ACCELERATOR PHYSICS ISSUES OF THE VEPP-4M AT LOW ENERGY

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Abstract

The VEPP-4M electron-positron collider is now operating for a high-energy physics experiments in the 1.5-2.0 GeV energy range. During the first experimental run with the KEDR detector (2001-2002), mass measurements of the J/ψ and ψ' mesons have been carried out with a record accuracy. To provide high performance, efforts for investigation and further development of the machine have been done, the most important results are described. A record absolute accuracy of energy measurement was achieved using the resonant depolarization method. For the first time, the Möller polarimeter based on an internal polarized gas jet target has been developed and successfully used at the VEPP-3 booster storage ring. A system of energy measurement using Compton backscattering has been put into operation. To increase the machine luminosity, operation with dipole wigglers is studied, and a project of turn-by-turn feedback system to suppress beam instabilities has been started. For beam diagnostics, a fast multi-anode photomultiplier tube and a white light coronograph have been installed.

INTRODUCTION

The VEPP-4M electron-positron collider is now operating with the general-purpose detector KEDR [1] in the 1.5-2.0 GeV energy range for high-energy physics (HEP) experiments with the J/ψ, ψ' and ψ'' mesons, which recently are objects of a substantial interest. As a sequel of our previous experiments [2], we continue data collection at the ψ' resonance (3686 MeV) to increase the data array already stored. Also we provide data acquisition at the ψ'' (3770 MeV) in order to measure its mass with the accuracy 3-4 times better than published in PDG table, and also to study $D^{\pm}$ and D^0 mesons.

This low-energy operation mode is not standard for the VEPP-4M designed for 6 GeV energy. To provide high performance, a number of works for investigation and further development of the accelerator facility have been done. The most essential of them are:

- high precision energy measurement by the resonant depolarization method and the Möller polarimeter;
- routine energy measurement using Compton backscattering;
- increase of luminosity in the low energy range;
- non-linear beam dynamics study;
- development of beam diagnostics instrumentation.

Modernization of the KEDR detector has been completed lately, the main super-conducting solenoid with maximal field of 6 T and two 20 T compensation coils have been successfully commissioned, the field compensation is good enough in the view of beam dynamics.

ENERGY MEASUREMENT

Resonant Depolarization Method

The method of high precision measurement of mean beam energy by spin depolarization has been developed in BINP in 1970-th [3]. An electron beam is polarized in the booster VEPP-3 and injected into the VEPP-4. Then a non-polarized beam is also injected. The depolarizer system excites beam oscillation by an RF signal, frequency of which sweeps with some step around the spin precession frequency. Special counters, introduced into the vacuum chamber, register electrons deflected by the intra-beam scattering, the count rate is $\dot{N}_1$ for polarized bunch and $\dot{N}_2$ for non-polarized one. Since the intra-beam scattering depends on the particle spin, the $\delta = 1 - \dot{N}_1/\dot{N}_2$ ratio increases step-wise, when depolarization of the polarized bunch occurs (see Fig. 1). The exciting signal frequency at this moment uniquely corresponds to the beam energy [4].

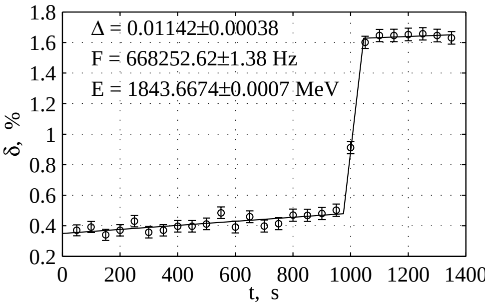

Figure 1: Resonant depolarization.

The energy measurement accuracy is limited mainly by the depolarizer bandwidth (~4 Hz) and comes to $\Delta E = \pm 1$ keV. Regular energy calibration with the record resolution of 10^{-6} are realized now at the VEPP-4M.

Compton Backscattering Method

A new system for absolute beam energy measurement uses the head-on interaction of the CO_2 laser radiation with the VEPP-4M electron beam. The maximal energy of the backscattered γ-rays is strictly coupled with the electron energy [5]. High purity Germanium detector Canberra GC2518 (120 ml active volume) is used to measure the spectrum of backscattered photons. The sharp edge of the Compton spectrum allows to determine the beam energy with statistical uncertainty about $3 \cdot 10^{-5}$ for the 6 min data

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acquisition cycle. At the same time the energy spread of the electron beam is measured with the 10% accuracy.

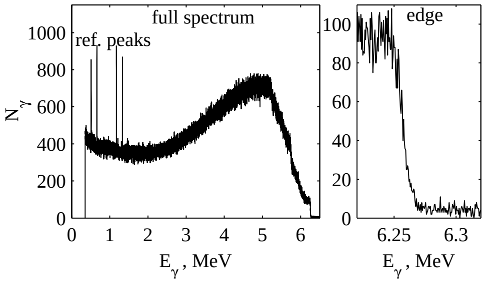

Figure 2: Compton spectrum.

This system is just started in May, 2004 with the goal of permanent beam energy monitoring in addition to relatively rare energy calibrations by the resonant depolarization technique. A preliminary measurement result is shown in Fig. 2, there are full Compton spectrum and its sharp edge, corresponding to the beam energy of 1845.1 MeV.

Möller Polarimemter

In the near future, one of the main task for the VEPP-4M will be measurement of the τ-lepton mass at its production energy threshold (1777 MeV) with the help of resonant depolarization technique. This energy is quite close to the strong integer spin resonance $\nu_s = 4$ (1762.6 MeV). Since a test electron beam is polarized in the VEPP-3 booster, the energy dependence of the VEPP-3 beam polarization degree is the crucial issue.

For the VEPP-3, we have developed a new method of polarization measurement based on the Möller scattering of polarized beam electrons in a polarized internal target. Angular distribution of the scattered electrons, depended on the polarization degree, can be measured by a detector system. In our Möller polarimeter, a polarized deuterium jet ($5 \cdot 10^{11}$ atoms per cm^2) is used as the internal target. The target polarization direction is controlled by a zero-integral vertical magnet producing an alternating-in-sign magnetic field. The scattered electrons are registered by two counters placed above and below the median plane.

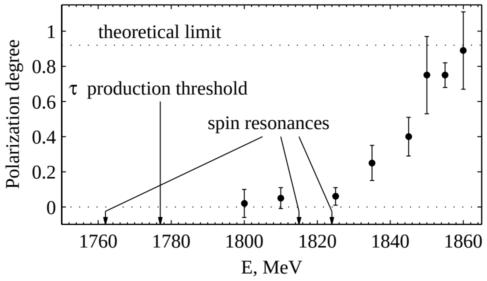

Figure 3: Polarization degree of the VEPP-3 beam.

Using the method proposed, we have measured the beam polarization degree as a function of the beam energy. In Fig. 3 one can see a significant decrease of the polarization degree in the vicinity of the τ-lepton energy. Because this effect makes impossible injection of polarized beams at the energy of experiment, the following work scenario has been chosen: beams are injected into the VEPP-4M at the 1850 MeV energy, then decelerated down to 1777 MeV.

Systematic errors

To reach high accuracy of energy measurement, a number of technical problems have been solved, such as fine adjustment of the depolarizer, suppression of 50-Hz pulsation of the power supplies down to 3 ppm, providing of the power supplies long-term stability at the level of $\pm 5 \div 20$ ppm, etc.

We have carried out careful investigation of the factors which can change the measured energy and in that way to contribute to the systematic error of particle mass measurement. The most significant of them are described below.

The cooling water temperature, change of which leads to the relative energy deviation -40 ppm$/°$C. Except a thermal movement of the tunnel and magnets, this is the main energy destabilizing factor. To take into account this effect, before each HEP experiment, the temperature dependence of energy is measured and then used in the experiment data processing.

Energy difference between electron and positron beams. Direct measurement has shown, that this effect does not exceed 4 ± 2 keV.

Influence of electrostatic beam separators, which are switched on during energy measurement but are off during a luminosity run. The measured value of this influence is less than 4 keV.

Slow deviation of the horizontal closed orbit, which can results in uncontrollable energy drift due to the orbit length change. The estimation and measurement show that to reach the required value of $\sigma_E \approx 5 \cdot 10^{-6}$, the horizontal orbit deviation should not exceed $\sigma_x \leq 0.1$ mm during a data collection run.

Chromaticity of the lattice functions in the interaction point, which leads to a shift of luminosity maximum from the beam mean energy. This effect can be minimized by tuning of sextupole magnets.

LUMINOSITY OPTIMIZATION

The energy lowering from the designed 6 GeV down to 1.5-2 GeV required for the HEP experiments, is a serious problem in the view of the collider performance because of strong energy dependence of the luminosity, $L \propto E^4$. We have managed doubling of luminosity in respect to the 2001 run due to change the VEPP-4M mode of operation from 1×1-bunch mode to 2×2-bunch one. We plan to increase the luminosity 1.5 times more by a moderate lattice modification: shift of the working point as close as possible to the half-integer resonance and decrease of vertical beta in the interaction point from actual 5 cm down to 2.5 cm.

Another common way of luminosity rise is the use of wigglers to increase the horizontal emittance, and thus to raise the beam-beam threshold current. However the wiggler fields produce such undesirable effects as increase of radiation damping time, aberration of linear optics, and reduction of dynamic aperture.

In our case, two 3-pole 1-m long dipole wigglers with the 1.8 T maximal field cause the vertical betatron tune shift of $\nu_y \approx 0.09$, and 50% beating of the vertical beta. We have managed to compensate the tune shift and reduce the beta beating down to 10% by proper adjustment of quadrupoles. Moreover the wigglers considerably change the nonlinear detuning coefficients, which can lead to the dynamic aperture reduction observed. We tried to bring back the nonlinear detuning by a local octupole magnet. Although we did not managed full compensation of all the coefficients, the dynamic aperture has been almost reached the non-perturbed one.

Computer simulations promise doubling of luminosity thanks to the wigglers, but the experiments show only 1.7 times luminosity rise. As it was also noticed, the maximum possible emittance growth (4 times) is not optimal from the point of view of the maximal luminosity.

BEAM DIAGNOSTICS

Efficiency of the collider operation noticeably depends on a beam diagnostics tool kit, which usually needs a continuous upgrade. To study beam dynamics, especially instabilities and beam-beam effects, two new optical devices have been developed and installed at the VEPP-4M.

The coronograph is an instrument similar to one using in astronomy to observe the Sun corona. In this device, while the central part of an intensive light source is obscured, the periphery is focused at a CCD camera. High sensitivity of the coronograph allows to register synchrotron radiation emitted by a beam of 1000 electrons only, its relative accuracy is 10^{-6}.

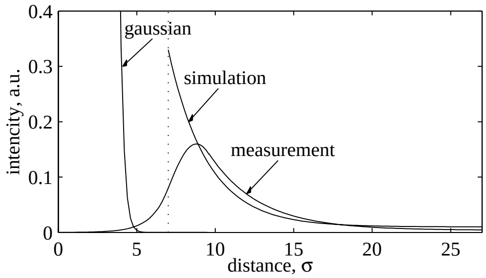

Figure 4: Beam ”tail” measured by coronograph.

This instrument is used to study a peripheral (beyond 7σ) transverse distribution of beam particles. In Fig. 4, there is a measured beam ”tail” in comparison with the computer simulation and with the Gaussian distribution. Zero distance is in the beam center. As one can see, the particle distribution in a real beam significantly differ from the Gaussian.

Another promising instrument is the fast multi-anode photomultiplier tube (PMT). This device can measure and store up to 2^{17} samples of transverse beam profile. Proper processing of the stored data gives a detailed picture of turn-by-turn evolution both of the beam center of mass and of the r.m.s. beam size.

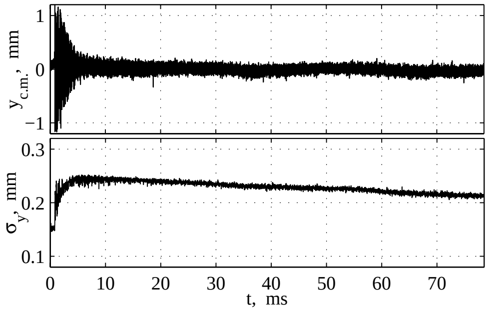

Figure 5: Decoherence of betatron oscillation.

As a measurement example, in Fig. 5 there is a decoherence (Landau damping) of betatron oscillation excited by a short kick. One can see how the center of mass oscillation (upper plot) damps while the r.m.s. beam size (lower plot) increases and then decreases slowly with a characteristic time of radiation damping. The PMT is also used for beam convergence observation

CONCLUSION

Precise energy calibration is an advantage of the VEPP-4M, which, in spite of moderate (in comparison with the modern factories) luminosity, makes our facility suitable for some classes of HEP experiments requiring accurate measurement of particle energy. After the present-day more accurate measurements of the ψ' and ψ'' masses, we plan to start a new experiment for high-precision mass measurement of τ-lepton at its production threshold. For this experiment, the polarization technique will be improved to obtain higher energy resolution. We project subsequent development of beam diagnostics instrumentation. Further upgrade of the control system is ongoing now to improve reliability of the VEPP-4M operation. To provide high-current beam injection, a project of turn-by-turn feedback is under development.

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