加速器束流诊断技术

冷用斌

上海光源

2010-08-03

参考文献

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2.马力先生，加速器束流测量，高能物理研究所加速器中心，2001
3.孙葆根博士，加速器中束流诊断技术，中国科学技术大学国家同步辐射实验室
4. Beam diagnostics for accelerator，*H. Koziol*，CERN, Geneva, Switzerland
5. Conference proceedings at Joint Accelerator Conferences Website (JACow):
http://accelconf.web.cern.ch/accelconf/
DIPAC
PAC
EPAC
APAC
…
6. AIP proceedings for Beam Instrumentation Workshop.
7. Paragraph 7.4, "Handbook of Accelerator Physics and Engineering", edited by Alexander Wu Chao & Maury Tigner.

主要内容

- 束流诊断技术概述
- 常用束流诊断设备
  - 束流流强测量
  - 束流位置测量
  - 工作点测量
  - 横向尺寸/分布测量
  - 纵向尺寸/分布测量
  - 能量/能谱测量
  - 束损测量
- 家庭作业

束流诊断技术概述

beam diagnostics
beam instrumentation

什么是加速器束流诊断?

- 通过束流检测器(beam monitor)与粒子束流(particle beam)的相互作用获得携带束流信息的光、电信号

- 对探头输出光、电信号进行处理，从中提取粒子束流空间分布信息（横向截面尺寸、纵向束团长度、运动轨迹、发射度等）、电特性参数（束团电荷量、平均流强等）、时变信息（束流寿命、束团不稳定性等）

- 根据测得的束流参数推算加速器特性参数：工作点、响应矩阵、Beta函数、色散函数、耦合度、色品等等

束流诊断系统的作用

不以规矩，不成方圆

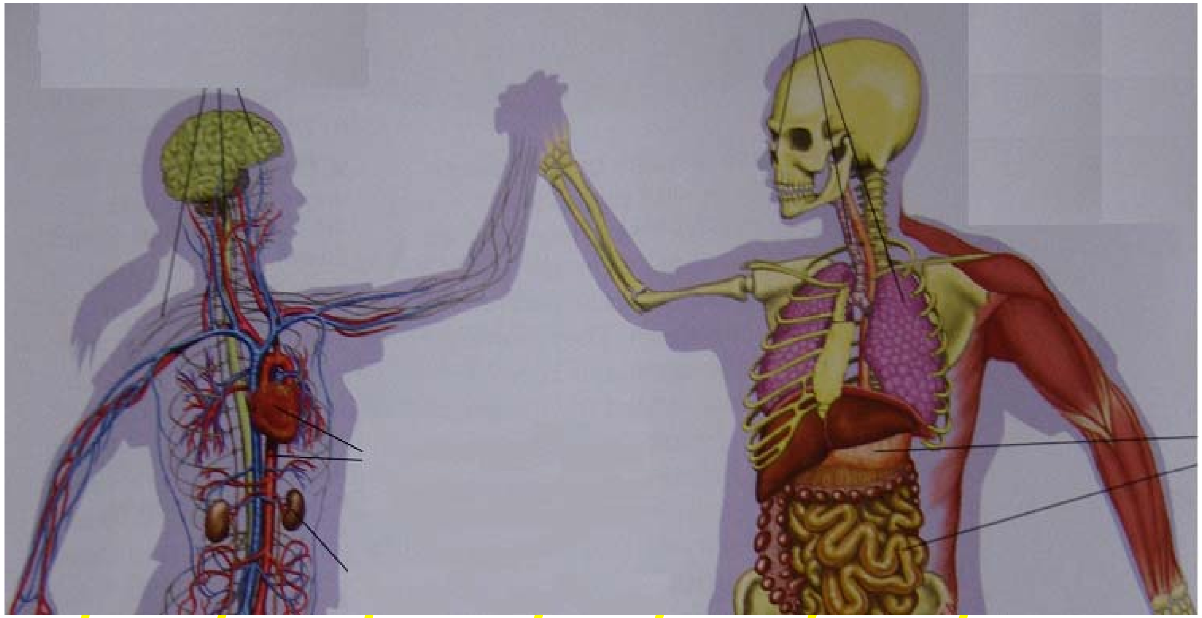
《孟子·离娄上》

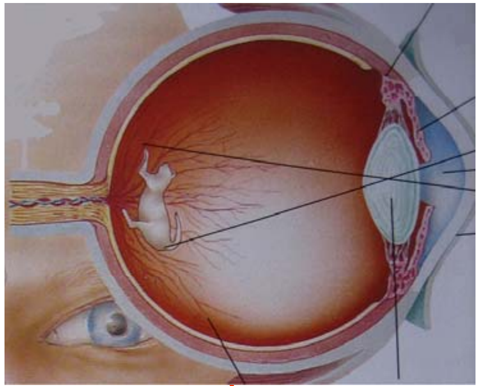
An accelerator is just as good as its diagnostics
加速器性能由束测系统性能决定

Beam Diagnostics for Accelerators, H.Koziol, CERN

- 加速器是否达标的验收手段 (gauge for machine acceptance test)
- 加速器正常工作的调试手段 (commissioning & operation toolkits)
- 了解加速器特性的研究手段 (machine study toolkits)

束流诊断系统的作用





物理系统	微波系统	控制系统	真空系统	机械支撑系统	电源系统	磁铁系统
大脑	循环系统	神经系统	皮肤	骨骼	消化系统	肌肉

束流诊断系统 感觉器官

- 行为基准
- 非生存必须
- 但决定系统性能

诊断设备及测量物理量

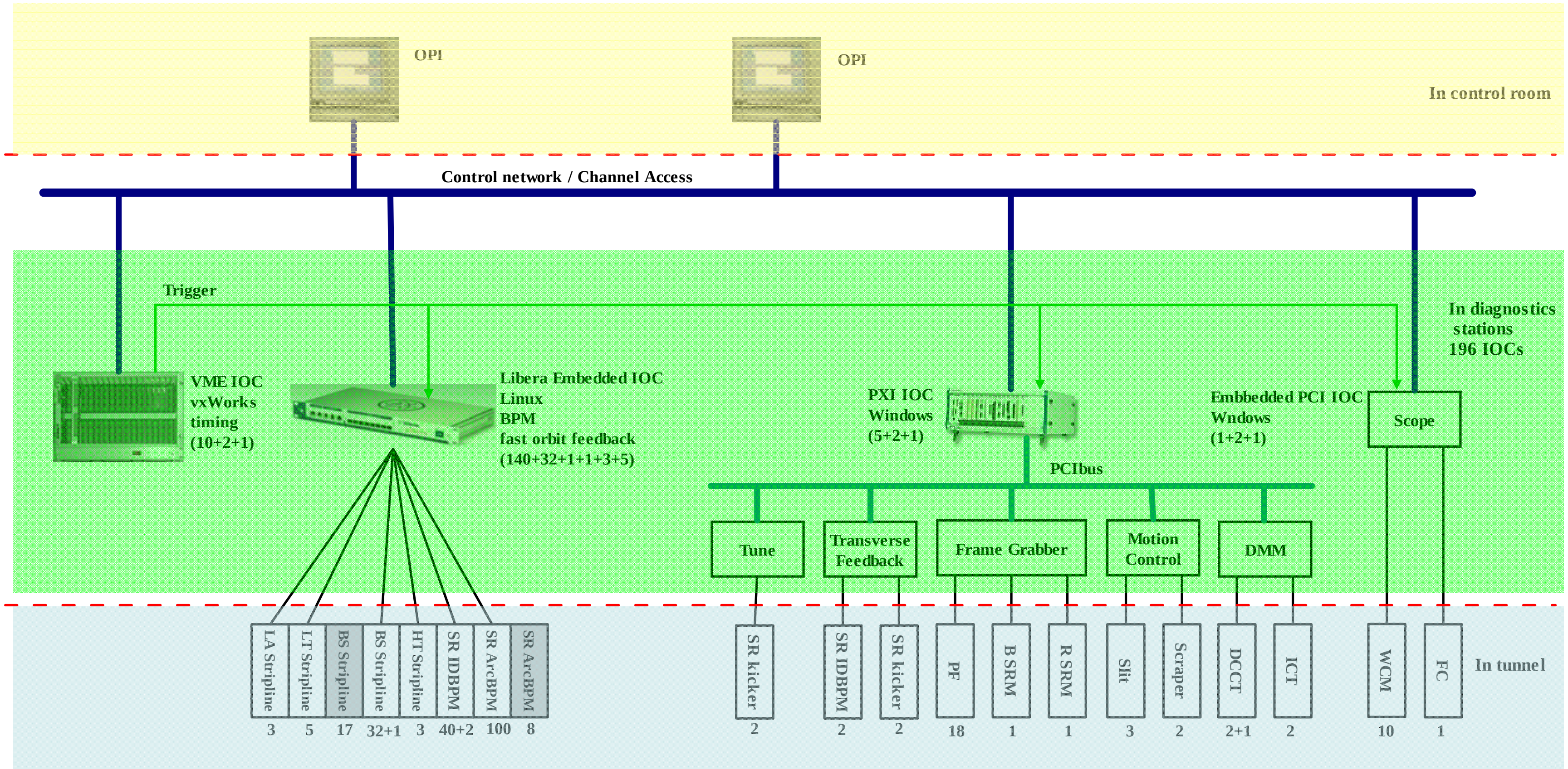
PROPERTY MEASURED →	Intensity I, Q	transverse: Position	transverse: Size/shape	transverse: Emittance	longit.: Size/shape	longit.: Emittance	Q-value + ΔQ	Energy + ΔE	Polarization	Effect on beam: N	–	+	D
Beam transformers	●				●	●				x			
Wall-current monitors	●	●			●	●				x			
Pick-ups	●	●	(●)		●	●				x			
Faraday cup	●												x
Secondary emission monitors	●	●	●	●				•			x	x	
Wire scanners		●	●	●				•			x		
Wire chamber		●	●								x	x	
Ionization chamber	●										x	x	
Beam loss monitors		•	•	•			•			x			
Gas curtain/jet		●	●	●							x		
Residual gas monitors		●	●	●						x			
Scintillator screens		●	●								x	x	x
Scrapers, targets		●	●	●									x
Schottky scan	●			●		•	●	●		x			
Synchrotron radiation		●	●		●	●				x			
LASER-Compton scattering			●	●					●	x			
Q-measurement							●			x	x		
Emittance measurement				●							x	x	x
Measurement of energy								●		x	x	x	x
Polarimeter									●	x			x

Effect on beam :
- N none
- – slight, negligible
- \+ perturbing
- D destructive

束流诊断系统结构

模块名 Module name	完成功能 functionality	实例1 Example 1	实例2 Example 2
		平均流强 测量	同步光 成像
数据表达 Information presentation	在人机界面中简洁、高效地显示测量物理量及其变化	XY plot	Image plot
数据服务器 Data server	按控制系统通讯协议提供数据服务	EPICS IOC	EPICS IOC
数据处理 Data processing	根据量化后的原始数据处理、计算得到待测物理量	Digital filtering	Image processing
数字化 digitizing	模拟信号量化为计算机可处理的数字信号	NI4070 DVM	CCD
前端信号调理 Signal conditioning	信号放大/衰减/整形/滤波…	NPCT FE	BP filter Lens
束流探头 Beam sensor	信号检测	NPCT175	Mirror

束流诊断系统结构



Three layers:

束流探头 In tunnel	前端电子学及数据服务器 In diagnostics station	操作员控制台 In control room

束流流强测量

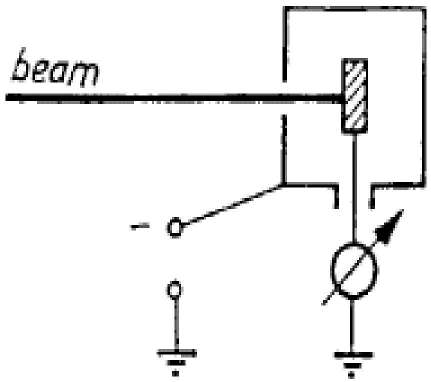
beam intensity measurement

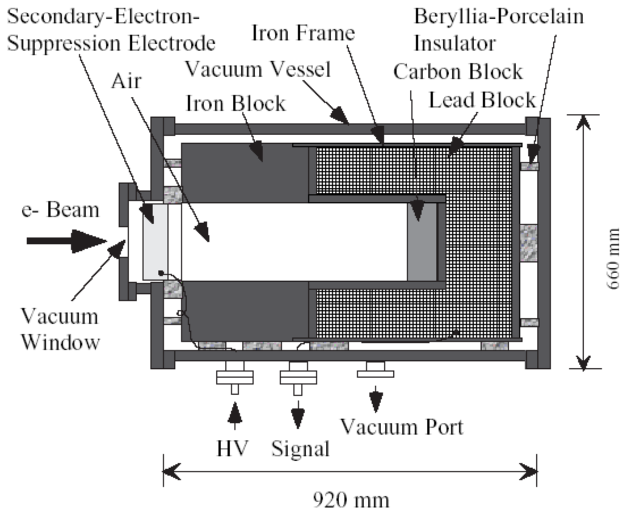
常用束流流强测量设备

- 法拉第桶（Faraday Cup, ns - us）
- 壁电流检测器（Wall Current Monitor, ns）
- 束流变压器（Beam Current Transformer）
  - 交流电流变压器（ACCT, us）
  - 快速电流变压器（Fast CT, ns）
  - 谐振式电流变压器（Tuned CT）
  - 积分电流变压器（ICT, ns - us）
  - 直流电流变压器（DCCT, ms - s）
- BPM和信号
- 同步光+快速光电二极管

法拉第桶：基本测量原理

- 主要用于低能束流的电荷量绝对测量
- 粒子束流撞击搜集极后损失全部能量，电荷沉积到搜集极
- 在搜集极和信号地之间跨接一个电流表，即可测得束流流强
- 考虑到信号带宽较宽，通常采用示波器充当数据采集设备
- 通常在屏蔽外壳上加负偏压以避免二次电子发射导致的信号失真



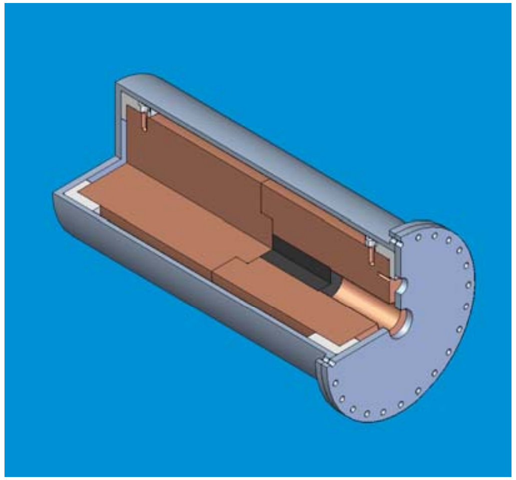


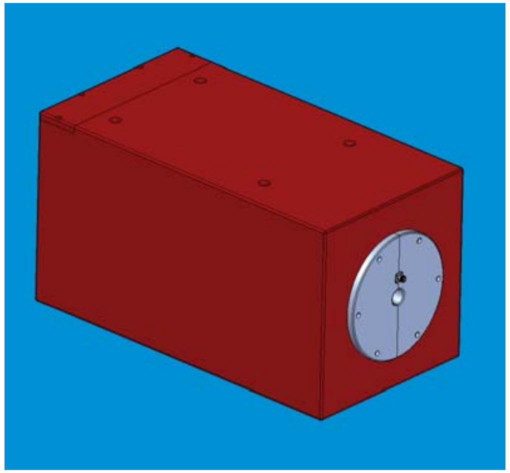
cross-sectional view of the FC of the KEKB injector linac (courtesy T. Suwada, 2003)

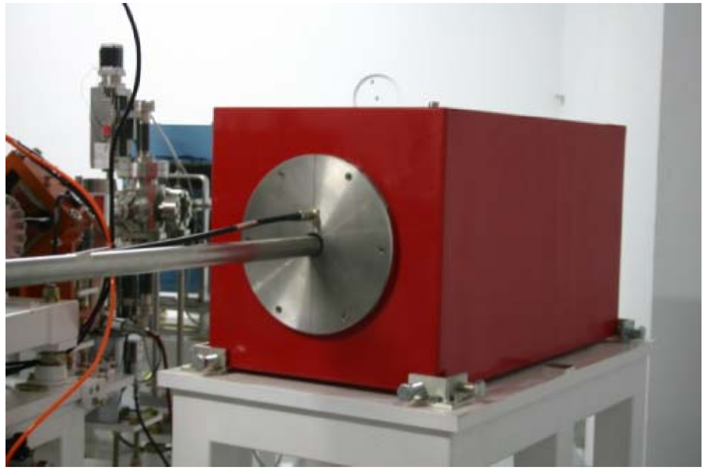
BEAM DIAGNOSTICS FOR ACCELERATORS，*H. Koziol*，CERN, Geneva, Switzerland

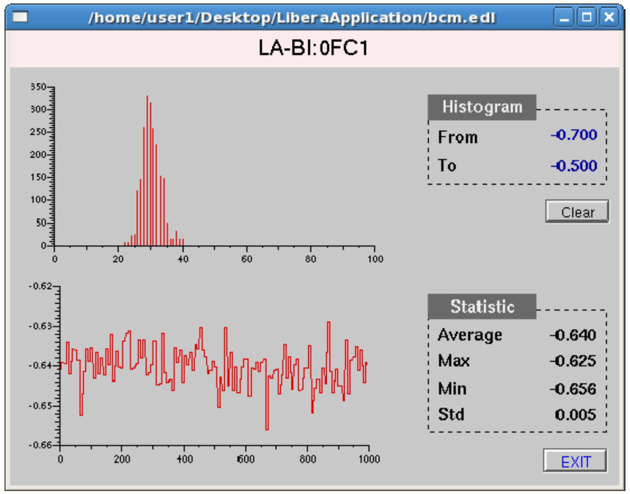
实例：上海光源直线加速器FC

数据采集： **TEK DPO7054 (模拟带宽500MHz，Windows操作系统)**







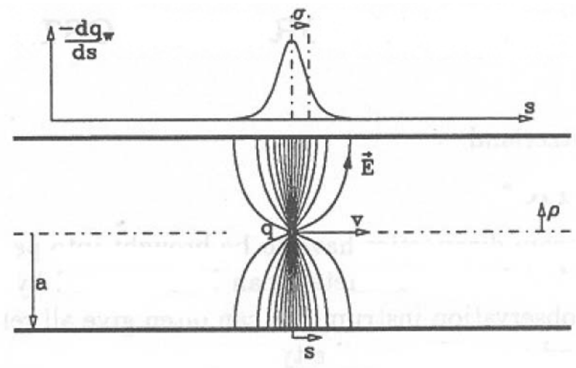


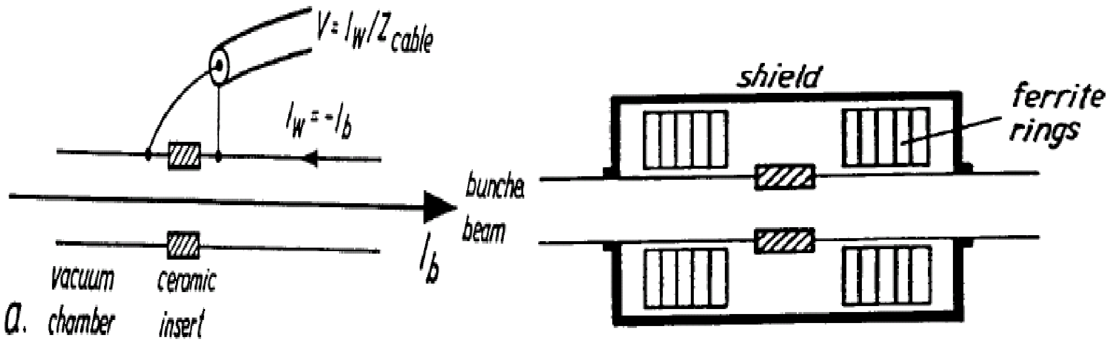
2007-7-7 单束团

相对测量精度 **0.005/0.640 = 0.8%**

壁电流检测器：基本测量原理

- 将取样电阻跨接在陶瓷隔离段两端，束流镜像电流流经取样电阻时即可获得**电压取样信号**
- 为降低外界电磁场的干扰且不对外界构成干扰，需要在探头外部加装**电磁屏蔽**
- 加装**铁氧体环，**改善探头低频响应
- 输出信号多点对称引出，获得位置无关的强度信号





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壁电流检测器：频幅响应

壁电流检测器等效电路为并联RLC电路

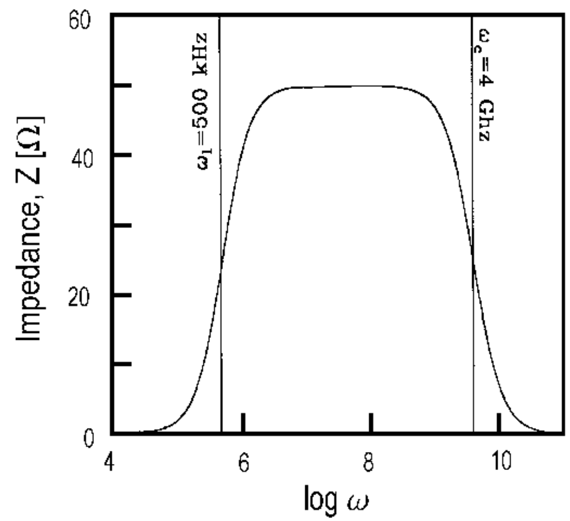
$$\frac{1}{Z} = \frac{1}{R} + \frac{1}{j\omega L} + j\omega C$$

其高频响应特性主要由电容C确定

$$|Z(\omega \to \infty)| = \frac{R}{\sqrt{1 + (\frac{\omega}{\omega_C})^2}}$$

其低频响应特性主要由电感L确定

$$|Z(\omega \to 0)| = \frac{R}{\sqrt{1 + (\frac{\omega_L}{\omega})^2}}$$



因此，为了增大检测器带宽，需要尽可能地增大L并减小C

壁电流检测器：基本测量原理

- $V = I_w(t)\,Z = -I_b(t)\,Z$
- 检测电压信号幅度与束团长度相关，电荷量不变时束团长度改变（I_b变化）则检测电压信号幅度改变
- 检测电压信号幅度与数据采集设备带宽相关，不同的采集设备（Z变化）获得的电压信号幅度不同
- 难以根据电压信号幅度计算电荷量

- 高频射信号连接器50Ω阻抗匹配难以完美实现，尾部的反射，振铃信号难以避免
- 屏蔽壳有可能构成谐振腔结构，引入干扰信号
- 对电流信号积分计算电荷量误差较大

- 可用于纵向分布观测、相对强度测量

实例： CERN & DLS

CTF3 in CERN, DIPAC2003, A NEW WIDE BAND WALL CURRENT MONITOR
Bandwidth 10GHz

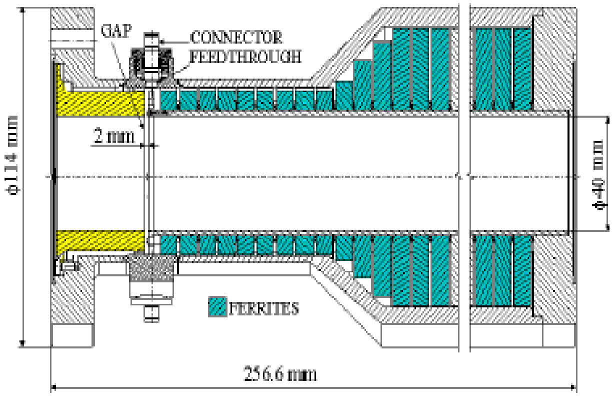
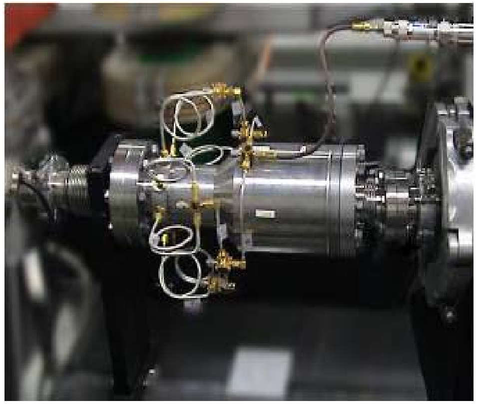


Figure 3: WCM general cross-section



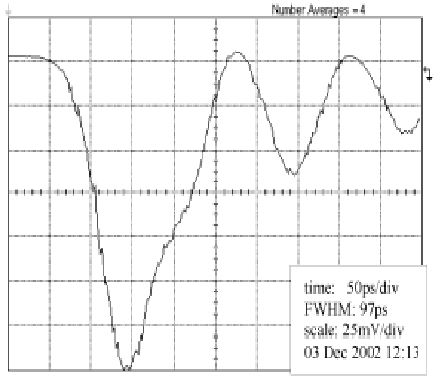
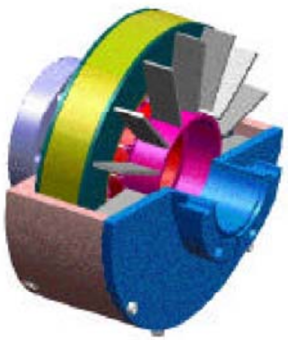


Figure 8: WCM signal on CTF2 beam

SLS in PSI, SLS LINAC AND TRANSFER LINE DIAGNOSTICS
Bandwidth 4-5GHz



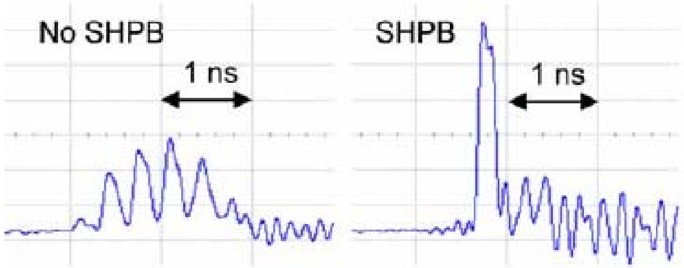


Figure 3: Beam at linac exit without (left) and with (right) SHPB recorded with wall current monitor.

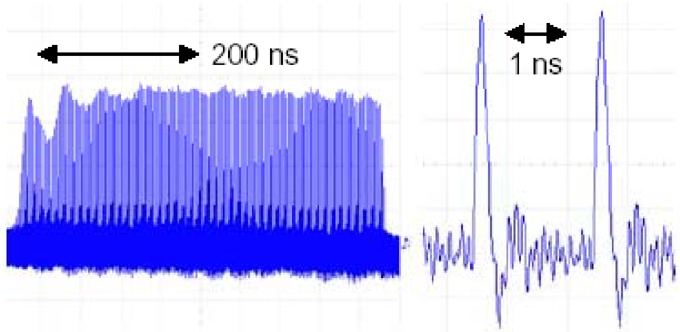
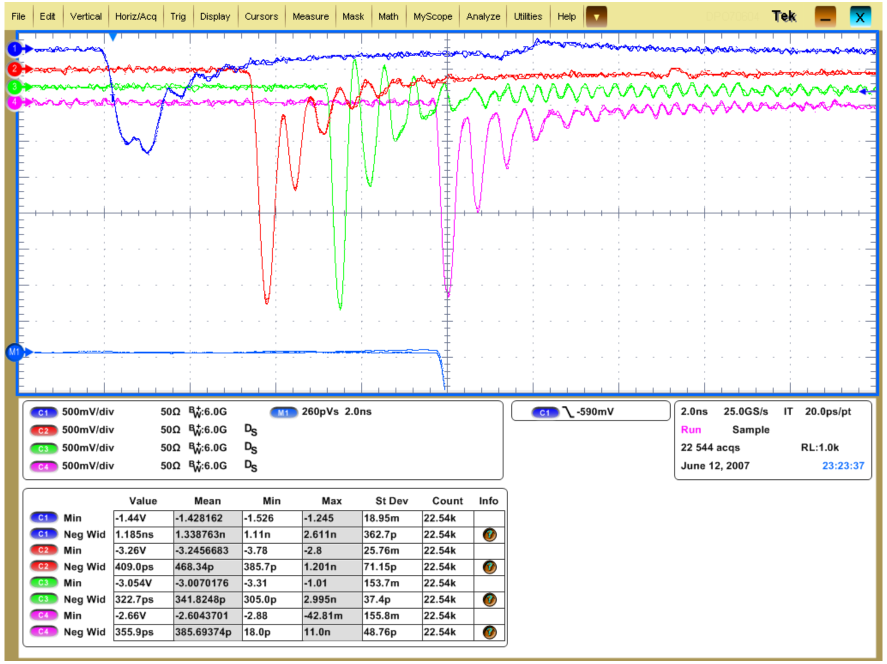
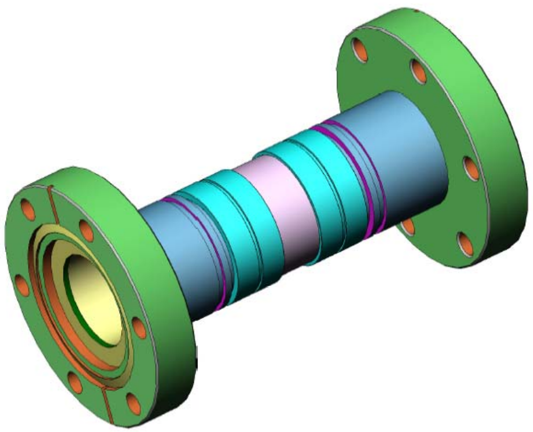


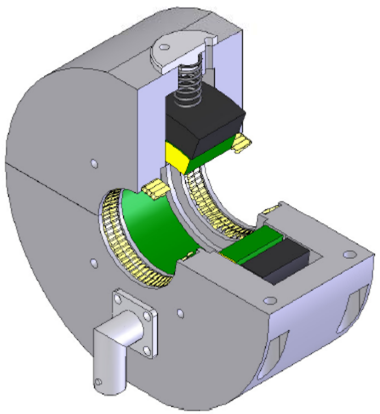
Figure 7: Multi bunch mode WCM2 trace: Entire pulse train (left) and detail (right).

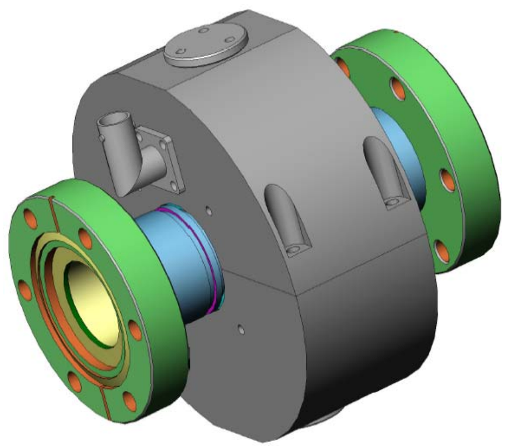
实例： SSRF



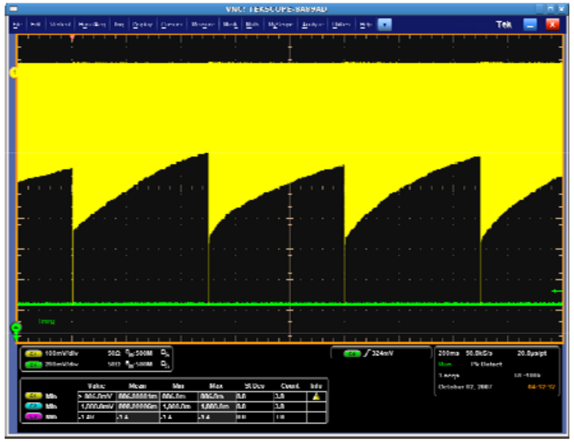
因阻抗匹配不理想，对于短束团，尾部出现反射信号，难以用于纵向分布观测，仅能用于相对强度测量





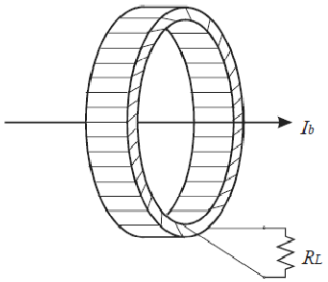


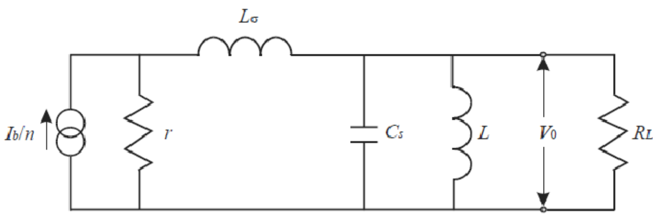
实例：壁电流检测器在增强器调束中的应用

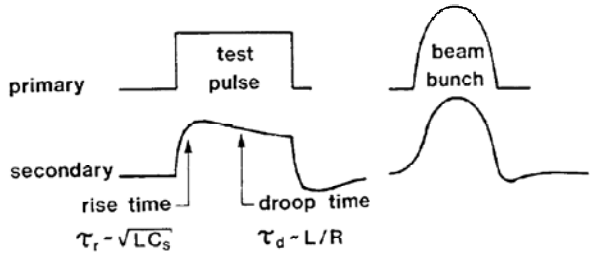


电流变压器：基本工作原理

- 磁芯上的二级线组耦合出电流信号，通过分析此信号获得原始束流强度信息
- 检测器频幅响应由L、C_S参数确定
- 高起始磁导率、低损磁芯材料，减小上升时间，FCT
- 优化R、L、C_S参数，展宽输出信号，输出电流脉冲积分正比于束团电荷量，ICT
- 输出端引入运算放大器反馈环路，改善低频特性，ACCT
- 优化L、C_S参数，检测器特征频率设定为束团谐振频率，降低输出信号幅度与束团长度之间的依赖关系，TCT
- 磁调制、零磁通反馈，低频响应扩展至DC，DCCT







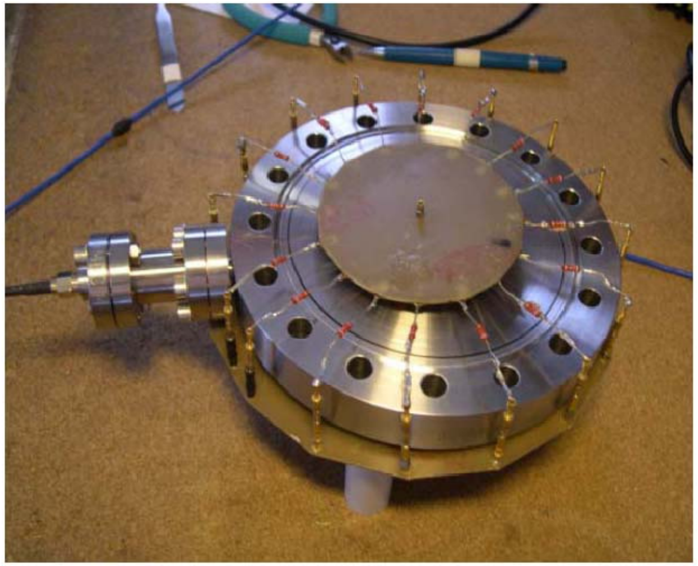
快速电流变压器

法国的 Bergoz 公司采用一种新型的非结晶钴合金磁芯材料，经过特殊的退火处理，在 2GHz 频率得到非常高的起始导磁率和非常低的损失，由此制成了快速束流变压器（FCT）。下表给出了这种 FCT 的特性。

线圈匝数	100	50	20	10	5
灵敏度（V/A)	0.25	0.5	1.25	2.5	5
上升时间（ps)	600	300	200	300	500
线性误差（%)	<1	<1	<1	<1	<1
顶降（%/μs)	<1	<3	<6	<10	<20
涡流损失（%)	<15	<15	<15	<15	<15
L/R 时间常数（μs)	<100	<35	<17	<10	<5

谐振式电流变压器

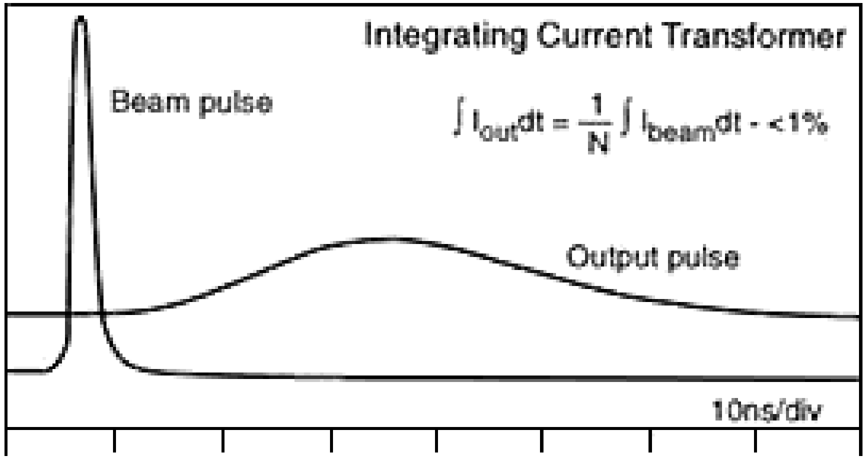
- It is not yet used in the medical field, but installations at heavy ion research institutes RIKEN and GANIL demonstrated sub-nanoamp beam current measurement



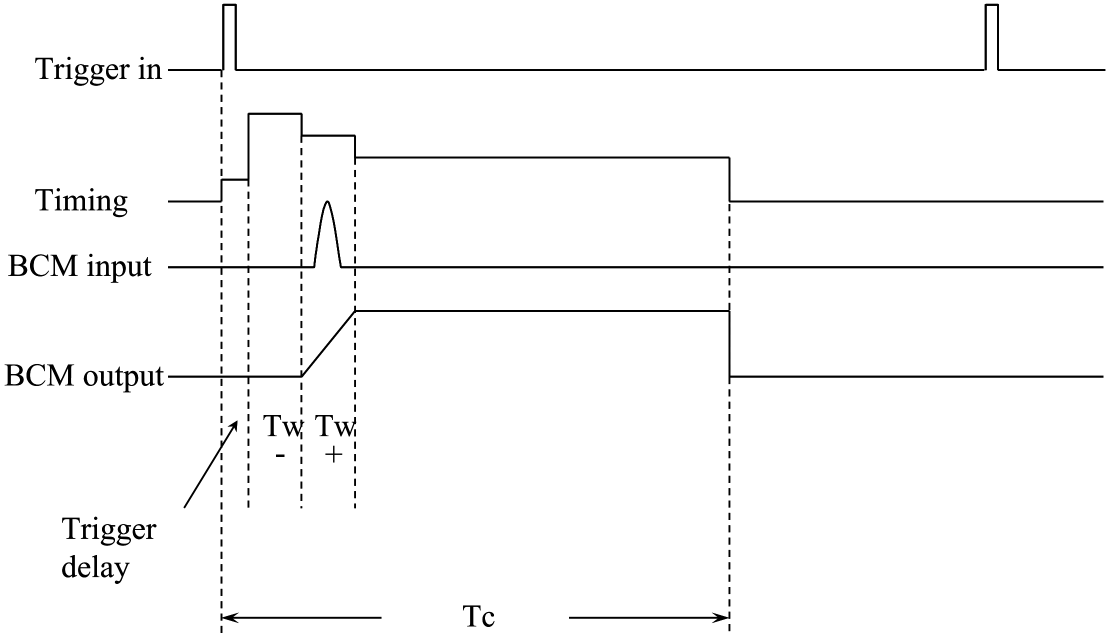
www.bergoz.com

STATUS OF BEAM DIAGNOSTIC SYSTEMS FOR THE PEFP
Sung-Ju Park, Jangho Park, Yong Woon Parc，PAC05

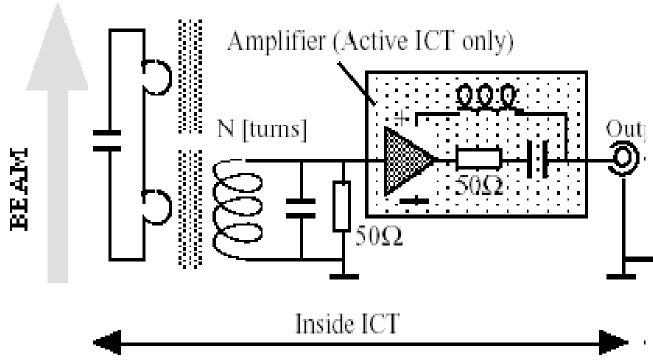
积分电流变压器及前端电子学



Bergoz ICT & BCM circuit



积分电流变压器：示波器直接采样处理

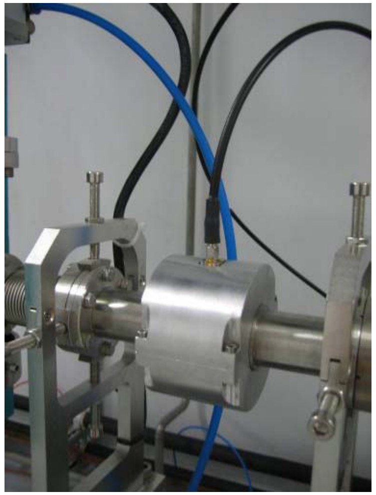


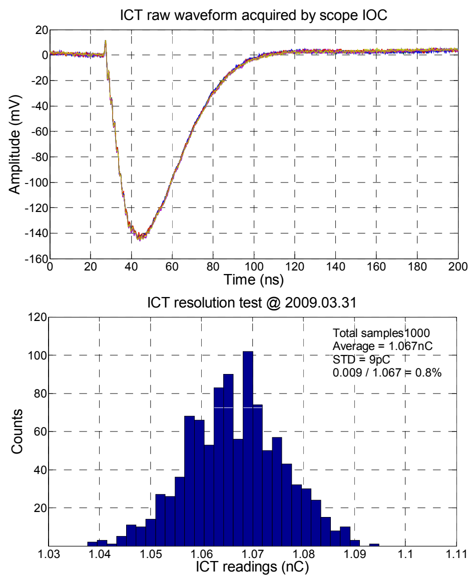
Scope embedded IOC

TEK DPO7054

BW 500MHz

Bergoz ICT



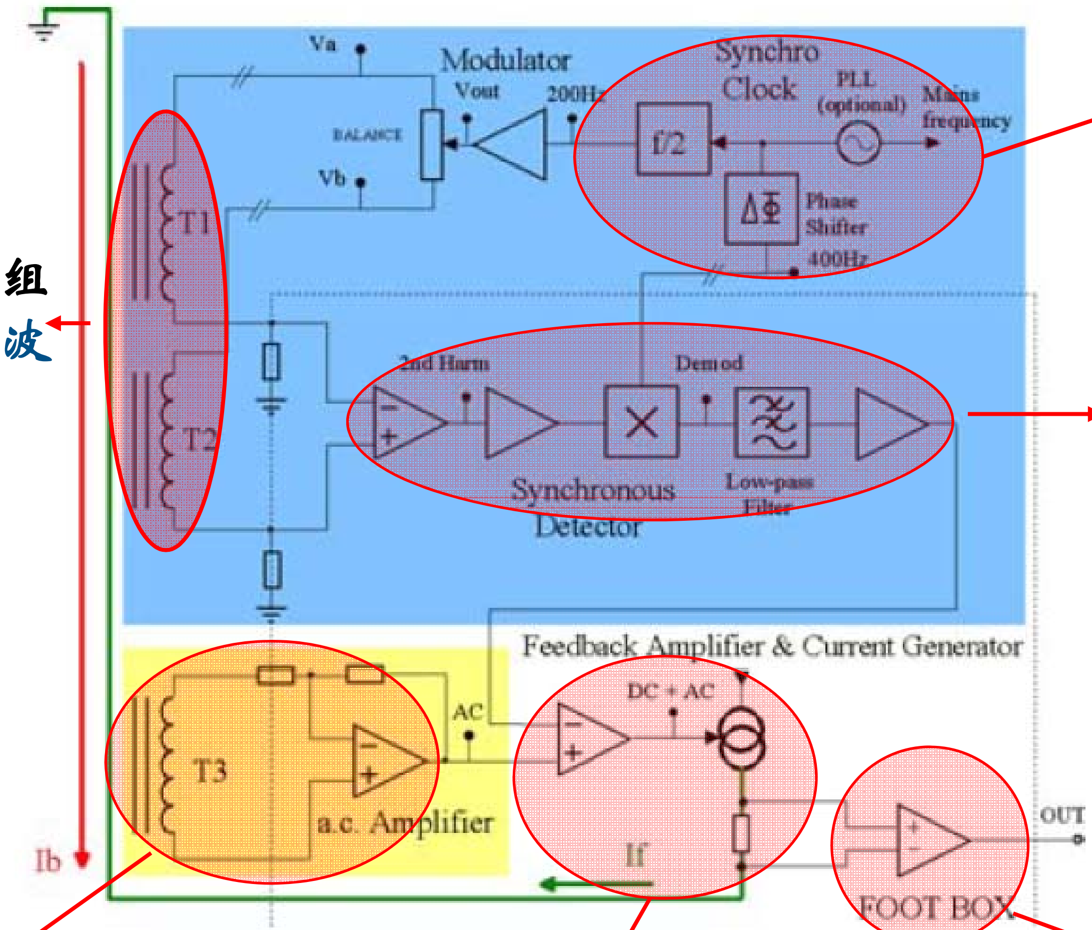


1000 samples **RMS: 0.009/1.067nC = 0.8%** **P-P: 0.06/1.067 = 5%**

直流流强变压器：基本原理

- DC Current Transformer，直流电流变压器，用于直流信号以及低频信号的精密测量
- 带宽通常为DC-几十kHz，用于平均流强测量以及流强慢变化的检测（注入效率、束流寿命）
- 核心器件为磁调制器
- 基本测量原理是采用非线性磁调制元件将待测DC信号调制到激励信号的二次谐波进行检测
- 具体精密检测技术采用的是包括反馈环路的零磁通检测技术
- 反向平衡激励线组在输出信号中消除奇次谐波分量

直流流强变压器：基本原理



激励信号

反相平衡绕组
消除奇次谐波

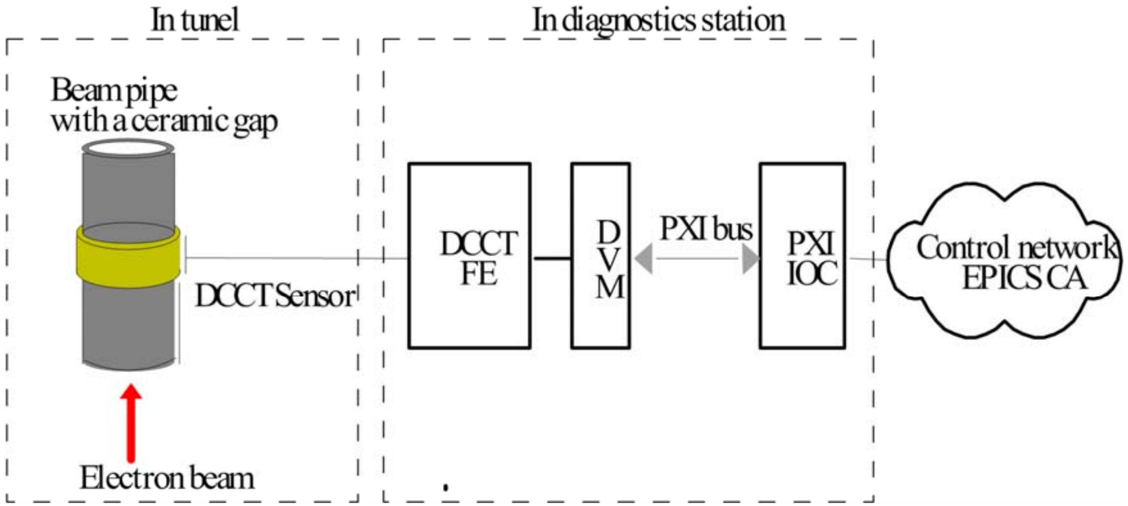
同步解调电路
二次谐波检测
DC分量检测

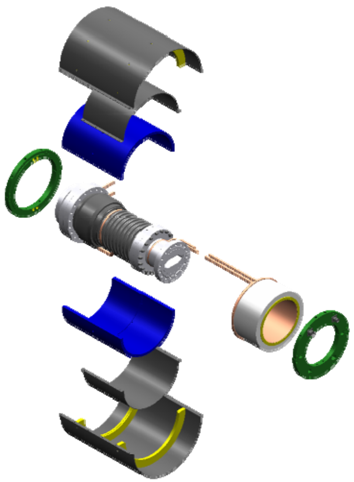
AC分量检测回路

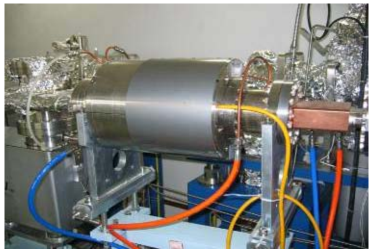
反馈零磁通平衡

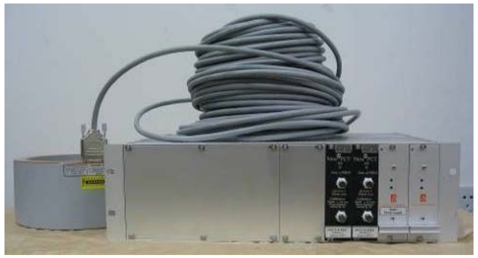
反馈电流检测回路
信号读出

DCCT实例：上海光源储存环平均流强测量









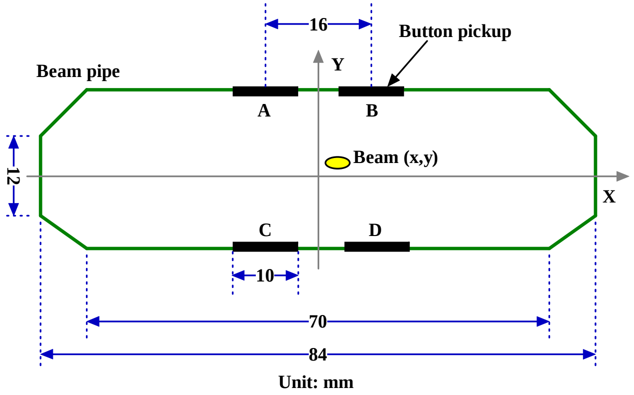
Shield design borrowed from SPEAR3

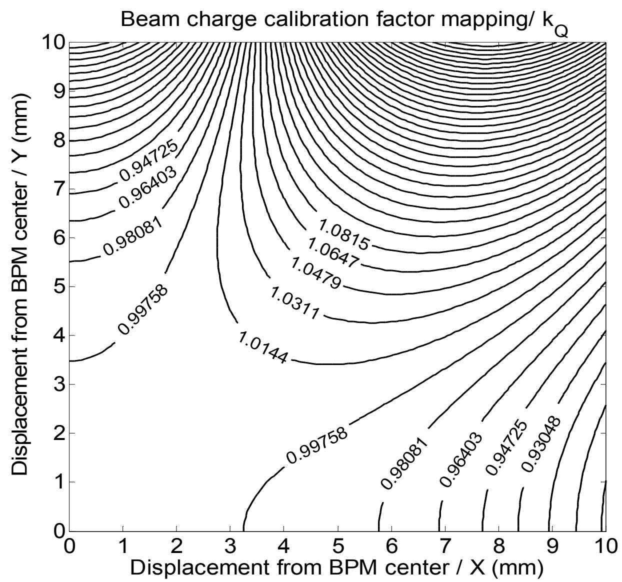
Bergoz NPCT175

NI 4070
DVM

NI 8187
PXI controller

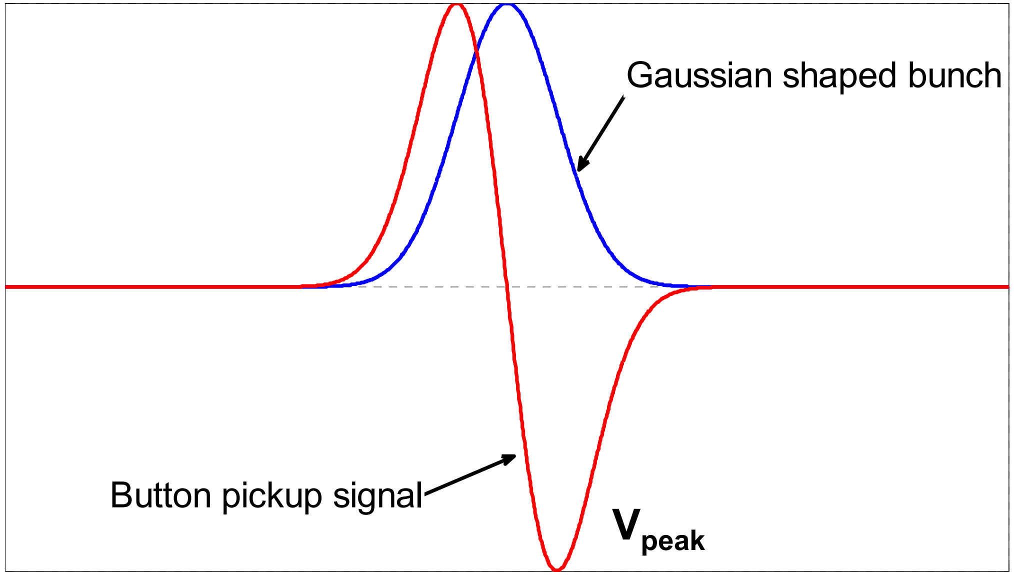
BPM和信号用于流强测量：基本原理





K mapping

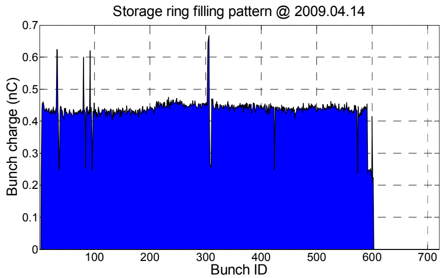
$$q(t) = \frac{Q_0}{\sqrt{2\pi\sigma}} \exp(-\frac{t^2}{2\sigma^2})$$

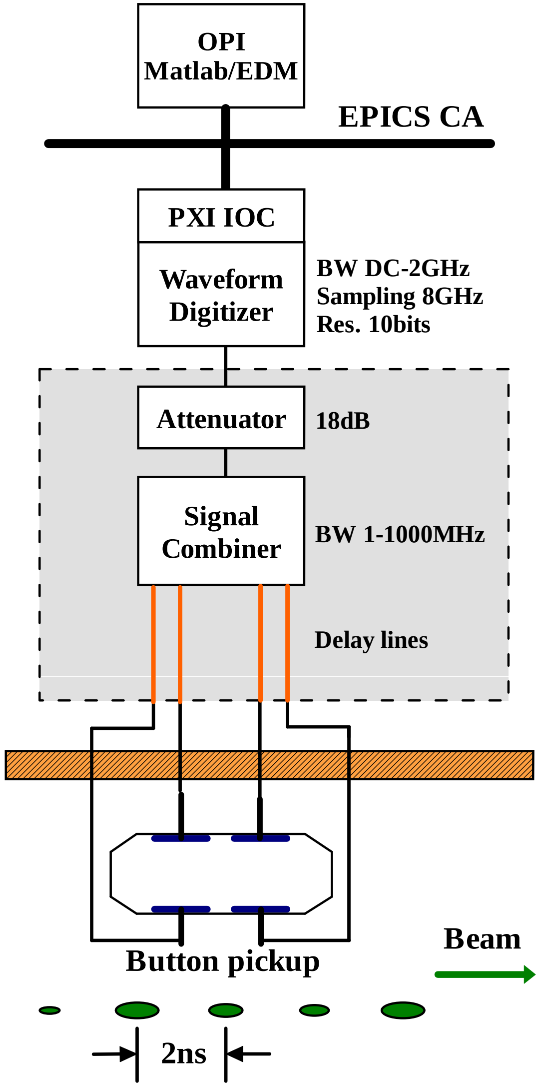


$$V_{peak} = k(r,\theta) \cdot Z \cdot \sqrt{\frac{e}{2\pi}} \frac{Q_0}{\sigma^2}$$

$$V_{peak} = K_Q \cdot Q_0, K_Q = k_0 \cdot Z \cdot \sqrt{\frac{e}{2\pi}} \frac{1}{\sigma^2}$$

BPM和信号+波形记录仪：BCM @ ring





Button pickup
Acquire beam signal, RF = 499.654MHz

Delay line
Compensate phase difference of signals form 4 buttons

Signal combiner
Filter out beam position independent intensity signal

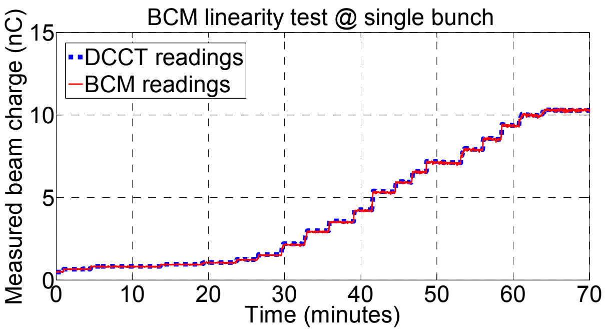
Attenuator
Adjust signal level of FE output to ADC input range

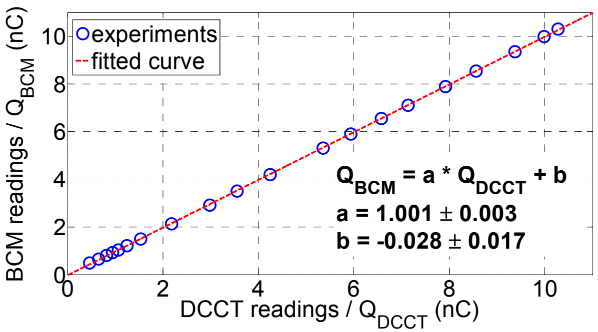
Waveform digitizer
ADC @ BW 2GHz, sampling rate 8GHz, resolution 10bits

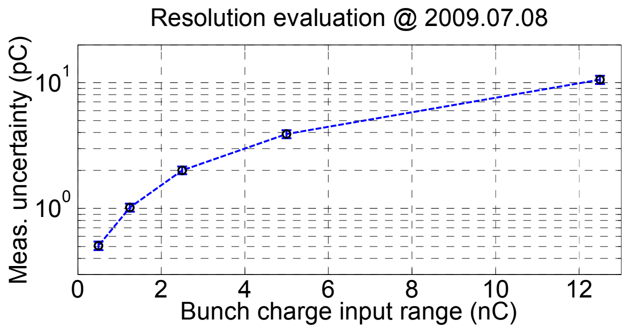
IOC
Rebuild waveform, calculate bunch charge

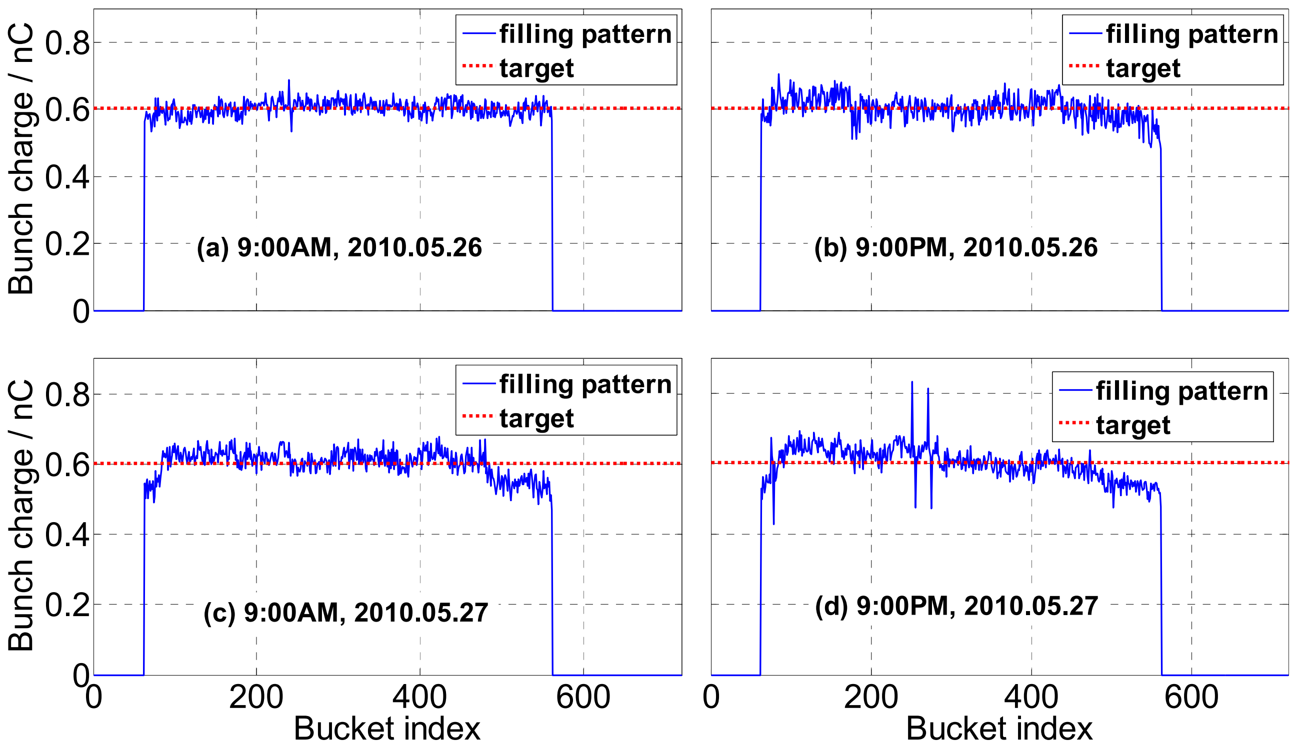
OPI
Provide human interface

BPM和信号+波形记录仪：标定及实验

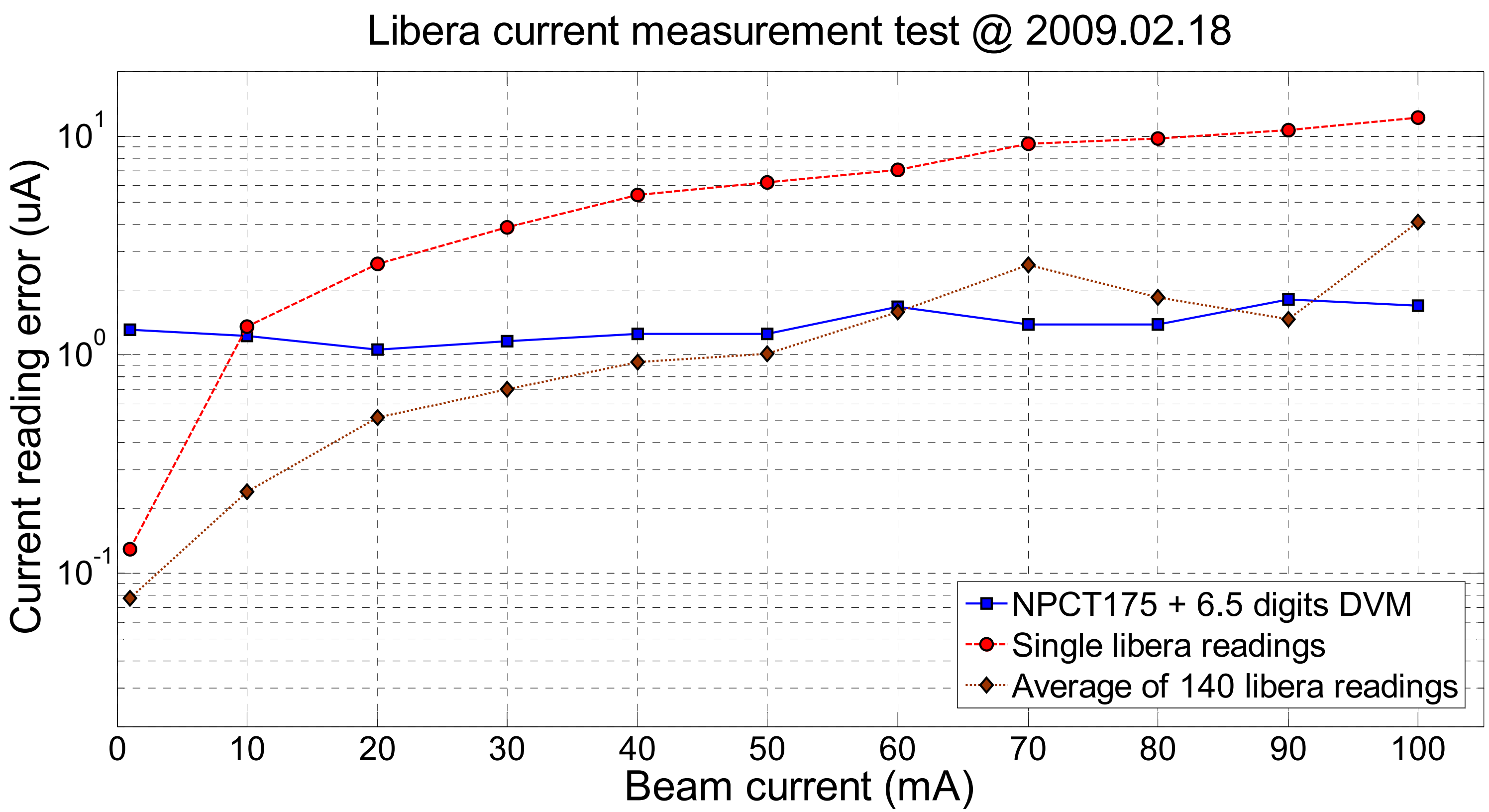






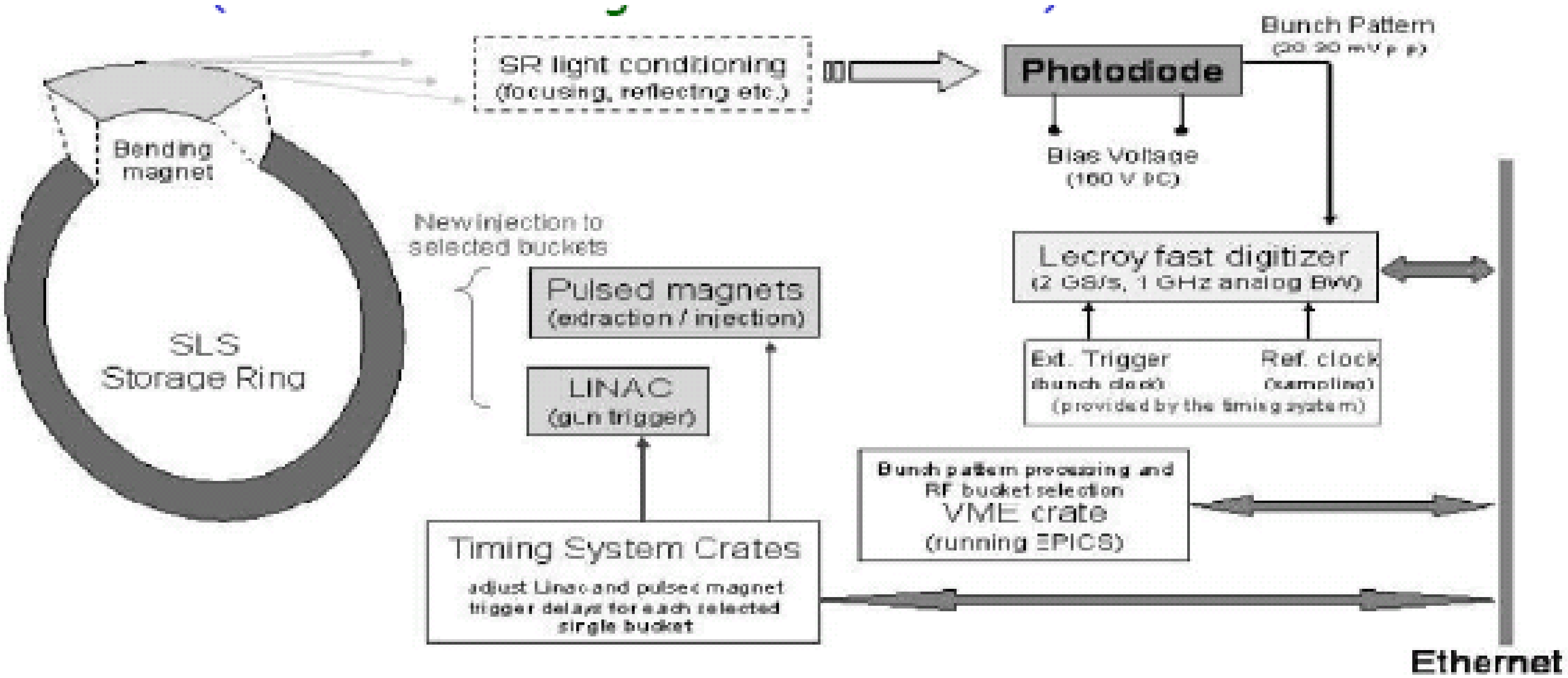


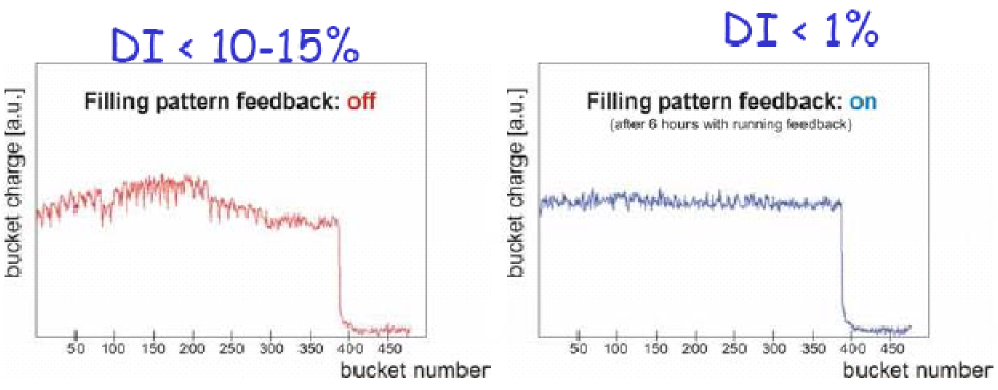
BPM和信号+Libera -> 平均流强



- **DCCT**探头在不同流强时的分辨率近似为常数（**<2μA**），主要限制为电子学噪声；
- 单个**BPM**探头用于流强测量时，流强分辨率在**10mA**以下优于**DCCT**，在**10mA**以上差于**DCCT**；
- 对全环**BPM**（对于上海光源为**140**个）流强数据求平均可以进一步提高测量分辨率，**60mA**以下优于**DCCT**，而**60mA**以上略差于**DCCT**。

同步光+Photodiode+scope -> bunch charge

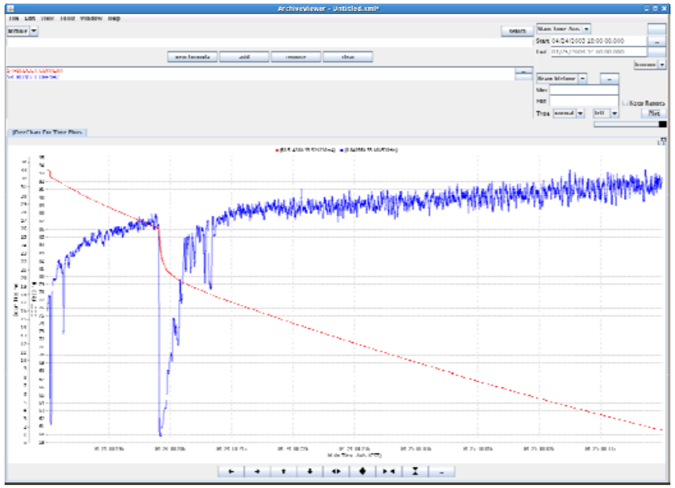




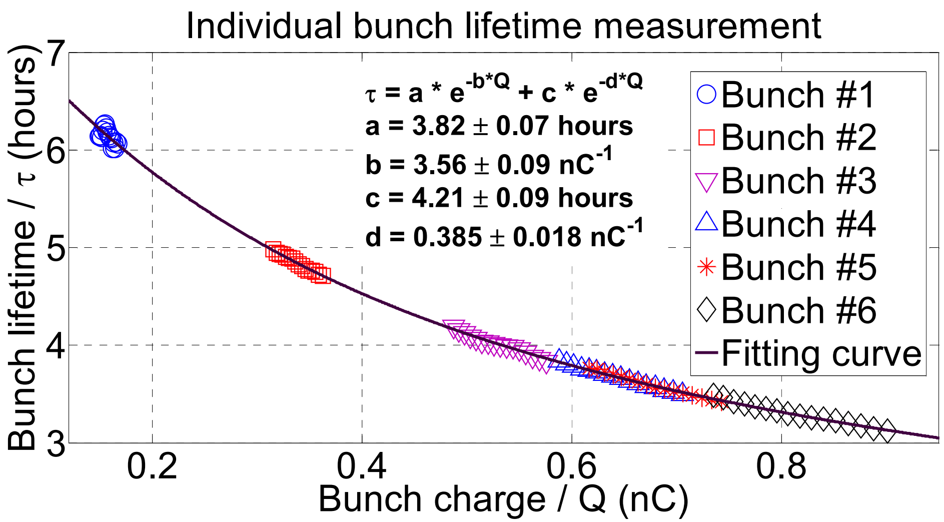
EPAC'04, Kalantari et al., SLS

束流寿命测量

$$I(t) = I_0 \bullet e^{-t/\tau} \approx I_0 \bullet (1 - t/\tau)$$



DCCT，平均束流寿命



BCM，单束团束流寿命

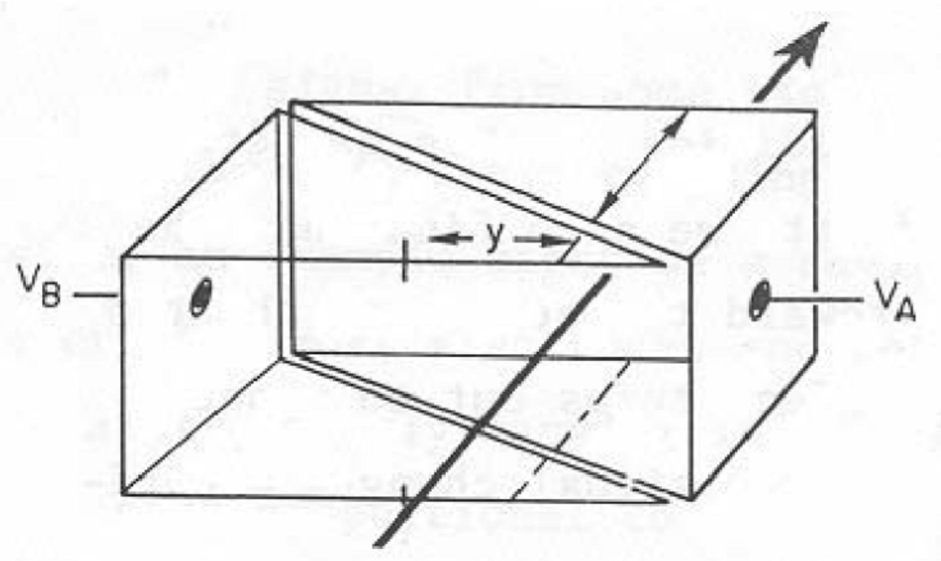
束流位置测量
beam position measurement

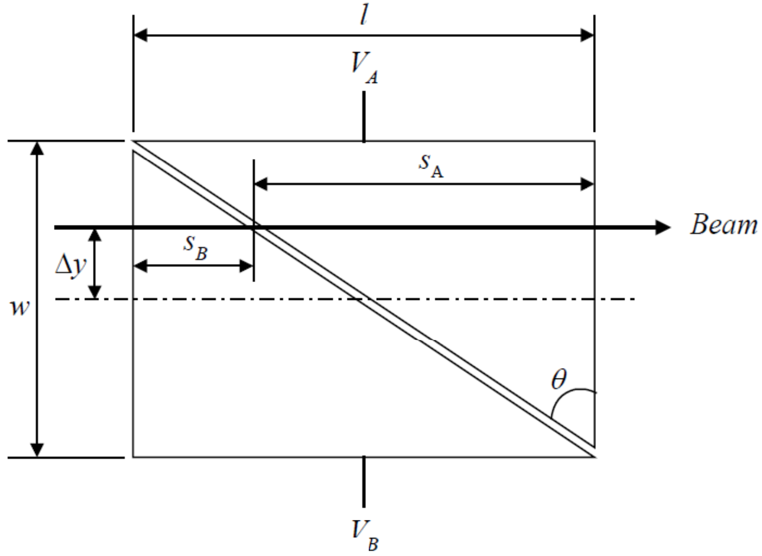
常用束流位置测量设备

- 静电感应型位置检测器 (electrostatic BPM)
- 钮扣电极型位置检测器 (button BPM)
- 条带形位置检测器 (stripline BPM)
- 腔式位置检测器 (Cavity BPM)，篇幅所限，从略
- 光子位置检测器 (Photon BPM)，篇幅所限，从略
- 荧光靶/OTR靶
- 同步光成像
- 丝靶
- 刮束器

（荧光靶/OTR靶、同步光成像、丝靶、刮束器：下一小节介绍）

静电感应型位置检测器



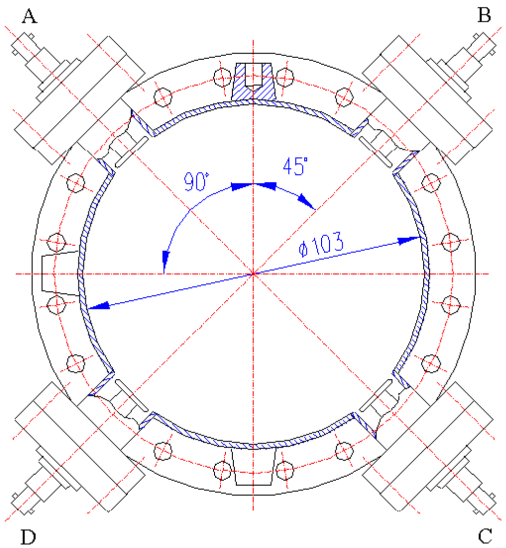


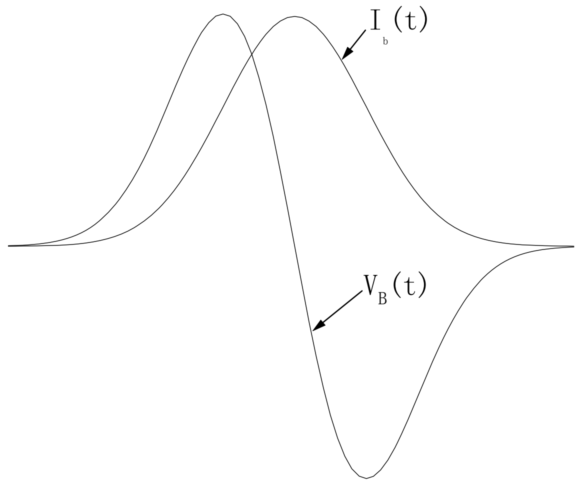
$$U = \frac{V_A - V_B}{V_A + V_B}$$

$$\Delta y = \frac{w}{2} \cdot U$$

- 检测电压信号幅度正比于S，全孔径内线性优良
- 高灵敏度
- 质子加速器中广泛应用
- 体积较大

钮扣型位置检测器



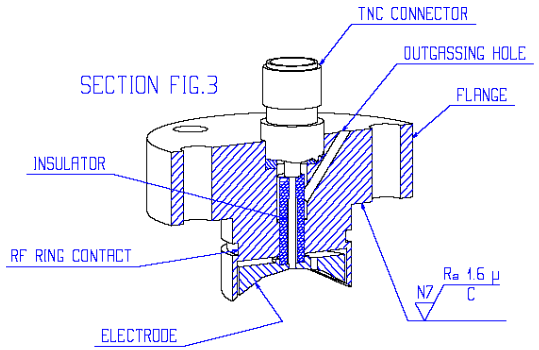


$$V_B(t) = \frac{-eN}{(2\pi)^{3/2}} \frac{\varphi l R}{\beta_b c} \frac{t}{\sigma^3} \exp\left(-\frac{t^2}{2\sigma^2}\right)$$

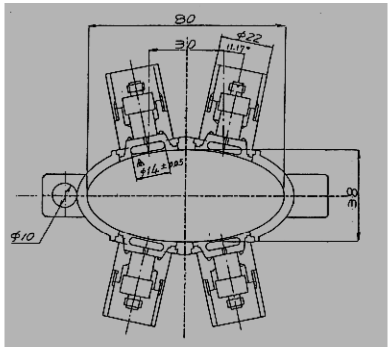
- 响应较快
- 线性区较小
- 较多用于电子/正电子环形加速器中
- 结构紧凑

$$\left.\begin{aligned} &\hat{V}_{A,B,C,D} \approx \frac{d^2}{8a} \cdot \frac{R\bar{I}c}{\sqrt{2\pi e}\,\sigma_z^2 f_0} F(\delta, \theta_{A,B,C,D}) \\ &\delta = \sqrt{x^2 + y^2} \\ &\theta_{A,B,C,D} = n\frac{\pi}{4} - \tan^{-1}\left(\frac{y}{x}\right) \end{aligned}\right\}$$

button electrode for use between the undulators of the TTF II SASE FEL (courtesy D. Noelle and M. Wendt, 2003)

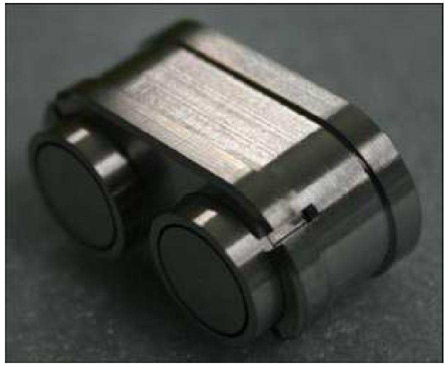


LHC



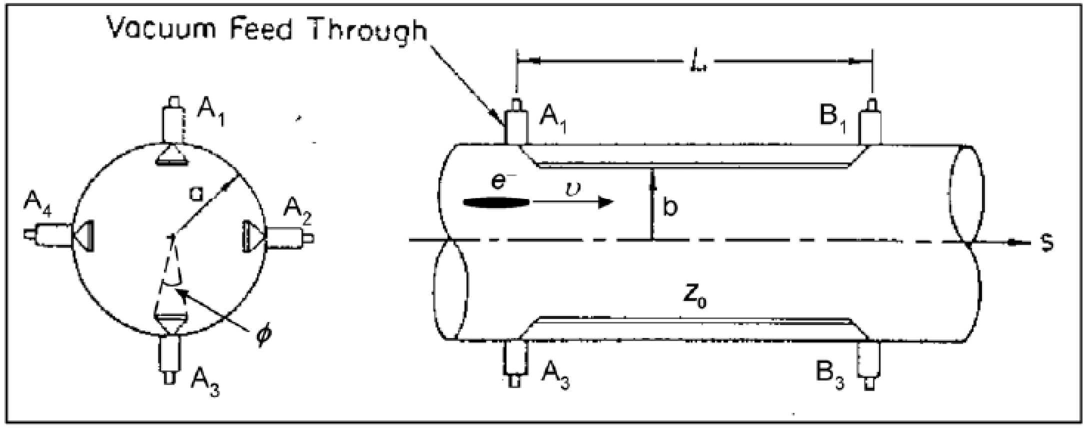
TLS

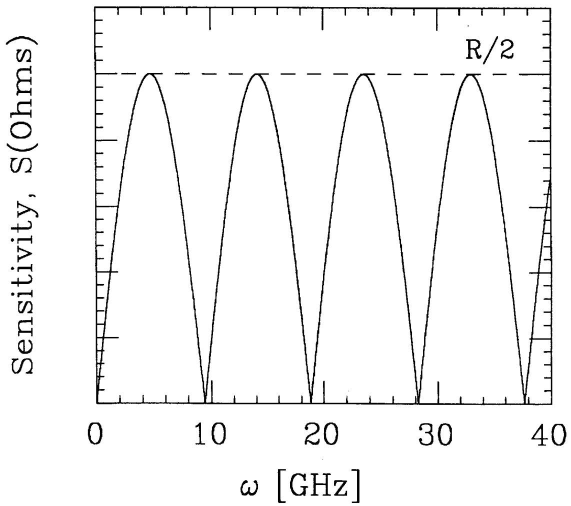
BEPC II



SSRF

条带型位置检测器





条带电极输出电压信号

$$u(t)=\frac{Z_0}{2}\cdot\frac{\phi}{2\pi}\cdot\left[i_b(t)-i_b(t-\frac{2L}{c})\right]$$

纵向耦合阻抗

$$Z_c(j\omega)=\frac{V(j\omega)}{I_b(j\omega)}=Z_0\frac{\phi}{2\pi}\sin\frac{\omega L}{c}e^{j(\frac{\pi}{2}-\frac{\omega L}{c})}$$

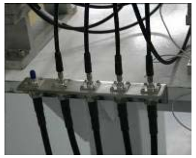
- 输出双极脉冲
- 输出信号幅度大于钮扣型检测器
- 较多用于直线加速器或束流输运线中
- 可用于束团纵向分布观测

实例：上海光源储存环束流位置测量系统

技术走廊束测本地站
数字化BPM处理器
电缆转接端子

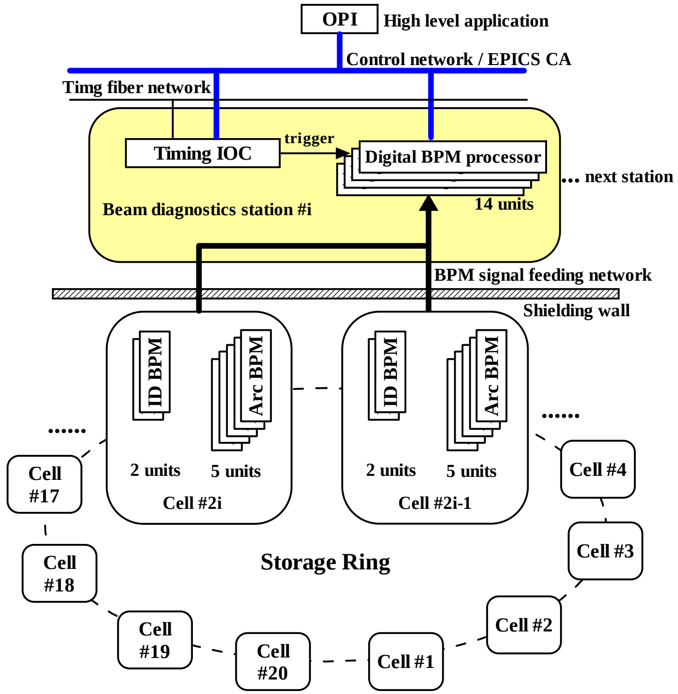


隧道内电缆转接端子
及主信号电缆架




每单元2个高精度
BPM探头及5个常
规BPM探头

纽扣型双电极BPM探头组件

工作点测量
tune measurement

基本测量原理

工作点定义为每圈的β振荡数ν $\nu = \frac{\phi(L)}{2\pi} = \frac{1}{2\pi}\oint_L \frac{ds}{\beta(s)}$ **= N + q**

无激励时束流横向运动简化模型

$$u(t) = u_{orbit} + u_{calib.\ offset} + u_\beta(t) + u_\delta(t) \quad + u_{noise}$$

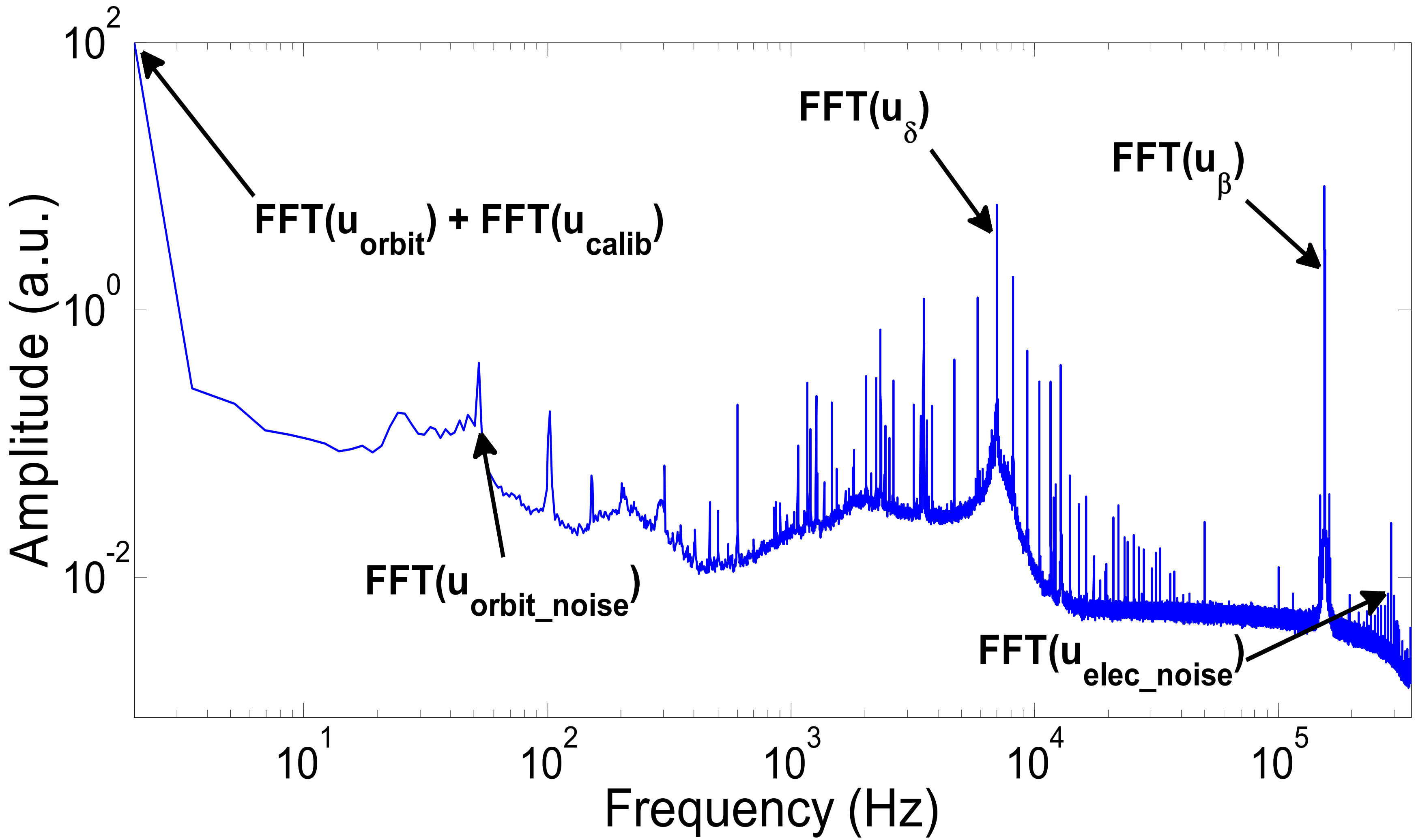
$$\begin{cases} x_\beta(t) = A_x \cos\omega_{\beta x} t \\ y_\beta(t) = A_y \cos\omega_{\beta x} t \end{cases}$$

$u_\beta(t)$为主导项时，直接测定束流频谱即可得到**tune**值

外加激励时的受迫振荡 $$u(t) = \frac{q^2\omega_0^2\beta_j^{3/2}\beta^{1/2}}{q^2\omega_0^2 - \omega_j^2}\frac{e}{E_0}E_{jm}\cos\omega_j t$$

孙葆根博士，束测技术讲义

基本测量原理：SSRF束流频谱



工作点测量系统的主要应用

- 工作点测量
- 色品测量

  Tune相对高频频率的变化
- 阻抗测量

  Tune相对于束流流强的变化
- 聚焦强度非线性效应研究

  Tune相对于beta振荡振幅的变化
- Beta函数测量

  Tune相对于聚焦铁强度的变化
- 耦合度测量

  Beta振荡振幅比

Beam Diagnostics and Applications，A. Hofmann，BIW1998

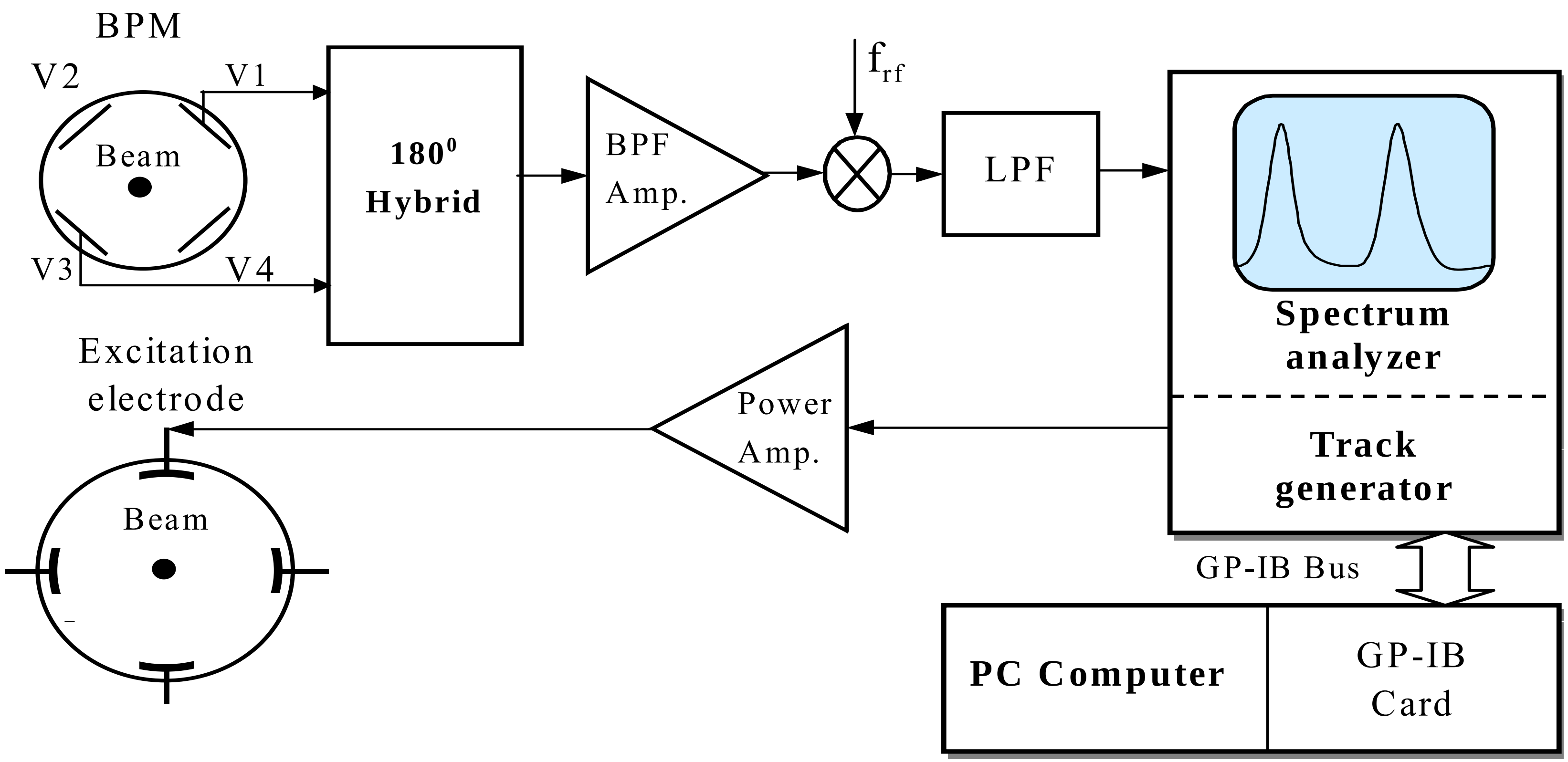
工作点测量的主要方法

	主要优点	主要缺点
扫频法	测量精度高 对激励信号总功率要求较低	采样时间长 对束流扰动较大
FFT法	数据处理方法灵活 系统结构简单（现代） 采样时间短，数据刷新率高 对束流扰动较小	白噪声激励时对激励信号总功率要求较高，现代高速高精度采集技术及数字信号处理技术发展前测量精度相对较低
锁相环法	可及时跟踪工作点的变化 测量精度高，数据刷新率高	需特殊硬件实现 对束流扰动最大

Tune and Chromaticity Measurements in LEP，H. Schmickler，BIW1992

工作点测量的主要方法：扫频法

基本思想：在频域逐点测出束流的频幅响应曲线，根据局部极大值确定工作点

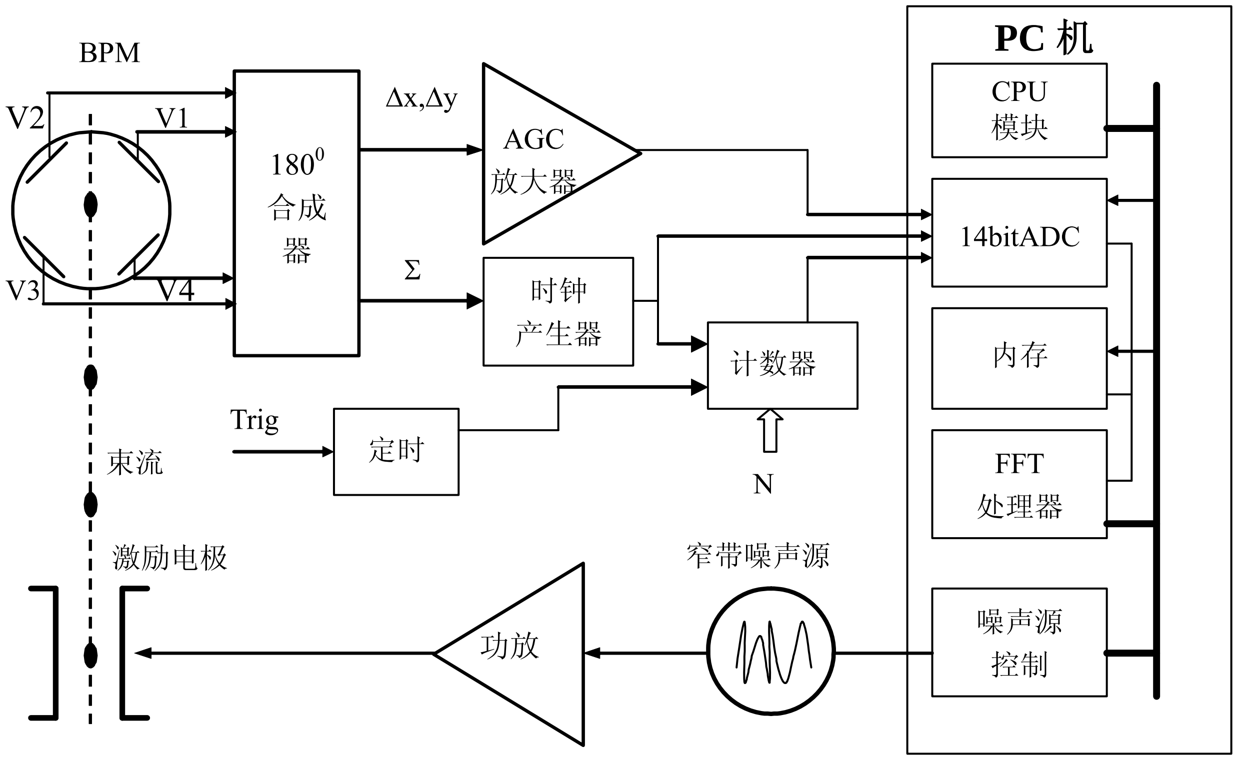


合肥光源Tune测量系统（旧）

孙葆根博士，束测技术讲义

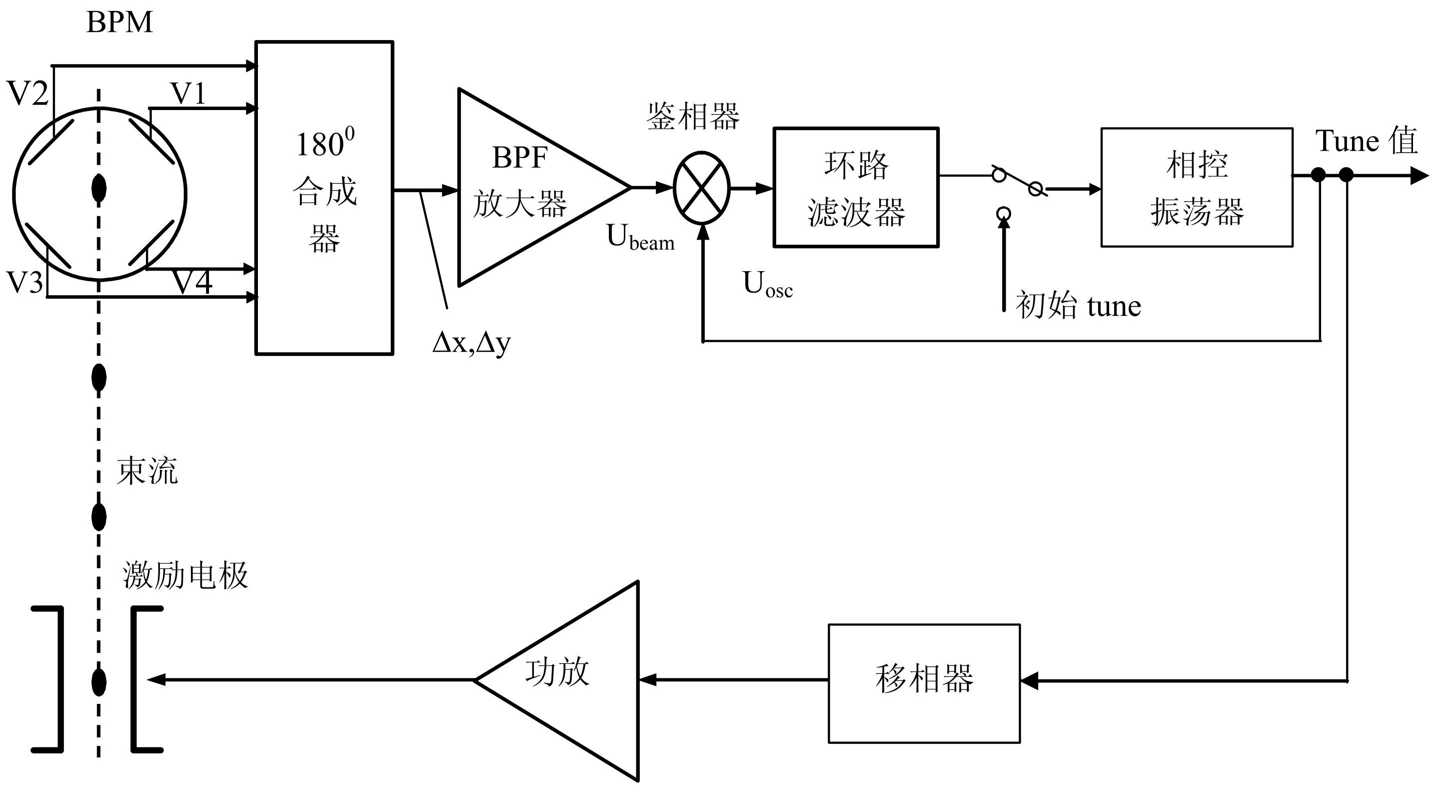
工作点测量的主要方法：FFT法

基本思想：对横向束流信号进行谐波分析，根据共振峰位置确定工作点



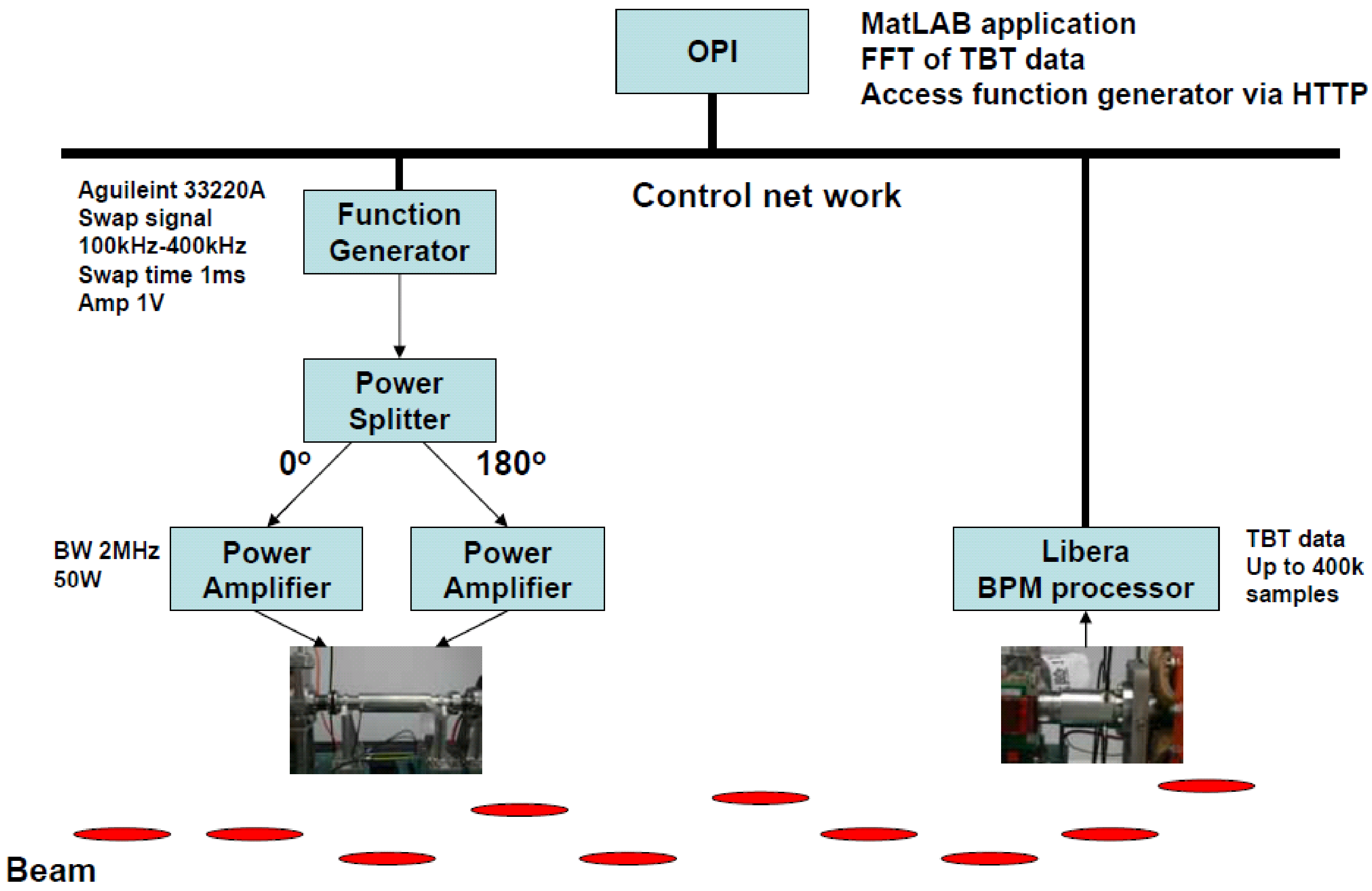
COSY的 FFT法工作点测量系统　　　　孙葆根博士，束测技术讲义

基本思想：采用带鉴相器的频率反馈回路锁定共振频率，反馈频率即为工作点



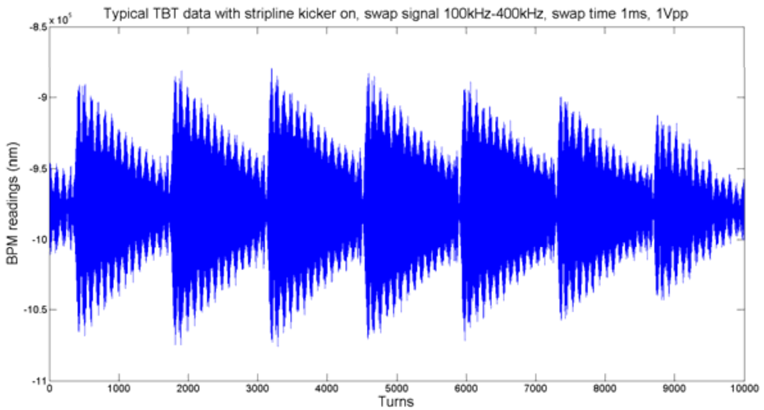
CERN锁相环法工作点测量系统　　　　孙葆根博士，束测技术讲义

实例：SSRF工作点测量系统

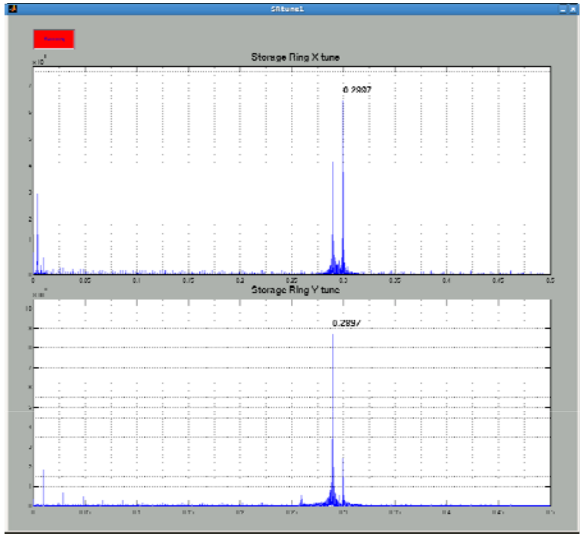


Configuration is the same for Booster and Ring

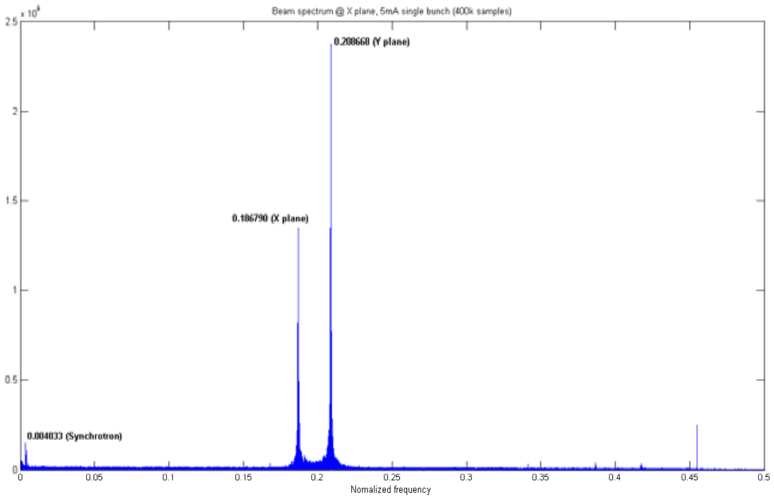
实例：SSRF工作点测量系统



Typical TBT data during tune measurement



Daily operation panel

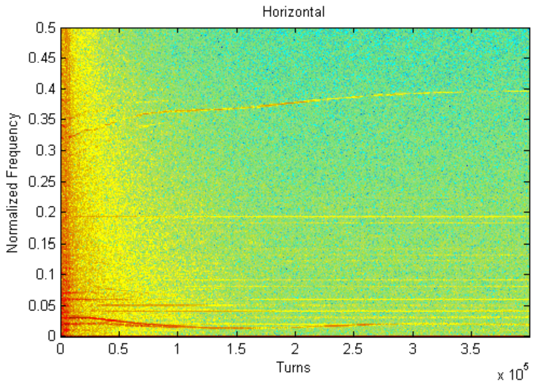


Precise tune measurement

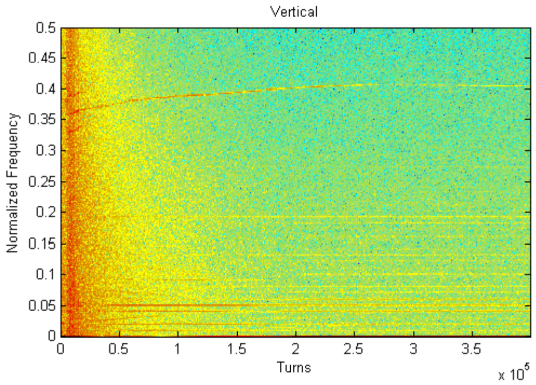
Daily operation:
FFT of 10k TBT data, uncertainty < E-4

Precise measurement:
FFT of 400k TBT data, uncertainty < E-5

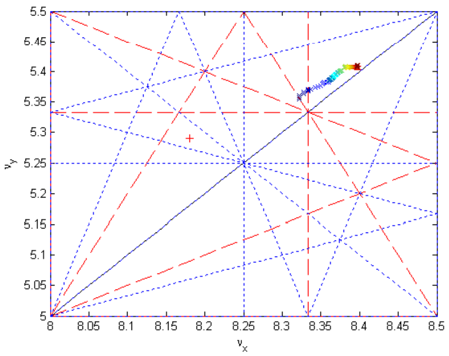
实例：SSRF工作点测量系统



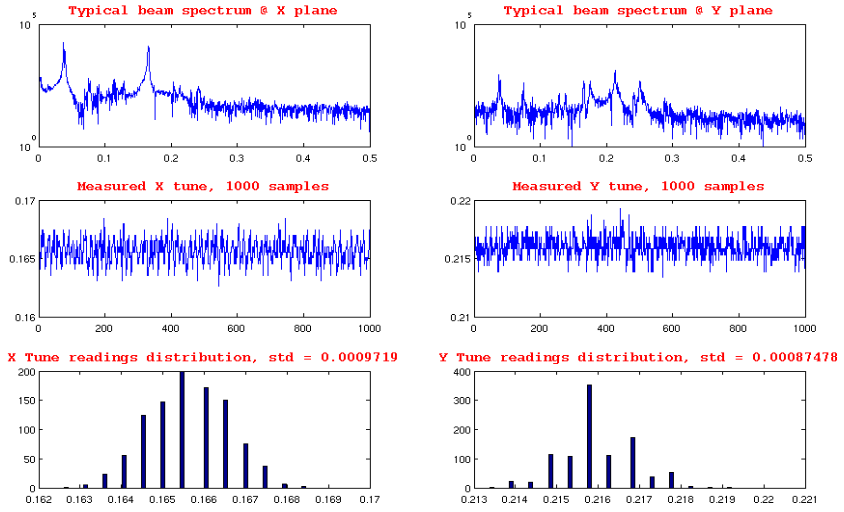
Horizontal ramping tune



Vertical ramping tune



Tune drift during ramping



TBT data 400k samples, cover 240ms
FFT windows size 2048, 1/1.23ms = 800Hz
Tune measurement uncertainty < E-3

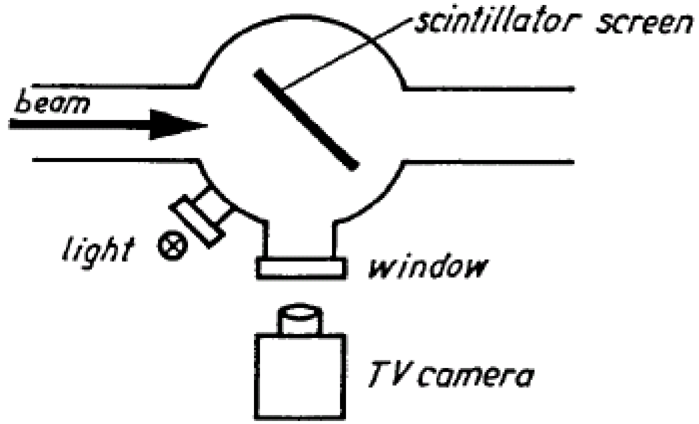
横向尺寸/分布测量
transverse beam size / distribution measurement

常用横向束斑分布测量设备

- 荧光靶/OTR靶
- 同步光成像
- 同步光空间干涉仪
- 丝靶
- 刮束板/刮束器，篇幅所限，从略

荧光靶

- 高能电子轰击荧光材料（Al_2O_3/YAG）后，被轰击部位释放荧光，光斑形状即反映了电子束团截面形状，采用成像系统采集处理光斑数据即可获得束团截面尺寸
- 存在荧光在多晶/单晶结构内的反射、折射问题
- 存在高流强射的饱和问题
- 存在转换效率/线性度问题



BEAM DIAGNOSTICS FOR ACCELERATORS，*H. Koziol*，CERN, Geneva, Switzerland

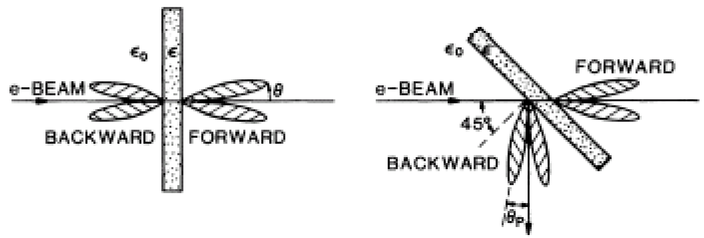
束流截面测量系统：基本测量原理

OTR靶

- 高能电子穿越不同电介质边界时所辐射电磁波，光斑形状即反映了电子束团截面形状，采用成像系统采集处理光斑数据即可获得束团截面尺寸
- 所有电子穿越靶片时均依照同样的机理辐射电磁波，近

$$\frac{d^2W}{d\omega d\Omega} \approx \frac{e^2}{\pi^2 c}\cdot\frac{\theta^2}{(\theta^2+\gamma^{-2})^2}\times F(\psi,\theta,\omega) \qquad N = \frac{2\alpha}{\pi}\left|\ln(2\gamma)-1/2\right| \ln \omega_2/\omega_1$$

- 连续谱，不单色则存在色散问题
- 信号较弱



a.) NORMAL INCIDENCE

b.) OBLIQUE INCIDENCE (φ = 45°)

ADVANCED, TIME-RESOLVED IMAGING TECHNIQUES FOR ELECTRON-BEAM CHARACTERIZATIONS*
Alex H. Lumpkin，Physics Division, Los Alamos National Laboratory

束流截面测量系统：数据处理方法

束团截面尺寸的精确测量需要考虑如下因素：

1. 测定靶片材料冲击响应（点扩散函数PSF）
2. 测定靶片材料电子/光子转换线性度
3. 测定成像系统冲击响应（点扩散函数PSF）
4. 测定成像系统线性度
5. 分析成像系统色差对测量结果的影响
6. 分析成像系统景深误差对测量结果的影响
7. 标定CCD两像素间距在物平面的投影距离
8. 确定截面尺寸算法
9. 测定随机测量误差

其中1、3、5、6项引入的为系统误差，且都使测量结果偏大。2、4、7项引入系统误差，影响可能偏大、可能偏小。7、8两项确定随机误差大小，即系统分辨率。

束流截面测量系统：数据处理方法

- 对得到的图象数据进行X和Y方向的积分计算，得到束流截面在Y和X方向的分布曲线
- 束团截面尺寸的计算方法先后采用过半高宽法和高斯函数拟合法
- 半高宽法的优点是计算简单，计算速度快。但受背景噪声（基线）的影响较大
- 高斯拟合的优点是直接得到σ值，可以将黑电平设置较高，基本不受背景噪声/束团光晕的影响，但计算量较大

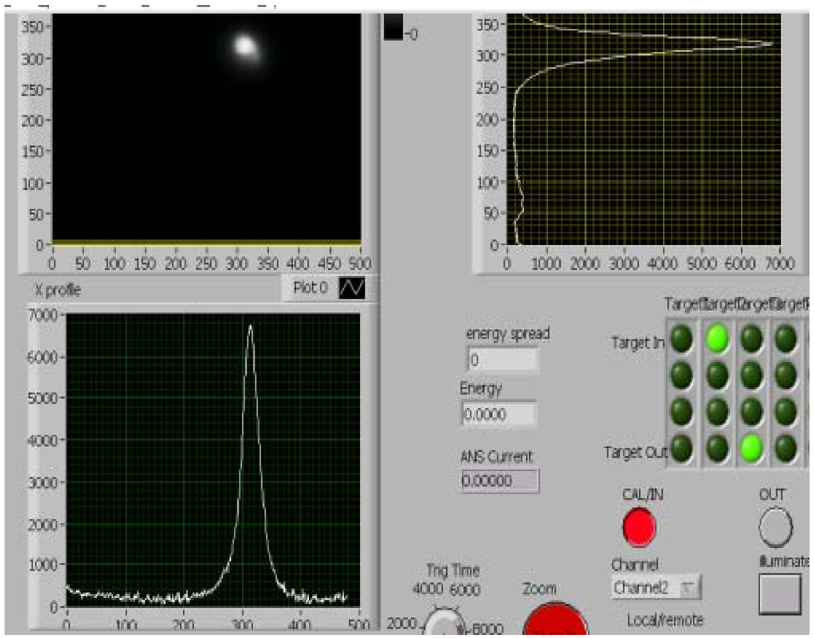
若电子束斑的截面分布服从高斯分布：

$$P(x) = \frac{A}{\sqrt{2\pi}\sigma} e^{\frac{-1(x-\mu)^2}{2\sigma^2}}$$

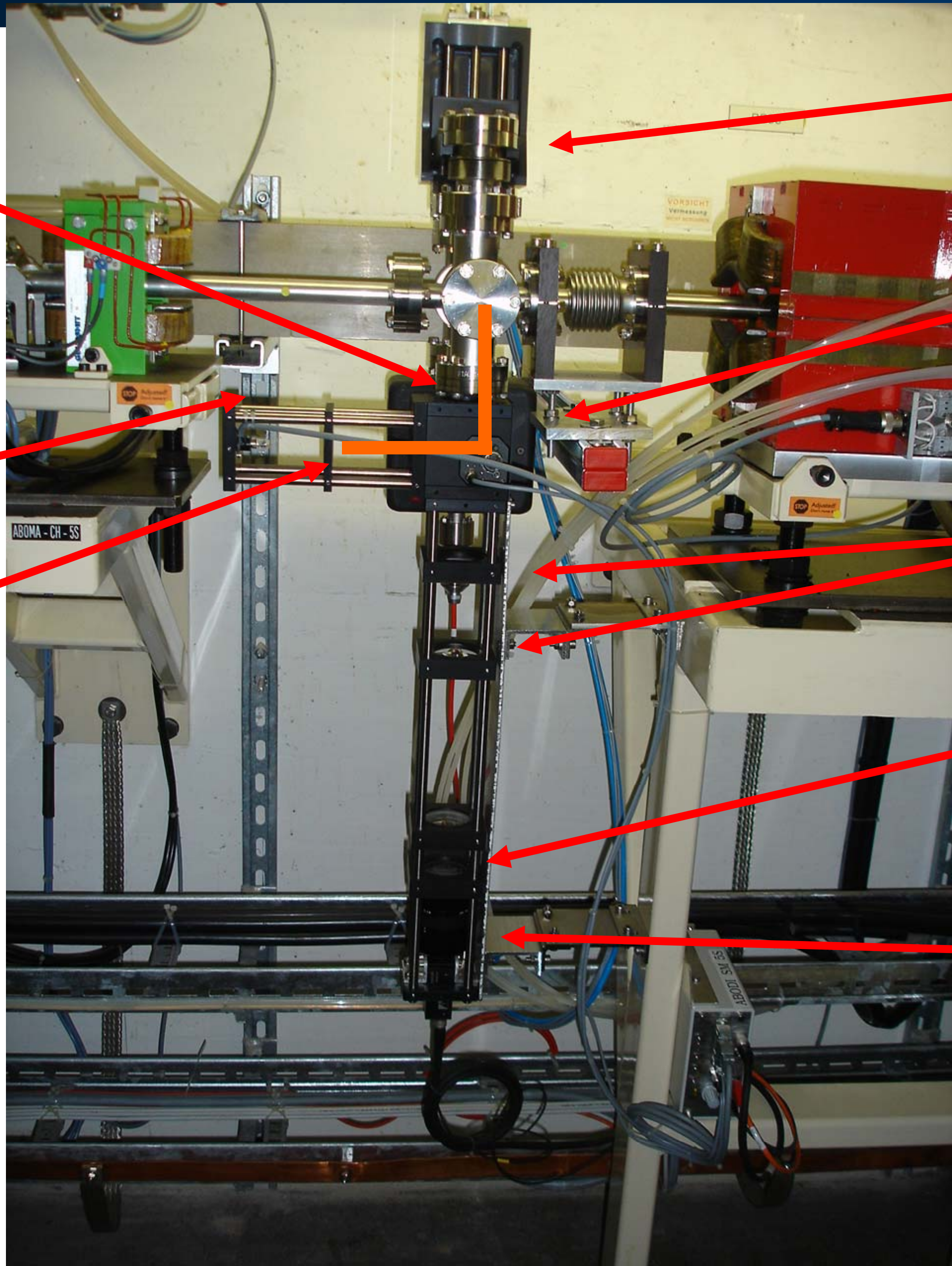
式中σ为标准方差

则半高全宽（FWHM）与σ的关系为

FWHM = 2.237σ



实例：SLS荧光靶



Actuator

等距

Moveable Mirror

Lamps

Lens

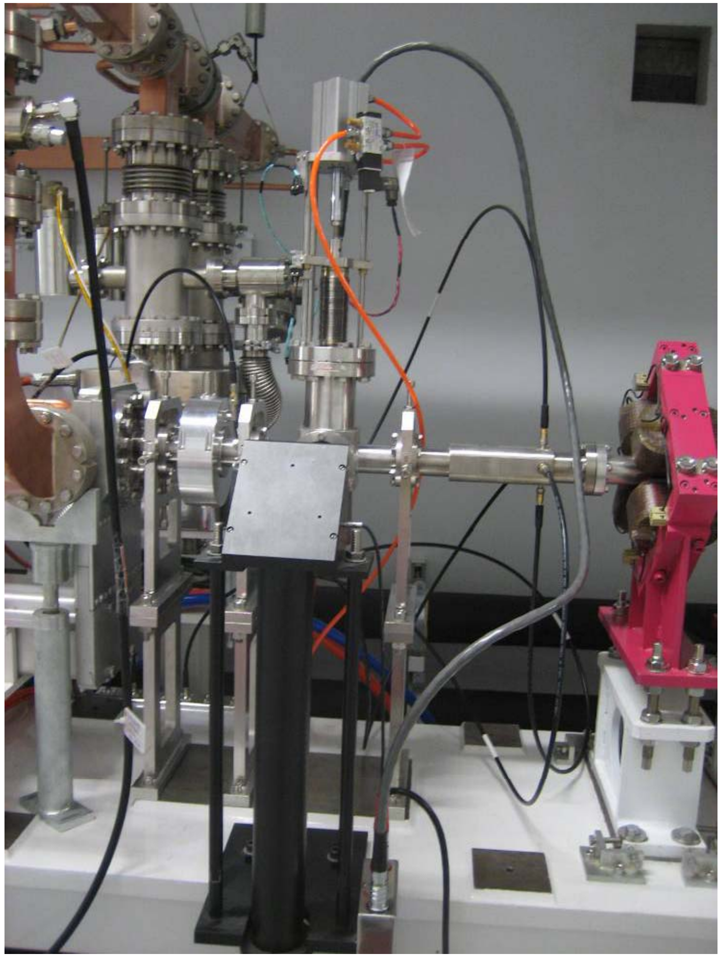
方格刻度

75 mm CCD Lens

Sony CCD

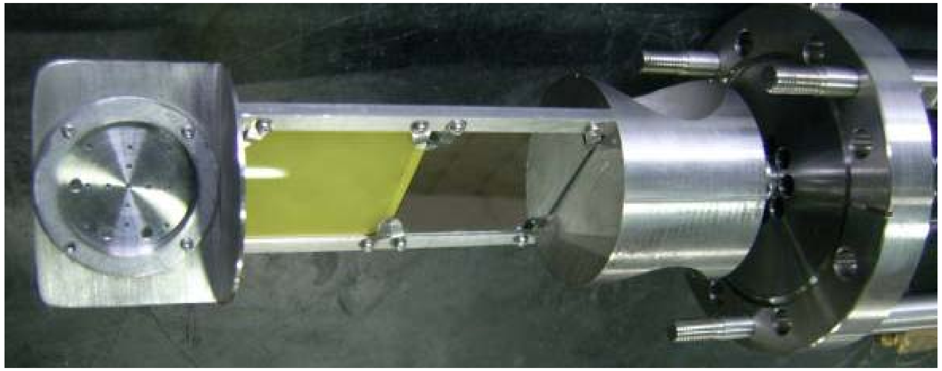
(SLS)

实例：SSRF直线加速器荧光靶



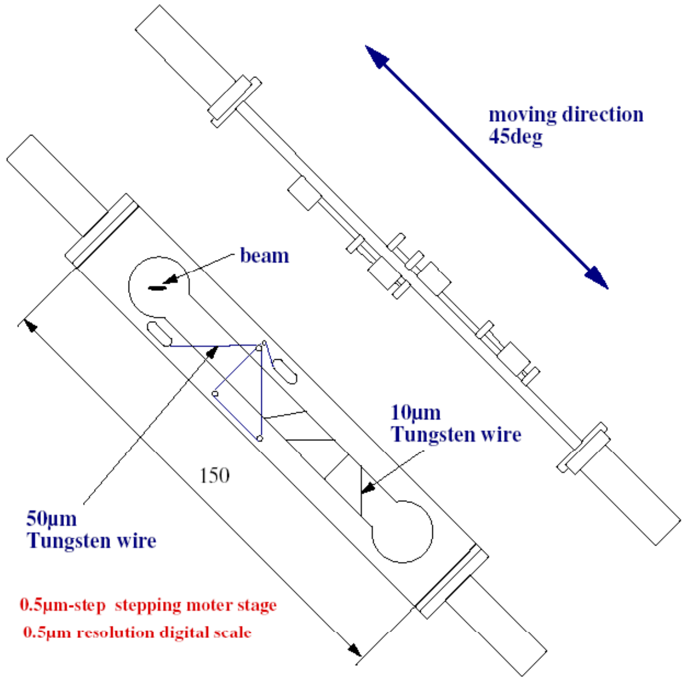
在加速器管以前截面探测器采用法国Desmarquest公司AF995R陶瓷荧光靶

在能量分析站上采用YAG/OTR多靶结构



丝扫描检测器（wire scanner）

principle: precision stage with precision encoder propels shaft with wire support
wires (e.g. C, Be, or W) scanned across beam (or beam across wire)
interaction of beam with wire detected, for example with PMT



wire velocity: depends on desired inter-point spacing and on the bunch repetition frequency

detection of beam with wire:

1. change in voltage on wire induced by secondary emission
2. hard Bremsstrahlung – forward directed γ's which are separated from beam via an applied magnetic field and converted to e+/e- in the vacuum chamber wall and detected with a Cerenkov counter or PMT (after conversion to γ's in front end of detector)
3. via detection at 90° (δ-rays)
4. using PMTs to detect scattering and electromagnetic showers

(5. via change in tension of wire for beam-tail measurements)

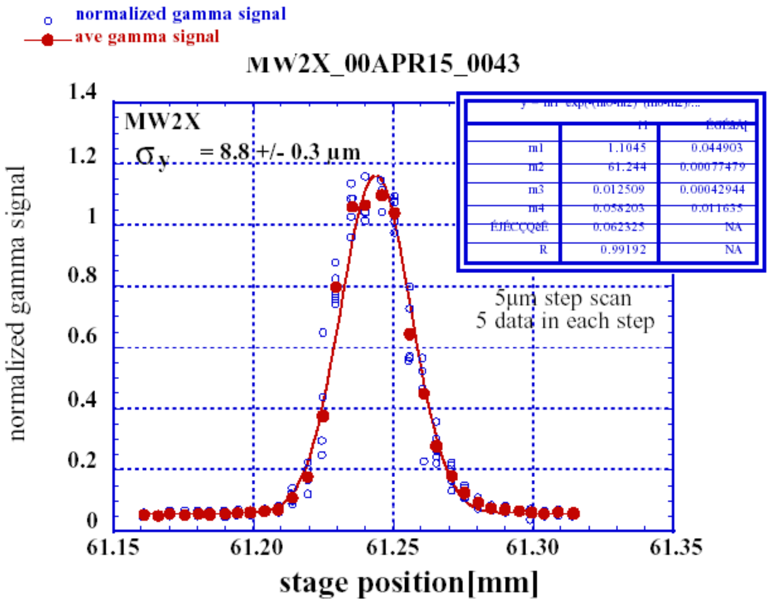
emittance measurement: as for screens (quad scan or 3-monitor method)

丝扫描检测器 （wire scanner）

issues:

- different beam bunch for each data point
- no information on x-y coupling with 1 wire (need 3 wires at common location)
- dynamic range: saturation of detectors (PMTs)
- single-pulse beam heating
- wire thickness (adds in quadrature with beam size)
- higher-order modes

(left) wire scanner chamber installed in the ATF (KEK) extraction line and (right) example wire scan (courtesy H. Hayano, 2003)



聚焦强度变换法

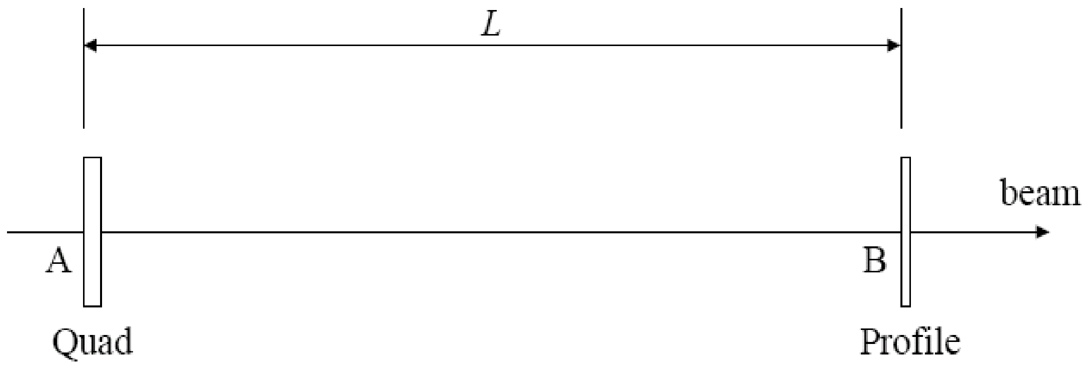


图 3-31 束流发射度的聚焦强度变换法测量设置

假设束流截面探头安放在 Q 铁下游的 B 点处，距离为 L，如图 3-31 所示，则在 B 点测得的束流 rms 半宽度可以用 Q 铁入口处 A 点的σ-矩阵元表示为

$$\sigma_{B11} = \sigma_{A11}\left(1 + \frac{\sigma_{A12}L}{\sigma_{A11}} - \frac{L}{f}\right)^2 + \frac{\varepsilon^2}{\sigma_{A11}}L^2 \qquad (3\text{-}32)$$

式中 f 为 Q 铁焦距，且

$$\frac{1}{f[\mathrm{m}]} = k[\mathrm{m}^{-2}]l[\mathrm{m}] = 0.2998\frac{g[\mathrm{T/m}]l[\mathrm{m}]}{p[\mathrm{GeV/c}]} \qquad (3\text{-}33)$$

其中 k，g 和 l 分别为 Q 铁的聚焦强度，场梯度和有效长度，p 为束流能量。

1. **Variable Quadrupole Strengths**
2. Multiple Profile Monitors
3. The “Pepper-Pot” Technique
4. …

加速器束流测量
马力
高能所加速器中心
2001年2月

直线加速器/输运线发射度测量：基本测量原理

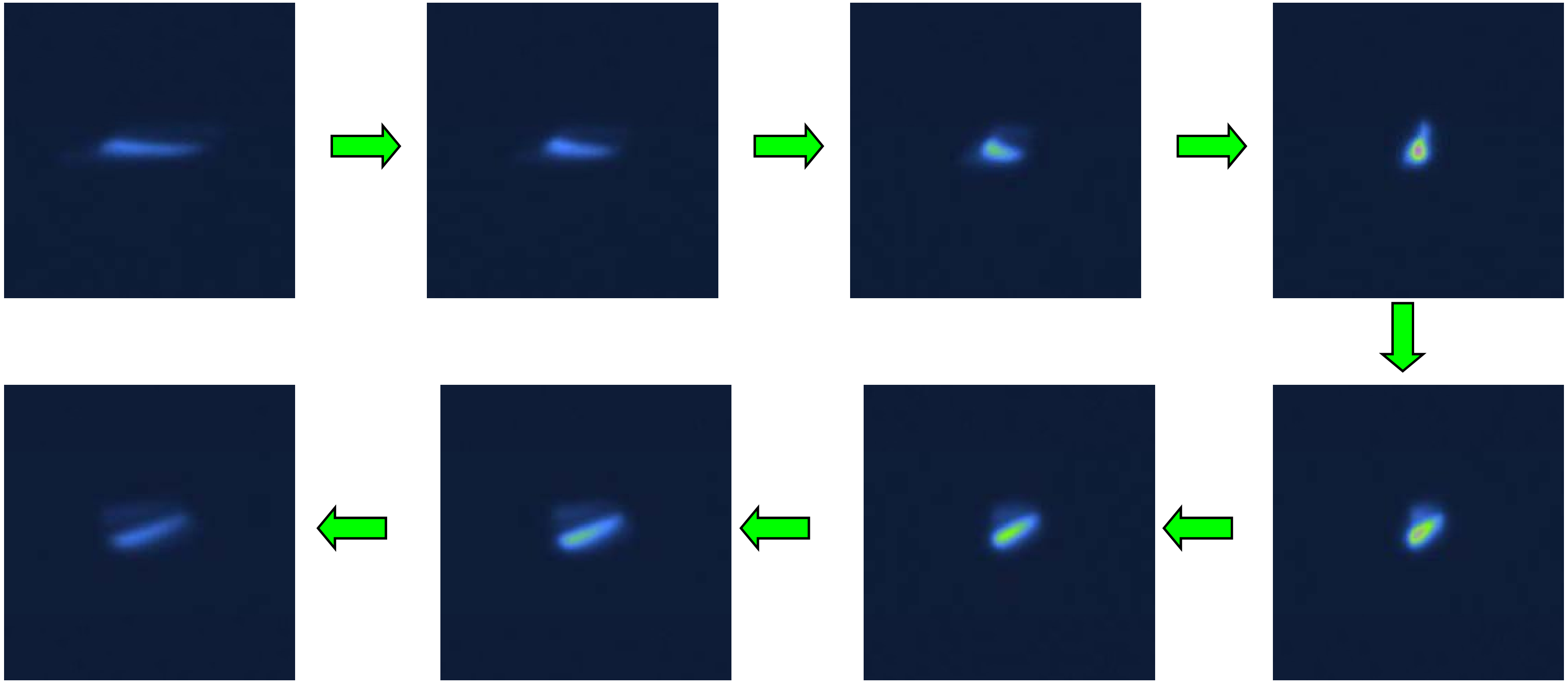
- Profile处束团截面尺寸与Q铁强度间的关系可表示为

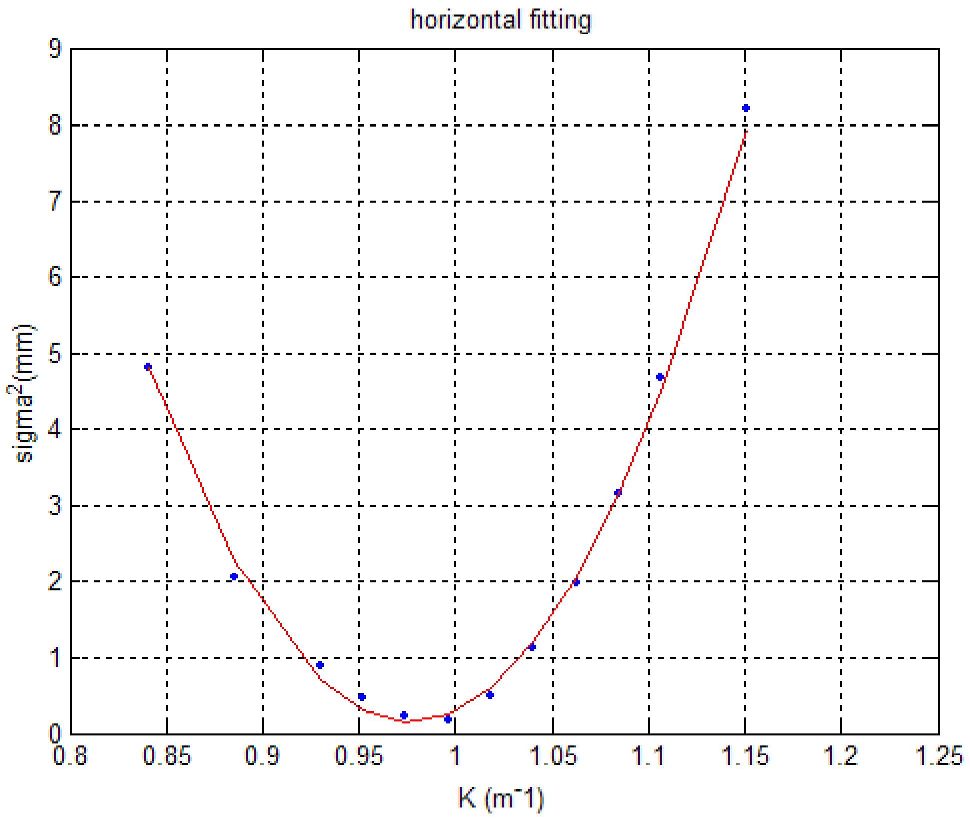
  $\sigma^2_K = a(K-b)^2+c$

- 设定不同的Q铁电流，测量相应的束团截面尺寸，采用上式进行最小二乘拟合，拟合点数设计为10-15点。

- 根据拟合系数可以计算得到发射度数据 $\varepsilon = \dfrac{\sqrt{a*c}}{Ld^2}$

- 发射度测量的精度与束流截面的变化量有关，束流截面随聚焦强度的改变越大，发射度测量精度越高。当束流截面为最小值时，此时的聚焦透镜的电流应为调节电流最大值的中间值，这样，二次曲线的形状对称，束流截面的变化在聚焦强度的两端都比较大





A: 255.22

B: 0.98

C: 0.15

S_{12}: 5.109

$$\varepsilon_x = \sqrt{AC} / S_{12}^2$$

Emittance Fitting Equation

$$\sum_{11} = \langle \sigma^2 \rangle = A(K-B)^2 + C$$

Beam emittance = 238.3 nm.rad

基于同步辐射的束斑截面测量

可见光成像法利用同步辐射中的可见光部分，采用折射式或反射式聚焦光学元件对储存环中的束团直接成像进而计算横向截面尺寸，优点在于结构简单、易于实现，但受曲轨成像误差、景深成像误差、衍射误差的影响，在**550nm**波段的空间分辨率极限约为数十微米，适用于一、二代同步辐射光源；

X射线聚焦成像法利用同步辐射中的**X**射线部分，采用菲涅耳衍射透镜（**Fresnel Zone Plate**）、组合折射透镜（**Compound Refractive Lens**）、**K-B**聚焦镜等特殊的聚焦元件对束团进行成像，因工作波长较短引入的衍射误差较小，这一方法的空间分辨率可优化至微米量级，但成本较高；

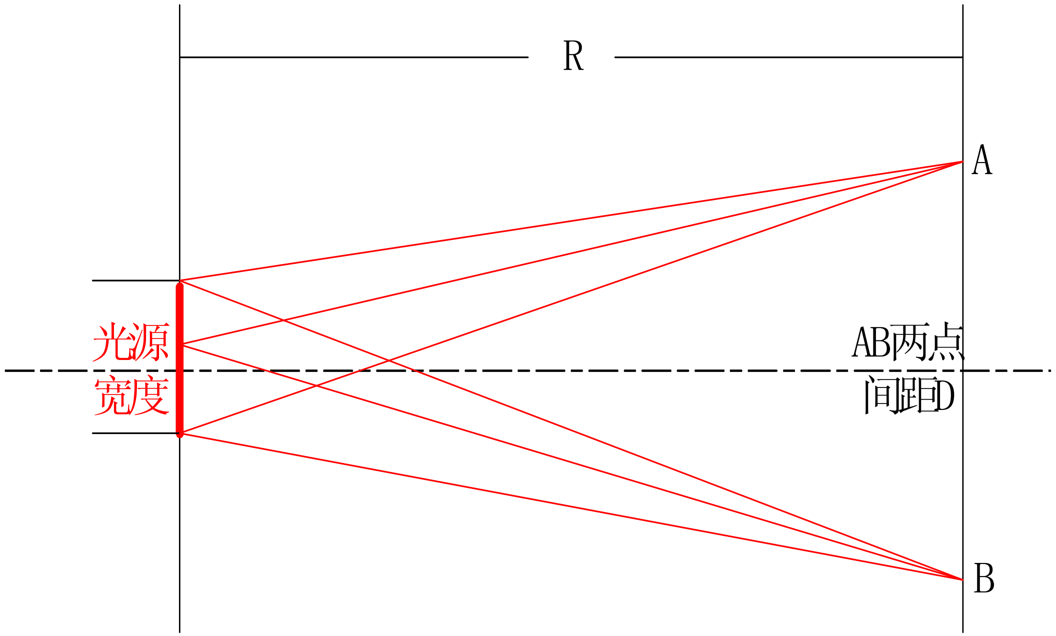
X射线小孔成像法同样利用同步辐射中的**X**射线部分，利用小孔成像原理对原始束团成像进而计算横向截面尺寸，同样具有结构简单、易于实现的优点，受小孔几何投影尺寸以及小孔衍射光斑尺寸的限制，目前技术条件下可以达到的最优空间分辨率在**10**微米左右；

空间干涉仪法直接在空间频率域测量束团发出同步光的相干度，从而推算原始束团的尺寸，具有结构简单、易于实现、分辨率高的特点，在**KEK ATF**装置上实验的结果表明该方法可测出小至**5**微米的束斑尺寸，但该方法对信号强度要求相对较高、数据处理分析相对复杂，数据刷新率不易做高，较适合用于电子储存环束斑平均尺寸的测量。

垂直方向直接投影法

空间干涉仪：基本原理

- 描述非点光源空间相干性的Van Cittert-Zernike原理：
  最早用于天文观测，KEK三桥利行博士最早引入束流诊断应用领域

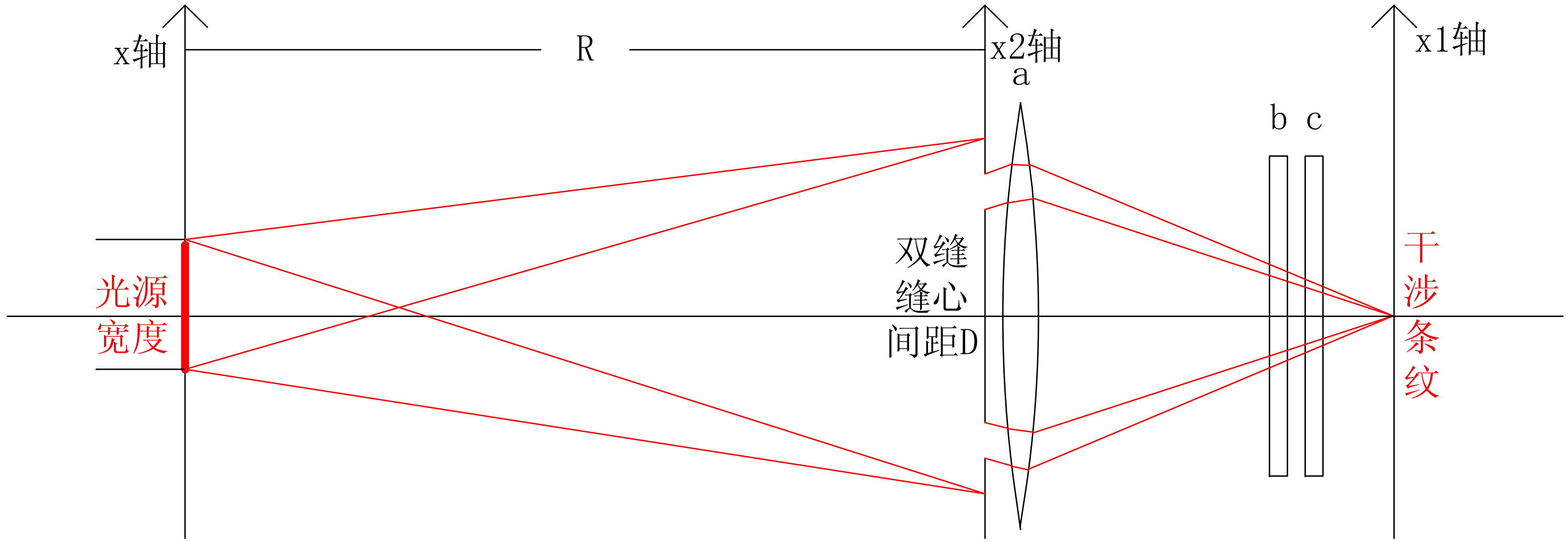


$$\gamma(\nu) = \int f(x) e^{-2\pi i(\nu x)} dx$$

$$\nu = \frac{2\pi D}{\lambda R}$$

在空间频率域测量空间相干度函数，反付氏变换即可求得实空间光源分布函数

空间干涉仪：基本原理



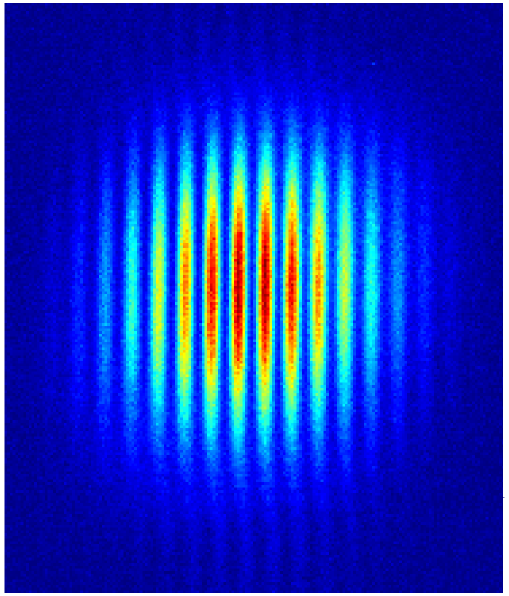
a. 消球差聚焦透镜组
b. 550nm±5%带通滤光片
c. 偏振片

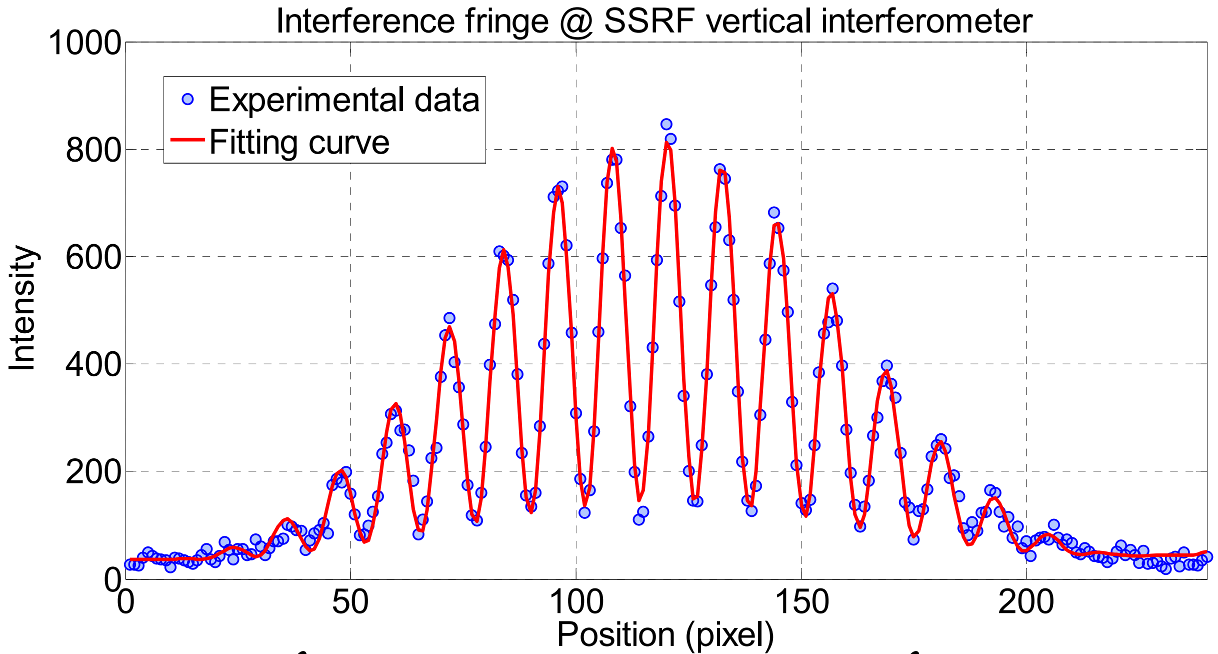
干涉条纹的强度分布

$$I = k(x_1)(I_1 + I_2 + 2\gamma\sqrt{I_1 I_2}\cos\phi)$$

k为与干涉条纹坐标相关的分布函数，可近似理解为干涉条纹强度的包络线

空间干涉仪：数据处理算法

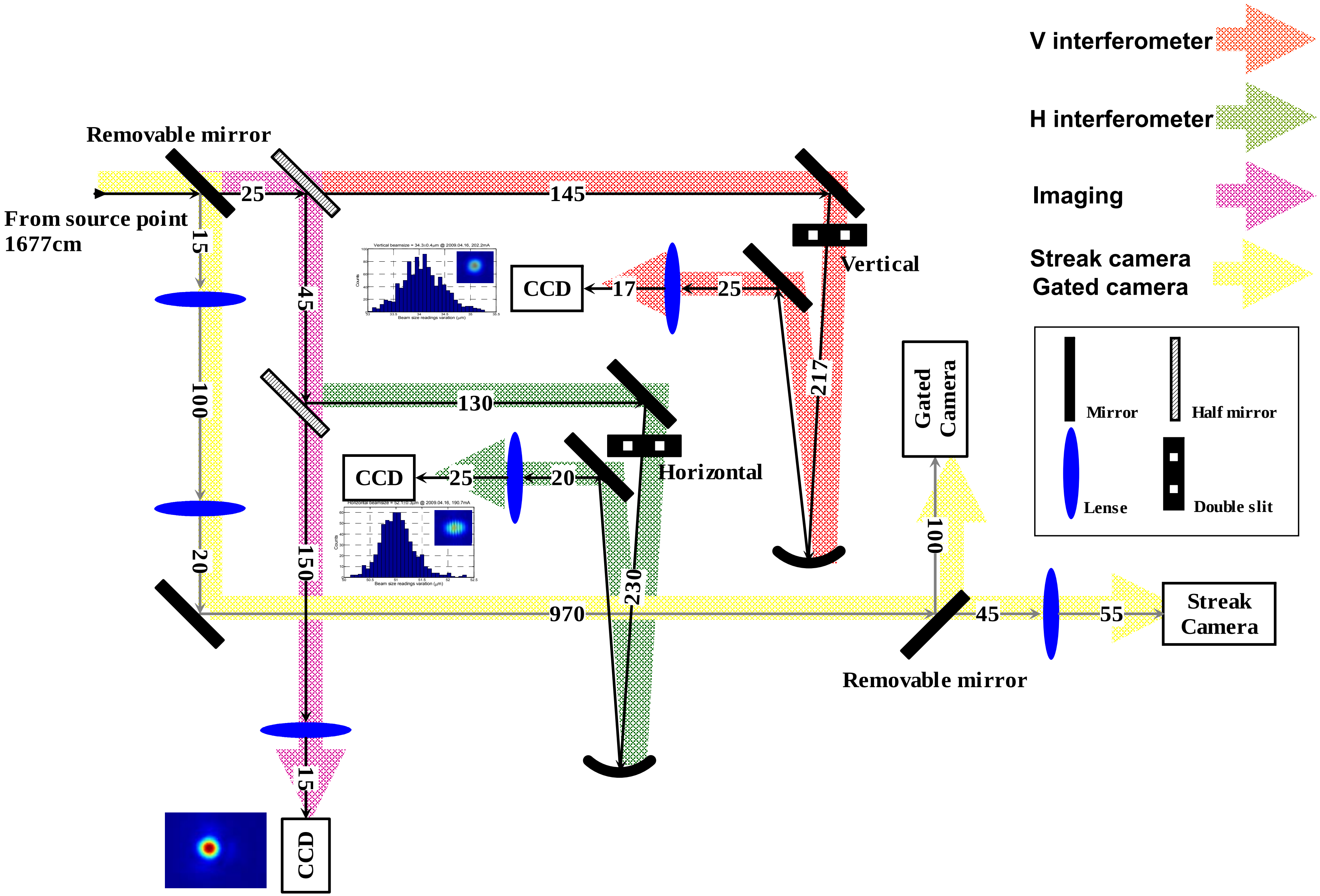




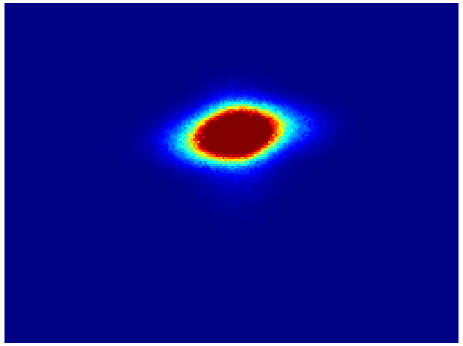
$$I(y) = a_1 + a_2 y + \sum_{i=1}^{n} f_i(\lambda_i) a_3 (\mathrm{sinc}(\frac{\lambda_0}{\lambda_i} a_4 (y - a_5)))^2 (1 + a_6 \cos(\frac{\lambda_0}{\lambda_i} a_7 (y - a_8)))$$

其中a1代表所获取图像中的随机本底噪声，a2代表因CCD芯片量化时间差异而引入的一个像素点位置相关的信号畸变误差，a3是由同步光光强确定的一个常数，a4是由狭缝点扩散函数宽度确定的一个常数，a5为狭缝点扩散函数中心位置（初始相位），a6为待测的空间相干度，a7是由干涉条纹周期确定一个常数，a8为干涉条纹中心位置（初始相位）。*fi(λi)*为带通滤波片频幅响应函数，*λ0*为带通滤波片中心频率。

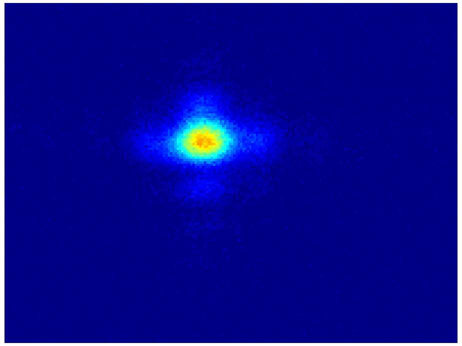
实例：SSRF同步光诊断线



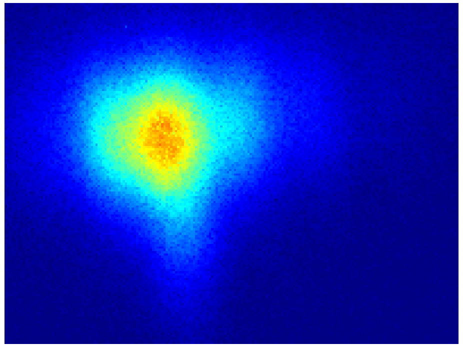
实例：SSRF可见光成像



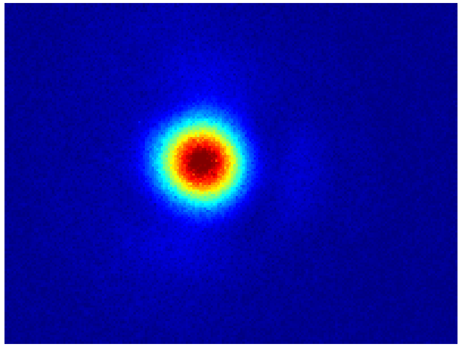
2008.01.03
80mA, no COD correction
copper cavity



2008.04.10
100mA, COD um level
copper cavity

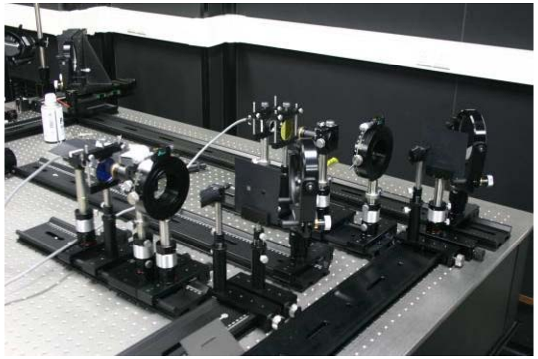


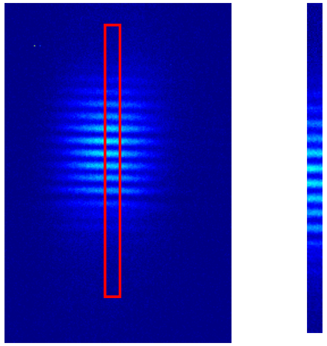
2008.10.01
150mA
SC cavity, noisy PS

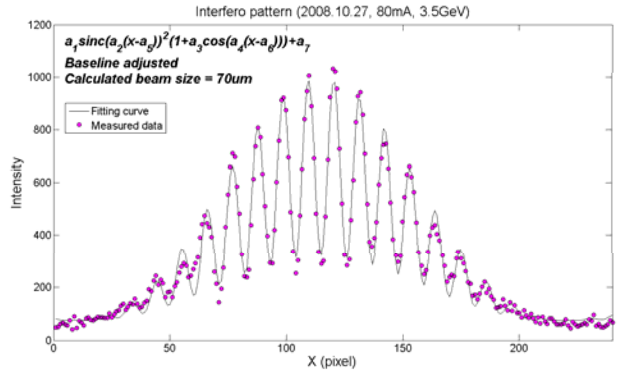


2008.10.27
86mA
SC cavity, noisy PS fixed

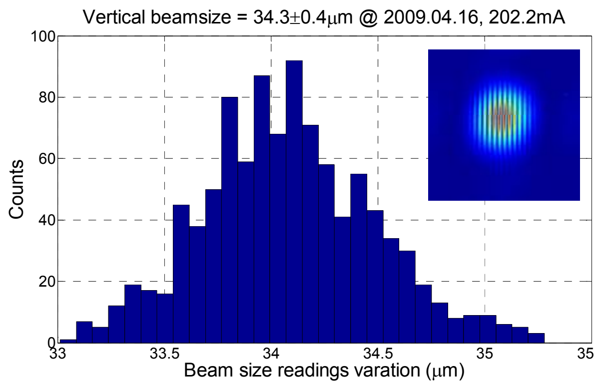
实例：同步光空间干涉仪（interferometer）

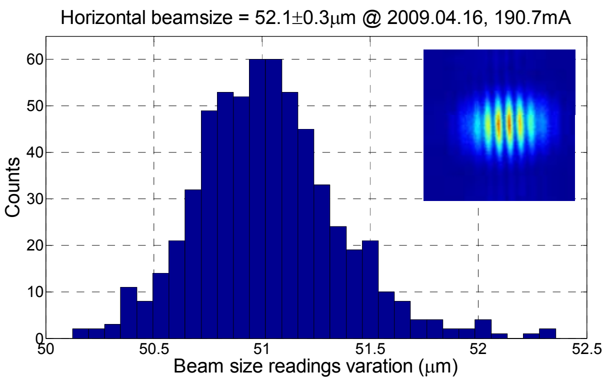


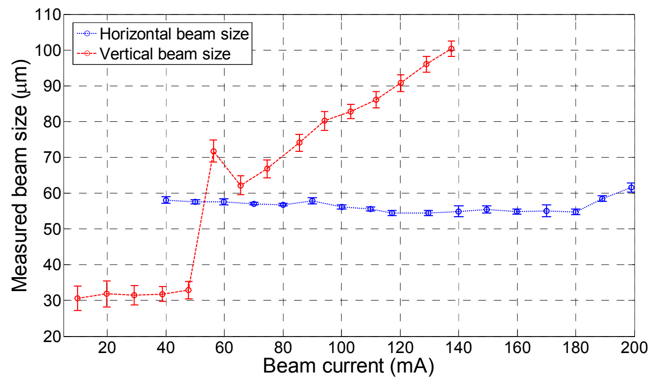




$$I(y_1)=I_0[\sin c(\frac{2\pi a}{\lambda R_1}y_1)]^2\cdot[1+|\gamma(\nu)|\cos(\frac{2\pi D}{\lambda R_1}y_1+\varphi)]$$







Measurement uncertainty um level, system resolution better than 10um

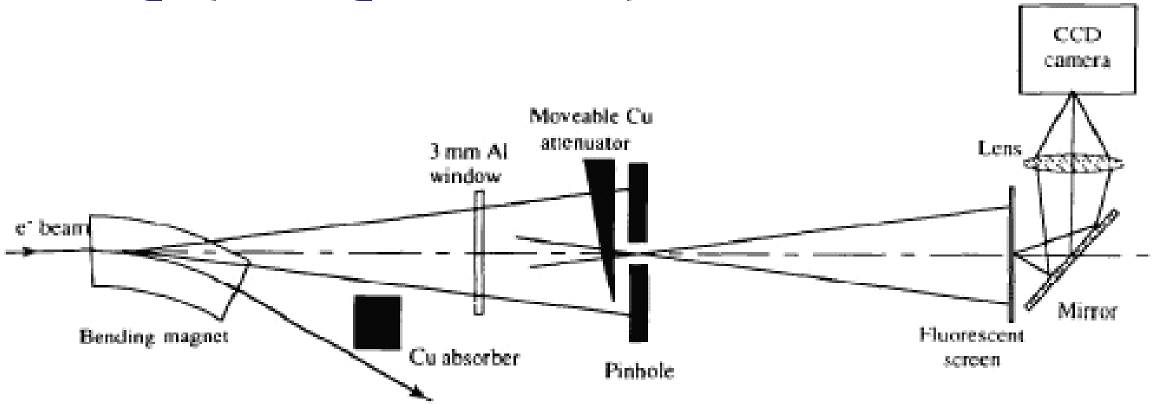
Xray 针孔相机（pinhole camera）：ESRF

- „Camera Obscura"

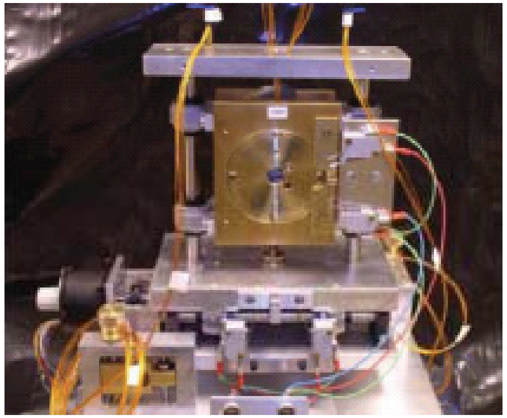
  description of phenomenon already by Aristoteles (384-322 b.C.) in „Problemata"

- Setup (example: ESRF)

P.Elleaume, C.Fortgang, C.Penel and E.Tarazona, J.Synchrotron Rad. **2** (1995) , 209



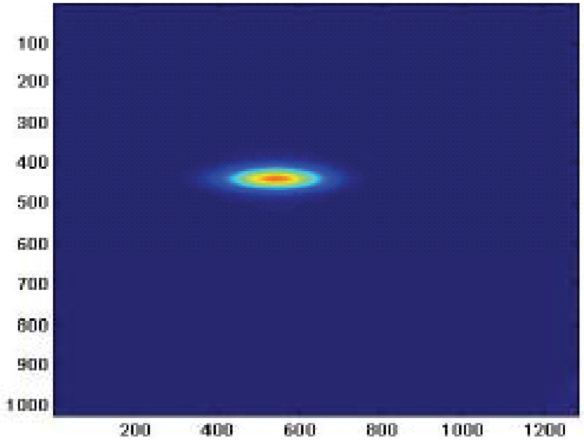
ID-25 X-ray pinhole camera:



pinhole setup @ DORIS

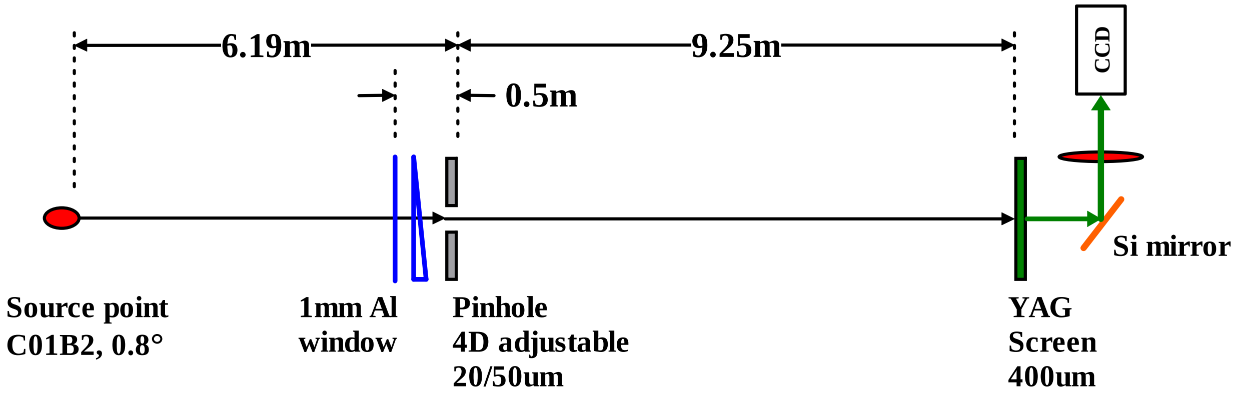
resolution:

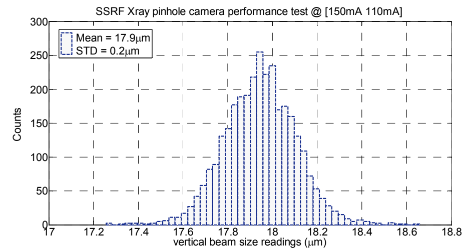
$$\sigma_{res} \approx 20\,\mu m$$

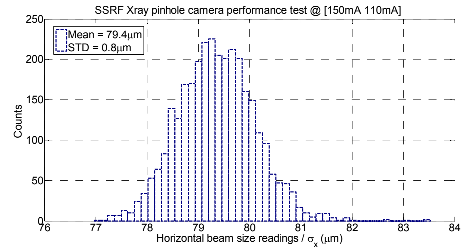


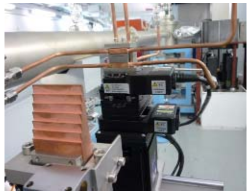
courtesy of K.Scheidt, ESRF

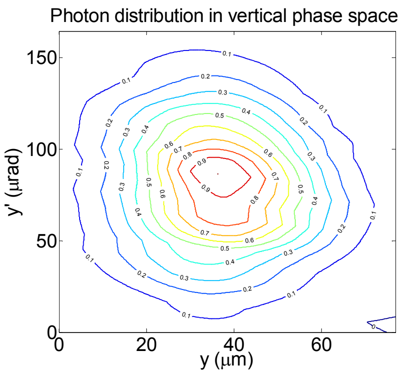
Xray 针孔相机（pinhole camera）：SSRF

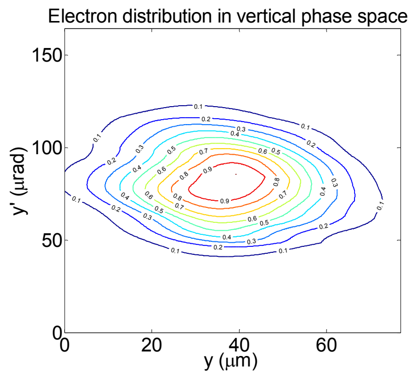


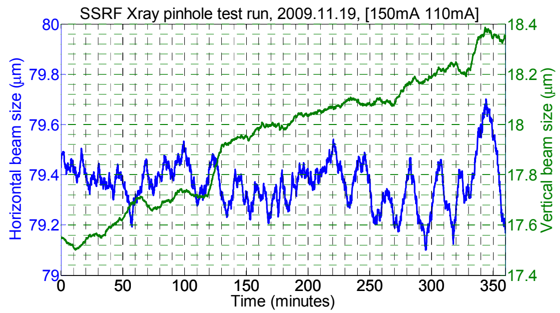




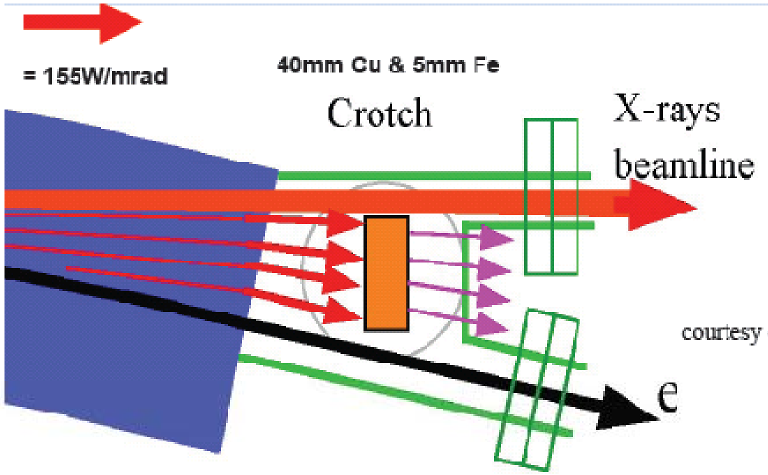








垂直方向投影

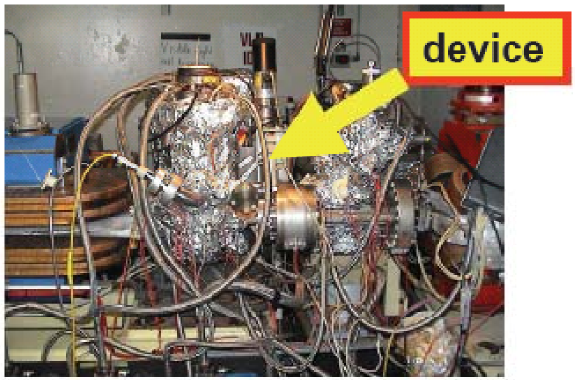


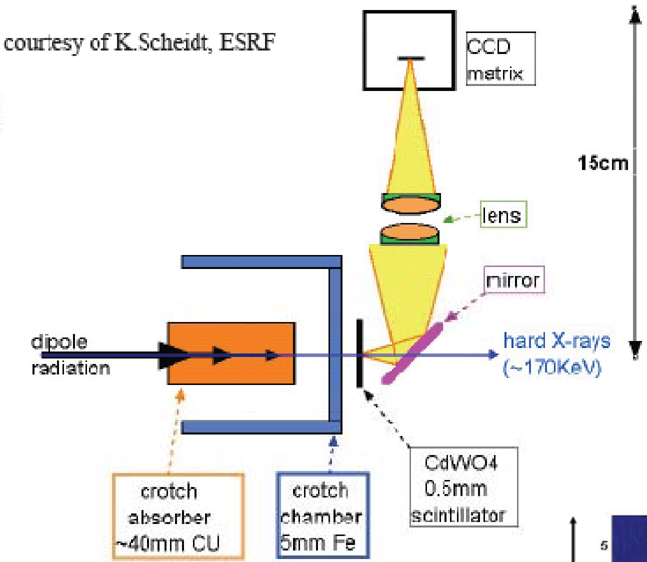
K.Scheidt, Proc. of DIPAC05 (2005), 238

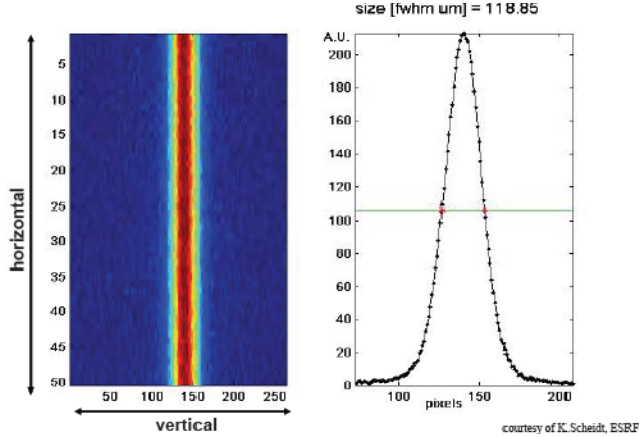
K.Scheidt, Proc. of BIW06 (2006), to be published

side-view i.e. in the vertical plane of the beam:

courtesy of K.Scheidt, ESRF





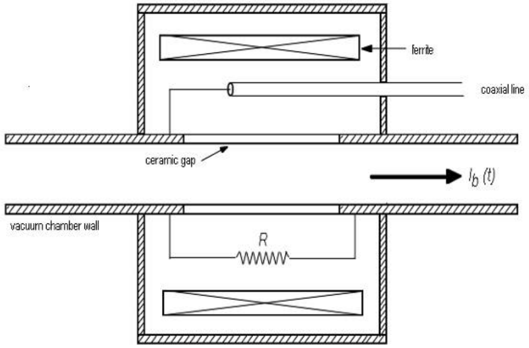


纵向尺寸/分布测量

longitudinal bunch length / distribution measurement

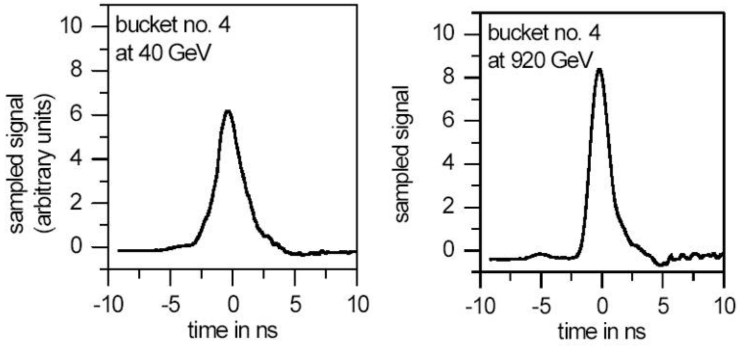
束长测量：壁电流检测器

recall: resistive wall gap monitor:

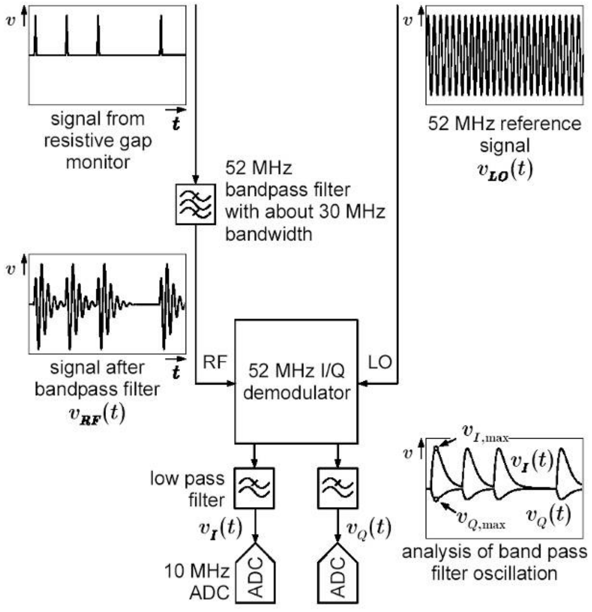


the wall current, after conversion to voltage, is measured with a high bandwidth (~GHz) scope

example: R-WGM bunch length measurements at HERA (courtesy E. Vogel, 2004)



with only a single monitor, not all bunches could be simultaneously measured (here ~s, possible: ~ms)
→ processing of rf signals for real-time measurements:



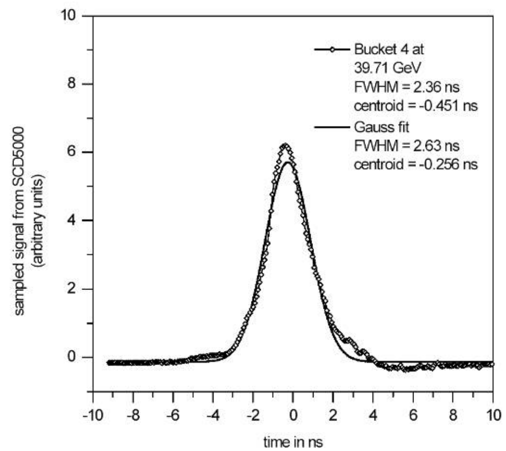
$$A(t) = \sqrt{(v_{I,max})^2 + (v_{Q,max})^2}$$

measurement of in-phase (I) and out-of-phase (Q) component of bunch spectrum at some frequency yields signal amplitude, A(t):

$$A(t) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{t^2}{2\sigma}}$$

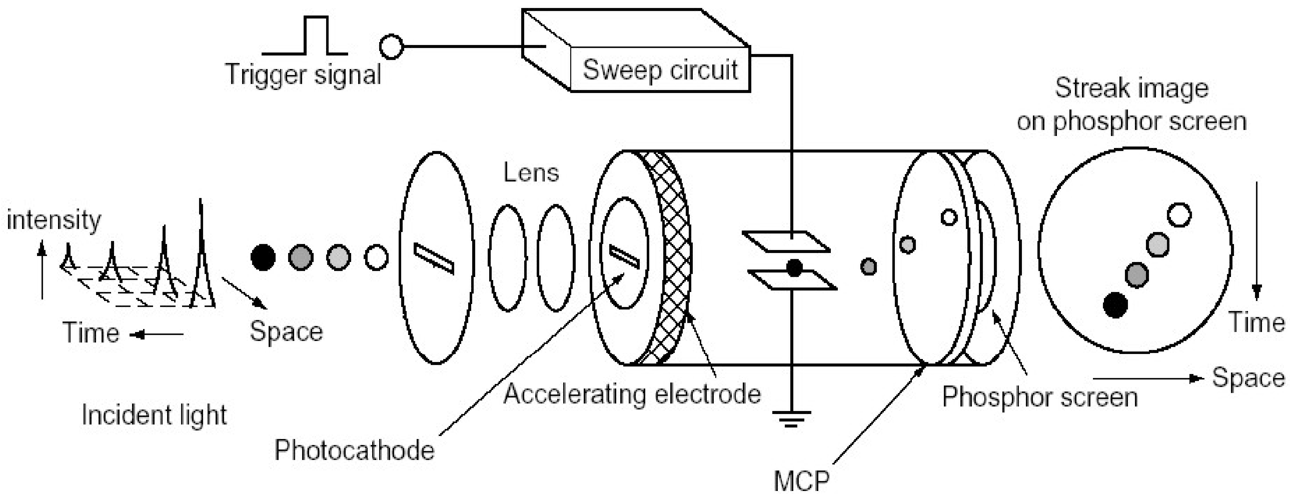
ratio of signals at two different frequencies → simple solution for the bunch length σ

example: bunch length measurements at HERA from frequency mixing (courtesy E. Vogel 2004)



束长测量：条纹相机（streak camera）

<u>principle</u>: photons (generated e.g. by SR, OTR, or from an FEL) are converted to e- (photocathode) , which are accelerated and deflected using a time-synchronized, ramped HV electric field; e- signal is amplified (MCP), converted to γ's (phosphor screen) and detected using an imager (e.g. CCD array), which converts the light into a voltage



from Hamamatsu home page, C5680 series (www.hama-comp.com)

<u>issues</u>: energy spread of e- from the photocathode (time dispersion)
space charge effects following the photocathode
chromatic effects ($dt/dE_\gamma(\lambda)$) in windows
trigger jitter

lower limit on resolution ~ 0.5 ps

束长测量：谐波分析法

If the longitudinal distribution of electron bunch is Gaussian with an rms length σ_l, the Fourier component of the nth harmonic can be expressed as

$$V(n\omega_o) = 2V_o e^{(-n^2 \omega_o \sigma_l^2 / 2)}$$

where ω_0 is the revolution frequency of particle, $V(n\omega_o)$ the induced voltage obtained on an ideal beam pickup and V_0 the DC component. Thus, the rms bunch length can be obtained by comparing the Fourier components as

$$\sigma_l = \frac{1}{\omega_o} \sqrt{\frac{2}{(n_2^2 - n_1^2)} \ln \frac{V_1(n_1\omega_o)}{V_2(n_2\omega_o)}}$$

Here, V_1 and V_2 are Fourier components at the n_1th and n_2th harmonics of the revolution frequency with n2 > n1.

=> Real-time measurement

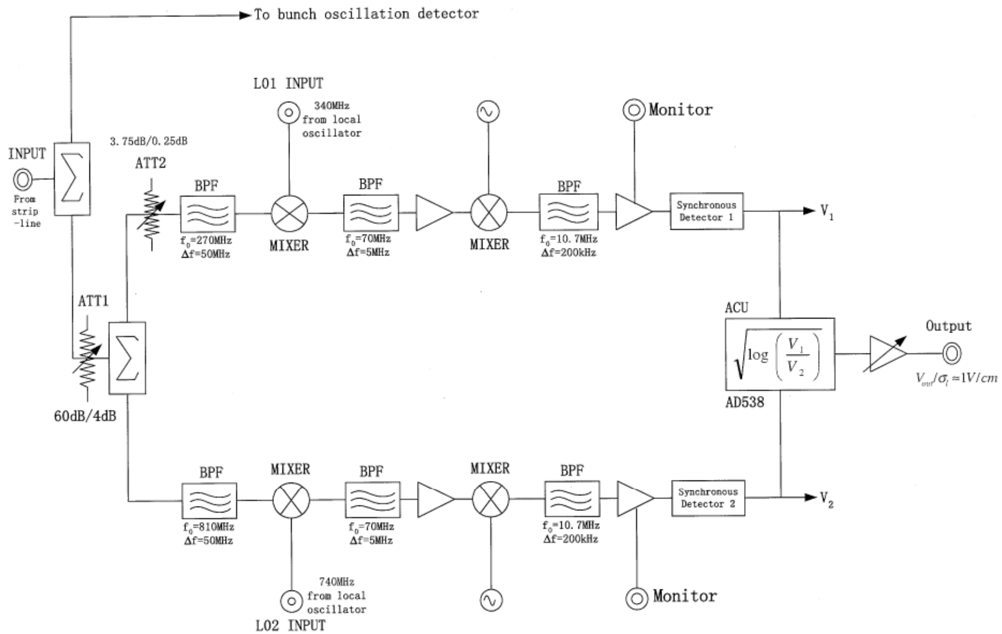
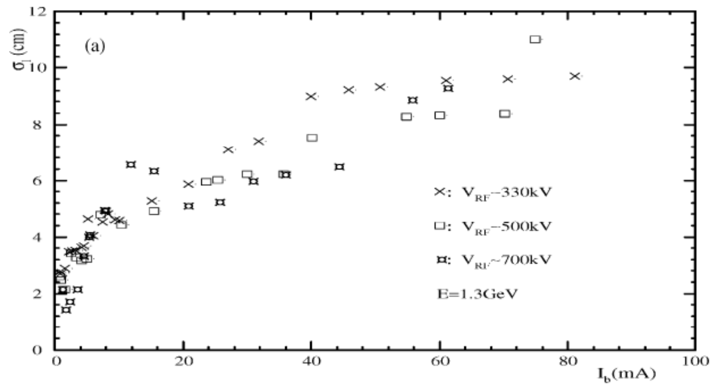


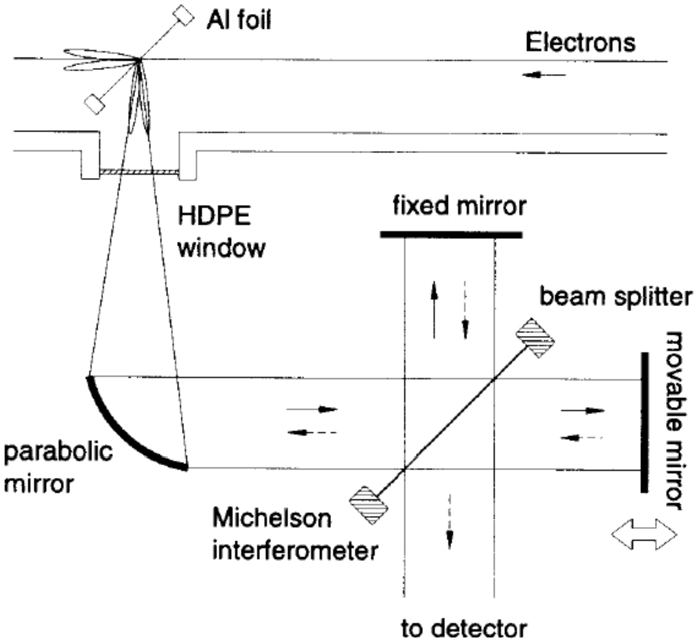
Fig. 1. Block diagram of the beam spectrum analysis system.



Q. Qin*, Z.Y. Guo, G. Xu, L. Ma, Z. Zhao, NIM A463 (2001) 77-85

束长测量：迈克耳逊干涉仪

<u>principle:</u> use the interferometer to probe the bunch-length dependent frequency spectrum of the bunch



spectrum of a monochromatic wave: $\frac{2\pi}{\lambda}$

$$S(\Delta x) = \underbrace{I(k)}(1 + \cos k\Delta x)$$

intensity of incoming radiation

path length difference between two arms of the spectrometer

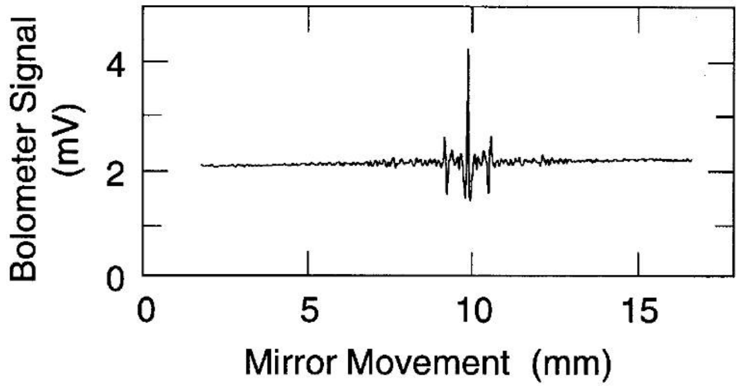
finite spectrum:

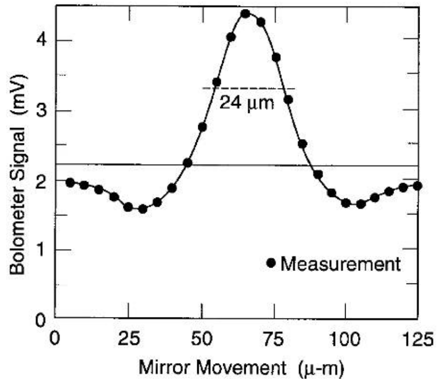
$$\begin{aligned} S(\Delta x) &= \int_0^\infty I(k)(1+\cos k\Delta x)\, dk \\ &= S_0 + \int_0^\infty I(k) \cos k\Delta x\, dk \end{aligned}$$

signal with large Δx

interferogram: S(Δx)-S_0

examples: interferograms measured at the Stanford "sunshine facility" (courtesy H. Wiedemann, 2004)





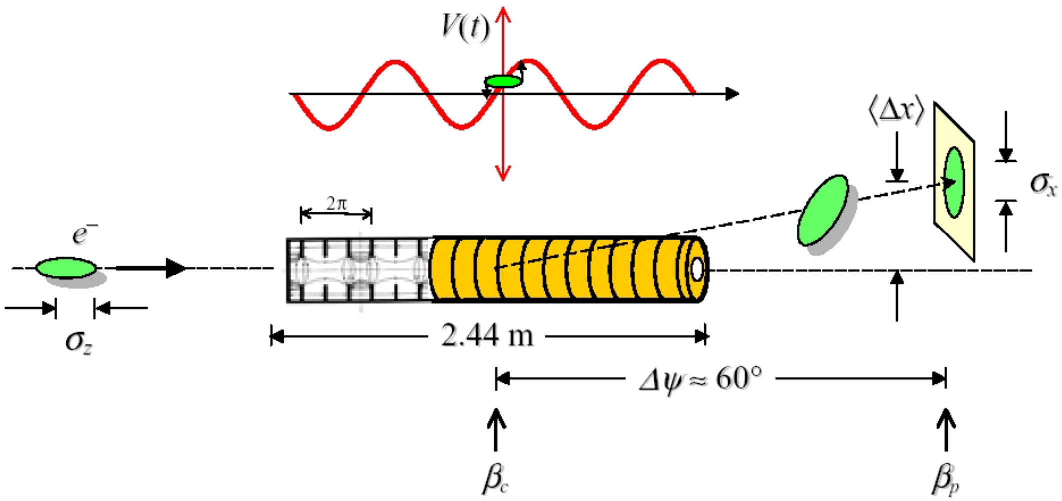
signal FWHM in interferogram (assuming Gaussian bunches):

$$\left(\frac{2.35}{\sqrt{2}}\right)\sigma_z$$

<u>issues:</u>
- long time averaging
- water absorption lines

束长测量：横向偏转腔

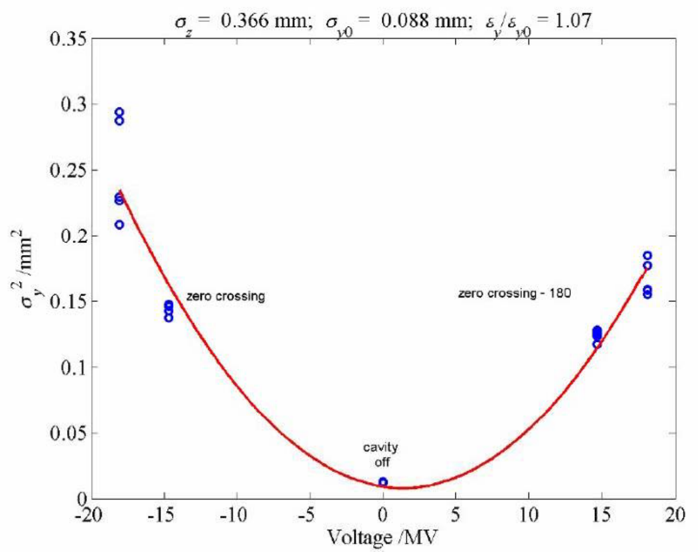
Principle: use transverse mode deflecting cavity to "sweep"/kick the beam, which is then detected using standard profile monitors



Principle of the TM_{11} transverse mode deflecting cavity

introduce x-z correlation

oriented to displace beam vertically while a horizontal bending magnet deflects the beam onto the screen



$\sigma_y^2 = A(V_{rf}-V_{rf,min})^2 + \sigma_{y0}^2$

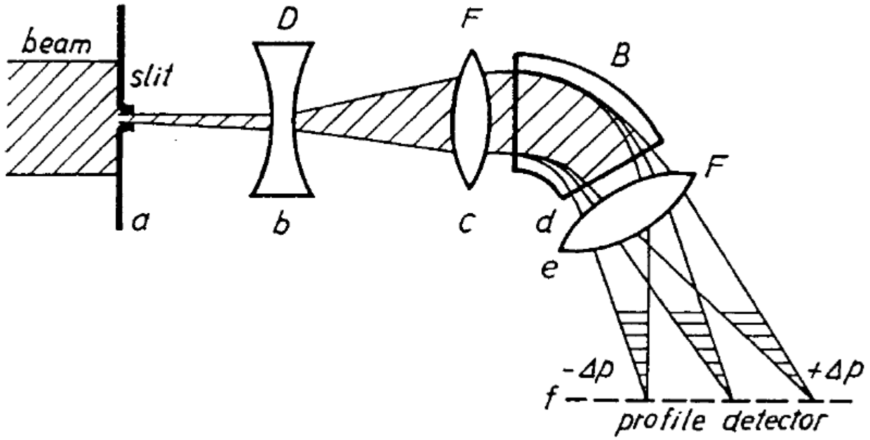
$\sigma_z = A^{1/2}E_0\lambda_{rf}/2\pi R_{34}$

σ_z expressed in terms of fit parameter, A

(R. Akre, 2003)

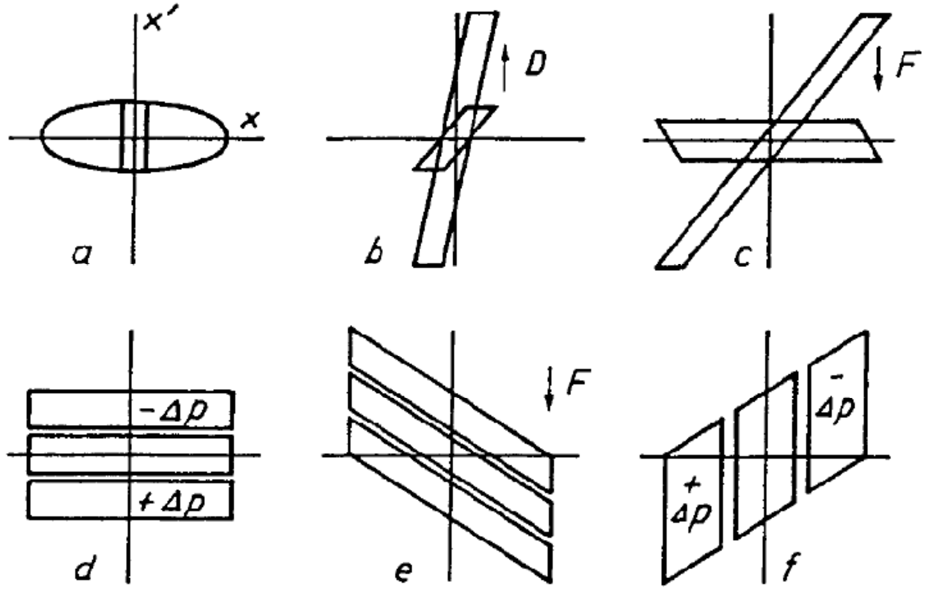
束流能量/能谱测量
beam energy / energy spread measurement

直线加速器束流能量/能散测量：基本原理



中心能量

$$E(GeV) = \frac{0.2998\int Bdl}{\theta} = \frac{0.2998 B^* L_{eff}}{\theta}$$



相空间束团分布变化

能散

$$\sigma = \sqrt{\beta_x \varepsilon_x + (\eta\delta)^2}$$

测量点处**Beta**函数较小时

$$\delta = \frac{\sqrt{\sigma^2 - \beta_x \varepsilon_x}}{\eta} \quad \textbf{<=} \quad \frac{\sigma}{\eta}$$

储存环能散测量

<u>principle</u>: in a storage ring, particles within the bunch perform phase and energy oscillations (out of phase by 90 deg) about a common reference point defined by the rf; measurement of the longitudinal distribution may therefore be used to determine the energy distribution of the bunch

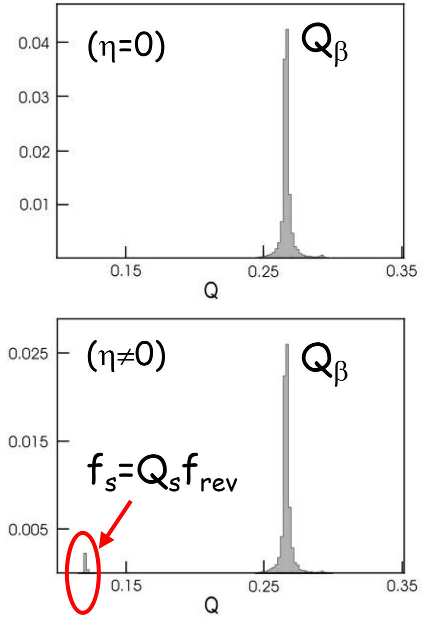
$$\sigma_t = \frac{\alpha}{2\pi f_s}\left(\frac{\sigma_\delta}{E}\right) \quad \rightarrow \quad \frac{\sigma_\delta}{E} = \frac{2\pi f_s}{\alpha}\sigma_t$$

synchrotron frequency (f_s)

bunch length (σ_t)

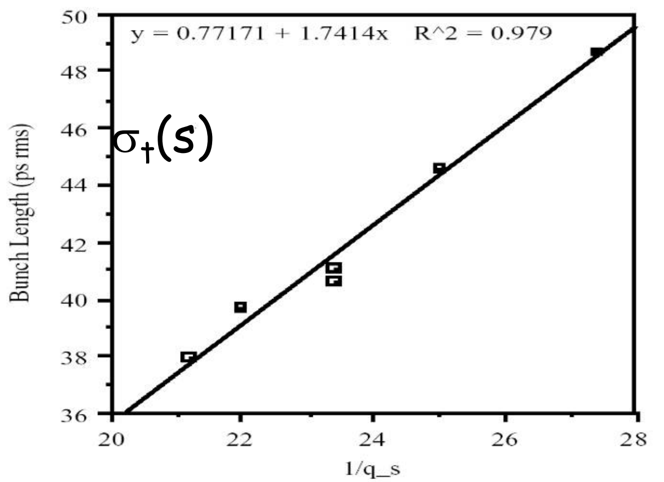
momentum compaction (α)

(ref: H. Wiedemann, Eq. 8.70)



synchrotron frequency measured using FFT of turn by turn data in LEP (courtesy A. Müller, 2001)

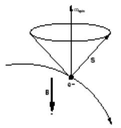
example: energy spread in PEP-II B-Factory streak camera data (courtesy A. Fisher, 2004)



储存环能量标定

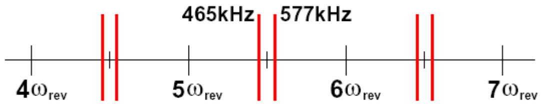
Energy Calibration With High Precision

- Bending magnet field measurements (Hall Probes): $\rightarrow \frac{\Delta E}{E} = (1-2)\cdot 10^{-3}$
- For higher precision $\rightarrow$ Resonant Spin Depolarization
- In a flat machine the ideal electron sees $\vec{B_\perp}$ $\rightarrow$ spin vector precesses according to Thomas-BMT equation:



$$\omega_{spin} = \omega_{rev}\nu_{ST} = \omega_{rev}\cdot a\gamma$$
$$a = \frac{g-2}{2} = 0.00115965(2)$$

- SLS: $E = 2.4$ GeV, $\omega_{rev} = 1042$ kHz
  $\rightarrow \nu_{ST} = 5.4465$ corresponding to $\omega_{res-depol} \approx 465/577$ kHz



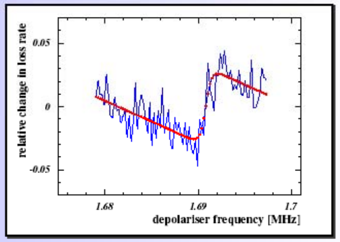
Polarization

- Spin-flip synchrotron radiation (only $\approx 10^{-11}$ of total radiation power) $\rightarrow$ polarization build-up anti-parallel to main bending field:
  $P(t) = P_0(1 - e^{-\frac{t}{\tau}})$ $\quad \frac{1}{\tau} = \frac{1}{\tau_p} + \frac{1}{\tau_d}$ $\quad P_0 = P_{ST}\frac{\tau_d}{\tau_p+\tau_d}$
  $P_{ST} = 92.4\%$ theoretical maximum for a flat ring
  $\tau_p = \left(\frac{5\sqrt{3}}{8}\cdot\frac{e^2\hbar}{m_e{}^2c^2}\right)^{-1}\cdot\frac{\rho^3}{\gamma^5}$ $\quad$ @SLS: $\tau_p = 1873$ s ($\gamma = 4700$)
  @LEP: $\tau_p = 360$ min ($\gamma = 86000$)
  $\tau_d \propto (a\gamma)^{-2}$ $\quad \tau_d \gg \tau_p$ for low-energy machines
- How to measure polarization without a polarimeter?
  - Touschek lifetime is polarization dependent: $\sigma_{ts} = f_1 - P^2 f_2$
  - Choose filling with high bunch current $\rightarrow \tau$ is dominated by τ_{ts}
  - Identify changes in $I\cdot\tau_{ts}$ with changes in P

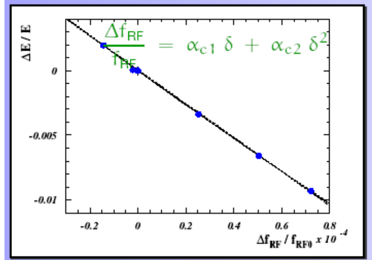
Some RDP Results

ANKA

- Fit to loss rate scans using
  $$r = a - \frac{\partial r_1}{\partial t}t + \frac{\Delta r}{1+\exp\left\{-\frac{t-t_d}{\sigma_d}\right\}}$$



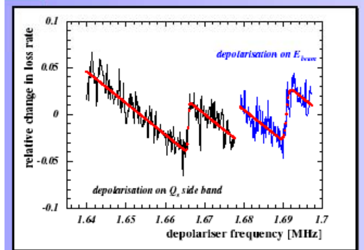
- Measure α_c using RDP scans for different f_{RF}:



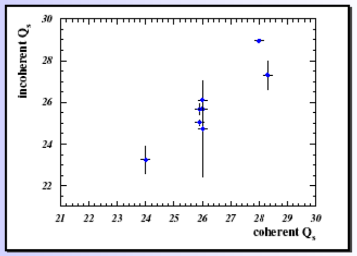
- Expectation for linear term: $7.2\cdot 10^{-3}$
- $\alpha_{c1} = (7.39 \pm 0.01)\cdot 10^{-3}$
- Quadratic term: $\alpha_{c2} = (4.1\pm 0.2)\cdot 10^{-2}$
  ➜ highly significant but small

Bunch Lengthening & RDP

ANKA



- Depolarisation can also occur on synchrotron side bands
- Due to the single particle nature of the depolarisation process, this happens at $f_{dep}/f_{rev} = [\nu] \pm Q_s^{inc}$
- RMS bunch length: $\sigma_s \propto 1/Q_s^{inc}$
- The coh./inc ratio is a measure for bunch lengthening with current
  $$\frac{Q_s^{coh}}{Q_s^{inc}} = 1 - \lambda I_{bunch}$$
- Average coherent/incoherent ratio: (1.02 ± 0.03)
  ➜ no significant lengthening



束损测量

beam loss measurement

常用束损测量设备

- 气体电离室，响应时间~us
- 同轴电缆长电离室，响应时间~ms
- 闪烁体+光电倍增管，响应时间~10ns
- PIN光二极管，响应时间＜100ns

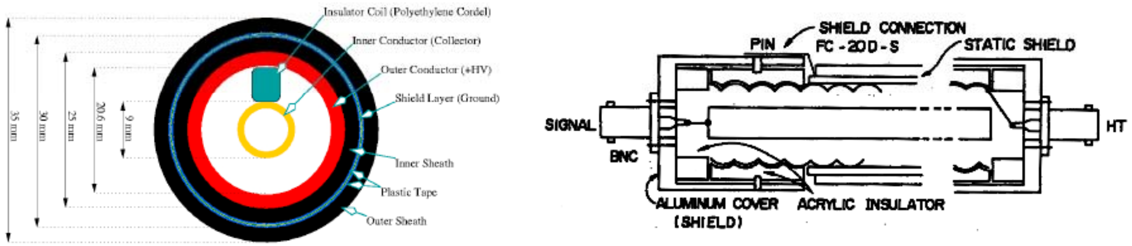


図5-1　FC-20D-S 中空導軸ケーブルを利用した空気イオンチェンバー