Central Mass Energy Determination in High Precision Experiments on VEPP-4M

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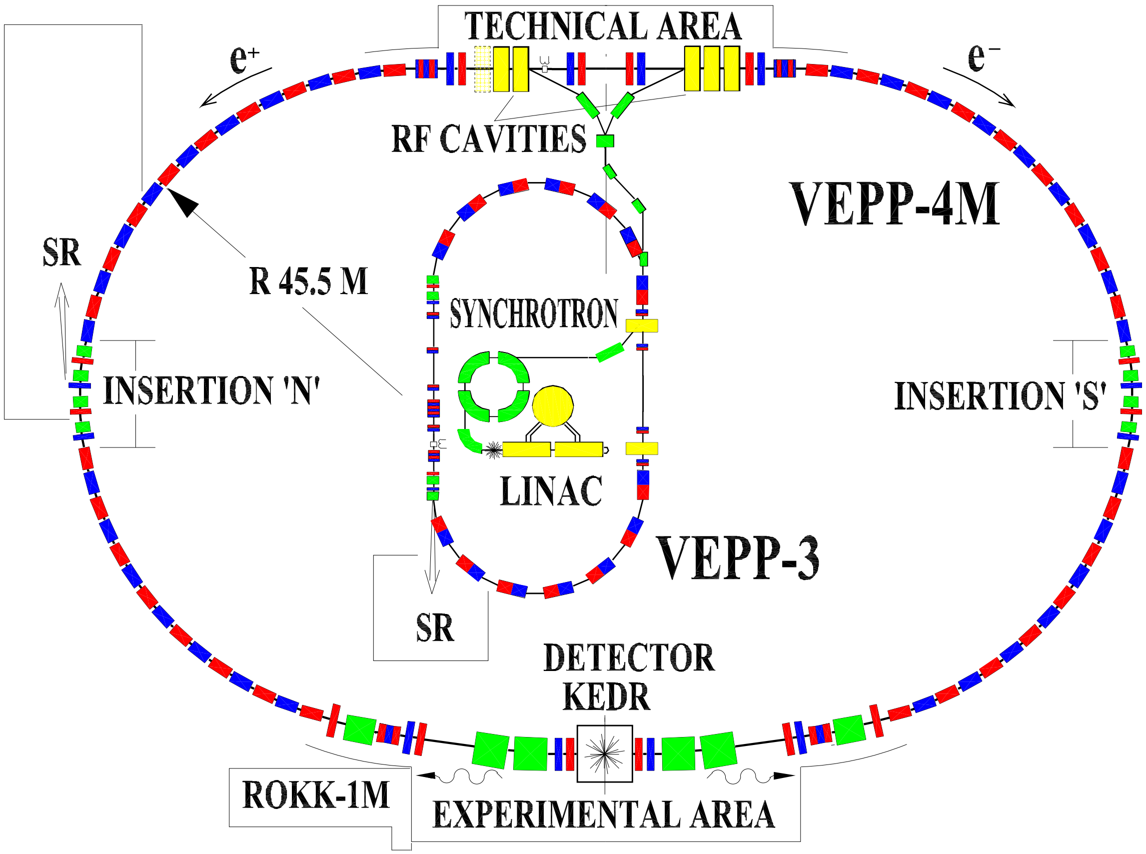
Introduction

- $M(J/\Psi) = 3096.917 \pm 0.010 \pm 0.007$ MeV.
- $M(\Psi') = 3686.111 \pm 0.025 \pm 0.009$ MeV.

Interaction energy definition:

1. the beam average spin tune is measured by resonant depolarization technique ($\Delta\nu/\nu \leq 10^{-6}$);
2. the average beam energy is calculated (*considering vertical orbit distortions, longitudinal detector field, spin tune width, orbital bumps, accuracy of depolarizer frequency measurements, 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 interaction energy (*requires knowledge of beam energy and spatial distributions*).

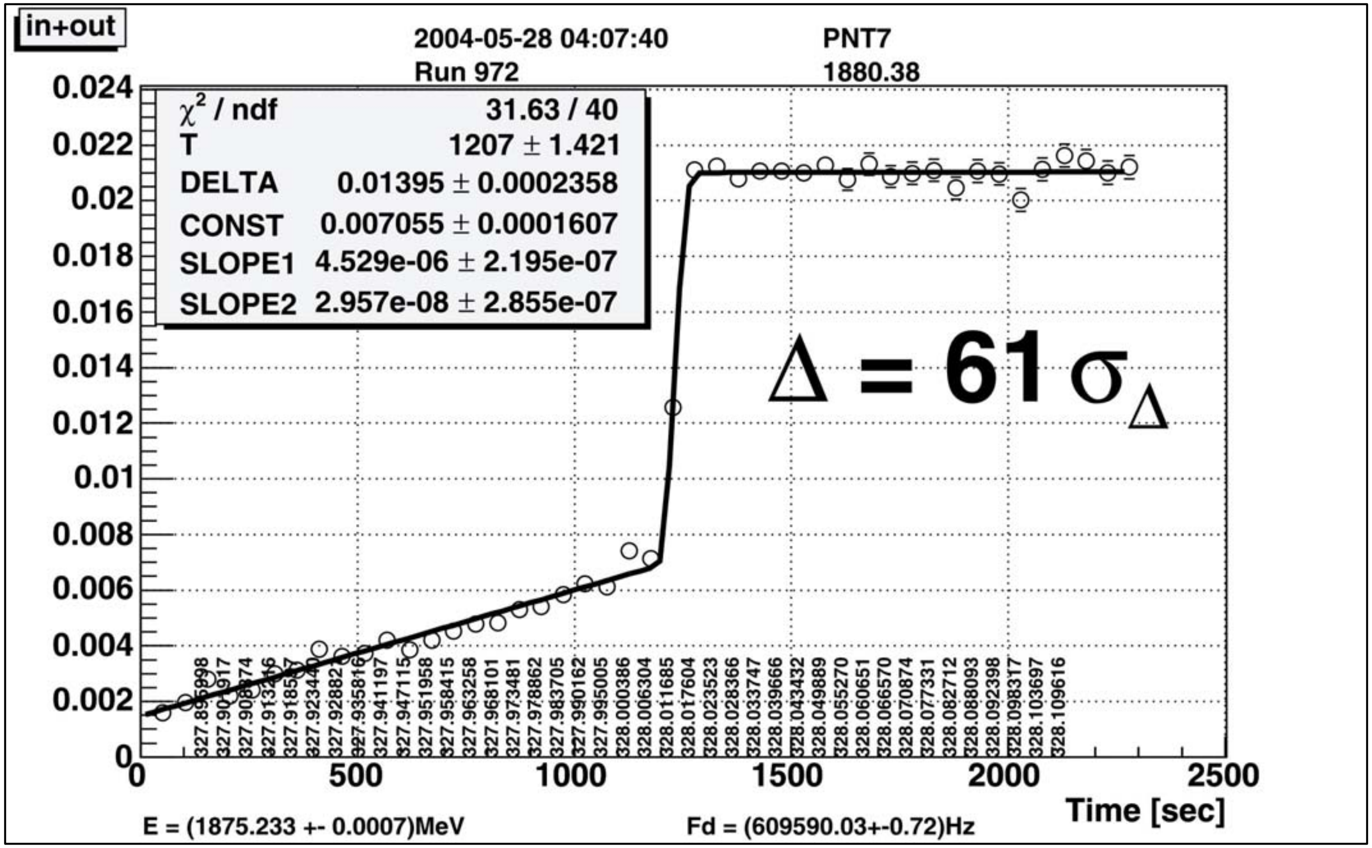
VEPP-4M



Circumference, m	366
β(IP) h/v, m	0.62 0.05
Dispersion at IP, m	0.78
Energy, Mev	1850
Energy spread	$5 \cdot 10^{-4}$
σ'(IP), rad	$4 \cdot 10^{-4}$
σ(IP) h/v, mkm	257/10
Bunches per beam	2
Beam current, mA	3
Luminosity	$2 \cdot 10^{30}$

Resonant depolarization technique

E[MeV]=440.64843(3)·ν



The depolarization is observed at the moment of the jump in counting rate of Touschek electrons.

Beam separation in parasitic IPs

During luminosity run beams are vertically separated in 3 parasitic IPs.

Energy shift due to vertical orbit distortion: $$\frac{\Delta E}{E} = -\frac{K_0^2}{2\pi\alpha}\oint \frac{z'^2}{2} d\theta$$

Invariant mass correction at E=1850 MeV

Origin place	Separation amplitude, mm	2ΔE, keV	Spin tune shift 2ΔE, keV
Arcs	4	-4	-1.4
Technical area	5	-4.6	0

Beam separation in parasitic IPs

- There is a skew sextuple in the center of technical area.

- Given orbit displacement x – horizontal, y – vertical (opposite sign for e^- and e^+) create vertical field causing energy shift

$$\frac{\Delta E}{E} = -\frac{1}{\alpha \Pi}\eta \frac{SxyL}{B\rho}$$

$$\Delta E^{\mp} = \mp 7.7\,\text{keV}$$

- Energy shift due to second order orbit distortion

$$\Delta E = -2.3\,\text{keV}$$

- During luminosity run e^- and e^+ energy difference is

$$E^+ - E^- \approx 15.4\,\text{keV}$$

- Energy calibration is performed with separation off, therefore correction is at E=1850 MeV

$$\Delta E^+ + \Delta E^- = -4.6 \pm 2\,\text{keV}$$

Azimuthal energy dependence

- Neglecting second order terms: $W = E_{IP}^{-} + E_{IP}^{+}$
- However, energy calibration gives $\langle E^{-} \rangle$, therefore

$$W = 2\langle E^{-} \rangle + \left(\langle E^{+} \rangle - \langle E^{-} \rangle\right) + \left(E_{IP}^{-} - \langle E^{-} \rangle\right) + \left(E_{IP}^{+} - \langle E^{+} \rangle\right)$$

Sources of azimuthal beam energy dependence

1. Azimuth dependence of energy loss
   - magnetic field errors
   - gradient wigglers
   - different impedances of vacuum chambers
2. Beam potential

Azimuthal dependence of energy loss

- Magnetic field errors: $\left(\langle E^- \rangle - \langle E^+ \rangle\right)/E_0 = 5\cdot 10^{-9} \pm 15\cdot 10^{-9}$

  $\sigma(\Delta B / B) \cong 1\cdot 10^{-3}$, orbit RMS 3 mm

- Gradient wigglers at the entrance into each arc:
  correction is negligible at orbital difference of 3 mm

- Impedance difference of arcs vacuum chambers
  (*4% difference in specific impedances of arc vacuum chambers*)

  Equal beam currents of 2 mA
  Energy loss per turn 5 keV/mA

  $\left(\langle E^- \rangle - \langle E^+ \rangle\right) \le 0.2\,\text{keV}$

Beam Potential

Beam potential depends on beam size and vacuum chamber radius. For beam currents of 2 mA invariant mass correction is 2±1 keV.

Invariant mass

Momentum averaged invariant mass

$$\langle W \rangle_p = \langle E^+ + E^- \rangle_p - \frac{\left(\sigma_{x'}^2 + \sigma_{y'}^2\right)}{2} \langle E \rangle_p - \frac{\sigma_E^2}{2\langle E \rangle_p} - \frac{\left(\langle E^+ \rangle_p - \langle E^- \rangle_p\right)^2}{4\langle E \rangle_p}$$

At $\langle E \rangle_p$=1850 MeV (Ψ' region)

$$\sigma_{x'} \cong \sigma_{y'} \cong 4 \cdot 10^{-4}$$

$$\sigma_E \cong 5 \cdot 10^{-4}$$

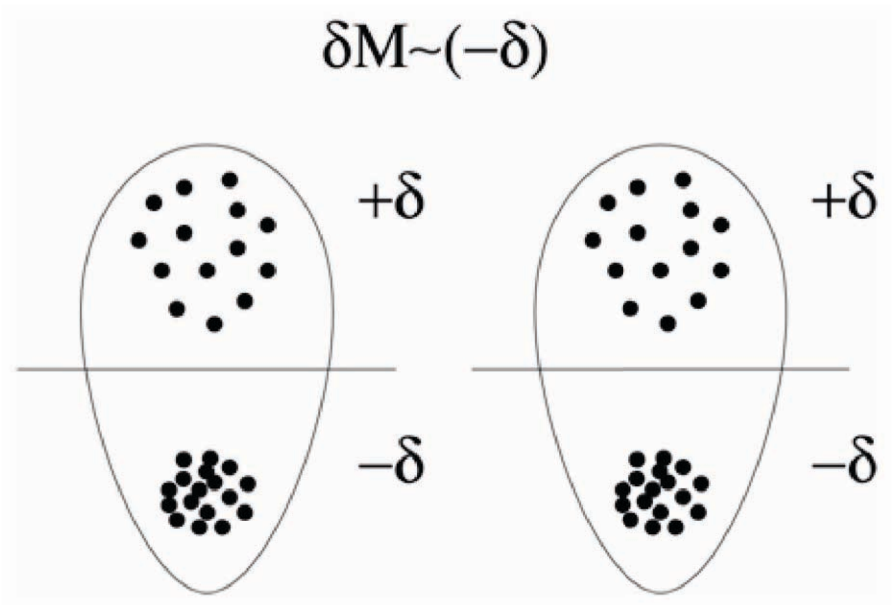
$$\frac{\left(\sigma_{x'}^2 + \sigma_{y'}^2\right)}{2} \langle E \rangle_p + \frac{\sigma_E^2}{2\langle E \rangle_p} \le 0.3 \text{ keV}, \quad \frac{\left(\langle E^+ \rangle_p - \langle E^- \rangle_p\right)^2}{4\langle E \rangle_p} \le 0.05 \text{ keV}$$

Second order corrections are less then 0.3 keV.

Luminosity weighted interaction energy

Chromaticity of optical functions

$$\begin{cases} \beta_{(x,y)} = \beta_{0(x,y)} + \beta_{1(x,y)}\delta \\ \eta = \eta_0 + \eta_1\delta \end{cases}$$



Example of measurements

$$\frac{1}{\beta_x(IP)}\frac{d\beta_x(IP)}{d\delta} = 38.5 \pm 21$$

$$\frac{1}{\beta_y(IP)}\frac{d\beta_y(IP)}{d\delta} = -11.7 \pm 3$$

$$\frac{1}{\eta}\frac{d\eta}{d\delta} = 3.46$$

Energy distribution of luminosity is not symmetrical.

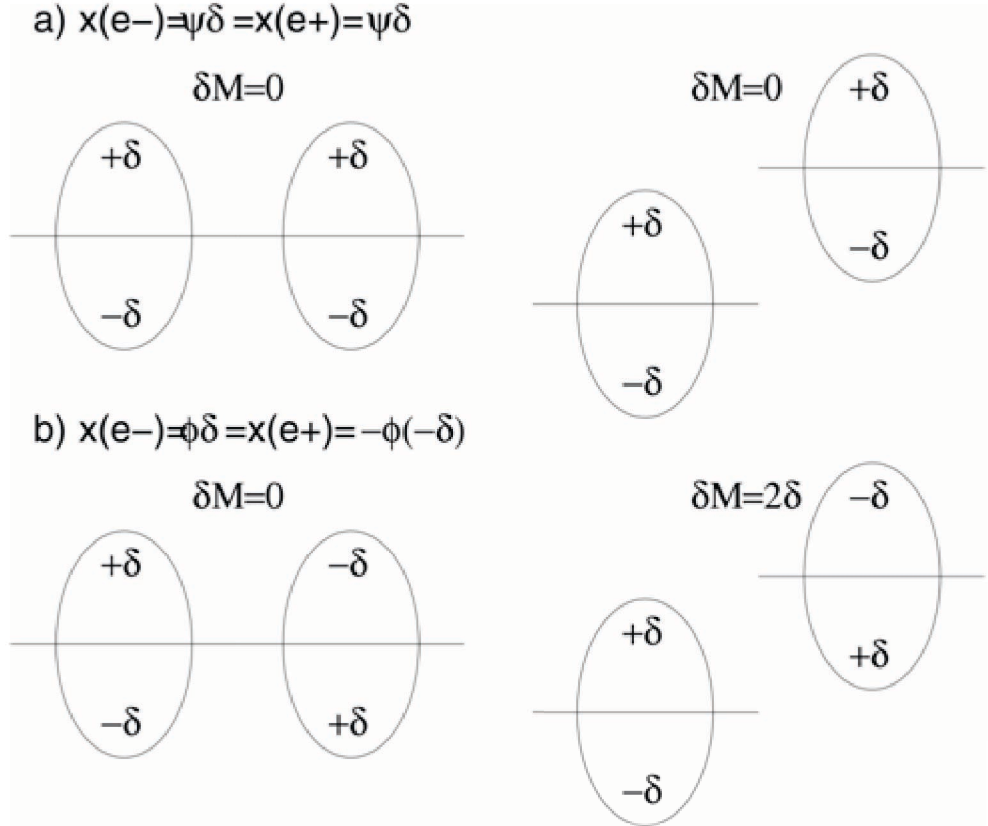
Invariant mass shift -4±2 keV for J/Ψ and +5±2.5 keV for Ψ'.

Vertical dispersion of opposite sign for electrons and positrons

Electrostatics gives rise to vertical dispersion of opposite sign for e- e+ – φ_y.

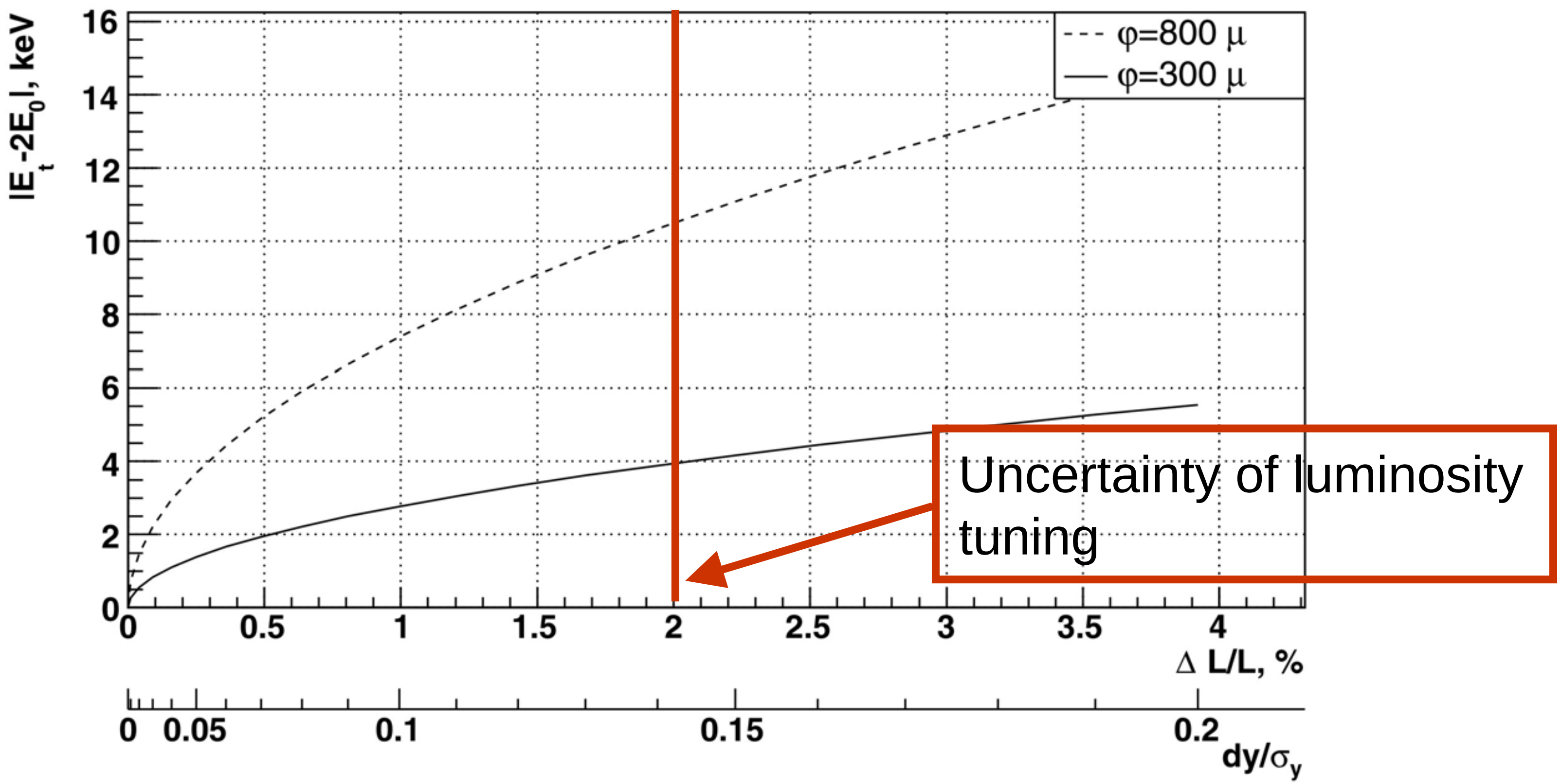
The energy shift is

$$\left\langle \frac{W - 2E_0}{E_0} \right\rangle = \frac{2\varphi_y d_y \sigma_\delta^2}{\varphi_y^2 \sigma_\delta^2 + \sigma_y^2}$$



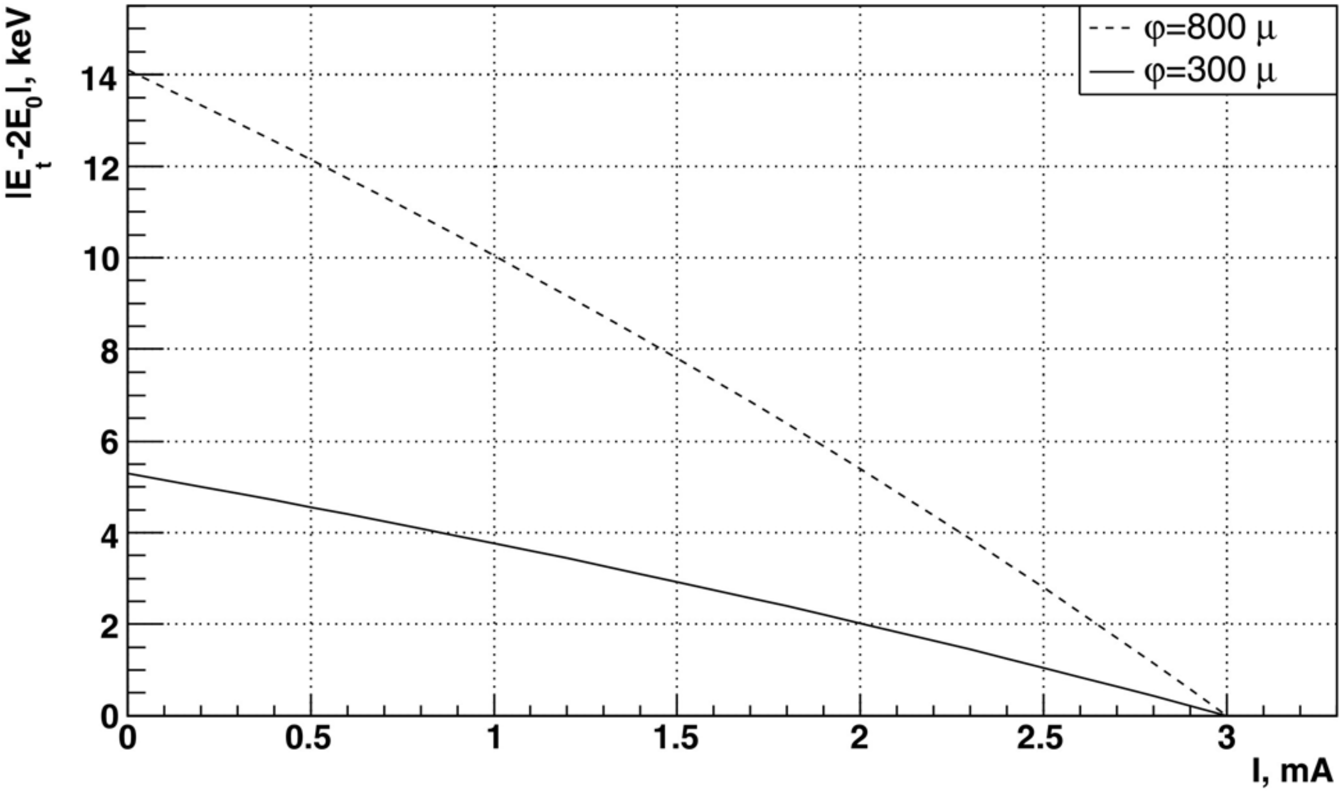
d_y – half of beam separation,
σ_δ and σ_y beam energy and spatial RMS

Separation from errors of luminosity tuning



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

Separation from beam-beam effects



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

Corrections of central mass energy definition in mass measurement experiments of J/Ψ- and Ψ′- mesons.

Source	J/Ψ, keV	Ψ′, 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|

Errors of central mass energy definition.

Source	Comment	J/Ψ, keV	Ψ′, keV
Accuracy of beam convergence	Statistical	3.4	4
Chromaticity of optical functions at IP	Correction error	2	2.5
Horizontal orbit distortion $\delta x \approx 20$ mkm	Statistical	1.5	1.8
Influence of the own beam potential	Correction error	1	1
Coherent energy loss	Correction error	0.1	0.1

The error due to energy assignment is 7÷15 keV