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METHOD FOR PRESERVING THE VEPP-4M
ELECTRON BEAM POLARIZATION
DURING ACCELERATION INCLUDING CROSSING
THE INTEGER SPIN RESONANCE ENERGY

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**Method for preserving
the VEPP-4M electron beam polarization
during acceleration including crossing
the integer spin resonance energy**

Sergei A. Nikitin

Abstract

In the experiment on the Hadron-Muon Branching Ratio measurement with the KEDR magnetic detector at the electron-positron collider VEPP-4M the beam energy calibration in the region 1.55 – 1.85 GeV is performed using the resonant depolarization technique. Beam polarization is obtained owing to the radiative mechanism in the booster storage ring VEPP-3. The critical feature is a necessity to accelerate additionally a polarized beam in the collider ring after injection crossing the energy value of 1763 MeV corresponding to the integer spin resonance. The method is proposed to preserve the beam polarization in the given conditions based on full decompensation of the 0.6×2.5 Tesla \times meter integral of the KEDR longitudinal magnetic field that means the acceleration with the anti-solenoids switch off.

**Метод сохранения поляризации электронного пучка ВЭПП-4М
при ускорении с пересечением энергии
целого спинового резонанса**

С.А. Никитин

Аннотация

В эксперименте по измерению отношения сечений рождения адронов и мюонных пар магнитным детектором КЕДР на электрон-позитронном коллайдере ВЭПП-4М энергия пучков в области 1.55-1.85 ГэВ калибруется методом резонансной деполяризации. Поляризация пучка осуществляется благодаря радиационному механизму в бустерном накопителе ВЭПП-3. Критической особенностью является необходимость дополнительно ускорять поляризованный пучок в кольце коллайдера после инжекции с пересечением значения энергии 1763 МэВ, отвечающего целому спиновому резонансу. Предложен метод для сохранения поляризации пучка в данных условиях, основанный на полной декомпенсации интеграла продольного магнитного поля детектора КЕДР величиной 0.6×2.5 Тесла \times метр за счет выключения анти-соленоидов.

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1. Introduction

Set of the beam energy values in the Hadron-Muon Branching Ratio measurement with the KEDR detector [1] at the electron-positron VEPP-M collider [2] in the region between J/Psi and Psi' resonances includes the several critical points. In particular, $E = 1764$ и $E = 1814$ МэВ. Beam energy calibration in this experiment is performed with the resonant depolarization technique (RD) so the polarized beams are needed. Polarization is obtained due to the radiative mechanism in the VEPP-3 booster storage ring. Both mentioned energy values are in the so-called 'Polarization Downfall' – the range of the VEPP-3 energy range of the approximately 160 MeV width where obtaining the polarization of a fairly high degree is significantly hampered because of strong depolarization effect of the guide field imperfections. The "Polarization Downfall" range was revealed in the 2003 year experiment with the polarimeter based on the internal polarized target [3].

The center of that critical range is the energy value $E_4 = 1763$ MeV which responds to the integer spin resonance $\nu = \nu_k = 4$ (in the conventional storage rings the $\nu = \gamma a$ is the spin tune parameter equal to a number of the spin vector precessions about the vertical guide field axis per a turn subtracting one; γ is the Lorentz factor; $a = (g - 2)/2$). Nevertheless, one can obtain the polarized beams in VEPP-4M with energies from the 'Polarization Downfall' excepting a small island in the vicinity of E_4 if using the method of 'auxiliary energy point' (which is similar to some extent to the military aviation term 'auxiliary airfield'). In the given experiment the magnetization cycle of the collider is of the 'upper' type. It means that the 'auxiliary energy points' should be below the energies of experiment as well as below 1660 MeV taking into account the 'Polarization Downfall' region lower boundary. In the cases when the method is valid the beam polarization in VEPP-3 is achieved at the 'auxiliary energy'. Then the beam is injected into the collider ring. After that its energy is raised to the energy of experiment. Radiative spin relaxation time in the collider ring is two orders larger than that in the booster (at $E = 1.85$ GeV $\tau_p = 70$ h in VEPP-4M and $\tau_p \cong 0.5$ h in VEPP-3). This allows us to use the beam polarization in the RD energy calibration procedures even at rather small detuning from the dangerous spin resonances. For instance, the RD calibrations of the beam energy in the tau-lepton mass measurement experiment [4] at energies close to the tau production threshold ($E = 1777$ MeV) were being performed with a delay of about half an hour after injection of the beam at the detuning $\delta\nu \approx 0.03$ ($\Delta E \approx 13$ MeV in the energy scale) and less from the resonance $\nu_k = 4$.

In the case under consideration one can apply the described method in the energy points below 1763 MeV at the detuning of $\Delta E \approx (9 \div 13)$ MeV as was in the tau mass measurement experiment. But there are the special additional measures needed for the point $E = 1814$ MeV and, apparently, for the points somewhat below the Psi' peak energy (for example. 1839 MeV), The reason is a necessity to cross the integer spin resonance at 1763 MeV during acceleration starting from the 'auxiliary energy'.

2. Estimate of possibilities for fast and slow crossing of the spin resonance

Fast change of the beam energy in a storage ring (during acceleration or deceleration) enables the polarization of particles to be preserved when crossing any spin resonance $\nu_0 = \nu_k$ (in a general case the spin tune ν_0 is not coincident with the definition given above for the storage rings with an unidirectional guide field) if the following condition is fulfilled [5]:

$$\frac{d\varepsilon}{dt} = \dot{\varepsilon} \gg |w_k|^2 \omega_0, \quad (1)$$

$\varepsilon(t) = |\nu_0(t) - \nu_k|$ is a time-dependent resonant detuning; w_k is a resonant harmonic amplitude of the field perturbations; ω_0 is an angular frequency of particle revolution. For instance, in the tau-mass measurement experiment the rate of change of the detuning while the beam energy lowering down to the tau-production threshold was $dE/dt \approx 1$ MeV/s or $\dot{\varepsilon} \approx 2.3 \times 10^{-3} \text{ s}^{-1}$.

Since the intersection of the combination spin resonances, $\nu_k + m\nu_x + n\nu_z = k$; $m, n_z = \pm 1, \pm 2, \dots$, with consideration of the betatron tunes, was successful (as proven by the fact of the RD energy calibrations in the final state), then the likely power of each of these minor resonances was significantly less than the amount $|w_k| \sim 2 \times 10^{-5}$ ($\omega_0 = 2\pi \times 8.19 \times 10^5$ rad/s). Data on measurement of the polarization lifetime (τ_d) at the tau-threshold gives an information about the natural power of the spin resonance $\nu_k = 4$. Minimal value of this time was fixed at the level of 1000 sec at 1777 MeV. (The tau mass measurement experiment at VEPP-4M-KEDR was performed in the conditions when the polarization lifetime was adjusted to the level of about 1 hour [3]). One can associate this quantity with the formal estimate of the resonant spin harmonic amplitude using the known equation [8, 9]

$$\tau_d \approx \tau_p / \left(1 + \frac{11}{18} \frac{|w_k|^2 v^2}{\varepsilon^4} \right), \quad (2)$$

where $\nu_0 - 4 = \varepsilon \ll 1$ (it is assumed that the KEDR field integral is fully compensated with the help of the anti-solenoids). Taking into account the fact that

the Sokolov-Ternov polarization time $\tau_p = 87$ h at $E = 1777$ MeV, we obtain $|w_k| \sim 4.8 \times 10^{-3}$ [2]. Therefore, a maximal necessary rate of the resonance crossing is $\dot{\epsilon} \gg 35 \text{ s}^{-1}$, or, $dE/dt \gg 1.5 \times 10^4$ MeV/s. The similarly large estimate of the rate will be if taking the polarization lifetime larger or about 1 hour which was characterized in the most runs of energy calibrations using RD at the tau-threshold (this time is inversely proportional to $|w_k|^2$). In practice, the maximal rate of the VEPP-4M energy change without the notable losses of particles usually does not exceed 5 MeV/s. So, a fast crossing of the integer spin resonance $E = 1763$ MeV is impossible.

Otherwise, if [5, 6]

$$\dot{\epsilon} \ll |w_k|^2 \omega_0, \quad (3)$$

a spin resonance crossing occurs adiabatically (slowly). Basing on the estimates made above, one can conclude that the rate of energy change of 1 – 10 MeV/s, in principle, may be appropriate. In the theory of adiabatic crossing of the spin resonances the polarization has a chance to survive when (3) is fulfilled and it changes a sign as result of the crossing.

Despite the feasibility of the condition of slow crossing of the resonance, it is necessary to bear in mind that there is a lower limit on the rate of the crossing due to the depolarizing effect of radiative diffusion and friction. Radiative depolarization time related to the vertical closed orbit distortions declines very quick when decreasing the detuning from the integer spin resonance: $\tau_d \propto \epsilon^{-4}$. For example, this time decreases as 16 times at $E = 1770$ MeV comparing with the value $\tau_d = 1$ h at $E = 1777$ MeV. In the case of high power resonance the spin diffusion depends also on a decrement Λ , the parameter of radiative friction [7]. In the resonant area where $|\epsilon| \sim |w_k|$ and in the case $\omega_0 |w_k| \gg \Lambda$, the depolarization time owing to radiative diffusion and friction achieves a minimal value $\tau_d \sim \Lambda^{-1} \sim 100$ msec. The given estimates allows us to infer that an adiabatic crossing the integer spin resonance at $E = 1763$ MeV will result in a loss of the beam polarization.

3. KEDR field decompensation as a means to detune from the spin resonance

Two cases of the polarization kinematics in the storage rings at the energy of an integer spin resonance ($\nu = k$) are clarified in the Fig. 1. If one turns off the current in the anti-solenoid coils, the KEDR detector longitudinal magnetic field integral of 0.6×2.5 Tesla \times meter becomes un-compensated that results in the spin and velocity rotation angle φ in the detector field (in particular, $\varphi = 0.26$ at $E = 1.75$ GeV). This causes a shift of the spin tune with regard to an unperturbed value. The latter is proportional to the beam energy and describes a spin precession in the storage ring with a flat closed orbit.

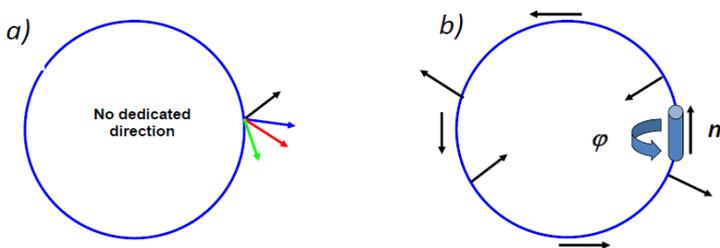


Figure 1. a) In an ideal storage ring with a flat closed orbit there is no the dedicated direction of spin polarization ($\nu = k$). b) If inserting a solenoid of an arbitrary spin rotation angle φ there exists an equilibrium direction of polarization (a vector n) which rotates in a median plane when changing an azimuth and is directed along velocity at the azimuth of solenoid.

Thus, a non-integer part of the perturbed spin frequency ν_0 does not accept a null value in the critical point near $E = 1763$ MeV. This fact is put in foundation of the proposal to preserve the beam polarization during acceleration for the sake of the R-experiment. The solid line in the Fig. 2 is a calculated for this case distance $|\nu_k - \nu_0|$ to the integer resonance $\nu_k = 4$ given in units of energy ($\Delta E = |\nu_k - \nu_0| \times 440.65$ [MeV]) versus the beam energy at the KEDR field $H = 0.6$ Tesla. The dashed curve responds to a conventional dependence of $\nu = \gamma a$ on E which takes a place when the detector field integral is fully compensated with the anti-solenoids.

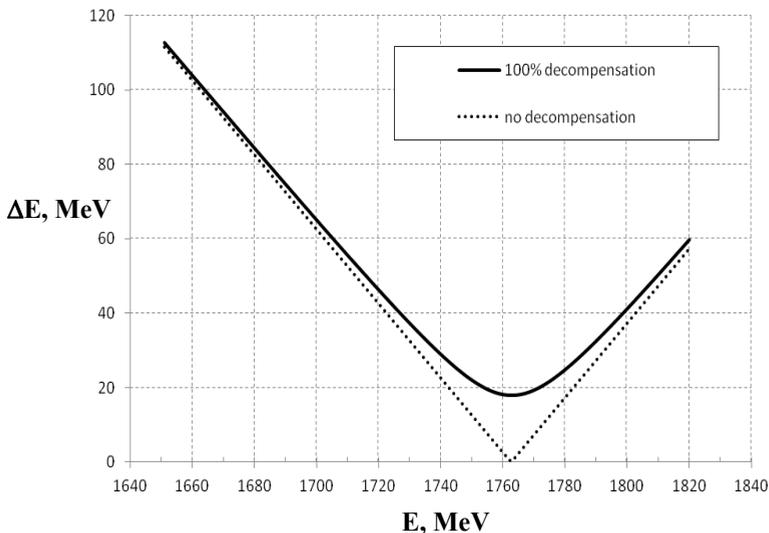


Figure 2. Spin tune shift (in the energy units) as function of the beam energy in the cases of no and full decompensation of the KEDR detector field integral of 0.6×2.5 Tesla \times meter.

The effective spin tune is calculated using an equation (see Appendix)

$$\cos \pi \nu_0 = \cos \pi \nu \cdot \cos(\varphi/2), \quad (4)$$

which follows from a spin kinematics consideration for an arbitrary storage ring with an insertion in the form of a solenoid rotating a spin around the particle velocity vector through an angle of $\varphi \approx \int H_{\parallel} ds/H\rho$ ($H\rho$ is the storage ring ‘rigidity’). The quantity $H_{\parallel}(s)$ describes the longitudinal magnetic field distribution along the detector axis. It is shown from the figure, the spin tune shift makes about $\Delta E \approx 18 \text{ MeV}$ in the vicinity of the critical energy 1763 MeV at a full decompensation that is two times larger than a minimal detuning (9 MeV) which was in the RD calibrations during the tau-mass measurement experiment.

The calculated depolarization time is plotted in Fig. 3 versus the beam energy at the 100% and 50% extent of decompensation of the KEDR field integral. The depolarizing mechanism is based on quantum fluctuations in the presence of a spin-orbit coupling related to the non-compensated longitudinal magnetic field. The formulae used are represented in the Appendix. Minimal depolarization time $\tau_d = 10$ seconds. A width of the energy area where $10 \text{ s} < \tau_d < 100 \text{ s}$ is about 30 MeV. It takes time of about 30 seconds to cross this area at a nominal rate of energy change $dE/dt = 1 \text{ MeV/s}$. See also the curve in Fig. 3 for the case involved the wiggler-magnets (EZM) turned on with a field varying proportionally to the energy and equal to 1.3 Tesla at $E = 1650 \text{ MeV}$.

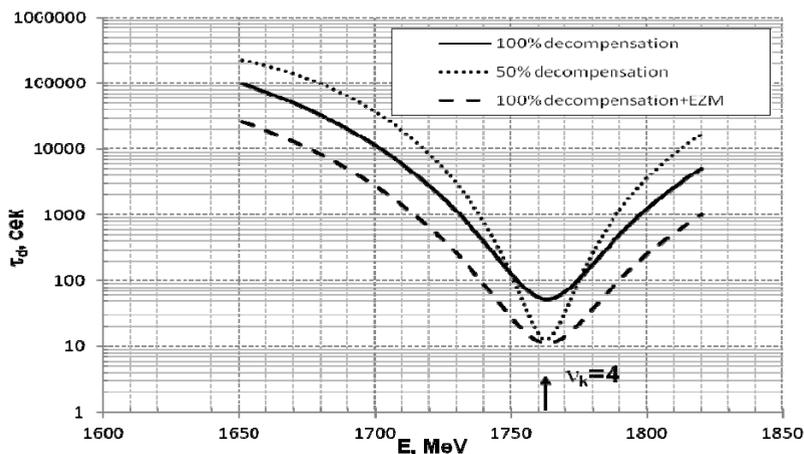


Figure 3. The radiative depolarization time vs. the beam energy under the influence of the 0.6 T KEDR field decompensation.

The result shows that it is almost impossible to have time to check for the presence of polarization, using RD or monitoring by the Touschek polarimeter, when the energy value $E = 1764 \text{ MeV}$ because of the expected fast depolarization

for a time of about 50 seconds. At the energy of 1810 MeV the time τ_d becomes of 3000 seconds. This gives a chance to measure the energy by a spin frequency.

Theoretical behavior of the polarization degree during the process of acceleration beginning from the injection energy $E = 1650$ MeV ('the auxiliary energy') with the use of the described method for the integer spin resonance energy crossing at the expense of the KEDR field decompensation is shown in Fig. 4 for the three cases. The current value of the degree in units of the initial one (P_0) is calculated from the equation

$$\frac{P}{P_0} \approx \exp \left\{ - \int_{E_1}^{E_2} \frac{dE}{(dE/dt) \cdot \tau_d} \right\}. \quad (5)$$

From the calculations it is seen that it is advantageous to apply the full decompensation of the KEDR field and accelerate with a rate not below 2 MeV/sec. (For comparison, braking of a polarized beam in the 80 MeV energy range without crossing the integer spin resonance $E = 1763$ MeV in the experiment on the tau lepton mass measurement at VEPP-4M was carried out with a rate of 1 MeV/sec.) At best, it can provide a 75% final polarization degree related to the initial after crossing the integer spin resonance. Beam energy RD calibration should be performed only after resetting the anti-solenoid field that leads to cancelation of the spin tune shift and, with this, a systematic error in the energy value. Moreover, the polarization lifetime significantly increases if the KEDR field is compensated.

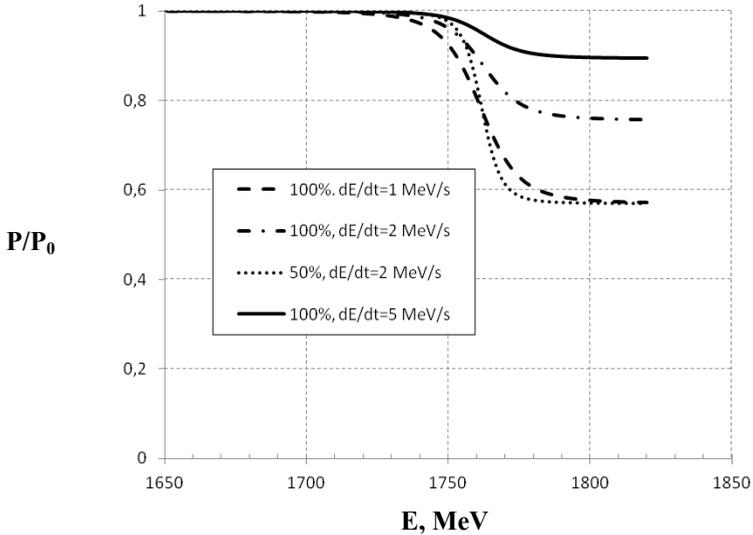


Figure 4. Designed change of the polarization degree related to initial one in a process of beam acceleration at a rate characterized by the parameter dE/dt in the cases of full and half decompensation of the KEDR field.

4. Compensation of the KEDR field influence on betatron coupling using two skew quads

If the anti-solenoids are turned off the special measures are needed to provide the alternative relevant operation modes of VEPP-4M at the beam injection and process of acceleration. In this case, it is convenient to use the scheme of betatron coupling localization proposed by [10] and based on application of two skew quadrupole lenses (rotated through an angle of 45^0) – see Fig. 5.

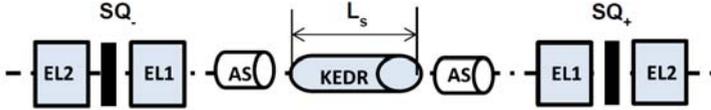


Figure 5. Scheme of compensation of the betatron coupling due to the KEDR main field with the help of two skew quadrupoles (SQ_+ and SQ_-) located near the VEPP-4M Final Focus lenses. Anti-solenoids (AS) are turned off. L_s is an effective length of the KEDR main solenoid.

Earlier the similar schemes were successfully applied at CESR (Cornell Univ., USA) and then at VEPP-4M [11, 12]. (Also it was used by an author for a concept of the cooler solenoid field compensation in the framework of the BINP project of the Carbon Ion Cooler Synchrotron for radiation therapy.)

Transport matrix for the vector of betatron variables (x, x', z, z') at the section from the skew lens SQ_+ to SQ_- with the lengths l_{\pm} including the KEDR can be approximately written as

$$M = Q_- \cdot M_- \cdot M_S \cdot L^2 \cdot M_+ \cdot Q_+, \quad (6)$$

with Q_{\pm} , the ‘‘thin’’ skew quad matrices corresponding to the correction field

strengths $g_{\pm} = \left(\frac{dH_x}{dx} \cdot l \right)_{\pm}$; L , a matrix of the empty section of the length $l = L_s/4$;

M_s , the half-solenoid matrix in the ‘thin magnet’ approximation ($\chi = \varphi/2$):

$$M_s = \begin{pmatrix} 1 & 0 & -\chi & 0 \\ 0 & 1 & 0 & -\chi \\ \chi & 0 & 1 & 0 \\ 0 & \chi & 0 & 1 \end{pmatrix}; \quad (7)$$

M_{\pm} , a matrix for transformation from the solenoid edge to the corresponding skew quads. The latter are placed symmetrically relative to the solenoid at the ‘magic’ azimuths for which some elements of the matrix M strictly or approximately satisfy a certain equation. The skew quad strengths are found from another equation to be proportional to χ , similar in value and opposite in sign ($g_+ = -g_-$). If you set

these found values for the skew quad strengths, then the matrix M will not contain the off-diagonal (coupling) 2×2 blocks or becomes close to such a kind. The simplicity of the scheme is based on the mirror symmetry of the magnetic structure at the section with the solenoid. Betatron coupling is localized at this site. Vertical and horizontal oscillations excited beyond the site are mutually independent with an accuracy the compensation scheme is designed and made. The scheme provides a minimal split of the normal betatron mode frequencies of the order of 10^{-3} (in units of the revolution frequency). If no any compensation applied this split reaches ≈ 0.1 at $H = 0.6$ T, whereby it is very difficult to ensure the normal parameters of the beam, especially its lifetime, during acceleration.

5. Spin kinematics and efficiency of the TEM wave –based depolarizer at switched-off anti-solenoids

Let consider a possibility to test polarization using the RD after completing the acceleration without the subsequent restoration of the anti-solenoid field. Such an approach seems like relevant while taking into account the finite horizon in the polarization lifetime (about 1000 sec) in the vicinity of the target energy (1810 MeV). (At the same time, the RD energy calibration by itself with the 100% KEDR decompensation makes no sense in the R-experiment because of a large spin tune shift, about 3 MeV at 1810 MeV, relative to the unperturbed value, according to the plot in Fig. 2). Time needed to restore a regular mode of the VEPP-4M operation with a full detector field compensation is about of 5 – 10 minutes. It corresponds to a significant polarization loss due to the KEDR decompensation taking into account the depolarization mechanism based on quantum fluctuations. The current VEPP-4M depolarizer with transverse field represents the matched double strip line in the form of plates of $l_d = 40$ cm length connected to the RF generator and mounted inside the vacuum chamber near the quadrupole lens (EL3) at the experimental hall. The plates spaced in vertical plane serve to create a counter-TEM wave.

In normal conditions supposing the vertical beam polarization the magnetic field H_x and the vertical electric field E_z of the depolarizer rotate the spin vector \vec{S} ($|\vec{S}| = 1$) around the X axis in a passage time dt through an angle

$$d\varphi \approx (dS_{\perp})_0 \approx \mu' [H_x(t) + E_z(t)] dt = W_x l_d / c. \quad (8)$$

μ' is the anomalous magnetic moment of electron; $(dS_{\perp})_0$ is a transverse increment of the spin vector ($dS_{\perp} = |d\vec{S}| \ll 1$, $d\vec{S} \cdot \vec{S} = 0$); $\vec{W} = W_x \vec{e}_x$ is an angular frequency of spin precession in the depolarizer field. In the case of small non-correlated increments an average depolarization rate or a rate of change of the spin projection $S_{\vec{n}} = \vec{S} \cdot \vec{n}$ on the dynamically stable polarization direction, the unit \vec{n} -vector, is given by the known equation [5]

$$\frac{d\overline{S_{\vec{n}}}}{dt} = -\frac{1}{2\overline{S_{\vec{n}}}} \frac{d}{dt} (\overline{dS_{\perp}})^2. \quad (9)$$

Notice that the depolarizer rotating a spin excites also the vertical oscillations of a particle over the ring. This leads to the additional spin perturbations due to the guide field gradient in focusing and defocusing magnets. As a whole, the rate of enforced depolarization is proportional to the square of product of the single pass spin rotation angle and the spin response factor depending on the beam energy, the magnetic structure design, the azimuth and the vertical betatron tune [8]. Here we will restrict ourselves to the consideration of the role of only one factor – the single pass rotation. Accounting of a change of the spin response factor in the conditions of the KEDR field decompensation (using, for example, a numerical simulation [13]) is also possible but it is beyond the scope of this article.

The vector \vec{n} in the case under consideration is calculated in the Appendix. Dependence of its longitudinal (n_y) and vertical (n_z) components upon the energy at the depolarizer azimuth (between this azimuth and the azimuth of the KEDR location the velocity vector rotates through an angle of 9° in the median plane) is represented in Fig. 4 (n_x is not shown since it does not matter in the depolarizer TEM wave field in the viewpoint of spin motion). At 1650 MeV (the ‘auxiliary energy point’) the vertical component $n_z \approx 0.1$; at the resonant energy $n_z \approx 0$ and at the target energy $E = 1810$ MeV $n_z \approx 0.1$. The single pass angle of spin rotation is defined by the equation

$$dS_{\perp} = W_x \sqrt{S_z^2 + S_y^2} \approx W_x \sqrt{n_z^2 + n_y^2}. \quad (10)$$

Therefore, the depolarizer efficiency related to its value corresponding to the full compensation with anti-solenoids ($n_z = 1$) can be described by the relation

$$\frac{(dS_{\perp})^2}{(dS_{\perp})_0^2} = \left(\frac{W_x \sqrt{n_z^2 + n_y^2}}{W_x} \right)^2 = n_z^2 + n_y^2. \quad (11)$$

The latter characteristic is plotted as a function of the energy in Fig. 4. Near the resonant energy the efficiency decreases by approximately one-third. But at the target energy 1810 MeV the relative efficiency defined above is close to unity.

Looking at the plots in Fig. 4 one can picture an evolution of the polarization vector during acceleration of the beam injected into the VEPP-4M ring starting from the vertical polarization state. The component n_z at the left margin of the plot determines the initial polarization degree in the units of P_0 , the beam polarization degree at the output from the booster VEPP-3. The acceleration rate of 2–5 MeV/sec is an adiabatic one. So the spins follow the changes of the vector \vec{n} according to the plotted dependence. In particular, the polarization vector lies in the median plane at the resonant energy 1763 MeV.

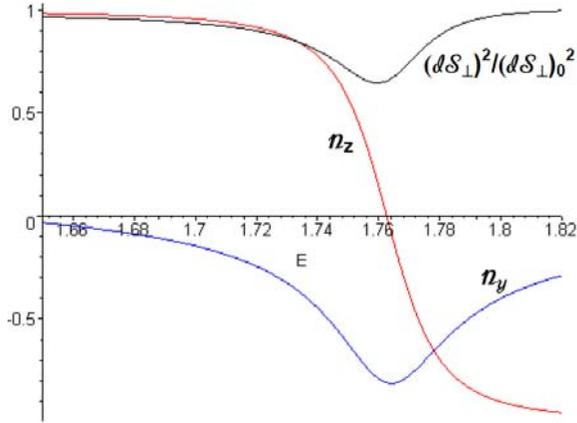


Figure 4. The vector \vec{n} components and the relative depolarizer efficiency vs the beam energy at the KEDR anti-solenoids turned off while the main KEDR field is of 0.6 Tesla.

Fast restoration of the mode with the anti-solenoids switched on just after the acceleration is completed is necessary to make the RD energy calibration when conducting the R-experiment. At the same time one can try to test the polarization preservation equality using the RD also without anti-solenoids activated provided that this procedure is carried out for a relatively short time.

6. Summary

The method is proposed to preserve the electron beam polarization at the VEPP-4M collider during acceleration of the beam with crossing the integer spin resonance energy $E = 1763$ MeV. It is based on full decompensation of the 0.6×2.5 Tesla \times meter integral of the KEDR detector longitudinal magnetic field. The acceleration occurs with the switched off anti-solenoids that are part of the KEDR magnetic system. In such conditions, to compensate strong unacceptable perturbations of the beam betatron parameters the special scheme based on the use of two skew quadrupoles is applied. According to the estimates made in the paper the alternative ways using the fast/slow crossing of the integer spin resonance without any additional external action on the spin kinematics are not effective.

The equilibrium polarization direction as a function of an azimuth in a storage ring containing the insertion with longitudinal magnetic field is calculated using the known formulae [14,15]:

$$\begin{aligned}
 n_x(\theta) &= \pm \frac{\sin \nu(\theta - \pi)}{\sin \xi} \sin \frac{\varphi}{2}, \\
 n_y(\theta) &= \mp \frac{\cos \nu(\theta - \pi)}{\sin \xi} \sin \frac{\varphi}{2}, \\
 n_z(\theta) &= \mp \frac{\sin \pi \nu}{\sin \xi} \cos \frac{\varphi}{2}, \\
 \sin \xi &= \sqrt{1 - \cos^2 \pi \nu \cos^2 \frac{\varphi}{2}}.
 \end{aligned} \tag{A.1}$$

Here φ is an angle of spin rotation in that longitudinal magnetic field. We use an approximation of the isomagnetic storage ring in which the azimuth can be considered as equal to the angle of a particle velocity rotation.

Characteristic time of the radiative depolarization τ_d due to a strong perturbation in the form of the KEDR detector longitudinal field is found from the equation [9]:

$$\tau_d \approx \frac{\tau_p}{\left\langle 1 - \frac{2}{9}(\vec{n}\vec{v})^2 + \frac{11}{18}\vec{d}^2 \right\rangle}, \tag{A.2}$$

Where τ_p is the Sokolov-Ternov polarization time (it is proportional to E^{-5} and makes up 72 hours at the VEPP-4M energy of 1.85 ΓB); $\langle \vec{d}^2 \rangle$ is an average over the azimuth square of the spin-orbit coupling function excited by the uncompensated KEDR field. The latter can be calculated as an derivative of \vec{n} on the particle Lorentz-factor γ using the formulae from, in particular, [15]:

(A3)

$$d_x = \gamma \frac{dn_x}{d\gamma} = \pm \left\{ F \cdot \sin v(\theta - \pi) \cdot \sin \frac{\varphi}{2} + \frac{1}{\sin \xi} \cdot [v(\theta - \pi) \cdot \cos v(\theta - \pi) \cdot \sin \frac{\varphi}{2} - \frac{\varphi}{2} \cdot \sin v(\theta - \pi) \cdot \cos \frac{\varphi}{2}] \right\},$$

$$d_y = \gamma \frac{dn_y}{d\gamma} = \mp \left\{ F \cdot \cos v(\theta - \pi) \cdot \sin \frac{\varphi}{2} - \frac{1}{\sin \xi} \cdot [v(\theta - \pi) \cdot \sin v(\theta - \pi) \cdot \sin \frac{\varphi}{2} + \frac{\varphi}{2} \cdot \cos \pi v(\theta - \pi) \cdot \cos \frac{\varphi}{2}] \right\},$$

$$d_z = \gamma \frac{dn_z}{d\gamma} = \mp \left\{ F \cdot \sin \pi v \cdot \cos \frac{\varphi}{2} + \frac{1}{\sin \xi} \cdot [\pi v \cdot \cos \pi v \cdot \cos \frac{\varphi}{2} + \frac{\varphi}{2} \cdot \sin \pi v \cdot \sin \frac{\varphi}{2}] \right\},$$

$$F = -\frac{1}{2 \sin^3 \xi} \left(\pi v \cdot \sin 2\pi v \cdot \cos^2 \frac{\varphi}{2} - \frac{\varphi}{2} \cdot \sin \varphi \cos^2 \pi v \right),$$

$$\sin \xi = \sqrt{1 - \cos^2 \pi v \cos^2 \frac{\varphi}{2}}.$$

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during acceleration including crossing
the integer spin resonance energy**

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при ускорении с пересечением энергии
целого спинового резонанса**

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