СИБИРСКОЕ ОТДЕЛЕНИЕ АН СССР

ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ

Ya.S.Derbenev, A.M.Kondratenko, E.L.Saldin

ON THE POSSIBILITY OF USING A FREE ELECTRON LASER FOR POLARIZATION OF ELECTRONS IN STORAGE RINGS

ПРЕПРИНТ 80-171

Новосибирск

ON THE POSSIBILITY OF USING A FREE ELECTRON LASER FOR POLARIZATION OF ELECTRONS IN STORAGE RINGS

Ya.S.Derbenev, A.M.Kondratenko, E.L.Saldin
Institute of Nuclear Physics
630090, Novosibirsk 90, USSR

A b s t r a c t

The possibility to polarize electrons (positrons) by colliding circular-polarized photons is discussed. The effect is based on the dependence of the Compton scattering cross section on the initial electron polarization. In the case of hard photons the spin dependence is used to knock out mainly a certain helicity from an electron beam in a single scattering. This method enables one to achieve very short polarization times (of the order of a few seconds). In the region of fairly soft quanta an alternative method, without particle escape from the beam, may be used to polarize the beam. This effect is based on the dependence of the energy losses in the multiple scattering on on the spin direction together with a spin-orbital coupling in the field of a storage ring (the coupling is necessary for the beam polarization by soft quanta). With the use of the above methods in high and superhigh energy storage rings one can employ the photon sources based on the generation of coherent radiation by a relativistic electron beam in a helix ondulator. In the present report, the possibility of polarization is illustrated by the concrete examples. To polarize the beam with the knocking out method, the cyclic variant of the source of hard coherent radiation (X-ray laser) is suggested. Another possibility of obtaining polarized beams in storage rings consists in creation of the intensive of polarized particles with the help of a free electron laser. Secondary γ-quanta obtained in the interaction of the high energy circulating beam with a colliding circular-polarized electromagnetic wave can be converted in the polarized electron-positron pairs in the Coulomb field of nuclei. As an example, it is shown that using of a free electron laser in the LEP storage ring allows to obtain the accumulation rate of polarized particles in LEP higher than that of unpolarized ones in the designed scheme.

1. Introduction

The papers /1,2/ concern the possibility to polarize electrons (positrons) by colliding circular-polarized photons. The effect is based on the dependence of the Compton scattering cross section on the initial electron polarization. This dependence is characterized by the ratio of the incident photon energy to the electron energy in the rest frame : $\chi = 2\gamma\hbar\omega_{ph}/m$. At $\chi \gtrsim 1$ the spin dependence of the total cross-section and the recoil energy become so large that this circumstance may be used to knock out mainly a certain helicity from the electron beam in a single scattering. In this case, it is necessary to provide the stability of longitudinal polarization of circulating electrons in the region of interaction with photons.

In the region of fairly soft quanta, when the scattering recoil energy does not exceed the storage ring energy aperture ΔE_{cr}

$$\chi \ll \Delta E_{cr}/m\gamma$$

we use another method, without particle loss from the beam. Besides the spin dependence of energy losses in the multiple scattering, this method employs the spin-orbital coupling in the field of a storage ring. It is worth noting that the processes with spin rotation in the scattering have the same probabilities in the laboratory system to an ultrarelativistic accuracy. Thus makes impossible their use with the aim to obtain the polarization. In view of this, the spin orbital coupling is necessary to polarize the beam by soft photons. Note, that for this method the most favorable direction of polarization on the interaction region is a direction normal to velocity.

The use of the above methods in high and superhigh energy storage ring requires powerful sources of circular-polarized radiation in a submillimeter range for polarization by soft photons and in the region of vacuum ultraviolet for polarization by hard photons. At present there is a realistic possibility to build up powerful sources in a broad range of spectrum, based on the generation of coherent radiation by a relativistic beam in an ondulator. Most prospective turn out to be the resonatorless systems the creation of which is a prerogative of accelerator technology.

In the present paper the possibility of polarization by soft photons illustrated by the concrete examples. To polarize the beam with the knocking out method, the cyclic variant of a source of hard coherent radiation is suggested.

2. Polarization by soft photons

Let us start with a concrete example illustrating the requirements for the magnetic system of a storage ring and the parameters of a source. In conventional storage rings the spin is subject to precession around the vertical direction ; the necessary spin-orbital coupling may be obtained if the solenoid is inserted into the straigt section of the storage ring. In optimal case, the required integral of longitudinal field is

$$H_s \cdot l_s \simeq 10^2 (\nu_s - K)^2 \text{ kGs}\cdot\text{m} \qquad (2.1)$$

where $\nu_s = \gamma \frac{g-2}{2} = E/440$ Мэв is the spin precession frequency, K - the nearest integer. Strictly speaking, the relation (2.1) holds at $|\nu_s - K|^2 \ll 1$. For example, at $|\nu_s - K| = 0.25$ the required field integral is equal to $\simeq 6$ kGs·m. Introduced with such a solenoid, the spin-orbital coupling will be determining under conditions when the parasite spin-orbital coupling due to imperfectness of the magnetic system is quite small. For storage rings with a large number of components producing statistically independent perturbations (connected with the vertical shift of lenses and caused by random tilts of bending magnets) these conditions in their simplified form can be written as follows /3/ :

$$\frac{\nu_s^4 \overline{\alpha^2}}{Q_m} \ll (\nu_s - K)^4 \ , \quad \nu_s^4 \cdot \nu_z^3 \cdot \overline{(\Delta Z_L)^2}/R^2 \ll (\nu_s - K)^4 . \qquad (2.2)$$

where Q_m is the number of bending magnets, $\overline{\alpha^2}$ and $\overline{\Delta Z_L^2}$ are the r.m.s. angular spread of alignment of magnets and vertical shift of lenses, R - is the storage ring radius, ν_z is the reduced frequency of betatron oscillations. For example, at $E = 20$ GeV, $Q_m = 200$, $R = 500$ m, $\nu_z = 20$, $\overline{\alpha^2} = 10^{-8}$, $\overline{\Delta Z_L^2} = 10^{-4} \text{cm}^2$ we have, correspondingly, $(\nu_s - K)^4 \gg 10^{-4}$, $(\nu_s - K)^4 \gg 4\cdot 10^{-4}$.

For a usual polarization by synchrotron radiation the fulfilment of the conditions (2.2) means that the polarizytion processes prevail the depolarization ones (i.e. the equilibrium degree of polarization by synchrotron radiation will be close to the maximum).

If the conditions (2.2) are not met, the influence of the parasitic spin-orbital coupling may be compensated by introducing, for example, a longitudinal magnetic field at two point of the orbit (the vertical spin rotation angle between which is not π-fold). The required values of these fields can be chosen by achieving a maximum polarization degree.

In our example the collision with photons must take place in the straight section lying opposite to the solenoid. In this case the degree of beam polarization constitutes $\left[\frac{5}{14}\right]^{1/2} \simeq$ $\simeq$ 60% from 100% photon circular polarization. The sign polarization is determined both by photon helicity and field direction in the solenoid. This makes it possible to prepare the colliding beams with any combination of spin directions.

The time of polarization is

$$\tau(\text{sec}) \simeq 0.8\cdot 10^{13} \lambda(\text{cm}) S(\text{cm}^2) / E^2(\text{GeV})\cdot W(\text{wt}) \qquad (2.3)$$

where λ and S are the wavelength and of the photon beam area*, W is the mean power of radiation under condition of its optimal use (operation in the pulsed regime with the phase correlation of the electron beam).

---

* It is assumed that S is not less than the electron beam area ; in the opposite case the electron beam area is meant by S.

For example, if $E = 20$ GeV, $\lambda = 10^{-2}$ cm, $S = 10^{-1}$ cm ^{2}, and $W = 15$ kW, the polarization time is 20 minutes. If the number of particles $N_e = 10^{12}$, the power consumed by the beam from the r.f. system of the storage ring during polarization process is

$$W_{rf} = 4W\sigma_{Th}\gamma^2 N_e S^{-1} \simeq 1.5 \text{ kw}$$

where σ_{Th} is the Thomson cross section.

Hardness of the incident radiation is limited by the following condition : in the recoil process the electrons should not be lost from the admissible energy aperture :

$$4\gamma^2\hbar\omega_{ph} < \Delta E_{cr} = \alpha E$$

where α is the relative energy aperture of a storage ring, (usually, of the order of 1%).

Multiple scattering will lead to increasing the energy spread. The rate of energy diffusion is, as known, directly proportional to the decrement of polarization. In our case, the decrease of the polarization time (it is Q times shorter in comparison with the usual duration of polarization), because of synchrotron radiation is accompanied by the following increase of the energy spread :

$$\Delta E = \Delta E_{S.R.} \cdot \left[1 + \frac{63}{110} Q\right]^{1/2}$$

For example, with reduction of the polarization time by 10 times the energy spread increases by a factor of 2.6.

An increase of the energy spread leads, generally speaking, to increasing the transverse sizes of an electron beam. If these sizes become larger than the transverse sizes of the light beam, this results in degrading the efficiency of the method. This is can be avoided by eliminating the dispersion function at the point of interaction with colliding photons. Also, one can make the time between the pulses of incident

radiation to be equal by the order of magnitude to a few times of radition damping of the beam in a storage ring (with the same mean power W). In this case, each subsequent pulse of radiation arrives at the already damped beam with the sizes determined only by quantum fluctuations of synchrotron radiation.

3. A source for polarization by soft photons

As a source of submillimeter radiation, one can use the beam of relativistic electrons traveling through a helical ondulator (transverse helical magnetic field). In this case, the single electrons radiate on the characteristic wavelength

$$\lambda = \lambda_0(1 - \beta_\parallel) = \lambda_0/2\gamma_\parallel^2 \qquad (3.1)$$

where λ_0 is the ondulator period, $\beta_\parallel$ the longitudinal electron velocity in the ondulator. Electron-electron interaction through radiation fields leads to the instability of density harmonics in longitudinal direction on this wavelength, i.e. to electron bunching and coherent radiation.

In a conventional scheme of the FEL, the ondulator is placed in the resonator where radiation is accumulated. However, quite powerful radiation can also be produced, as known /4-9/, in an open ondulator because the presence of a resonator is not obligatory for the development of the instability. For polarization of high energy particles, the open FEL-systems become preferable owing to a large period of the particle revolution in a storage ring.

The density modulation increment is determined by a peak current in the beam $e\dot{N}$, its tranverse area $2\pi\sigma^2$, the value of the tranverse rotation velocity u driven by the ondulator and by the effective mass of longitudinal motion $\mu\varepsilon = (d\beta_\parallel/d\varepsilon)^{-1}$ (ε is the energy of an electron source). For a wide beam, when

$$\sigma^2 \gg \sigma_{cr}^2 = \frac{\lambda\!\!\!^{-2}}{u} \left[\frac{\gamma\mu}{\dot{N} r_e}\right]^{1/2}$$

($r_e = \frac{e^2}{m}$), the growth length is minimum at the exact resonance and is equal to /4-9/

$$l_g = \frac{2}{\sqrt{3}} \frac{1}{\lambda} (\sigma^2 \sigma_{cr}^4)^{1/3} \qquad (3.2)$$

In the case of a narrow beam ($\sigma^2 \ll \sigma_{cr}^2$), the growth length is approximately equal to /7,8/

$$l_g \simeq [\lambda^2 \cdot \ln(\sigma_{cr}/\sigma)/\sigma_{cr}^4]^{-1/2} \qquad (3.3)$$

The beam, after its passage of the length $L = l_g \cdot \ln \frac{1}{a}$ where a is the degree of initial beam modulation on the resonant harmonic, will have the modulation degree of the order of unity, and in this state it will radiate on a length of the order of l_g. The coherent radiation power W_p will constitute, in an order of magnitude,

$$W_p \approx \hat{N} m\gamma (\mu\lambda/l_g) \qquad (3.4)$$

The statistical fluctuations of beam density, which are caused by a finite number of particles, will play a role of the initial excitation of modulation. For example, for a narrow beam

$$a_{fl} \approx \left[\frac{2\gamma_{\parallel}^2}{\hat{N} l_g}\right]^{1/2}$$

In development of the modulation from the spectrum of density fluctuations the angular divergence of the output radiation is approximatly equal to $(\lambda/l_g)^{1/2}$ (the degree of non-monochromaticity is $\Delta\lambda/\lambda \approx \lambda_0/l_g \ll 1$).

Radiation instability occurs if the particle shifts due to the spread of longitudinal velocities may be ignored on the lengths of the order of l_g :

$$\Delta\beta_{\parallel} l_g < \lambda$$

Hence, we conclude that the energy and angular spreads in the beam should not exceed the following values:

$$\Delta\varepsilon/\varepsilon < \mu\lambda/l_g , \qquad \frac{(\Delta\theta)^2}{2} < \lambda/l_g \qquad (3.5)$$

The minimum possible longitudinal size of an electron bunch is determined by the distance at which the radiation leaves behind the particle during the time period l_g :

$$l_b > l_g(1 - \beta_{\parallel})$$

Let us present the concrete expressions for u and μ in a helical ondulator with the longitudinal magnetic field $H_{\parallel}$ applied additionally to the helical magnetic field H_0 /8/:

$$u = K_0(\gamma - K_{\parallel})^{-1} , \quad \mu^{-1} = \gamma^{-2} + u^2\gamma(\gamma - K_{\parallel})^{-1}$$

where $K_0 = eH_0\lambda_0/m$, $\quad K_{\parallel} = eH_{\parallel}\lambda_0/m$

The helical ondulator also provides its natural focusing in the transverse direction, which is characterized by the frequency of free oscillations λ_b^{-1} equal (at $H_{\parallel} = 0$) to $\lambda_b^{-1} = eH_0/\sqrt{2}\, m\gamma$. Introduction of a longitudinal field in the ondulator enables one to regulate the mass of longitudinal motion with no change of transverse rotation (u = const). According to (3.2) and (3.3), the decrease of μ leads to the growth of increments. There is another possibility to increase considerably, in accordance with (3.4), the fraction of the beam energy converting into radiation by increasing μ on the final straight section of the ondulator. Let us consider a numerical example. Let there exists a source of electrons with the following parameters: ε = 6 MeV, $e\hat{N}$ = 300 A, the emittance $\sigma\Delta\theta$ is 10^{-3} cm. If the beam with such parameters passes through the ondulator with period λ_0 = 2 cm and helical magnetic field H_0 = 2,5 kGs ($H_{\parallel}$ = 0) it will bunch and radiate on the wavelength $\lambda = 10^{-2}$ cm. The growth length is calculated by the narrow beam formulae and is equal to l_g = 10 cm. To achieve a full modulation during generation from the spectrum of fluctuations, the ondulator length should be approximately equal to 1.5 m. The frequency of free oscillations λ_b^{-1} is 0.1 cm^{-1}. Introduction of the longitudinal magnetic field $H_{\parallel}$ = 60 kG on the generation section will enable the fraction of the electron energy converting into radiation to be increased up to a value of the order of 10%. In this case, the peak power of radiation will be equal to $\simeq 1.5\ 10^8$ W. At angular divergence $\hat{\theta} \approx 10^{-2}$ the area of transverse cross section of radiation beam at its exit will be of the order of 10^{-1} cm^2.

Relatively low energy and mean power of a source of electrons required for polarization of particles in a storage ring, as well as relatively weak limitations on the local energy and angular spreads allow conventional resonators (of the same type as those used in the storage ring rf system) to be used for linear acceleration. The length of bunches and the peak current may be chosen approximately the same as those for the bunches of polarized particles. The repetition frequency of the bunches must be chosen to be equal to the revolution frequency of particles in a storage ring (or integer times lesser).

Such a source may be combined with a storage ring by locating the ondulator in the straight section of the storage ring. Moreover, the resonators of the storage ring and this source are locked with each other in phase*. Apparently, the helical field of an ondulator and the bending magnets for a beam source do not, practically, affect the beam under polarization. The longitudinal field which may be applied to the ondulator with the aim of improving the source efficiency, must be compensated on the adjacent section of the same straight section.

Thus, at the 30 cm bunch length and 10^5 sec^{-1} repetition frequency a source with the parameters listed in the numerical example, makes it possible to polarize electrons in a storage ring at an energy of 20 GeV during 20 minutes. The mean power of the electrons of the source will constitute 150 kW. Recuperation, there is no difficulty in performing it in a given scheme, enables the active power to be decreased approximately by one order of magnitude.

4. On Possibilities of using a free lectron laser in the conversion method of polarized e^+e^- pair

The above-described generator of coherent radiation can also be used for the creating of an intensive source of polarized particles.

* Of interest is the possibility of accelerating the electrons from a source with the resonators of the storage ring rf system directly.

Polarized electrons and positrons may be produced by converting the circular-polarized photons in the Coulomb field of a nucleus. Quanta of required hardness are produced when in irradiating the high energy electrons in the beam circulating in a storage ring by the counter-incident circular-polarized radiation of the FEL. The secondary γ - quanta of energy $\approx 4\gamma^2\hbar\omega_{ph}$ are emitted within a very small angle $\approx \gamma^{-1}$ with the polarization dependent on the radiation angle $\hat{\theta}$ the polarization sigh alters at $\hat{\theta}=\gamma^{-1}$)/11/. In view of this, in order to produce a circular-polarized photon beam an a converter, it is necessary that the angular spread in the circulating high-energy electron beam should be considerably less* than $\gamma^{-1}((\gamma\Delta\theta)^2 \ll 1)$.

Let us present an example where the design parameters of the LEP injection system are taken for their current values.

For the storage ring LEP /13/ the injection energy is 22 GeV, the number of the particles stored in the bunch is $\simeq 10^{13}$, the repetition frequency of the linear accelerator - - injector is 100 Hz. If one places 10 coherent sources of the above type in the storage ring LEP, which emit a radiation pulse of 10^{-9} sec duration and peak power of $2\cdot10^8$ W on $\lambda = 10^{-2}$cm (it is focused to the $\approx10^{-1}$ cm^2area) 100 times per second, then $\approx10^{13}$ photons per second with an energy of 50 MeV will be produced.

The requirement that the angular spread of the beam in the LEP should be much less than $1/\gamma$, the beam emittance at injection energy is $\sigma\Delta\theta \approx 5\cdot10^{-7}$ cm, leads to the following conditions for the horizontal β - function at the interaction point

* In the paper /12/ the possibility has been considered of conversion of e^+e^- pairs with the help of the ondulator radiation of the beam with energy $E \geqslant 100$ GeV in the colliding linear electron-positron beam projects. From the standpoint of principle, the suggested here method is equivalent to that proposed in the work /12/ with substitution of an ondulator by a colliding electromagnetic wave. In practice, such a substitution allows this method to be used for storage rings.

with FEL radiation:

$$\beta \gg 10 \text{ m}$$

This means that there is no need for arranging a special magnetic focusing in this place. The converter should be placed far enough ($l \gg \gamma\sigma \sim 10$ m) from the point of secondary quanta production so as to avoid the mixing of their helicities in the converter. A small size of the photon beam in the converter ($S \approx 10^{-2}$ cm^2)allows the positrons to be produced in a small phase space volume. With the conversion coefficient $\simeq 10^{-2}$ we have $\approx 10^{11}$ sec^{-1} polarized positrons (electrons). This exceeds the design rate of accumulation of unpolarize positrons in LEP project.

In the subsequent energy build-up of the produced polarized particles is necessary to avoid the influence of spin resonances. In principle, this problem may be considered to have been solved today /14/.

5. A source for polarization by hard photons

To generate radiation in the region of vacuum ultraviolet and shorter wavelengths the linear acceleration method becomes inexpedient due to a high energy of the electrons of a source. More adequate is the cyclic variant: use of a storage ring as a source, in which small beam emittances can be obtained using radiation damping.

Let us first formulate the typical requirements for the parameters of radiation used for polarization with the knock-out method. The period during of which the degree of polarization (longitudinal in the interaction region) is achieved is determined by the equation:

$$T = \frac{S}{W}|\sigma_{\uparrow} - \sigma_{\downarrow}|^{-1} \ln \frac{1+\zeta}{1-\zeta}$$

where $\sigma_{\uparrow}$ and $\sigma_{\downarrow}$ are the total scattering cross sections the circular-polarized photons by the electrons of positive and negative helicities, respectively. In this case, the fraction of the particles remained in the storage ring is equal to

$$N/N_0 = (1+\zeta)^{-1}[(1-\zeta)/(1+\zeta)]^{\delta}$$

where

$$\delta = \frac{1}{2}|(\sigma_{\uparrow} + \sigma_{\downarrow})/(\sigma_{\uparrow} - \sigma_{\downarrow})| - \frac{1}{2}$$

With increase of the parameter χ the electron scattering with helicity opposite to that of a photon, becomes more and more prevailing ($\sigma_{\uparrow}/\sigma_{\downarrow} \to \frac{2}{3} \ln \chi$) *. The polarization time increases proportionally to $\chi/\ln \chi$

$$(|\sigma_{\uparrow} - \sigma_{\downarrow}| \to 2\pi r_e^2(\ln 2\chi)/\chi)$$

Let us come to a numerical example. At the parameters: radiation wavelength λ is $2\cdot 10^{-6}$ cm, mean power of a source W is 10 kW, photon beam area S is 10^{-3} cm^2, it is possible to polarize the beam at an energy of 40 GeV to the polarization degree $\zeta = 0{,}5$ during 15 sec. The remaing fraction of the beam constitutes 20%.

It is worth of emphasizing that so short polarization times are not, in practice, achievable in any other known methods of circular beam polarization (radiation polarization in a conventional storage ring or the polarization with the "snakes", or by soft circular-polarized photons because of an in admissible increase of the beam energy spread.

A source of such radiation may be arranged as follows. The bunch of electrons circulating in a special storage ring with an energy of 0.5 GeV travels through a helical ondulator with period 2 cm, field H_0 = 5 kG, and length ~ 6 m. If the num-

* Asymptotically at $\chi \to \infty$ the predominant contribution to the total cross-section of the photon-electron interaction is that of the pair production. However, in the range $\chi \lesssim (e^2/\hbar c)^{-1}$ of practical interest the Compton scattering is still predominant.

ber of particles N_e is 10^{12} in a bunch of 2 cm long, transverse beam cross section $2\pi\sigma^2=6\cdot10^{-4}cm^2$ in the ondulator, the growth length is equal to 60 cm (it is calculated from equation (3.2)). The wavelength of coherent radiation is $2\cdot10^{-6}$ cm, peak power of radiation is $\simeq 10^{10}$ W at the angular divergence $\theta \approx 10^{-4}$ (and non-monochromaticity degree $\Delta\lambda/\lambda \approx 10^{-2}$). The energy and angular spread of electrons in the ondulator should not exceed 10^{-2} and 10^{-4}.

In the polarization regime, the electrons of a source are passed through the ondulator installed in the straight section of the main storage ring, one time during one (or a few) revolution periods of the beam subjected to polarization. During the remainder of the revolution period the beam-generator circulates in a small storage ring and with radiation cooling. The encounter with radiation occurs outside the ondulator when the low-energy beam leaves the orbit of the polarized beam. For a single-revolution passage of the electrons through an ondulator the existing systems for one-time injection-extraction may be employed.

A quite strong radiation damping is required to polarize the beam with the above parameters. It may be realized with wiggler-magnets.

The basic diffusion process determining the beam emittance is the intra-beam scattering of electrons (multiple Touschek effect).

The following parameters of storage ring are taken:
electron energy E = 0.5 GeV
bending radius of magnets R = 10 m.
frequency of betatron oscillations $\nu_b = 10$
The length of the wiggler-magnets in two opposite straight sections l_W is 2 x 20 m. The field in the wiggler magnets H_W = 60 kGs. In this case, the radiation damping decrement is $A_r \approx r_e^2\gamma H_W^2 l_W (l_W + 2\pi R)^{-1} \approx 10^4$ sec^{-1} (the wiggler magnets have increased the damping decrement by a factor of 10^3). For such a decrement the mean power of the ondulator radiation achieves $\approx$ 10kW. The power of synchrotron radiation from wiggler magnets is 0.5 MW. The beam emittance is found from the equilibrium condition of diffusion processes and

radiation friction: $\langle \frac{d}{dt}\left[\frac{\delta\gamma}{\gamma}\right]^2_T \rangle = A_r \langle \left[\frac{\delta\gamma}{\gamma}\right]^2 \rangle$ where

$$\langle \frac{d}{dt}\left[\frac{\delta\gamma}{\gamma}\right]^2_T \rangle \simeq \frac{2cN_e r_e^2 L_c}{\gamma^3\Delta\theta\sigma^2 l_b} \qquad (5.1)$$

is the energy diffusion coefficient because of intra-beam scattering in the round beam (it is preferable to have the same transverse sizes of the beam in order to reduce the intrabeam scattering);

$$\sigma \simeq \frac{R}{\nu_b^2}\frac{\Delta\gamma}{\gamma}, \quad \Delta\theta \simeq \frac{1}{\nu_b}\frac{\Delta\gamma}{\gamma} \quad \text{are}$$

the size and angular spread of the beam; l_b is the bunch length, L_c - the Coulomb logarithm approximately equal to 7. From the relation (5.1) we get

$$\frac{\Delta\gamma}{\gamma} \simeq 10^{-3}, \quad \sigma \simeq 10^{-2} \text{ cm}, \quad \Delta\theta \simeq 10^{-4}$$

In a single flight through the ondulator the energy of the particles steps down by about 1%.

Due to a high density of the particles in a bunch the lifetime of the beam is determined by the processes of single electron scattering (Touschek effect):

$$\tau_T^{-1} \simeq N_e r_e^2 c/(\gamma^3\sigma^2\Delta\theta l_b \alpha^2)$$

For an energy aperture $\alpha \simeq$ 3% the lifetime of the beam will be of the order of the beam polarization time in a large storage ring ($\simeq$ 10 sec). In our example, the sizes of a beam in the ondulator and in the storage ring are assumed to be equal. It is clear that the storage ring sizes may be made larger in order to decrease the Touschek effect. Lastly, it is possible to continue the beam accumulation during the polarization process.

6. Polarization in a super-high energy storage ring by the coherent radiation of the counter-rotating beam

Sometimes, when polarization is performed by the knock out method, instead of a special storage ring-hard radiation generator, one can use the coherent radiation of a counter-rotating beam in a storage ring in which polarized beams should be produced. Let us try to exemplify such a possibility with the LEP storage ring. We take the electron beam with the following parameters: $\gamma \simeq 4\cdot10^4$, the number of particles in the beam $N_e \simeq 10^{13}$, the bunch length $l_b \simeq 5$ cm, the horizontal beam emittance $\sigma_x\cdot\Delta\theta_x \approx 5\cdot10^{-7}$ cm, the vertical beam size $\sigma_z \approx 0{,}1\cdot\sigma_x$. Let this beam pass through the helical ondulator with period $\lambda_0 = 7$ cm and magnetic field $H_0 = 20$ kG. In this case, the resonant wavelength of the coherent radiation is equal to $\lambda = (2\gamma_\parallel^2)^{-1}\lambda_0 \sim 5\cdot10^{-7}$ cm. The characteristic growth length of the density modulation, with the transverse beam sizes in the ondulator $\sigma_x\cdot\sigma_z \approx 10^{-5}$ cm^2, is calculated by the equation* (3.2) and is equal to $l_g \approx 2$ m. To perform the beam self-modulation it is necessary that the angular and energy spreads should satisfy the conditions

$$(\Delta\theta)^2 \lesssim 10^{-9} \qquad , \quad \frac{\Delta\gamma}{\gamma} \lesssim 5\cdot10^{-3}$$

For a given phase space volume of the circulating beam, these conditions may be fulfilled if the value of the β - function in the ondulator is of the order of 5 m. The required length of the ondulator in the development of modulation from the spectrum of fluctuations is of the order of 15 m. The fraction of the beam energy converted into radiation during one flight will constitute about 0.5%. The area of the radiation beam at its exit from the ondulator is of the order of that of the circulating electron beam in the ondulator and the radiation beam divergence angle is $\simeq 3\cdot10^{-5}$. The peak radiation power (on a wavelength of $5\cdot10^{-7}$ cm and with the degree of monochromaticity $\frac{\Delta\lambda}{\lambda} \approx 10^{-2}$) will constitute approximately 10^{12} W.

The polarization process proceeds as follows. A pulsed ondulator is installed near the interaction point of the electron-positron bunches and is switched on for the time shorter

* Calculation of the quantity l_g by equation (3.2) for a wide beam may be considered as an estimate because the actually intermediate case occurs when $\sigma_z \approx \sigma_{cr}$

than the revolution period in the storage ring* ($\tau \lesssim 10^2$ ks) in the time intervals of the order of radiation damping time in the storage ring τ_{rad}. τ_{rad} may be decreased at the injection energy by introducing a special magnetic snake. The horizontal phase-space volume is not enlarged in this case, if the dispersion function Ψ is compensated at the place where the snake is located. At $\tau_{rad} \approx 10^{-1}$ sec the mean power of coherent radiation is $W \approx 1$ kW. The time of polarization up to the degree $\zeta = 50\%$ will be equal to $\simeq 10^2$ sec. The portion of the remaining particles will constitute 30%.

In conclusion, we would like to mention that the storage rings-generators are, in essence, X-ray lasers. In our opinion, the creation of devices of such a type is within the scope of the present-day possibilities of acceleration technology.

The authors are indebted to A.N.Skrinsky for his interest to this work.

* Building up a pulsed ondulator with the inducated parameters does not be a matter of any technical difficulty but it requires that a certain section of the vacuum chamber should be non-metallic (for example ceramic) because of a small thickness of the skin in metals.

References

1. Ya.S.Derbenev, A.M.Kondratenko, E.L.Saldin. Nucl. Instr. and Meth. 165, 15 (1979).
2. Ya.S.Derbenev, A.M.Kondratenko, E.L.Saldin. Nucl. Instr. and Meth., 165, 201 (1979).
3. Ya.S.Derbenev, A.M.Kondratenko, A.N.Skrinsky. Pat. Ac. 9 (1979).
4. N.M.Kroll, W.A.McMullin. Phys. Rev. A17, 300 (1978).
5. V.L.Bratman, N.S.Ginzburg, M.I.Petelin. ZhETF 76 930 (1979).
6. L.A.Vainstein. ZhTF 49 1129-1140 (1979).
7. A.M.Kondratenko and E.L.Saldin. Doklady Akad. Nauk SSSR, 249, 843 (1979).
8. A.M.Kondratenko and E.L.Saldin. /Pat. Ac. 10 (1980)/ INP 79-48 (1979).
9. P.Sprangle, R.Smith. Phys. Rev. A21, 293 (1980).
10. V.N.Baier, V.M.Katkov, V.S.Fadin. The radiation of relativistic electrons. Atomizdat, Moscow, 1973.
11. D.E.Alferov, et al., Pat. Ac. 9, 223 (1979).
12. V.B.Balakin, A.A.Mikhailichenko. INP 79-85 (1979).
13. Design study of a 22 to 130 GeV e^+e^- colliding beam machine (LEP). CERN/ISR-LEP/79-33, 22 August 1979.
14. Ya.S.Derbenev, A.M.Kondratenko. Doklady Akad. Nauk SSSR 222, 830 (1975). Doklady Akad. Nauk SSSR, 246, 301 (1979). Proc. III Intern. Symp. on High Energy Physics with Polarized Beam and Polarized Targets, Argone, 1978.

Работа поступила - 15 мая 1980 года.

Ответственный за выпуск - С.Г.Попов.

Подписано к печати 29.08.80 МН 06887 Формат 30 x 42 1/8

Бумага офсетная № 1. Печать офсетная. Усл. 1,0 печ.л.

Учётно - изд. 1,0 л. Тираж 150 экз. Заказ № 171 Бесплатно

Отпечатано на ротапринте Института Ядерной Физики

Сибирского Отделения Академии Наук СССР

630090, Новосибирск - 90, Проспект Науки, 11