

ACCELERATOR ASPECTS OF THE PRECISION MASS MEASUREMENT EXPERIMENTS AT THE VEPP-4M COLLIDER WITH THE KEDR DETECTOR *

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Abstract

Two methods for particle energy measurement are realized at the electron-positron collider VEPP-4M: one based on the resonant depolarization technique and another using the Back Compton Scattering. KEDR detector measurements of the J/ψ -, Ψ ' mesons and the tau-lepton masses performed with the help of these methods is better in accuracy now in the world. Peculiarities of the beam energy calibration as well as of the mass measurement experiments are represented in the viewpoint of requirements on beam parameters and accelerator systems.

INTRODUCTION

The VEPP-4 accelerator facility with electron-positron colliding beams is known by the experiments on high precision calibration of the fundamental mass scale since the early eighties [1]. In 2002, the new series of similar experiments was started at VEPP-4M, the modernized collider ring, with the KEDR versatile magnetic detector. We improved the J/ψ and $\psi(2s)$ mass accuracy by a factor of 3-4 as compared with the world average one which had been based on our results of 80s. Owing to this fact, the J/ψ and $\Psi(2s)$ meson masses are now among the ten most accurate elementary particle masses measured over the entire history of physics. The measurement of the tau-lepton mass at its production threshold performed at the VEPP-4M collider is most accurate to date [2]. We obtained the D^0 - and D^\pm -meson mass values (the second and the best results in accuracy, respectively) matching with the world average data.

The following activities at VEPP-4 contributed to so high precise results:

- the beam polarization measurement and beam energy monitoring methods including the new ones were developed and applied;
- the problems on accuracy of energy calibration by spin precession frequency were studied at new level;
- the questions on optimal tuning of VEPP-4 systems and operation modes for obtaining and application of beam polarization in mass measurements were set and resolved.

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BEAM ENERGY CALIBRATION

Resonant Depolarization technique

The Resonant Depolarization (RD) technique for measuring the beam energy was proposed and implemented for the first time at BINP [3]. This approach was widely used thereafter both at the BINP and in other laboratories throughout the world.

In an ideal storage ring with the planar orbits, the average energy of electrons in a beam E is related to the average spin precession frequency Ω by the simple equation

$$E = mc^2\gamma = mc^2 \cdot \frac{q_0}{q'} \cdot \left(\frac{\Omega}{\omega_0} - 1 \right) = 440.64843(3) \cdot \nu,$$

with q' and q_0 , the anomalous and normal parts of the gyro-magnetic ratio; ω_0 , the revolution frequency; $\nu = \gamma q' / q_0$, the spin tune parameter. Limiting accuracy of the energy determination by the spin frequency $\delta E / E \approx 7.8 \cdot 10^{-8}$ is due to errors in knowledge of the fundamental constants. To measure Ω one needs to have a polarized beam in a storage ring, a system to observe the beam polarization as well as a system for enforced beam depolarization at the external spin resonance.

State of the VEPP-4M beam polarization at energies up to 2 GeV is observed by comparison of the Touschek electron/positron counting rate from the polarized and unpolarized bunches separated by a half turn ("two bunch method") [4]. The system of scintillation counters installed at several azimuths and put into the dynamic aperture provides a total counting rate ~ 1 MHz/mA at the distance of counters to the beam orbit ≈ 1 cm. The relative counting rate experiences a jump $\sim 1\%$ at the moment of depolarization proportional to squared level of polarization.

The two matched striplines of the VEPP-4 kicker are used to create a TEM wave propagating towards the beam. The signal source is a frequency synthesizer with a minimal frequency step of 0.35 mHz [4]. Scan rate and the TEM wave amplitude are tuned to provide the depolarization time ~ 1 second. The reference frequency signal for the synthesizer as well as for the VEPP-4M RF system is generated by the rubidium frequency standard (10^{-10}). Typical behavior of the measured effect in a time and the depolarization jump are shown in Fig.1. Absolute energy RD calibration accuracy is of a record level: $\delta E / E \sim 10^{-6}$. It is determined by the spin tune spread $\delta\nu / \nu \sim 5 \cdot 10^{-7}$ due to quantum diffusion of particle trajectories taking into account a quadratic non-linearity of the VEPP-4M guide field. To date more than 3000 RD calibrations has been performed.

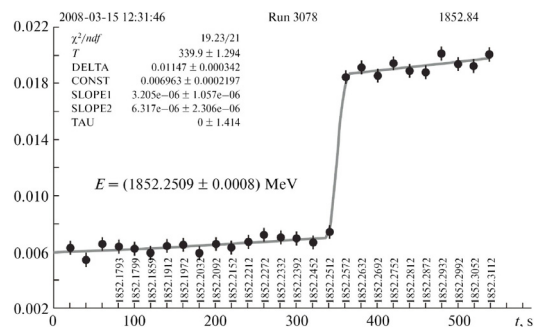


Figure 1: The ratio of counting rates from polarized and unpolarized bunches. Statistical error for the energy found is 0.8 keV.

Compton Backscattering monitor

First beam energy measurements based on the Compton Back Scattering (CBS) was made at the BESSY-I and BESSY-II SR storage rings in Berlin. In 2005 this method was realized at VEPP-4M, for the first time for colliders. Since then, it is a routine instrument for monitoring the VEPP-4M beam energy. At $E < 2$ GeV it was achieved a record accuracy about $5 \cdot 10^{-5}$ in determination of the energy by this method for a half hour of scattered photon statistics acquisition. The method consists in measurement of the CBS spectrum edge (ω_{max}) related to the electron beam energy:

$$E = \frac{\omega_{max}}{2} \left(1 + \sqrt{1 + \frac{m^2}{\omega_{inc}\omega_{max}}} \right),$$

ω_{inc} is the incident photon energy. The infrared CO₂ laser with the wave length 10.6 μm and 50 W CW power is used for radiation generation. The laser spot size in the interaction area is approximately 10 times larger than the electron beam horizontal transverse size to provide a correct measurement of average beam energy. Maximal energy of γ -quanta scattered towards the High Purity Germanium (HPGe) detector lies in the range 4-6 MeV. At first, the available γ -ray sources provided the HPGe energy scale calibration only in the 0.5 – 3 MeV range. Calibration at the 6000 keV edge was made by extrapolation of the low energy data or using RD data of the VEPP-4M energy. Extrapolation gave ~ 100 keV difference between CBS and RD energy measurements. At present, we have the 6.13 MeV γ -quanta source in conjunction with a precise pulse generator. It solves a problem of the independent energy scale calibration. In Fig.2 the experimental spectrum is shown with the fitting applied to its edge. The "edge place" parameter is determined with a relative statistical accuracy $< 3 \cdot 10^{-5}$, while the "edge width" parameter has a statistical uncertainty of about 3%. These parameters together with the energy scale calibration are used to obtain the on-line data of the VEPP-4M beam energy and beam energy spread.

01 Circular Colliders

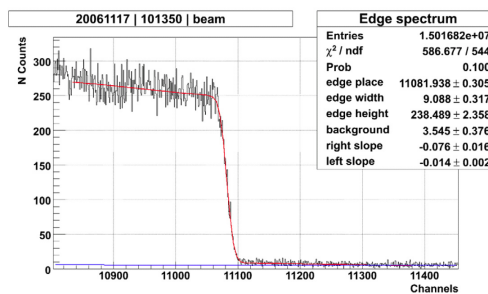


Figure 2: Fragment of the energy spectrum of backscattered photons measured by the HPGe detector.

BEAM POLARIZATION

Polarized beams are obtained in the VEPP-3 booster storage ring owing to the natural radiative mechanism. Polarization rise time $\tau_p \propto E^{-5}$ amounts about 30 min at $E = 1.85$ GeV. For comparison, at VEPP-4M $\tau_p = 70$ hr at the same energy. It makes impossible to obtain the beam polarization in the collider ring. At the same time, it allows to have an acceptable polarization life-time in VEPP-4M even at small off-tunings from the spin resonances. VEPP-3 and VEPP-4M tunes ν_x, ν_y are kept in free cells of the spin resonance grid $\nu + m \cdot \nu_x + n \cdot \nu_y = k$ up to the $|m| + |n| = 10$ order. Feed back system on the VEPP-3 work point stabilization with an accuracy $\delta(\nu_x, \nu_y) = \pm 0.002$ is applied to control the betatron tunes during the radiative polarization process.

VEPP-3 beam polarization degree vs. the beam energy (see Fig.3) was measured in 2003 using a method realized for the first time [6]. New method is based on measuring the asymmetry in scattering of polarized beam electrons on the internal polarized gas jet target. The internal target with the thickness of $\sim 5 \cdot 10^{11}$ electron/cm² is formed by the jet of polarized deuterium atoms from the Atomic Beam Source of Deuteron Facility. The polarization appeared to be small in a wide range below 1840 MeV down to the threshold energy of τ -lepton production (1777 MeV) because of the spin resonances: $E \approx 1815$ ($\nu_x - \nu = 1$), $E \approx 1825$ MeV ($\nu_y - \nu = 1$) and $E = 1763$ MeV ($\nu = 4$). Taking into account this fact, a scenario of τ -mass measurement experiment near the threshold energy was elaborated. Radiative polarization in VEPP-3 and the injection into VEPP-4M of the polarized and unpolarized bunches, needed for RD calibration, occur at $E = 1.85$ GeV. Then the circulating particles are decelerated down to the experiment energy with a rate ≈ 10 MeV/sec.

Because of the integer spin resonance $\nu = 4$ closeness, a depolarizing effect of quantum fluctuations related to the field imperfections is enhanced that leads to decrease of a polarization life-time (PLT). Influence of different sources of such imperfections on PLT was numerically analyzed. Statistically, PLT is estimated to be most likely about or more than 1 hr at energies nearby the " τ - threshold", that is enough for the RD energy calibrations. At first, never-

theless, a rather small PLT, about several hundreds of seconds, was observed [7]. PLT grew to a level ≥ 1 hr after we turned off the vertical orbit bumps in the parasitic interaction points and carried out the global vertical orbit correction. As a whole, it may indicate the existence of an additional factor, for instance, the out of control spin resonant diffusion. Recently, it was suggested to consider from this point of view the second harmonic of the 12.5 kHz ripples in the magnetic correction coils supplied by PWM-generators (an off-tuning from the integer spin resonance at the τ - threshold" makes up about 27 kHz; the instant spin tune spread is 1.4 kHz).

The vertical spin projection of polarized positrons injected at 1.85 GeV is 1.5 times less than that of electrons (having the analogous projection close to 1). It gives a design decrease of depolarization jump in the RD technique by a factor of 2.5. With the aim to eliminate this defect we installed and applied the 2.5 T-m pulse solenoid at the VEPP-3-VEPP-4M beam-line section before the outlet 90° bend magnets. As result, the depolarization jump for positrons increased by a factor 2. This contributed to improvement of an accuracy in the electron-positron energy gap measurement (~ 1 keV) which is important for the systematic error study.

ACCURACY AND STABILITY

We studied and resolved the different questions concerning the instant absolute energy calibration accuracy, the central mass (CM) energy determination errors as well as the collider energy stability.

Suppression of 50 Hz and 100 Hz ripples in the non-linearity corrections improved the RD calibration accuracy from 10^{-4} to 10^{-6} . To avoid the error related to depolarization at the modulation spin resonances we thoroughly calculate the depolarizer efficiency and properly tune the scan mode [8].

Spin tune shift due to a compensation error of the KEDR detector longitudinal field integral does not conserve the "spin tune - energy" ratio. We measured this spin tune shift vs. the anti-solenoid strength [9]. It resulted in minimization of the KEDR field compensation error with an accuracy $\sim 1\%$ and in reduction of the RD systematic energy error down to 1 keV.

Another source of the systematic error is the vertical orbit distortions [10]. The spin tune shift can be written as a quadratic form of the vertical orbit deflection angles composed of two terms: non-correlation and correlation ones. We performed the analytical estimates and Monte-Carlo simulation for the statistically independent perturbations model. It was found that the correlation term can play a determinant role. Correct estimate of the systematic error at the 1.5 mm rms orbit distortions, $E = 1777$ MeV is $\delta E = 1.5 \pm 1.5$ keV, but it is ~ 100 keV when excluding the correlation.

Taking into account the non-uniform distribution of radiative energy losses over the ring, the systematic error in

the CM energy determination by the RD calibration of a single beam can be found in a special experiment as a difference of electron and positron energies. According to our tentative experiments on simultaneous RD calibrations with electron and positron beams their energy gap is ~ 1 keV. We also studied the contributions to the CM energy error from the IP chromaticity, the beam potential, the orbit separation in parasitic IPs and others [11]. At the begin-

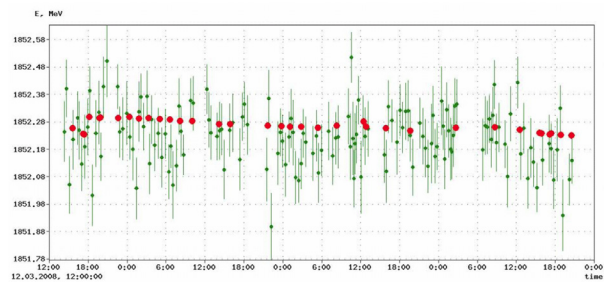


Figure 3: RD (circles blown-up to show) and CBS (dots with dispersion) energy data during 3 days and nights.

ning of regular RD calibrations at the 1.5 GeV VEPP-4M without the water cooling of magnets, the round-the-clock energy oscillations with a several tens of keV amplitude were found caused, presumably, by the tunnel temperature variations. Later on, the system for heatset of the distilled water for cooling of magnets was created [1]. If operating with the heatset system and no changes in VEPP-4M magnet settings the round-the-clock energy drift is \sim one or more keV. In Fig.3 the long-term energy stability run with RD and CBS data is presented.

To improve the energy stability in our most precise RD experiments with the depolarization frequency resolution of $\sim 10^{-9}$ we developed the NMR magnetometer-based field stabilization system [5]. It reduces the field ripples with a period of more than 10 seconds by a factor of ten.

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