束流能量测量系统(BEMS)的原理与实现

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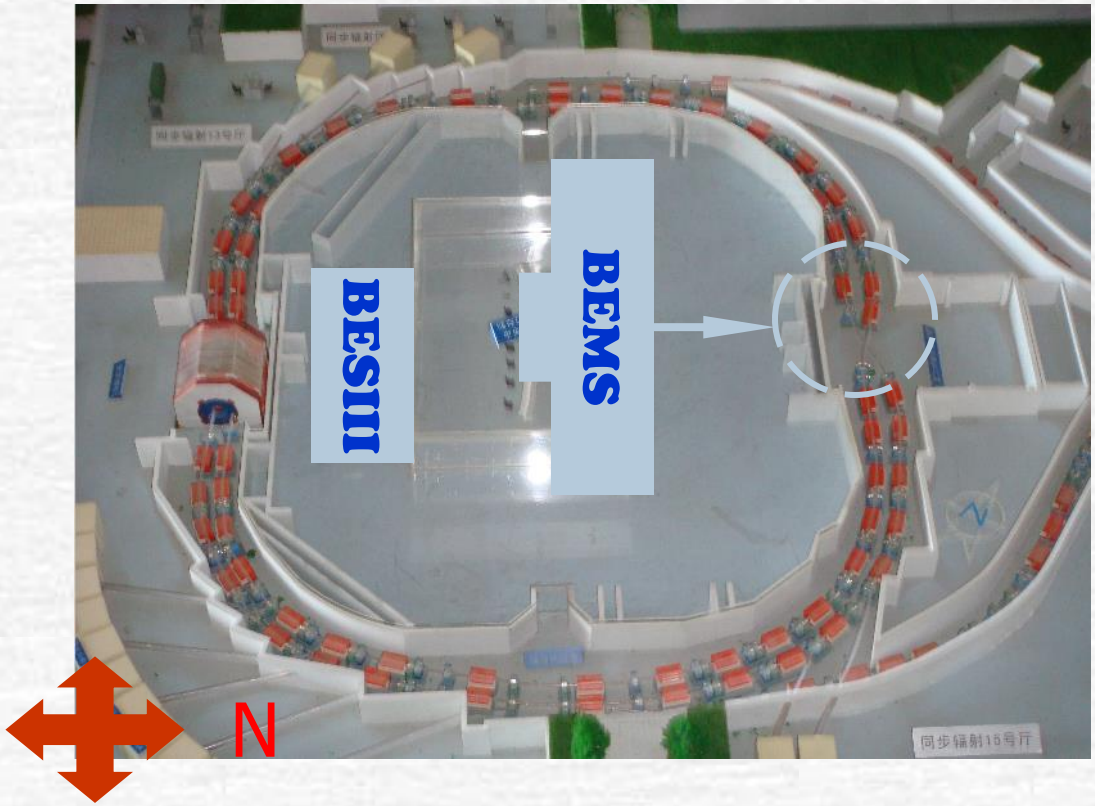
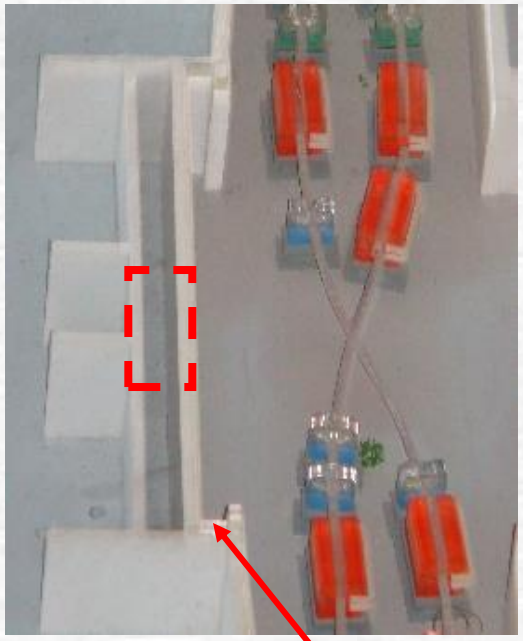
主要内容

- 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)

BEMS位置





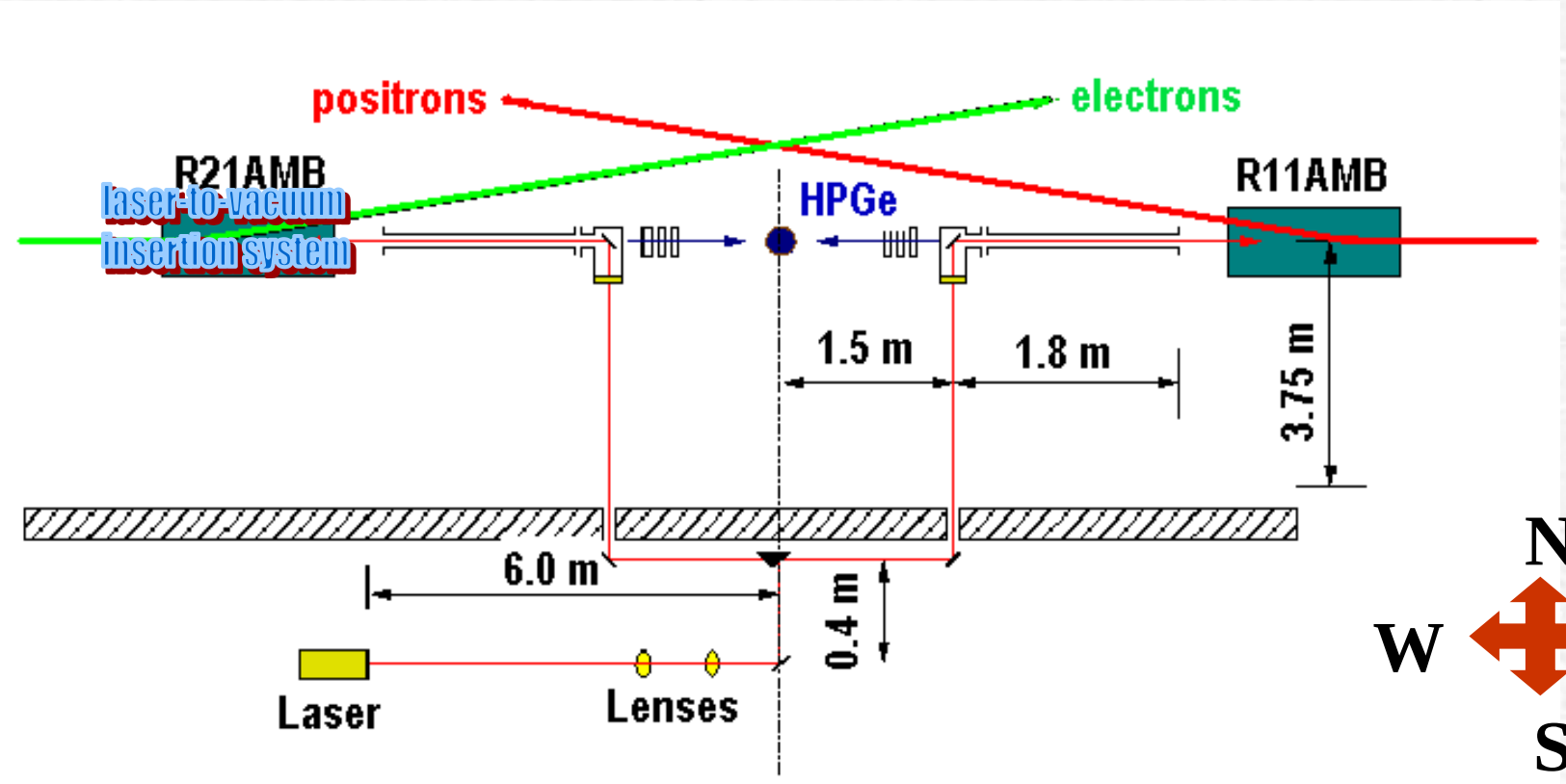
Corridor where optics system is located

The beam energy measurement system locates at the north crossing point.

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}

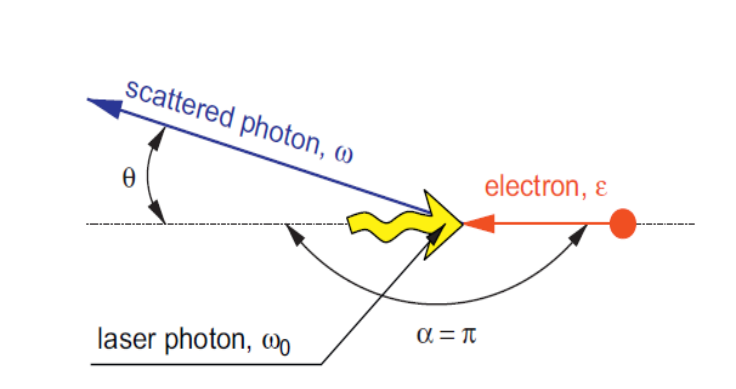
BEMS示意图



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



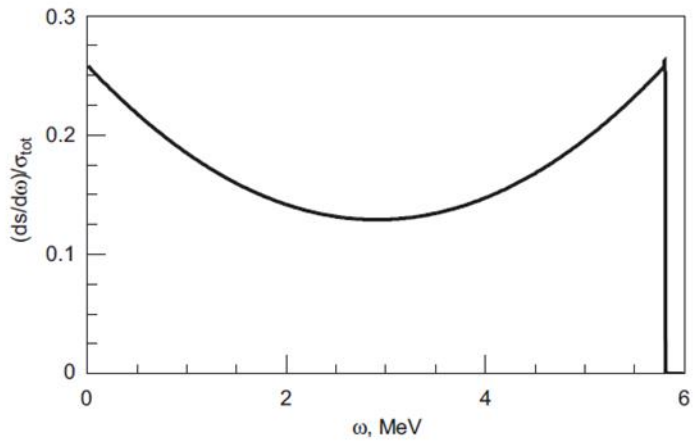


Fig. 3. Energy spectrum of scattered Compton photons. The initial electron and photon energies are $\omega_0 = 0.12$ eV and $\varepsilon = 1770$ MeV, respectively, and $\alpha = \pi$.

散射光子的能量：

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

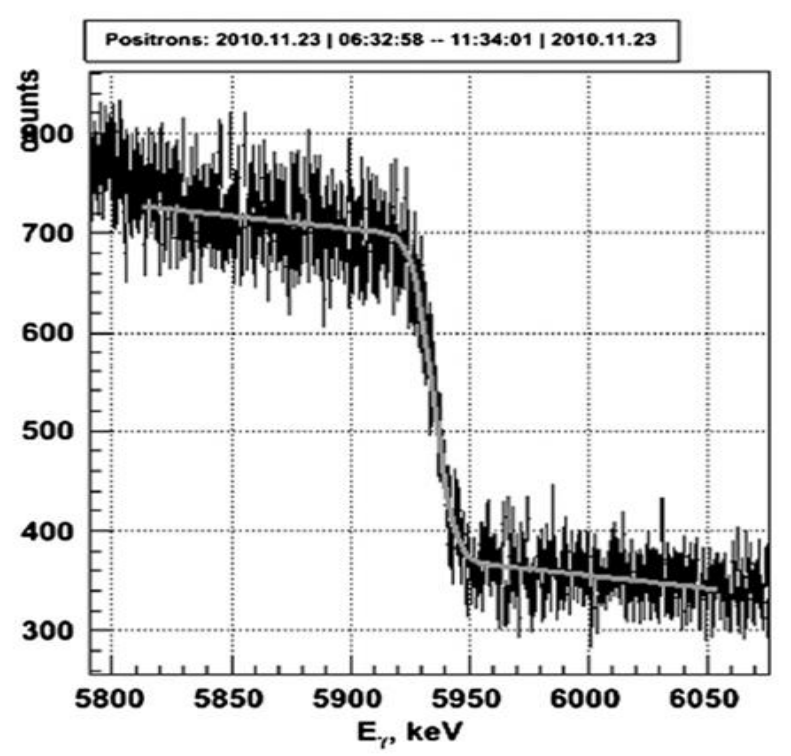
康普顿背散射时：

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

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）



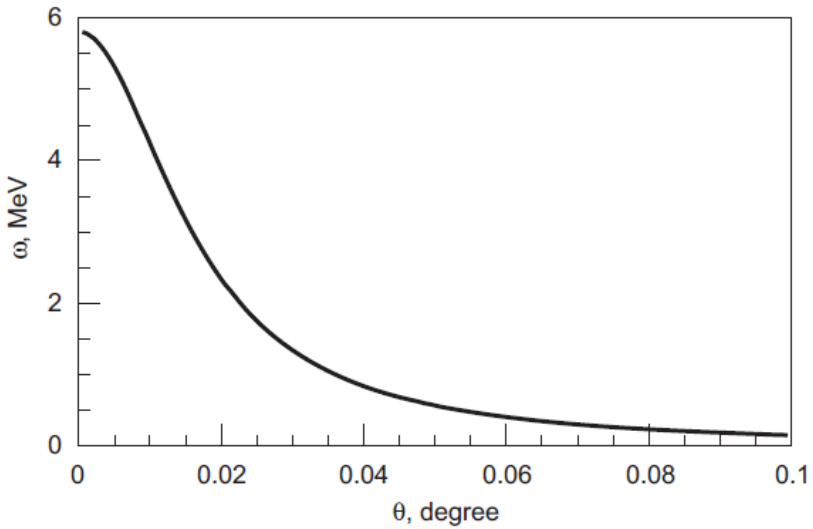


Fig. 2. The dependence of the scattered photon energy ω on the angle θ between the initial electron and the final photon in the Compton scattering process. The initial electron and photon energies are $\omega_0 = 0.12$ eV and $\varepsilon = 1770$ MeV, respectively, and $\alpha = \pi$.

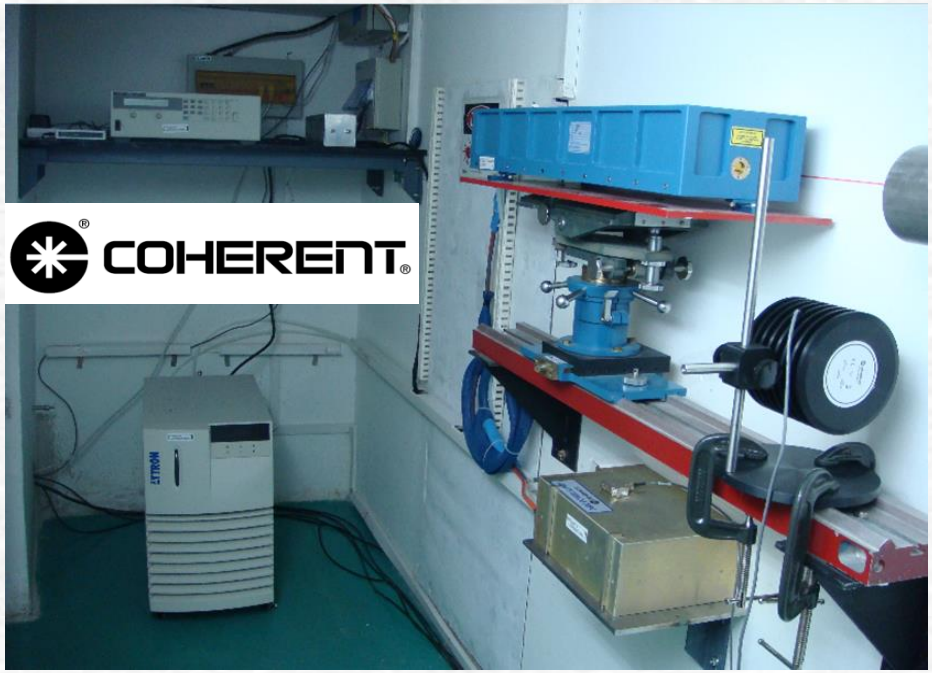
$$g(x, p_{0...5}) = \frac{1}{2}(p_4(x - p_0) + p_2)) \times erfc\left[\frac{x - p_0}{\sqrt{2}p_1}\right] - \\ -\frac{p_1 p_4}{\sqrt{2\pi}} \times exp\left[-\frac{(x - p_0)^2}{2p_1^2}\right] + p_5(x - p_0) + p_3,$$

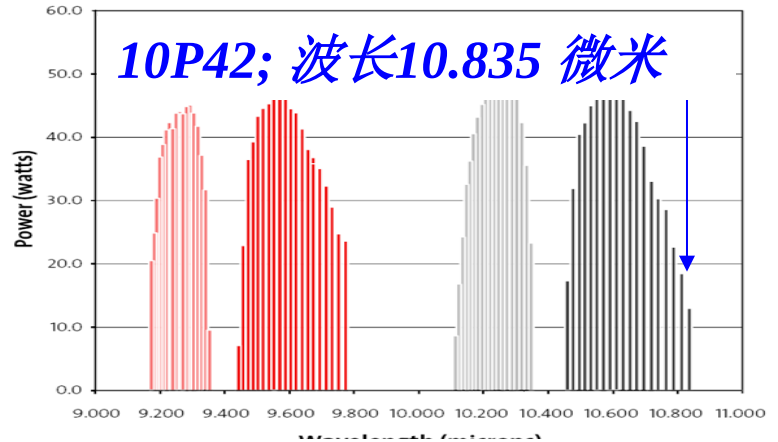
p_0：edge位置，p_1：edge宽度，

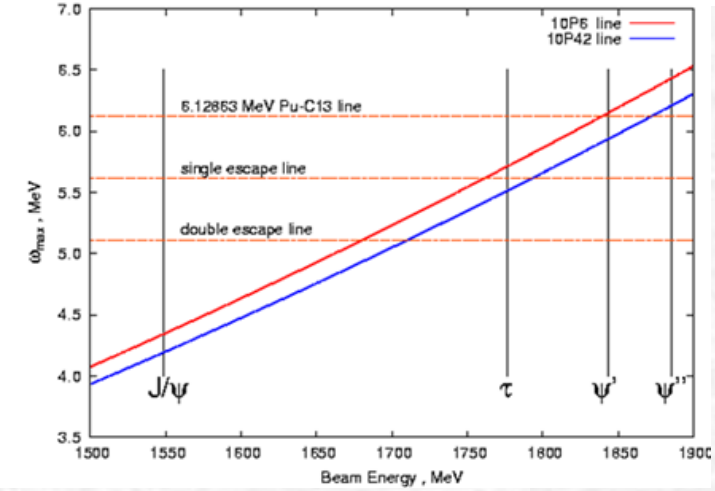
P_2：edge幅度，p_3：本底，

$P_{4,\ 5}$：edge左，右的斜率

BEMS的实现-激光器

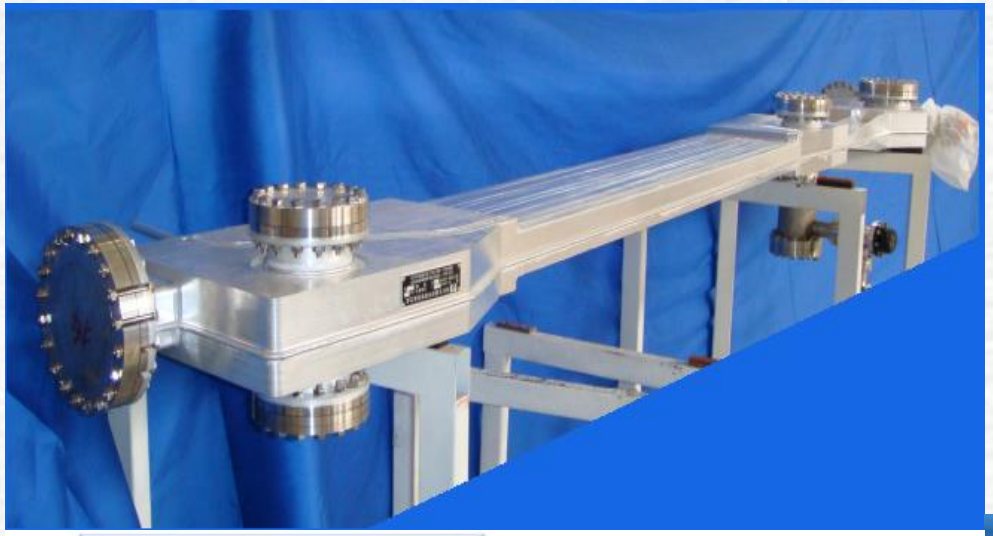


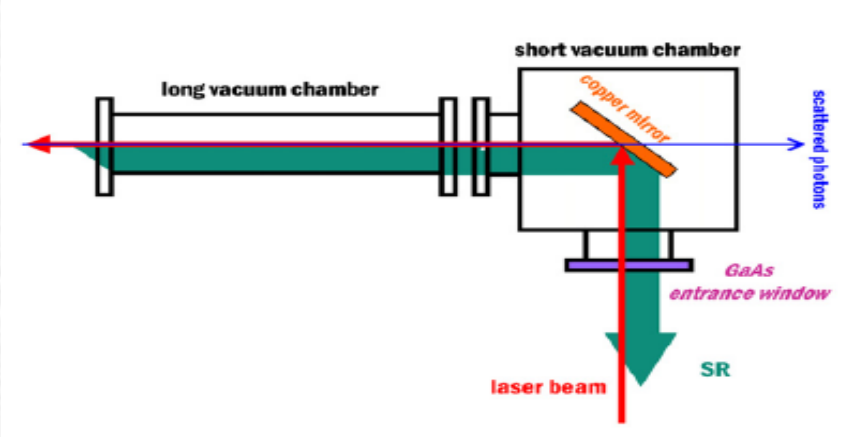


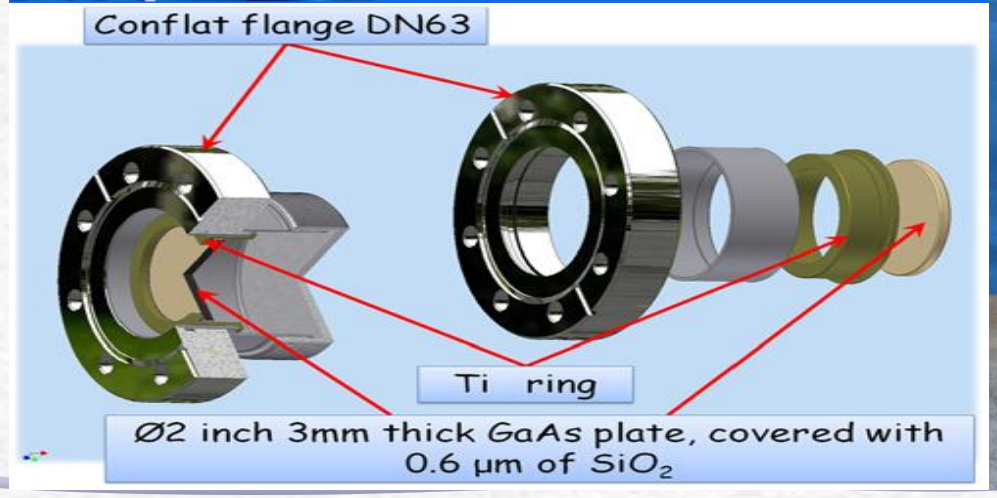


GEM-select50 型二氧化碳激光器
功率：25W，能量：0.12 eV

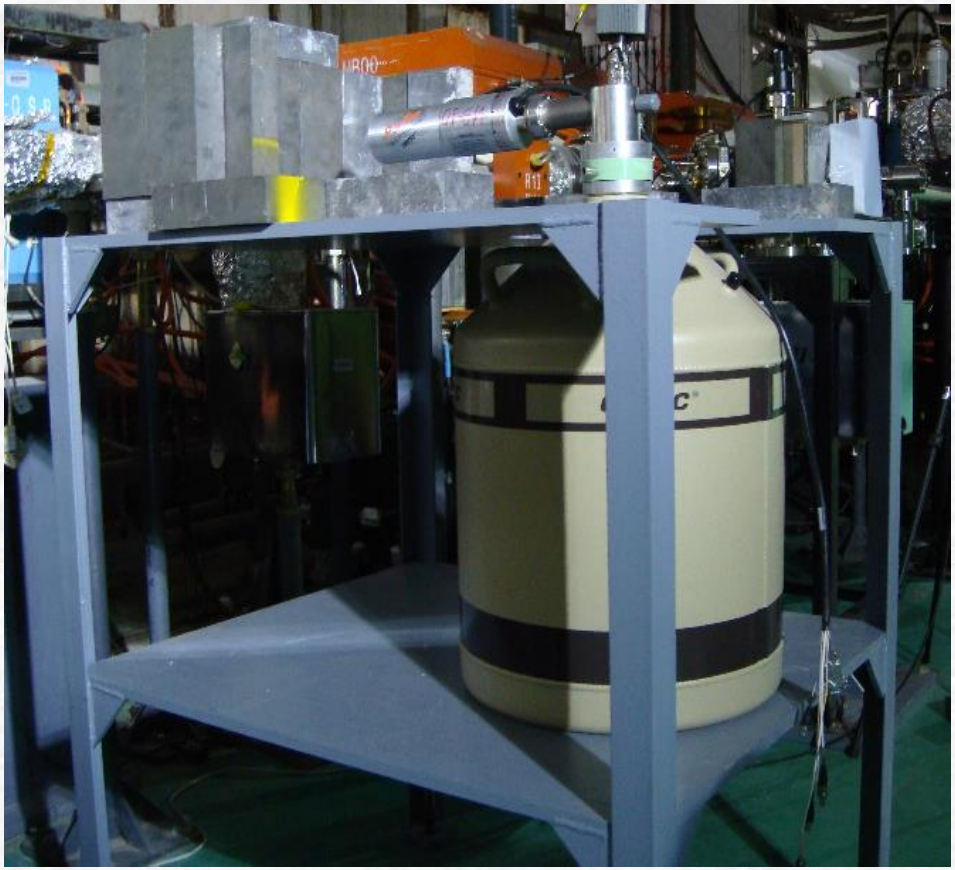
BEMS的实现-真空部分



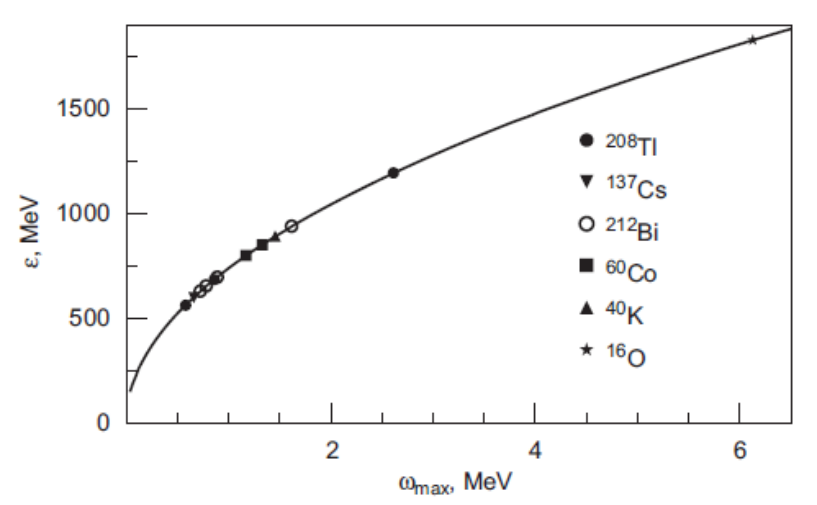




BEMS的实现-高纯锗探测器



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



chamber installation

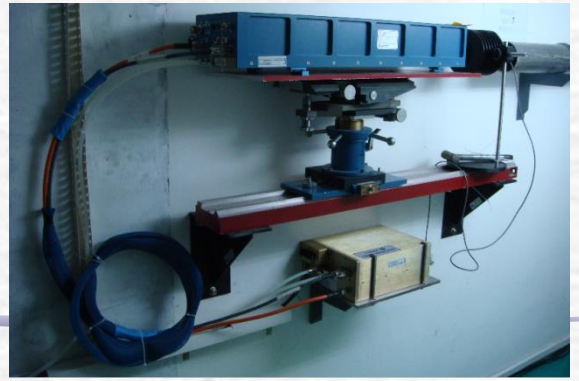
Pump Installation

laser-to-vacuum insertion part

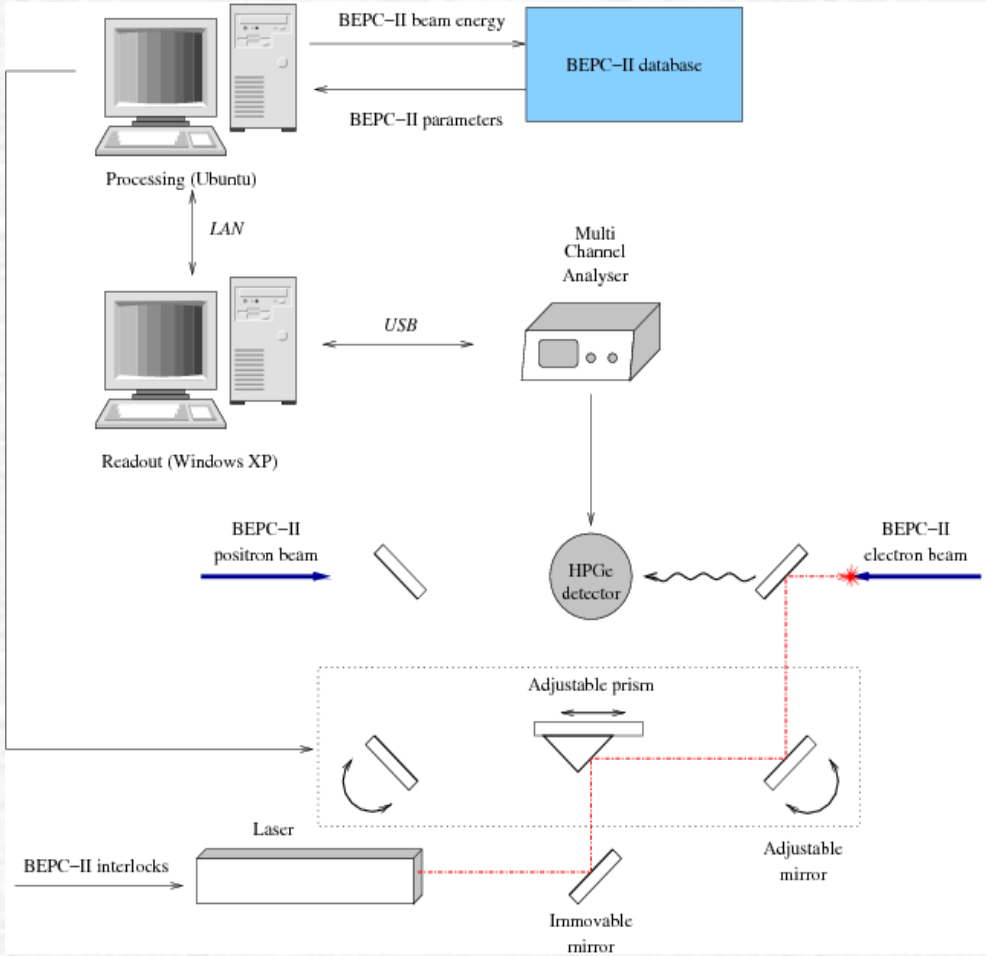
Backing, vacuum up to 2.0×10^{-10} torr

Alignment

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

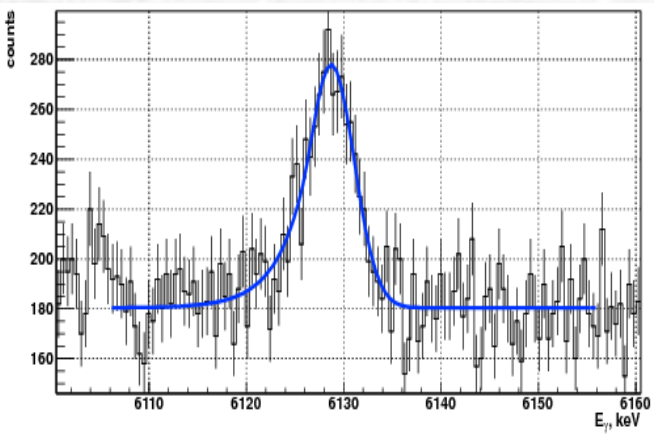
The process of the beams energy measurement is fully automated

数据处理-高纯锗刻度

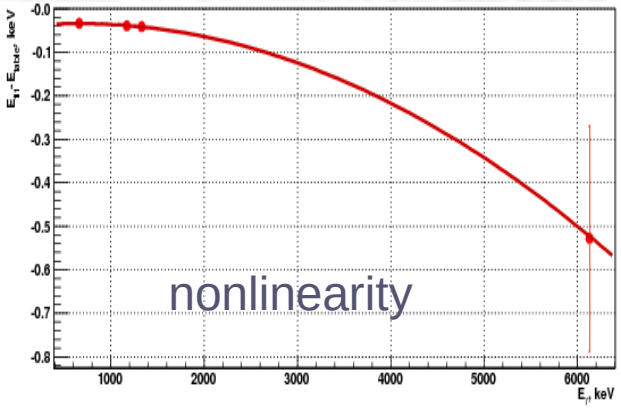
1) The peaks searching and identification

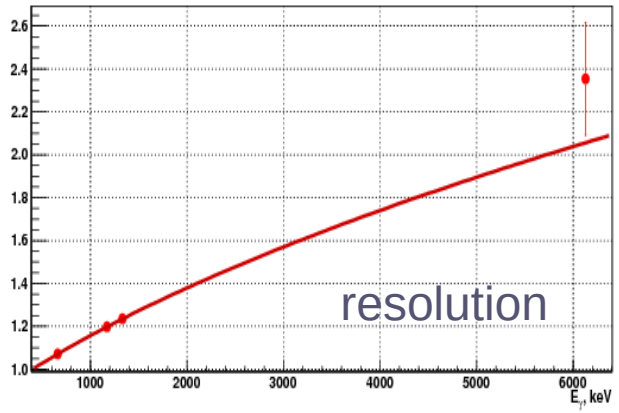
2) Peaks which correspond to calibration lines are fitted by response function:

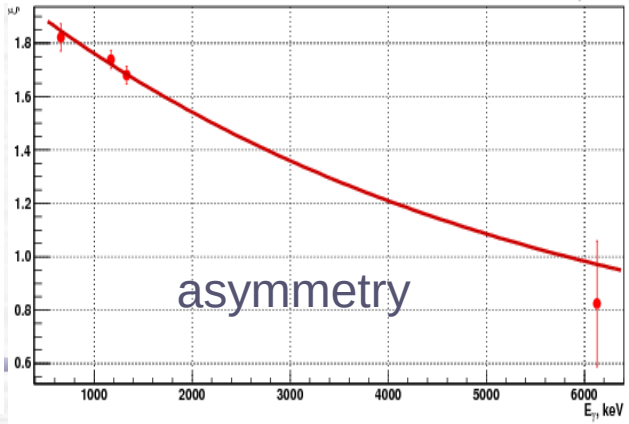
$$f(x, x_0, \sigma, \xi) = \frac{N}{\sqrt{2\pi}\sigma} \begin{cases} \exp\left\{-\frac{(x-x_0)^2}{2\sigma^2}\right\}, x > x_0 - \xi\sigma \\ \exp\left\{\frac{\xi^2}{2} + \frac{(x-x_0)^2}{2\sigma^2}\right\}, x < x_0 - \xi\sigma \end{cases}$$



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





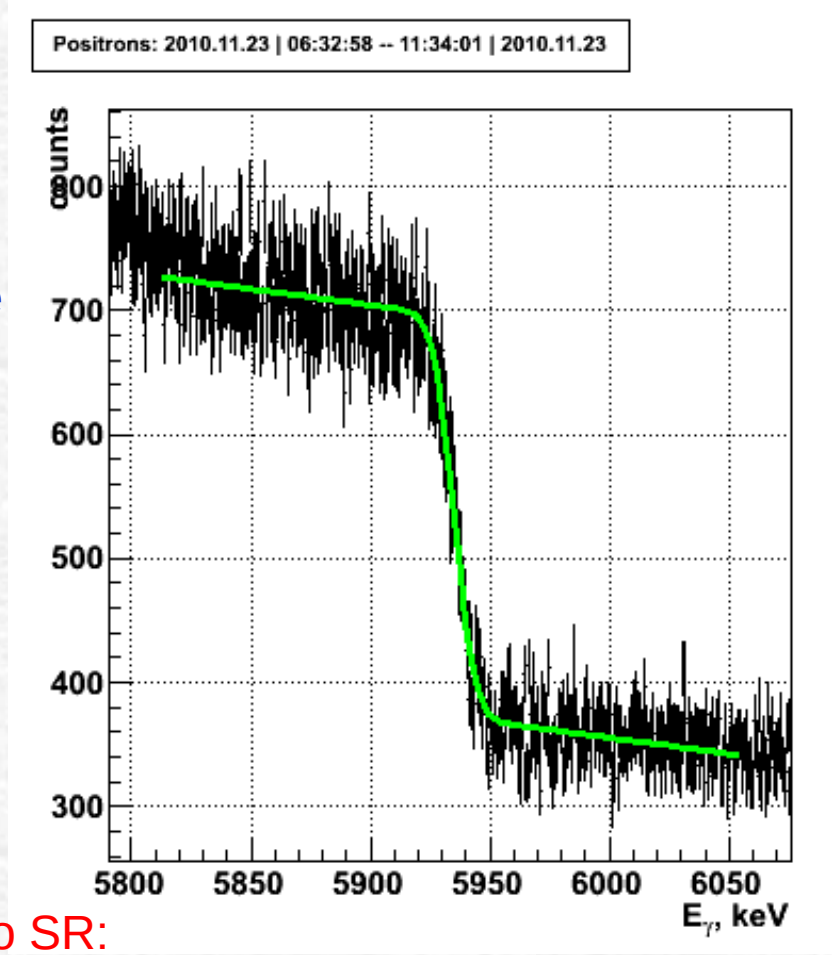


数据处理-康普顿edge拟合

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 ω_{max} and the Compton photons energy spread σ_ω are obtained from the fit.



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

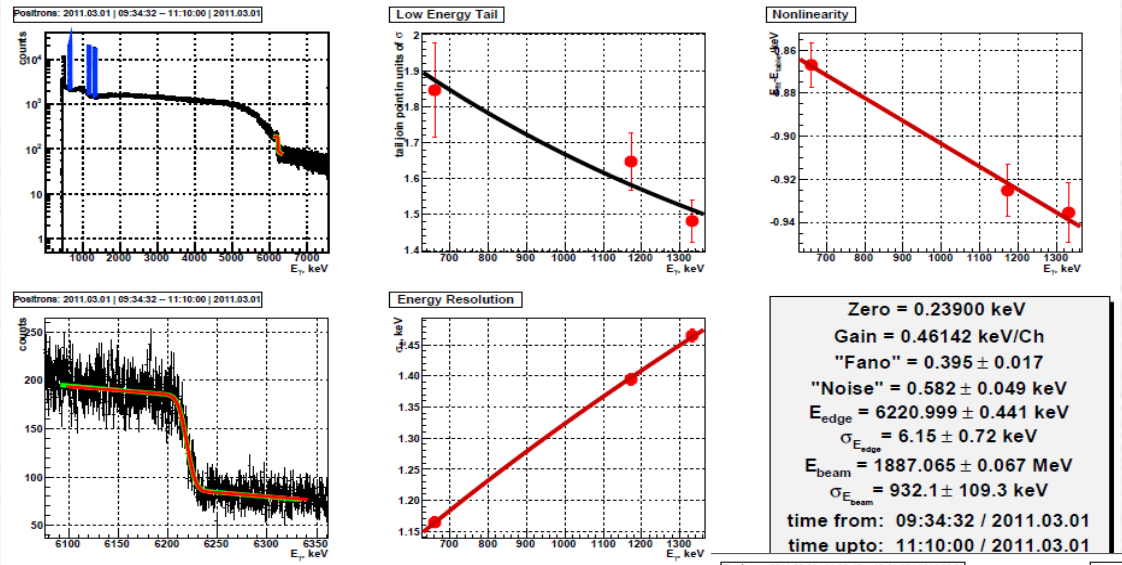
$$\varepsilon_{nip} = \frac{\omega_{\max}}{2}\left(1+\sqrt{1+\frac{m_e^2}{\omega_{\max}\omega_0}}\right)$$

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}

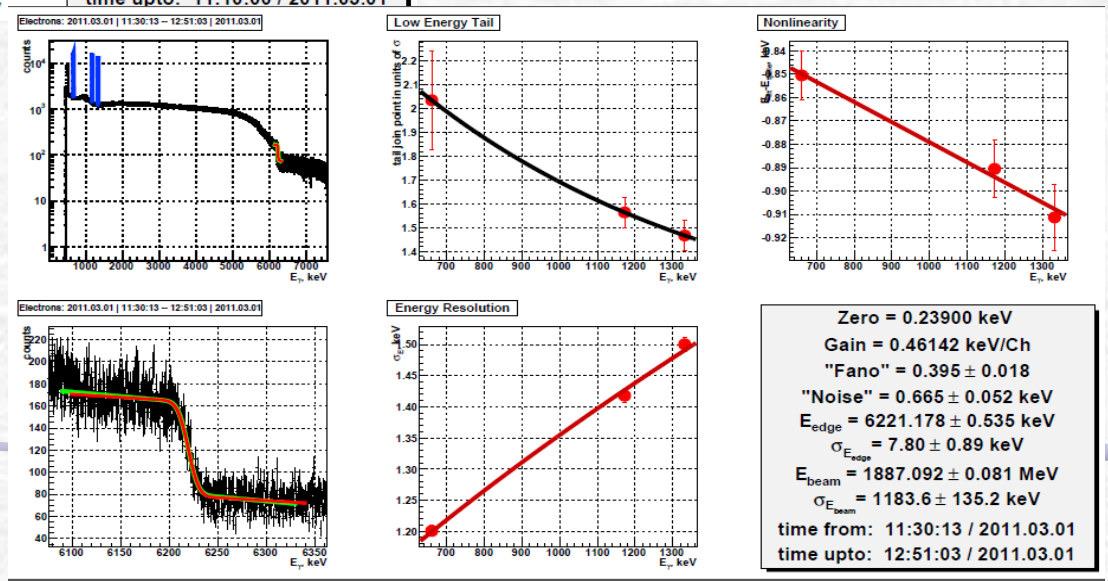
设计指标: 5×10^{-5}

E_{edge} = 6221.178 ± 0.535 keV

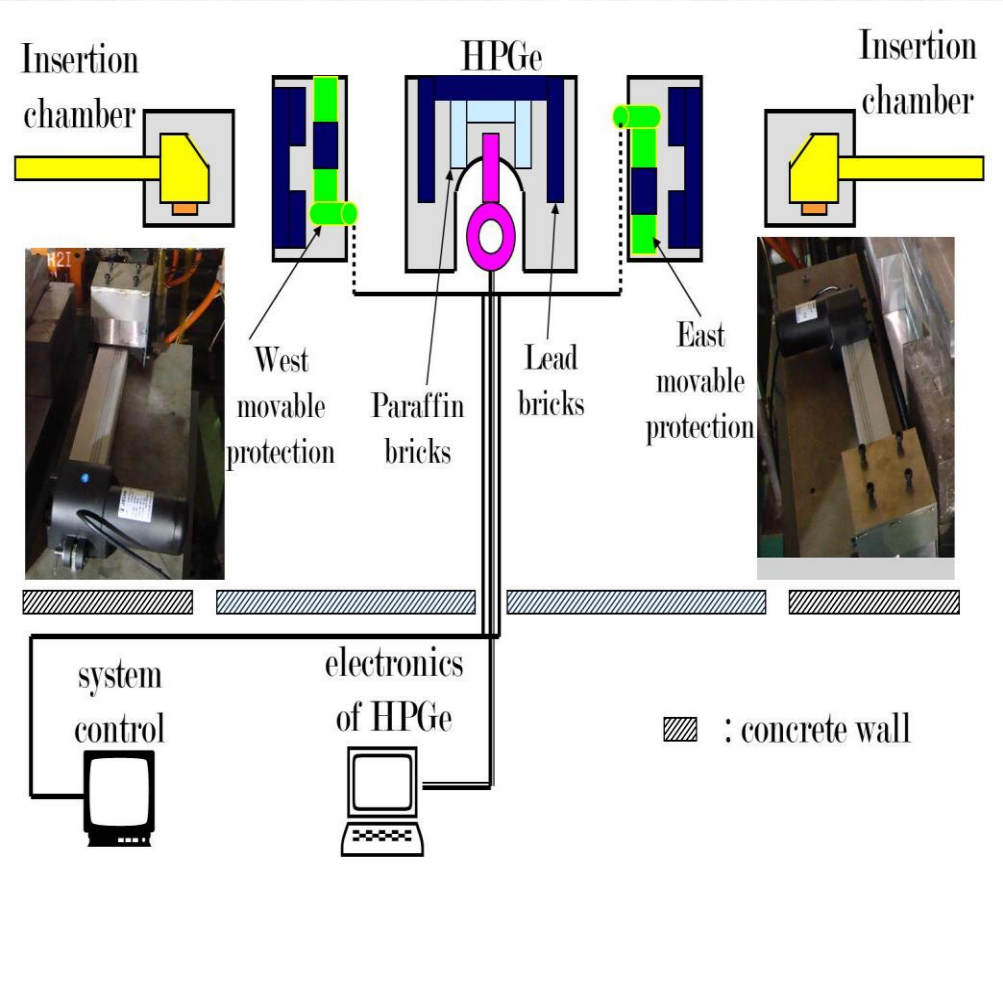
$\sigma_{E_{edge}}$ = 7.80 ± 0.89 keV

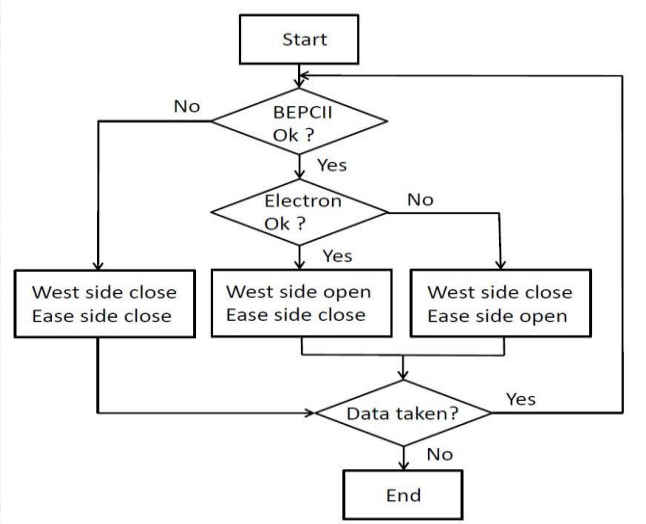
E_{beam} = 1887.092 ± 0.081 MeV

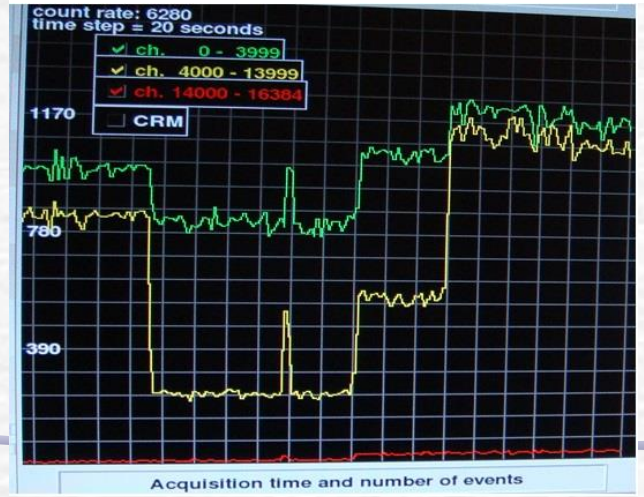
$\sigma_{E_{beam}}$ = 1183.6 ± 135.2 keV



提高信噪比-可移动屏保体安装

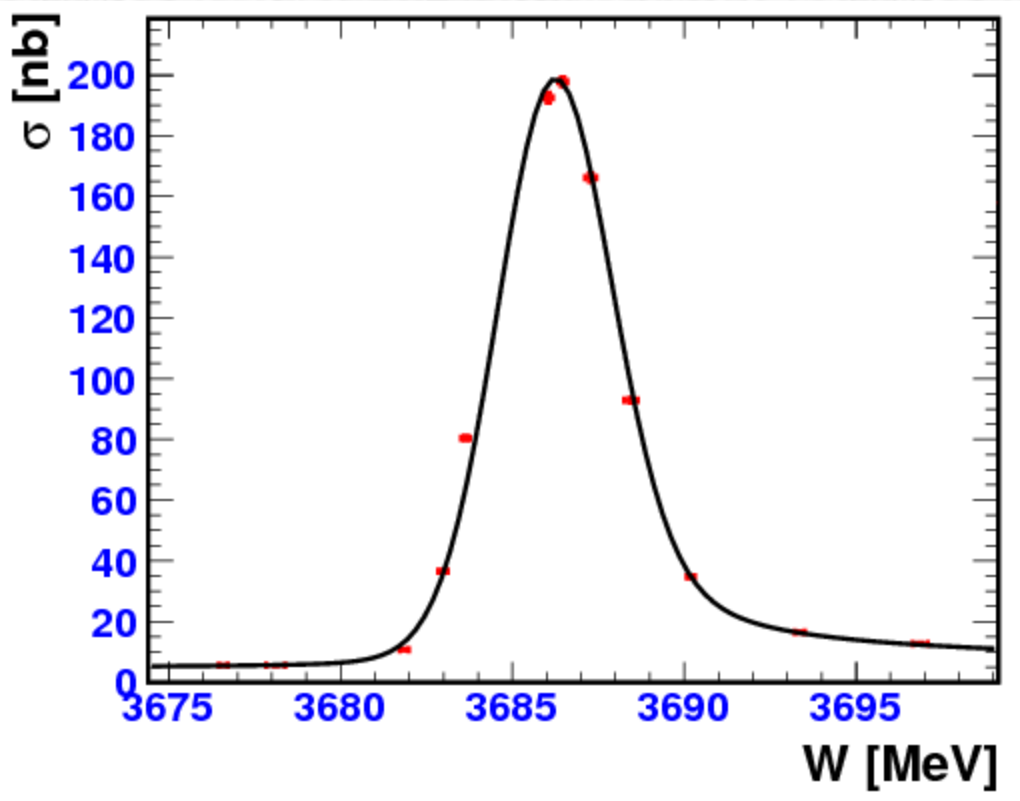






束流能量测量系统性能

The accuracy of beam energy measurement was studied by comparison of ψ(2s) resonance mass 3686.09± 0.040 MeV, with its value obtained using the energy obtained using BEMS data.



Two scans of ψ(2s) with integrated luminosity about 4 pb^{-1}.

Mass difference:

$$\Delta m = m - m_{\psi} = 0.02 \pm 0.05 MeV$$

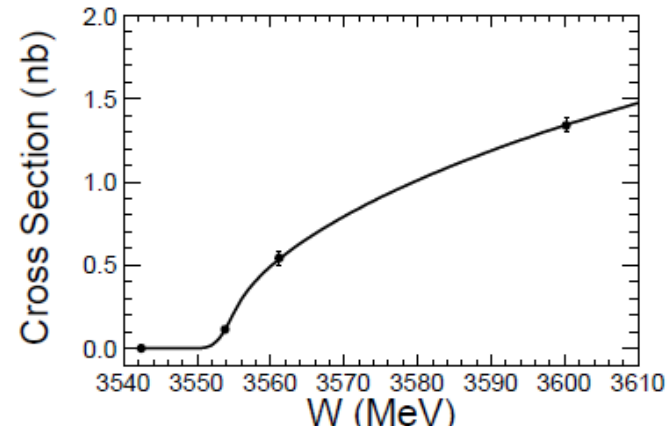
Deviation of the measured beam energy of the beam from true value:

$$\delta\varepsilon = \frac{\Delta m}{2} = 0.01 \pm 0.03$$

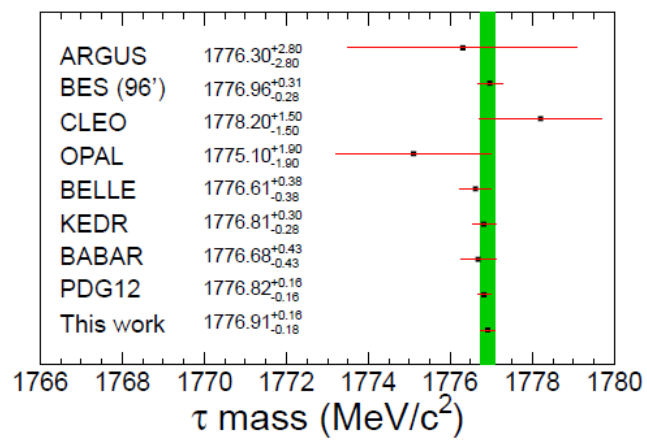
Accuracy of the beam energy measurement: $\delta\varepsilon/\varepsilon \sim 2\times10^{-5}$

Tau质量测量预扫描

Scan	E_{CM} (MeV)	$\mathcal{L}(\mathrm{nb}^{-1})$
J/ψ	3088.7	78.5 ± 1.9
	3095.3	219.3 ± 3.1
	3096.7	243.1 ± 3.3
	3097.6	206.5 ± 3.1
	3098.3	223.5 ± 3.2
	3098.8	216.9 ± 3.1
	3103.9	317.3 ± 3.8
τ	3542.4	4252.1 ± 18.9
	3553.8	5566.7 ± 22.8
	3561.1	3889.2 ± 17.9
	3600.2	9553.0 ± 33.8
ψ'	3675.9	787.0 ± 7.2
	3683.7	823.1 ± 7.4
	3685.1	832.4 ± 7.5
	3686.3	1184.3 ± 9.1
	3687.6	1660.7 ± 11.0
	3688.8	767.7 ± 7.2
	3693.5	1470.8 ± 10.3



$$m_\tau = (1776.91 \pm 0.12^{+0.10}_{-0.13})\ \mathrm{MeV}/c^2.$$



小结

- 用康普顿背散射原理建成了BEMS
- BEMS测试结果好于设计指标
- 23 pb^{-1} 扫描数据获得的tau质量精度与PDG12精度相当
- 预计BESIII 16年将为tau质量取数

谢谢！