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G.I. Budker INSTITUTE OF NUCLEAR PHYSICS

V.A. Kiselev, N.Yu. Muchnoi, O.I. Meshkov,
V.V. Smaluk, V.N. Zhilich, A.N. Zhuravlev

BEAM ENERGY SPREAD MEASUREMENT AT THE VEPP-4M ELECTRON-POSITRON COLLIDER

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V.A. Kiselev, N.Yu. Muchnoi, O.I. Meshkov,
V.V. Smaluk, V.N. Zhilich, A.N. Zhuravlev

Budker Institute of Nuclear Physics
630090, Novosibirsk, Russia

Abstract

The VEPP-4M electron-positron collider is now operating with the KEDR detector for the experiment of precise measurement of tau-lepton mass. In this experiment, monitoring of beam energy spread is important to know the energy spread contribution into the total systematic error. Information about the energy spread gives an opportunity to reduce the error of the tau-lepton mass measuring. Several techniques or measuring the energy spread are described in the paper. Width of the ψ' resonance measured with the KEDR detector is used as a reference.

Измерения энергетического разброса пучка на электрон-позитронном коллайдере ВЭПП-4М

В.А. Киселев, А.Н. Журавлев, В.Н. Жилич,
О.И. Мешков, Н.Ю. Мучной, В.В. Смалюк

Институт ядерной физики им. Г.И. Будкера
630090, Новосибирск, Россия

Аннотация

Текущая физическая программа коллайдера ВЭПП-4М и детектора КЕДР состоит в прецизионном измерении массы тау-лептона. Определение и контроль энергетического разброса пучка в этих экспериментах важно для оценки вклада этого параметра в общую систематическую ошибку. Информация об энергетическом разбросе дает возможность снизить ошибку измерения массы. В препринте описаны несколько методов, использованных для измерения энергетического разброса пучка. В качестве репера использовалась ширина ψ' резонанса, определенная детектором КЕДР.

1. INTRODUCTION

The basic physical program of the VEPP-4M collider consists in precise measurements of mass of J/ψ, ψ', ψ'' narrow resonances and $c-\tau$ lepton mass on the threshold production. Value of beam energy spread σ_E is directly included into accuracy of the mass measurement. Knowledge of exact value of the beam energy spread enables us to reduce significantly a systematical error in the experiment of $c-\tau$ lepton mass measurement. It is also an essential supplement to the precise measurement of average beam energy.

Clear understanding of the reasons influencing the beam spread and the ability to control this value are important tasks for our experiments.

The VEPP-4M collider (Fig.1) is operating in 2×2 bunch mode with vertical electrostatic separation of the beams at parasitic interaction points.

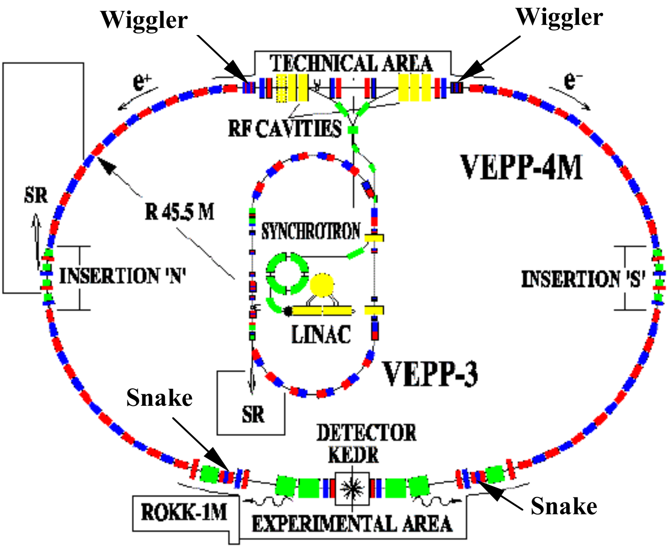

Fig. 1. VEPP-4M general layout.

Optical structure of the VEPP-4M is reflection symmetric about an axis, passing through centers of experimental and technical area. Values of functions β_y, β_x, η_x at the interaction point are β_y = 5 cm, β_x =70 mm and η_x = 80 cm.

Radial beam size σ_x and beam currents limited by beam-beam effects are basically determined by energy spread.

Feature of the VEPP-4M magnet structure is the usage of compatible focusing elements. Historically, the accelerator was designed as a proton machine. The selected parameters of the periodical cells lead to the negative value of radial decrement $\alpha_x < 0$.

The radial radiation damping of the beam is provided by two gradient Robinson wigglers installed in the technical area at the points with non-zero dispersion function $D_x \neq 0$. Wiggler field variation enables us to redistribute the damping decrements between radial and longitudinal beam motion resulting in the variation of the beam energy spread σ_E . Wiggler field value is selected through the compromise between the desirable precision of the mass measurement and the acceptable level of luminosity.

Energy spread of the beam can be increased with the 3-pole snakes established in the experimental area (Fig.1). Snakes have a length about 1 m and 1.8 T maximal strength of magnetic field. They were applied only during the beam energy spread measurements described below.

2. MODES OF THE VEPP-4M OPERATION

The target of our experiments was not only the definition of the beam energy spread for basic modes of the collider operation, but also the comparison of several procedures for measurement of relative energy spread $\delta_E = \frac{\sigma_E}{E}$.

The experiments were carried out at the four modes of the collider operation (Tab. 1). The modes differ both in the energy E and in the energy spread σ_E value.

Table 1. Operation modes of the VEPP-4M used for energy spread measurements

Name	E, MeV	I_{WG}, A	I_{SN}, A	Comments
PNT4	1843	1055	0	$c - \tau$ lepton production. KEDR magnetic field is on.
PSIS	1843	1055	0	KEDR magnetic field is off.
ZMEJ	1843	1055	2000	KEDR magnetic field is off.
JPSI	1548	620	0	J/ψ meson peak. KEDR magnetic field is off.

Application of several methods to determine the energy spread for different modes of the VEPP-4M operation enables us to realize a cross-validation of the measurements and to compare the diagnostics considering convenience and efficiency.

3. METHODS

Spectrum of chromatic sideband peak of beam betatron oscillation (I)

Optical system [3, 6] was applied to measure the beam dimensions $\sigma_{x,y,z}$ and spectrum of vertical betatron oscillations.

Chromaticity of a storage ring causes appearing of synchrotron sideband peaks in a spectrum of beam oscillation. The amplitude of the central betatron frequency and the synchrotron satellites is [4]:

$$R_m(y) = \frac{1}{y^2}\int_0^\infty J_m^2(x)\, e^{-x^2/2y^2}\, x dx \ , \tag{1}$$

where $y = \left(\frac{\omega_\beta \alpha}{\omega_s} + \frac{\omega_0 C_y}{\omega_s}\right)\delta_E$, m is the number of harmonic, δ_E is the relative energy spread. Fig. 2 represents peak height normalized to the peak of $m = 0$ at $y = 0$ for $\alpha = 0.017$, $\nu_s = 0.061, \nu_y = 7.571, \delta_E = 4 \cdot 10^{-4}$.

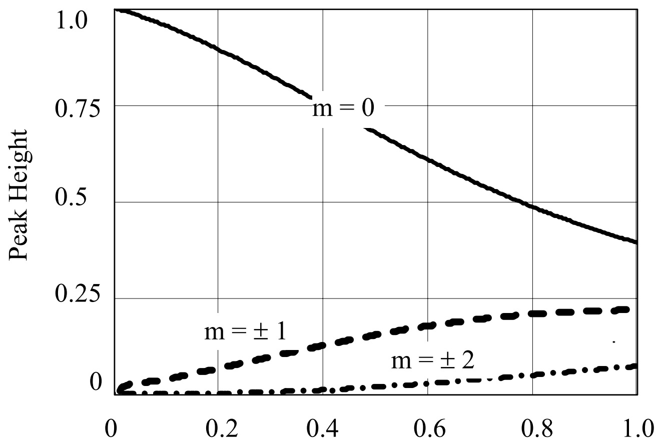

Fig. 2. Relative intensities of the betatron peak and synchrotron satellites.

Determination of energy spread is based on the measurement of the ratio of synchrotron satellites to the main peak height.

Chromaticity dependence of envelope of betatron oscillations (II)

This approach was proposed in [5]. It was shown that envelope $A(t)$ of free coherent betatron oscillations excited by kick with an amplitude b is described as

$$A(t) \propto \exp\left(-\frac{t^2}{2\tau^2}\right) \cdot \exp\left(-\left(\frac{\partial\omega_y}{\partial E}\frac{\sigma_E}{\omega_s}\right)^2 \cdot \left(1-\cos(\omega_s t)\right)\right) , \qquad (2)$$

where $\tau = \left(2\frac{\partial\omega_y}{\partial a^2} b \cdot \sigma_y\right)^{-1}$. Experimentally, energy spread was determined comparing the measured beam betatron motion with the theoretical curve $A(t)$.

Current dependence of energy spread (III)

The experiments with methods (*I*) and (*II*) were carried out at the small beam current $I_0 = 10 \div 50$ mkA, when collective effects are negligible. In the course of experiments with mesons mass measurements the beam currents were close to beam-beam effect threshold restriction. This value was from 1.5 to 3.5 мA depending on the beam energy spread. Radial and longitudinal beam dimensions $\sigma_{x,z}$ were taken to determine current dependence of the beam energy spread.

Energy spread of the beam was derived from the measured radial size σ_x and known amplitude functions β_x= 620 cm, η_x= 94 cm at the observation point. It was supposed that the main reason, which caused the growth of size σ_x and energy spread σ_E, was Touschek effect.

The experiments performed at [1] allowed us to obtain a semi-empirical formula to estimate the contribution of Touschek effect into beam energy spread. This formula (3) was used to adjust the energy spread dependence with the beam current:

$$\sigma_x = \left[\beta_x \varepsilon_x + \left(\eta_x \delta_{ET}\right)^2\right]^{1/2}, \qquad (3)$$

where $\delta_{ET} \approx \frac{5.1 \cdot 10^{-4}}{E[Gev]}\left(\frac{I_0[mA] \cdot \nu_s}{K}\right)^{1/6}$, $K = \sqrt{\frac{\varepsilon_y}{\varepsilon_x}}$ – coupling coefficient,

$\varepsilon_y, \varepsilon_x$ – beam emittance, $\delta_E = \sqrt{\delta_o^2 + \delta_{ET}^2}$, δ_0 – energy spread at $I_0 = 0$.

Compton Back Scattering (IV)

VEPP-4M collider has a system of Compton Back Scattering for permanent measurement of average beam energy and energy spread. The CBS system is placed at the ROKK-1M installation [8], Fig.1.

When the monochromatic laser radiation with the photon energy w_0 interacts with the contrary relativistic electron beam with average particle energy E_0, the energy spectrum of backscattered photons $\frac{dN}{dw}(w)$ has a shape illustrated in Fig.3.

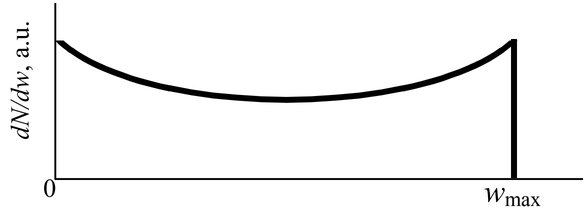

Fig. 3. Energy Spectrum of Backscattered Photons (illustration).

The scattered photons with maximal energy W_{max} form a narrow edge in the spectrum in Fig.3. The value of W_{max} is strictly coupled with the average energy of the beam electrons by a simple equation: $W_{max} \approx 4w_0 \cdot \left(\frac{E}{m_e c^2}\right)^2$. The width of the edge is mostly determined by the resolution of the photons detector and the energy spread in the electron beam. Thus, direct measurement of the energy spectrum of scattered photons allows us to measure both the electron beam average energy and the energy spread.

At the VEPP-4M collider we use the infrared laser radiation with $w_0 = 0.117$ eV. In this case, W_{max} is from 4 to 7 MeV for the beam energy in the range from 1.5 to 2 GeV. The energy spectrum of backscattered photons is measured by High Purity Germanium (HPGe) coaxial detector Canberra GC2518 with the energy resolution around W_{max} about $\delta w/w = 4 \cdot 10^{-4}$. The spectrum in Fig.4 was gathered with the average electron beam current about I_e = 1 mA and the electron beam energy ε = 1842 MeV at the ZMEJ mode of the VEPP-4M. The resulting value of the measured energy spread is $\delta E = 1.03 \pm 0.04$ MeV.

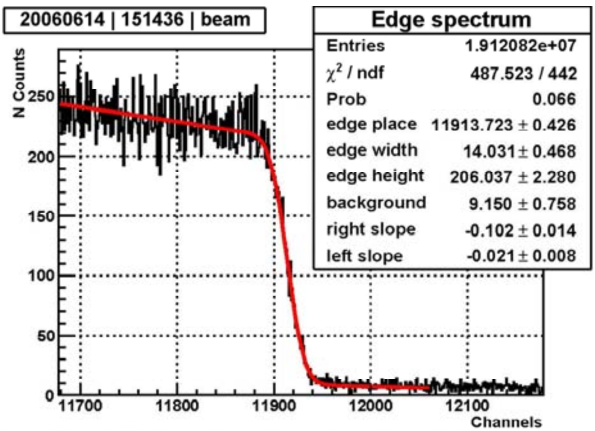

Fig. 4. The edge of the energy spectrum of backscattered photons with fitting function.

4. EXPERIMENT

Method (I)

Beam oscillation was excited by a short kick with amplitude $b \geq \sigma_y$. Spectrum of betatron motion was derived with FFT. Frequency and amplitude of the peaks were defined more exactly with the approach proposed in [7]. Blackman-Harris window was also applied. All the measurements were made during 1024 beam turns following the kick. An example of measured spectrum is presented in Fig.5. Three sideband satellites are clearly seen.

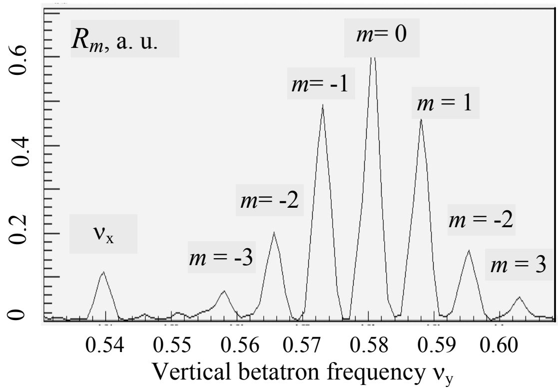

Fig. 5. A spectrum of vertical betatron oscillations.

The same measurements were made for various values of vertical chromaticity $C_y = 5 \div 20$. Chromaticity was changed with sextupole magnets and was measured from the dependence of betatron tune on the *rf* frequency shift.

The measured ratio of synchrotron satellite height at $m = 1$ to the main peak is shown in Fig.6. The best fit of experimental points corresponds to the energy spread $\delta_E = 3.2 \cdot 10^{-4}$ for JPSI mode, $\delta_E = 4.6 \cdot 10^{-4}$ for PSIS mode and $\delta_E = 6.6 \cdot 10^{-4}$ for ZMEJ mode.

Method (II)

The reverse Fourier transform was applied to the measured spectrum of betatron oscillations but only $\nu_y \pm m\nu_s$ harmonics were taken into account. The result of this operation for ZMEJ mode and $C_y = 18.5$ is shown in Fig.7.

The envelope of the derived betatron motion $En(t)$ was compared with (2). Energy spread δ_E was used as fitting parameter. The fitting was done for the same measurements, i.e. for the same values of chromaticity C_y as for method (*I*). An example of comparison between theoretical curve $A(t)$ with experimental data is presented in Fig. 8.

The averaged derived data are:

$\delta_E = (3.2 \pm 0.3) \cdot 10^{-4}$ for JPSI mode,

$\delta_E = (4.6 \pm 0.5) \cdot 10^{-4}$ for PSIS mode,

$\delta_E = (6.6 \pm 0.6) \cdot 10^{-4}$ for ZMEJ mode.

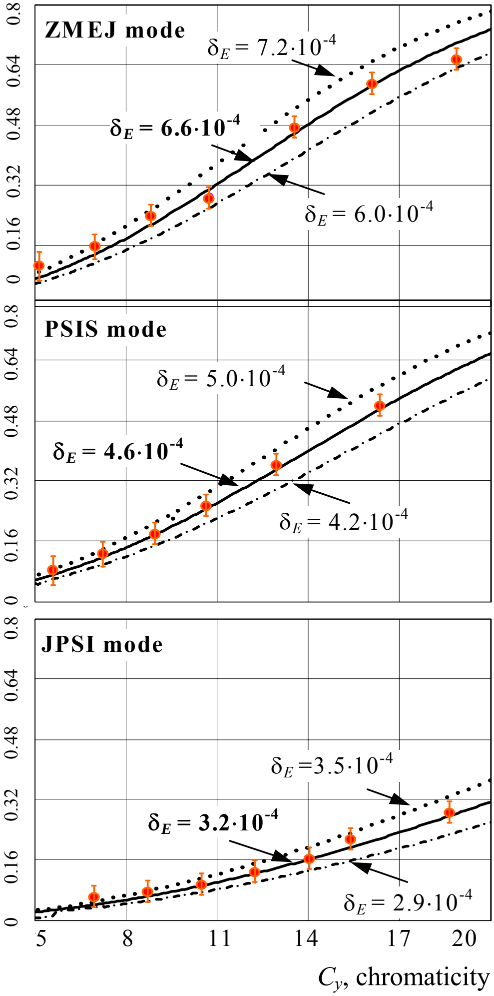

Fig. 6. Ratio of R_1/R_0 for different modes of the VEPP-4M operation. Experimental points and theoretical curves are shown.

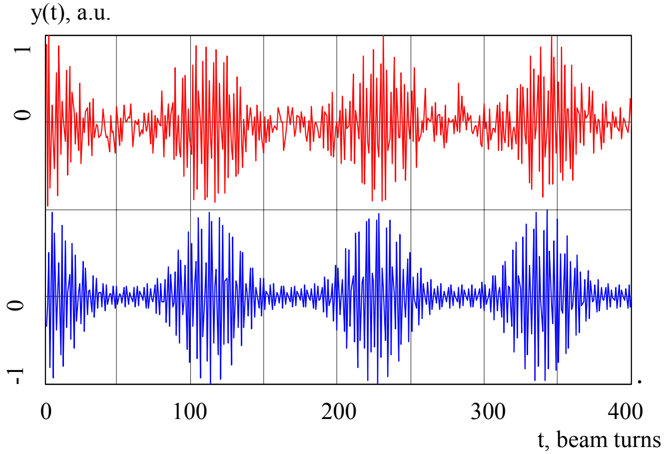

Fig. 7. Comparison between initial betatron motion of the electron beam (upper curve) and result of the reverse Fourier transform (lower curve).

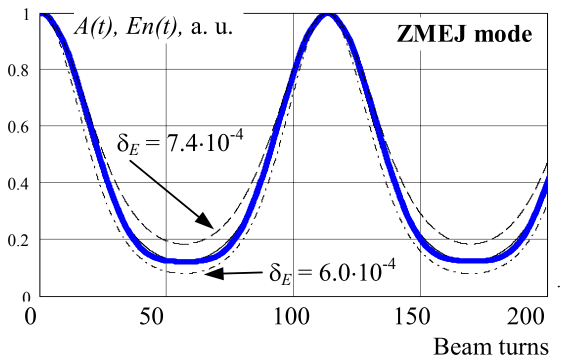

Fig. 8. The comparison between *A(t)* (2) and the envelope *En(t)* of the lower curve presented in Fig.5. Only the upper part of the symmetrical curves is shown. $C_y = 18.5$, $\delta_E = 6.7\cdot10^{-4}$, $\nu_s = 0.0089$.

Method (III)

Fit of radial size σ_x vs beam current I_0 with (3) is shown in Fig.9. The fit declines from the experimental points at the value of $I_0 = 4$ мA. Further dependence $\sigma_y(I_0)$ has a threshold behavior and requires additional studying. Declination might be caused by microwave instability with the threshold depending on accelerating voltage V_{rf} .

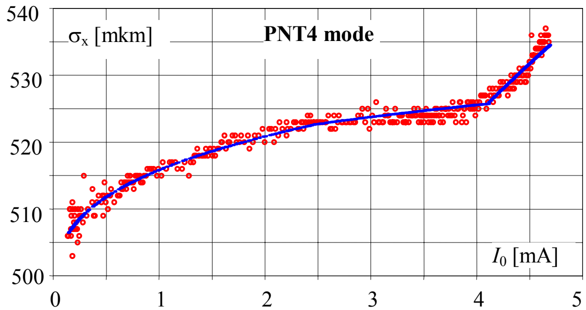

Fig. 9. Dependence of beam radial size σ_x on beam current I_0 at PNT4 mode: O – CCD matrix measurement; — derived with energy spread variation (3).

Methods (*I*) and (*II*) were applied with reduced value of V_{rf} = 150÷250 kV to decrease a synchrotron frequency ν_s, which improves a resolution of the measurements described above. The collider runs in 2002-2006 were performed at $V_{rf} \geq 400$ kV and instability threshold was significantly higher than the currents of the operated beams restricted by the beam-beam effects.

Measurement of the longitudinal beam size σ_z enables us to derive the energy spread at $I_0 = 0$ (Fig.10). Further beam lengthening $\sigma_z \propto I_0^{1/3}$ is caused by the ring longitudinal impedance $\left(\frac{Z_{II}}{n}\right) \approx 6$ Om of an inductive type [2].

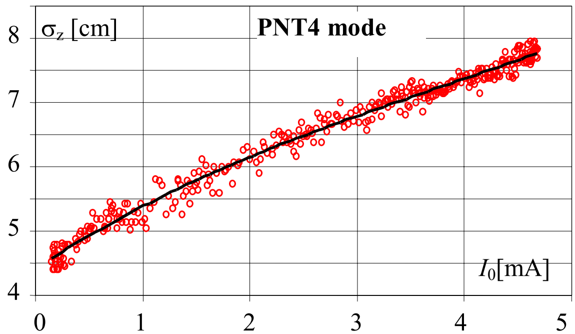

Fig. 10. Dependence of the longitudinal beam size σ_z on beam current I_0 at the PNT4 mode; $\nu_s = 0.0089$, $\delta_0 = 3.96 \cdot 10^{-4}$.

We must mention that all the data of method (III) were obtained under collider modes very similar to the modes listed in Table 1, but with the KEDR field switched on.

5. DISCUSSION

One can note that measurements by method (*III*) are in a good agreement with data of ψ' resonance scan at $E_0 = 1843 \pm 10$ MeV performed in 2006 (Tab. 2). This method has the same good agreement for J/ψ meson scan (Tab.2) with reduced wiggler current $I_{WG} = 620$ A .

Methods (*I*) and (*II*) demonstrate a good agreement for PSIS, ZMEJ and JPSI mode of the collider as well.

Table 2. Data of ψ' and J/ψ resonance scanning

	E, MeV	dW, MeV	$\sigma_E \cdot 10^{-4}$	I_{WG}, A	I_0, mA	Year
ψ’ width	1843	1.33	5.15	1135	2.0	2002
		1.24	4.77	1135	2.0	2004
		1.15	4.42	1055	2.5	2005
		1.09	4.19	1055	2.5	2006
J/ ψ width	1548	0.858	3.93	952	1.7	2002
		0.664	3.04	652	1	2002

Fig.11 represents the collected data of energy spread measurements of the beam for collider modes listed in Table 1.

Unfortunately, we did not have enough time for machine study and did not perform the measurements with method (*III*) with the KEDR magnetic field switched off. Nevertheless, the data of all the three methods are in a satisfactory agreement.

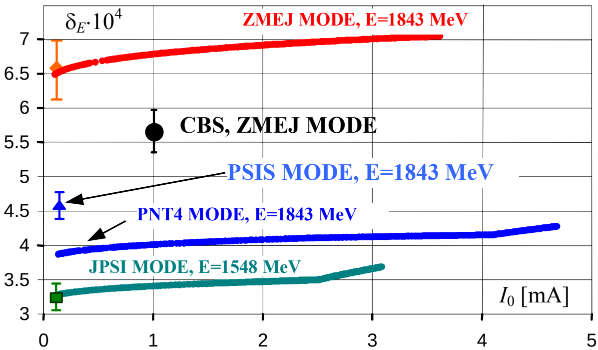

Figure 11. Data comparison of all the methods.

Lines – data of (*III*)

◆ – data of (*I*), (*II*) for ZMEJ mode;

△ – data of (*I*), (*II*) for PSIS mode;

■ – data of (*I*), (*II*) for JPSI mode.

One can see the distinctions of ψ' resonance width obtained with the equal wiggler current (Tab. 2). It indicates the radial orbit stability and the control of dispersion function in the wigglers because the value of energy spread depends on these parameters as well as on the current of the wigglers. These relationships were verified experimentally using method (*III*). The results are represented in Fig.12.

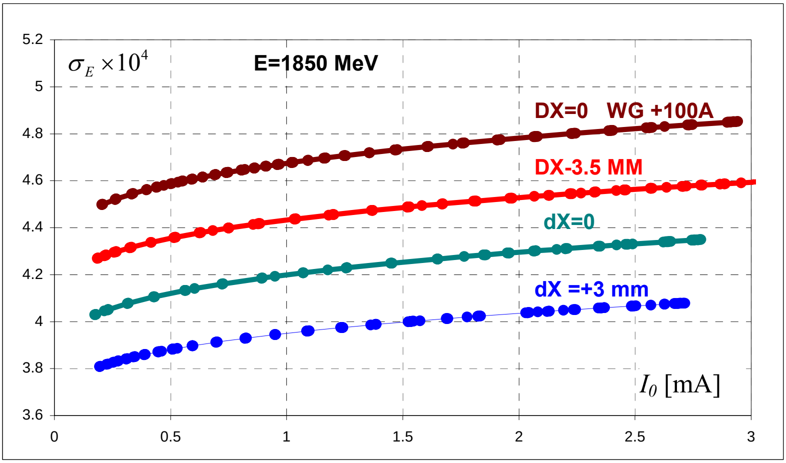

Fig. 12. Variation of the energy spread with the wiggler current variation and beam orbit displacement.

We suppose, that variation of beam orbit could be the reason of distinction of energy spread for PSIS and PNT4 modes. It should be mentioned that reduction of δ_E by CBS data took place only during the run in 2006 and requires additional investigation. The data of (*III*) and CBS are in a good agreement with the runs in 2004/ 2005.

In conclusion we should admit that beam energy spread measurement is a nontrivial task and requires the comparison of data of several diagnostics.

6. SUMMARY

The measurements of the beam energy spread of the VEPP-4M collider have been done. The collider modes correspond to energy area of 1.5 – 1.8 GeV. Several experimental methods have been applied for each mode. The methods data are in a satisfactory agreement. The following experiments of precise measurement of tau-lepton mass should be performed with an accurate control of beam radial position as well as with the control of the dispersion function in the wigglers.

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