VEPP-4M collider beam energy measurement by inverse Compton scattering of laser radiation

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- Compton scattering kinematics
- Application for beam energy measurement
- Experiments at BESSY-I and BESSY-II
- VEPP-4M collider
- Resonant depolarization method
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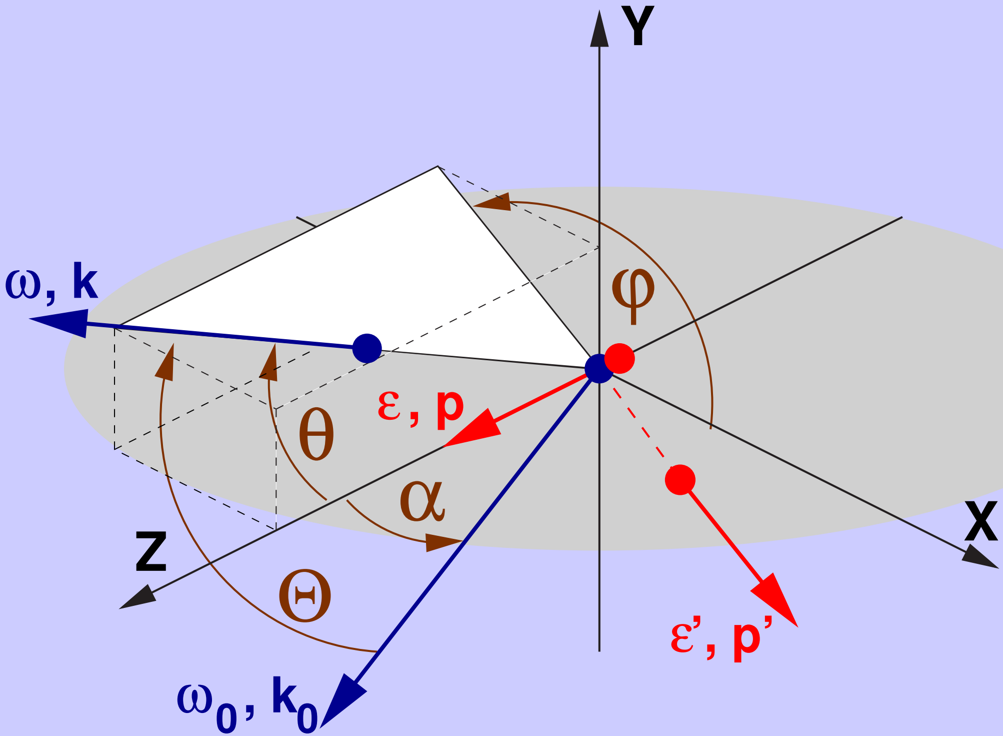
- Scattered photons flux simulations
- HPGe detector
- One measurement example
- System performance

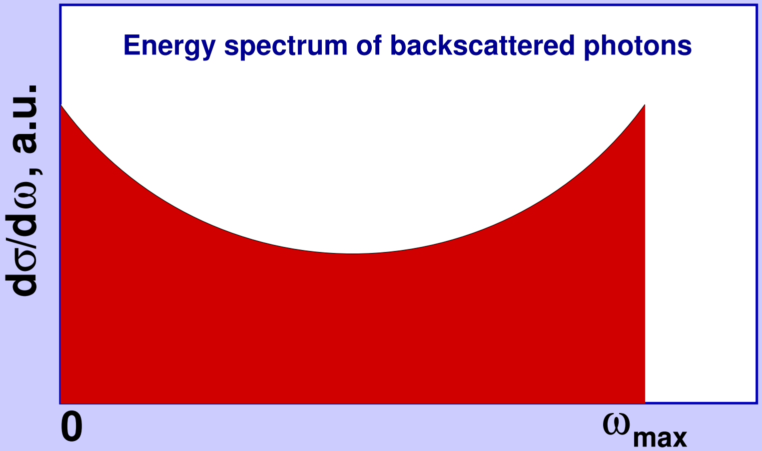
Compton scattering kinematics



$$\omega = \omega_0 \frac{1 - \beta\cos\alpha}{1 - \beta\cos\theta + \frac{\omega_0}{\varepsilon}(1 - \cos\Theta)}$$

$$\cos\Theta = \cos\alpha\cos\theta + \sin\alpha\sin\theta\cos\varphi$$

Inverse Compton scattering of laser radiation (ω_0) allows to measure the electron beam energy ε through the sharp edge (ω_{max}) of the scattered photons (or electrons) energy spectrum.



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

in that way:

$$\varepsilon = \frac{\omega_{max}}{2}\left(1 + \sqrt{1 + \frac{m^2}{\omega_0 \omega_{max}}}\right)$$

As far as m, ω_0 can be treated as constants, the accuracy in ε is given by:

$$\frac{\Delta\varepsilon}{\varepsilon} \simeq \frac{\Delta\omega_{max}}{\omega_{max}}\left(1 - \frac{1}{2} \cdot \frac{1}{1 + \frac{4\omega_0\varepsilon}{m^2}}\right)$$

Energy spread measurement

Visible edge width is mostly defined by the energy spread in the electron beam and the γ-detector energy resolution $\frac{\delta r}{r}$:

$$\sigma_\omega \equiv \frac{\delta\omega_{max}}{\omega_{max}} \simeq 2\frac{\delta\varepsilon}{\varepsilon} \oplus \frac{\delta r}{r}\left(\oplus\frac{\delta\alpha}{\mathrm{tg}(\alpha/2)}\right)$$

One can derive energy spread in the electron beam from σ_ω:

$$\sigma_\varepsilon \equiv \frac{\delta\varepsilon}{\varepsilon} \simeq \frac{1}{2}\sqrt{\sigma_\omega^2 - \sigma_r^2}$$

Energy spread measurement accuracy is thus given by:

$$\frac{\Delta\sigma_\varepsilon}{\sigma_\varepsilon} \simeq \frac{\sigma_\omega d\sigma_\omega \oplus \sigma_r d\sigma_r}{\sigma_\omega^2 - \sigma_r^2}$$

Absolute beam energy with better then 10^{-4} accuracy

- Use of HPGe detector with unique energy resolution to measure ω_{max}
- Energy scale is calibrated by the radio nuclides γ-lines
- Has sense if ω_{max} is less then 10 keV

1) **Measurement of the BESSY II electron beam energy by Compton-backscattering of laser photons.** *R. Klein, R. Thornagel, G. Brandt, G. Ulm, P. Kuske, R. Gorgen (BESSY, Berlin) 2002.* Published in Nucl.Instrum.Meth.A 486: 545-551, 2002

2) **Beam diagnostics at the BESSY I electron storage ring with Compton backscattered laser photons: Measurement of the Electron energy and related quantities.** *R. Klein, R. Thornagel, G. Ulm, T. Mayer, P. Kuske (BESSY, Berlin) 1997.* Published in Nucl.Instrum.Meth. A384: 293-298, 1997

VEPP-4M e^+e^- Collider (BINP, Novosibirsk)

- Energy per bunch $E = 1.5 - 6$ GeV
- Circumference 365 m
- One sign particles current $2 \cdot 3$ mA
- Luminosity $2.5 \cdot 10^{30}$
- Precise beam energy measurement by resonant depolarization $\Delta E/E \simeq 3 \cdot 10^{-6}$
- Constant beam energy and energy spread monitoring by CBS
- Last results with KEDR detector
  - world best mass measurement for $c\bar{c}$ mesons

$$M_{J/\Psi} = 3096.917 \pm 0.010 \pm 0.007 \text{ MeV}$$
$$M_{\Psi'} = 3686.111 \pm 0.025 \pm 0.009 \text{ MeV}$$

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- Current experiment: τ-lepton mass measurement

Resonant depolarization technique

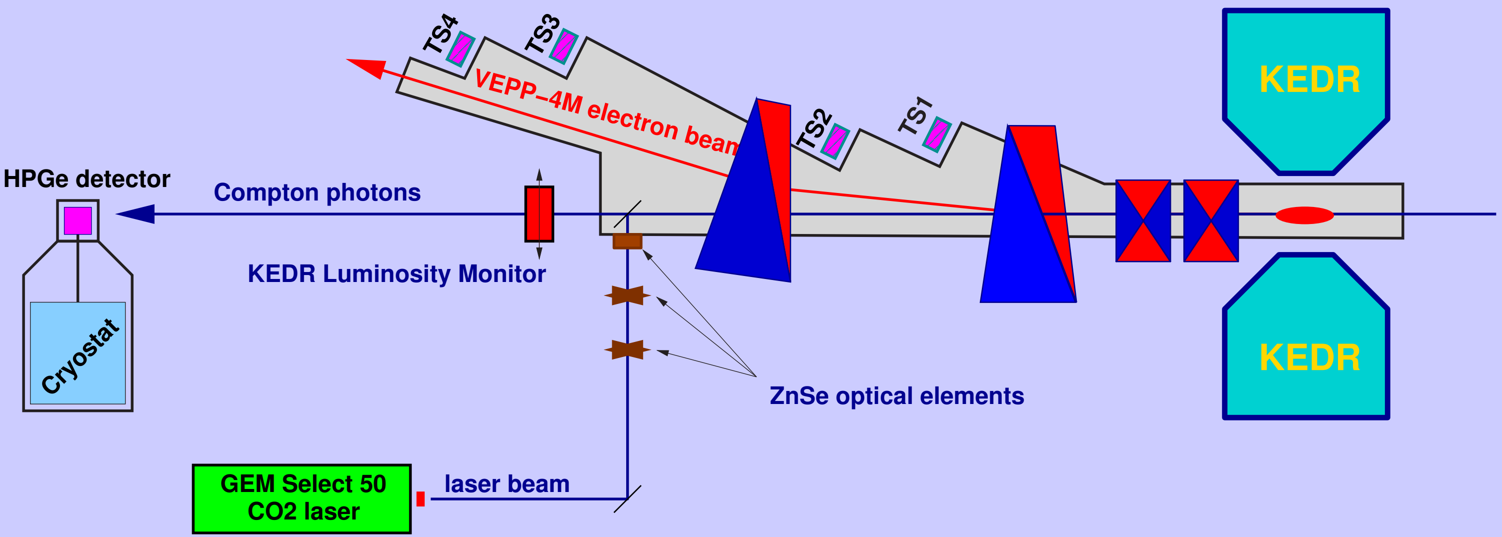
Electrons and positrons in storage rings can become polarized due to emission of synchrotron radiation according to the SokolovTernov effect. Spins of polarized electrons precess around the vertical guiding magnetic field with the precession frequency Ω, which in the plane orbit approximation is directly related to the particle energy E and the beam revolution frequency ω:

$$\boldsymbol{\Omega/\omega = 1 + \gamma\mu'/\mu_0 = 1 + \nu}$$

where $\gamma = E/m$, m 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 precession frequency can be determined using the resonant depolarization.

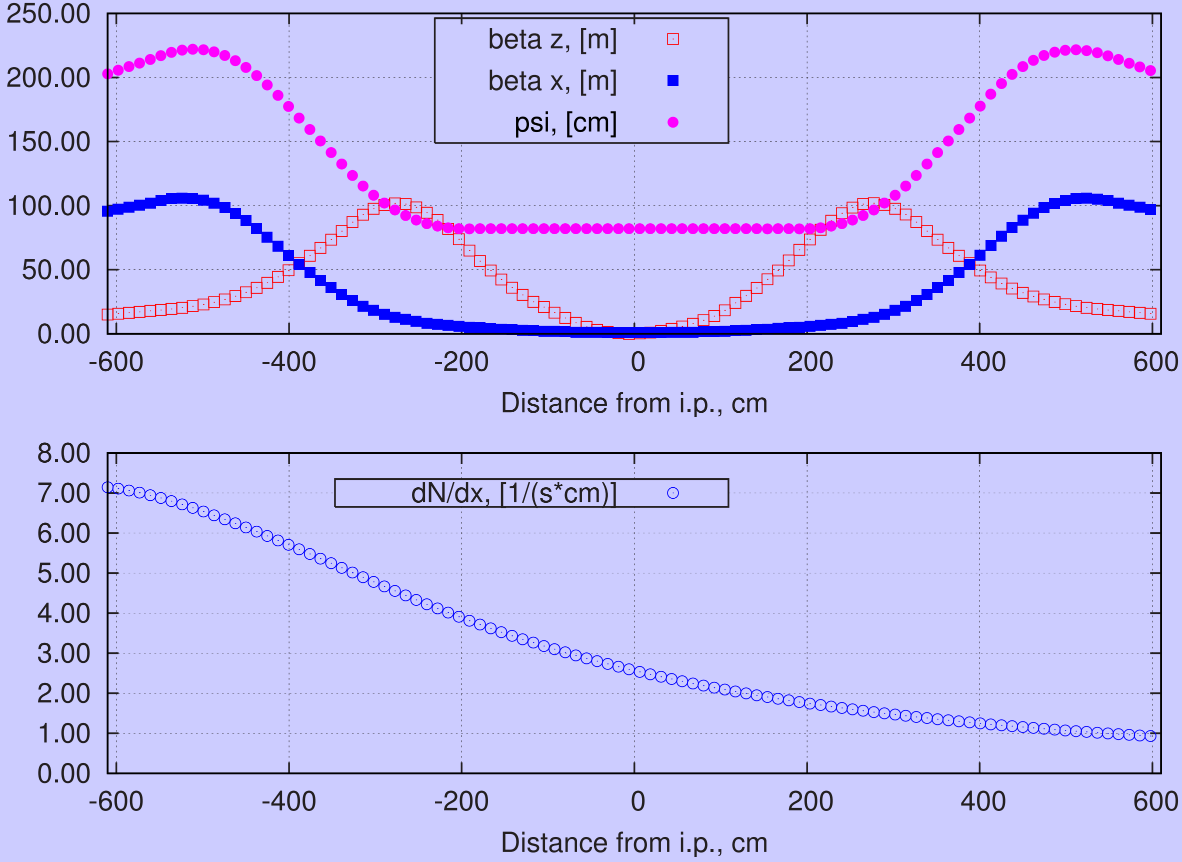
VEPP-4M Compton Beam Energy Monitor (started from May, 2005)



Laser COHERENT *GEM Select 50*

- Carbon dioxide laser
- 25–50 W CW Power, RF discharge – long lifetime
- Single 10P20 line λ=10.5910 μm (ω_0=0.1170656 eV)
- $\Delta\omega_0/\omega_0 \simeq 10^{-9}$

VEPP-4M lattice functions and photon flux



HPGe - High Purity Germanium Detector

- Model: Canberra GC2518
- 120 ml active volume

For 6 MeV photons:

- 5% efficiency
- $4 \cdot 10^{-4}$ energy resolution

Compton spectrum edge shape

$$g(x, p_{0\ldots5}) = \frac{1}{2}(p_2(x - p_0) + p_3) \cdot \mathrm{erfc}[\frac{x - p_0}{\sqrt{2}p_1}] -$$
$$-\frac{p_1 p_2}{\sqrt{2\pi}} \cdot \exp[-\frac{(x - p_0)^2}{2p_1^2}] + p_4(x - p_0) + p_5 \ ,$$

where:

p_0 – edge position;

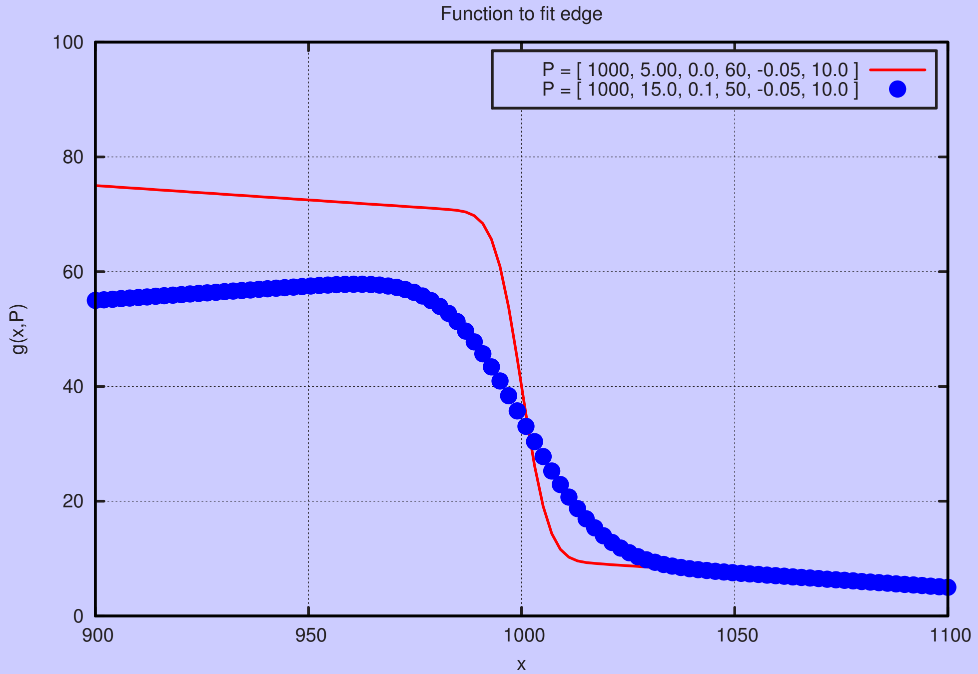
p_1 – edge width;

p_2 – slope left;

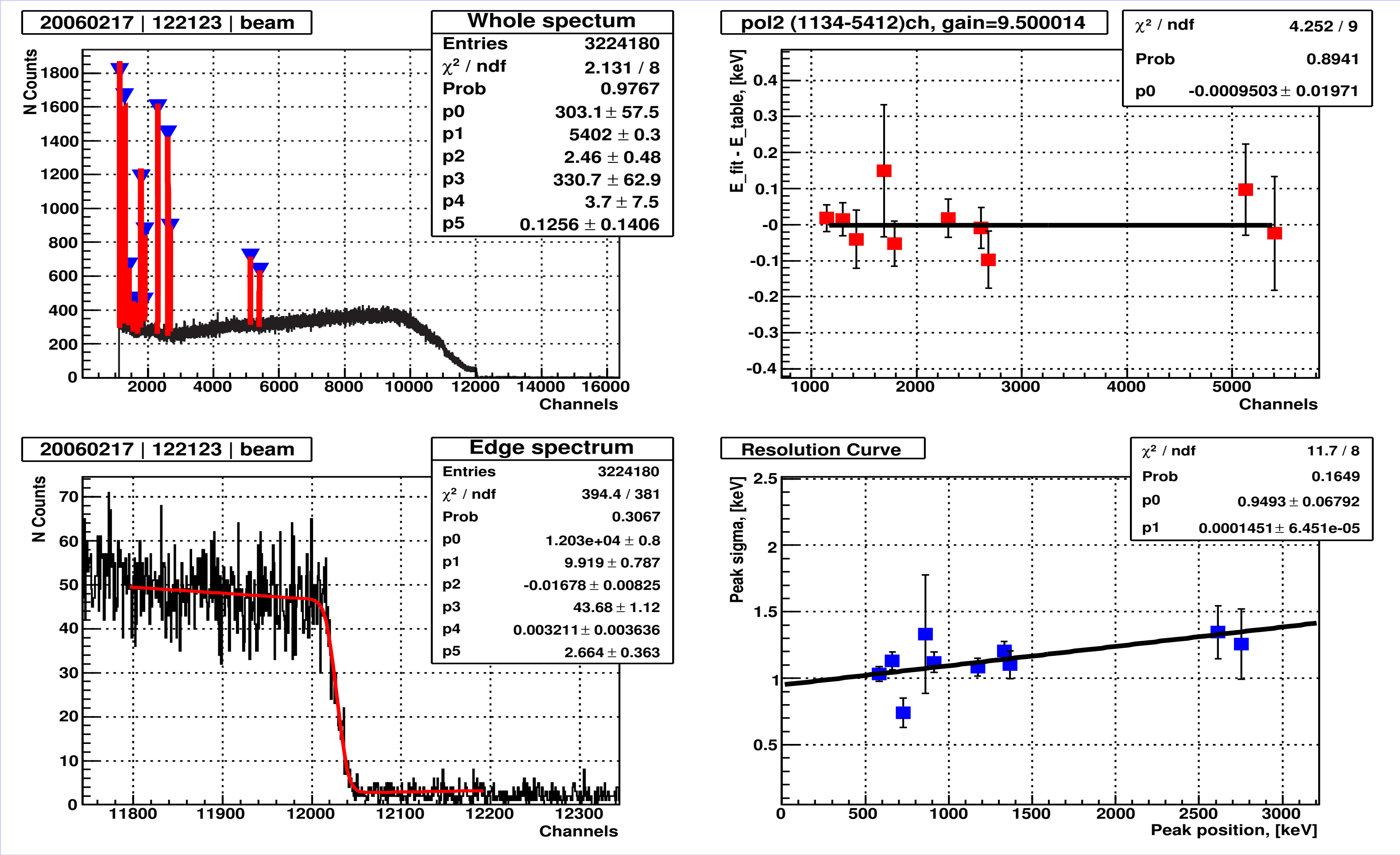
p_3 – edge amplitude;

p_4 – slope right;

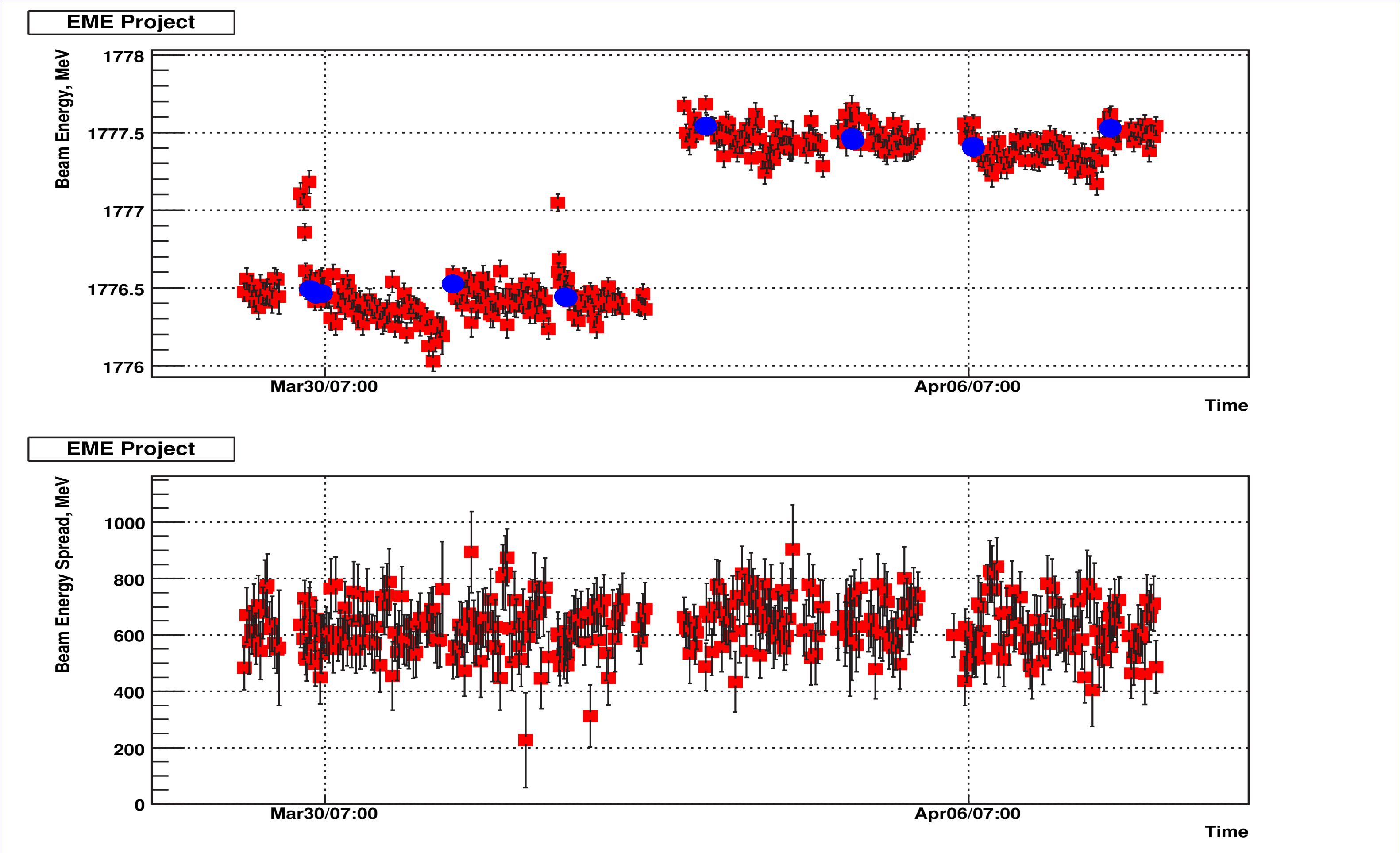
p_5 – background.



Experimental spectrum example



Energy measurements in 2006



Achieved system performance

- One measurement cycle takes 5 – 30 min data acquisition time, depending on the electron beam current
- Continuous operation provides on-line information about the average beam energy and energy spread
- One cycle provides $\Delta\varepsilon/\varepsilon \simeq 5 \cdot 10^{-5}$ statistical accuracy for the beam energy measurement
- The same data allows to measure the beam energy spread with 15% accuracy
- The absolute values of the measured beam energy conforms within $2 \cdot 10^{-5}$ accuracy to the energy, measured by the resonant depolarization technique (preliminary)