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# HIGH-PRECISION MEASUREMENT OF THE BEAM ENERGY IN A STORAGE RING USING THE SPIN PRESESSION FREQUENCY OF POLARIZED PARTICLES

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Abstract. A method for the determination of the absolute particle energy value in an electron-positron storage ring by measuring the spin precession frequency is described which is performed with the help of the resonance beam depolarization by a high-frequency field. A problem of the measurement accuracy for the mean beam particle energies with the account of energy spread and synchrotron oscillations is discussed. In practice the accuracy limitation primarily consists in irregular pulsations of the guiding magnetic field. The energy of the electron beam in the storage ring VEPP-2M has been measured experimentally with an accuracy $\pm 1 \cdot 10^{-4}$.

## 1. Introduction

A set of experiments on studying vector mesons performed on electron - positron storage rings has demonstrated the advantages of a new investigation method. Among these is high energy resolution. It is restricted by the natural beam energy width accounting for about $10^{-3}$ in the $\Phi$ -meson - region. Methods used up to now for the absolute calibration of the particle energy in storage rings (the measurement of the magnetic field distribution, the phase oscillation frequencies, etc.) provided accuracy slightly better than $10^{-2}$, while of practical interest is the accuracy $10^{-4}$ being an order higher than the energy spread.

In addition, the energy spread contribution to the reaction energy uncertainty can markedly be decreased by energy decomposition of the beam particles in the collision point. The energy decomposition should be fairly strong to eliminate "mixing" of the particles due to betatron (transverse) oscillations. If the direction of decompositions for both particles coincides (more energetic electrons collide with more energetic positrons) the reaction identification requires high accuracy of the collision point coordinates in the direction of decomposition. Provided that the direction of decomposition for electrons and positrons is opposite, the collision energy will be the same over the whole section of the colliding beams accurate to the betatron mixing and the corrections of the order $(\Delta\gamma/\gamma)^2$.

This assumption results in a problem of absolute calibration of the particle energy in a storage ring with the accuracy much better than $10^{-4}$. The urgency of these problems has grown in connection with the discovery of new narrow resonances (Gypsy-mesons).

The progress of experiments on the beam radiation polarization /1,2/ achieved recently on several electron-positron storage rings /3,4/ provides a new method of the absolute energy measurement. This method is based on the dependence of the spin precession frequency of polarized relativistic particles on their energy. The accuracy of this method to a first approximation is not related with the energy spread of the beam particles and even in the first experiments reached the value $1\cdot10^{-4}$.

## 2. The Method Accuracy Evaluation

For a relativistic electron the frequency of spin precession about the direction of the storage ring guiding field $H_z$ after averaging over betatron oscillations can be written in the form

$$\Omega=\omega_s(1+\gamma q'/q_0)$$

where $\omega_s(\gamma)=e\overline{H}_z/\gamma mc$ is the particle revolution frequency, $\gamma$ is the relativistic factor, $q'$, $q_0=e/mc$ is the anomalous and normal parts of the gyromagnetic ratio.



To measure the precession frequency a method of the beam resonance depolarization by a radio-frequency longitudinal magnetic field $H_v$ is used /2,3/. The resonance condition can be written in the form

$$\omega_s(1+\gamma q'/q_0)\approx\omega_d+k\omega_s$$

where $\omega_d$ is the introduced field $H_v$ frequency, $k$ is the integer.

In the presence of accelerating RF-voltage the particle energy and hence mistuning $\varepsilon(\gamma)=\omega_s(1-k+\gamma q'/q_0)-\omega_d$ undergo oscillations of the synchrotron frequency $\omega_\gamma$: $\varepsilon=\overline{\varepsilon}+\Delta\cos(\omega_\gamma t+\varphi_\gamma)$. The modulation amplitude $\Delta=\frac{\partial\varepsilon}{\partial\gamma}\Delta\gamma$ is equal to

$$\Delta=\left[\alpha(k-1)+(1-\alpha)\gamma q'/q_0\right]\frac{\Delta\gamma}{\gamma}\omega_s$$

$\alpha$ is the momentum compaction factor. As a result of this modulation the spin motion spectrum will have a central frequency and side ones at a distance $\pm n\omega_\gamma$ from it ($n$ is the integer).

The phase-motion averaged mistuning has a spread determined by that of the mean spin frequency: $\overline{\varepsilon}=\varepsilon_s+\delta\Omega$, where $\varepsilon_s$ is the frequency shift for the synchronous particles, $\delta\Omega=\left(\omega_s\gamma\frac{q'}{q_0}\right)\left\{\frac{\delta\gamma}{\gamma}-\frac{\alpha}{2}\left(\frac{\Delta\gamma}{\gamma}\right)^2\right\}$, $\delta\gamma=\overline{\gamma}-\gamma_s$ is the mean particle energy shift proportional to the squared amplitudes of betatron and synchrotron oscillations.

In practice, if no special care is taken, the value $\delta\Omega$ will be governed by the squared nonlinearity of the guiding magnetic field $\partial^2 H_z/\partial x^2$:

$$\delta\Omega\approx\omega_s\gamma\frac{q'}{q_0}\left(\frac{\overline{X^2}}{H_z}\cdot\frac{\partial^2 H_z}{\partial x^2}\right)$$

where $\overline{X^2}$ - is the squared radial size. The estimation for the VEPP-2M storage ring gives $\delta\Omega\simeq10^{-6}\omega_s$. With the squared non-linearity compensation the spin frequency spread can be reduced to a value of the order $\alpha\omega_s\left(\frac{\gamma q'}{q_0}\right)\left(\frac{\Delta\gamma}{\gamma}\right)^2$, which in our case will be determined by quantum fluctuations of the synchrotron radiation and equals to $\lesssim10^{-7}\omega_s$.

In an experiment the beam depolarization time is measured versus the frequency $\omega_d$. The effective resonance width $\delta\mathcal{E}$ is characterized by the frequency band where the depolarization rate is about maximum. The central resonance width $\delta\mathcal{E}_0$ is equal to the spin-frequency spread in the beam $\delta\Omega$, if $\delta\Omega$ exceeds the decrement of the radiative damping of particle oscillations $\lambda$ /5/. When $\delta\Omega \ll \lambda$ and $\Delta \ll \omega_\gamma$ the resonance width is /5,6/:

$$\delta\mathcal{E} = (\delta\Omega)^2/\lambda$$

The side resonance widths $\mathcal{E}_\delta = \pm n\omega_\gamma$ are determined by the synchrotron frequency spread $\omega_\gamma$ $(\delta\omega_\gamma \gg \lambda)$ and usually they are much higher than that of the central one. In our case $\lambda \approx 10^{-5}\omega_s$ and $\delta\mathcal{E} \approx 10^{-7}$, while $\Delta\gamma/\gamma \approx 10^{-3}$.

Thus, inspite of the spread in the beam particles energy the spin dynamics is such that the measurement of the central frequency of the spectrum, in principle, enables us to determine the absolute value of the mean energy to the limiting accuracy, preset by a value known for the anomalous magnetic moment of an electron /7/

$$q'/q_c = (1.1569157 \pm 0.000003) \cdot 10^{-3}$$

At present, however, the energy measurement accuracy for the storage ring VEPP-2M is restricted by harmonical pulsations of the magnetic field with an amplitude of about $10^{-5} H_z$ and frequency 50 Hz and slow irregular field pulsations also leading to "smearing" of the mean frequency of spin precessions up to the level $10^{-4}\ \omega_s$.

### 3. The Precession Frequency Measurement

For the present study a longitudinal field $H_v$ on the orbit was produced by a depolarizer represented by a current-carrying loop around a ceramic section of the vacuum chamber. The loop is a part of the resonance circuit being swung by an external generator at a frequency close to $\overline{\omega_d} = \omega_s \cdot (2-\gamma q'/q_0)$. A quick search for a resonance can readily be done by utilizing a depolarizing field with frequency modulation at $\omega_d = \overline{\omega_d} + \Delta\omega_d \cdot \cos\Omega_d t$



Provided that the successive resonance crossings are uncorrelated and rapid, the depolarization time $\tau_d = \Delta\omega_d / W_0^2$, where $W_0 = \omega_s \frac{H_v}{H_z}\frac{\ell}{2L}$ is the frequency of the spin precession about the direction $H_v$, $\ell/L$ is the effective relative length of the longitudinal field.

In our case the synchrotron modulation index $\frac{\Delta}{\omega_\gamma} \approx 0.1 \ll 1$. Under these conditions the depolarization rate at side frequencis $\mathcal{E}_\delta = \pm n\omega_\gamma$ is exponentially small, and the central spectrum line is readily separated by measuring the depolarization time versus mistuning $\mathcal{E}_s$.

The measurements were made in the following way: an electron beam after polarization at a high energy was switched over the experimental energy: the polarization-dependent counting rate $\dot{N}$ of particles escaped from the beam due to elastic scattering within a bunch was measured /8,3/. At the moment T a depolarizer was switched on at a frequency $\omega_d$ and a relative measurement of the counting rate $\Delta\dot{N}/\dot{N}$ was performed. Provided that the resonance condition $\omega_d = \omega_s \gamma \frac{q'}{q_c} \pm \omega_\gamma$ is met, the counting rate increases with time, representing the process of beam depolarization (Fig. 1).

The results of the depolarization measurement for the central and side resonances are given in Fig. 2, from which it is seen that the qualitative resonance pattern corresponds to that expected. Between the resonances depolarization was not observed. The depolarization band width $\Delta\omega_d$ thus measured was equal to about 30 kHz. Then that band was reduced to 2 kHz (Fig. 3). This enabled the mean particle energy to be determined by the central line depolarization with an accuracy $\Delta\gamma/\gamma \approx 10^{-4}$ (Fig. 4) which was an order lower than the energy spread.

The first application of this method for measuring the beam energy consisted in the measurement of the $\Phi$-meson mass /9/. Before the experiment absolute calibration of the storage ring energy scale was made. Fig. 5 shows a calibration plot where the X-axis represents values of the nuclear magnetic resonance (NMR) by which the storage ring magnetic field value was controlled. The measured value of the $\Phi$-meson mass accounts for 1019.4 $\pm$ 0.3 MeV that is in good agreement with the results of other experiments /10/.

Thus, the resonance depolarization method even in the first experiments provided the record accuracy of determination of the mean energy of the storage ring particles and enabled an important physical result to be obtained. In further development of the method (a reduction in the magnetic field pulsations, etc ) it might be real to measure energy accurate to $\Delta\gamma/\gamma \approx 10^{-5}$ that offers strong possibilities for performing a number of high-precision experiments. Of particular interest is verification of the CPT-theorem which can be done in the following way:

1. Compare masses of the $K^{\pm}$ and $K^{-}$ mesons efficiently produced with low kinetic energies in the $\Phi$-meson maximum.
2. Compare the anomalous magnetic moments of electrons and positrons during their simultaneous resonance depolarization.

In conclusion, the authors wish to acknowledge the useful discussions with V.N. Baier, L.M. Kurdadze, V.A. Sidorov and the whole team of VEPP-2M for the participation in the experiment.

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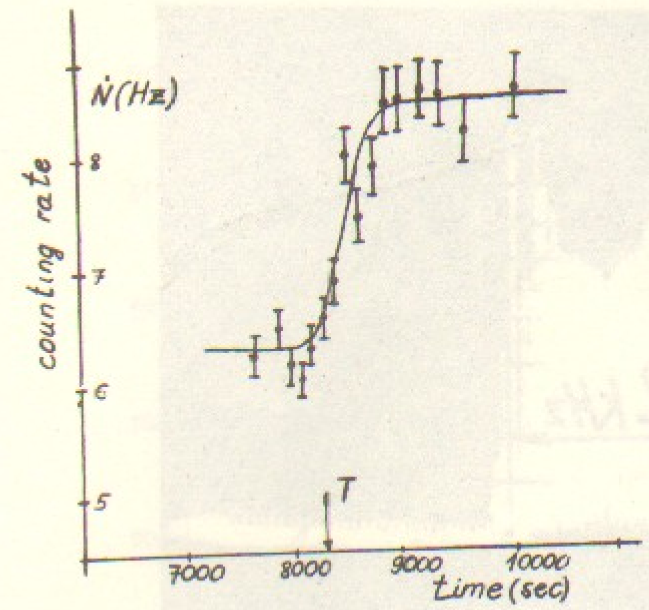


Fig. 1. The dependence of the counting rate on time in the process of beam depolarization.

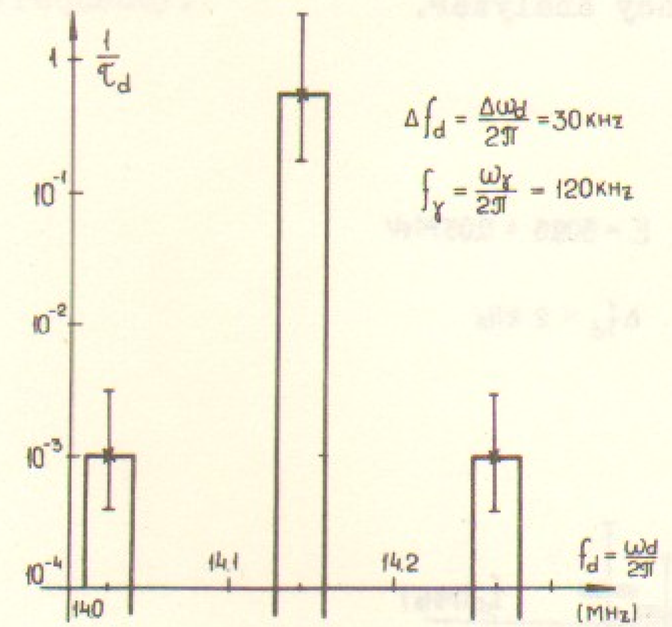


Fig. 2. The dependence of the inverse depolarization time on the depolarizer frequency.

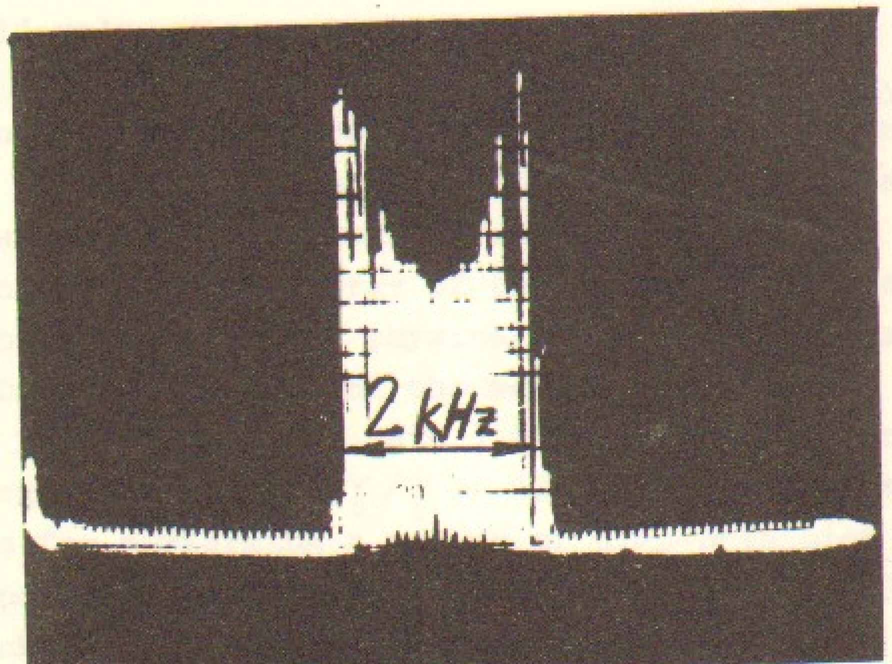


**Fig. 3. The spectrum of depolarization frequencies measured by a frequency analyzer.**

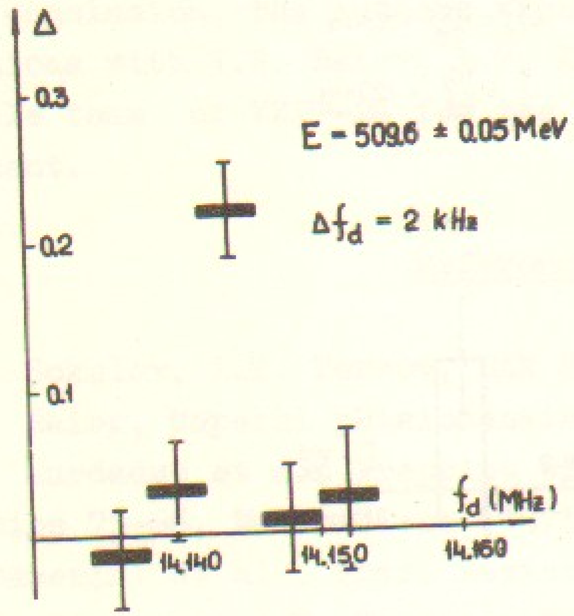


**Fig. 4. The counting rates versus the depolarizer frequency.**



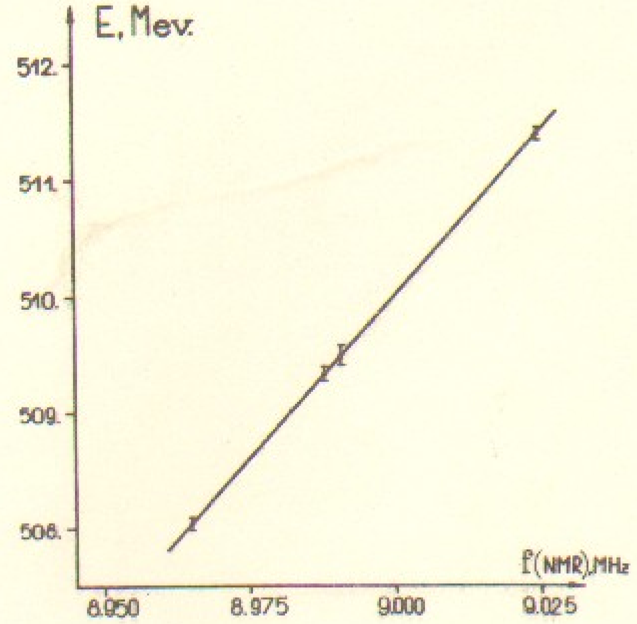


Fig 5. The value of measured energy versus depolarizer frequency.

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