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ABSTRACT

A short review is given of the main results obtained in the studies of the particle polarization behaviour in storage rings and accelerators. The certain variants are described on obtaining the longitudinally polarized particles by introducing magnetic fields into the sections. The method is proposed to accelerate the process of radiative polarization for electrons and positrons and rotate its direction in accelerators by the strong magnetic field with alternative sign which is introduced in the part of the orbit. The means of suppressing the resonance depolarization at the particle acceleration up to high energies are considered.

I. At present, there are two basic methods of obtaining high energy polarized beams. The first one is an obtaining a beam from available low energy sources with its subsequent acceleration in accelerators. In the second method, which is applicable to light particles, a radiative self-polarization effect is used. It is known, that ultrarelativistic electrons or positrons moving long enough in a storage ring can be polarized because of synchrotron radiation[1].

In this connection, one of the main problem here is to determine the requirements which the accelerator of the storage ring magnetic field should meet to maintain the particle polarization. For the electrons and positrons in storage rings the question arises of establishing conditions which provide for the occurence of natural polarization.

An important problem is the creation of the polarized particle beams with the required direction of polarization. For this it is necessary to study the spin behaviour without being restricted to the usual geometry of magnetic fields in present storage rings and accelerators.

These questions are considered in quite a large number of works. The conducted experiments reveal wide possibilities for the control of the particle polarization in the storage rings and accelerators and also to carry out the experiments with polarized beams.

2. In the works[2-4] an existence was established of the spin periodic motion under stationary conditions of particle motion in storage rings or accelerators in magnetic fields arbitrarily varying (in direction) which do not violate the orbital motion stability. When a particle is moving along the closed orbit, its spin motion is a precession around movable axis(precession axis). The direction of the precession axis varies periodically along the orbit and returns to its initial direction whatever complicated would be its variation along the orbit when the particle returns to its initial position. This axis is the stable polarization direction. This is an important practical result which allows one (by introducing special fields) to produce any preassigned stable direction of polarization at any point required.

In the general case, just as in the case of motion in an almost constant (in direction) magnetic field, the periodic spin motion is unstable only in a narrow range of spin resonances for which the spin rotation frequency around the precession axis coincides with the orbital frequencies or one of its integer number combinations.

A study of the radiative polarization stability carried out in works[5-11] taking into account the real factors has been shown that a high degree of polarization of electrons and positrons can be provided in storage rings. In works[9-11] there are formulas which enable one to obtain the value of the equilibrium polarization and relaxation time in storage ring with arbitrary fields. In the inhomogeneous field an additional polarizing mechanism occurs due to the spin-orbital coupling which is absent for motion in a constant (in direction) magnetic field. An example is considered below in which the radiative polarization is entirely due to this mechanism. It is interesting to note that the maximum polarization level is achieved in the inhomogeneous field of a special kind to be 95% (in homogeneous - 92%).

In the work$^{/10/}$ a possibility was shown of a long-time existence for polarized particles in colliding beam storage rings. It turned out that the maximum number of colliding particles which do not disturb the selfpolarization process is approximately the same as that permitted by conditions of orbital stability for colliding beams.

3. The well-known situation, in which polarized beams may exist is the motion in an accelerator or a storage ring with a constant (in direction) magnetic field. The natural direction of the stable polarization lies along the field transversal to the particle velocity.

Already in this case, the polarized beams substantially expand the possibilities for carrying out experiments in physics. In particular, one can determine the spin properties of final states by measuring the azimuthal distribution of the reaction products for the transversally-polarized colliding beams.

It becomes also possible to carry out precise experiments. Examples of experiments of this sort are the method of absolute measurement of the mean beam energy$^{/12/}$(obtained accuracy is 1 10^{-4}) and the experiment (to be carried out in near future at the Institute of Nuclear Physics (INP), SD USSR Acad.of Sci., Novosibirsk) on comparison of anomalous magnetic moments for electron and positron with a relative accuracy of about 10^{-5}. In these experiments a small RF magnetic field is employed which (at resonant tuning) depolarizes the beam$^{/4,6,11/}$. Such a depolarizer was used in the experiments on radiative polarization detection in the storage rings VEPP-2, VEPP-2M at the INP, SD USSR Academy of Sciences$^{/13,14/}$. Polarization state variation was detected by the frequency variation of the particle scattering events inside the bunch under which the particle energy changed of about 10% greater. This variant of detection is the development of the method proposed in the work /15/.

Of great interest is the problem of obtaining beams with any preassigned polarization direction. As an example, in experiments with the longitudinally-polarized (parallel to velocity) electron-positron colliding beams of the same helicity, the one-photon electro-dynamic channel is closed and therefore, all the rest of the annihilation processes, either non-one-photon or non-electrodynamic, are emphasized.

First suggestions (1970) on obtaining the polarization direction required (longitudinal, in particular) are given in papers/2,3/(see also review /6/ p.477 (714)). One can obtain longitudinally polarized beams in various ways. From the methodical point of view it is reasonable to note that a possibility to realize the stable spin motion with given direction at a certain point of an orbit by selection of the field geometry is analogous to that of obtaining the stability in orbital motion of particles in storage rings with a complicated shape of an equilibrium trajectory. As is known, one can also provide the orbital motion stability with respect to radiation effects. In exactly the same, by selecting in proper way the magnetic field geometry near the equilibrium orbit, one can achieve a high degree of radiative polarization.

4. Let us consider simple examples of how it is possible to obtain logitudinally polarized electron-positron (electron-electron) colliding beams/3/. Introduce a radial magnetic H_z field into the straight section of a storage ring. A value required for the spin revolution at an angle $\pi/2$ relative to velocity for electrons is equal to $H_z \ell =$ 23 KG x m where ℓ is a length of the section with introduced magnetic field (for protons 27 KGxm). Varying the H_z value along the section, one can obtain any required direction of polarization at the point of collision. In order to resume the polarization direction along the field and its velocity after passing the section, one should set the condition $\int_s H_z d\ell = 0$.

There is no substantial difficulty in resuming the orbit at the output from the section. In such the variant the high level of polarization is also provided.

With rotations in the given plane by the fields transverse to velocity, there is a relation between bending angles for the velocity φ relative to the main plane of the orbit and those for the spin ψ relative to velocity

$$\frac{\varphi}{\psi} = \frac{2}{\gamma(g-2)}$$

(γ is the relativistic factor, g is the particle g-factor). With rotation by the radial fields, at the pont where longitudinal polarization occurs, the velocity slope angle with respect to the main plane of the orbit is equal to $\pi/\gamma(g-2)$. Thus, the amplitude of the orbit vertical distortions in the section with the radial field introduced will depend on energy.

The certain variant selection is determined by the experimental conditions available. A particle trajectory in the section may, for example, have the form given in Fig.1.

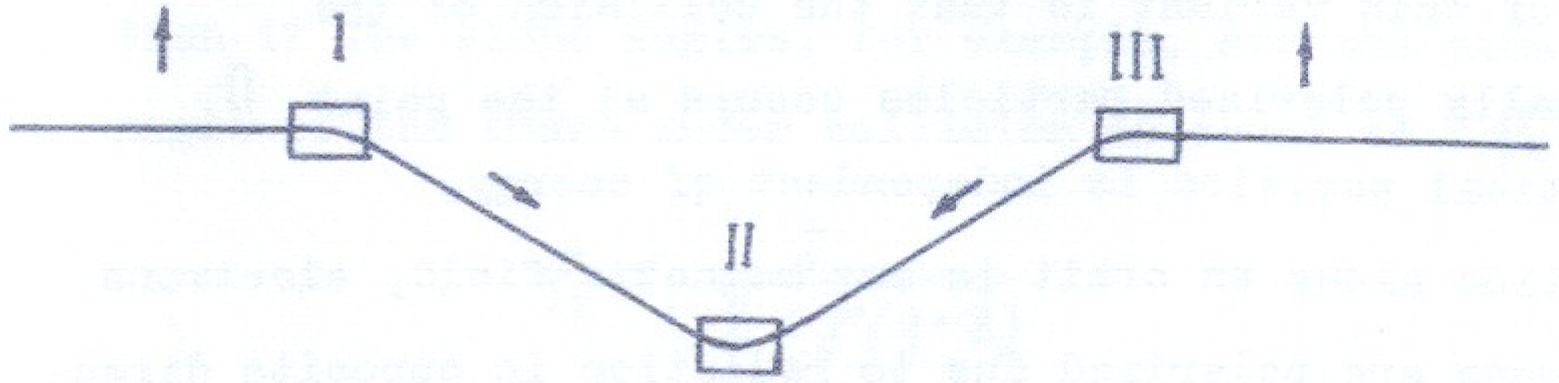

Fig.1

A radial magnetic field transverse to the plane of the Fig.1. introduced in the regions I,II and III. A longitudinal polarization along the opposite directions occurs between the regions I,II and II,III. (Polarization directions are indicated by arrows).

Another example is the variant proposed in the paper /16/ (see Fig.2).

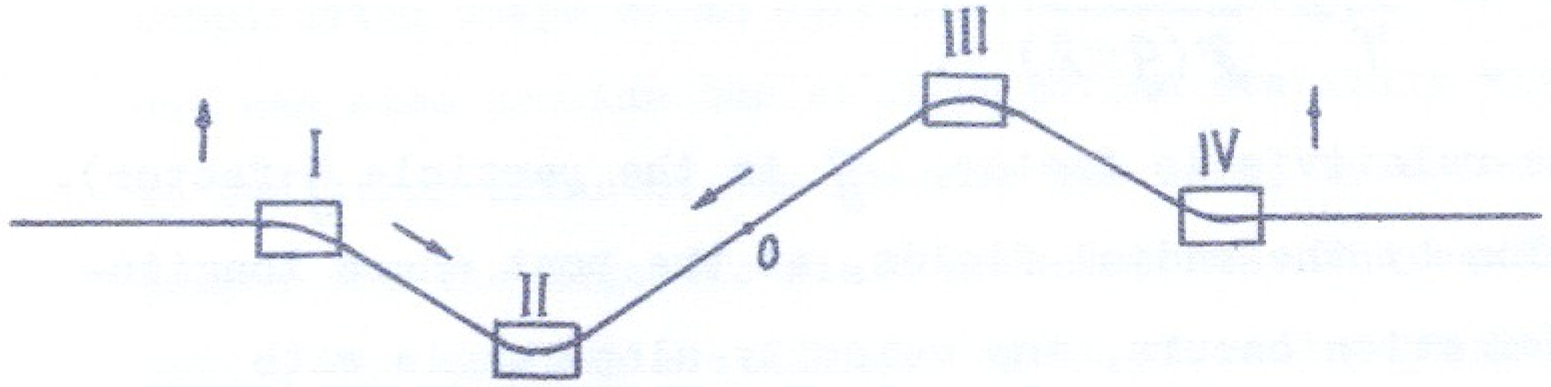

Fig.2

Here, longitudinal polarization is realized inbetween regions II and III (longitudinal polarization of the opposite direction may take place between regions I,II,III and IV). A feature of this variant is that the collision of the longitudinally polarized particles occurs at the point 0 whose vertical position is independent of energy.

For motion along an orbit in any magnetic field, electrons and positrons are polarized due to radiation in opposite directions(in particular, it is maintained at the point where longitudinal polarization occurs).One can obtain electron-positron

colliding beams with the same polarization directions. For this, it is sufficient to separate the beam energies by the radial electric field and reverse the polarization direction of one of the beams by making it pass adiabatically through the spin resonance produced /4/. Polarization state with reversed direction is dynamically as stable as the "natural" state and former will slow relaxate to the latter only due to radiation processes.

With the beam motion along various trajectories, for example, in the storage ring DORIS (BRD) or DCI(France) the states of beams with any relative sign of longitudinal polarizations may be stable with respect to radiation processes. So, with concentric trajectories (in the accelerators mentioned above) the states of the same helicity are only occured if at the point of their collision the slope angle of trajecories to the orbit main planes (the orbit planes are assumed parallel) are the same (head-on collision):

$$\varphi_1 = \pi/\gamma(g-2)$$

The state with different helicities occurs under the condition if the slope angles, for example, are the same (the angle of the beams under collision is equal to $2\varphi_2$):

$$\varphi_2 = \frac{\pi}{2+\gamma(g-2)}$$

Then, polarization of both beams is turned out to be longitudina in their center of mass system (spin vectors being parallel to the orbit main plane of beams at their collision point).

Other examples of obtaining longitudinal polarization in straight section are the variant in which combinations of longitudinal and vertical fields are used (instead of radial fields[17] and combinations of radial and vertical fields[18].

A study of radiative polarization stabitlity in the variants mentioned may be performed qualitatively by using the results given in the papers [8,9], where formulas for the level equilibrium radiative polarization were obtained and also formulas for its relaxation time in the storage rings with arbitrary variation of fields along orbits with account of all the substantial polarizing and depolarizing effects.

5. To achieve a longitudinal polarization, one can also use a logitudinal magnetic field which does not disturb the equilibrium orbit of particles. Let us consider an interesting variant in which an additional polarizing mechanism occuring in inhomogeneous field[8] is also demonstrated most clearly. Let there be two oppositely placed straight sections in a storage ring. If one introduces into one of the sections a longitudinal field H_v which turns a spin vector half a turn around the velocity, then in the opposite section an equilibrium polarization will be directed along the velocity[3]. The field value required (for electrons) is:

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$$H_v l = 26\; 10^{-3}\gamma \quad \text{KG x m}$$

In this variant, the stable direction of polarization on the main part of the orbit is transverse to the guiding magnetic field direction (lies in the orbit plane). At first sight, there should be no radiative polarization, but in an inomogeneous field (apart from quantum fluctuations of synchrotron radiation which was firstly noted by authors of the work[5]), an additional polarizing mechanism appears due to the spin dependence of the radiation breaking force[8].

In the variant under consideration a radiative polarization is entirely due to this mechanism. For particle energies at which $\gamma(g-2)\approx 1$ the degree of natural polarization may achieve 60-70%. A high degree of radiative polarization can be maintained at higher energies by the appropriate selection of the focusing system of the storage ring. The order of magnitude for polarization time, in this case, is the same as that for the storage ring without longitudinal field. (This variant will be described in more detail in a separate paper).

One can also obtain longitudinal polarization by intoroducing a small longitudinal field near the energy values*), when $\gamma(g-2)/2 = 1,2,\dots$.

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*) At these energy values, a longitudinal polarization occurs in both oppositely placed sections by inroducing the field of an arbitrary value. To provide dynamic stability it is only necessary to have a bending angle of the spin vector (by longitudinal field) in the section higher than the non-coheren angle spread for the spin pressecion axes in the beam.

In this case, though, the effect quantum fluctuations of synchrotron radiation becomes dominant and depolarizes the beam. In this case an injected beam should be polarized (taken, for example, from another storage ring). One can also introduce (adiabatically) the longitudinal field after the beam is polarized in the main field of a storage ring. The longitudinal field value should be sufficiently high to maintain polarization during the experiment.

As it has been already mentioned, the spin motion will only be unstable within narrow regions of spin resonances. Relatively small perturbations outside these regions do not cause substantial distortion of the spin motion. It is interesting to note that, in the variant having a longitudinal field. which turns the spin through a half turn within the section, the fractionalpart of the spin precession frequency (precession axis lies in the orbit plane) is always equal to the half of the particle revolution frequency in a storage ring irrespective of energy value. Therefore, all the spin resonances (involving also those with betatron harmonics) practically become impossible since the resonance would mean the presence of instability in the orbital motion too.

With high energies the spin-flip can be easier achieved in the section by means of magnetic fields transverse to the orbit, since their required value is by about $\gamma(g-2)$ less than that of the longitudinal field. Simultaneously the condition of the orbit resuming can be satisfied. Longitudinal

polarization will occur stably in the opposite section irrespective of the energy value. With high energies when $\gamma(g-2)\gg 1$ in this method it is apparently possible to provide the radiative polarization by a special selection of the focusing system of the storage ring as in the case of longitudinal field.

Principally, the variants possible for electrons (positrons) are applicable to heavy particle also. Due to the absence of radiative polarization in the case of heavy particle beam they should be injected either already polarized or one should polarize them in a storage ring in some way. One can hope, for example, to obtain polarized beams of protons (antiprotons) by the use of the spin dependence of the nuclear interactions of particles with the polarized targets and employing the electron cooling method to maintain the beam dimensions sufficiently small.

6. Some possibilities also exist to accelerate the process of radiative polarization. Let us introduce the strong vertical magnetic field with alternative sign $H(l)$ into the straight sections (minimum number of the field oscillations is determined by the permitted amplitude of the orbit space pulsation in the section). According to /6,8,19,20/ the reverse time of polarization T^{-1} is proportional to the value

$$T^{-1} \sim \gamma^2 \oint |H^3| dl$$

Hence it is clear that by the field increase on the relatively short part of the orbit one can substantially decrease the time of polarization. The level of equilibrium polarization ζ being equal to

$$\zeta = \frac{8}{5\sqrt{3}} \oint H^3 dl / \oint |H^3| dl$$

Apparently, by introducing a "snake" one can provide a high level of polarization without distortion of the orbit in its main parts. The condition

$$\oint_S |H^3| dl - \oint_S H^3 dl \ll \oint_S |H^3| dl$$

is satisfied if the fields having different signs strongly differ in magnitude from each other. Simultaneously, one can satisfy the condition $\int_S H dl = 0$. It is essential to note that with this method one can change the sign of equilibrium polarization by varying the field sign in the "snake".

One should take into account that the strong field introduction leads to the increase of radiative losses and in decrements of particle oscillation damping (with redistribution of the radial and energy oscillation decrements). The energy diffusion speed is increasing proportionally to T^{-1} due to the radiation quantum fluctuations:

$$\frac{d}{dt}\overline{(\Delta\gamma/\gamma)^2} = \frac{11}{9} T^{-1}$$

The beam energy spread being increased.

7. One of the important problem is an acceleration of polarized particles (protons, antiprotons) up to high energies. Usually, during acceleration a beam has to cross a row of the spin resonance which are able to depolarize the beam. Obvious recomendations are: either compensation for dangerous harmonics of the disturbing fields or an increase of the resonance crossing velocity.

Some other possibilities based on the increase of dangerous harmonics (instead of their suppression) by introducing special fields are considered in /21/. The harmonics are increased up to a level for which the resonance crossing becomes adiabatic. As an ultimate variant in which an introduced field produces a strong distortion of the spin motion, one notes the examples described above with the introduction of magnetic fields in the straight sections making the spin execute half a turn. With low energies (at the initial stage of acceleration) it is convenient to use the longitudinal magnetic field(the distortion of focusing properties of a magnetic system one can, if necessary, compensate by intoducing additional lenses). In the region of high energies ($\gamma(g-2) \gg 1$) it is reasonable to use the transverse magnetic fields (with resuming the orbit). It is possible to switch on or off the bending fields adiabatically with conservation of the spin and orbital motion stability. It is convenient to inject a longitudinally polarized beam directly into the opposite straight section where an equilibrium polarization direction is parallel to velocity. Since the spin resonances are impossible in these variants at any energy, the level of beam polarization will be maintained during acceleration.

The problem of the polarization conservation during acceleration or deceleration may also be essential for light particle. For example, one can rapidly polarize electrons at high energy and after that decelerate them down to the energy value required in the given experiment$^{/21/}$.

Possibilities of polarization control are, of course, not exhausted by the examples given above. But the considered variants already show that it is necessary to take into account these possibilities when designing new accelerators and storage rings at high energies.

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