PRECISE ENERGY MEASUREMENTS IN EXPERIMENTS ON VEPP-4M COLLIDER*

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Abstract

The series of experiments on mass measurements of J/Ψ, Ψ', X and D mesons have been done on VEPP4-M collider. The accuracy of obtained masses values for Ψ mesons exceeded world value more than 3 times. Experiment on mass measurement of tau lepton is in progress. All these experiments require absolute energy calibration of the beams. Resonant depolarization technique has been used for most accurate energy measurement with relative accuracy of 1 ppm (10^{-6}). Compton backscattering effect is used in developing facility for fast energy measurements. Möller scattering of the beam on polarized gas jet target has been used for beam polarization measurements.

INTRODUCTION.

High accuracy energy calibration of the particle beams is inevitable part of precise mass measurement experiments. The most effective technique for a high-accuracy calibration of the particle energy in electron-positron storage rings is the method of resonant depolarization (RD) [1, 2], based on measurement of the particle's spin precession frequency in the guiding magnetic field. To use RD, one must have an ability to obtain polarized beams, to observe theirs polarization in the storage ring and to depolarize beam on an external spin resonance created by oscillating electromagnetic field (TEM wave or longitudinal magnetic field) whose frequency is scanned. All the necessary tools have been developed and successfully used in recent experiments on mass measurements of J/Ψ, Ψ' mesons [3] and achieved relative accuracy of energy calibration was 10^{-6}. The polarized beam for energy calibration by RD technique is obtained in VEPP-3 booster storage ring.

Preparation for the experiment on τ lepton mass measurement (experiment is in the progress now) brought a necessity to study a radiative polarization in VEPP-3 storage ring. The beam energy in the mentioned experiment is in the vicinity of the tau-lepton production threshold (E = 1777 MeV), where the closeness of the machine integer spin resonance (1763 MeV) significantly enhances the depolarizing effect of the magnetic field imperfections in accelerator. Therefore, the search of the energy range acceptable for obtaining the polarized beams in VEPP-3 and injecting them into the VEPP-4M was very important. To accomplish this task we have developed a method of measurement of the beam polarization in VEPP-3 by a non-destructive way, based on measuring the asymmetry in Möller scattering of polarized electron beam on an internal polarized gas jet target (IPT) [4]. Möller polarimeter provides an absolute measurement of the polarization degree and does not require to destroy the beam polarization.

At the energy range of J/Ψ, Ψ' mesons the necessary time for preparation of the polarized beam is 2 to 1 hours correspondingly and about half an hour the process of energy calibration plus about the same time of overheads. Assigning energy to the statistics acquisition runs between the calibrations cycles is done by known influence on the beam energy of the monitored accelerator parameters, like temperature of the magnets, orbit position, nmr measurements of the magnetic field etc [5]. In contrast to RD technique, a method of compton backscattering (CBS) allows a continuous monitoring of the electron beam energy during the luminosity runs. Therefore it was developed and applied. The CBS method does not require polarized beam and it is based on measuring the maximum energy of scattered photons, which is proportional to squared energy of the beam. This method requires to organize collision of low energy photons with particle beam and calorimeter to measure energy of scattered photons. In order to measure energy of the photons with high accuracy one needs to calibrate his detector, which could be done by isotopes or by RD technique. The CBS method also allows to measure beam energy spread, what is very important for precise mass measurement experiments. Achieved accuracy of the beam energy calibration was $5 \cdot 10^{-5}$.

MEASUREMENT SYSTEMS

Resonant depolarization technique

Spins of polarized electrons precess around the vertical guiding magnetic field with the precession frequency Ω, which in the plane orbit approximation is directly related to the particle energy E and the beam revolution frequency

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ω:

$$\Omega/\omega = 1 + \gamma \cdot \mu'/\mu_0 = 1 + \nu\,, \qquad (1)$$

where $\gamma = E/m_e$, m_e is the electron mass, μ' and μ_0 are the anomalous and normal parts of the electron magnetic moment. The ν is a spin tune, which represents the spin precession frequency in the coordinate basis related to the particle velocity vector. The relation (1) could be rewritten in the form $E = \nu \cdot 440.648434(1)$.

Obtaining polarized beams At the energy range of J/Ψ and Ψ' peaks the VEPP-3 booster storage ring serves as a source of polarized particles for VEPP-4M. Electrons and positrons in VEPP-3 can become polarized due to emission of synchrotron radiation according to the Sokolov-Ternov effect [6] with the design characteristic time $\tau_p \approx 80$ minutes at $E = 1550$ MeV (J/Ψ) and $\tau_p \approx 30$ minutes at $E = 1840$ MeV (Ψ'). Very large polarization time in VEPP-4M ($\sim 10^2$ hours) does not allow to obtain polarized beams immediately in the main ring. The operation time designated for the polarization process is about $2\tau_p$; through this time, the special automatic control system keeps the betatron tunes at VEPP-3 away from the nearest dangerous depolarizing spin resonance, determined by a combination of the spin and betatron frequencies. Because of a 3D spin evolution in the injection beam-line from VEPP-3 to VEPP-4M, the obtained vertical projection of the polarization vector differs from maximum achievable 0.92. The maximal degree of polarization for injected electrons (P_-) and positrons (P_+) does not exceed $P_- = 0.82$, $P_+ = 0.85$ at the injection energy $E = 1550$ MeV and $P_- = 0.88$, $P_+ = 0.54$ at $E = 1840$ MeV.

Forced depolarization The precession frequency can be determined using the resonant depolarization, which could happen if a polarized beam in the storage ring is suffering the external electromagnetic field with the frequency Ω_D given by the relation

$$\Omega \pm \Omega_D = \omega \cdot n \qquad (2)$$

with any integer n (for VEPP-4M in the J/Ψ region $n = 3$). The precession frequency is measured at the moment of the polarization destruction detected by the polarimeter, while the depolarizer frequency is being scanned. The process of forced depolarization is slow enough compared to the period of the synchrotron oscillations of the particle energy. This allows to determine the average spin tune $\langle\nu\rangle$ and corresponding average energy of the particles $\langle E\rangle$ with higher accuracy than the beam energy spread σ_E. Due to modulation of the precession frequency by particle orbital motion, the resonant depolarization could happen at the sideband resonances, which are distant from the main one by multiples of the synchrotron frequencies. Besides, it could happen at the weak sideband resonances caused by extraneous low frequency modulation of the guide field, caused, for example, by pulsations in the power supply system (50 Hz gives an energy shift of about 25 keV). Therefore, it is necessary to identify the main resonance by special means. Also, there is a question about relation of the average beam energy with average spin tune and it was discussed in [7].

The two matched strip-lines of the VEPP-4 kicker are used to create the TEM wave. The signal source is the frequency synthesizer controlled by a computer with the minimal band width of Δf_d lower than 1 Hz and the minimal rearrangement step of 1 Hz. For VEPP-4M, 1 keV in the beam energy scale corresponds to 1.85 Hz in the depolarizer frequency f_d. At J/Ψ energy, the synthesizer frequency is scanned in the vicinity of a half revolution frequency f_0 ($f_d \approx 400$ kHz), i.e. an non-integer part of the spin precession frequency. A stability of f_0 is about 10^{-8} that ensures the energy stability better than 10^{-6}. The power wide-band amplifier can provide the voltage amplitude on strip-lines up to $U_d \approx 200$ Volts. The rate τ_d^{-1} of forced depolarization with the transverse field crucially depends on the absolute value of the spin response function $|F^\nu|$ [8] at the place of the depolarizer location: $\tau_d^{-1} \propto U_d^2 \cdot |F^\nu|^2/\Delta f_d$. At VEPP-4M, the design depolarization time τ_d is about 1 seconds at $E = 1550$ MeV with $U_d \approx 9$ Volts, $\Delta f_d \approx 0.9$ Hz (0.5 keV), $|F^\nu|^2 = 130$. The corresponding accuracy in the current energy determination is $\delta E \approx \pm 1$ keV (the scanning speed is 0.19 Hz/sec (0.1 kev/sec)). In the experiment on τ-lepton mass measurement the plates located at the different place of the accelerator are used for depolarizer due to higher value of the spin response function at the given energy.

Touschek polarimeter The polarimeter [9] is based on observation of the intra-beam (Touschek) scattering. The cross section of the intra-beam scattering is dependent on beam polarization, it is lower for polarized beam. Therefore at the moment of resonant depolarization, the counting rate of scattered electrons will experience a jump proportional to the squared value of the beam polarization degree [8].

The polarimeter device is installed in the technical straight section of VEPP-4M and consist of two counters on opposite sides of the vacuum chamber. The counters can be moved inward the aperture in the horizontal plane and register the electrons scattered at the most part of the ring. Since the trajectories of Touschek pair electrons lie symmetrically on each side of the closed orbit, the two-fold coincidence circuit might be used. To exclude the influence of changes in beam sizes, the closed orbit variations and dependence on the beam life time, the method of "two bunches" is used. The quantity $1 - N_2/N_1$ is under observation, where N_1 and N_2 are respectively the counting rates of the polarized and unpolarized bunches spaced at the half of the turn. Positioning counters at the distance of 1 cm from the beam gives the counting rate in experiments about $10 \div 100$ kHz at the beam current of $2 \div 4$ mA with the jump of $2 \div 3$ % what is in a good agreement with the calculation (polarization degree is 80 %).

Möller polarimeter The polarimeter is based on measuring the asymmetry in Möller scattering of polarized electrons on an internal polarized gas jet target (IPT) [4]. In contrast to the polarimeter based on intra-beam scattering effect, Möller polarimeter provides an absolute measurement of the polarization degree without beam polarization being destroyed. Given $\xi_t = |\vec{\xi_t}|$ target polarization degree and geometrical factor A_g allow to find the beam polarization $\xi = |\vec{\xi}|$ by the experimentally observed value of asymmetry:

$$A \equiv \frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}} = A_g \xi \xi_t \,, \qquad (3)$$

where $N_{\uparrow\uparrow}$ and $N_{\uparrow\downarrow}$ are amount of scattering events registered in two states of the relative polarization orientation, provided by changing sign of the target polarization. The internal target with the thickness of $\sim 5 \cdot 10^{11}$ electron/cm^2 is formed by the jet of polarized deuterium atoms. The direction of target polarization is flipped periodically (every 20 sec) from parallel to anti-parallel relative to the electron beam polarization. It is done by the holding field magnet, which creates a magnetic field with magnitude of 300 Gauss near the beam-jet interaction region. The polarimeter detector system consists of two nearly identical arms, installed symmetrically in vertical plane. They detect both electrons (from the beam and from the gas jet) in coincidence taking into account their coordinate correlation in horizontal plane. Design parameters of the polarimeter provide a counting rate of about 6 Hz at the beam current of ~ 100 mA. It takes about 8 minutes for data acquisition to measure the asymmetry with a 20% statistical error in case of 80% beam polarization.

The application of a new method allowed to carry out an absolute measurement of polarization degree in a wide range of VEPP-3 energy with sufficient efficiency [10]. The result of this is that for tau lepton mass measurement experiment injection of the polarized particles should be done at energy about $E = 1850$ MeV and than beam is deaccelerated in VEPP-4M to the tau-threshold energy [11, 12].

Compton backscattering technique

The head-on interaction of the intense monochromatic laser light with the electron beam gives a flux of backscattered photons. In case of the low energy photon and ultrarelativistic electron ($\varepsilon \gg m \gg \omega$), the highest possible energy of backscattered photon is given by:

$$\omega_{max} = \frac{\varepsilon^2}{\varepsilon + m^2/4\omega_0} \,, \qquad (4)$$

where ε is an energy of electron, ω_0 is an energy of laser photon, m is an electron rest mass. Knowing the electron mass m and the laser photon energy ω_0 one can get the average energy of the particles in the electron beam from the measured value of ω_{max}. The width of the energy spectrum edge allows to measure the beam energy spread. This technique was originally implemented at the BESSY-I and BESSY-II storage rings [13].

To satisfy the needs of the experiment the infrared CO_2 laser with wave length of 10.591 μ and output continuous power of $25 \div 50$ Wt was chosen. The photon spectrometer is based on the High Purity Germanium (HPGe) calorimeter (Canberra model GC2518 detector, 120 ml active volume). The maximum energy of scattered photons is about 6 MeV at the energy range of the tau lepton threshold. Detector calibration is done by RD technique and spectrometer energy resolution is 1.5 keV.

The CBS technique allowed energy calibration with accuracy of $5 \cdot 10^{-5}$ and beam energy spread measurement with accuracy of 20%.

CONCLUSION

The developed resonant depolarization technique together with Touschek polarimeter allowed us to accomplish mass measurement experiments of J/Ψ, Ψ', X and D mesons. Obtained masses of J/Ψ, Ψ' mesons have an accuracy of 3 times better than in previous experiments [3]

$M_{J/\Psi} = 3096.917 \pm 0.010 \pm 0.007$ MeV,

$M_{\Psi'} = 3686.111 \pm 0.025 \pm 0.009$ MeV.

X and D mesons data is in processing.

Application of Möller polarimeter allowed us to study spin resonances in VEPP-3 and prepare experiment on τ lepton mass measurement. Study and following correction of the integer spin resonance influence allowed to increase depolarization time in VEPP-4M and apply RD technique for energy calibration. The τ lepton mass measurement experiment is under progress and Compton backscattering method is applied to monitor energy and energy spread of the beam.

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