle experiment of the Compton-based positron source concept has been carried out at the Accelerator Test Facility (ATF) at KEK in Japan [29]. A 1.28 GeV low-emittance electron beam was brought into a head-on collision with a NdYAG laser beam, generating circularly-polarised photons with energies up to 56 MeV through Compton scattering. The photons were subsequently incident on a tungsten target generating polarised electrons and positrons. The polarisation of the positrons was measured to be 73%±15%±19%, where the first error represents the statistical uncertainty on the measurement, and the second represents the systematic uncertainties in the computer simulations that were used to extract the polarisation measurement from the data. Approximately 10^4 high-energy positrons were extracted for each bunch of approximately 10^{10} electrons. Further experiments employing a high-finesse optical cavity to enhance the rate of Compton scattering are envisaged. Compton-based sources have been proposed for both the ILC and CLIC, and there are two main variants: a linac scheme [30] and a ring scheme [31].

In the linac scheme for the ILC, it is proposed that a 2 J photon pulse from a CO_2 laser beam be scattered from the bunches of a 4 GeV electron drive beam at ten interaction points, where each electron bunch will have a charge of 15 nC, leading to the creation of scattered photons with an average energy of approximately 30 MeV. By synchronising the laser and linac operation to generate one hundred scattered photon bunches separated by an interval of 12 ns and repeating this process at a rate of 150 Hz it would be possible in principle to generate 3000 such bunches in 200 ms, with sufficient bunch charge to meet the ILC specifications. In the analogous CLIC design, the same procedure is proposed, but the charge of the electron drive beam could be reduced to reflect the lower bunch charge of the CLIC positron beam.

In the Compton ring scheme, it has been suggested that an electron beam of 1.3 GeV with 10 nC bunches be stored in a ring with a circumference of order one hundred metres containing thirty optical cavities powered by YAG or CO_2 lasers. If realisable, this arrangement should allow the generation of 1.36×10^{10} photons per electron bunch per turn around the ring, where the photons would have energies in the range 23 MeV to 29 MeV. This scheme requires that positrons be accumulated by stacking and coalescing bunches in the damping ring over a period of 100 ms in order to achieve the required ILC bunch charge. For CLIC, a far smaller ring, approximately 40 m in circumference, containing only one optical cavity has been proposed. In this case, stacking and accumulation of positrons would take place in the CLIC pre-damping ring. In a further variant which combines aspects of both the linac and ring schemes, it has recently been suggested [32] that an energy-recovery linac could be used in the Compton ring lattice to maintain the quality of the electron beam.

In all the above cases, the requirements on the conversion target are relaxed by comparison to the undulator-based source discussed in the previous section, and the operation of the collider is simplified by decoupling the operation of the main electron and positron beams. However, there are substantial additional technical challenges associated with the development of the optical cavities, the bunch stacking schemes, etc, such that significant further work is required to demonstrate that it is practical to build a Compton-based positron source that meets the requirements of CLIC or the ILC. Nevertheless, compact sources of x-rays based on the same principle are now in operation [33] and the technology has a wide range of future applications.

Following from the above discussion, it is natural to consider whether an initially unpolarised positron beam could be polarised directly by Compton scattering using circularly-polarised photons, but this technique has been shown not to be viable as the loss of beam intensity is too great [34].

4 Conclusion

Intense sources of polarised positrons with fluxes up to 10^{14} have been described. Although not optimised for the purpose, variants of these sources may have application in the production of polarised anti-protons by spin transfer. Special attention has been given to undulator-based sources for high-energy colliders as this is the focus of the author's own research, but, although well-suited to operation at the ILC, such devices typically require large amounts of specialised infrastructure which limits their application in other areas. The flexibility of Compton-based positron sources makes them an appealing possibility for smaller-scale projects, although it remains to be shown whether they can be used as sources for the next generation of high-energy linear colliders. In addition, contemporary radio-isotope sources can be used to provide polarised positrons at rates in excess of 10^7 positrons per second, and it is reasonable to expect that this number can be increased by another order of magnitude before cost and safety concerns curtail further extrapolation.

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