

BESIII Collaboration Meeting in Winter of 2015
BEAM ENERGY MEASUREMENT SYSTEM

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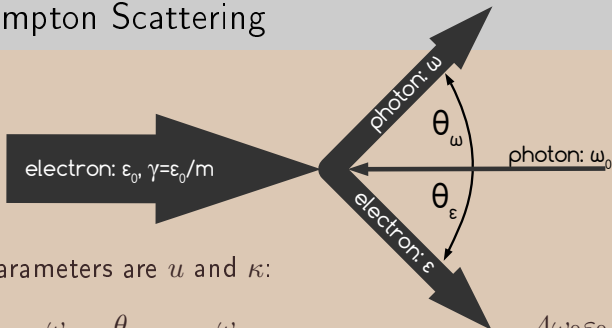
TALK OUTLINE

- 1 BEMS history & principles of operation
- 2 Energy scale calibration
- 3 BEMS-2015: scale calibration
- 4 BEMS-2015: beam energy determination
- 5 Conclusion

BEMS HISTORY

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

Inverse Compton Scattering



Scattering parameters are u and κ :

$$u = \frac{\omega}{\epsilon} = \frac{\theta_\epsilon}{\theta_\omega} = \frac{\omega}{\epsilon_0 - \omega}; \quad u \in [0, \kappa]; \quad \kappa = \frac{4\omega_0\epsilon_0}{m^2}.$$

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

Maximum energy of scattered photon ($\theta_\omega = \theta_\epsilon = 0$): $\omega_{max} = \frac{\epsilon_0\kappa}{1 + \kappa}$.

Initial electron energy: $\epsilon_0 = \frac{\omega_{max}}{2} \left(1 + \sqrt{1 + \frac{m^2}{\omega_0\omega_{max}}} \right) \simeq \frac{m}{2} \sqrt{\frac{\omega_{max}}{\omega_0}}$.

Accurate energy scale transfer: eV \rightarrow MeV \rightarrow GeV

- IR optics, 10P20 CO₂ laser line: $\omega_0 = 0.117065228$ eV
- γ -lines from excited nuclei as a good reference for ω_{max} :

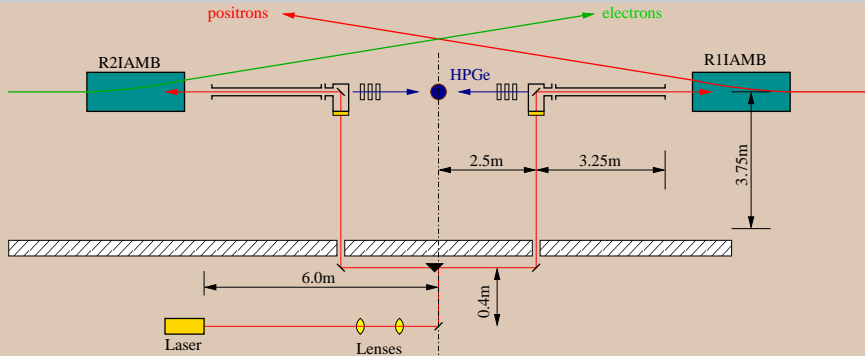
¹³⁷ Cs	$\tau_{1/2} \simeq 30.07$ y	$E_\gamma = 0661.657 \pm 0.003$ keV
⁶⁰ Co	$\tau_{1/2} \simeq 5.27$ y	$E_\gamma = 1173.228 \pm 0.003$ keV
		$E_\gamma = 1332.422 \pm 0.004$ keV
²⁰⁸ Tl	$\tau_{1/2} \simeq 3$ m	$E_\gamma = 2614.511 \pm 0.013$ keV
¹⁶ O*		$E_\gamma = 6129.266 \pm 0.054$ keV

- High energy physics scale¹:

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

¹Final 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 shield², 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.

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

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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

HPGe energy response function

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

A – amplitude,

$x = 0$ – line energy,

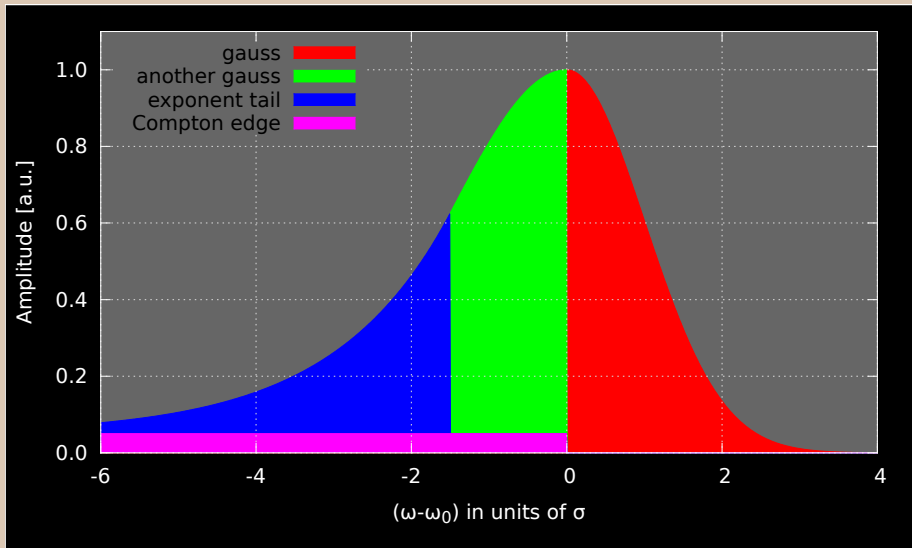
σ – normal width,

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

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

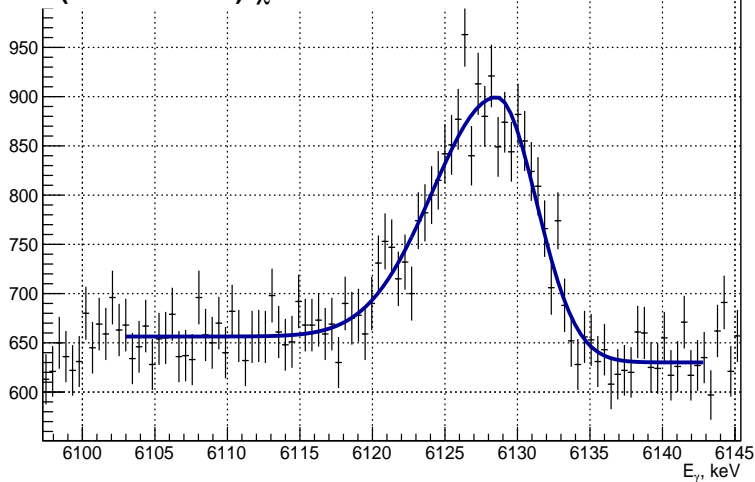
C – is for low-angle scattering of γ -s on their way to detector.

HPGe energy response function



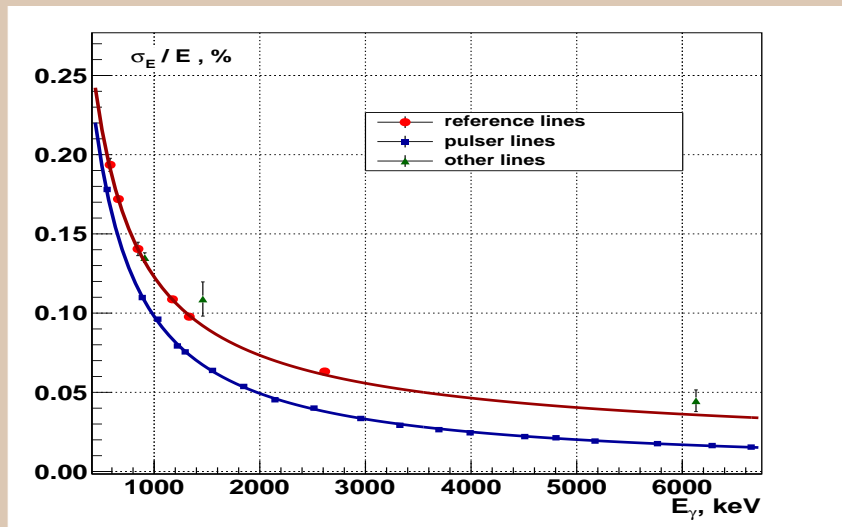
6129 keV peak (2011 data)

^{16}O (6129.266 keV) $\chi^2/\text{ndf} = 61.8/82$

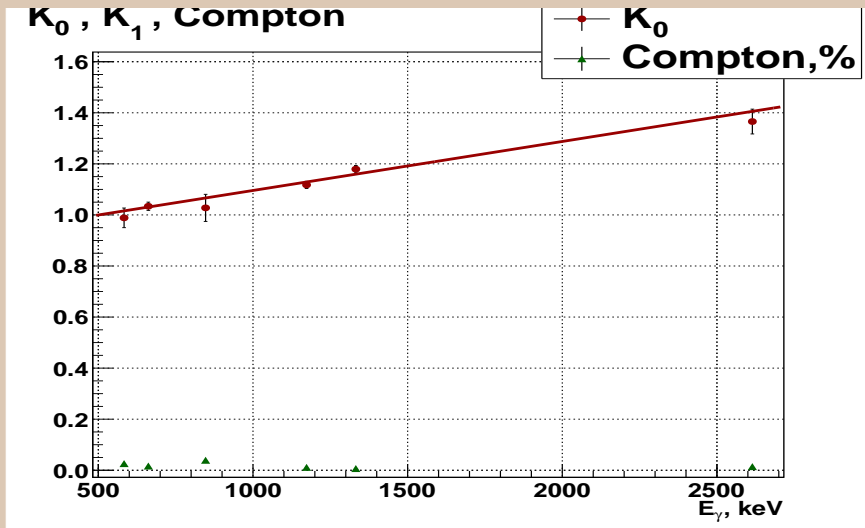


HPGe energy resolution (2011 data) $\sigma_E = \sqrt{\sigma_0^2 + \varepsilon F E}$

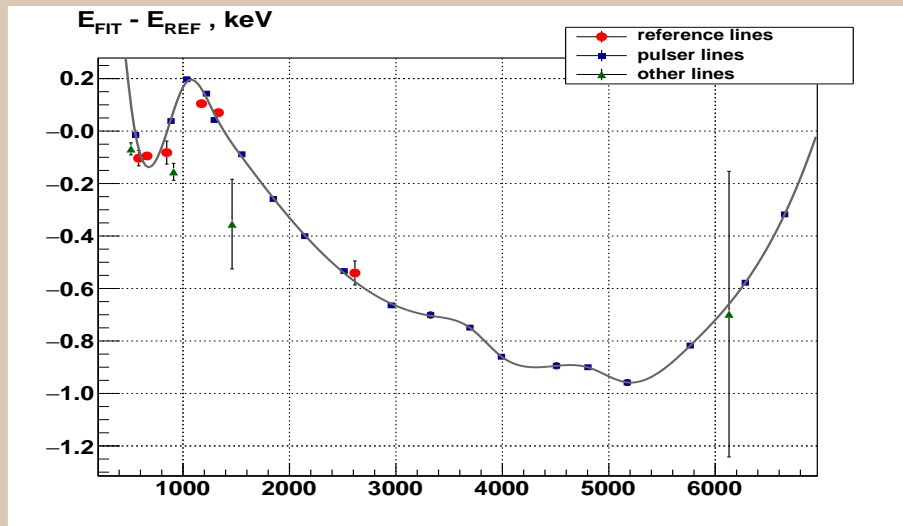
ε – electron-hole creation energy in Ge, F – Fano factor



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



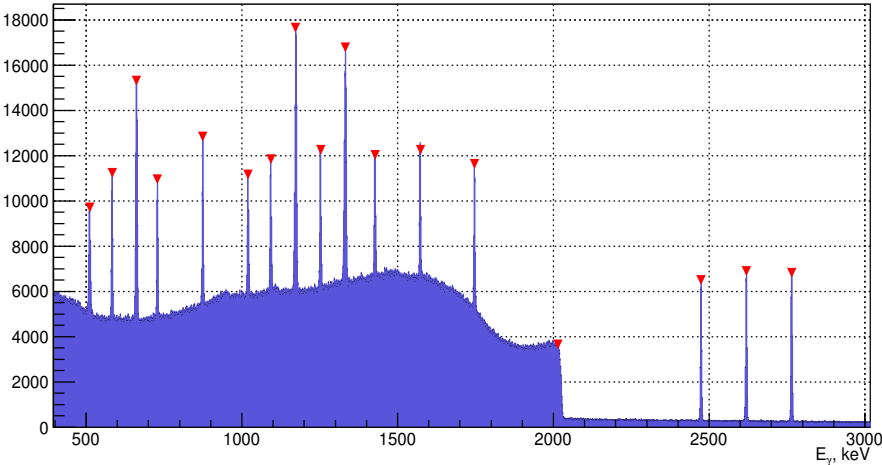
Wide-range scale calibration (2011 data)



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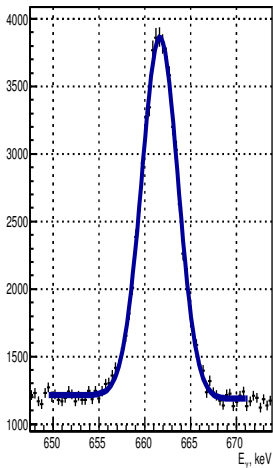
BEMS test in May, 2015: spectrum example

Electrons: 2015.05.01 [09:08:46 - 10:44:12] 2015.05.01. Live-time: 0 hours 44 min 20 s.

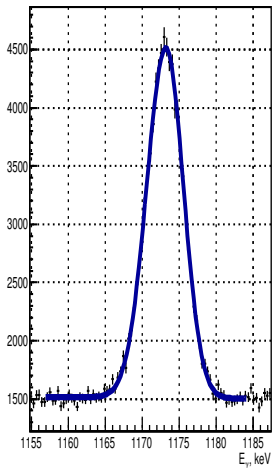


BEMS test in May, 2015: calibration lines fit

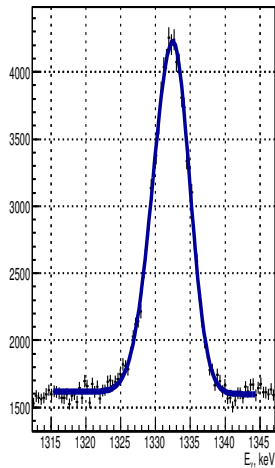
^{137}Cs (661.657 keV) $\chi^2/\text{ndf} = 58.5/54$



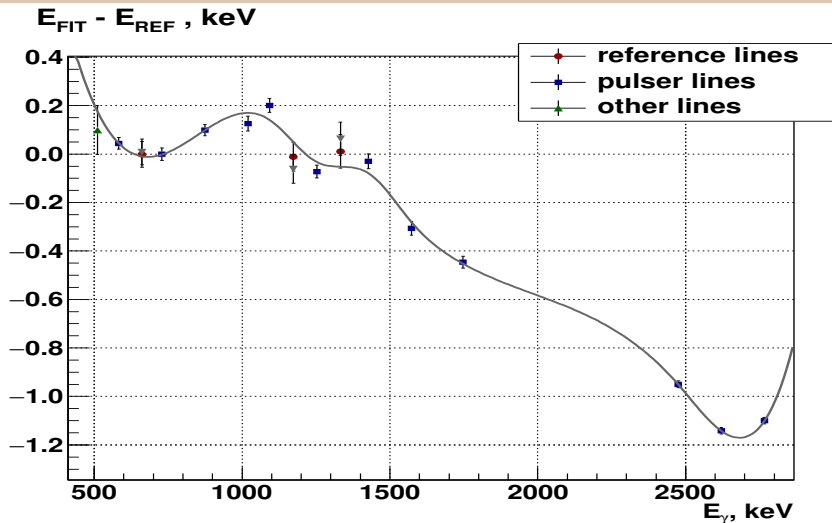
^{60}Co (1173.228 keV) $\chi^2/\text{ndf} = 65.8/68$



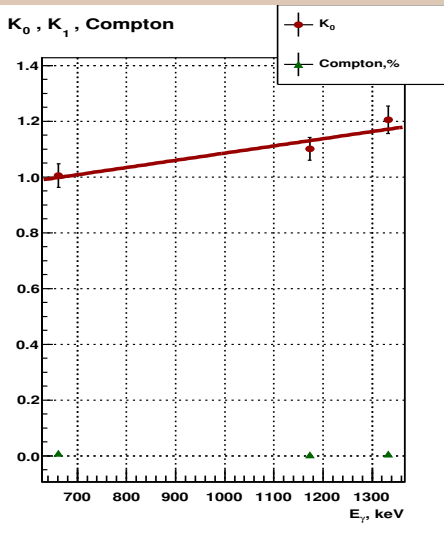
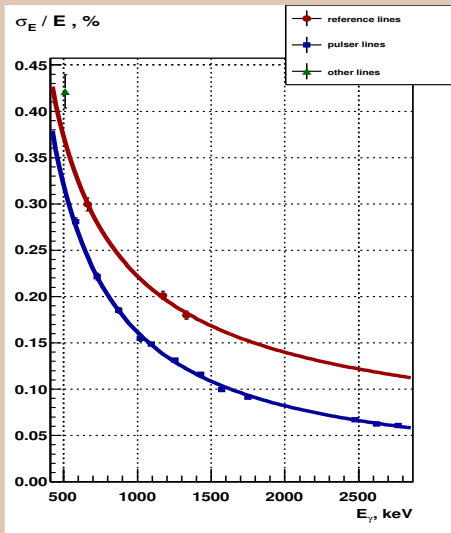
^{60}Co (1332.492 keV) $\chi^2/\text{ndf} = 86.2/74$



BEMS test in May, 2015: energy scale

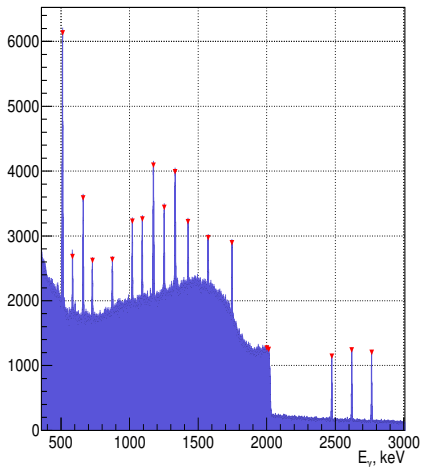


BEMS test in May, 2015: resolution and K_0

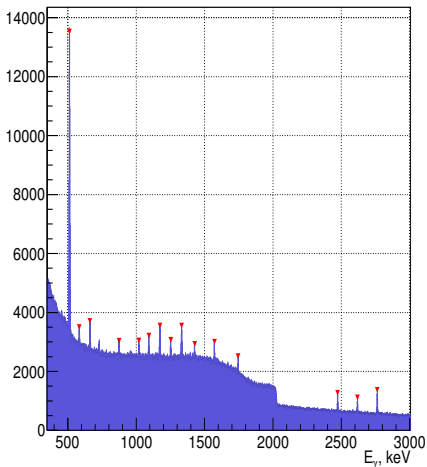


BEPC orbit influence example: GOOD (e^-) & BAD (e^+)

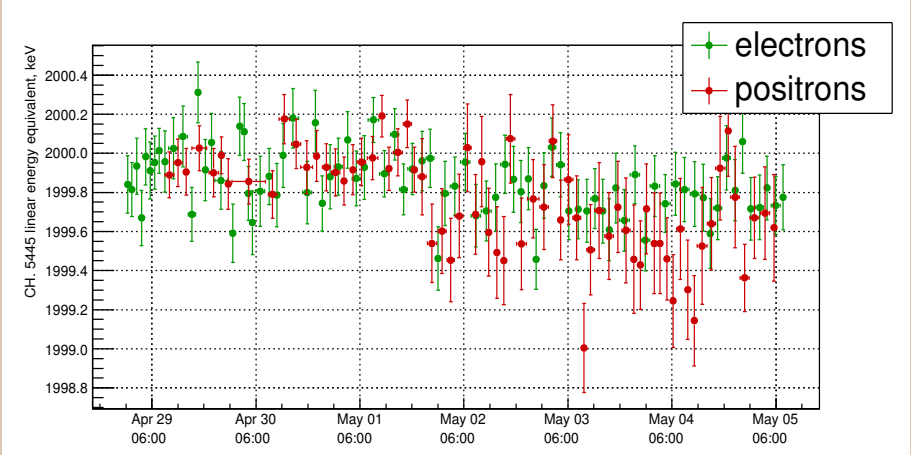
Electrons: 2015.05.04 [08:50:05 - 09:02:07] 2015.05.04. Live-time: 0 hours 7 min 43 s.



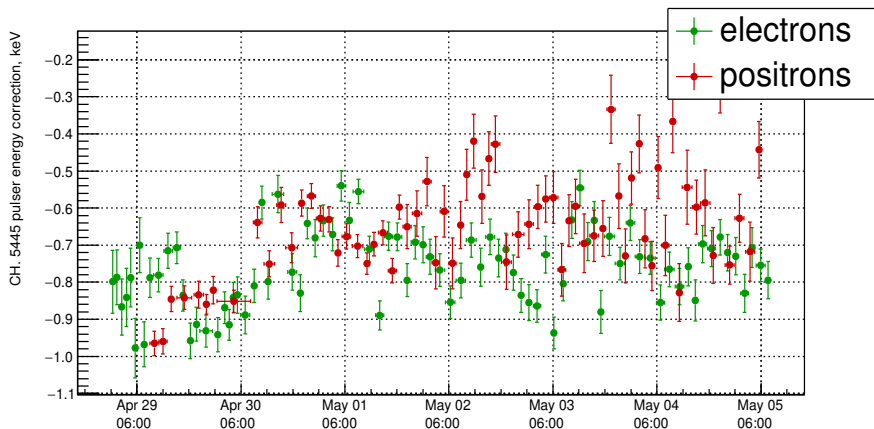
Positrons: 2015.05.04 [09:32:09 - 09:43:28] 2015.05.04. Live-time: 0 hours 4 min 32 s.



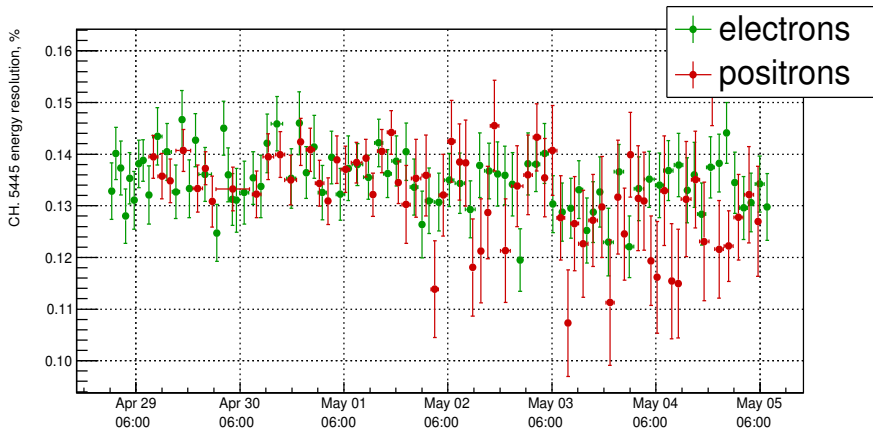
Energy equivalent of the MCA Channel №5445



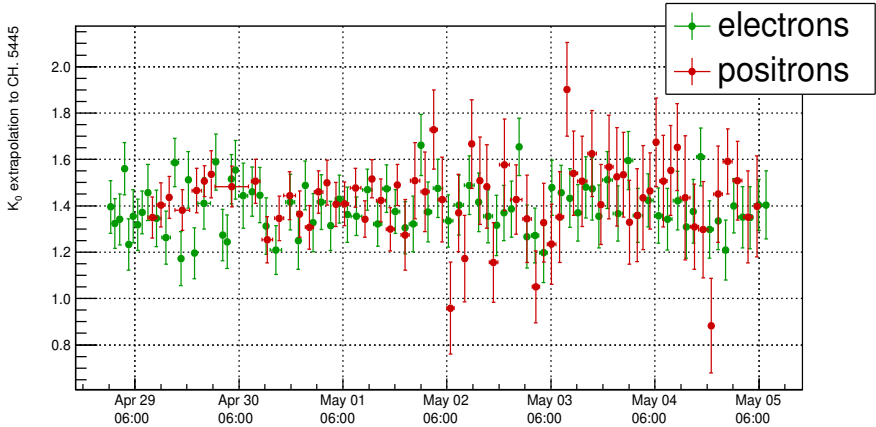
Scale correction (by pulser) for MCA Channel №5445



Energy resolution at 2000 keV



Peak shape parameter K_0 at 2000 keV



Conclusions about energy scale calibration

- Absolute energy scale is based on γ -quanta emitted by excited nuclei.
- During BEMS-2015 test ^{137}Cs and ^{60}Co γ -sources were used.
- With only three lines the statistical uncertainties for all calibration coefficients are rather large.
- The arbitrary uncertainty of scale calibration is at the level of 10^{-4} , it can be significantly reduced by adding 2614 keV line (^{208}Tl), as it was done before, during routine BEMS operation in 2010-2013.
- Unstable beam orbit leads to large background fluctuations.
This is the main reason of instabilities in the calibration procedure.
- Special care should be paid to satisfy BEMS requirements for beams orbits in the laser interaction area.

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Compton edge fitting

Add additional Gaussian spread σ_s to the peak-shape, which comes from electron beam energy spread ($x = \omega - \omega_{max}$, $\sigma_m \equiv K_0\sigma$, $K_1 = \infty$):

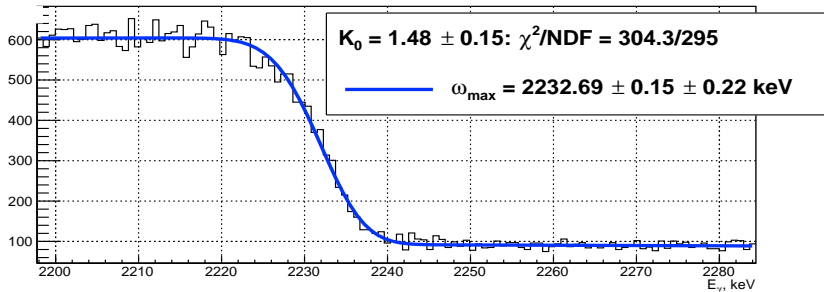
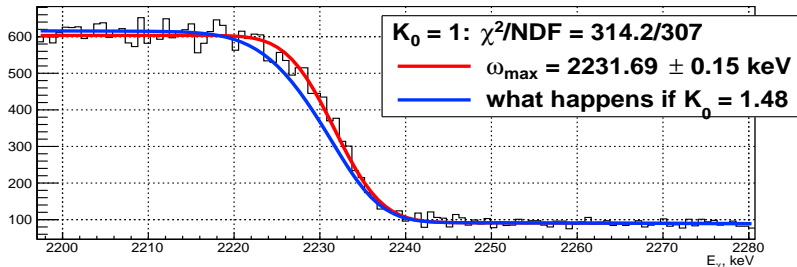
$$S(x) = \frac{1}{2\sqrt{2\pi}} \left\{ \frac{1}{\sqrt{\sigma^2 + \sigma_s^2}} \exp\left(\frac{-x^2}{2(\sigma^2 + \sigma_s^2)}\right) \operatorname{erfc}\left(\frac{-x\sigma}{\sigma_s\sqrt{2(\sigma^2 + \sigma_s^2)}}\right) + \frac{C}{\sigma} \operatorname{erfc}\left(\frac{x}{\sqrt{2}\sigma_s}\right) + \frac{(1-C)K_0}{\sqrt{\sigma_m^2 + \sigma_s^2}} \exp\left(\frac{-x^2}{2(\sigma_m^2 + \sigma_s^2)}\right) \operatorname{erfc}\left(\frac{x\sigma_m}{\sigma_s\sqrt{2(\sigma_m^2 + \sigma_s^2)}}\right) \right\}$$

The convolution to describe the edge of Compton spectrum:

$$E(\omega, \omega_{max}) = \int_{\omega}^{+\infty} S(\omega' - \omega_{max}) d\omega' + \text{Background}$$

Edge Fit

Electrons: 2015.05.01 [00:05:25 - 00:17:27] 2015.05.01. Live-time: 0 hours 7 min 32 s.



Copy of fitting output

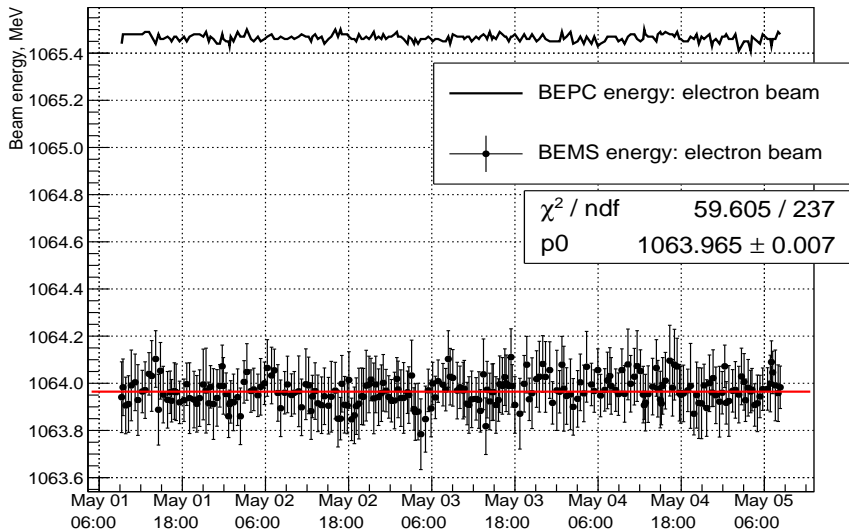
Simple Edge Fit:		
Range from 2126.8 to 2356.2 keV	E_beam = 1119.13 MeV	W_max = 2241.506 keV
Edge amplitude : 511.271 ± 5.3719	Edge slope: 0.078 ± 0.0812	Background level: 92.455 ± 1.7183
Edge wmax, keV: 2231.694 ± 0.1519	Background slope: -0.069 ± 0.0227	
Edge width, keV: 4.368 ± 0.1832		
$\chi^2/\text{NDF} = 314.2/307$		Probability: 0.376

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	Background level: 92.455 ± 0.0000
Edge amplitude : 502.029 ± 4.6094	Background slope: -0.069 ± 0.0000	Compton slope: -0.001 ± 0.0013
HPGe resol, keV: 2.764 ± 0.0000		
HPGe K0 : 1.478 ± 0.0000		
$\chi^2/\text{NDF} = 304.3/295$		Probability: 0.342

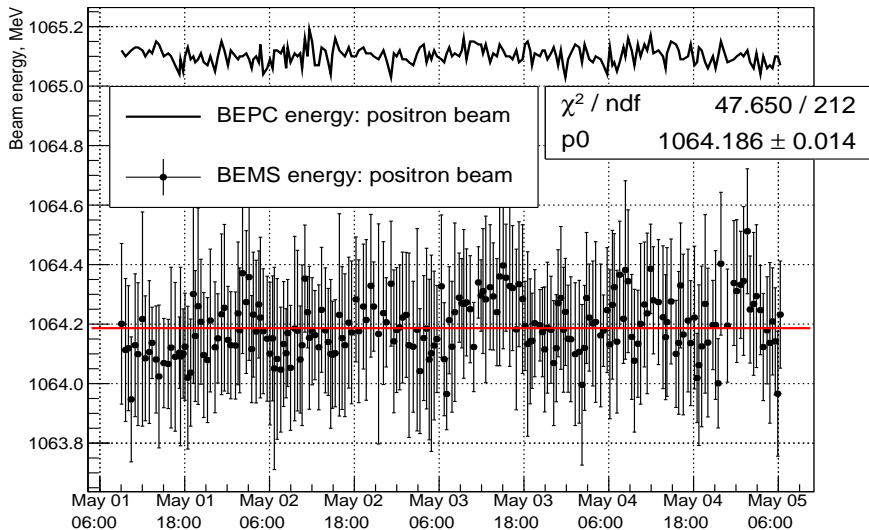
Wmax: 2231.69 ± 0.15 keV (symmetric fit)
Wmax: 2232.69 ± 0.26 keV (asymmetric fit)
Wmax: 2232.69 ± 0.32 keV (linear scale error)
Wmax: 2233.43 ± 0.32 keV (spline correction)

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

BEMS results: electron beam energy. $\Delta E^* \simeq 1.5$ MeV



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



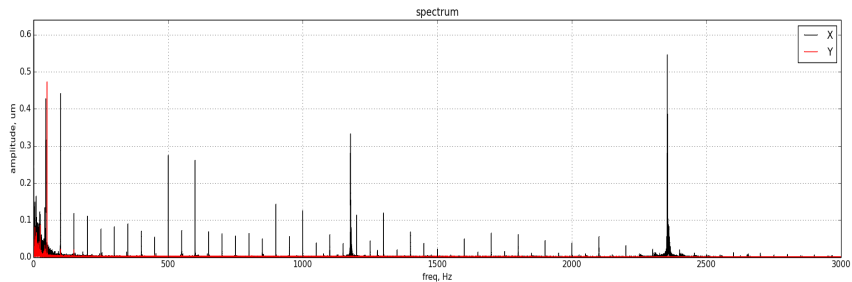
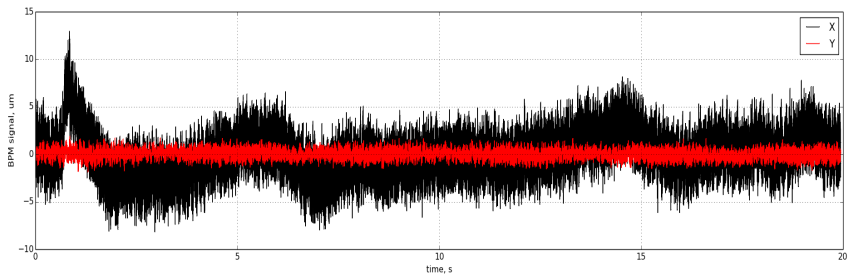
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Conclusion

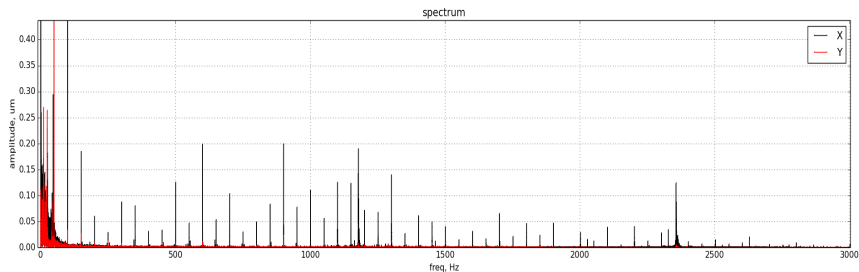
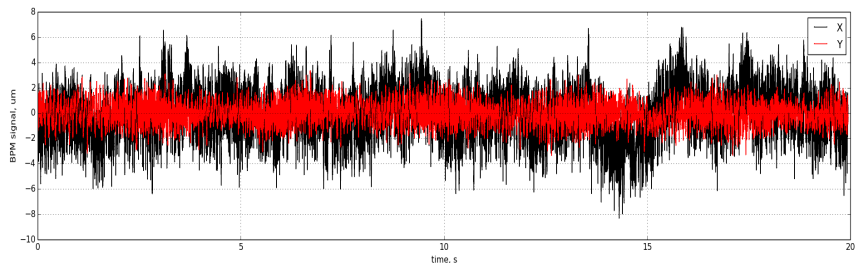
- BEMS is ready for new experiments.
- Whenever accurate beam energy determination is important in a particular experiment, the following steps should be performed:
 - Contact BEMS group for joint planning of experiment.
 - Contact BEPC team to provide special care on orbits at the North IP (even with possible luminosity loss).
 - Perform fast scans of J/ψ or (and) $\psi(2S)$ resonances for better understanding of systematic uncertainties.
 - Do offline study of BEMS data to check everything prior and along with BES-III data acquisition runs.
- Long-term BEMS operation without performing the above steps leads to rise of low quality data records. Analysis and understanding of such data becomes more difficult, resulting in increase of systematic errors.
- Our experience convinces that BEMS should not operate in cases when beam energy is not a matter of interest.

THANK YOU!

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.