# RECORD-HIGH RESOLUTION EXPERIMENTS ON COMPARISON OF SPIN PRECESSION FREQUENCIES OF ELECTRON BUNCHES USING THE RESONANT DEPOLARIZATION TECHNIQUE IN THE STORAGE RING*

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*Abstract*

The opportunity of performing an experiment on CPT theorem test based on high precision comparison of the spin precession frequencies of electron and positrons measured by the resonant depolarization technique in the storage ring is under study at the VEPP-4M facility.

## INTRODUCTION

This work is devoted to preparation of the experiment for CPT-theorem test. CPT-theorem predicts that the g-factor, mass, charge, absolute value of magnetic moment, lifetime, etc., of particle and anti-particle are equal [1]. Today, it's completely unclear how and in what a violation of CPT symmetry could appear. Therefore, it is very important that in our experiment the spin precession frequencies depending on fundamental constants $(g-2)/2$ and $e/mc$ for electrons and positrons can be simultaneously measured and compared using the resonant depolarization technique (RD) [2]. At present time, the most precise comparisons of (g-2)/2, masses and charges for electron and positron are made in [3, 4, 5]. The relative difference smaller than $4\times10^{-12}$, $8\times10^{-9}$ and $4\times10^{-8}$ for $(g-2)/2$, masses and charges were measured. At the first stage of our experiments, we compare the spin precession frequencies of two electron bunches, simultaneously circulating in the VEPP-4M storage ring, with the aim to reach a minimal statistic error and to investigate some systematic errors.

## METHOD FOR CPT TEST

Anomalous part of the spin precession frequency relates to the average guide field $<H>$ in an ideal storage ring through the equation $\Omega=\nu\Omega_0=q'<H>$, $q'=(g-2)/2\cdot(e/mc)$. If the electron and positron bunches circulate simultaneously in the same ring, they anyway have the same revolution frequency $\Omega_0=\Omega_0^+=\Omega_0^-$ dictated by the RF system. In accordance with Lorentz force equation, $\Omega_0=e^{\pm}c<H/E>_{\pm}$, where averaging over the ring allows for the azimuthal dependence of the particle energy $E$ resulting from distributed radiation and coherent losses as well as a local energy recovery in the RF cavity. The closed orbits of electrons and positrons are not coincident even in an ideal storage ring not containing any static electric fields but having a mirror symmetry of its magnetic structure relative to an axis throughpassing the RF cavity. Just in this case the orbits are reciprocally symmetrical. Ideally, in the case of CPT symmetry the equalities $<H/E>_+=<H/E>_-$ as well as $<H>_+=<H>_-$ take a place. Generally, under assumption that the electron charge and mass are not identical with positron ones ($e^-\neq e^+$ and $m_+\neq m_-$), the closed orbits of electrons and positrons differ from the reciprocally symmetrical orbits noticed above. Thus, the average fields along the orbits of opposite in sign particles also mismatch: $<H>_+\neq<H>_-$. Besides, it is not $q'_+\neq q'_-$. Therefore it is possible, in principle, to examine a CPT violation by measuring the frequency difference $\Delta\Omega=\Omega_+-\Omega_-=q'_+<H>_+-q'_-<H>_-$. This possibility depends on the answer to the question: what an accuracy of the mirror symmetry for the storage ring must one provide to exclude systematic errors in $<H>_{\pm}$? Partially, this problem is discussed in one of sections below.

Methods applied in [3, 6], most precise measurements on comparison of anomalous magnetic moments (AMM) of electrons and positrons, differ from a direct comparison of depolarization frequencies. In [6] the final polarization degrees of the electron and positron bunches were compared after the adiabatic spin resonance crossing (with flipping of spins). Authors interpreted their results as the AMM comparison with an accuracy $10^{-8}$ assuming an equality of all remaining parameters. By indirection, the achieved accuracy proves that the fine precision mirror symmetry of the storage ring can be realized in practics. In [3] the ratio $(g-2)/2$ was measured separately for electrons and positrons captured in the Penning trap. The result obtained corresponds to the relative accuracy $\delta q'/q'\sim3\cdot10^{-9}$ in AMM comparison.

## RD TECHNIQUE AT VEPP-4M

The system of absolute calibration of the particle energy at VEPP-4M by measuring the average spin precession frequency in the beam includes a polarimeter based on IBS

* This work is supported in a part by RFBR 04-0216745, 04-02-16665
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(Intra-Beam-Scattering) effect and a TEM wave-based depolarizer [7, 8, 9].

### *Transverse field depolarizer*

TEM wave is generated with the help of two parallel, vertically-spaced conductive plates connected to a variable-frequency RF generator. The type of connection corresponds to a stationary wave formation at the plates, that provides a concurrent action of the depolarizer with an equal efficiency on electrons and positrons. The frequency is set by a BINP-developed computer-controlled synthesizer with an ultimate resolution for frequency step better than $10^{-4}$ Hz. The intrinsic linewidth of synthsizer is of the same order as it has been proved in special experiment on measurement of its phase noise. The reference frequency signal for the synthesizer is created by the rubidium frequency standard with a frequency stability $\sim 10^{-10}$. In our "superfine scans" experiments at $E = 1.85$ GeV we were scanning the depolarizer frequency $f_d$ with a rate $\dot{f}_d = 10$ mHz/sec and a step of 20 mHz, which corresponds to a relative frequency resolution of $5 \times 10^{-9}$.

### *IBS-based polarimeter*

The quantity $S = 1 - \dot{N}_1/\dot{N}_2$, denoted in the figures below as $delta$ and determined through the ratio between the counting rates of scattered electrons from a non-polarized bunch ($\dot{N}_2$) and polarized one ($\dot{N}_1$), is measured with the help of two scintillation counters entered inside the vacuum chamber. The beam depolarization event is observed by the related jump in $S$ which is practically proportional to a square of the polarization degree and is $\sim 1\%$. Our Monte Carlo simulation of the depolarization process shows that for achievement the frequency resolution of $5 \cdot 10^{-9}$ the total counting rate up to 1 MHz is required. By now, the counting rate makes about 200 kHz per 2 mA current in a bunch by summing the loads from each of counters. In nearest future we plan to increase this rate in a few times by means of mounting the additional counters.

### *"Two-bunch" and other methods*

We use the following combinations of simultaneously circulating bunches. "Two bunches" is the case of one polarized and one polarized/unpolarized electron bunches which are equalized in current. "2+1" is the case of two polarized and one unpolarized bunches. The latter serves for normalization of the counting rate. Two pairs of electron bunches are used in "2+2". Each pair represents the "1+1" case. This case is suitable to study the systematic error depending on bunch current if the pairs differ in this parameter.

### *RF separation*

The RF scheme for controled separation of the spin precession frequencies of two electron bunches has been proposed and realized. For this aim we use the plates of horizontal electrostatic separation of electron and positron orbits. The plates are connected as an element of the resonant circuit to the RF generator working at the revolution frequency. Because of $\pi$-shift in a phase of passing the plates between two electron bunches, their closed orbits are disturbed symmterically in respect to the initial undisturbed orbit. The resulting relative energy (spin tune) gap between two bunches is estimated as $\delta E/E \approx 2\phi\eta_x/(\alpha\Pi)$, where $\phi$ is the deflection angle in the field of plates; $\eta_x$ is the dispersion function at the azimuth of plates location; $\alpha$ is the momentum compaction; $\Pi$ is the machine circumference.

## RESULTS OF EXPERIMENTS

Figures 1 and 2 demonstrate the results of one of "2+1" experiments at $E = 1.85$ GeV, in which the record accuracy $2 \times 10^{-8}$ in comparison of depolarization frequencies has been achieved.

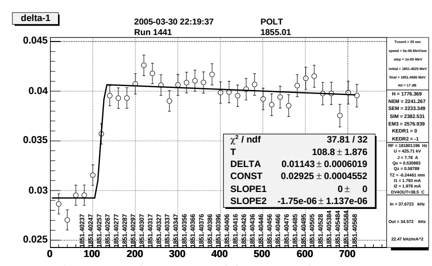


Figure 1: The jump at the combination "First polarized bunch/Unpolarized bunch". The scan rate is $\dot{E} = 5$ eV/s. The abscissa is the current time from the start of scan, the ordinate is the relative counting rate. The energy is determined by the jump with an error $\pm 24$ eV.

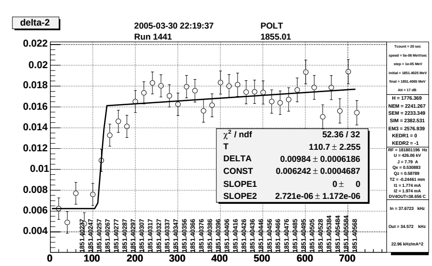


Figure 2: The jump at the combination "Second polarized bunch/Unpolarized bunch" at the same run that in Fig.1. The difference between the energy values determined in Fig.1 and Fig.2 is $(10 \pm 34)$ eV or $2 \cdot 10^{-8}$ in realive units.

In the case of small depolarizer amplitudes, the jump in the "superfine scan" becomes of the "long-drawn" type as in Figure 3. Since the depolarizer linewidth is much less than the spin linewidth of $\sim 5 \cdot 10^{-7}$ (about 1 keV), resulting from an influence of quadraric nonlinearity of the VEPP-4M guiding field, the kinetics of depolarization is determined by the radiation diffusion of spin tunes. The observed depolarization rate is in accordance with estimates using the value of spin linewidth [9]. In RF separation experiment most reliable results like in Figure 4 have been obtained at the controlled energy gap between electron bunches larger than $\sim 100$ Volts.

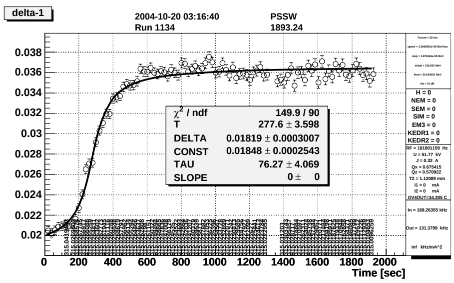


Figure 3: Long-drawn jump at the reduced strength of depolarizer. Duration time of the jump corresponds to $\sim 3.5$ keV interval in the energy scale and is determined by the spin frequency linewidth.

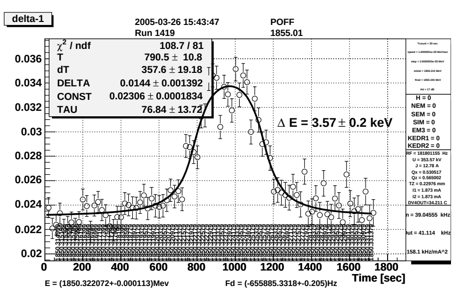


Figure 4: RF separation experiment with two polarized bunches (the scan rate is 12 eV/sec). The counting rate of one of them is normalized by the counting rate of another. The controlled energy gap is 3 keV, the measured one is $3.6 \pm 0.2$ keV.

## SOME SYSTEMATIC ERRORS

### *Energy and spin tune shift due to energy losses*

The energy of equilibrium particles varies with the azimuth $\theta$ according to: $E(\theta) = E_0(1 + f + \epsilon)$. Here $E_0$ is the eqilibrium energy determined for the hypothetic case of zero energy losses, the function $f(\theta)$ describes the loss distribution, the energy shift $\epsilon$ is defined through the conservation of $\Omega_0$: $\epsilon = - < K\eta_x f > / < K\eta_x >$ . $K$ is the orbit curvature, $\eta_x$ is the radial disperion function. Since the function $f$ is defined to an arbitrary constant, let define its values at the interval from $-U/2$ to $+U/2$, where $U$ is the energy loss of a particle per one turn in units of the beam energy. Hence, the energy gap between electrons and positrons, circulating in the same ring, can be estimated as $< E_+ > - < E_- > = 2(< f > + \epsilon)$. For the azimuthally symmetric storage ring ($K = const$, $\eta_x = const$), as well as in the ring with mirror symmetry, the gap equals zero. Generally, an error in the mirror symmetry $\ll U \propto E^3/\rho$, $\rho$ is the the orbit radius in bending magnets. For VEPP-4M ($\rho \approx 45$ m) at $E = 1.5$ GeV the measure $U \sim 10^{-5}$. Note, the same value of $U$ was for VEPP-2M in the AMM experiment with achieved accuracy of $10^{-8}$.

### *Tilting of the RF cavity axis about the beam axis*

If the RF cavity axis and the beam orbit makes an angle $\phi$ in the median plane, the effect of the energy and of the spine tune shift appears which is due to the radial accelerating field component and estimated as $\delta E/E \approx \delta\nu/\nu \approx \pm\phi\eta_x U/(\alpha\Pi)$, $\eta_x$ is the dispersion function value at the RF cavity location. A sign "+" or "−" distincts the electrons and positrons. For VEPP-4M ($\alpha \sim 0.017$, $\Pi = 366$ m) the resulting gap at $E$=1.8 GeV, $E \cdot U = 34$ keV and $\phi \sim 0.01$ is significant: $2\delta\nu/\nu \sim 5 \cdot 10^{-8}$, if the corresponding $\eta_x-$function value is close to the regular one of 100 cm. To decrease this effect, one can use that of the VEPP-4M RF cavities, in which the $\eta_x$-function, changing a sign, is close to zero.

## CONCLUSIONS

A record accuracy of $2 \cdot 10^{-8}$ has been achieved in the experiment on comparison of depolarization frequencies of two electron bunches. New RD techniques in the different multi-bunch regimes have been proposed and mastered. Estimates of some sources of systemtic errors which can affect an accuracy of the comparison of spin frequencies of electrons and positrons have been considered. We will continue our experiments in the direction of decreasing statistic errors and studying systematic errors turning to measurements including positrons.

## ACKNOWLEDGEMENTS

Authors thanks Yu.Shatunov and E.Perevedentsev for discussions on some questions cosidered in the work.

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