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A B S T R A C T

Results are reported for obtaining longitudinal polarization without beam orbit distortion in which the radiative polarization is entirely due to polarizing mechanism discovered by the authors in 1973. In the straight section of the storage ring a constant longitudinal magnetic field is introduced which turns the spin for half a turn around the velocity. In the opposite section an equilibrium polarization is directed along the velocity. The polarization degree may achive 62-67%.

The effect of radiative self polarization of ultra-relativistic electrons and positrons in a homogeneous magnetic field was discovered by A.A.Sokolov and I.M.Ternov in 1963. Further theoretical and experimental investigations of radiative polarization in inhomogeneous magnetic fields showed that under some conditions a high degree of polarization can be achieved in real storage rings.

In the usual case with small deviations of the magnetic field direction from the axial direction, the radiation polarizes particles in the direction transverse to the velocity (along the field). For high energy physics the question of obtaining longitudinally polarized beams is also of great interest.

In references /1,2/ it has been shown that in storage rings and accelerators one can obtain (introducing additional fields) any required direction of polarization $\vec{n}_s(\theta)$ at any given point of the orbit (with an azimuth θ), which is no less dynamically stable than the case with motion in a nearly axial magnetic field.

The simplest examples of obtaining longitudinal polarization are the methods in which the spin is turned by a radial magnetic field introduced into the straight section with the subsequent recovery of the spin orientation (and an orbit) at the output from section /2/. The polarization here is ensured by the usual direct spin-radiation interaction mechanism which makes the spin orientation along the guide field on the main part of the orbit.

A study of radiation effects in arbitrary inhomogeneous fields showed that the self polarization may take place in storage rings with large deviations of the equilibrium polarization direction from the axial on the main parts of an orbit. An additional effective mechanism of radiative polarization was discovered which is absent in a nearly constant (in direction) magnetic field. The effect has a classical interpretation and is due to spin-dependence of a radiative braking force. In the cases when direction $\vec{n}_s(\theta)$ does not coincide with the velocity rotation axis the direction $\vec{n}_s$ appears to be resonantly modulated with the spin procession frequency due to dependence on the particle trajectory. This leads to appearance of the decrement (increment) of an angle between the spin and $\vec{n}_s$. In certain situations when the usual effect of self polarization is entirely absent, the described mechanism can provide a high degree of polarization.

Let us consider an example of obtaining longitudinal polarization where radiative polarization is entirely due to this new mechanism. Assume that in the storage ring there are two oppositely placed straight sections I and II. Let us introduce the longitudinal magnetic field H_v into section I in a distance ℓ. The field turns the spin for half a turn around the velocity. The field value required for electrons and positrons is equal to:

$$\ell H_v = 26 \cdot 10^{-3} \gamma \quad \text{KGauss x m}$$

where $\gamma = (1-v^2)^{-\frac{1}{2}}$ is the relativistic factor (velocity of light $c = 1$). According to the general result of the work /I/ an equilibrium stable polarization $\vec{n}_s$ is the periodic solution of the equation for the spin particle motion along the closed orbit. This solution always exists and is the only one. It is easy to check that the motion of a spin directed along the velocity in section II will be periodic. On the main sections the vector $\vec{n}_s(\theta) = \vec{n}_s(\theta + 2\pi)$ is transversal to the guiding field and its orientation in the orbit plane depends on the energy /2/.

Any other motion of the spin along the equilibrium orbit is the precession around $\vec{n}_s$ $\left(\frac{d}{dt}\vec{n}_s\vec{S} = 0\right)$. A fractional part of the mean frequency of this precession ν in the example under consideration is equal to $^1/_2$ (in terms of the particle rotation frequency in the storage rings) independent of the energy value ($\nu = {}^1/_2$). That is easy to see by following the motion of the spin transverse to $\vec{n}_s$ and directed along the guiding field on the main part of orbit. In one particle revolution the spin appears to be turned over.

The particle spin motion transverse to $\vec{n}_s$ is intermixed due to the beam trajectory spread and the beam polarization appears to be directed along $\vec{n}_s(\theta)$. It is interesting to note that the spin motion in this example is more stable dynamically than that in the usual situation of a single-direction magnetic field: all the spin resonances (including those with betatron oscillations as well) become practically impossible since the resonance would mean at the same time an instability of the orbital motion.

The general analysis of the radiative polarization with an account of all the existing polarizing and depolarizing factors in the storage rings with arbitrary fields has been carried out in the works /3,5/. In the non-resonance case, the equilibrium polarization degree ζ and the time of its setting T are defined by formulas /3/:

$$\zeta = \alpha_-/\alpha_+ , \quad T = \alpha_+^{-1}$$

$$\alpha_- = \hbar\left(\frac{e}{m}\right)^2\gamma^5\left\langle|\dot{\vec{v}}|^2\,\dot{\vec{v}}\times\vec{v}\,\left(\vec{n} - \gamma\,\partial\vec{n}/\partial\gamma\right)\right\rangle \qquad \text{(I)}$$

$$\alpha_+ = \frac{5\sqrt{3}}{8}\hbar\left(\frac{e}{m}\right)^2\gamma^5\left\langle|\dot{\vec{v}}|^3\left[1 - \frac{2}{9}(\vec{n}\vec{v})^2 + \frac{11}{18}\left(\gamma\,\partial\vec{n}/\partial\gamma\right)^2\right]\right\rangle$$

Here brackets $\langle\ldots\rangle$ mean an averaging along the orbit, $\vec{n}$ - is the spin procession axis direction which is a function of coordinates and momentum defined with an account of deviation of the particle trajectory from the equilibrium one (on the equilibrium orbit $\vec{n} = \vec{n}_s(\theta)$): The deviation $\vec{n} - \vec{n}_s$ is small and can be found by the perturbation theory. In formulas (1) the terms which do not include $(\gamma\,\partial\vec{n}/\partial\gamma)$ describe the direct radiation effect on the spin /6,I/. In the term proportional to $(\gamma\,\partial\vec{n}/\partial\gamma)^2$ takes into account the depolarizing effect of stochastic trajectory jumps which can appear due to quantum fluctuations of radiation / 7,4/. Finally, the term with $(\gamma\,\partial\vec{n}/\partial\gamma)$ in α_- corresponds to the additional mechanism of radiative polarization /3,5/. In the homogeneous magnetic field $\gamma\,\partial\vec{n}/\partial\gamma = 0$, $\vec{n} = \dot{\vec{v}}\times\vec{v}/|\dot{\vec{v}}|$, and the equilibrium polarization degree is equal to 92%.

In the example under consideration the direction $\vec{n}$ on the main part is transverse to the guiding field and the direct radiation effect on the spin cannot polarize the beam. The equilibrium polarization degree is defined by the formula

$$\zeta = \frac{8}{5\sqrt{3}} \cdot \frac{\langle |\dot{\vec{v}}|^2 \vec{v}\times\dot{\vec{v}}\, \gamma\partial\vec{n}/\partial\gamma \rangle}{\langle |\dot{\vec{v}}|^3 [1 - \frac{2}{9}(\vec{n}\vec{v})^2 + \frac{11}{18}(\gamma\partial\vec{n}/\partial\gamma)^2] \rangle} \qquad (2)$$

The value $\gamma\partial\vec{n}/\partial\gamma$ is determined by the focusing system of the storage ring.

In the region of low energies $(\gamma \le 2/(g-2) = 10^3)$, $|\gamma\partial\vec{n}/\partial\gamma| \sim 1$. With higher energies, generally speaking, $|\gamma\partial\vec{n}/\partial\gamma| \gg 1$. Though, by the special choice of the focusing system one can reduce to the value of the order of unity and provide a high degree of equilibrium polarization.

The study of formula (2) showed that the maximum of ζ lies in the region 62-67%. The vector $\gamma\partial\vec{n}/\partial\gamma$ on the main part of the orbit is directed along the guiding field and its value is:

$$|\gamma\partial\vec{n}/\partial\gamma| = \left[\frac{2}{\pi}\left(8 - \frac{\sin\phi}{\phi}\right)\right]^{1/2}$$

where $\phi = \pi\gamma(g-2)$ is an angle of the spin rotation around the vertical direction on the main section of the storage ring.

Let us consider, for example, the strong-focusing storage ring with the following properties of its magnetic system. Let us choose the field decreasing factor on the sections with the vertical field to be equal to unity ($R\partial H/H\partial x = -1$) and the focusing components between these sections are chosen in such a way that angular deviations X' (in the orbit plane) on the input and output of each straight section should be the same except the section with the longitudinal field introduced. In this section the additional components introduced to compensate the X - Z coupling due to the longitudinal field and also

provide both dynamic and radiation stability of the orbital motion. For the equilibrium polarization degree we obtain:

$$\zeta = \frac{8}{5\sqrt{3}} \cdot \frac{\frac{\pi}{2}\sin\frac{\phi}{2}}{\frac{8}{9} - \frac{\sin\phi}{9\phi} + \frac{11}{18}\frac{\pi^2}{4}\sin^2\frac{\phi}{2}}$$

With energies when $\sin^2\frac{\phi}{2} = \frac{8}{11\pi^2}\left(8 - \frac{\sin\phi}{\phi}\right)$, the maximum polarization is achieved and the polarization time becomes less by a factor of two than in the storage ring without longitudinal field.

The method presented here is convenient in that longitudinal polarization occurs in the other section along its length without equilibrium orbit distortion.

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