

INTEGER SPIN RESONANCE CROSSING WITH PRESERVING BEAM POLARIZATION ON VEPP-4M

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Abstract

A method to preserve the electron beam polarization on the VEPP-4M collider during acceleration with crossing the integer spin resonance energy $E=1763$ MeV is described. It is based on the use of non-compensated longitudinal magnetic field of the KEDR detector as a partial Siberian Snake.

MOTIVATION

In 2015, on the VEPP-4M collider with the KEDR detector, an experiment was performed to measure the fundamental ratio R in the region between the J/ψ and ψ' peaks with beam energy calibration by the resonant depolarization technique (RD) [1]. Beam polarization for VEPP-4M is prepared due to the natural radiative mechanism in the VEPP-3 booster storage ring. One of the energy points in that experiment, $E = 1814$ MeV, is very close to the critical value $E_4 = 1763$ MeV, which corresponds to the integer spin resonance $\nu = \nu_k = k = 4$. Here $\nu = \gamma a$, the spin tune parameter; γ is the Lorentz factor; a is the anomalous part of the gyromagnetic ratio. In the vicinity of E_4 , there is a large energy region of 160 MeV where obtaining the polarization on VEPP-3 is strongly hampered [2]. Therefore, it was impossible to inject a polarized beam into the collider directly at 1.81 GeV. To overcome this difficulty, we decided to polarize the beam in VEPP-3 outside the critical region, at the so-called 'advance' energy. The beam with that energy is injected and then accelerated/decelerated to the 'target' energy. In our experiment, the magnetization cycle of the collider was of the 'upper' type. Considering this fact, we chose an 'advance' energy of 1.65 GeV. The radiative polarization time τ_p in the collider ring ($\tau_p = 72$ h at 1.85 GeV) is two orders larger than that in the booster. Since τ_p scales the rate of depolarizing processes (τ_d^{-1}) driven by radiation, we can use beam polarization for the RD energy calibrations even at a rather small detuning from dangerous spin resonances. To obtain a polarized beam at 1.81 GeV, we had to solve the problem of crossing the resonance at 1763 MeV, which was done [3, 4].

FAST AND SLOW CROSSINGS

Let ν_0 be an actual spin tune, which can differ from the ν parameter defined for the case of unidirectional guide field. One can preserve the beam polarization when crossing any spin resonance $\nu_0 = \nu_k = k + m\nu_x + n\nu_y + l\nu_s$ with a sufficiently high rate of beam energy change (k, m, n and l are integers; $\nu_{x,y}$ and ν_s are the betatron and synchrotron tunes,

respectively). The following condition must be fulfilled for the fast crossing [5]:

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

where $\varepsilon(t) = |\nu_0(t) - \nu_k|$ is a time-dependent resonant detuning; w_k is the resonant harmonic amplitude of the field perturbations; ω_0 is the angular frequency of particle revolution. Basing on the data [6] obtained during preparation of the tau-mass measurement experiment we estimate the resonant spin harmonic related to the vertical orbit distortions as $|w_k| \sim 2.8 \times 10^{-3}$ ($k = 4, m = n = l = 0$). Therefore, the necessary rate of the resonance crossing is $\dot{\varepsilon} \gg 50$ s $^{-1}$ or $dE/dt \gg 2 \cdot 10^4$ MeV/s. In practice, dE/dt on VEPP-4M does not exceed 5 MeV/s. So, the fast crossing is excluded. Otherwise, if

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

then the spin resonance crossing occurs adiabatically slowly. A rate of $1 \div 10$ MeV/s, in principle, may be appropriate. In the limiting case of the theory of adiabatic resonance crossing and without taking into account the radiation effects, the polarization retains its value but changes the sign to opposite. The lower limit on the slow crossing rate is determined by the rate of spin diffusion due to quantum fluctuations [7]:

$$\dot{\varepsilon} \gg \frac{\nu^2}{|w_k|} \frac{d}{dt} \left(\frac{\delta E}{E} \right)^2. \quad (3)$$

An estimate shows that requirement (3) is not feasible. So, both adiabatic and fast crossings of the resonance at $E = 1763$ MeV under the natural conditions of VEPP-4M would result rather in loss of the beam polarization.

ELIMINATION OF RESONANCE

A simple method to preserve the VEPP-4M beam polarization in the conditions under consideration was proposed and substantiated in [3]. It is based on the Partial Siberian Snake (PSS) conception. A PSS was first tested with protons at IUCF and is currently used in the BNL's AGS [10, 11]. As applied to electron-positron storage rings, it was used in the VEPP-2M experiment at a resonance energy of 440 MeV [7]. If one switches off the anti-solenoids of the KEDR detector, its 0.6 T longitudinal magnetic field becomes uncompensated. The resulting PSS rotates the spin through an angle $\varphi \approx 0.34$ rad at $E = 1.75$ GeV. At $\nu = k$, the unit vector of polarization \vec{n} , periodic in the azimuth, rotates in the median plane and is directed along a velocity at the location of a solenoid for any φ . The PSS causes a

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spin tune shift with regard to an unperturbed value ν . With a full Siberian Snake [12], the perturbed spin tune is constant: $\nu_0 = 1/2$. In general, ν_0 is found from the equation $\cos \pi \nu_0 = \cos \pi \nu \cos \frac{\varphi}{2}$. The non-integer part of ν_0 , the detuning ε , changes with the energy but does not vanish at the critical point 1763 MeV, achieving a minimum value of 22 MeV ($\varepsilon_{min} \approx 0.050$) - see Fig. 1. This is a basis for preservation of the beam polarization during acceleration which is performed adiabatically slow, in accordance with (2). Formally, the resonant spin harmonic due to the KEDR

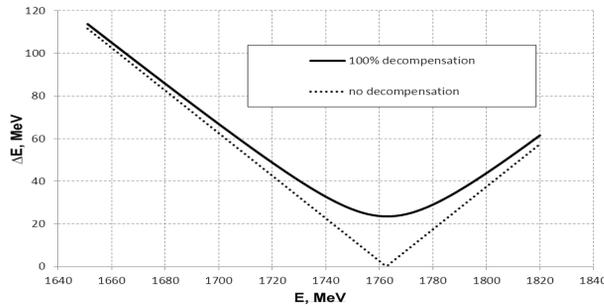


Figure 1: Spin tune shift in energy units due to decompensation of KEDR field versus beam energy.

field decompensation $\varphi/2\pi \approx 0.054$ is much larger than that associated with the vertical orbit distortions ($\sim 10^{-3}$). This allows us to consider our PSS not as a perturbation but as a part of the design magnetic structure. Because of the relatively narrow range of energy adjustment, the intrinsic resonances $\nu_0 \pm \nu_{x,y}$ did not fall into it. Weaker resonances of the types of $\nu_0 + \nu_x + \nu_y = k$ and $\nu_0 \pm \nu_s = k$ were intersected in the 'fast' mode.

RADIATIVE DEPolarIZATION RATE

We treat depolarization under our resonance crossing as non-resonant spin diffusion due to quantum fluctuations. The radiative depolarization time τ_d can be found from the generalized equation [8]:

$$\tau_d \approx \frac{\tau_p}{\left\langle 1 - \frac{2}{9}(\vec{n}\vec{\beta})^2 + \frac{11}{18}\vec{d}^2 \right\rangle}. \quad (4)$$

Here, \vec{n} depends on the solenoid strength; \vec{d}^2 is the square of the spin-orbit coupling function, periodically dependent on azimuth; $\vec{\beta}$ is the particle velocity in the units of light speed; $\langle \dots \rangle$ means averaging over the ring. The uncompensated part of the KEDR field excites strong spin-orbit coupling, which is easy to calculate. Approximately, $\vec{d} = \gamma \partial \vec{n} / \partial \gamma$; the betatron contribution to \vec{d} can be neglected. The depolarization time is plotted in Fig. 2 versus the beam energy at 100% and 50% KEDR decompensation. With approaching to an integer resonance, a PSS brings stronger spin-orbit coupling than a full Siberian Snake: $\tau_d(\varphi = \pi) / \tau_d(\varphi \ll 1) \approx 12 / \varphi^2$. The weaker is a PSS, the more problems with preservation of polarization. However, its technical realization is easier. Theoretical behavior of the polarization degree during the

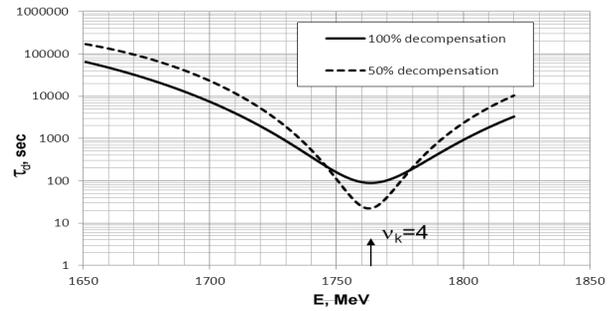


Figure 2: Radiative depolarization time vs. beam energy.

process of acceleration is shown in Fig. 3 for two ramping rates. It can be seen that it is advantageous to apply the

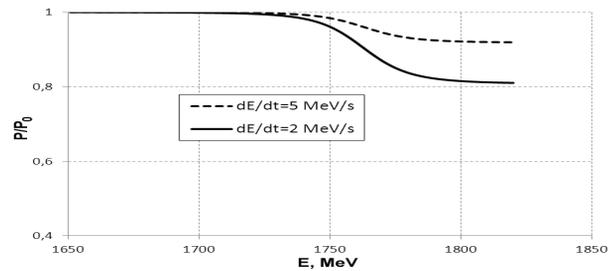


Figure 3: Calculated change of polarization degree under acceleration at two ramping rates (full decompensation).

full decompensation and accelerate particles with a rate not below 2 MeV/s.

BETATRON COUPLING COMPENSATION

To compensate the betatron coupling caused by the decompensated KEDR magnet we used a scheme based on two quadrupole lenses rotated through 45° (Fig. 4) [13, 14]. The scheme provides a smallest split of the normal mode tunes of $\sim 10^{-3}$. If no compensation is applied, this split achieves 0.1, which precludes sustainable maintenance of the beam during acceleration.

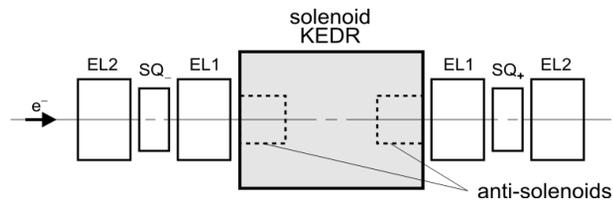


Figure 4: Betatron coupling is localized at the section with the skew quads (SQ₊ and SQ₋) and KEDR between them.

EXPERIMENTAL RESULTS

One of the results of the beam energy calibration using the RD technique at the 'advance' energy is presented in Fig. 5. The polarization effect is measured by the Touschek polarimeter [15], which includes a few plastic scintillator counters located inside the accelerator vacuum chamber,

as well as the TEM wave-based depolarizer. The counting rate of the Intra-Beam Scattering (IBS) depends on the beam polarization. The effect is manifested by a jump in the normalized counting rate difference $\Delta = f_1/f_2 - 1$ of scattered electrons from the polarized (f_1) and unpolarized (f_2) bunches at coincidence of the depolarizer frequency with the resonant value. The jump is proportional to the polarization degree squared (P^2).

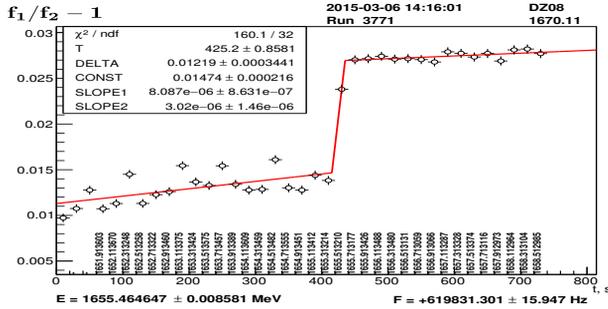


Figure 5: Depolarization jump of 1.2% during depolarizer frequency scan at ‘advance’ energy (1655 MeV).

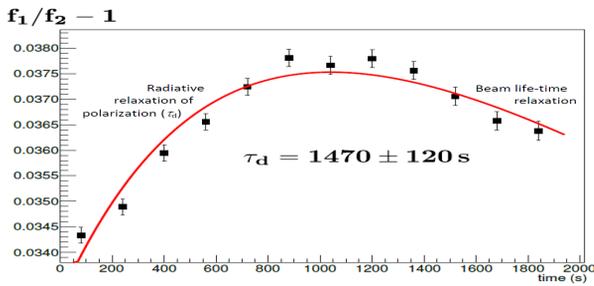


Figure 6: Relaxation process after acceleration up to 1806 MeV with rate of 5 MeV/s. Anti-solenoids shut down before acceleration remain in the same state after completion of acceleration.

First of all, the proposed method was tested on observation of polarization relaxation (depolarization) at a ‘target’ energy $E \approx 1.81$ GeV in the case when the anti-solenoids remained switched off after acceleration (Fig. 6). The observed relaxation is an evidence of conservation of polarization in the beam. The fit of the experimental points accounts for contributions of two processes. One is the radiative depolarization with the characteristic time τ_d . The other is the relaxation of Δ due to the Touschek losses of particles when the bunches are not equal in population. The determined time $\tau_d = 1470 \pm 120$ s in Fig. 6 is in good agreement with the calculated time of about 1400 s (Fig. 2). The fact of beam polarization preservation has been fully confirmed by the RD technique in the mode with the anti-solenoids switched on in 385 s after completion of acceleration (Fig. 7).

DISCUSSION

The calculated degradation of the depolarization jump becomes $(P/P_0)^2 \approx 0.5$ at the end of acceleration. The mea-

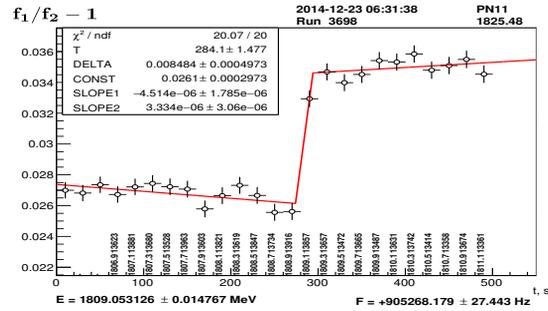


Figure 7: Depolarization jump of 0.8% at target energy of 1.81 GeV after 2.4-MeV/s acceleration and subsequent restoration of anti-solenoid field in 385 s.

sured jumps at 1.81 GeV lie in the range $(0.8 \div 0.4)\%$, while the jumps fixed at the ‘advance’ energy were 0.9% and 1.2%. According to accumulated experience, the stability of beam polarization obtained from VEPP-3 is $\Delta P_0 \sim (10 \div 20)\%$ in the same controlled conditions. Basing on the specified data, we can conclude that the experiment and the calculation are in satisfactory quantitative agreement. It is implied that using the method described one can cross the resonance $E = 1322$ MeV ($\nu = 3$) practically without polarization loss under a 2 MeV/s deceleration starting from 1550 MeV. However, acceleration in the same manner from 1.85 GeV up to 2.4 GeV with crossing the resonance $E = 2203$ MeV ($\nu = 5$) leads to a three-fold decrease in polarization.

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