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Colloquia: Channeling 2010

POSIPOL: From polarized and unpolarized photons to positrons

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Summary. — POSIPOL represents a series of workshops dedicated, mainly, to polarized positrons for linear colliders using circularly polarized photons. Two methods were considered: the Compton backscattering of circularly polarized laser photons on electron beams and radiation from high-energy electrons in a helical undulator. The items have been progressively extended to other polarized beams and also to unpolarized positron beams generated by photons emitted by channeled electrons in oriented crystals. After a short historical survey, this article will emphasize on the last scientific and technical developments associated to the positron sources concerning the target resistance to high incident powers, the capture with magnetic lenses, the polarimetry, the emittance preservation, ... A description of the main issues and some preliminary conclusions will also be given.

PACS 29.25.-t – Particle sources and targets.
PACS 29.27.Hj – Polarized beams.
PACS 41.85.Lc – Particle beam focusing and bending magnets, wiggler magnets, and quadrupoles.
PACS 61.85.+p – Channeling phenomena (blocking, energy loss, etc.).

1. – Introduction

POSIPOL represents a series of workshops devoted to positron sources. The French acronym for POSIPOL is POSItons POLarisés indicating the first purpose of such activity dedicated to polarized positron sources.

The first meeting, in 2006 at CERN [1], concerned mainly the Compton scheme with an electron ring and a laser which has been first proposed at Snowmass in 2005 by Moenig *et al.* [2]. Other Compton schemes involving linacs, as first proposed by Omori at the 1997 positron workshop at SLAC [3] and later by Yakimenko (BNL) were also discussed. Important technical aspects related to the Compton scheme (focusing lattices for the ring, laser systems, optical cavities, polarimetry, ...) or more generally to any part of the positron source installation like the conversion target or the optical matching

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device (OMD) were also analyzed. A proof of principle experiment with a magnetic helical undulator, considered as a baseline for ILC, was presented with the E-166 SLAC experiment (see [4]) with performant results on yield and polarization. The associated polarimetry was also discussed. The second workshop held at LAL-Orsay extended the kind of electron machines, for the Compton scheme to ERL (Energy Recovery Linac). The importance of polarized positrons was emphasized and the associated polarimetry was more deeply described. Progresses in laser techniques for high-power lasers, like the fiber technology, were studied in some details. Capture and emittance preservation of the positron beams were also considered with some details. Applications of the Compton scheme in a low-energy regime for the production of X-rays for medicine and biology appeared, generating a strong interest.

The 2008 workshop held at Hiroshima extended the items to the unpolarized positron source using channeling [5]. Such a scheme has been studied for many years by Franco-Russian and Japanese teams [6-8]. The main interest of such device was, by separating the crystal-radiator from the amorphous converter, to lower significantly the amount of PEDD (Peak Energy Deposition Density) [9, 10]. Mainly for this reason, it has been selected for the CLIC positron source baseline. The applications of Compton schemes (in γ-domain) were also extended to the analysis of radioactive wastes.

Some synergy on the R&D on positron sources for ILC and CLIC appeared also clearly. The Compton scheme and the related techniques (optical cavities, lasers, accelerator type —ring, linac, ERL—, ...) stand as the main parts of the POSIPOL program for 2009 (IPNL-Lyon) and 2010 (KEK). The presentation of a method using polarized bremsstrahlung has also been discussed. The R&D on the ILC baseline solution (undulator) are presented with interesting aspects on the targetry. Progresses in the simulation of the hybrid source using channeling allow a better understanding of all the aspects, especially for the thermal effects. Important contributions from theoreticians (Novosibirsk, Lyon) provide a rigorous description of the physical phenomena for the polarized positrons especially in the target where depolarization may occur. If ILC and CLIC are the main projects discussed in POSIPOL, other colliders (SuperKEKB, SuperB and LHeC) are also considered. We are presenting, here, the last developments on positron sources deriving from the investigations discussed in POSIPOL.

2. – The polarized positron sources

The needed longitudinally polarized positrons at the interaction point of a linear collider [11] are generated by the materialization of circularly polarized photons in amorphous targets. So the main challenge is to create these circularly polarized photons in an energy range allowing positron production with an energy of some MeV to tens of MeV able to be easily captured by known optical matching systems. Various methods can be considered to generate polarized photons [12].

Three main ways have been considered in that framework:

- Compton backscattering of circularly polarized laser photons on energetic electron beams (some GeV, for visible laser photons);
- radiation of high-energy electrons in a helical magnetic undulator;
- method using polarized bremsstrahlung generated by longitudinally polarized electrons in amorphous targets.

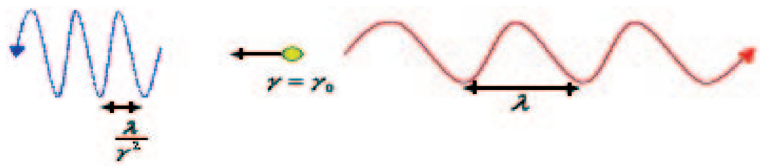

Fig. 1. – Compton process.

2˙1. *The Compton photons.* – The electrons with the Lorentz factor γ are colliding with a circularly polarized laser beam [2] (see fig. 1). The Compton photons may have 30 to 60 MeV at the spectral edge if the e-beam has 1.3 to 1.8 GeV and for the laser a wavelength of 1 μm. This beam is provided by a ring, a linac or an ERL. As the Compton cross-section is small, to increase the positron intensity we may:

– use a multi-cavity optical system (5 to 10 cavities);

– improve the stacking of positron bunches in the DR by reducing the longitudinal emittance prior to the injection in the DR.

The edge of the Compton backscattered photon spectrum is given roughly by

$$\omega_2 = 4\gamma^2\omega_1, \qquad (1)$$

where ω_1 is the laser photon frequency and ω_2 is that of the Compton photon. It is then possible with visible laser photons and GeV electrons to obtain γ photons with enough energy ($\sim$ 20 MeV) to generate positrons. As the Compton interaction cross-section is rather small, it is appropriate to use many optical cavities (Fabry-Perot) to increase the number of interactions with the electron beam. For that, three options have been considered:

1) Use of a ring in which the electron beam is interacting with the laser each time its orbit is crossing the optical cavities. Such solution was first proposed at 2005 Snowmass meeting by Moenig *et al.* [2]. Storage rings with electron beams from 1.3 to 1.8 GeV and Nd:YaG laser with 5 to 10 Fabry-Perot cavities have been considered. For instance, if 5.3 nC buckets with an energy of 1.8 GeV are colliding a laser beam ($\lambda \sim 1\,\mu$m) in 5 optical cavities where 600 mJ are available, we can get $2.3 \cdot 10^{10}$ γ-rays and obtain $1.0 \cdot 10^8$ positrons in a thin ($0.4X_o$) tungsten target as reported by Omori in [13].

2) Use of a linac in which the beam is crossing once the laser beam. This solution was first proposed by Omori *et al.* at a positron workshop at SLAC in 1997 [3] (see also [14]). It is now under study at BNL. They consider a 4 GeV electron beam a CO_2 laser and 10 Fabry-Perot cavities. The intensity of the electron beam is higher than with a ring due to the fact that the beam collides once with the laser. 15 nC bunches are considered.

3) Use of an Energy Recovery Linac (ERL) which has the advantage of energy recuperation. Two additional advantages are that of high electron intensity and high repetition rate. Moreover, the recuperation of the electron beam energy is an interesting thing. The bunch charge is 0.5 nC with a repetition rate of 54 MHz. Electron beam energy is ranging from 1.3 to 1.8 GeV.

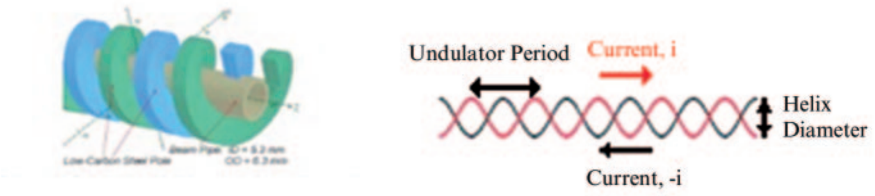

Fig. 2. – Helical undulator. Left: view of a double-helix undulator. Right: the helical undulator wiring.

A particular attention is given to the Fabry-Perot cavities in which it is foreseen to stack a fraction of Joule of laser energy. In particular, cavities with 2 and 4 mirrors have been constructed by KEK and LAL and tested on the Accelerator Test Facility of KEK (ATF). More precisely, a high-finesse cavity (~ 3000) with 4 mirrors has been realized by LAL, tested and installed on ATF/KEK. This device allows: circularly polarized eigenmodes and a high stability [15].

It is noticeable that Compton facilities operating with low or moderate energy beams (50 to 500 MeV) have powerful applications in medical and industrial domains as X-ray production for medical diagnosis and γ-rays for the detection of the isotopic components of a material using the Nuclear Resonance Fluorescence (NRF) [16].

2·2. *The undulator scheme* [17]. – An electron beam crossing a helical magnetic undulator on its axis exhibits an oscillating trajectory with the same period as the undulator and emits radiation (see fig. 2). The circularly polarized photons are emitted in an angle $\sim 1/\gamma$ with a wavelength given by

$$\lambda = (\lambda_u/2\gamma^2)(1+K^2), \tag{2}$$

where $K = eB\lambda_u/2\pi mc$ is the undulator strength, λ_u and λ being the undulator and photon wavelengths, respectively. For $\lambda_u \sim 1\,\text{cm}$, we should use an electron beam of 150 (250) GeV to get a first harmonic cut-off of 10 (20) MeV for the photon spectrum, which is useful to create electron positron pairs of interest.

This method of generation of polarized positrons has been tested some years ago with the 50 GeV beam of SLC; details of production and measurements of the polarized photons and positrons have been worked out in ref. [4].

2·3. *Polarized bremsstrahlung*. – Circularly polarized bremsstrahlung photons may be obtained using a longitudinally polarized electron beam impinging on an amorphous target. The electron longitudinal polarization is transferred to the positrons; maximum positron polarization corresponds to the highest ratio E^+/E_γ [18, 19]. The method relies on the promising capabilities of strained photocathodes (GaAs) for which a polarization of 85% can be reached. Experiments are foreseen at JLab [20].

2·4. *Polarimetry*. – The effective polarization of colliding longitudinally polarized electron and positron beams is

$$P_{\text{eff}} = (P^- - P^+)/(1 - P^- P^+). \tag{3}$$

The electron polarization can reach a level of 80–90%. The positron beam produced with a helical undulator-based scheme is polarized; the scheme described in the RDR will provide a positron polarization of 30% yielding an effective polarization of almost 90% for $P^- = 80\%$. More important, with positron polarization, the helicity of the initial state can be chosen to study exclusive processes of the Standard Model and beyond. So, it is important to control the positron polarization at the sources and to measure it with high precision at the interaction point.

Different methods have been worked out for polarimetry at the source:

– The Compton Transmission Method: it consists in measuring the transmission of circularly polarized photons through a magnetized iron. As the Compton cross-section is depending on the polarisation, the measurement of transmission asymmetry for the two opposite senses of iron magnetization provides the polarization value. As for the positrons, they have to be first converted into photons via bremsstrahlung and, as polarization conservation is assumed, this method provides also measuring of the positron polarization. This method has been used first at KEK [Omori] and then at SLAC on the E-166 experiment [4] with low-energy photons (30–60 MeV for KEK, and 5 to 10 MeV for E-166) as well as with positrons created by these photon beams. However, to utilize this method at the polarized source of a future collider where the intense photon and positron beam would destroy the magnetized iron and, respectively, the reconversion target, it can be applied only for a few bunches out of the bunch train; this is particularly true for ILC.

– The Laser Compton Method: laser photons hit the electron or positron beam; the distributions of scattered photons and leptons depend on the degree of polarization of the incoming particles. This method allows high-precision polarimetry but needs small lepton beam sizes to ensure high-signal rates. Hence, for positron beams this method can be applied only downstream a damping ring. More details can be found in ref. [21].

– The Bhabha scattering: in that method, the longitudinally polarized positrons are crossing a thin magnetized iron (20–30 μm); as the angular distribution of the scattered positrons and electrons depends on the polarization, it is measured for two magnetization states of the iron target. The measured asymmetry can reach 2–3% for realistic beams and target magnetization. To achieve a better S/N ratio, the analysis of the scattered electron distribution is preferred. Such method has been proposed by Riemann *et al.* [22].

– The bremsstrahlung method: it uses the dependence of bremsstrahlung on polarization. This method was proposed by Potylitsyn [23].

2˙5. *The conservation of polarization in the target.* – Due essentially to bremsstrahlung and also to multiple scattering, depolarization of the created positrons in the target may occur. Strakhovenko studied this aspect considering different target thicknesses.

3. – The hybrid source using channeling

The conventional way, using high-intensity electron beams impinging on thick targets with high Z, presents some problems due to the worse emittance and the high rate of power deposition. Some improvements on the conventional source are presently undergoing mainly at KEK and Hiroshima.

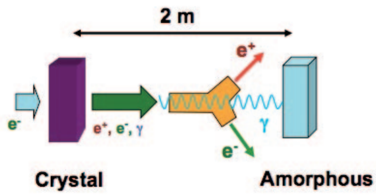

Fig. 3. – The hybrid target scheme.

An alternative and promising way is to replace the magnetic undulator by an axially oriented crystal, in order to get a large amount of soft photons with quasi-channeling radiation. Such a method has been proposed more than 20 years ago by a French team [5] and has since been developed by strong collaborations with Russian and Japanese teams [6-8, 24, 25]. Crystal converters where radiation and pair creation occurred in the same target were simulated and experimented. This is also the case for *hybrid targets* where the crystal radiator and the amorphous converter were separated. In order to lower the amount of deposited power in the targets, a hybrid scheme associating a crystal radiator and an amorphous converter separated by 2–3 meters distance has been proposed in the POSIPOL sessions [10].

Assuming thin crystal target and, hence, moderate heating in it and in order to lower the amount of energy deposited in the amorphous target and also the PEDD, the following scheme has been proposed by Chehab, Strakhovenko and Variola in [10]. Putting a drift between the 2 targets allows sweeping off the charged particles coming from the crystal; only the γ impinge on the amorphous target. In fig. 3 the scheme of this hybrid target is presented.

Many simulations have been operated with this configuration. A particular attention has been given to the PEDD value. An experimental test at KEK, on the KEKB linac, is undergoing and first very encouraging results obtained. Observation of the thermal density on the exit face of the converter is carrying out.

4. – The Optical Matching Devices (OMD)

The capture of the positrons after the target is determinant. The positrons coming out from the target with large angles due essentially to the multiple scattering and having, generally, small-spot dimensions must be transferred by the OMD to the entrance of the accelerator with small angles and larger dimensions being, then, better transmitted by the accelerator. We present briefly three kinds of OMD.

- Two OMD with an axial magnetic field: the Adiabatic Matching Device (AMD) and the Quarter Wave Transformer (QWT).
- One OMD with an azimuthal magnetic field: the Lithium Lens.

4·1. *The AMD.* – This matching device has a magnetic field tapering adiabatically, *i.e.* with conservation of the adiabatic invariant, between a maximum value B_o and a minimum value B_s on a length L. A parameter of smallness ε is defined as

$$\varepsilon = (P/eB^2)\mathrm{d}B/\mathrm{d}z, \tag{4}$$

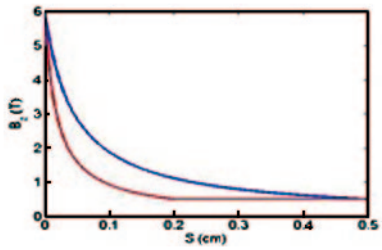

Fig. 4. – Magnetic-field law for the AMD; upper curve, 50 cm length, bottom curve, 20 cm.

and this parameter must be much lower than the unity to conserve the adiabatic invariant $\pi p_t^2/eB$, where p_t is the transverse momentum and B the field [26]. The magnetic-field law for this device is

$$B = B_o/(1 + \mu z), \tag{5}$$

and is represented in fig. 4 for two values of the tapering length (20 and 50 cm). One essential feature of this device is its large-momentum acceptance making it one of the best for the accepted yields.

4·2. *The QWT.* – The Quarter Wave Transformer (QWT) is made of a strong-field coil followed by a low-field solenoid with an abrupt change between the two fields. The momentum acceptance is rather narrow: with 2-3 teslas as maximum field, 0.5 T for the minimum field and a length of 4–8 cm, the FWHM momentum acceptance is about 3-4 MeV. A simplified scheme is given in fig. 5.

4·3. *The lithium lens.* – The lithium lens, as the plasma lens, is using a *longitudinal current* I in a lithium cylinder of radius R_o, with the same direction as the incident electron beam. Such current creates an azimuthal magnetic field, which may focus the positrons and defocuses the electrons. The magnetic-field variation, with the radial distance r, is represented in fig. 6. The magnetic field is defined as

$$\begin{aligned} B &= (\mu_0 I/2\pi R_o^2)r \quad \text{for } r < R_o, \\ B &= \mu_I/2\pi r \quad \text{for } r > R_o. \end{aligned} \tag{6}$$

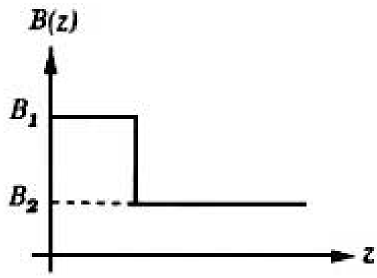

Fig. 5. – The Quarter Wave Transformer.

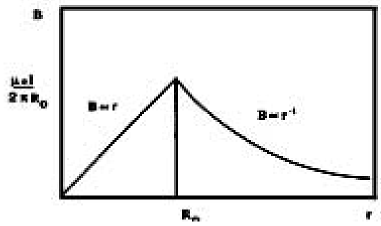

Fig. 6. – The azimuthal magnetic field.

The lithium lens was first proposed by Silvestrov from BINP and later developed by Mikhailichenko *et al.* It has been successfully used to focus antiprotons.

5. – Conclusions

Since the starting of POSIPOL meetings many perspectives have been opened thanks to these meetings:

- Closer collaborations on the starting subject (Compton scheme) between the different partners (France and Japan).
- A better synergy between the CLIC and ILC efforts on positron sources: a common working group managed by CERN and Daresbury has been created.
- Extension of the meeting contents to:
  - other kinds of e^+ sources (polarized-undulator and polarized bremsstrahlung or unpolarized like channeling and conventional),
  - technical developments (Optical Matching, Target Cooling and stacking in DR).
- As was shown by the last POSIPOL's, the positron community is now largely represented in such meetings.

* * *

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