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A b s t r a c t

The method for polarizing electrons and positrons by colliding photons is considered, which uses a strong spin dependence of Compton scattering in the region where the recoil energy during scattering becomes close to the particle energy. The predominant knock-out of particles of one helicity results in the polarization of a remaining beam. The schemes and possible sources of circularly-polarized photons ensuring the fast beam polarization are discussed.

1. In the paper /1/ the method is considered in which the polarization of electrons and positrons in storage rings results from the irradiation by a colliding circularly-polarized laser wave. The effect arises due to the spin dependence of radiation in a wave field and orbit-spin coupling in the field of a storage ring. The polarization rate is proportional to the frequency of incident radiation. The applicability of this method is limited since multiple Compton scattering of the particles results in either increasing the beam sizes or, at a sufficiently high quantum recoil. in knocking-out the particles from the beam due to single scattering.

On the other hand, at sufficiently hard colliding circularly-polarized photons the use of just the single knock-out processes becomes possible for obtaining a polarized beam, since their probability becomes strongly dependent on the helicity of electrons.

The spin dependence of the scattering cross-section is characterized by the ratio of the incident photon energy in the accompanying system to the electron rest energy:

$$\chi = \frac{2\hbar\omega_\phi}{m^2}E$$

In the region where the recoil energy approaches the energy of a particle ($\chi \gtrsim 1$), the particles of one of the helicities are mainly knocked out. This will lead to the polarization of the remaining beam when the stable longitudinal direction of polarization* exists in the region of interaction with photons.

* The realization of the dynamically stable longitudinal direction of polarization in storage rings is described in the review paper /2/.

It is important that the beam sizes remain practically the same during the polarization process, and therefore there are no upper limitations on a polarization rate, which characterize the methods utilizing the radiation of soft quanta by the particles.

2. Let us present the principal dependences characterizing the polarization process. The sum and the difference of total scattering cross-sections of the electrons with negative and positive helicity by the circularly-polarized photons are equal to /3/:

$$\sigma_\uparrow+\sigma_\downarrow = 2\pi r_e^2\left\{\frac{1}{\chi}\ln(1+2\chi)-\frac{2(1+\chi)}{\chi^3}\ln(1+2\chi)+\frac{4}{\chi^2}+\frac{2(1+\chi)}{(1+2\chi)^2}\right\}, \qquad (1)$$

$$\sigma_\uparrow-\sigma_\downarrow = \pm 2\pi r_e^2\left\{\frac{1+\chi}{\chi^2}\ln(1+2\chi)-\frac{2(1+4\chi+5\chi^2)}{\chi(1+2\chi)^2}\right\},$$

where the signs (+) and (-) correspond to the right- and left-polarized photons, respectively, $r_e=\frac{e^2}{m}$ $(c=1)$.

Assuming that each scattering leads to a particle knock-out, it is easy to find the fraction of particles remaining in the beam when the polarization degree ζ is achieved:

$$\frac{N}{N_0}=\frac{1}{1+\zeta}\left(\frac{1-\zeta}{1+\zeta}\right)^{\ae}, \qquad (2)$$

$$\ae=\frac{1}{2}\left|\frac{1}{\xi_2}\left(\frac{\sigma_\uparrow+\sigma_\downarrow}{\sigma_\uparrow-\sigma_\downarrow}\right)\right|-\frac{1}{2}$$

where ξ_2 is the degree of circular polarization of the photon beam. The time during which the polarization degree becomes

equal to ζ is determined by the formula

$$T=\left|\dot N_\phi\,\xi_2(\sigma_\uparrow-\sigma_\downarrow)\right|^{-1}\ln\left(\frac{1+\zeta}{1-\zeta}\right) \qquad (3)$$

where $\dot N_\phi$ is the photon flux density. The dependence of a parameter $\ae$ and that of the cross-section differences on the photon parameter χ are given in Figs.1, 2.

Formulae (2) and (3) well describe the polarization process in the region $\chi\gtrsim 1$ being of practical interest, since the fraction of the particles remained in the beam after scattering is very small because of a relative smallness of the energy aperture (usually $\Delta E_{max}/E\simeq 10^{-2}$).

Note that with increase of the parameter χ the scattering of the electrons with a helicity opposite to that of the photon becomes more and more predominant (at $\chi\to\infty$ $\ae\to 0$). In particular, at a very high photon frequency ($\chi\to\infty$) one can achieve a high polarization degree, losing only half a beam. With increase of χ the polarization time (at $\chi\gg 1$) increases proportionally to $\chi/\ln\chi$.

One must pay attention to the fact that a degree of circular polarization of the photons does not limit the maximally attainable polarization degree of the beam particles. The decrease in the polarization degree ξ_2 of the photons results only in increasing the polarization time and decreasing the fraction of remained particles. Note also that the choice of a sign of the photon helicity enables one to obtain any sign of the helicity of beam particles.

3. Let us discuss the possible ways for realizing this method. In super-high energy storage rings (of the order of

100 GeV and higher) the use of lasers is natural. Let us present a numerical example. The particles in the designed storage ring LEP /4/ may be polarized at a 100 GeV energy by the lasers radiating the light with a wavelength $\lambda_W \leq 2\cdot 10^{-5}$ cm. Presently, there are the lasers operating in the ultraviolet range /5/. The pulsed mode of operation with the phase synchronization* to the electron beam in a storage ring, at consistent sizes of the light beam and the colliding beam, enables one to polarize, at a mean laser power W = 100 W, $\lambda_w = 2\cdot 10^{-5}$ cm, $\xi_2 = \pm 1$, the beam area $S = 10^{-4}$ cm² and a 100 GeV energy of the particles, electrons or positrons at 15 sec up to the degree ζ = 30%, with the decrease of the number of particles in the beam by a factor of 5 (at ζ = 50% the number of particles decreases by a factor of 17, the beam is polarized during 25 sec) (see formulae (2) and (3)). Note that the loss of the laser part of the stored beam does not always mean the decrease in the maximum luminosity of colliding beams in a storage ring. In the absence of collisions the maximally stored current exceeds essentially the current corresponding to the optimum luminosity of colliding beams.

Emphasize that so short polarization times are practically unattainable (due to unpermissible increase of the beam energy spread) in any other known method of polarization in storage rings (radiative polarization in a conventional storage ring or that accelerated with the 'wigglers', polarization by 'soft' circularly-polarized photons).

For lower-energy storage rings the ondulator (helical mag-

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* Interactions with a laser wave can occur in an arbitrary number of the particle revolutions in a storage ring.

netic field) located in the straight section /6, 7/ can serve as a source of sufficiently intense fluxes of circularly-polarized hard photons. Consider the ondulator of a length ℓ with a field period λ_0, and a magnetic field strength H_0. The characteristic wavelength of radiation is equal to λ_0/γ^2, where γ is the relativistic factor of electrons in a storage ring. The mean radiation power W apparently equals

$$W = \frac{2}{3} r_e^2 H_0^2 \gamma^2 N_e f \ell$$

where N_e is the number of electrons in a storage ring, is the revolution frequency. The transverse dimension of a light beam diverges in the angle of approximately $1/\gamma$. The mutual polarization of electron-positron colliding beams by means of an ondulator installed in the interaction region can serve as one of the possible realization schemes. In such a scheme the electrons polarize the positrons and conversely. Here, the photon beam is automatically alighined with the electron (positron) colliding beam*. In this scheme χ is proportional to γ^3 and at the electron and positron energy of several GeV is considerably more than unity.

The beam-beam effects not allowing to obtain sufficiently intense photon fluxes provide a limitation here. The higher power fluxes of photons can be obtained with two ondulators located in the straight section of a storage ring, separating the electrons and positrons in the interaction regions. This enables

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* The field deviations leading to average curvature of the orbit are usually negligibly small.

the considerable increase of the stored number of particles*. One of the possible schemes of spatial separation of the electrons and positrons, not distorting the collision of one of the beams with radiation is presented in Fig.3. In this scheme the use of the constant crossed electric and magnetic fields makes it possible to deviate one of the beams, not affecting the other. A simple switching of the fields in this scheme enables one to polarize another beam as well**.

The ondulator radiation requires some generalization of the formulae (2) and (3) for the case of nonmonochromatic radiation ($\Delta\omega_\phi/\omega_\phi \sim 1$). Then, when the photon beam area coincides with that of a colliding beam of particles, the formulae for T and $\varkappa$ are of the form:

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* Note that this scheme may be also used to measure the beam polarization in a storage ring. Periodically varying the direction of rotation of a magnetic field in the ondulator, it is possible to control by the number of secondary γ-quanta a degree and a sign of the longitudinal polarization without its distortion for each beam separately. At $\chi \sim 1$, the transverse polarization of the beams can be determined, by measuring the azimuthal anisotropy of secondary γ -quanta which can attain a maximum value of the order of 30%.

** In order to polarize simultaneously both the beams, one can locate one of the ondulators in the straight section wherein another beam is deviated.

$$T = \left| \int_0^\infty \frac{d\omega}{\hbar\omega}\left(\frac{dI^+}{d\omega} - \frac{dI^-}{d\omega}\right)(\sigma_\uparrow - \sigma_\downarrow)\right|^{-1} \frac{S}{N_e f \ell} \ln\left(\frac{1+\zeta}{1-\zeta}\right)$$

$$\varkappa = \frac{1}{2}\left| \frac{\int_0^\infty \frac{d\omega}{\hbar\omega}\left(\frac{dI^+}{d\omega} + \frac{dI^-}{d\omega}\right)(\sigma_\uparrow + \sigma_\downarrow)}{\int_0^\infty \frac{d\omega}{\hbar\omega}\left(\frac{dI^+}{d\omega} - \frac{dI^-}{d\omega}\right)(\sigma_\uparrow - \sigma_\downarrow)} \right| - \frac{1}{2} \tag{4}$$

where S is the area of interaction of colliding beams ($S = \left(\int \rho^2 ds\right)^{-1}, \int \rho\, ds = 1$), and $dI^\pm/d\omega$ is the spectrum density of the right- and left-polarized radiation of the ondulator, respectrively (an explicit form of the integrals of formulae (4) is given in Appendix).

The values T^{-1} and $\varkappa$ depend on a parameter χ equal in this scheme to $\chi = 4\gamma\gamma_\parallel^2 \lambda_c/\lambda_o \; (\lambda_c = \frac{2\pi\hbar}{m})$, where $\gamma_\parallel = \frac{1}{\sqrt{1-v_\parallel^2}} = \gamma/\sqrt{1+\mathcal{K}^2}$ is the relativistic factor of the particle motion along the ondulator axis, $\mathcal{K} = \frac{eH_o\lambda_o}{2\pi m}$ is a parameter of the ondulator character of radiation.

Let us present a numerical example. Using the ondulator of a length ℓ = 1 m with period λ_o = 2 cm, field H_o = 10 kGS ($\mathcal{K}$ = 2) at the current 300 mA and the beam area $S = 10^{-4}\,cm^2$ in the region χ = 100÷200 (E = 5 GeV) it is possible to polarize the beam up to the degree of polarization ζ = 30% at the time T = 3000 sec, decreasing the number of particles by a factor of 6 (to ζ = 50% at T = 4500 sec with decreasing the number of particles by a factor of 22).

It is worthwhile sometimes to eliminate the radiation at the angles $\gg \frac{1}{\gamma}$. Then, operating within the region $\chi \simeq 10$ ($E \simeq 2.5$ GeV), one can decrease, in comparison to the presented example, the polarization time approximately by a factor of 3 at the same decreasing of the number of particles in the beam. In the region of large values of χ the loss of particles can be essentially smaller.

If the average size of the beam in the ondulator is larger than its size at the place of its collision with radiation, it is useful to focus the ondulator radiation, for example, with mirrors. The possibility of focusing in X-ray range was shown in /8/. The focusing enables one to increase the intensity of a photon flux due to elongation of the ondulator, thereby additionally shortening the polarization time (proportionally to the ondulator length).

In prospect, special storage rings with two long straight sections, high current, and comparatively low energy of the particles (of the order of 1 GeV) can become high-power sources of X-ray radiation. The radiation from an ondulator located in one of the straight sections of a storage ring-source can be directed to a storage ring with circulating electrons or positrons for their polarization.

Let us give a numerical example for the optimal case, when perimeters of the storage ring-source and of the storage ring with a polarized beam are equal, the ondulator radiation is focused by the mirrors to the transverse dimensions of the polarized beam and the radiation angles $\theta \gg \frac{1}{\gamma}$ are eliminated. Using the ondulator of a 50 m length with period $\lambda_0 = 2$ cm,

field $H_0 = 5$ kGs ($\mathcal{K} = 1$) at a 0.5 A current in the storage-ring-source. and the polarized beam area $S = 10^{-4}$ cm^2 at the place of particle collision with radiation (at the length of the order of bunch lengths in storage rings), at $\chi = 10$ (the particle energy in the storage ring-source is 1 GeV, the polarized beam energy is 5 GeV), one can polarize the beam during 21 sec to the degree of polarization $\zeta = 30\%$ with the decrease of the number of particles by a factor of 5 (during 33 sec to $\zeta = 50\%$ with the decrease of the number of particles by a factor of 13). Choosing a larger value of χ it is possible to decrease a particle loss, if the polarization time increases (at $\chi = 20$, $T = 26$ sec, $\zeta = 30\%$, $N/N_0 = 0.3$).

In order to obtain the polarized beams of superhigh energies, it is expedient to polarize the particles in an intermediate storage ring, being an injector for the main one. Multiple injection of the particles in a main storage ring opens up further possibilities to store a necessary number of polarized electrons and positrons.

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APPENDIX

For calculations it is convenient to proceed in formulae (4) from integration over a frequency $d\omega$ to integration over a solid angle $dO = 2\pi \sin\theta \, d\theta$, by using the formula:

$$\frac{dI^{\pm}}{d\omega} = \sum_{K=1}^{\infty} \int \frac{dI_K^{\pm}}{dO} \, \delta\left(\omega - \frac{2\pi K/\lambda_0}{1 - v_{\parallel} \cos\theta}\right) dO$$

where $\delta(\ )$ is a δ-function, and the expression for $\frac{dI_K^{\pm}}{dO}$ can be found, for example, in /6/. In the ultrarelativistic approximation, the integrals T^{-1} and $\mathcal{K}$ in formulae (4) may be transformed to the form:

$$\int_0^{\infty} \frac{d\omega}{\hbar\omega}\left(\frac{dI^+}{d\omega} - \frac{dI^-}{d\omega}\right)(\sigma_{\uparrow} - \sigma_{\downarrow}) = \frac{2e^2}{\hbar}\frac{2\pi}{\lambda_0}\frac{\mathcal{K}^2}{1+\mathcal{K}^2}\sum_{K=1}^{\infty} K \int_0^{\infty} dx \, \frac{x(1-x^2)}{(1+x^2)^3}\left[J_{K-1}^2 - J_{K+1}^2\right](\sigma_{\uparrow} - \sigma_{\downarrow}), \tag{5}$$

$$\int_0^{\infty} \frac{d\omega}{\hbar\omega}\left(\frac{dI^+}{d\omega} + \frac{dI^-}{d\omega}\right)(\sigma_{\uparrow} + \sigma_{\downarrow}) = 2\frac{e^2}{\hbar}\frac{2\pi}{\lambda_0}\frac{\mathcal{K}^2}{1+\mathcal{K}^2}\sum_{K=1}^{\infty} K \int_0^{\infty} dx \, \frac{x}{(1+x^2)^4}\left[(1+x^4)(J_{K-1}^2 + J_{K+1}^2) - 2x^2 J_{K-1} J_{K+1}\right](\sigma_{\uparrow} + \sigma_{\downarrow}) \tag{6}$$

where J_K is Bessel function of the argument equal to $\left(\mathcal{K}/\sqrt{1+\mathcal{K}^2}\right)\frac{2Kx}{1+x^2}$, the values $\sigma_{\uparrow} \pm \sigma_{\downarrow}$ are determined by formulae (1) at the points

$$\mathcal{X} = \frac{4K\gamma\gamma_{\parallel}^2}{1+x^2}\frac{\lambda_c}{\lambda_0} .$$

If the ondulator parameter $\mathcal{K}$ is very small, then it suffices to restrict oneself to a dipole approximation in formulae, retaining only the term with $K = 1$ in the sum. In the optimal case, the parameter is of the order of unity and it is required to take into account several terms of the sum. Note that if one neglects the dependence of the difference between the scattering cross-sections on the frequency (on $\mathcal{X}$), then the integral (6)

vanishes. The coincidence of the number of the left- and right-polarized photons radiated from the ondulator is best obvious in the accompanying system (wherein $v_{\parallel} = 0$), where the radiation is symmetric with respect to the rotation plane.

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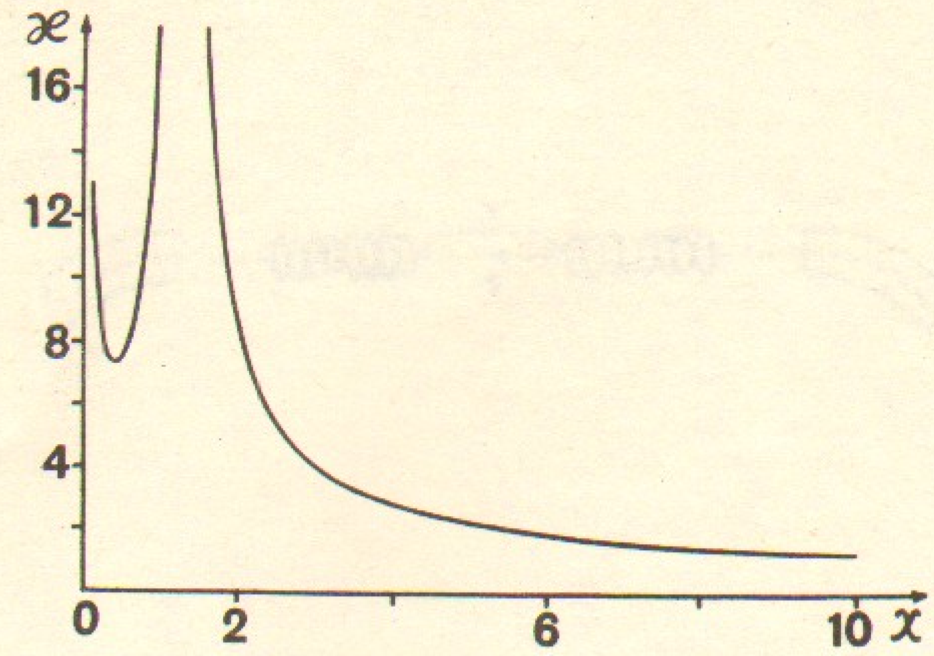

Fig. 1.

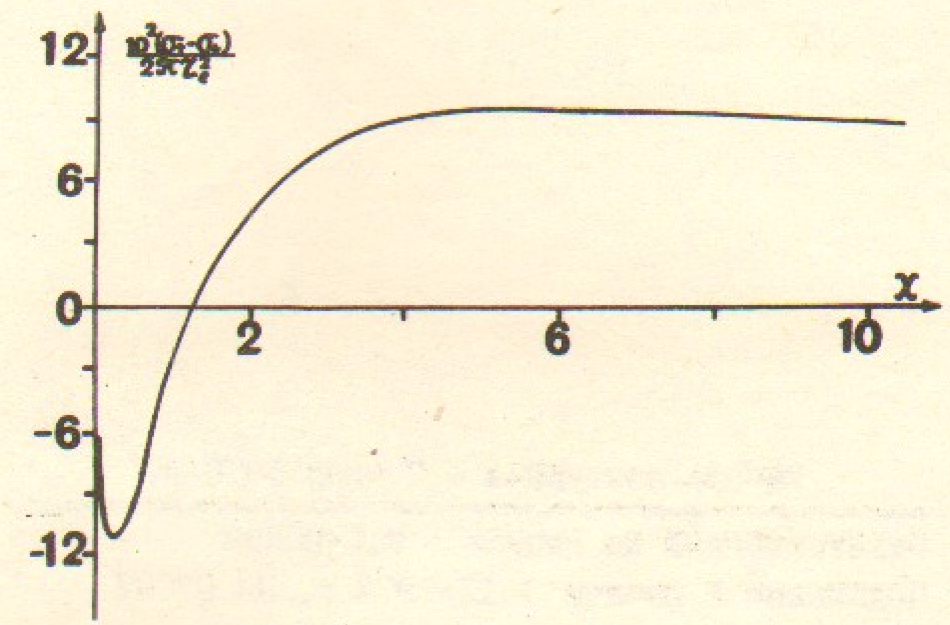

Fig. 2.

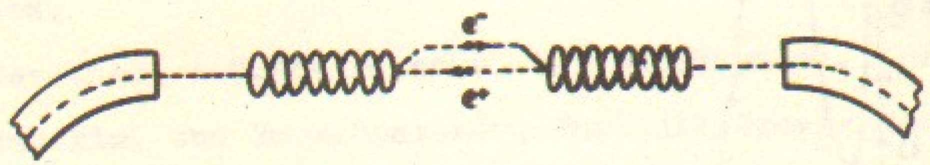

Fig. 3.

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