IHEP-BINP CEPC accelerator collaboration workshop
Beam energy calibration without polarization

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TALK OUTLINE

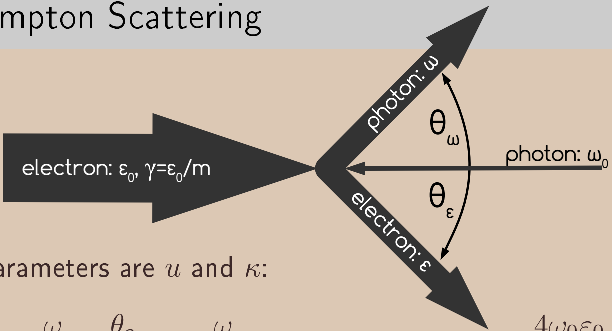
Introduction

- The energy released in the annihilation of an electron and positron is an important property: it establishes kinematic bounds for any processes under investigation.
- The processes with resonance or threshold cross section dependence on the c.m.s. energy allow accurate determination of particle masses.
- World-wide experience shows that beam energy calibration usually consumes additional time and efforts.
- For future high energy colliders it is necessary to accumulate and extend the experience gathered at low energy machines.

BEPC-II Beam Energy Measurement System (BEMS)

- Project was started in 2008
- First tests and $\psi(2S)$ scan – December, 2010
- τ mass measurement experiment – December, 2011
- Continuous operation, “1MeV” problem – 2012
- Malfunction of the laser – 2013
- Laser repair, new ZnSe vacuum windows - 2014
- BEMS beam test with a “new” laser – May, 2015

Inverse Compton Scattering



Scattering parameters are u and κ:

$$u = \frac{\omega}{\varepsilon} = \frac{\theta_\varepsilon}{\theta_\omega} = \frac{\omega}{\varepsilon_0 - \omega}; \quad u \in [0, \kappa]; \quad \kappa = \frac{4\omega_0\varepsilon_0}{m^2}.$$

Scattering angles: $\gamma\theta_\omega = \sqrt{\kappa/u - 1}$; $\gamma\theta_\varepsilon = u\sqrt{\kappa/u - 1}$.

Maximum energy of scattered photon $(\theta_\omega = \theta_\varepsilon = 0)$: $\omega_{max} = \frac{\varepsilon_0 \kappa}{1+\kappa}$.

Initial electron energy: $\varepsilon_0 = \frac{\omega_{max}}{2}\left(1 + \sqrt{1 + \frac{m^2}{\omega_0\omega_{max}}}\right) \simeq \frac{m}{2}\sqrt{\frac{\omega_{max}}{\omega_0}}$.

Accurate energy scale transfer: eV $\to$ MeV $\to$ GeV

- IR optics, 10P20 CO_2 laser line: $\omega_0 = 0.117065228$ eV
- γ-lines from excited nuclei as a good reference for ω_{max}:

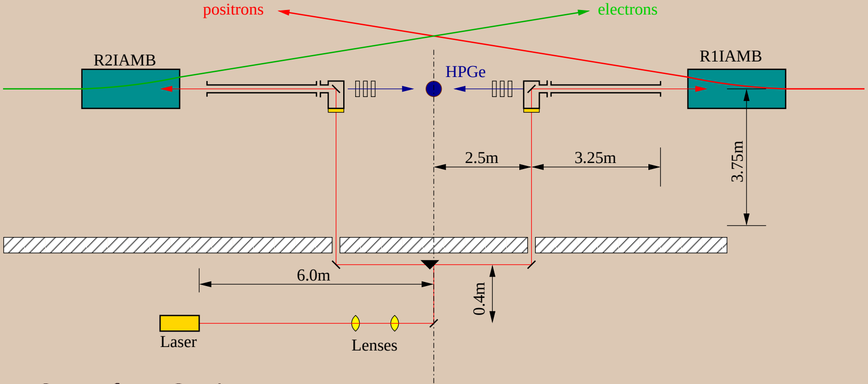
^{137}Cs	$\tau_{1/2} \simeq 30.07$ y	$E_\gamma = 0661.657 \pm 0.003$ keV
^{60}Co	$\tau_{1/2} \simeq 5.27$ y	$E_\gamma = 1173.228 \pm 0.003$ keV
		$E_\gamma = 1332.422 \pm 0.004$ keV
^{208}Tl	$\tau_{1/2} \simeq 3$ m	$E_\gamma = 2614.511 \pm 0.013$ keV
^{16}O*		$E_\gamma = 6129.266 \pm 0.054$ keV

- High energy physics scale[1]:

J/ψ	$3096.900 \pm 0.002 \pm 0.006$ MeV
$\psi(2S)$	$3686.099 \pm 0.004 \pm 0.009$ MeV

[1] Final analysis of KEDR data, Physics Letters B 749 (2015) 50-56

BEMS layout at the North BEPC I.P.



- Size of HPGe detector $D \simeq 4$ cm
- Distance between HPGe and $\gamma e^+/\gamma e^-$ scattering area $L \simeq 8$ m
- Beam orbit angle should be "zero" within $\theta \simeq D/L \simeq \pm 2.5$ mrad

If θ is outside these limits, measurements are impossible!
THIS IS №1 BEMS PROBLEM: NO DATA = NO MEASUREMENT!

BEMS SUBSYSTEMS

- **Laser & optics system** – provides laser transportation and necessary focusing to the interaction area.
- **Control system** – provides change of laser direction to electron or positron beam, control over additional moving shield[2], tune (maximize) the rate of backscattered photons. It uses DAQ system counting rates as a feedback signal.
- **DAQ system** – reads HPGe data from MCA, saves the raw data to disk. Uses Control system status to distinguish electron/positron records. ALL RAW DATA IS AVAILABLE!
- **On-line analysis system** provides online beam energy determination results and writes them to the BEPC database.
- **Off-line analysis** role is to make various checks and get better results.

[2] Up to 18 cm of lead shielding was installed to suppress beam background!

Absolute energy measurements by HPGe spectrometers

Practical experience has been gained in the field of nuclear spectroscopy. "Idaho group" recommendations for precise absolute measurements:

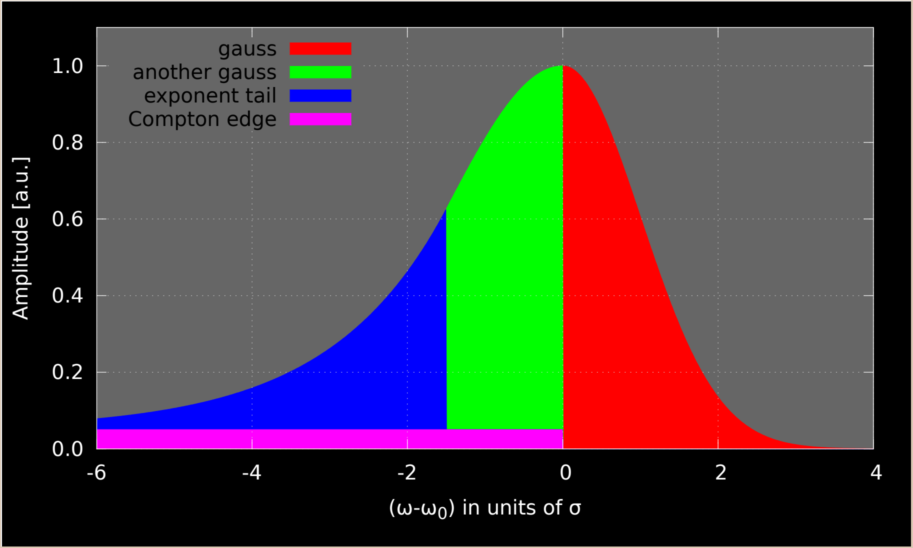
- use more than one spectrometer
- simultaneous and unidirectional measurement of calibration lines and energies under investigation
- perform energy calibration in a narrow range instead of polynomial extrapolation of the whole scale
- avoid using m_0c^2 or $2m_0c^2$ values for determination of energy difference between photo-peak and escape-peaks
- avoid using pulsers for calibration

Our approach is different…

… cause the range where we work is rather wide. So we will try to:

- find an appropriate function to describe the total total absorption peak shape;
- check that the parameters of this function have a smooth energy dependence;
- use BNC PB-5 precise amplitude pulser with declared integral linearity as small as 15 ppm.

HPGe energy response function



HPGe energy response function

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

A – amplitude,

$x = 0$ – line energy,

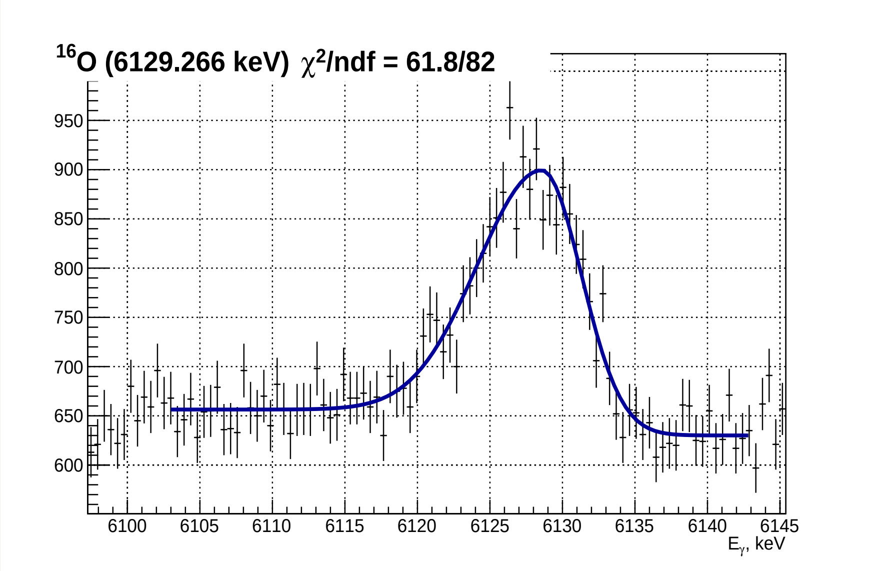
σ – normal width,

$K_0\sigma$ – width from-the-left modification,

$K_1K_0\sigma$ – exponential low-energy tail,

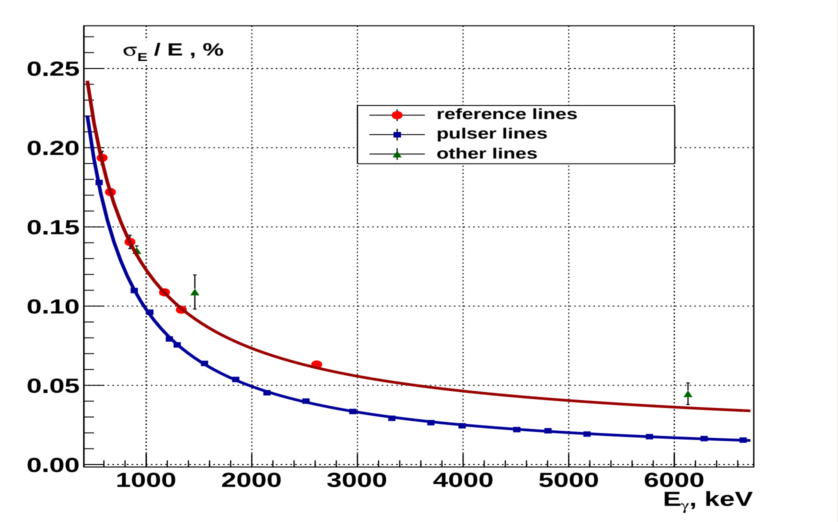
C – is for low-angle scattering of γ-s on their way to detector.

6129 keV peak (2011 data)

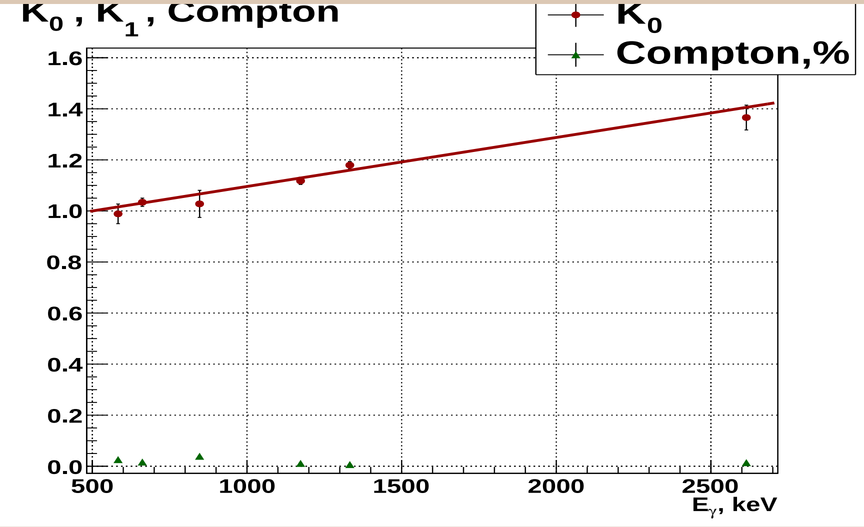


HPGe energy resolution (2011 data) $\sigma_E = \sqrt{\sigma_0^2 + \varepsilon F E}$

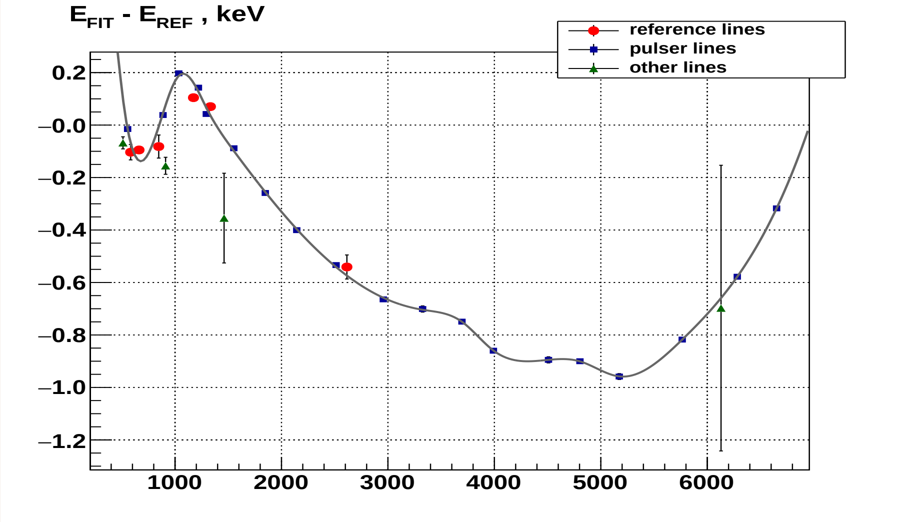
ε – electron-hole creation energy in Ge, F – Fano factor



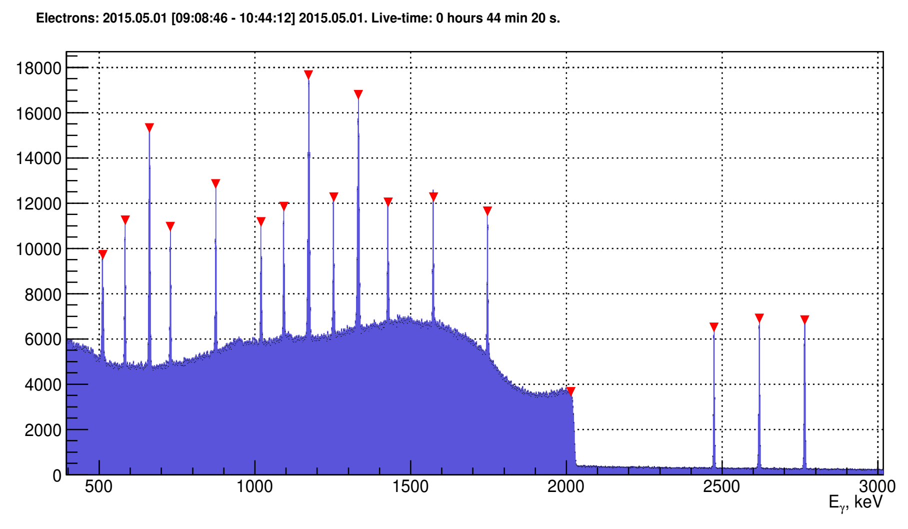
Peak shape widening, K_0 ($K_1 = \infty$)



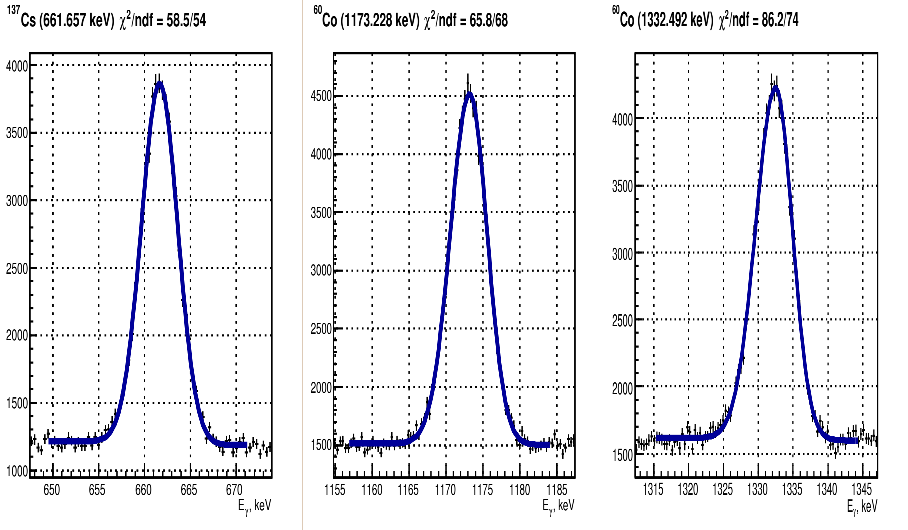
Wide-range scale calibration



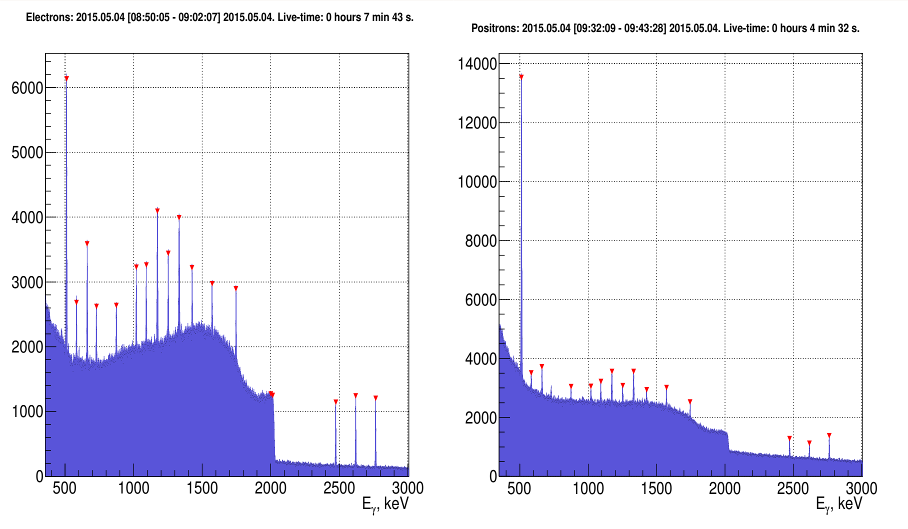
BEMS test in May, 2015: spectrum example



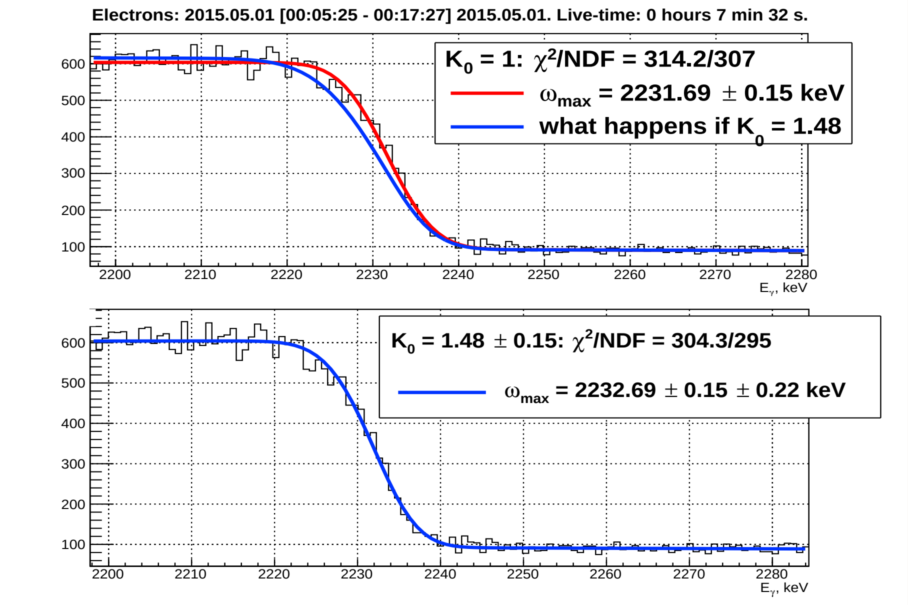
BEMS test in May, 2015: calibration lines fit



BEPC orbit influence example: GOOD (e^-) & BAD (e^+)



Edge Fit


Electrons: 2015.05.01 [00:05:25 - 00:17:27] 2015.05.01. Live-time: 0 hours 7 min 32 s.
K0 = 1: χ2/NDF = 314.2/307
ωmax = 2231.69 ± 0.15 keV
what happens if K0 = 1.48
Eγ, keV
K0 = 1.48 ± 0.15: χ2/NDF = 304.3/295
ωmax = 2232.69 ± 0.15 ± 0.22 keV
Eγ, keV

Copy of fitting output

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Simple Edge Fit:
Range from 2126.8 to 2356.2 keV | E_beam = 1119.13 MeV | W_max =  2241.506 keV

Edge amplitude :    511.271 ±  5.3719 | Edge slope:              0.078 ±  0.0812
Edge wmax,  keV:   2231.694 ±  0.1519 | Backgrond level:        92.455 ±  1.7183
Edge width, keV:      4.368 ±  0.1832 | Background slope:       -0.069 ±  0.0227

χ2/NDF = 314.2/307                    | Probability: 0.376
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Complex Edge Fit:
Range from 2117.1 to 2346.3 keV | Amplitude =  511.3 | W_max  =  2231.694 keV
HPGe resolution =     2.764 keV | HPGe K0 =    1.478 | Spread =     3.383 keV

Edge wmax: 2232.69 ± 0.15 ± 0.22 keV | Beam σE impact:  2.73 ±  0.28 ±  0.18 keV
Edge amplitude :    502.029 ±  4.6094 | Backgrond level:      92.455 ±  0.0000
HPGe resol, keV:      2.764 ±  0.0000 | Background slope:     -0.069 ±  0.0000
HPGe K0        :      1.478 ±  0.0000 | Compton slope:        -0.001 ±  0.0013

χ2/NDF = 304.3/295                    | Probability: 0.342
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Wmax: 2231.69 ± 0.15 keV (symmetric fit)
Wmax: 2232.69 ± 0.26 keV (asymmetric fit)
Wmax: 2232.69 ± 0.32 keV (linear scale error)
Wmax: 2233.43 ± 0.32 keV (spline correction )
```

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electron Beam Energy Determination:
           BEPC beam energy = 1119.132 ± 0.146 MeV was taken from database
           Measurement time from 2015.05.01 00:05:25 to 2015.05.01 00:17:27.

BEMS beam energy = 1117.119 ± 0.080 MeV  (SR correction to IP +0.007 MeV was added)
BEMS beam spread =      682 ±    83 keV
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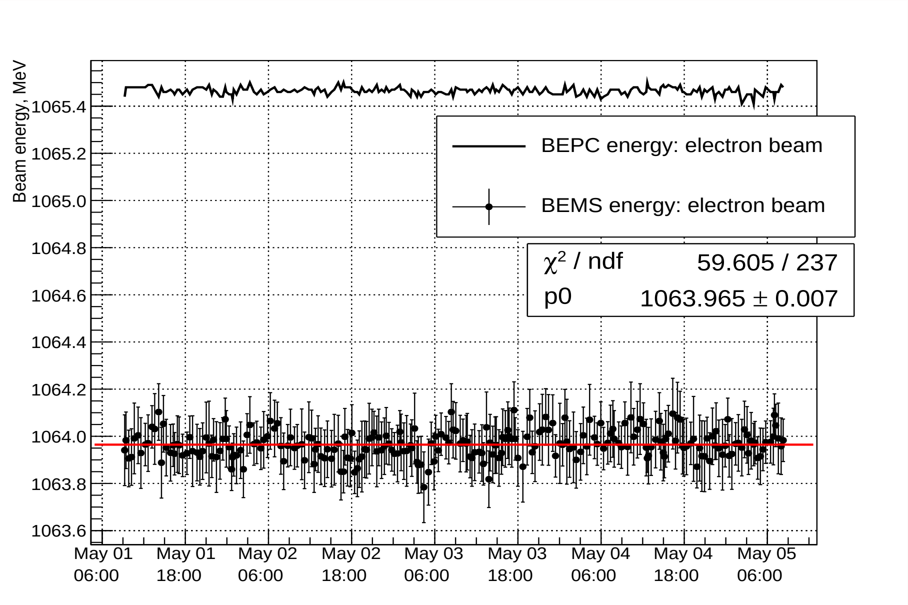
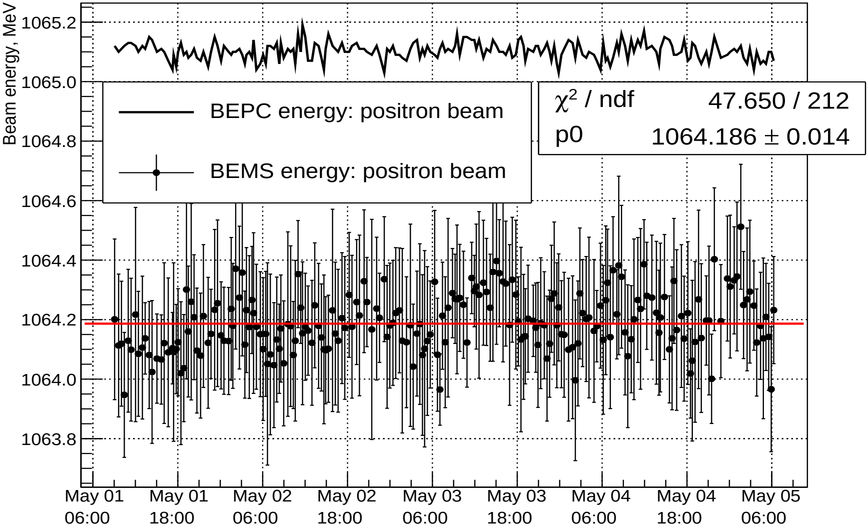
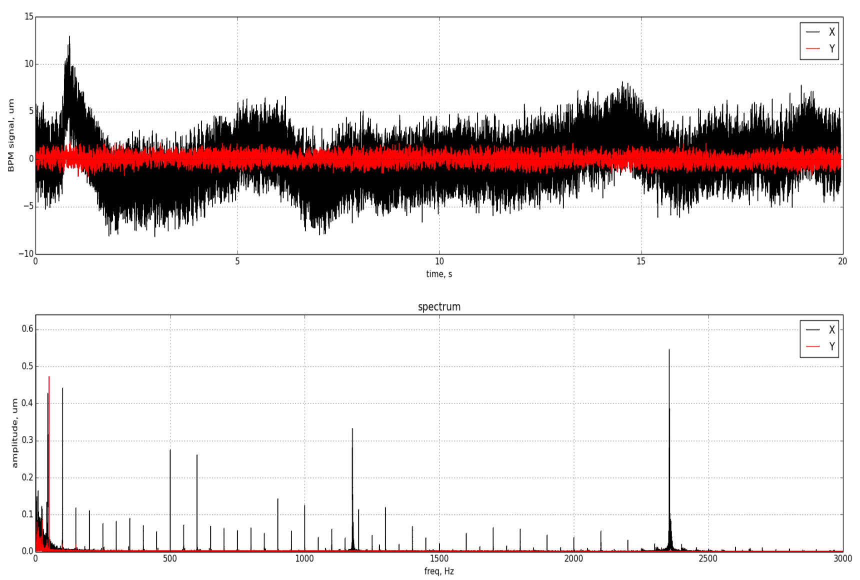
BEMS results: electron beam energy. $\Delta E^* \simeq 1.5$ MeV



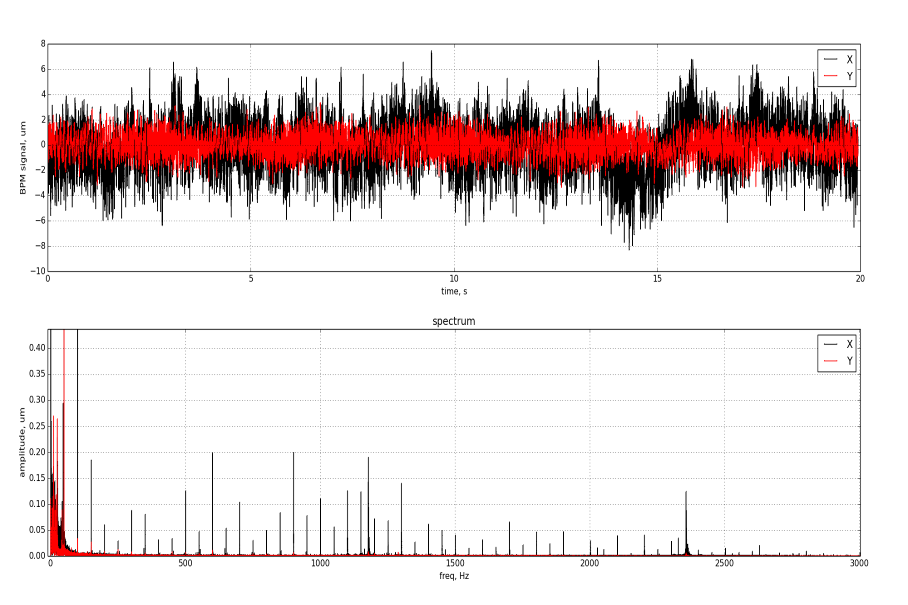
BEMS results: positron beam energy. $\Delta E^* \simeq 0.9$ MeV



Orbit radius oscillations (BPR) from BPM signal



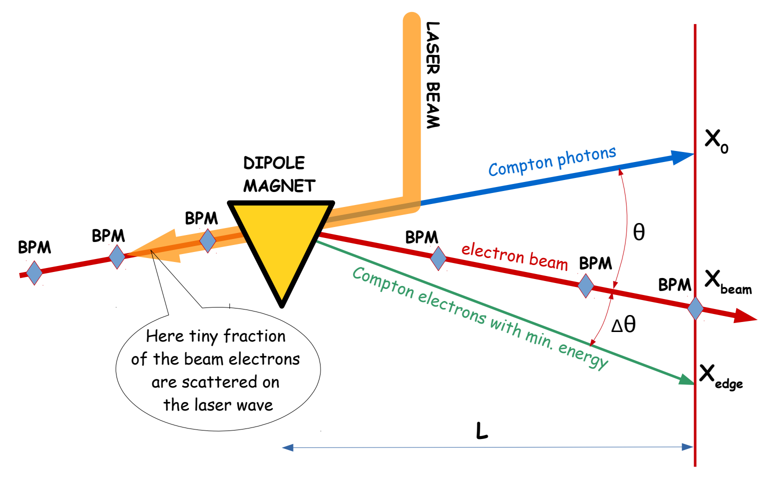
Orbit radius oscillations (BER) from BPM signal



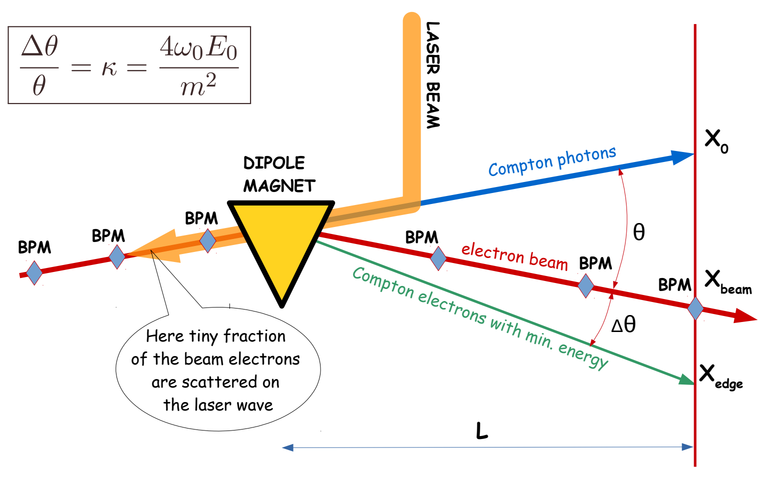
Orbit radius oscillations (BER) from BPM signal

- Most probable explanation for the observed oscillations is the oscillations in BEPC guide field, where frequencies are the multiples of AC line frequency.
- If so, this definitely leads to average energy oscillations.
- Long-time average distribution of the electrons energies is no more a Normal distribution.
- If so, the edge fitting procedure becomes incorrect, leading to systematic shift of results.
- We are going to implement direct field oscillations measurement by induction probes.

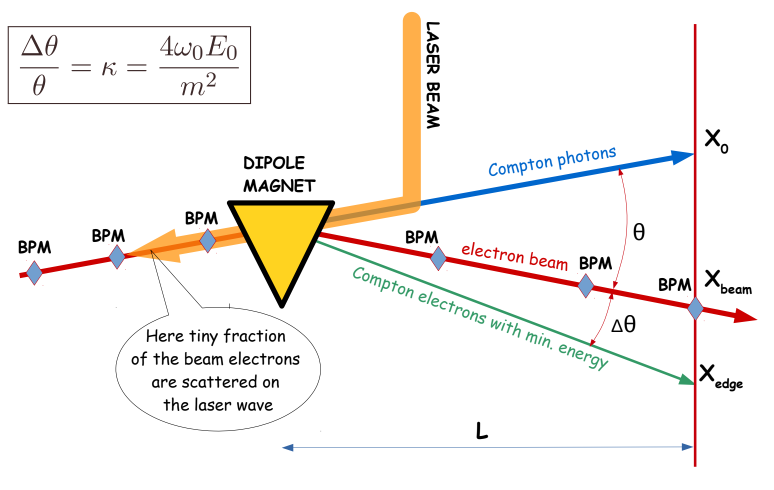
Spectrometer with laser calibration



Spectrometer with laser calibration



Spectrometer with laser calibration

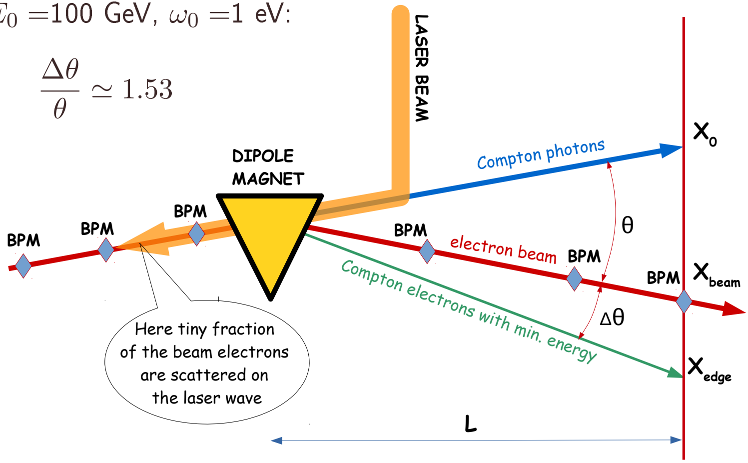


Access to the beam energy: $E_0 = \frac{\Delta\theta}{\theta} \times \frac{m^2}{4\omega_0}$

Spectrometer with laser calibration

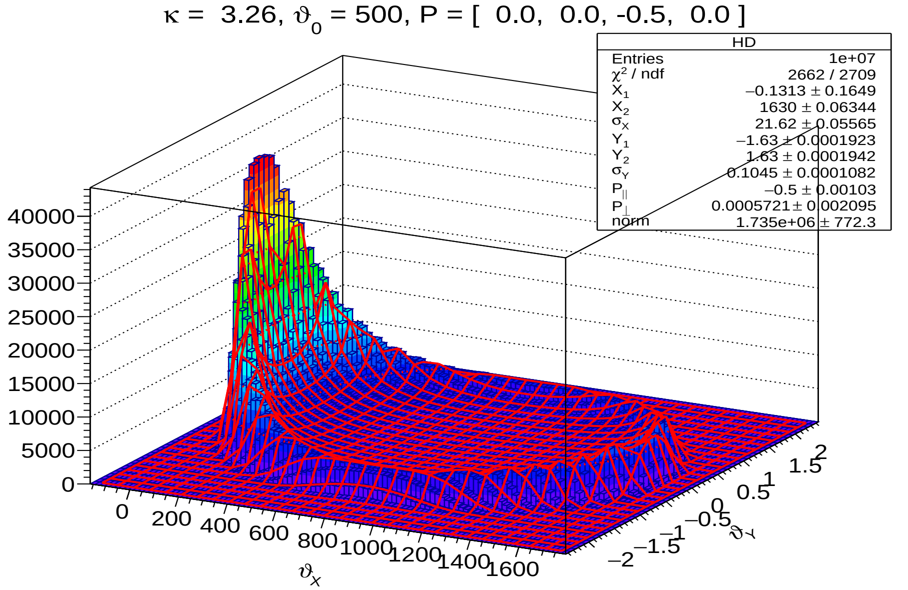
E_0 =100 GeV, ω_0 =1 eV:

$$\frac{\Delta\theta}{\theta} \simeq 1.53$$

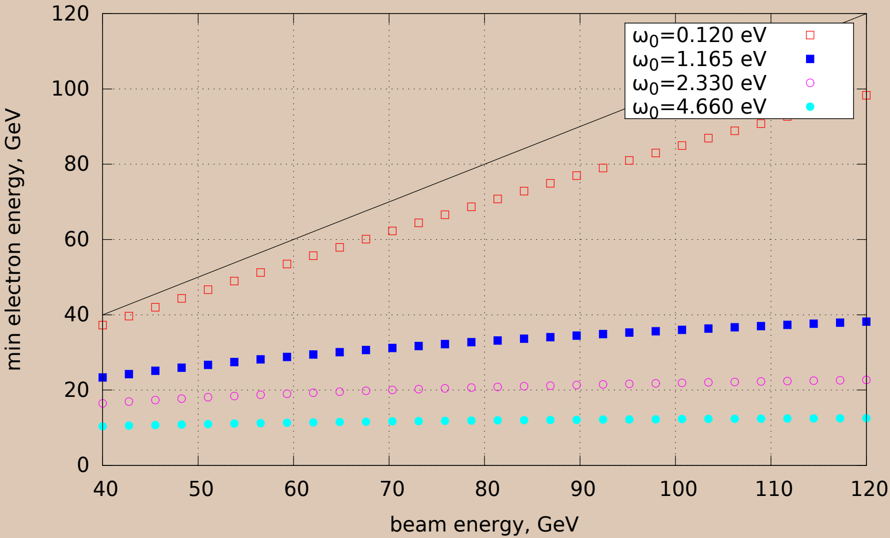


Access to the beam energy: $E_0 = \frac{\Delta\theta}{\theta} \times \frac{m^2}{4\omega_0}$

Use of 2D pixel detector for scattered electrons?



Energy of scattered electrons? $E_{min} = E/(1 + \frac{4\omega_0 E}{m^2})$



Conclusion

- Beam energy calibration extends the field of possible physics.
- BEPC-II has the Beam Energy Measurement System (since 2010).
- BEMS operation should be studied and understood by IHEP accelerator community cause many of relevant problems are energy independent.
- The low-energy experience should be accumulated and used for future collider projects.
- As for CEPC and other high energy machines – some ideas exist already and should be studied in details.

THANK YOU!