10-th INTERNATIONAL CONFERENCE ON INSTRUMENTATION FOR COLLIDING BEAM PHYSICS

Review of beam energy measurement methods

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Talk outline

- Beam energy measurements
- I. Resonant depolarization technique
- II. Compton backscattering energy monitor
- Cross-check for both approaches
- Conclusion

How to know the beam energy?

$$E = \frac{e}{2\pi}\int B(l)\,dl$$

- Accurate knowledge of the accelerator magnetic structure allows to know absolute beam energy with ~ 0.1% accuracy
- Relative accuracy for beam energy variations ~ 100 ppm
- In HEP experiments narrow hadron resonances with well established masses (ρ, ω, φ, J/Ψ, Ψ', $\Upsilon^{(1s)}$, $\Upsilon^{(2s)}$, $\Upsilon^{(3s)}$) could be used for energy scale calibration
- All these masses were accurately measured in collider experiments with application of the resonant depolarization technique for the beam energy determination

Particle Spin Dynamics

The Resonant Depolarization technique for a precise measurement of the beam energy was developed at BINP in early 70th.

Sokolov-Ternov effect: spins of beam particles are oriented in the same way under the influence of synchrotron radiation when they circulate in storage rings for a long time.

$$\frac{1}{\tau_p} = \frac{5\sqrt{3}}{8} \alpha \left(\frac{\lambda_e}{R} \right)^2 \gamma^5 \omega_0$$

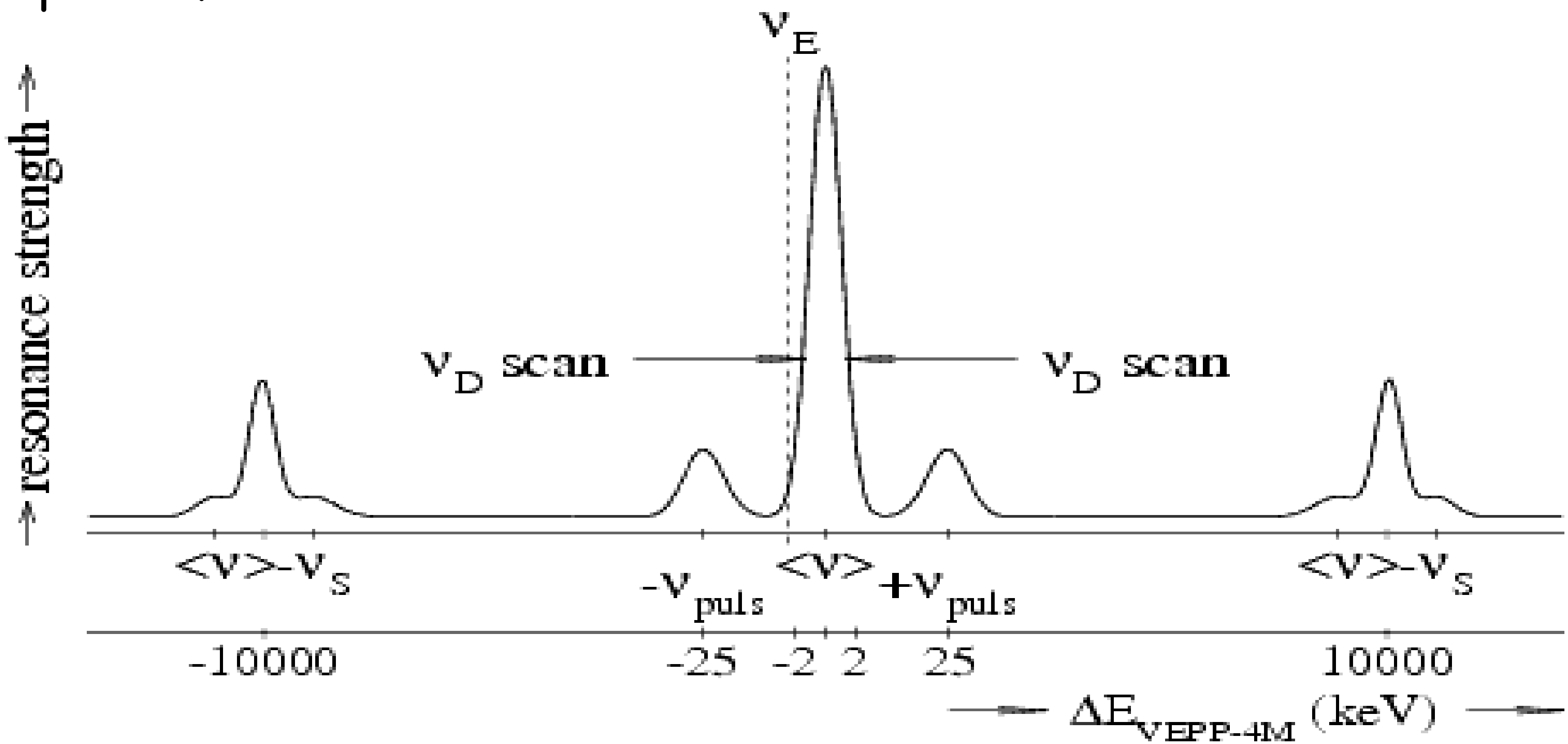
Spins precess around the guiding magnetic field with frequency:

$$\frac{\Omega}{\omega_0} = 1 + \gamma \frac{\mu'}{\mu_0} = 1 + \nu$$

where: γ - particle Lorentz factor, Ω - spin precession frequency, ω_0 - beam revolution frequency, μ' and μ_0 - anomalous and normal parts of the electron magnetic momentum.

I. Resonant Spin Depolarization

Polarization can be destroyed by an external field of frequency ν_D:
$\Omega = n\omega_0 \pm \nu_D$, where n - any integer number. Fourier image of spin response function looks like :



Central peak is corresponded to average beam energy. Its width is about 1 ppm in our case. Side peaks exist due to synchrotron oscillations and guide field pulsation.

Polarimetry

The external modulation frequency can destroy the beam polarization when it is in resonance with spin precession. One needs to measure the beam polarization degree while scanning this frequency. In different experiments the beam polarization was measured in different ways:

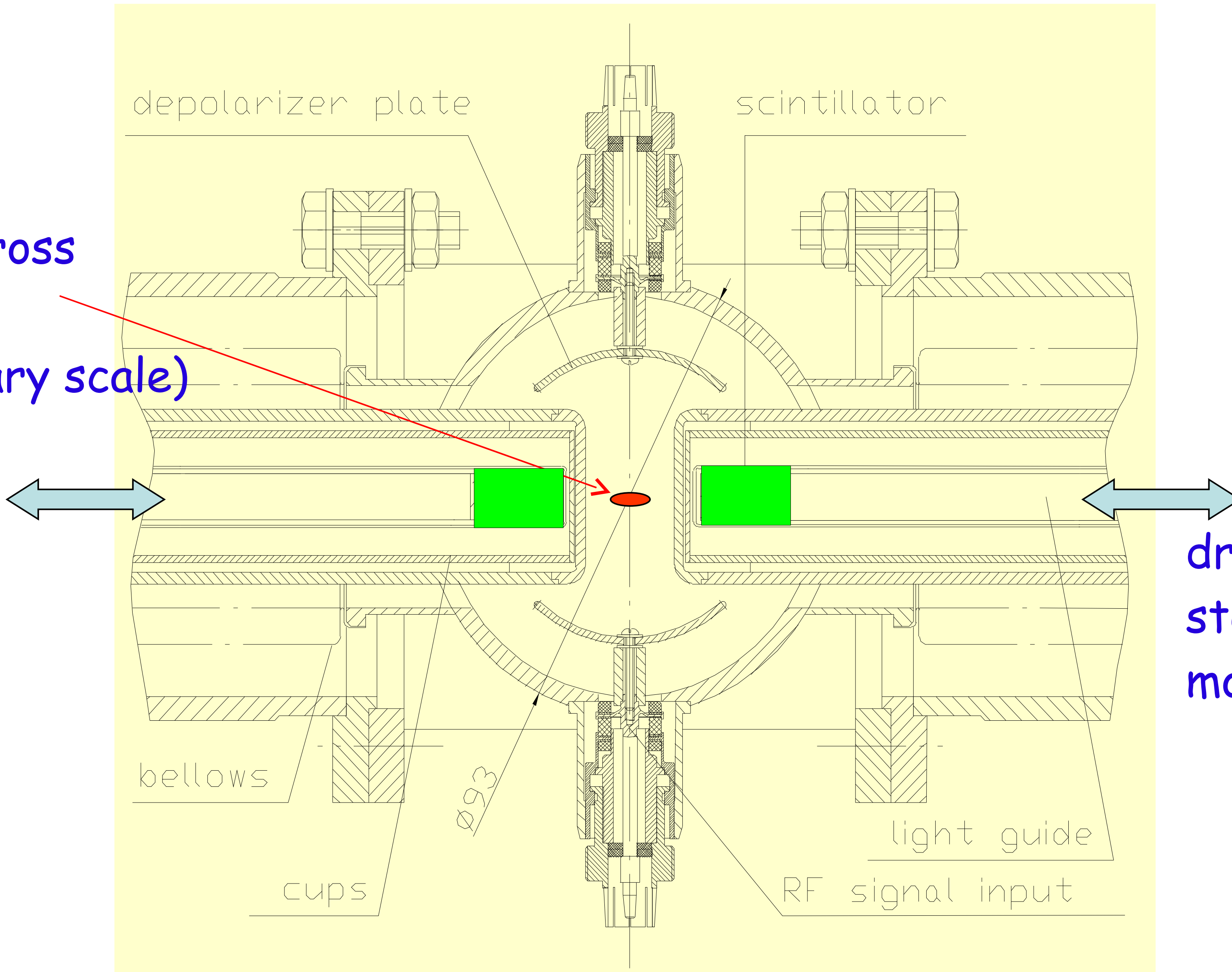
- Touschek effect (BINP, BESSY ...)
- Compton backscattering (BINP, CERN, DESY ...)
- Møller scattering (SLAC, JLAB, BINP ...)
- SR intensity spin-dependence (BINP)
- ...

At the VEPP-4M the Touschek effect is used for beam polarization measurement

$$d\sigma = d\sigma_0 \left(1 - \zeta^2 \frac{\sin^2\theta}{1+3\cos^2\theta} \right)$$

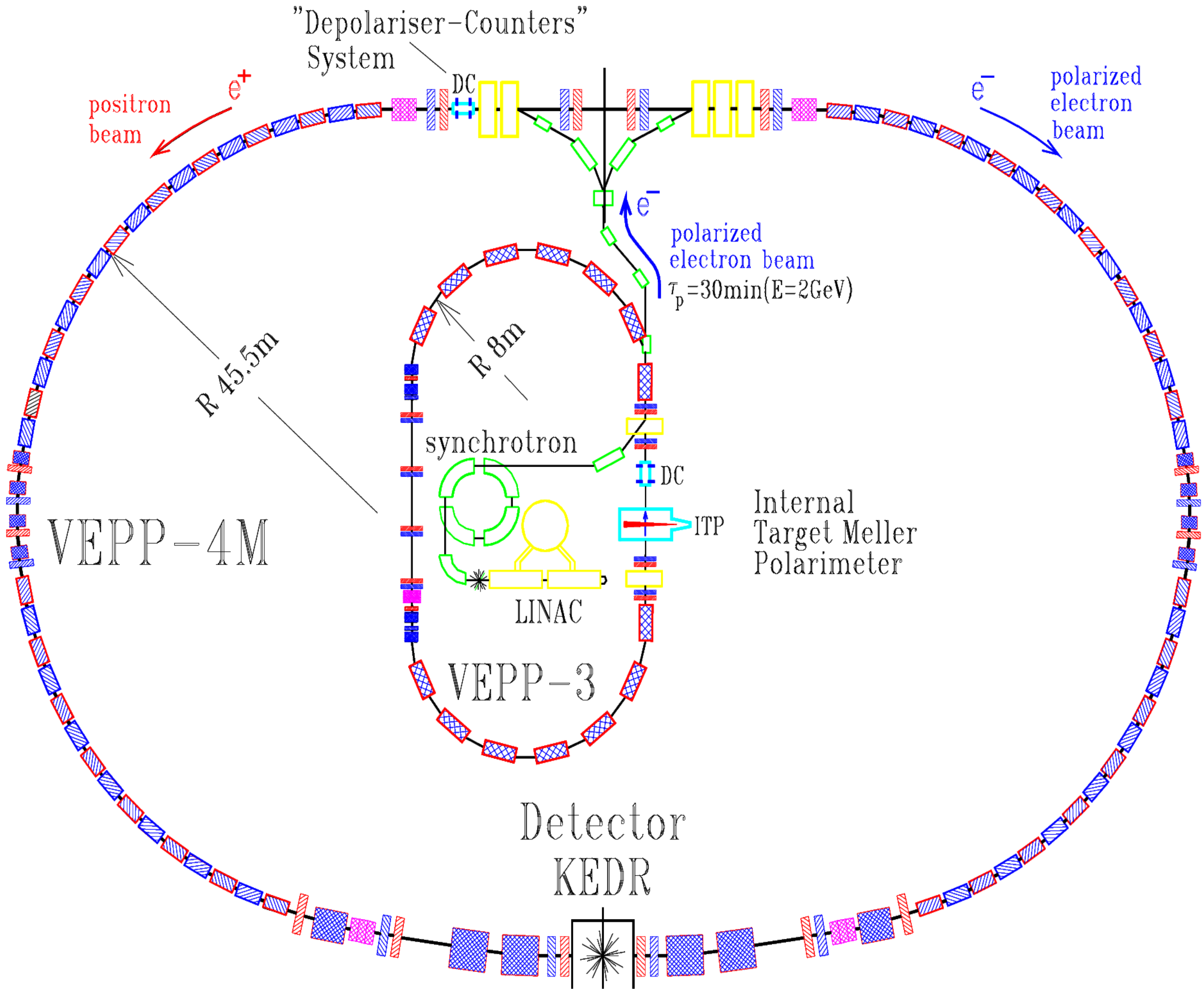
VEPP-4M Touschek Polarimeter

Beam cross section (arbitrary scale)



driven by stepping motors

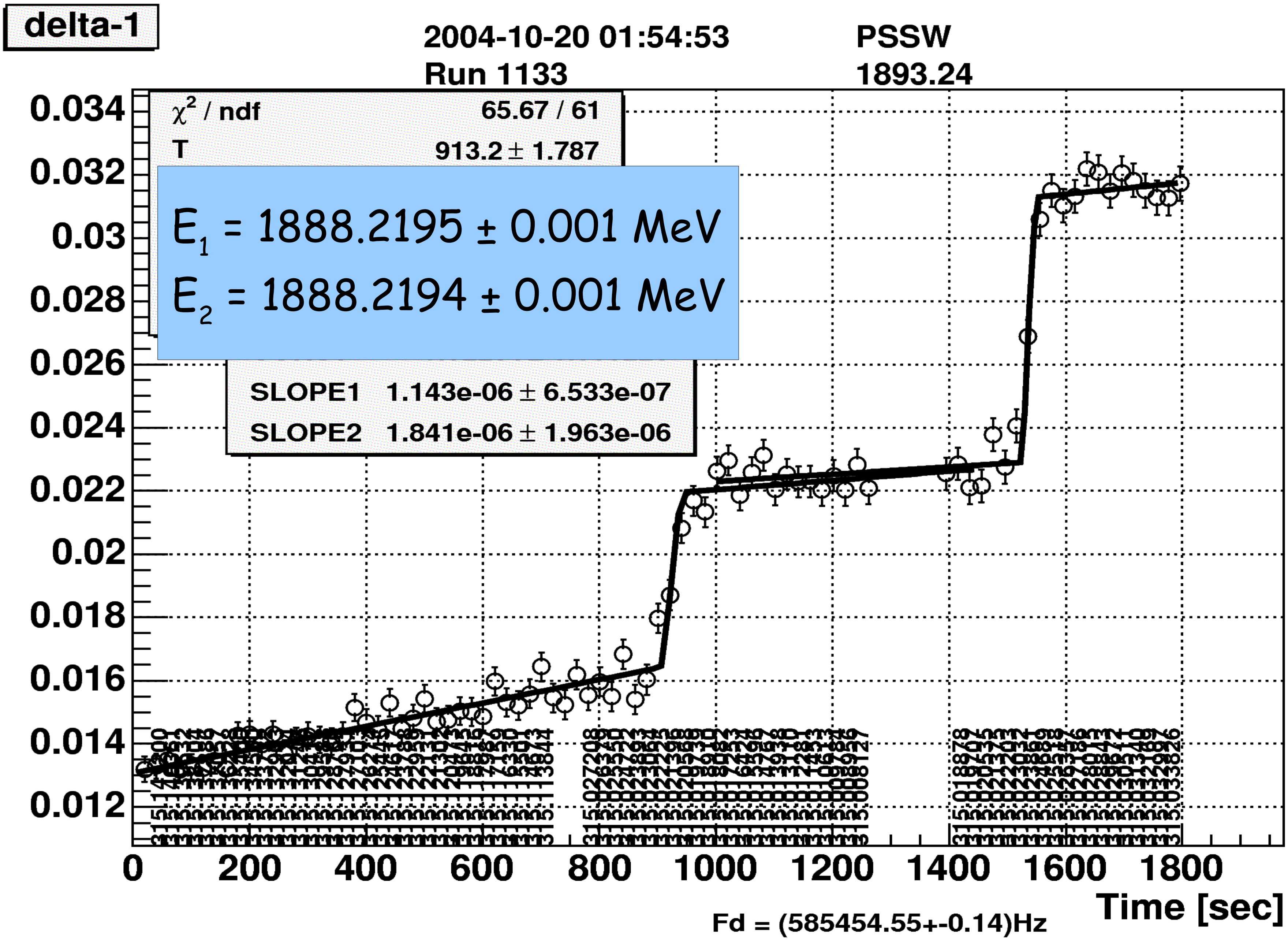
VEPP-4 accelerator complex (Novosibirsk)



Energy calibration procedure

- Polarized bunch (I_P) preparation & injection from the VEPP-3
- Second (unpolarized) bunch (I_U) injection
- Adjustment of both bunches to the same charge ($I_P = I_U$)
- Frequency scan: dE/dt = 0.3 keV/s, ΔE = 0.75 keV, range ~ 100 keV
- Observation of the polarimeter measurements: $\Delta = N_P/N_U - 1$
- Each point is measured during 20 s
- Second frequency scan with opposite direction to control the correct width of the spin resonance

Energy calibration (1875.233 ± 0.001 MeV)



Energy interpolation between measurements

Although the beam energy at the moment of depolarization is measured with ultimate accuracy, the matter of interest in HEP experiments on colliders is the beams energies during the data accumulation runs. This means that some interpolation procedure need to be found to describe the energy behaviour between resonant depolarization calibrations.

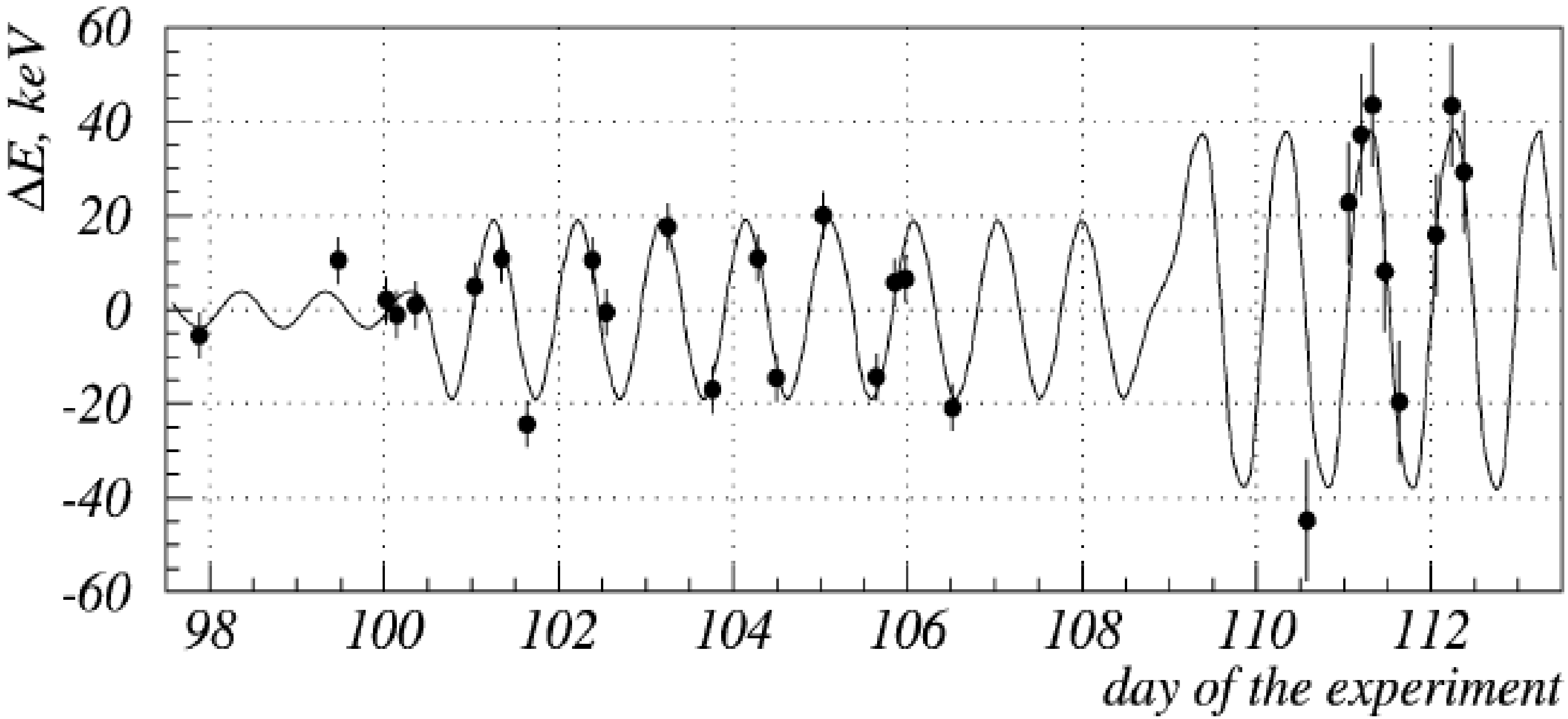
The beam energy is a function of parameters

$$E = E_{RD} + \sum \alpha_i P_i(time)$$

where P_i are the essential machine parameters (B-fields, temperatures, geometry, etc.) and α_i are their empirically founded coefficients.

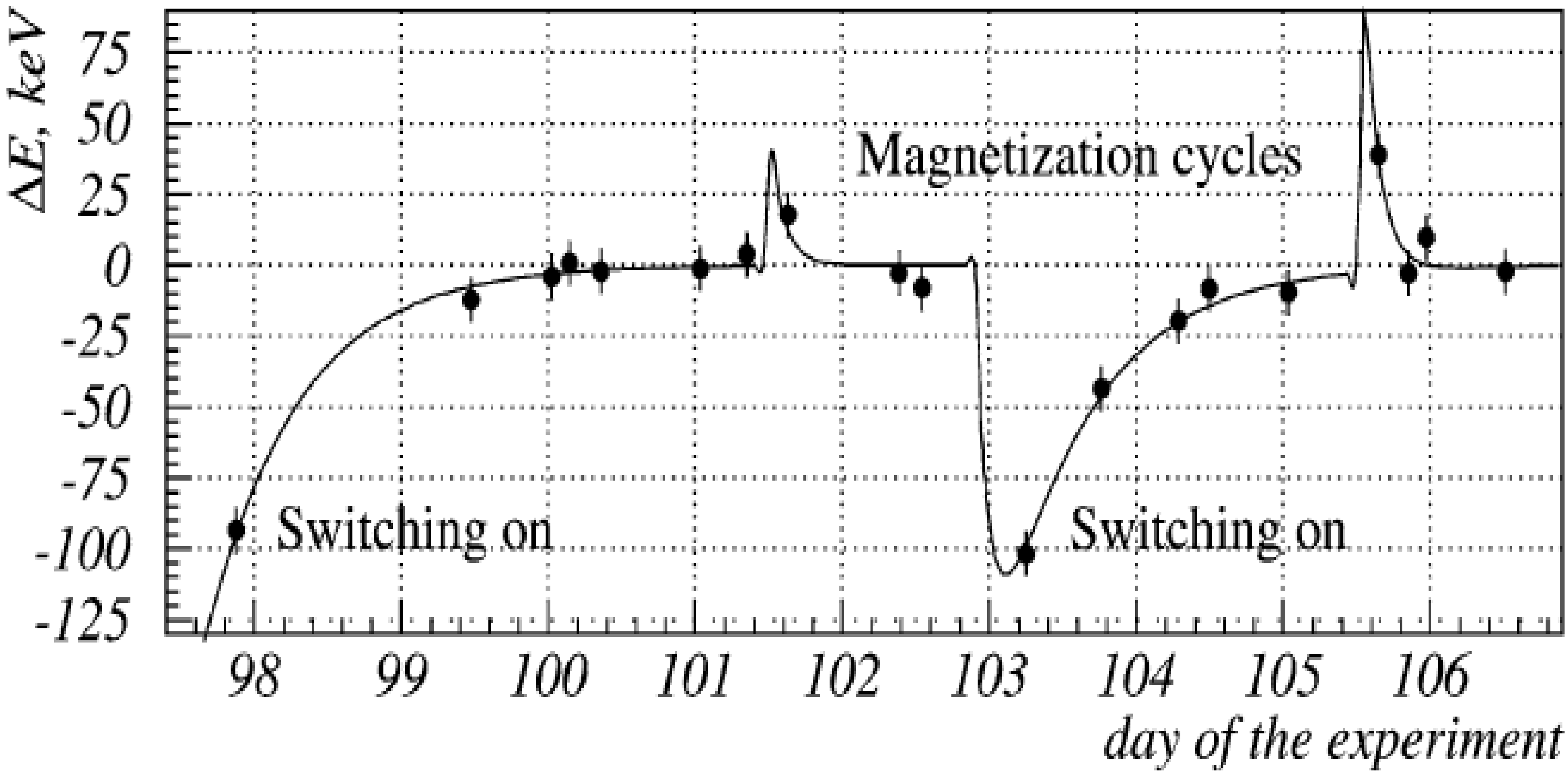
Predicted Energy and Day-to-Night Oscillations

KEDR Collaboration / Physics Letters B 573 (2003) 63–79



- Points are RD energy measurements
- Aperiodic dependencies are removed

Predicted Energy in operation cycles (periodic behavior removed)

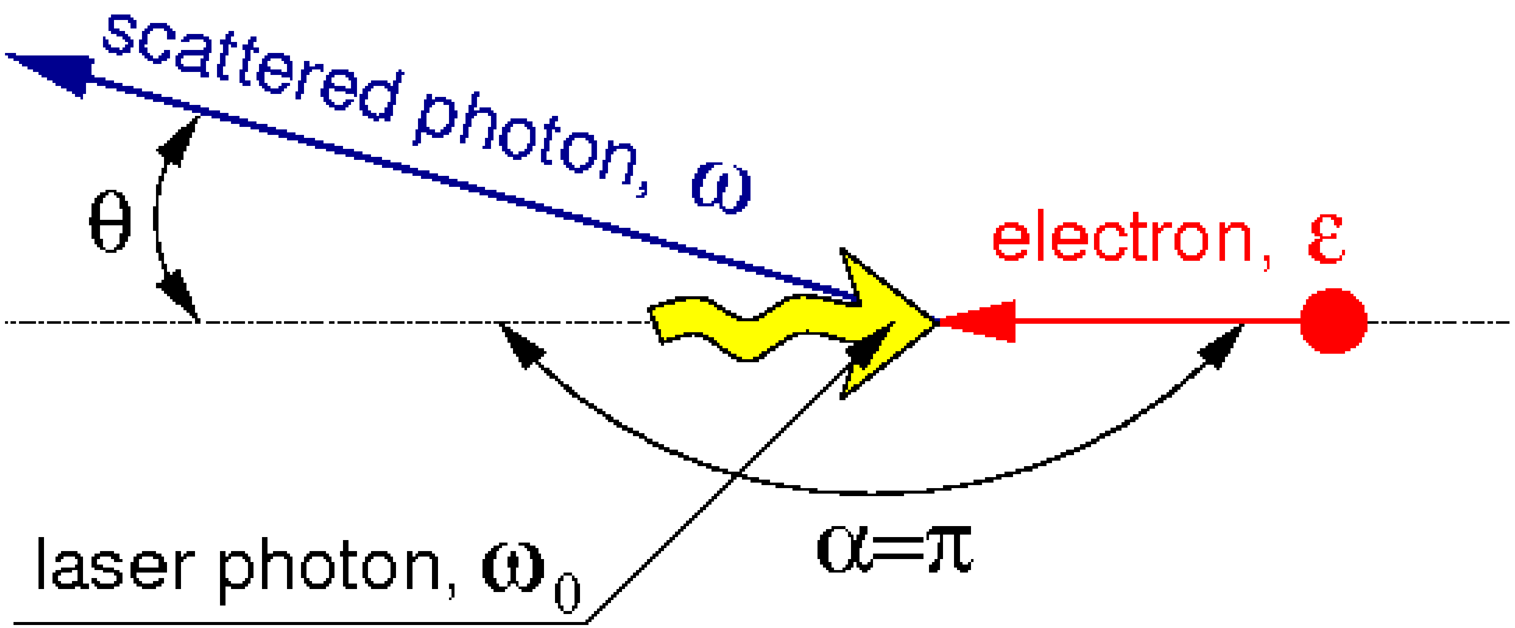


Resonant Depolarization at the VEPP-4M: results and performance

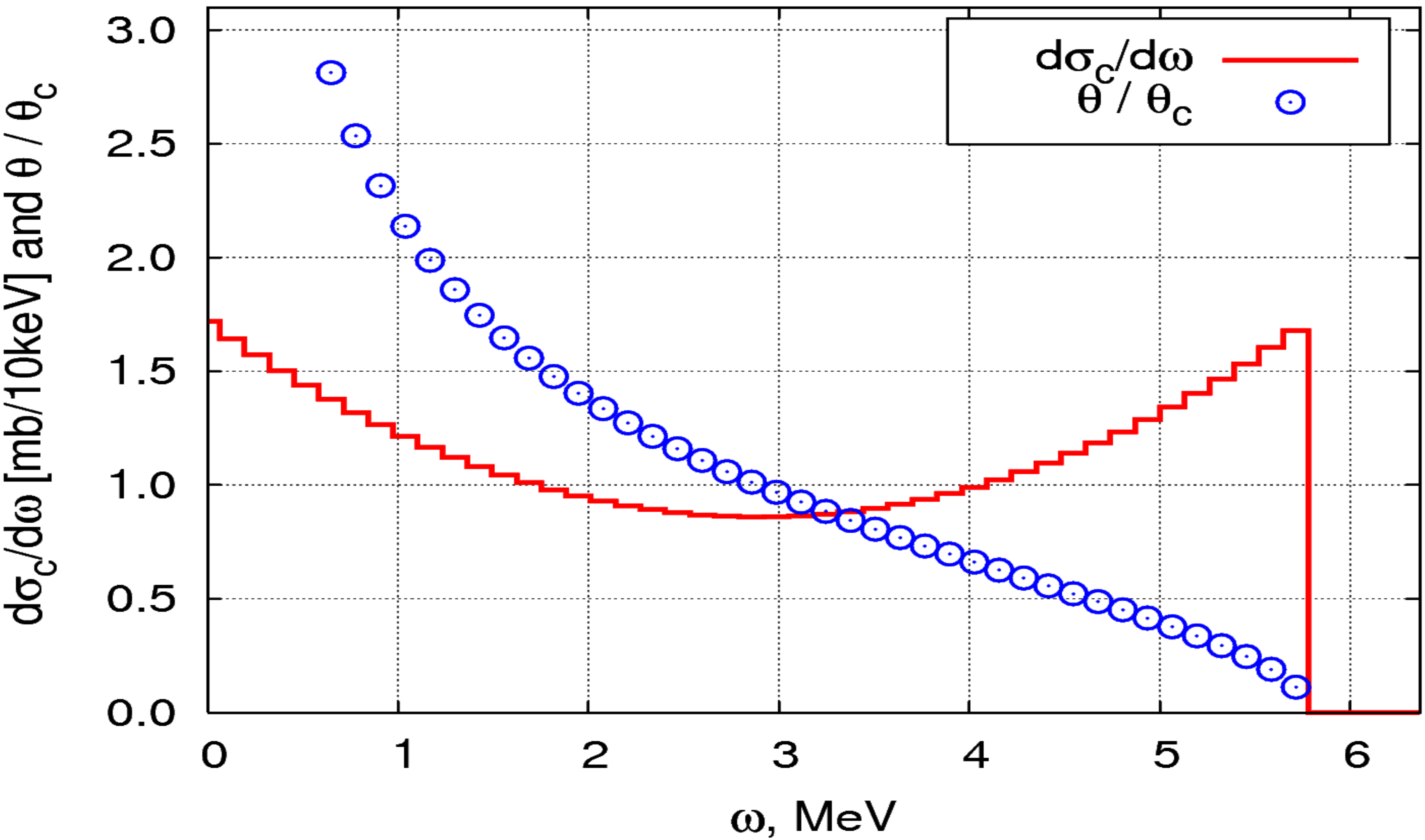
- More then 1500 energy calibrations performed since 2004
- Counting rate of Touschek polarimeter about 1 MHz
- The beam energy range covered by these calibrations is in the range from 1.5 GeV upto 2.0 GeV
- Accuracy of single calibration ≤ 1 ppm
- Detailed machine studies allow to perform energy interpolation between calibrations with an absolute accuracy in the range from 7 keV upto 30 keV, depending on experimental conditions

II. Compton back-scattering energy monitor

Compton scattering kinematics:



Compton back-scattering cross section



$\omega_0 = 0.12$ eV, $\varepsilon = 1777$ MeV, $\theta_c = 1/\gamma$, $\sigma_c = 665$ mb

Beam Energy Measurement

Maximal energy of backscattered photon is given by:

$$\omega_{max} = \frac{4\gamma^2\omega_0}{1+4\gamma\omega_0/m_e}$$

where ω_0 is the laser photon energy, γ - electron Lorentz factor. If one measures $\boldsymbol{\omega}_{\mathbf{max}}$, the electron energy is given by:

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

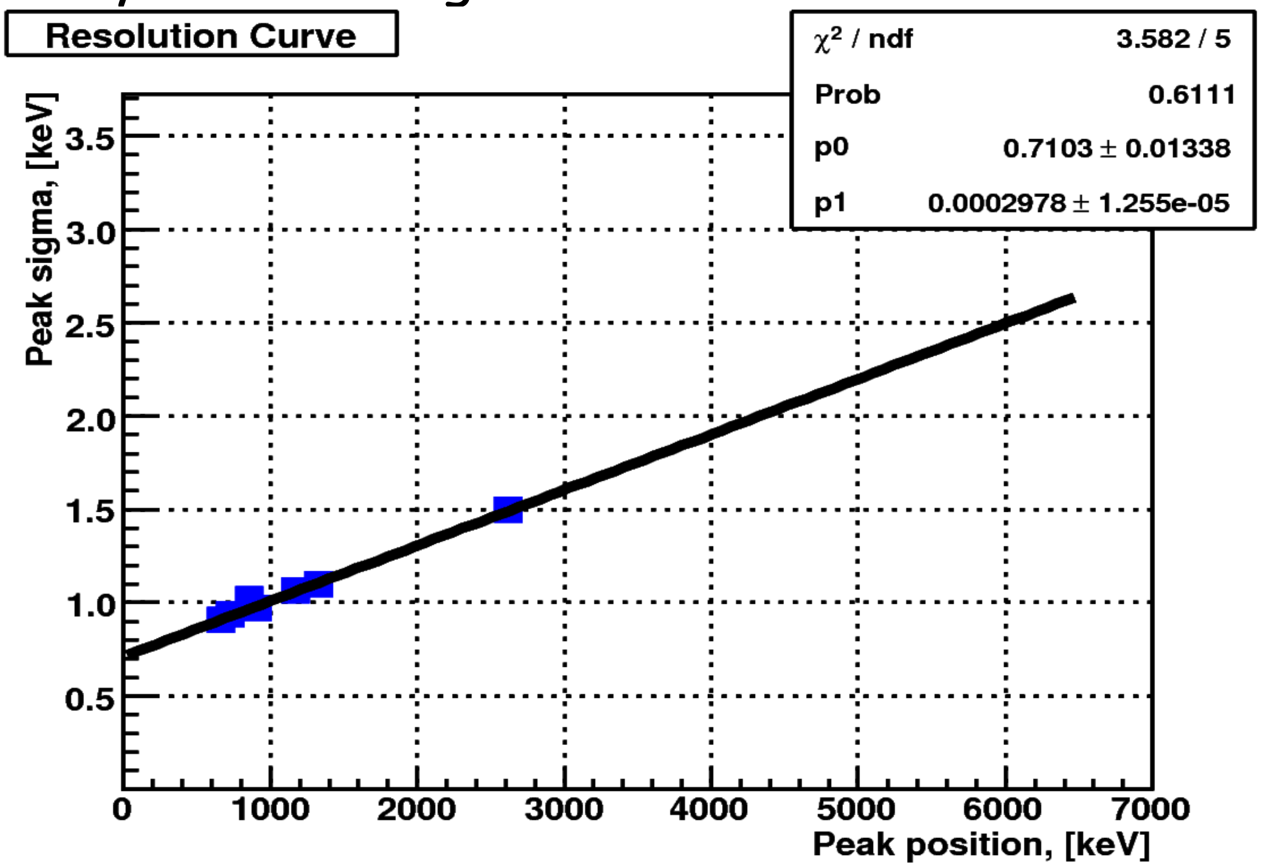
Absolute beam energy measurement with <10^{-4} accuracy:

- Use of HPGe detector with excellent energy resolution (T=80°K)
- HPGe energy scale calibration by the radio nuclides γ-lines
- Proved while ω_{max} < 10 MeV
- Experimentally tested and proved by RDP measurements at BESSY (Berlin), BINP (Novosibirsk)

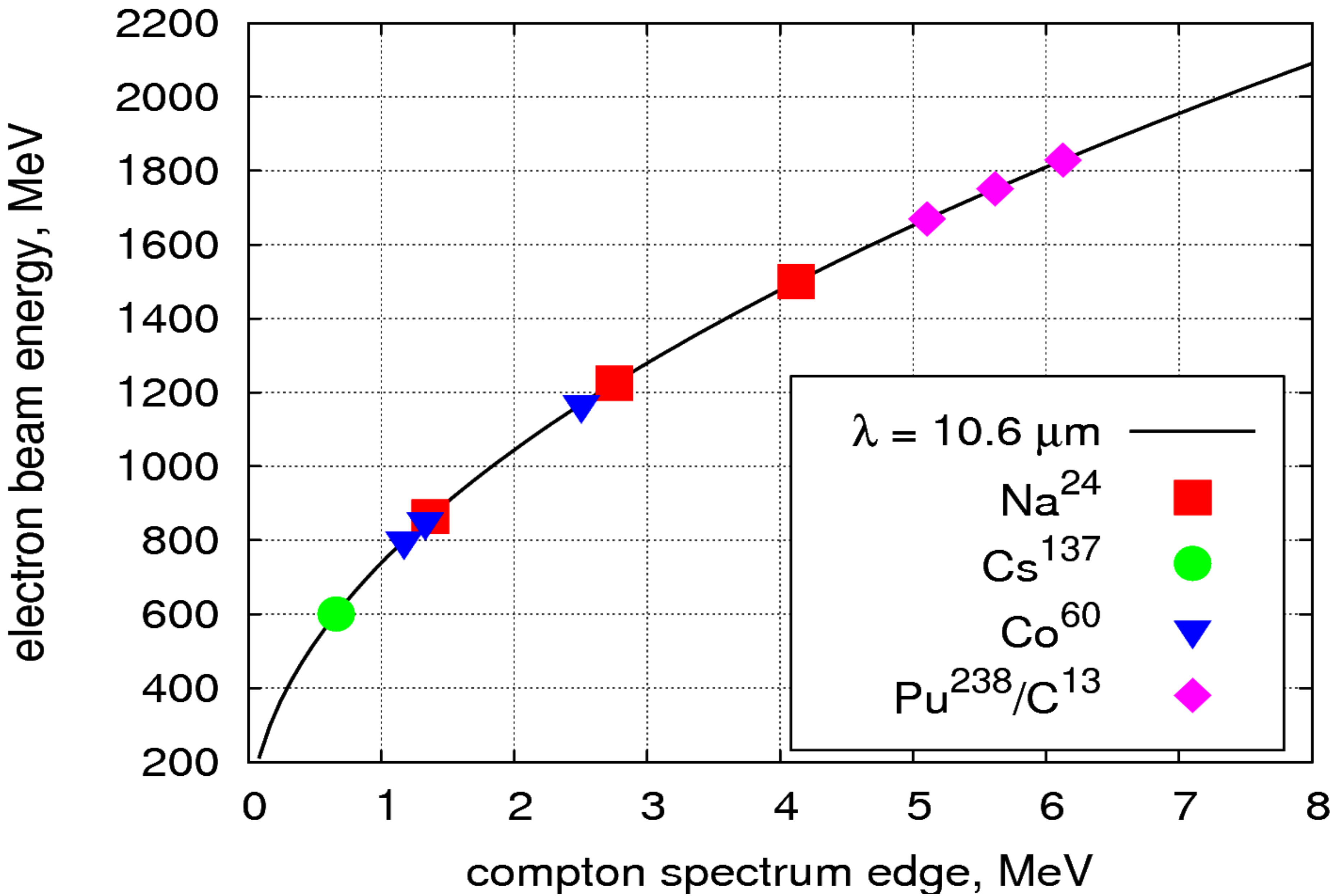
High Purity Germanium (HPGe) detectors

- HPGe detector is a large germanium diode operated in the reverse bias mode. At a suitable operating temperature (normally ~85°K), the barrier created at the junction reduces the leakage current to acceptably low values. Thus an electric field can be applied that is sufficient to collect the charge carriers liberated by the ionizing radiation.

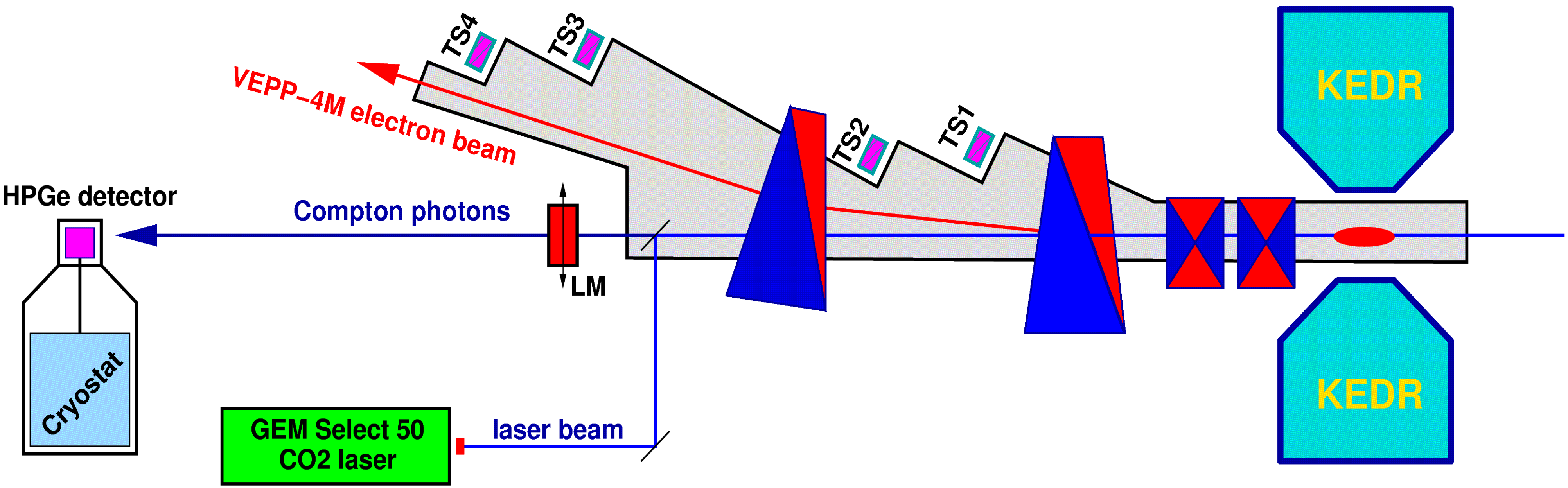
- The energy, lost by ionizing radiation in semiconductor detectors, ultimately results in the creation of electron-hole pairs. The average energy necessary to create a pair is 2.95 eV .

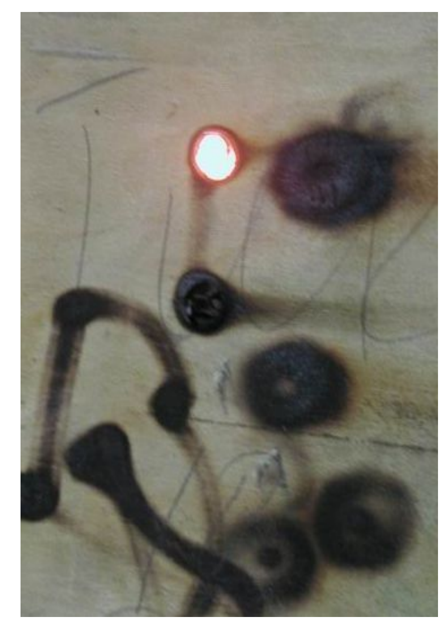


Beam Energy Range with CO_2 Laser



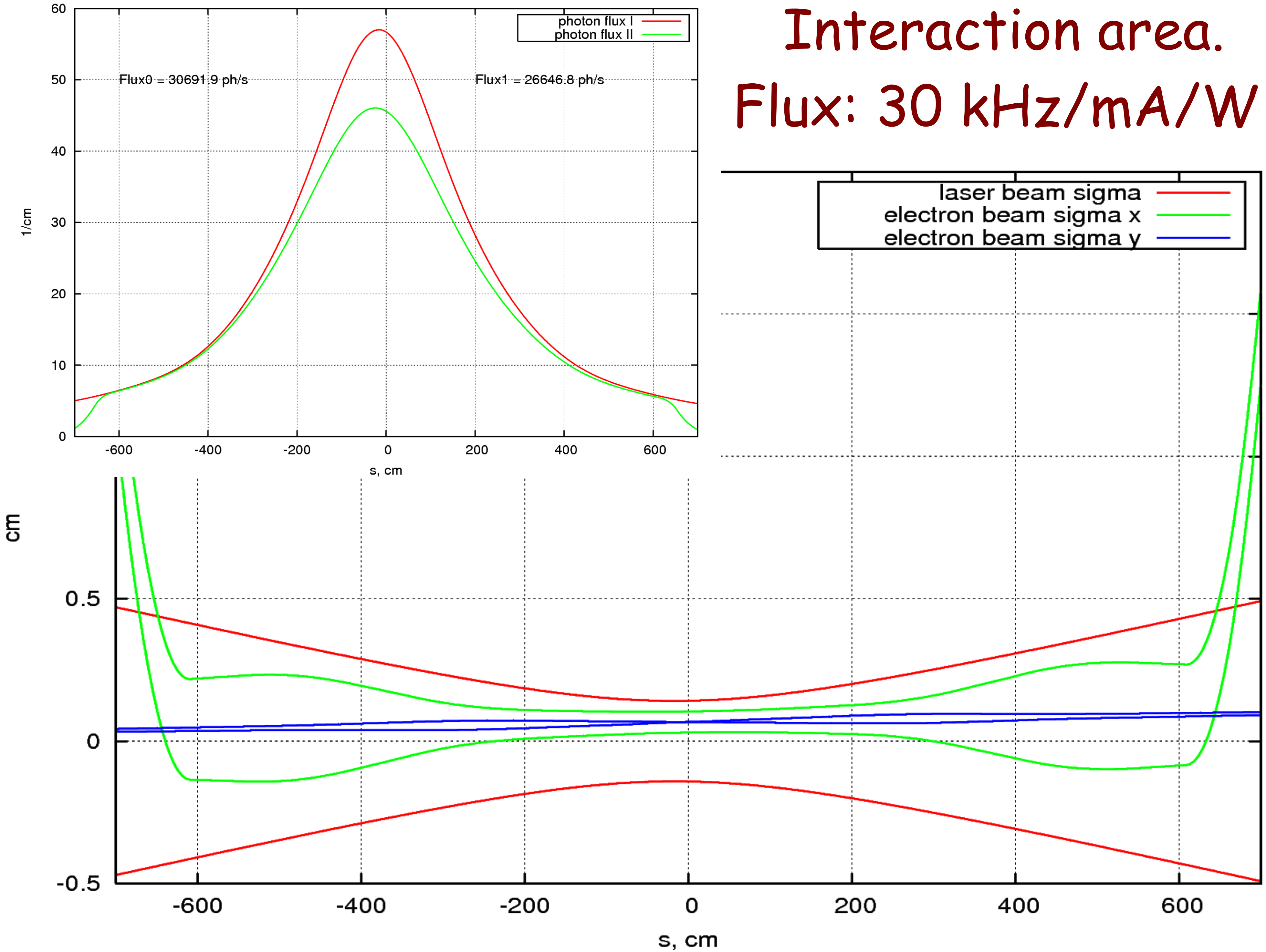
VEPP-4M Compton energy monitor layout



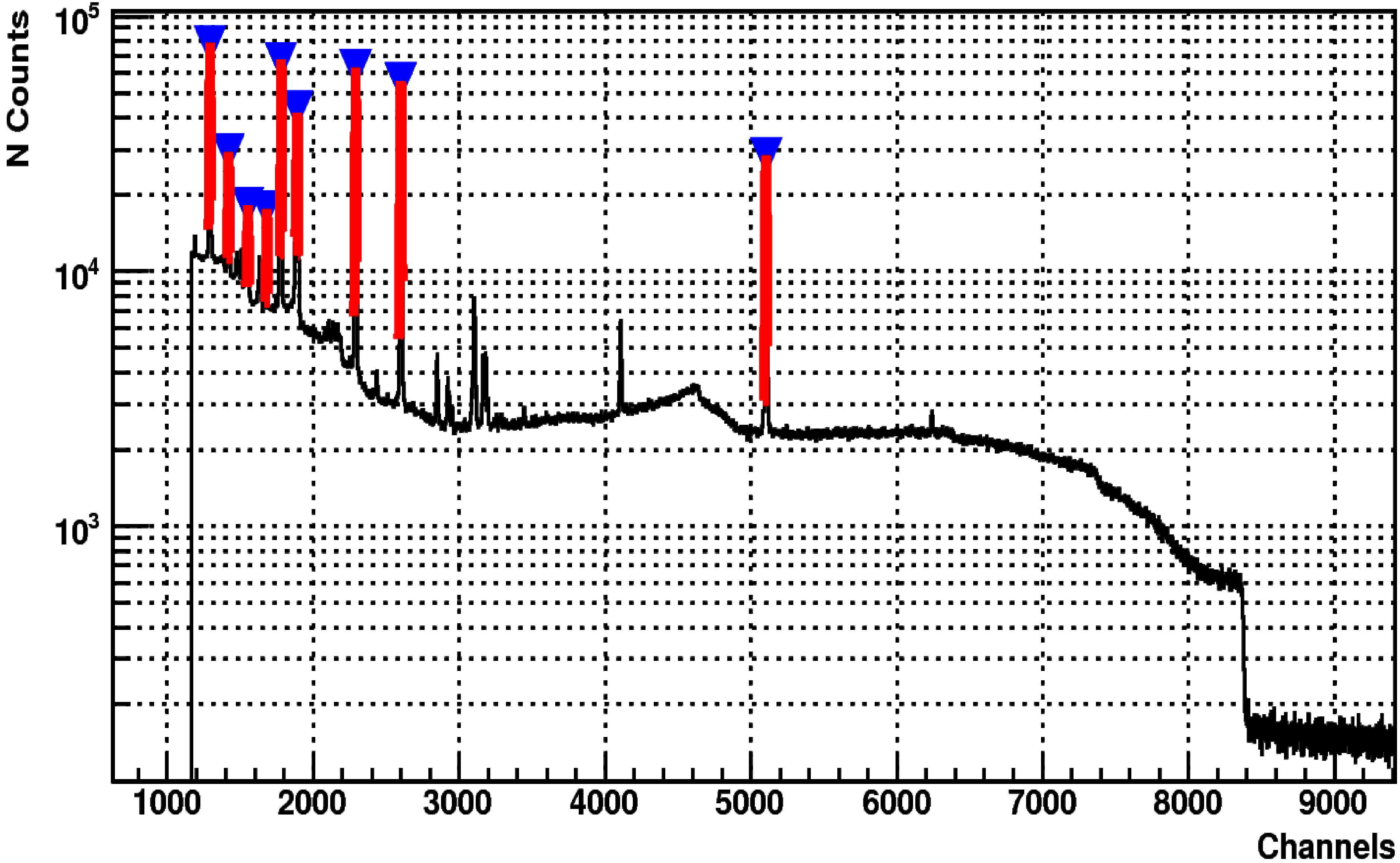


Interaction area.

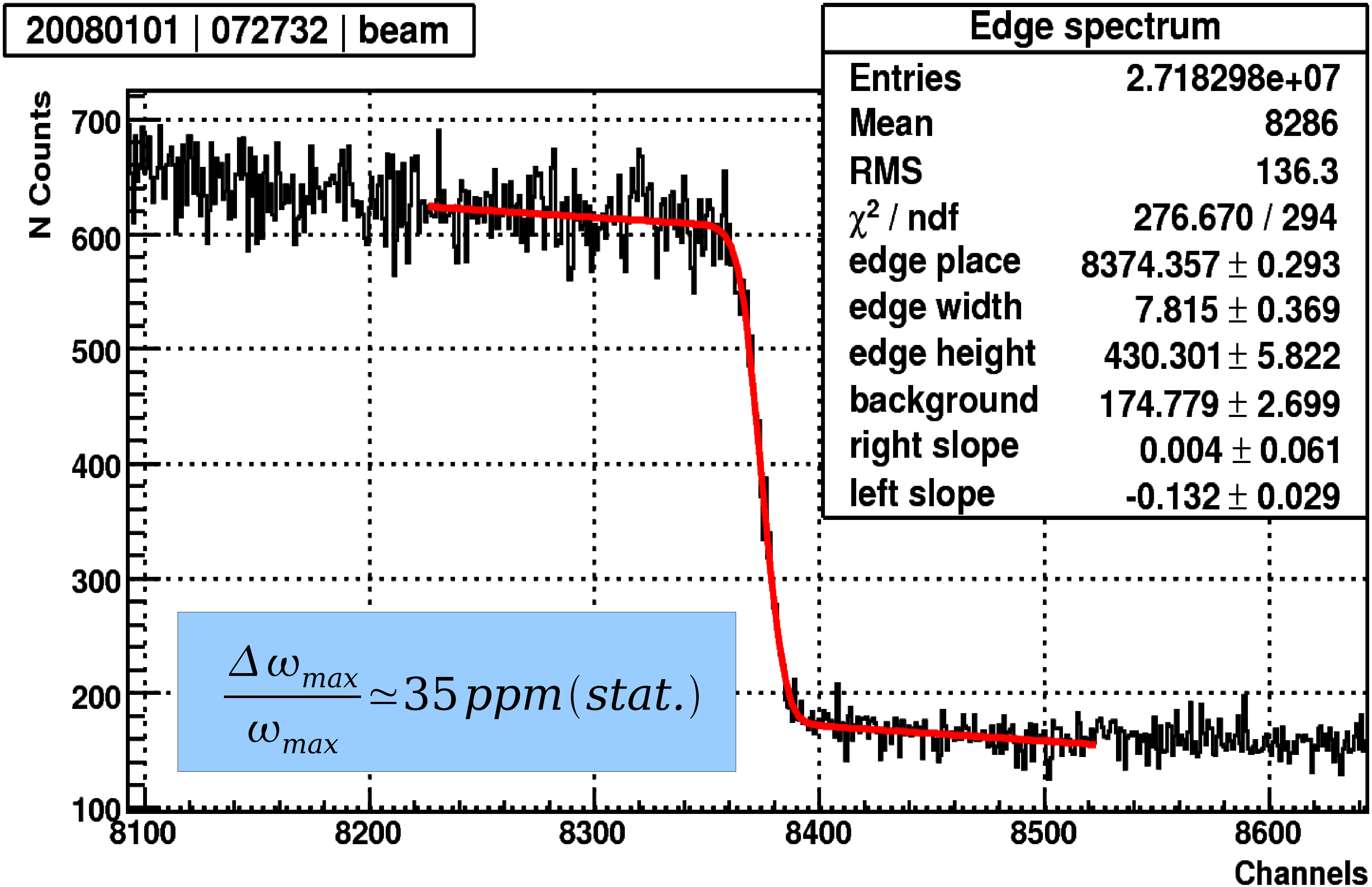
Flux: 30 kHz/mA/W



Scattered photons energy spectrum (VEPP-4M)

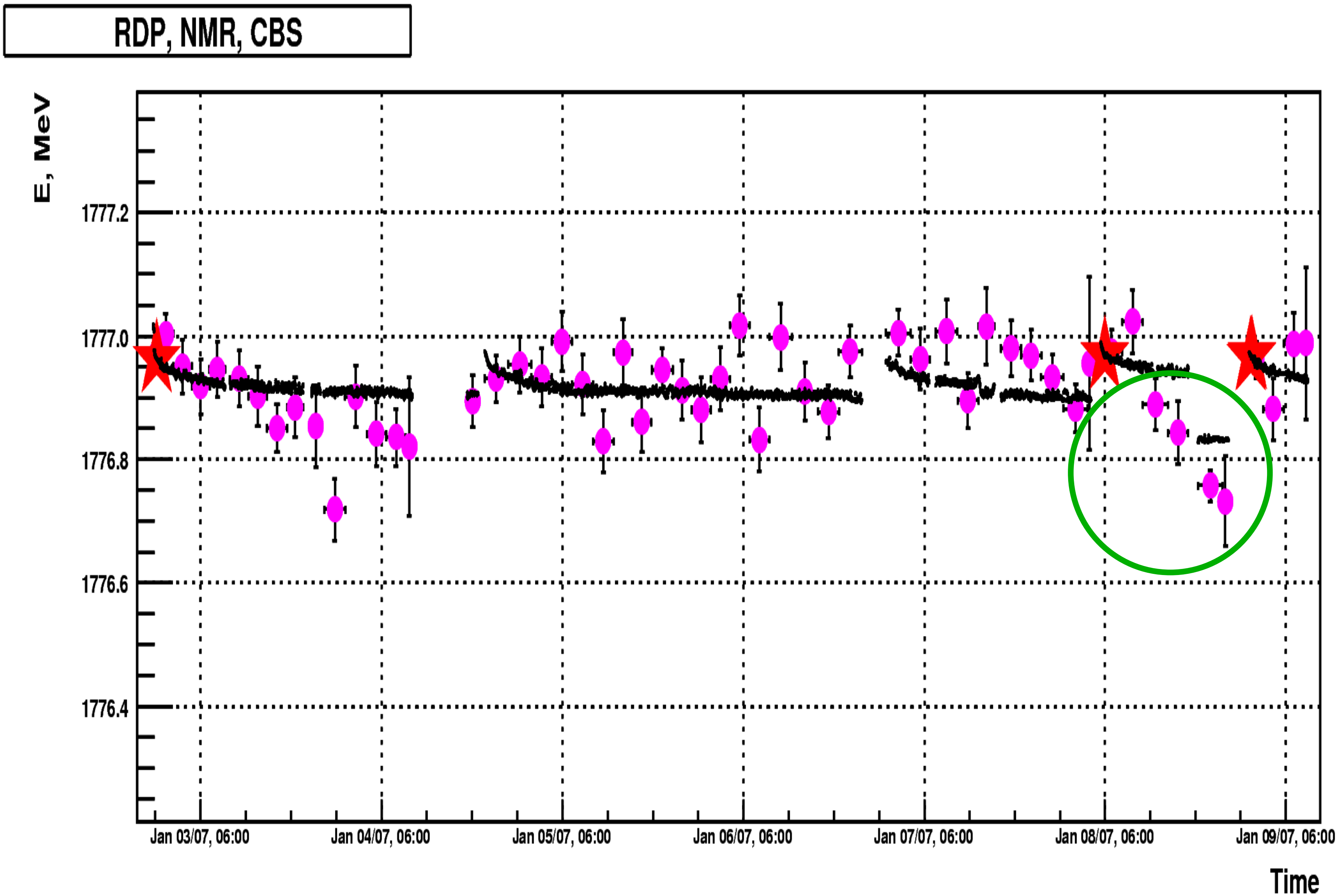


Scattered photons energy spectrum edge

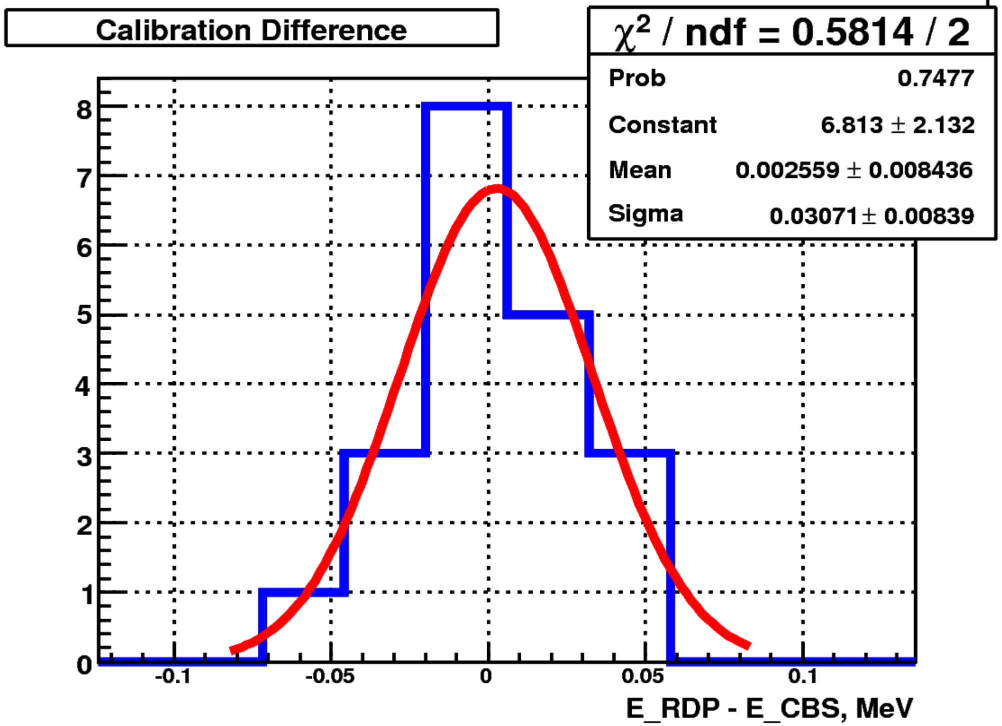


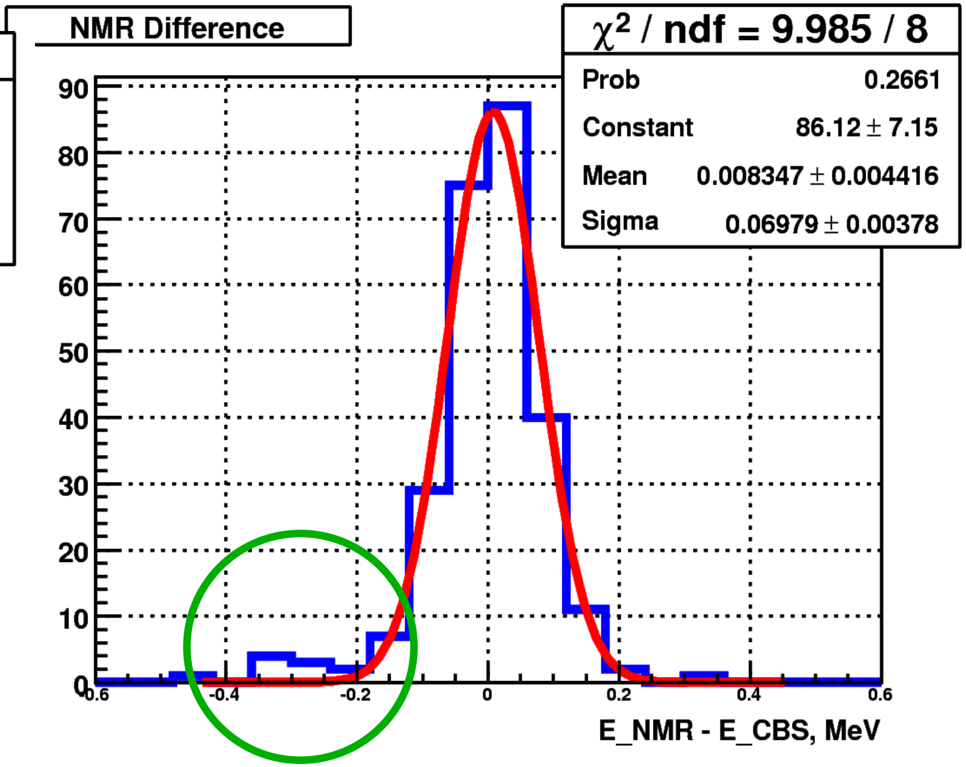
$$\frac{\Delta\omega_{max}}{\omega_{max}} \simeq 35\,ppm\,(stat.)$$

Fragment of 2007 tau-threshold scan . VEPP-4M energy with RD, Compton and NMR.



Cross check of resonant depolarization and Compton energy measurements





Average Compton stat. error 30 keV

Average Compton stat. error 50 keV

VEPP-4M Compton energy monitor performance

- Coaxial type HPGe detector (Canberra GC 2518) provides ~5% total photo-absorption efficiency for 6 MeV photons with energy resolution $\sigma \sim$ 2-3 keV.
- The HPGe counting rate is limited by pile-up effect and spectrometer electronics at the value about 10 kHz (for Compton backscattered photons above 3 MeV)
- GEM Select carbon dioxide laser with wavelength stability $< 10^{-7}$
- Under this conditions the statistical accuracy of 30 ppm is reached within 20-40 min data acquisition time
- Absolute energy scale of the HPGe detector is determined using radionuclides gamma lines. RD data was applied to fix small non-linearity of energy scale at higher energies (~0.5 keV for 6 MeV photons).
- Unlike resonant depolarization technique, the system provides continuous monitoring of the collider beam energy, and does not require interpolation procedure

Conclusions

- During the KEDR detector experiments the VEPP-4M collider beam energy is always known with accuracy better than 30 keV.
- Two completely different methods are applied for energy measurement.

- Resonant depolarization approach provides ultimate accuracy for instant beam energy (≤ 1ppm), but consumes a lot of time and require interpolation of the energy behavior between measurements.

- The Compton energy monitor provides continuous monitoring of the collider beam energy along with KEDR data taking, and does not require interpolation procedure. Stat. error is about (25 ppm / 1 hour) with comparable systematical accuracy.