CENTRAL MASS ENERGY DETERMINATION IN HIGH PRECISION EXPERIMENTS ON VEPP-4M*

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Abstract

The series of experiments on mass measurements of J/Ψ, Ψ' and Ψ'' mesons have been done on VEPP-4M collider. The accuracy of obtained mass values for J/Ψ- and Ψ'- mesons exceeded the world values about 3 times, based on experiments on VEPP-4 [1] and E760[2]. The ongoing experiment on τ lepton mass measurement is expected to achieve accuracy 1.5-2 times better than the present world value. The present paper describes the process and uncertainties of luminosity weighted interaction energy definition. The errors of interaction energy include uncertainties due to beam energy calibration by resonant depolarization technique and errors of interaction energy calculation.

INTRODUCTION

Successful accomplishing of the experiments with colliding beams requires precise knowledge of the average energy of the particles interaction. The process of interaction energy determination on VEPP-4M [3] consists of the following steps:

1. the beam average spin tune is measured by resonant depolarization technique (RD) [4];
2. the average beam energy is calculated considering vertical orbit distortions, solenoid field of the detector, spin tune width etc [5, 6, 7, 8] (uncertainties are less than 2 keV);
3. calculation of the average beam energy at the IP (azimuthal energy dependence);
4. calculation of the luminosity weighted average interaction energy (requires knowledge of beam energy and spatial distributions).

The goal of this paper is to describe a process of central mass energy calculation starting from obtained average beam energy.

BEAM SEPARATION IN PARASITIC IPS

During the luminosity run beams in VEPP-4M are vertically separated in three parasitic IPs. Vertical orbit bumps are causing second order horizontal orbit distortions due to constancy of the closed orbit length and thus changing beam average energy. The energy shift is given by formula

$$\frac{\Delta E}{E} = -\frac{1}{\alpha\Pi}\int\frac{z'^2}{2}ds\,, \qquad (1)$$

where α is momentum compaction, Π – circumference, $z' = dz/ds$, s – azimuth. Since energy calibration is done with all separations being off than invariant mass correction is $2\Delta E$. If vertical orbit correctors are interleaved by bending magnets (bump in the arcs) the spin tune is not proportional to energy any more. This correction was calculated and taken into account during the energy calibration.

Table 1: Invariant mass correction, $E = 1850$ MeV.

Origin place	amplitude of the separation, mm	$2\Delta E$, keV
arcs	4	-4
technical area	5	-4.6

There is a skew sextupole in the center of the technical area (one of the parasitic IPs). Given orbit displacements x – horizontal and $\pm y$ – vertical (different sign for electrons and positrons due to separation) in the skew sextupole create vertical field causing an energy shift of opposite sign for electrons and positrons

$$\frac{\Delta E}{E} = -\frac{1}{\alpha\Pi}\eta\frac{SxyL}{H\rho}\,, \qquad (2)$$

where $H\rho(kGs\cdot cm) = E(MeV)/0.3$ is mean field and radius of the machine, $S = -23$ Gs/cm^2 – skew sextupole strength, $\eta = -140$ cm – dispersion at the center of the skew sextupole. During the experiments horizontal orbit was displaced at $x = -5.5$ mm, $y = -4.5$ mm for electrons and $y = +4.5$ mm for positrons. Thus at $E = 1850$ MeV the energy shift for electrons is $\Delta E = -7.7$ keV and for positrons $\Delta E = +7.7$ keV. Also energy of the beams is shifted due to vertical orbit distortion on the value of 2.3 keV (the same sign for electrons and positrons). So, during the luminosity run energies of the electrons and positrons differ by $E^+ - E^- \approx 15.4$ keV which would have been an invariant mass correction if calibration was performed in the same conditions as luminosity run. However, calibration was done without separation, therefore giving invariant mass correction of $\Delta E^- + \Delta E^+ = -4.6 \pm 2$ keV (due to second order orbit distortion) at $E = 1850$ MeV.

AZIMUTHAL ENERGY DEPENDENCE

Energy calibration by RD allows one to obtain energy averaged over ensemble of particles and the closed orbit. However, in order to calculate average interaction energy it is necessary to know beam average energy at the interaction

* The work is supported by RFFR 07-02-00426-a, 07-02-00661-a and SS-8621.2006.2
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point. Energy calibration on VEPP-4M is performed on electron beam and as a result electron beam energy $\langle E^- \rangle$ is defined.

Neglecting second order terms (which are evaluated lower), the central mass energy is given by summation of electrons end positrons energies at IP: $W = E^-(IP) + E^+(IP)$, which should be written as

$$\begin{aligned} W = &\; 2\left\langle E^- \right\rangle + \left(\left\langle E^+ \right\rangle - \left\langle E^- \right\rangle\right) \\ + &\; \left(E^-(IP) - \left\langle E^- \right\rangle\right) + \left(E^+(IP) - \left\langle E^+ \right\rangle\right) . \end{aligned} \quad (3)$$

The sources of azimuthal beam energy dependence are: azimuthal dependence of energy losses which arises from magnetic field errors in elements of VEPP-4M and different impedances of the vacuum chambers in the arcs, and beam potential.

Numerical calculations showed that $(\langle E^- \rangle - \langle E^+ \rangle)/E_0 = 5 \cdot 10^{-9} \pm 15 \cdot 10^{-9}$ with RMS magnetic fields errors of $\sigma(\Delta B/B) \simeq 1 \cdot 10^{-3}$ and corresponding orbital distortions RMS 3 mm.

There are gradient wigglers at the entrance into each arc of the VEPP-4M. The orbital difference in each wiggler will result in different energy loss thus creating difference of average energies of electrons and positrons. The estimation showed that invariant mass correction is negligible at orbital differences of 3 mm.

The measurements of transverse impedance of the VEPP-4M are described in [9] and show 4% difference of specific impedances ($k\Omega m/m^2$) of arcs vacuum chambers. Using that longitudinal impedance is proportional transverce one and knowing coherent energy loss per turn (5 keV/mA) it was estimated that absolute value of cenral mass energy shift is lower than 0.2 keV.

Every particle of the beam experiences influence of electrical field of particles either own beam or incoming beam. The potential of the beam depends on beam sizes, vacuum chamber radius, which are changing along the azimuth. Energy calibration by RD determines average Lorentz factor γ of the beam which is different from one at the IP. Estimation [10] showed that invariant mass correction is 2 ± 1 keV for beam currents of 2 mA.

INVARIANT MASS

Taking into account beam angular and energy spreads it is possible to calculate invariant mass averaged over momenta of colliding particles. This will give an estimation of second order terms. For VEPP-4M energy $E = 1850$ MeV (Ψ'-meson) angular spread RMS are $\sigma_{x'} \sim \sigma_{y'} \sim 4 \cdot 10^{-4}$, energy RMS is $\sigma_E/E \sim 5 \cdot 10^{-4}$ and corrections of the invariant mass do not exceed 0.3 keV.

LUMINOSITY WEIGHTED INTERACTION ENERGY

Chromaticity of optical functions is distorting beam density in energy dimension, thus making luminosity energy distribution not symmetrical and shifting the mean interaction energy [10]. The measurements of beta function chromaticity allowed to calculate invariant mass shift: -4 ± 2 keV for J/Ψ and $+5 \pm 2.5$ keV for Ψ'.

VERTICAL DISPERSION OF OPPOSITE SIGN FOR ELECTRONS AND POSITRONS

The electrostatic separation of the beams in parasitic IPs excites dispersion, which has opposite sign for electrons and positrons due to opposite deflections of the beams. Existence of such a dispersion will disturb the energy distribution of luminosity and in presence of nonzero impact parameter will shift the luminosity weighted central mass energy E_t from the doubled mean energy of the beams E_0 in the IP [10]. In case of VEPP-4M collider the interaction energy shift is

$$\left\langle \frac{E_t - 2E_0}{E_0} \right\rangle = \frac{2\varphi_y d_y \sigma_\delta^2}{\varphi_y^2 \sigma_\delta^2 + \sigma_y^2} , \quad (4)$$

where φ_y – dispersion of opposite signs for electrons and positrons, d_y – half of the beams separation in vertical plane, σ_δ – and σ_y – beam energy and vertical RMS.

Separation from errors of luminosity tuning

The beam separation in the IP could have origin in orbit distortions from vertical separation in the parasitic IPs. During the accelerator tuning the maximum of the luminosity is achieved with an error defined by luminosity measurement uncertainty. On the VEPP-4M accuracy of the luminosity tuning to maximum is about $\Delta L/L \sim 2\%$, with corresponding $|d_y| = 1.4\,\mu$m, $\sigma_y = 10\,\mu$m, $\sigma_\delta = 5 \cdot 10^{-4}$, $|\varphi_y| = 800\,\mu$m and the interaction energy shift is $|E_t - 2E_0| = 10.5$ keV at $E_0 = 1850$ keV (Ψ'). During the experiment a special study showed a way to reduce the vertical dispersion to $|\varphi_y| = 300\,\mu$m. Fig. 1 shows dependance of the interaction energy shift on luminocity deviation from maximum and beam separation at $E_0 = 1850$ keV (Ψ').

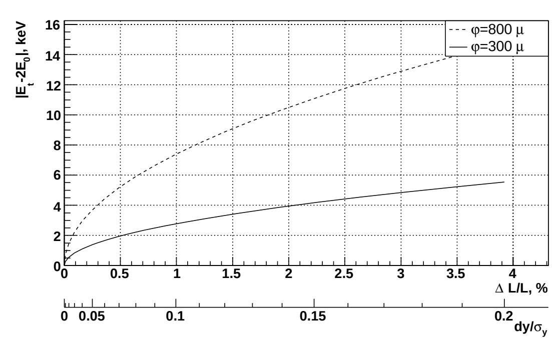

Figure 1: Interaction energy shift versus luminosity deviation from maximum and beam impact parameter.

1-4244-0917-9/07/$25.00

Separation due to beam-beam effects

Beams separated in parasitic IPs experience an opposite sign kick from the each others fields leading to orbit distortions and beam separation in IP. The strength of the kick depends on the beam current, therefore beam separation and interaction energy shift depend on beam current also. At VEPP-4M consideration of such a kick gives beam separation of $2d_y = 0.4\,\mu$m ($\Delta L/L = 0.2\%$) for 2 mA beams and interaction energy shift is $|E_t - 2E_0| = 3$ keV at $E_0 = 1850$ keV and $|\varphi_y| = 800\,\mu$m. The beam separation at IP could be written as

$$d_y = \frac{d_0 + \Delta y_{tech}(I) + \Delta y_{arc}(I)}{1 + 4\pi\xi_y(I)\cot(\pi\nu_y)}\,, \qquad (5)$$

where d_0 – initial constant to provide zero impact parameter at initial beam current I, $\Delta y_{tech}(I)$ and $\Delta y_{arc}(I)$ are representing the influence of beam separation in technical area and in two arcs correspondingly, $\xi_y(I)$ – space charge parameter, ν_y – vertical betatron tune. The calculations for VEPP-4M are shown on Fig. 2 at $E_0 = 1850$ keV (Ψ'). When beam current is reduced from 3 mA to 1 mA, emerging beam separation leads to interaction energy shift of 4 keV ($\varphi_y = 300\,\mu$m). This shows an importance of periodical adjusting of the beams convergence, thus averaging energy shift to zero, only creating an RMS of interaction energy determination.

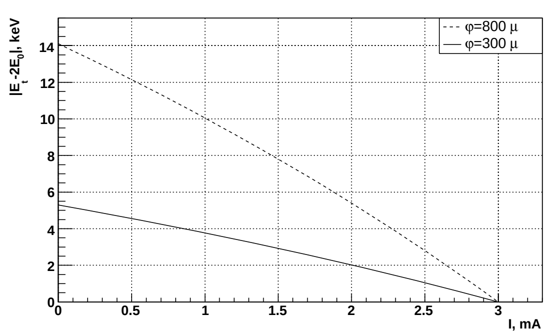

Figure 2: Interaction energy shift versus beam current. Impact parameter is zero at beam current 3 mA.

CONCLUSION

All uncertainties in definition central mass energy could be divided on corrections and errors. Correction means that corresponding value should be added to invariant mass $W = 2E_{RD}$, where E_{RD} is obtained from energy calibration (with all corrections related to RD applied) and errors are values defining confidence interval. The summary of corrections and errors in J/Ψ– and $\Psi(2S)$– mesons mass measurement experiments on VEPP-4M collider is presented in Tables 2 and 3. During the luminosity run the radial orbit variations contribute into statistical error of central mass energy definition.

Table 2: Corrections of central mass energy definition in mass measurement experiments of J/Ψ– and Ψ'– mesons

Source	J/Ψ keV	$\Psi(2S)$ keV
Separation in parasitic IP	-3.8	-4.6
Chromaticity of optical functions at IP	-4	$+5$
Influence of the own beam potential	$+2$	$+2$
Energy and angular spread	-0.2	-0.3
Coherent energy loss	$< \|0.2\|$	$< \|0.3\|$

Table 3: Errors of central mass energy definition in mass measurement experiments of J/Ψ– and Ψ')– mesons

Source	Comment	J/Ψ keV	$\Psi(2S)$ keV
Accuracy of beam convergence	statistical	3.4	4
Chromaticity of optical functions at IP	correction error	2	2.5
Horizontal orbit distortion $\delta x \sim 20\,\mu$m	statistical	1.5	1.8
Influence of the own beam potential	correction error	1	1
Coherent energy loss	correction error	0.1	0.1

During the luminosity run, beam energy was interpolated with the help of magnetic fields measurements in bending magnets by NMR sensors, temperatures of the magnets and tunnel, correctors currents and orbit position. The error due to energy assignment is $7 \div 15$ keV [8].

In this paper we presented most significant factors defining accuracy of the experiments. Consideration of other less important factors is not presented.

ACKNOWLEDGEMENT

The authors are very grateful to V. Kiselev, V. Smaluk, E. Levichev, V. Blinov for numerous helpful discussions.

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