束流能量测量系统(BEMS)的原理与实现

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第10届BESIIIR值与QCD强子结构研讨会
乌鲁木齐
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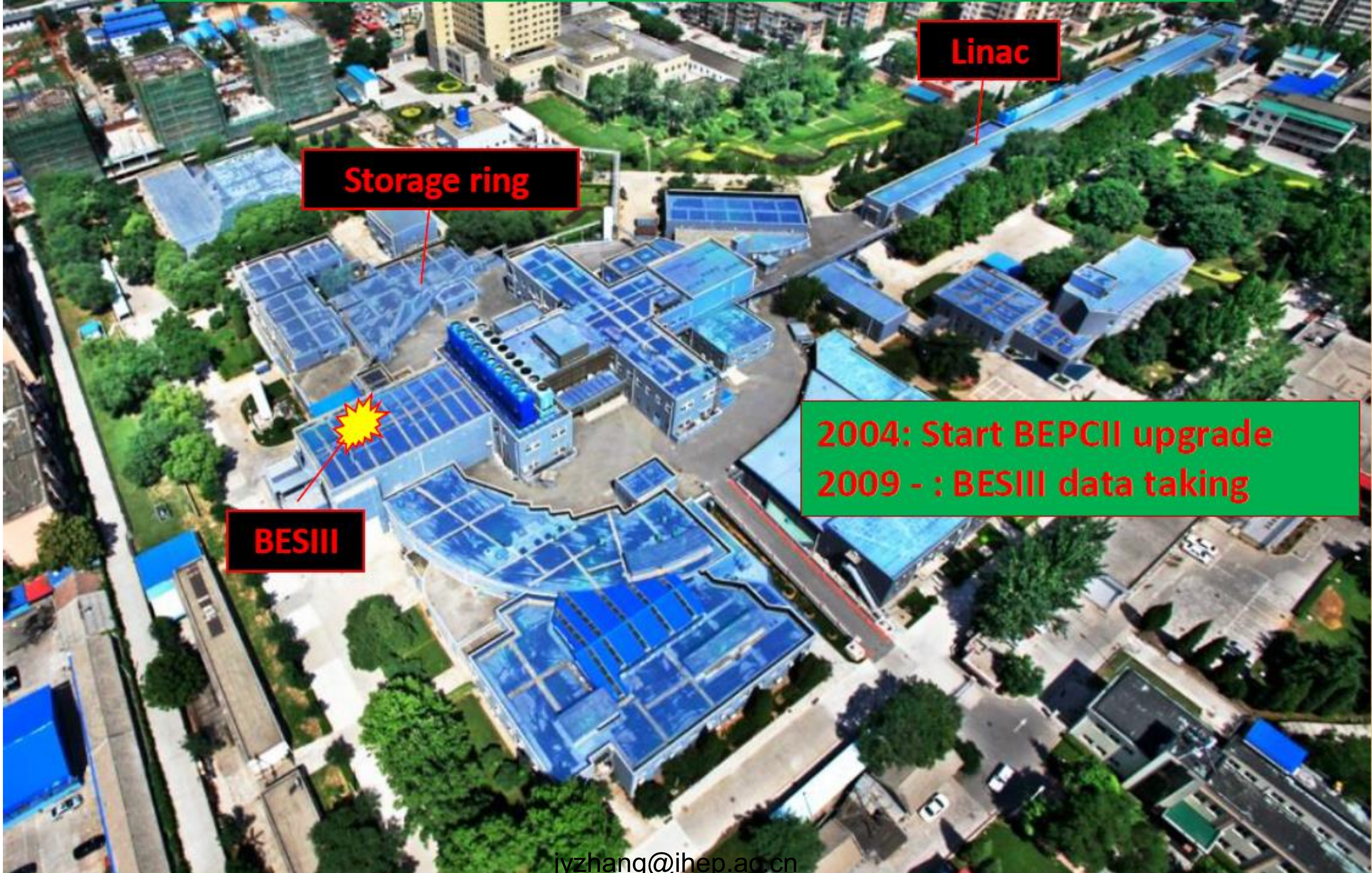
主要内容

- BEMS简介
- BEMS的工作原理
- BEMS的实现
- BEMS的测量结果
- 小结

Beijing Electron Positron Collider (II)



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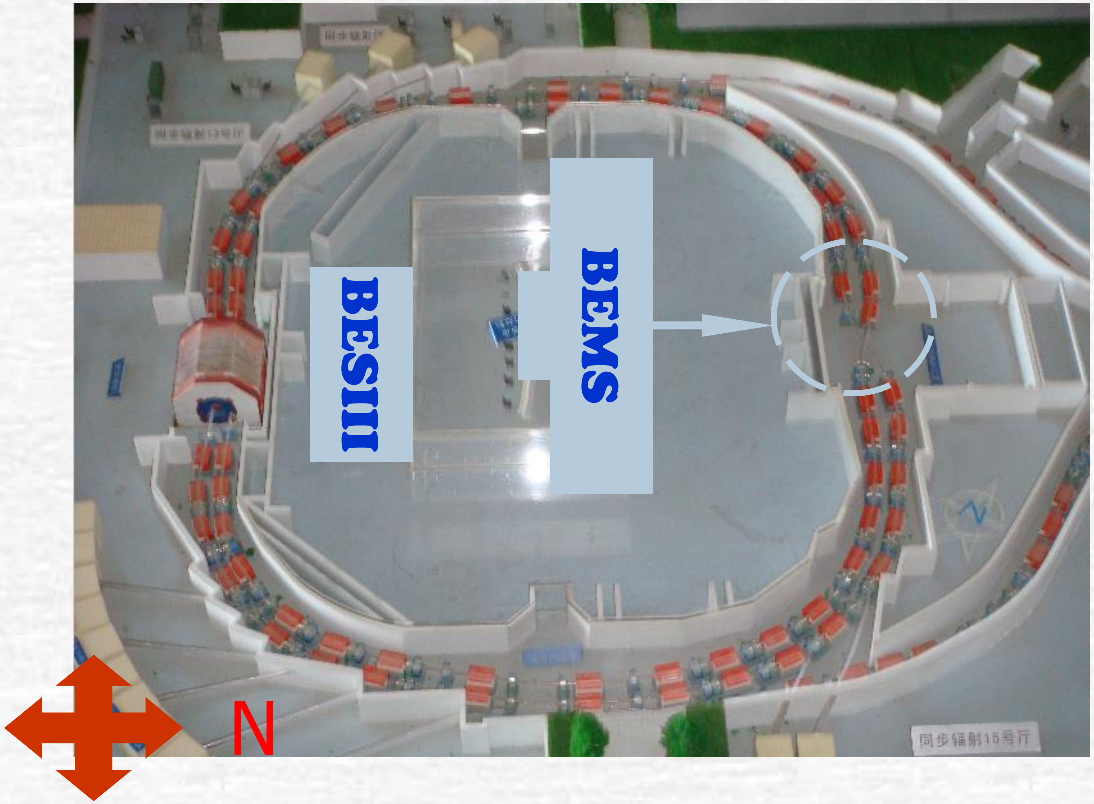
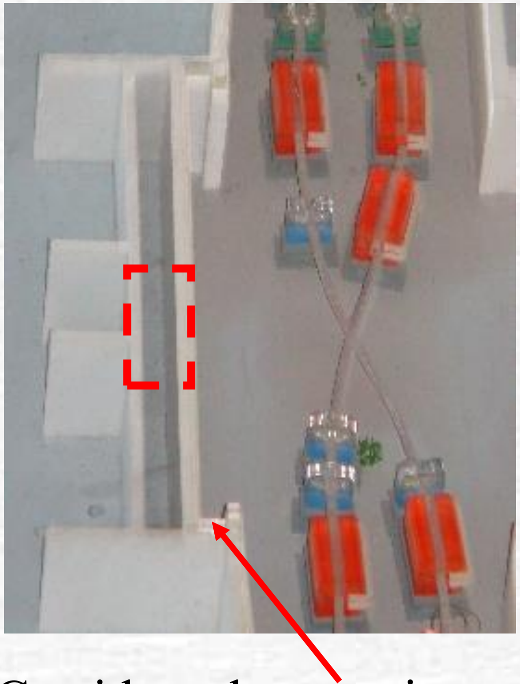
BEMS位置





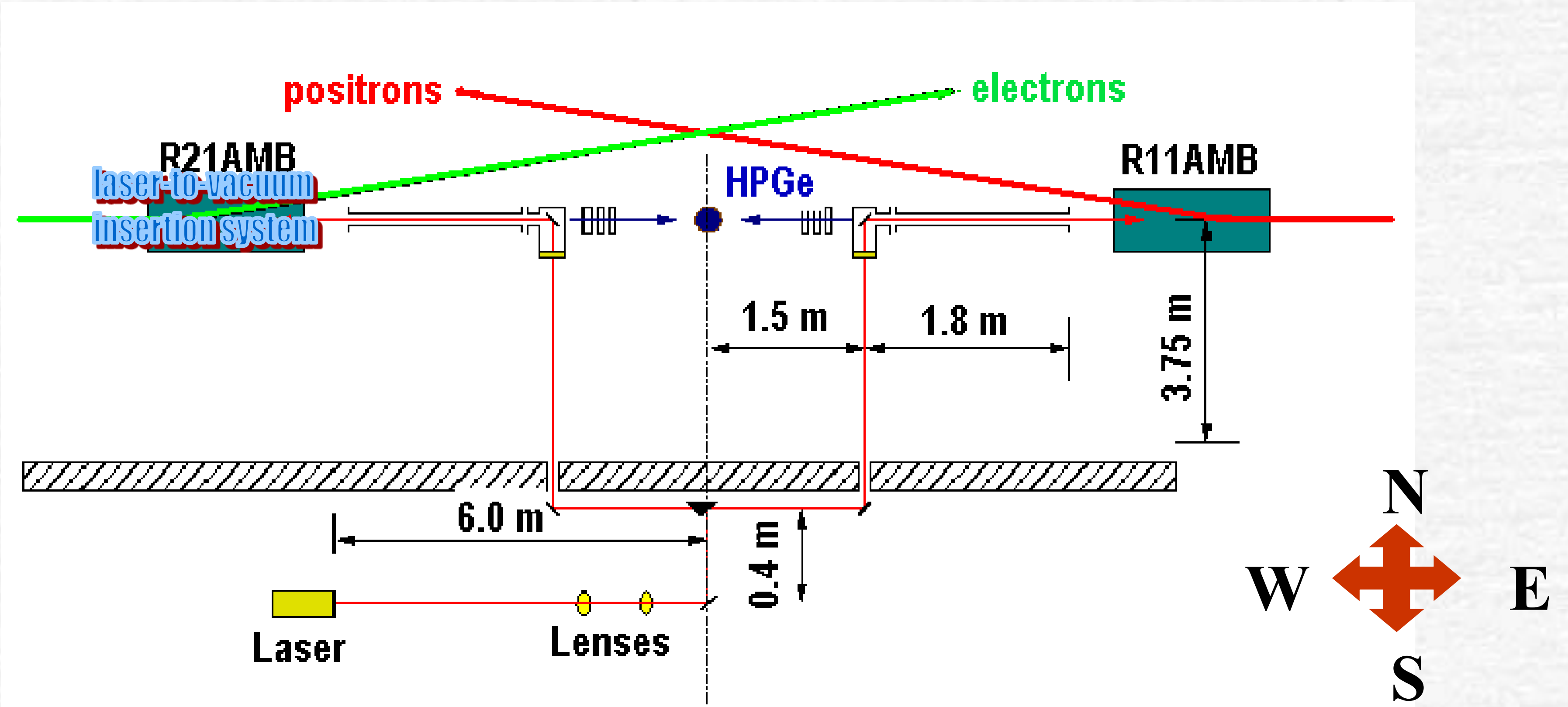
Corridor where optics system is located

The BEMS locates at the north crossing point SR of BEPCII.

BEMS简介

- 精确测量束流能量对加速器和北京谱仪都有重要的意义
- 对于共振态质量测量，特别是Tau 轻子的质量测量来说，能量不确定度是改善其测量精度的瓶颈
- 目标：相对精度 5×10^{-5}

BEMS示意图



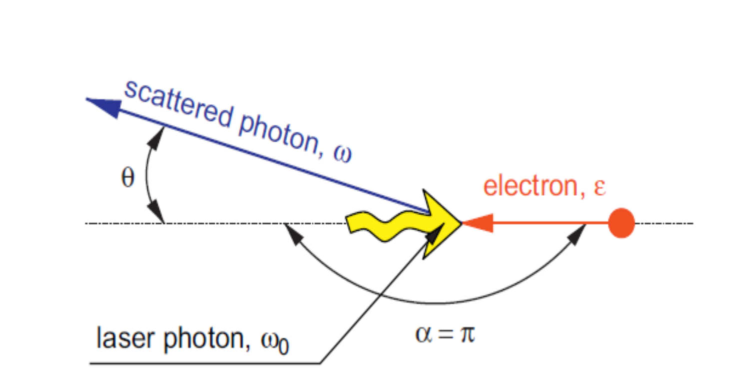
Laser and optics system

Laser to beam interaction system

HPGe detection system

Data acquisition system

BEMS工作原理：康普顿散射



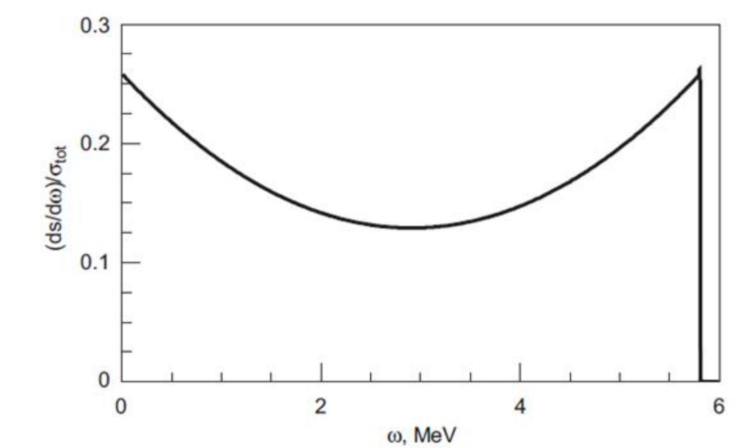


Fig. 3. Energy spectrum of scattered Compton photons. The initial electron and photon energies are $\omega_0 = 0.12$ eV and $\varepsilon = 1770$ MeV, respectively, and $\alpha = \pi$.

散射光子的能量：

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

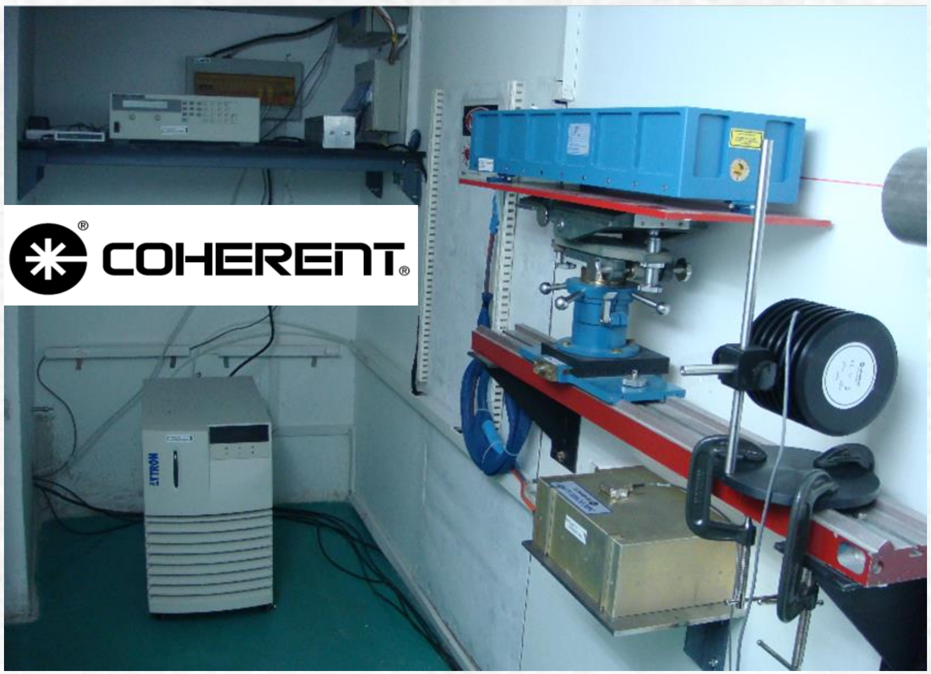
康普顿背散射时：

$$\omega_{max} = \frac{\varepsilon^2}{\varepsilon + m_e^2/4\omega_0^2},$$

反解出束流能量：

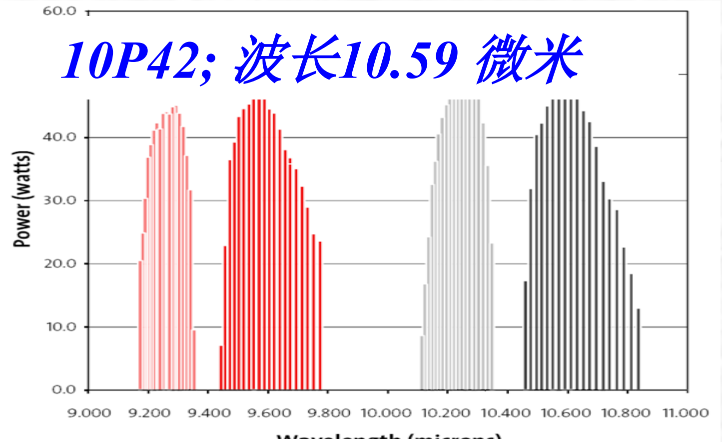
$$\varepsilon = \frac{\omega_{max}}{2}\left[1 + \sqrt{1 + \frac{m_e^2}{\omega_0\omega_{max}}}\right].$$

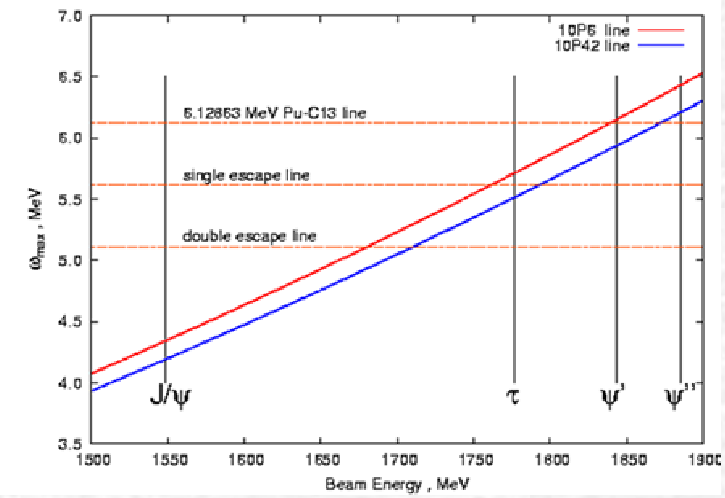
BEMS的实现-激光器



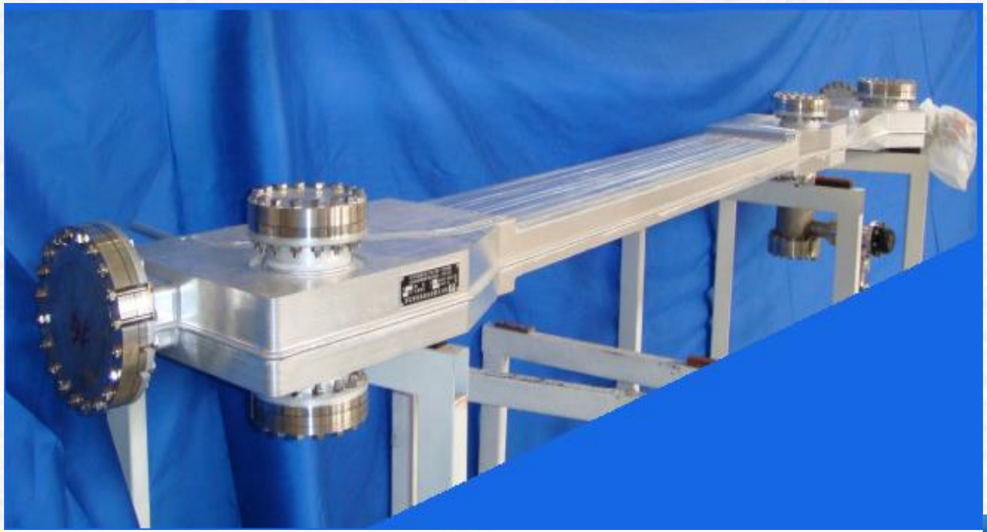
GEM-select50 型二氧化碳激光器

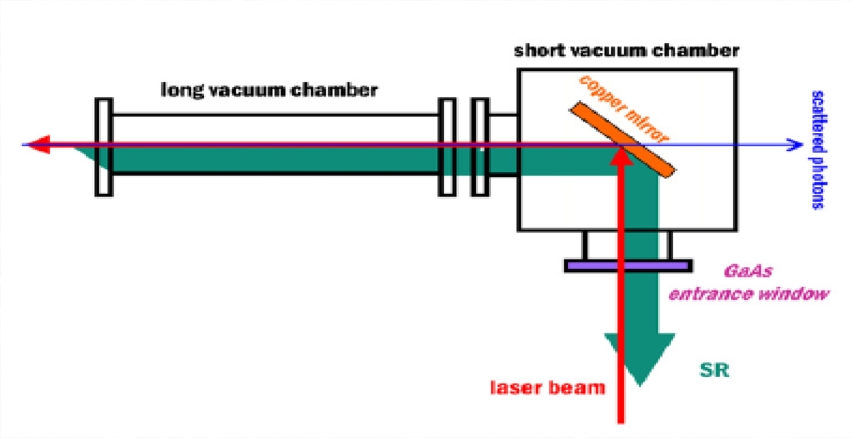
功率：45W，能量：0.12 eV

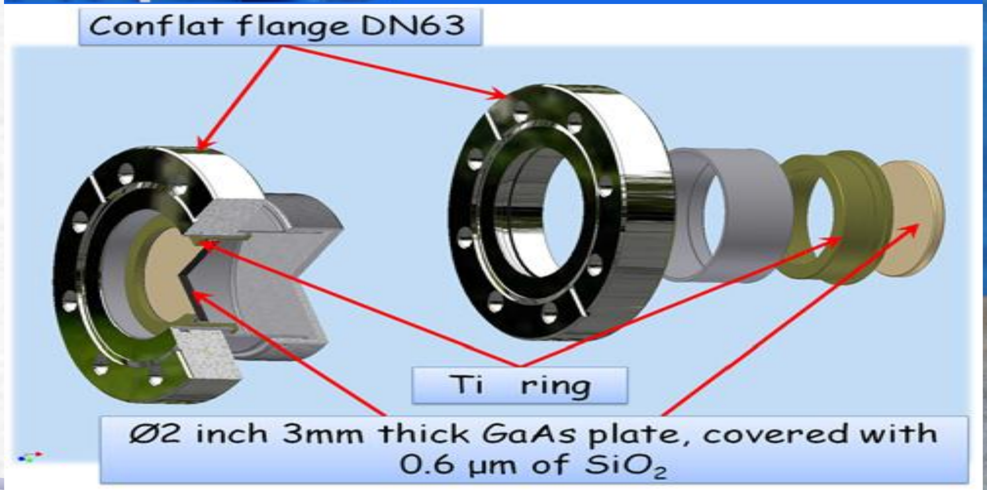




BEMS的实现-真空部分

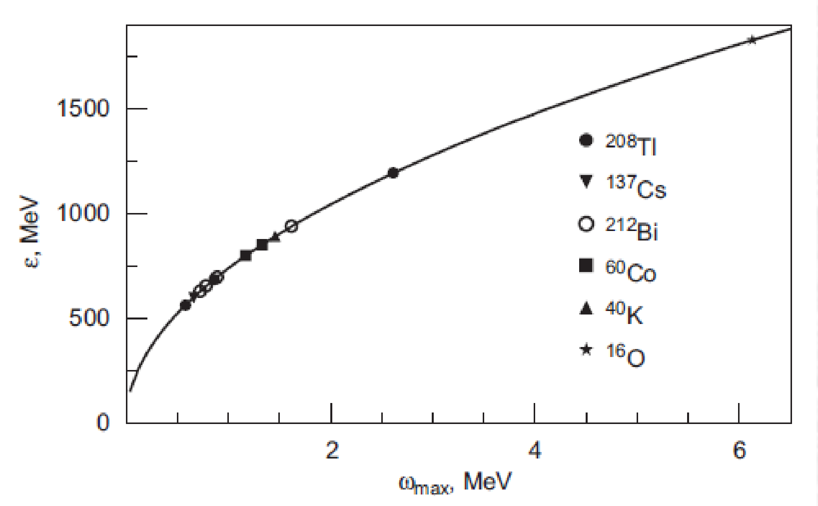






BEMS的实现-高纯锗探测器

ORTEC P型，
晶体尺寸：直径 57.8, 长 52.7 毫米
相对效率：25%
分辨率：1.74 keV （^{60}Co 1.33MeV)
配备了Dspec-pro



laser-to-vacuum insertion part

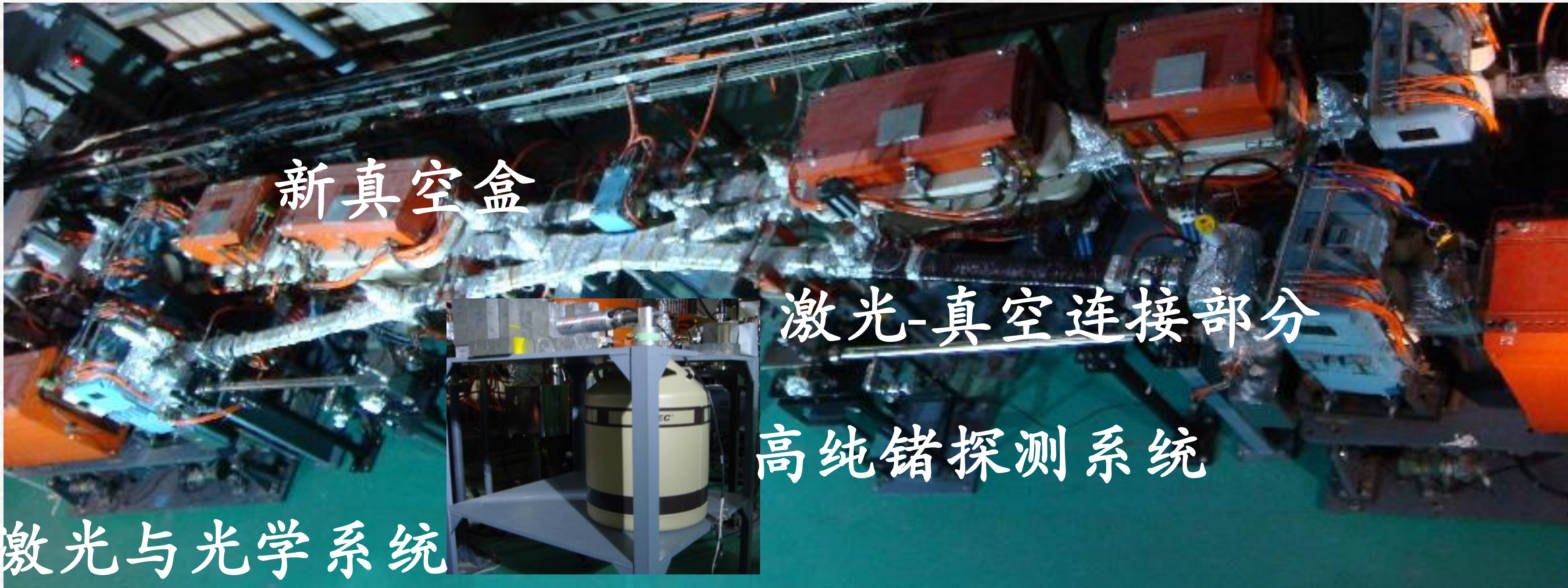
chamber installation

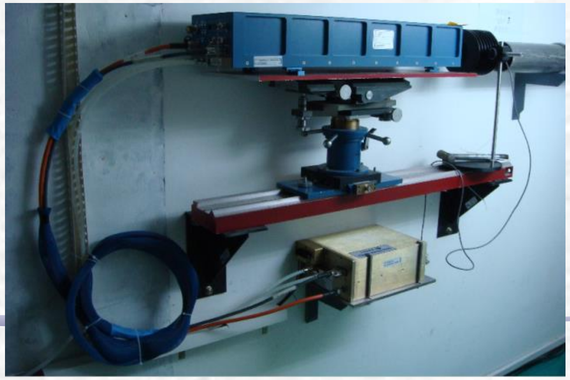
Pump Installation

Alignment

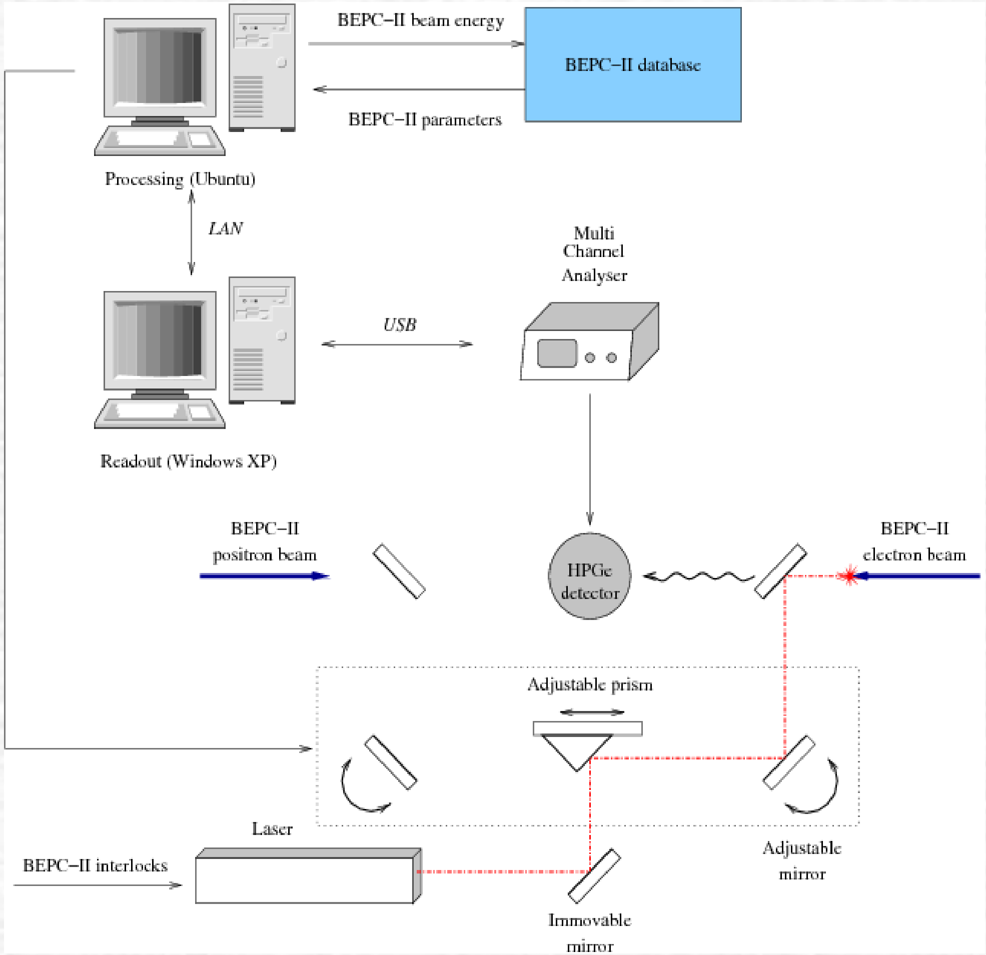
Backing, vacuum up to 2.0×10^{-10} torr

BEMS总装图





BEMS数据获取系统

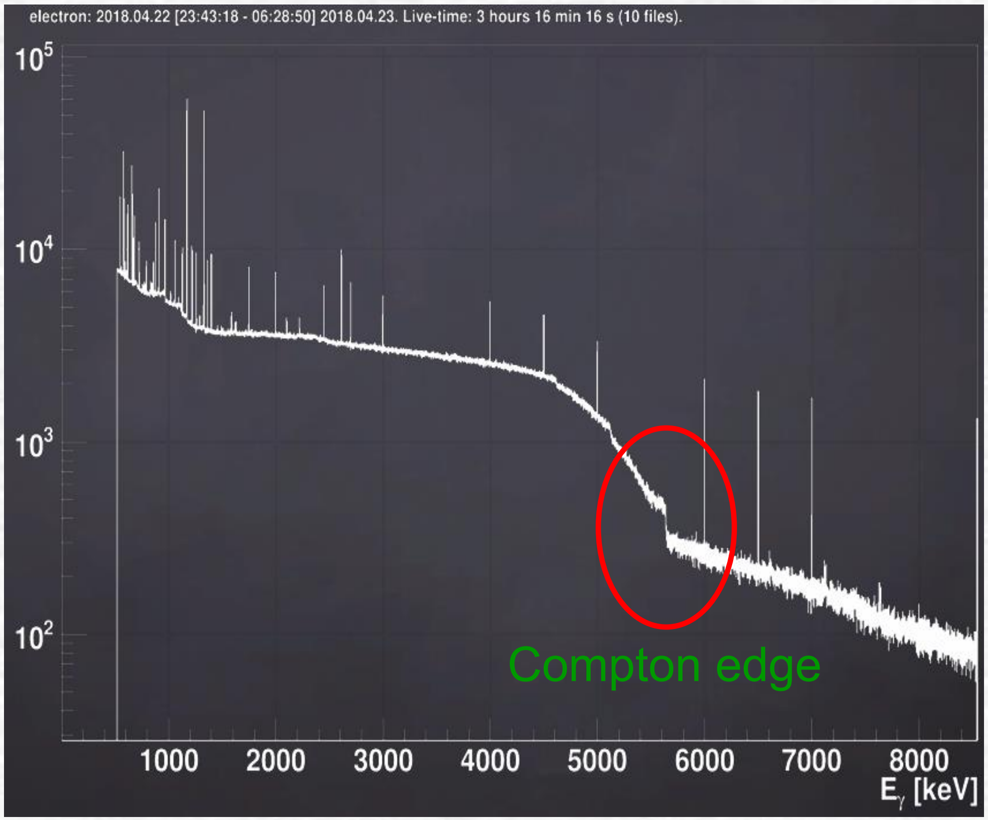


Multi-channel analyser digitises the signal from HPGe and converts it to spectrum. It is connected to PC under control of Windows XP

Spectra processing, monitoring, control over devices (mirrors, movable prism and protection) and exchange with BEPC-II database are concentrated in PC under Ubuntu Linux

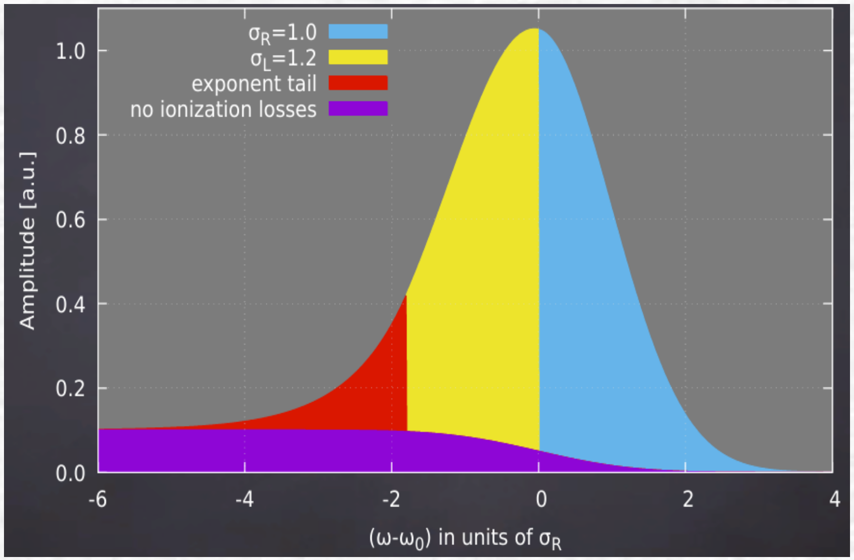
The process of the beams energy measurement is fully automated

能谱与刻度



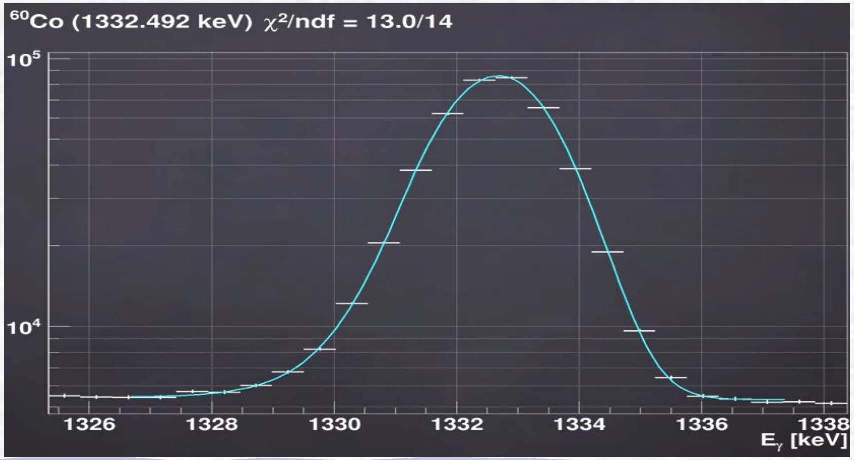
Source	γ-rays energies, keV	Reference *
^{137}Cs	661.657 ± 0.003	vol.4, 2008
^{60}Co	1173.228 ± 0.003 1332.492 ± 0.004	vol.4, 2008
^{228}Ac (^{232}Th)	911.209 ± 0.006	vol.6, 2011
^{212}Bi (^{232}Th)	727.330 ± 0.030 1620.740 ± 0.010	vol.2, 2004
^{208}Tl (^{232}Th)	583.187 ± 0.002 860.560 ± 0.030 2614.511 ± 0.010	vol.2, 2004

探测器刻度

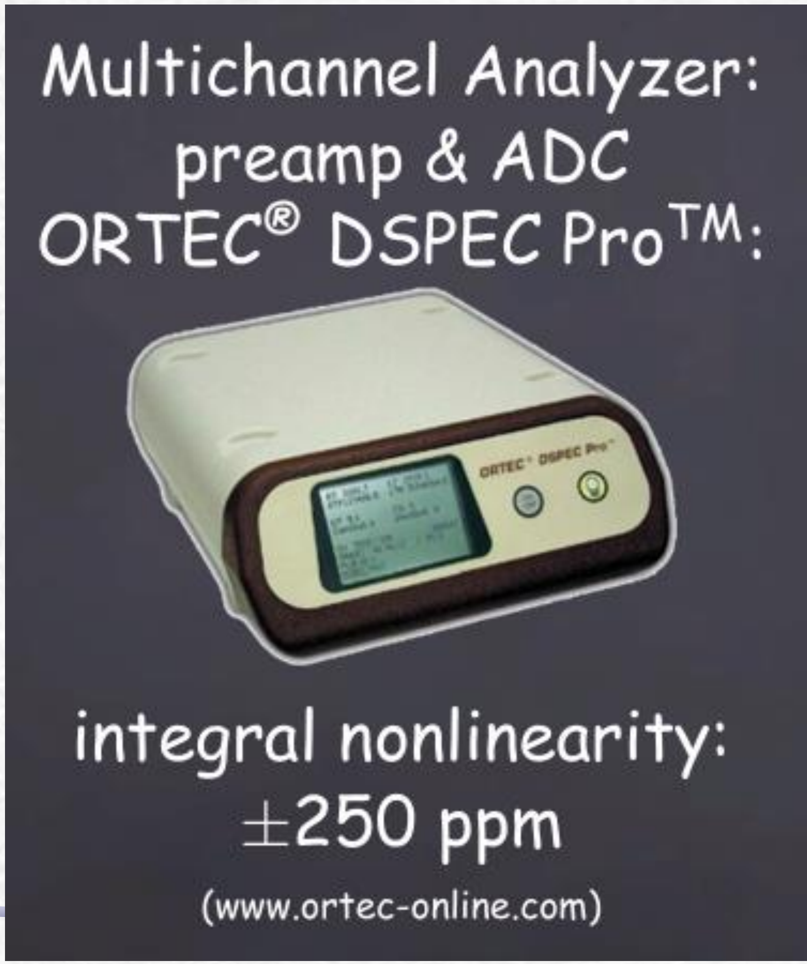


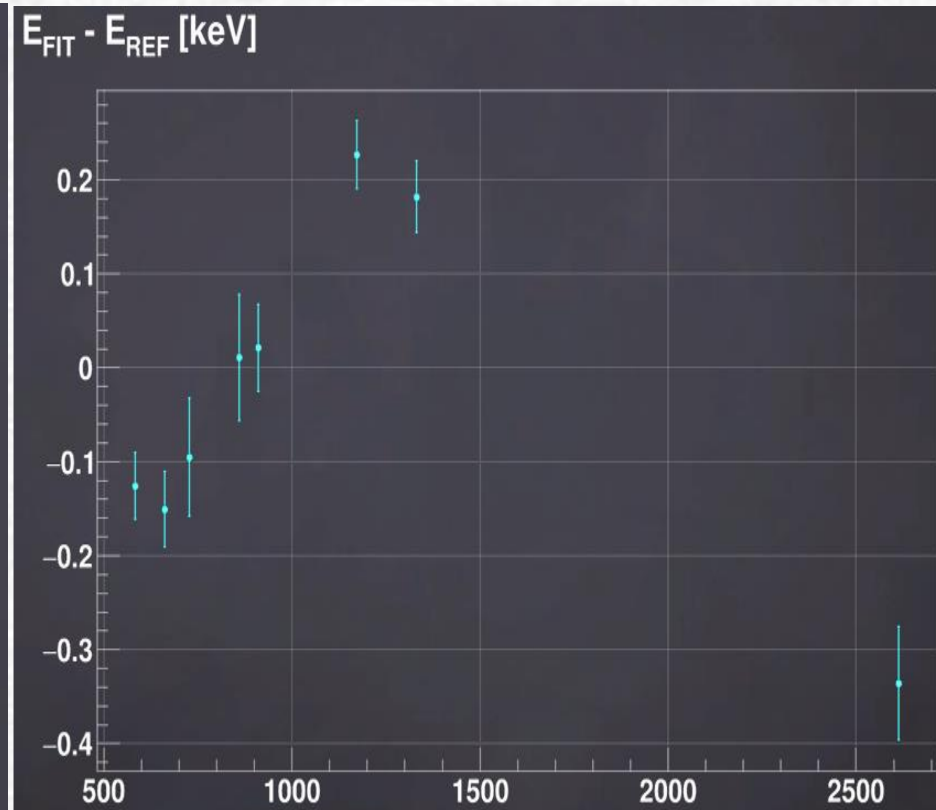
$$f(x) = B + \frac{C}{2}\mathrm{erfc}\left(\frac{x}{\sqrt{2}\sigma_R}\right) + \frac{N}{N_1}\begin{cases} \exp\left(-\frac{x^2}{2\sigma_R^2}\right) & \text{if } x > 0; \\ \exp\left(-\frac{x^2}{2\sigma_L^2}\right) & \text{if } -\kappa\sigma_L < x \le 0; \\ \exp\left(\frac{\kappa x}{\sigma_L} + \frac{\kappa^2}{2}\right) & \text{if } x \le -\kappa\sigma_L \end{cases}$$

- 寻找并鉴别特征峰
- 通过响应函数与本底拟合特征峰
- 通过产生数据，获得MCA非线性特性
- 利用放射源，确定响应函数参数的能量依赖性



探测器刻度

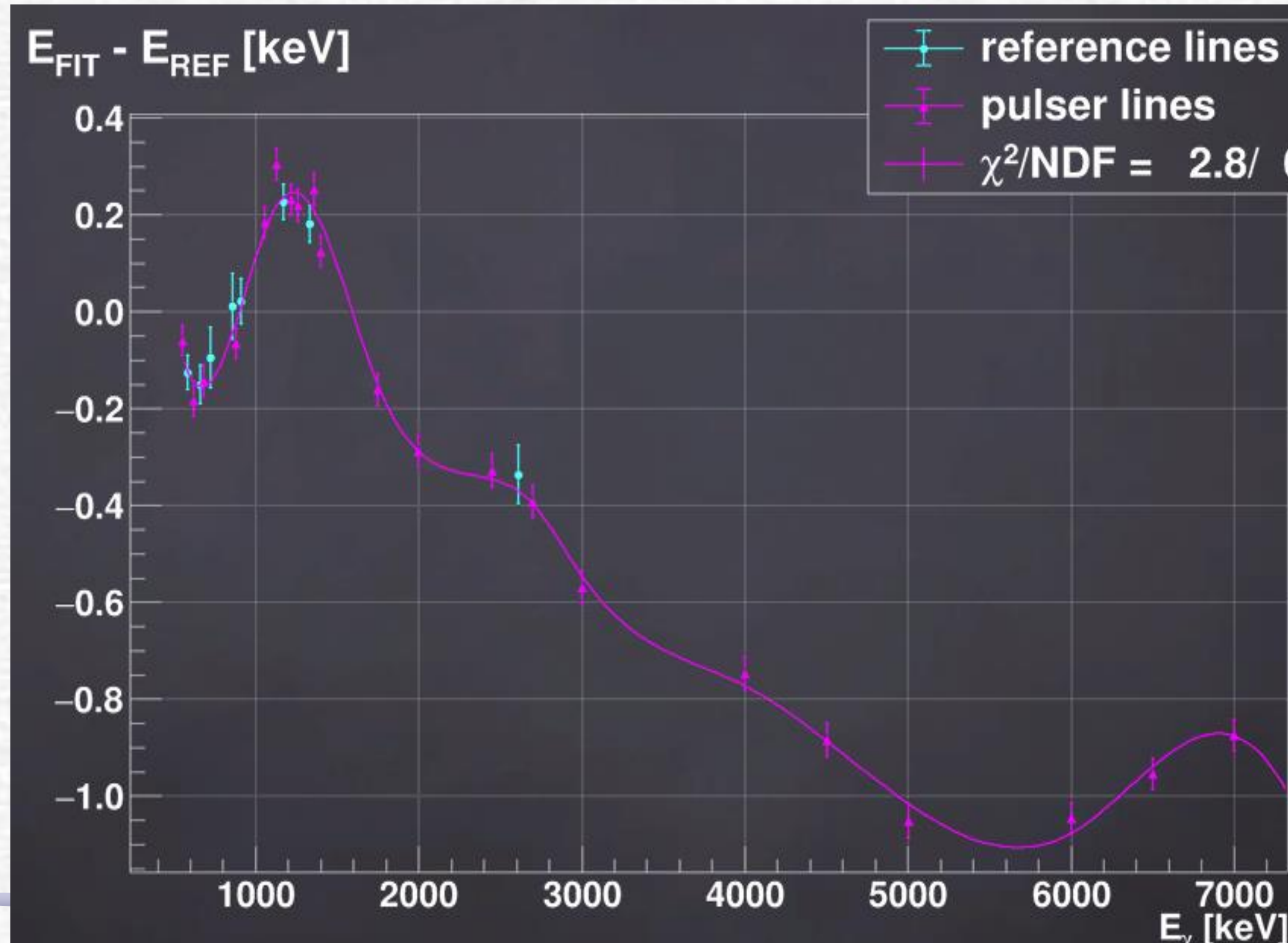




Syst. error is: $\frac{|\Delta E_\gamma|}{E_\gamma} \simeq \frac{1\ \text{keV}}{6000\ \text{keV}} \simeq 200\ \text{ppm}$

探测器刻度


Precision Pulse Generator (PPG)
Berkeley Nucleonics Corp PB-5
BNC
MODEL PB-5
PULSE GENERATOR
PUSH TO SELECT
EXT TRIG
TRIG OUT
PULSE OUT
BERKELEY NUCLEONICS CORP.
amplitude nonlinearity
±15 ppm
(www.berkeleynucleonics.com)


E_{FIT} - E_{REF} [keV]
reference lines
pulser lines
χ^2/NDF = 2.8/ 6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
1000
2000
3000
4000
5000
6000
7000
E_γ [keV]

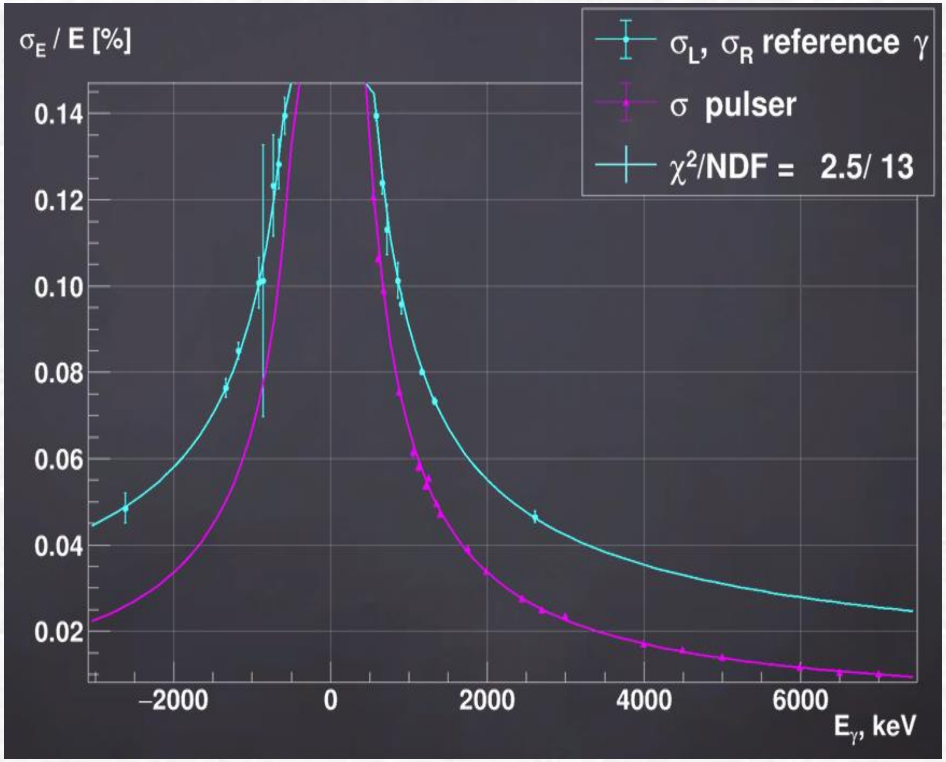
探测器的能量分辨

Combined fit for σ_R and σ_L dependence on E_γ:

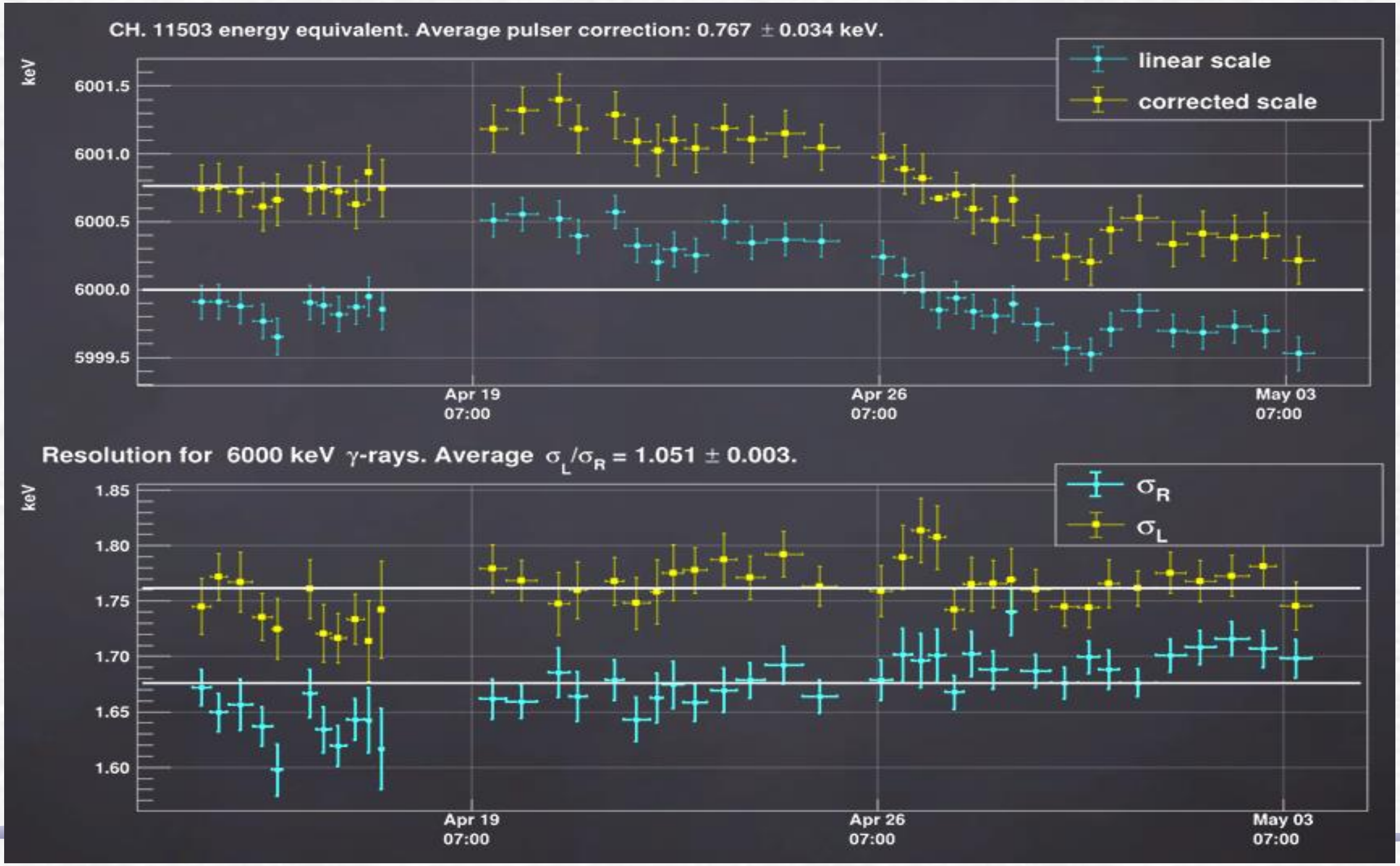
$$\sigma_R = \sqrt{p_0^2 + \epsilon f_R E_\gamma}$$

$$\sigma_L = \sqrt{p_0^2 + \epsilon f_L E_\gamma}$$

- σ_R and σ_L are in [keV],
- p_0 is the noise impact to the resolution,
- ϵ =2.96 eV is the e-hole pair creation energy in Ge,
- f_R, f_L - dimensionless parameters (Fano factor).



探测器的刻度与能量分辨

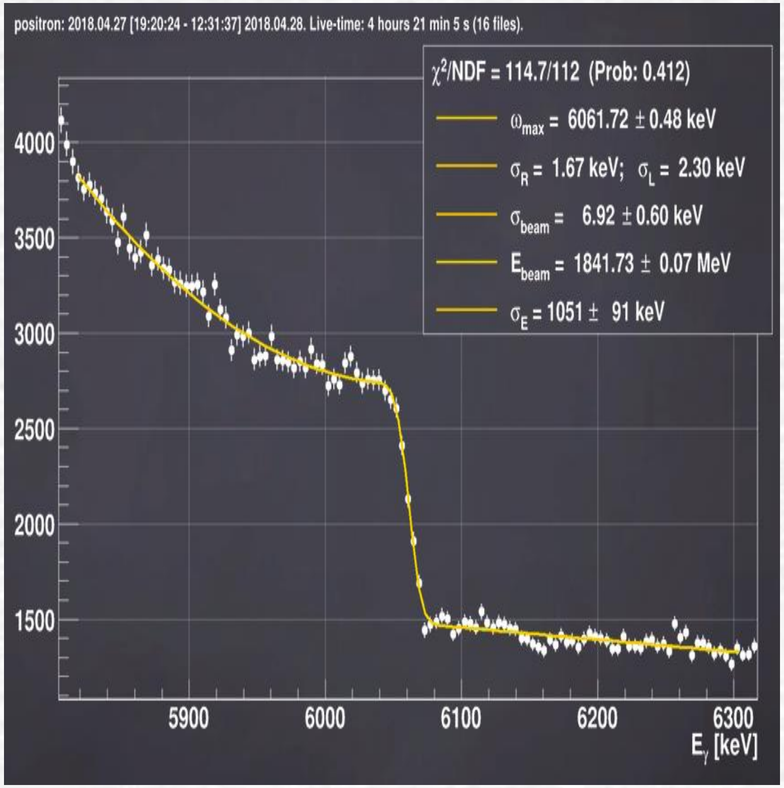


数据处理-康普顿edge拟合

The edge of backscattered photons spectrum is fitted by the function, which tacks into account:

- the “pure” edge shape,
- detector's response function,
- energy spread of backscattered photons due to the energy distribution of the collider beam

The edge position $\boldsymbol{\omega_{max}}$ and the Compton photons energy spread $\boldsymbol{\sigma_{\omega}}$ are obtained from the fit.



The average beam energy in the north interaction point is calculated as:

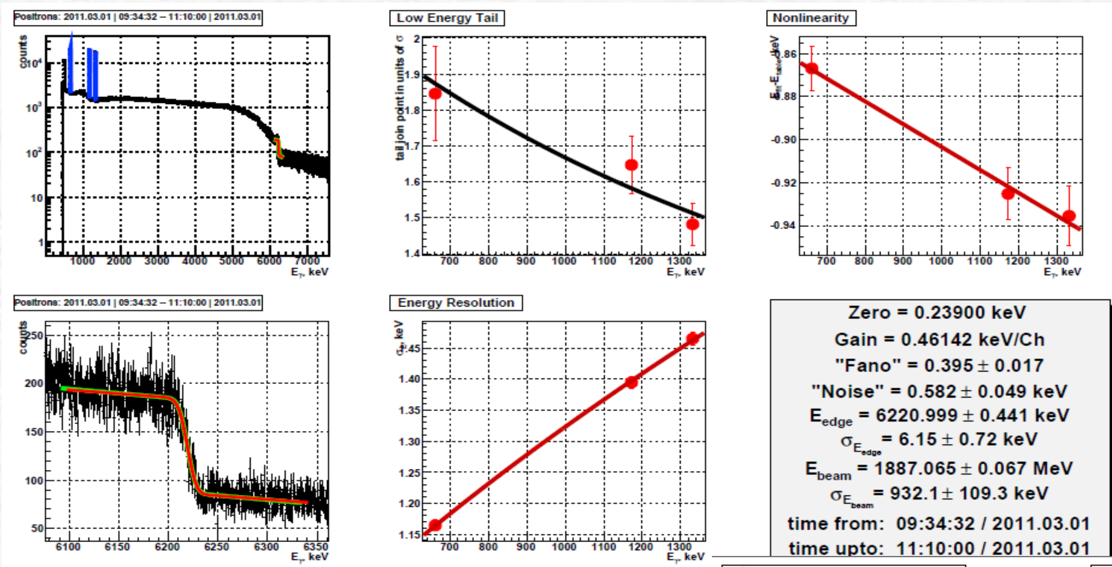
$$\varepsilon_{nip} = \frac{\omega_{max}}{2}\left(1+\sqrt{1+\frac{m_e^2}{\omega_{max}\,\omega_0}}\right)$$

Tacking into account the energy losses due to SR:

$$\varepsilon_{sip}(MeV) = \varepsilon_{nip}(MeV) + 4.75\cdot 10^{-3} \times (0.001\cdot \varepsilon_{nip}(MeV))^4$$

Beam energy in the south interaction point

BEMS测量结果-验收



正电子

测量的相对误差

实测结果: 3.55×10^{-5}

设计指标: 5×10^{-5}

E_{edge} = 6220.999 ± 0.441 keV

$\sigma_{E_{edge}}$ = 6.15 ± 0.72 keV

E_{beam} = 1887.065 ± 0.067 MeV

$\sigma_{E_{beam}}$ = 932.1 ± 109.3 keV

负电子

测量的相对误差

实测结果: 4.29×10^{-5}

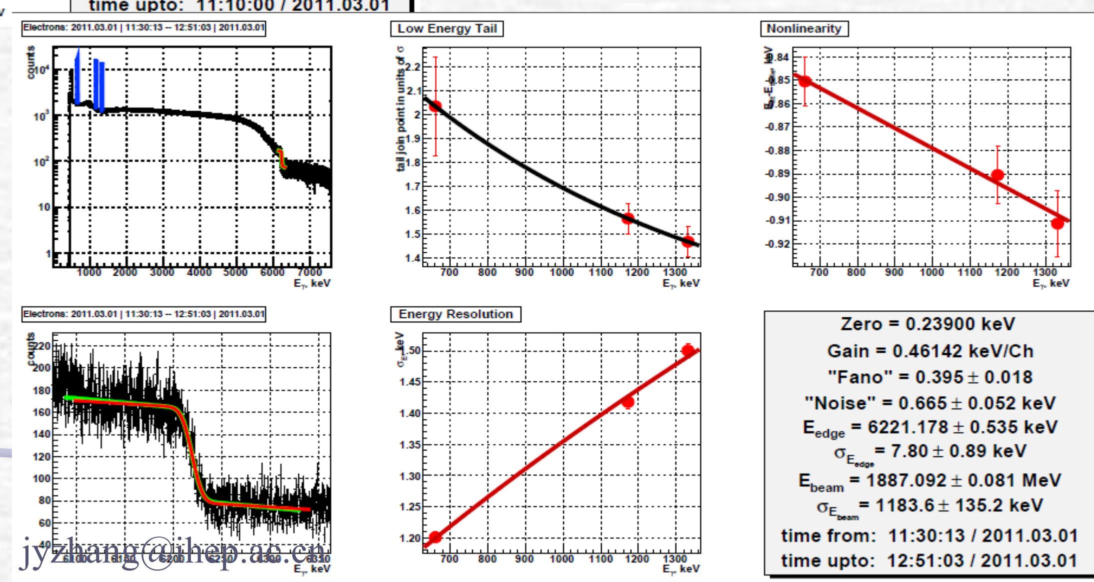
设计指标: 5×10^{-5}

E_{edge} = 6221.178 ± 0.535 keV

$\sigma_{E_{edge}}$ = 7.80 ± 0.89 keV

E_{beam} = 1887.092 ± 0.081 MeV

$\sigma_{E_{beam}}$ = 1183.6 ± 135.2 keV



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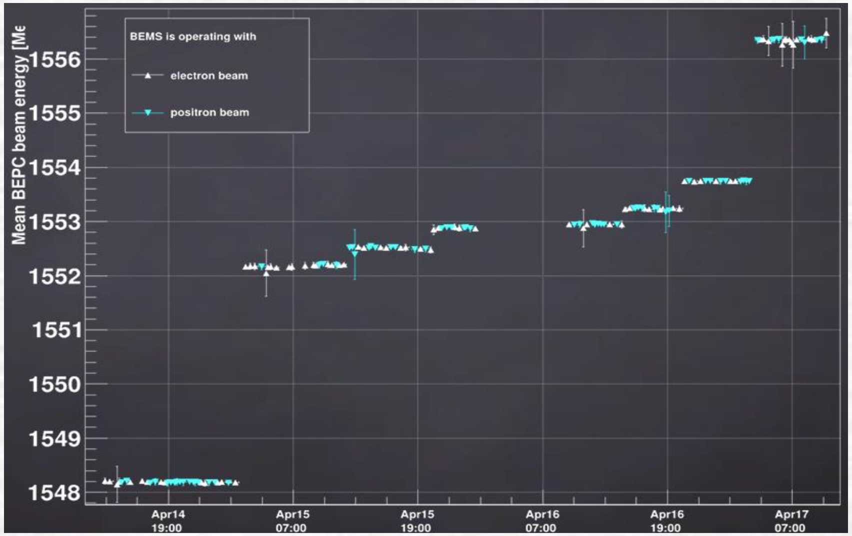
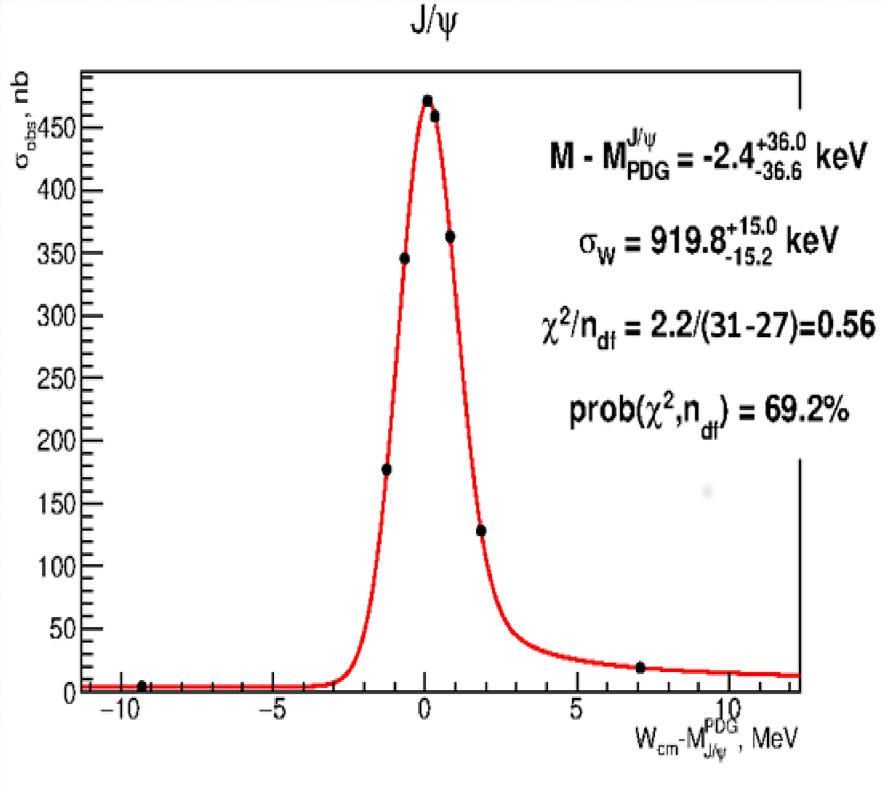
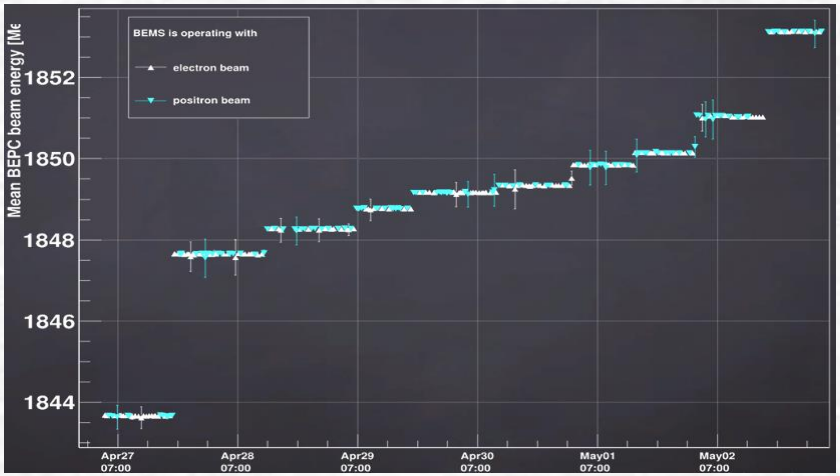
J/Ψ扫描



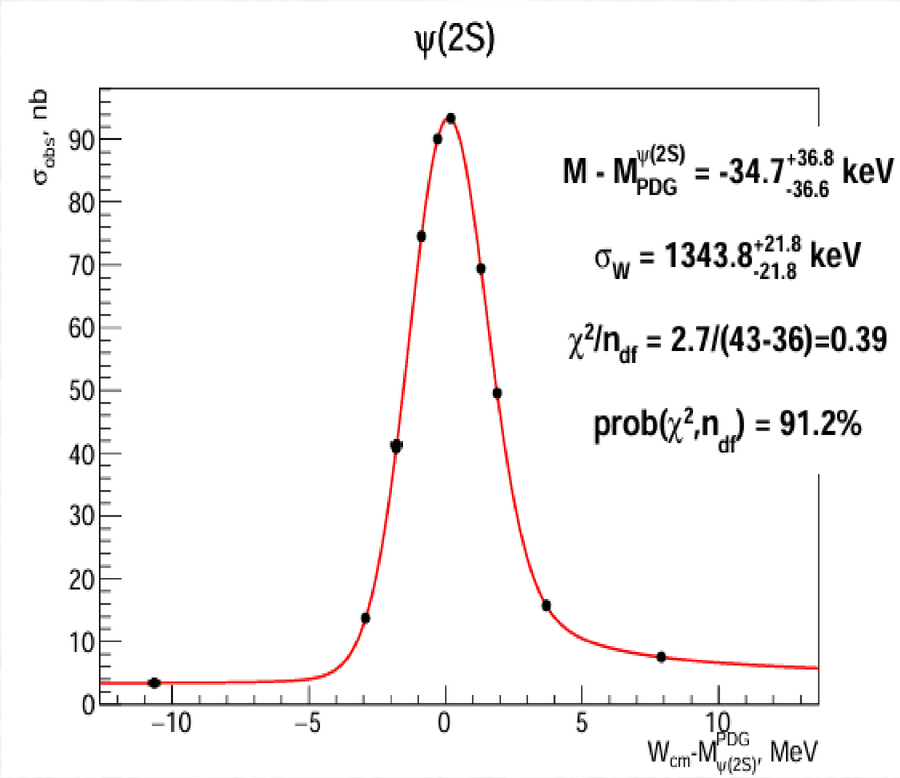
point	W^{BEMS}, MeV	L^{online}, pb^{-1}	BES3 runs
1	3087.593 ± 0.125	2.46390	55060–55065
2	3095.726 ± 0.077	3.02796	55066–55073
3	3096.203 ± 0.069	5.22500	55074, 55079–55083
4	3096.986 ± 0.083	3.18454	55084–55088
5	3097.226 ± 0.099	1.76280	55089–55091
6	3097.654 ± 0.082	4.78633	55092–55097
7	3098.728 ± 0.078	5.61725	55098–55103
8	3104.000 ± 0.082	5.71792	55104–55109



Ψ(2S)扫描



point	W^{BEMS}, MeV	L^{online}, pb^{-1}	BES3 runs
1	3675.442 ± 0.191	5.17638	55258–55263
2	3683.193 ± 0.096	15.60458	55264–55276
4	3684.193 ± 0.115	2.18118	55286, 55288
3	3684.393 ± 0.201	3.30610	55278–55285
5	3685.306 ± 0.101	4.62110	55289–55294
6	3685.833 ± 0.095	7.38168	55295–55308
7	3686.302 ± 0.096	6.12081	55309–55318
8	3687.305 ± 0.101	5.13150	55319–55325
9	3687.993 ± 0.096	5.08032	55326–55332
10	3689.773 ± 0.098	5.97002	55333–55339
11	3694.027 ± 0.098	5.03245	55340–55346

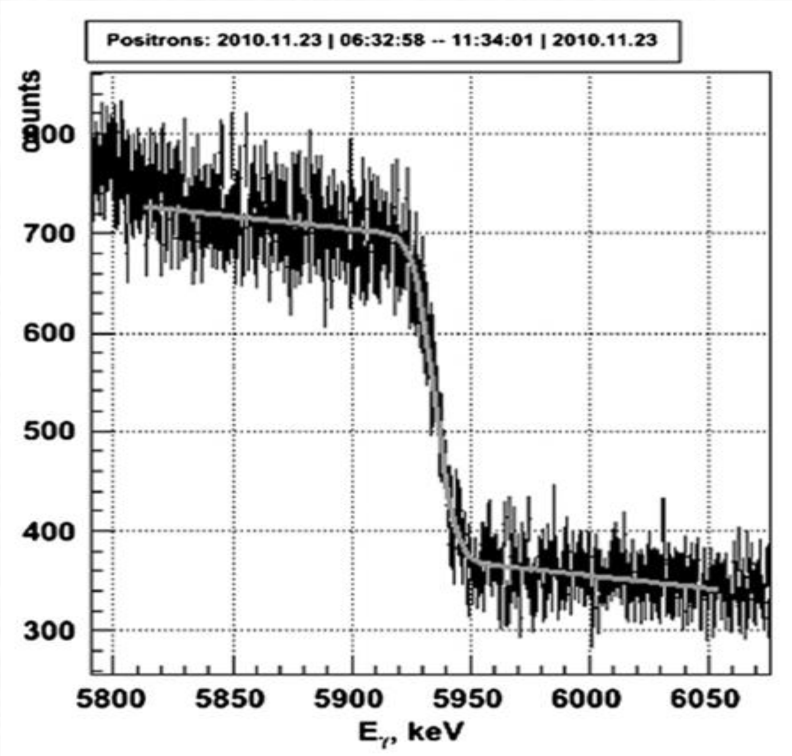


小结

- 利用康普顿背散射原理在BEPCII上研制了束流能量测量系统
- BEMS测试结果好于设计指标
- 束流能量的精度约为20 keV

谢谢！

BEMS工作原理：康普顿散射（II）



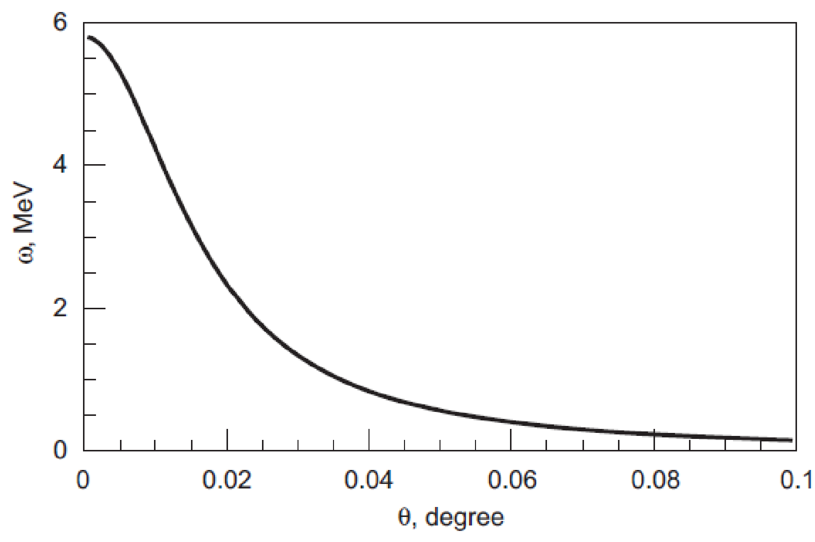


Fig. 2. The dependence of the scattered photon energy ω on the angle θ between the initial electron and the final photon in the Compton scattering process. The initial electron and photon energies are $\omega_0 = 0.12$ eV and $\varepsilon = 1770$ MeV, respectively, and $\alpha = \pi$.

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

p_0：edge位置，p_1：edge宽度，

P_2：edge幅度，p_3：本底，

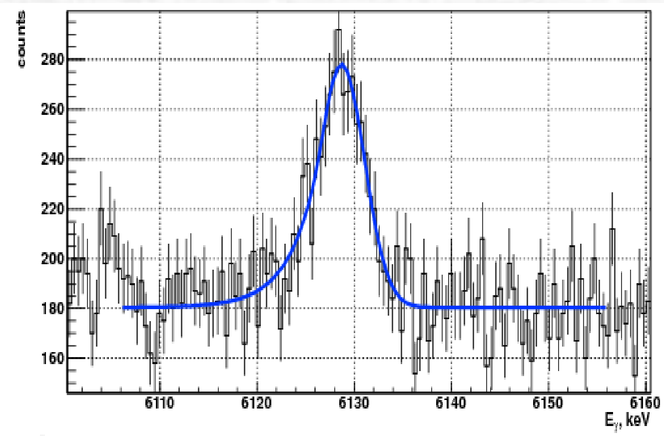
$P_{4,\ 5}$：edge左，右的斜率

数据处理-高纯锗刻度

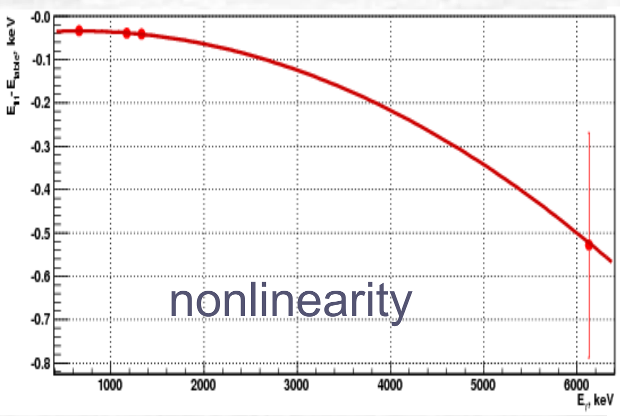
1) The peaks searching and identification

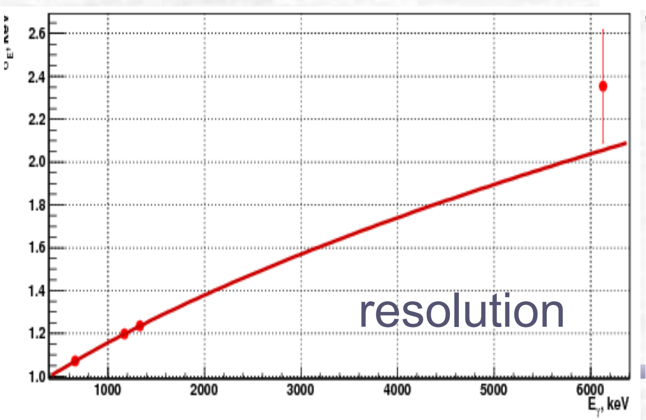
2) Peaks which correspond to calibration lines are fitted by response function:

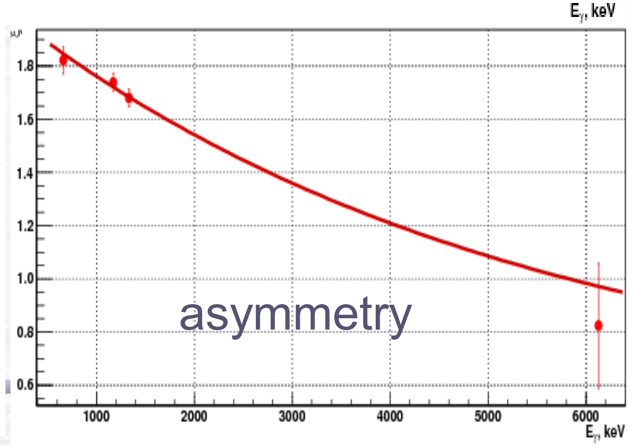
$$f(x, x_0, \sigma, \xi) = \frac{N}{\sqrt{2\pi}\sigma} \begin{cases} \exp\left\{-\frac{(x-x_0)^2}{2\sigma^2}\right\}, x > x_0 - \xi\sigma \\ \exp\left\{\frac{\xi^2}{2} + \frac{(x-x_0)^2}{2\sigma^2}\right\}, x < x_0 - \xi\sigma \end{cases}$$

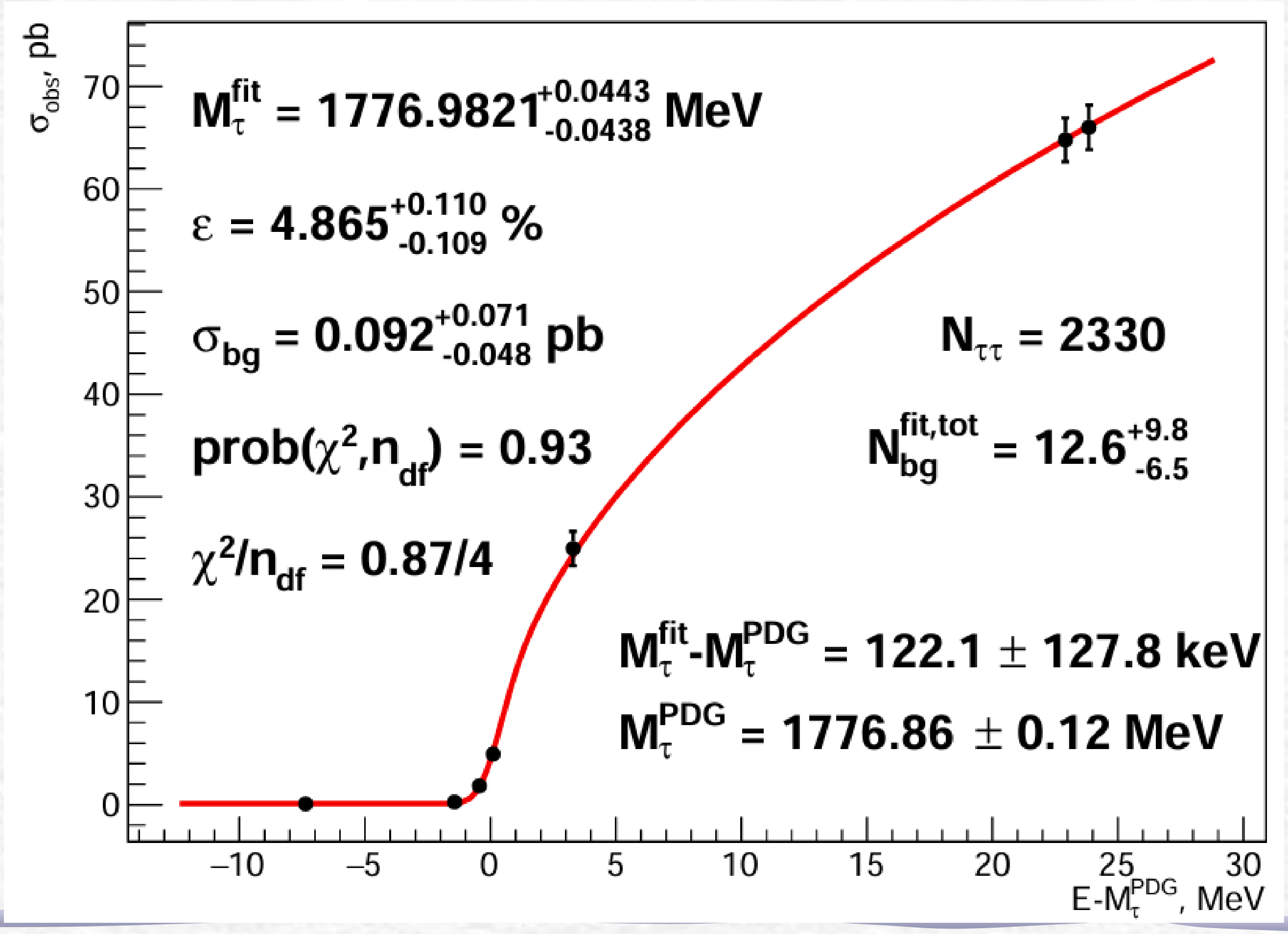


3) Using the results of the fits the energy dependence of the response function parameters and HPGe detector scale nonlinearity are obtained









$M_\tau^{fit} = 1776.9821^{+0.0443}_{-0.0438}$ MeV
$\varepsilon = 4.865^{+0.110}_{-0.109}$ %
$\sigma_{bg} = 0.092^{+0.071}_{-0.048}$ pb
$prob(\chi^2, n_{df}) = 0.93$
$\chi^2/n_{df} = 0.87/4$
$N_{\tau\tau} = 2330$
$N_{bg}^{fit,tot} = 12.6^{+9.8}_{-6.5}$
$M_\tau^{fit} - M_\tau^{PDG} = 122.1 \pm 127.8$ keV
$M_\tau^{PDG} = 1776.86 \pm 0.12$ MeV
σ_{obs}, pb
$E - M_\tau^{PDG}$, MeV