

# SINGLE-PASS LASER POLARIZATION OF ULTRARELATIVISTIC POSITRONS.

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## Abstract

The new method for producing of the polarized relativistic positrons is suggested. A beam of unpolarized positrons accelerated up to a few GeV can be polarized during a head-on collision with an intense circularly polarized laser wave. After a multiple Compton backscattering process the initial positrons may lose a substantial part of its energy and, as consequence, may acquire the significant longitudinal polarization. The simple formulas for the final positron energy and polarization degree depended on the laser flash parameters have been obtained. The comparison of efficiencies for the suggested technique and known ones is carried out. Some advantages of the new method were shown.

The experiments with polarized electron-positron beams in future linear colliders will furnish a means for studying a number of intriguing physical problems [1]. While the problem of generation and acceleration of longitudinally polarized electron beams seems to be solved [2], the approach for production of polarized positron beams with the required parameters has not been finally defined yet. In [3-7] methods were proposed for the generation of longitudinally polarized positrons during  $e^+e^-$  pair production by circularly polarized photons with the energy  $\omega \sim 10^1$  MeV, which are, in their turn, generated by either passing electrons with the energy  $\sim 10^2$  GeV through a helical undulator [3], or through Compton backscattering of circularly polarized laser photons on a beam of electrons with the energy  $\sim 5$  GeV [4,5], or through bremsstrahlung of longitudinally polarized  $\sim 50$  MeV electrons [6,7]. To achieve the needed intensity of a positron source ( $N_{e^+,pol} \sim 10^{10}$  particles/bunch) it is suggested to use an undulator of the length  $L > 100$  m [8], or to increase the laser power [9], or to use a high-current accelerator of polarized electrons [10].

The present paper considers an alternative way to approach this problem.

A beam of unpolarized positrons from a conventional source being cooled in a damping ring and preliminary accelerated to an energy  $E_0$  can be polarized during a head-on collision with a high-intensity circularly polarized laser wave.

It is well known that during Compton backscattering of circularly polarized laser photons on unpolarized positrons (electrons) with the energy  $E_0 \sim 100$  GeV the scattered photon takes up to 90% of the initial positron energy while the recoil positron acquires  $\sim 100\%$  longitudinal polarization [11,12]. At  $E_0 \leq 10$  GeV, however, the positron loses too little of its energy during single Compton backscattering (a few percent), and the longitudinal polarization of the recoil positron is, therefore, of the same order of magnitude. Current advances of laser physics make it possible to obtain parameters of laser flash such

that the positron successively interacts with  $N \gg 1$  identical circularly polarized photons. It is apparent that in this case the positron can lose a substantial fraction of its energy (comparable with  $E_0$ ). To evaluate the resulting polarization of the recoil positron, let us consider multiple Compton backscattering in greater detail.

Let us carry out calculations in a positron rest frame (PRF) and in a laboratory frame (LF). Following [13], let us write the Compton scattering cross section in PRF where spin correlations of three particles will be viewed— initial photon, and initial and recoil positrons (upon summation over the scattered photon polarizations):

$$\frac{d\sigma}{d\Omega} = 2r_0^2 \left(\frac{k}{k_0}\right)^2 \left\{ \Phi_0 + \Phi_2(P_c, \vec{\xi}_0) + \Phi_2(P_c, \vec{\xi}) + \Phi_2(\vec{\xi}_0, \vec{\xi}) + \Phi_3(P_c, \vec{\xi}_0, \vec{\xi}) \right\} \quad (1)$$

Here  $r_0$  is the electron classical radius;  $k_0, k$  are the initial and scattered photon energy;  $P_c = \pm 1$  is the circular polarization of the initial photon; and  $\vec{\xi}_0, \vec{\xi}$  are the spin vectors of the initial and final positrons. Functions  $\Phi_0, \Phi_2, \Phi_3$  were obtained in paper [13].

In (1) and further in the paper use is made of the system of units  $\hbar = m_e = c = 1$ , unless otherwise indicated.

Since the scattered photons are not detected, the cross section (1) has to be integrated over the photon outgoing angles. Due to azimuthal symmetry, it will depend on the average longitudinal polarization components  $\xi_{0l}, \xi_l$  solely. On this basis we will keep only these components which remain the same in LF.

For positrons with  $\gamma_0 \leq 10^4$  ( $\gamma_0$  is the Lorentz-factor of the initial positron), the laser photon energy in PRF ( $\omega_0 \sim 1$  eV in LF) will satisfy the relation

$$k_0 = 2\gamma_0 \omega_0 \ll 1 \quad (2)$$

Using (2) let us write the expression for the scattered photon energy in PRF:

$$k = \frac{k_0}{1 + k_0(1 - \cos \theta)} \approx k_0[1 - k_0(1 - \cos \theta)] \quad (3)$$

Here  $\theta$  is the polar angle of the scattered photon in PRF.

Leaving the terms not higher than  $k_0^2$ , let us write in explicit form the  $\Phi_i$  functions derived in [13] for electrons :

$$\begin{aligned} \Phi_0 &= \frac{1}{8} [1 + \cos^2 \theta + k_0^2(1 - \cos \theta^2)] , \\ \Phi_2(P_c, \xi_{0l}) &= -\frac{1}{8} P_c \xi_{0l} k_0 \cos \theta , \\ \Phi_2(P_c, \xi_l) &= -\frac{1}{8} P_c \xi_l (1 - \cos \theta) [2k_0 \cos \theta - k_0^2(\cos \theta - \cos^2 \theta + \sin^2 \theta)] , \\ \Phi_2(\xi_{0l}, \xi_l) &= \frac{1}{8} \xi_{0l} \xi_l [1 + \cos^2 \theta - k_0^2 \cos \theta \sin^2 \theta] , \\ \Phi_3(P_c, \xi_{0l}, \xi_l) &= 0 . \end{aligned} \quad (4)$$

Upon routine integration we obtain:

$$\sigma = \frac{\pi r_0^2}{2} \left\{ \frac{8}{3}(1 - 2k_0) + \frac{4}{3}P_c \xi_{0l} k_0 (1 - 2k_0) + \xi_l \left[ \frac{8}{3} \xi_{0l} (1 - 2k_0) + \frac{4}{3} P_c k_0 \right] \right\} \quad (5)$$

It is obvious that in averaging with respect to the initial particles spin and taking the summation with respect to two spin states of the recoil positron, instead of (5) we get Klein-Nishina's cross section for  $k_0 \ll 1$  [11]:

$$\sigma = \frac{8}{3} \pi r_0^2 (1 - 2k_0) \quad (6)$$

From (5) follows that longitudinal polarization of a recoil positron (electron) is determined by both its initial polarization and the circular polarization of a photon (later the longitudinal polarization indices  $l$  will be omitted):

$$\xi = \frac{\xi_0 \mp \frac{k_0}{2} P_c}{1 \mp \frac{k_0}{2} P_c \xi_0} \quad (7)$$

The upper (lower) sign refers to a positron (electron).

If the initial positron is unpolarized ( $\xi_0 = 0$ ), then upon a single interaction with a laser photon the recoil positron becomes polarized :

$$|\xi_{(1)}| = \left| \frac{-k_0}{2} P_c \right| \ll 1. \quad (8)$$

In order to consider the next scattering act, let us calculate the average longitudinal momentum  $\langle k_{\parallel} \rangle$  along the initial photon direction and the average energy  $\langle k \rangle$  of the scattered photon in PRF using the same approximation as before:

$$\begin{aligned} \langle k_{\parallel} \rangle &= \frac{\int k \cos \theta \left( \frac{k}{k_0} \right)^2 \Phi_0 d\Omega}{\int \left( \frac{k}{k_0} \right)^2 \Phi_0 d\Omega} = \frac{6}{5} k_0^2, \\ \langle k \rangle &= \frac{\int k \left( \frac{k}{k_0} \right)^2 \Phi_0 d\Omega}{\int \left( \frac{k}{k_0} \right)^2 \Phi_0 d\Omega} = k_0 (1 - k_0). \end{aligned} \quad (9)$$

Thus, upon the first event of interaction, the photon in LF acquires, on average, the energy

$$\langle \omega_{sc} \rangle = \gamma_0 (\langle k \rangle - \beta_0 \langle k_{\parallel} \rangle) \approx \gamma_0 \langle k \rangle = \gamma_0 k_0. \quad (10)$$

In (10)  $\beta_0 = 1 - \frac{\gamma_0^{-2}}{2}$  is the velocity of PRF with respect to LF.

It is apparent that the recoil positron loses its energy (10) and hence

$$\gamma_{(1)} = \gamma_0 - \langle \omega_{sc} \rangle = \gamma_0(1 - k_0) = \gamma_0(1 - 2\gamma_0\omega_0) . \quad (11)$$

In PRF before the second interaction the initial photon, in view of (11), will have a lower energy

$$k_{(1)} = 2\gamma_{(1)}\omega_0 = 2\gamma_0\omega_0(1 - 2\gamma_0\omega_0) = k_0(1 - k_0) , \quad (12)$$

and the recoil positron will have a polarization:

$$\xi_{(2)} = \frac{\xi_{(1)} - \frac{k_{(1)}}{2}P_c}{1 - \frac{k_{(1)}}{2}P_c\xi_{(1)}} . \quad (13)$$

Substituting its value from (8) for  $\xi_{(1)}$ , we obtain:

$$\xi_{(2)} = -P_c \frac{\frac{k_0}{2} + \frac{k_{(1)}}{2}}{1 - P_c \frac{k_0}{2} \frac{k_{(1)}}{2}} , \quad |\xi_{(2)}| > |\xi_{(1)}| \quad (14)$$

It follows from (14) that as a result of multiple Compton backscattering the longitudinal polarization of positrons builds up, while their energy decreases in LF (so-called laser cooling, see [14, 15]).

Let us write expressions relating the polarization and energy for two subsequent acts of scattering:

$$\gamma_{(i+1)} = \gamma_{(i)}(1 - 2\omega_0\gamma_{(i)}) , \quad (15)$$

$$\xi_{(i+1)} = \frac{\xi_{(i)} - \gamma_{(i)}\omega_0 P_c}{1 - \gamma_{(i)}\omega_0 P_c \xi_{(i)}} . \quad (16)$$

From these we can obtain the equations for the finite differences:

$$\Delta\gamma_{(i)} = \gamma_{(i+1)} - \gamma_{(i)} = -2\omega_0\gamma_{(i)}^2 , \quad (17)$$

$$\Delta\xi_{(i)} = \xi_{(i+1)} - \xi_{(i)} \approx -\omega_0 P_c \gamma_{(i)}(1 - \xi_{(i)}^2) . \quad (18)$$

When  $N \gg 1$ , instead of (17) and (18) we can arrive at differential equations, whose solution with proper initial conditions will yield

$$\gamma_{(N)} = \frac{\gamma_0}{1 + 2\gamma_0\omega_0 N} \quad (19)$$

$$\xi_{(N)} = \frac{\gamma_0\omega_0 N}{1 + \gamma_0\omega_0 N} . \quad (20)$$

When deriving the above relation, there was taken the left circular polarization  $P_c = -1$  for the sake of simplicity.

Equations (19) and (20) describe the positron characteristics after  $N$  collisions with circularly polarized laser photons. The number of collisions  $N$  is controlled by the luminosity of the process  $L$ :

$$N = \frac{N_{\text{scat}}}{N_e^+} = N_0 L = N_0 \frac{\frac{8}{3} \pi r_0^2}{2\pi(\sigma_{e^+}^2 + \sigma_{\text{ph}}^2)} . \quad (21)$$

In (21)  $N_0 = A/\omega_0$  is the number of photons per laser flash,  $A$  is the laser energy, and  $\sigma_{\text{ph}}$ ,  $\sigma_{e^+}$ , are the laser focus and positron bunch radii. We can expect that after cooling in the damping ring  $\sigma_{e^+} \ll \sigma_{\text{ph}}$ . In this case, substituting (21) into (19) and (20), we obtain the following simple formulas for positron's characteristics:

$$\gamma_{(N)} = \frac{\gamma_0}{1 + 2\mu} , \quad (22)$$

$$\xi_{(N)} = \frac{\mu}{1 + \mu} , \quad (23)$$

which depend on the dimensionless parameter  $\mu$  solely

$$\mu = \gamma_0 \omega_0 N = \frac{4}{3} \frac{A}{mc^2} \gamma_0 \left( \frac{r_0}{\sigma_{\text{ph}}} \right)^2 . \quad (24)$$

It follows from (24) that the  $\mu$  parameter depends linearly on the laser flash energy and the initial positron energy, but it is inversely proportional to the laser focus area and does not depend on the interaction time (duration flash). Having written (22) as:

$$\frac{\gamma_0}{\gamma_{(N)}} = 1 + 2\mu , \quad (25)$$

we will compare the result with the estimate by V. Telnov [15] obtained in a classical approximation. Substituting into (24) the estimate used in [15]  $\sigma_{\text{ph}}^2 = \frac{\lambda_0 l_e}{8\pi}$  ( $\lambda_0$  is the laser photon wavelength and  $l_e$  is the positron bunch length), we get :

$$\frac{\gamma_0}{\gamma_{(N)}} = 1 + \frac{64}{3} \frac{A}{mc^2} \gamma_0 \frac{\pi r_0^2}{\lambda_0 l_e} . \quad (26)$$

The resulting expression is closed to a similar one in [15] but the second term in (26) is by a factor of  $\pi$  smaller. This discrepancy is connected with rough calculation of the luminosity (constant area of the laser focus) used in (21).

By way of illustration let us consider an example (see [15]):

$$\gamma_0 = 10^4, \quad A = 5 \text{ J}, \quad \lambda_0 = 500 \text{ nm}, \quad l_e = 0.2 \text{ mm}, \quad \sigma_{\text{ph}}^2 = \lambda_0 l_e / 8\pi . \quad (27)$$

In this case  $\mu = 1.6$  and, therefore,  $\gamma_{(N)} \approx 0.3\gamma_0$ ;  $\xi_1 \approx 60\%$ .

Thus, when a positron bunch interacts with a laser flash of the given parameters, all the positrons acquire longitudinal polarization of about 60%. The change in the polarization sign is obtained by inverting the sign of the circular polarization of laser radiation.

It should be noted that with a proper selection of the sign of circular polarization, the process of laser cooling would give rise to a longitudinal polarization increase of the electrons rather than to depolarization of electrons beam (as in the case of unpolarized laser radiation considered in [15]).

Note that, generally speaking, the laser parameters (27) correspond to the so-called "strong" field, when the contribution from non-linear Compton scattering [4] would be considerably high.

Non-linear processes, i.e., simultaneous scattering of a few laser photons on the moving positron, are characterized by an increase in the effective positron mass in PRF, which, in its turn, leads to a decrease in the Lorentz-factor and the energy transferred to the positron through scattering. It is to be expected that the  $\mu$  parameter (24) for a fixed value of the laser flash energy  $A$  will be sufficiently lower for a non-linear case as compared to the linear one, and hence a lower attainable polarization (23).

In order to reach a linear mode of the Compton scattering process, one has to stretch the laser flash (the length of its interaction with the positron bunch) (see, for instance, [16]).

In conclusion, let us estimate the energy  $A_{+,pol}$  necessary to obtain one polarized positron with the energy  $E_+ > 10^1$  MeV and the longitudinal polarization  $\xi_l > 0,5$  i.e., the parameters acceptable for consequent acceleration.

i) According to the estimates [8] an electron with the energy  $E_- \sim 200$  GeV passing through a helical undulator of the length  $L \sim 150$  m can generate a number of circularly polarized photons needed to obtain one polarized positron to be later accelerated (conversion efficiency  $\eta = N_{e+,pol}/N_{e-} \approx 1$ ). Hence,  $A_{+,pol} \sim E_-/\eta = 200$  GeV.

ii) The author of the paper [9] considered a scheme for production of  $\sim N_{e+} = 10^9$  polarized positrons when the laser radiation of the total energy  $A_\Sigma \sim 20$  J is scattered on an electron bunch with  $E_- = 5$  GeV and  $N_{e-} = 10^{10}e^-$  / bunch. Thus

$$A_{+,pol} \approx \frac{N_{e-}E_- + A_\Sigma}{N_{e+}} \approx 170 \text{ GeV} .$$

iii) In [6] the author estimated the conversion efficiency for longitudinally polarized electrons with the energy  $E_- = 50$  MeV:

$$\eta \approx 10^{-3} .$$

Therefore  $A_{+,pol} \sim E_-/\eta = 50$  GeV.

iv) For the method suggested in the present paper, evaluation of  $A_{+,pol}$  can be made for parameters of the unpolarized positron source used in SLAC [17].

The conversion efficiency for the electron energy  $E_- = 33$  GeV equals:

$$\eta \approx 1 .$$

Therefore, for a bunch with  $N_{e^+} = 10^{10}$  and the positron energy  $E_0 = 5$  GeV interacting with the laser flash ( $A = 5$  J) we have:

$$A_{+,pol} = \frac{E_-}{\eta} + E_0 + \frac{A}{N_{e^+}} = 33 \text{ GeV} + 5 \text{ GeV} + 3 \text{ GeV} \sim 40 \text{ GeV} .$$

Thus, the scheme proposed here seems to be most energy effective.

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## References

1. P.M. Zerwas. Preprint DESY 94-001, 1994.
2. J.E. Clendenin, R. Alley, J. Frish, T. Kotseroglou, G. Mulhollan, D. Schultz, H. Tang, J. Turner and A.D. Yeremian. The SLAC Polarized Electron Source. AIP Conf. Proceedings, N. 421, pp. 250-259, 1997.
3. V.E. Balakin, A.A. Mikhailichenko. Preprint INP 79-85, Novosibirsk, 1979.
4. Yung Su Tsai. Phys. Rev. D, v.48 (1993), pp.96-115.
5. T. Okugi, Y. Kurihara, M. Chiba, A. Endo, R. Hamatsu, T. Hirose, T. Kumita, T. Omori, Y. Takeuchi, M. Yoshioka. Jap.J.Appl.Phys. v. 35(1996), pp. 3677-3680.
6. A.P. Potylitsyn. Nucl. Instr. and Meth. v. A398 (1997), pp.395-398.
7. E.G. Bessonov, A.A. Mikhailichenko. Proc. of V European Particle Accelerator Conference, 1996, pp. 1516-1518.
8. K. Flottmann. Preprint DESY 93-161, 1993.
9. T. Omori. KEK- Proceedings 99-12, 1999, pp. 161-179.
10. T. Kotseroglou, V. Bharadwaj, J.E. Clendenin, S. Ecklund, J. Frisch, P. Krejcik, A.V. Kulikov, J. Liu, T. Maruyama, K.K. Millage, G. Mulhollan, W.R. Nelson, D.C. Schultz, J.C. Sheppard, J. Turner, K. Van Bibber, K. Flottmann, Y. Namito. Particle Accelerator Conference (PAC'99). Proceedings (to be published).
11. H. Tolhoek. Rev. of Mod. Phys. v. 28 (1956), pp. 277-298.
12. G.I. Kotkin, S.I. Polityko, V.G. Serbo. Physics of Atomic Nuclei, v. 59 (1996), pp. 2229-2234.
13. F.W. Lipps, H.A. Tolhoek. Physika, v. 20 (1954), pp. 395-405.
14. P. Sprangle, E. Esarey. Phys. Fluids. v.B4 (1992), pp. 2241-2248.
15. V. Telnov. Phys. Rev. Lett. v.78 (1997), pp.4757-4760.

16. I.V. Pogorelsky, I. Ben-Zvi, T. Hirose. BNL Report No.65907, October, 1998.
17. S. Ecklund. SLAC-R-502 (1997), pp. 63-98.