Beam energy determination in collider experiments using backscattering of laser light.

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Introduction (physical motivation).

Precise beam energy detrmination in experiments at **e+e–** colliders is important for

- Particles masses and widths measurements
- Study of interference effects in the cross sections
- Measurements of cross sections themselves

Examples.

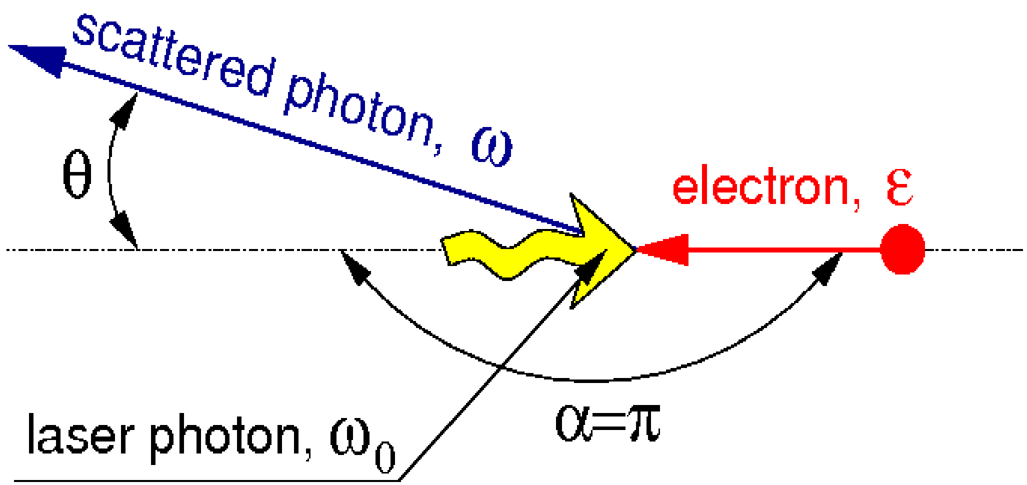
- ***Z***-boson mass $\mathbf{m_Z = 91187.6 \pm 2.1}$ **MeV**. Common LEP energy error lead to uncertainty **1.7 MeV**.
- In order to measure the $\mathbf{e^+e^- \to \pi^+\pi^-}$ cross section below **1 GeV** (center-of-mass energy) with accuracy about **0.5%**, the beam energy should be measured with error $\mathbf{\delta E/E \sim 10^{-4}}$.

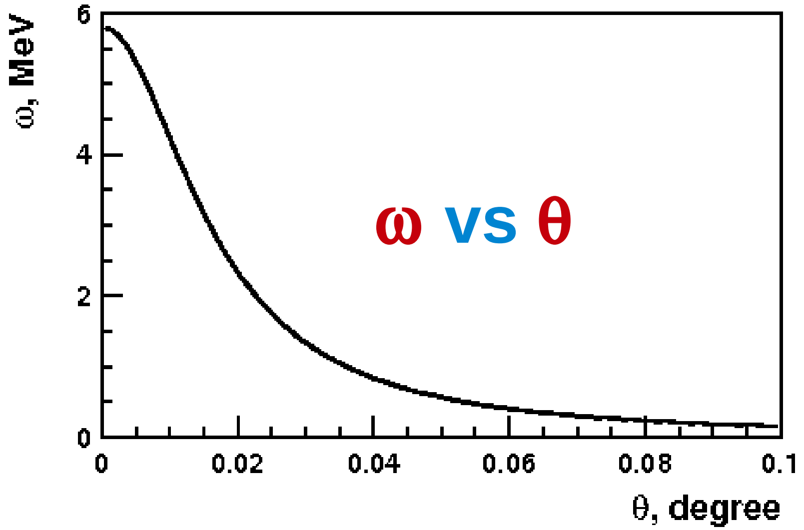
Introduction (beam energy determination methods).

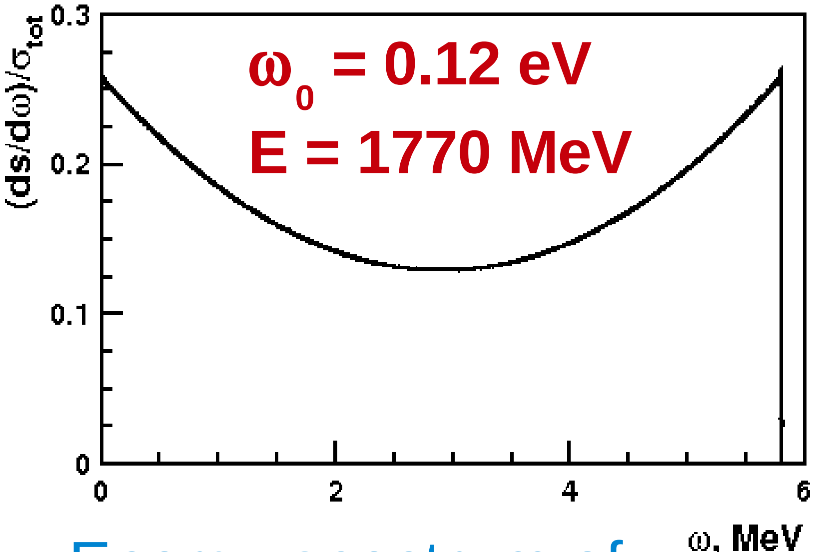
- **E(MeV) = 300Bρ+Δ$_{corr}$**, B is magnetic field, **ρ** is radius of the dipole magnet, **Δ$_{corr}$** is nonlinear corrections. **δE/E>10^{-3}**.
- Beam energy determination by measurement of the momentum of particles in collinear events. Example **$e^+e^- \to \phi(1020) \to K^+K^-$**.
  $E=\sqrt{p_K^2+m_K^2}+\Delta_{corr}$, **$p_K$** is average momentum of **K^+K^-**, **Δ$_{corr}$** is correction due to kaon energy losses inside the detector, radiative losses of initial electrons, ... **δE/E~5×10^{-5}** (CMD-2 at VEPP-2M).
- Beam energy determination using positions of the narrow and precisely measured resonances peaks (**ω**, **φ**, **ψ**, **ϒ**).
- Resonance depolarization. **δE/E~10^{-6}**.
  $$E=\left(\frac{\Omega}{\omega_s}-1\right)\frac{\mu_0}{\mu'}m_e c^2, \quad \omega_d \pm k\omega_s=\Omega(k\in\mathbb{Z}).$$
  The polarized beam is necessary.
- Compton backscattering (CBS) of laser photons on the collider beam.

Compton backscattering.

CBS of laser light on electron beams is a well known method of generation of quasimonochromatic photon beams.







Energy spectrum of scattered photons.

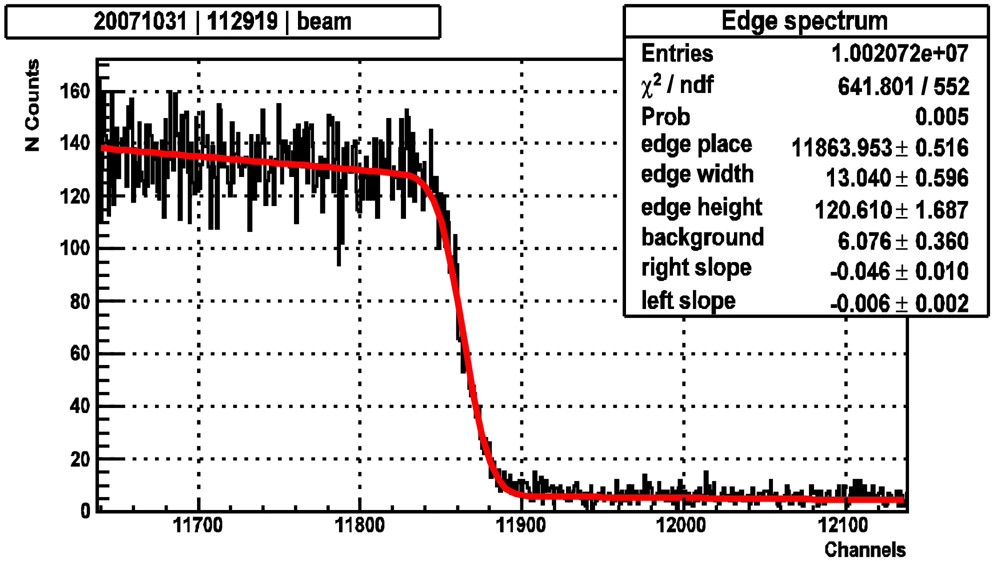
The maximal energy of backscattered photon $\omega_{max} = \frac{E^2}{E + m_e^2/4\omega_0}$

If one have measured ω_{max} then the electron energy can be obtained as

$$E = \frac{\omega_{max}}{2}\left[1 + \sqrt{1 + \frac{m_e^2}{\omega_0 \omega_{max}}}\right]$$

Brief description of the CBS method

- The monochromatic laser radiation is put in collisions with the beam.
- The energy of the backscattered photons is measured with High Purity Germanium (HPGe) detector.



- The beam energy **E** is calculated from the maximum energy ω_{max}.

The method was used to measure the beam energy

E ~ 0.3 – 2.0 GeV, δE/E ~ 10^{-4} – 10^{-5}.

CBS method

- provides rather high accuracy,
- provides measurements in a wide energy region,
- allows to measure beam energy during data taking.

Application of the CBS method of beam energy determination.

• **Compton backscattering has been proposed as a diagnostic tool for electron beam energy in**
T. Yamazaki et. al., IEEE Trans. on Nucl. Sci., Vol. NS-32, No 5, 1985.

• **First measurement of the beam energy E≈1.3 GeV at storage ring of Taiwan Light Source with accuracy $\delta E/E \sim 10^{-3}$ was reported in**
Ian C. Hsu, et al., Phys. Rev. E 54 (1996).

• **The accuracy of the measurements was improved at SR sources BESSY-I and BESSY-II (Berlin):**
$\delta E/E \sim 2\times10^{-4}$, **E≈0.8 GeV** [*R. Klein, et al., Nucl. Instr. and Meth. A 384 (1997) 293*],
$\delta E/E \sim 3\times10^{-5}$, **E≈1.7 GeV** [*R. Klein, et al., Nucl. Instr. and Meth. A 384 (2002) 545*].
The accuracy was proved by comparison with results of resonance depolarization method.

• **In collider experiments CBS was first applied at VEPP-4M (Novosibirsk), E=1–2 GeV**
[*V.E. Blinov, et. al. Nucl. Instr. and Meth. A 598 (2009) 23*]

• **Then at τ–charm factory BEPC-II (Beijing), E=1–2 GeV**
[*V.E. Abaqumova, et. al. Nucl. Instr. and Meth. A 659 (2011) 21*] **and**

• **VEPP-2000 (Novosibirsk), E<1 GeV**
[*V.E. Abaqumova, et. al. Nucl. Instr. and Meth. A 744 (2014) 35*]

The beam energy measurement system includes:

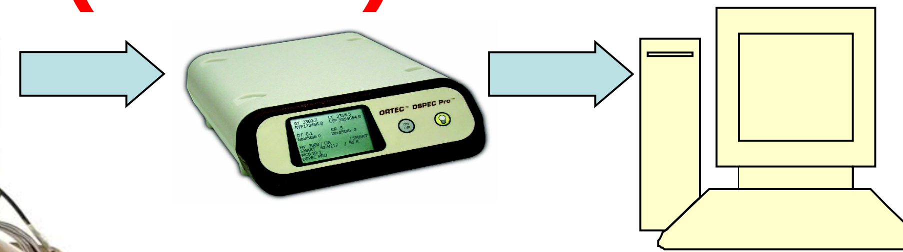
- Laser and optical system to provide initial photons and their transportation.
- Laser-to-vacuum insertion system provides insertion of the laser beam into the vacuum chamber of collider.
- HPGe detector to measure backscattered photons spectrum
- Data acquisition system
- Data processing

High Purity Germanium (HPGe) detector.

Commercially available HPGe detector can measured the γ–quanta with energy below **10 MeV**.

Typical parameters of coaxial HPGe detector:

- **∅ 5 – 6 cm**, height **5 – 7 cm**
- Energy resolution $\delta\omega/\omega \sim 10^{-3}$.
- Operating temperature **≈100K**



HPGe detector in cryostat with electronics.

The detector is connected to multichannel analyzer, which transfers data using The USB port to the computer.

The statistical accuracy of beam energy measurement about **$5\times(10^{-4} - 10^{-5})$** can be achived in a reasonable time (**≤ 1 hour**).

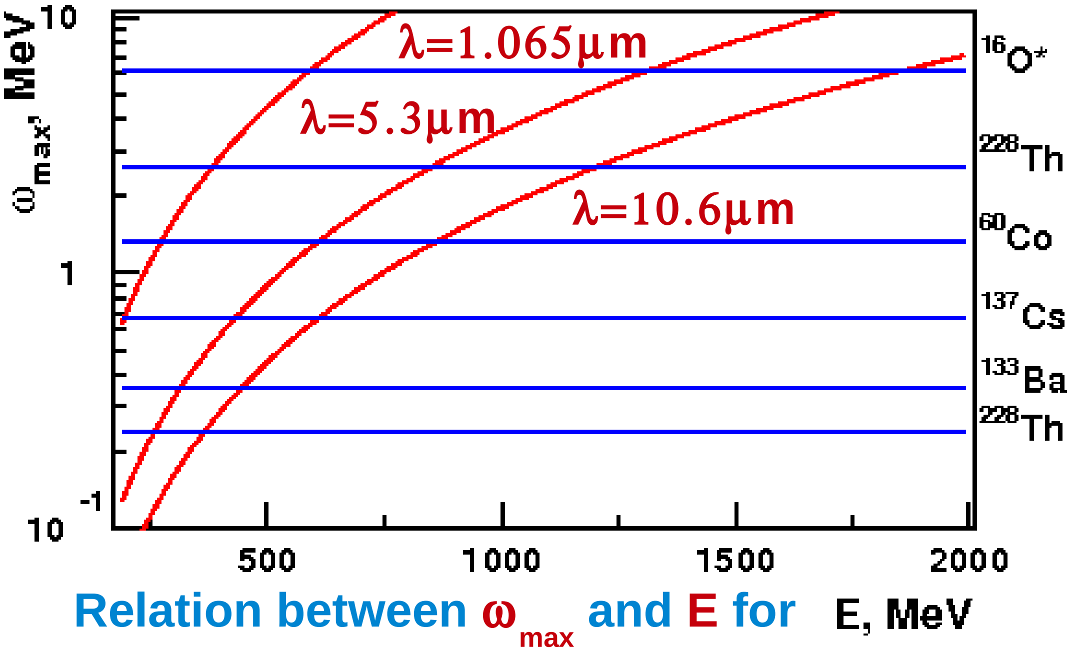
The systematic accuracy is mostly defined by absolute calibration of the detector . The accurate calibration could be done in the photon energy range up to 10 MeV by using the γ–active radionuclides.

Radiative sources for HPGe calibration:

- ^{208}Tl E_γ = 583.191 ± 0.002 keV
- ^{137}Cs E_γ = 661.657 ± 0.003 keV
- ^{60}Co E_γ = 1173.237 ± 0.004 keV
- ^{60}Co E_γ = 1332.501 ± 0.005 keV
- ^{208}Tl E_γ = 2614.553 ± 0.013 keV
- ^{16}O* E_γ = 6129.266 ± 0.054 keV

[^{238}Pu^{13}C]: $\alpha + {}^{13}C \rightarrow n + {}^{16}O^*$

Laser – the source of initial photons.



Relation between ω_{max} and E for different laser wavelength.

The main requirements:

- the single generated line,
- high stability of parameters,
- easy maintance,
- **ω_{max}≈0.2 – 6 MeV** (posibility of HPGe detector calibration using γ−active radionuclides.)

λ≈1.065μm – solid state laser. Can be used at low energy region **E<0.5 GeV**.

λ≈5.3 μm – CO laser was used below **1 GeV** at VEPP-2000.

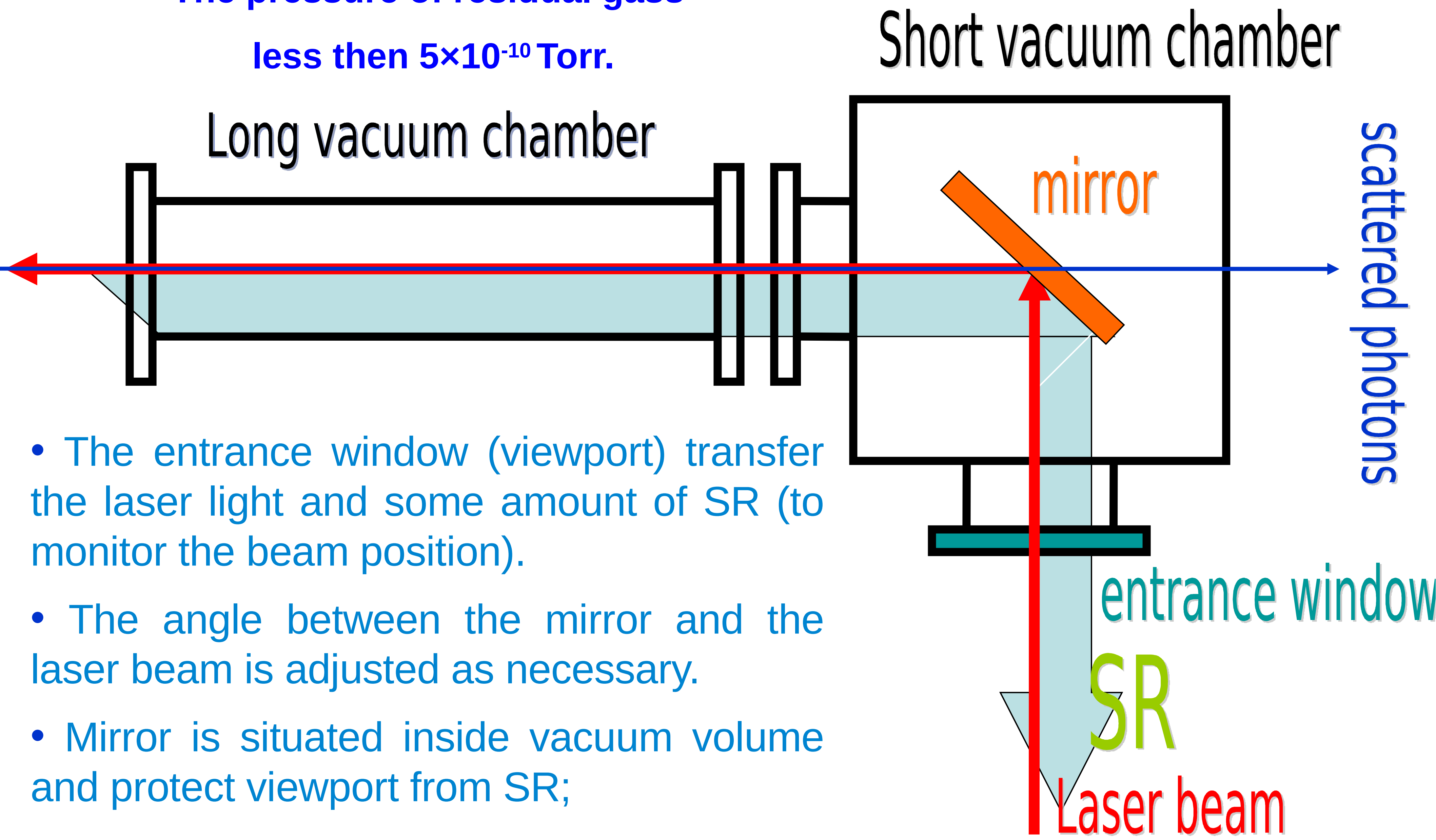
PL3 CO laser from Edinburgh instruments. **P=2W**.

λ≈10.6 μm – CO_2 laser was used in the energy region **1<E<2 GeV** at VEPP-4M and BEPC-II.

GEM Selected 50^{TM} CO_2 laser from Coherent, Inc. **P=25 W**.

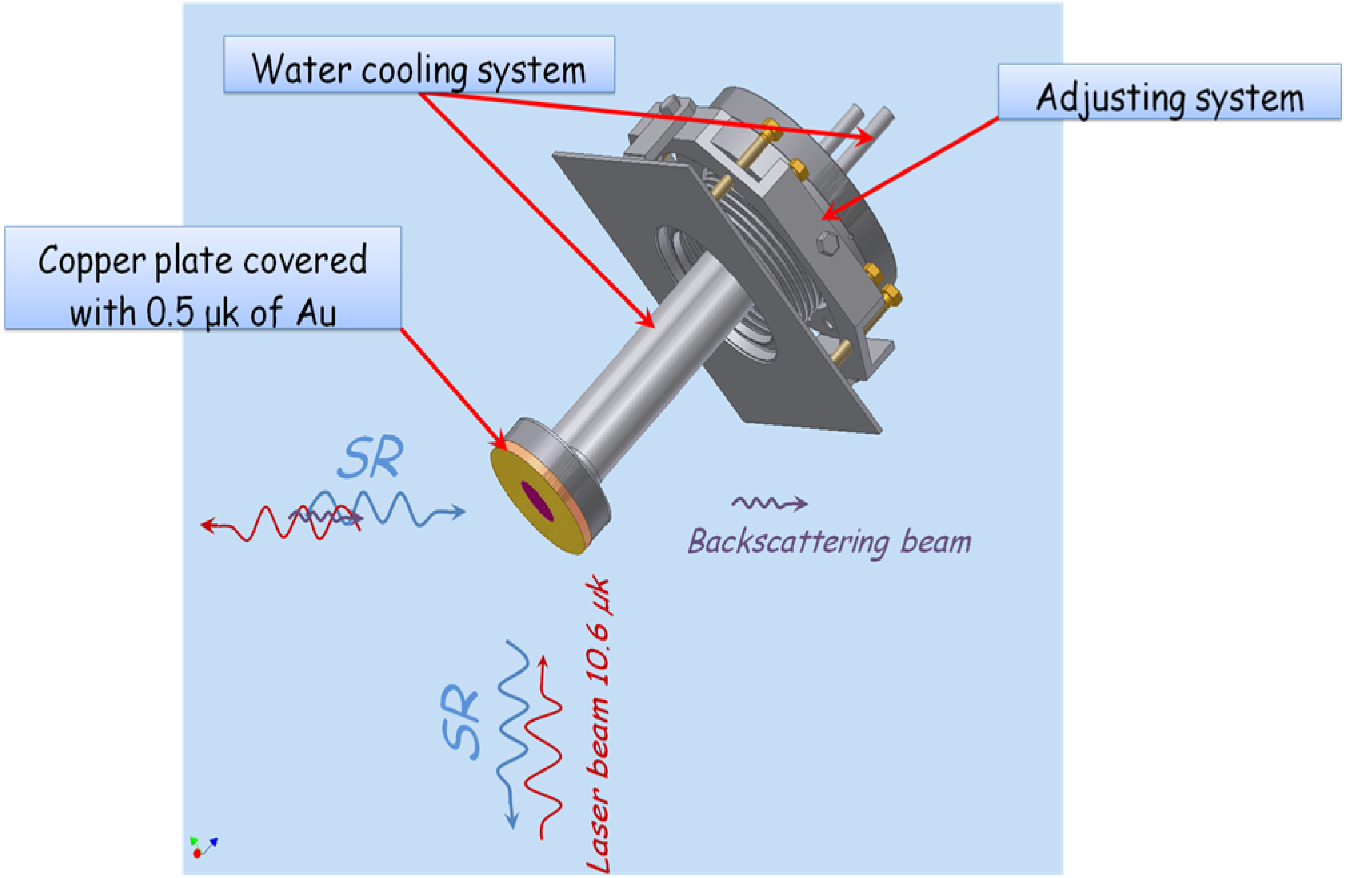
Simplified layout of the laser-to-vacuum insertion system.

The pressure of residual gass less then 5×10^{-10} Torr.



- The entrance window (viewport) transfer the laser light and some amount of SR (to monitor the beam position).
- The angle between the mirror and the laser beam is adjusted as necessary.
- Mirror is situated inside vacuum volume and protect viewport from SR;

Copper mirror.



The mirror is mounted to the support.

Support can be turned by bending the vacuum flexible bellow, so the angle between the mirror and the laser can be adjusted as necessary.

The SR power absorbed by the mirror is extracted by the water cooling system.

High vacuum *GaAs* and *ZnSe* viewports.

The viewports are based on ***GaAs*** mono-crystal plate **∅50.8 mm**, thikness of **3mm** and ZnSe polycrystal plate **∅50.8 mm**, thikness of **8 mm** provide:

- baking out of the vacuum system up to **250°C**,
- extra high vacuum,
- transmission spectrum from **0.9 to 18 μm** (***GaAs*** viewport)

  and from **0.45 to 20 μm** (***ZnSe*** viewport).

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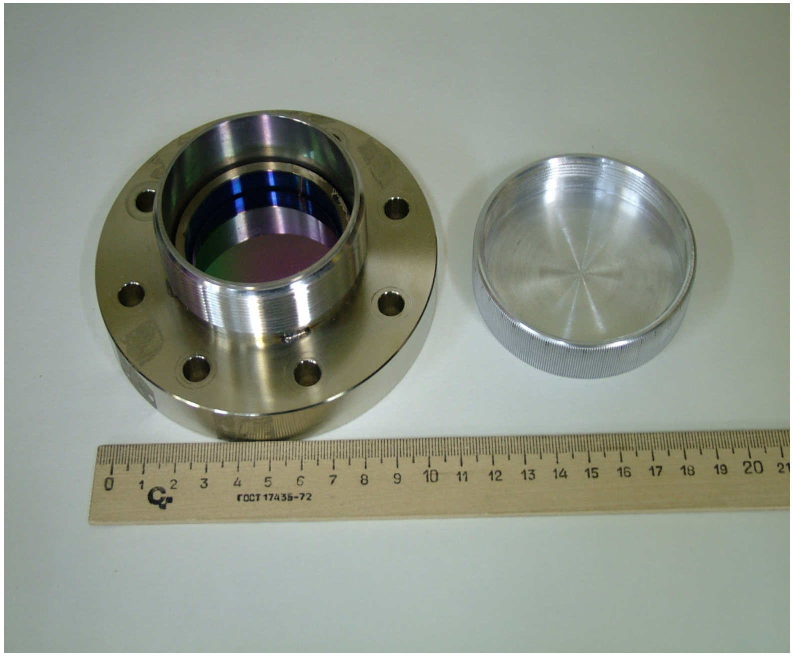
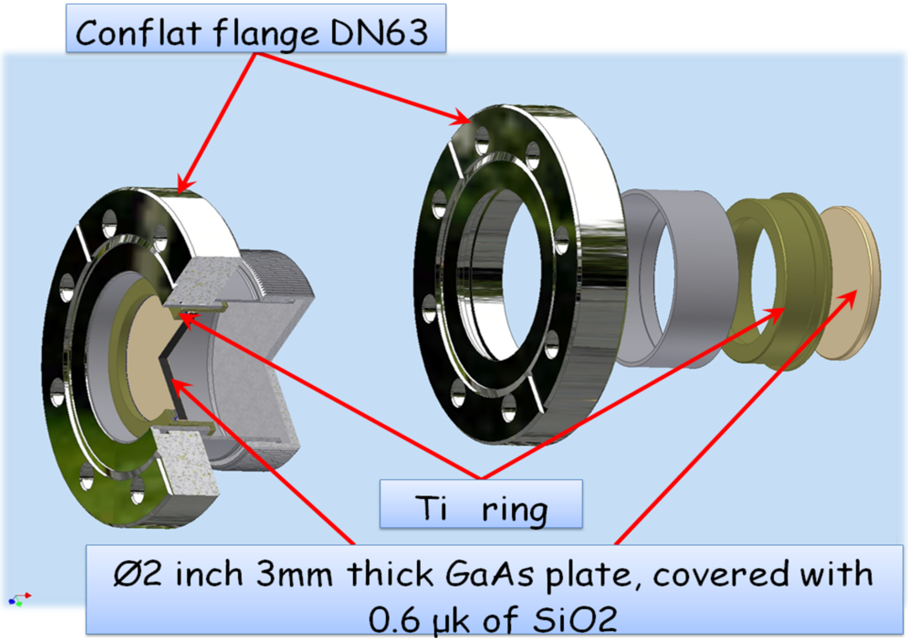
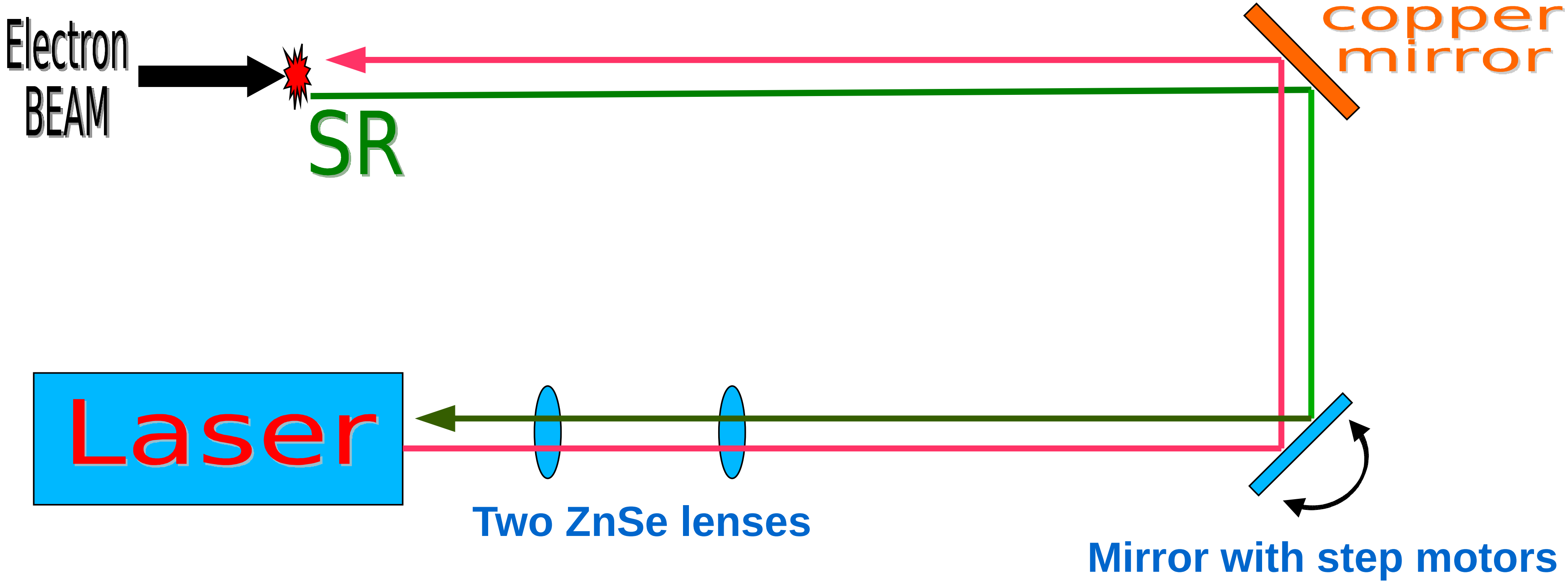
The advantage of ***ZnSe*** viewport is that it is transparent for the visible part of SR light. This makes the CBS system adjusting more convenient.

The viewport based on *GaAs* crystal plate.





Laser and Optical system



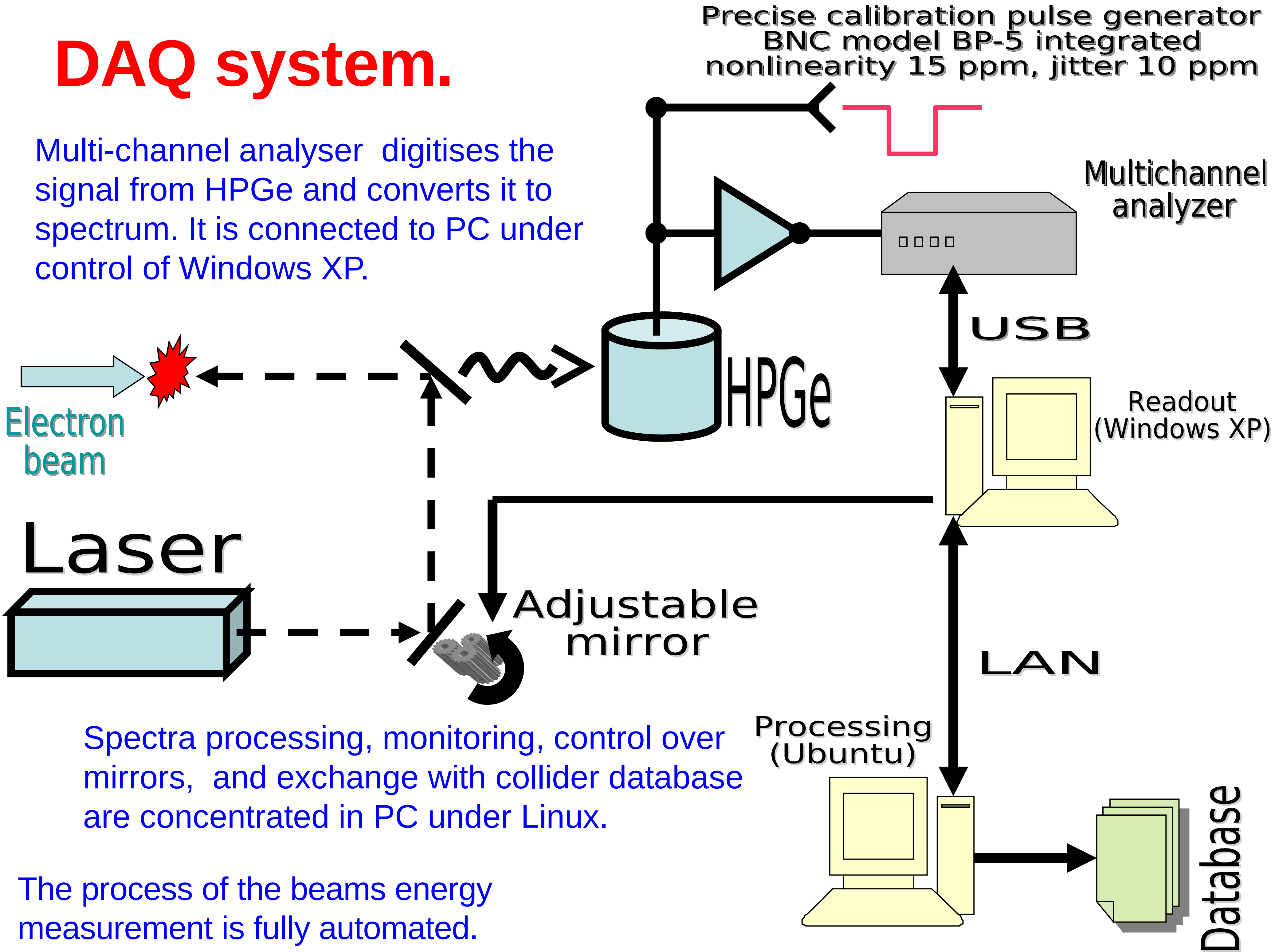
Two ***ZnSe*** lenses focus a laser beam at **e–γ** interaction region.

The mirror of the optical system reflects laser beam to a viewport in a vacuum system. The mirror is installed on a special support that allow precise vertical and horizontal angular alignment by using stepping motors (one step – **1.5×10^{-6} rad**).

The copper mirror and the mirror of the optical system are adjusted in such a way that the SR light comes to the laser output window.

DAQ system.

Multi-channel analyser digitises the signal from HPGe and converts it to spectrum. It is connected to PC under control of Windows XP.



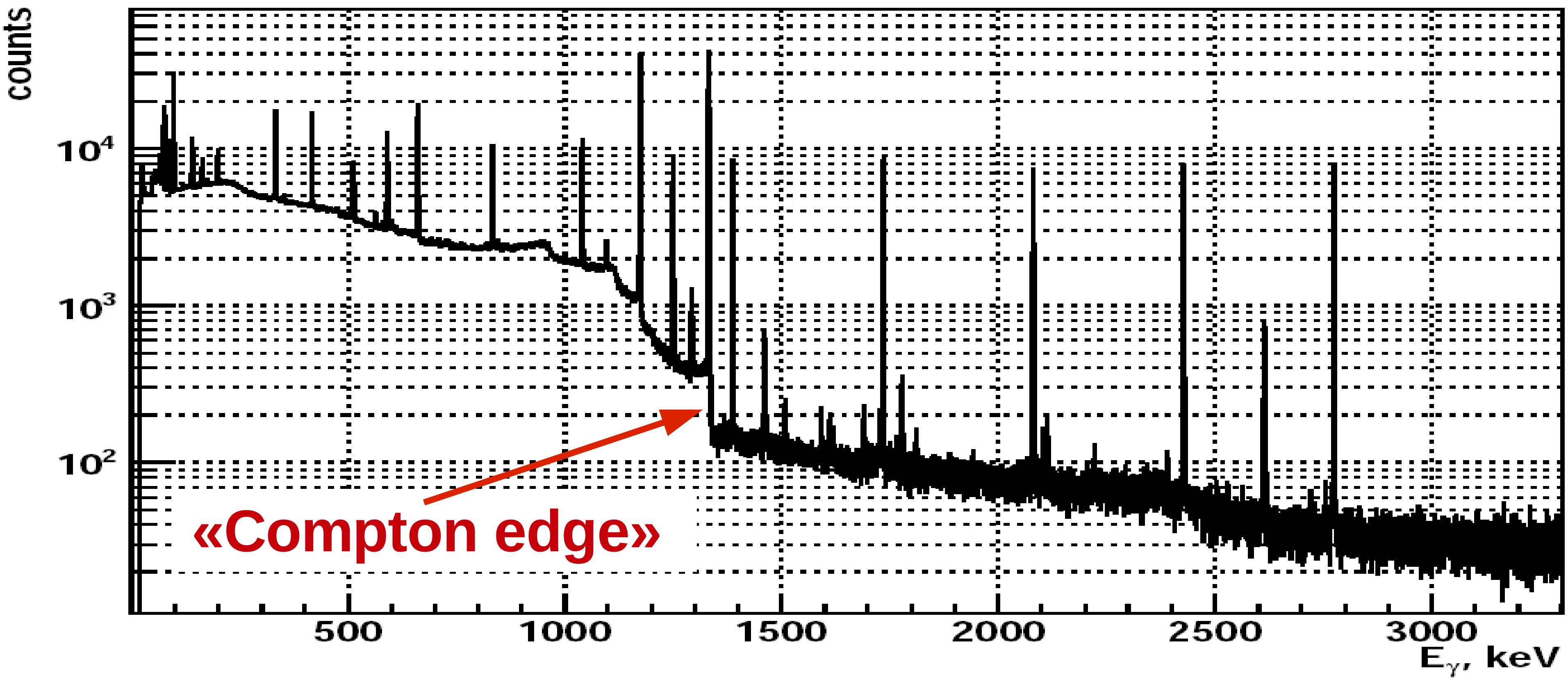
Spectra processing, monitoring, control over mirrors, and exchange with collider database are concentrated in PC under Linux.

The process of the beams energy measurement is fully automated.

Data processing.

Spectrum processing includes:

- **HPGe energy scale calibration.**
- **Fitting of the Compton edge.**
- **Calculation of the beam energy.**



The energy spectrum detected by HPGe detector at VEPP-2000. Peaks correspond to the calibration generator and monochromatic γ–radiation sources.

HPGe detector scale calibration.

The goals of calibration:

- To obtain the coefficients for conversion of ACD counts to corresponding energy deposition in the units of MeV.
- Determination of the parameters of the detector responce function:

$$f(x) = A \times \begin{cases} 0 < x < +\infty : & \exp\left\{-\dfrac{x^2}{2\sigma^2}\right\} \\ -K_0K_1\sigma < x \leq 0 : & C + (1-C)\exp\left\{-\dfrac{x^2}{2(K_0\sigma)^2}\right\} \\ -\infty < x \leq -K_0K_1\sigma : & C + (1-C)\exp\left\{K_1\left(\dfrac{x}{K_0\sigma} + \dfrac{K_1}{2}\right)\right\} \end{cases}$$

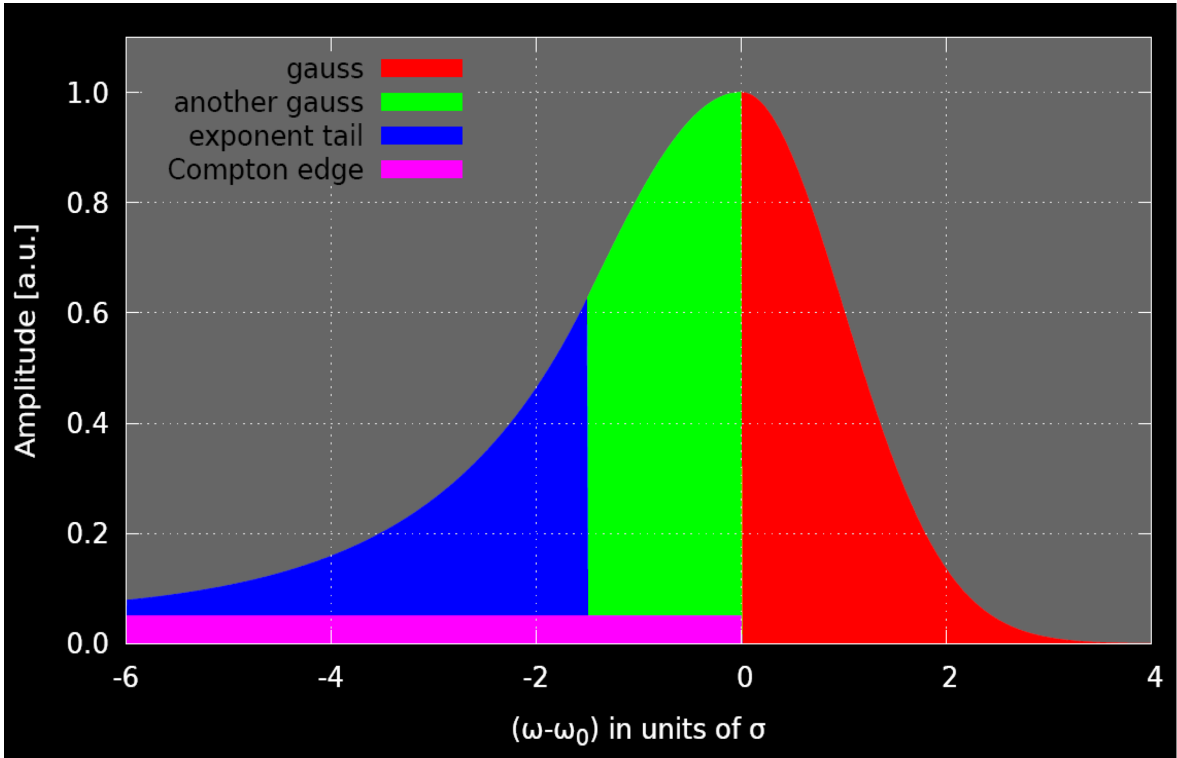
A is normalization,

$x=\omega-\omega_0$ is the position of maximum,

σ and **$K_0\sigma$** are RMS of the Gaussian distribution to the right and the left of the **x**, respectively,

C is responsible for the small-angle Compton scattering of **γ–**quanta in the passive material between the sources and the detector,

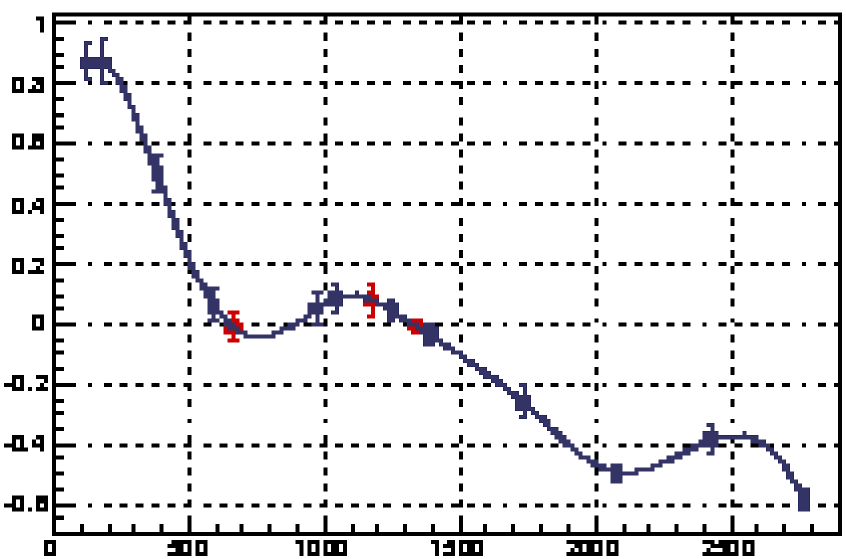
K_1 is asymmetry parameter.



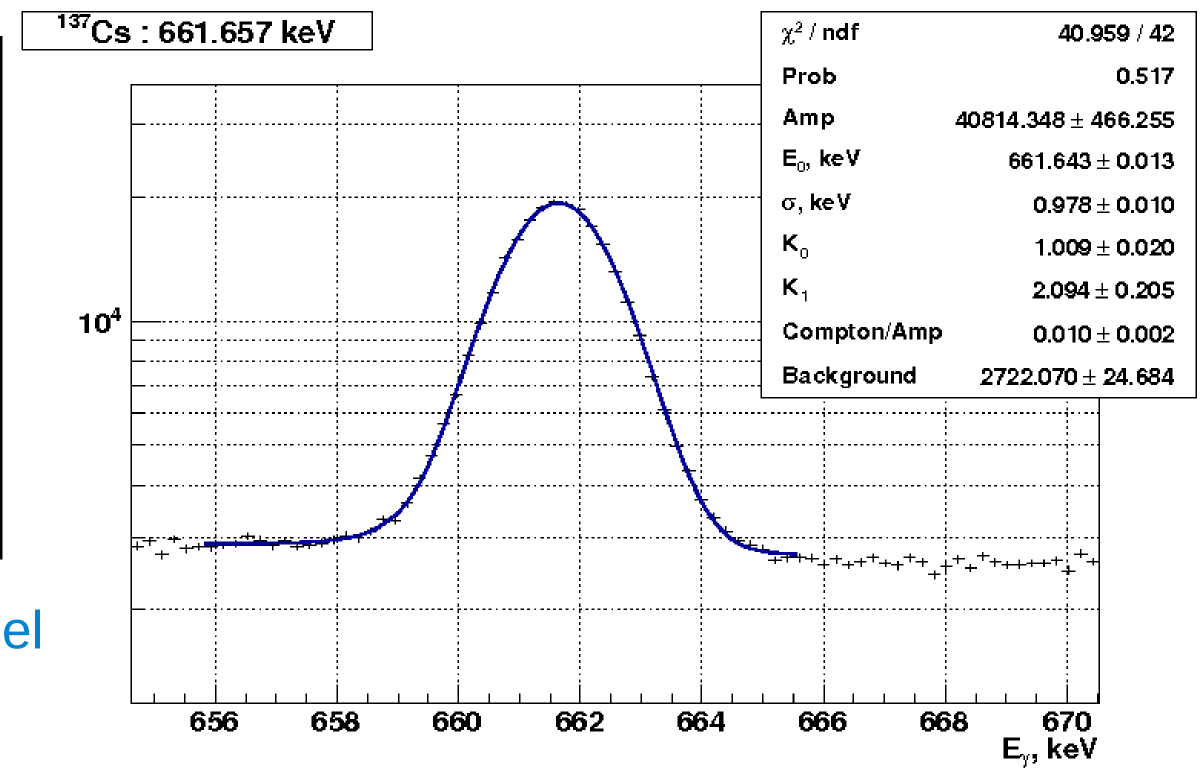
HPGe detector scale calibration.

The calibration procedure:

1. Peak search and identification of calibration lines.
2. The calibration peaks are fitted by responce function + background.
3. Using calibration pulser data the nonlinearity of multichannel analyzer is obtained.
4. Using the results of isotope peak approximation the energy dependence of **σ**, **K_0**, **K_1** and **C** is determined.



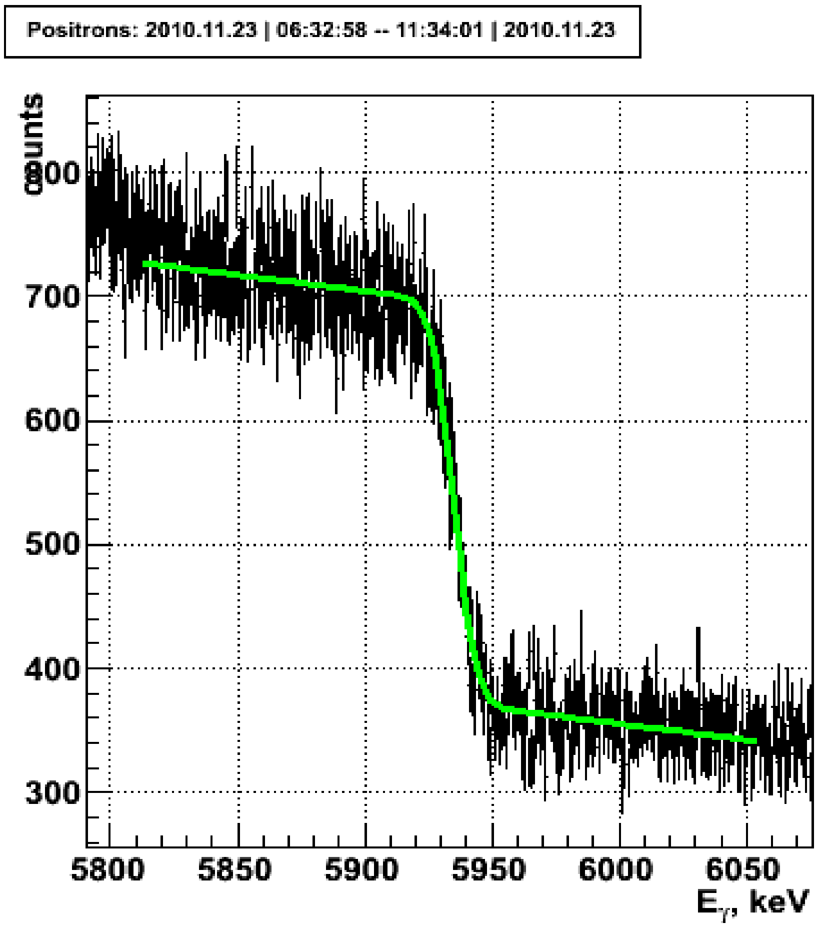
Energy dependence of multichannel analyzer scale nonlinearity.
Blue squares – generator peaks,
Red circles – isotope peaks,
Curve – spline approximation.



The fit of the ^{137}Cs 661 keV peak.

The fit of backscattered photons spectrum.

Actually the width of spectrum edge depends on the HPGe detector resolution and the electron beam energy spread.



The fit to the edge of the photons backscattered at BEPC-II.

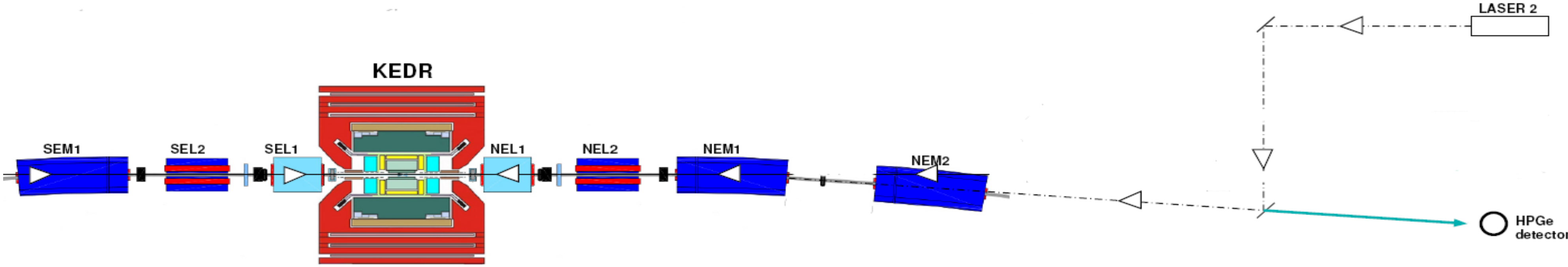
The spectrum edge is fitted by the function, which takes into account:

- the «pure» edge shape,
- detector responce function,
- energy spread of scattered photons due to the energy distribution of the collider beam.

The edge position ω_{max} and the photons energy spread σ_ω are obtained from the fit.

The beam energy E and energy spread σ_E are calculated from ω_{max} and σ_ω.

BEMS for VEPP-4M.



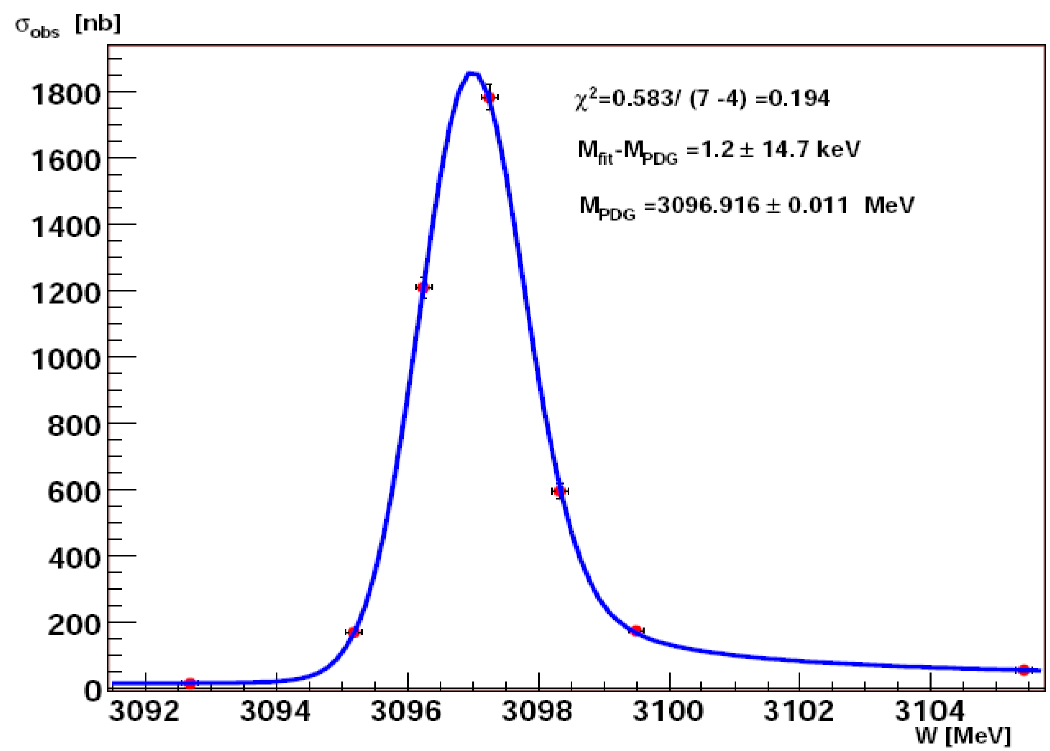
Layout of VEPP-4M beam energy measurement system. The source of initial photons is CO_2 laser. **ω_{max}≈2–7 MeV** for **E=1–2 GeV**.

The RD technique provides precise instantaneous energy calibration. CBS method allows continous on-line monitoring of the beam energy.

Test of CBS method accuracy by comparison of the **J/ψ** resonance mass **3096.916±0.011 MeV** with its value obtained using BEMS.

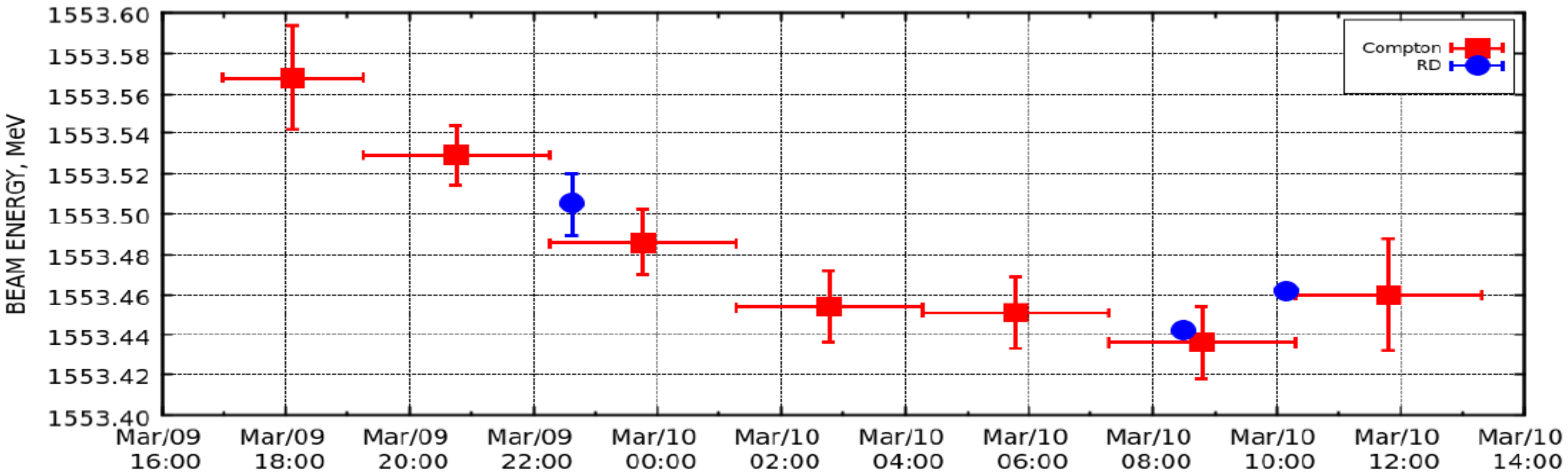
Mass difference **Δm=1.2±14.7 keV**. Deviation of the measured beam energy **ΔE** from the actual value **ΔE=Δm/2=0.6±7.4 keV**.

The realtive accuracy of the beam energy determination can be estimated as **$\delta E/E=5\times10^{-6}$**.



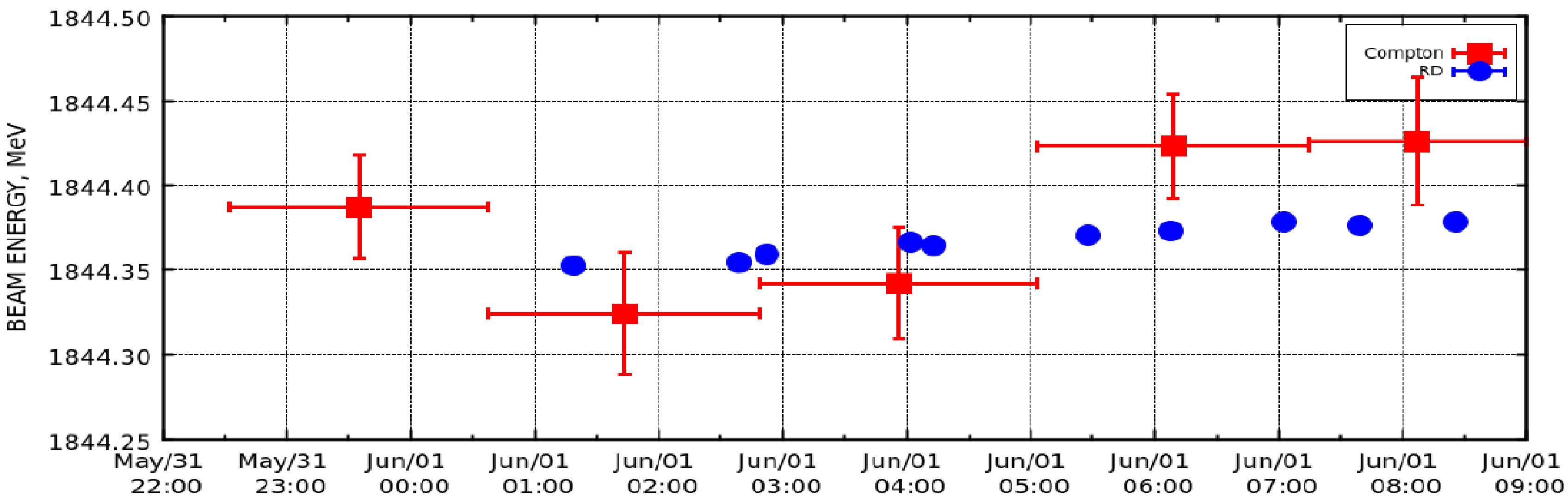
BEMS for VEPP-4M.

Direct comparison of CBS and RDP methods.



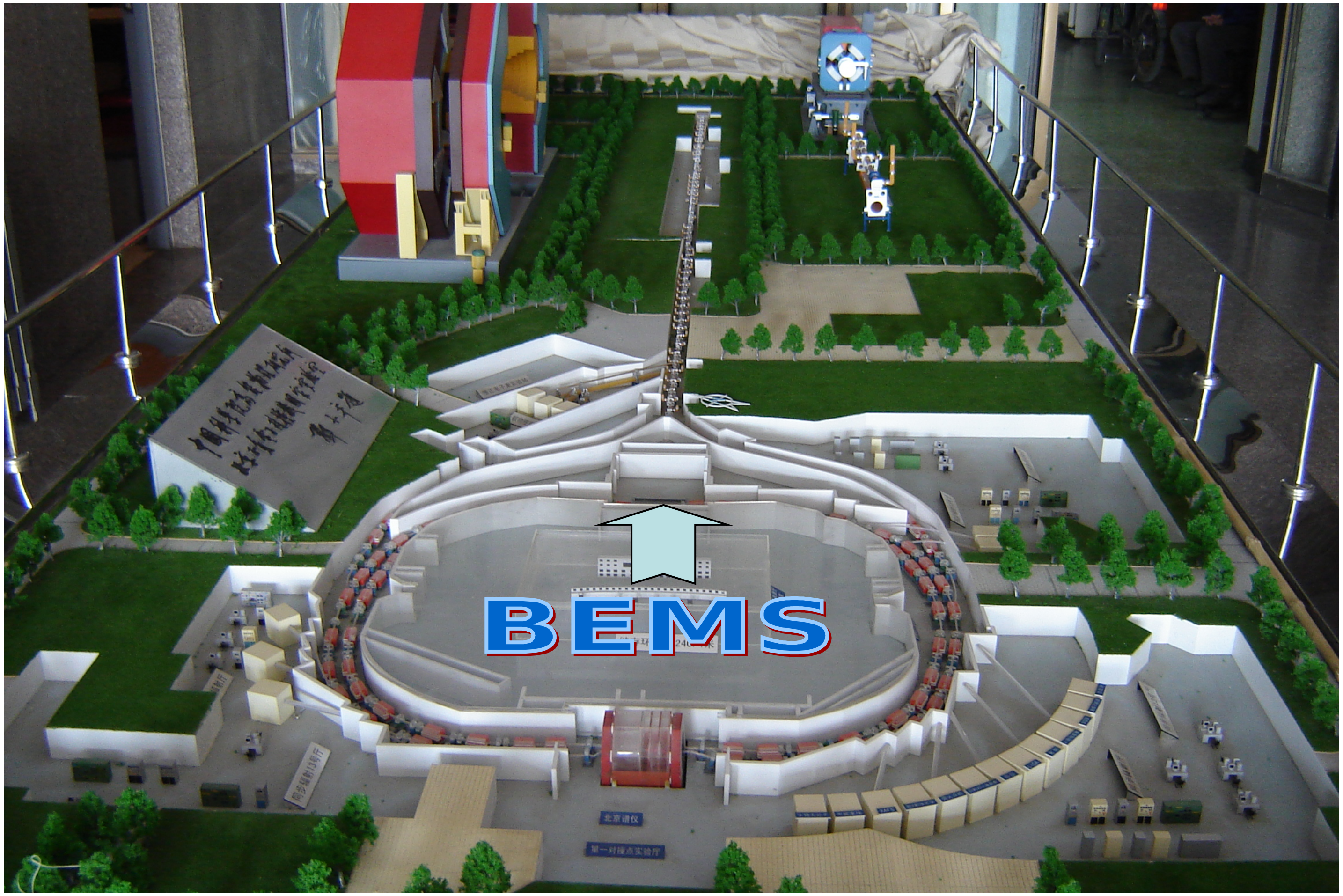
Beam energy E=1553.4 MeV.

No systematical bias between RD and CBS results. $\delta E/E=1.3\times10^{-5}$.



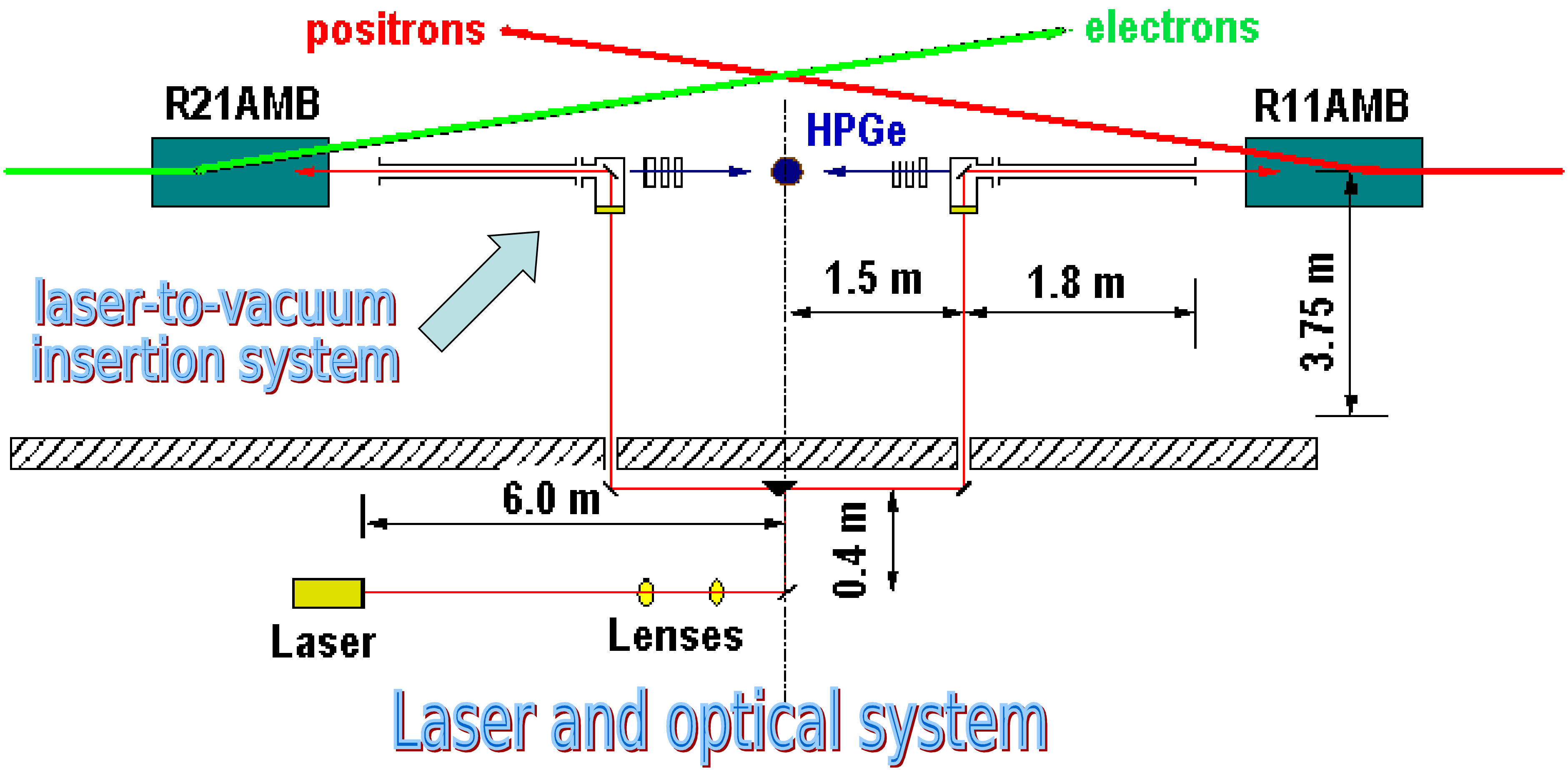
Beam energy E=1884 MeV. $E_{RD} - E_{CBS}$=13±38 keV. $\delta E/E=2\times10^{-5}$.

BEMS for BEPC-II.



The beam energy calibration system is located at the north interaction point. This location provides measurement of the e+ and e- beams energy by the same HPGe detector

BEMS for BEPC-II.

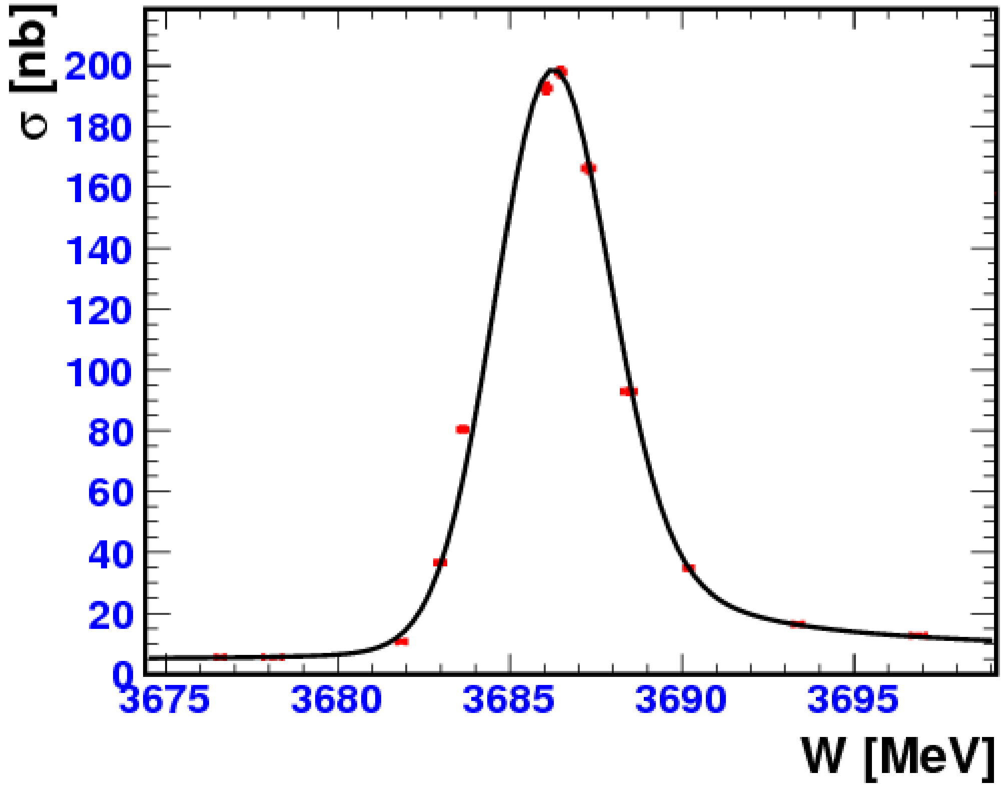


Layout of BEPC-II beam energy measurement system. The source of initial photons is CO_2 laser. ω_{max}≈2–7 MeV for E=1–2 GeV.

The energy of the electron and positron beams are measured one after another, in turn.

BEMS for BEPC-II.

Test of CBS method accuracy by comparison of the J/ψ and ψ′ resonances masses with its value obtained using BEMS.



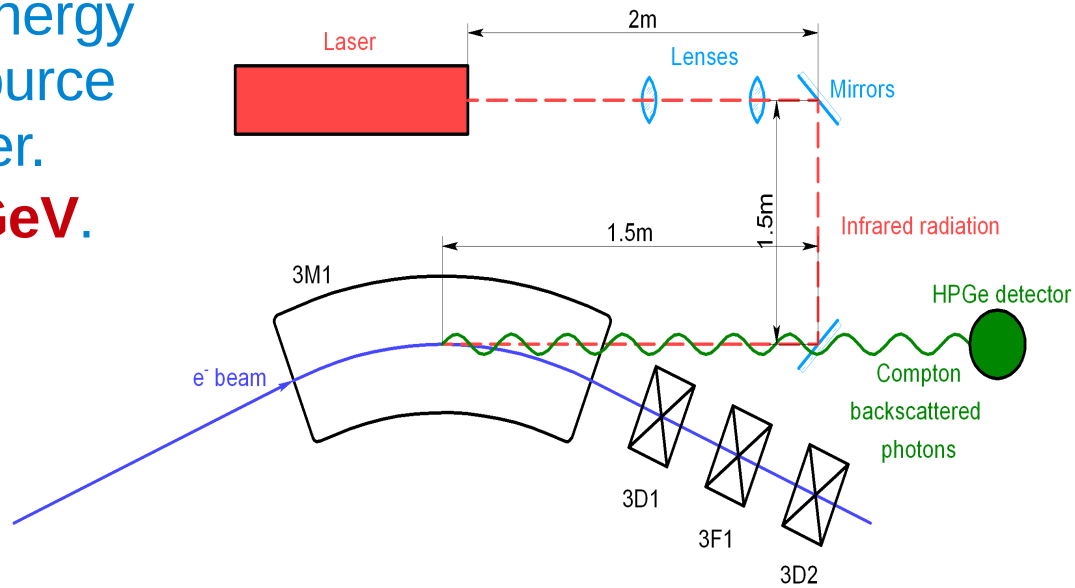
Scan	ΔE, keV	δE/E
J/ψ	74 ± 57	6×10^{-5}
ψ′	118 ± 79	7×10^{-5}
ψ′	1 ± 36	2×10^{-5}

ΔE=Δm/2

BEMS for VEPP-2000.

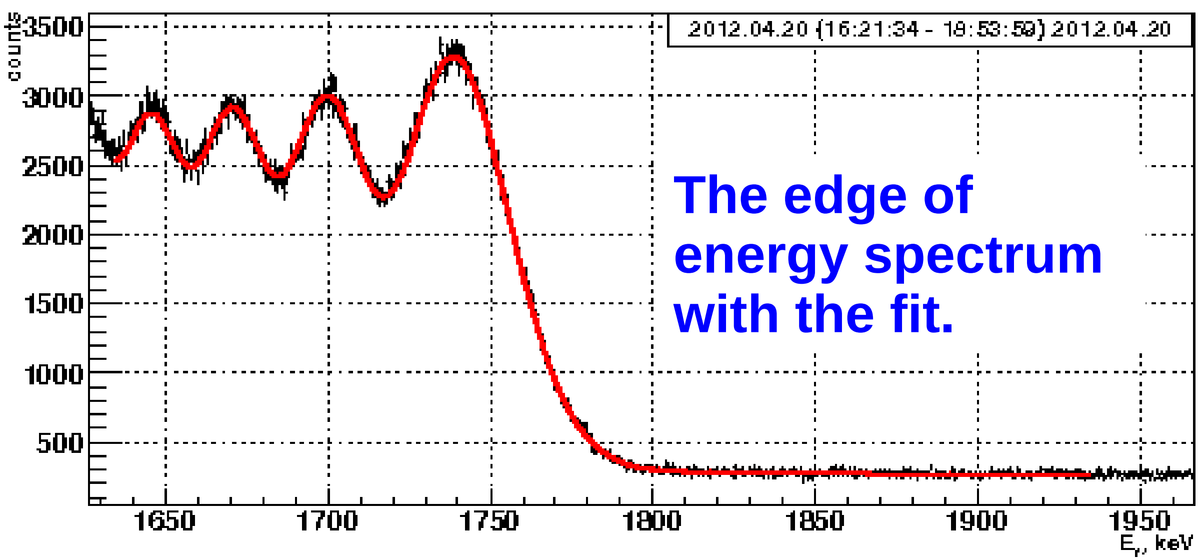
Layout of VEPP-2000 beam energy measurement system. The source of initial photons is CO laser.

$\omega_{max}\approx$**0.2–2.0 MeV** for **E<1 GeV**.



The interaction of laser photons with electrons occurs inside bending magnet (**ρ=140 cm**) at the curvulinear part of orbit.

In this case the spectrum of backscattered photons differs from that defined by the Klein-Nishina cross section and scattering kinematics of free electrons.

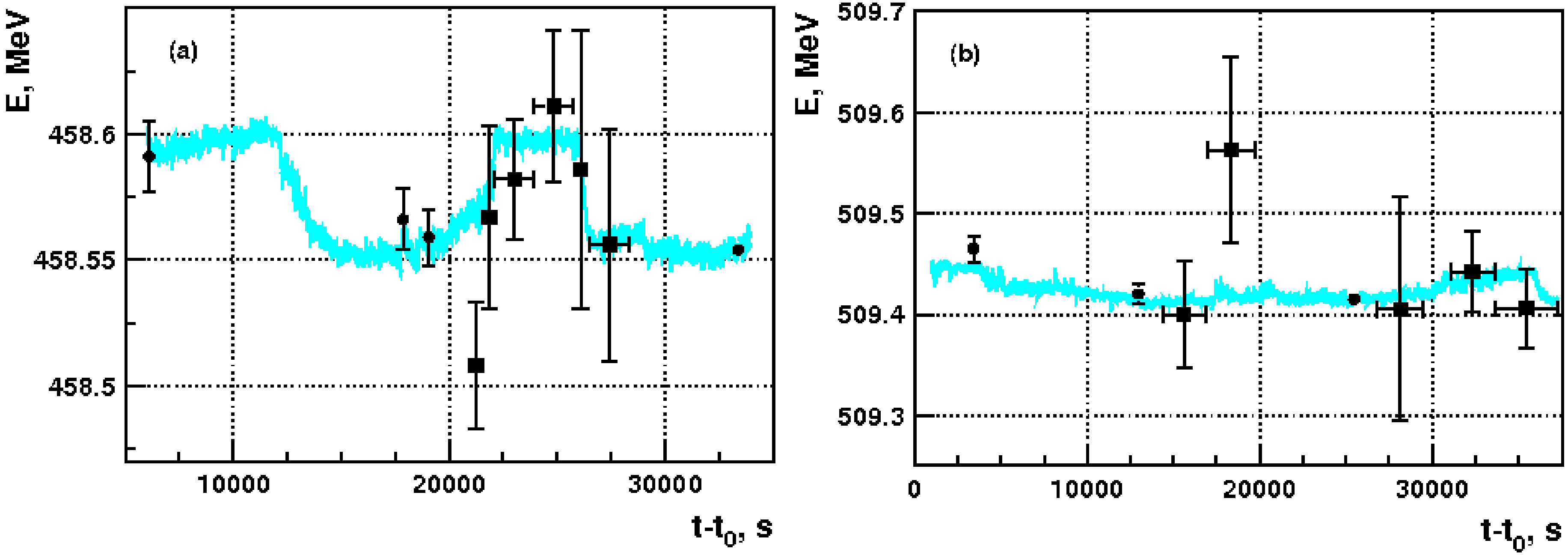


The interference of scattered photons is observed in the energy spectrum.

[*E.V. Abakumova, et.al., Phys. Rev. Lett., 100, 140402 (2013)*]

BEMS for VEPP-2000.

Comparison of CBS measurements with RD method.

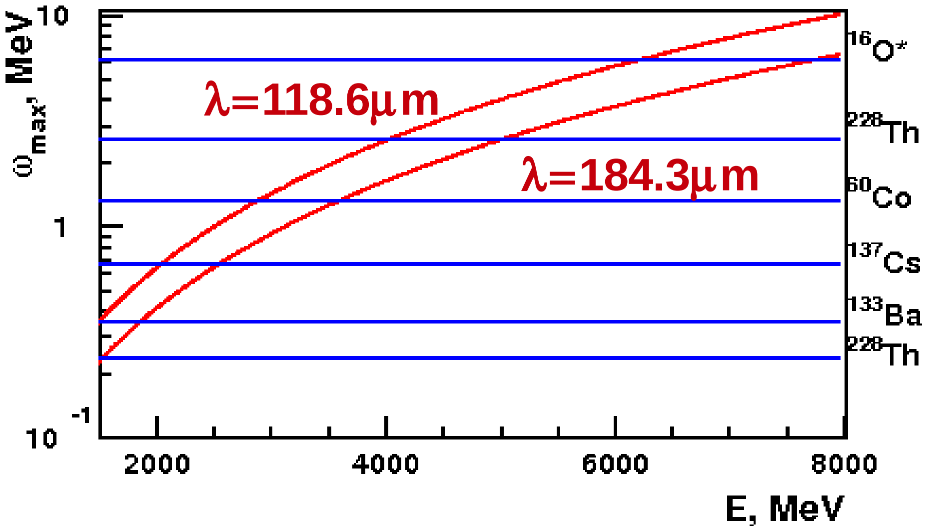


Dots are results of RD mesurements.
Squares are results of CBS measurements.

The line shows the energy calculated using magnetic field of the collider, which was measured by NMR sensors.

Estimated accuracy of the beam energy determination: $\delta E/E \approx 6\times10^{-5}$.

BEMS for beam energies above 2 GeV ?



Relation between ω_{max} and E for FIR laser.

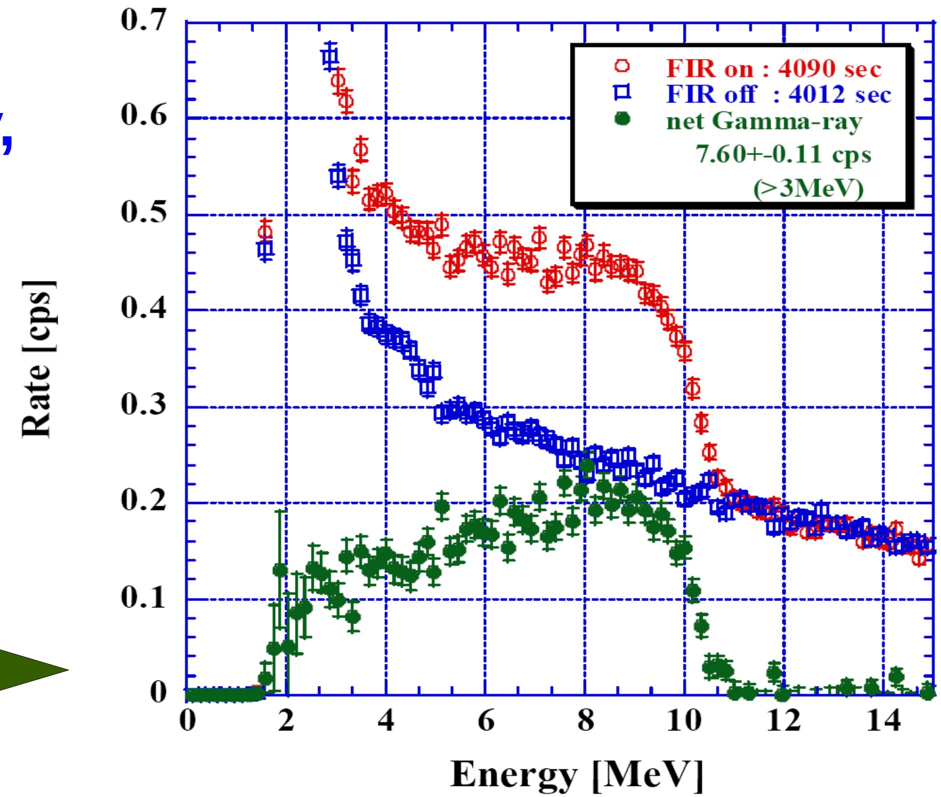
Edinburgh Instruments.

FIRL 100 far infrared output specification

λ(μm)	FIR Molecule	CO_2 pump line	Typical Power
96.5	CH_3OH	9R10	60mW
118.8	CH_3OH	9P36	150mW
184.3	CH_2F_2	9R32	150mW
432.6	HCOOH	9R20	30mW
513.0	HCOOH	9R28	10mW

Spring-8 synchrotron radiation facility,
beam energy E=8 GeV.
FIR laser 119 m, P=1W.

Scattered photons energy spectrum measured by LYSO:Ce scintillator.



Conclution.

The CBS method is effective tool for collider energy beam measuring and monitoring.

The method can be applied for the electron beam energy upto **2 GeV**.

The relative accuracy of the method $\delta E/E \approx 10^{-4} - 10^{-5}$.

The FIR laser can be used for CBS method for the beams with energy **2 – 8 GeV**. Special studies are necessary.