INFLUENCE OF ERRORS IN KEDR DETECTOR FIELD COMPENSATION ON THE SPIN TUNE SHIFT AND THE BEAM POLARIZATION LIFETIME IN VEPP-4M COLLIDER AT ENERGY OF TAU LEPTON PRODUCTION THRESHOLD

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Abstract

We have studied the effects of the KEDR detector field compensation error on an accuracy of beam energy calibration by the the spin precession frequency as well as on a ‘lifetime‘ of beam polarization in the VEPP-4M storage ring in the tau lepton mass measurement experiment.

INTRODUCTION

In the tau-lepton mass measurement at the VEPP-4M e+e- collider with the KEDR magnetic detector [1] we apply the technique of resonant depolarization (RD) for an absolute calibration of the VEPP-4M beam energy [2, 3, 4]. The energy of this experiment, in the vicinity of the tau production threshold $E = 1777$ MeV, is close to the integer spin resonance $\nu = k = 4$ ($E \approx 1763$ MeV, $\nu = E[\text{MeV}]/440.65$, an effective spin precession frequency in units of a revolution frequency). Because of a small distance to the resonance $\epsilon = \nu - k \approx 0.03$ a polarized beam is injected in VEPP-4M from the VEPP-3 booster at ≈ 70 MeV above the ’tau-threshold’. Then the beam is deccelerated down to the experiment energy. A ’life time’ of beam polarization (PLT) in the VEPP-4M ring may appear rather small (< 10 minutes [4]) depending on the strength of various depolarizing factors. One of such important factors is an error in compensation of the KEDR longitudinal magnetic field $H_{||}$ ($H_0 = 0.6$ T is a nominal value) with the help of two ‘anti-solenoids‘ (AS). In the case of inaccurate compensation, the polarization vector of electrons rotates about the longitudinal axis by an angle $\varphi \propto \delta \int (H_{||} d\theta$ as shown in Fig.1 ($\varphi << 1$). In the viewpoint of RD application, this leads to two deleterious effects. First, the compensation error may strongly worsen PLT, hampering the experiment performance. Second, the spin precession frequency is shifted that yields a systematic error in an absolute energy calibration [2, 5]. Below we present our calculation and experimental results concerning both those effects.

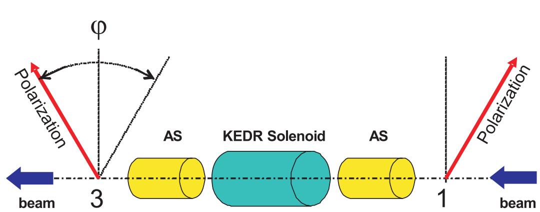

Figure 1: Polarization vector rotation due to an error of the KEDR field compensation.

BETATRON COUPLING DIAGNOSTICS

An error in the longitudinal field compensation enhances the betatron coupling resonance resulting in the frequency split of the transverse oscillation normal modes by the value ΔQ_C. Another coupling effect is an excitation of the vertical dispersion function η_Z. The calculations and measurements were performed to study a possibility for diagnostics of the compensation error by the betatron coupling. They showed that at really achieved accuracy in the measurement of ΔQ_C ($\delta(\Delta Q_C)$ is a few of 10^{-3}) and η_Z (a few cm) one can provide an accuracy in the KEDR field compensation of not better than 5%.

SPIN TUNE SHIFT

RD technique is based on a known relation between the average angular frequency Ω_S of spin precession relative to the basis connected with the velocity vector and the average particle energy in an electron (positron) beam: $\Omega_S = (q'/ec)\Omega_0 E = \nu\Omega_0$. Here q' is the anomal part of gyromagnetic ratio and Ω_0 is the revolution angular frequency. This equation breaks down in the presence of the guiding field perturbations making the closed orbit to become, generally, unflat. As consequence, the spin vector evolution is complicated and the effective spin frequency differs from that which is simply proportional to the energy. To account for this one need to consider the corresponding shift $\Delta\nu$ in the measured spin frequency ν_{meas}: $E = ec(\nu_{meas} - \Delta\nu)/q'$. The tune shift is found by considering the trace of a spin rotation matrix at one revolution. Inaccurate compensation of the longitudinal magnetic field integral gives the spin tune shift [2, 5]

$$\Delta\nu \approx \frac{\varphi^2}{8\pi} \frac{\cos \pi\nu}{\sin \pi\nu}. \quad (1)$$

A difference between the beam energy determined by the spin precession frequency at the compensaton solenoid current $I_{cs} = 94$ A and the energies found at the different values of I_{cs} has been measured. This experiment results are presented in Fig.2 (the dots) in comparison with the estimate by the formula (1) and the parabolic fit.

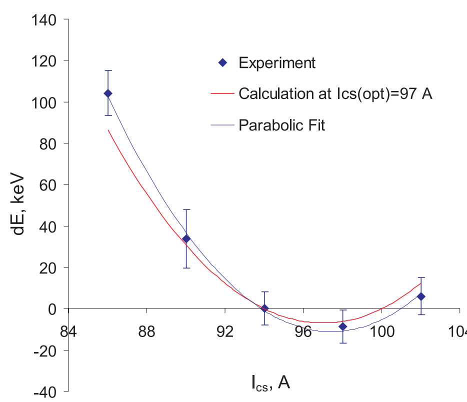

Figure 2: Influence of the compensation error on the absolute energy calibration ($E = 1784.1$ MeV, $H_0 = 0.6$ T).

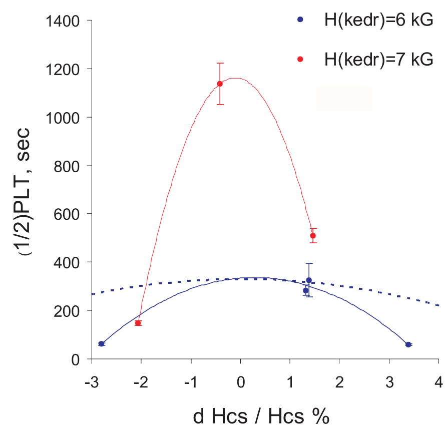

Figure 3: Depolarization time vs. the compensation error at two values of the KEDR field, $E = 1777.3$ MeV (the solid lines). The estimate of combined depolarizing effect of the main imperfections and the compensation error at $H_0 = 0.6$ T is presented by the dashes.

POLARIZATION LIFE TIME

The relaxation time of beam polarization is $\tau_r^{-1} = \tau_p^{-1} + \tau_d^{-1}$ [6] where τ_d^{-1} describes a rate of depolarizing processes; τ_p is a design time of radiative polarization. The extent of depolarization can be characterised by the factor $G = \tau_r/\tau_p = P/P_0$ where $P_0 = 0.92$ is the equilibrium degree of radiative polarization in the ideal machine and $P \le P_0$ is that in the real machine with imperfections. Quantum emission scatters particle trajectories and causes a diffusion of the vertical component of polarization in the presence of the spin-orbital coupling (SOC) which is owing to the guiding field perturbations. SOC can be described by the vector function $\vec{d}(\theta)$ [6] periodical with the azimuth θ. G-factor depends upon $\vec{d}(\theta)$ as:

$$G =< |\mathcal{K}|^3 > / < |\mathcal{K}|^3(1 + 11/18|\vec{d}|^2) >, \qquad (2)$$

where $\mathcal{K}$ is the orbit curvature, $< \dots >$ means averaging over the azimuth. As result, the equilibrium extent (P) and the time of relaxation (τ_r) may significantly decline, especially near the machine spin resonances: $\nu + m\nu_X + n\nu_Z = k$. Here m, n, k are integer; ν_X and ν_Z are respectively the radial and vertical betatron tunes. The design polarization for VEPP-4M is rather large: $\tau_p \approx 72$ hours at $E = 1777$ MeV. The measurements of PLT by the intra-beam scattering rate reinforced our expectation that $\tau_d \le 1$ hour and the relaxation process is actually the process of full depolarization ($PLT = \tau_d << \tau_p$, $\tau_r \approx \tau_d$, $G << 1$) [3, 4]. Results of the experimental study of the compensation error effect on PLT at two values of the KEDR field are shown in Fig.3. The difference between two presented dependencies at a zero error ($dH_{cs} = 0$) can be explained by a difference in the states of main depolarizing perturbations of the guiding field at a given H_0. In the next sections we consider a spin-orbital coupling caused by the solenoid compensation error and estimate its depolarizing effect.

SPIN-ORBITAL COUPLING

Off-energy function for the polarization axis

The periodical with an azimuth θ unit vector $\vec{n}(\theta) = \vec{n}(\theta+2\pi)$, defining the equilibrium polarization direction in a storage ring, can be found by using the spin matrix technique [6]. In our case, the difference of this vector from the strictly vertical ort is entirely defined by the parameter $\varphi << 1$. The differentiation of $\vec{n}$ with respect to the energy parameter γ, the Lorentz factor, yeilds the off-energy function for the polarization axis, contributing to the SOC function $\vec{d}(\theta)$,($d_Z \approx 0$):

$$\gamma\frac{dn_X}{d\gamma} = d_X = -\frac{\varphi}{2\sin\pi\nu}[\sin(\pi\nu - \chi) + \qquad (3)$$

$$+\chi\cos(\pi\nu - \chi) - \frac{\pi\nu\sin\chi}{\sin\pi\nu}],$$

$$\gamma\frac{dn_Y}{d\gamma} = d_Y = -\frac{\varphi}{2\sin\pi\nu}[\cos(\pi\nu - \chi) -$$

$$-\chi\sin(\pi\nu - \chi) + \frac{\pi\nu\cos\chi}{\sin\pi\nu}], \quad \chi = \nu\int_0^{\theta_0} K d\theta,$$

$\theta = 0$ at the point "1" in Fig.1. Below we consider another term contributing to SOQ, arised from the betatron oscillations.

Betatron oscillation contribution

We use the method [7, 8] based on summation of spin vector perturbations over all revolutions of the electron in the storage ring in a radiation damping time starting from the instant of quantum emission that changes the current energy by $\delta\gamma/\gamma$. In our case, the perturbations of the unit vector $\vec{S}$, determined as a 3D spin vector in the rest particle system, are found at the $k-$th revolution in the form ($\delta S_Z = 0$):

$$\delta S_\perp^{(k)} = \delta S_X^{(k)} + i\delta S_Y^{(k)} = i(\nu\varphi/2)x_1' \exp i\chi.$$

Here, to avoid much algebraic manipulation the 'thin solenoid' approximation [9] for the betatron phase space transformation through the longitudinal field insert is applied; $x_1' = dx_1/d\theta$ is the slope of the x-trajectory at the input of the KEDR insert (the point "1" in Fig.1) at the $k-$th revolution. For simplicity, let also use the smooth approximation for the betatron radial oscillations: $x = \delta\gamma/(\gamma\nu_X)[1 - \cos\nu_X(\theta - \theta_0)]$. The SOC function $d_\perp = d_X + id_Y$ is defined by

$$d_\perp(\theta_0) = -(\frac{\delta\gamma}{\gamma})^{-1}\sum_{k=1}^{\infty}\delta S_\perp^{(k)} \exp\left(-i2\pi k\nu\right) =$$

$$= \frac{\nu\varphi}{8\nu_X}\{[1 + i\cot\pi(\nu - \nu_X)]e^{-i(\nu-\nu_X)\theta_0} -$$

$$-[1 + i\cot\pi(\nu + \nu_X)]e^{i(\nu+\nu_X)\theta_0}\}.$$

The smooth approximation results in only the combination spin resonances $\nu \pm \nu_X = k$. Those two resonances are rather far from the integer spin resonance $\nu = 4$ and therefore negligible ($\nu_X \approx 8.54$). Not using the smooth approximation, one can find the betatron contribution near the integer resonance in the form $|\vec{d}| \approx \nu\varphi\eta_1' \cot\pi\nu/4$, where $\eta_1' = d\eta_X/d\theta$ is the dispersion function slope at the point "1". The ratio between the betatron and the off-energy terms (3) is of the order of $\eta_1\epsilon/2 << 1$. So, in the 'thin solenoid' approximation the betatron term of SOC is negligible in comparison with the $\gamma\vec{n}/d\gamma$ term.

Estimate of the depolarization time

PLT related to the compensation error, calculated by the formulas (2) and (3), is plotted in Fig.4 versus the beam energy for two values of the error at $H_0 = 0.6$ T. To compare this calculation with the measured data in Fig.3, one needs to estimate an interference of the contributions to SOC from the initial imperfections, resulting in the PLT value measured at $dH_{cs} = 0$, and that from the detuning of AS. Assuming these contributions to be added just constructively, one can find an estimate of the resultant PLT illustrated in Fig.3 by the dashed curve.

CONCLUSIONS

The measured and calculated spin tune shifts in Fig.2 are in a good agreement. To provide an allowable systematic error in the beam energy calibration by RD ≤ 10 keV one must keep the KEDR field compensation error $\leq 2\%$. With respect to the decrease of PLT, the requirement on this error is the same according to the results in Fig.3. The measured

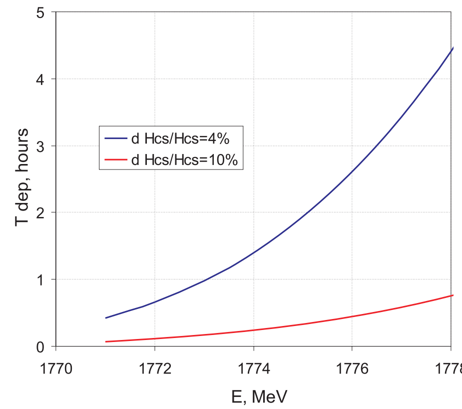

Figure 4: Depolarization time calculated versus the energy.

dependence of the PLT on the compensation error is distinctly more stronger than that estimated. Noticeable decrease of PLT takes a place at the error of not 10%, as in the model, but 4%. This suggests, at least, that the very simple 'thin solenoid' approximation is not entirely adequate, so, in fact, the betatron contributiont to SOC may not be too small. A closer approximation can be based on a "distributed solenoid" model like in [8]. In the viewpoint of the tau mass measurement experiment, it is preferably to control the KEDR field compensation error at the level of $\sim 1\%$ by measuring PLT. A corresponding accuracy attainable by the betatron coupling diagnostics is several times worse ($> 5\%$).

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