



中山大學
SUN YAT-SEN UNIVERSITY



中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences



深圳综合粒子设施研究院
Institute of Advanced Science Facilities, Shenzhen

粒子加速器原理

加速器发展历程简要回顾

邵佳航

➤ 2007.9-2011.7 清华大学 电子工程系

❖ 工学学士

➤ 2011.9-2016.7 清华大学 工程物理系

❖ 工学博士

❖ 研究方向：高梯度加速结构中的射频击穿现象

➤ 2016.10-2021.5 美国阿贡国家实验室 高能物理部

❖ 博士后、助理研究员

❖ 研究方向：尾场加速、先进阴极高梯度测量

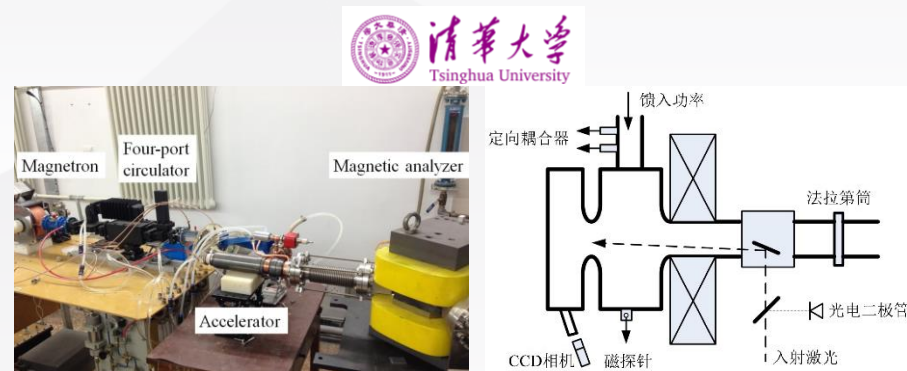
➤ 2021.5 至今 深圳综合粒子设施研究院 自由电子激光项目经理部

❖ 研究员

❖ 研究方向：自由电子激光装置中的常温微波结构

➤ 2021.8 至今 南方科技大学 理学院

❖ 访问学者

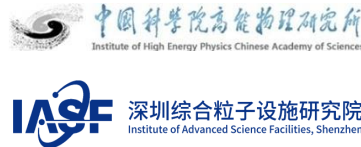




课程相关介绍

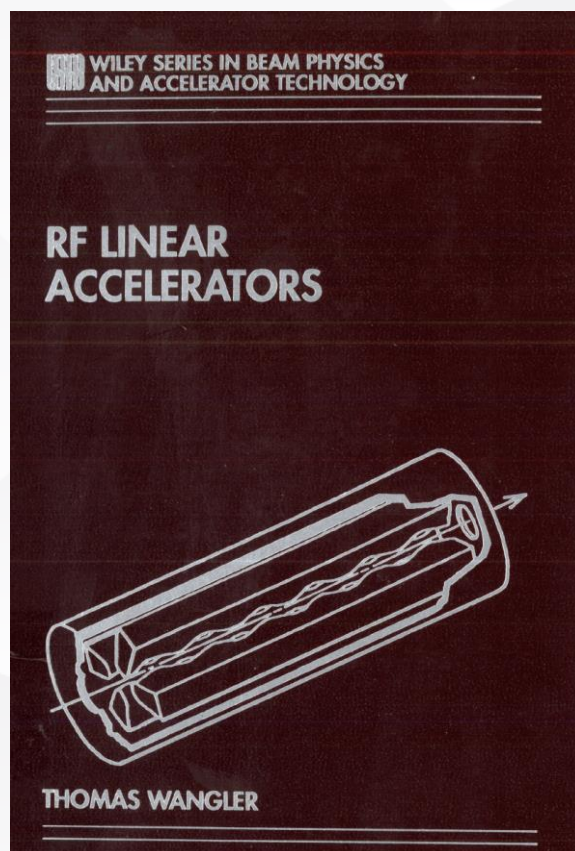


中山大學
SUN YAT-SEN UNIVERSITY



➤ 参考教材

❖ T. Wangler, RF Linear accelerators, John Wiley & Sons, 1998

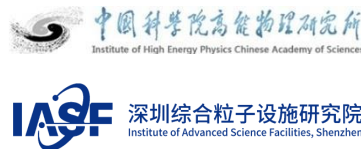




课程相关介绍

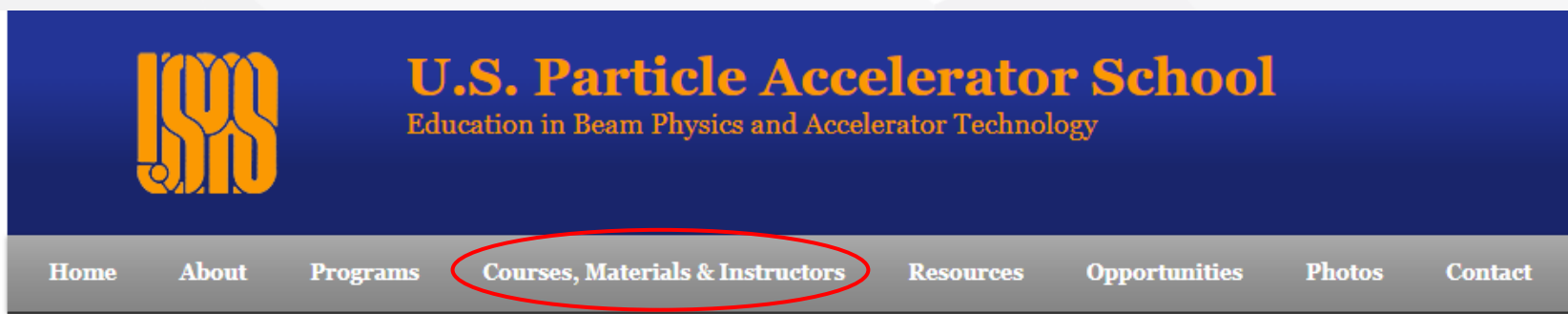


中山大學
SUN YAT-SEN UNIVERSITY



➤ 更多参考资料

- ❖ US Particle Accelerator school (USPAS)
 - <https://uspas.fnal.gov/>



- ❖ CERN Accelerator school (CAS)
 - <https://cas.web.cern.ch/>





目录

01

早期发展历史

02

近期主要发展

03

未来研究方向

04

粒子加速器主要应用



➤ 仅涉及本课程重点介绍的粒子加速器类型

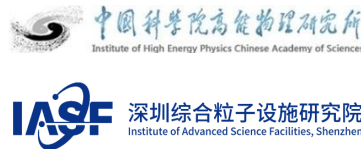




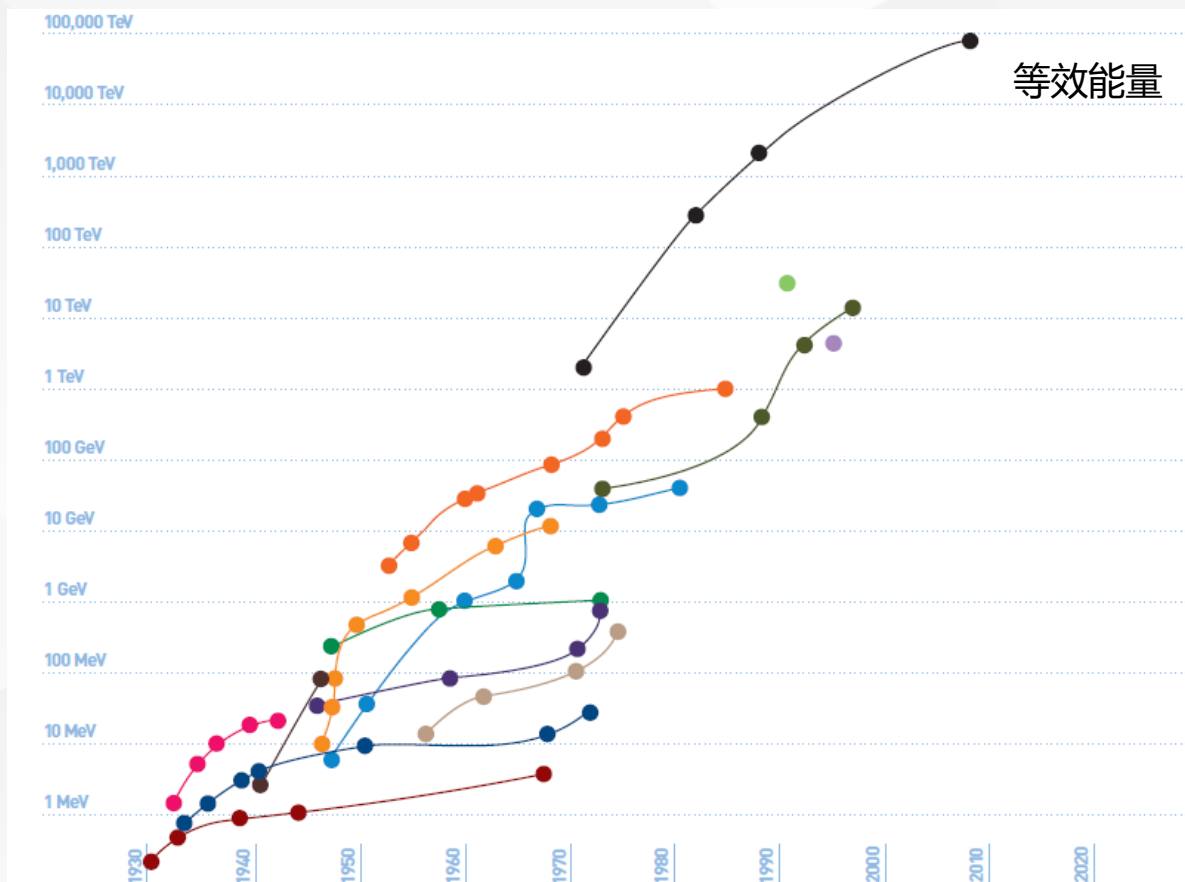
简要发展历史



中山大學
SUN YAT-SEN UNIVERSITY



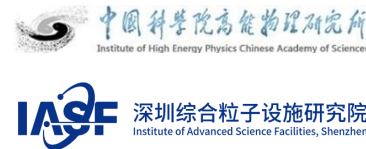
- 粒子加速器最高能量基本遵循Livingston规律（每六年提高一个量级）
 - ❖ 得益于新原理、新技术的不断发展



Accelerators for America's Future, DOE report (2010)



中山大學
SUN YAT-SEN UNIVERSITY



01

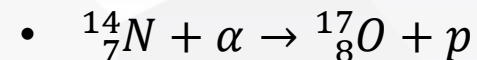
早期发展历史

➤ 粒子加速器的最初需求来自于核物理研究

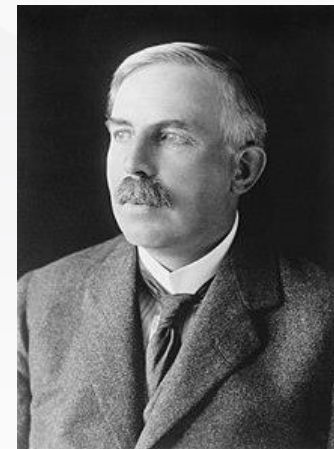
➤ 新西兰物理学家卢瑟福 – 核物理之父

- ❖ 1909年卢瑟福散射实验
- ❖ 1919年首次通过 α 粒子轰击氮气发现质子

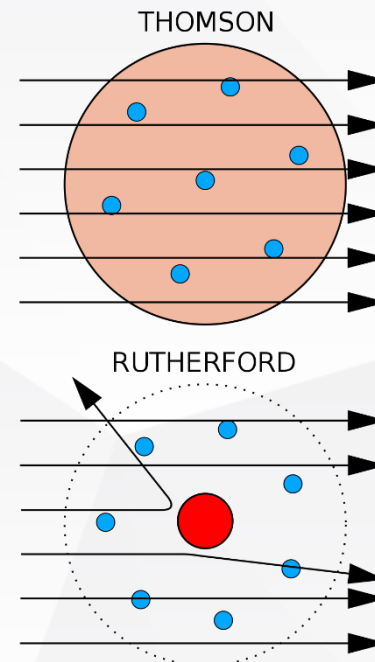
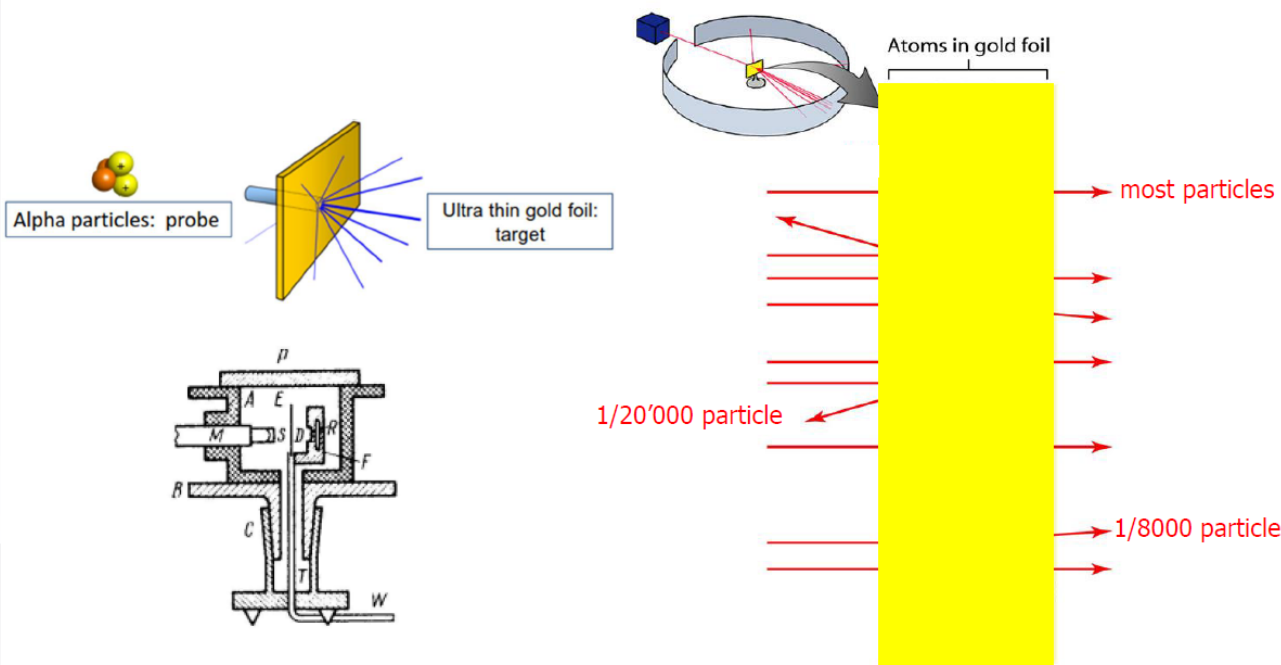
❖ 第一个人工核反应



❖ 后续研究迫切需要更高能量的粒子



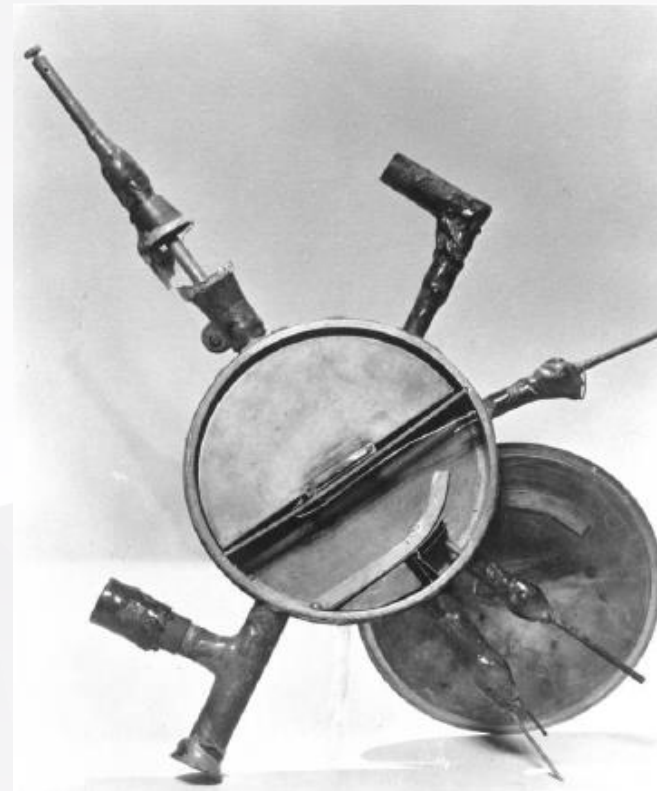
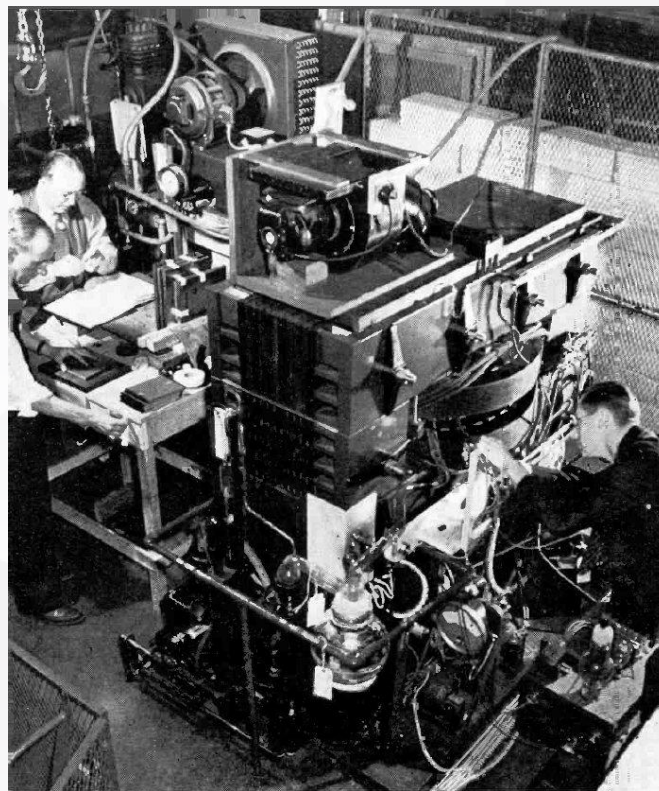
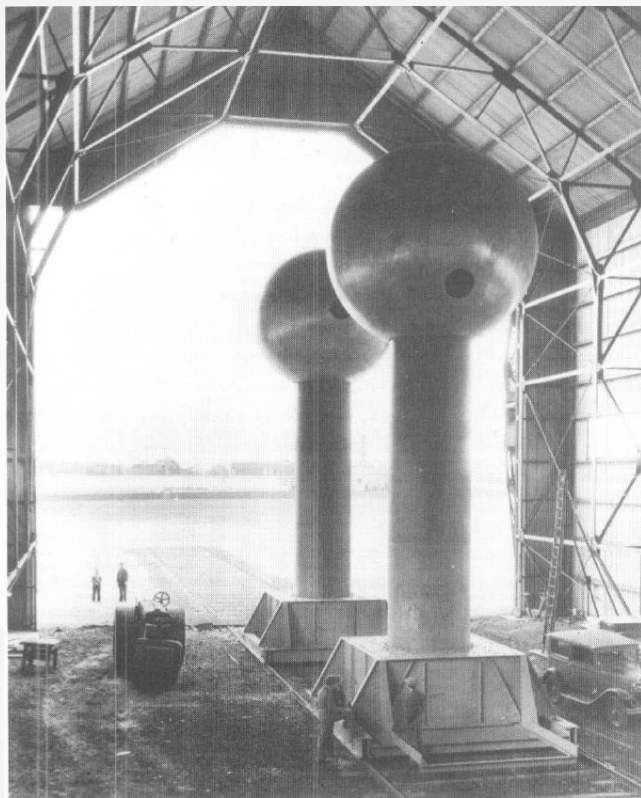
1908年诺贝尔化学奖





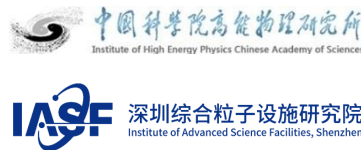
➤ 早期加速器发展的三条主线

- ❖ 直流高压加速器
- ❖ 感应加速器
- ❖ 回旋加速器





中山大學
SUN YAT-SEN UNIVERSITY



中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences
IASF 深圳综合粒子设施研究院
Institute of Advanced Science Facilities, Shenzhen

01A

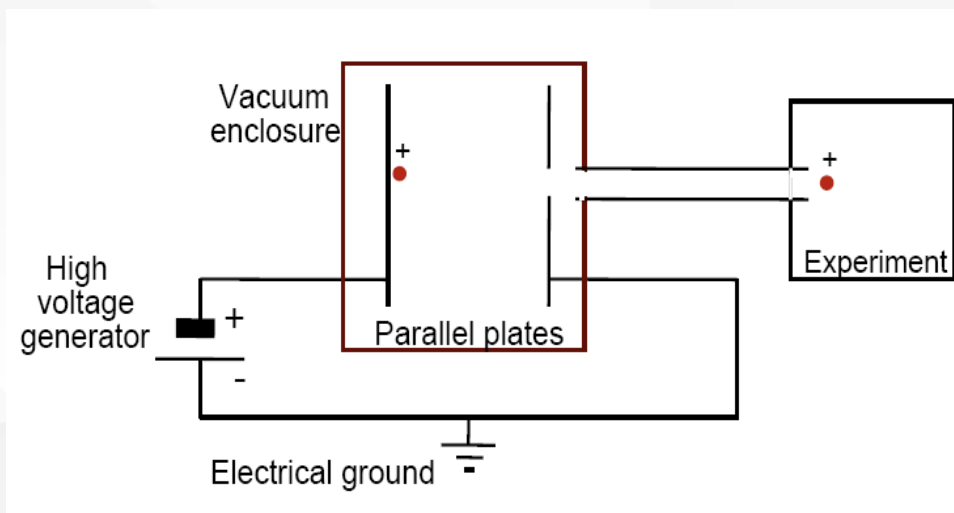
直流高压加速器



➤ 基本原理

❖ 利用阴阳极之间的直流电压加速带电粒子

- $\Delta W = qV$
- 能量增益与沿途场分布形式无关
- 可加速电子、质子、重离子
- 可加速直流束



➤ 难点：如何获得更高的电压



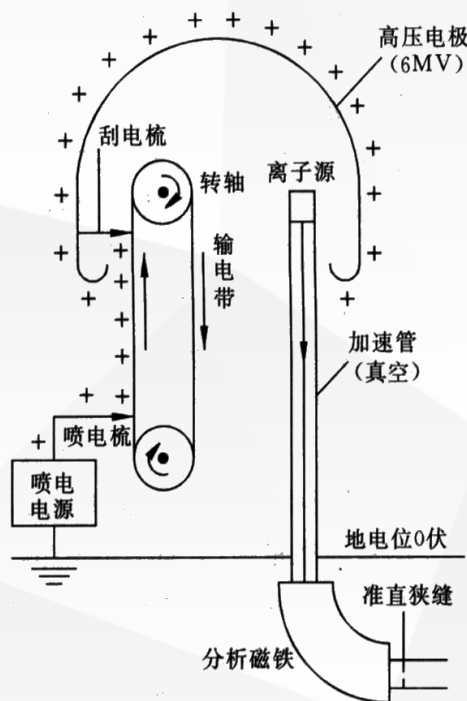
➤ Van de Graaf静电加速器 (Van de Graaf generator)

- ❖ 由美国物理学家Robert J. Van de Graaff提出并研制
- ❖ 由高压电极、绝缘支柱和输电系统组成
- ❖ 机械传送的方法将电荷不断的输送到与地绝缘的固定电极上
- ❖ 动带式输电系统由输电带、上下转轴、喷电与刮电针排、喷电电源等组成
- ❖ 电极对地的电压随电荷量的积累而升高

$$V = Q/C$$

电极电容

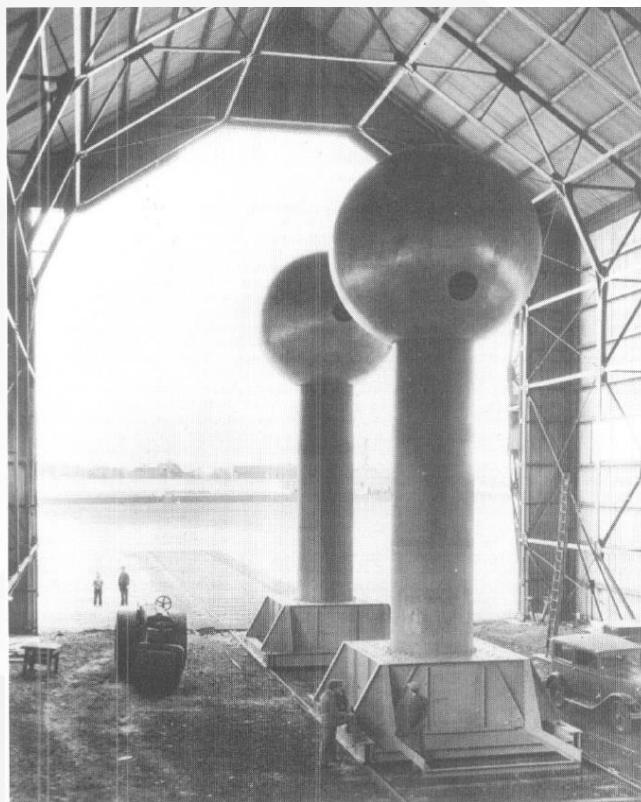
➤ 1931年左右研制成功





➤ Van de Graaf静电加速器 (Van de Graaf generator)

❖ 最高电压受限于电极放电



高压电极直径4.6米，高6.7米，
电压5.1MV (MIT)

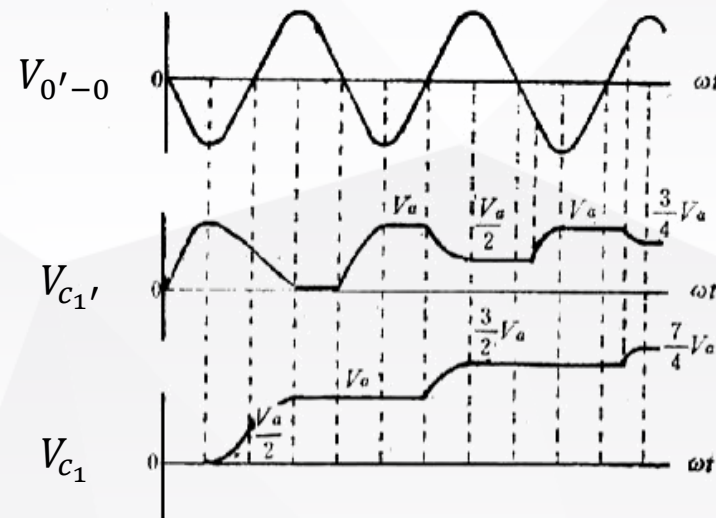
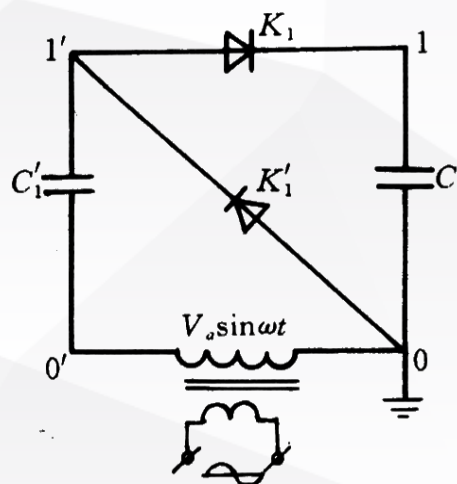
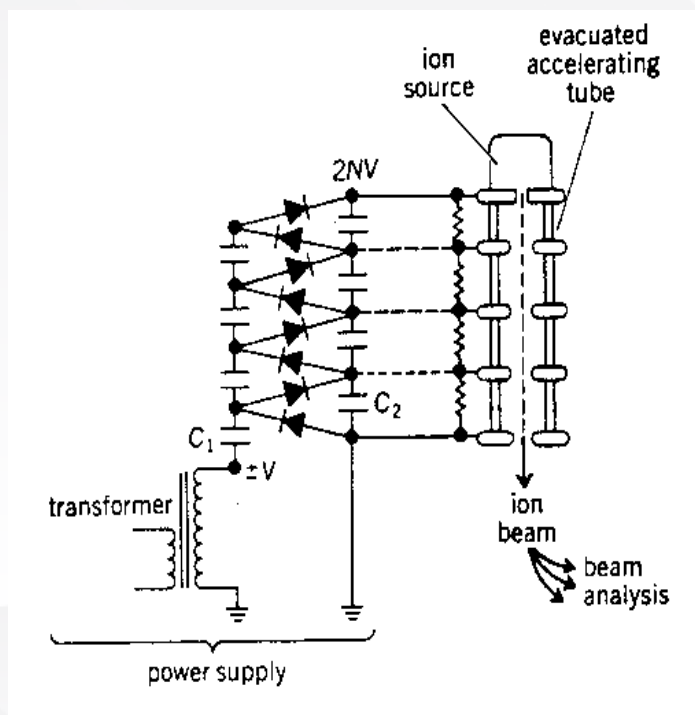


高30.5米，电压24.5MV (ORNL)



➤ Cockcroft-Walton高压倍加器 (Cockcroft-Walton generator)

- ❖ 由英国物理学家Ernest Walton与John Cockcroft提出并研制
- ❖ 采用整流充电单元对交流电进行整形
- ❖ 将多个整流充电单元串联以提升电极电压



N. Juntong, A brief history of Particle Accelerators (2014)

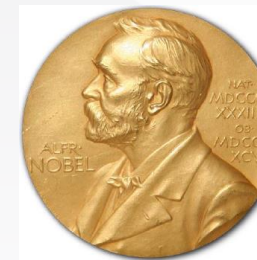
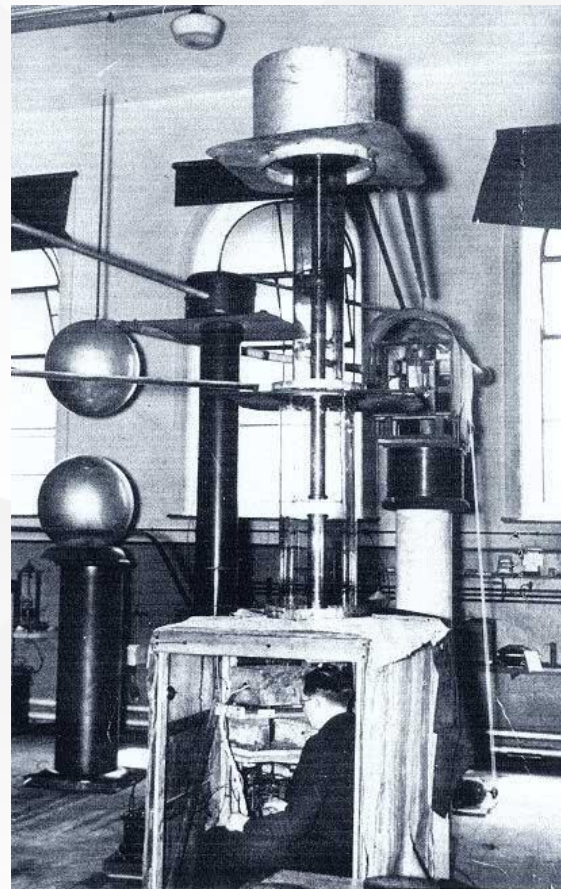


➤ Cockcroft-Walton高压倍加器 (Cockcroft-Walton generator)

- ❖ 1932年研制成功
- ❖ 完成首个人工控制的核裂变反应
 - ${}^7_3\text{Li} + p \rightarrow {}^8_4\text{Be} \rightarrow 2{}^4_2\text{He} + 17.2 \text{ MeV}$



P. Lebrun, CAS 2019



1951年诺贝尔物理学奖

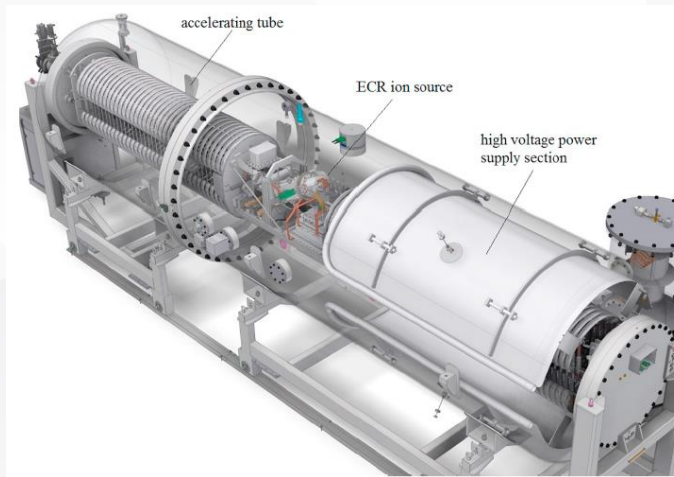
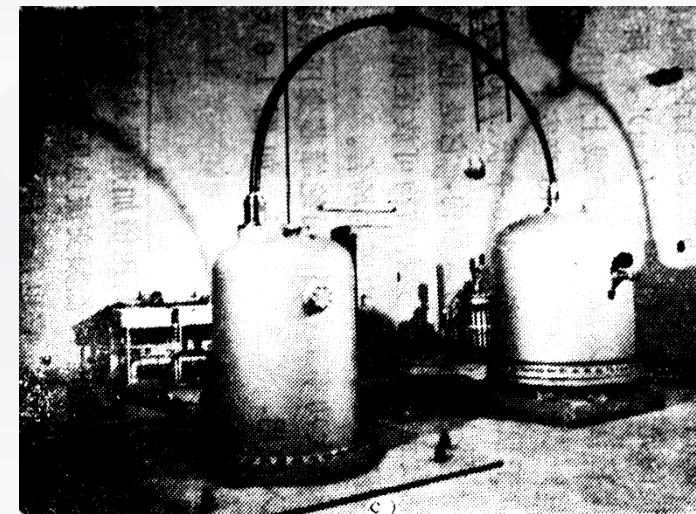
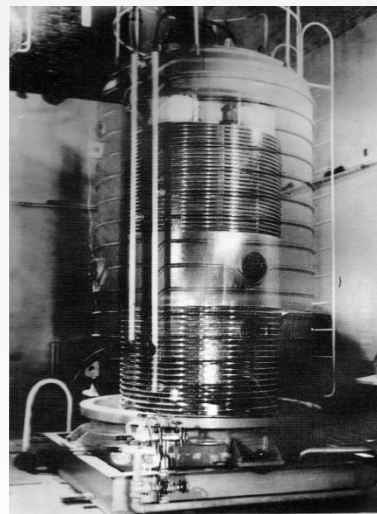
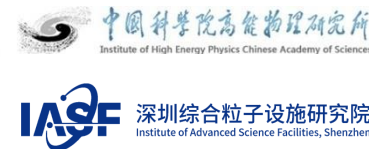
N. Juntong, A brief history of Particle Accelerators (2014)



直流高压加速器

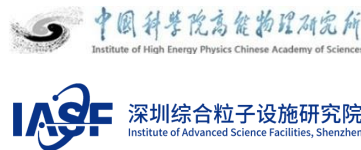


中山大學
SUN YAT-SEN UNIVERSITY





中山大學
SUN YAT-SEN UNIVERSITY



中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences
IASF 深圳综合粒子设施研究院
Institute of Advanced Science Facilities, Shenzhen

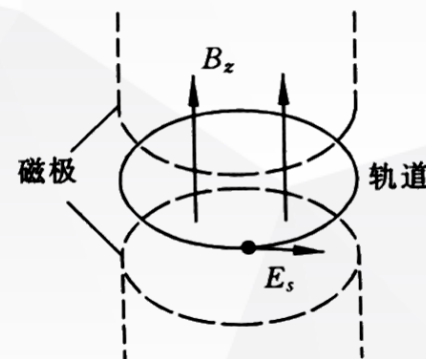
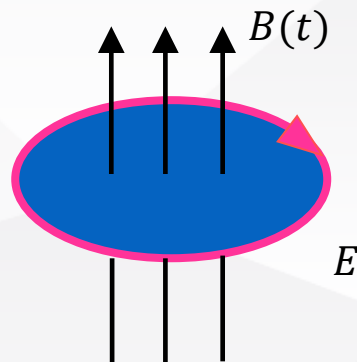


感应加速器



➤ 感应加速器 (betatron)

- ❖ 1922年, 美国工程师Joseph Slepian提出基本概念
- ❖ 1923年, 挪威物理学家Rolf Wideroe提出运动稳定条件
- ❖ 粒子在固定圆周轨道加速
- ❖ 基本原理
 - 随时间变化的磁场感生涡旋电场 (楞次定律)
 - $\oint \vec{E} \cdot d\vec{l} = - \iint_s \frac{\partial \vec{B}}{\partial t} \cdot d\vec{S} = - \frac{\partial \Phi}{\partial t}$
 - 轨道上的轴向磁场保证电子作圆周运动所需的向心力



➤ 感应加速器 (betatron)

❖ 粒子每圈可获得的能量

- $\frac{dw}{dN} = \oint (-ZeE) dl = Ze \frac{\partial \Phi}{\partial t}$
- $\frac{dw}{dN} = \frac{dw}{dt} \frac{dt}{dN} = \frac{dw}{dt} \frac{2\pi r}{v}$

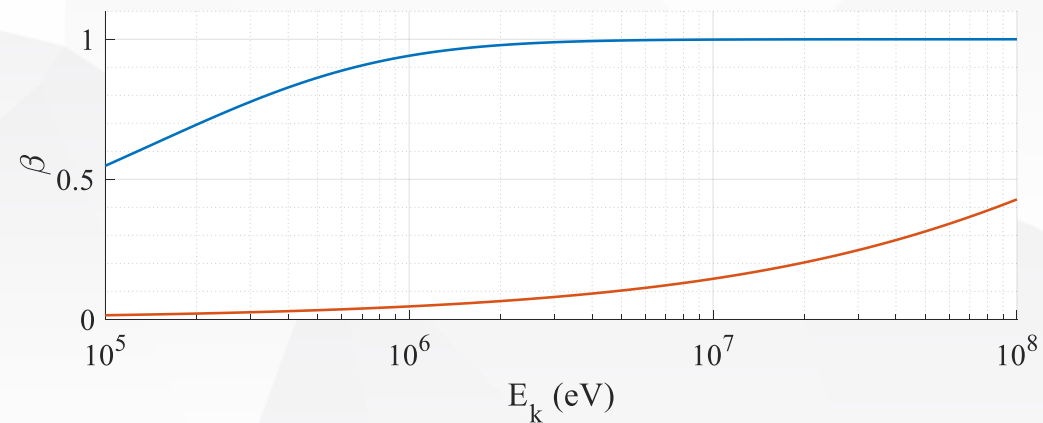
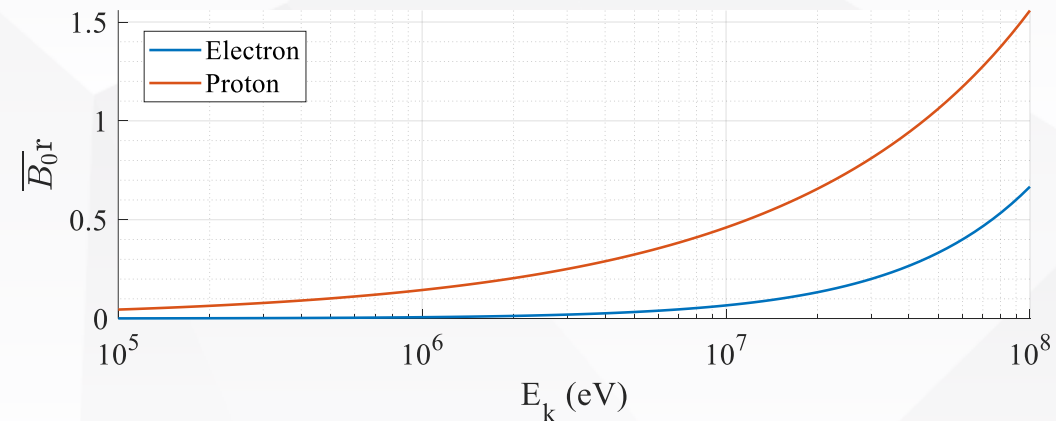
平均速度

❖ 粒子获得的总能量

- $w = \frac{vZe\Phi}{2\pi r} = \frac{vZe\bar{B}_0 r}{2}$

❖ 更适合加速电子

- 磁场饱和为1T量级
- 名称的由来: β 粒子即高速电子
- 能量多为10-50 MeV
- 更高能量受限于同步辐射效应





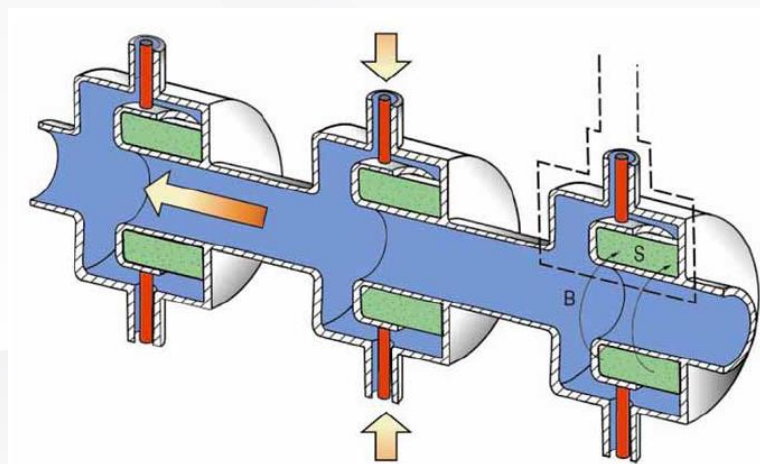
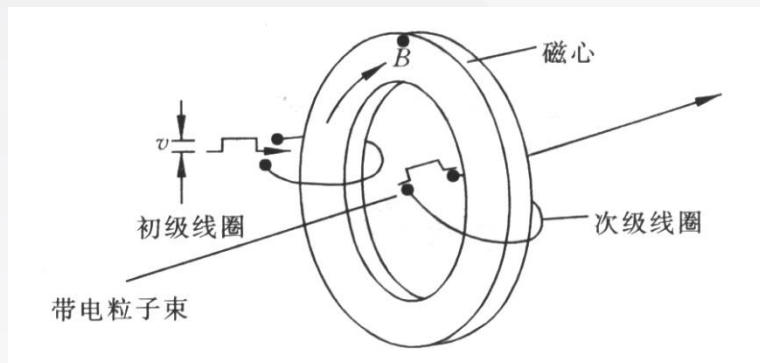
➤ 感应加速器 (betatron)

- ❖ 1940年由美国物理学家Donald Kerst首次建造
- ❖ Kerst先后建成2.3 MeV-300 MeV多台感应加速器



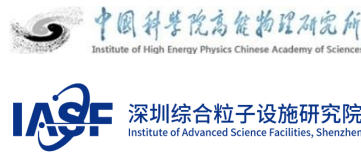
➤ 感应加速器 (betatron)

❖ 直线感应加速器





中山大學
SUN YAT-SEN UNIVERSITY



中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences
IASF 深圳综合粒子设施研究院
Institute of Advanced Science Facilities, Shenzhen



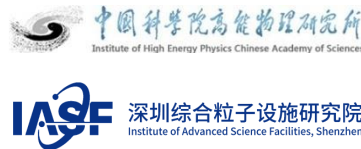
回旋加速器



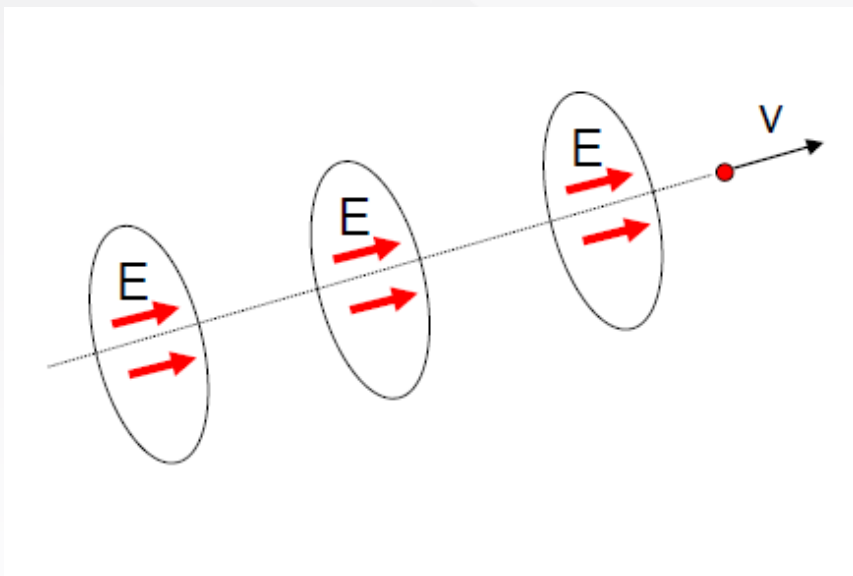
回旋加速器



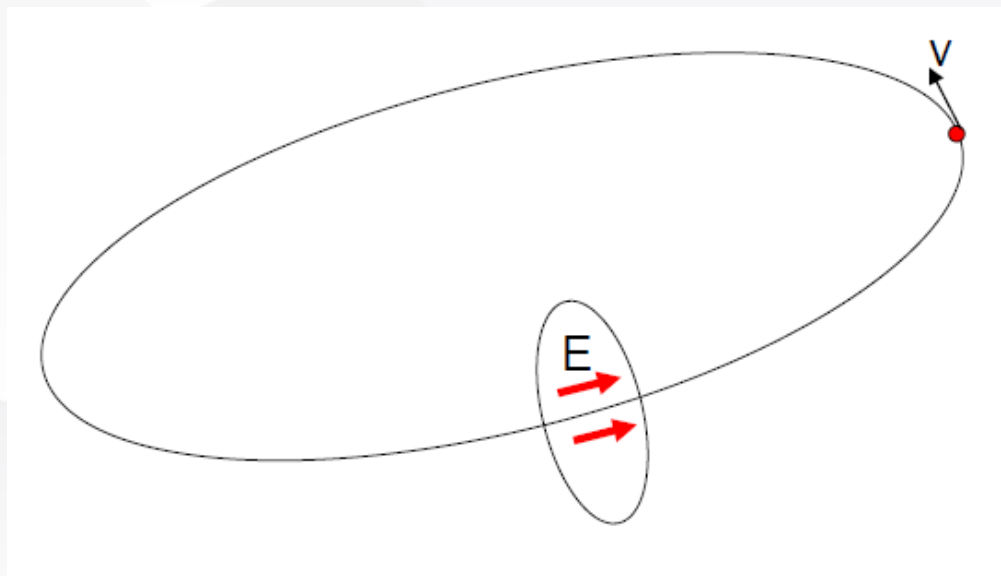
中山大學
SUN YAT-SEN UNIVERSITY



➤ 如何重复利用电源电压，提高加速电压？



直线加速器



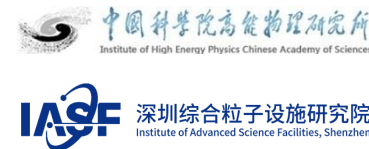
环形加速器



回旋加速器



中山大學
SUN YAT-SEN UNIVERSITY



➤ 射频直线加速器 (RF linear accelerator)

- ❖ 1924年由瑞典物理学家Gustav Ising提出基本概念
- ❖ 将交流电压加至多个串联排列的分离管道中
- ❖ 加速过程
 - 电压为正时，粒子在管道间缝隙中加速
 - 电压为负时，粒子进入管道，不受减速
 - 管道长度随着粒子速度的提高而增加

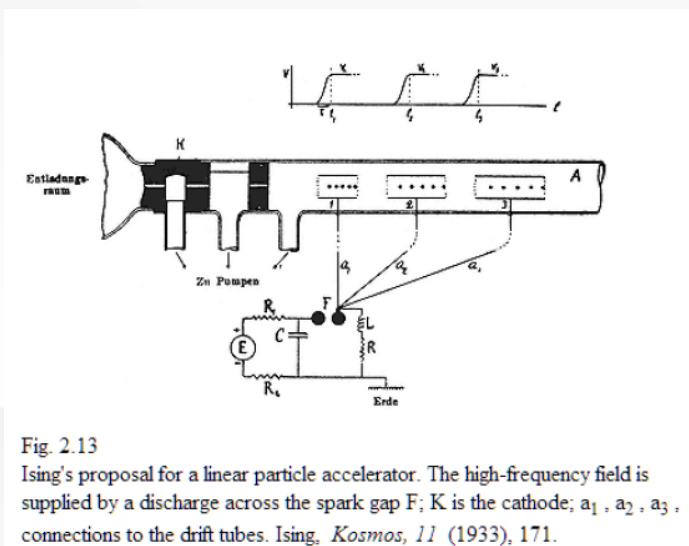
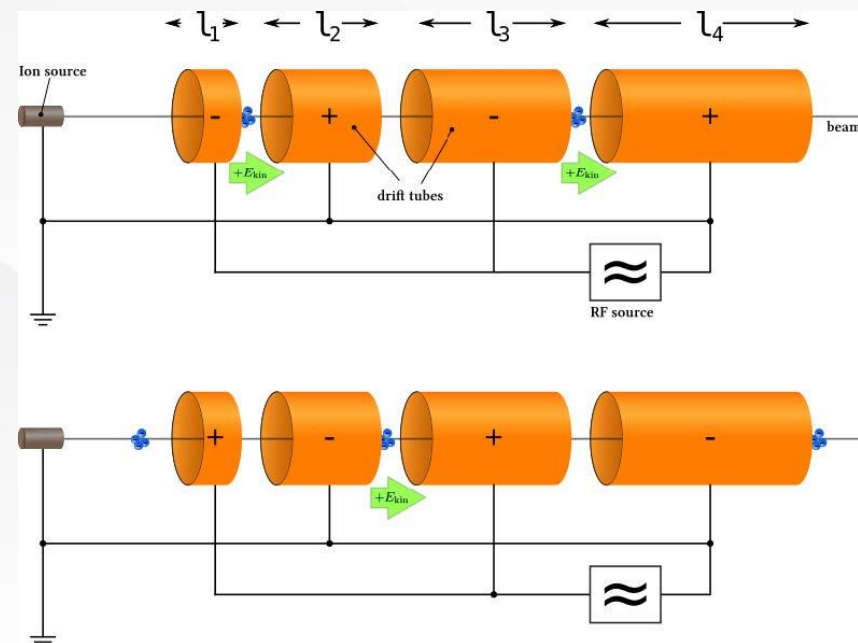
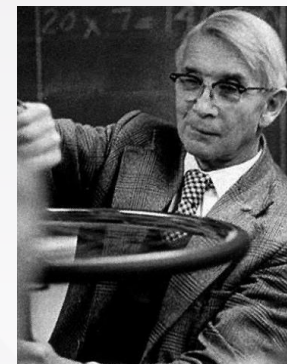


Fig. 2.13

Ising's proposal for a linear particle accelerator. The high-frequency field is supplied by a discharge across the spark gap F; K is the cathode; a_1 , a_2 , a_3 , connections to the drift tubes. Ising, *Kosmos*, 11 (1933), 171.

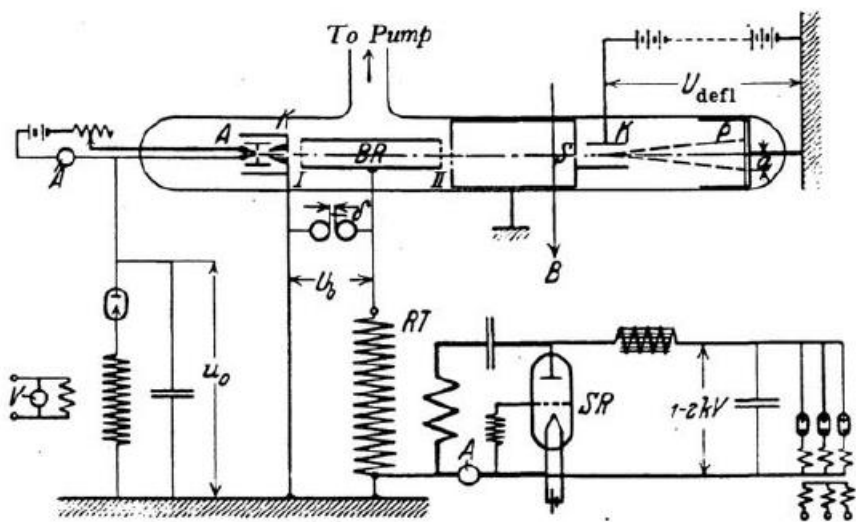




➤ 射频直线加速器 (RF linear accelerator)

❖ 1928年由挪威物理学家Rolf Wideroe真正建造

- 88厘米长; 1 MHz, 25 kV交流电源
- 将钠、钾离子加速至50 keV



"My little machine was a primitive precursor of this type of accelerator which today is called a '**linac**' for short. However, I must now emphasize one important detail. The drift tube was **the first accelerating system which had earthed potential on both sides**, i.e. at both the particles' entry and exit, and was still able to accelerate the particles exactly as if a strong electric field was present."

- Rolf Wideroe

N. Juntong, A brief history of Particle Accelerators (2014)

S. Sheehy, CAS 2021

➤ 回旋加速器 (Cyclotron)

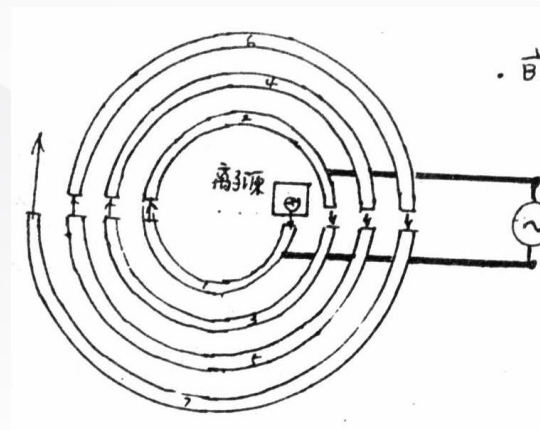
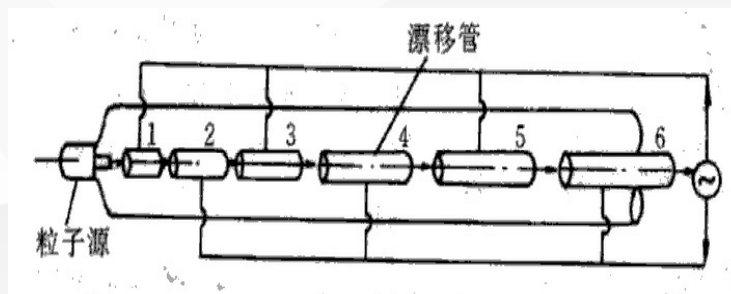
❖ 1929年由美国物理学家Ernest Lawrence受Rolf Wideroe启发而发明

"Not being able to read German easily, I merely looked at the diagrams and photographs of Wideroe's apparatus... and readily understood his general approach to the problem, i.e. the **multiple acceleration** of the positive ions by application of **radio-frequency oscillating voltages** to a series of cylindrical electrodes."

- Ernest Lawrence



1939年诺贝尔物理学奖



➤ 回旋加速器 (Cyclotron)

❖ 1930年由Ernest Lawrence及其学生Stanley Livingston建造

❖ 回旋频率

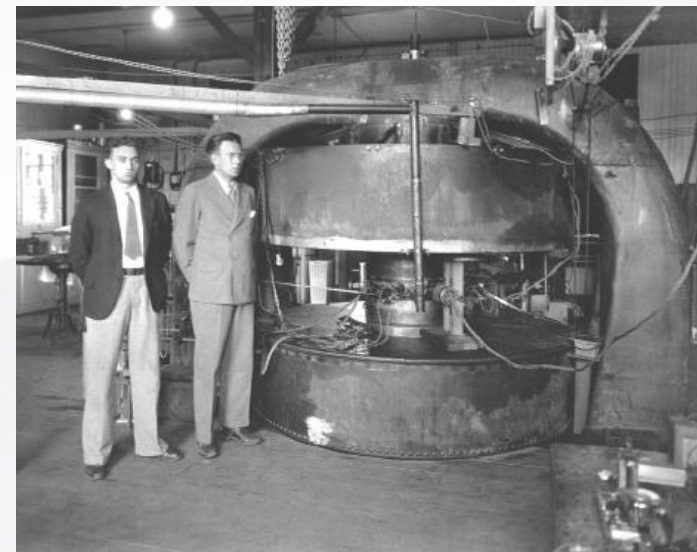
$$\omega_c = \frac{qB_z}{m}$$

$$qB_z\omega r = m\omega^2 r$$

"He came bursting into the lab. . . , his eyes glowing with enthusiasm, and pulled me over to the black board. He drew the equations of motion in a magnetic field. ' Notice that r appears on both sides,' he said. 'Cancels out. r cancels r. Do you see what that means? **The resonance condition is not dependent on the radius. . .Any acceleration!**"

- Lawrence' s graduate student J. J. Brady

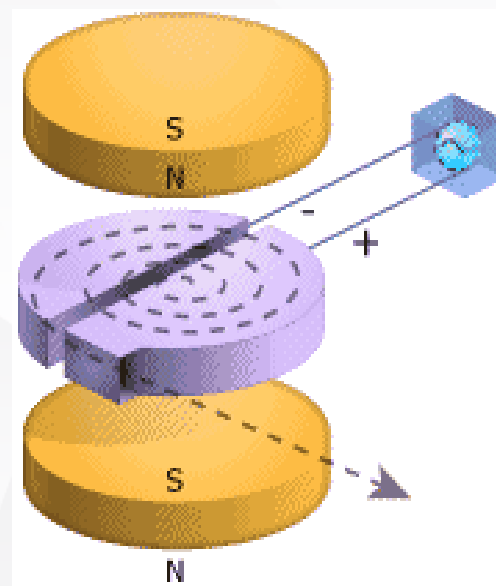
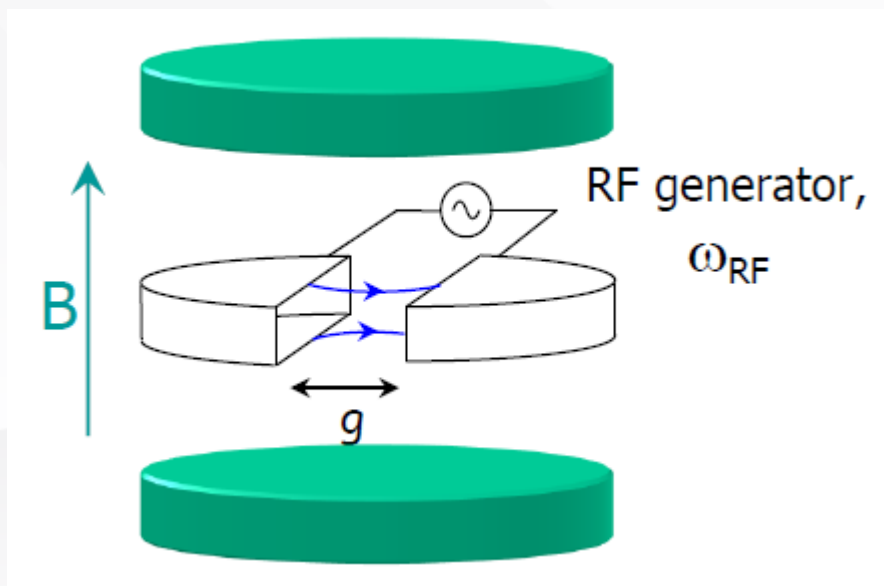
❖ 适合加速质子、重离子 (为什么不适合加速电子?)





➤ 回旋加速器 (Cyclotron)

- ❖ 弯曲的奇数和偶数漂移管发展为D形盒电极，置于真空室内；分别与外部的高频电源的两极相连
- ❖ 上下圆柱形磁极建立垂直于轨道平面的均匀分布的轴向磁场
- ❖ 中心离子源发出的带电离子，经过D电极间隙被加速
- ❖ 加速的带电离子，随能量增长，回转半径不断扩大，最后经静电偏移引出

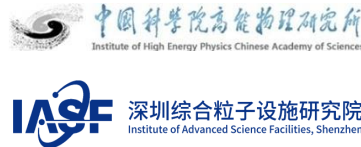




回旋加速器



中山大学
SUN YAT-SEN UNIVERSITY



➤ 经典回旋加速器 (Cyclotron)

❖ 离子每旋转一圈，被加速两次

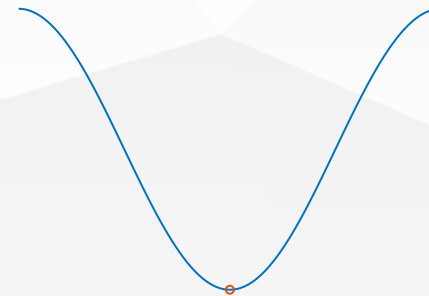
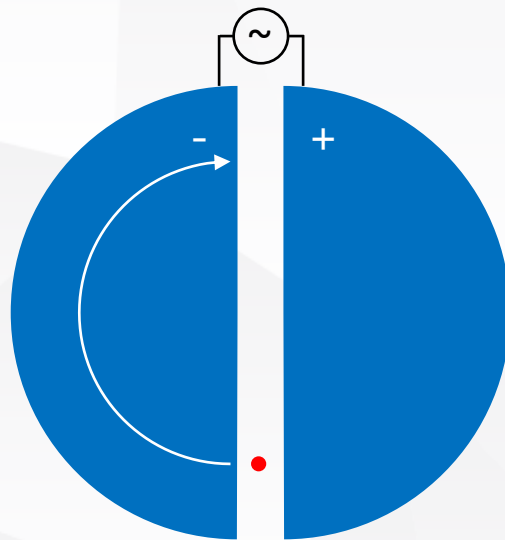
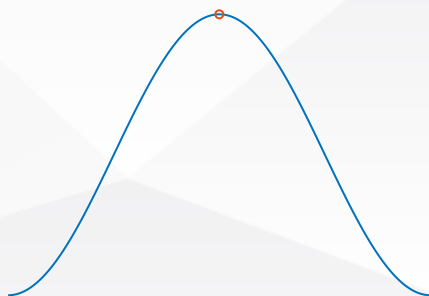
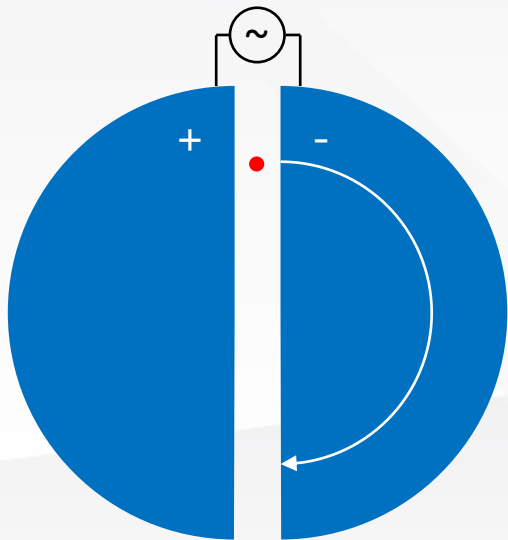
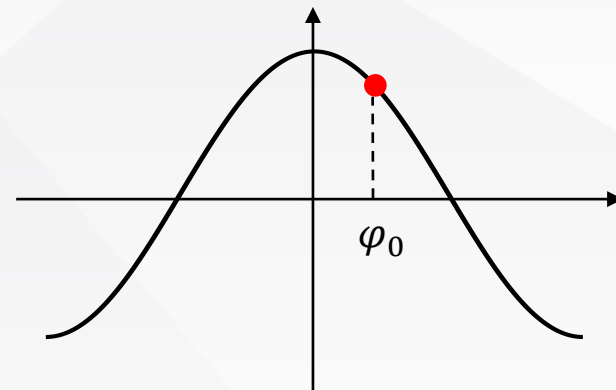
- $(\Delta w)_1 = ZeV_a \cos \varphi_0$

❖ 射频频率等于回旋频率

- $f_{RF} = f_c = \frac{qB_z}{2\pi m} = 1.75 \times 10^7 B \frac{Z}{A}$

电荷数

核子数

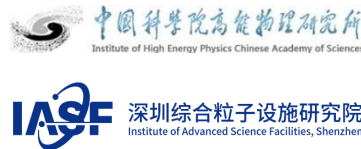




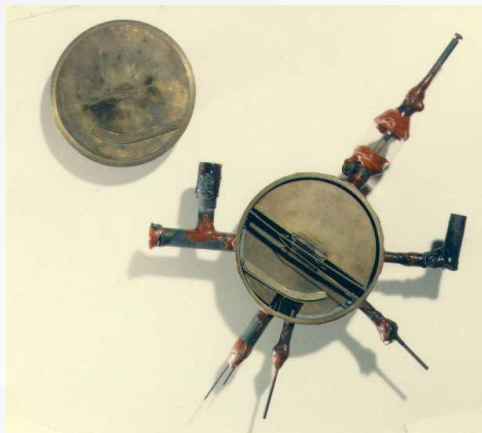
回旋加速器



中山大學
SUN YAT-SEN UNIVERSITY

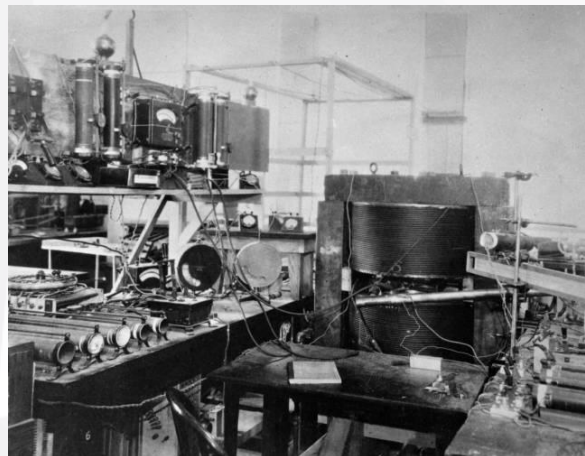


➤ 经典回旋加速器 (Cyclotron)

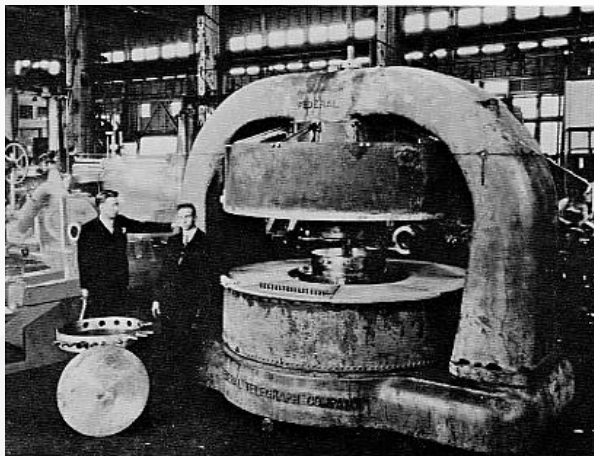


直径0.11 m

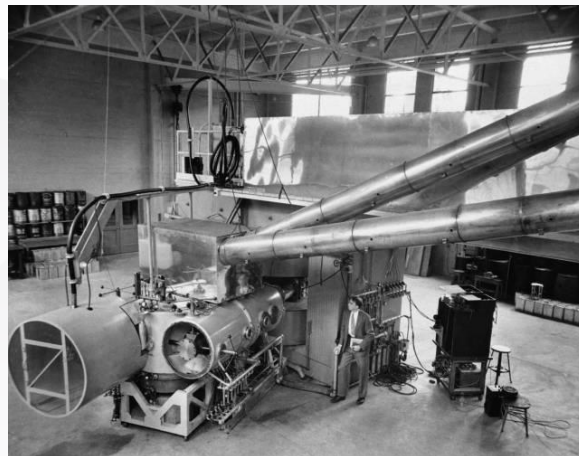
最大能量约25 MeV (氘核)



直径0.28 m



直径0.69 m



直径1.52 m



直径2.24 m

➤ 回旋加速器中的相移现象

❖ 上述讨论中，仅考虑非相对论情况

- $m = m_0$

❖ 相对论情况下，粒子质量随加速而增加

- $m = \gamma m_0 = m_0 / \sqrt{1 - \beta^2}$

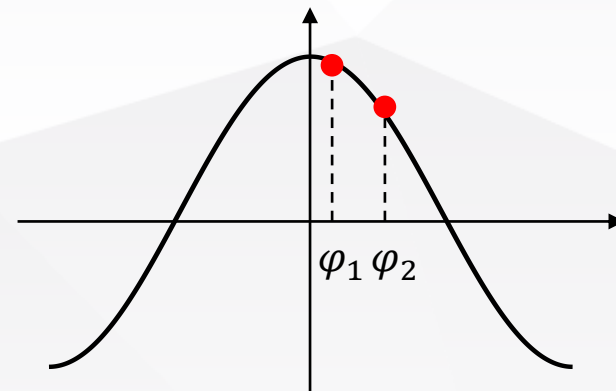
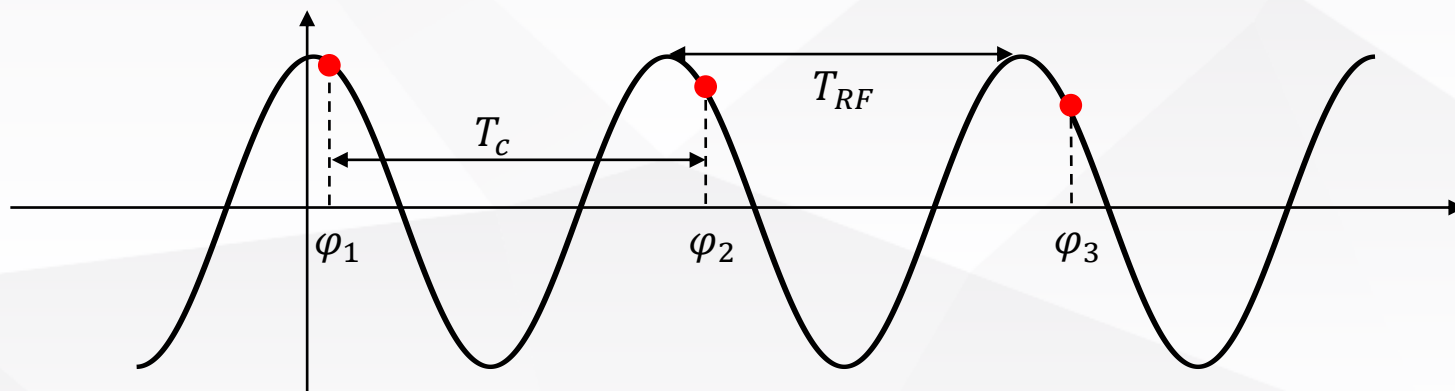
❖ 回旋频率进而随粒子加速而降低，与射频频率出现失配

- $T_c = \frac{2\pi m}{qB_z} \neq T_{RF}$

❖ 频率失配导致加速相位出现相移，限制加速能量

- $T_c > T_{RF}$ ，右移

- $T_c < T_{RF}$ ，左移

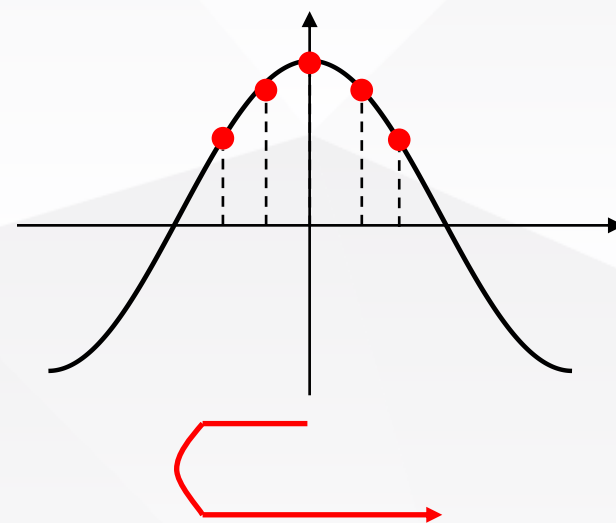
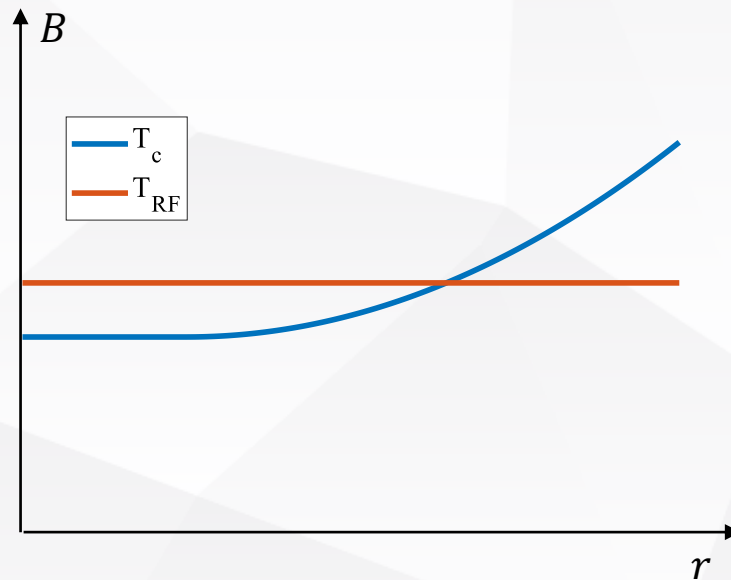
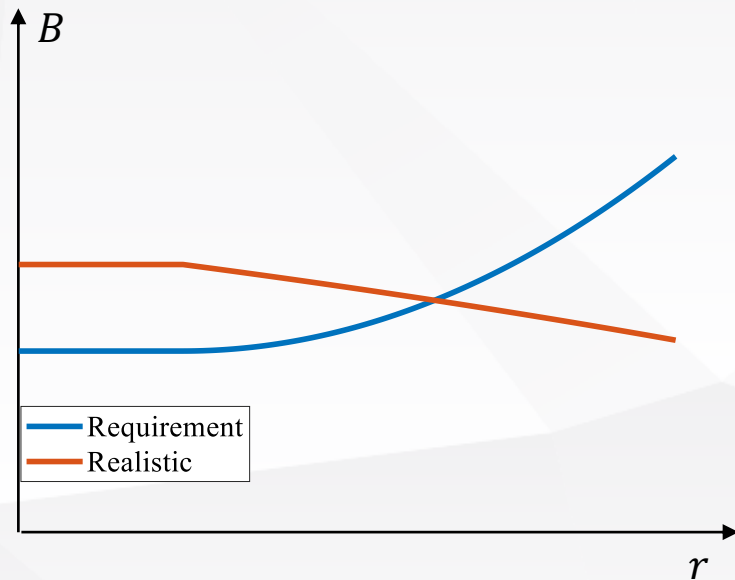


➤ 回旋加速器中的相移现象

❖ 若要保持同步，则需要磁场强度随半径而增大

$$\bullet T_c = \frac{2\pi m}{qB_z}$$

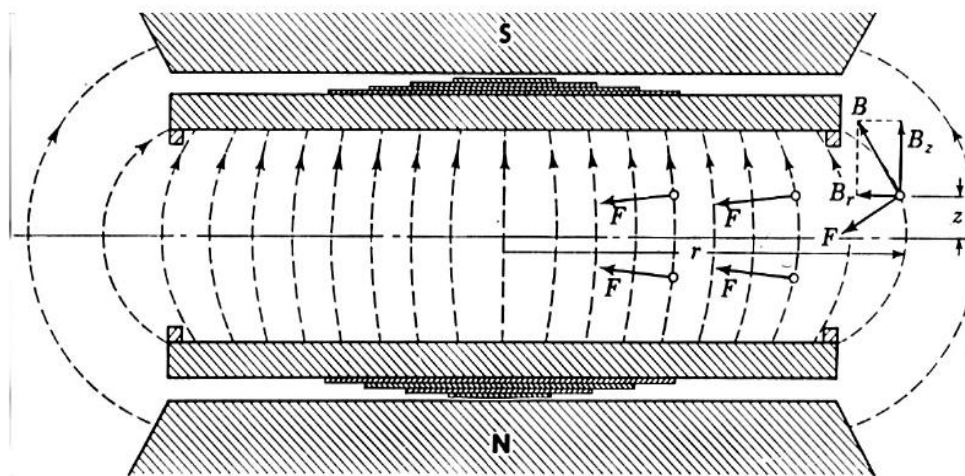
❖ 而实际设计则要求磁场强度随半径而降低



➤ 回旋加速器中的横向稳定性

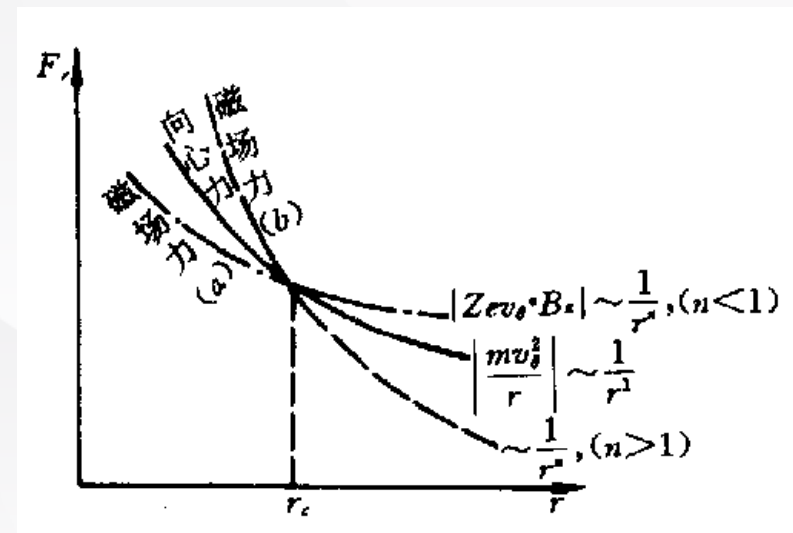
❖ 横向稳定性要求

- $B_z \propto \frac{1}{r^n}, 0 < n < 1$



轴向稳定性: $n > 0$

$$\omega_z = \sqrt{n}$$



径向稳定性: $n < 1$

$$\omega_r = \sqrt{1 - n}$$

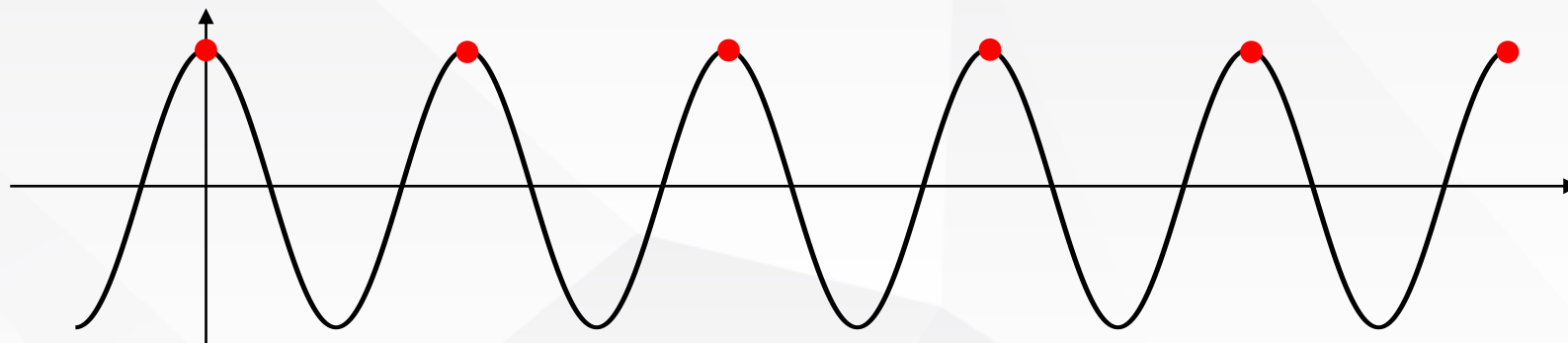
➤ 稳相回旋加速器 (Synchrocyclotron)

❖ 通过降低射频频率以保证持续加速

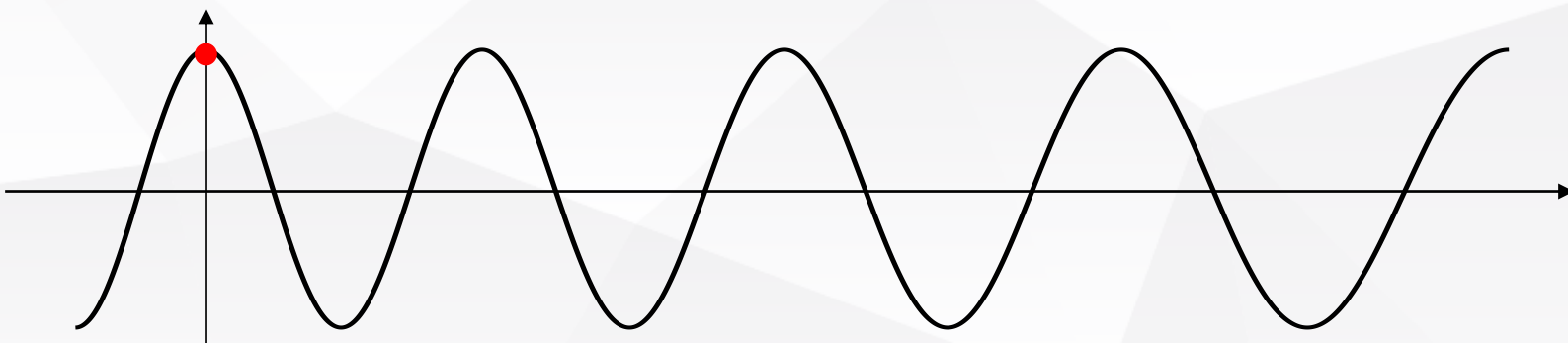
$$\bullet T_c = \frac{2\pi m}{qB_z} = T_{RF}$$

❖ 平均电流强度低于经典回旋加速器的1%

经典回旋加速器



稳相回旋加速器





➤ 稳相回旋加速器 (Synchrocyclotron)



直径4.7 m, 质子能量350 MeV



直径6.0 m, 质子能量1 GeV

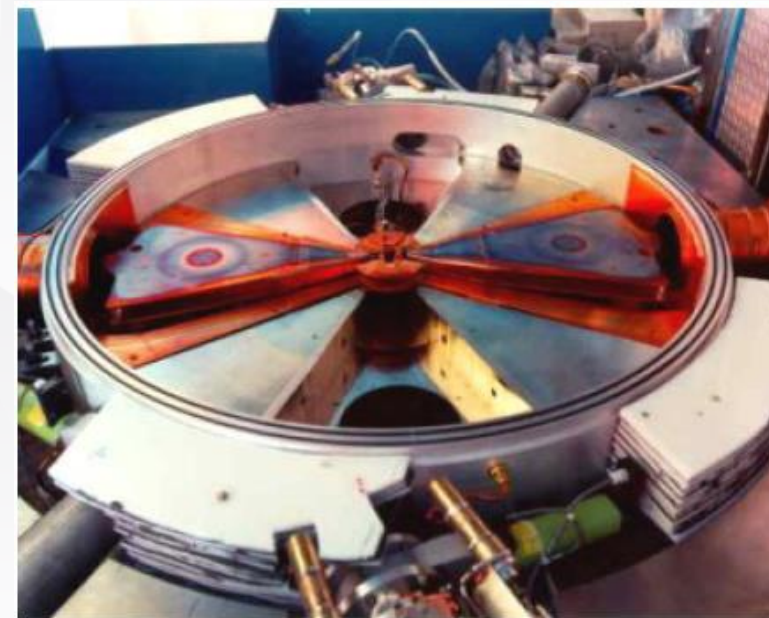
➤ 等时回旋加速器 (Isochronous Cyclotron)

- ❖ 固定射频频率
 - 平均流强类似经典回旋加速器
- ❖ 引入角向不均匀磁场，在保证平均值满足持续加速条件的同时，提供额外轴向聚焦
 - 解决对磁场的矛盾需求，提升加速能量
- ❖ 发展出多种磁场形式
 - 径向扇型
 - 螺旋扇型
 - 分离扇形



➤ 等时回旋加速器 (Isochronous Cyclotron) - 径向扇型

- ❖ 1938年由英国物理学家Llewellyn Thomas提出
- ❖ 由于磁铁设计难度大，1950年后才开始尝试建造





➤ 等时回旋加速器 (Isochronous Cyclotron) - 径向扇型

❖ 磁场沿方位角调变

- $B(r, \theta) = B_m(r)(1 + F \cos n\theta)$
- F 为调变度
- N 一般大于3

❖ 磁场沿角向平均值满足同步条件

$$\frac{B_m}{B_0} = \frac{m}{m_0} = \gamma, \quad B_m = \frac{B_0}{\sqrt{1 - \omega_c^2 r^2 / c^2}}$$

❖ 粒子轨道不为圆形

- 与圆形夹角称为托马斯角 κ

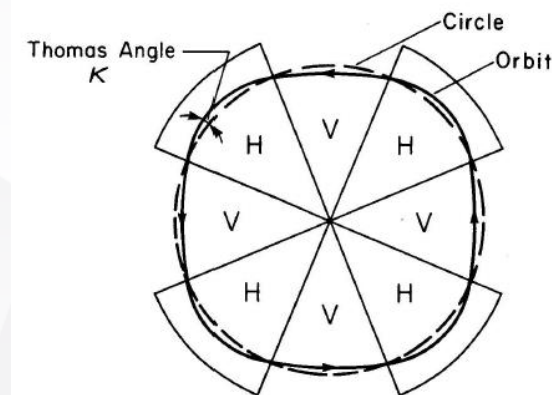
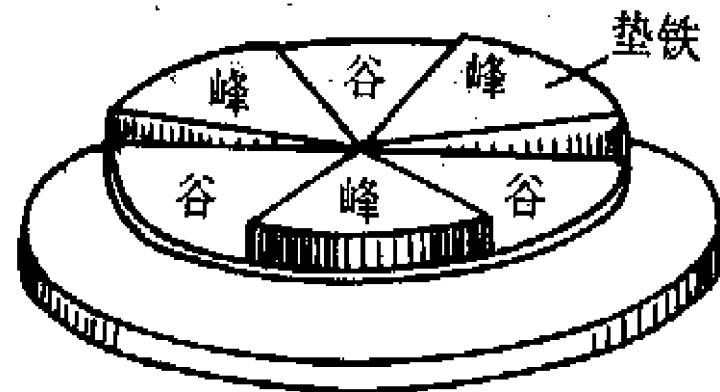
$$\kappa = \frac{\pi}{N} \frac{(B_h - B_m)(B_m - B_v)}{B_m(B_h - B_v)}$$

❖ 在峰谷交接处得到轴向聚焦

$$\omega_z^2 = -\frac{r}{B_m} \frac{\partial B_m}{\partial r} + F^2 \equiv -k + F^2 = -\beta^2 \gamma^2 + F^2$$

❖ 径向聚焦形式同经典回旋加速器相同

$$\omega_r^2 = 1 + k = \gamma^2$$

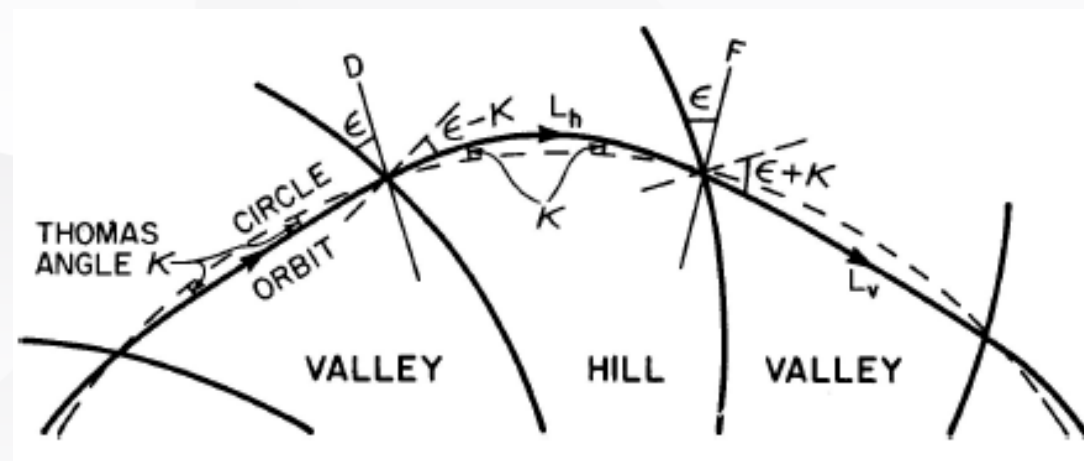




➤ 等时回旋加速器 (Isochronous Cyclotron) - 螺旋扇型

❖ 使粒子在峰谷交接处的角度不同，得到额外轴向聚焦

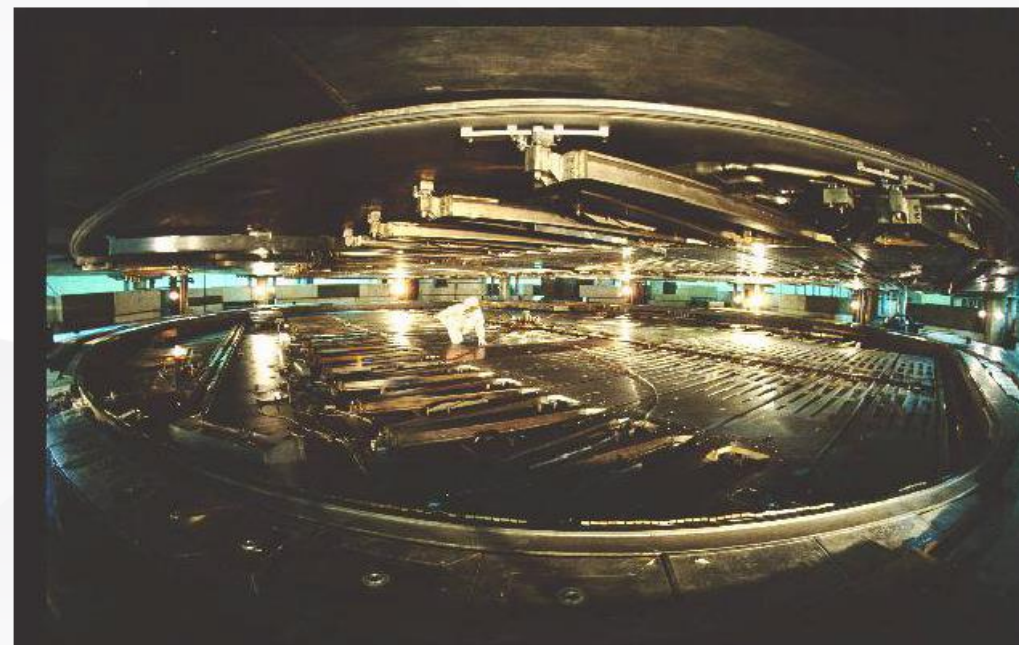
- 谷至峰, $\varepsilon - \kappa$, 较弱散焦
- 峰至谷, $\varepsilon + \kappa$, 较强聚焦
- $\omega_z^2 \approx -\beta^2 \gamma^2 + F^2(1 + 2\tan^2 \varepsilon)$





➤ 等时回旋加速器 (Isochronous Cyclotron) - 螺旋扇型

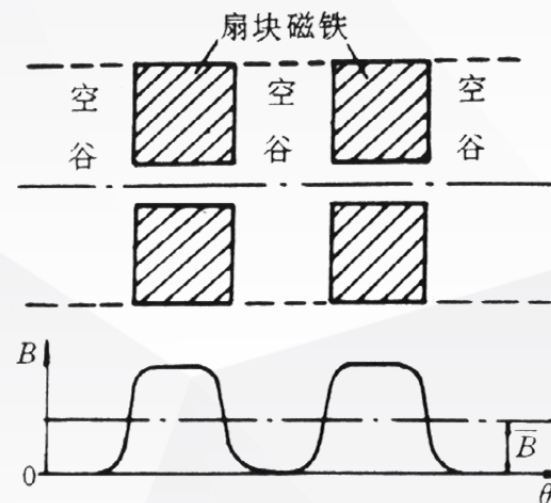
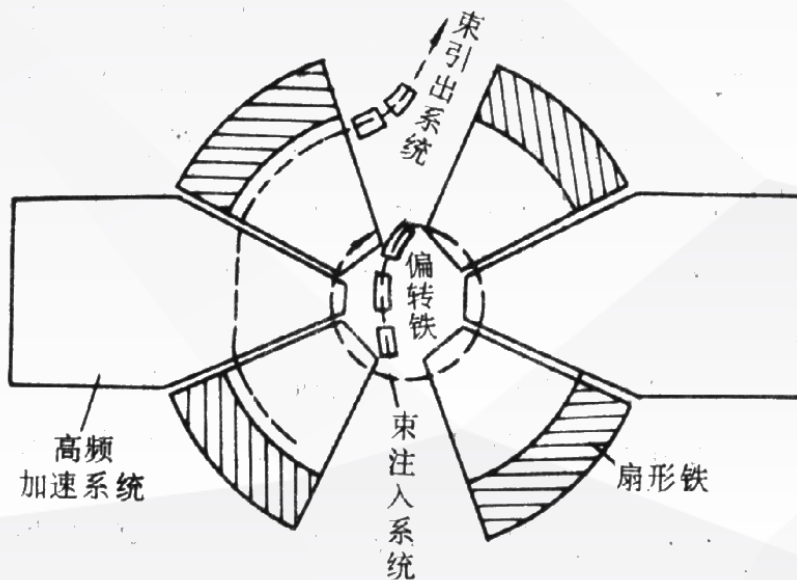
直径17.2 m, 质子能量520 MeV





➤ 等时回旋加速器 (Isochronous Cyclotron) - 分离扇型

- ❖ 相比径向扇型回旋加速器具有更高的磁场调变度、更强的轴向聚焦力
- ❖ 高频结构可放置在空谷处，因此磁铁间隙可做得较小、励磁效率高
- ❖ 常用于重离子加速器，流强和能量性能优良
- ❖ 离子轨道在磁场峰区弯曲，在谷区是直线



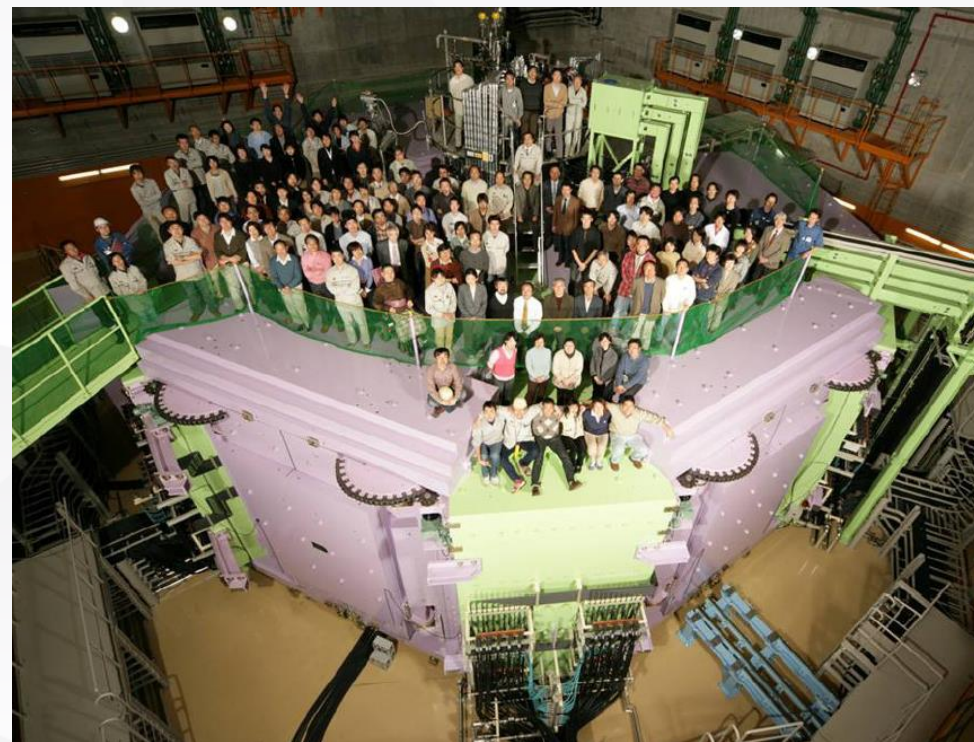


➤ 等时回旋加速器 (Isochronous Cyclotron) - 分离扇型

兰州近物所, 直径7.2 m, 粒子能量K450 MeV



日本理化学研究所, 直径12.4 m, 超导磁铁, 粒子能量K2600 MeV



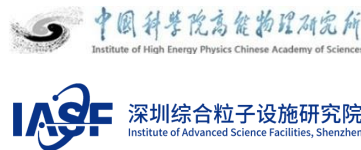


➤ 仅涉及本课程重点介绍的粒子加速器类型





中山大學
SUN YAT-SEN UNIVERSITY



中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

IACF 深圳综合粒子设施研究院
Institute of Advanced Science Facilities, Shenzhen

02

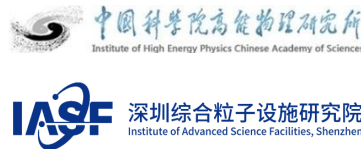
近期主要发展



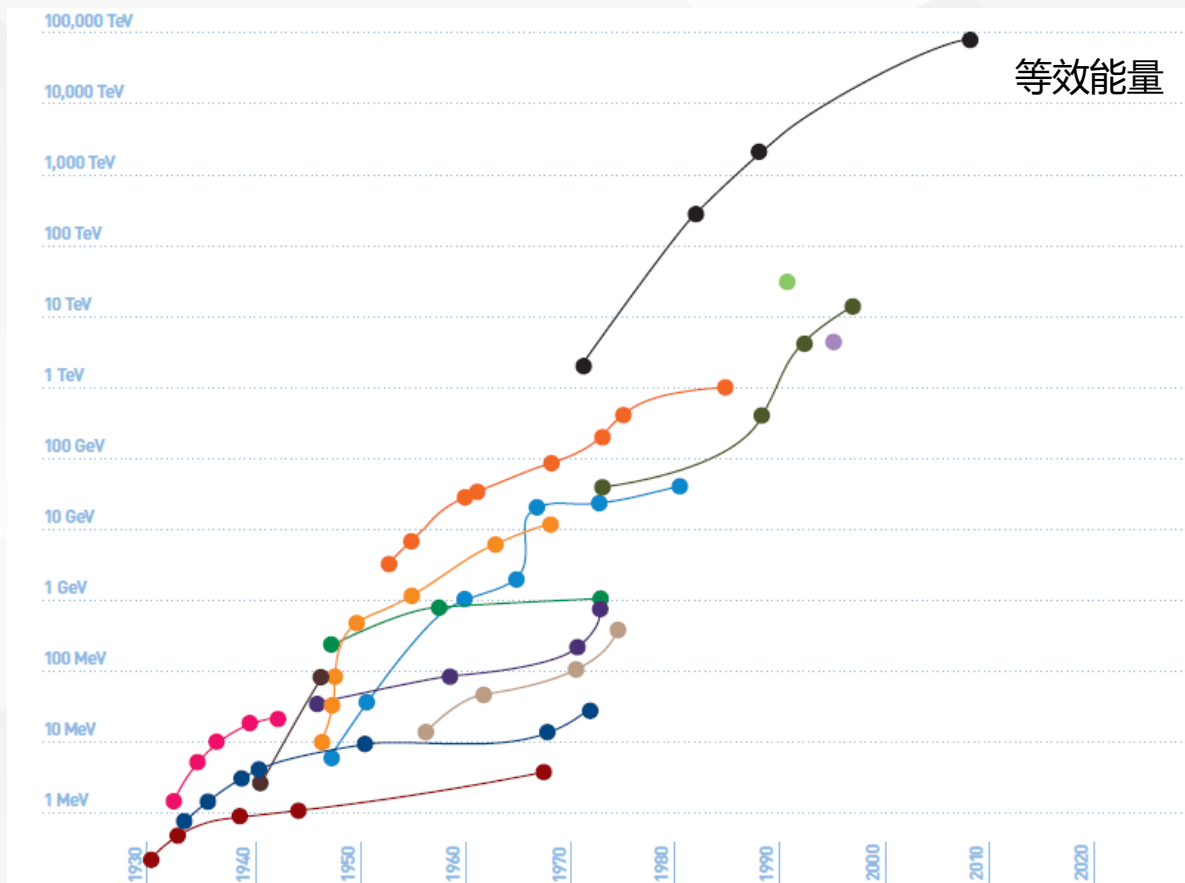
近期主要发展



中山大學
SUN YAT-SEN UNIVERSITY



➤ 1950年以来，粒子加速器能量的提高主要得益于同步加速器和微波直线加速器的进步



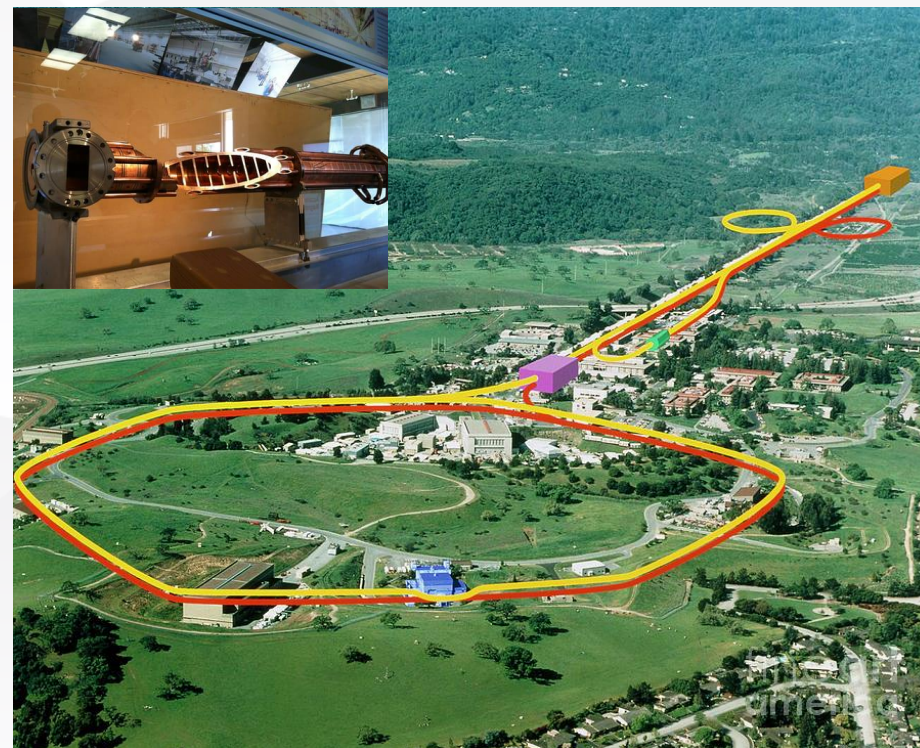
Accelerators for America's Future, DOE report (2010)



➤ 1950年以来，粒子加速器能量的提高主要得益于同步加速器和微波直线加速器的进步



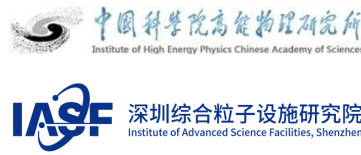
CERN 27 km同步加速器对撞机



SLAC 3 km直线加速器对撞机



中山大學
SUN YAT-SEN UNIVERSITY



02A

同步加速器

➤ 如何保持环形加速器中的持续加速条件

❖ 持续加速条件

- $T_c = \frac{2\pi m}{qB_z} = T_{RF}$

❖ 经典回旋加速器 (Cyclotron)

- 非相对论情况

❖ 稳相回旋加速器 (Synchrocyclotron)

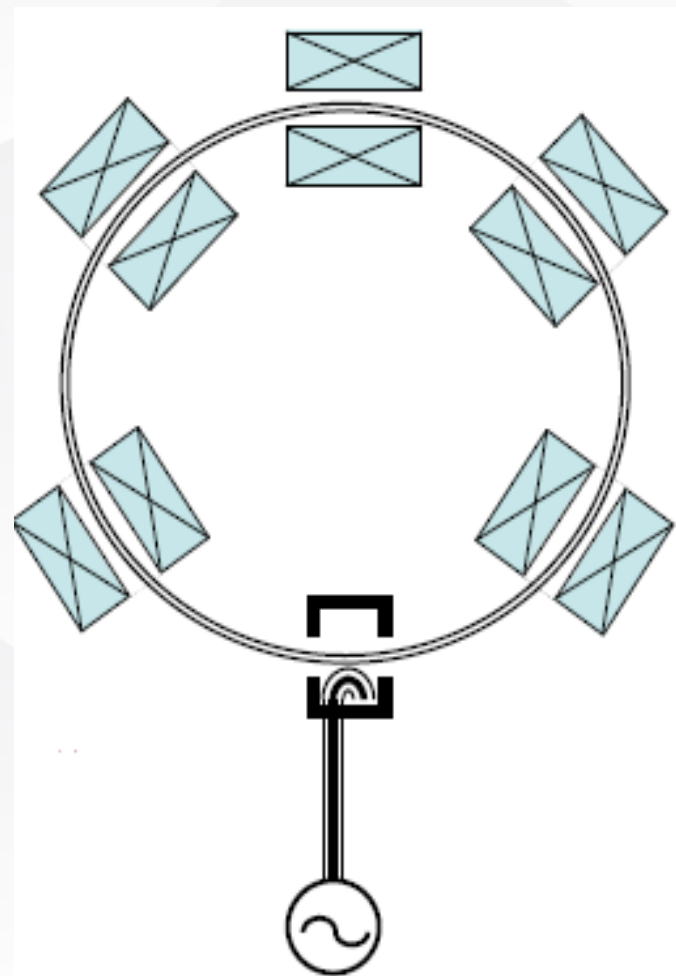
- 射频频率随加速降低

❖ 等时回旋加速器 (Isochronous Cyclotron)

- 磁场沿角向调变

❖ 同步加速器 (Synchrotron)

- 磁场随时间增大

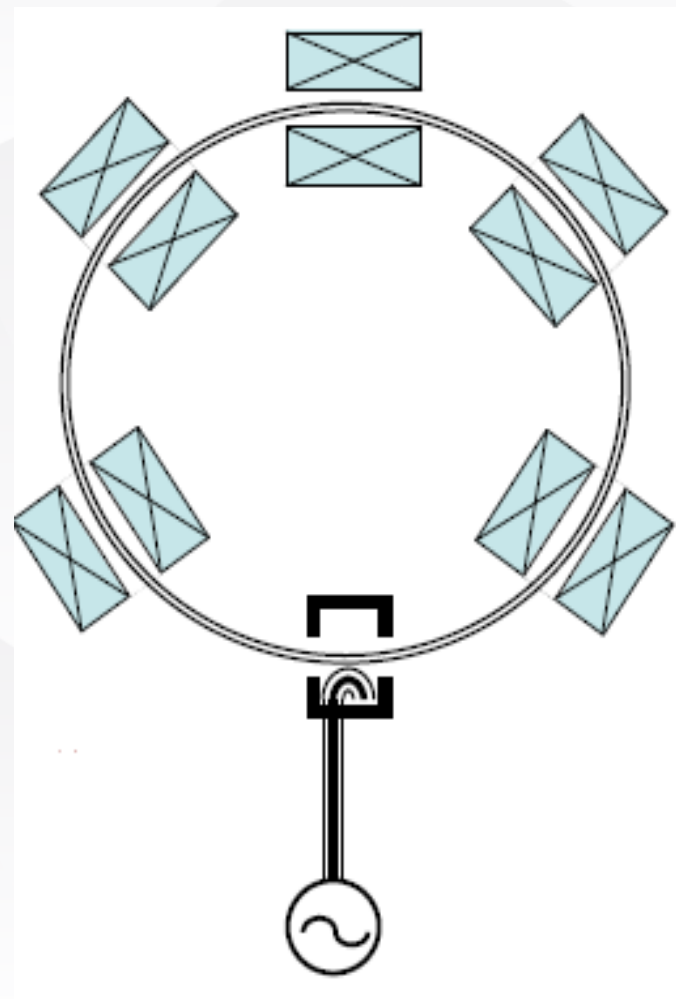


➤ 同步加速器 (Synchrotron)

- ❖ 1940年左右由澳大利亚物理学家Mark Oliphant提出 (师从卢瑟福)
- ❖ 粒子在同一环形轨道运动
 - 环形运动通过偏转磁铁来实现
 - 偏转磁场随能量增大而提高
- ❖ 采用射频腔加速带电粒子
 - 射频场的频率需要和粒子的回旋频率锁定，可以调变或不调变

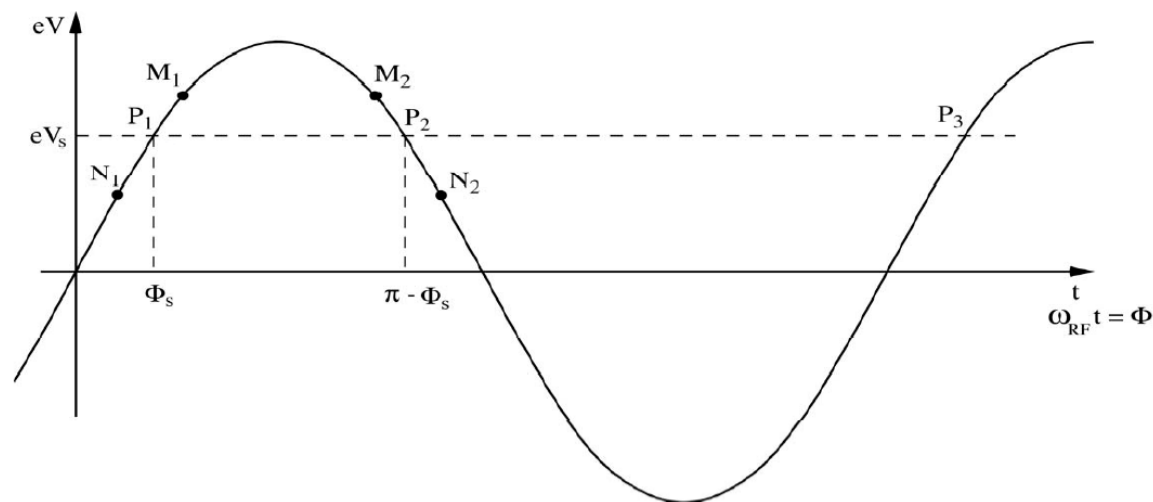


黄文会，加速器原理，清华大学



➤ 同步加速

- ❖ 在同步加速器中，束团由大量粒子组成，其中大部分为非同步粒子
- ❖ 非同步粒子
 - 同步粒子 P_1 看到相位 φ_s ，获得能量增益 Δw
 - 粒子 N_1 较早到达射频腔，看到相位 $\varphi = \varphi_s - \phi$ ，将获得较低的能量增益
 - 粒子 M_1 较晚到达射频腔，看到相位 $\varphi = \varphi_s + \phi$ ，将获得较高的能量增益



同步加速关键技术：自动稳相原理

- ❖ 1944年由美国物理学家Edwin McMillan与苏联物理学家Vladimir Veksler各自独立提出
- ❖ 在准共振加速器中，那些相位与同步相位 φ_s 有一定偏差的大量非同步粒子，不会中断加速，其加速相位将围绕 φ_s 来回地摆动，从而得以围绕同步粒子“平均”地得到加速，最终达到和同步粒子相当的能量

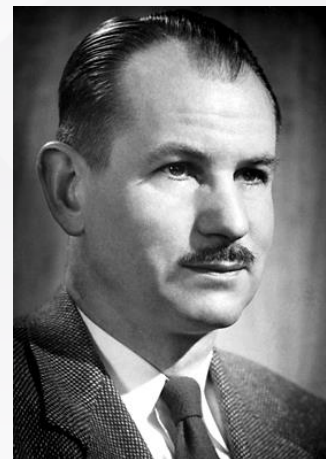
❖ 滑相因子

- 表征回旋时间与能量的依赖关系

$$\eta = \frac{dT_r/T_r}{dp/p}$$

回旋时间

动量



❖ 动量压缩因子

$$\alpha = \frac{dr/r}{dp/p}$$

轨道半径

- 与同步加速器聚焦元件有关

$$\eta = \alpha + \beta_s^2 - 1$$

相对论因子

➤ 同步加速关键技术：自动稳相原理

❖ 临界能量

- 在粒子加速的初期, $\beta_s < 1$, $\eta < 0$, 平衡相位 $0^\circ < \varphi_s < 90^\circ$
- 粒子获得较高速度后, $\beta_s \sim 1$, $\eta > 0$, 平衡相位 $90^\circ < \varphi_s < 180^\circ$
- $\gamma_c = \frac{1}{\sqrt{\alpha}}$

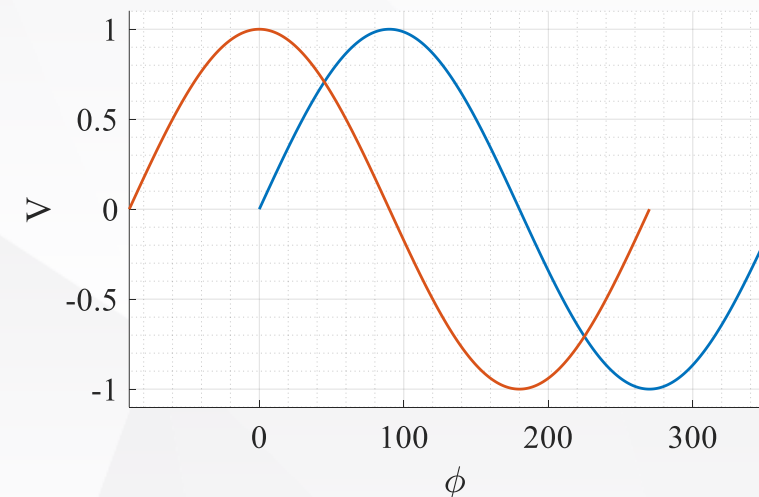
❖ 示例: $\alpha = 0.01$

- 质子: $E_c = m_0 \gamma_c = 9.39 \text{ GeV}$
- 电子: $E_c = m_0 \gamma_c = 5 \text{ MeV}$

❖ 克服临界能量的方法

- 提高入射粒子的能量, 使入射能量高于临界能量
- 提高临界能量, 使粒子最终加速能量小于临界能量
- 在粒子能量刚好为临界能量时, 使射频场相位跳变

$$\eta = \alpha + \beta_s^2 - 1$$

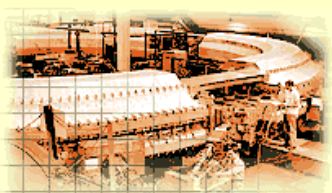




➤ 同步加速器

❖ 在发现自动稳相原理的基础上，同步加速器得到了较快发展

- 1952年，美国Brookhaven国家实验室建成3GeV同步质子加速器Cosmotron



Machine Statistics

Diameter: 75 feet

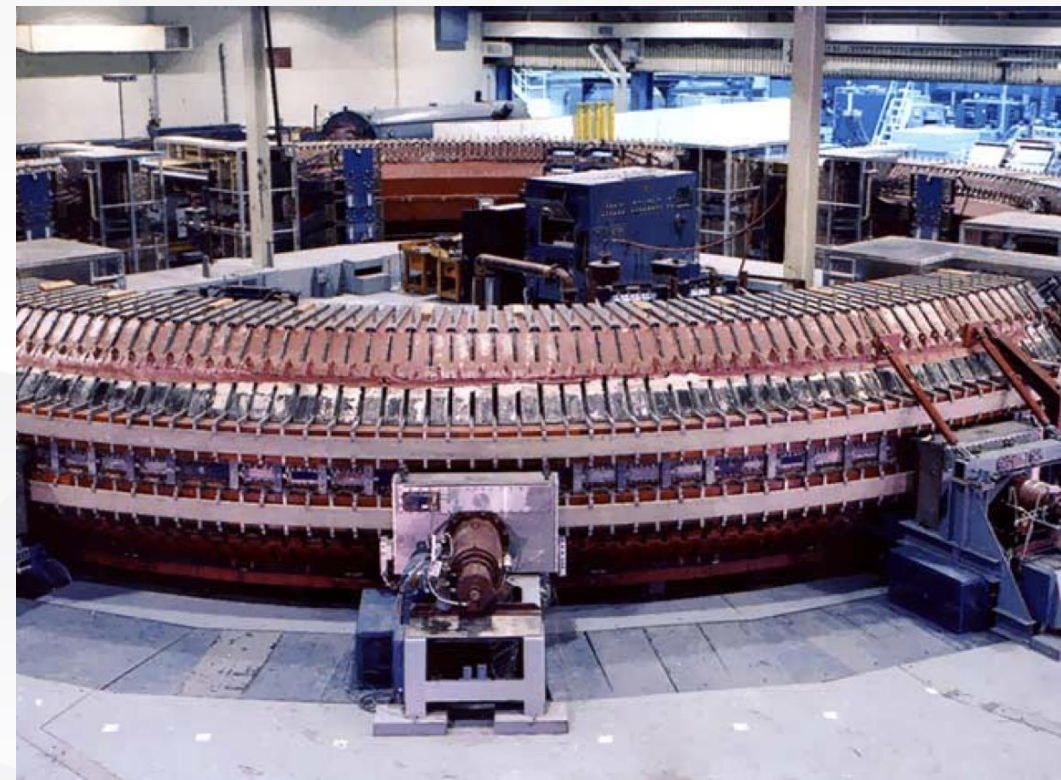
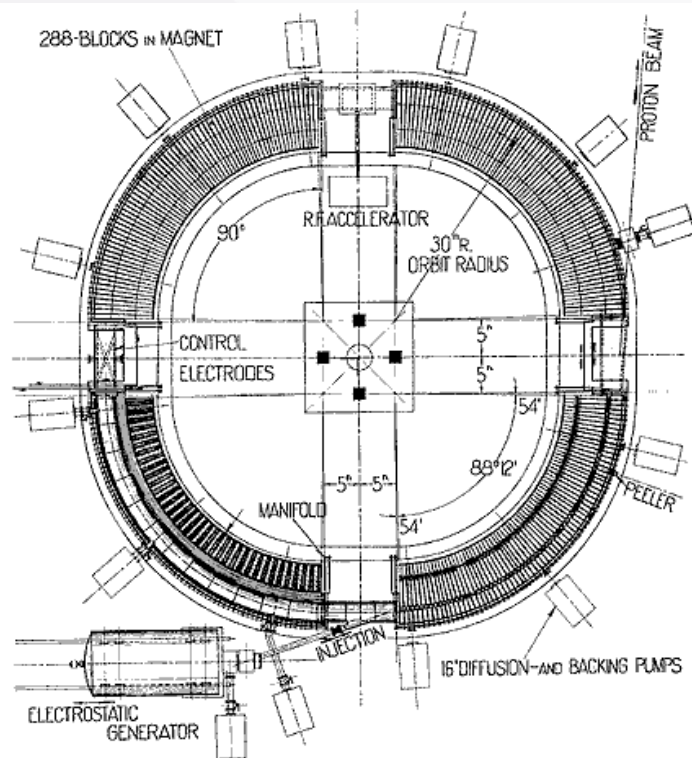
Total magnets in machine: 288

Magnet size: 8 feet high and 8 feet wide.

Machine composition: 1,700 tons of steel, 70 tons of copper.

Four magnet quadrants, each with a radius of 30 feet, separated by four 10-foot straight sections

Proton injection source: 3.6 million electron volt (MeV) Van de Graaff electrostatic generator.





➤ 同步加速器

- ❖ 在发现自动稳相原理的基础上，同步加速器得到了较快发展
 - 1954年，美国Lawrence Berkeley国家实验室建成6GeV同步质子加速器Bevatron



发现反质子
1959年诺贝尔物理学奖

➤ 大型同步加速器面临的困难

❖ 轴向运动方程的解

- $$z = z_i \cos \omega_z \theta + \frac{z_i'}{\omega_z} \sin \omega_z \theta$$

❖ 轴向振荡幅度（关于角度 θ 的导数）

- $$\sqrt{z_i^2 + \frac{z_i'^2}{\omega_z^2}}$$

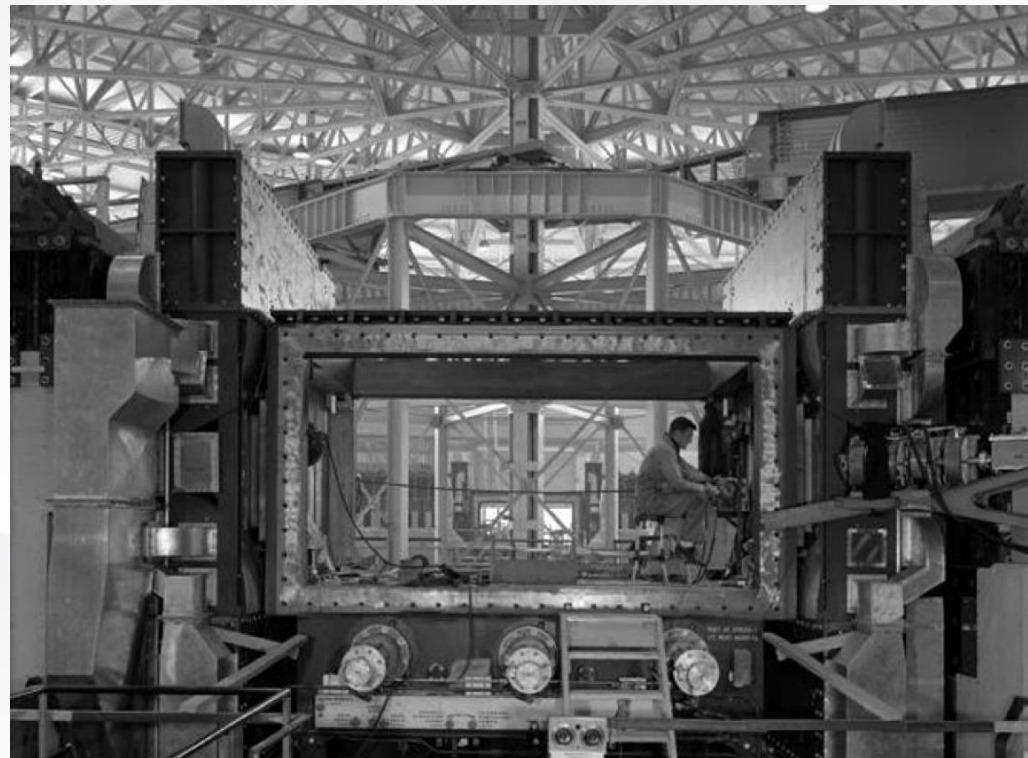
❖ 轴向振荡幅度（关于纵向位置 s 的导数）

- $$\frac{dz}{ds} = \frac{1}{r} \frac{dz}{d\theta}$$

- $$\sqrt{z_i^2 + \frac{r^2 z_i'^2}{\omega_z^2}}$$

回旋半径

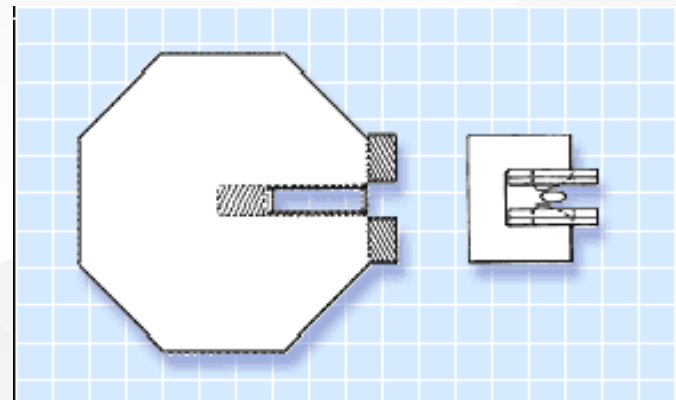
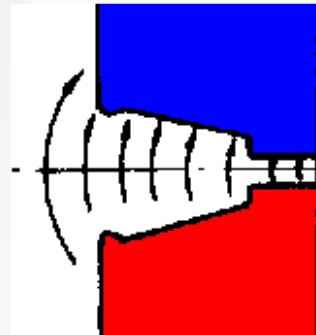
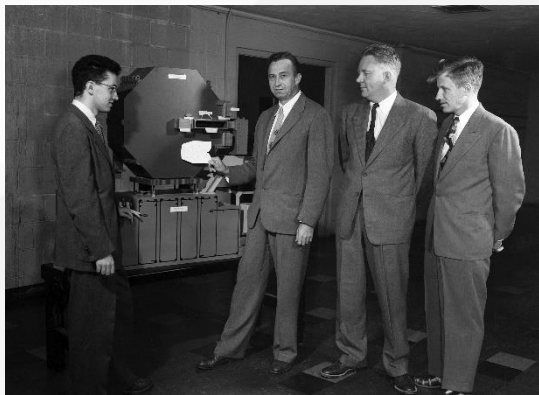
❖ 径向运动有类似的形式



横向振荡的幅度正比于环的尺寸，能量越高，环越大，束流管道越大，磁铁越重

同步加速关键技术：强聚焦原理

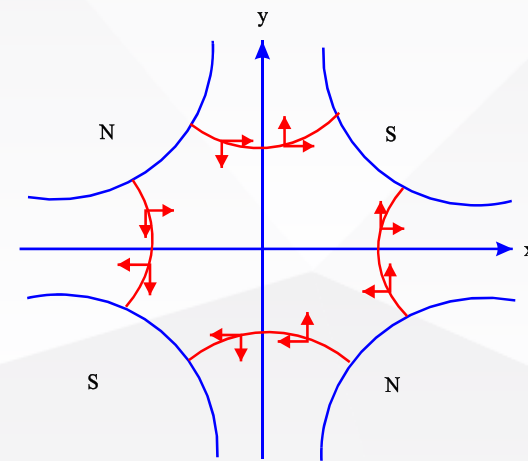
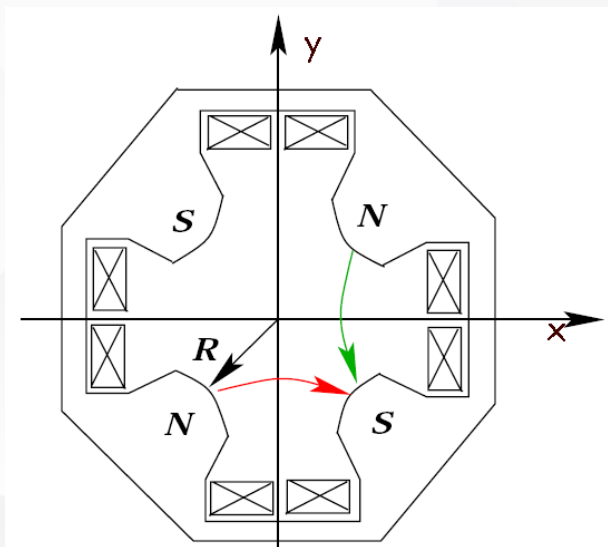
- ❖ 早期同步加速器仍然采用弱聚焦技术
 - 依赖偏转磁铁提供横向聚焦力
 - $B_z \propto \frac{1}{r^n}, 0 < n < 1$
 - 受限于磁铁重量与造价，推断同步加速器最大能量不超过10 GeV
 - 早期同步加速器仍然采用弱聚焦技术
- ❖ 1950年由希腊物理学家Nicholas Christofilos首先提出强聚焦原理
- ❖ 1952年由美国物理学家Ernest Courant, Stanley Livingston, Hartland Snyder进一步发展



Size comparison between the
Cosmotron's weak-focusing magnet (L)
and the AGS alternating gradient focusing
magnets

同步加速关键技术：强聚焦原理

- ❖ 偏转磁铁仅偏转束流，不再负责聚焦
- ❖ 使用独立元件四极磁铁 (quadrupole) 提供横向聚焦 (径向和轴向)
- ❖ 聚焦力强度较大，且聚散焦交替出现
 - $n \ll 0, n \gg 1$



$$\begin{aligned} B_x &= ky \\ B_y &= kx \end{aligned}$$

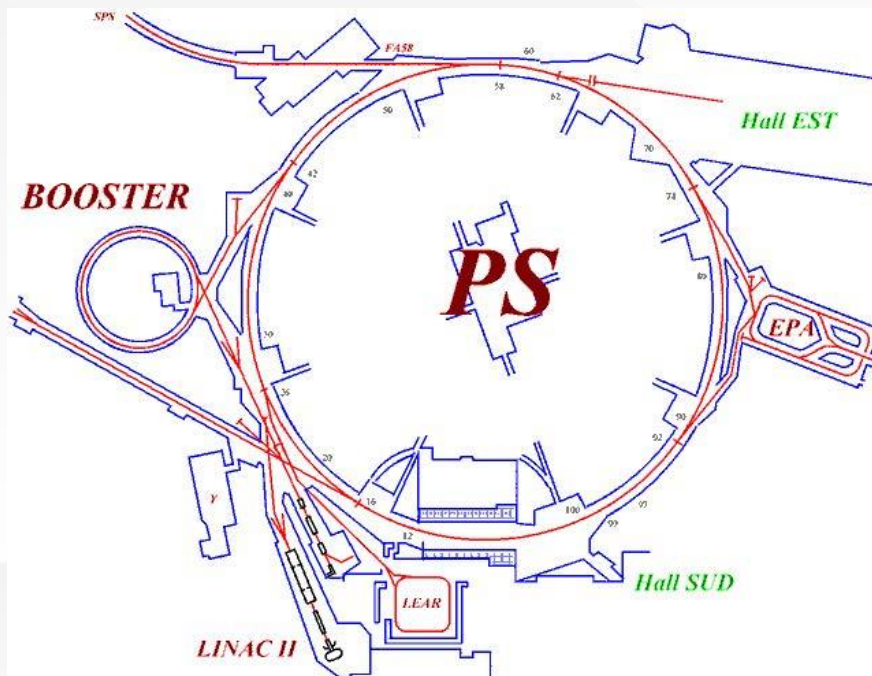
$$\begin{aligned} F_x &= -Zevkx \\ F_y &= Zevky \end{aligned}$$



➤ 同步加速器

❖ 自动稳相原理与强聚焦两大关键技术推动同步加速器快速发展

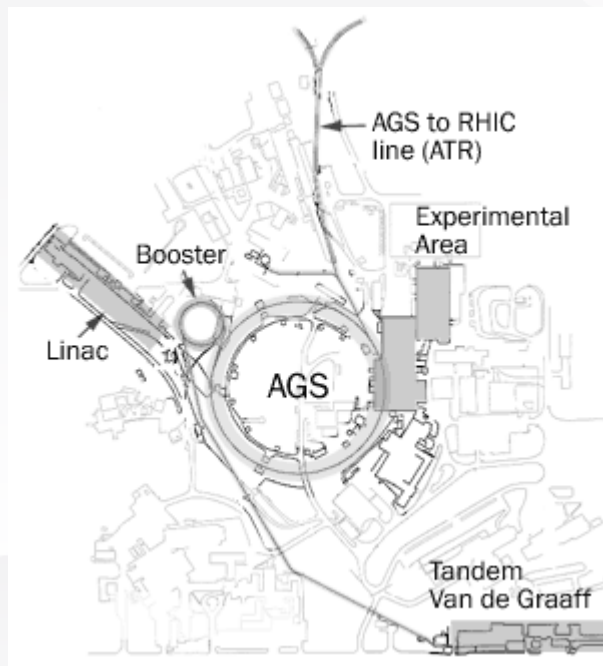
- 1959年，欧洲核子中心CERN建成28GeV同步质子加速器Proton Synchrotron (PS)
- 首个采用强聚焦原理的大型同步加速器，磁铁重量4000 t，为原计划（弱聚焦）的1/10
- 周长628 m



➤ 同步加速器

❖ 自动稳相原理与强聚焦两大关键技术推动同步加速器快速发展

- 1960年, 美国Brookhaven国家实验室建成33GeV同步加速器Alternating Gradient Synchrotron (AGS)
- 磁铁重量3400 t, 周长810 m



1976年诺贝尔物理学奖: 发现J粒子

1980年诺贝尔物理学奖: 发现CP不守恒现象

1988年诺贝尔物理学奖: 发现 μ 中微子

➤ 对撞机

- ❖ 完成加速的高能量粒子与静止靶相互作用
- ❖ 在质心坐标系中（两粒子动能相同）

$$\bullet \quad W' = E_0 \left(\sqrt{\frac{W+2E_0}{2E_0}} - 1 \right)$$

$$\bullet \quad E_{eff} = 2W' = 2E_0 \left(\sqrt{\frac{W+2E_0}{2E_0}} - 1 \right) \approx W \sqrt{\frac{2E_0}{W}} \ll W$$

有效作用能

高能近似

实验室坐标系

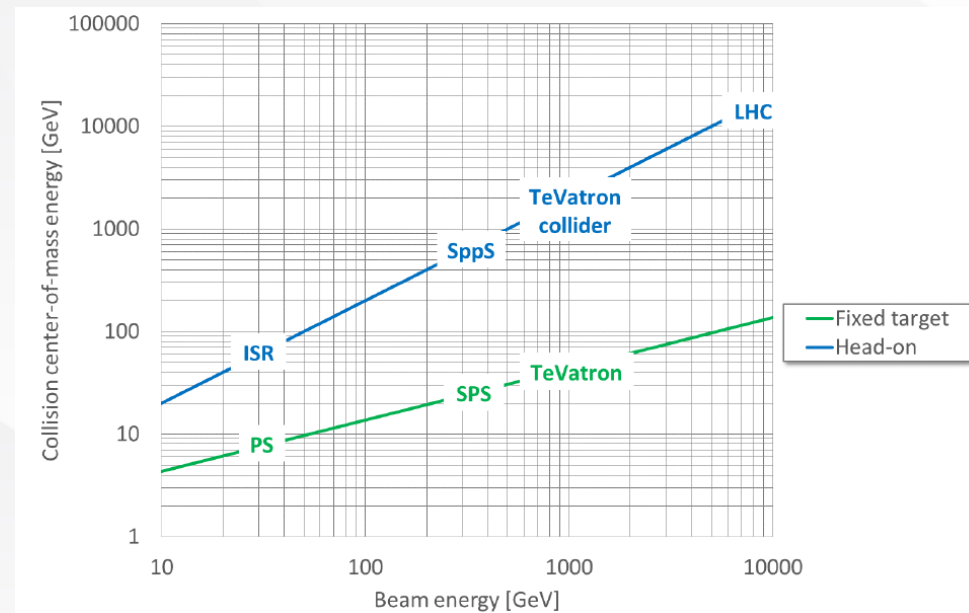


质心坐标系



➤ 对撞机

- ❖ 完成加速的高能量粒子与反方向运动的同样动能的另一个高能量粒子对撞
- ❖ 在质心坐标系中（两粒子动能相同）
 - $W' = W$
 - $E_{eff} = 2W' = 2W$
- ❖ 等效为更高能量的粒子与静止靶相互作用
 - $W^* = 2 \left(\frac{W}{E_0} \right) W \gg W$
- ❖ 示例
 - 在北京正负电子对撞机（BEPC）中，电子与正电子的动能为1.4 GeV，等效于动能为 7671 GeV的电子轰击静止靶

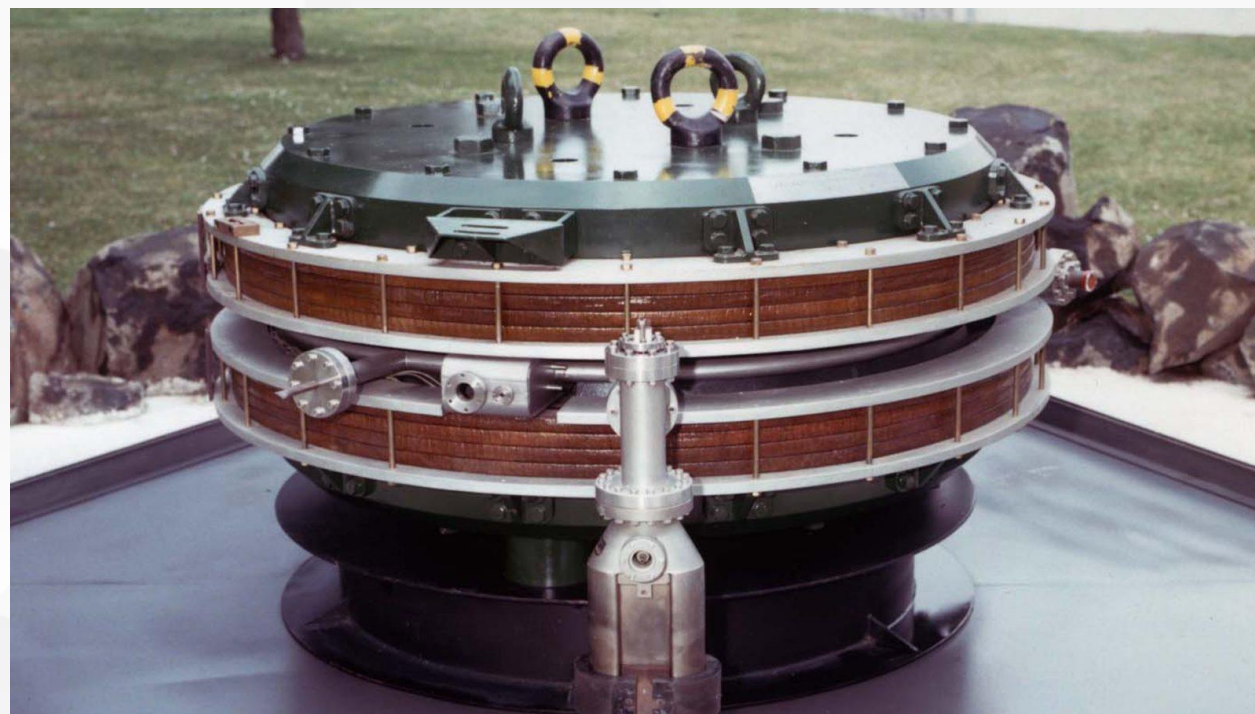
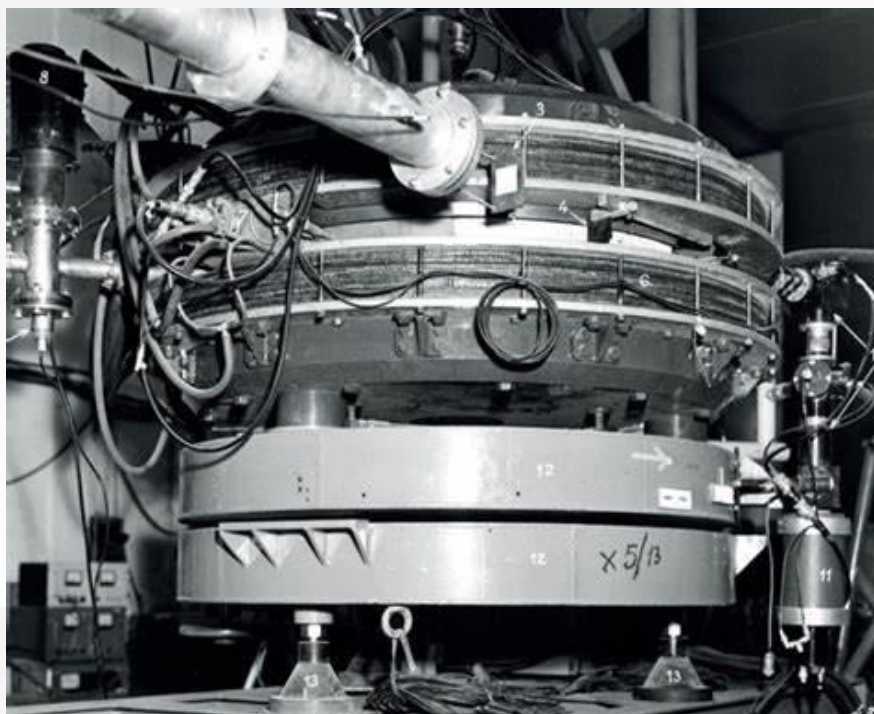




➤ 同步加速器对撞机

❖ 对撞机技术与同步加速器的结合开启了高能物理研究的新篇章

- 1961年，意大利Frascati国家实验室建成250MeV正负电子同步加速器对撞机Anello Di Accumulazione (AdA)，直径1.3 m





➤ 同步加速器对撞机

❖ 对撞机技术与同步加速器的结合开启了高能物理研究的新篇章

- 1976年, CERN建成450GeV正负质子同步加速器对撞机Super Proton Synchrotron (SPS), 周长6.9 km



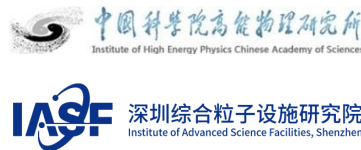
1984年诺贝尔物理学奖：发现 W 粒子与 Z 粒子



同步加速器



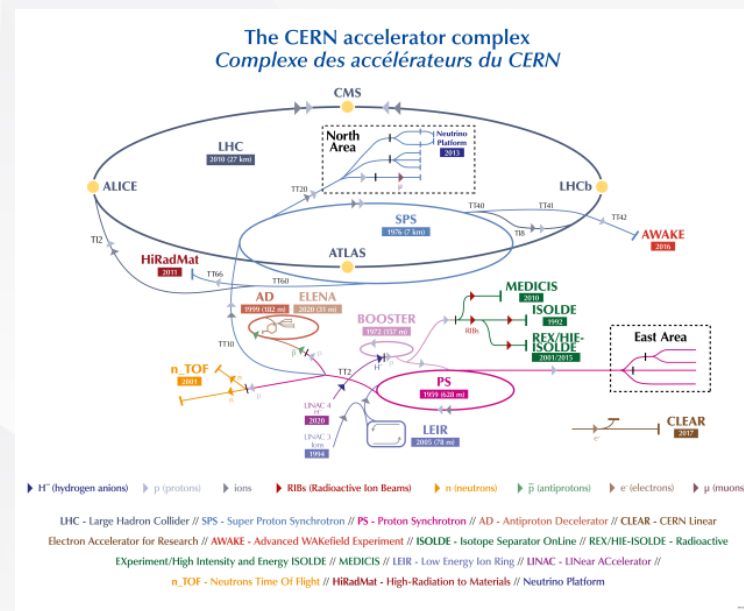
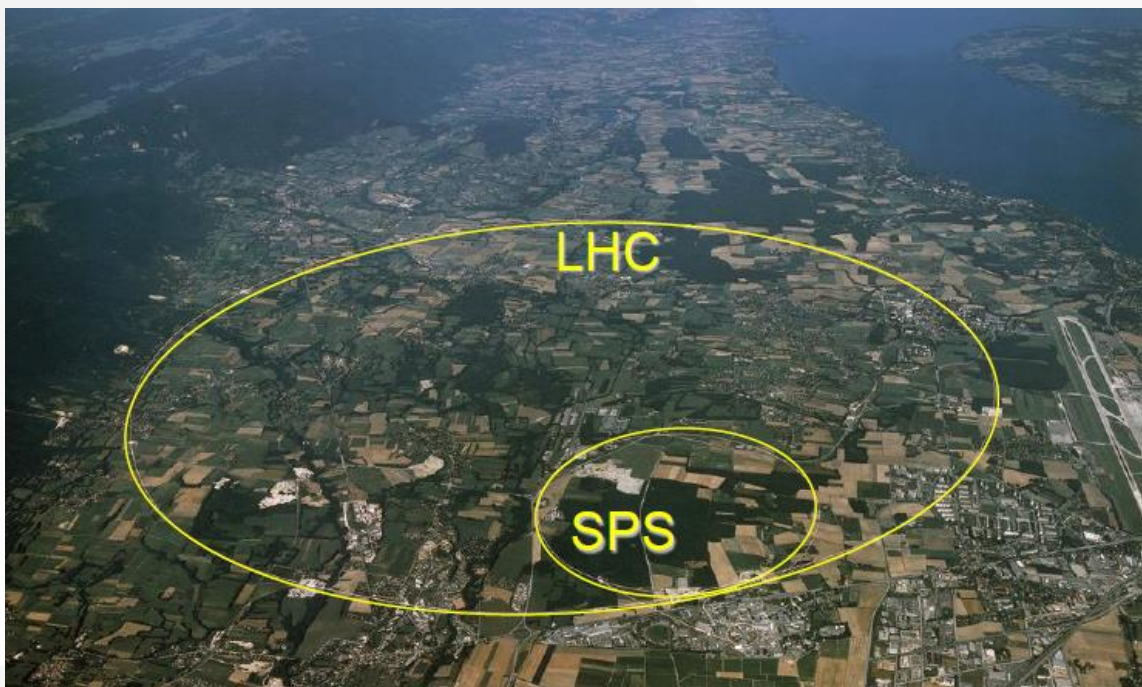
中山大學
SUN YAT-SEN UNIVERSITY



➤ 同步加速器对撞机

❖ 对撞机技术与同步加速器的结合开启了高能物理研究的新篇章

- 世界上最大的7TeV强子同步加速器对撞机Large Hadron Collider (LHC)，周长27 km

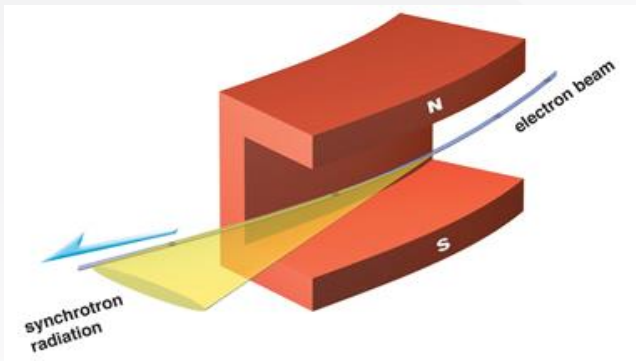


2013年诺贝尔物理学奖: *Higgs*粒子

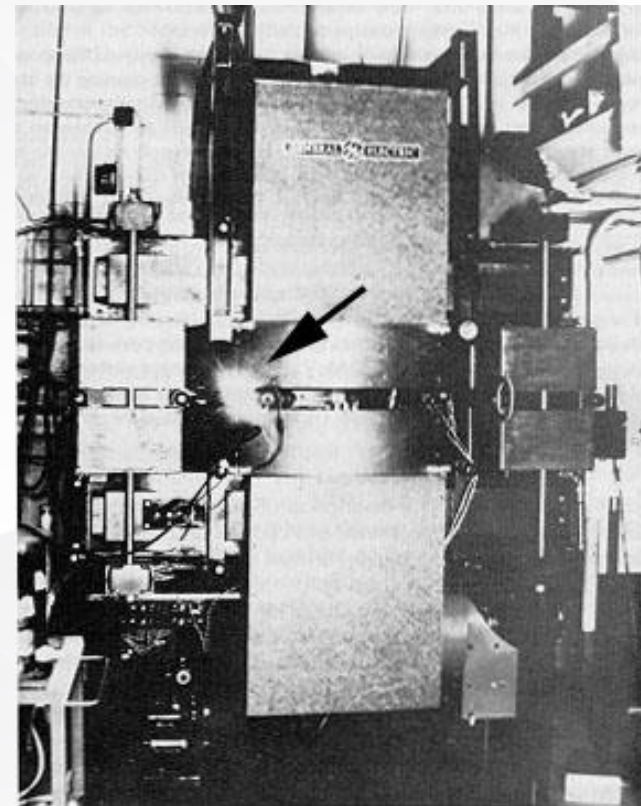
P. Lebrun, CAS 2019

➤ 同步辐射

- ❖ 高速电子在磁场中转弯时，在切线方向发出的光
- ❖ 1947年，在美国通用电器公司的70 MeV电子同步加速器上首次发现



"On April 24,[1947]... some intermittent sparking had occurred and we asked the technician to observe with a mirror around the protective concrete wall. He immediately signaled to turn off the synchrotron as "he saw an arc in the tube." The vacuum was still excellent, so Langmuir and I came to the end of the wall and observed. At first we thought it might be due to Cerenkov radiation, but it soon became clearer that we were seeing Ivanenko and Pomeranchuk [i.e., **synchrotron**] radiation."



➤ 同步辐射

❖ 辐射功率

$$\bullet P_{\gamma} = \frac{ec^2}{6\pi\epsilon_0} \left(\frac{E}{m_0c^2}\right)^4 \frac{\beta^4}{R^2}$$

❖ 每圈辐射能量

$$\bullet U_{\gamma} = P_{\gamma} \frac{2\pi R}{\beta c} = \frac{ec}{3\epsilon_0} \left(\frac{E}{m_0c^2}\right)^4 \frac{\beta^3}{R}$$

❖ 同步辐射是环形加速器达到高能量的主要限制因素之一

- 加速腔需要补偿每圈由于同步辐射损失的能量
- 为降低同步辐射损耗，大型环形对撞机多采用质子等强子

❖ 示例

- CERN LEP-II轻子对撞机：17.4 MW
- CERN LHC强子对撞机：3.8kW

同步辐射

❖ 辐射功率

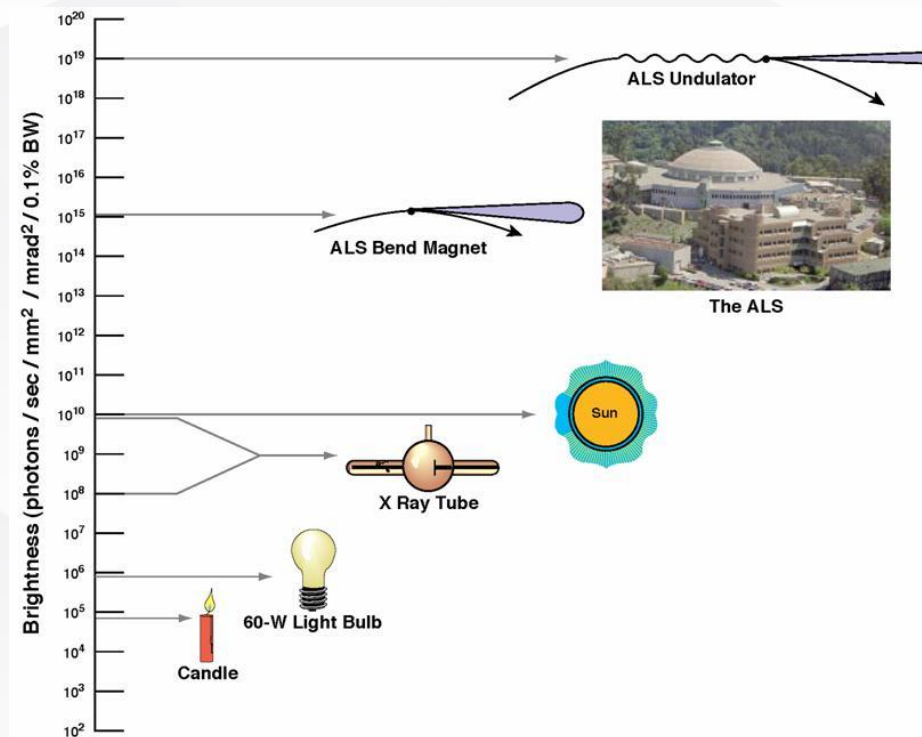
$$P_{\gamma} = \frac{ec^2}{6\pi\epsilon_0} \left(\frac{E}{m_0c^2}\right)^4 \frac{\beta^4}{R^2}$$

❖ 每圈辐射能量

$$U_{\gamma} = P_{\gamma} \frac{2\pi R}{\beta c} = \frac{ec}{3\epsilon_0} \left(\frac{E}{m_0c^2}\right)^4 \frac{\beta^3}{R}$$

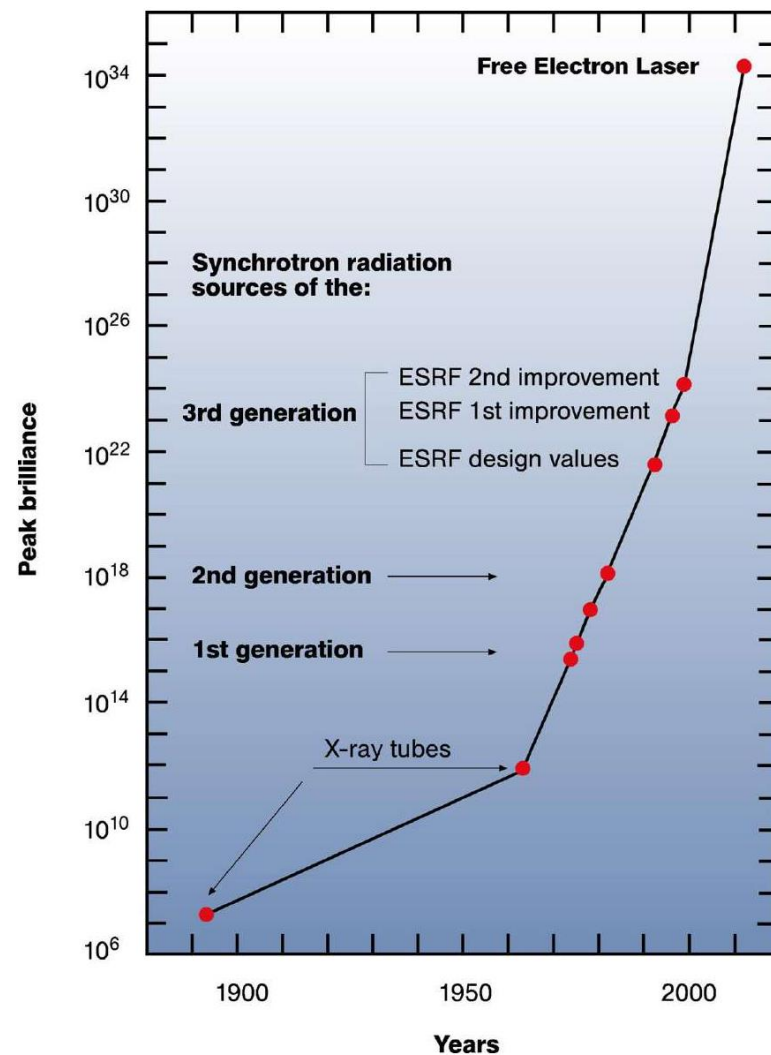
❖ 另一方面，同步辐射光具有优异的性质，可以为众多学科的基础研究提供强有力的工具

- 加速腔不提供加速，仅补偿每圈同步辐射的损耗
- 所有的同步辐射光源均为电子装置
- 每圈辐射能量为 $U_{\gamma}[keV] = 88.5E^4[GeV]/R[m]$



同步辐射

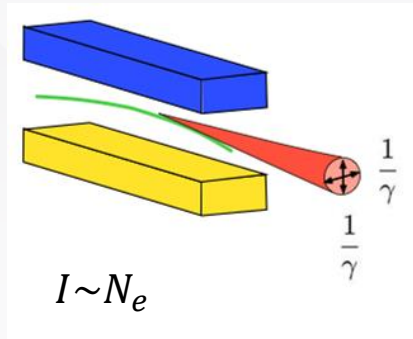
- ❖ 第一代同步辐射光源
 - 用于粒子物理的同步加速器的兼用模式
- ❖ 第二代同步辐射光源
 - 专门用于光子科学的同步加速器/储存环
- ❖ 第三代同步辐射光源
 - 专用、优化的储存环，采用插入设备（扭摆磁铁和波荡器）产生辐射



➤ 同步辐射

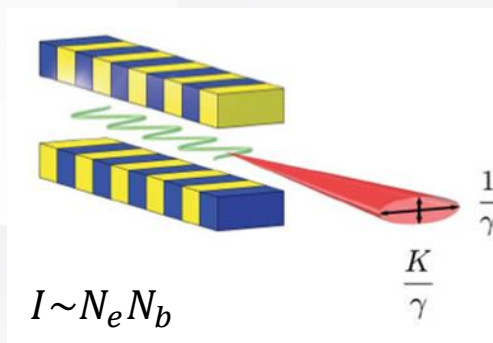
❖ 偏转磁铁

- 单块强的磁铁
- 锥角辐射沿偏转磁铁扫过
- 宽谱输出



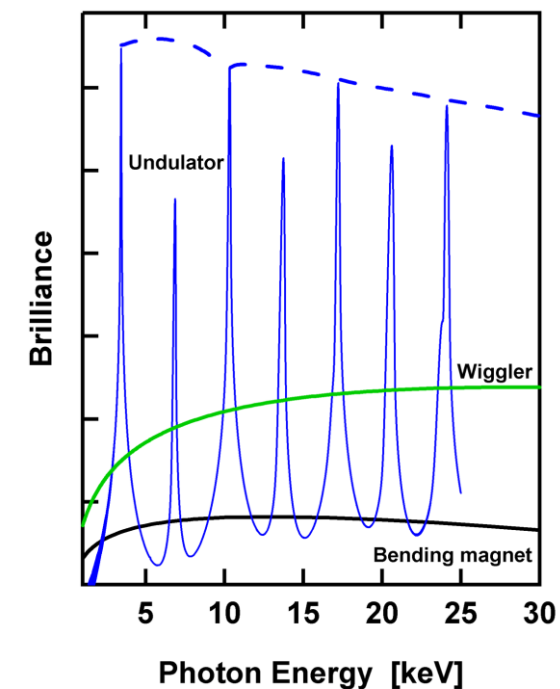
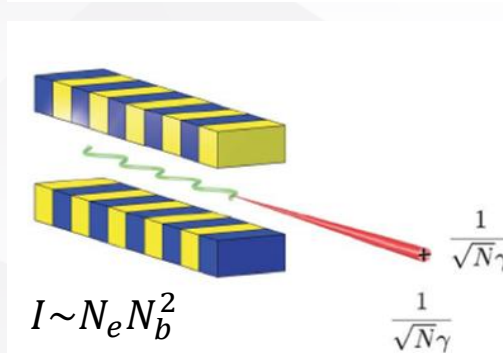
❖ 扭摆磁铁 (Wiggler)

- 小数量的强偏转磁铁
- 水平方向散角比辐射锥角大
- 宽谱输出
- 从不同偏转磁铁产生的辐射的非相干叠加



❖ 波荡器 (Undulator)

- 大数目的弱磁铁
- 散角小于辐射锥角
- 频谱输出限制在一些谐波线
- 不同偏转磁铁产生的辐射的相干叠加





➤ 同步辐射装置

❖ 作为用户装置的优异特点

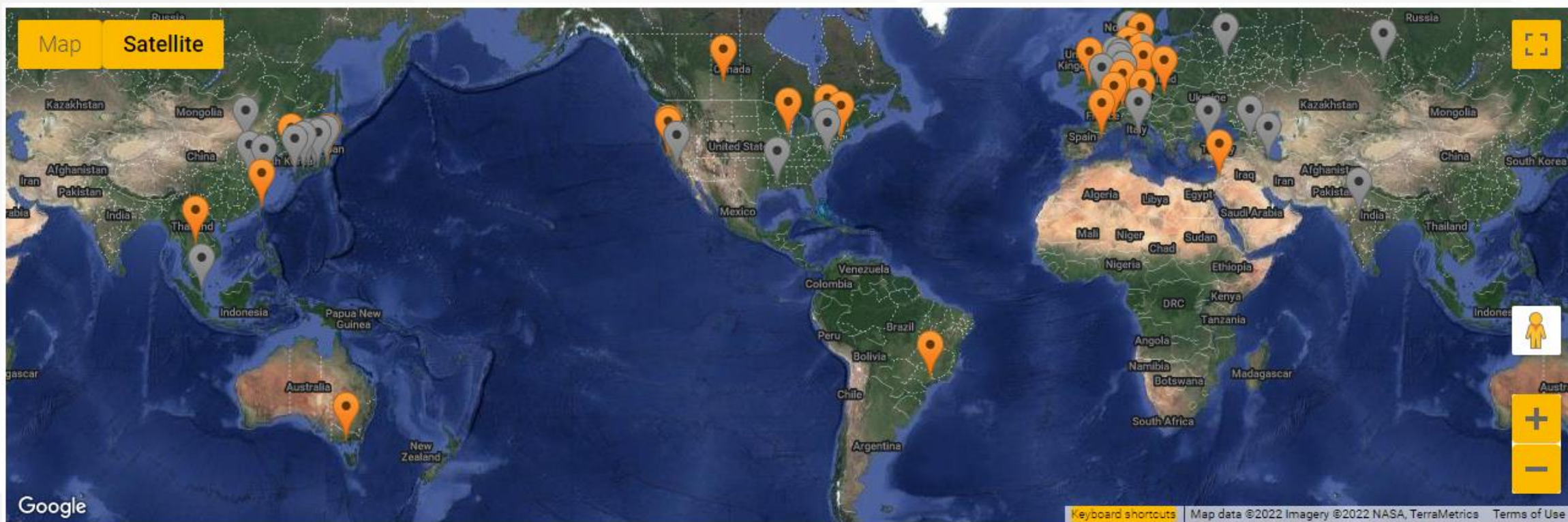
- 光谱频带宽并连续可调
- 方向性强准直性好
- 亮度极高
- 具有特定的时间结构
- 光性能高度稳定
- 高清洁环境
- 同步辐射是偏振光
- 同时为多个用户服务





➤ 同步辐射光源

❖ 世界范围内共有超过50台基于加速器的高亮度光源，服务生物、材料、化学、能源等众多学科





➤ 同步辐射光源

❖ 世界范围内共有超过50台基于加速器的高亮度光源，服务生物、材料、化学、能源等众多学科

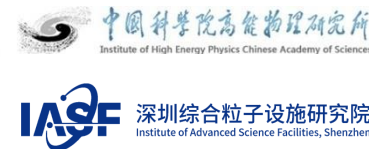




同步加速器



中山大學
SUN YAT-SEN UNIVERSITY

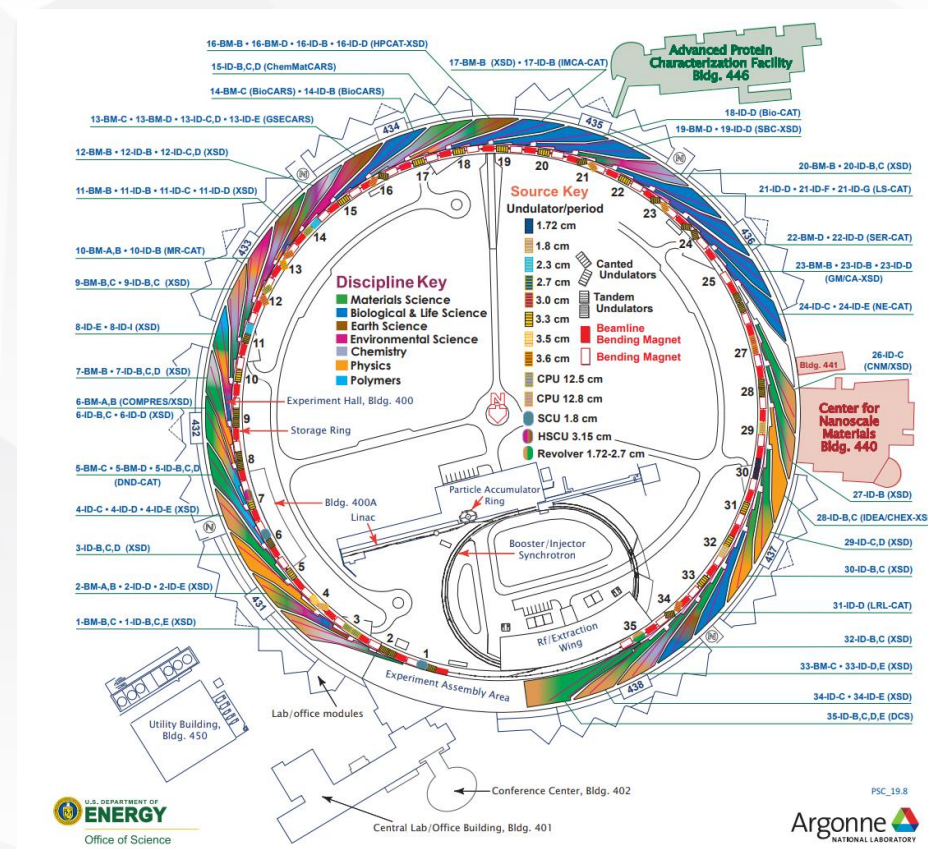


➤ 同步辐射光源

❖ 世界范围内共有超过50台基于加速器的高亮度光源，服务生物、材料、化学、能源等众多学科



APS
每年用户数 > 5000



同步辐射光源

❖ 世界范围内共有超过50台基于加速器的高亮度光源，服务生物、材料、化学、能源等众多学科



一期 BL08U1-A

软X射线谱学显微光束线站

一期 BL08U1-B

软X射线干涉光刻 (XIL) 分支光束线站

一期 BL13HB

X射线成像及生物医学应用光束线站(原 BL13W1)

一期 BL14W1

XAFS光束线站

一期 BL14B1

衍射光束线站

一期 BL15U1

硬X射线微聚焦及应用光束线站

一期 BL16B1

X射线小角散射光束线站

一期 BL09U

梦之线 (2站)

一期 BL01B1

时间分辨红外谱学线站 (2站)

一期 BL17B

高通量蛋白质晶体结构线站

一期 BL18U

蛋白质微晶体结构线站

一期 BL19U1

一期 BL19U2

X射线小角散射光束线站

一期 BL02B

SIPME2线站

二期 BL02U2

表面衍射光束线站

二期 BL03HB

微束白光衍射光束线站

二期 BL03SSID

激光驱动马格光束线站

二期 BL05U

动力学研究光束线站

二期 BL06B

动力学研究分支光束线站

二期 BL07U

纳米尺度与磁学光束线站

二期 BL09U

共振非弹性X射线散射光束线站

二期 BL09B

X射线光学测试光束线站

二期 BL10U1

时间分辨小角散射光束线站

二期 BL10U2

P2生物防护蛋白晶体学光束线站

二期 BL11B

硬X射线通用谱学光束线站

二期 BL12SW

超硬多功能光束线站

二期 BL13U

硬X射线纳米探针光束线站

二期 BL13SSW

稀有元素分析光束线站

二期 BL16U1

中能谱学光束线站

二期 BL16U2

快速X光成像光束线

二期 BL17MU

高性能膜蛋白晶体学光束线站

二期 BL18B

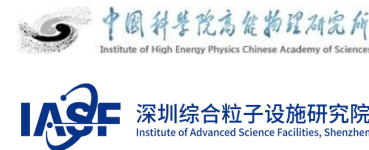
三束纳米成像光束线站

二期 BL20U

能源材料研究光束线站



中山大學
SUN YAT-SEN UNIVERSITY



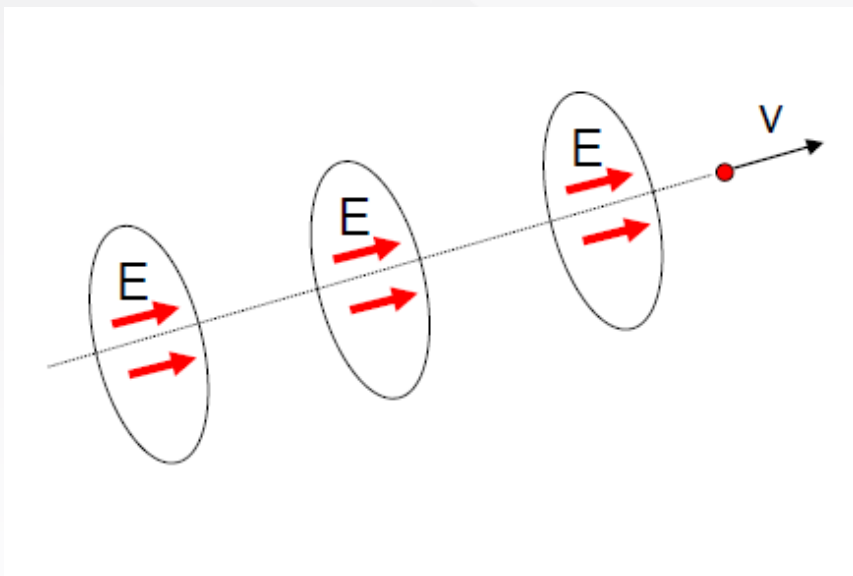
中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences
IASF 深圳综合粒子设施研究院
Institute of Advanced Science Facilities, Shenzhen

02B

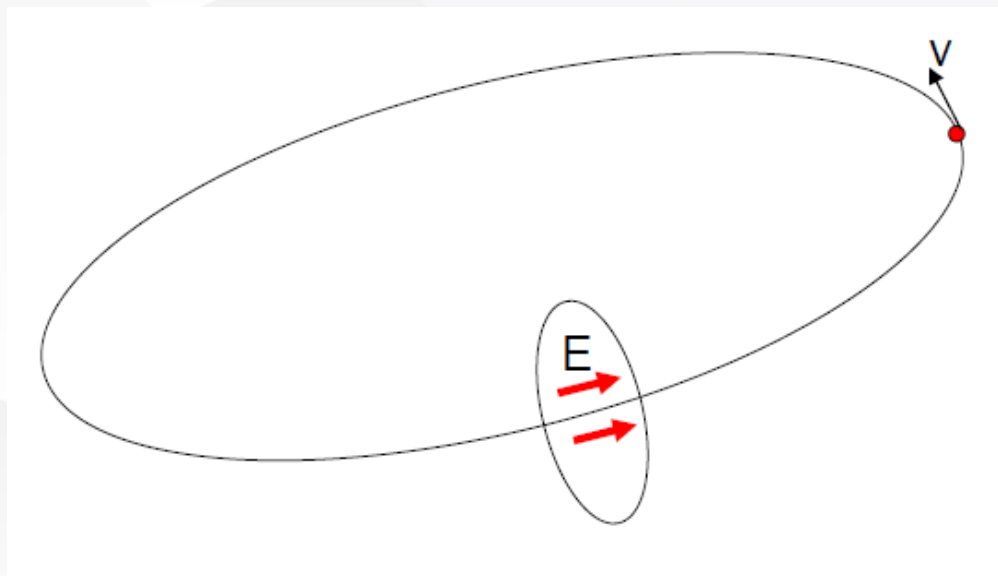
微波直线加速器



➤ 如何重复利用电源电压，提高加速电压？



直线加速器



环形加速器



➤ 射频直线加速器 (RF linear accelerator)

- ❖ 1924年由瑞典物理学家Gustav Ising提出基本概念
- ❖ 将交流电压加至多个串联排列的分离管道中
- ❖ 加速过程
 - 电压为正时，粒子在管道间缝隙中加速
 - 电压为负时，粒子进入管道，不受减速
 - 管道长度随着粒子速度的提高而增加

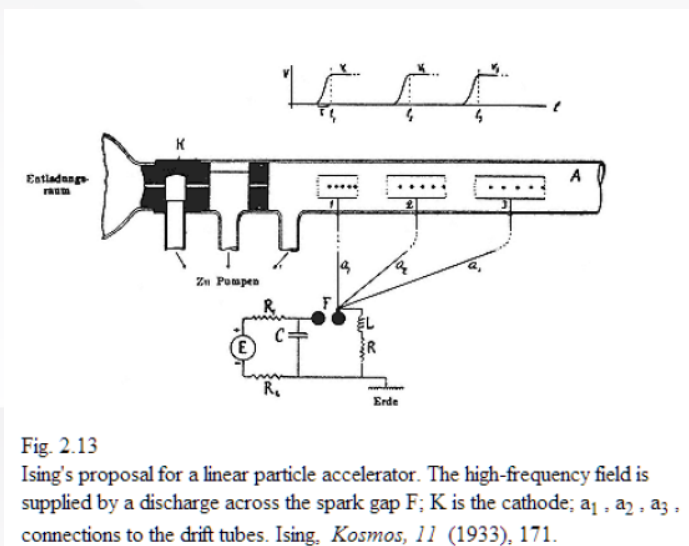
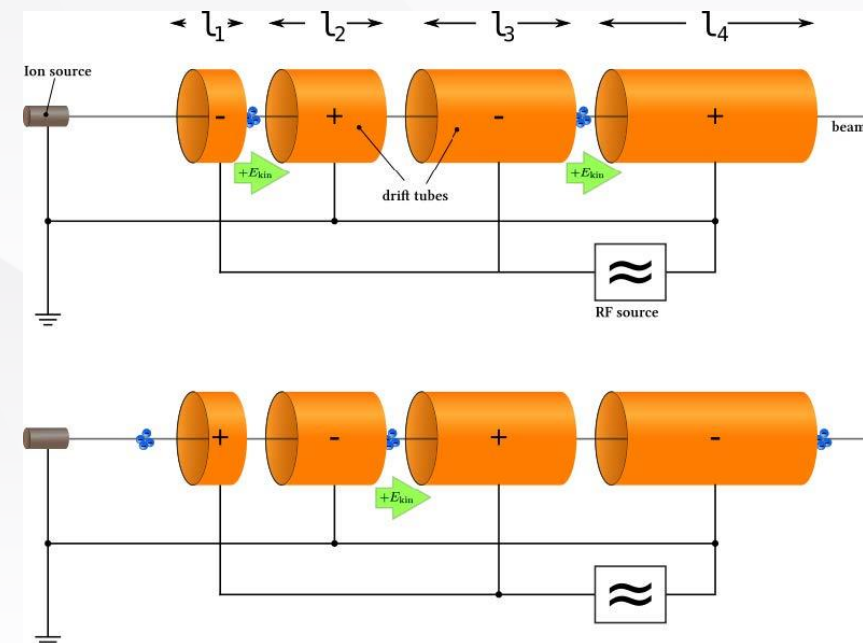
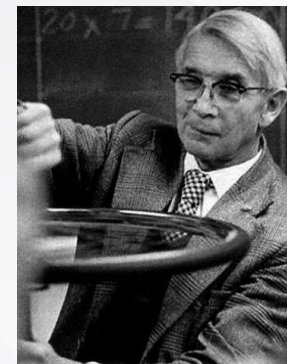


Fig. 2.13

Ising's proposal for a linear particle accelerator. The high-frequency field is supplied by a discharge across the spark gap F; K is the cathode; a_1 , a_2 , a_3 , connections to the drift tubes. Ising, *Kosmos*, 11 (1933), 171.

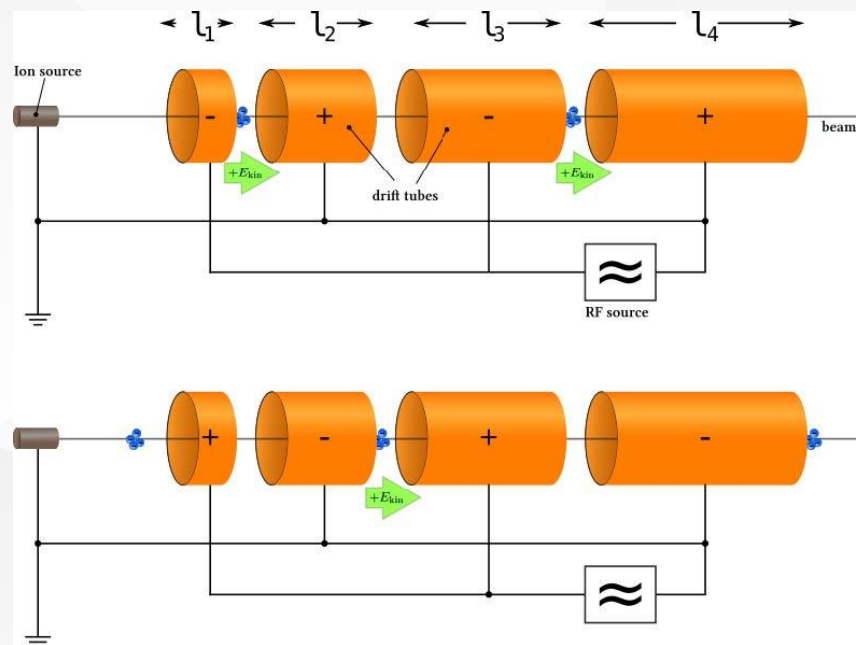




➤ 射频直线加速器 (RF linear accelerator)

❖ 同步条件

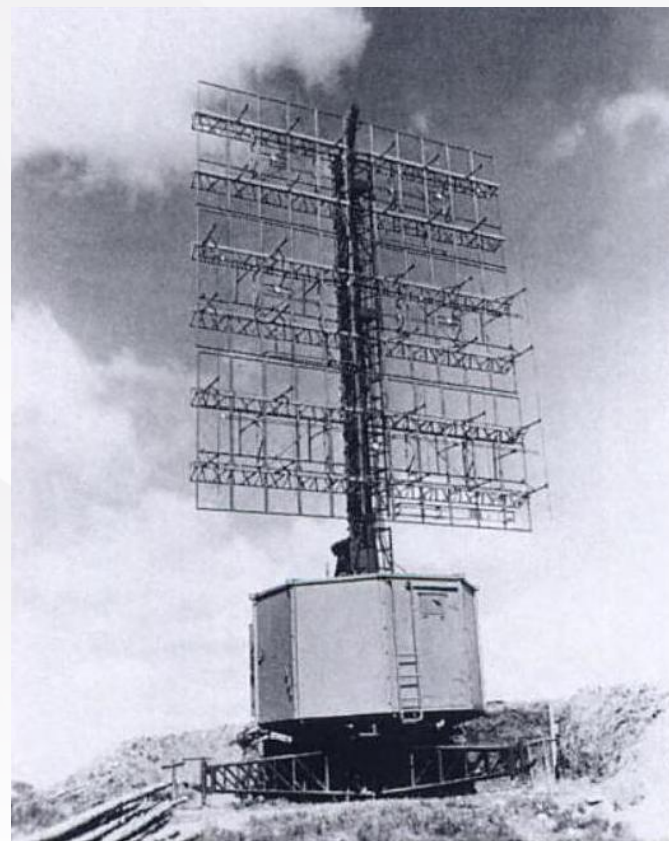
- $L_{drift} = \frac{1}{2} \frac{v}{f_{RF}} = \frac{1}{2} \beta \lambda_{RF}$
- 概念提出后, 由于当时射频频率仅为1-10 MHz, 故未得到广泛关注





➤ 射频直线加速器 (RF linear accelerator)

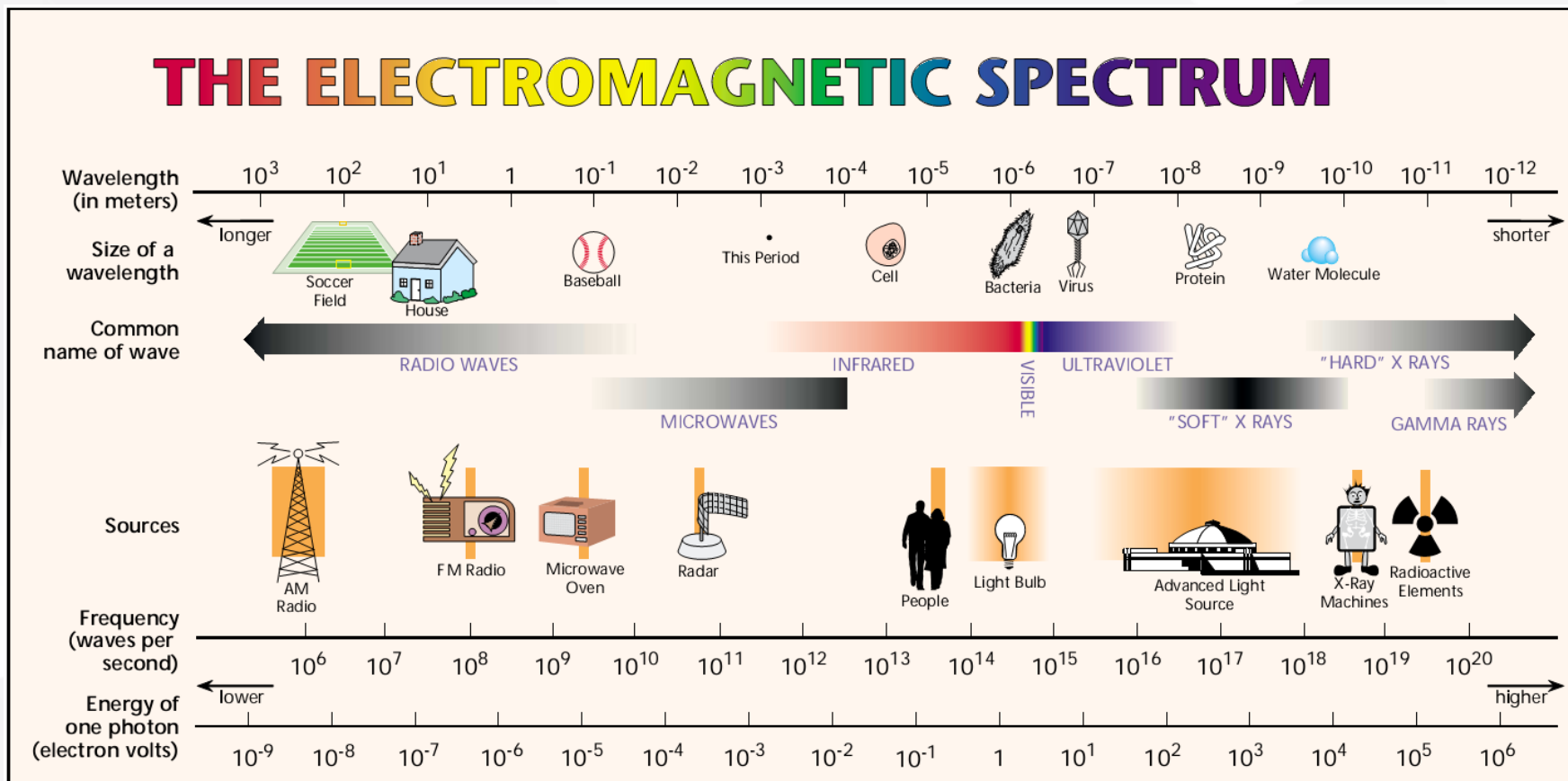
❖ 第二次世界大战中，雷达的发展大大推动了射频功率源的进步





➤ 射频直线加速器 (RF linear accelerator)

❖ 狭义地定义微波 (microwave) 为300 MHz-300 GHz之间的电磁波



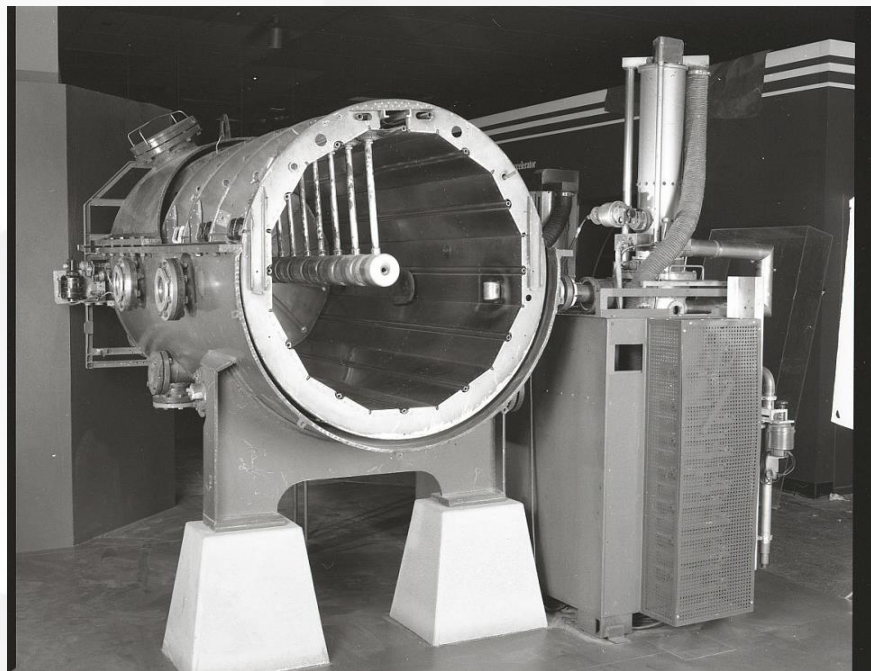
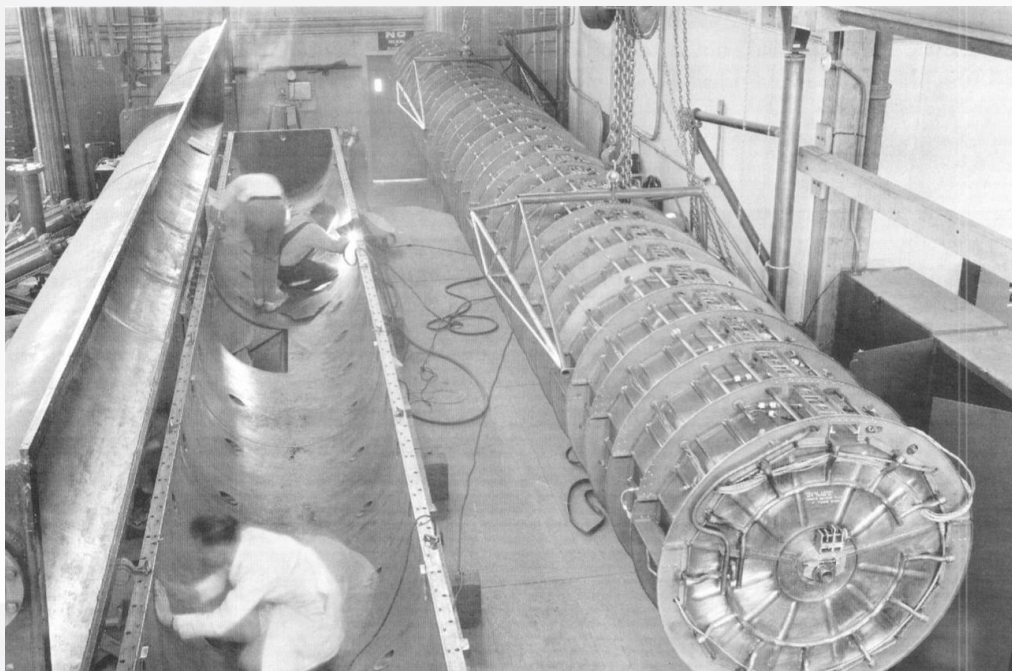
Band	Frequency range
HF Band	3 to 30 MHz
VHF Band	30 to 300 MHz
UHF Band	300 to 1000 MHz
L Band	1 to 2 GHz
S Band	2 to 4 GHz
C Band	4 to 8 GHz
X Band	8 to 12 GHz
Ku Band	12 to 18 GHz
K Band	18 to 27 GHz
Ka Band	27 to 40 GHz
V Band	40 to 75 GHz
W Band	75 to 110 GHz
mm Band	110 to 300 GHz



➤ 漂移管加速器 (Drift tube linac, DTL)

❖ 1947年, 美国物理学家Luis Alvarez于伯克利制造了第一台高频率DTL

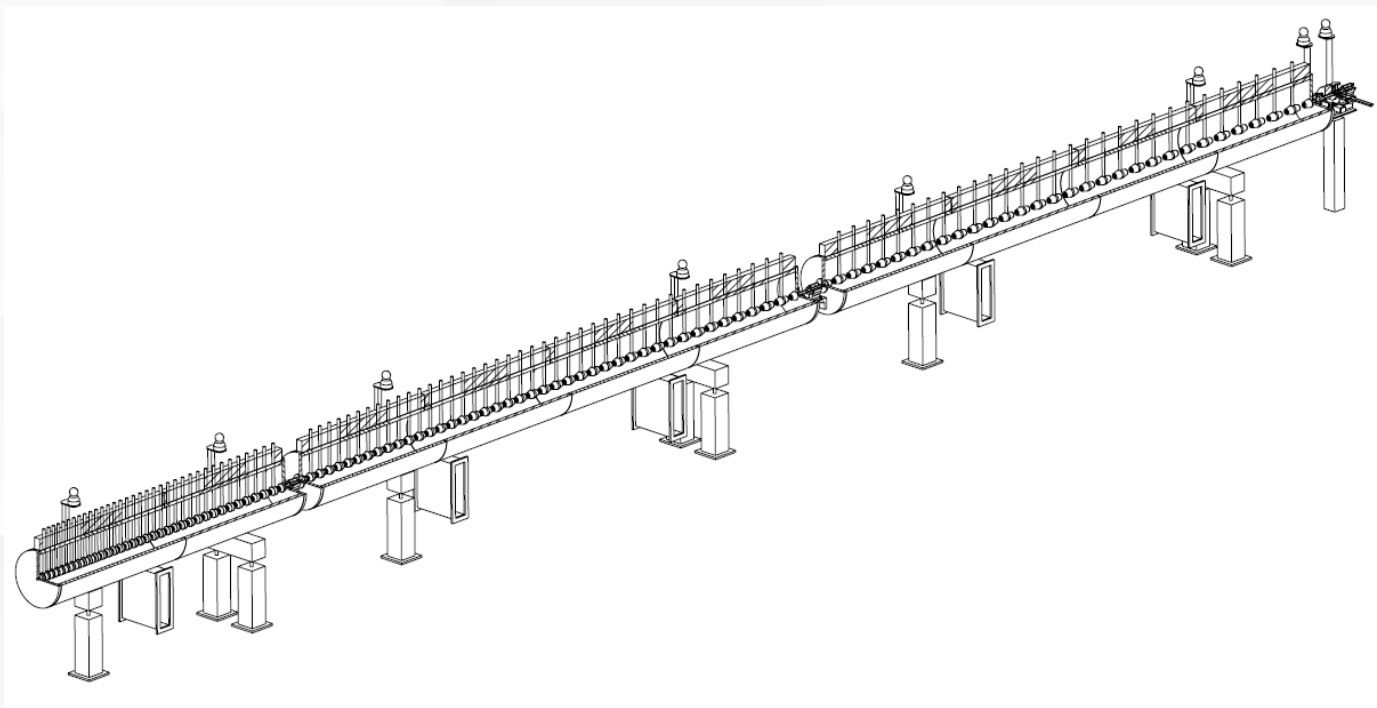
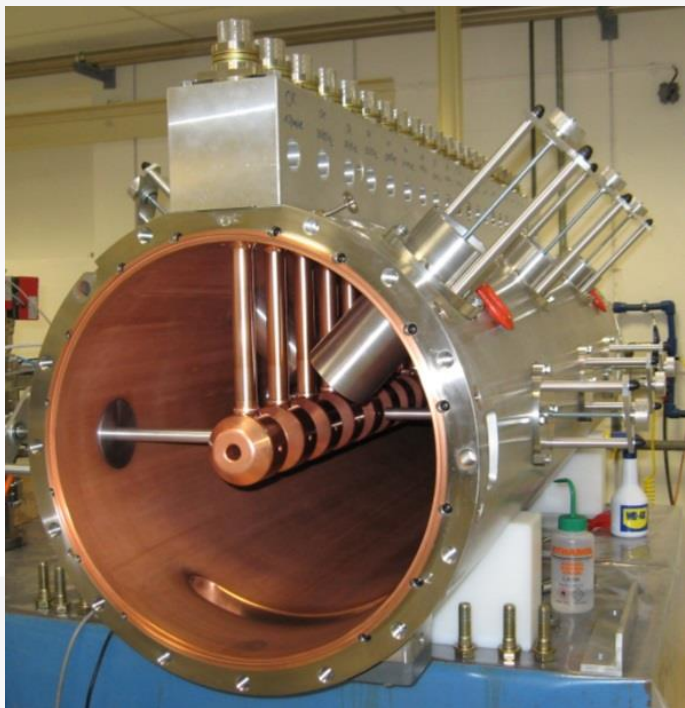
- 频率200 MHz
- 由4 MeV直流高压加速器注入质子, 在12m距离内将能量提高至32 MeV





➤ 漂移管加速器 (Drift tube linac, DTL)

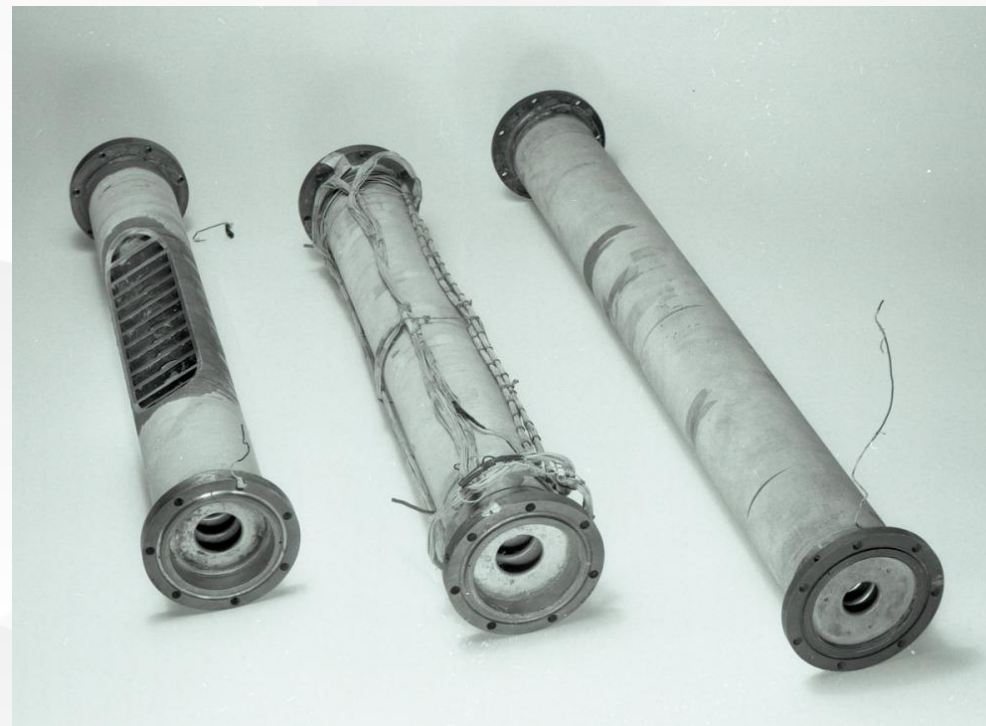
- ❖ 可作为环形加速器的注入器
- ❖ LHC注入段的LINAC4
 - 频率352 MHz
 - 将3 MeV ($\beta = 0.08$) 氢离子加速至50 MeV ($\beta = 0.31$) , 腔体长度68-264 mm





➤ 微波直线加速器 (Linac)

- ❖ 1950年左右，美国物理学家William Hansen与Russell Varian、Sigurd Varian等人制造了MARK I型电子微波直线加速器
- ❖ 频率2856 MHz，加速电子至6 MeV



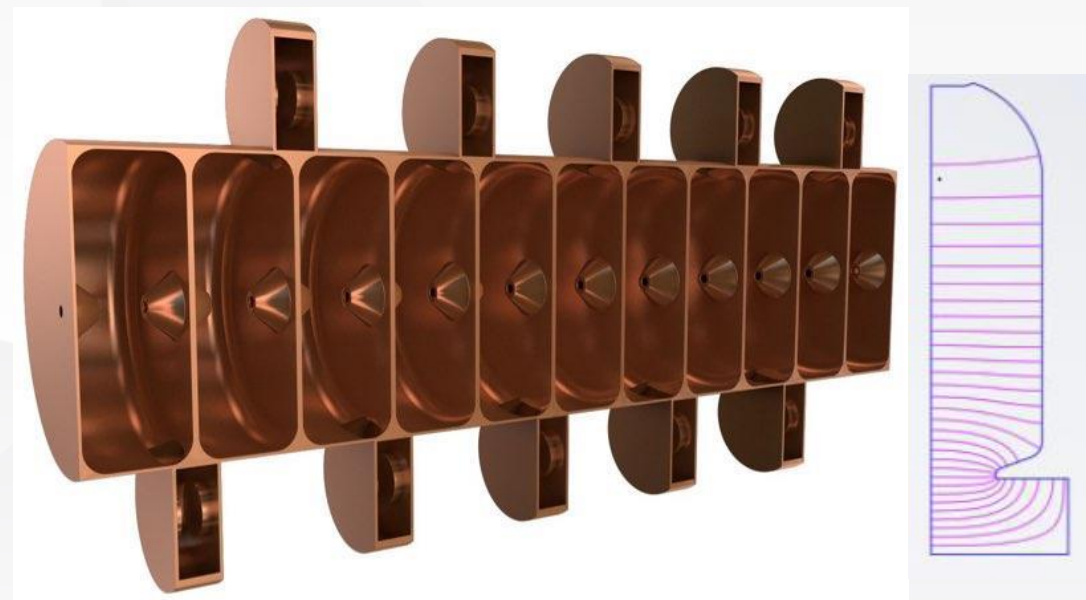


➤ 微波直线加速器 (Linac)

- ❖ 加速原理与DTL近似
- ❖ 利用盘荷波导组成谐振腔链 (后续课程将详细讨论其原理)



DTL

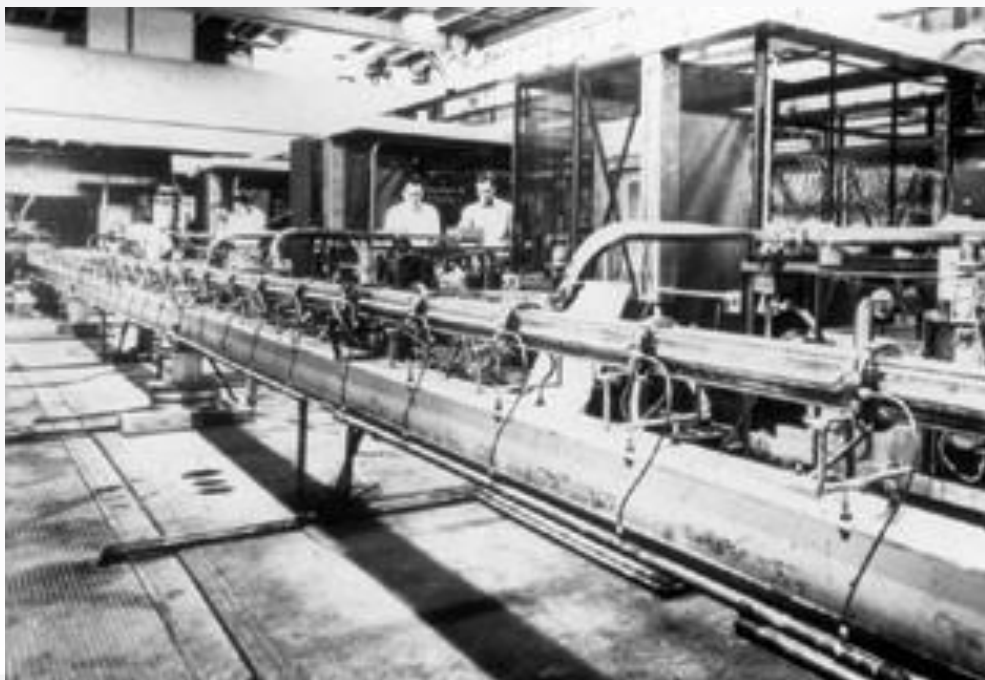


LINAC



➤ 微波直线加速器 (Linac)

- ❖ 1950年后，斯坦福国家实验室成为电子微波直线加速器发展的中心
- ❖ 建成了一系列能量75 MeV-50 GeV的直线加速器



MARK-III 75 MeV

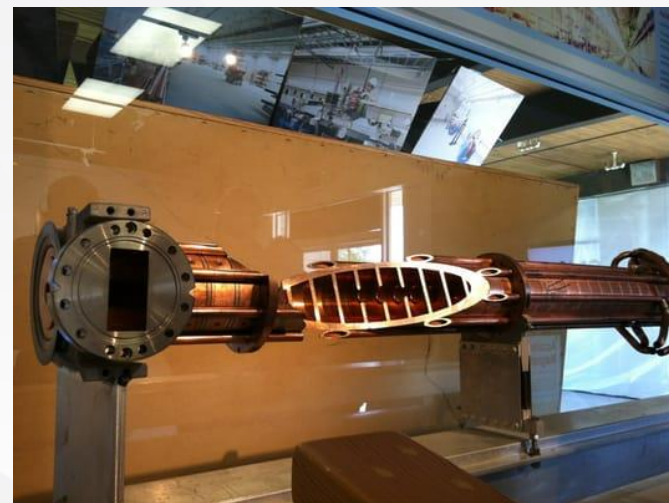
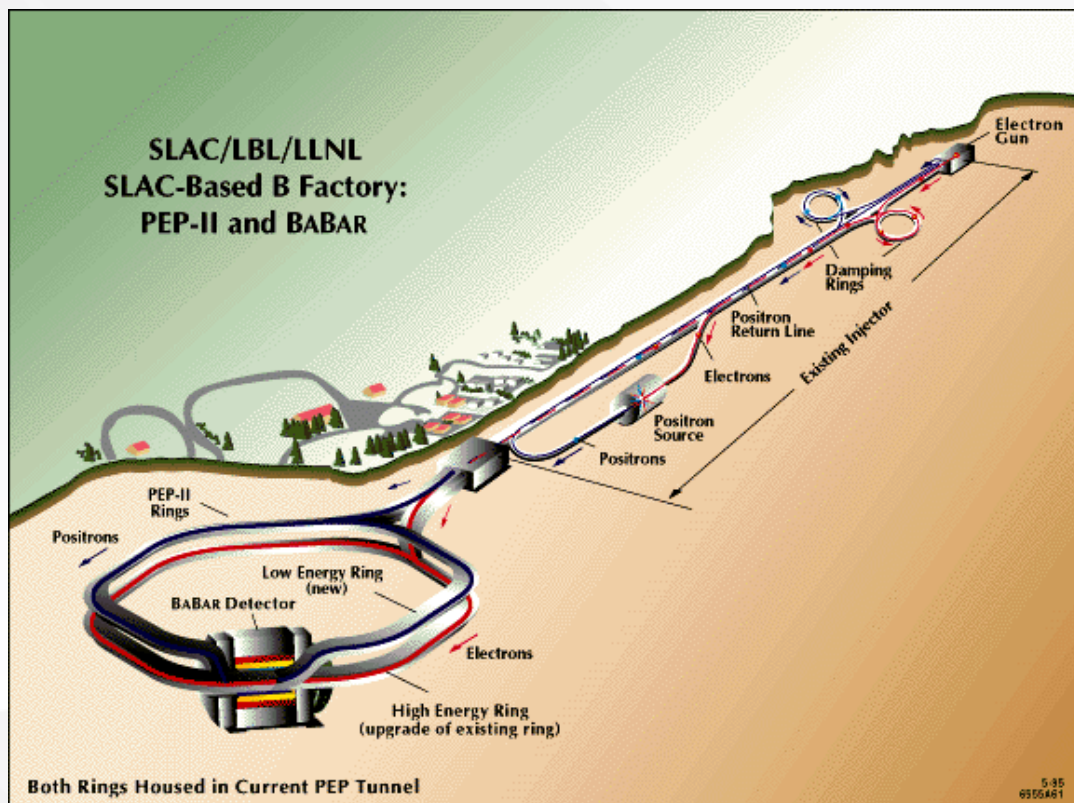


SLC 50 GeV



➤ 微波直线加速器 (Linac)

- ❖ 斯坦福直线对撞机 (SLC)
- ❖ 世界上最长的直线加速器, 3 km

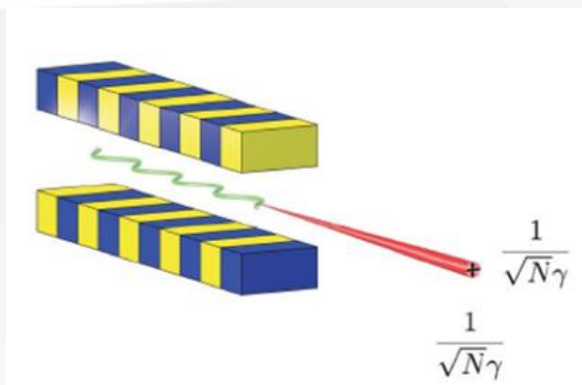


1990年诺贝尔物理学奖：质子与中子的夸克结构



➤ 自由电子激光

❖ 基于电子微波直线加速器



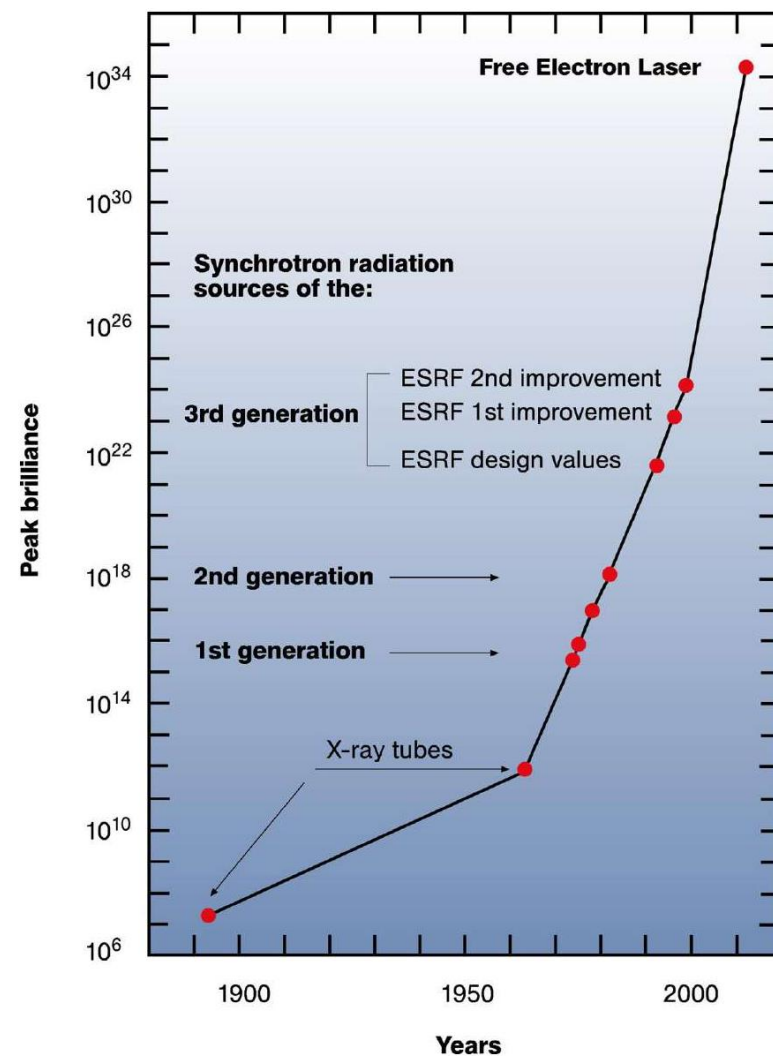
同步辐射: $I \sim N_e N_b^2$

自由电子激光: $I \sim N_e^2 N_b^2$

	Synchrotrons	X-ray FELs
Pulse energy	~nJ	~mJ
Relative bandwidth	$\gg 10^{-4}$	$\sim 10^{-4}$
Peak brilliance	$10^{25} - 10^{27}$	$10^{35} - 10^{37}$
Repetition rate	~500 MHz	0.1 kHz - 1 MHz
User accessibility	Good >50 facilities, up to 50 beamlines per facility	Worse 5-10 facilities, up to 10 beamlines per facility

E. Prat, CAS 2021

黄文会, 加速器原理, 清华大学





➤ 仅涉及本课程重点介绍的粒子加速器类型





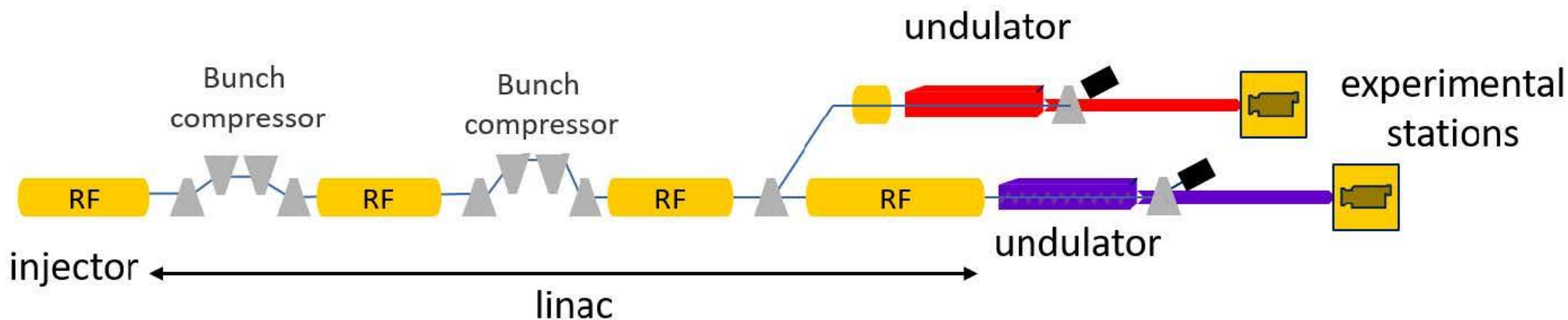
➤ 自由电子激光

❖ 基于电子微波直线加速器

波荡器周期

波荡器强度

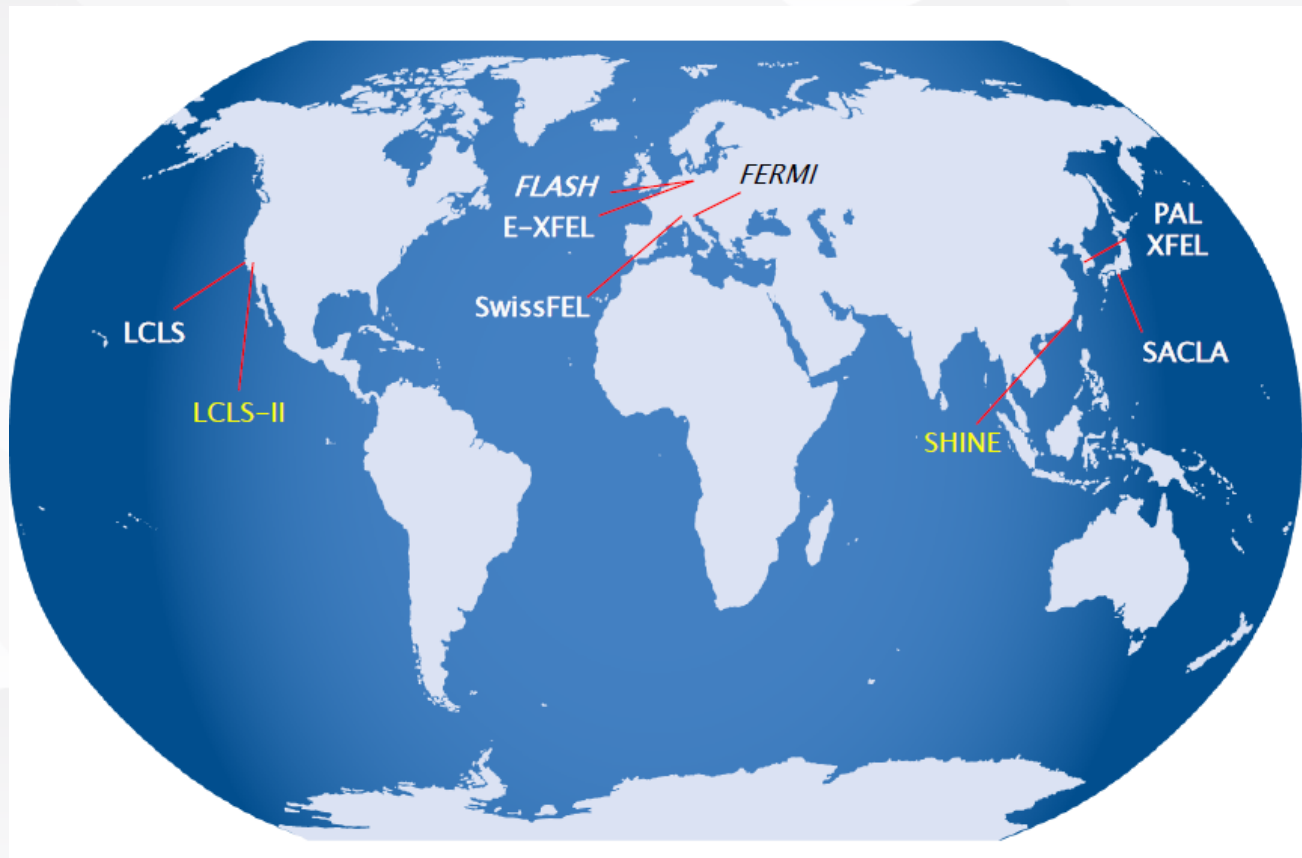
❖ 激光波长: $\lambda = \frac{\lambda_u}{2\gamma^2} \left(1 + \frac{K^2}{2}\right)$





➤ 自由电子激光

❖ 世界范围内共有10台左右X射线自由电子激光装置





➤ 自由电子激光

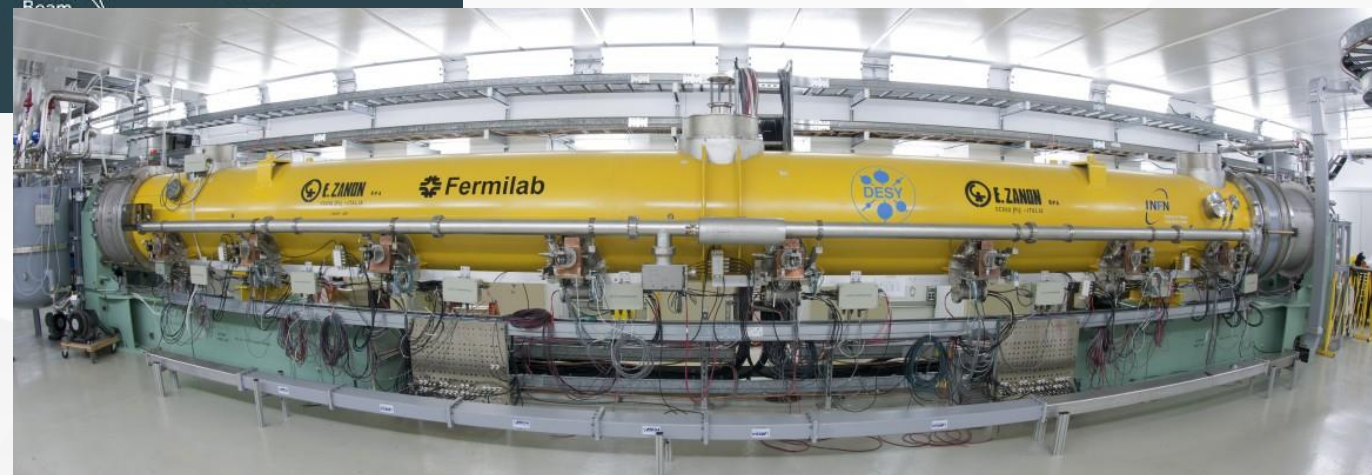
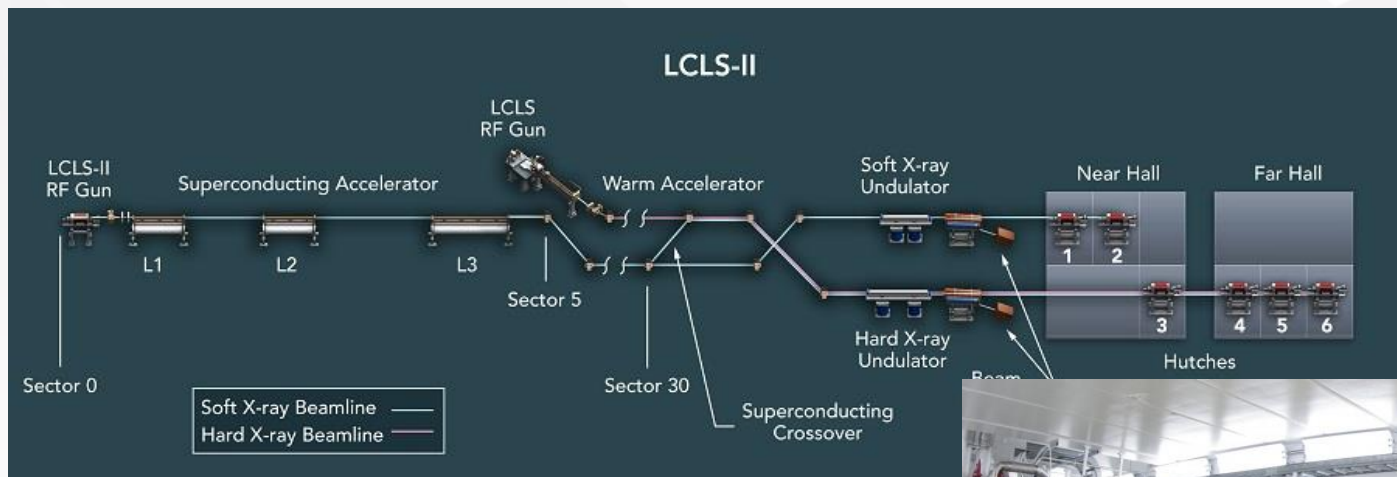
- ❖ 直线相干光源 (LCLS), 利用SLC的后三分之一加速管, 加速电子能量至14.3 GeV
- ❖ 2009年饱和出光, 波长0.15-1.5 nm





➤ 自由电子激光

- ❖ 直线相干光源二期 (LCLS-II)，采用超导加速结构，预计将重复频率由120 Hz提升至1 MHz，将大幅提高光源的平均亮度





➤ 自由电子激光

- ❖ 中科院上海应用物理研究所近年来对自由电子激光装置开展了大量研究
- ❖ 在上海光源园区运行软X射线自由电子激光装置 (SXFEL) , 0.5 km长, 1.5 GeV, 常温结构
- ❖ 正在建设上海硬X射线自由电子激光装置 (SHINE) , 3.1 km长, 8 GeV, 超导结构





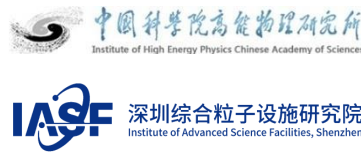
➤ 自由电子激光

- ❖ 杨学明院士与赵振堂院士领导建设了大连相干光源 (DCLS), 150 m长, 0.3 GeV
- ❖ 我国首台自由电子激光用户装置, 2016年出光, 波长50-150 nm





中山大學
SUN YAT-SEN UNIVERSITY



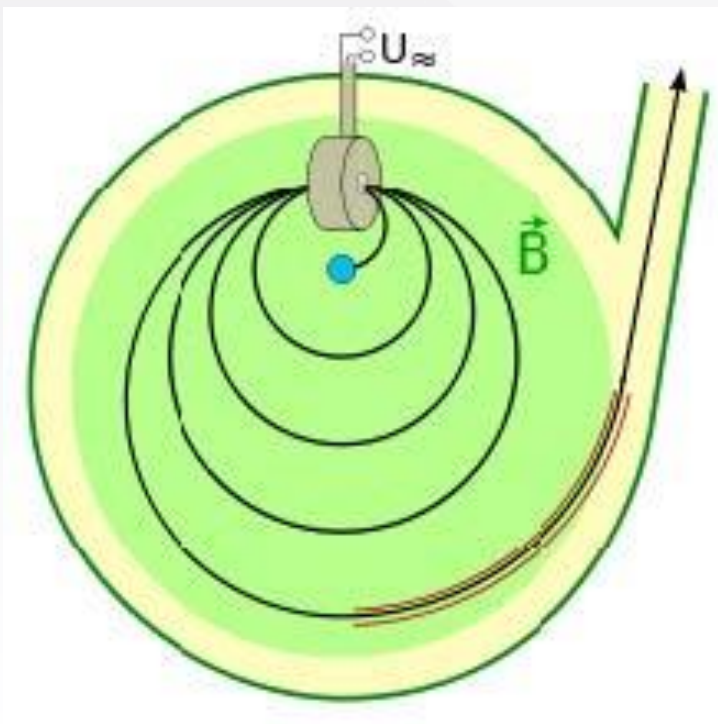
中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences
IASF 深圳综合粒子设施研究院
Institute of Advanced Science Facilities, Shenzhen



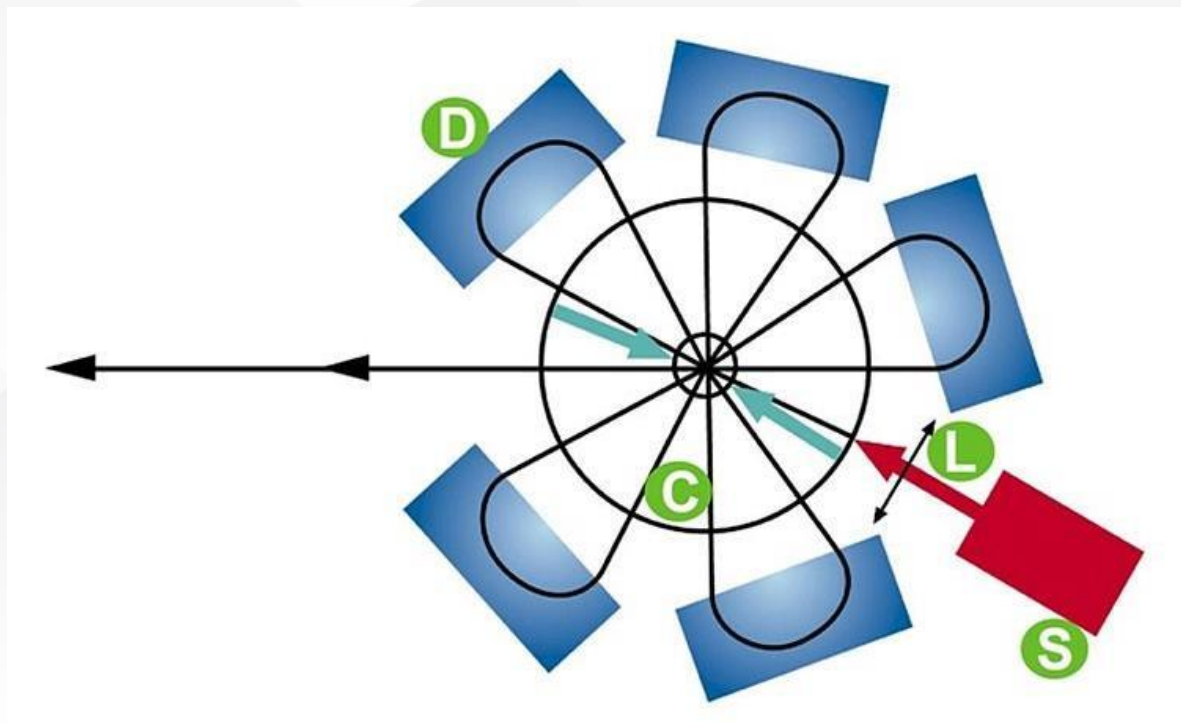
其它类型加速器



➤ 环形



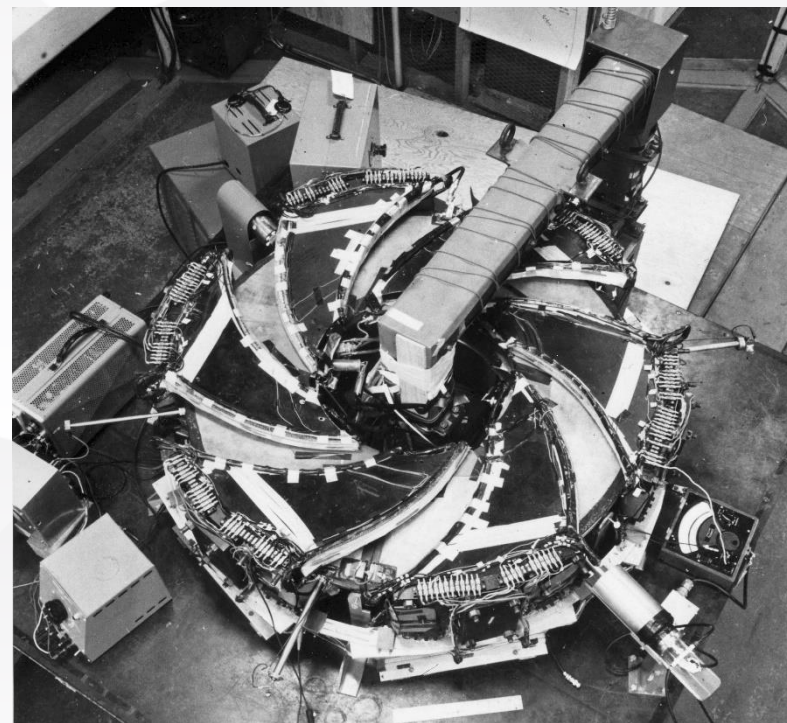
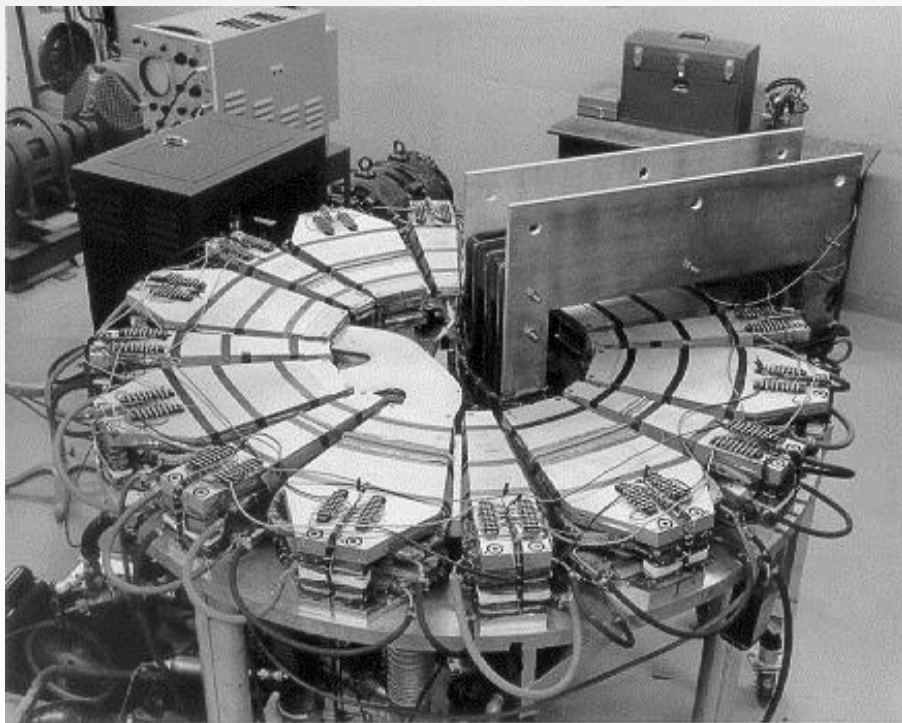
Microtron



Rhodotron



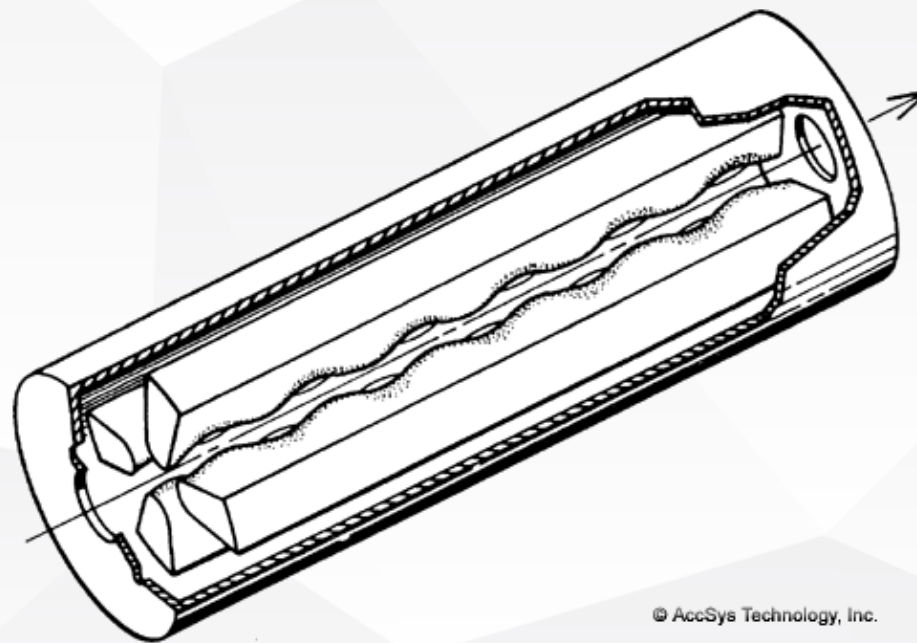
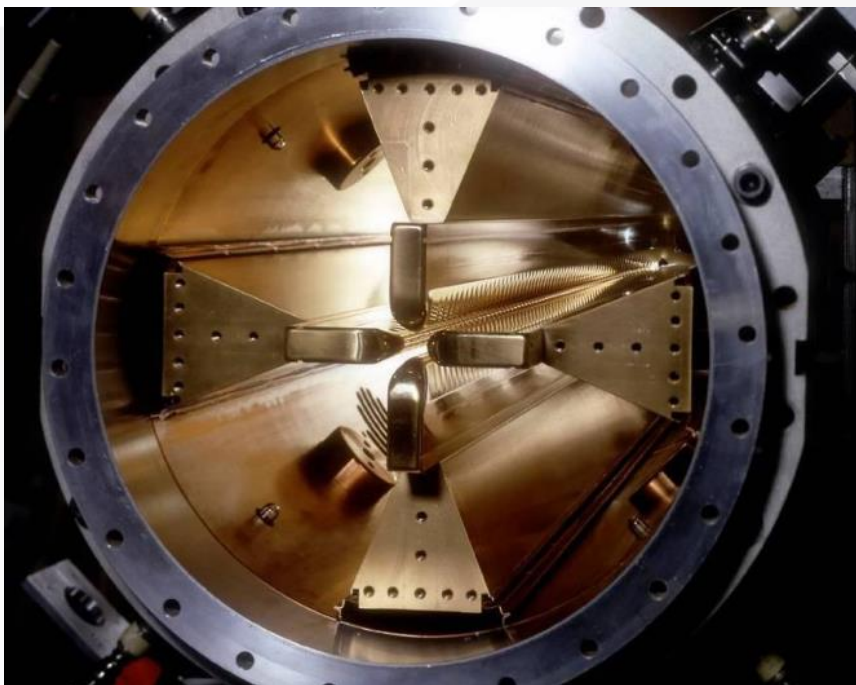
➤ 环形



固定磁场交变梯度加速器 Fixed-Field Alternating-Gradient (FFAG)



➤ 直线形



© AccSys Technology, Inc.

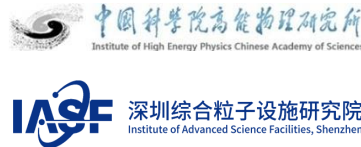
射频四极加速器 (Radio Frequency Quadrupole, RFQ)



简要发展历史



中山大學
SUN YAT-SEN UNIVERSITY

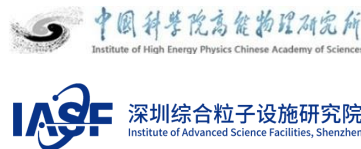


➤ 仅涉及本课程重点介绍的粒子加速器类型





中山大學
SUN YAT-SEN UNIVERSITY



中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences
IASF 深圳综合粒子设施研究院
Institute of Advanced Science Facilities, Shenzhen

03

未来研究方向

➤ 高能加速器

- ❖ 高能环形对撞机
- ❖ 高能直线对撞机

➤ 先进光源

- ❖ 衍射极限环
- ❖ 高重复频率自由电子激光
- ❖ 其它先进概念

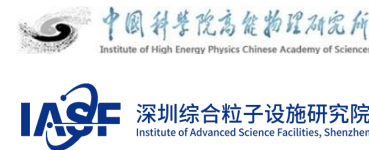
➤ 高梯度加速（通用技术）

- ❖ 基于结构的高梯度加速（与本课程密切相关）
- ❖ 基于等离子体的高梯度加速

仅涵盖整个加速器领域未来研究方向的一小部分



中山大學
SUN YAT-SEN UNIVERSITY



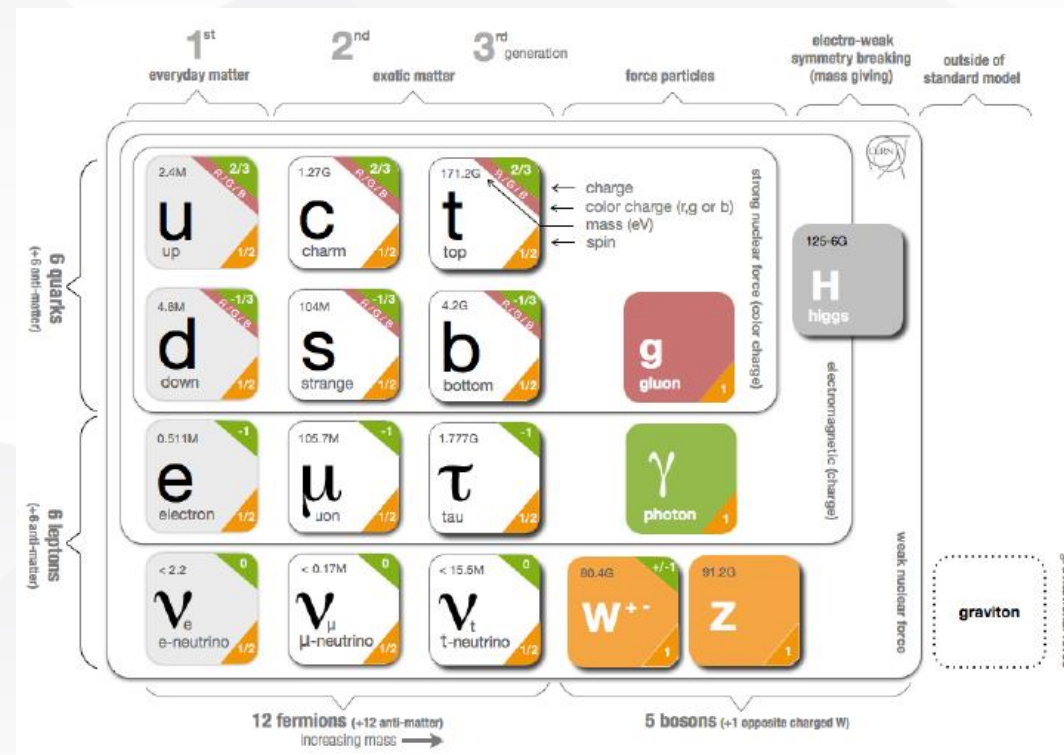
03A

高能对撞机

未来高能物理研究对大型对撞机的需求

❖ 回答基础物理问题

- 标准模型对更高能量/更小尺度是否依然适用?
- 标准模型如何针对物质-反物质不对称性、宇宙中暗物质、宇宙膨胀、量子引力等现象做出修正?

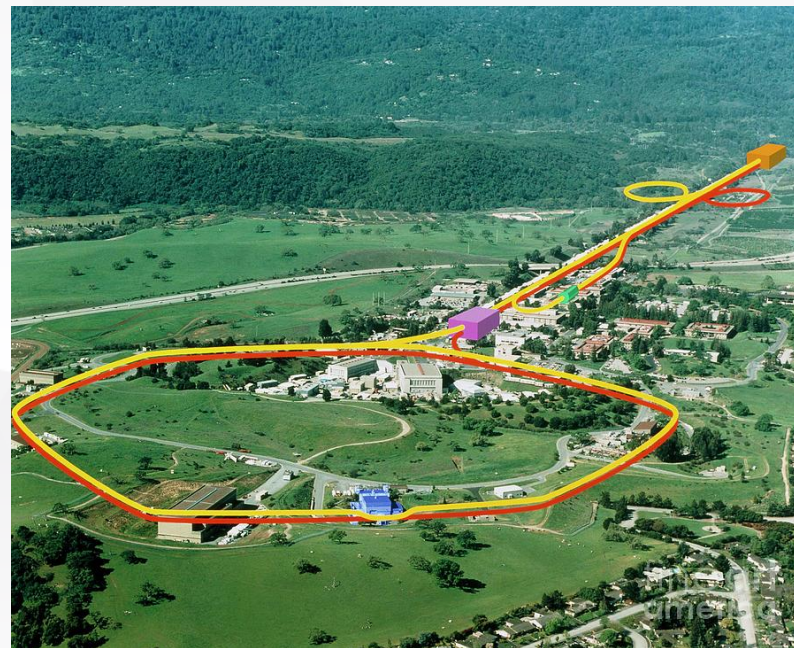


➤ 未来高能物理研究对大型对撞机的需求

- ❖ 在Higgs粒子被发现的基础上，需要轻子对撞机已提高对其各项性质的测量精度
- ❖ 未来还需要更高能量强子对撞机以探索未知粒子



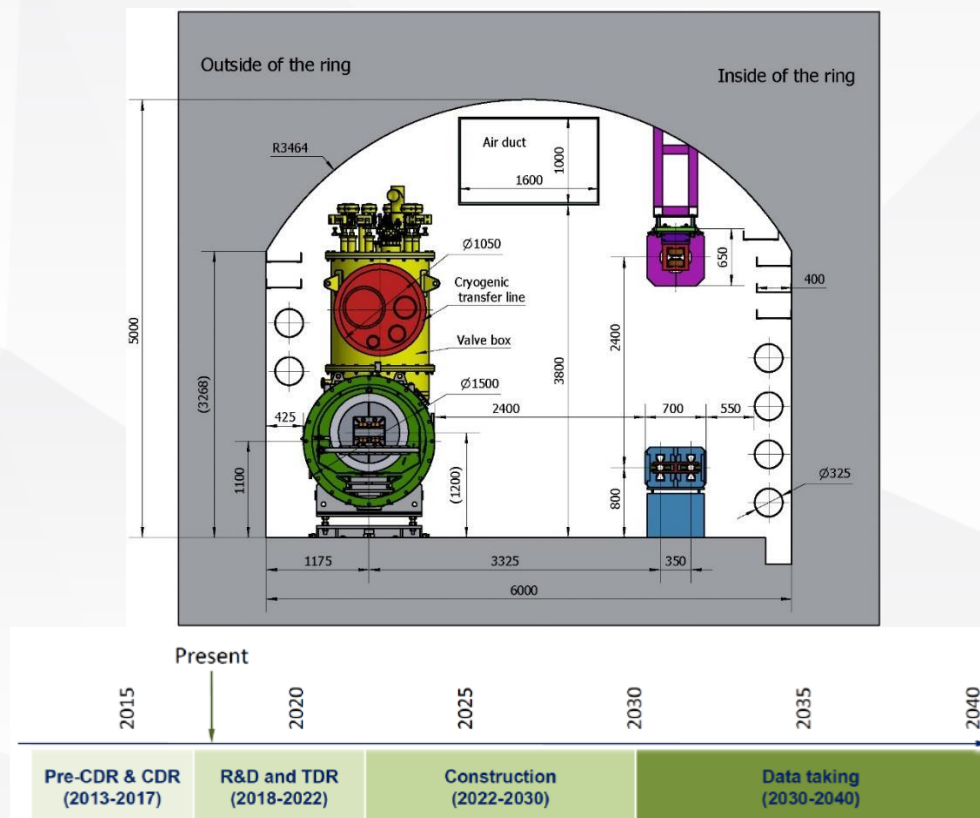
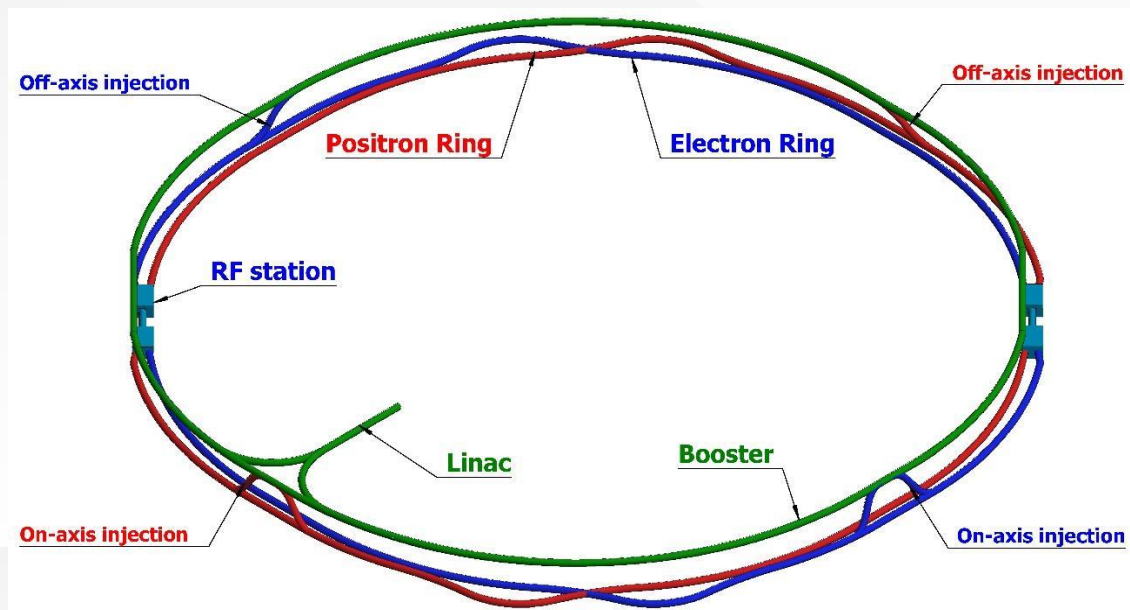
1981年，SPS发现Z粒子



1987-1998年，SLC对Z粒子性质精确测量

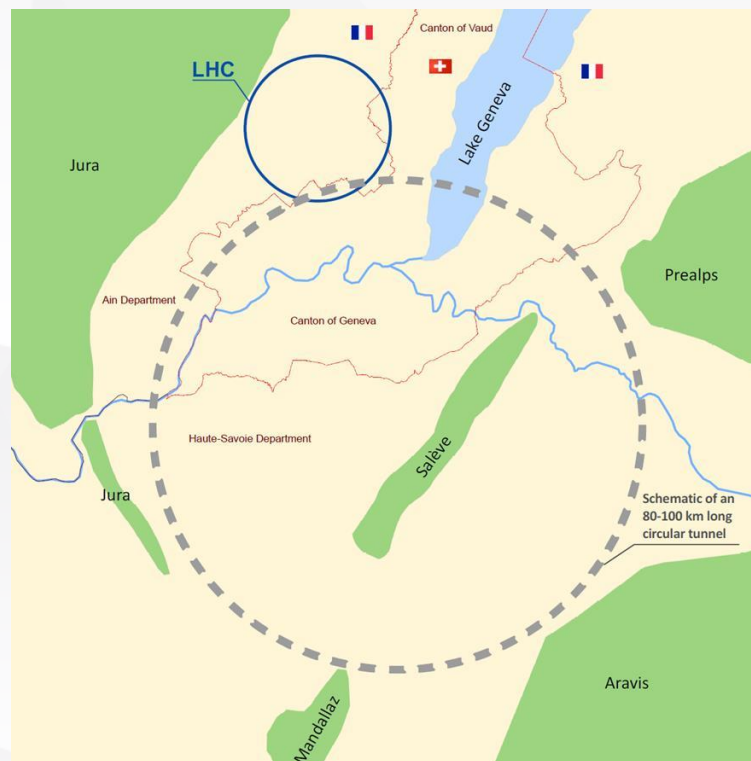
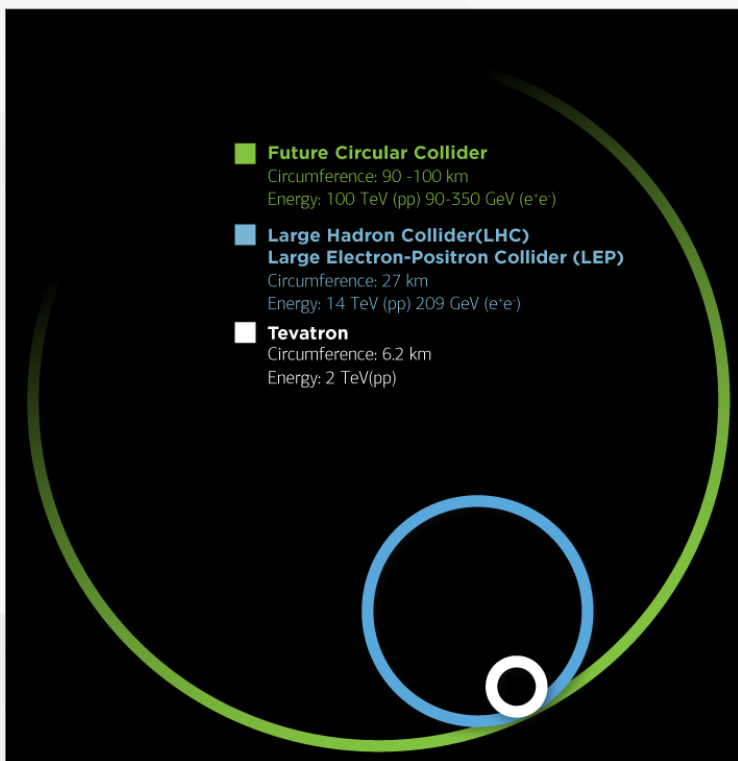
➤ 高能环形对撞机

- ❖ 由我国高能所主导的同步加速器对撞机Circular Electron Positron Collider (CEPC) 项目
- ❖ 周长100 km, 最大对撞能量240 GeV
- ❖ 后续可建设为Super Proton Proton Collider (SPPC), 对撞能量75-125 TeV



➤ 高能环形对撞机

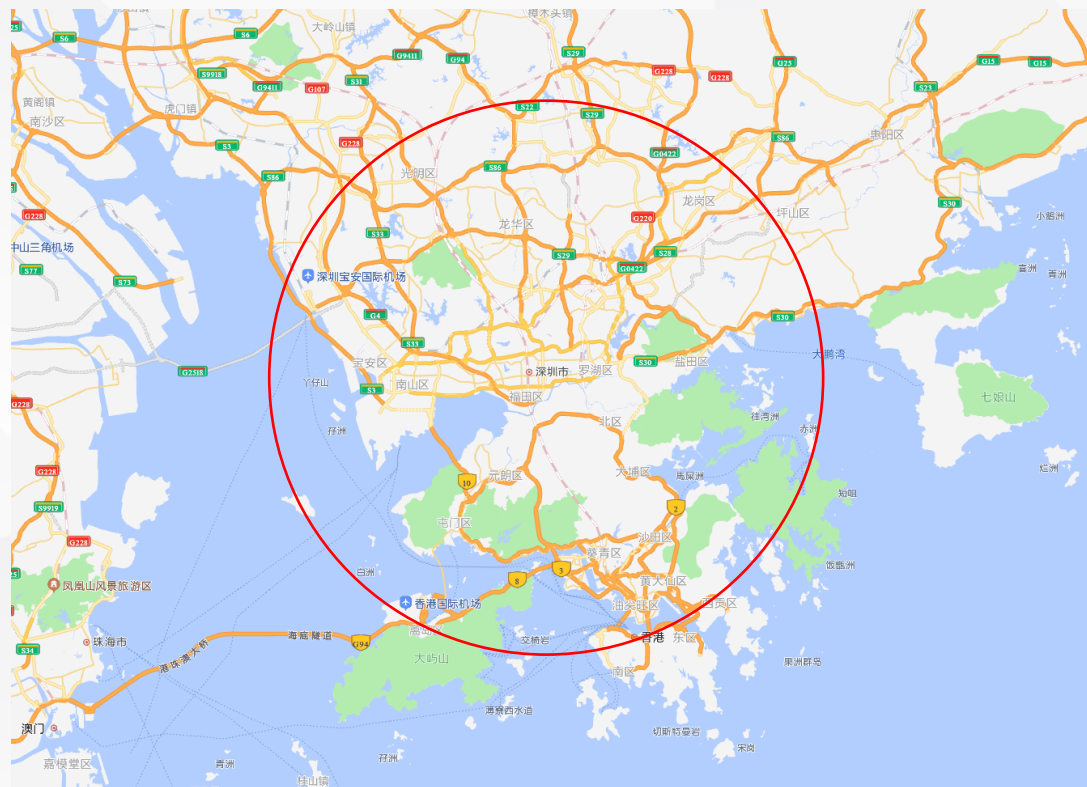
- ❖ 由CERN主导的同步加速器对撞机Future Circular Collider (FCC) 项目
- ❖ 周长100 km
- ❖ 分为轻子对撞机FCC-ee与强子对撞机FCC-hh两步



➤ 高能环形对撞机

- ❖ 由CERN主导的同步加速器对撞机Future Circular Collider (FCC) 项目
- ❖ 周长100 km
- ❖ 分为轻子对撞机FCC-ee与强子对撞机FCC-hh两步

$$U_\gamma = P_\gamma \frac{2\pi R}{\beta c} = \frac{ec}{3\epsilon_0} \left(\frac{E}{m_0 c^2} \right)^4 \frac{\beta^3}{R}$$

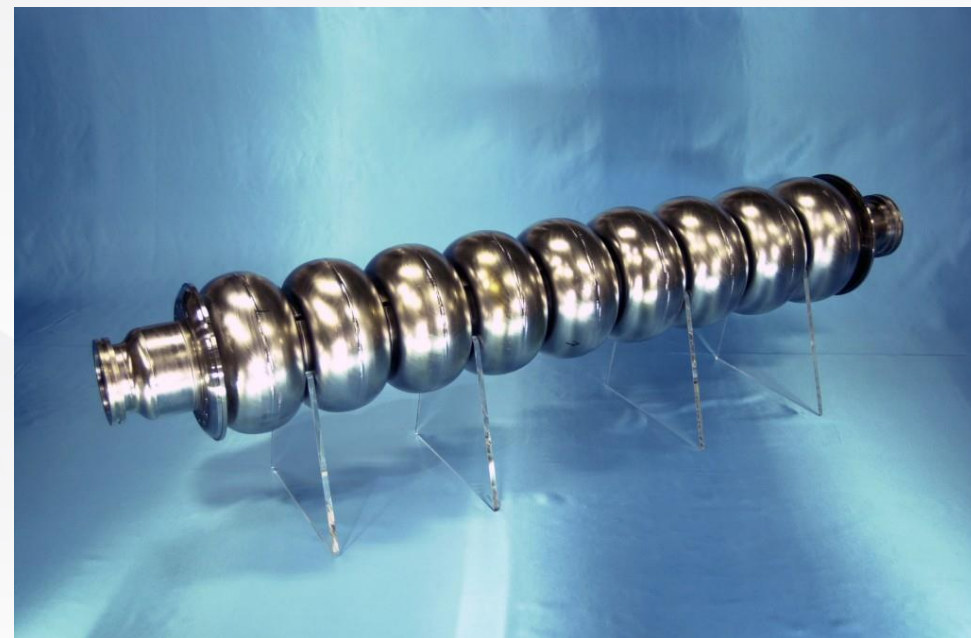
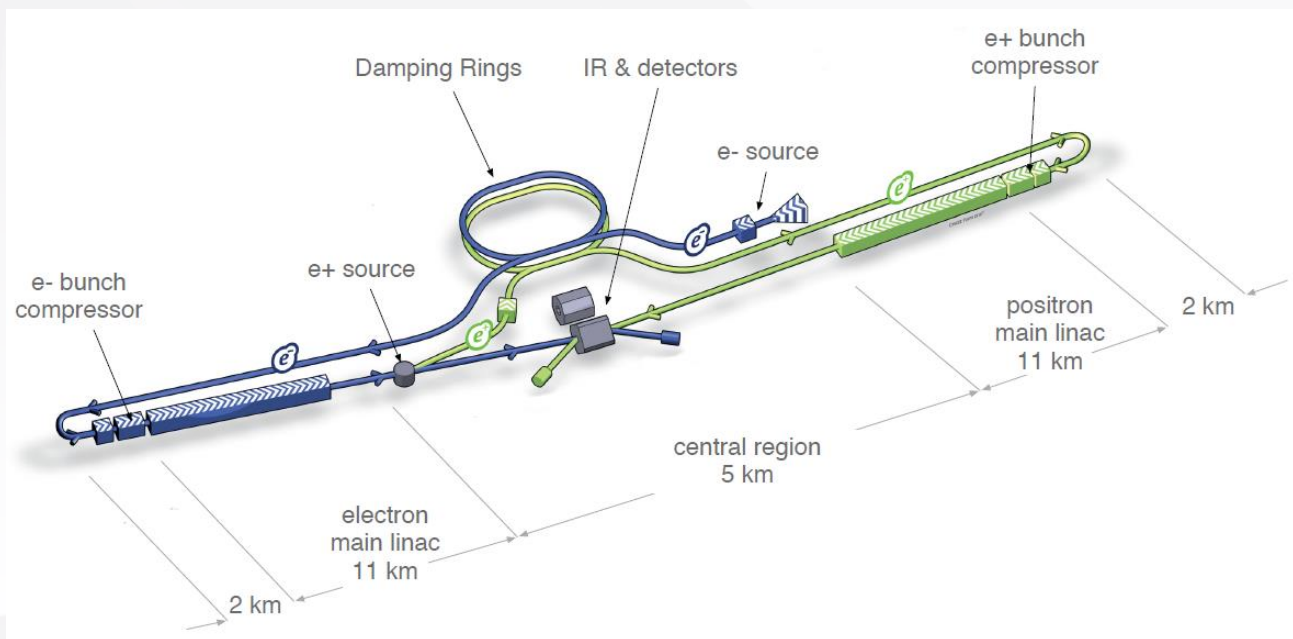


深圳至香港直线距离约30 km



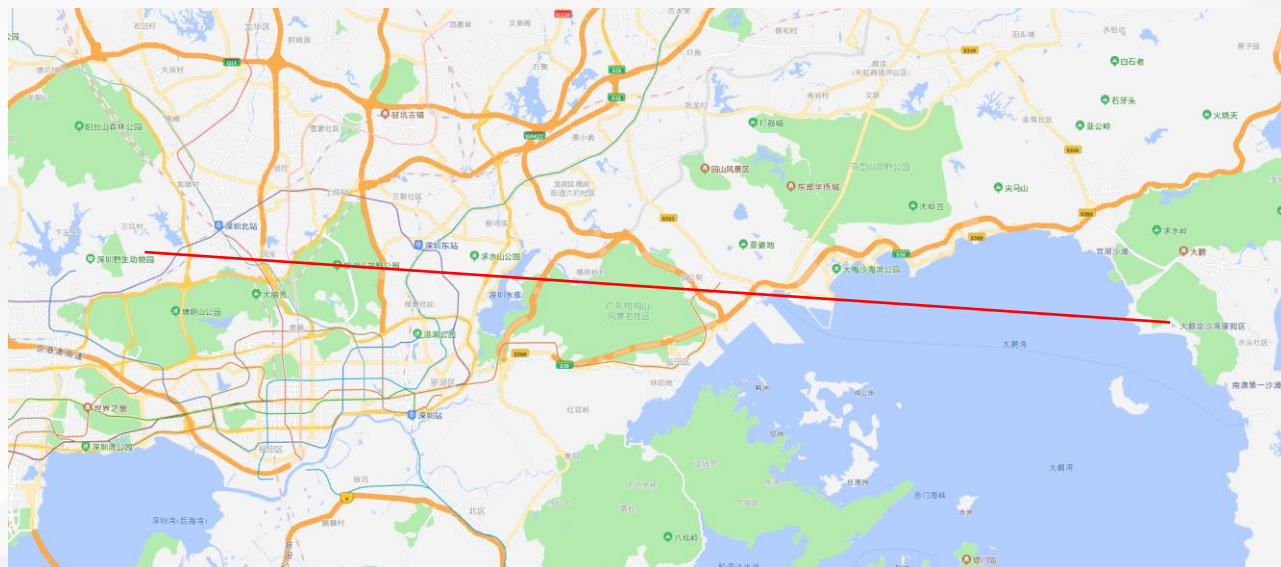
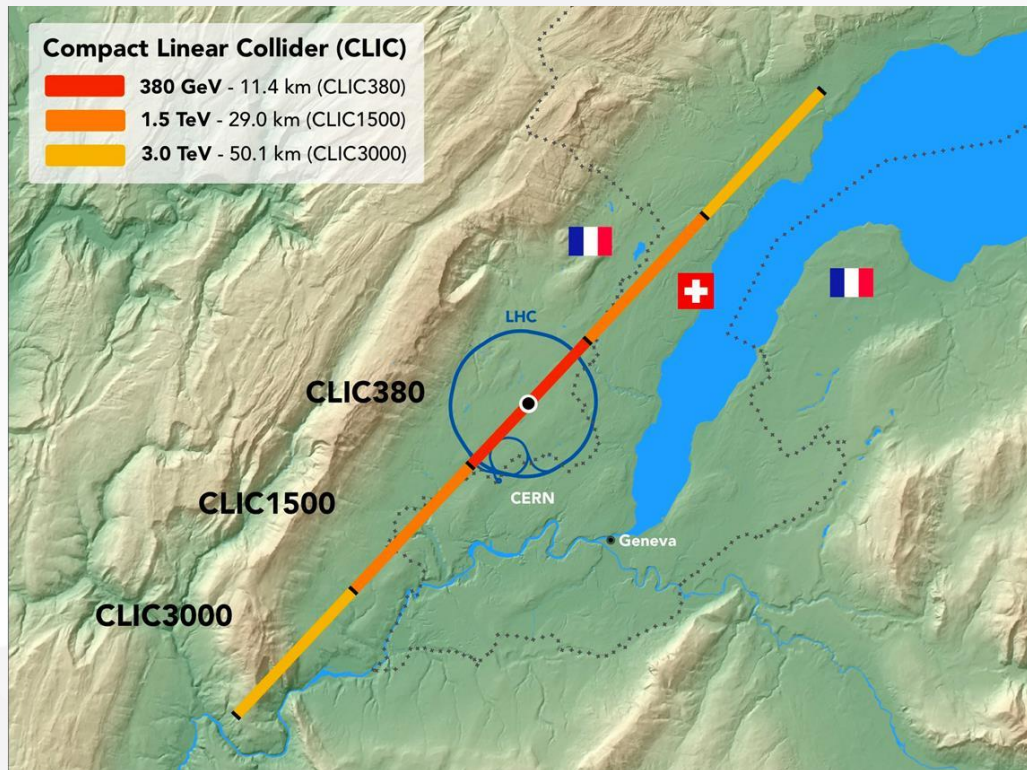
➤ 高能直线对撞机

- ❖ 由多国合作推进的直线对撞机International Linear Collider (ILC) 项目
- ❖ 全长31 km，最大对撞能量1 TeV
- ❖ 采用超导加速结构，加速梯度~31 MV/m



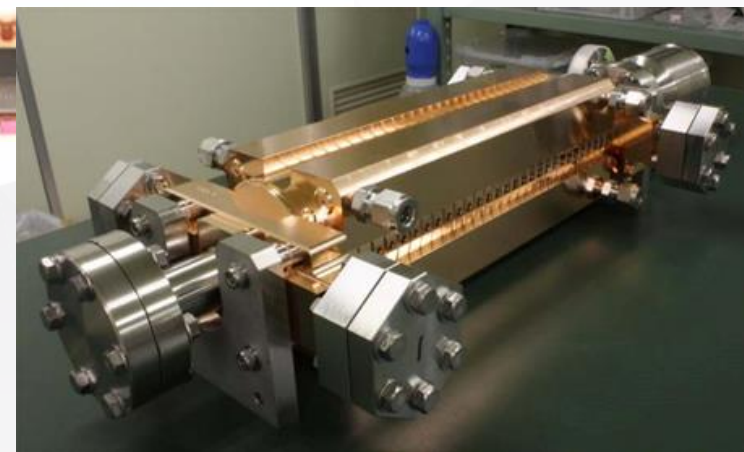
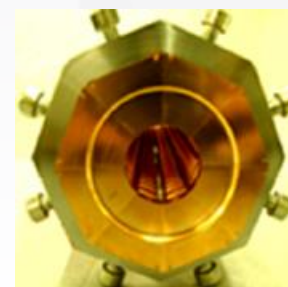
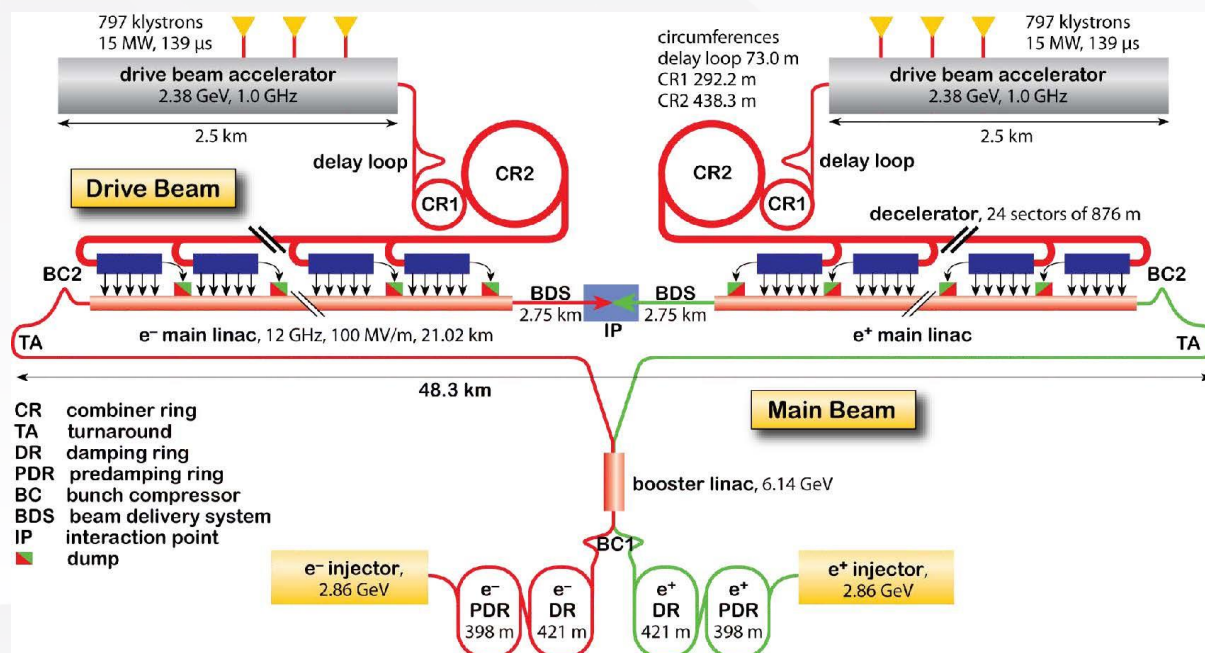
➤ 高能直线对撞机

- ❖ 由CERN主导的直线对撞机Compact Linear Collider (CLIC) 项目
- ❖ 全长48 km，最大对撞能量3 TeV
- ❖ 采用X波段高梯度常温加速结构，加速梯度~100 MV/m



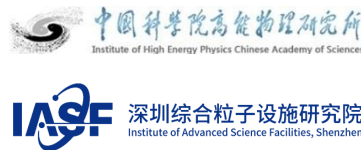
➤ 高能直线对撞机

- ❖ 由CERN主导的直线对撞机Compact Linear Collider (CLIC) 项目
- ❖ 全长48 km，最大对撞能量3 TeV
- ❖ 采用X波段高梯度常温加速结构，加速梯度~100 MV/m





中山大學
SUN YAT-SEN UNIVERSITY



中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences
IASF 深圳综合粒子设施研究院
Institute of Advanced Science Facilities, Shenzhen



先进光源

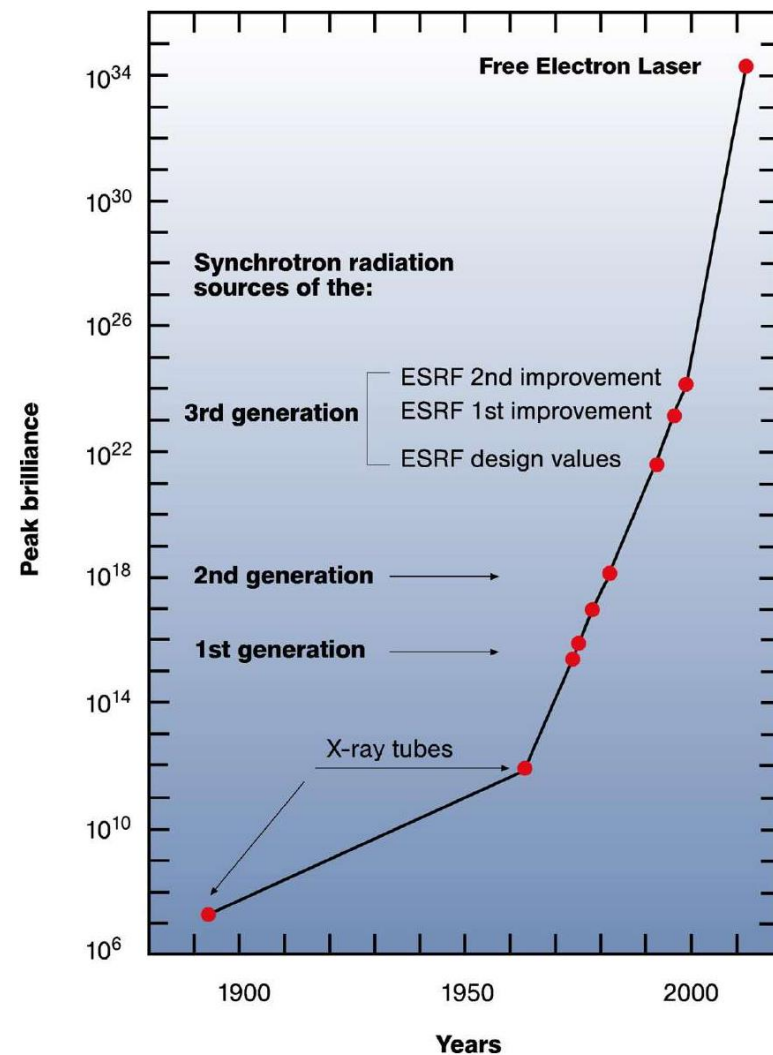
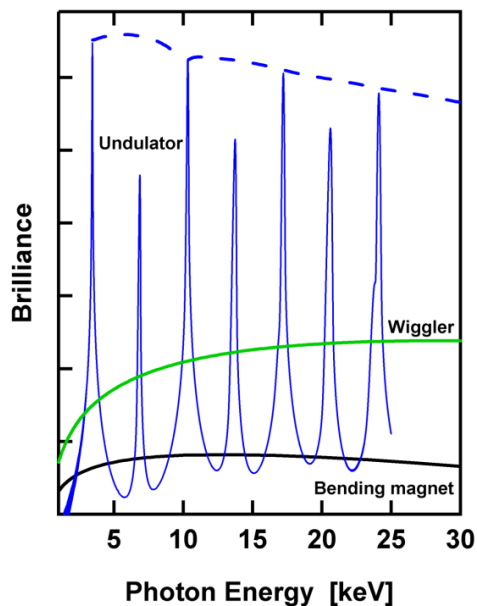
➤ 衍射极限环

❖ 同步辐射光源的亮度

$$B = \frac{N_\gamma}{4\pi^2(\Delta\lambda/\lambda)\Delta t\Sigma_x\Sigma_{x'}\Sigma_y\Sigma_{y'}}$$

❖ 第三代同步辐射光源

- 专用、优化的储存环，采用插入设备（扭摆磁铁和波荡器）产生辐射



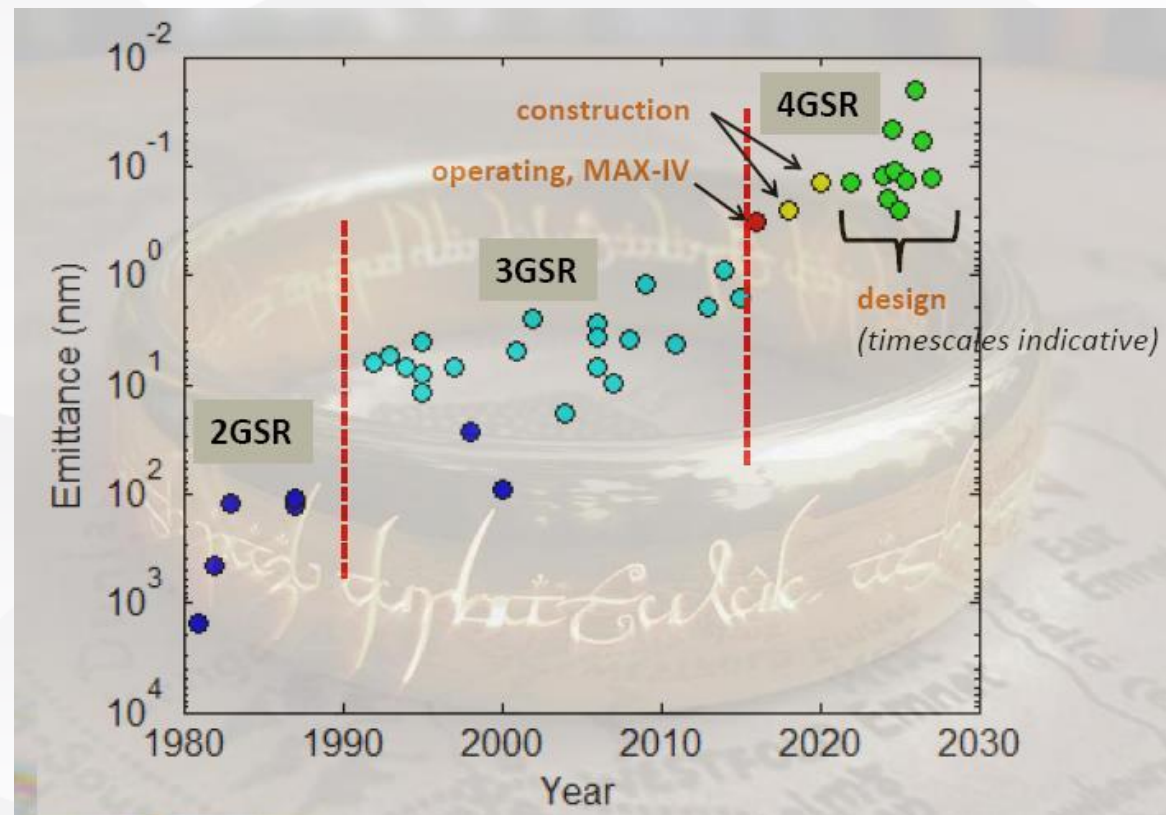
➤ 衍射极限环

❖ 同步辐射光源的亮度

$$B = \frac{N_\gamma}{4\pi^2(\Delta\lambda/\lambda)\Delta t\Sigma_x\Sigma_{x'}\Sigma_y\Sigma_{y'}}$$

❖ 第四代同步辐射光源 – 衍射极限环

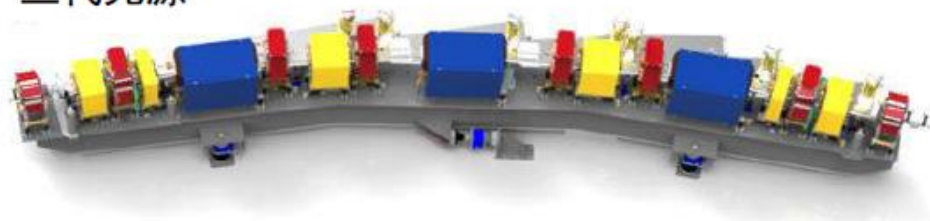
- 通过大幅降低束团横向发射度提高亮度
- 横向发射度接近或达到衍射极限 $\varepsilon_r = \frac{\lambda}{4\pi}$, 较第三代光源低1-2个量级



➤ 衍射极限环

❖ 主要依靠多弯铁消色散结构 (Multi Bend Achromat, MBA) 降低横向发射度

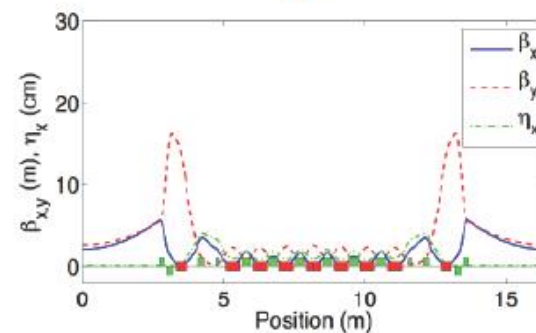
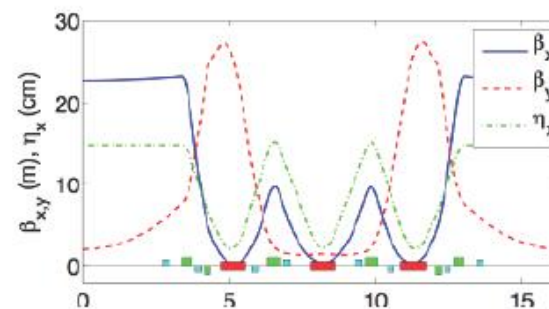
三代光源



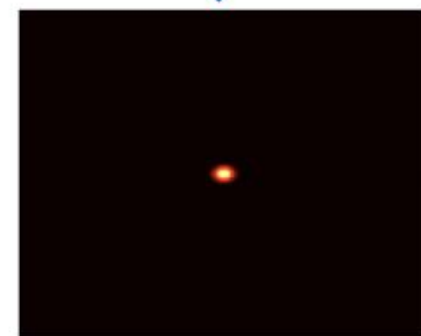
四代光源



元件布局



磁聚焦结构束流光学

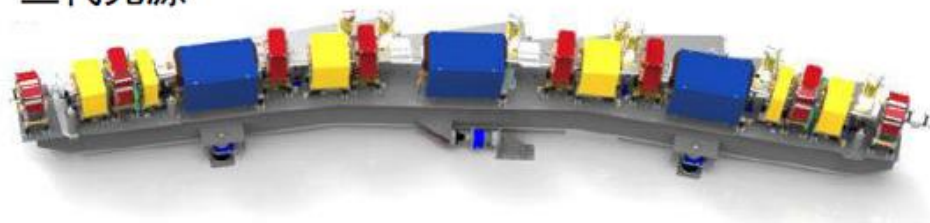


1 mm
束斑截面

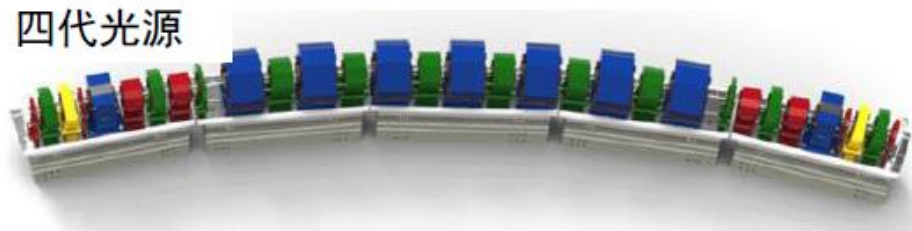
➤ 衍射极限环

❖ 主要依靠多弯铁消色散结构 (Multi Bend Achromat, MBA) 降低横向发射度

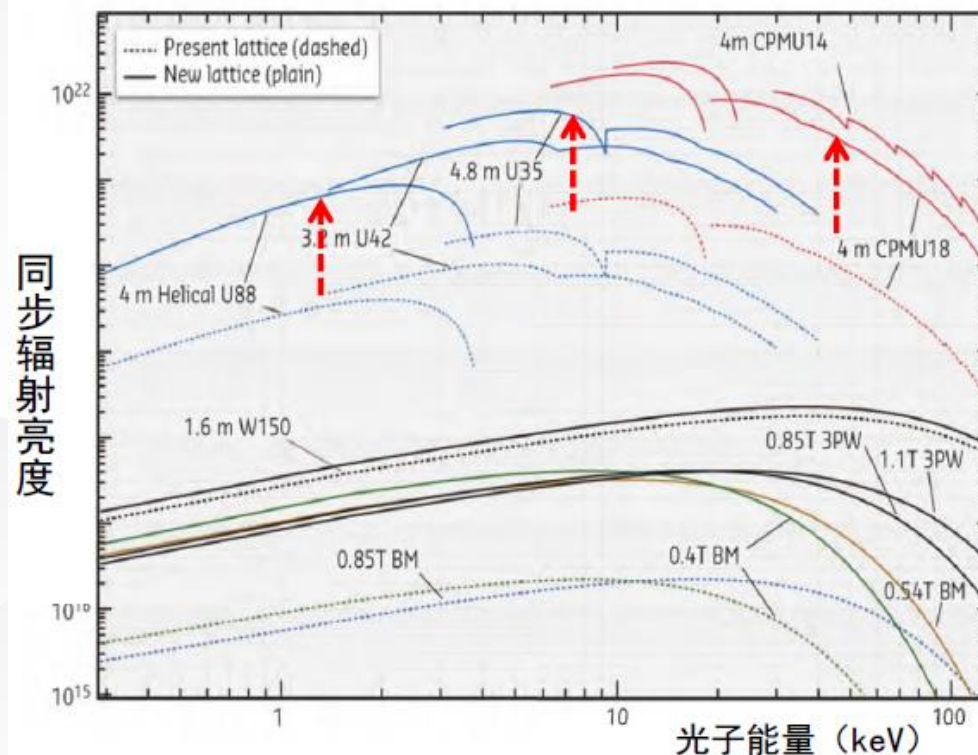
三代光源



四代光源



元件布局

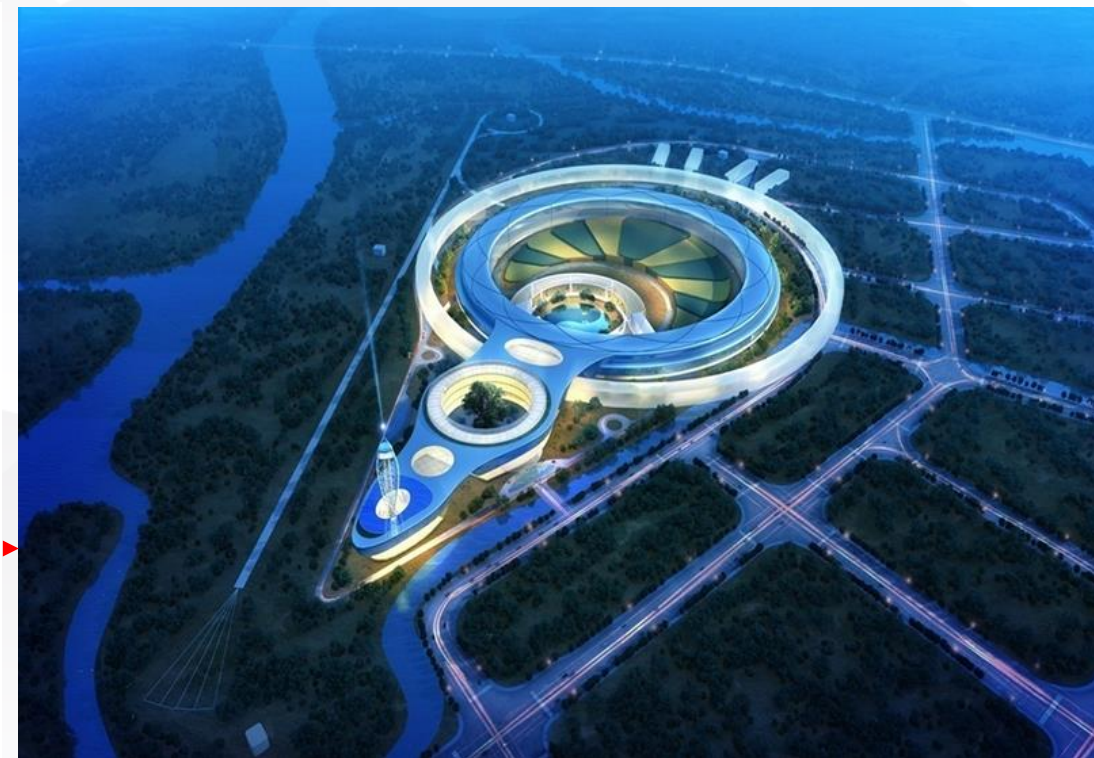
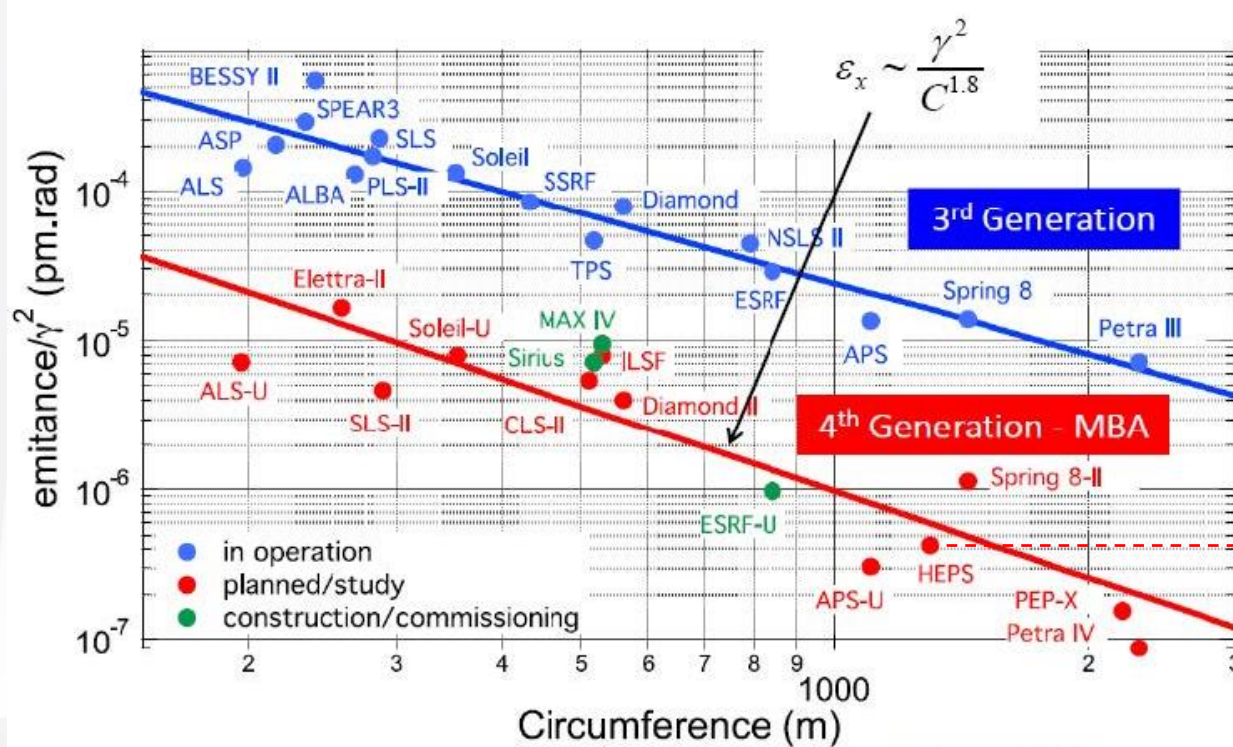


欧洲ESRF光源亮度曲线

虚线：三代水平；实线：升级之后

➤ 衍射极限环

❖ 世界各国正积极设计、建造衍射极限光源

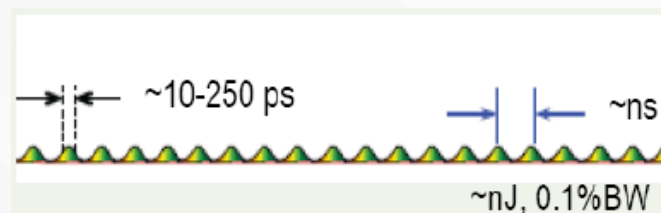


北京高能同步辐射光源，能量6 GeV，横向发射度59 pm

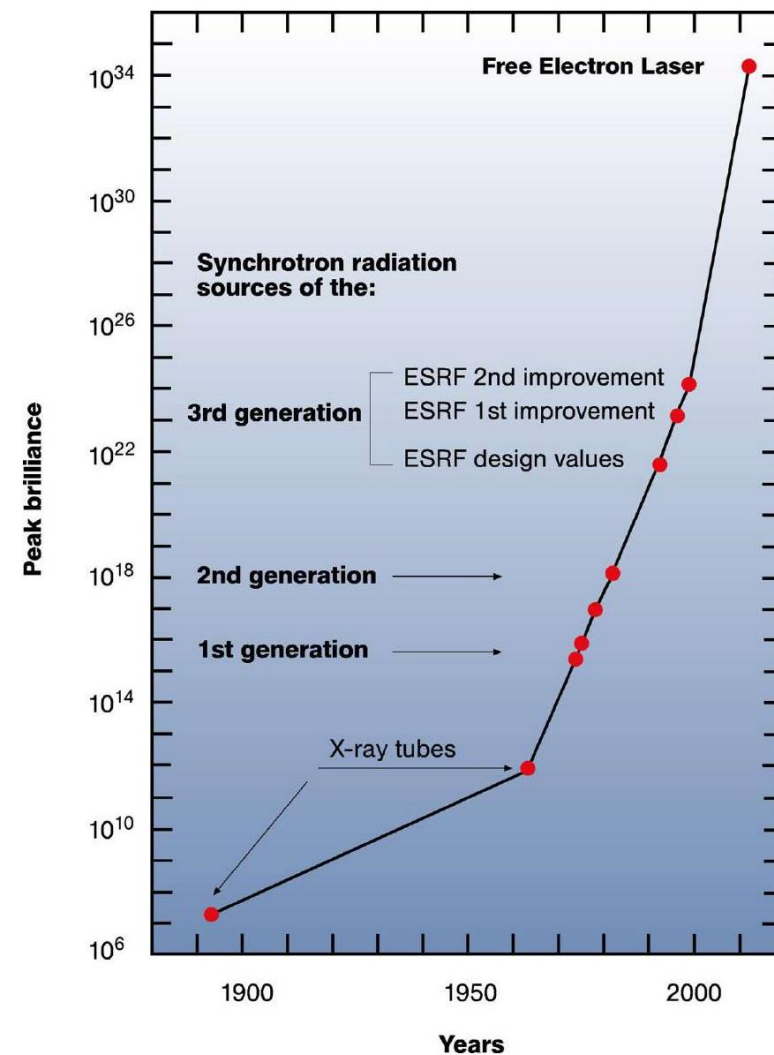
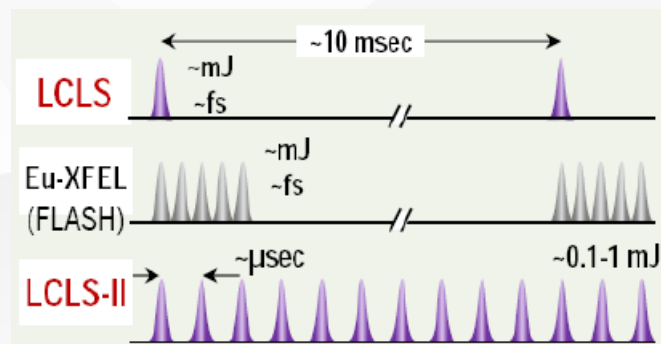
➤ 高重复频率自由电子激光

- ❖ 同步辐射光源重复频率可达数百MHz
- ❖ 受限于常温加速结构，自由电子激光重复频率仅为100 Hz左右，严重限制了其平均亮度
- ❖ 使用超导加速结构，可将自由电子激光重复提升至1 MHz

同步辐射

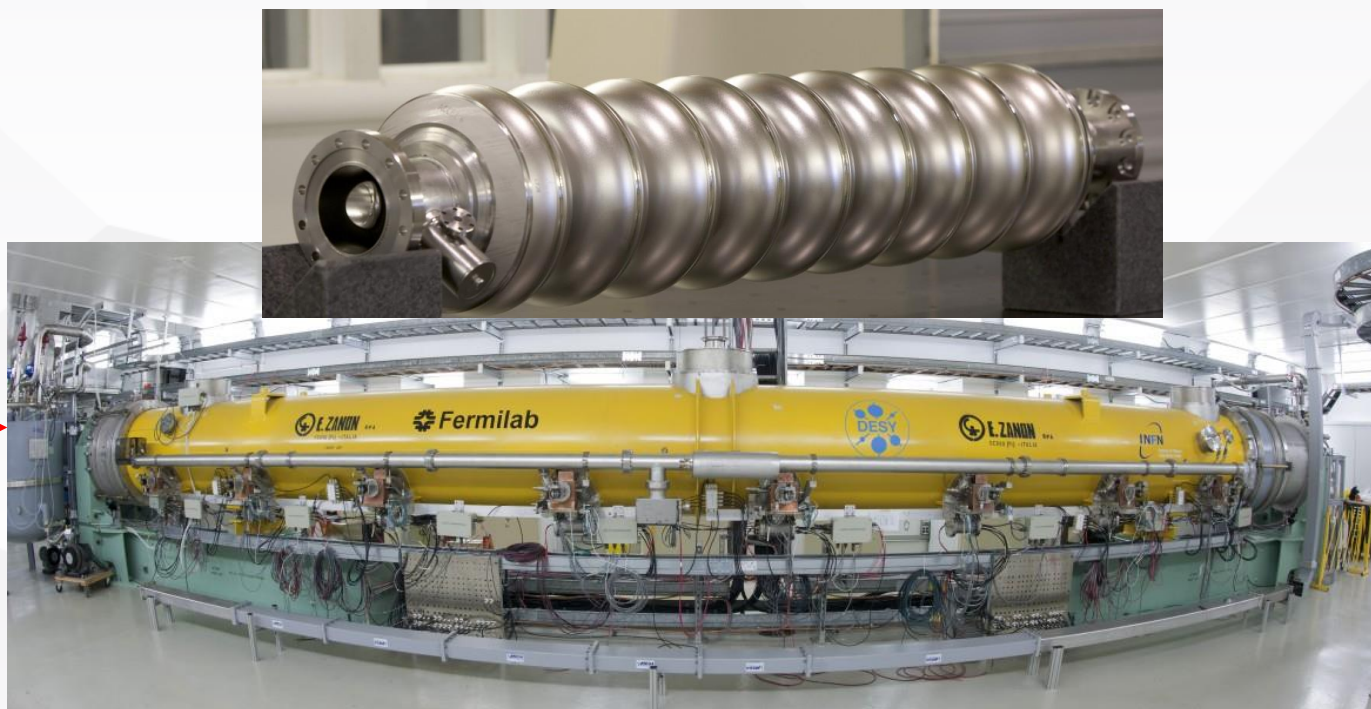
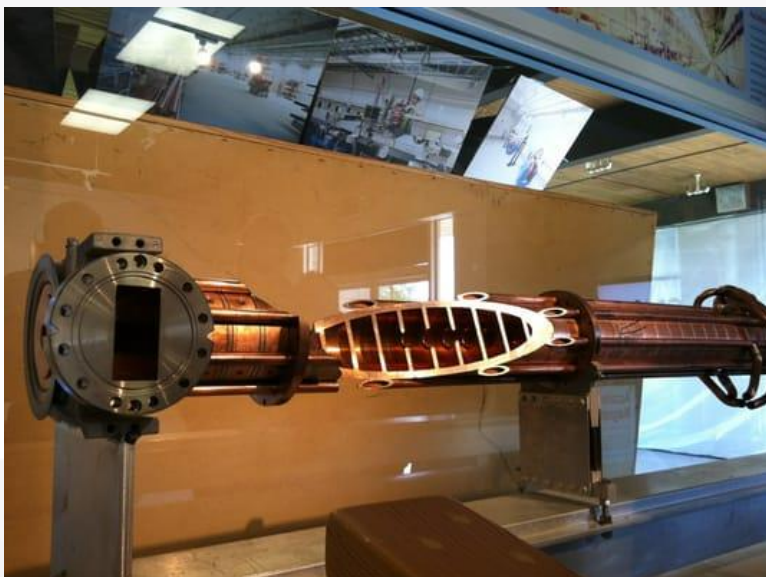


自由电子激光



➤ 高重复频率自由电子激光

- ❖ 同步辐射光源重复频率可达数百MHz
- ❖ 受限于常温加速结构，自由电子激光重复频率仅为100 Hz左右，严重限制了其平均亮度
- ❖ 使用超导加速结构，可将自由电子激光重复提升至1 MHz



➤ 高重复频率自由电子激光

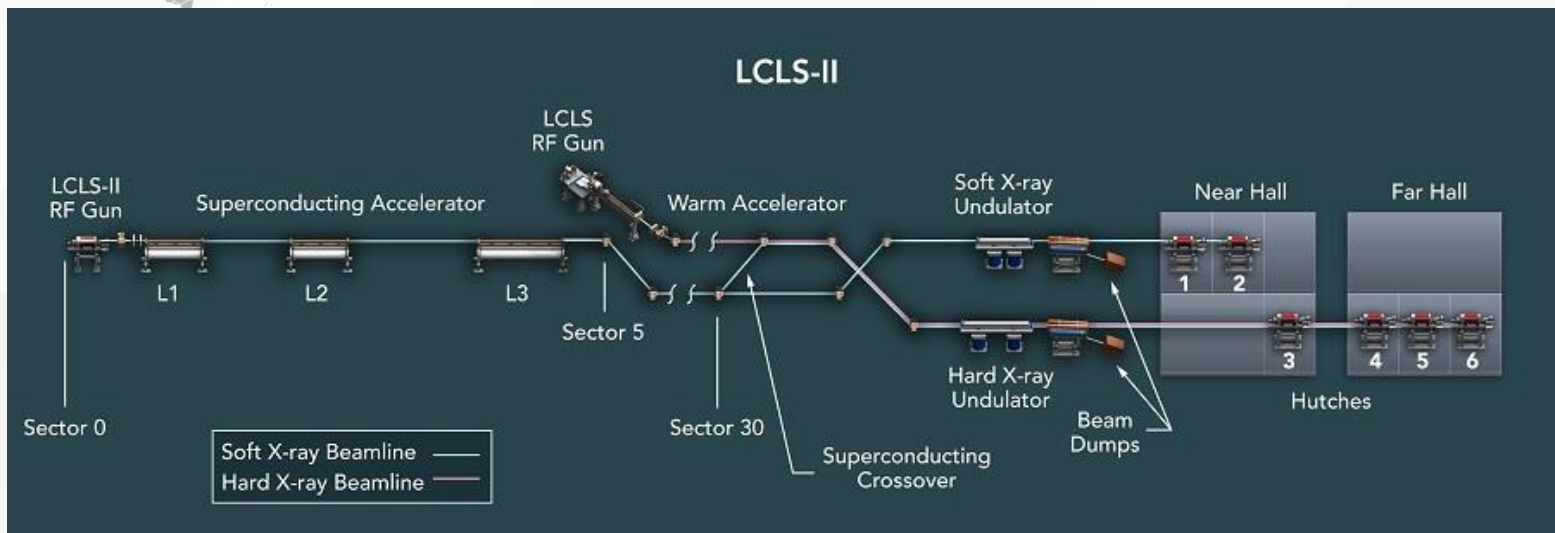
❖ 世界各国同样正积极设计、建造高重复频率自由电子激光



May 10, 2022

SLAC's superconducting X-ray laser reaches operating temperature colder than outer space

The facility, LCLS-II, will soon sharpen our view of how nature works on ultrasmall, ultrafast scales, impacting everything from quantum devices to clean energy.

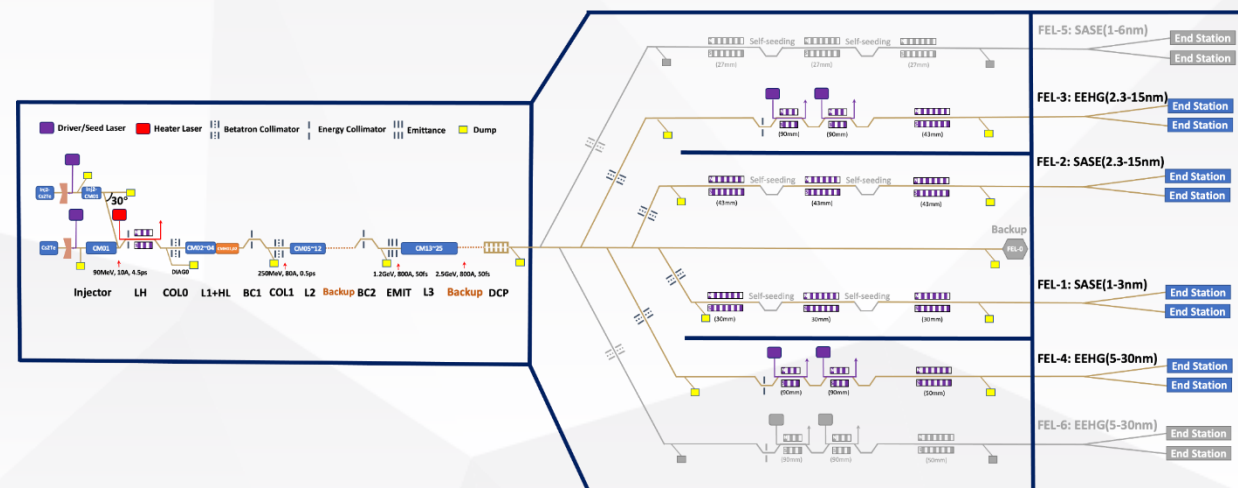


► 高重复频率自由电子激光

❖ 世界各国同样正积极设计、建造高重复频率自由电子激光



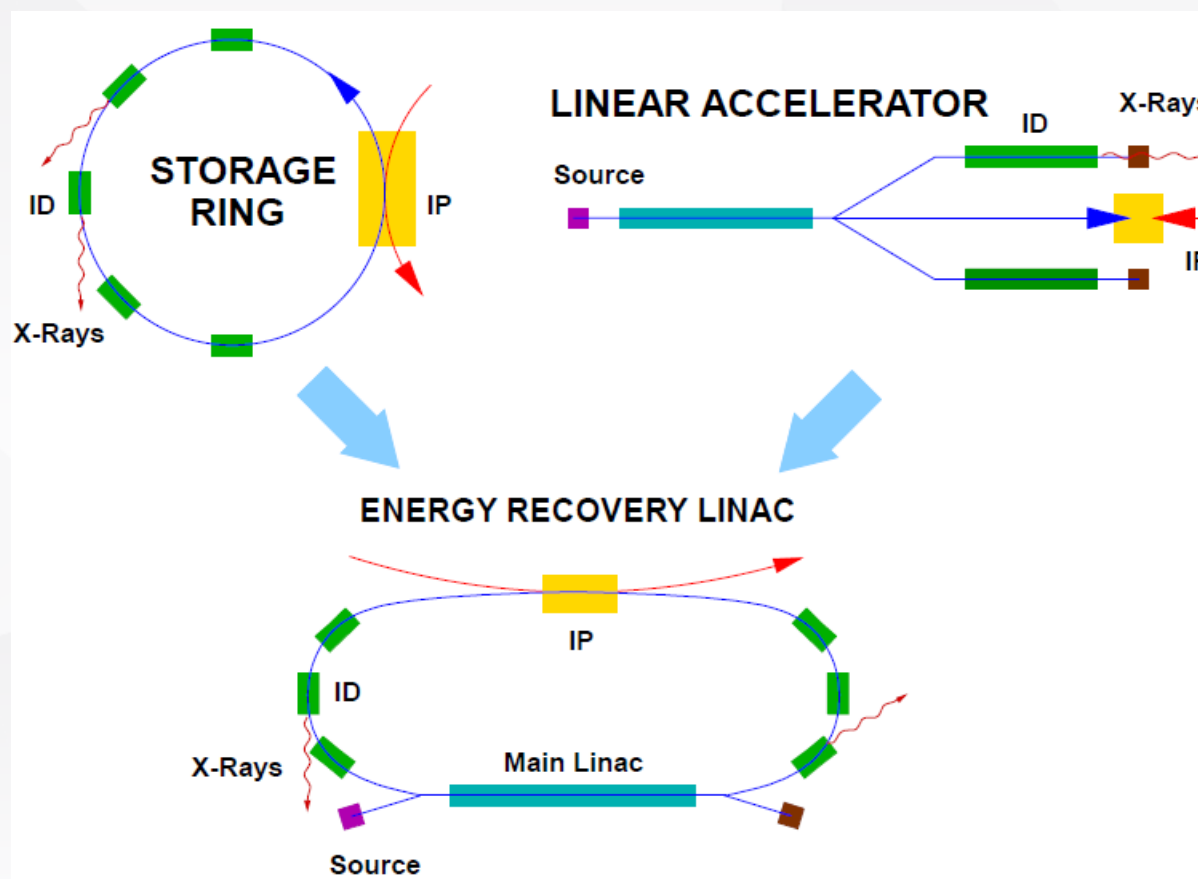
深圳综合粒子设施研究院S³FEL



➤ 其它先进概念

❖ 能量回收加速器 (Energy Recovery Linac, ERL)

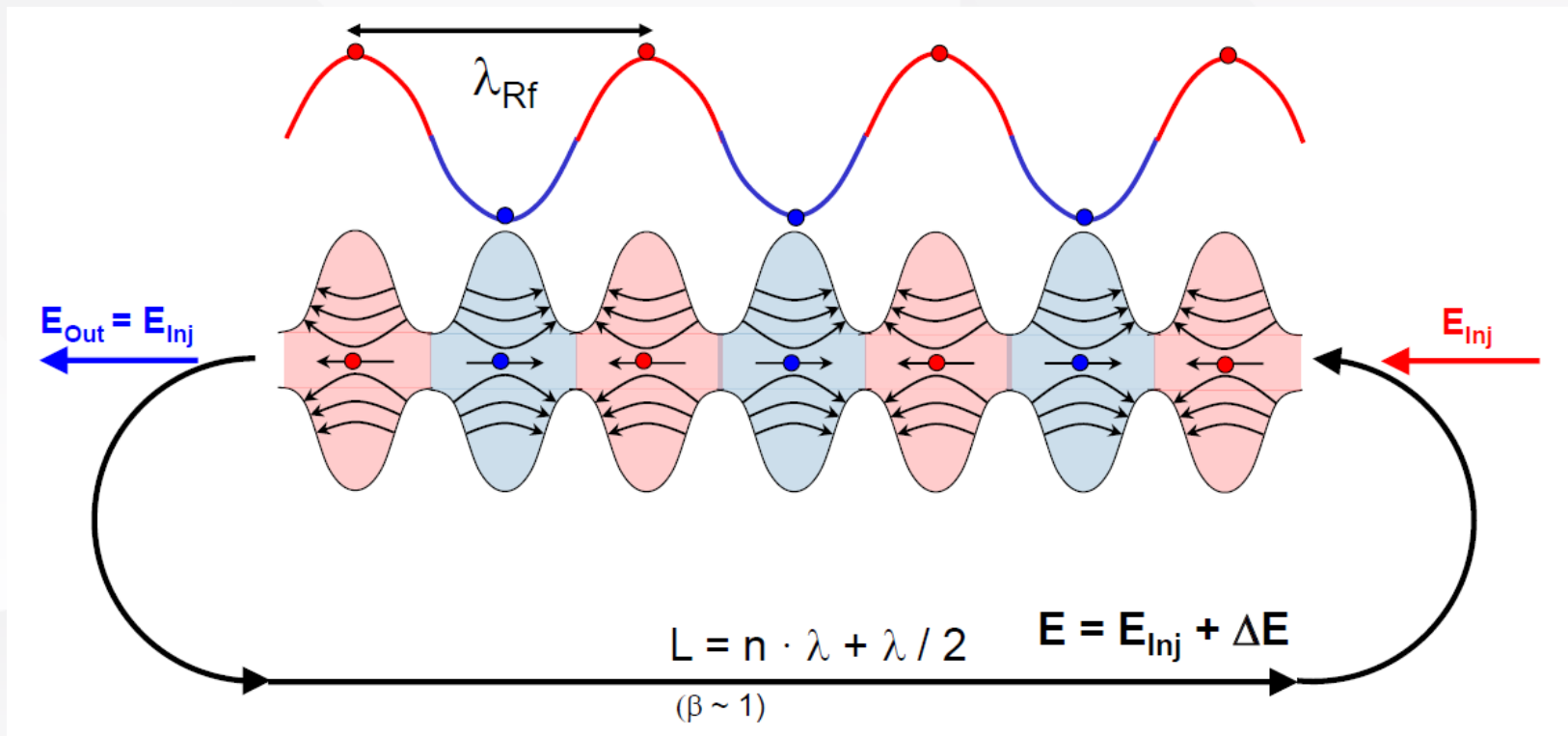
- 结合环形加速器与直线加速器优点, 有望大幅提高光源亮度



➤ 其它先进概念

❖ 能量回收加速器 (Energy Recovery Linac, ERL)

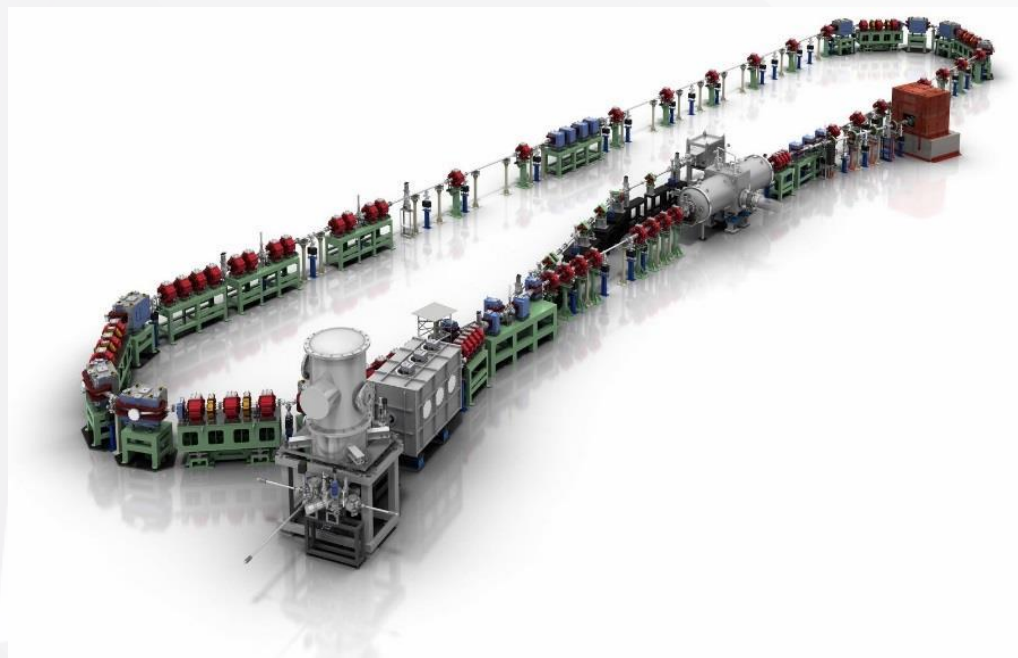
- 束团首先被加速器加速，吸收能量；在下一圈中被加速器减速，释放能量



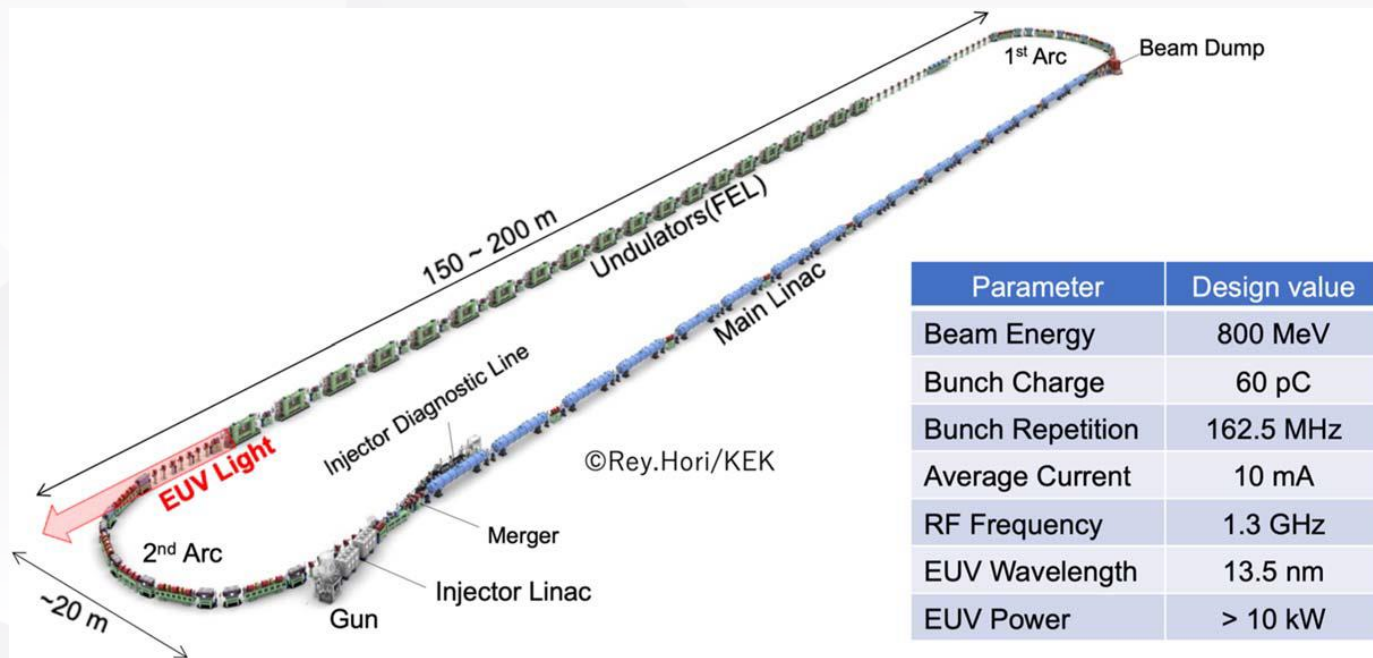
➤ 其它先进概念

❖ 能量回收加速器 (Energy Recovery Linac, ERL)

- 目前高效率能量回收已被实验证实, 正在探索基于ERL方案的光源装置



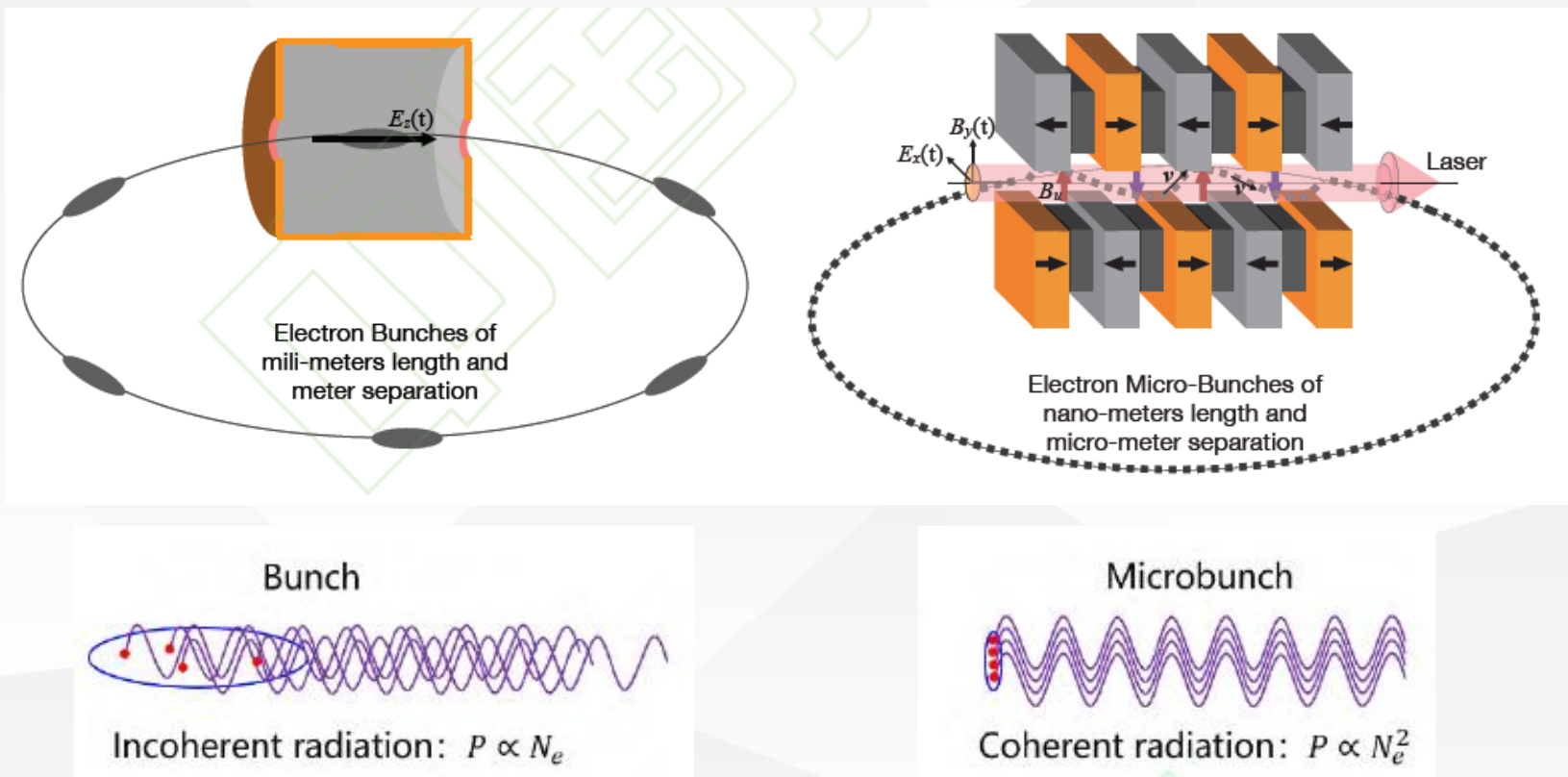
KEK紧凑ERL装置



KEK 800 MeV ERL概念设计

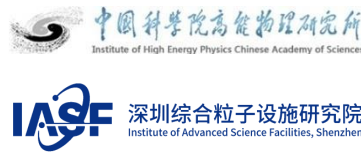
其它先进概念

稳态微聚束加速器 (Steady state micro-bunching, SSMB)





中山大學
SUN YAT-SEN UNIVERSITY

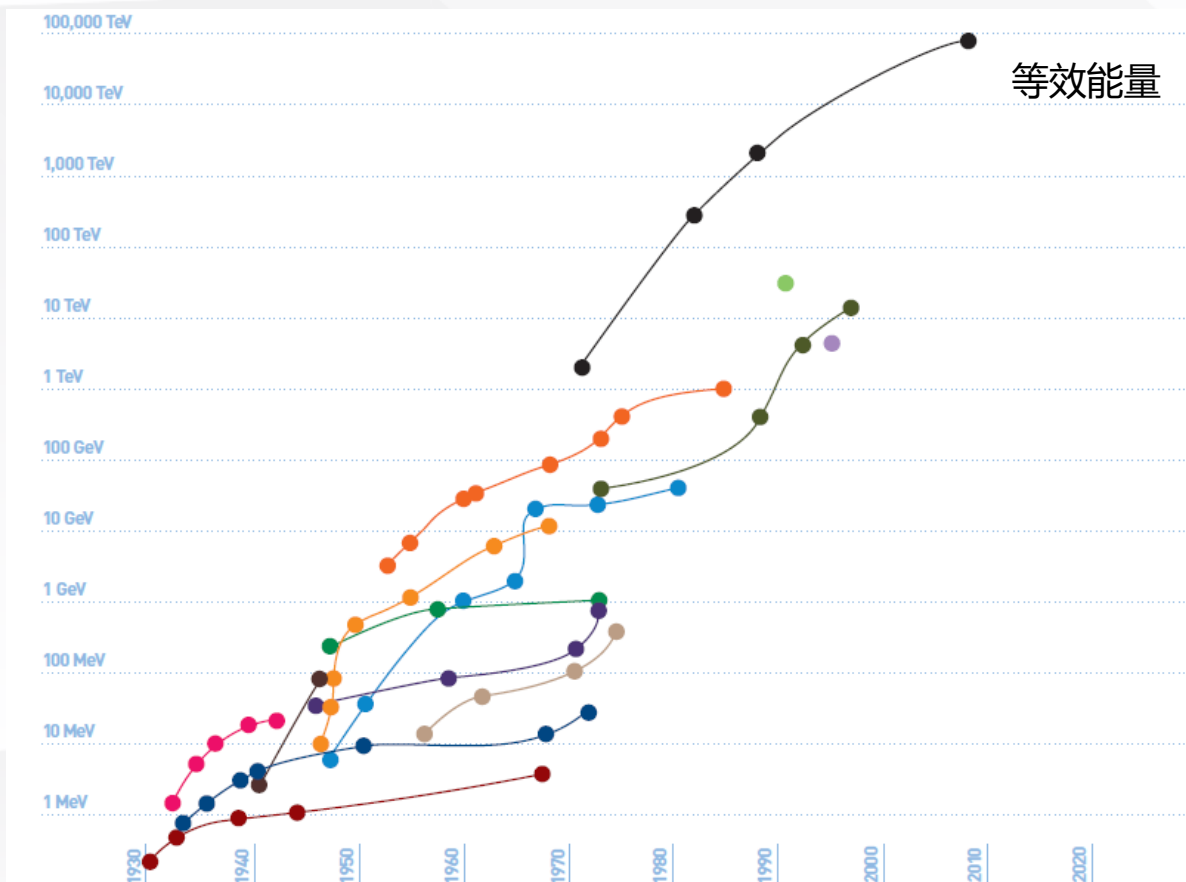


中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences
IASF 深圳综合粒子设施研究院
Institute of Advanced Science Facilities, Shenzhen

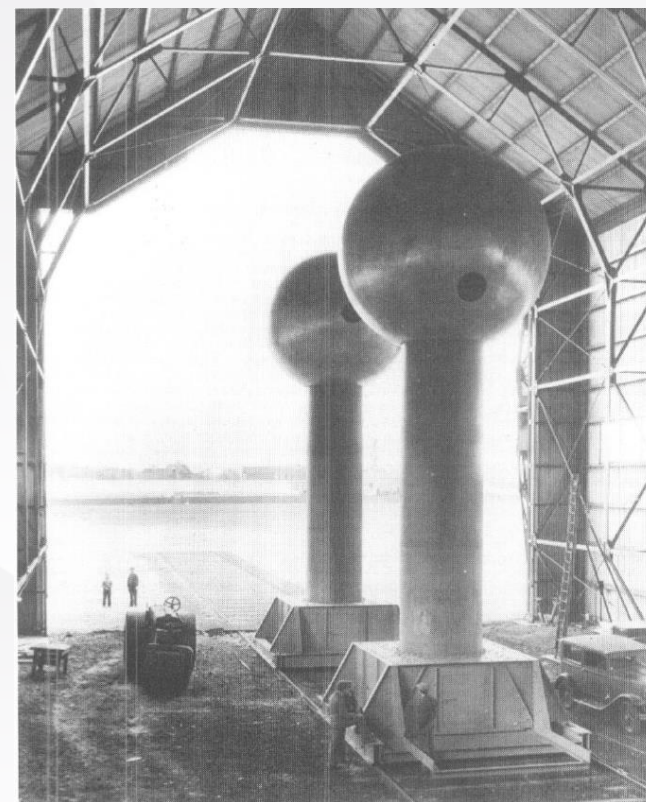


高梯度加速

- 粒子加速器最高能量基本遵循Livingston规律（每六年提高一个量级）
 - ❖ 得益于新原理、新技术的不断发展



Accelerators for America's Future, DOE report (2010)



高压电极直径4.6米，高6.7米，
电压5.1MV（MIT）

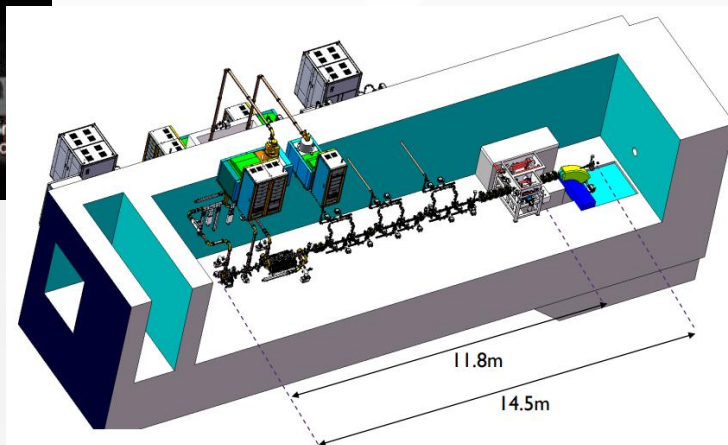
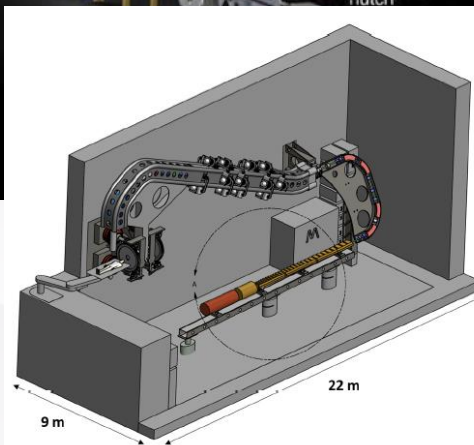
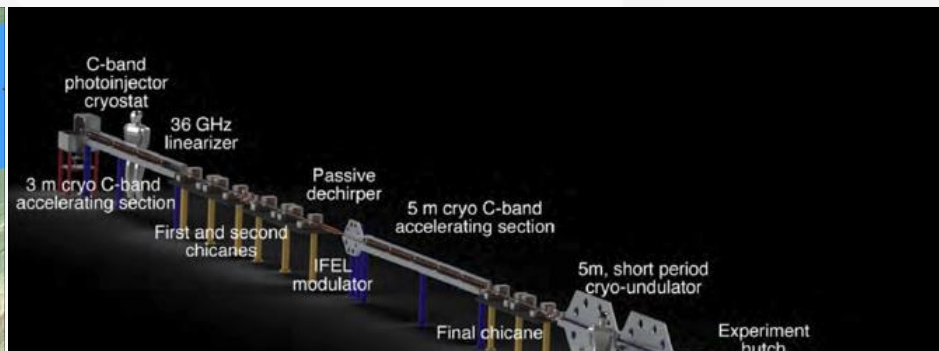
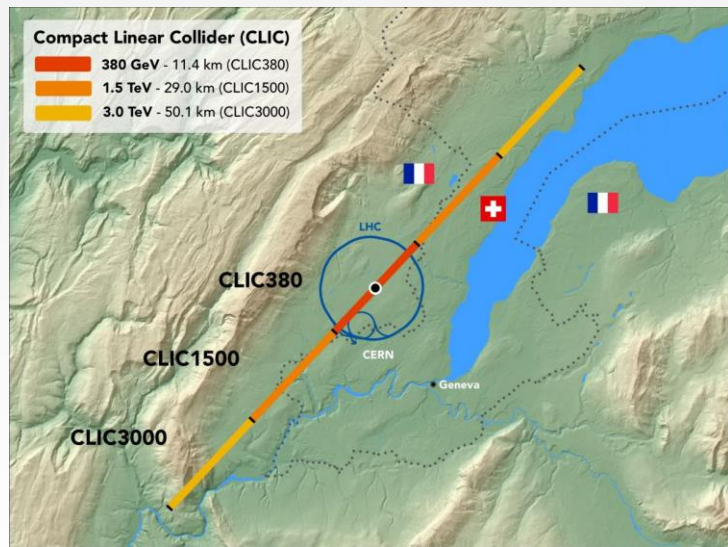


➤ 高梯度加速

❖ 加速梯度是衡量加速器性能的重要概念

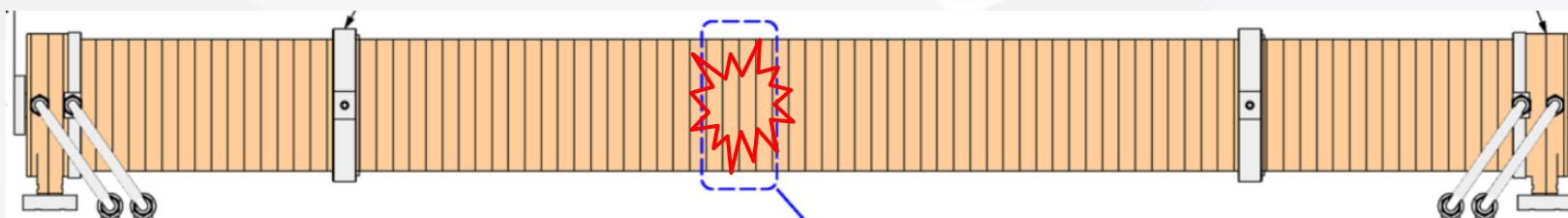
$$G = W/L$$

❖ 未来大型对撞机、紧凑型光源、小型化医疗/工业用加速器的实现迫切需要加速梯度的进一步提高

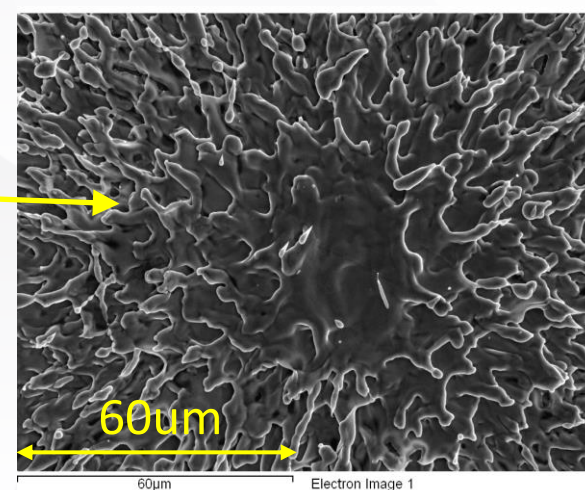
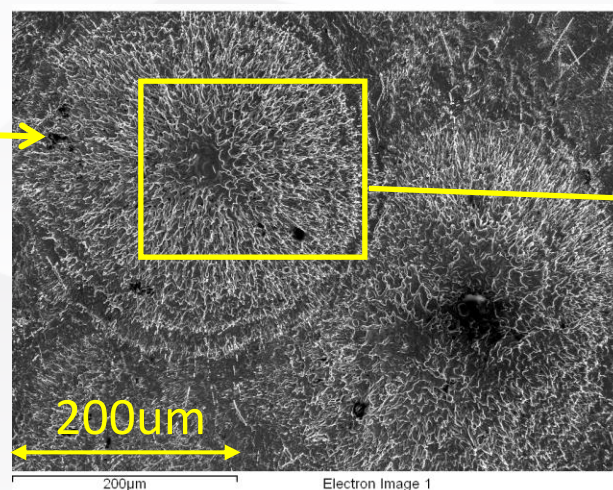
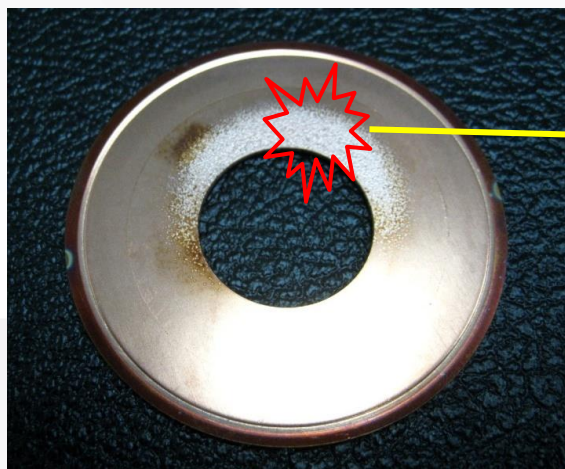


➤ 基于结构的高梯度加速（常温结构）

❖ 在常温结构中，加速梯度主要受限于射频击穿现象（RF breakdown）



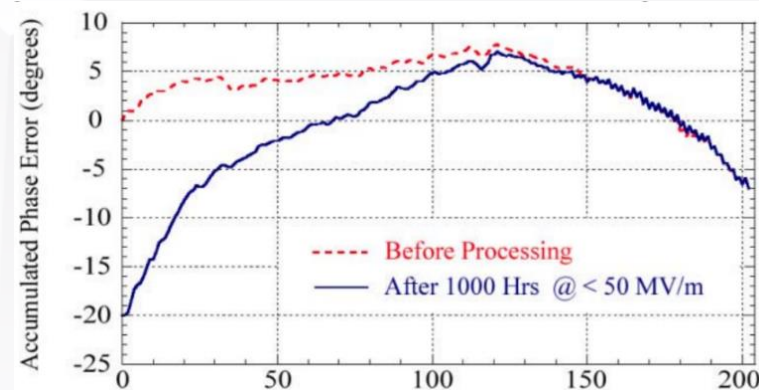
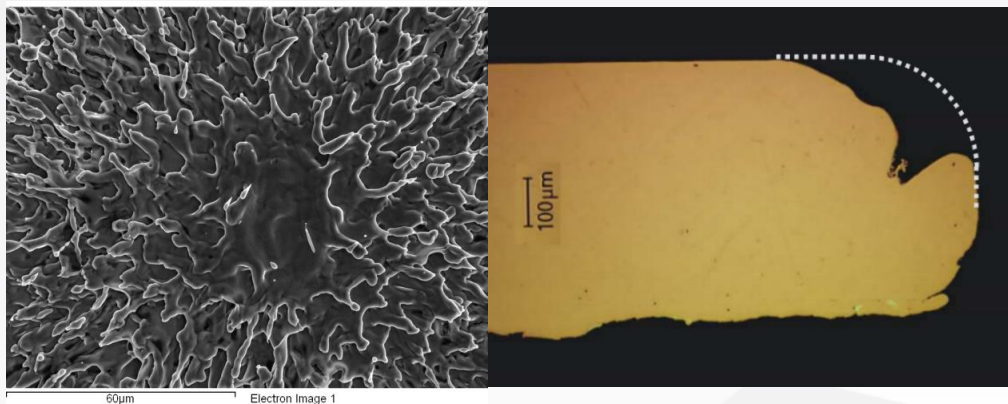
反射功率急剧增大、传输功率急剧降低、暗电流水平迅速提高真空度下降、X射线、发光、发声



➤ 基于结构的高梯度加速（常温结构）

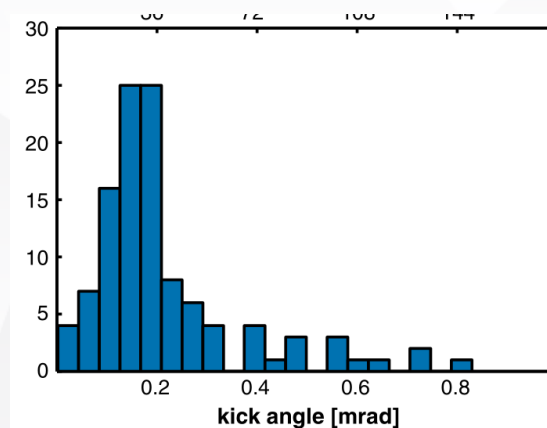
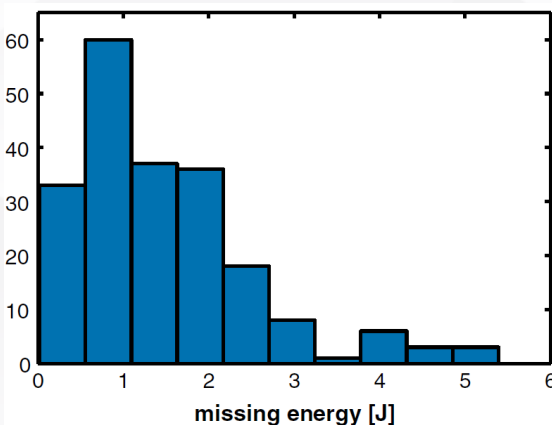
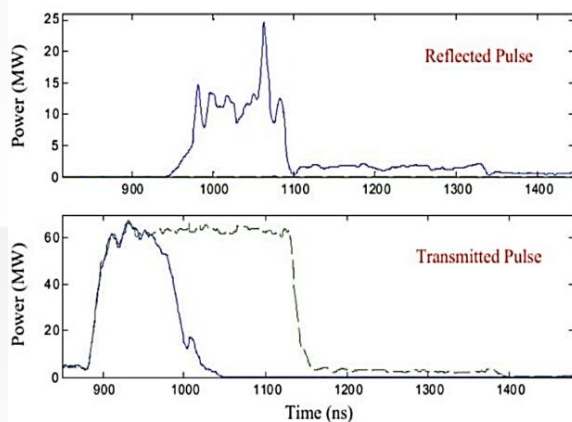
❖ 在常温结构中，主要受限于射频击穿现象（RF breakdown）

损伤结构



改变腔间相移

降低束团能量

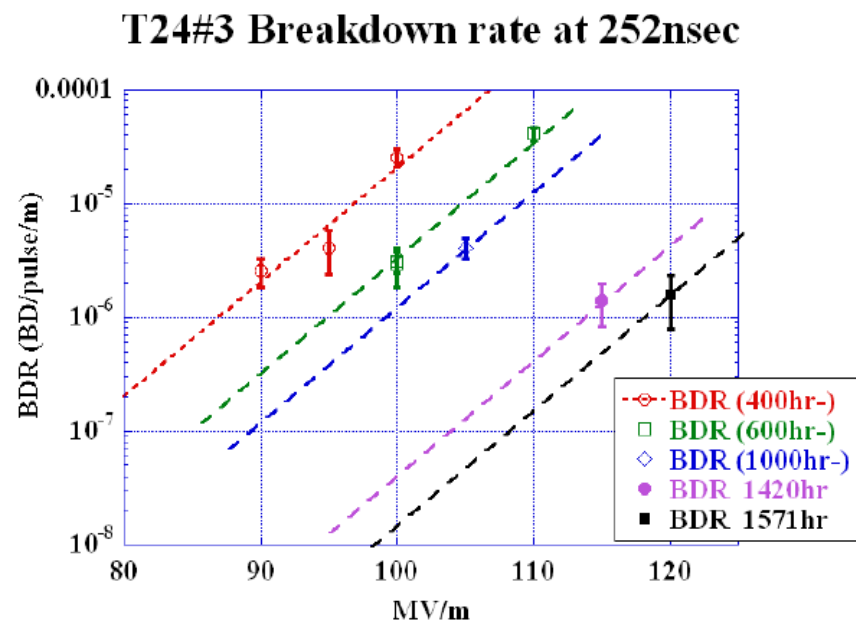
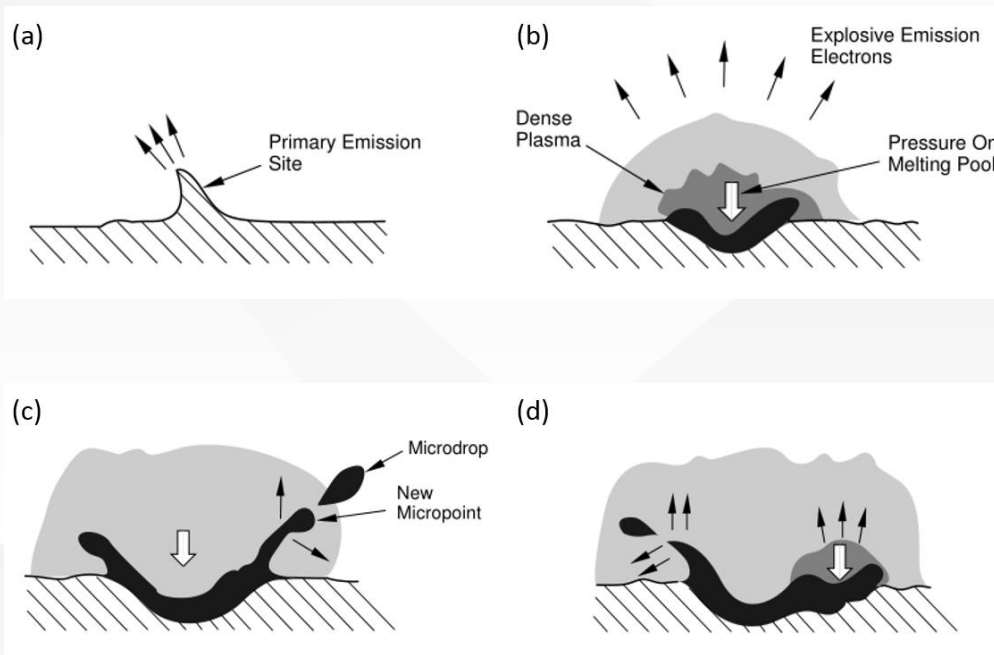


增大束团偏角

➤ 基于结构的高梯度加速（常温结构）

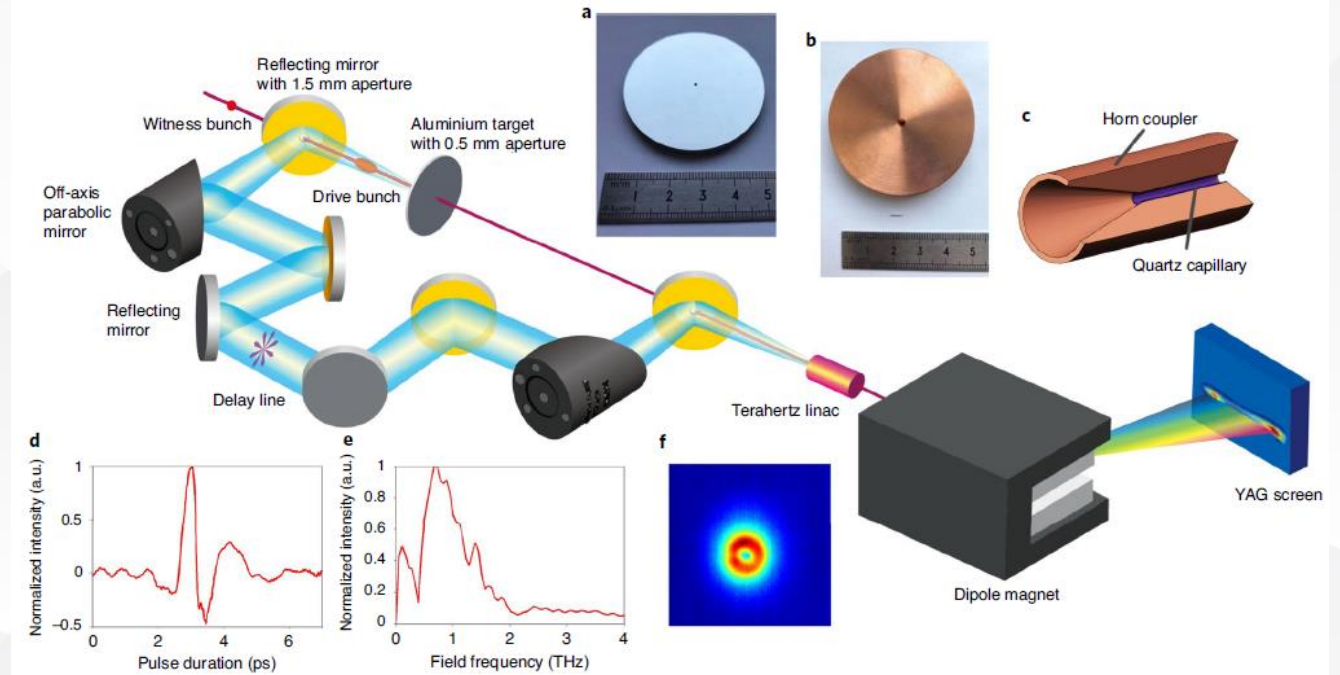
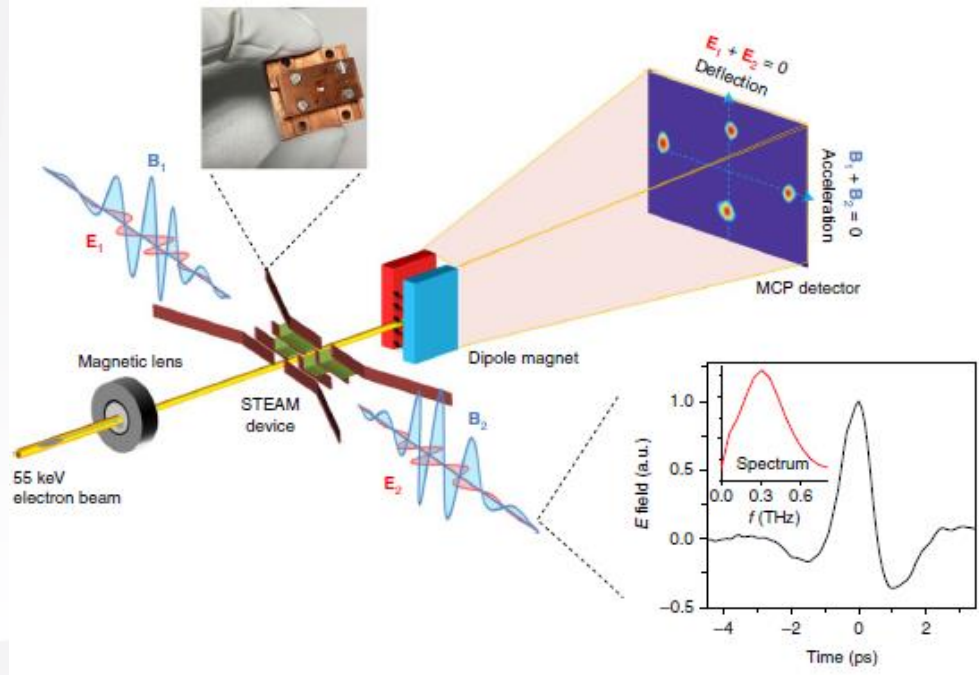
❖ 在常温结构中，主要受限于射频击穿现象（RF breakdown）

- 涉及复杂物理过程，详细机制尚未完全明确，一般认为由表面局部场致发射电流引起
- 射频击穿概率与表面场强、微波脉冲宽度密切相关： $BDR \propto E^{30} \tau^5$

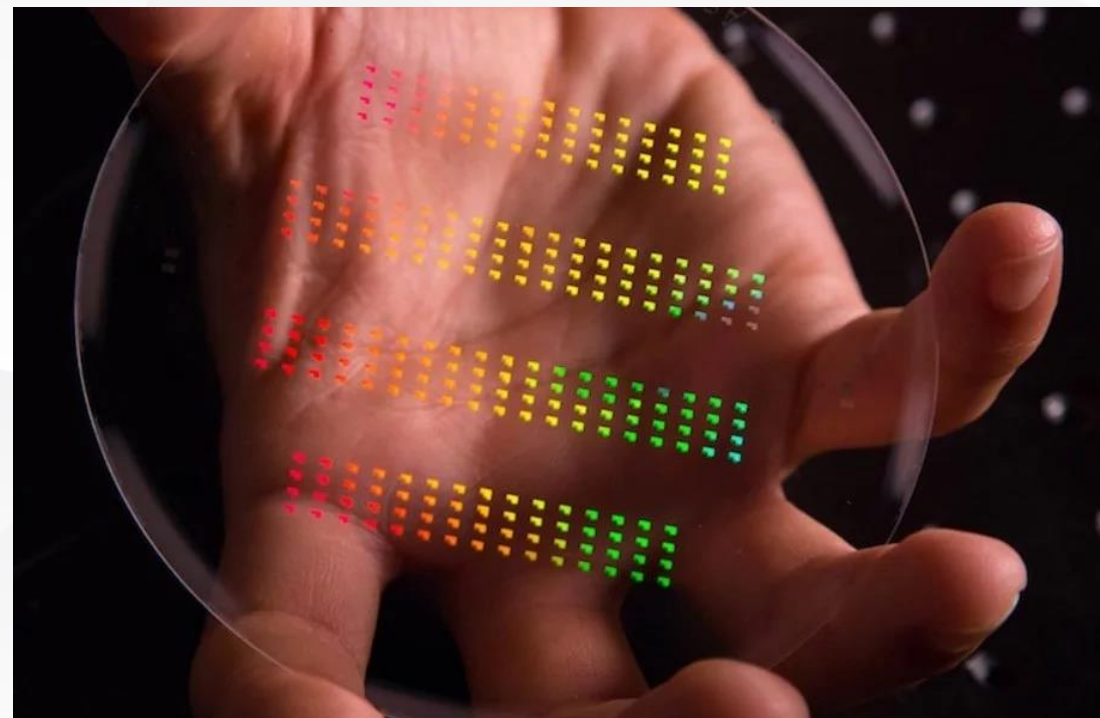
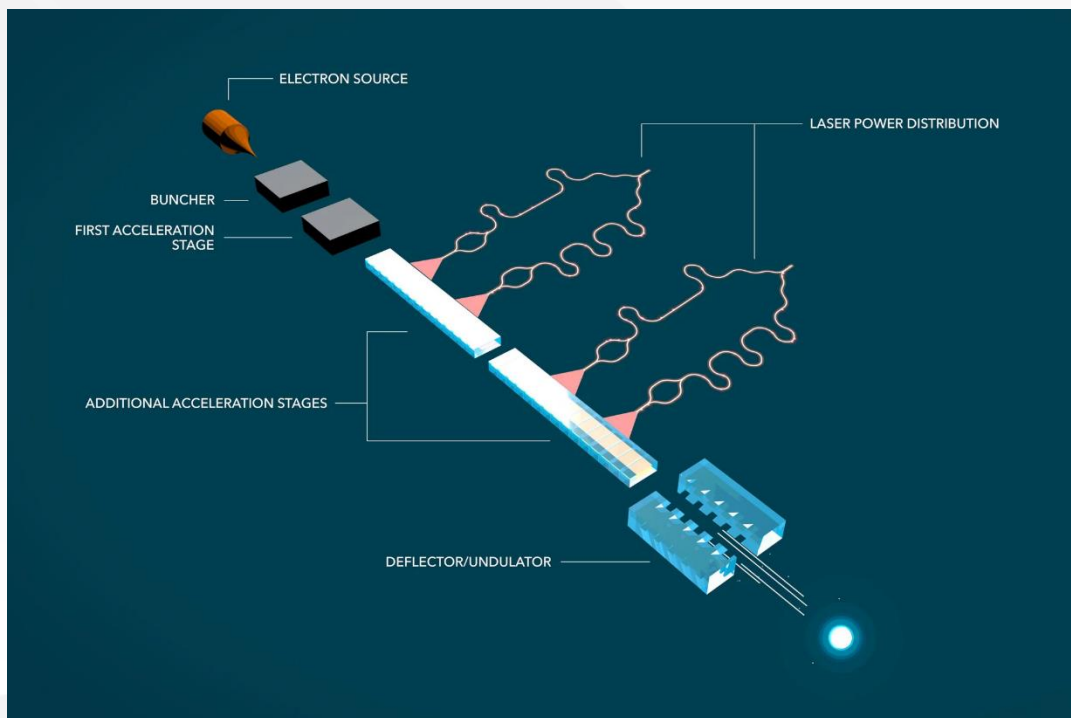


基于结构的高梯度加速 (常温结构)

- 此外, 世界上多个实验室正在探索更高频段的高梯度研究
 - 毫米波、太赫兹加速



- 基于结构的高梯度加速（常温结构）
 - ❖ 新加速原理：激光驱动介质加速器

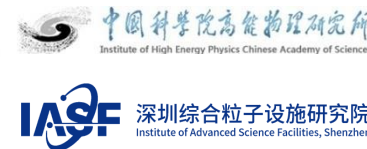




高梯度加速

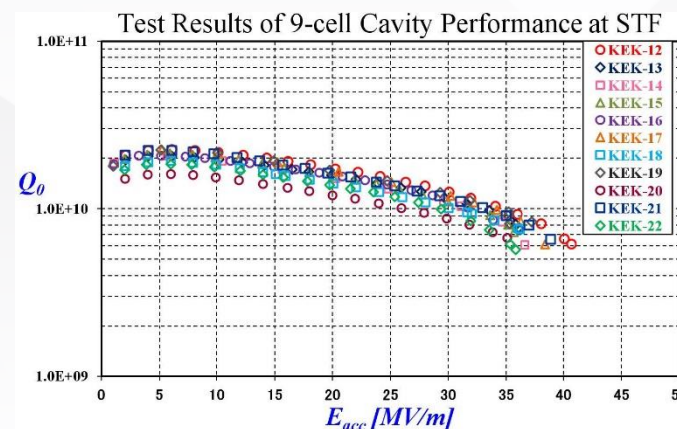
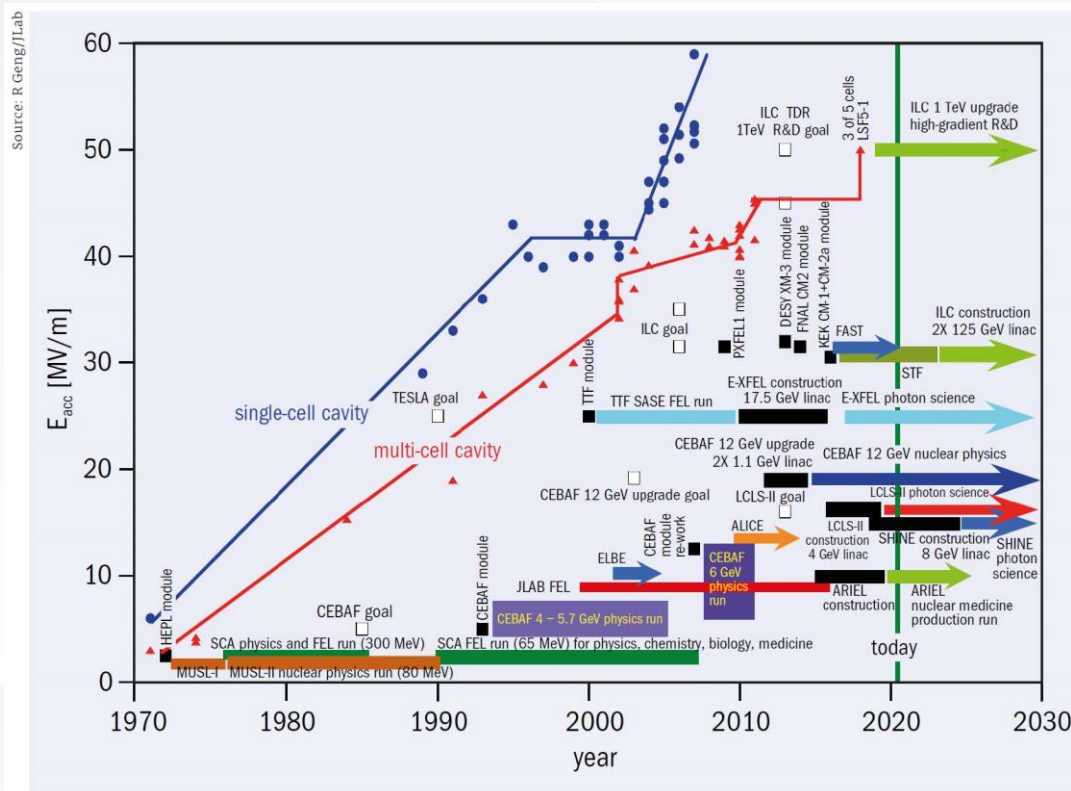


中山大學
SUN YAT-SEN UNIVERSITY



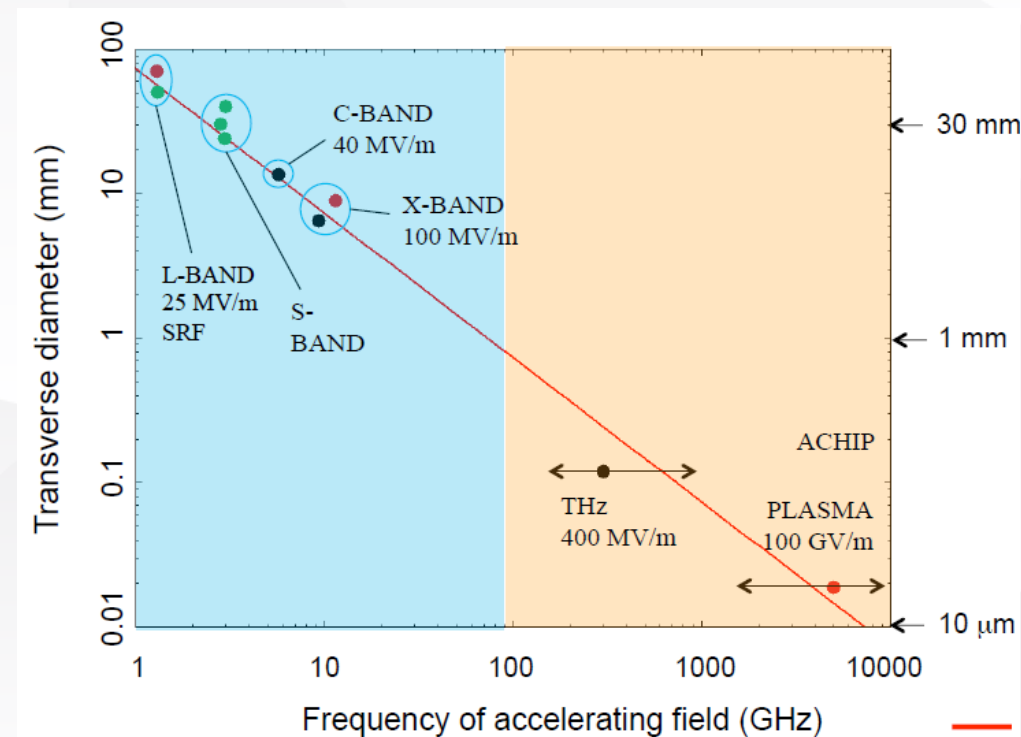
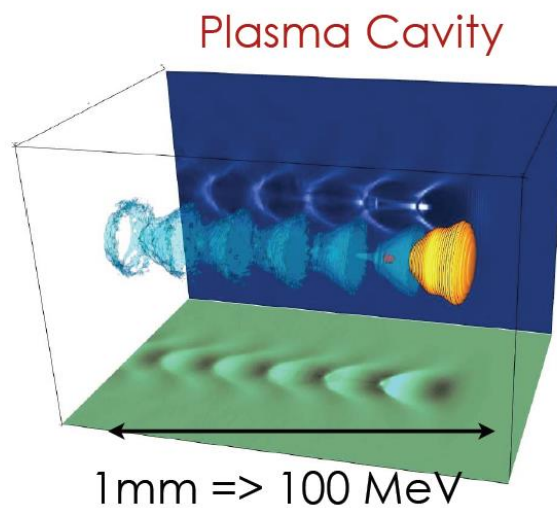
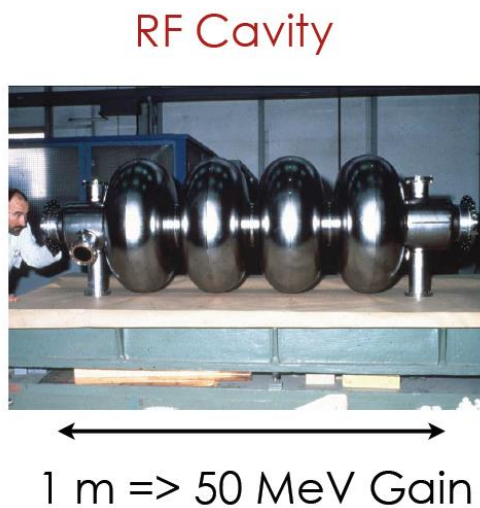
➤ 基于结构的高梯度加速（超导结构）

- ❖ 近年来，受ILC项目的推动，L波段超导高梯度加速结构得到了广泛研究
- ❖ L波段超短微波结构已实现 > 30 MV/m 加速梯度，满足ILC需求



➤ 基于等离子体的高梯度加速

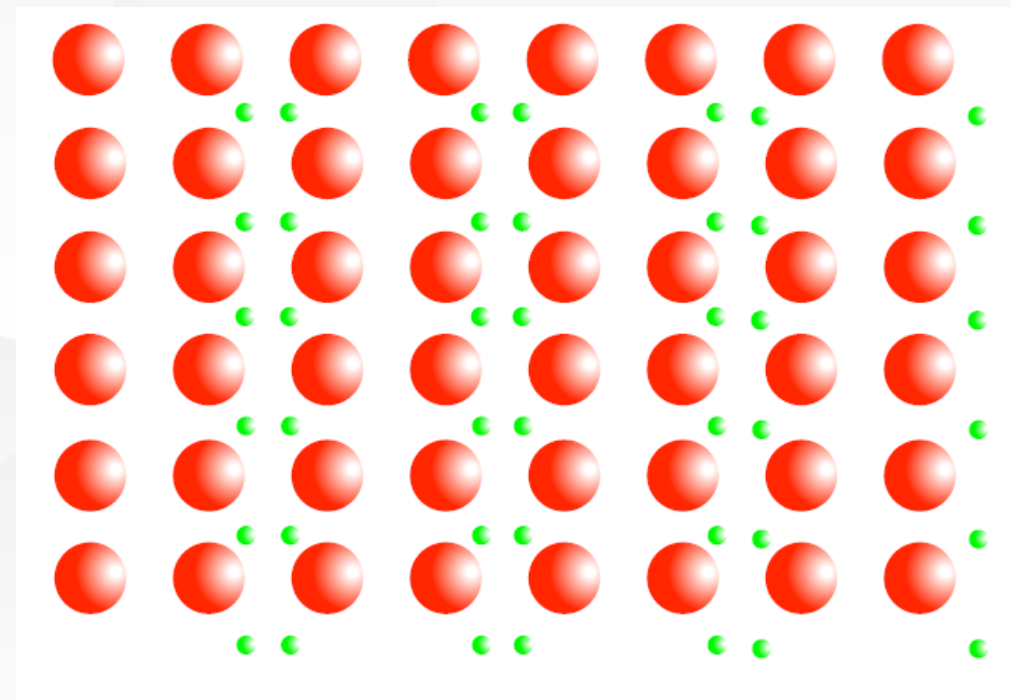
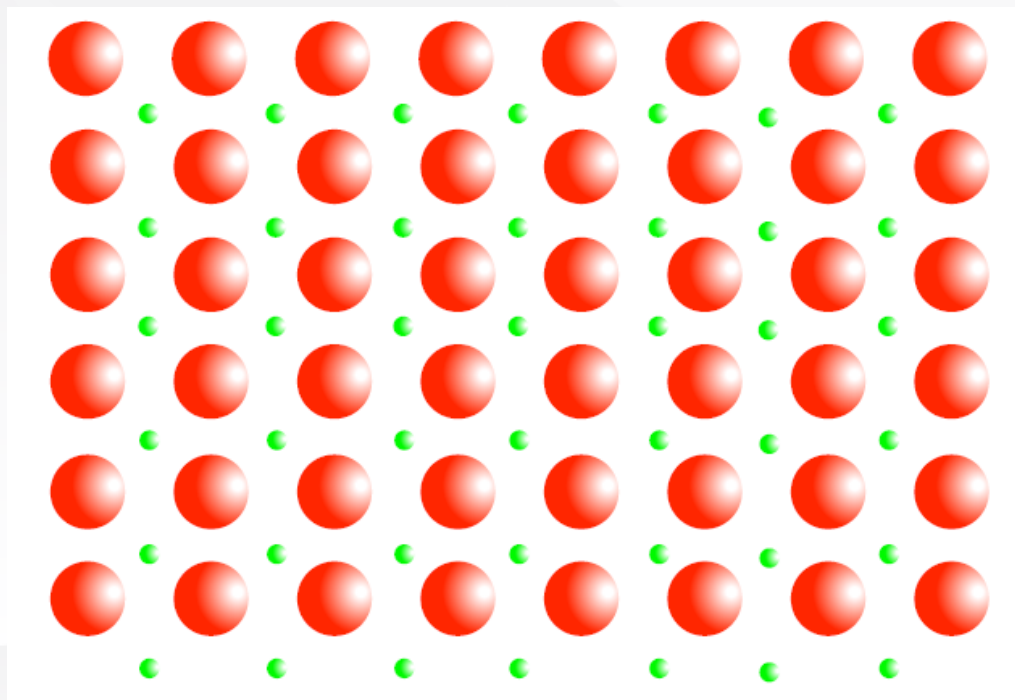
❖ 等离子加速不存在结构限制，加速梯度可达1-100 GV/m





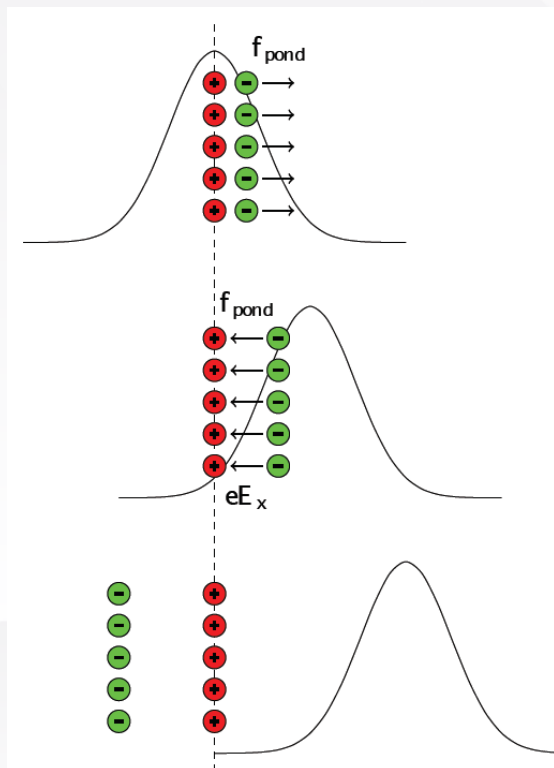
➤ 基于等离子体的高梯度加速

- ❖ 等离子呈电中性，电子密度与离子密度相等 $n_e \approx Zn_i$
- ❖ 当发生扰动时，电子较离子更容易运动



➤ 基于等离子体的高梯度加速

- ❖ 等离子加速可分为激光驱动与电子束驱动两类
- ❖ 激光驱动时，强激光场的有质动力改变等离子体分布
- ❖ 电子束驱动时，高能电子束的空间电荷力改变等离子体分布



- A laser generates a plasma wave from its ponderomotive force

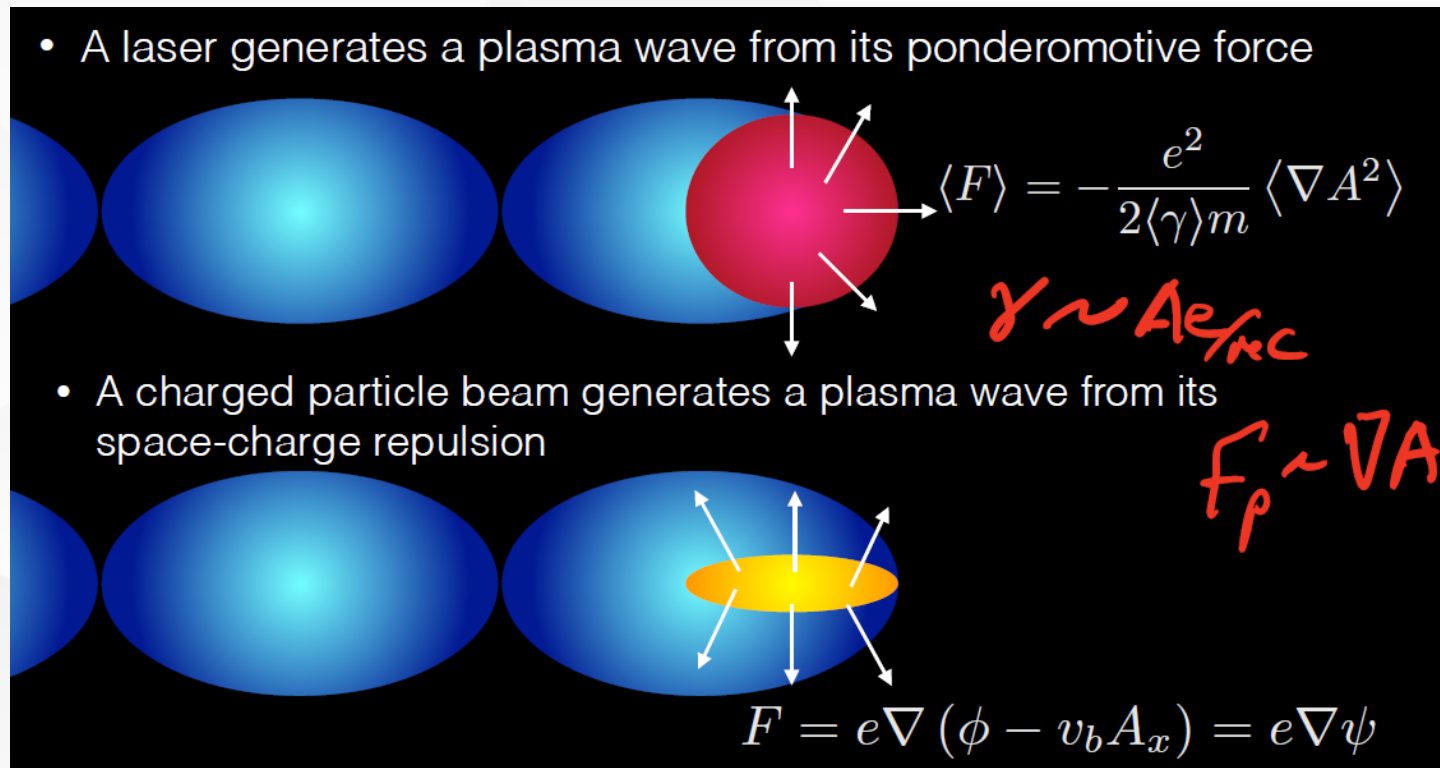
$$\langle F \rangle = -\frac{e^2}{2\langle \gamma \rangle m} \langle \nabla A^2 \rangle$$

$\gamma \sim A e / m c$

- A charged particle beam generates a plasma wave from its space-charge repulsion

$$F = e \nabla (\phi - v_b A_x) = e \nabla \psi$$

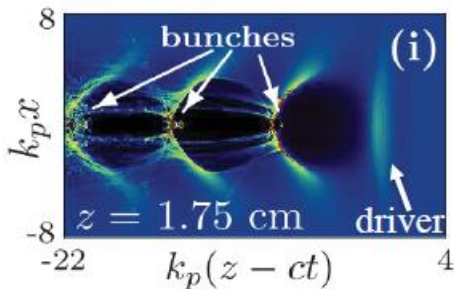
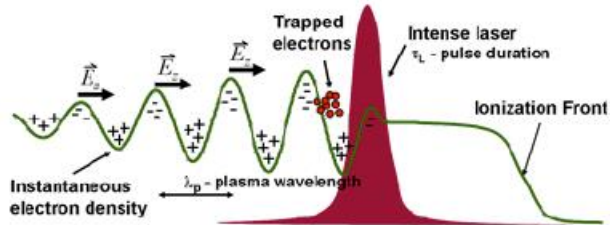
$F_p \sim \nabla A$



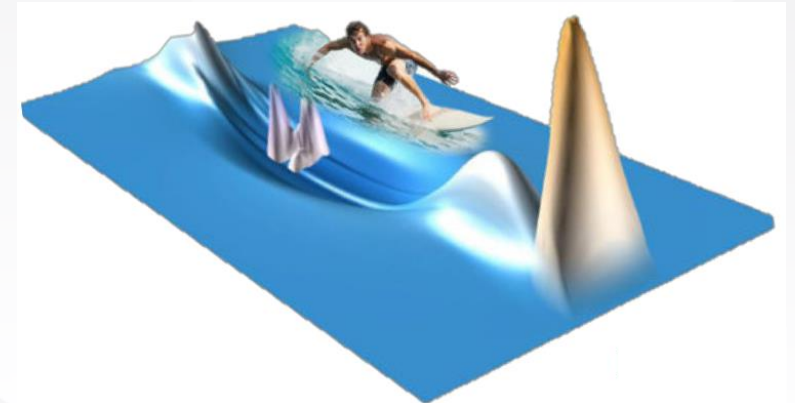
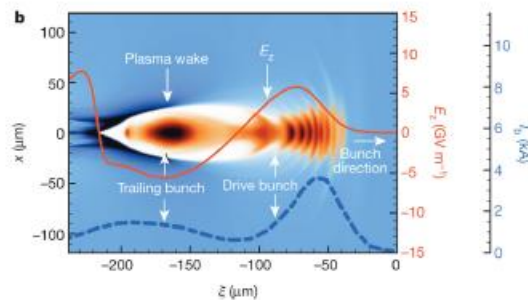
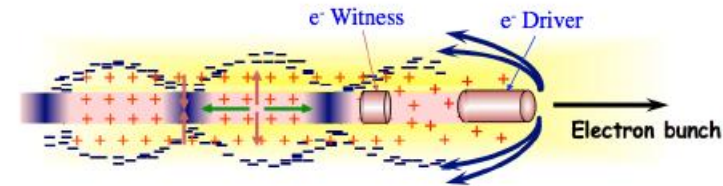
➤ 基于等离子体的高梯度加速

❖ 高功率激光或高能电子束在等离子体中激发尾场/尾波，探针束团可其中被加速

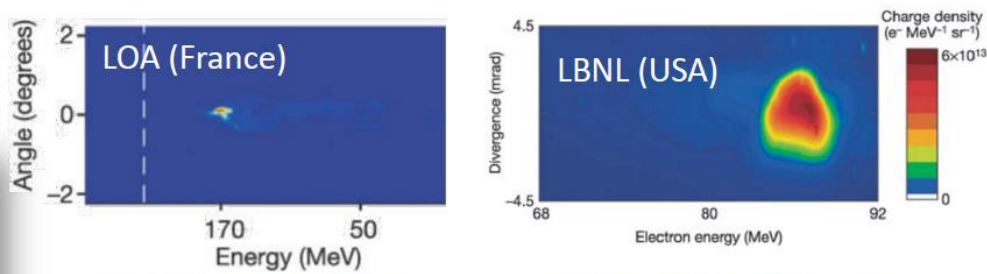
Laser WakeField Accelerator



Plasma WakeField Accelerator

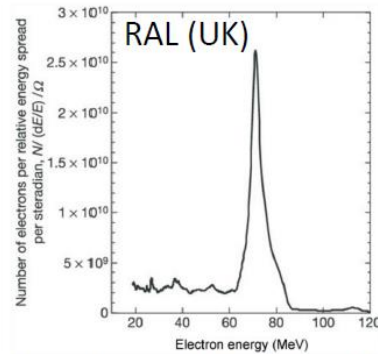


- 基于等离子体的高梯度加速
 - ❖ 已取得一系列重要结果
 - 高梯度加速，米级加速



J. Faure, et al. *Nature* **431** 541 (2004)

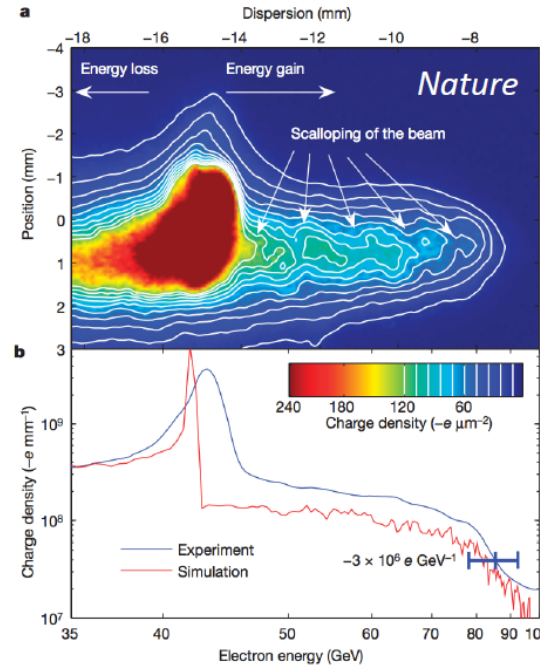
C.G.R. Geddes, et al. *Nature* **431** 538 (2004)



S.P.D. Mangles, et al. *Nature* **431** 535 (2004)

Gradient:
~100 GeV/m

Net energy gain:
~100 MeV



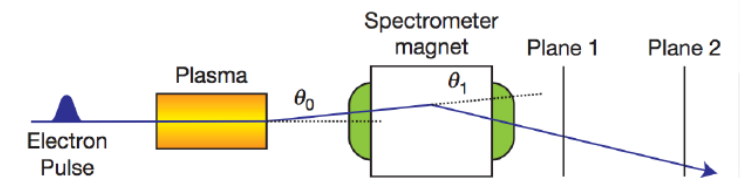
I. Blumenfeld, et al. *Nature* **445** 741 (2007)

SLAC, UCLA, USC collaboration at SLAC's FFTB facility

3 nC, 42 GeV electron beam

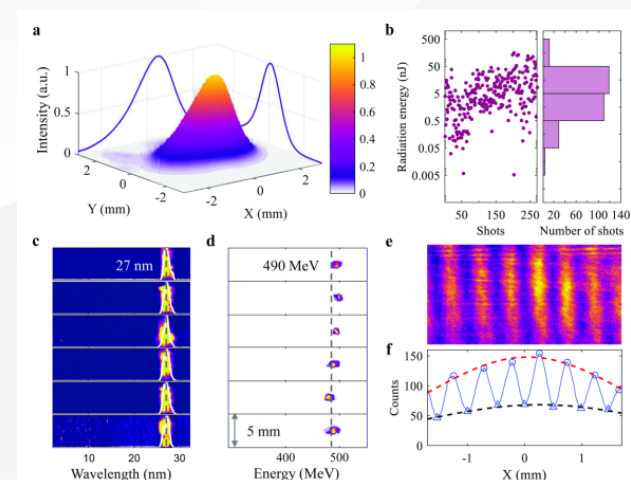
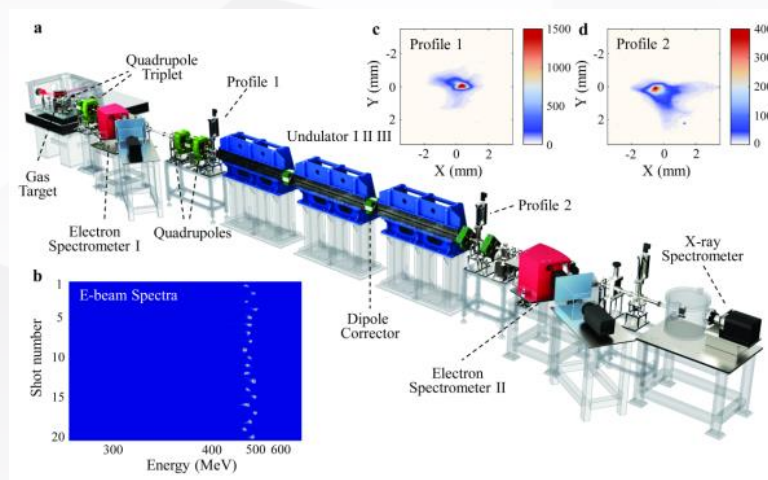
2007: Tail particles gained 40 GeV over 85 cm of plasma

We're off to the races!



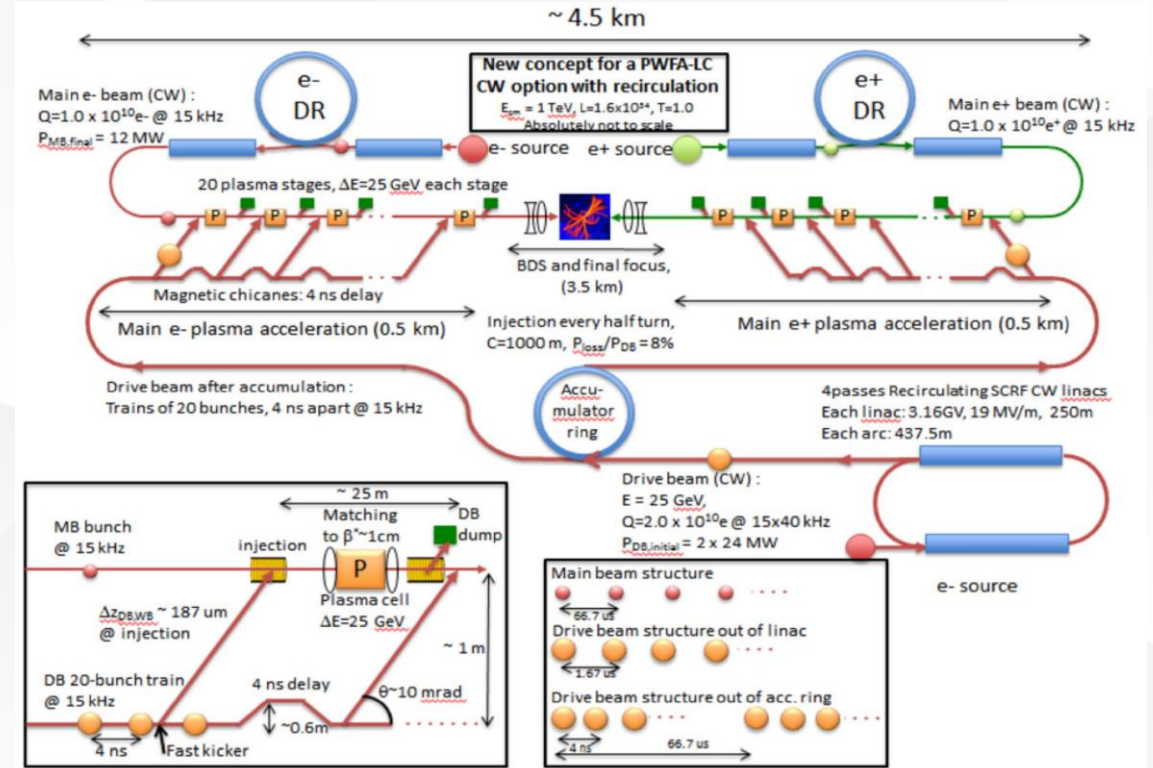
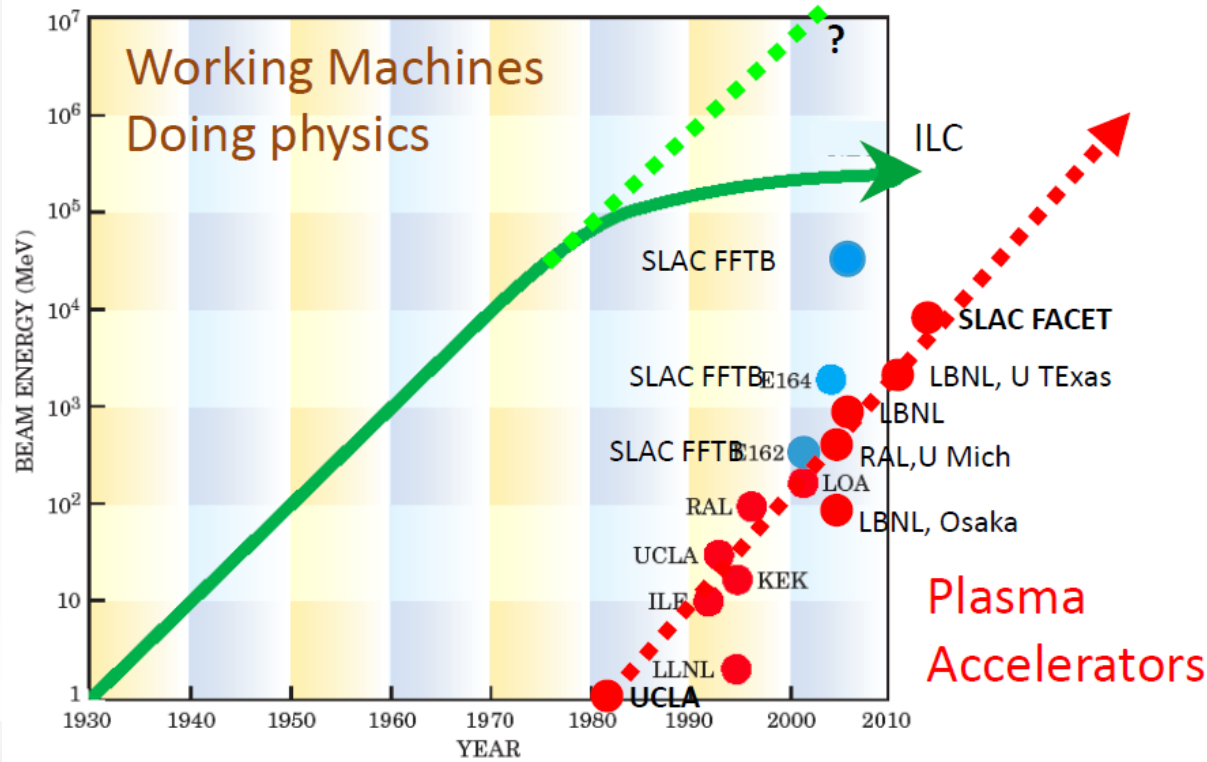
I. Blumenfeld, et al. *Nature* **445** 05538 (2007)

- 基于等离子体的高梯度加速
 - ❖ 已取得一系列重要结果
 - 自由电子激光

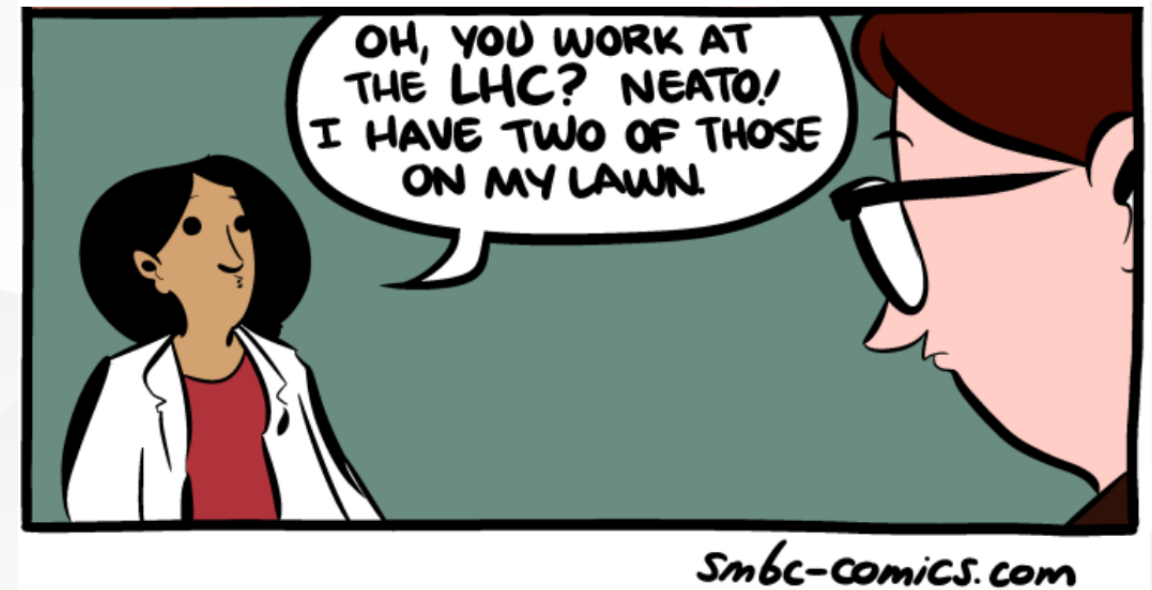


基于等离子体的高梯度加速

❖ 未来有可能广泛使用于高能对撞机、自由电子激光光源、小型加速器等应用

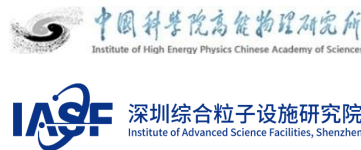


- 基于等离子体的高梯度加速
 - ❖ 有望为整个加速器领域带来全新的突破





中山大學
SUN YAT-SEN UNIVERSITY



中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences
IASF 深圳综合粒子设施研究院
Institute of Advanced Science Facilities, Shenzhen

04

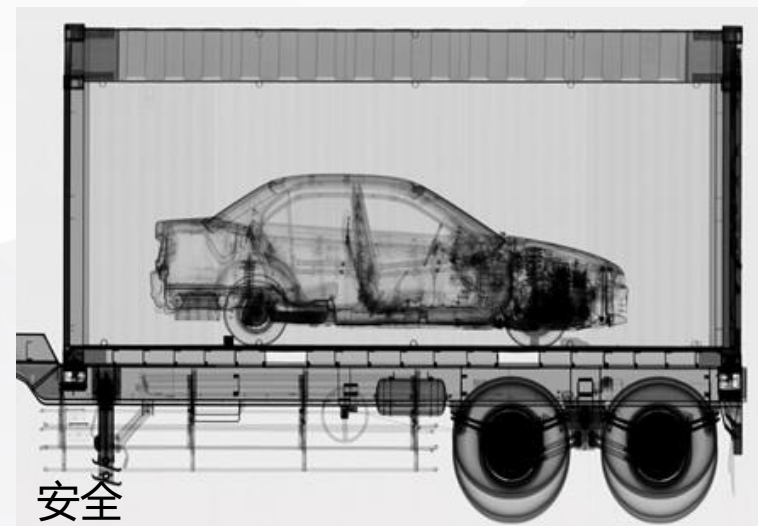
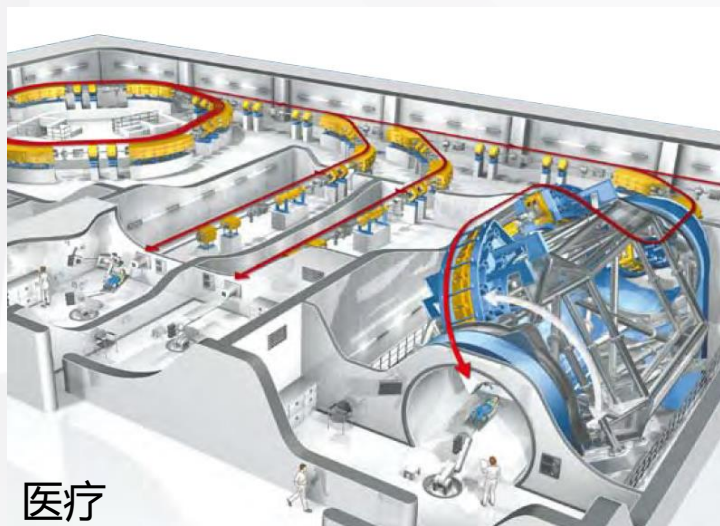
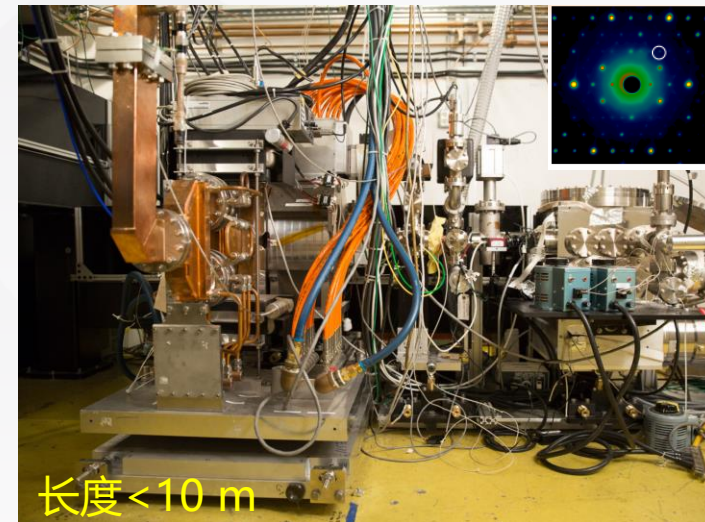
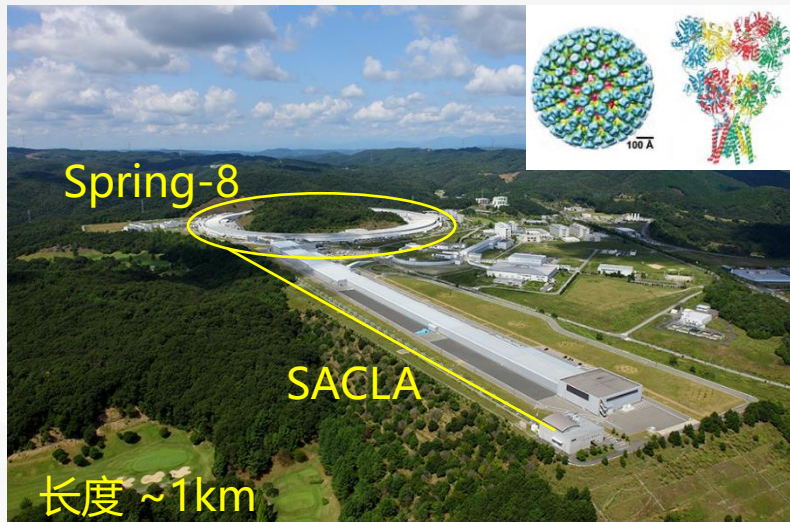
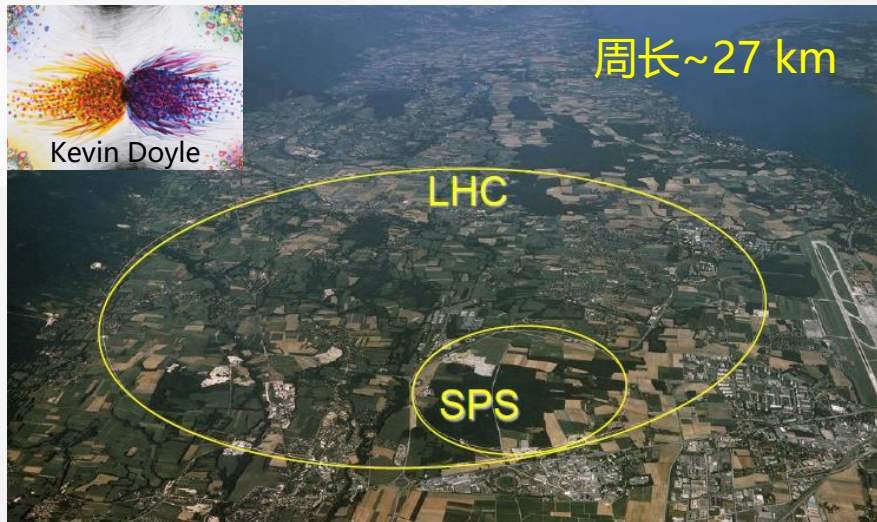
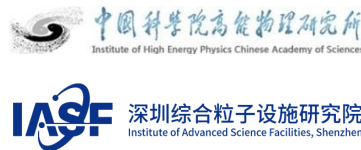
粒子加速器主要应用



粒子加速器



中山大學
SUN YAT-SEN UNIVERSITY





➤ 对物理研究的巨大推动作用

- ❖ 1939-2009年间, 28%的物理研究得益于加速器科学
- ❖ 1939-2009年间, 由加速器贡献和推动的研究平均每3年产生一项诺贝尔物理学奖



25 Nobel Prizes in Physics that had direct contribution from accelerators

Year	Name	Accelerator-Science Contribution to Nobel Prize-Winning Research
1939	Ernest O. Lawrence	Lawrence invented the cyclotron at the University of California at Berkeley in 1929 [12].
1951	John D. Cockcroft and Ernest T.S. Walton	Cockcroft and Walton invented their eponymous linear positive-ion accelerator at the Cavendish Laboratory in Cambridge, England, in 1932 [13].
1952	Felix Bloch	Bloch used a cyclotron at the Crocker Radiation Laboratory at the University of California at Berkeley in his discovery of the magnetic moment of the neutron in 1940 [14].
1957	Tsung-Dao Lee and Chen Ning Yang	Lee and Yang analyzed data on K mesons (θ and τ) from Bevatron experiments at the Lawrence Radiation Laboratory in 1955 [15], which supported their idea in 1956 that parity is not conserved in weak interactions [16].
1959	Emilio G. Segrè and Owen Chamberlain	Segrè and Chamberlain discovered the antiproton in 1955 using the Bevatron at the Lawrence Radiation Laboratory [17].
1960	Donald A. Glaser	Glaser tested his first experimental six-inch bubble chamber in 1955 with high-energy protons produced by the Brookhaven Cosmotron [18].
1961	Robert Hofstadter	Hofstadter carried out electron-scattering experiments on carbon-12 and oxygen-16 in 1959 using the SLAC linac and thereby made discoveries on the structure of nucleons [19].
1963	Maria Goeppert Mayer	Goeppert Mayer analyzed experiments using neutron beams produced by the University of Chicago cyclotron in 1947 to measure the nuclear binding energies of krypton and xenon [20], which led to her discoveries on high magic numbers in 1948 [21].
1967	Hans A. Bethe	Bethe analyzed nuclear reactions involving accelerated protons and other nuclei whereby he discovered in 1939 how energy is produced in stars [22].
1968	Luis W. Alvarez	Alvarez discovered a large number of resonance states using his fifteen-inch hydrogen bubble chamber and high-energy proton beams from the Bevatron at the Lawrence Radiation Laboratory [23].
1976	Burton Richter and Samuel C.C. Ting	Richter discovered the J/ψ particle in 1974 using the SPEAR collider at Stanford [24], and Ting discovered the J/ψ particle independently in 1974 using the Brookhaven Alternating Gradient Synchrotron [25].
1979	Sheldon L. Glashow, Abdus Salam, and Steven Weinberg	Glashow, Salam, and Weinberg cited experiments on the bombardment of nuclei with neutrinos at CERN in 1973 [26] as confirmation of their prediction of weak neutral currents [27].
1980	James W. Cronin and Val L. Fitch	Cronin and Fitch concluded in 1964 that CP (charge-parity) symmetry is violated in the decay of neutral K mesons based upon their experiments using the Brookhaven Alternating Gradient Synchrotron [28].
1981	Kai M. Siegbahn	Siegbahn invented a weak-focusing principle for betatrons in 1944 with which he made significant improvements in high-resolution electron spectroscopy [29].
1983	William A. Fowler	Fowler collaborated on and analyzed accelerator-based experiments in 1958 [30], which he used to support his hypothesis on stellar-fusion processes in 1957 [31].
1984	Carlo Rubbia and Simon van der Meer	Rubbia led a team of physicists who observed the intermediate vector bosons W and Z in 1983 using CERN's proton-antiproton collider [32], and van der Meer developed much of the instrumentation needed for these experiments [33].
1986	Ernst Ruska	Ruska built the first electron microscope in 1933 based upon a magnetic optical system that provided large magnification [34].
1988	Leon M. Lederman, Melvin Schwartz, and Jack Steinberger	Lederman, Schwartz, and Steinberger discovered the muon neutrino in 1962 using Brookhaven's Alternating Gradient Synchrotron [35].
1989	Wolfgang Paul	Paul's idea in the early 1950s of building ion traps grew out of accelerator physics [36].
1990	Jerome I. Friedman, Henry W. Kendall, and Richard E. Taylor	Friedman, Kendall, and Taylor's experiments in 1974 on deep inelastic scattering of electrons on protons and bound neutrons used the SLAC linac [37].
1992	Georges Charpak	Charpak's development of multiwire proportional chambers in 1970 were made possible by accelerator-based testing at CERN [38].
1995	Martin L. Perl	Perl discovered the tau lepton in 1975 using Stanford's SPEAR collider [39].
2004	David J. Gross, Frank Wilczek, and H. David Politzer	Gross, Wilczek, and Politzer discovered asymptotic freedom in the theory of strong interactions in 1973 based upon results from the SLAC linac on electron-proton scattering [40].
2008	Makoto Kobayashi and Toshihide Maskawa and Yoichiro Nambu	Kobayashi and Maskawa's theory of quark mixing in 1973 was confirmed by results from the KEKB accelerator at KEK (High Energy Accelerator Research Organization) in Tsukuba, Ibaraki Prefecture, Japan, and the PEP II (Positron Electron Project II) at SLAC [41], which showed that quark mixing in the six-quark model is the dominant source of broken symmetry [42].

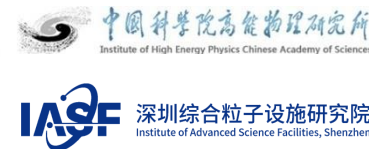
2013: François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"



粒子加速器



中山大學
SUN YAT-SEN UNIVERSITY

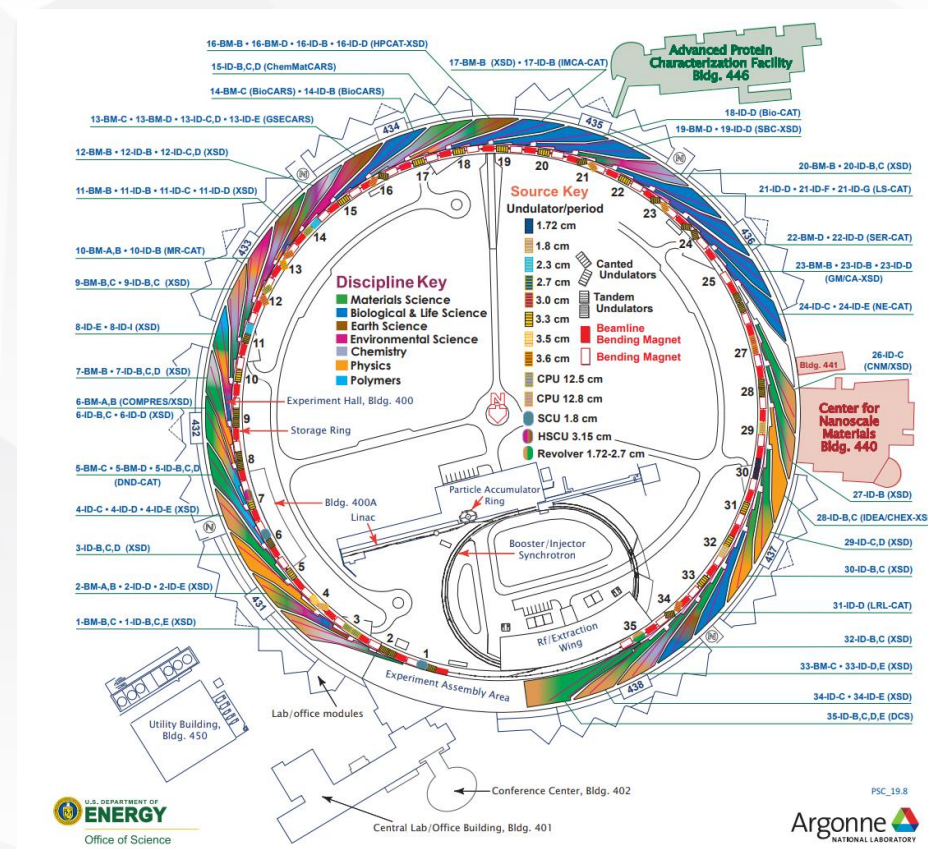


➤ 对多学科基础研究的重要意义

❖ 世界范围内共有超过50台基于加速器的高亮度光源，服务生物、材料、化学、能源等众多学科



APS
每年用户数 > 5000



Argonne
NATIONAL LABORATORY

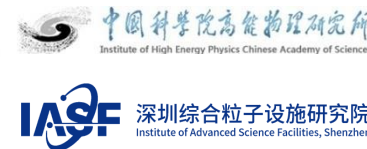
APS Brochure



粒子加速器主要应用

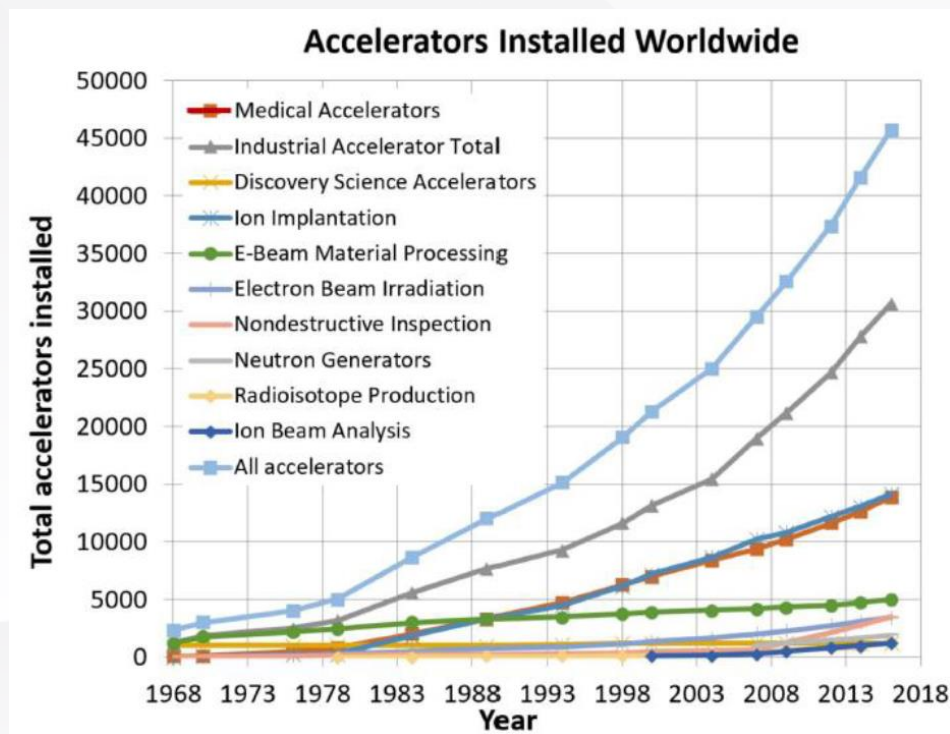


中山大学
SUN YAT-SEN UNIVERSITY



➤ 粒子加速器主要应用

- ❖ 高能量 (>10 GeV) : 粒子物理研究
- ❖ 中能量 (1-10 GeV) : 化学、生物、材料、信息、交叉学科基础研究
- ❖ 低能量 (<100 MeV) : 医用及工业用加速器



Application	Systems (thru 2008)
-------------	---------------------

Ion Implantation	10,000
------------------	--------

Electron beam modification	7,000
----------------------------	-------

Electron and X-ray irradiators	2,000
--------------------------------	-------

Ion beam analysis and AMS	200
---------------------------	-----

Radioisotope production	600
-------------------------	-----

High energy x-ray inspection	750
------------------------------	-----

Neutron generators	2000
--------------------	------

Radiotherapy	8000
--------------	------

Hadrontherapy	25
---------------	----

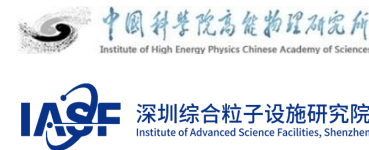
Photon Sources (synchrotron radiation, ...)	80
---	----

Nuclear and Particle Physics Research	110
---------------------------------------	-----

Total	~30,000
-------	---------



中山大學
SUN YAT-SEN UNIVERSITY



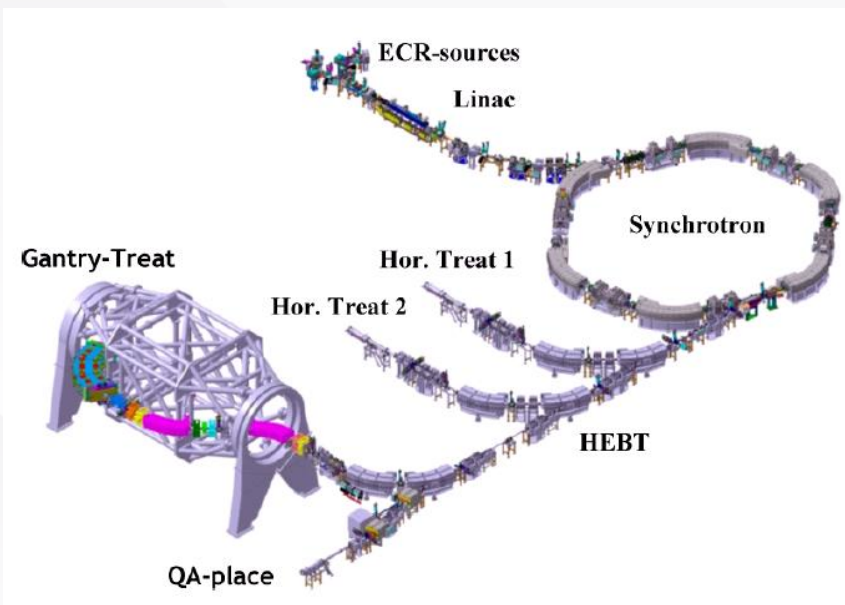
04A

医疗应用

仅涵盖整个低能加速器应用领域的一小部分

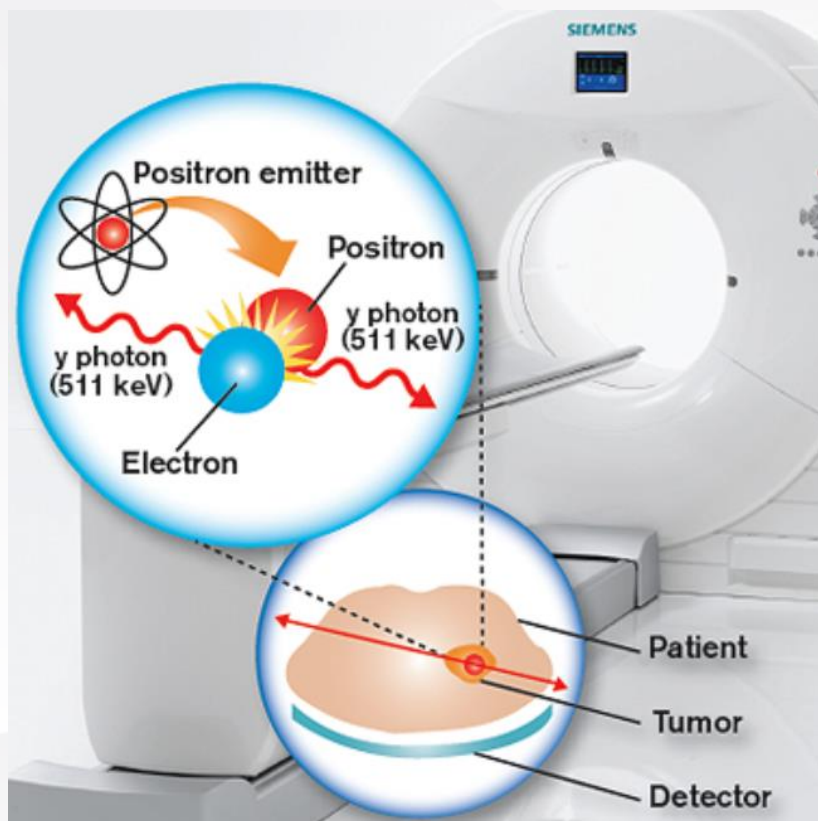
➤ 在医疗健康领域的重要作用

- ❖ 放疗是当前癌症治疗的三大主要手段之一
- ❖ 2010年数据，每年有数百万患者接受基于粒子加速器的诊断与治疗



生产医用同位素

❖ 放射性同位素在肿瘤检测、治疗方面发挥着日益重要的作用

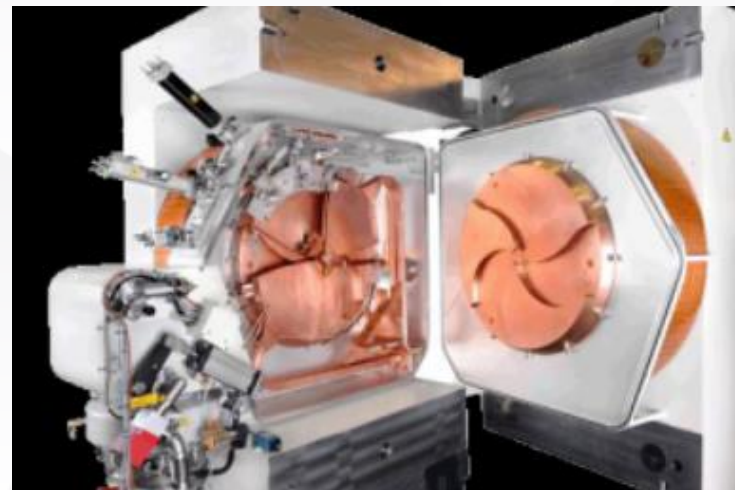


Nuclide	Half-life (min)	Decay mode	Maximum energy (MeV)	Mean energy (MeV)	Max. range (mm)	Max. SA (theoretical) (Ci/μmol) ^a
C-11	20.4	100% β^+	0.96	0.386	4.1	9 220
N-13	9.98	100% β^+	1.19	0.492	5.4	18 900
O-15	2.03	100% β^+	1.7	0.735	8.0	91 730
F-18	109.8	97% β^+	0.69	0.250	2.4	1 710
Cu-62	9.74	99.7% β^+	2.93	1.314	14.3	19 310
Ga-68	68.0	89% β^+	1.9	0.829	9.0	2 766
Br-75	96.0	75.5% β^+	1.74	0.750	8.2	1 960
Rb-82	1.25	95.5% β^+	3.36	1.5	16.5	150 400
I-122	3.62	75.8% β^+	3.12	1.4	15.3	51 950
I-124	6019.2	23.3% β^+	2.13	0.8	10.2	31

➤ 生产医用同位素

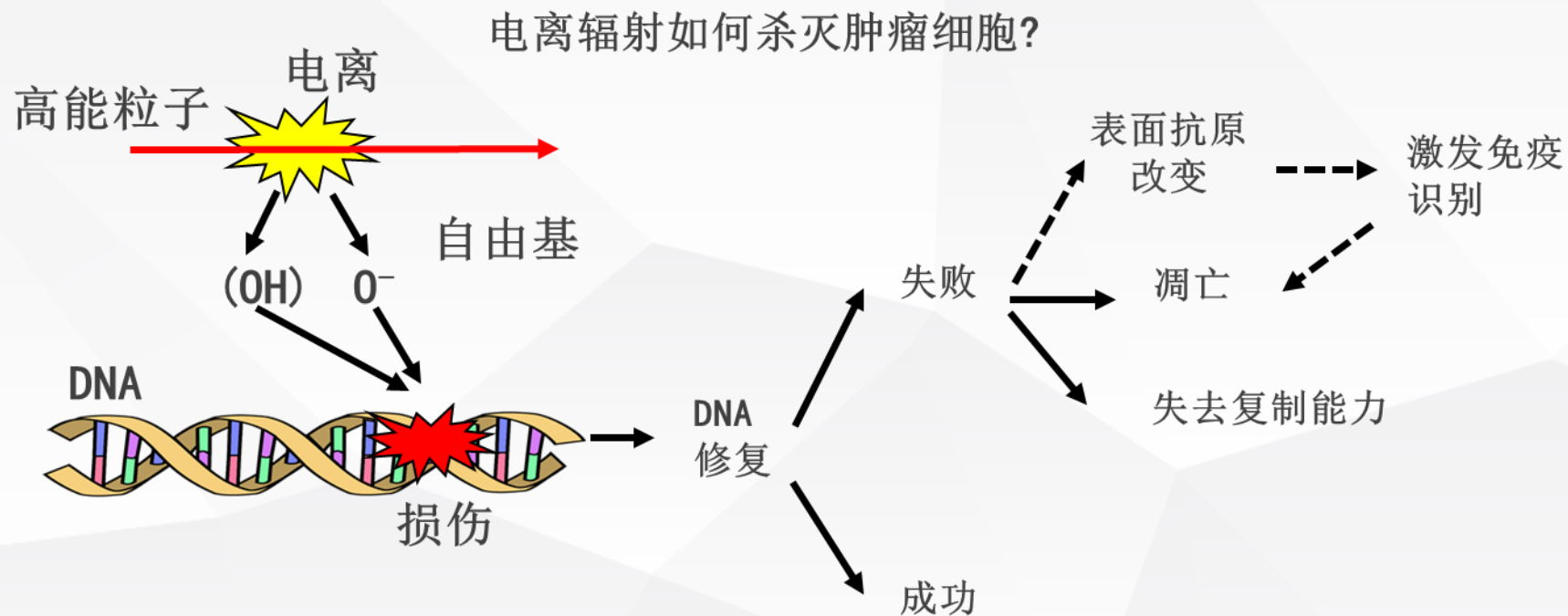
❖ 粒子加速器是放射性同位素生产的关键器件

- (p,n), (p,2p), (p, α), (p,X), (p, α n), etc... $p^+ A/q=1$
- (d,n), (d,p), etc... $d^+ A/q=2$
- (^3He ,n), (^3He , α), etc... $^3\text{He}^{++} A/q=1.5$
- (α ,n), (α ,2n), (α ,p), etc... $\alpha^{++} A/q=2$
- (^7Li ,Xn), etc ... $\text{Li}^{++} \text{Li}^{+++} A/q=3.5, 2.33$
- (n, γ), (n,2n), (n,p), etc... $n^0 A/q=0$



➤ 放射治疗

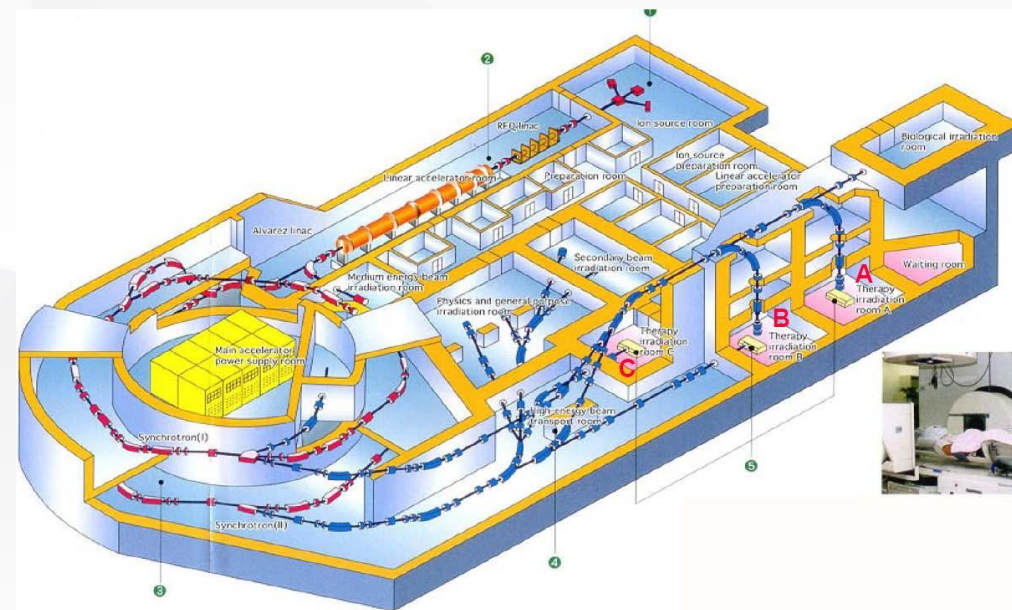
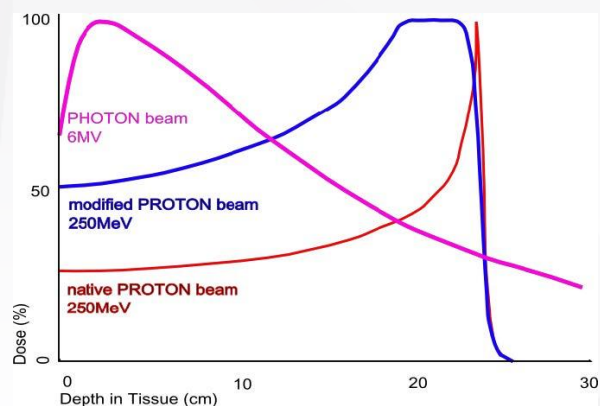
- ❖ 通过电离辐射损伤肿瘤细胞DNA (同时影响正常细胞, 即副作用)
- ❖ 相对于正常细胞, 很多类型的肿瘤细胞对电离辐射耐受的程度低 (修复能力差, 复制频繁)



➤ 放射治疗

❖ 主要采用X射线、质子、重离子等手段

- X射线穿透性强，但剂量率随深度指数衰减
- 质子、重离子具有布拉格峰，可减少表面正常组织损伤



➤ 放射治疗

❖ 随着医学成像技术和电子计算机技术的进步，放疗技术正在加速发展

- 适形治疗技术 (Conformal Radio Therapy, CRT)
- 调强放疗技术 (Intensity Modulated Radio Therapy, IMRT)
- 图像引导治疗 (Image Guided Radiation Therapy, IGRT)
- 立体定向治疗技术 (Stereotactic body radiotherapy, SBRT)
- 闪疗 (Flash-RT)

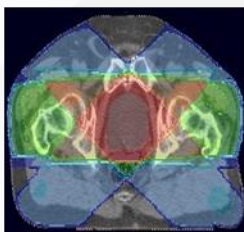
肿瘤组织
照射剂量

40 Gy



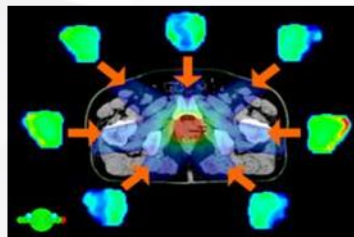
LINAC

50 Gy



CRT

60 Gy



IMRT & VMAT

80 Gy



IGRT & SBRT

1950

1960

1970

1980

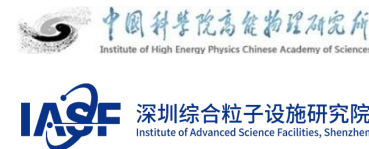
1990

2000

2010



中山大學
SUN YAT-SEN UNIVERSITY



中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

IAEF 深圳综合粒子设施研究院
Institute of Advanced Science Facilities, Shenzhen

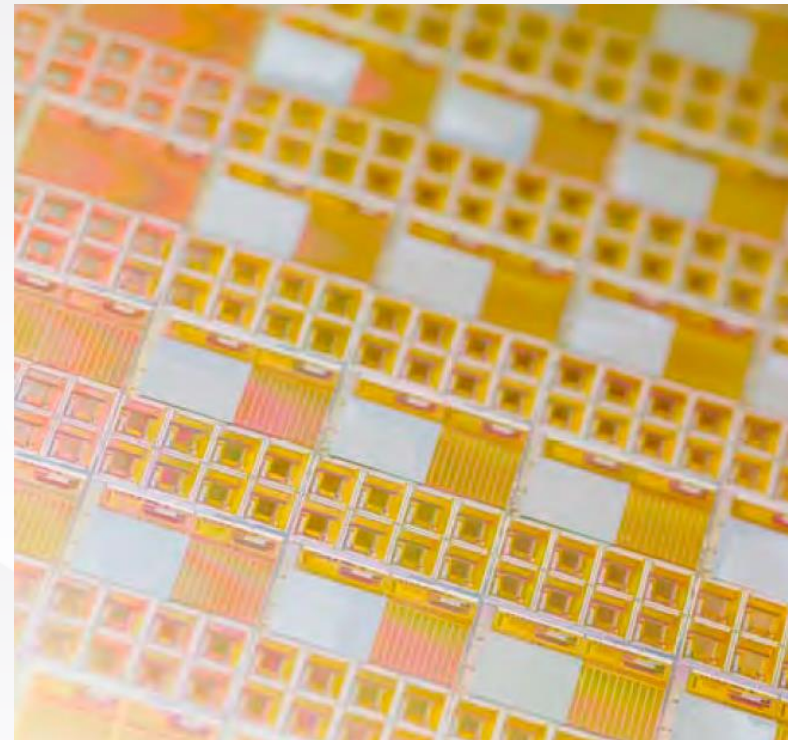
04B

工业应用

仅涵盖整个低能加速器应用领域的一小部分

➤ 在工业发展中的广泛应用

❖ 2012年数据，由粒子加速器生产、消毒、检验的工业产品年产值超过5000亿美元

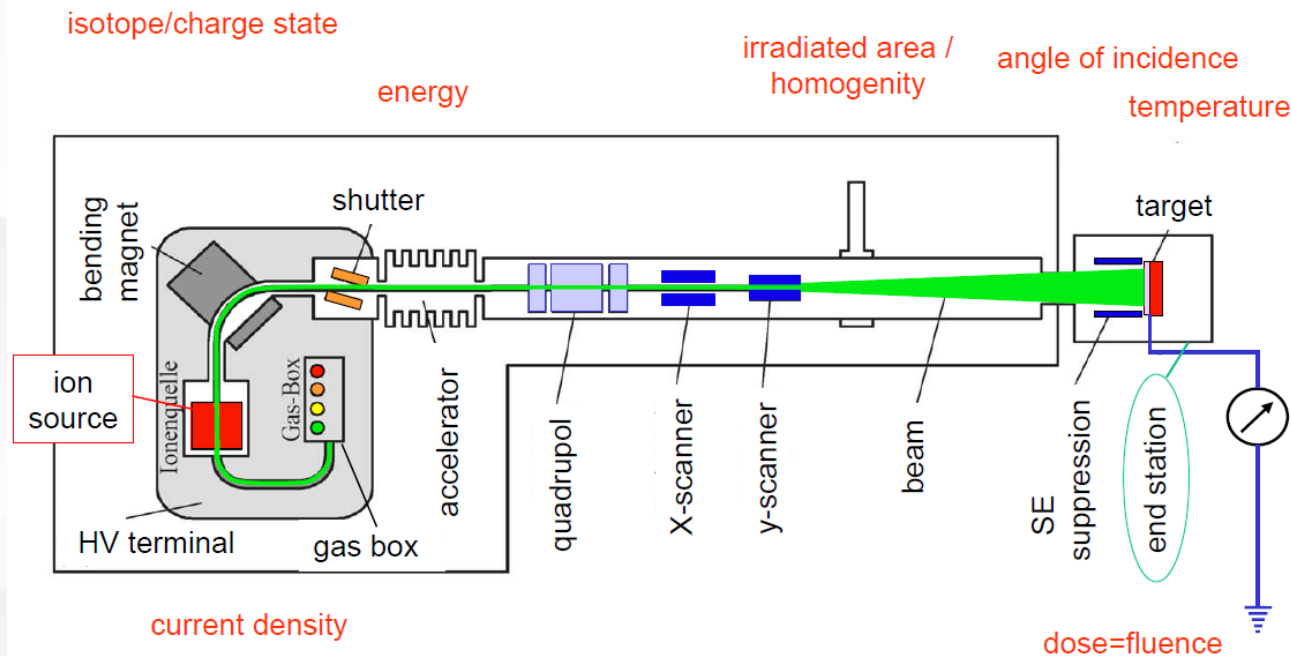
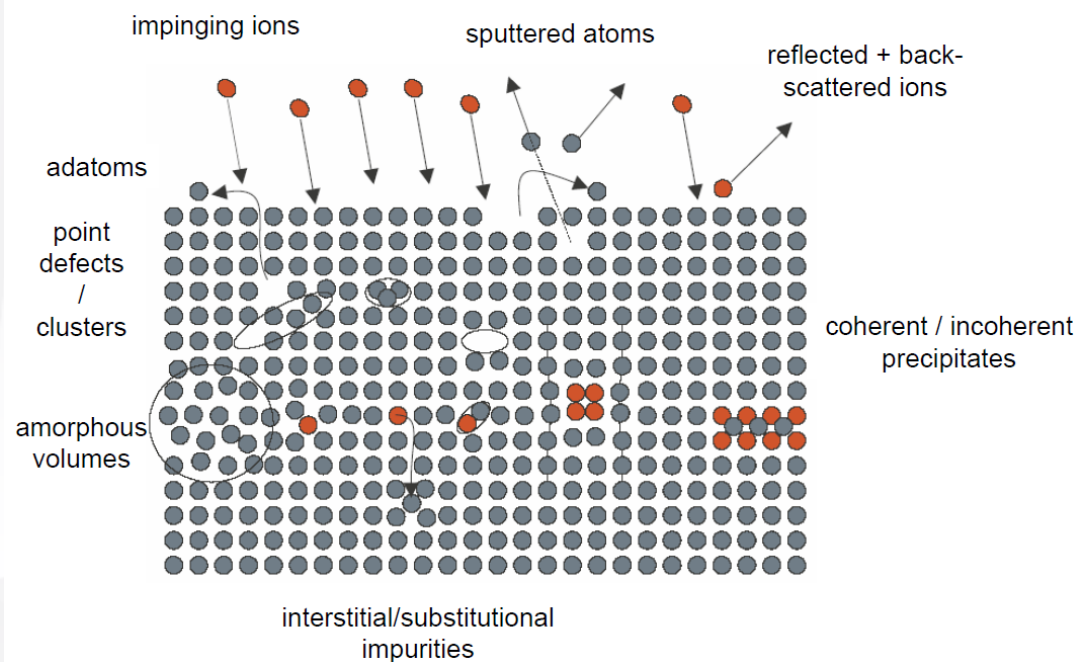


R. Hamm and M. Hamm, Introduction to the beam business, World Scientific (2012)
Accelerators for America's Future, DOE report (2010)
查皓，辐照灭菌中的加速器技术

➤ 离子注入

❖ 令高速离子轰击并掺入材料表面，改变材料电特性

- 广泛应用于半导体行业
- 主要使用低于10 MeV的低能离子
- 主要使用高流强的直流高压加速器



➤ 无损检测与安检

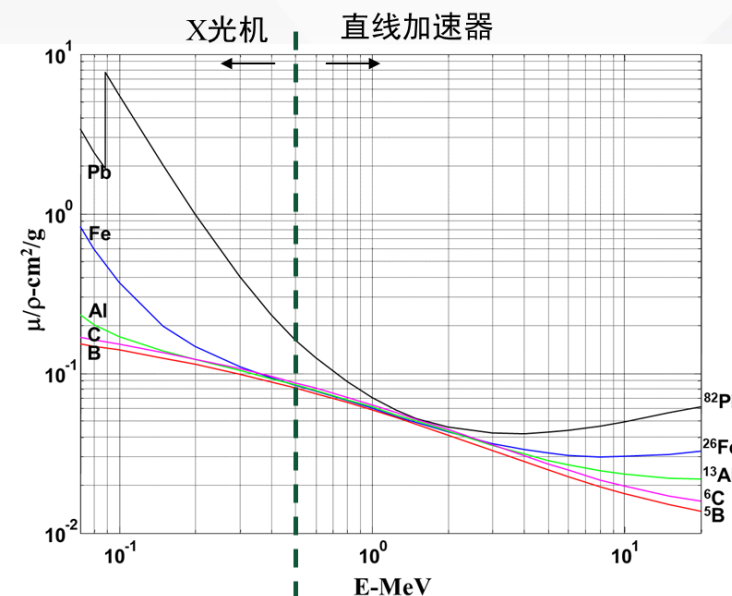
❖ 利用X射线透视成像

- X射线在物体中的衰减 $I = I_0 e^{-\mu x}$

物体厚度

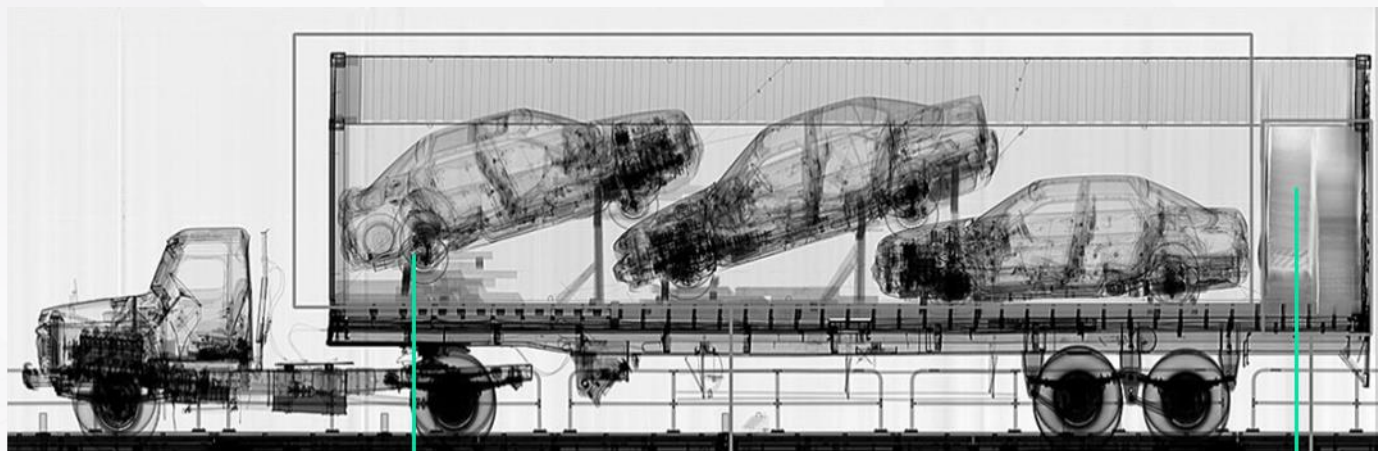
线性衰减系数

- 医用透视成像常用X光机/X光管；但穿透更大型或重Z物质则需要能量更高的X射线



➤ 无损检测与安检

❖ X射线透射特别适合在货流量极大的海关口岸稽查走私

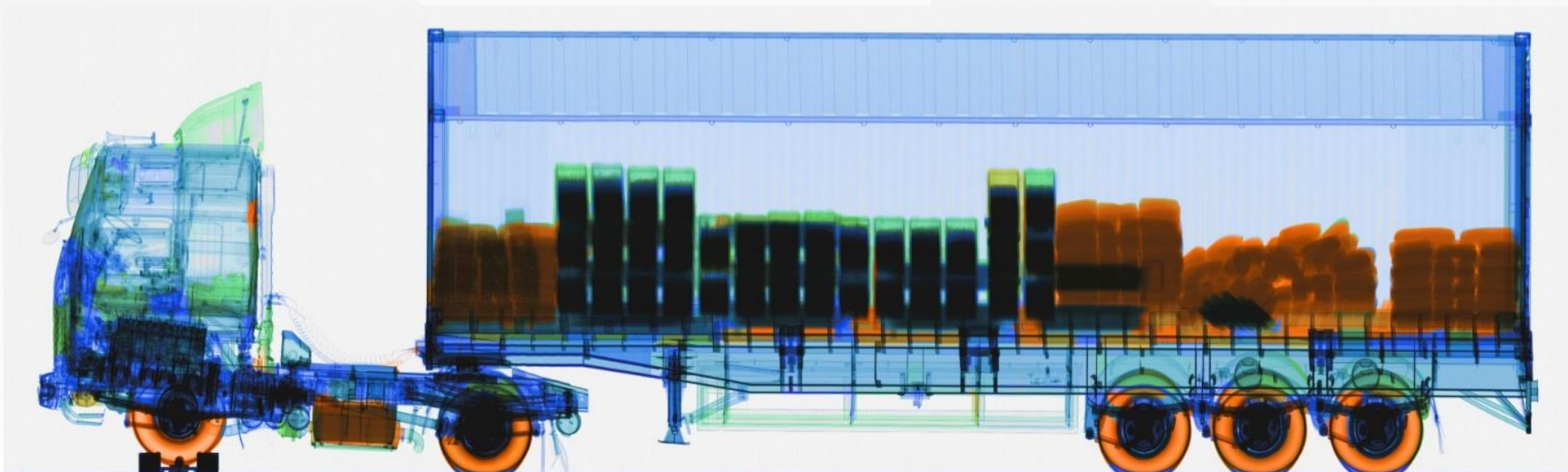


3辆走私汽车

申报货物：地毯

➤ 无损检测与安检

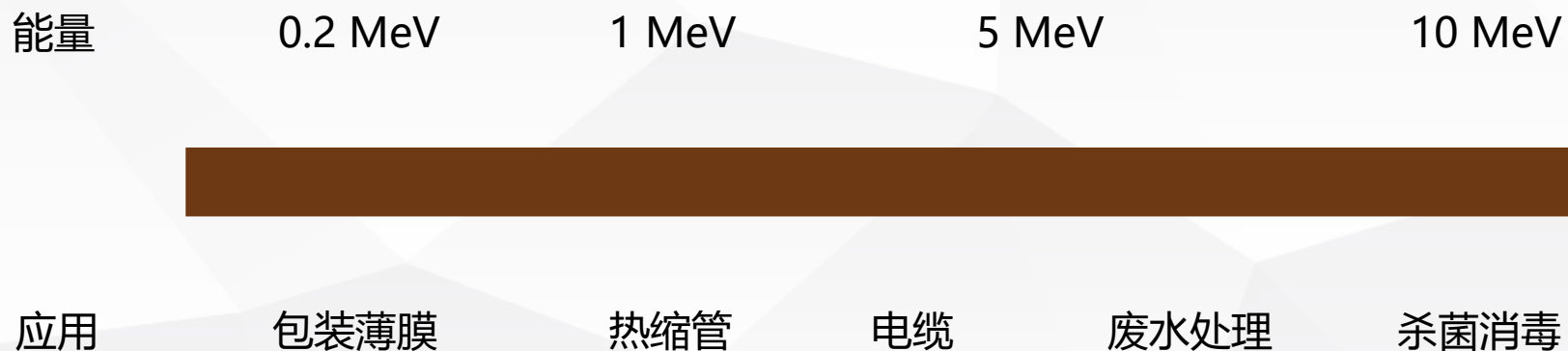
❖ 还可利用双能加速管，通过衰减系统的差异，对物品材料进行分辨



➤ 辐照消毒与加工

❖ 电离辐射能量足以打断能量为eV级的化学键

- 消毒灭菌：破坏DNA与蛋白质
- 污水处理：降解大分子变为小分子
- 化学键重建：高分子铰链，材料改性



➤ 辐照消毒与加工

❖ 消毒灭菌

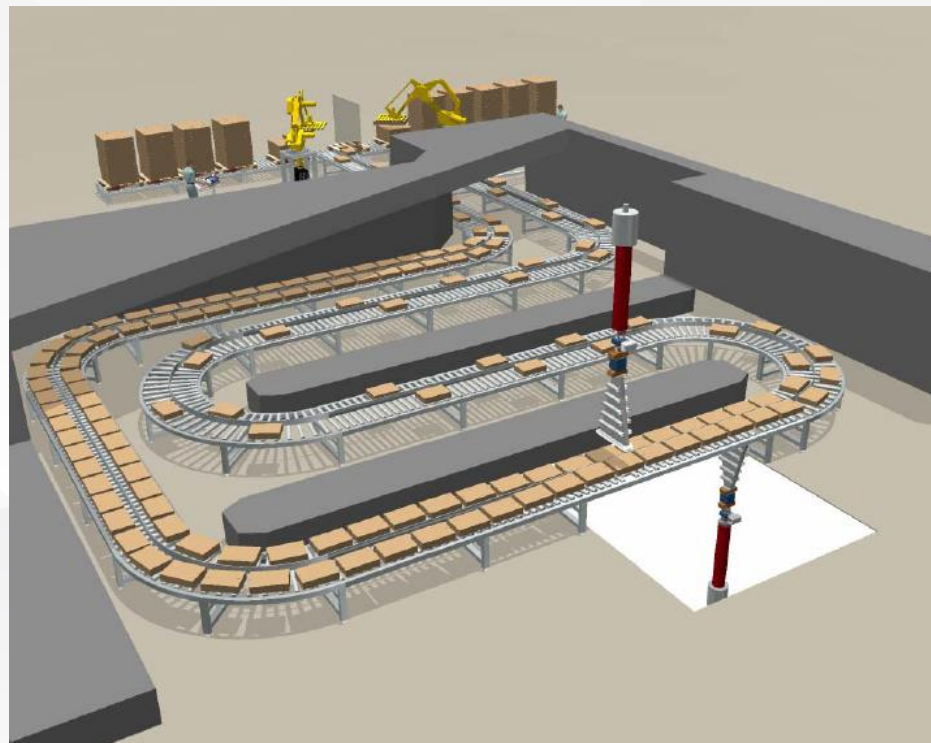
- 电离辐射的热效应非常小，属于“冷消毒”，常用于食品、化妆品和医疗器械等的加工
- 对于食物还能抑制发芽并延迟成熟；辐照在常温下进行，因此还可以保留原有风味并增加品质



➤ 辐照消毒与加工

❖ 消毒灭菌

- 电离辐射的热效应非常小，属于“冷消毒”，常用于食品、化妆品和医疗机械等的加工
- 对于食物还能抑制发芽并延迟成熟；辐照在常温下进行，因此还可以保留原有风味并增加品质



➤ 辐照消毒与加工

❖ 辐照改性

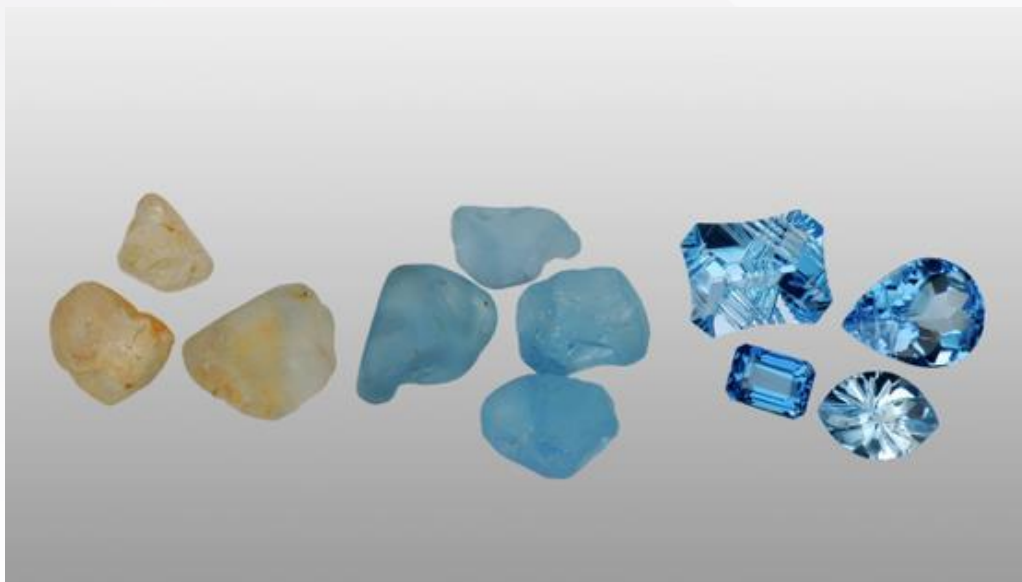
- 应用范围包括：增加材料的强度、绝缘性和隔热性，用于橡胶加工、电缆、热缩管、复合材料、凝胶等领域



➤ 辐照消毒与加工

❖ 辐照改性

- 应用范围包括：增加材料的强度、绝缘性和隔热性，用于橡胶加工、电缆、热缩管、复合材料、凝胶等领域



宝石改色

TABLE 2. Effects of irradiation treatment on various gem materials.^a

Material	Starting color	Ending color
Beryl	Colorless Blue	Yellow Green
Maxixe-type	Pale or colorless	Blue
Corundum	Colorless Pink	Yellow Padparadscha
Diamond	Colorless or pale to yellow and brown	Green or blue (with heating, turns yellow, orange, brown, pink, red)
Fluorite	Colorless	Various colors
Pearl	Light colors	Gray, brown, "blue," "black"
Quartz	Colorless to yellow or pale green	Brown, amethyst, "smoky," rose
Scapolite ^b	Colorless, "straw," pink, or light blue	Blue, lavender, amethyst, red
Spodumene	Colorless to pink	Orange, yellow, green, pink ^c
Topaz	Yellow, orange Colorless, pale blue	Intensify colors Brown, blue (may require heat to turn blue), green
Tourmaline	Colorless to pale colors Blue	Yellow, brown, pink, red, bicolor green-red Purple
Zircon	Colorless	Brown to red

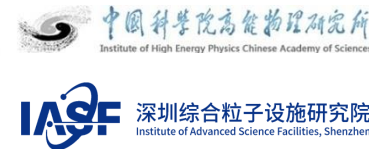
^aAdapted from Nassau (1984).

^bCharles Key, pers. comm., 1988.

^cGeorge Drake, pers. comm., 1988.



中山大學
SUN YAT-SEN UNIVERSITY



中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences
IASF 深圳综合粒子设施研究院
Institute of Advanced Science Facilities, Shenzhen



其它应用

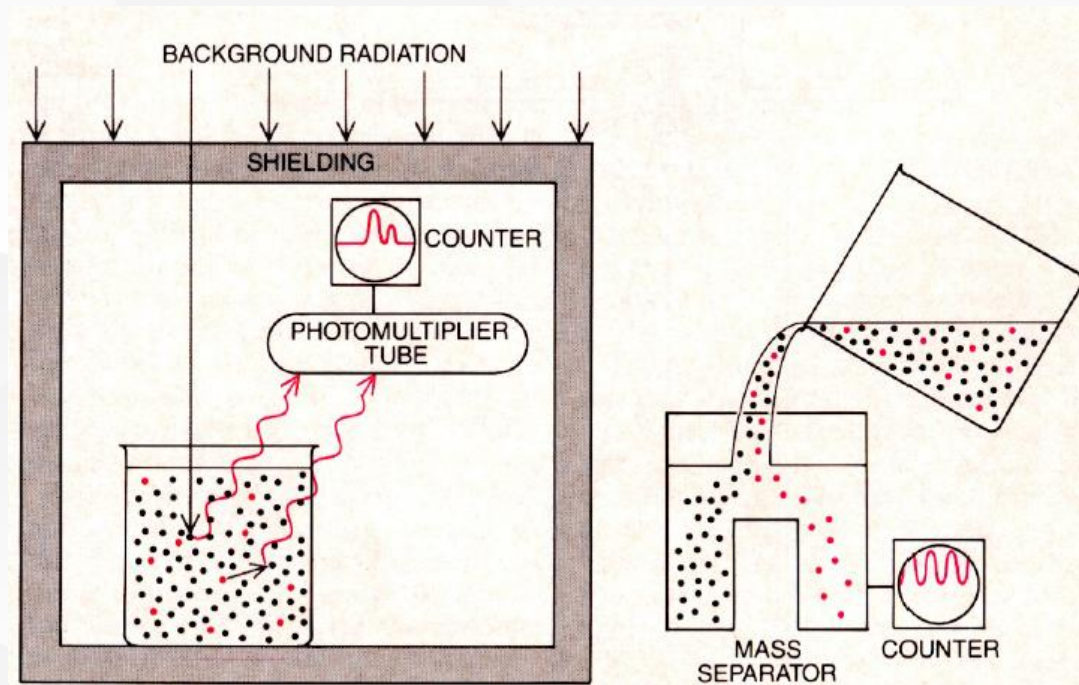
仅涵盖整个低能加速器应用领域的一小部分

➤ 文化领域：考古断代

- ❖ 加速器质谱技术：探测丰度极低的同位素
- ❖ 对样品材料进行加速，在质谱仪中分析样品组成
- ❖ $^{14}_6\text{C}$ 参数
 - 半衰期： $T_{1/2} = 5730 \pm 40 \text{ yr}$
 - 天然丰度： $\frac{^{14}\text{C}}{\text{C}} = 1.2 \times 10^{-12}$
 - 天然放射性： $226 \pm 1 \text{ Bq/kg}$

➤ 示例

- ❖ 1 mg样品，达到5‰精度
- ❖ 放射计数法需要七年计数时间
- ❖ 加速器质谱仅需1小时计数时间

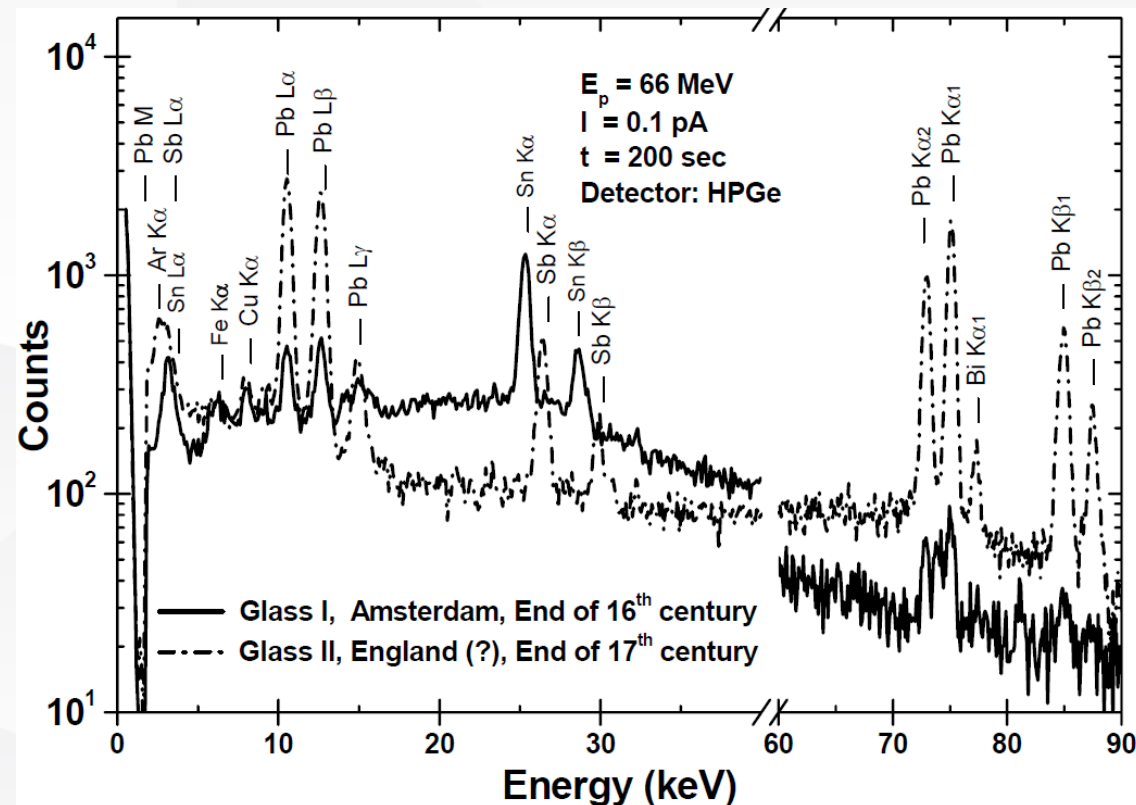


文化领域：材料分析

- ❖ 利用加速器产生的高速离子，配合质子激发X射线荧光分析、卢瑟福背散射等方法，无损分析物体表面材料



A. Denker, CAS 2005



► 文化领域

❖ 一般采用直流高压加速器



卢浮宫博物馆，2 MeV直流高压加速器