The 40th ICFA Advanced Beam Dynamics Workshop on High Luminosity e+e- Factories

High precision beam energy measurement at VEPP-4M

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on behalf of the
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Talk outline

- Resonant depolarization at VEPP-4M
- Compton backscattering at VEPP-4M
- Cross-check the results
- BEPC-II energy calibration system
- Extensions for higher beam energies
- Conclusions

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:

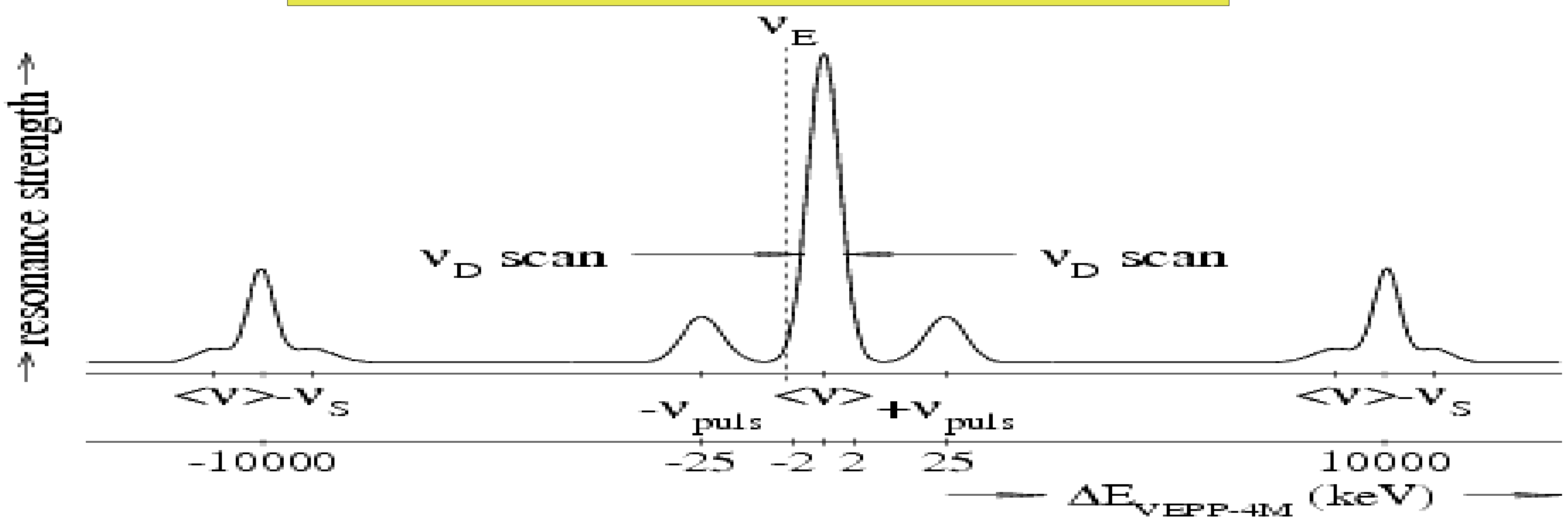
$$\frac{\Omega}{\omega_0} = 1 + \gamma\frac{\mu'}{\mu_0} = 1 + \nu$$

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.

Polarimetry

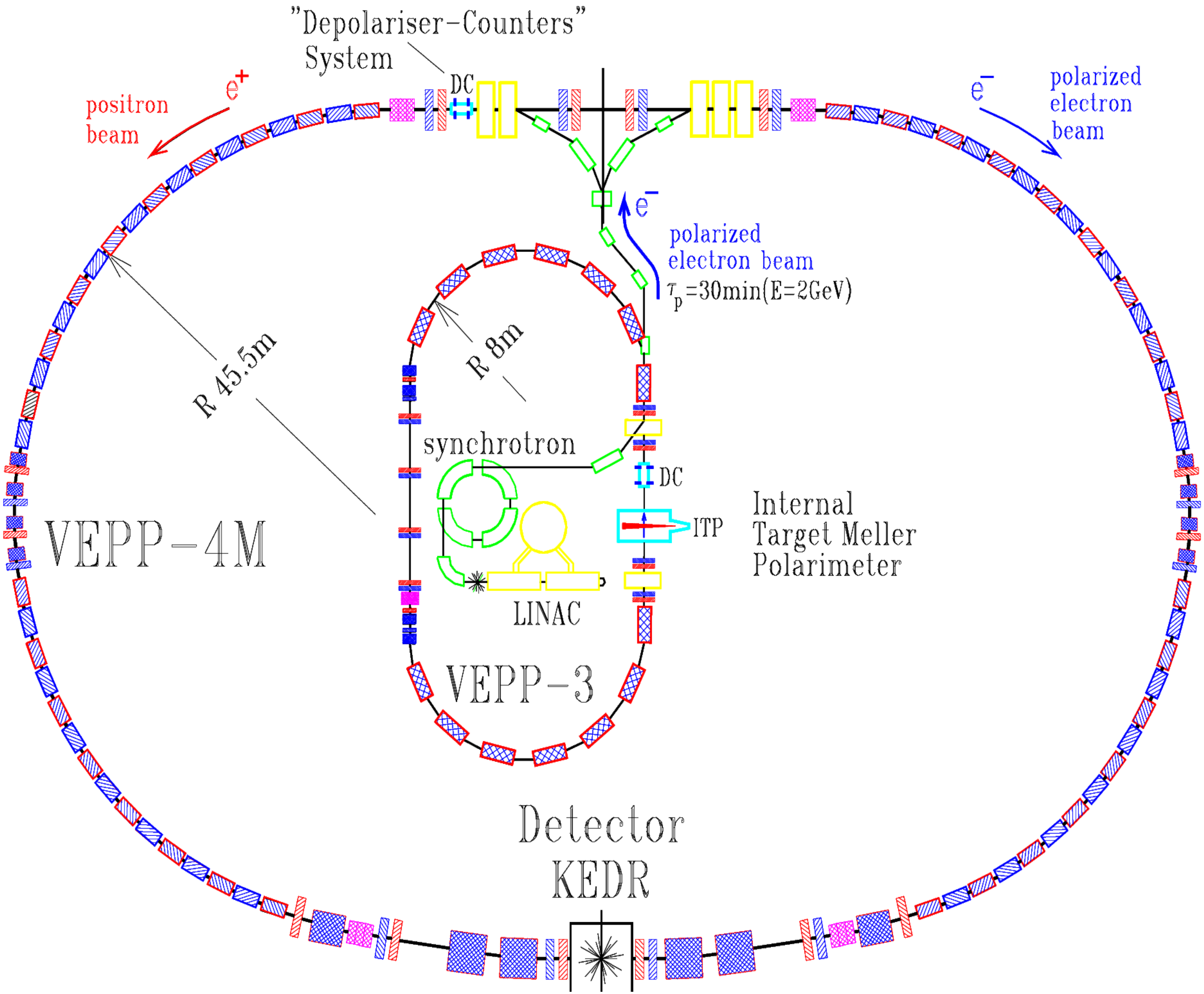
The external modulation frequency can destroy the beam polarization when it is in resonance with spin precession. At the VEPP-4M the Touschek effect is used for beam polarization measurement

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



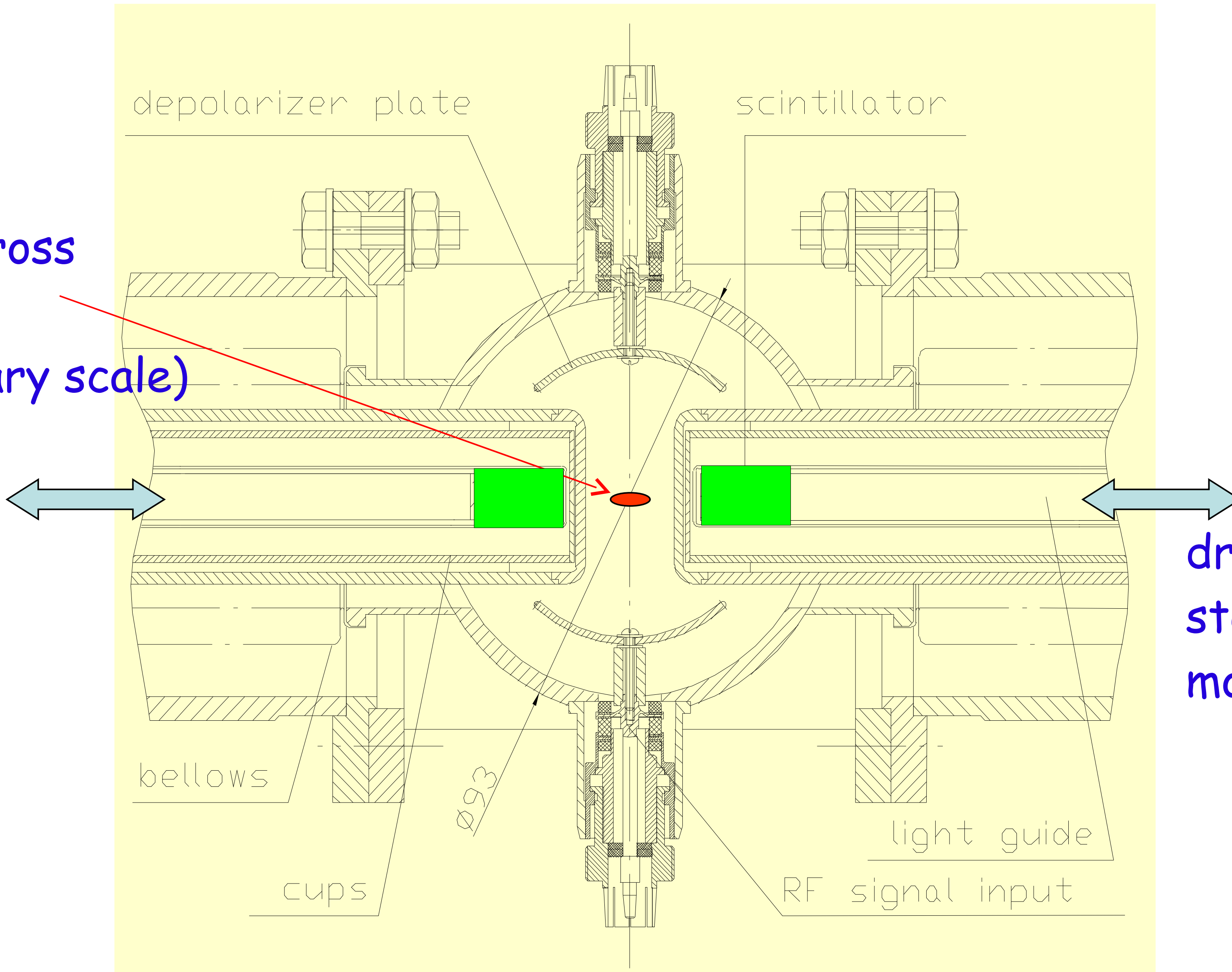
Spin response function: central peak corresponds to average particle energy

VEPP-4 complex



VEPP-4M Touschek Polarimeter

Beam cross section (arbitrary scale)

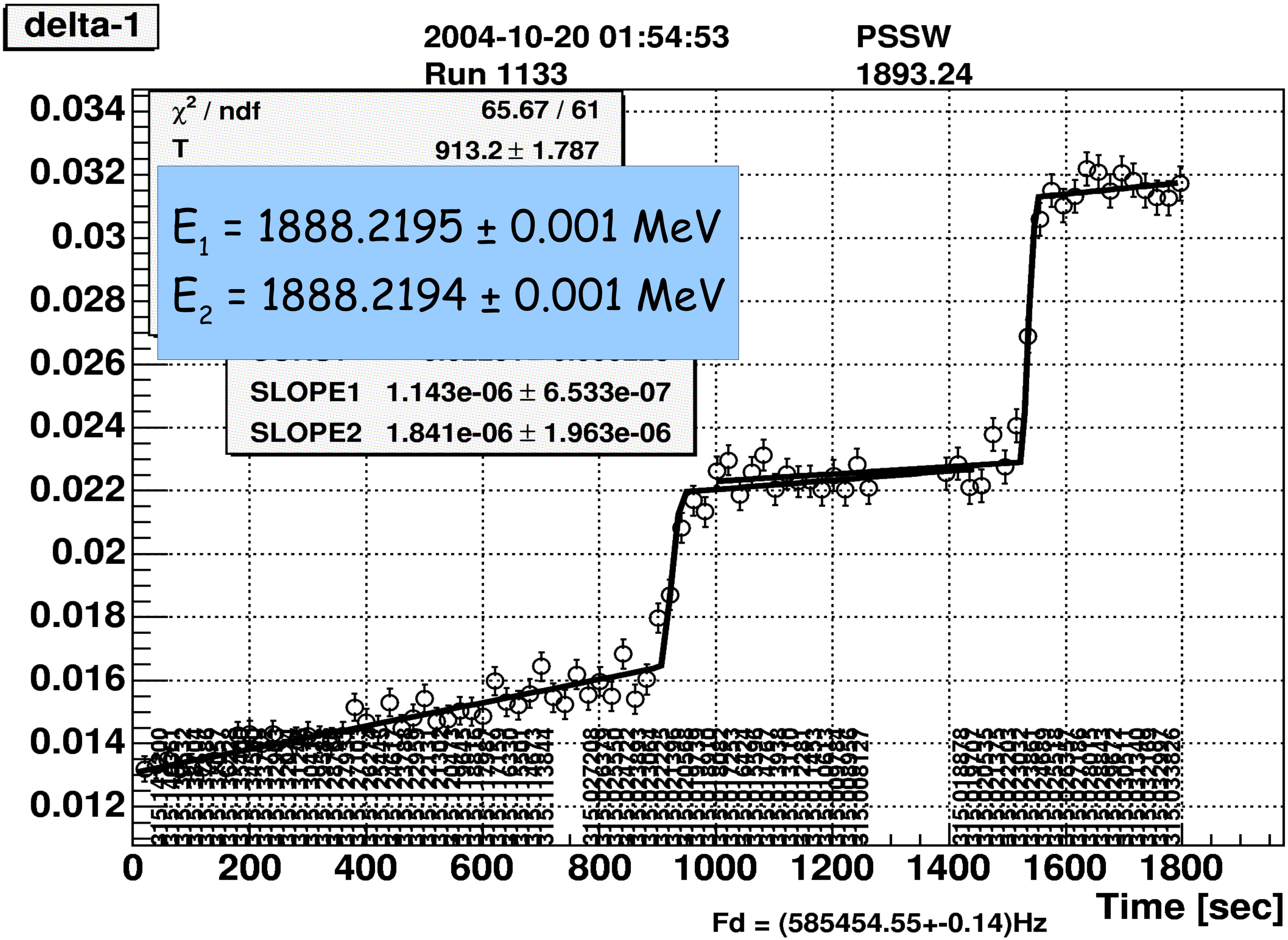


driven by stepping motors

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

RD energy calibration



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 is the beams energies during the data runs. Some interpolation procedure need to be found to describe the energy behavior between resonant depolarization calibrations.

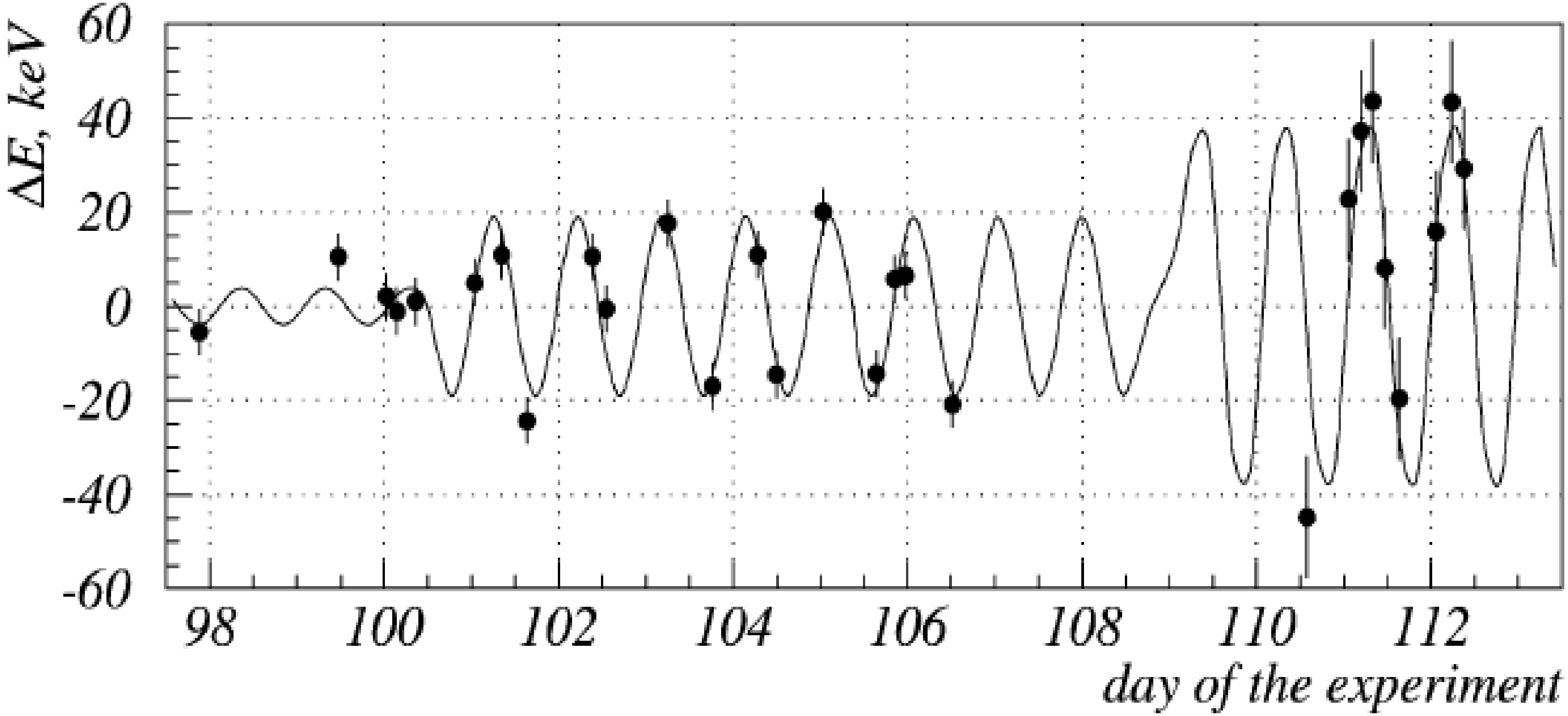
The beam energy is a function of parameters

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

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

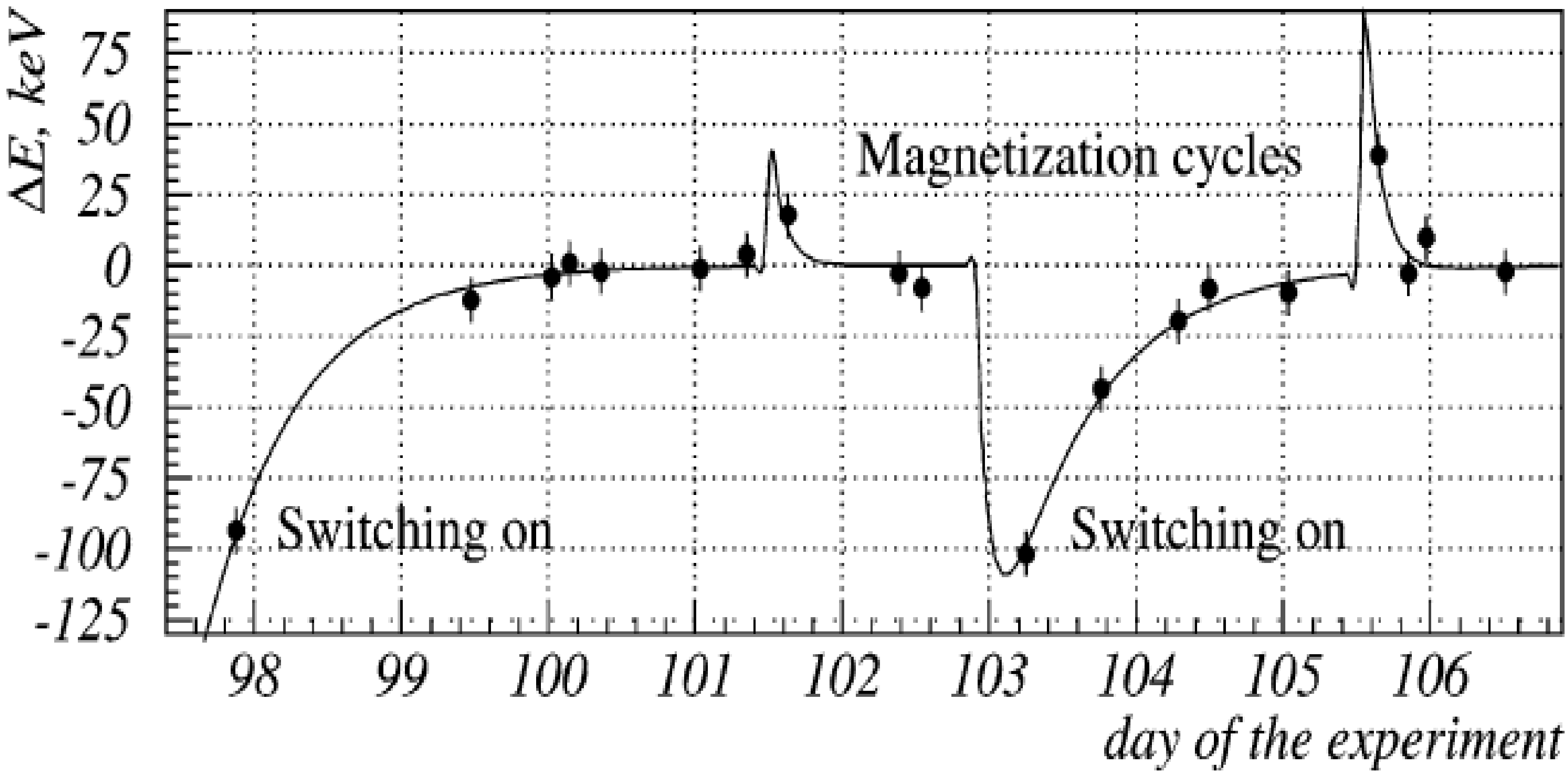
Predicted Energy and Day-to-Night Oscillations

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



- Points are RD energy measurements
- Aperiodic dependencies are removed

Predicted Energy in operation cycles

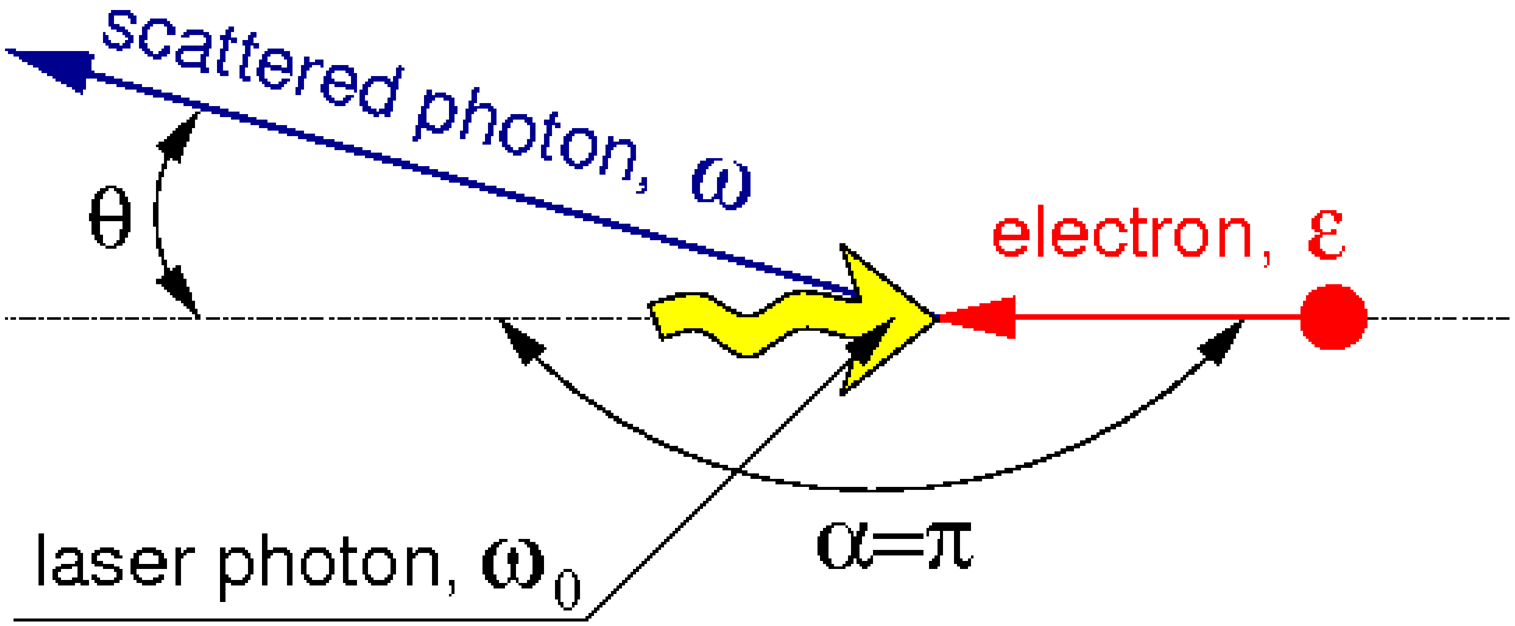


- Points are RD energy measurements
- Periodic dependencies are removed

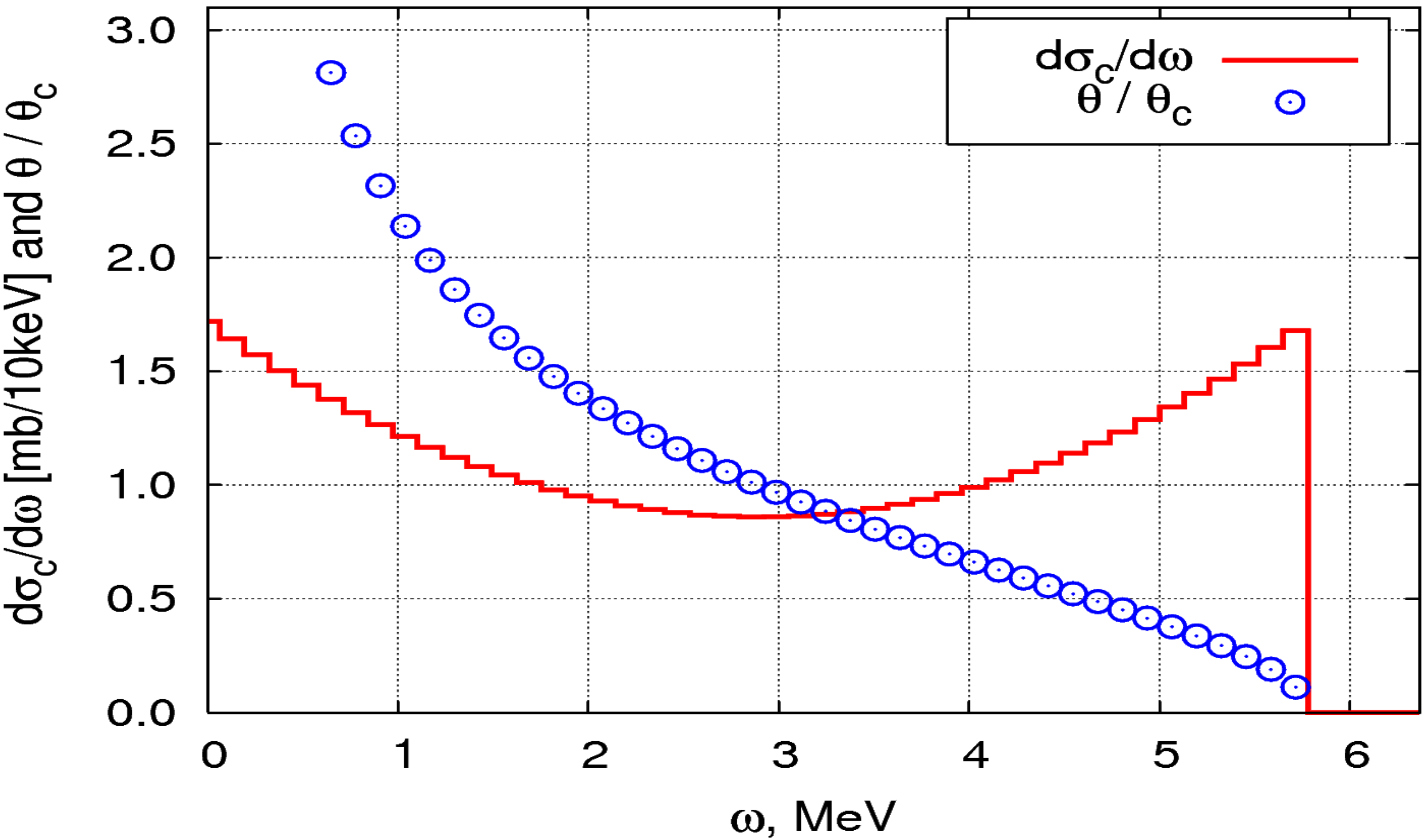
Resonant Depolarization at the VEPP-4M: results and performance

- More then 1500 energy calibrations performed since 2004
- Counting rate of Touschek polarimeter ~ 1 MHz
- Beam energy range 1.5 GeV - 2.0 GeV
- Accuracy of single calibration ≤ 1 ppm
- Beam energy interpolation accuracy 7 keV - 30 keV

Compton back-scattering energy monitor



Compton back-scattering cross section



ω_0= 0.12 eV, ε = 1777 MeV, θ_c= 1/γ, σ_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:

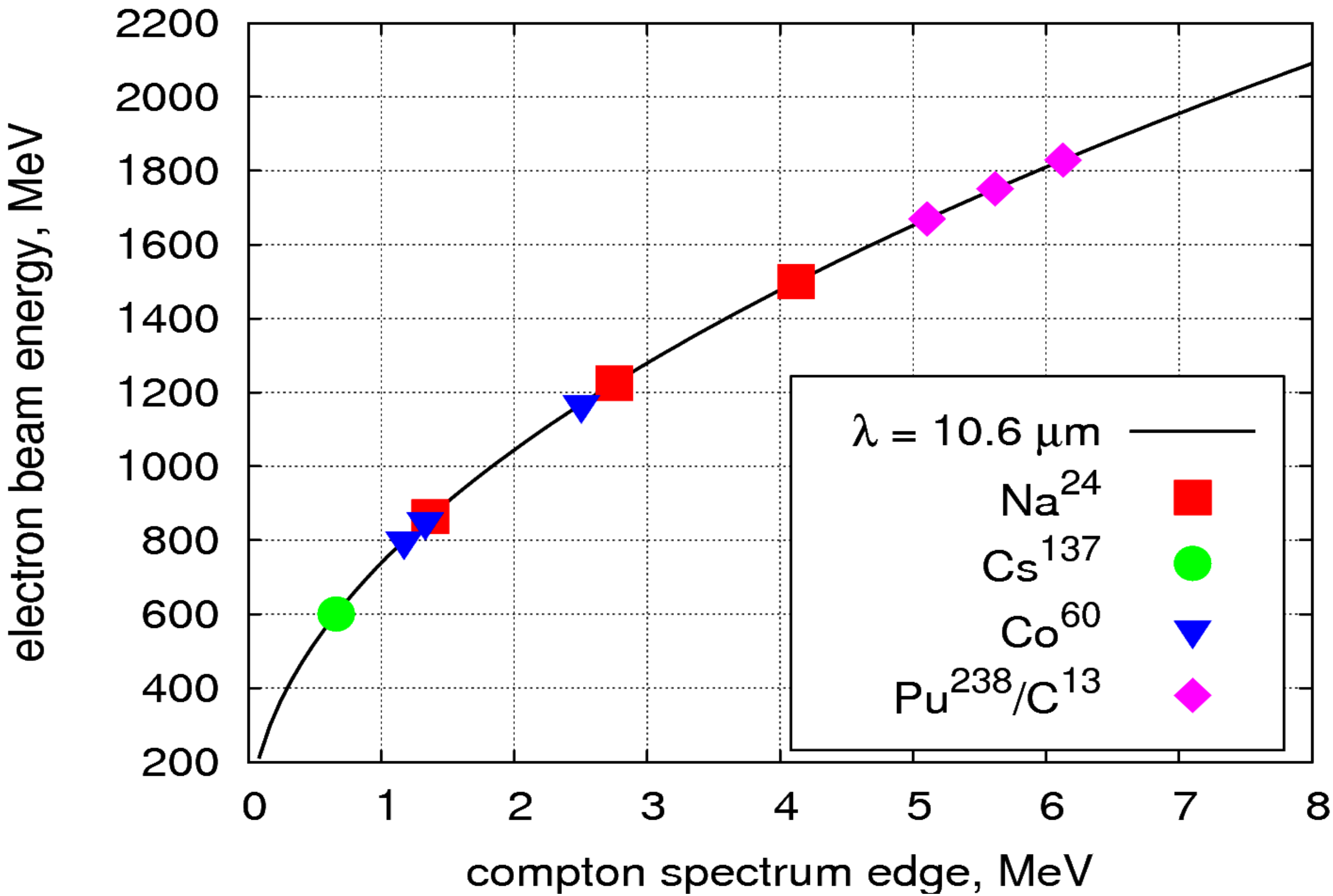
$$\varepsilon = \frac{\omega_{max}}{2}\left(1+\sqrt{1+\frac{m_e^2}{\omega_0\,\omega_{max}}}\right)$$

Accuracy <10^{-4} requires:

- High Purity Ge detector with excellent energy resolution
- Absolute scale calibration by the radio nuclides γ-lines
- ω_{max} < 10 MeV

- Proved by RD measurements at BESSY (Berlin), BINP (Novosibirsk)

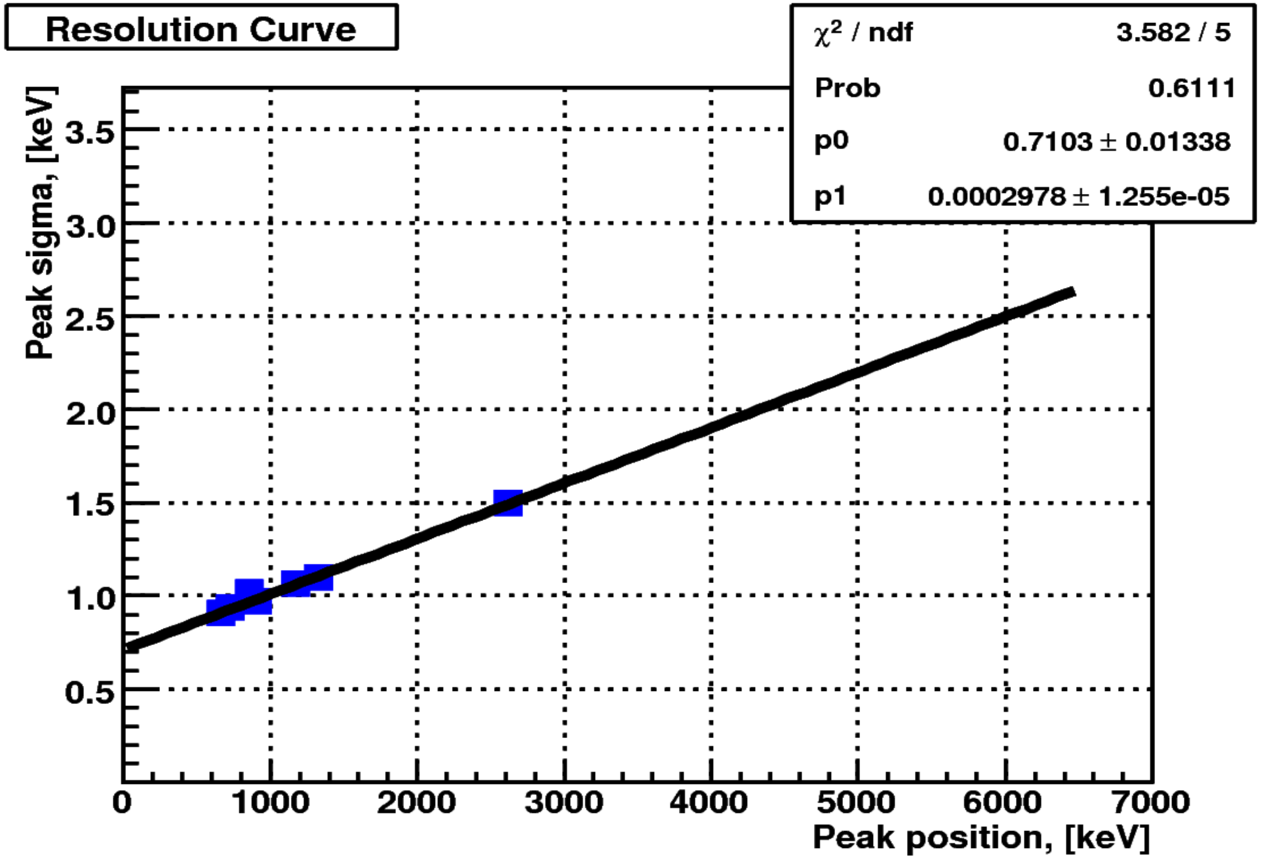
Beam Energy Range with CO_2 Laser



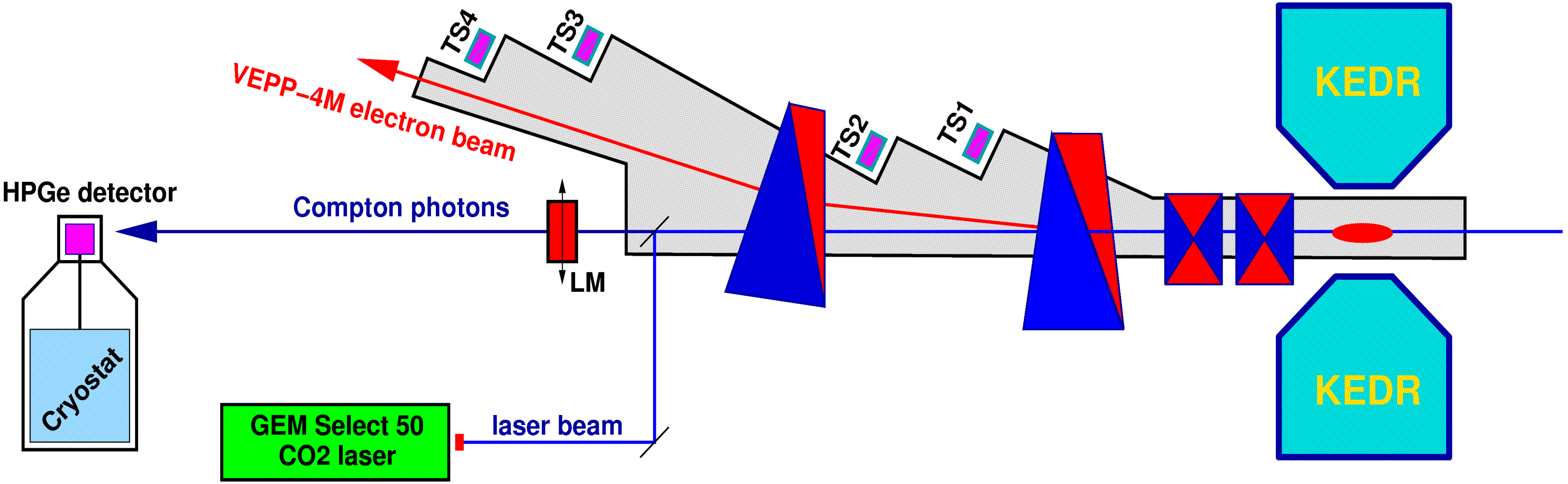
High Purity Germanium (HPGe) detectors

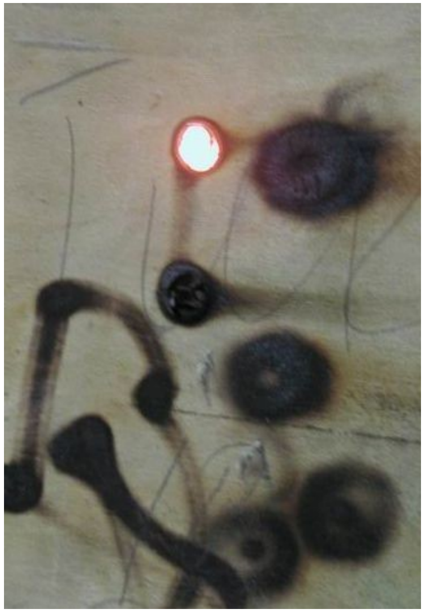
- HPGe detector is a large germanium diode operated in the reverse bias mode. At a suitable operating temperature ~85°K, the barrier created at the junction reduces the leakage current to acceptably low values. Thus an electric field can be applied that is sufficient to collect the charge carriers liberated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

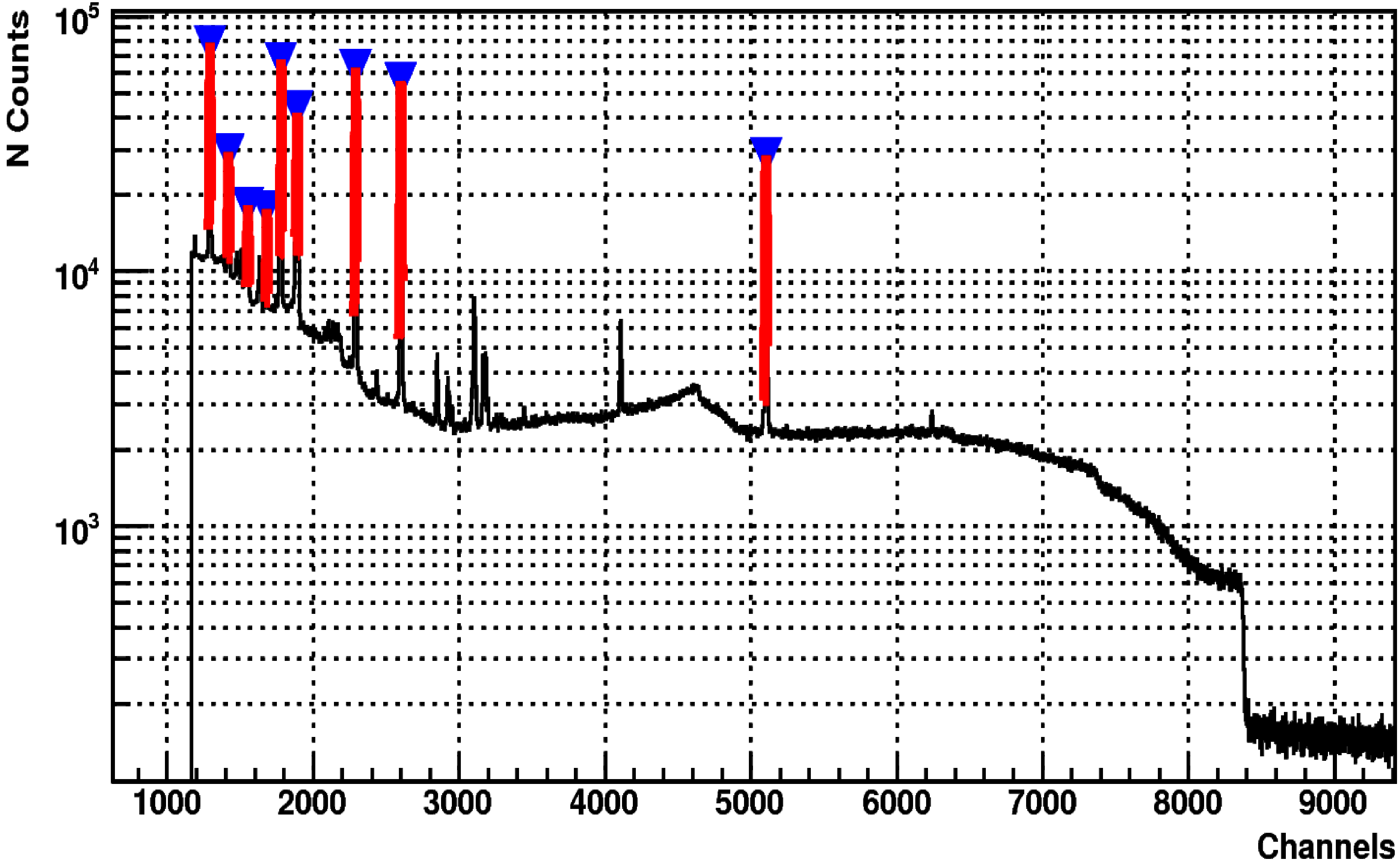


VEPP-4M Compton energy monitor layout

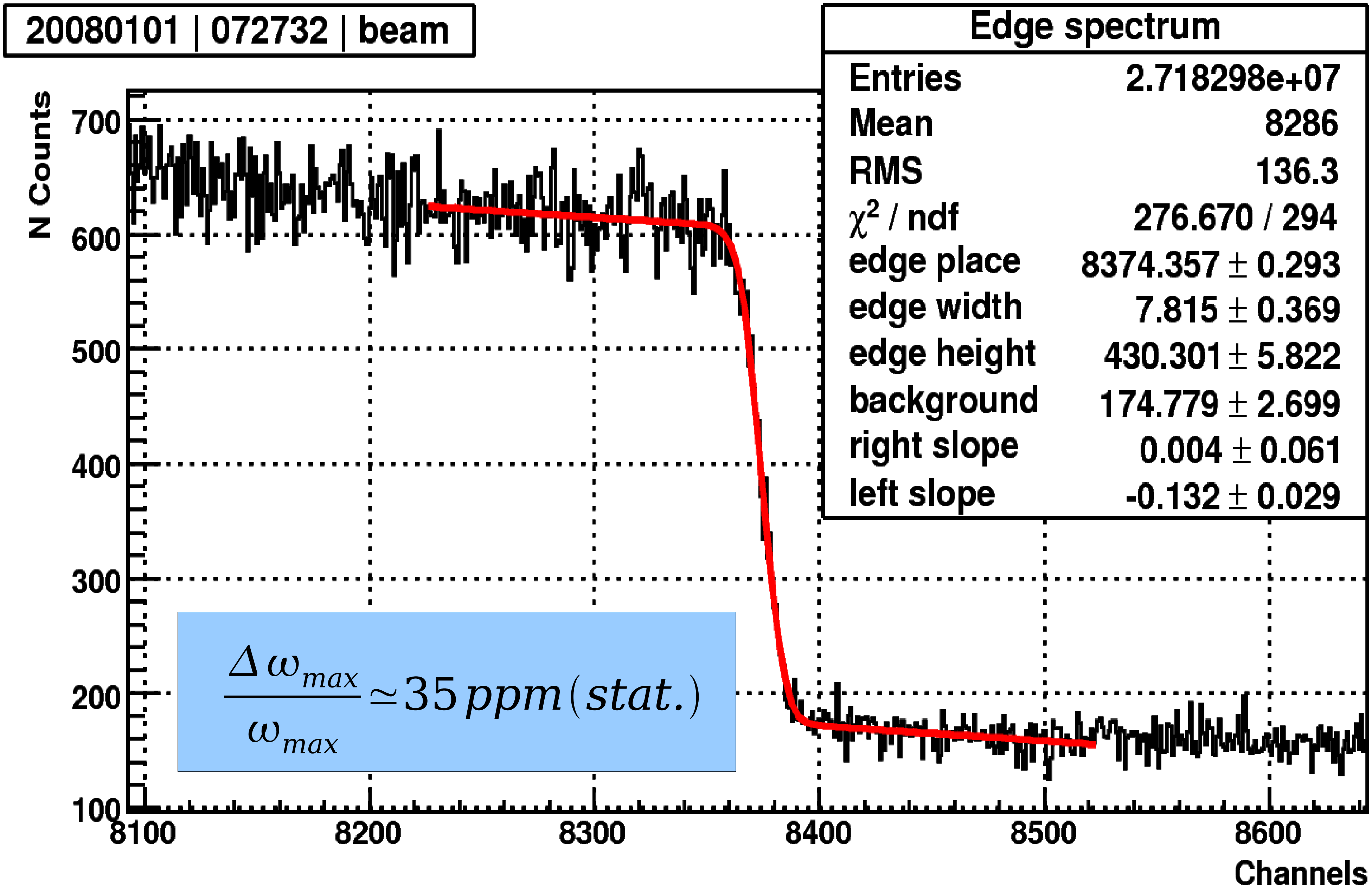




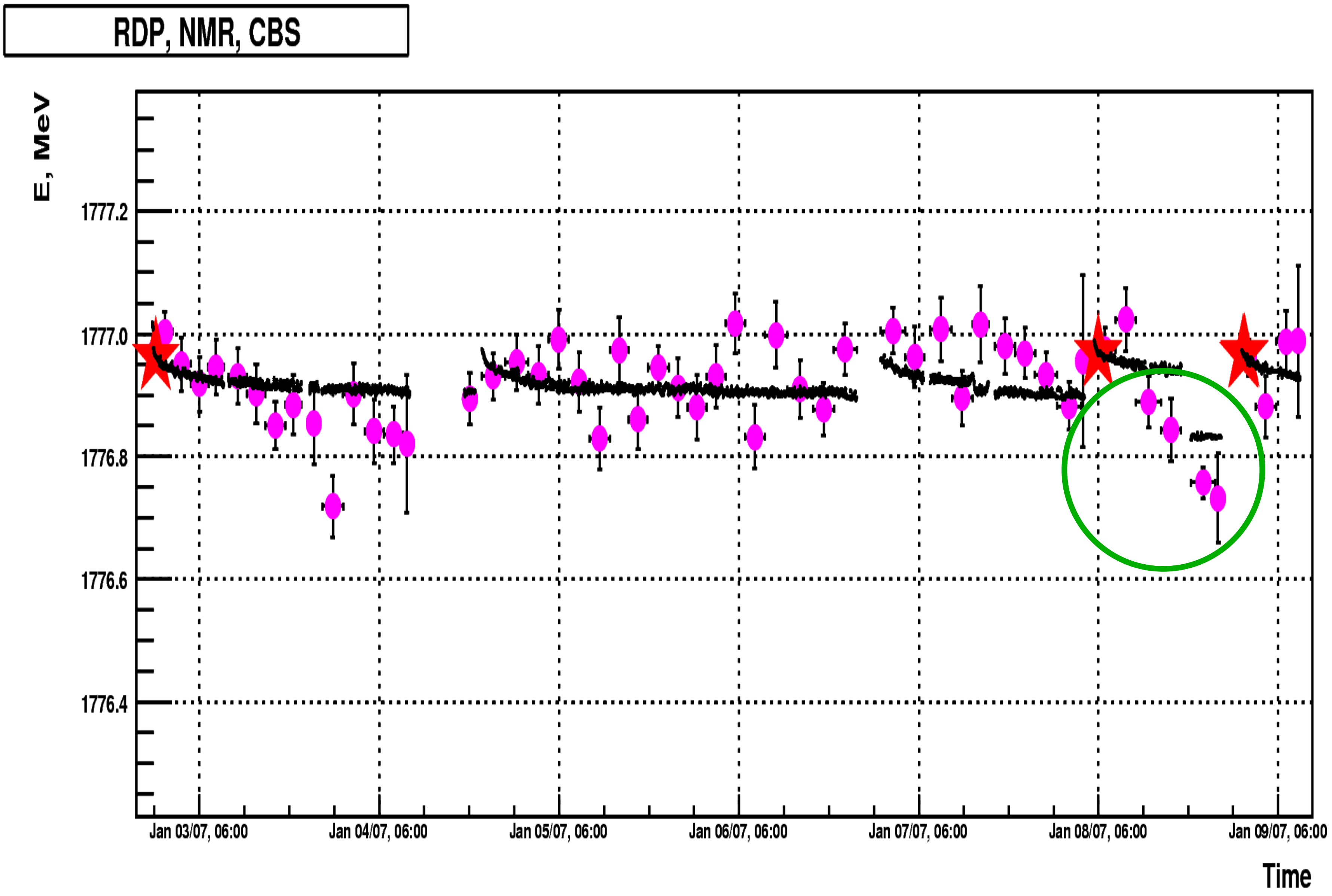
Scattered photons energy spectrum (VEPP-4M)



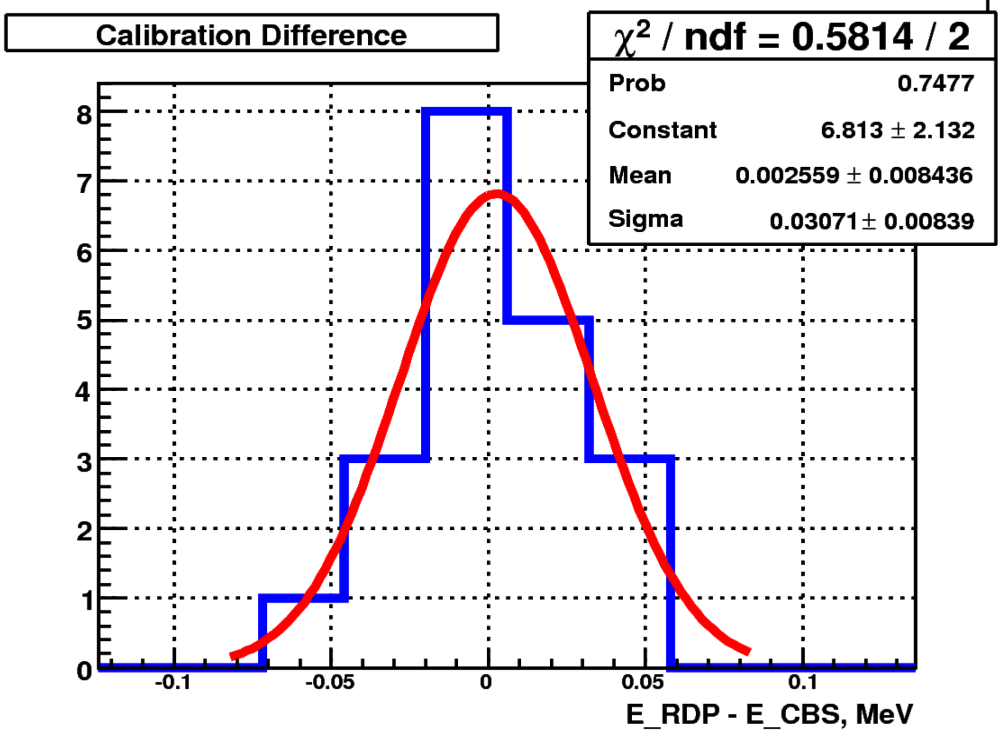
Scattered photons energy spectrum edge

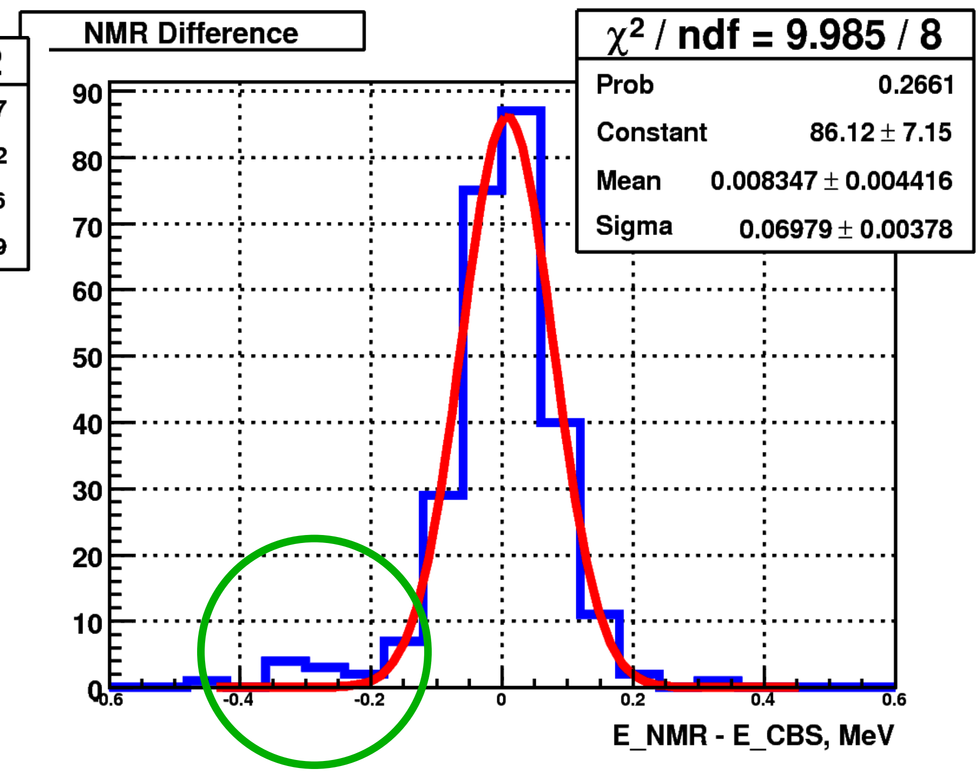


Fragment of 2007 tau-threshold scan .
VEPP-4M energy with RD, Compton and NMR.



Cross check of resonant depolarization and Compton energy measurements





Average Compton stat. error 30 keV

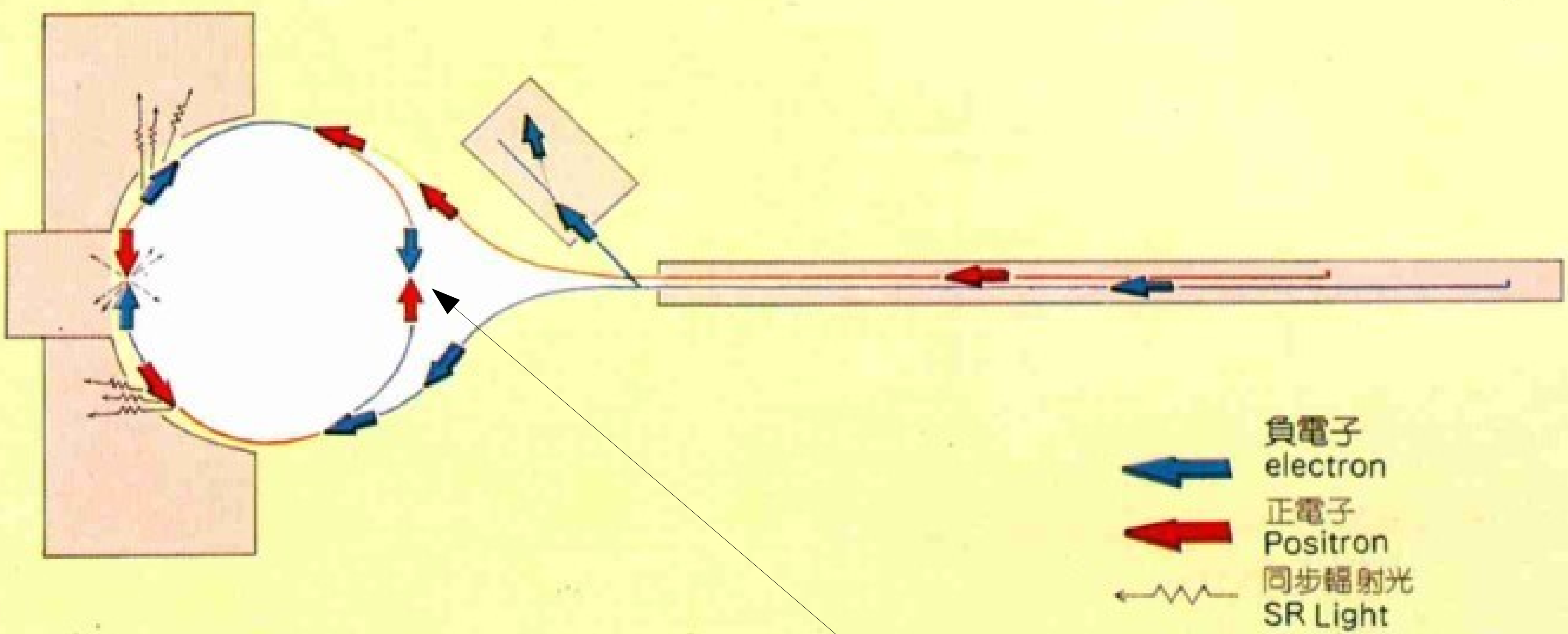
Average Compton stat. error 50 keV

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 energies 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

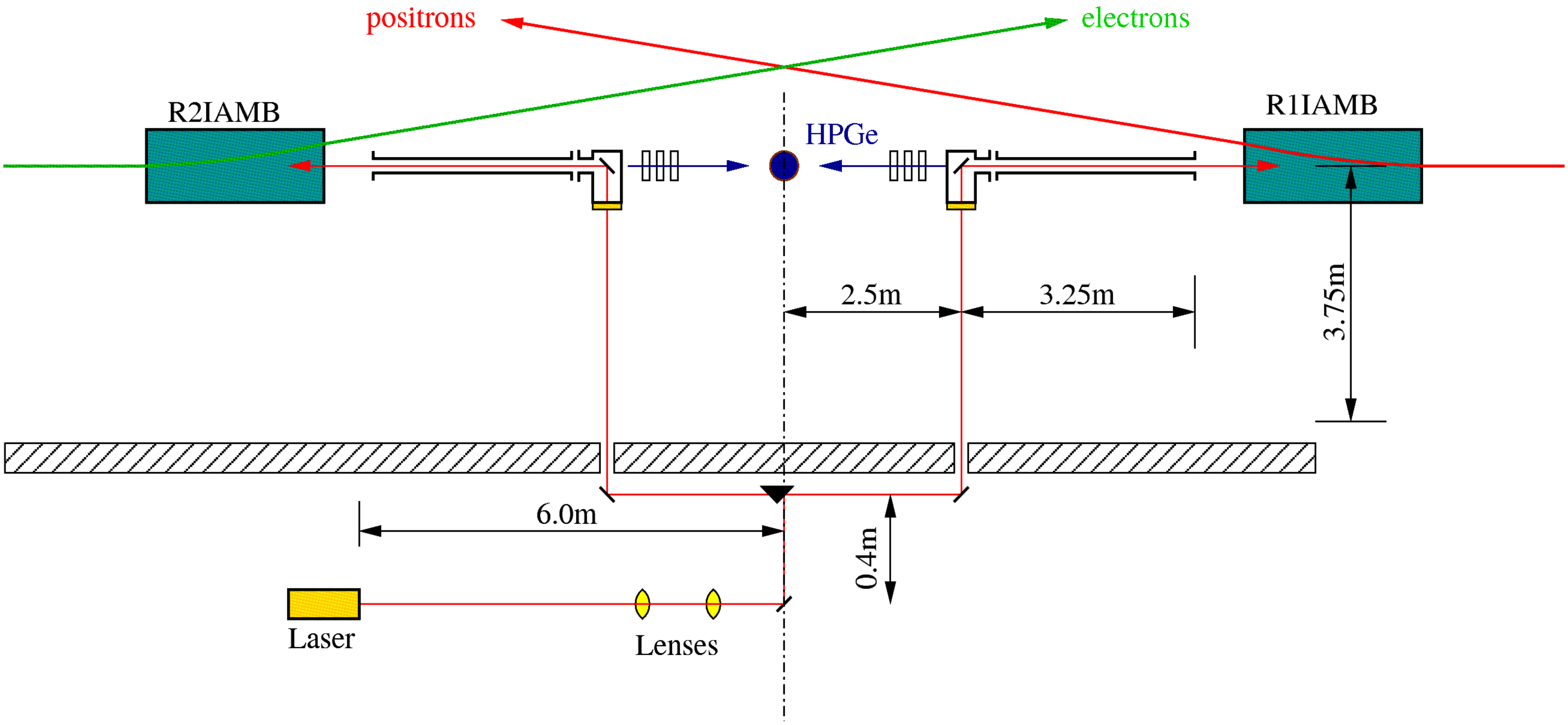
BES-III collaboration:

The beam energy calibration system for the BEPC-II collider



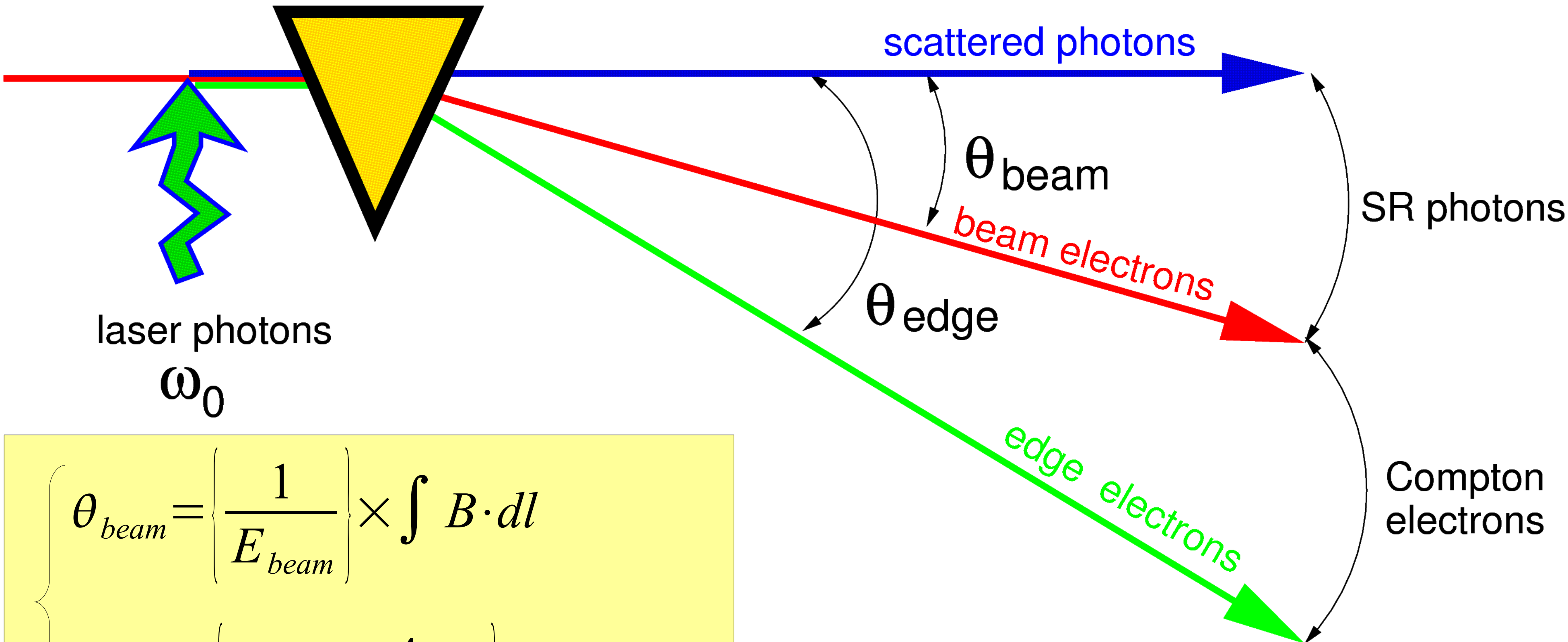
e-/e+ beam energy monitor location

BEPCII energy calibration system layout



- Will allow to measure both e+ and e- beams energy

Whatever the energy range is ...



$$\begin{cases} \theta_{beam} = \left\{ \dfrac{1}{E_{beam}} \right\} \times \int B \cdot dl \\ \theta_{edge} = \left\{ \dfrac{1}{E_{beam}} + \dfrac{4\omega_0}{m^2} \right\} \times \int B \cdot dl \end{cases}$$

$$\theta_{edge} - \theta_{beam} = \frac{4\omega_0}{m^2} \times \int B \cdot dl$$

Conclusions

- During the KEDR detector experiments the VEPP-4M collider beam energy is always known with accuracy better than 30 keV.
- Two independent approaches are used for beam energy measurement.
- Resonant depolarization provides ultimate accuracy for instant beam energy (≤ 1ppm), but consumes a lot of time and requires 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.
- The beam energy calibration system is now under construction for the BES-III collaboration experiments
- New approaches are required for future facilities (ILC, CLIC, etc.) and VEPP-4M is a good place to test new ideas