Crossing integer spin resonance at VEPP-4M with conservation of beam polarization

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A method proposed to preserve the electron beam polarization at the VEPP-4M collider during acceleration with crossing the integer (imperfection) spin resonance at energy $E=1763$ MeV has been successfully applied. It is based on full decompensation of the $0.6 \times 3.3$ Tesla meter integral of the KEDR detector longitudinal magnetic field due to the anti-solenoids 'switched-off'.

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I. MOTIVATION

The set of the beam energy values in the Hadron-Muon Branching Rate measurement with the KEDR detector [1] at the electron-positron VEPP-M collider [2] in the region between $J/\psi$ and $\psi'$ resonances includes several critical points, in particular, $E = 1764$ MeV and 1814 MeV. The beam energy calibration in this experiment is performed using the Resonant Depolarization technique (RD), and thus polarized beams are required. Polarization is obtained due to the natural radiation mechanism at the VEPP-3 booster storage ring (see Fig. 1). Both mentioned energy values are in the so-called 'Polarization Downfall' (Fig. 2), which is the VEPP-3 energy range of approximately 160 MeV width, where obtaining of a fairly high degree of polarization is significantly hampered because of the strong depolarization effect of different field imperfections. The 'Polarization Downfall' range was found in the 2003 year experiment with the polarimeter based on an internal polarized target [3].

The center of that critical range is the energy value $E_4 = 1763$ MeV, which corresponds to the forth imperfection spin resonance $\nu = \nu_4 = 4$. In a conventional storage ring without any imperfections, $\nu = \gamma a$ is the spin tune parameter equal to the number of the spin vector precessions about the vertical guide field per a turn minus one; $\gamma$ is the Lorentz factor; $a = (g - 2)/2$ is the magnetic dipole moment anomaly. Nevertheless, one can obtain polarized beams at VEPP-4M with the energies from the 'Polarization Downfall', except for a small island in the vicinity of $E_4$ using the method of ‘advance energy point’. In the given experiment, the magnetization reversal cycle of the collider is of the ‘upper’ type. It means that the ‘advance energy points’ should be below the energies of experiment, as well as below 1660 MeV because of the ‘Polarization Downfall’ region lower boundary. In

FIG. 1. Scheme of the VEPP-4 complex from the point of view of polarization experiments. ITP is the internal target setup based on the use of a jet of polarized deuterium atoms from the Atomic Beam Source (ABS).
from the resonance \( \nu_k = 4 \). The magnetization rever-
sal cycle of the ‘lower’ type was used, and the ‘advance’
ergy was 1.85 GeV. After the beam was injected into
VEPP-4M, its energy decreased to the energy of the tau
production threshold.

In the case under consideration, one could apply a sim-
ilar method at energy points below 1763 MeV. However,
there was a need for special measures in relation to the
energy \( E = 1814 \text{ MeV} \), as well as to the points of energy
somewhat below the \( \psi' \) peak (for example, \( E = 1839 \text{ MeV} \)). The reason was the necessity to cross the integer
spin resonance at 1763 MeV during acceleration starting from the ‘advance’ energy.

II. ISSUES OF FAST/SLOW CROSSING

A sufficiently high rate of beam acceleration or de-
celeration in a storage ring can save the polarization of particles to a considerable extent in crossing of any spin resonance \( \nu_0 = \nu_k \). Generally, an actual spin tune \( \nu_0 \) differs from the parameter \( \nu \) defined for storage rings with
an unidirectional guide field. For fast crossing, the follow-
ing condition must be fulfilled [5, 6]:

\[
\frac{\Delta \xi}{\Delta t} = \xi \gg |w_k|^2 \omega_0, \tag{1}
\]

where \( \xi(t) = |\nu_0(t) - \nu_k| \) is the time-dependent resonant
detuning; \( w_k \) is the resonant harmonic amplitude of the
field perturbations; \( \omega_0 = 2\pi f_0 \) is the angular frequency
of particle revolution (at VEPP-4M, \( f_0 = 819 \text{ kHz} \)). The
corresponding loss in the degree of polarization at a sin-
gle crossing of the resonance is \( \sqrt{\pi |w_k|^2 \omega_0/\xi} \ll 1 \). The
data on the polarization lifetime \( \tau_d \) due to radiative depo-
larization in the vicinity of \( E = 1777 \text{ MeV} \), obtained dur-
ging the preparation of the tau-lepton mass measurement
experiment, contain the information about the natural
strength of the spin resonance \( \nu_k = \nu = 4 \). The polarization
lifetime was adjusted to the level \( \tau_d \geq 1 \text{ h} \) [7]. One
can associate this quantity with the formal estimate of the
resonant spin harmonic amplitude using the known
equation [8, 9]:

\[
\tau_d \approx \frac{\tau_p}{1 + \frac{11}{18} \frac{|w_k|^2 \nu^4}{\xi^2}}, \tag{2}
\]

where \( \xi = \nu_0 - \nu \approx 0.03 \ll 1 \), and \( \tau_p \) is the Sokolov-
Ternov polarization time [10]. For VEPP-4M, at \( E = 1777 \text{ MeV} \), \( \tau_p = 87 \text{ h}, \tau_d = 1 \text{ h} \), and \( \xi \approx 0.03 \); so the
estimate is \( |w_k| \sim 2.8 \times 10^{-3} \). Therefore, the maximum
necessary rate of the resonance crossing is \( \xi \gg 20 \text{ s}^{-1} \), or
\( dE/dt \gg 10^{3} \text{ MeV/s} \). In practice, the achievable ramp-
ing rate at VEPP-4M does not exceed 10-20 MeV/s. So, fast crossing of the integer spin resonance \( E = 1763 \text{ MeV} \) is
impossible.

If the ramping rate is reduced so that the following
condition [5, 6, 8]

\[
\xi \ll |w_k|^2 \omega_0, \tag{3}
\]
is satisfied, then the spin resonance intersection occurs
adiabatically slowly. Basing on the estimates made
above, one can conclude that, in principle, a rate of
\( 1 \div 10 \text{ MeV/s} \) may be appropriate. In the theoretical
limit of the adiabatic crossing without taking into ac-
count the radiation effects, the polarization retains its
value and changes the sign (the spin flip mode).

Despite the feasibility of the condition of slow crossing, it is necessary to bear in mind that there is a lower limit
on the rate of the crossing because of the depolarizing
effect of radiation diffusion and damping. The radiation
depolarization time related to the vertical closed orbit
distortions declines very quickly with the detuning from the
integer spin resonance: \( \tau_d \propto \xi^4 \). For example, this
time decreases as 16 times at \( E = 1770 \text{ MeV} \) as compared
with \( \tau_d = 1 \text{ h} \) at \( E = 1777 \text{ MeV} \). In the case of strong resonance, the spin diffusion also depends on the decrement \( \Lambda \), the parameter of radiation damping. While passing
the resonant region \( |\xi| \sim |w_k| \) at \( \omega_0 |w_k| \gg \Lambda \), due to
radiation diffusion and damping, the depolarization time
reaches the minimum value of \( \tau_d \sim \Lambda^{-1} \sim 100 \text{ ms} \) [11].
The estimates given in [12] allow us to conclude that the
adiabatic crossing of the forth spin resonance in VEPP-
4M will lead to a notable loss of beam polarization.

III. SPIN KINEMATICS AT KEDR DETECTOR FIELD DECOMPENSATION

A simple approach to preserve the VEPP-4M beam po-
larization in the conditions under consideration was pro-
posed and numerically substantiated in [12] and then suc-
cessfully implemented in the experiment [13]. It is based
on the well-known idea of a partial Siberian snake [14].

If one switches off the current in the anti-solenoid coils, the
0.6 Tesla KEDR detector longitudinal magnetic field
integral becomes uncompensated, which results in the rotation of the spin around the velocity through an angle $\varphi$. In particular, $\varphi \approx 0.34$ rad at $E = 1.75$ GeV.

![FIG. 3. Two cases of the spin kinematics at $\nu = \text{integer}$. a) There is no a preferable direction of the spin polarization in an ideal storage ring with a flat orbit. b) There is a dynamically stable vector $\vec{n}$, the periodical precession axis, when an arbitrary solenoid is introduced.](image)

In our experiment, there is an intersection of some combination spin resonances $\nu_0 \approx \nu = \nu_k$, which depend on the betatron tunes $\nu_x = 8.536$ and $\nu_z = 7.572$.}

The equilibrium polarization axis as a function of the azimuth $\vartheta$ in a storage ring having at $\vartheta = 0$ an insertion with longitudinal magnetic field is calculated using the known formulae [15] [16]:

$$
\begin{align*}
n_x(\vartheta) &= \pm \frac{\sin \nu (\vartheta - \pi)}{\sin \xi} \cdot \sin \frac{\varphi}{2}, \\
n_y(\vartheta) &= \pm \frac{\cos \nu (\vartheta - \pi)}{\sin \xi} \cdot \sin \frac{\varphi}{2}, \\
n_z(\vartheta) &= \pm \frac{\sin \pi \nu}{\sin \xi} \cdot \cos \frac{\varphi}{2} \\
\sin \xi &= \sqrt{1 - \cos^2 \pi \nu \cos^2 \frac{\varphi}{2}}.
\end{align*}
$$

Here

$$
\varphi \approx \frac{\pi}{4.6 \nu} \cdot \int H_{||} |ds|
$$

is the angle of electron spin rotation in the longitudinal magnetic field with the integral of $\int H_{||} |ds|$ in Tesla-meter. The symbols $x, y,$ and $z$ denote the horizontal, longitudinal, and vertical orts of the movable coordinate basis, respectively. We use an approximation of an isomagnetic storage ring in which the azimuth $\vartheta$ equals the angle of the particle velocity rotation. The effective spin precession tune is determined from the equation

$$
\cos \pi \nu_0 = \cos \pi \nu \cos \frac{\varphi}{2}.
$$

In our case, $\int H_{||} |ds| = H_{KEDR} \cdot L_{eff}$, where $H_{KEDR} = 0.6$ Tesla, the KEDR detector field; the effective KEDR solenoid length $L_{eff} = 3.3$ m if the anti-solenoids are switched off. Fig. 3 shows the calculated spin tune shift $|\nu_0 - \nu| \propto \Delta E$ versus the beam energy at full decompensation. This shift is about $\Delta E = 22$ MeV in the vicinity of the critical energy 1763 MeV.

![FIG. 4. Spin tune shift in the energy units vs. the beam energy in the cases of no and full decompensation of the KEDR detector field integral of 0.6 $\times$ 3.3 Tesla$\times$meter.](image)

IV. COMBINATION SPIN RESONANCES

In our experiment, there is an intersection of some combination spin resonances $\nu_0 \approx \nu = \nu_k$, which depend on the betatron tunes $\nu_x = 8.536$ and $\nu_z = 7.572$.}
Because of the relatively narrow range of energy adjustment, the main spin-betatron resonances \( \nu \pm \nu_z = k_z \) and \( \nu \pm k_x \) did not fall into it. According to the results of the experiment, it can be argued that the subsequent weaker resonances \( \nu + \nu_z - \nu_z = 20 \) (1715 MeV) and \( \nu - \nu_z - \nu_z = -12 \) (1810.2 MeV) were successfully crossed. To comment on this, we estimate the amplitude of the harmonic of the spin resonances of the \( \nu \pm \nu_z \pm \nu_z = k_{xz} \) type by the formula

\[
|w_{k_{xz}}| \sim |\langle \nu h \sqrt{\sigma_x \sigma_z} F' e^{i\nu x + (\nu_z + \nu_z \mp k_{xz}) t} \rangle| \sim 10^{-5}.
\]

Here, \( h = \partial^2 H_z / \partial x^2 \) is the quadratic non-linearity due to the sextupole correction (in the units of the mean field \( \langle H_z \rangle \); \( \sigma_x \) and \( \sigma_z \) are the transverse beam sizes; \( \mu_{x,z} \) are the betatron phase advances; \( \langle \ldots \rangle \) is averaging over azimuth; \( F' \) is the periodic spin response function [8]. The function \( F' \) takes into account the depolarization effect of vertical betatron oscillations excited by any local perturbation. The results of the calculation of this characteristic for VEPP-4M are given, for example, in [17]. Fast crossing of such weak resonances becomes possible, starting from the very low rates of change in the energy: \( dE/dt \gg 10 \) eV/s.

V. RADIATIVE DEPOLARIZATION RATE DURING ACCELERATION

The characteristic time \( \tau_d \) of the radiative depolarization due to quantum fluctuations in the presence of a strong perturbation in the form of the KEDR detector longitudinal field can be found from the generalized equation [19]:

\[
\tau_d \approx \frac{\tau_p}{\left( 1 - \frac{2}{3} \left( \bar{n} \bar{\beta} \right)^2 + \frac{11}{18} \beta^2 \right)^2}.
\]  
(5)

Here \( \tau_p \) is the Sokolov-Ternov polarization time (it is proportional to \( E^{-5} \) and amounts to 72 h at the VEPP-4M energy of 1.85 GeV); \( \beta^2 \) is the square of the periodical spin-orbit coupling vector function of the azimuth. In our case, the spin-orbit coupling is excited by the uncompensated part of the KEDR field integral. It can be found as the derivative of vector \( \vec{d} \) with respect to the Lorentz-factor \( \gamma \) of particles [16]:

\[
d_x = \gamma \frac{\partial n_x}{\partial \gamma} = \pm \left\{ F \sin \nu(\vartheta - \pi) \sin \frac{\varphi}{2} + \frac{1}{\sin \xi} \right\} \\
d_y = \gamma \frac{\partial n_y}{\partial \gamma} = \mp \left\{ F \cos \nu(\vartheta - \pi) \sin \frac{\varphi}{2} + \frac{1}{\sin \xi} \right\} \\
d_z = \gamma \frac{\partial n_z}{\partial \gamma} = \mp \left\{ F \sin \pi \nu \cos \frac{\varphi}{2} + \frac{1}{\sin \xi} \right\}
\]

(6)

\[
F = \frac{1}{2 \sin^3 \xi} \left[ \pi \nu \sin 2 \pi \nu \cos^2 \frac{\varphi}{2} - \frac{\varphi}{2} \sin \varphi \cos^2 \pi \nu \right].
\]

Formula [5] is valid outside of spin resonances. We use it together with set of equations [6] to calculate the radiative diffusion of polarization during acceleration, since in the presence of a solenoid, the effective spin precession frequency does not take integer values.

Another contribution to the spin-orbit coupling is given by the betatron oscillations excited by quantum fluctuations. In consideration of various cases with spin rotators based on solenoids, the contribution of betatron oscillations far from the spin-betatron resonances to the depolarization rate is small as compared with the effect of the dependence of the polarization axis \( \vec{n} \) on the energy [16, 18, 19]. By this reason we neglect the betatron oscillations.

The depolarization time is calculated using formulas [5,6] and plotted in Fig. 5 versus the beam energy at 100% and 50% decompensation of the KEDR field integral. The minimum depolarization time \( \tau_d = 20 \) s. The width of the energy area where \( 20 < \tau_d < 100 \) s is about 30 MeV. It takes about 30 s to cross this area at a nominal rate of energy change \( dE/dt = 1 \) MeV/s.

At 1810 MeV, the time \( \tau_d \) becomes long enough, 2000 s. This gives a chance to measure the energy from the spin frequency using the RD technique after the end of the acceleration process, followed by the restoration of the field in the anti-solenoids.

The theoretical behavior of the polarization degree during acceleration from the injection ("advance") energy \( E = 1650 \) MeV is shown in Fig. 6 for two values of the acceleration rate. The current value of the degree in the
units of the initial one \((P_0)\) is calculated from the equation

\[
P = P_0 \approx \exp \left[ - \int_{E_1}^{E_2} \frac{dE}{(dE/dt) \cdot \tau_d} \right].
\]

It is seen that it is advantageous to apply the full decompensation of the KEDR field and perform acceleration with a rate not below 2 MeV/s. In the best case, it can provide about 80% of the initial polarization degree in the final state. RD calibration of the beam energy should be performed only after restoration of the anti-solenoid field, which leads to the elimination of the spin tuning shift, and with it a systematic error in the energy value. Moreover, the polarization lifetime increases manifold if the KEDR field is compensated.

**VI. COMPENSATION OF BETATRON COUPLING FROM KEDR FIELD**

If the anti-solenoids are switched off, the special measures are needed to provide the relevant alternative operation modes of VEPP-4M. It is convenient to use the scheme of betatron coupling localization by K.Steffen [20], which includes two skew quadrupole lenses (Fig. 7). This scheme has already been successfully tested at VEPP-4M [21, 22].

The transport matrix for the vector of betatron variables \((x, x', z, z')\) in the section from the skew lens \(SQ_+\) to \(SQ_-\) including KEDR can be approximately written as

\[
M = Q_- \cdot M_- \cdot M_s \cdot L^2 \cdot M_s \cdot M_+ \cdot Q_+.
\]

Here \(Q_{\pm}\) are the ‘thin’ skew quad matrices; \(L\) is the empty section matrix for the length \(l = L_s/4\); \(L_s = 3.3\) m is the effective length of the KEDR main solenoid \((L_s = 2.5\) m when the anti-solenoids are switched on); \(M_s\) is the half-solenoid matrix in the ‘thin magnet’ approximation \((\chi = \varphi/2)\):

\[
M_s = \begin{pmatrix}
1 & 0 & -\chi & 0 \\
0 & 1 & 0 & -\chi \\
\chi & 0 & 1 & 0 \\
0 & \chi & 0 & 1
\end{pmatrix};
\]

\(M_{\pm}\) are the matrices for transformation from the center of the right (left) half of the KEDR solenoid to the corresponding skew quad. The skewquads are placed symmetrically relative to the solenoid in the ‘magic’ azimuths, for which some elements of the matrix \(M\) exactly or approximately satisfy a certain equation. The strengths of the \(SQ_{\pm}\) lenses are found from another equation, proportional to \(\chi\), similar in value, and opposite in sign. If we set these found skew quad strengths, then the matrix \(M\) will not contain the off-diagonal (coupling) 2x2 blocks or will be close to such kind. The simplicity of the scheme is based on the mirror symmetry of the magnetic structure in the section with the solenoid. The betatron coupling is localized in this section. The vertical and horizontal oscillations excited beyond the section are mutually independent within the accuracy of the compensation scheme design and realization. The scheme provides a minimum split of the normal betatron mode frequencies of the order of \(10^{-3}\) (in the units of the revolution frequency). If no compensation is applied, this split achieves 0.1, and this hampers sustainable maintenance of the beam during acceleration.

**VII. TOUSCHEK POLARIMETER**

To observe the beam polarization, a system of absolute calibration of the beam energy by the frequency of the spin precession was used [23, 24]. The system includes
the Touschek polarimeter, based on the IBS (Intra-Beam-Scattering) effect, and the TEM wave-based depolarizer. The polarimeter consists of eight plastic scintillator counters, pushed inside the accelerator vacuum chamber to register the particles scattered from the beam (Fig. 1). The rate of counting IBS events depends on the square of beam polarization. To eliminate the influence of the depolarization jump is determined by the square of beam polarization breaking, a jump occurs in the rate of counting the Touschek electrons. The magnitude of the depolarizer frequency, associated with the jump, reaches the accuracy of determination of the particle energy from the count rates from the polarized bunch and unpolarized bunches; \( \delta f(t) = f_{\text{pol}}/f_{\text{unpol}} - 1 \) is calculated. These experimental data are fitted using the following formulae, which are a solution to (7):

\[
\begin{align*}
\frac{dN}{dt} &= \frac{1}{\tau_{\text{tsh}}} N^2(t) V(0) \left( 1 - \delta(t) \right) + \frac{N(t)}{\tau_{\text{bg}}}.
\end{align*}
\]

Here, the first term corresponds to the IBS and \( \tau_{\text{tsh}} \) is the characteristic Touschek beam lifetime; the second term with \( \tau_{\text{bg}} \), the characteristic background lifetime, describes background scattering on the residual gas; \( \delta(t) \) is the polarization contribution to IBS, proportional to the square of the degree of polarization; \( V(t) \) is the beam volume.

During the experiment, the beam volume \( V \) (more precisely, the transverse beam sizes because it is assumed that the longitudinal size varies slightly), the beam currents \( I_{\text{pol}}, I_{\text{unpol}} \) and the count rates \( f_{\text{pol}}, f_{\text{unpol}} \) for the first (polarized) and the second (unpolarized) bunches are measured. The relative count rate difference \( \delta f(t) = f_{\text{pol}}/f_{\text{unpol}} - 1 \) is calculated. Experimental data are fitted using the following formulae, which are a solution to (7):

\[
\begin{align*}
I_{\text{t}}(t) &= \frac{p_{\text{tsh}}}{\tau_{\text{tsh}}} \frac{I_{\text{pol}}}{I_{\text{unpol}}} \left[ 1 + \alpha V I_{\text{pol}}(0) \left( 1 - \delta_1(t) \right) + \frac{p_{\text{bg}}}{\tau_{\text{bg}}} I_{\text{t}}(t) \right] \\
V(t) &= V_0 \left( 1 + \frac{\alpha V}{2} (I_1(t) + I_2(t)) \right) \\
\delta f(t) &= \frac{f_{\text{pol}}}{f_{\text{unpol}}} - 1 \approx -\epsilon(t,1) e^{-t/\tau_{\text{tsh}}} \left( \delta_{\text{pol}}(t) - \delta_{\text{unpol}}(t) \right) + \\
&\quad + \epsilon(t,2) \left( \delta N + \int_0^t e^{-t'/\tau_{\text{tsh}}} \frac{\delta_{\text{pol}}(t) - \delta_{\text{unpol}}(t)}{\tau_{\text{tsh}}} \right) dt/\tau_{\text{tsh}}.
\end{align*}
\]

Here, the index \( i \) marks the polarized and unpolarized bunches; \( \epsilon(t,j) \) is the factor taking into account the relative probabilities \( p_{\text{tsh}} \) and \( p_{\text{bg}} \) of registration of the Touschek particles and the beam particles scattered by the residual gas, respectively:

\[
\epsilon(t,j) = \left[ \frac{p_{\text{bg}}}{p_{\text{tsh}}} \left( 1 + \frac{\tau_{\text{tsh}}}{\tau_{\text{bg}}} \right) + \left( j - \frac{p_{\text{bg}}}{p_{\text{tsh}}} \right) e^{-t/\tau_{\text{bg}}} \right]^{-1};
\]

\( e_{f_0} \) is the current of a single electron; \( \delta N = I_{\text{pol}}(0)/I_{\text{unpol}}(0) - 1 \) is the relative difference in the particle population of the bunches. We introduce a time-dependent correction \( \delta V(t) \) to the volume of bunches,
using its dependence on the current in the linear approximation:

\[
\delta V(t) = \alpha V (I(t) - I(0)) \approx \\
\approx -\alpha V I(0) \left(1 - e^{-t/\tau_{pe}}\right) \left(\tau_{sh} + \tau_{bg}\right). 
\]

(9)

After the end of the acceleration process, the state of polarization of both bunches changes with time. In this connection, their polarization contributions to the rate of counting the Touschek particles are described by the equations

\[
\delta_{pol}(t) = \eta \left[P e^{-t/\tau_{d}} + P_{\infty} (1 - e^{-t/\tau_{d}})\right]^2, \\
\delta_{unpol}(t) = \eta \left[P_{\infty} (1 - e^{-t/\tau_{d}})\right]^2. 
\]

(10)

Here, \(\eta\) is the Touschek polarization factor; \(\tau_{d}\) is the radiative depolarization time; \(P\) is the residual degree of polarization of the polarized bunch at the end of acceleration, and \(P_{\infty} = (8 \sqrt{3}/15) \tau_{d}/\tau_{p} \approx 4 \cdot 10^{-3}\) is the equilibrium polarization degree at \(t \to \infty\).

The following free parameters are used for the fitting: \(\Delta = \eta P^2 \approx 1\%\) is the polarization Touschek effect; \(\tau_{d}\) is the polarization life time, which is an object of interest; \(\tau_{sh} \approx 8000\) s is the Touschek life time; \(\tau_{bg} \approx 30000\) s is the background life time; \(p_{sh} \approx 0.2\) is the relative probability of registration of Touschek particles; \(p_{bg} \approx 0.05\) is the relative probability of registration of particles scattered by the residual gas; \(I_{pol}(0) \approx I_{unpol}(0) \approx 2\) mA are the initial currents of the first and second bunches, respectively; \(V_0\) is the initial beam volume; \(\alpha V \approx 0.1\% / \text{mA}\) is the coefficient of dependence of the beam volume on the beam current.

Time evolution of the measured quantity \(\delta f(t)\) in the conditions when the acceleration to the target energy was just done, but the compensating solenoids stay switched off can be described as follows. At the 'advance energy', the ratio of the bunch currents is adjusted to a level of \(\delta N \approx 1 \div 2\%\) because of the necessity to minimize the slope of the dependence \(\delta f(t)\) as a whole and the associated systematic error. For this purpose, we kick out portion by portion the redundant bunch particles using the VEPP-4M inflector. If the bunch current ratio mentioned above is provided, then \(\delta f(t) > 0\) during all the time of observation. The depolarization process is enhanced during crossing of the critical energy area and goes on after completion of the acceleration to the target energy. By this reason, the quantity \(\delta f(t)\) grows somewhat exponentially in the positive direction. The characteristic time of this growth for a given target energy is calculated (see Fig. 5). The polarization in the beam drops to zero and then another process becomes dominating — relaxation due to the difference in the bunch currents. Because of the difference in the IBS beam lifetime, the quantity \(\delta f(t)\) begins to change in the negative direction. Asymptotically, it goes to zero.

VIII. EXPERIMENTAL RESULTS

One of the RD beam energy calibrations in the 'advance energy' mode is presented in Fig. 8a. Basing on these data, one can get an idea of the magnitude of the polarization effect measured with the Touschek polarimeter. The time allotted for the radiative polarization at the VEPP-3 booster ring at the energy \(E = 1.65\) GeV was 5000 \(\pm\) 6000 s at the estimated characteristic time of polarization \(\tau_p \approx 4000\) s. On average, the depolarization jump on the 'advance' energy was \(\Delta_0 = 0.99 \pm 0.15\%\).

\[
\frac{f_{pol}}{f_{unpol}} - 1 \\
\Delta_0 = 0.89 \pm 0.02\% \\
E = 1655.228 \pm 0.001\text{ MeV}
\]

(a)

\[
\frac{f_{pol}}{f_{unpol}} - 1 \\
\Delta = 0.63 \pm 0.05\% \\
E = 1808.985 \pm 0.025\text{ MeV}
\]

(b)

FIG. 8. Depolarization jumps in two typical scans of the depolarizer frequency: at the advance energy 1655 MeV (a), i.e. before acceleration, and at the target energy 1809 MeV after acceleration with a rate of 2.4 MeV/s (b). In the second case, before scanning, the compensatory solenoid field was restored in 385 s. Each graph additionally shows the values of the measured depolarization jump and the beam energy, as well as the corresponding errors.

First of all, the effectiveness of the method was verified by observing the process of beam polarization relaxation (depolarization) after the acceleration at the point \(E = 1.81\) GeV was completed, but the anti-solenoids remained switched off. The observed relaxation may indicate that
the polarization in the beam is conserved by the end of the acceleration. The time evolution of the normalized Touschek electron counting rate is shown in Fig. 9. In accordance with (7), the fit of the experimental points takes into account the contributions of two processes. One is the radiative depolarization with the characteristic time $\tau_d$. The other is the relaxation because of the Touschek losses of particles provided that the polarized and unpolarized bunches are not equal in population. In the limit, the observed characteristic $f_{\text{pol}} / f_{\text{unpol}} - 1$ tends to zero due to the natural leveling of the bunches. Qualitatively, the relaxation process proceeds as described in the previous section. The relaxation (depolarization) time $\tau_d = 1470 \pm 120$ s determined from the data in Fig. 9 is in good agreement with the estimated time of about 1400 s (see Fig. 5).

![Graph showing the process of beam polarization relaxation following the acceleration from the 'advance' energy up to 1806 MeV with a rate of 5 MeV/s. The compensatory solenoids remain switched off. In the time diagram of the ratio of the IBS rates in the polarized bunch and unpolarized one, differing in the number of particles, two stages are clearly distinguished.](image)

FIG. 9. The process of beam polarization relaxation following the acceleration from the ‘advance’ energy up to 1806 MeV with a rate of 5 MeV/s. The compensatory solenoids remain switched off. In the time diagram of the ratio of the IBS rates in the polarized bunch and unpolarized one, differing in the number of particles, two stages are clearly distinguished.

The fact of beam polarization preservation has been fully confirmed in the runs on the beam energy measurement by the resonant depolarization technique applied after the acceleration (Fig. 5).

In contrast to the ‘spin relaxation’ runs, the storage ring mode with the anti-solenoid field switched on was restored before every start of the RD procedure. This measure stops the non-resonant (radiative) depolarization process related to the contribution of strong longitudinal magnetic fields to the spin-orbit coupling. An additional time of 385 s was required to restore the anti-solenoid field and, concurrently, to make necessary corrections to the collider magnetic structure. In accordance with the calculation, if the acceleration stops at 1810 MeV with $P/P_0 = 0.84$, then the relative degree falls down to 0.77 in 385 s. In general, the estimated degradation of the depolarization jump $\Delta \sim P^2$ is $(P/P_0)^2 \approx 0.6$ in magnitude.

At the same time, the square root of the ratio of depolarization jumps measured in several runs before and after acceleration is $\sqrt{\Delta / \Delta_0} \approx 0.76 \pm 0.12$. Taking into account the above additional degradation of polarization during the anti-solenoid field recovery time, the result of the experiment to intersect an imperfection spin resonance at a rate of 2.4 MeV/s is characterized by the degree of polarization conservation $P/P_0 = 0.83 \pm 0.13$. Comparing all data in Fig. 9, one can conclude that the experiment and the calculation are in satisfactory quantitative agreement.

**IX. DISCUSSION**

The Partial Siberian Snake technique was first tested with protons at IUCF [29] and is currently used in routine operation of BNL’s AGS [30]. The specificity of its application to electron-positron storage rings is the additional complication associated with the depolarizing effect of synchrotron radiation.

Prior to our experiment at VEPP-4M, only one similar experiment was conducted, at VEPP-2M [31]. The radiative polarization was carried out at 600 MeV. Then the beam energy was lowered to 380 MeV. The polarization was preserved due to the adiabatic crossing of the integer spin resonance at 440 MeV ($\nu = 1$) at a rate of 10 MeV/s using a solenoid described in [14]. In our opinion, [31] and our work differ substantially in analysis of the experiment conditions. In [31], the authors considered the adiabatic condition as decisive. It was briefly noted that the criterion for high-rate crossing in relative to the rate of radiative depolarization was satisfied. At the same time, no attention was paid to the fact of the significant spin tune shift. For the parameters of the solenoid at VEPP-2M, the angle of spin rotation in it could be 0.2 radians. This yields a shift from the integer resonance of about 12 MeV. Neither rigorous estimate of the radiative depolarization rate taking into account changes of an equilibrium polarization direction, nor its comparison with the experiment was made.

An interesting experiment [32] on the acceleration of polarized electrons from 1.2 to 3.5 GeV without using the partial Siberian snake method was performed on the ELSA (Bonn Electron Stretcher Accelerator). The polarization was measured in the extracted beams using the Moeller polarimeter, which is sensitive to the sign of polarization. The ramping rate was varied between 0.1 and 7 GeV/s, which is orders of magnitude greater than rate possible with the non-laminated magnets at VEPP-4M. The polarization was preserved at acceleration up to 1.9 GeV in the spin-flip (adiabatic) mode with respect to the imperfection resonance crossing. According to the data presented, in ELSA this should take place in the working range of the ramping rate from 0.1 to 5 GeV/s. In contrast to our case, due to the much higher ramping rate, the difficulties in maintaining the polarization in the adiabatic mode, caused by the influence of radiation and noted in section II, could be avoided.
The complete Siberian Snake technique ($\varphi = \pi$) requires a much greater integral of magnetic field: $4.6\nu$ Tesla\times meter. The corresponding spin tune shift is 1/2, or about 220 MeV. Thus, the detuning from the integer spin resonances is maximum at any energy. The radiative depolarization factor is approximately $\tau_p/\tau_d \approx (11/54)\pi^2\nu^2$. With approaching to integer spin resonances, the Partial Siberian Snake solenoid ($\varphi \ll 1$) yields stronger spin-orbit coupling than the Siberian Snake solenoid does. In accordance with (5) and (6), the ratio of the respective depolarization times is ($\nu = k$)

$$\frac{\tau_d(\varphi = \pi)}{\tau_d(\varphi \ll 1)} \approx \frac{12}{\varphi^2}.$$ 

In the VEPP-4M experiment, the longitudinal field integral is $0.6 \times 3.3 \approx 2$ Tesla\times meter against 18.4 Tesla\times meter in the Siberian Snake option. The ratio of the depolarization times is about 102: $\tau_d(\varphi = \pi) = 2.7$ h and $\tau_d(\varphi = 0.34 \text{ rad}) = 97$ s. With the distance from the integer resonance, the ratio of the relaxation times for the cases of strong and weak solenoids is reversed in a qualitative sense. To see this, compare, for example, the curves in Fig.5 for the 50% and 100% decompensation of the detector field. As applied to our case, a complete Siberian snake could be better since it eliminates all possible spin resonances and has a much smaller depolarizing effect at the resonance energy. At the same time, economically, the method based on decompensation of the longitudinal field of the detector cost us nothing. With its help we easily solved the practical problem that arose during our experiment on high energy physics.

At VEPP-4M, the radiative depolarization can limit the effectiveness of the method developed with growth of the target beam energy. Estimates show that it is possible to intersect the third resonance $E = 1322$ MeV practically without polarization loss during beam deceleration with a rate of 2 MeV/s starting from 1550 MeV. However, acceleration in the same manner from 1.85 GeV up to 2.4 GeV, while crossing the fifth resonance $E = 2203$ MeV, will lead to a three-fold decrease in the polarization degree. In this case, we plan to increase the ramping rate to $10 \div 20$ MeV per second. In addition, it will be necessary to study the possibilities of crossing the resonances $3 - \nu_{x,z}$, $4 + \nu_{x,z}$ and $5 - \nu_{x,z}$ falling within the specified ranges.

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