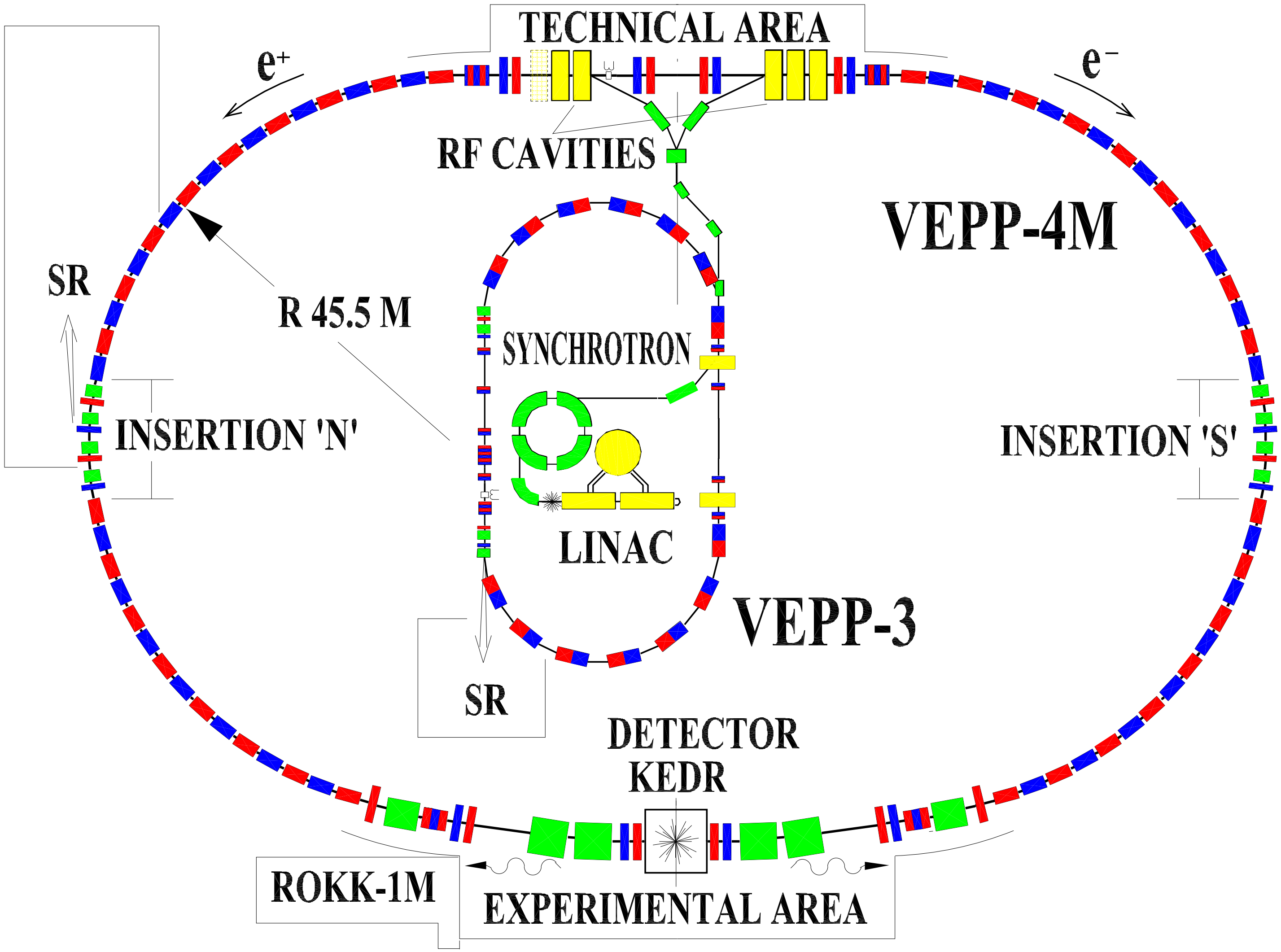
Electron Beam Energy Measurement at the VEPP-4M Collider

Nickolai Muchnoi

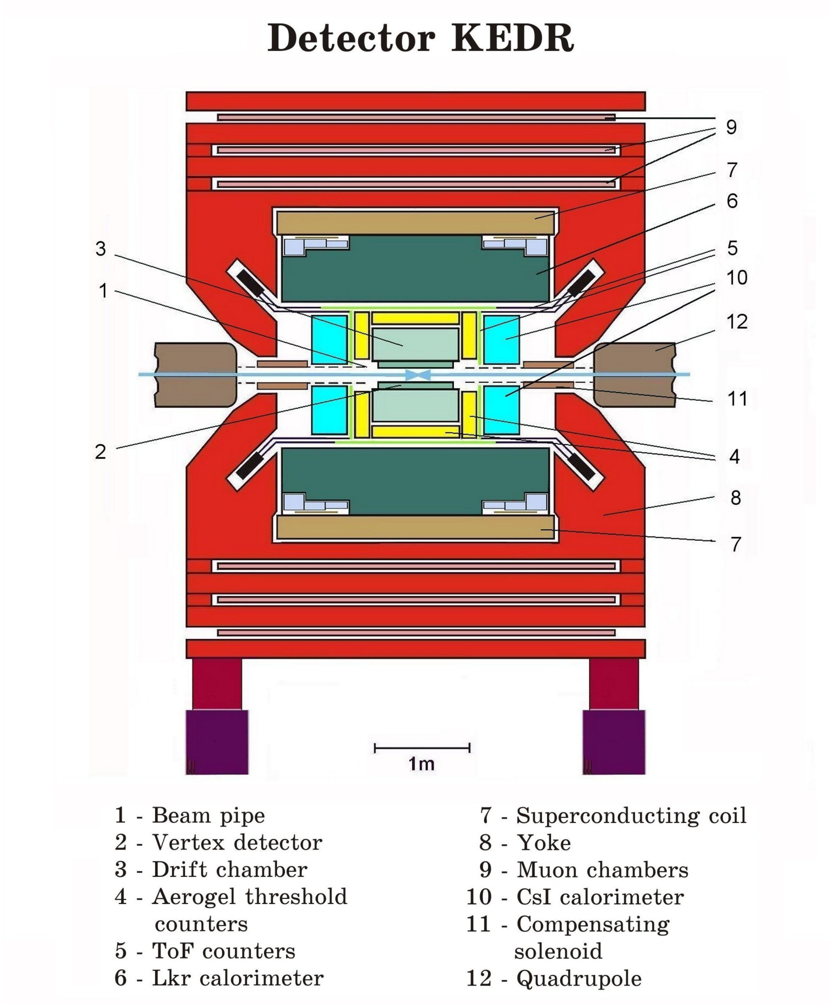
- Budker INP, Novosibirsk
- VEPP-4 complex, KEDR detector, ROKK-1M facility
- Resonant depolarization technique for precise beam energy calibration
- Current experiment: the τ-lepton mass measurement
- Compton scattering kinematics
- HPGe detector
- Laser as a source of monochromatic photons
- Scattered photon flux and related properties
- One measurement example
- Achieved system perfomance

Novosibirsk on the Map

VEPP-4 Complex at Budker INP, on since 1992

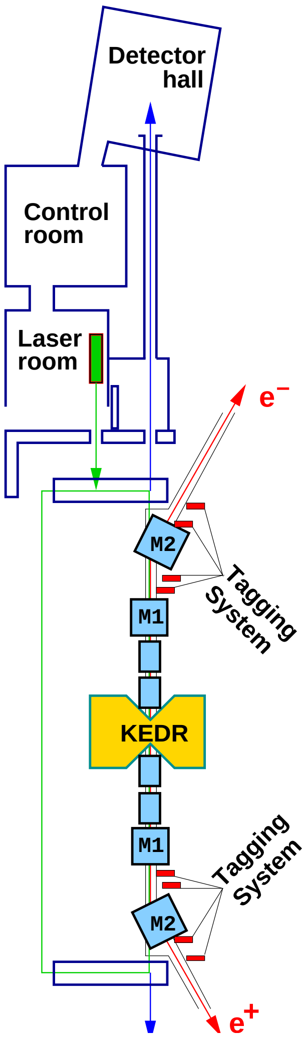


KEDR Detector, on since 2002



- VEPP-4M Beam Energy $E = 1 - 6$ GeV
- Luminosity $2.5 \cdot 10^{30}$ ($E = 1.8$ GeV)
- Beam energy calibration by resonant depolarization $\Delta E/E \simeq 3 \cdot 10^{-6}$
- World Best Precision for:
  $M_{J/\Psi} = 3096.917 \pm 0.010 \pm 0.007$ MeV
  $M_{\Psi'} = 3686.111 \pm 0.025 \pm 0.009$ MeV
  (Phys. Lett. B 573, 2003)

ROKK-1M Facility



ROKK-1M facility is a source of high energy gamma-ray beam obtained by inverse Compton scattering of laser light on the VEPP-4M electron beam.

Applications:

- Detector calibration
  KEDR Tagging System (1993-1998)
  KEDR LKr calorimeter prototype (1994)
  BELLE CsI calorimeter prototype (1996-1998)
- Study of non-linear QED processes
  Photon Splitting (1994-1997)
  Delbrük Scattering (1994-1997)
- Electron beam energy and energy spread measurement
  τ-lepton mass measurement (2005–2007)

Resonant depolarization for beam energy calibration

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:

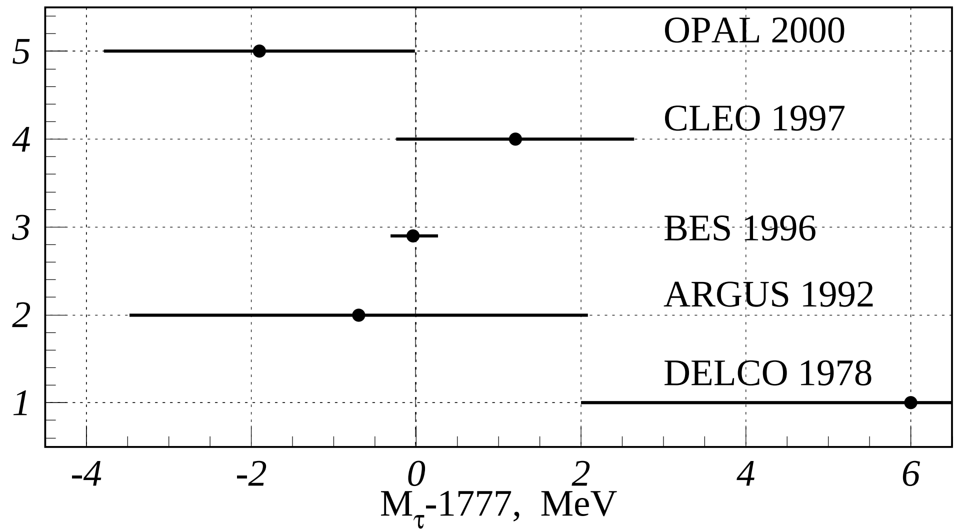
$$\boldsymbol{\Omega/\omega = 1 + \gamma\mu'/\mu_0 = 1 + \nu}$$

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 polarization of the beam is measured by the Toushek polarimeter, and the precession frequency can be determined using the resonant depolarization with weak RF field with well-known frequency applied to special plates inside the beam pipe.

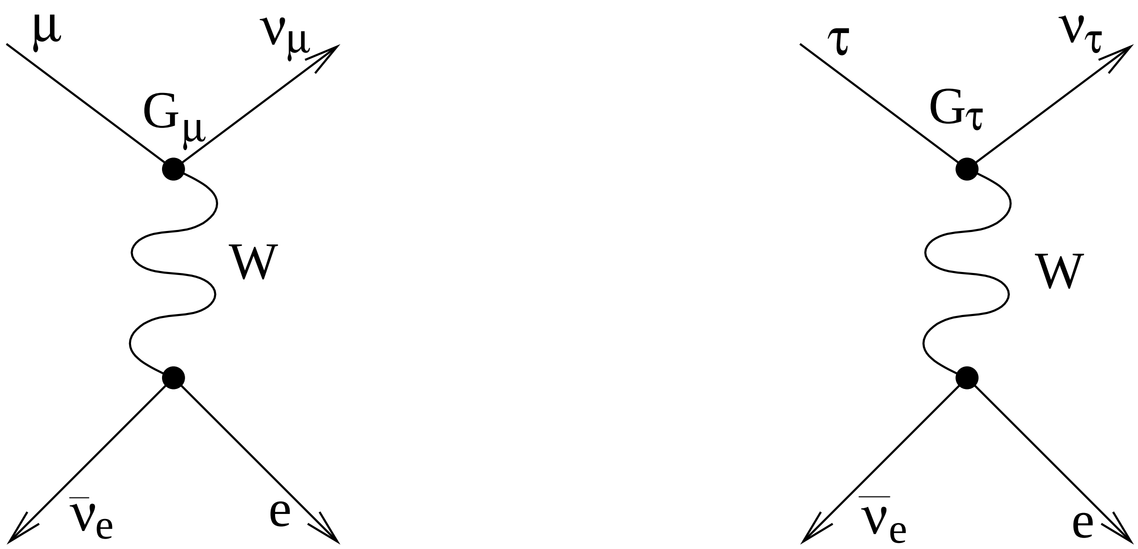
Current VEPP-4M & KEDR activity: τ-lepton mass measurement

M_τ, PDG 2004



The world knowledge of M_τ was based on a single BES experiment

$$G_e \equiv G_\mu \equiv G_\tau$$

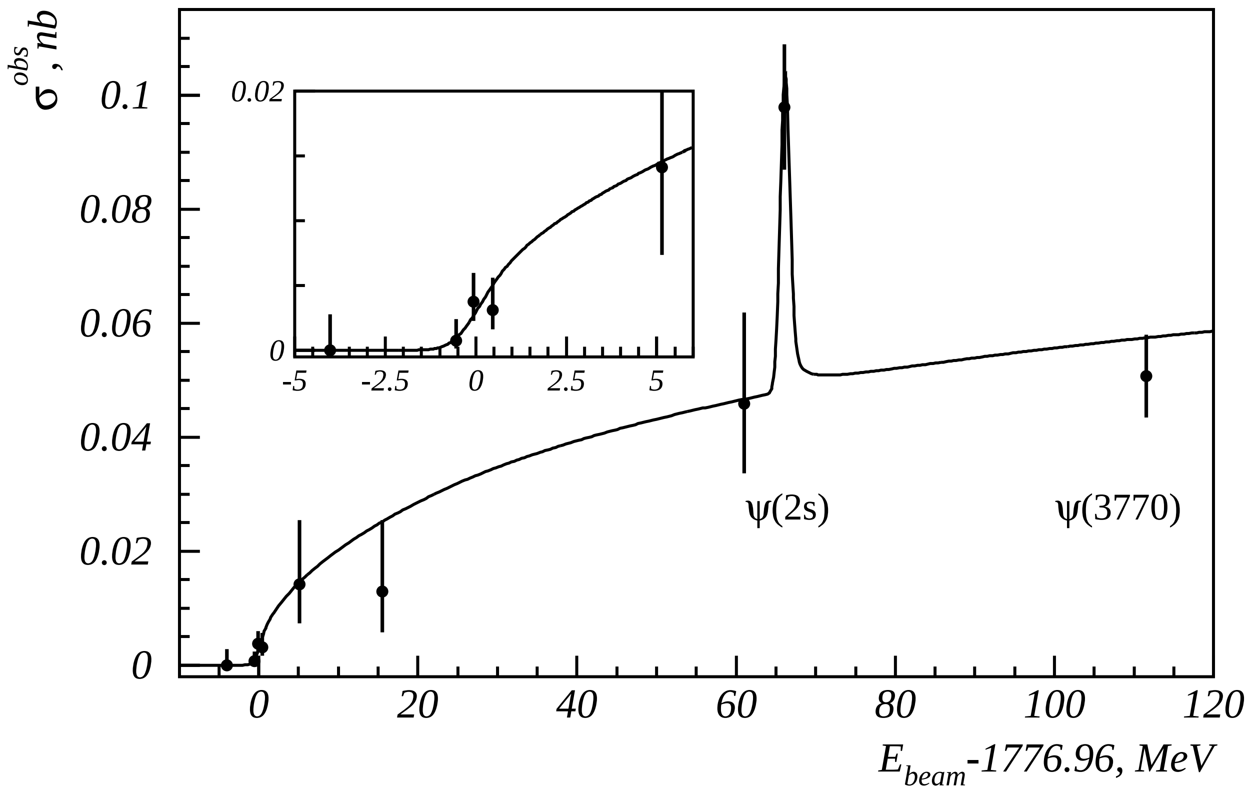


$$(\frac{G_\tau}{G_\mu})^2 = (\frac{m_\mu}{m_\tau})^5(\frac{t_\mu}{t_\tau}) \cdot Br(\tau \longrightarrow e\nu_\tau\overline{\nu}_e) \cdot \frac{F_{cor}(m_\mu, m_e)}{F_{cor}(m_\tau, m_e)} \equiv 1$$

Measuring the τ Mass

The most direct way to measure the mass of the τ-lepton is to study the behavior of the $e^+e^- \to \tau^+\tau^-$ cross section near the reaction threshold.

$$e^+e^- \to (\tau \to e\nu_\tau\bar{\nu}_e)(\tau \to \mu\nu_\tau\bar{\nu}_\mu, \pi\nu_\tau, K\nu_\tau, \rho\nu_\tau)$$

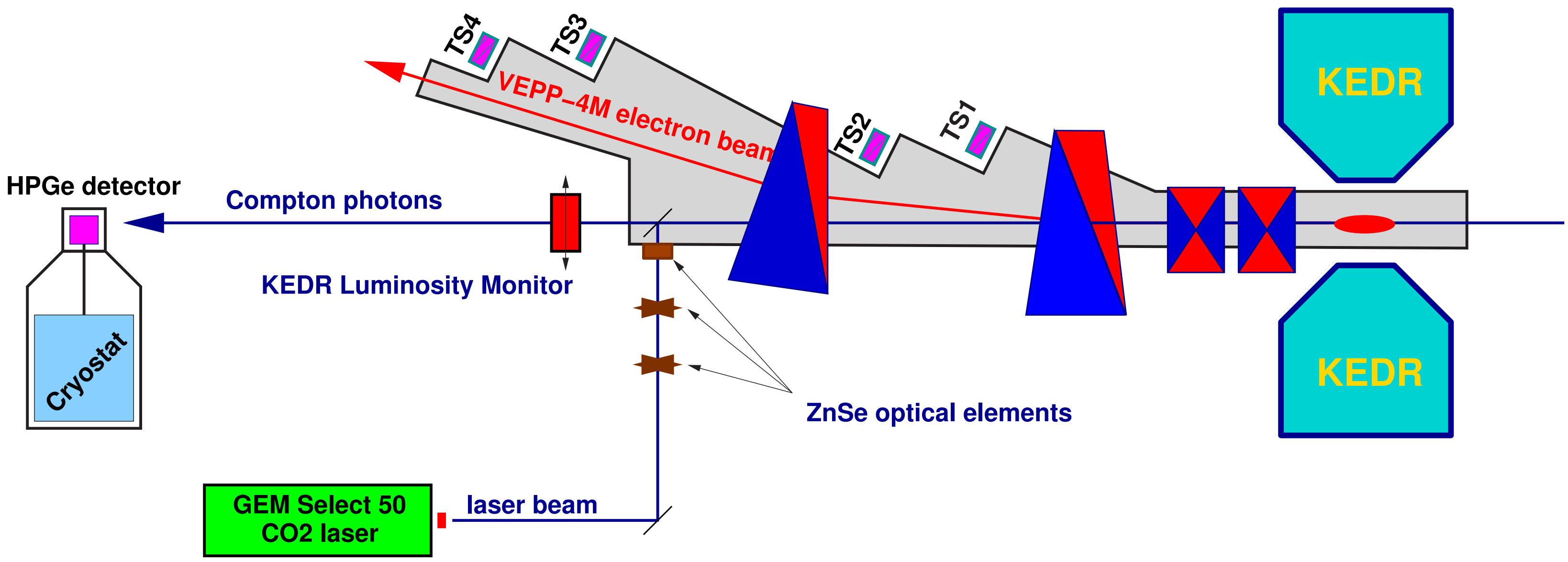


PDG 2006

	τ-lepton mass
PDG 2006	$1776.90^{+0.29}_{-0.26}$ MeV
BES 1996	$1776.96^{+0.18}_{-0.21}\,^{+0.25}_{-0.17},\ (^{+0.31}_{-0.27})$ MeV
BELLE 2006	$1776.77 \pm 0.13 \pm 0.32,\ (\pm 0.35)$ MeV
KEDR 2006	$1776.80^{+0.25}_{-0.23} \pm 0.15,\ (^{+0.29}_{-0.27})$ MeV

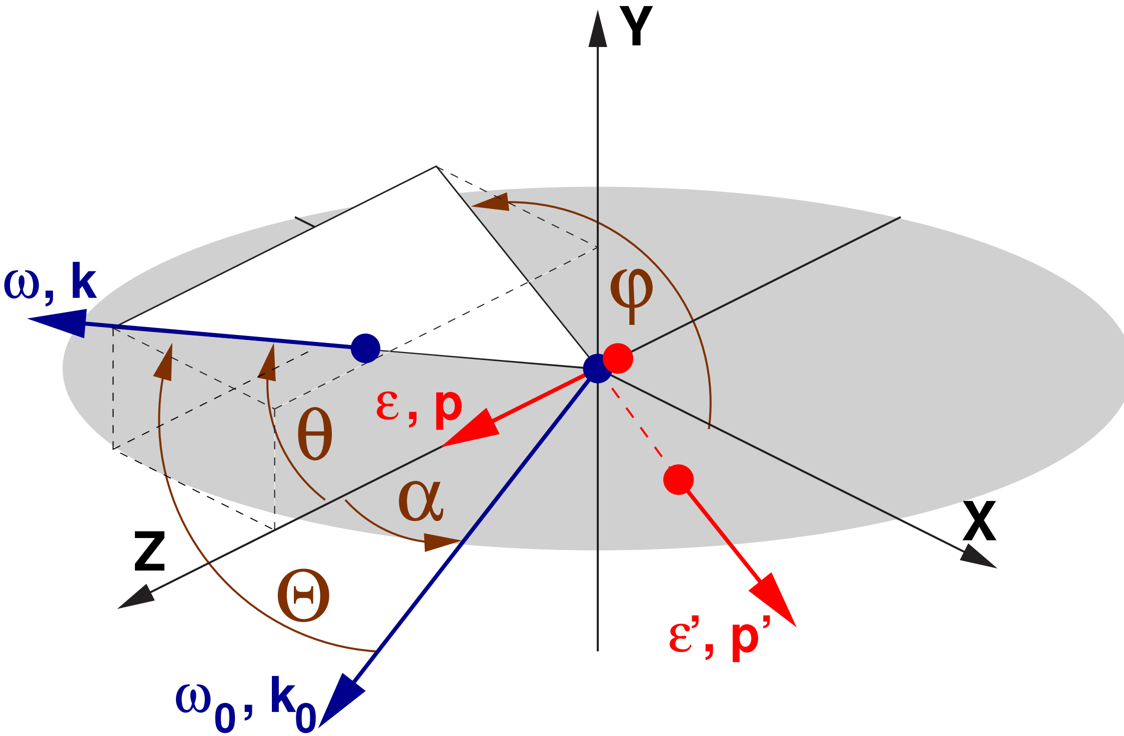
VEPP-4M + KEDR is going to increase the $\int L dt$ up to 9–11 pB^{-1} and decrease the error in τ mass down to 0.15 MeV

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



Laser COHERENT *GEM Select 50*

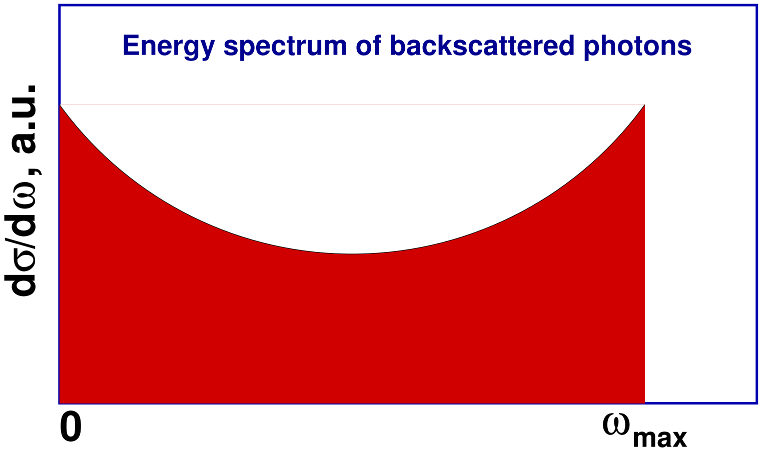
- Carbon dioxide laser
- 25–50 W CW Power, RF discharge – long lifetime
- Single 10P20 line λ=10.5910 μm (ω_0=0.1170656 eV)



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

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

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 MeV

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.* 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.* Nucl.Instrum.Meth. A384: 293-298, 1997

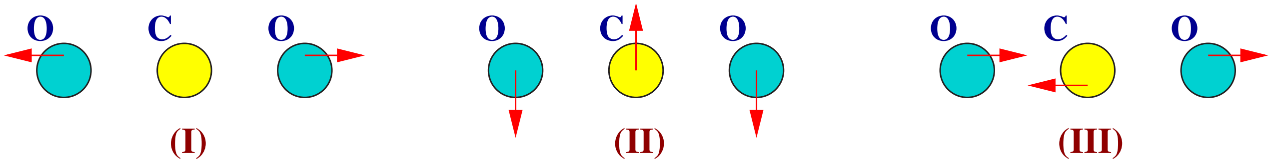
HPGe - High Purity Germanium Detector

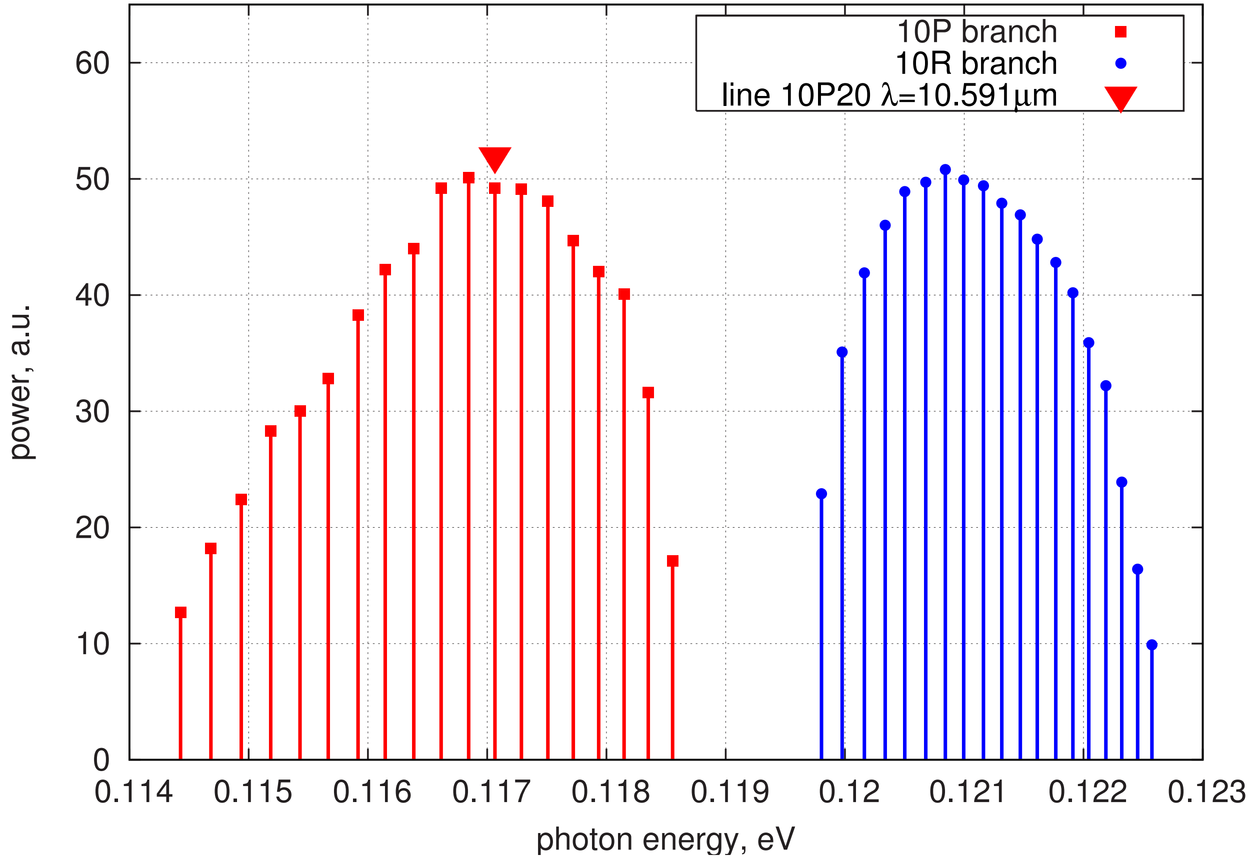
- Model: Canberra GC2518
- 120 ml active volume

For 6 MeV photons:

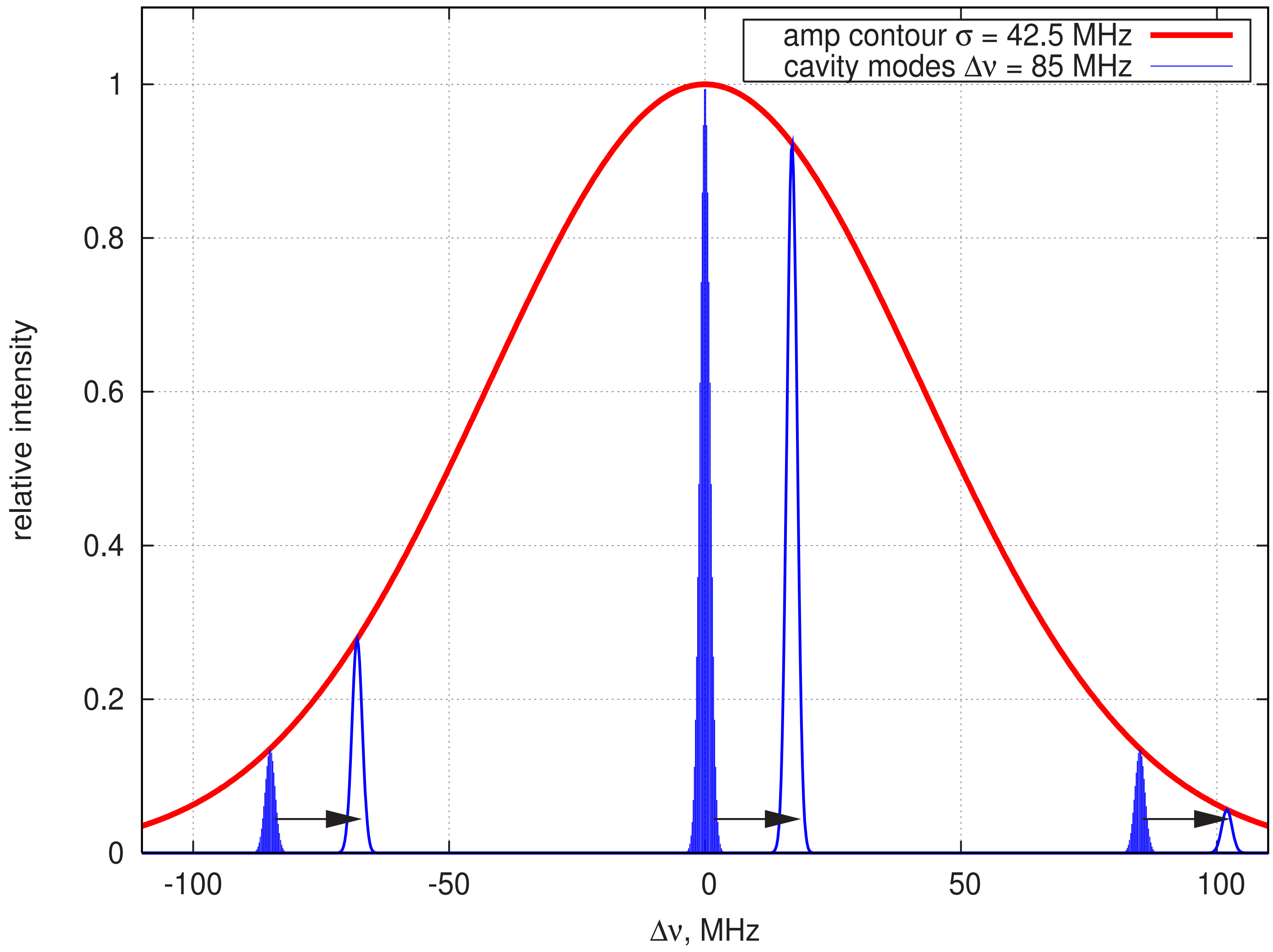
- 5% total absorption efficiency
- $4 \cdot 10^{-4}$ energy resolution

Carbone Dioxide Laser as a Source of Monochromatic Radiation

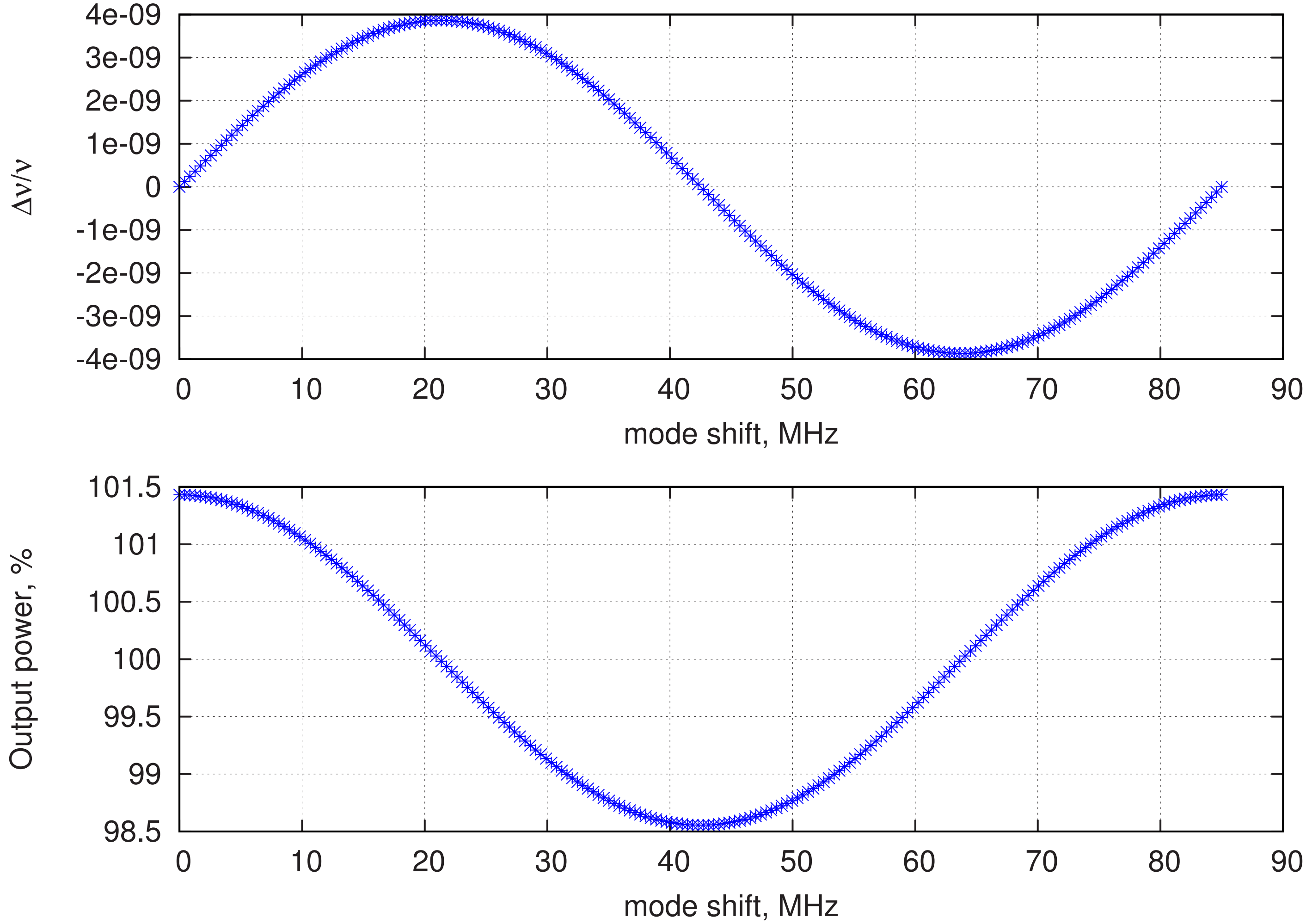




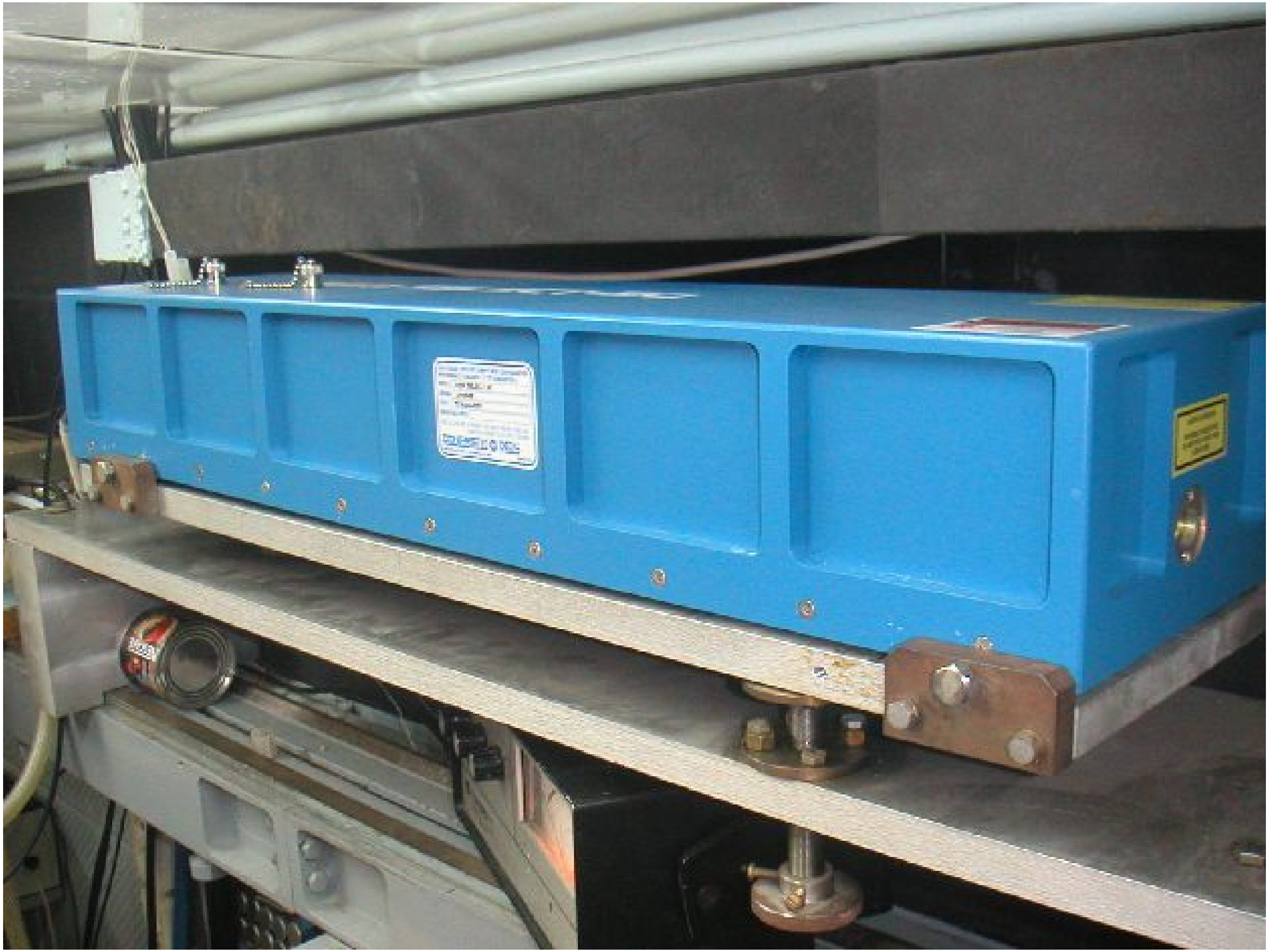
Cavity Longitudial Modes and Temperature Drift



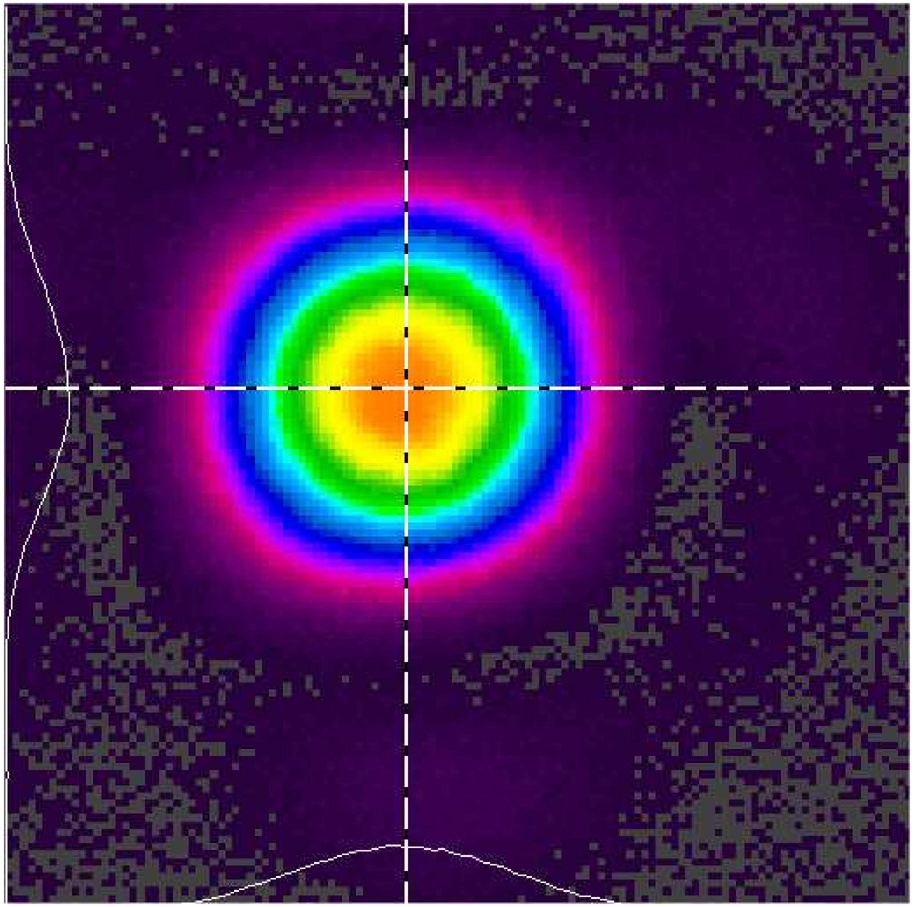
Output Power and Average Photon Energy



GEM Select 50 Laser by Coherenent Radiation Inc.



Cavity Mode TEM_{00q}



Electron-photon luminosity and related properties

Let's consider the interaction of the electron beam with the laser beam. If the laser is operating in CW mode, the density of the photon target does not vary with time. Thus one can introduce the electron-photon luminosity $L_{e\gamma}$, so that the rate of scattered photons and electrons will be defined as:

$$\dot{N} = L_{e\gamma} \cdot \sigma_c(\omega_0, \varepsilon)$$

where $\sigma_c(\omega_0, \varepsilon)$ is the total cross section of Compton scattering.

For our case $\sigma_c \simeq \sigma_{Thompson} \simeq 0.665$ mB.

Longitudinal photon density

To describe the number of laser photons per one unit of length along the beam axis it's convenient to use the following cross-system formula:

$$n_{ph} = \frac{dN_{ph}}{ds} = \frac{P}{\omega_0 ce} \equiv \frac{P\lambda}{hc^2}$$

where

- P, [W] – laser CW power,
- ω_0, [eV] – laser photon energy,
- λ, [m] – laser wavelength,
- $c = 299792458$ [m/s] – speed of light in vacuum,
- $e = 1.60217653(14) \times 10^{-19}$ [C] – elementary charge,
- $h = 6.6260693(11) \times 10^{-34}$ [J s] – Plank constant.

Gaussian Beams

Gaussian beams are the simplest and often the most desirable type of beam provided by a laser sources. By definition, the transverse profile of the intensity of the beam with a power P can be described with a Gaussian-style function:

$$I(r, s) = \frac{P}{\pi w(s)^2/2} \exp\{-2\frac{r^2}{w(s)^2}\}$$

where the beam radius $w(s)$ is the distance from the beam axis where the intensity drops to $1/e^2$.

The modes of a cavity with the lowest order in the transverse direction (called TEM_{00} or fundamental transverse modes) are Gaussian modes, if the cavity is stable, all optical media in the cavity are homogeneous, and all surfaces between media are either flat or have a parabolic shape. In any case, the deviation from a Gaussian beam shape can be quantified with the M^2 factor.

The beam radius in free space varies along the propagation direction according to:

$$w(s) = w_0 \cdot \sqrt{1 + (\frac{\lambda s}{\pi w_0^2})^2}$$

$w_0 = w(s = 0)$ – beam radius at the beam waist.

The radius of curvature R of the wavefronts evolves according to:

$$R(s) = s \cdot [1 + (\frac{\pi w_0^2}{\lambda s})^2]$$

The state of a Gaussian beam at a certain s position can be specified with a complex q parameter:

$$\frac{1}{q(s)} = \frac{1}{R(s)} + \frac{i\lambda}{\pi w(s)^2}$$

When a Gaussian beam passes an optical elements, this can be described by transforming its parameters with an $ABCD$ matrix of the optical system according to

$$q' = \frac{Aq + B}{Cq + D}$$

After all, we can describe the photon density in the laser beam by the real Gaussian function

$$\rho_{ph}(x, y, s) = \frac{n_{ph}}{2\pi\sigma(s)^2} \exp\{-\frac{x^2}{2\sigma(s)^2} - \frac{y^2}{2\sigma(s)^2}\}$$

with the

$$\sigma(s) \equiv \frac{1}{2} w(s)$$

Electron Beam

Number of particles in the electron bunch N_e for the storage ring with circumference Π, beam current I, and number of bunches n will be:

$$N_e = \frac{I\Pi}{ecn}$$

In case of the VEPP-4M collider we have the situation, when there is a correlation between electron transverse horizontal coordinate x and its energy shift $\varepsilon - \varepsilon_0$ from the average electron energy ε_0. The parameters to describe the electron beam are:

$\sigma_x(s) = \sqrt{\epsilon_x \beta_x(s)}$ – horizontal betatron size

$\sigma_y(s) = \sqrt{\epsilon_y \beta_y(s)}$ – vertical betatron size

σ_ε – beam energy spread

$\varepsilon, \varepsilon_0$ – particle energy and average particle energy

$\Delta x(s) = (\varepsilon - \varepsilon_0) \cdot \psi(s)/\varepsilon$ – shift in x due to dispersion function ψ

Space-Energy Distribution of the Electrons

$$\rho_e(x, y, \varepsilon, s) = \frac{N_e}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_\varepsilon} \times$$

$$\times \exp\{-\frac{(\varepsilon-\varepsilon_0)^2}{2\sigma_\varepsilon^2} - \frac{(y-y_0)^2}{2\sigma_y^2} - \frac{(x-x_0-(\varepsilon-\varepsilon_0)\cdot\psi/\varepsilon)^2}{2\sigma_x^2}\}$$

Here we add $x_0 = x_0(s), y_0 = y_0(s)$ to indicate possible shift between axes of the electron and laser beams.

Luminosity over $ds, d\varepsilon$

Now to get the luminosity one have to multiply $\rho_e(x, y, s)$ and $\rho_{ph}(x, y, s)$, and integrate the result over x and y:

$$\frac{dL_{e\gamma}}{ds d\varepsilon} = \frac{\nu n_{ph} N_e}{(2\pi)^{3/2}\sigma_\varepsilon\sqrt{(\sigma^2+\sigma_x^2)(\sigma^2+\sigma_y^2)}}\times$$

$$\times \exp\{-\frac{y_0^2}{2(\sigma^2+\sigma_y^2)}\}\times$$

$$\times \exp\{-\frac{(\varepsilon-\varepsilon_0)^2}{2\sigma_\varepsilon^2} - \frac{(x_0+(\varepsilon-\varepsilon_0)\cdot\psi/\varepsilon)^2}{2(\sigma^2+\sigma_x^2)}\}$$

Possible Shift in Measured Average Energy and Energy Spread

From the previous expression one can see that if the $x_0 \neq 0$ the average energy of the electron that scatters on the laser photon differs from the average electron energy in the beam:

$$\Delta\varepsilon = (\varepsilon - \varepsilon_0) = -\frac{x_0\,\sigma_s\,\sigma_\varepsilon}{\sigma^2 + \sigma_x^2 + \sigma_s^2}$$

where $\sigma_s = \psi \cdot (\sigma_\varepsilon/\varepsilon)$ is the synchrotron part of the horizontal electron beam size. Moreover, the energy dispersion of the electrons that scatter on the laser beam differs from the beam energy spread:

$$\sigma'_\varepsilon = \sigma_\varepsilon \sqrt{\frac{1}{1 + \dfrac{\sigma_s^2}{\sigma^2 + \sigma_x^2}}}$$

Luminosity over ds

Finally we integrate the luminosity over $d\varepsilon$:

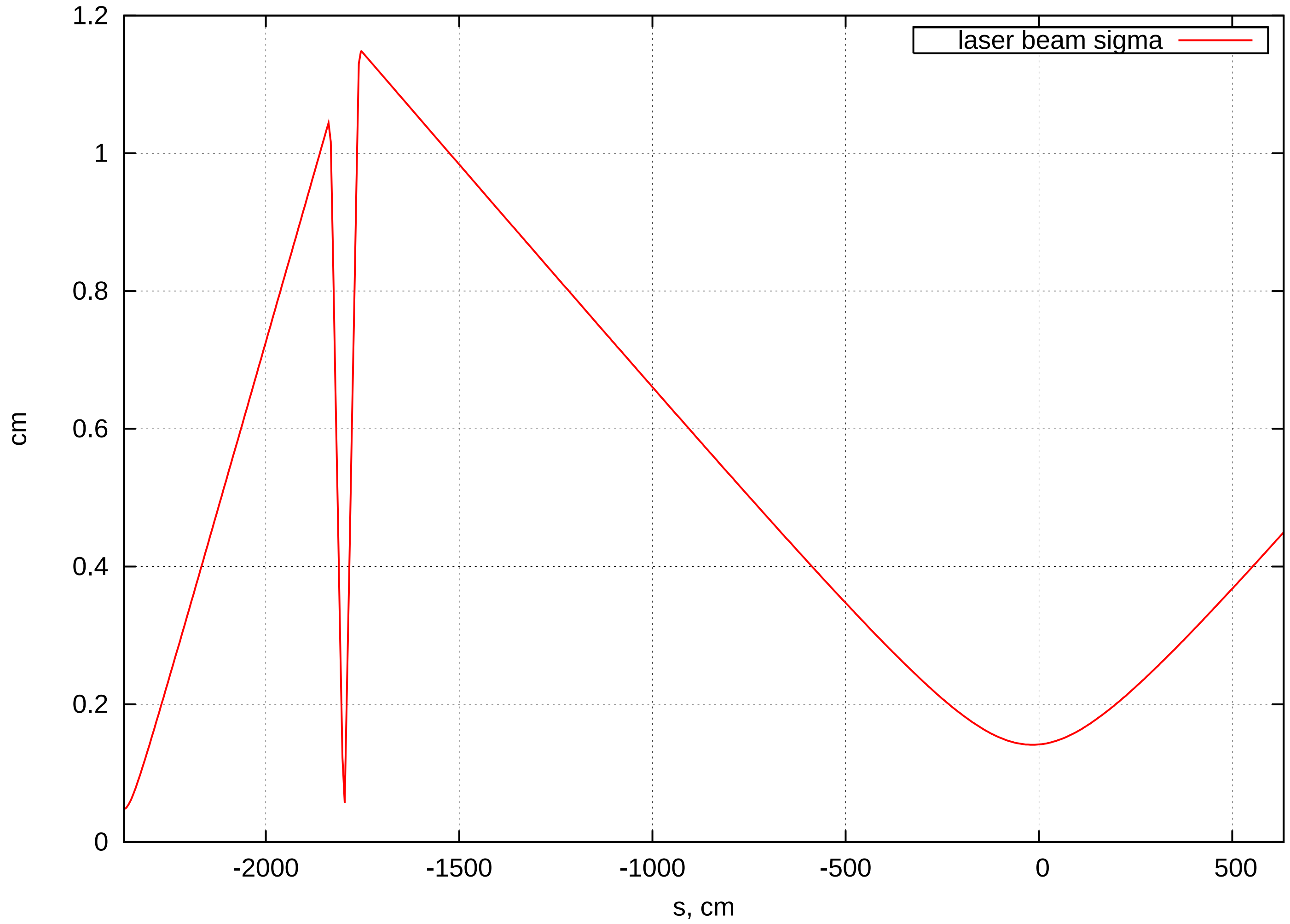
$$\frac{dL_{e\gamma}}{ds} = \frac{\nu n_{ph} N_e}{2\pi\sqrt{(\sigma^2+\sigma_x^2+\sigma_s^2)(\sigma^2+\sigma_y^2)}} \times$$

$$\times \exp\{-\frac{y_0^2}{2(\sigma^2+\sigma_y^2)}\} \times$$

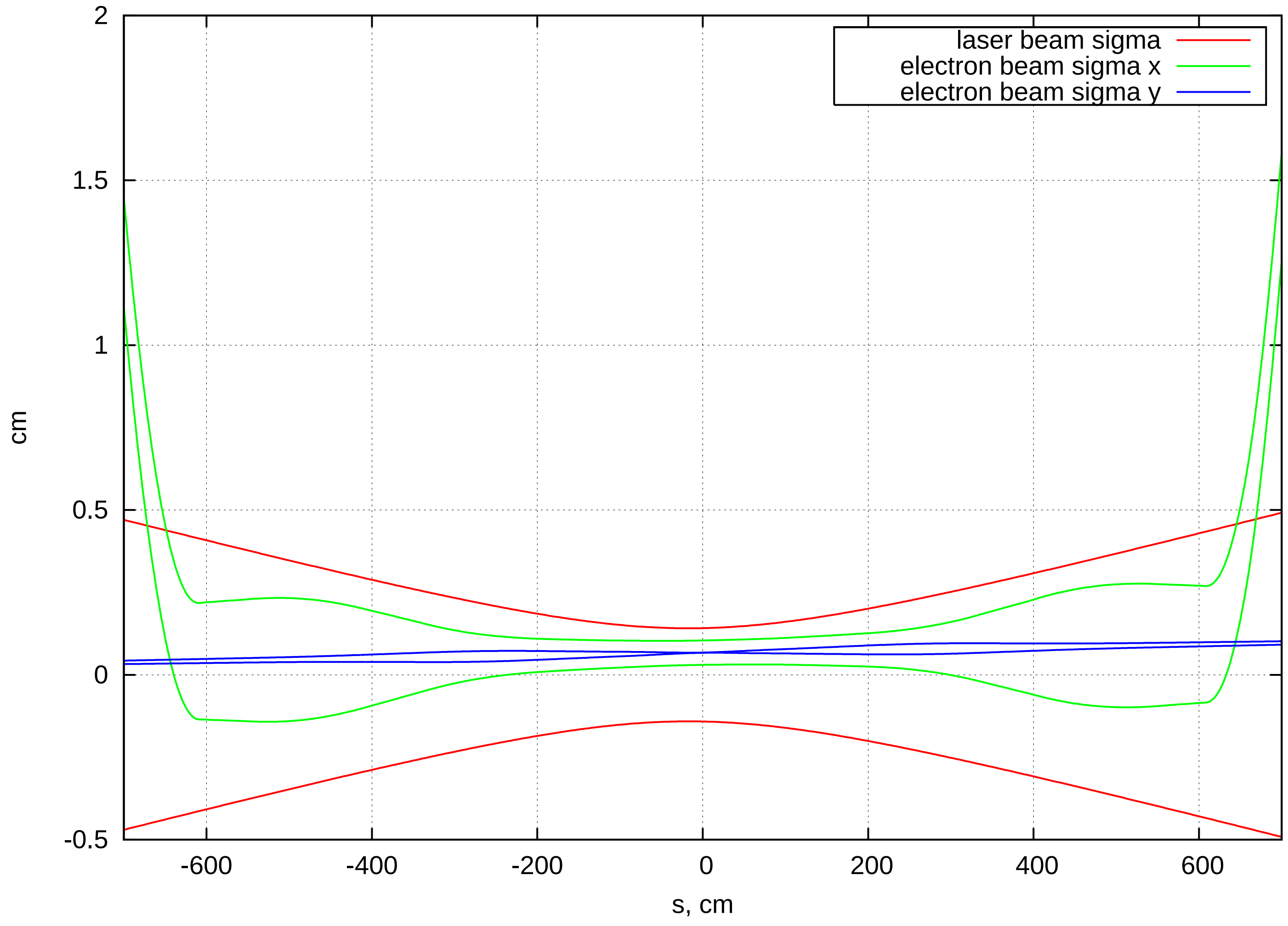
$$\times \exp\{-\frac{x_0^2}{2(\sigma^2+\sigma_x^2+\sigma_s^2)}\}$$

Further integration over ds is performed numerically, taking into account all the dependencies in the list: $x_0(s)$, $y_0(s)$, $\sigma(s)$, $\psi(s)$, $\beta_x(s)$, $\beta_y(s)$.

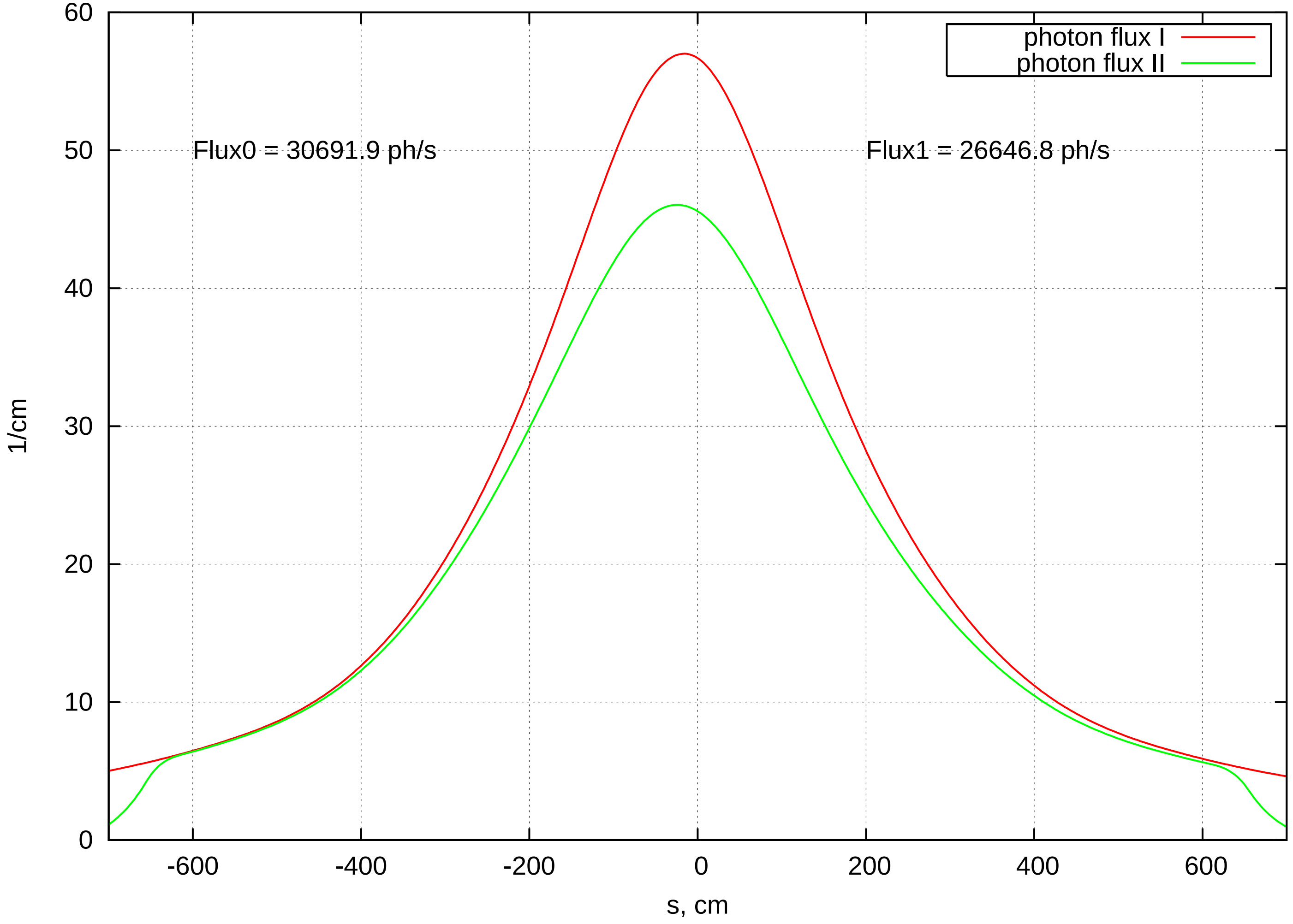
Forming the laser beam waist near the senter of interaction region



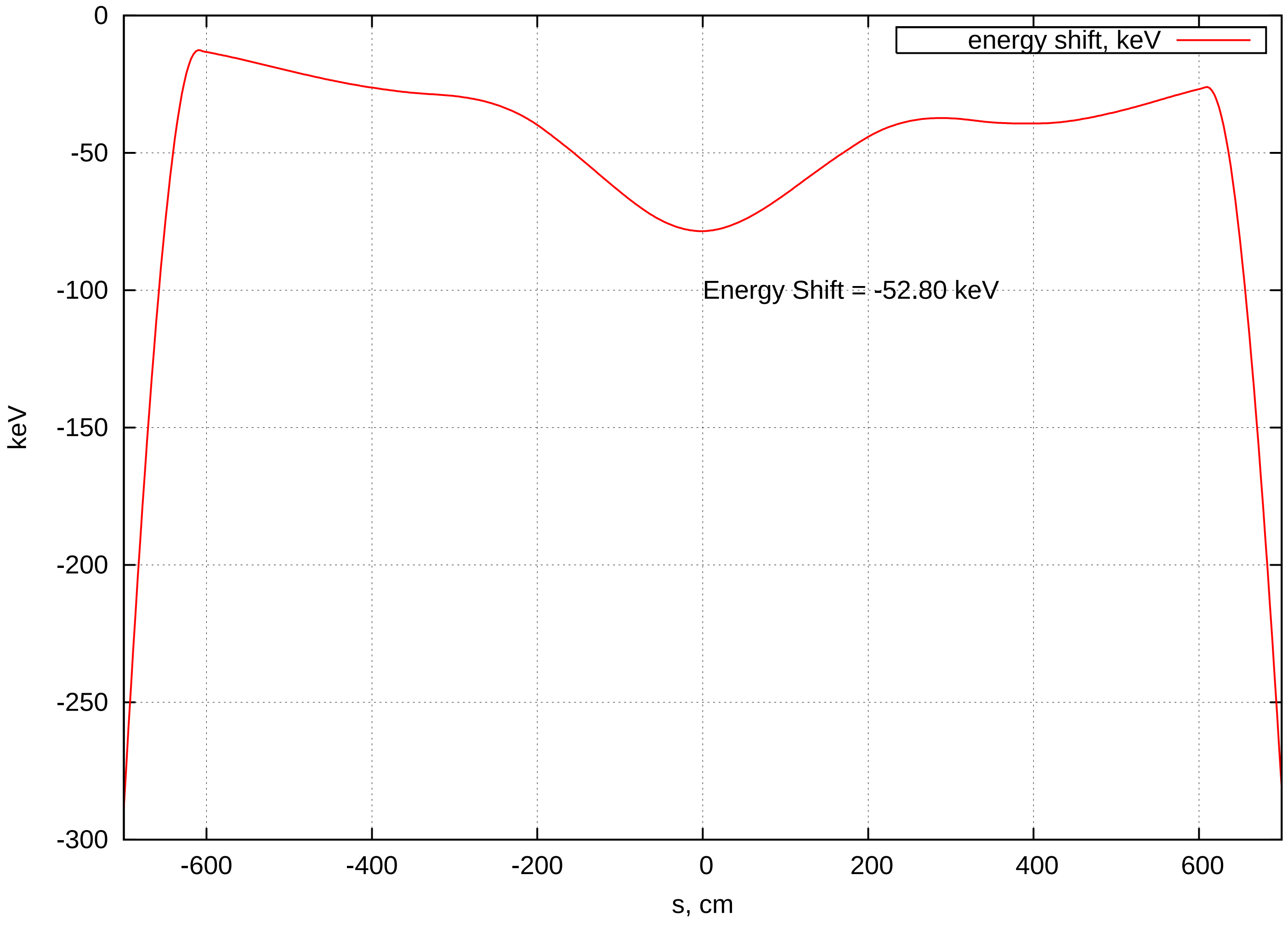
Laser and electron beams sizes inside the vacuum chamber



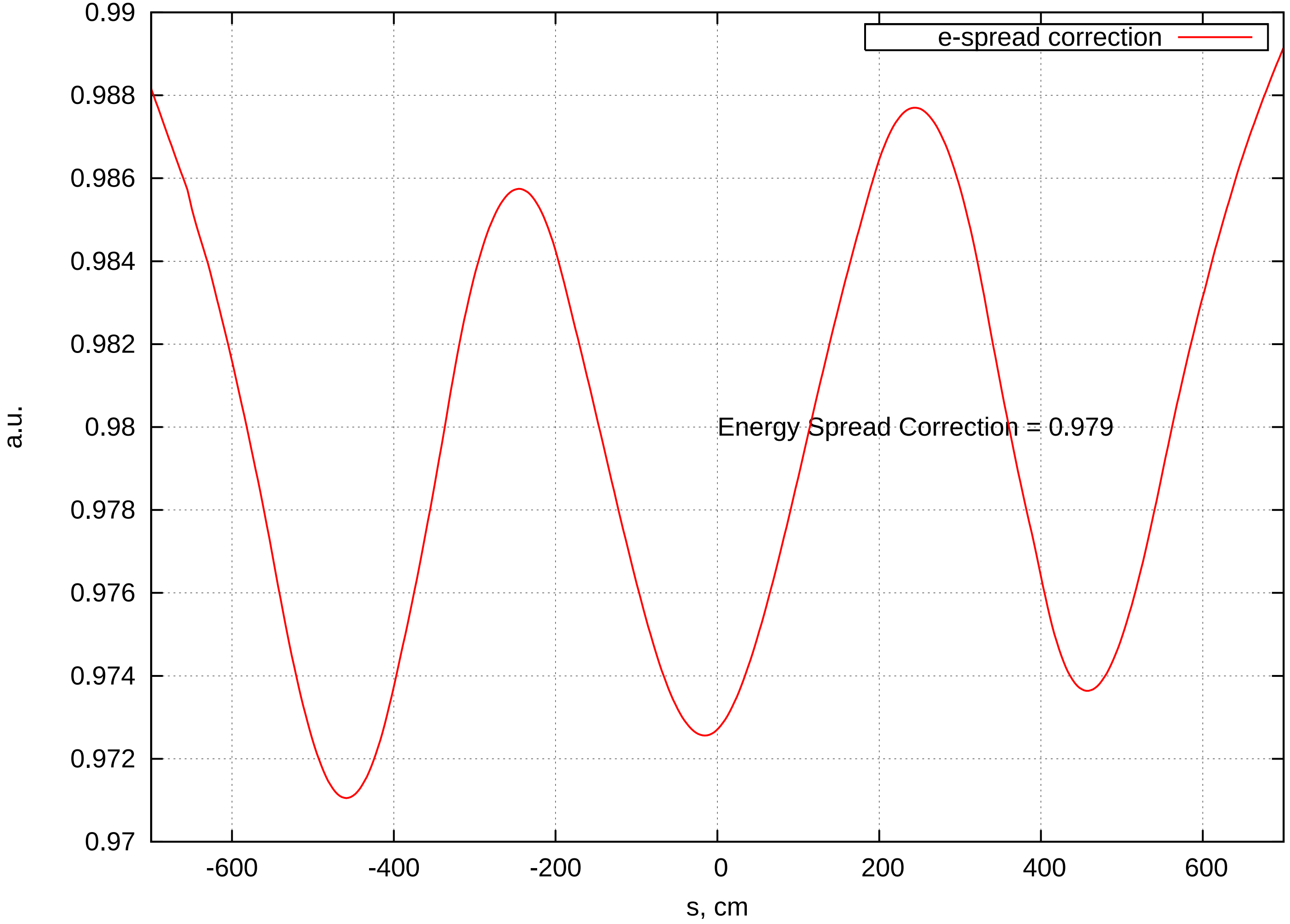
Backscattered photons flux (1 W laser, 1 mA electron beam)



Average energy shift due to beams misalignment



Energy spread correction factor



Compton spectrum edge shape

$$g(x, p_{0...5}) = \frac{1}{2}(p_2(x - p_0) + p_3) \cdot \mathrm{erfc}[\frac{x - p_0}{\sqrt{2}p_1}] -$$
$$- \frac{p_1 p_2}{\sqrt{2\pi}} \cdot \exp[-\frac{(x - p_0)^2}{2p_1^2}] + p_4(x - p_0) + p_5 \ ,$$

where:

p_0 – edge position;

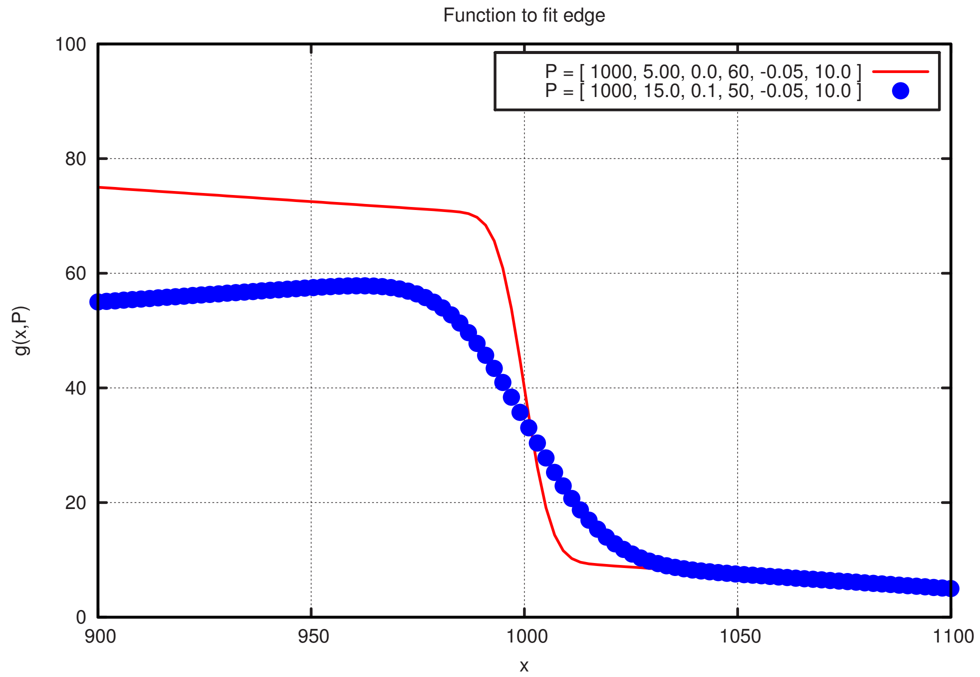
p_1 – edge width;

p_2 – slope left;

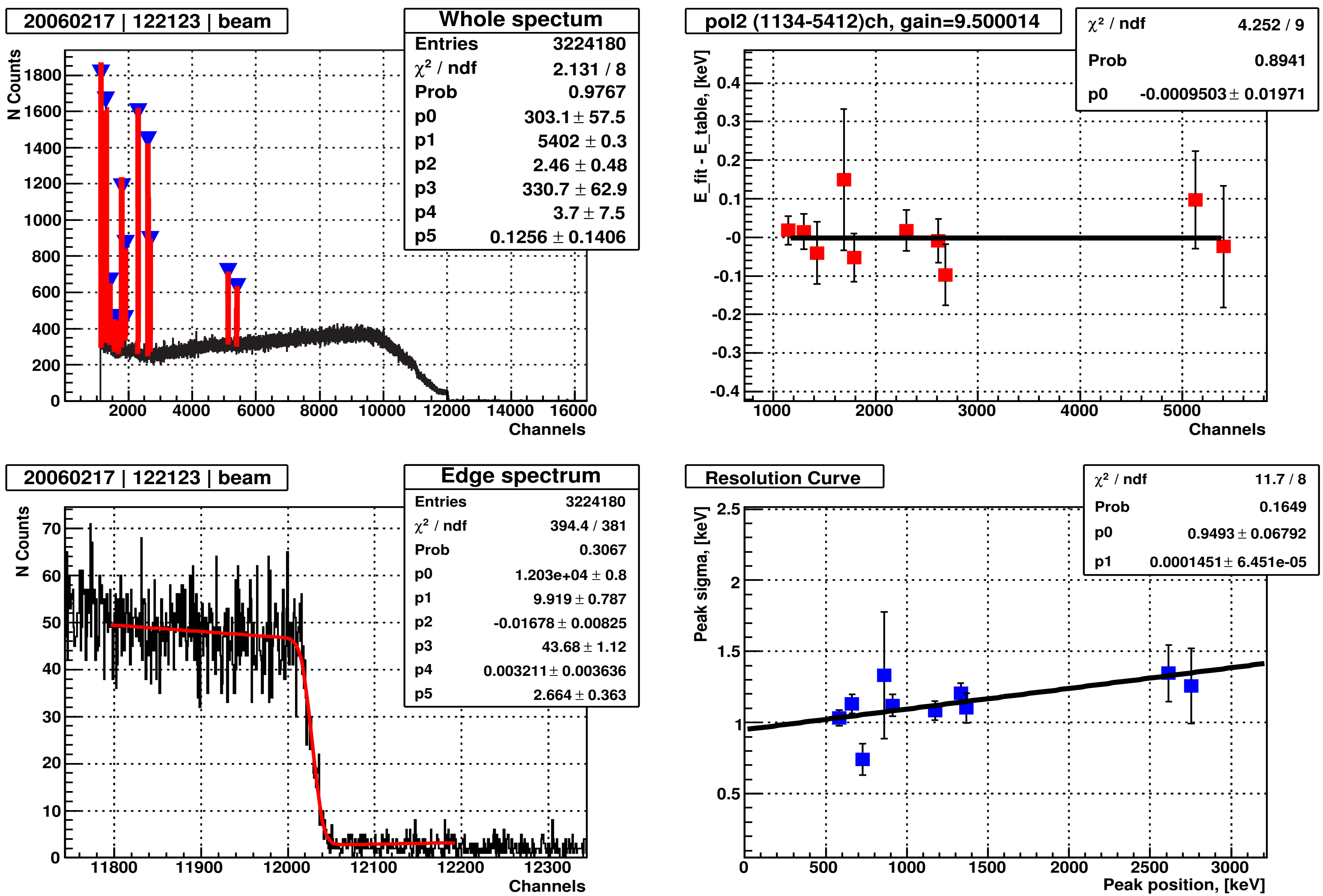
p_3 – edge amplitude;

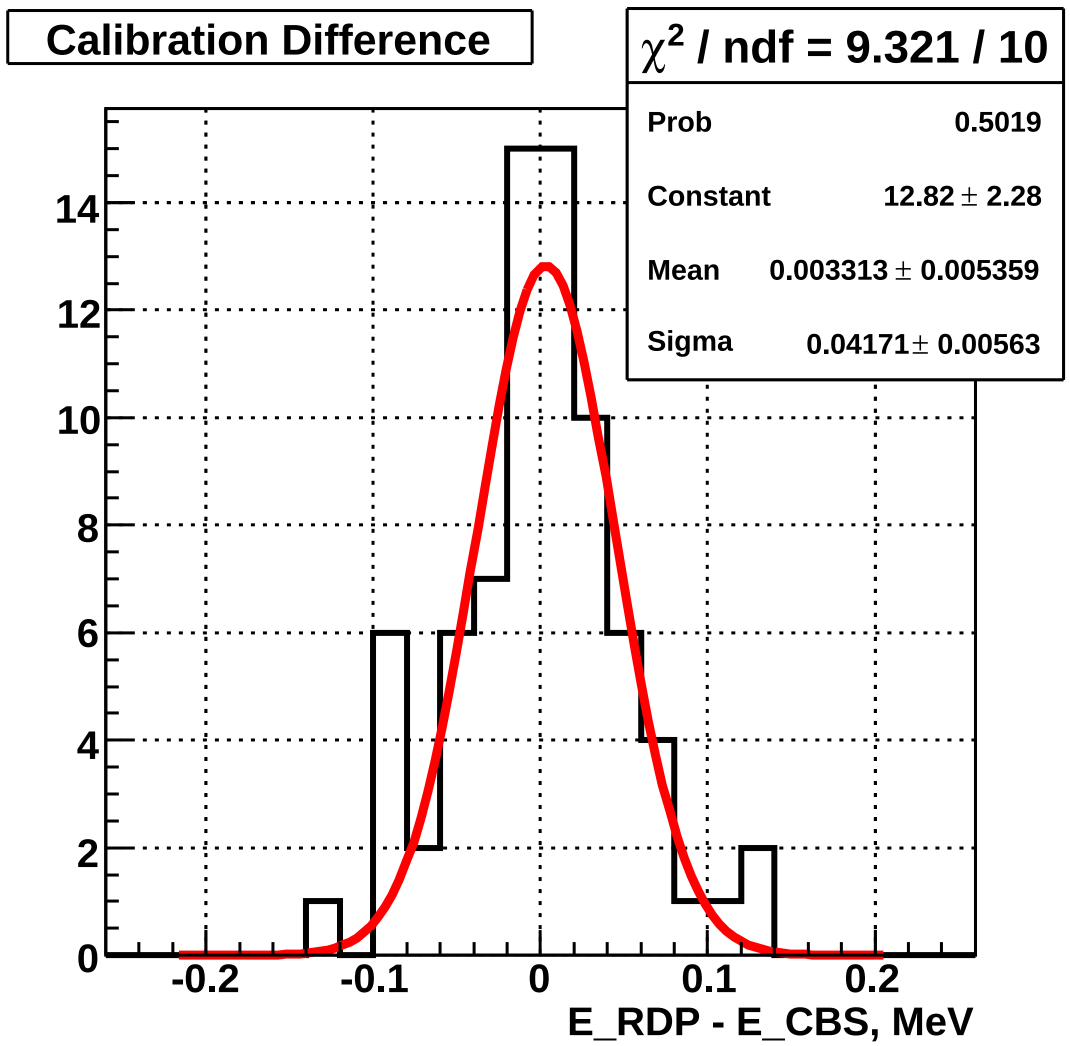
p_4 – slope right;

p_5 – background.

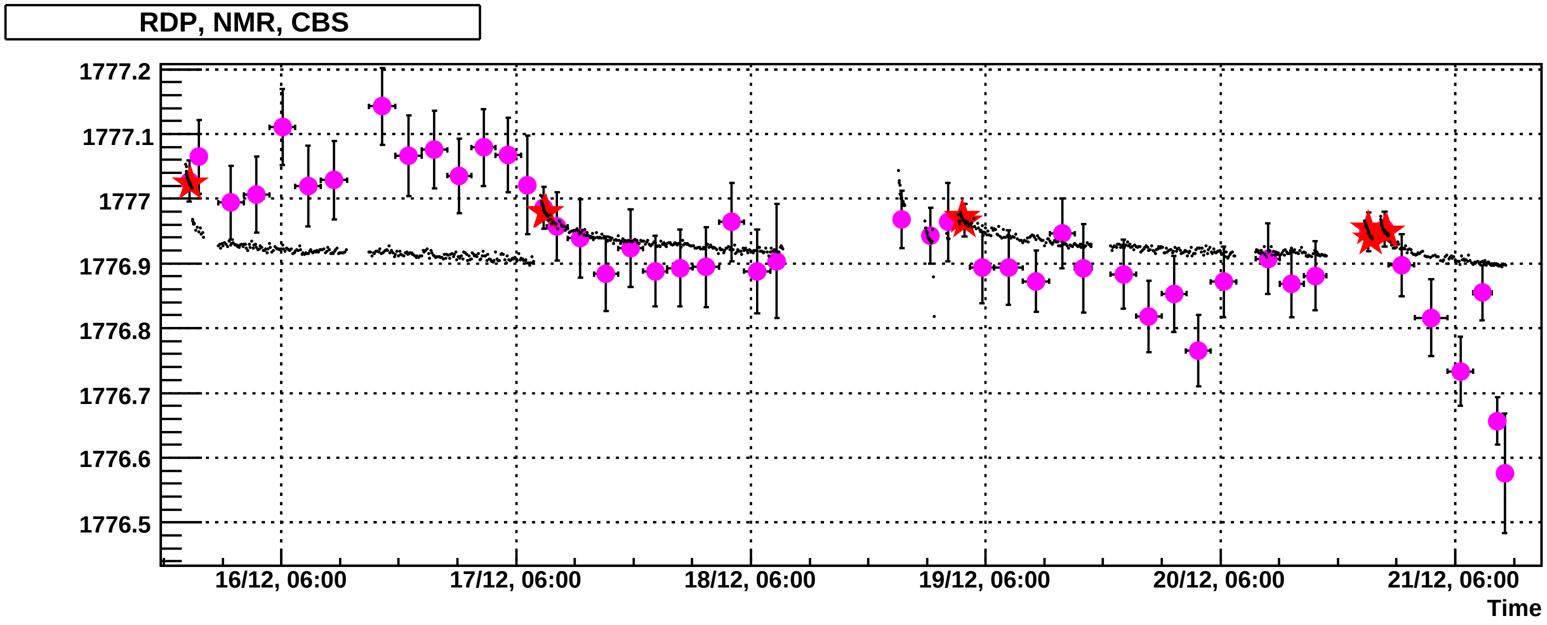


Experimental spectrum example




Calibration Difference
χ^2 / ndf = 9.321 / 10
Prob 0.5019
Constant 12.82 ± 2.28
Mean 0.003313 ± 0.005359
Sigma 0.04171 ± 0.00563
0
2
4
6
8
10
12
14
-0.2
-0.1
0
0.1
0.2
E_RDP - E_CBS, MeV

Continuous Monitoring of the Beam Energy



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)