

Introduction of BEPCII

张源

代表 BEPCII 加速器团队

2024-07-20

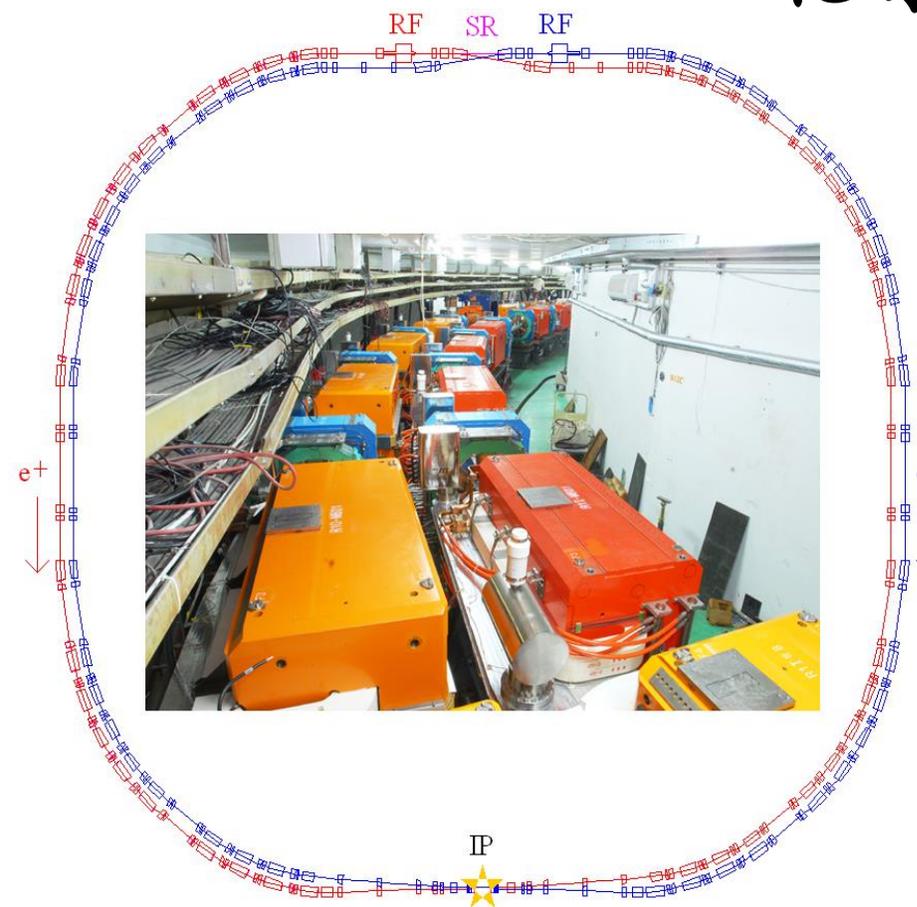
RQCD, 哈尔滨

直线加速器部分特别感谢：刘渭滨、钱磊

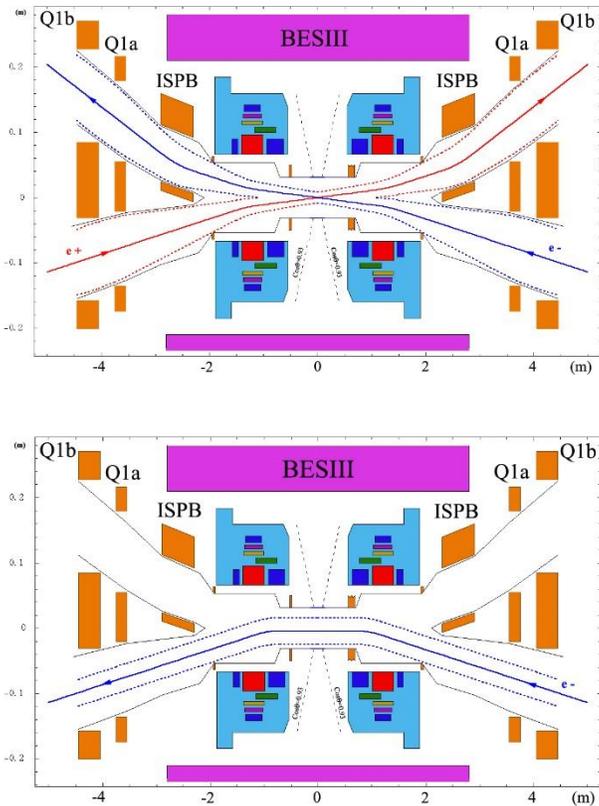


7个月 → BESIII取数 + BSRF兼用光
 2个月 → BSRF专用光用户实验+ 试验束装置实验
 1个月 → 加速器专用机器研究 + 设备检修 +
 2个月 → 暑期停机, 设备修护

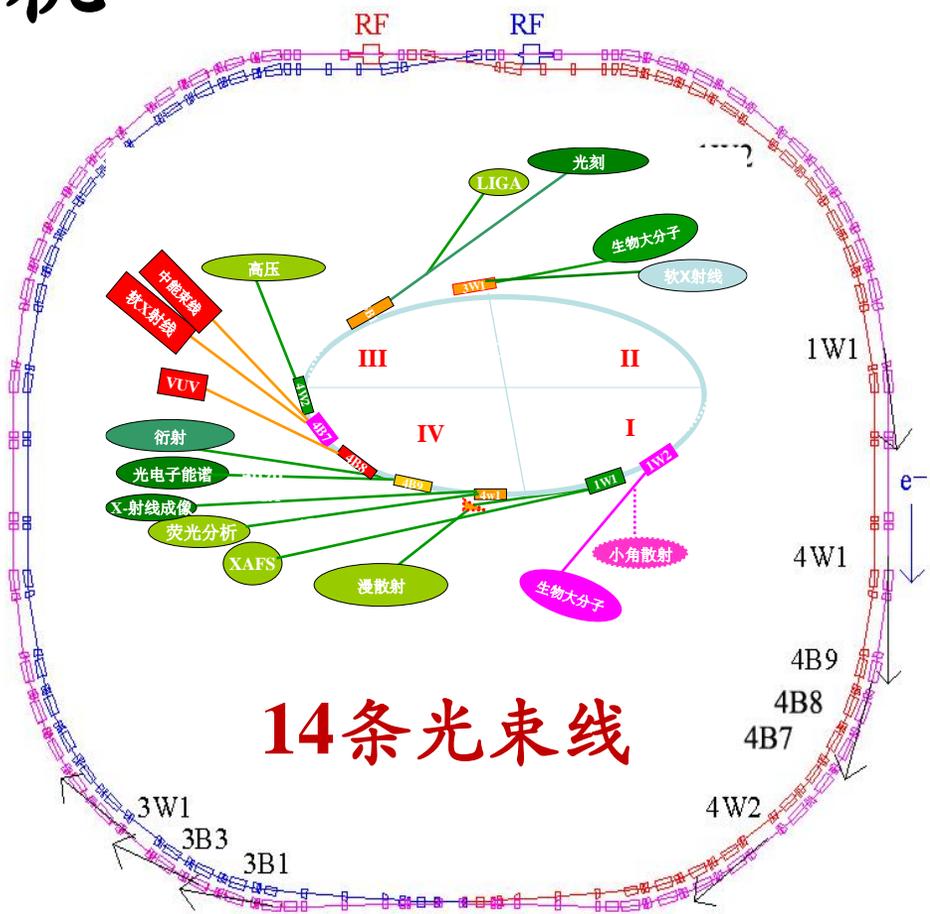
北京正负电子对撞机



对撞机



高效率、高产出的同步辐射光源
 粒子工厂级双环对撞机

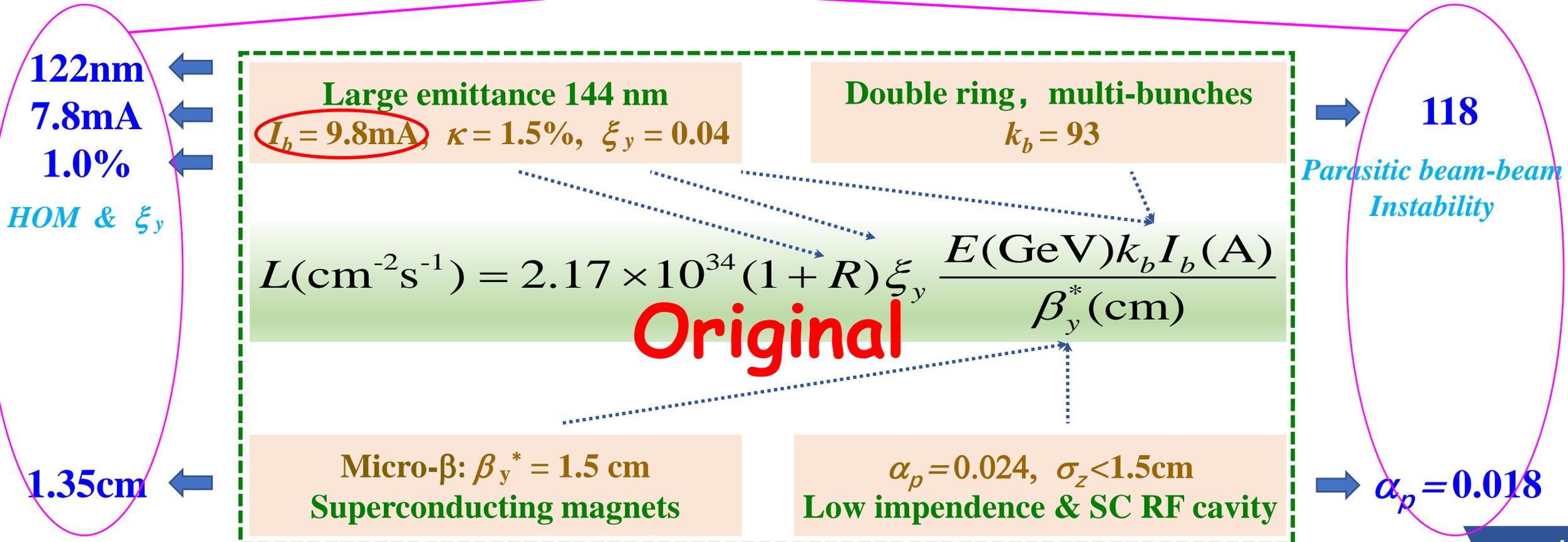


14条光束线

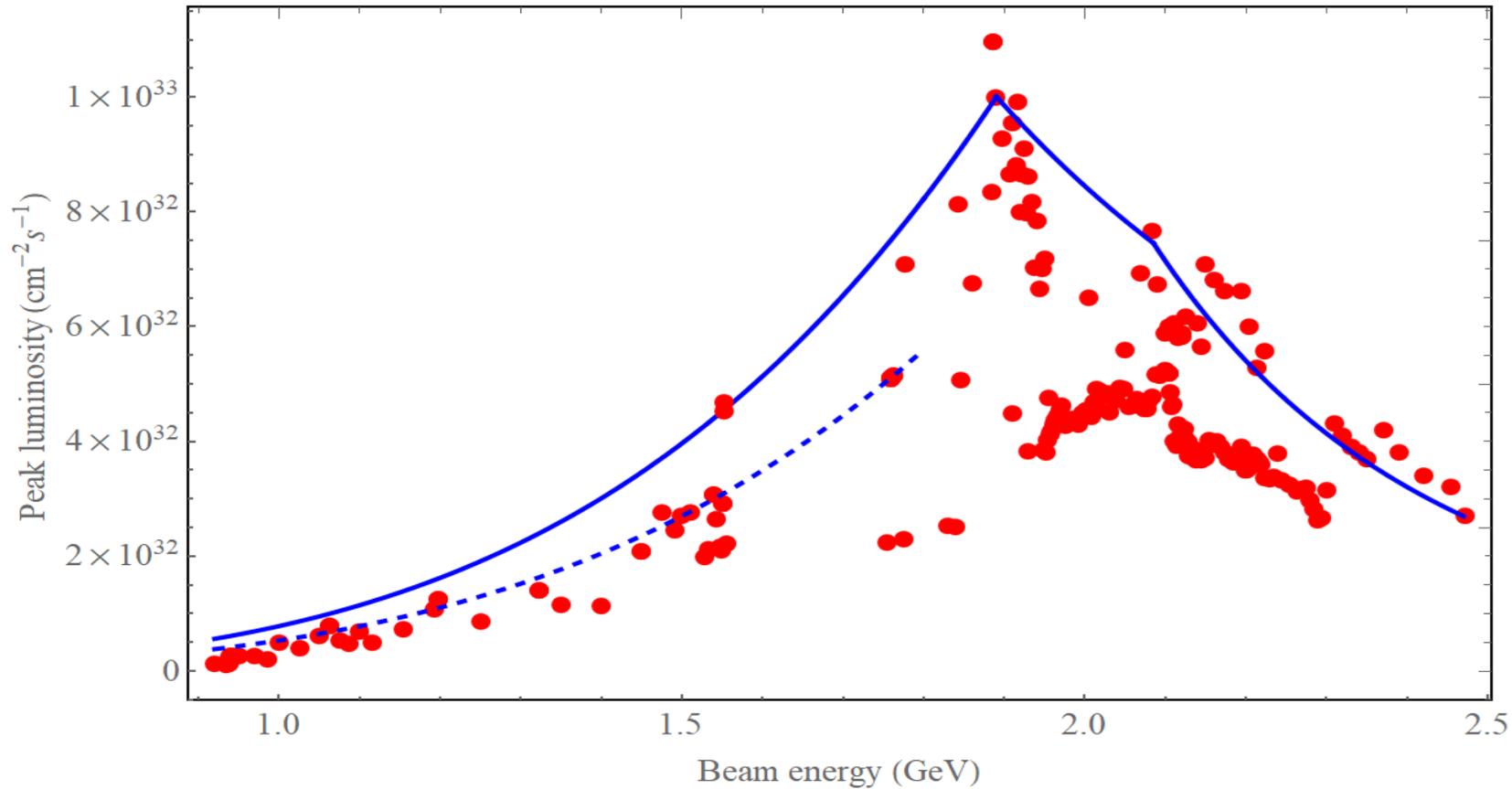
同步辐射装置

$$L_{\text{BEPC}} = 1.0 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1} \quad \Rightarrow \quad L_{\text{BEPCII}} = 1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$$

加速器物理用了6年半的时间确定了最终方案，硬件系统用了15年攻克了1A强流技术关卡

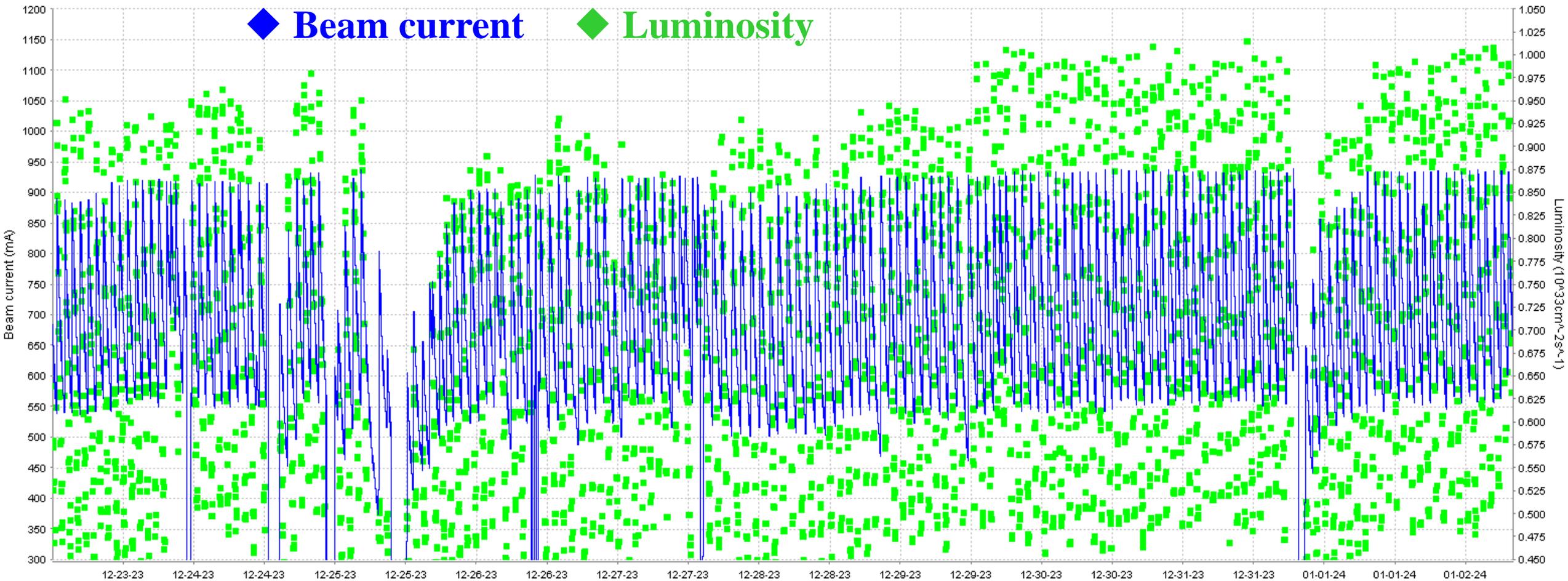


BEPCII曾在223个能量点运行取数



- 对撞能量最高达到**2.472 GeV**，完成了具有重要物理意义的粲重子 $e^+e^- \rightarrow \Sigma_c \bar{\Sigma}_c$ 首次测量
- 对撞能量最低达到**0.920 GeV**，完成了具有重要物理意义的R-QCD扫描

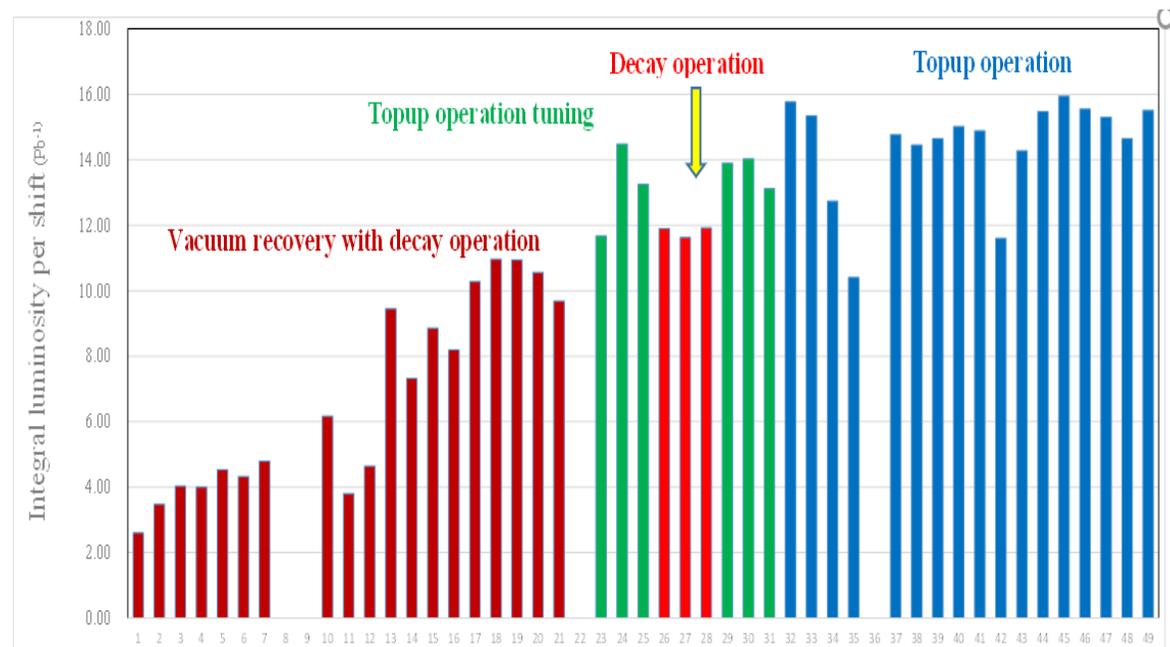
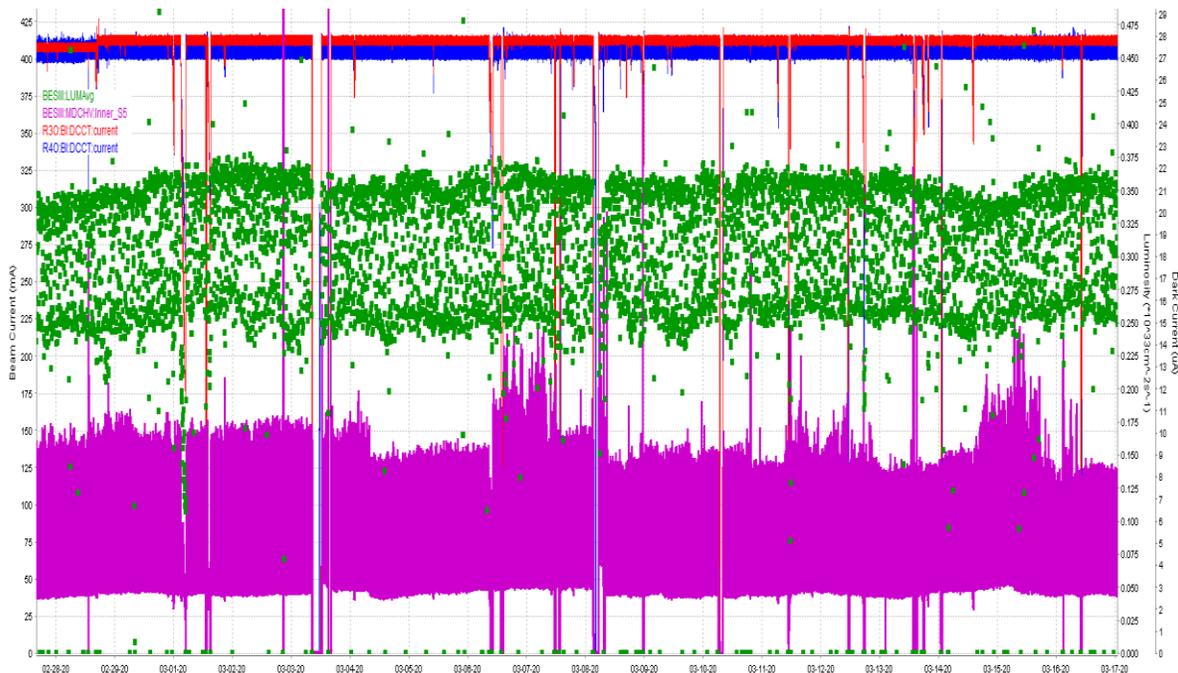
Data taking at ψ (3770)



Beam current **930mA** & Peak luminosity **$1.02 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$**

对撞模式恒流运行的束流性能

2020年2月27日至3月17日连续三个星期恒流运行情况



◆ 正电子流强 ◆ 负电子流强 ◆ 对撞亮度 ◆ 探测器暗电流

Topup / Decay

15.94 pb⁻¹ / 11.92 pb⁻¹

积分亮度提升 33%

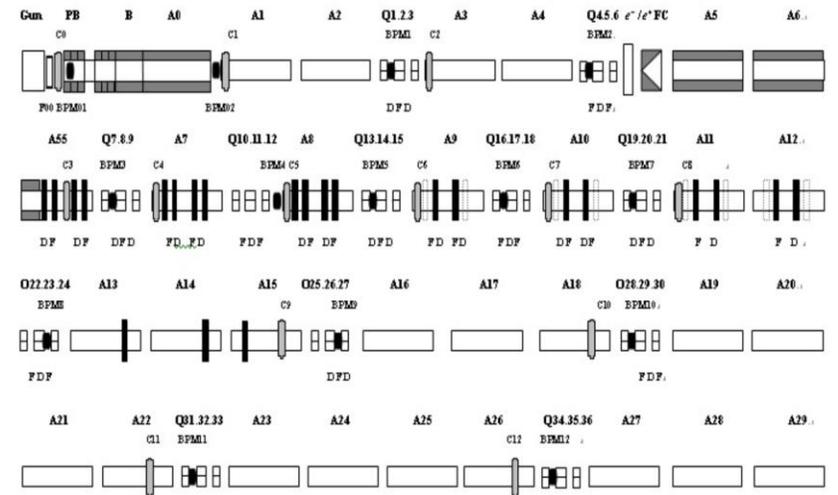
Topup与Decay两种运行方式数据质量相同

直线加速器概貌

直线加速器1987年束流进环，2005年完成 BEPCII 改造。2009年增加双次谐波聚束。七成以上微波器件有36年历史。

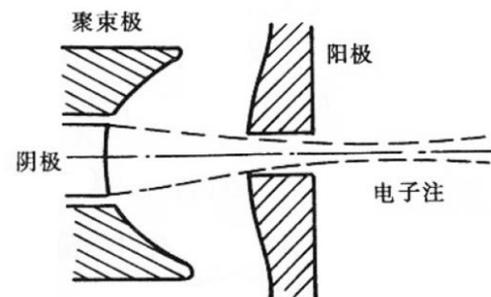
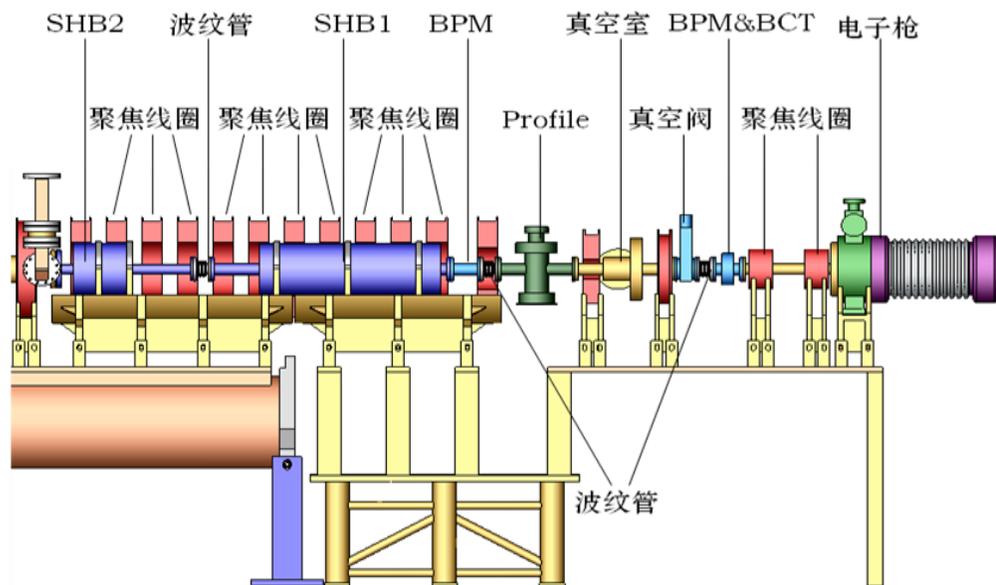
- 主加速频率2856MHz
- 主体结构为20套功率源和56根加速管
- 电子束最高能量可达2.85-2.9GeV
- 正电子束流能量可达2.55-2.6GeV
- 直线出口束流性能
 - 能散度 (e^+ 0.37%, e^- 0.29%)
 - 能量稳定度 0.05%
 - 发射度 (e^+ 0.35mm·mrad, e^- 0.1mm·mrad)

BEPCII直线加速器元件布局示意图

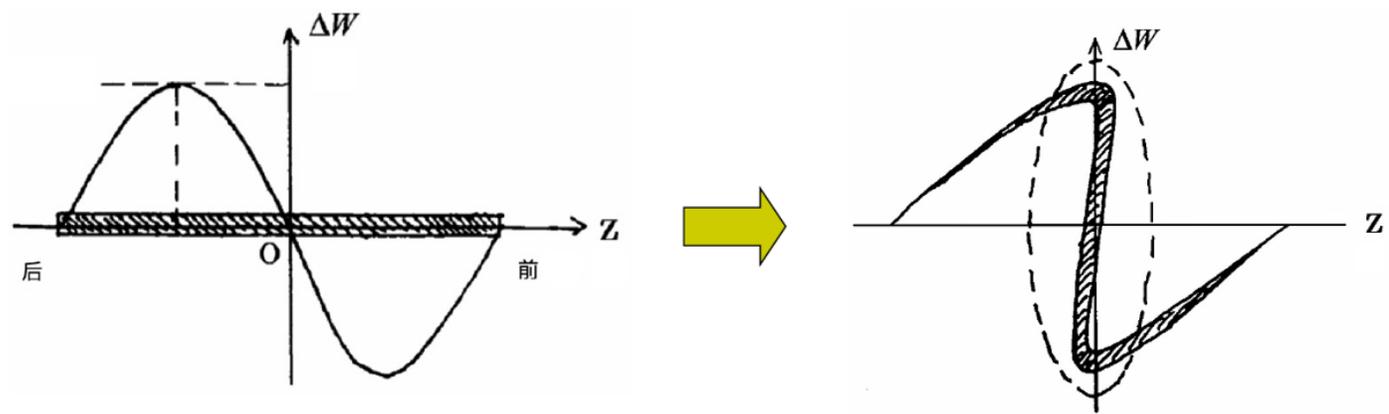
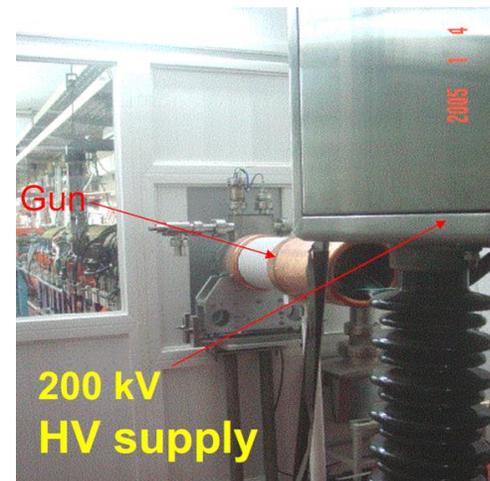


直线加速器前端区：电子枪和聚束系统

BEPCII电子枪:峰值流强10A, 脉冲宽度1ns, 重复频率50Hz



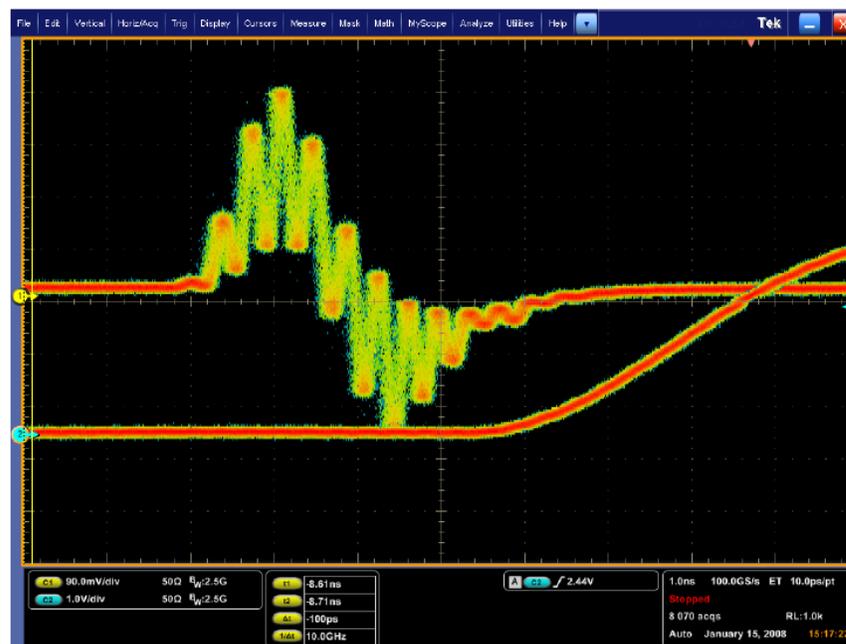
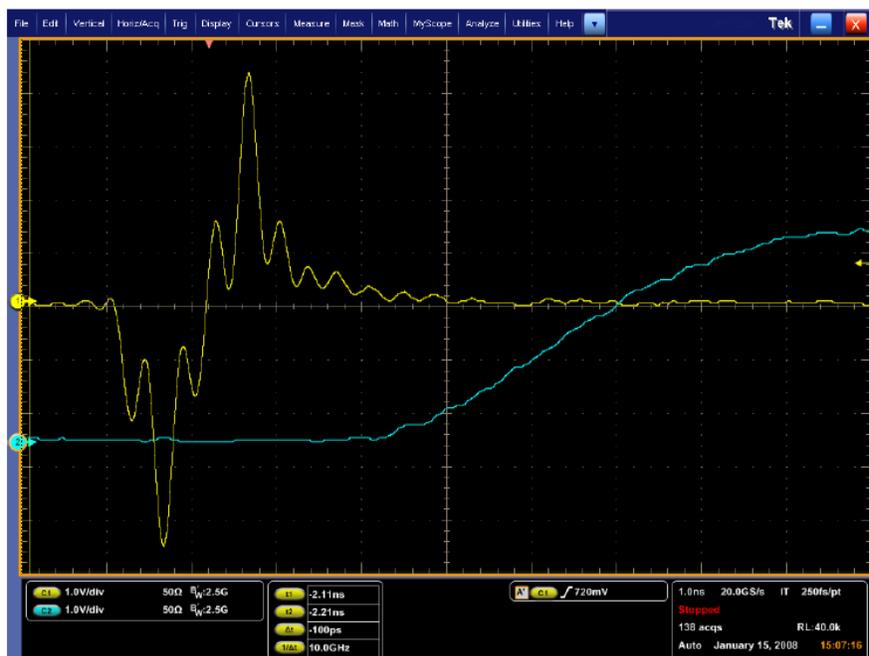
强流电子枪示意图





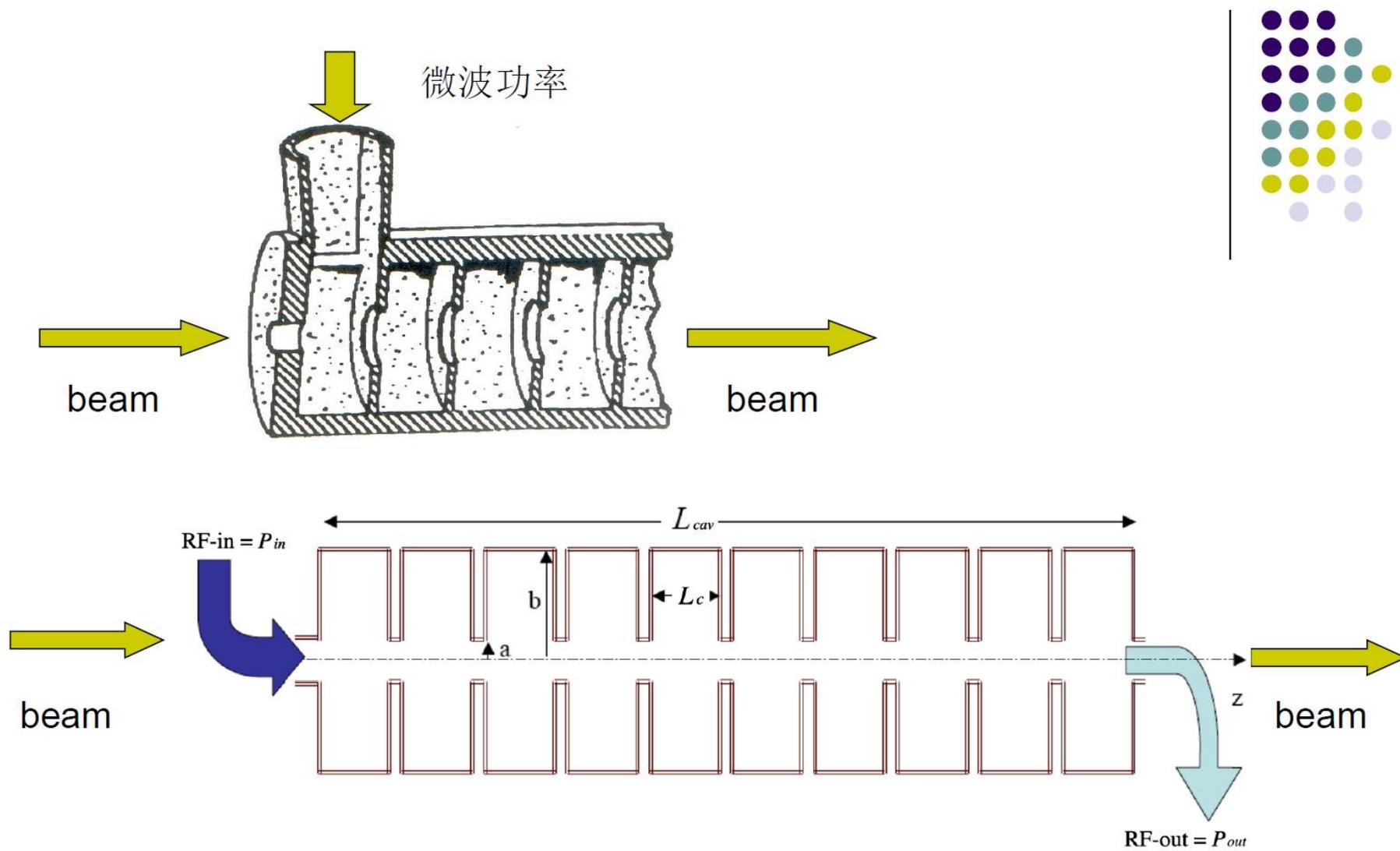
BEPCII电子和正电子束流的微脉冲

电子有3个清晰的微脉冲，总长度在1ns左右，正电子则有约6或7个微脉冲，总长度在2ns左右。

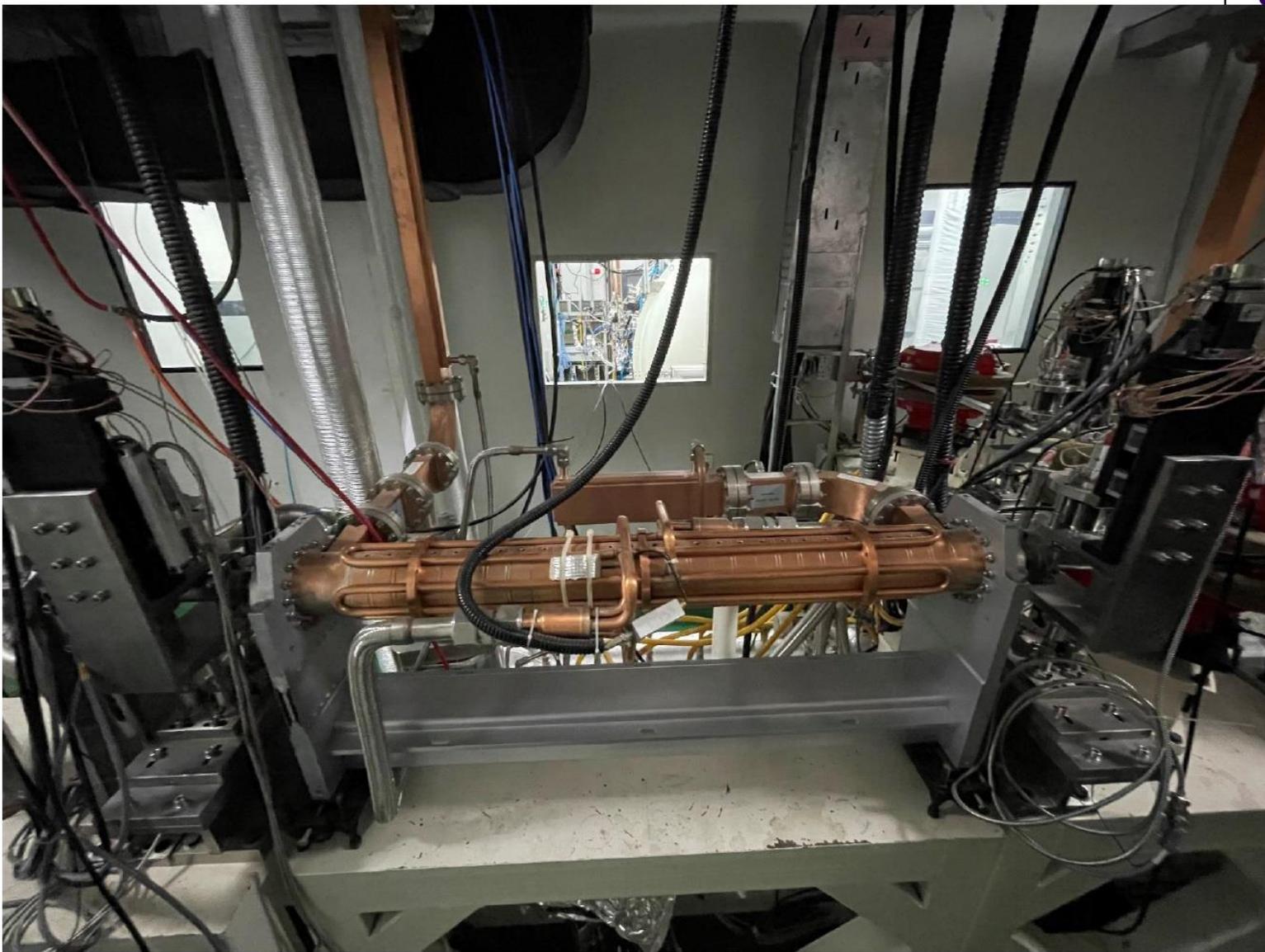


高能电子（240 MeV）轰击重金属靶（W）而产生电磁级联簇射来获得次级正电子

电磁级联簇射：高能电子（或正电子）在物质原子核的电磁场中通过韧致辐射放出一个光子而损失部分能量，高能光子在核电场转化为能量较低的正负电子对。这些产生出来的次级电子、正电子及光子，只要能量够高，就会继续上述的过程。



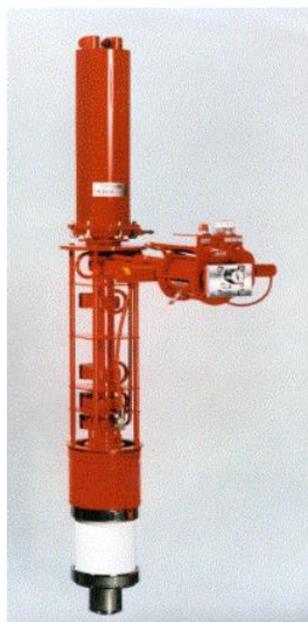
行波加速结构中，电磁场的能量一部分损耗在腔壁上，一部分被加速的束流获得，剩余的能量在加速结构的末端被吸收负载吸收。



波导、加速管、吸收负载

高频功率源和脉冲压缩器

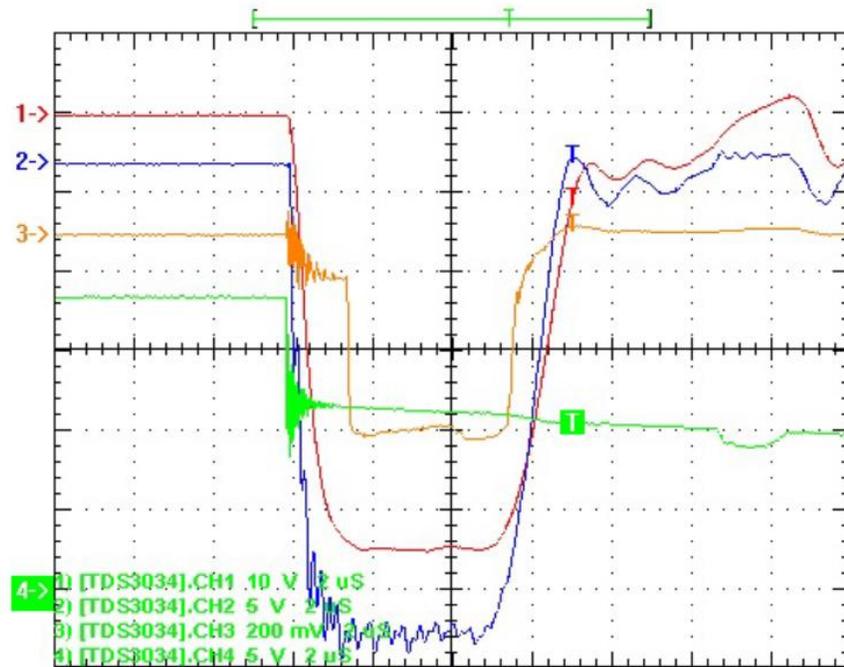
- 高能直线加速器的高频功率源由速调管（klystrons）和高压调制器（modulators）两部分。
- 峰值功率高（10- 80 MW），占空比低（例如：重复频率 $\sim 100\text{Hz}$ ，脉冲长度 \sim 几 μs ）

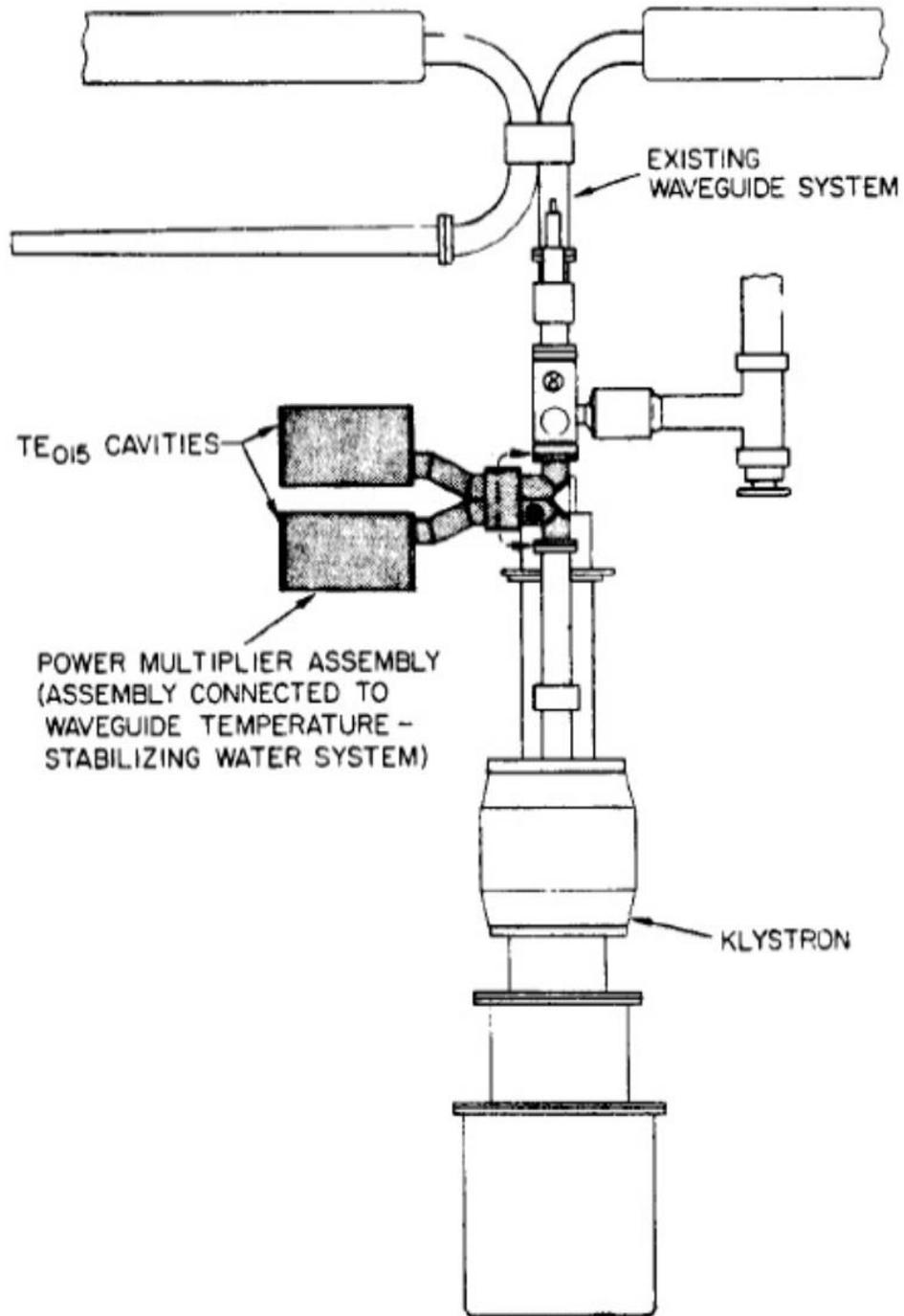


BEPCII-Linac New RF Power Source

New modulators with high power 320 kV \times 360 A.

High voltage stability $\leq \pm 0.15\%$





高频脉冲压缩器: 把低功率的长脉冲, 压缩为高功率的短脉冲

SLED for BEPCII-Linac



- 聚焦元件和横向运动

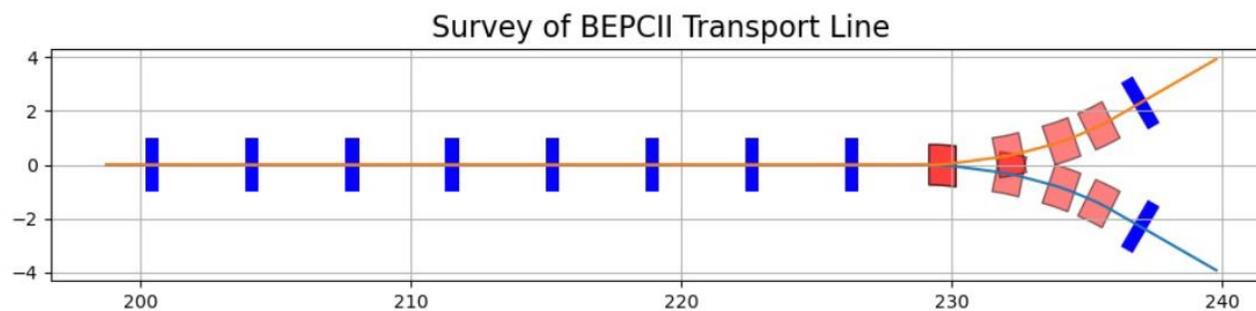
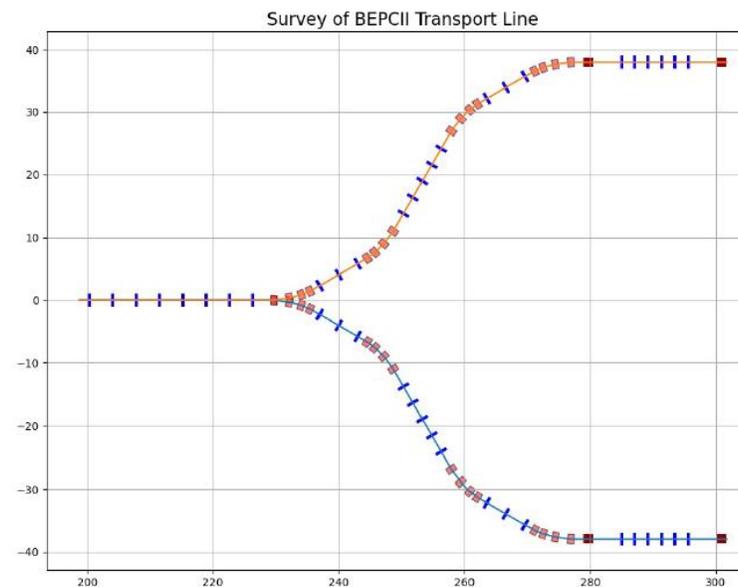
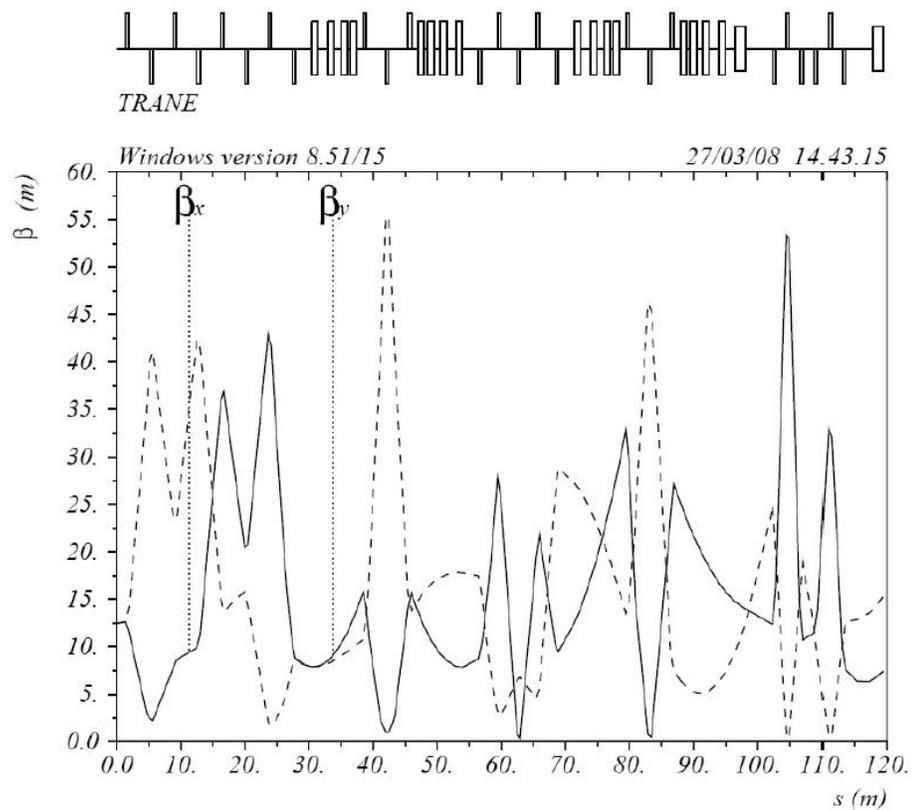
螺线管磁铁 (Solenoid) (能量较低情况下)



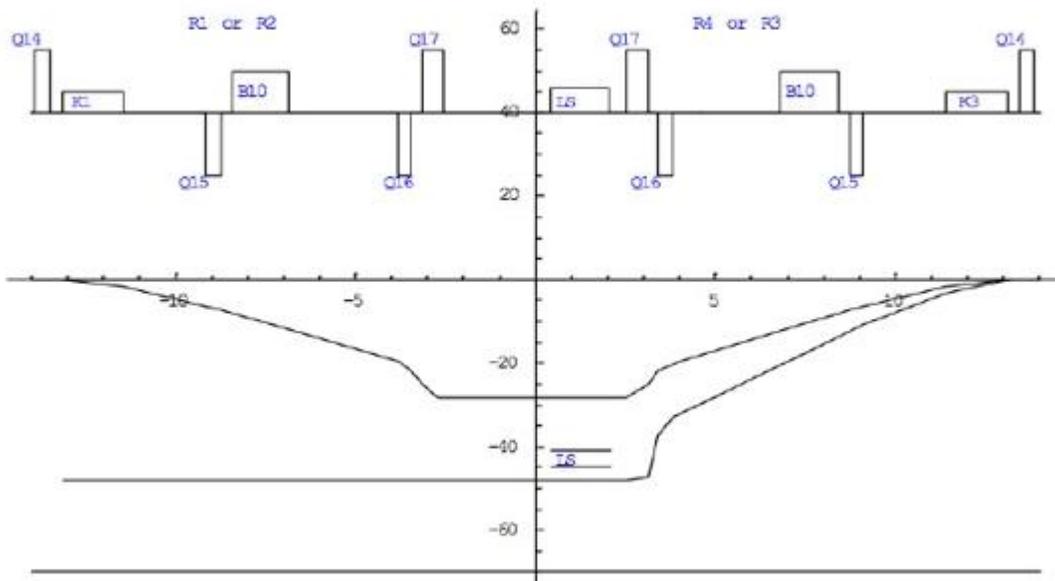
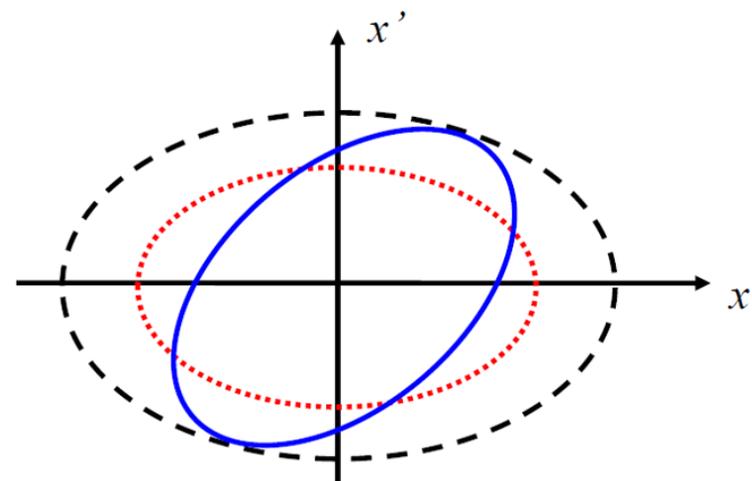
四极透镜 (Quadrupole, 磁四极透镜或电四极透镜) (能量较高情况下)



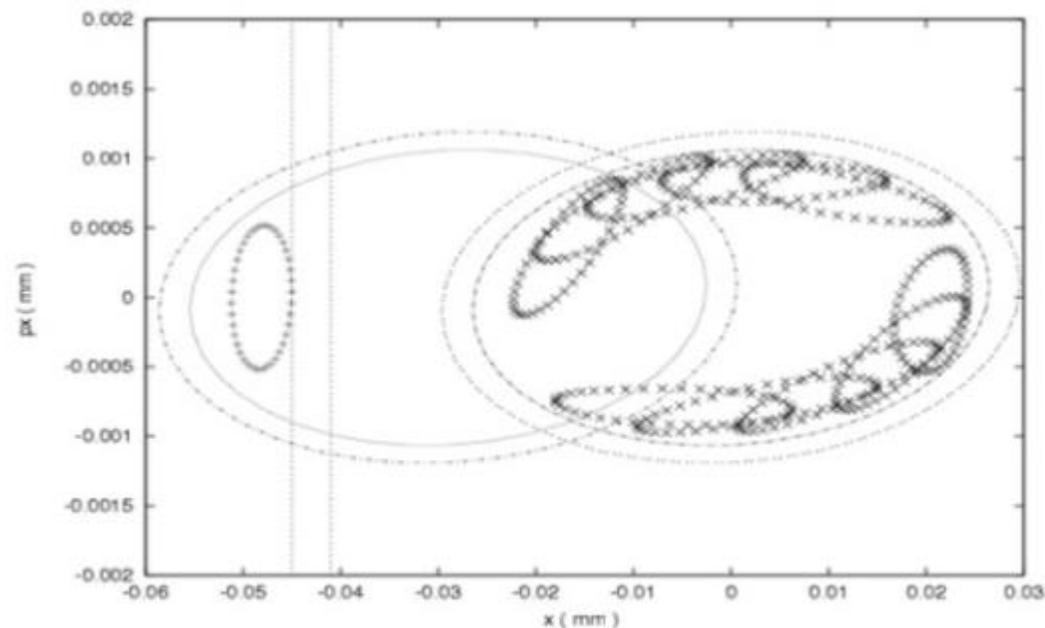
BEPCII 运输线 Lattice



储存环的注入



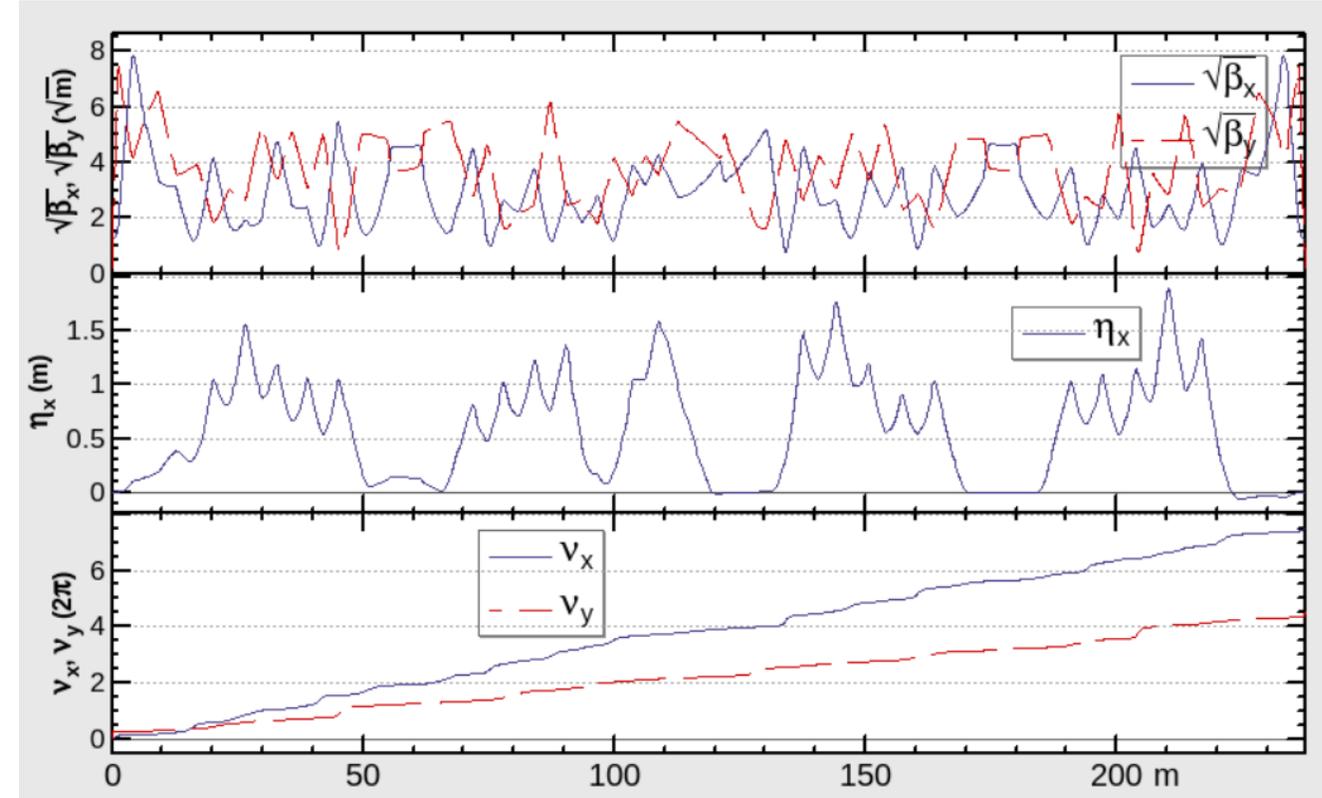
BEPCII 注入布局图



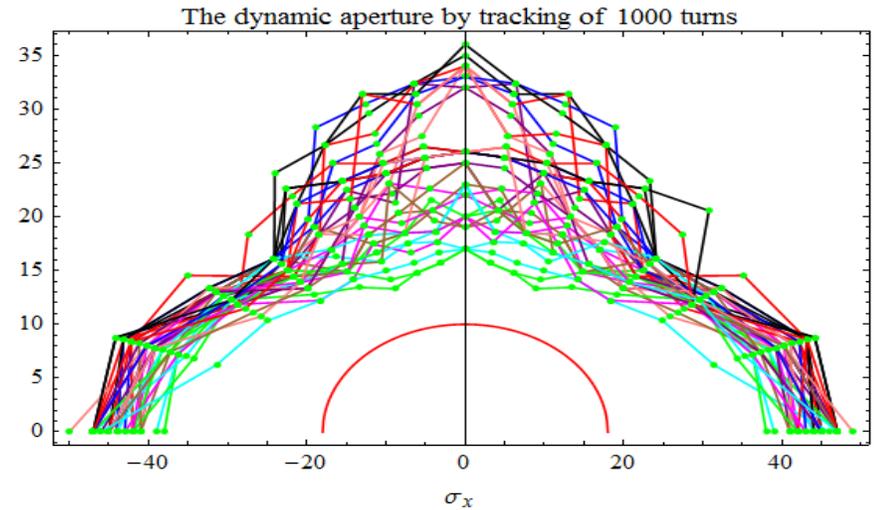
注入束团前10圈在水平相空间中的运动

BEPCII当前运行的Lattice

- 腔压1.65MV， Bucket高度： 0.69%
- 在 $\pm 0.6\%$ 能散 范围内， 动力学孔径大于注入孔径要求的1.5倍

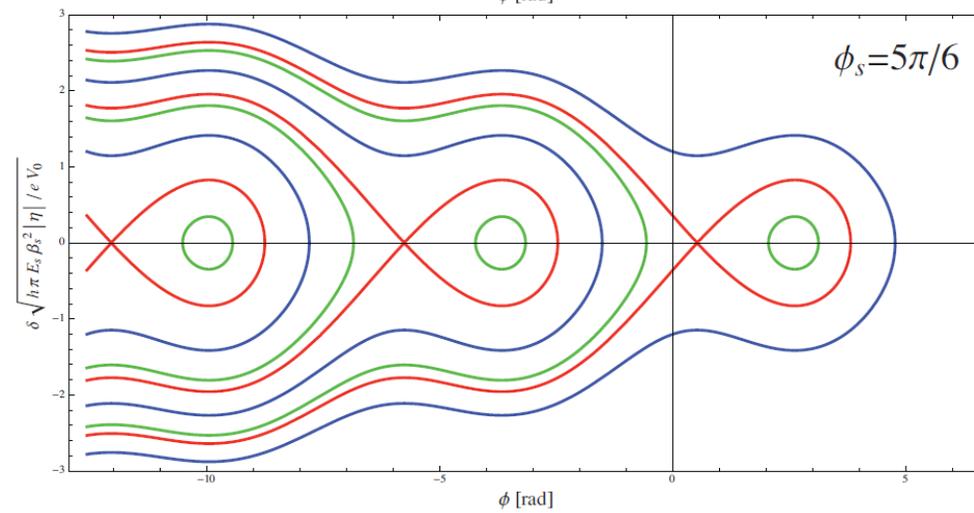
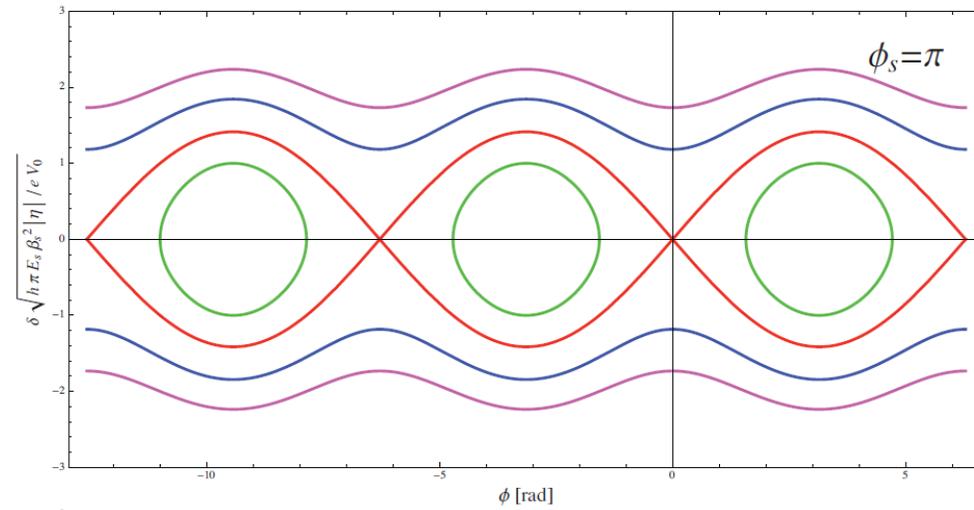


- $dp/p = -0.60\%$
- $dp/p = -0.45\%$
- $dp/p = -0.30\%$
- $dp/p = -0.15\%$
- $dp/p = 0\%$
- $dp/p = 0.15\%$
- $dp/p = 0.30\%$
- $dp/p = 0.45\%$
- $dp/p = 0.60\%$



RF bucket

$$\underline{\eta > 0}$$

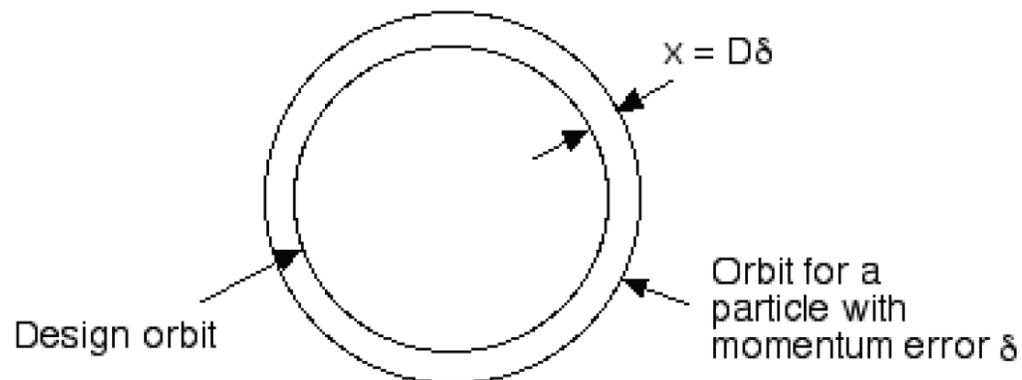


束流能量

(弯转铁、高频腔、校正子、准直误差)

弯转磁铁 (Bending magnet or Dipole magnet)

$$\rho = \frac{P_0}{qB_0}, \quad B_0\rho[T \cdot m] = \frac{P_0}{q} = 3.33564P_0[GeV/c]$$



动量压缩因子定义为

$$\frac{\Delta C}{C} = \alpha_c \delta, \quad \text{or} \quad \alpha_c = \frac{1}{\delta} \frac{\Delta C}{C}$$

\Rightarrow

$$\alpha_c = \frac{1}{C} \oint \frac{D(s)}{\rho(s)} ds$$

- 有色散处的 B 铁扰动会带来闭轨长度的变化

$$\Delta C = \theta D(s_0)$$

- 相稳定性原理使得束流能量发生改变 (高频腔)

$$\delta = -\frac{1}{\alpha_c} \frac{\Delta C}{C} = -\frac{1}{\alpha_c} \frac{\theta D(s_0)}{C}$$

- 高频腔频率的改变也会带来平衡轨道周长的变化以及相应能量的改变

Empirical scaling laws

It is instructive to examine deeper into the rough expressions of the beam sizes obtained so far. To summarize,

$$\begin{aligned}\sigma_\delta &\approx \gamma \sqrt{\frac{C_q}{2R}} \\ \sigma_z &= \frac{c|\eta|}{\omega_s} \sigma_\delta \\ \sigma_{x\beta} &\approx \sqrt{2} \frac{R}{\nu_x^2} \sigma_\delta \\ \sigma_{x\delta} &\approx \frac{R}{\nu_x^2} \sigma_\delta \\ \sigma_x &\approx \sqrt{3} \frac{R}{\nu_x^2} \sigma_\delta \\ \sigma_y &\approx \begin{cases} \frac{1}{\nu_y} \sqrt{\frac{C_q R}{2}} & \text{natural} \\ \sqrt{2} D_y \sigma_\delta & \text{vertical dispersion} \\ \sqrt{\kappa} \sigma_{x\beta} & \text{x-y coupling} \end{cases}\end{aligned}$$

where $C_q = \frac{55}{32\sqrt{3}} \frac{\hbar}{mc} = 3.83 \times 10^{-13} m$

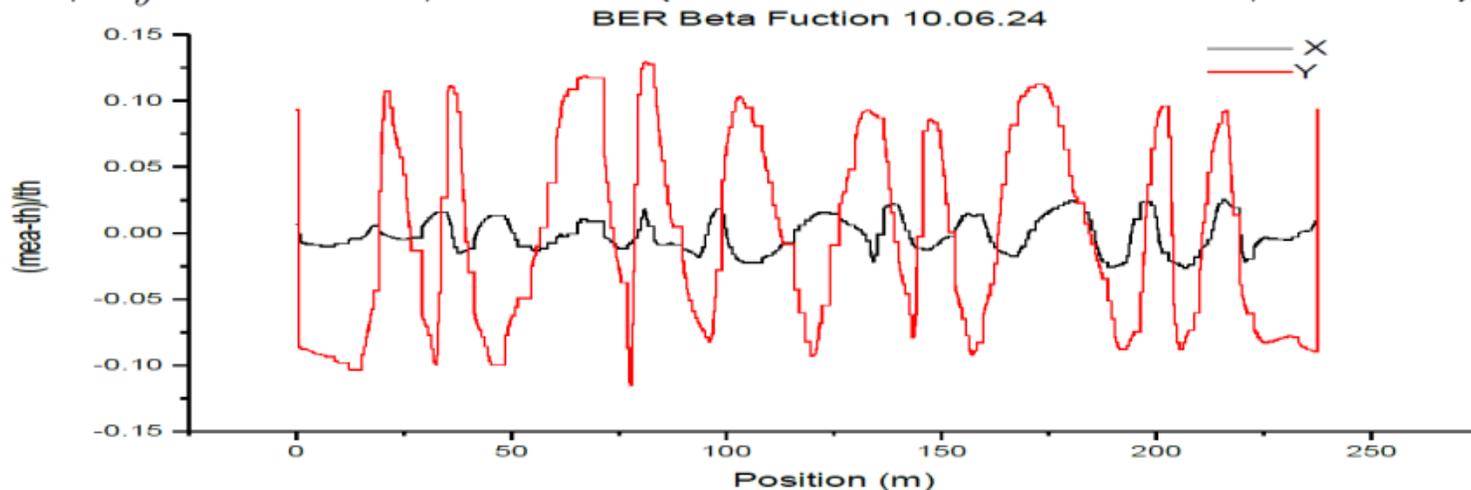
Online Optics correction

$$\begin{pmatrix} \Delta x \\ \Delta y \end{pmatrix} = R_{meas,mod} \begin{pmatrix} \Delta\theta_x \\ \Delta\theta_y \end{pmatrix}$$

$$\chi^2 = \sum_{i,j} \frac{(R_{mod,ij} - R_{meas,ij})^2}{\sigma_i^2} \equiv \sum_{i,j} V_{i,j}^2$$

- 校准：四极铁强度、校正子强度、BPM 系数
- 测量： β 函数，色散和耦合
- 轨道校正和束流能量微调

e^- ring (BER): $\beta_x/\beta_y@IP = 1.0/0.013$ m (Offline Model: 1.0/0.015);
 $\nu_x/\nu_y = 6.5395/5.5787$ (Offline Model: 6.5400/5.5838)



How to Get High Luminosity

$$\xi_{x,y} = \frac{r_e \beta_{x,y} N_b}{2\pi\gamma\sigma_{x,y}(\sigma_x + \sigma_y)}$$

$$\mathcal{L} = f_{\text{coll}} \frac{N_1 N_2}{4\pi\sigma_x^* \sigma_y^*}, \quad L = 2.17 \times 10^{34} \frac{n \xi_y E I_b}{\beta_y^*}$$

Parameters:

ξ_y	Vertical beam-beam parameter
I_b	Bunch current (A)
n	Number of bunches
β_y^*	IP vertical beta (cm)
E	Beam energy (GeV)

Answer:

Increase

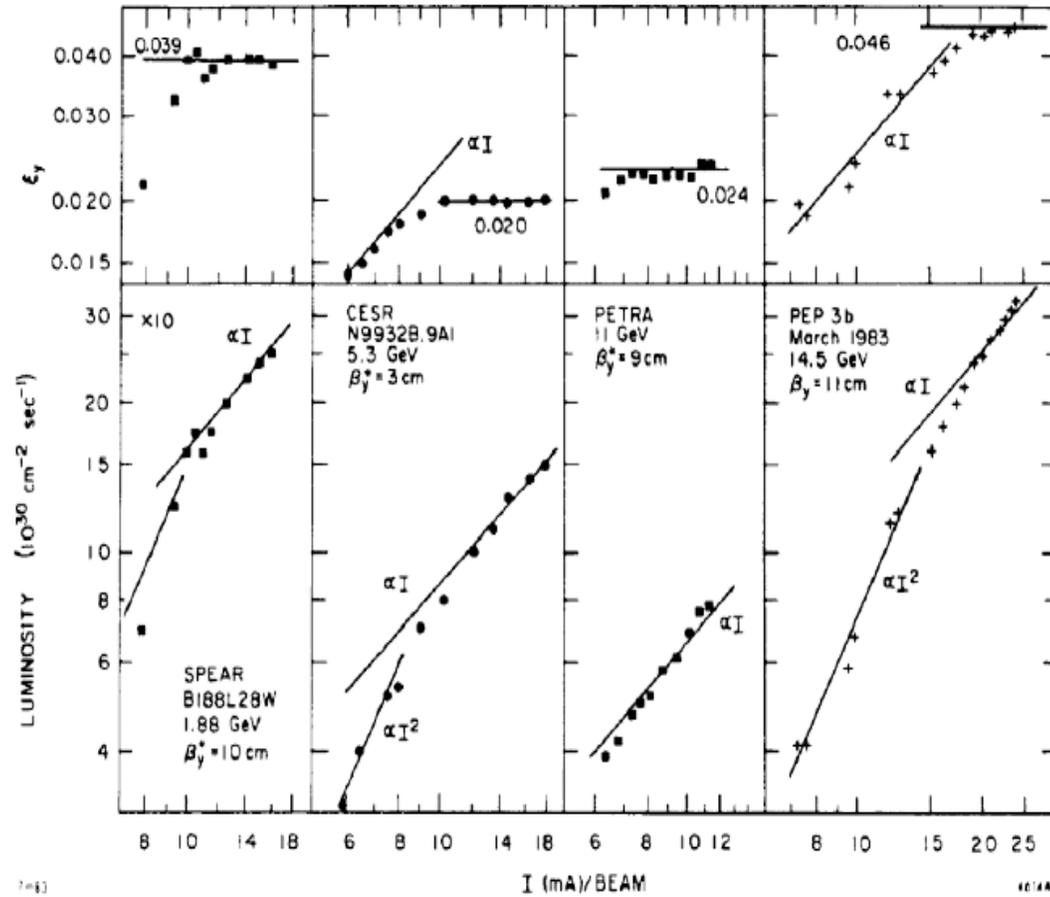
Decrease

Increase

Increase

I_b
 β_y^*
 ξ_y
 n

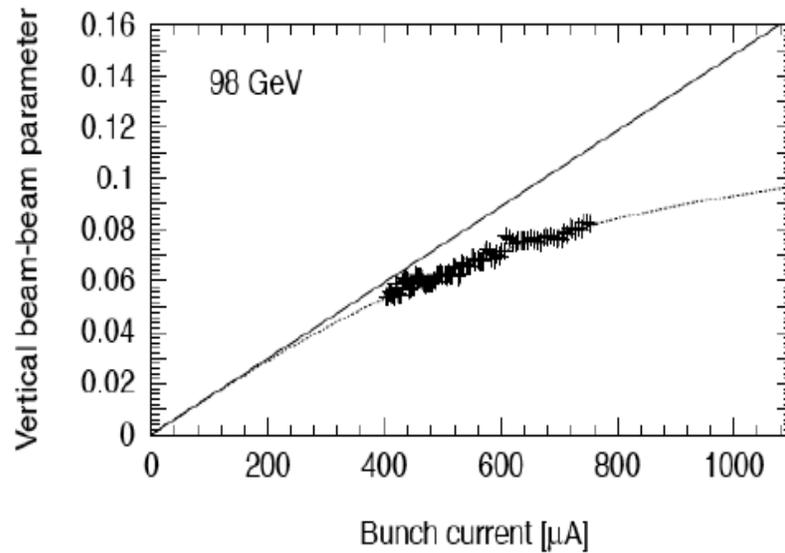
Beam-beam parameter in early machines



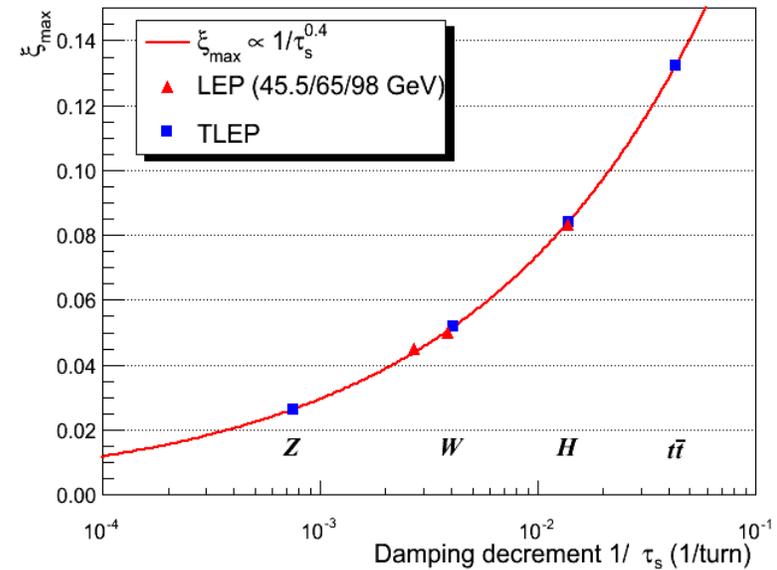
Collider	Energy (GeV)	ξ_y	Nb of IP
VEPP-2M	0.5	0.050	2
DCI	0.8	0.041	2
ADONE	1.5	0.070	6
SPEAR	1.2	0.018	2
	1.9	0.056	2
	2.1	0.055	2
BEP-C	1.6	0.035	2
DORIS-2	5.3	0.026	2
VEPP-4	5.0	0.050	1
	5.0	0.045	1
KEK-AR	5.0	0.030	2
	5.0	0.045	1
	5.0	0.030	2
	5.0	0.030	2
	5.0	0.030	2
CESR	4.7	0.018	2
	5.0	0.022	2
	5.3	0.026	2
	5.5	0.028	2
	5.4	0.020	2
PEP	14.5	0.045	6
	14.5	0.065	2
	14.0	0.050	1
PETRA	7.0	0.014	4
	11.0	0.024	4
	17.0	0.040	4
TRISTAN	30.4	0.034	4
LEP	45.6	0.035	4

Beam-Beam Parameter at LEP2

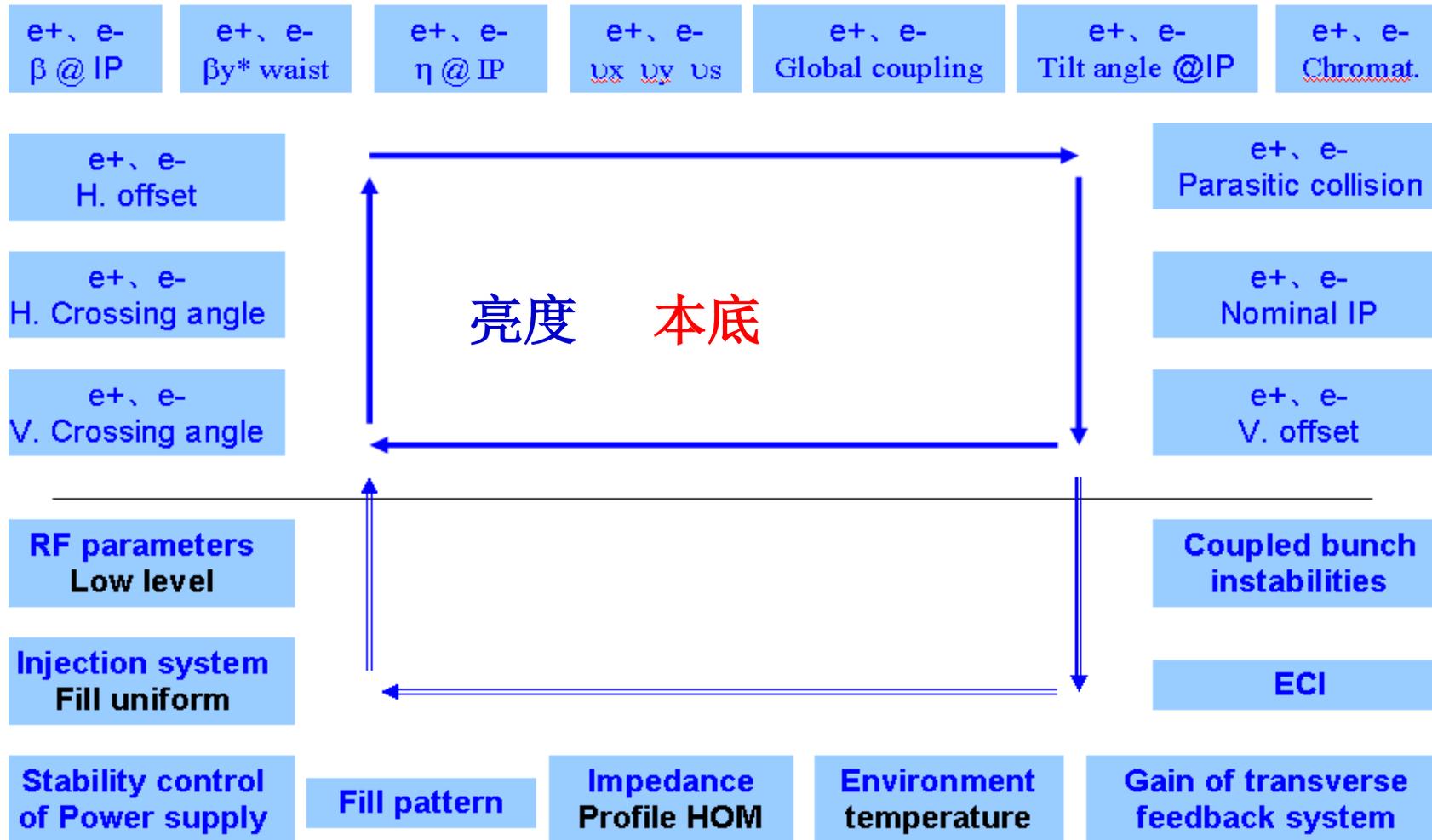
- Vertical Beam-Beam Parameter measured at LEP2



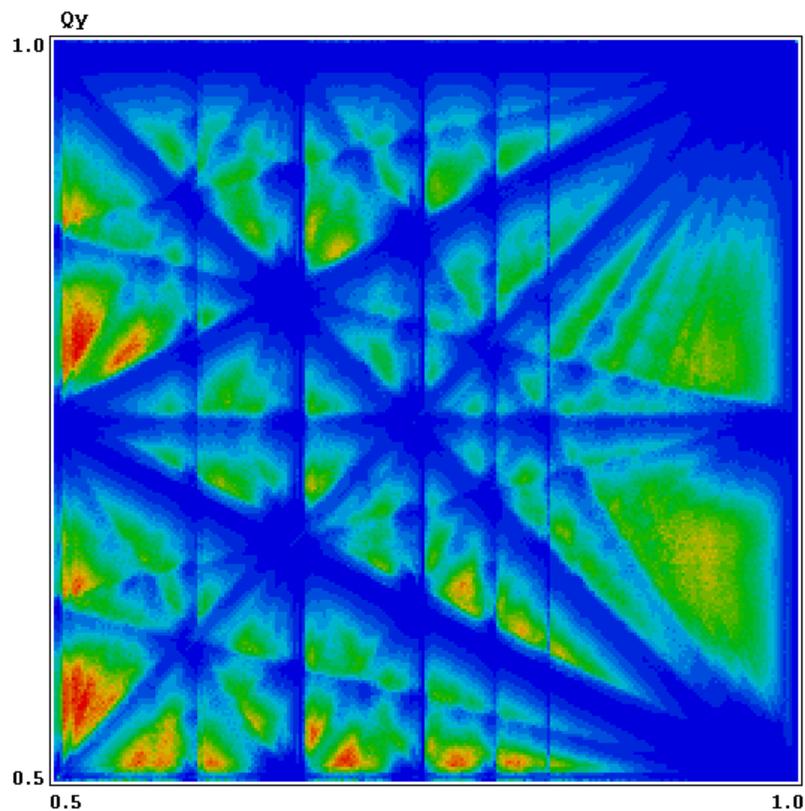
<http://tlep.web.cern.ch/content/accelerator-challenges>



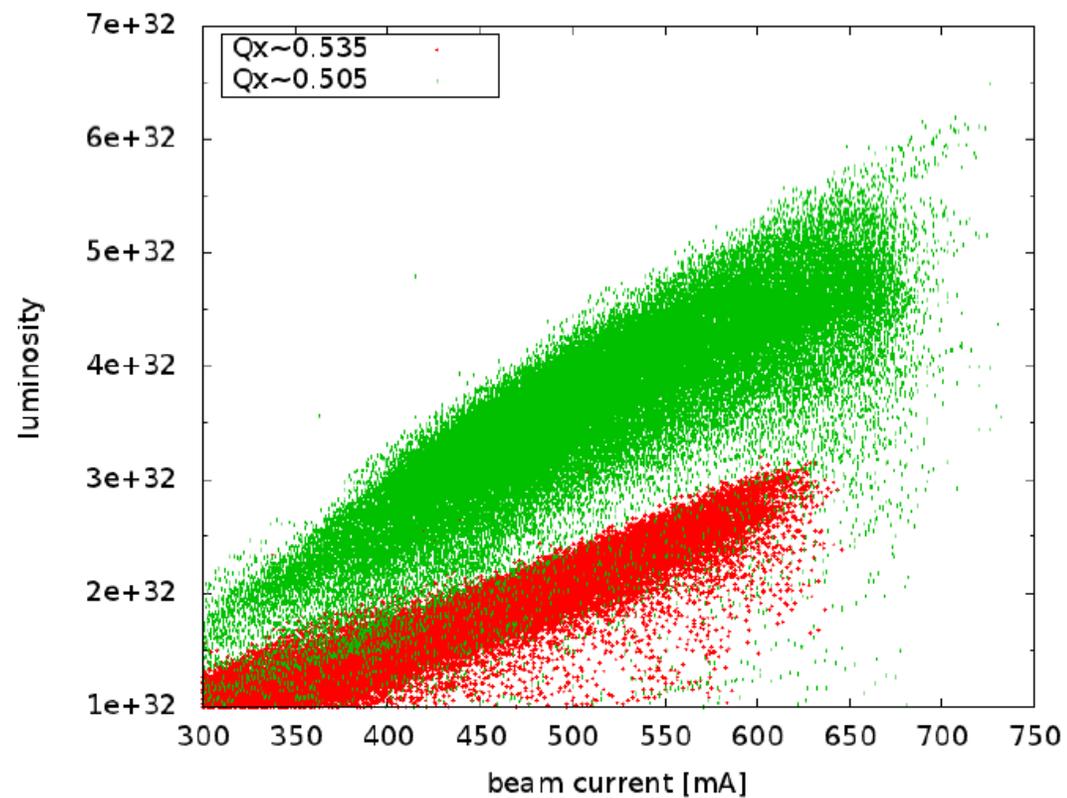
影响亮度的参数 ~70个



工作点对亮度的影响



Mainly synchro-betatron resonances



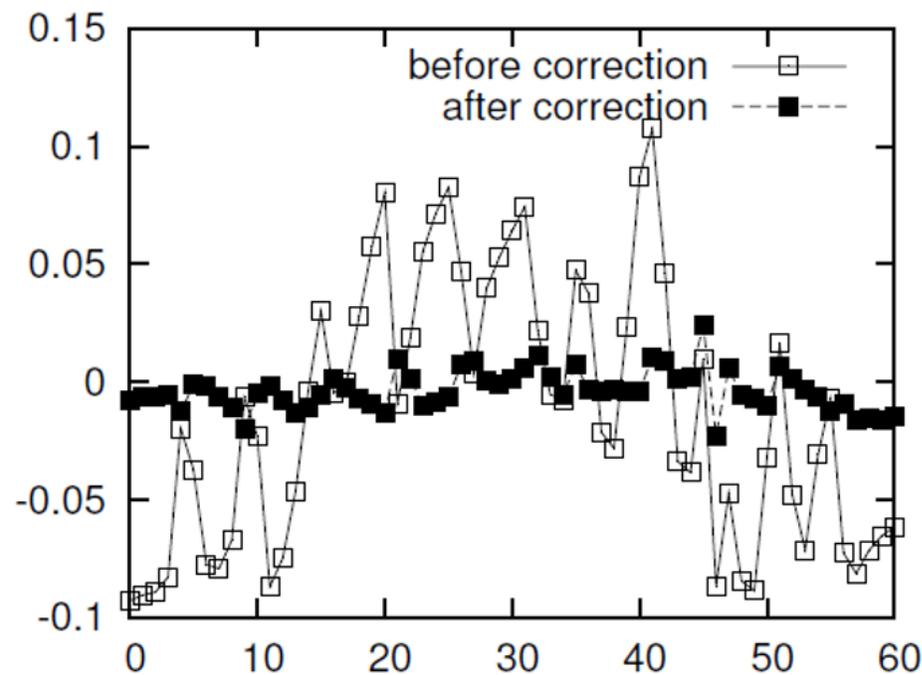
耦合校正

$$\sigma_y^2(0) \sim \sigma_{y,0}^2 + \sigma_x^2 \left[R_1^2 + \frac{R_2^2}{\beta_x^2} \right]$$

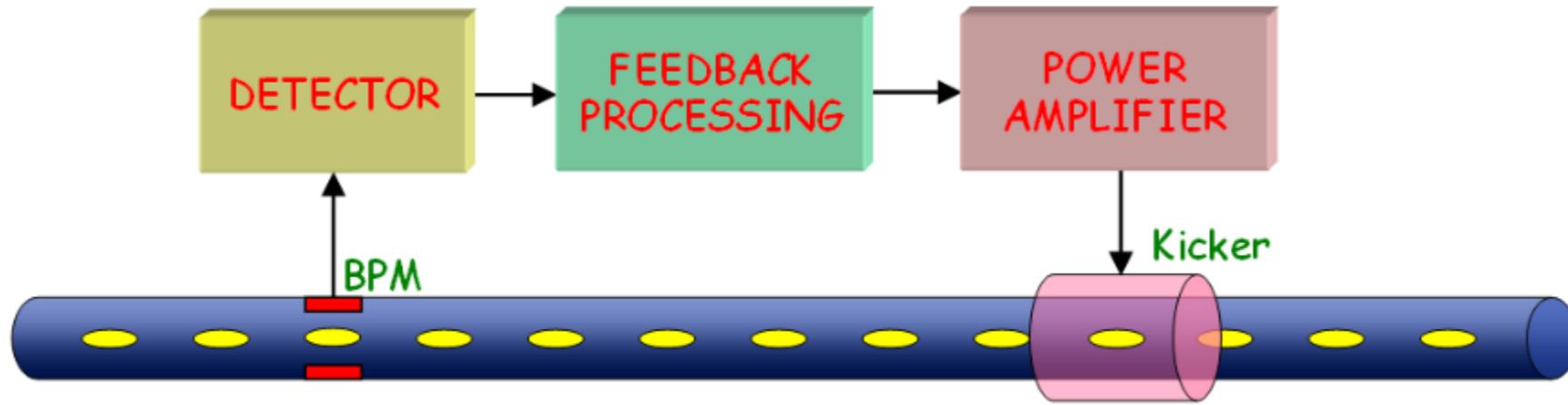
$$\sigma_y^2(s) \sim \epsilon_x \left[\beta_x (-R_1 + R_3 s)^2 + \frac{1}{\beta_x} (R_2 + R_4 s)^2 \right] + \epsilon_y \left[\beta_y + \frac{s^2}{\beta_y} \right]$$

BEPCII, $\beta_x = 1\text{m}$, $\beta_y = 1.5\text{cm}$, $\frac{\epsilon_y}{\epsilon_x} \sim 0.8\%$, $\sigma_z \sim 1.5\text{cm}$

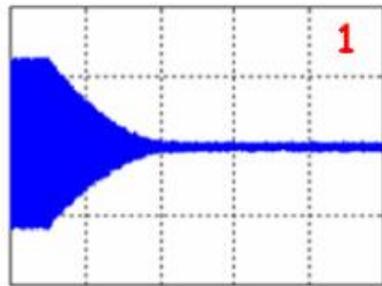
- $\frac{\sigma_x^2}{\sigma_{y,0}^2} \sim 8000$, if $R_1 = 0.01$, $\frac{\sigma_x^2 R_1^2}{\sigma_{y,0}^2} \sim 0.8$, 亮度会受到明显扰动
- R_2 与 R_1 的贡献相当
- R_3 若与 R_1 的贡献相当, 要求 $\frac{R_3}{R_1} \sim 60$
- R_4 与 R_3 的贡献相当



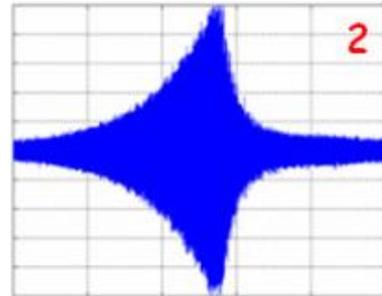
\bar{C}_{12} 的实际测量和校正



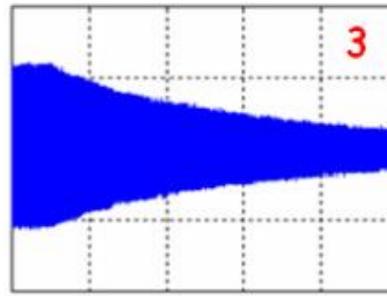
Block diagram of a multi-bunch feedback system



(a)

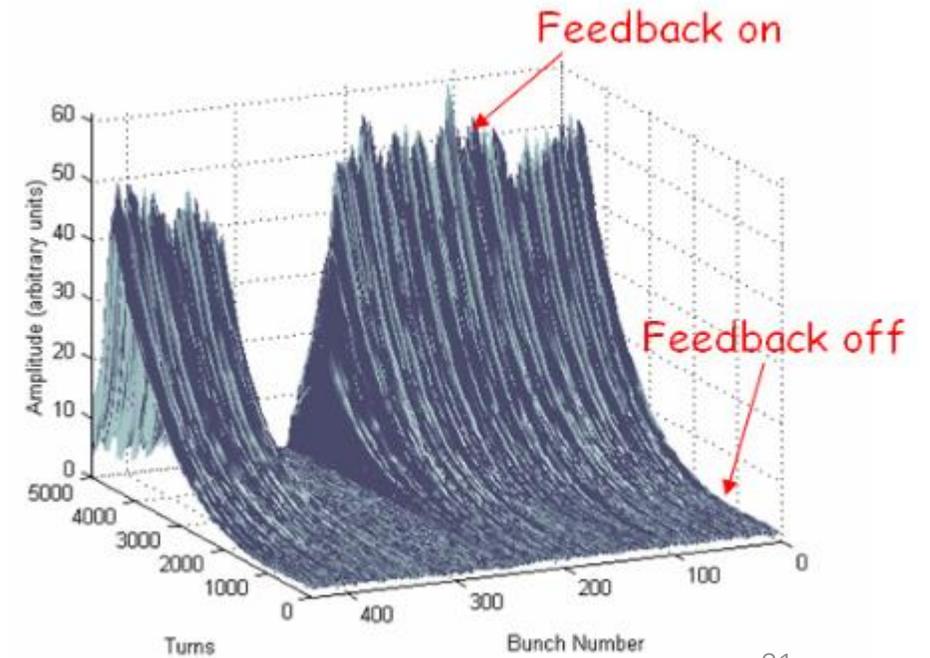


(b)



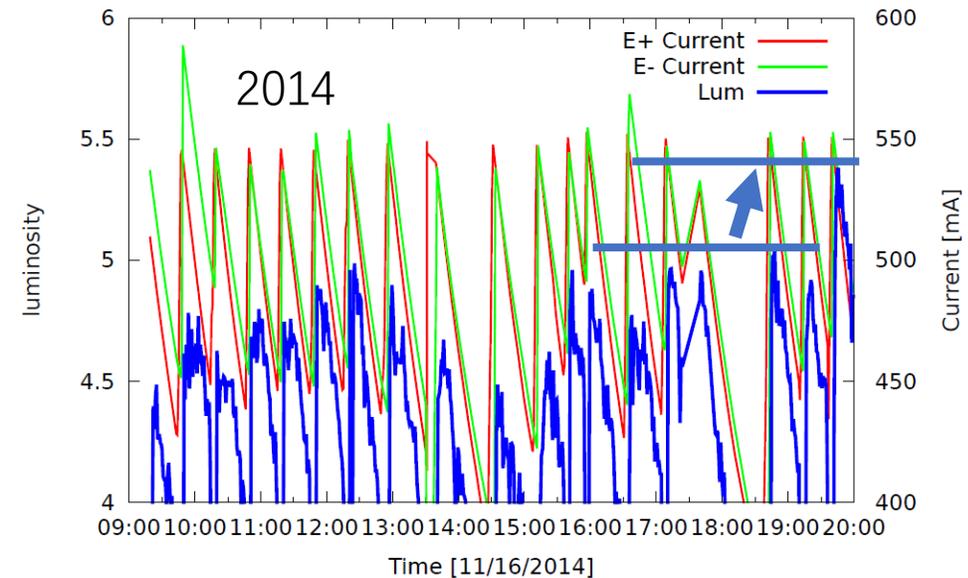
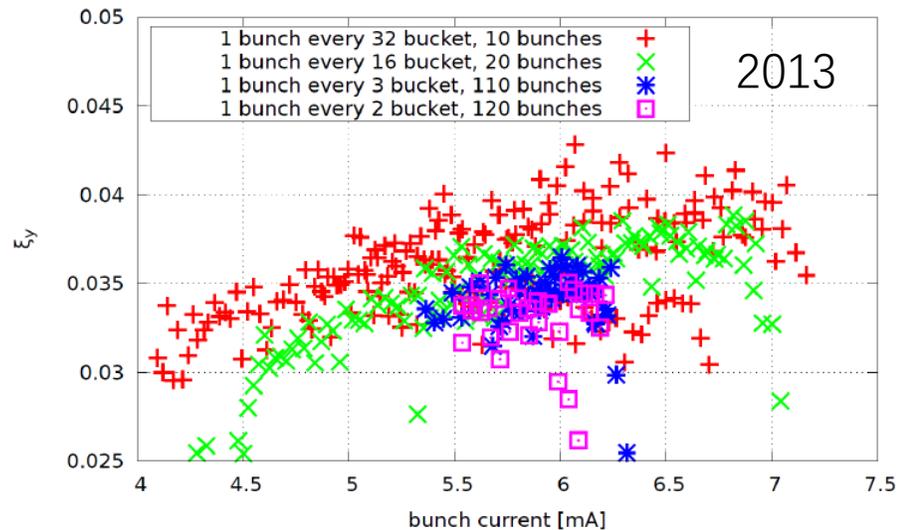
(c)

Examples of transient generation

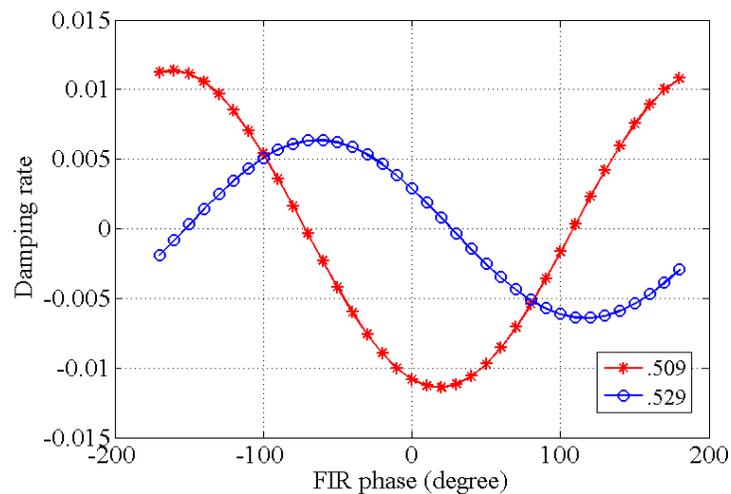
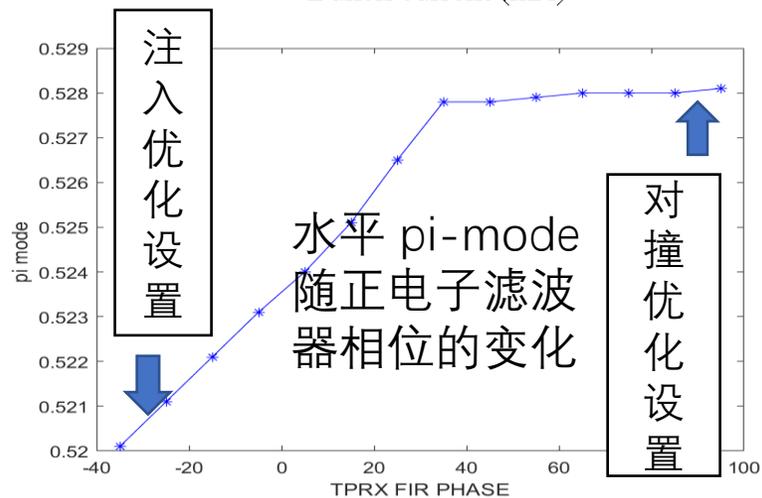
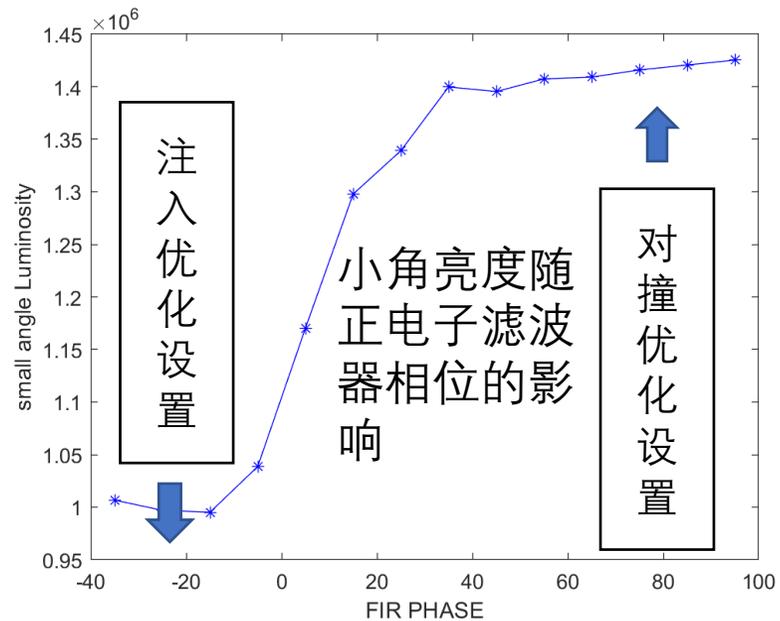
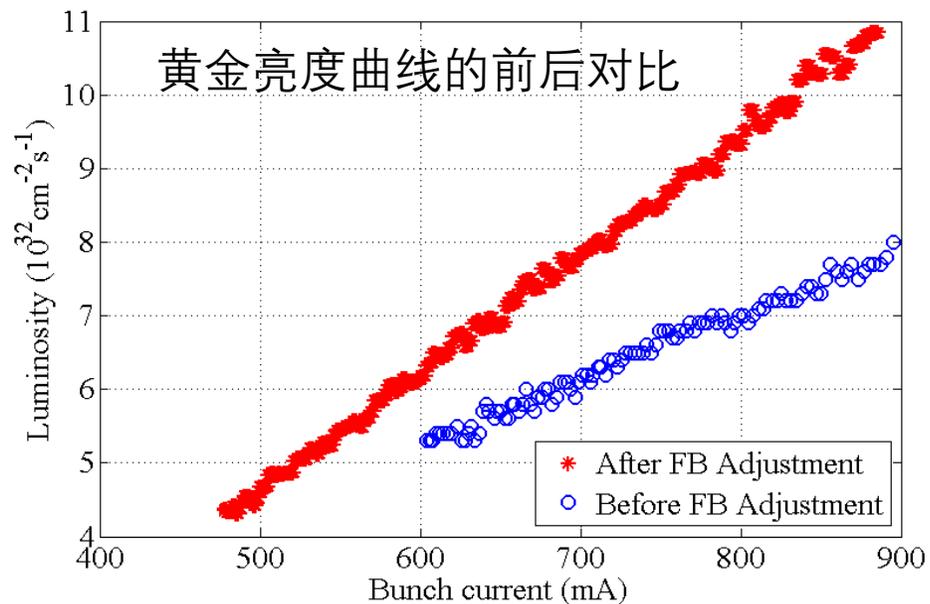


Feedback Noise

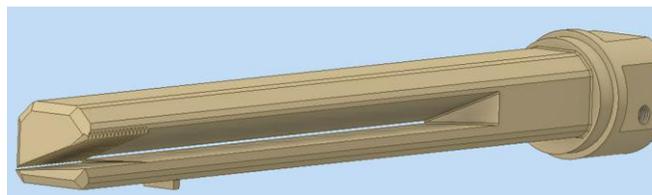
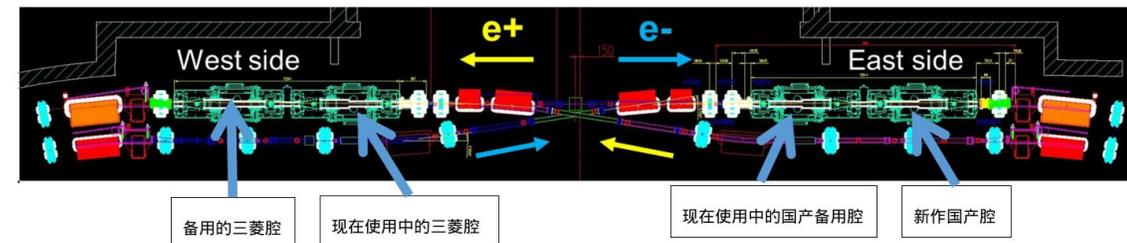
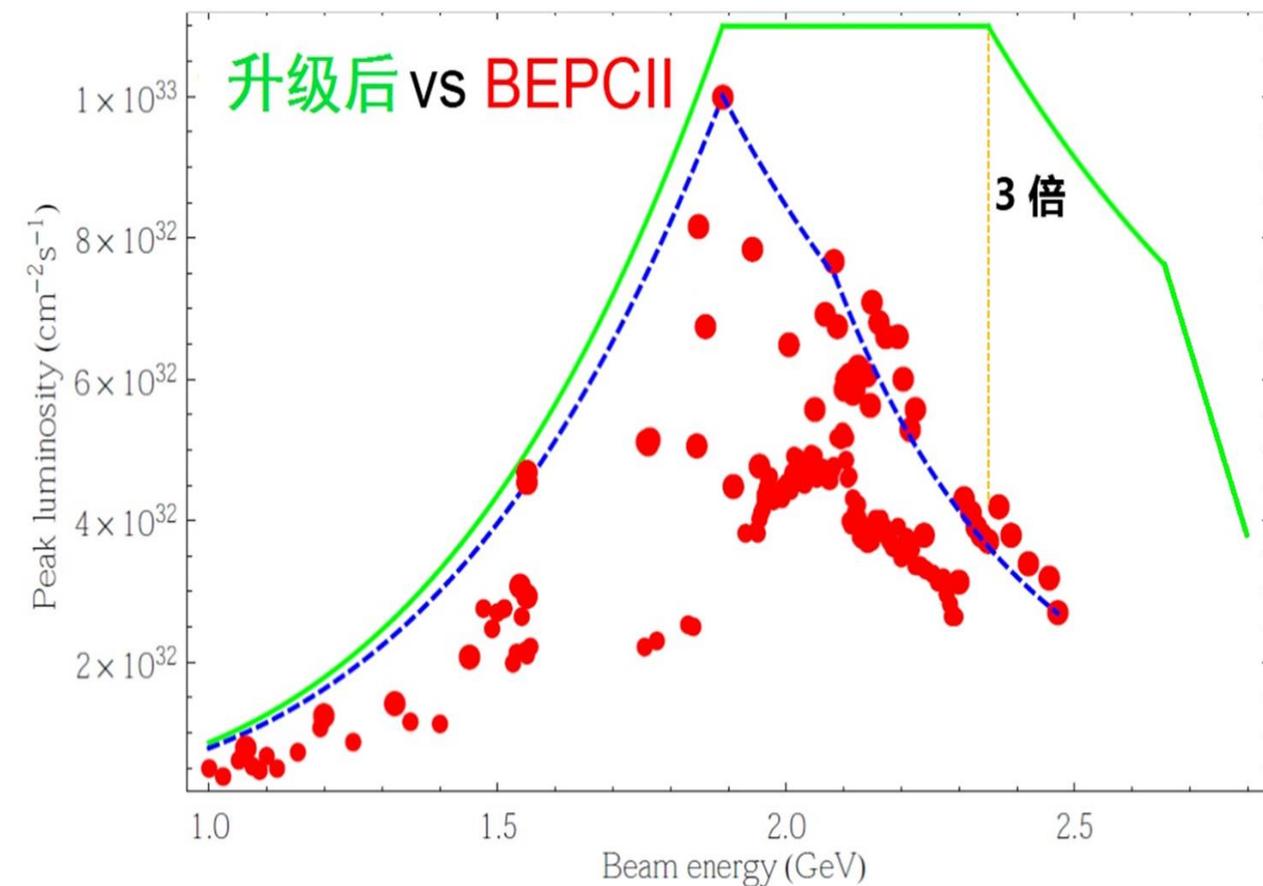
- 在 2014 年之前，一直受困于束团数增加会降低对撞性能的问题
- 2014-11，在实际调束中发现了反馈系统的工作条件对亮度性能的影响，随后峰值亮度很快破 $8e32 \text{ cm}^{-2}\text{s}^{-1}$



2023的物理取数亮度突破



- @ 2.35GeV亮度*3
- 最高束流能量2.47GeV-» 2.80GeV



BEPCII升级：高能区的取数效率和最高对撞能量