



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

粒子加速器原理

~加速器的发展及基本理念概述~

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01

静电加速器

Electrostatic Accelerators

➤ 什么是加速器

带电粒子加速器，是将带电粒子能量提高的装置或设施。

➤ 什么是加速器物理

研究与带电粒子加速器相关的基本加速原理和方式、束流运动和加速器设计相关的学科。

➤ 什么是束流动力学

描述和研究带电粒子在电磁场中的运动特性的理论及方法。

➤ 什么是加速器技术

围绕带电粒子加速器的工程实践需求而发展起来的一系列学科，例如粒子源、加速结构、磁铁、控制、真空、束流测试、辐射防护等学科。

➤ 什么是加速器应用

以加速器为基础，直接或间接利用束流开展的一系列应用研究。直接利用束流的比如说对撞机，肿瘤治疗等，间接利用束流的比如散裂中子源、辐射探测、同步辐射和自由电子激光等。

天然放射性的发现 Radioactivity



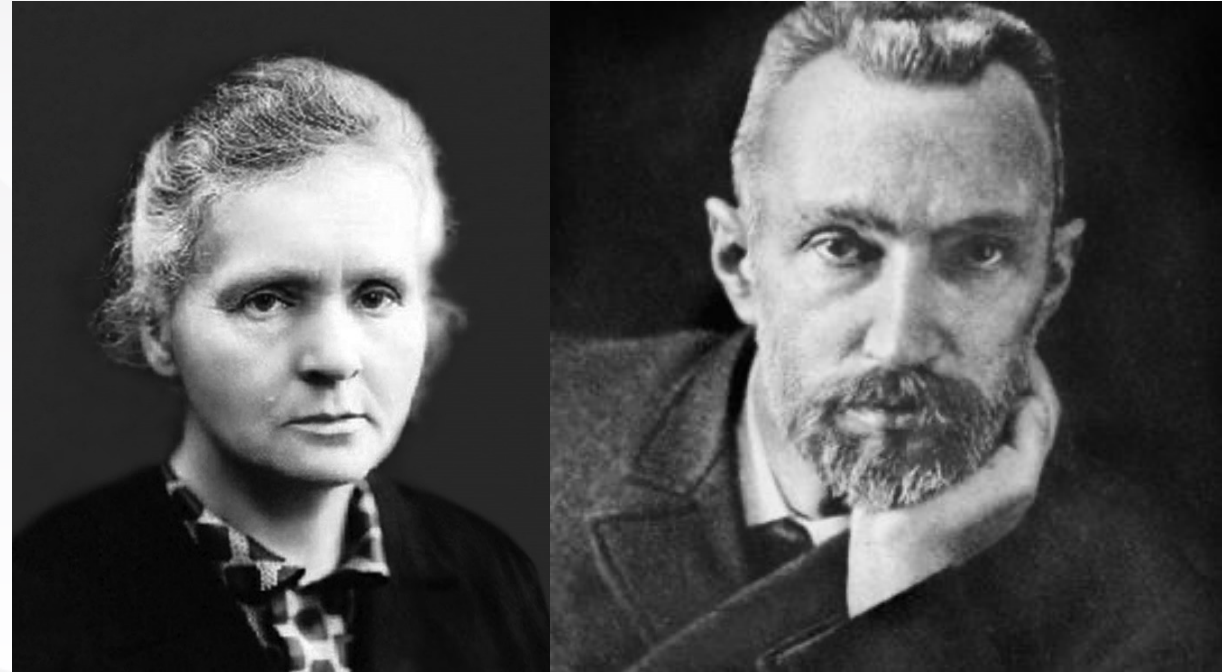
亨利·贝克勒尔
Henri Becquerel
(1852-1908)

天然放射性

α	He^+	正电
β	e	负电
γ	γ	电中性

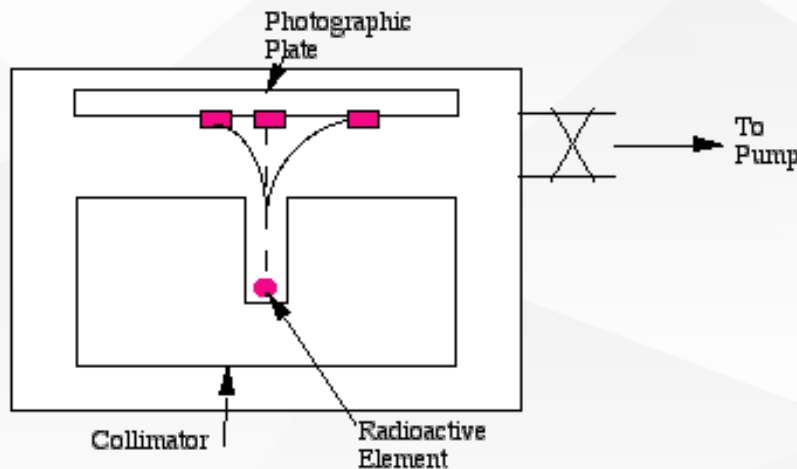


1903 诺贝尔奖



居里夫妇
Marie Curie & Pierre Curie
(1867-1934, 1859-1906)

Polonium(Po-84) & Radium(Ra-88), 1898





卢瑟福
Ernest Rutherford
(1871–1930)

1908 诺贝尔奖

我一直希望能找到一个比天然放射性物质发出的粒子更具能量的正粒子源

-- 卢瑟福, 1928

"I have long hoped for a source of positive particles more energetic than those emitted from natural radioactive substances."

如何加速带电粒子

带电粒子电荷 (离子源)



$$K = q \cdot V = q \cdot E \cdot d$$

获得的能量

电压

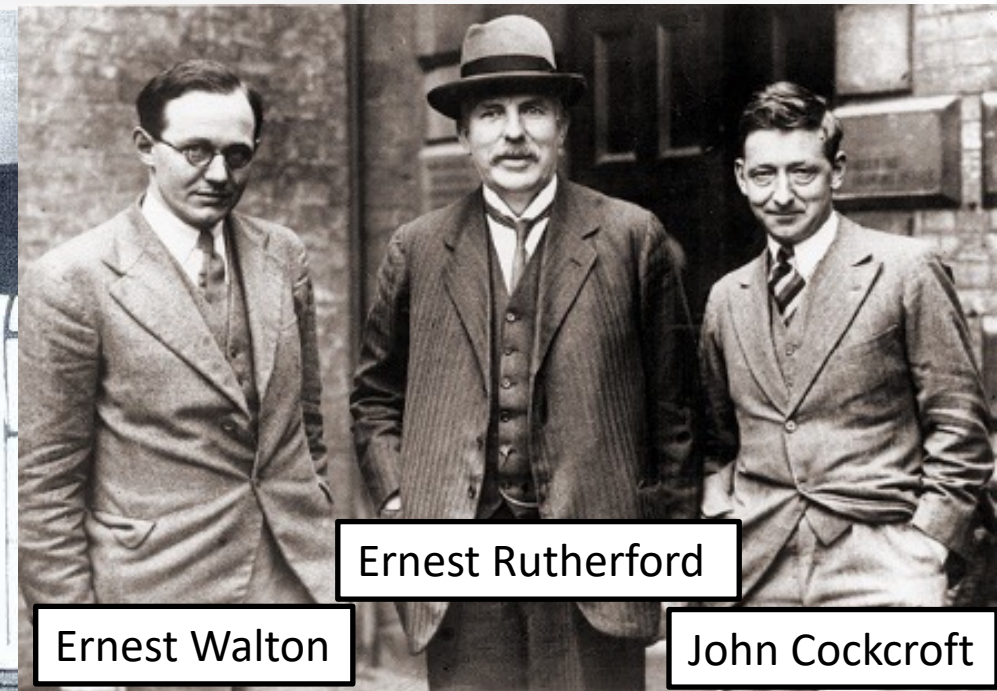
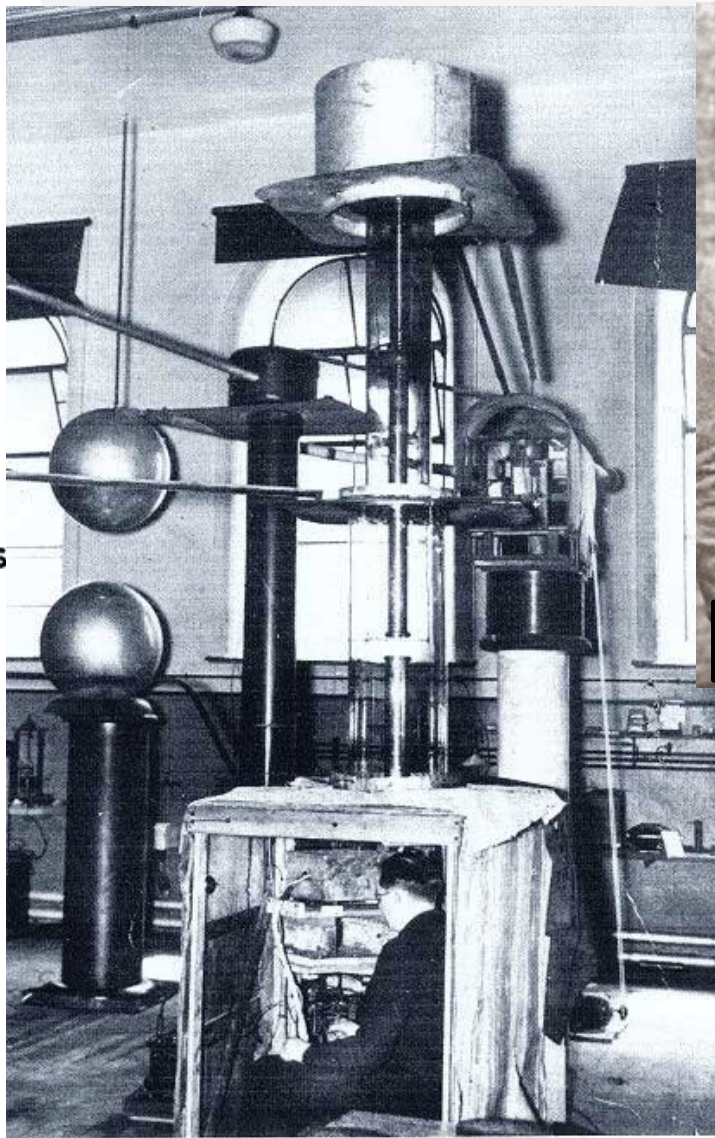
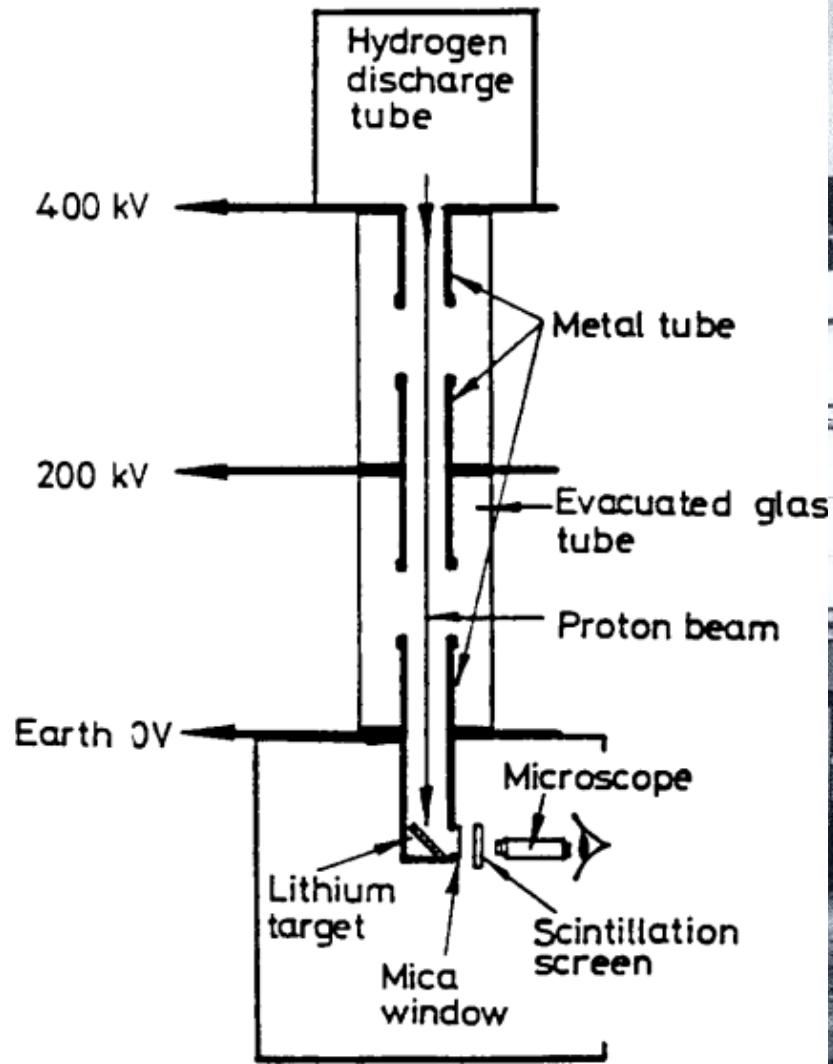
电场 距离

(加速方式, 加速结构)

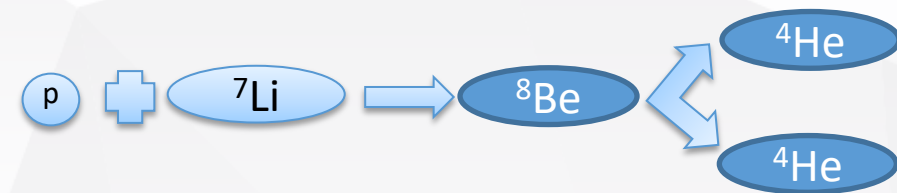


有哪些可以用于加速带电粒子的方法?

静电加速器 Cock-Croft Voltage Multiplier



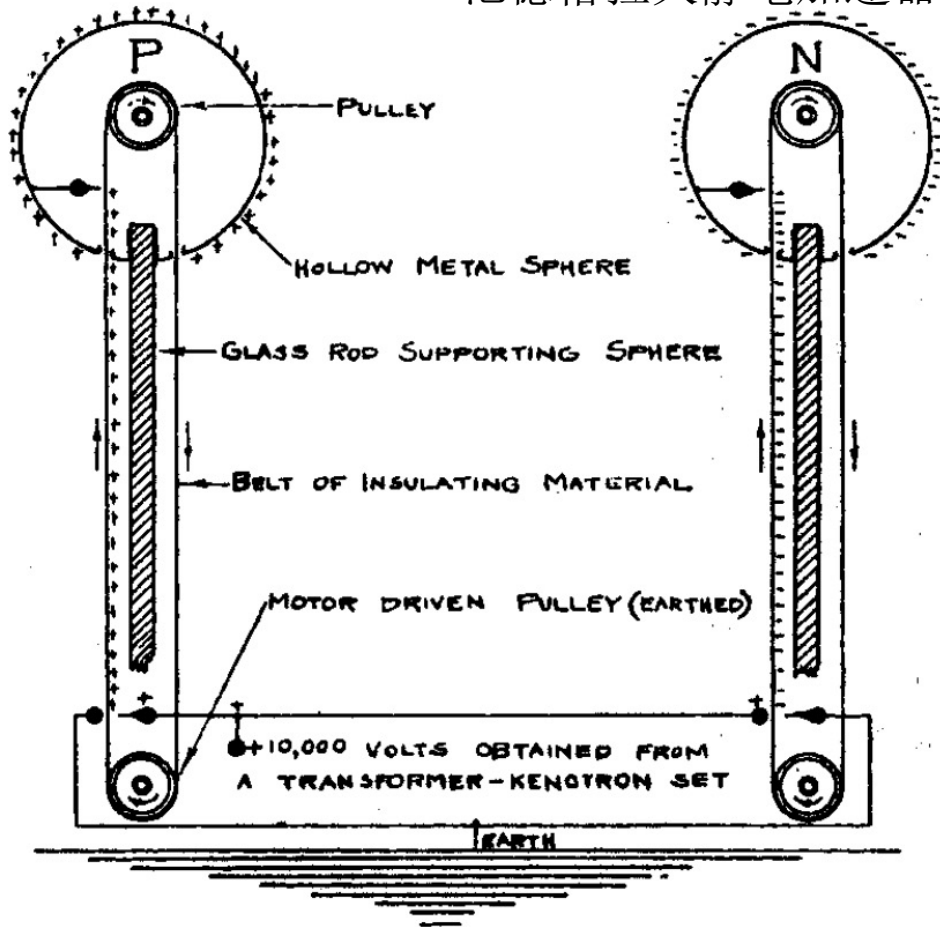
1951 诺贝尔奖



静电加速器 Van De Graaff Generator

“丝绸摩擦的玻璃棒带正电，毛皮摩擦的橡胶棒带负电”

范德格拉夫静电加速器



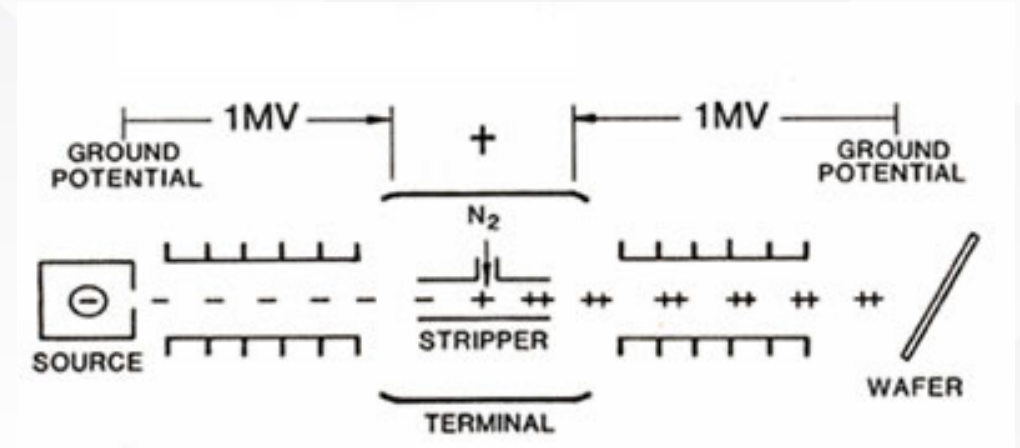
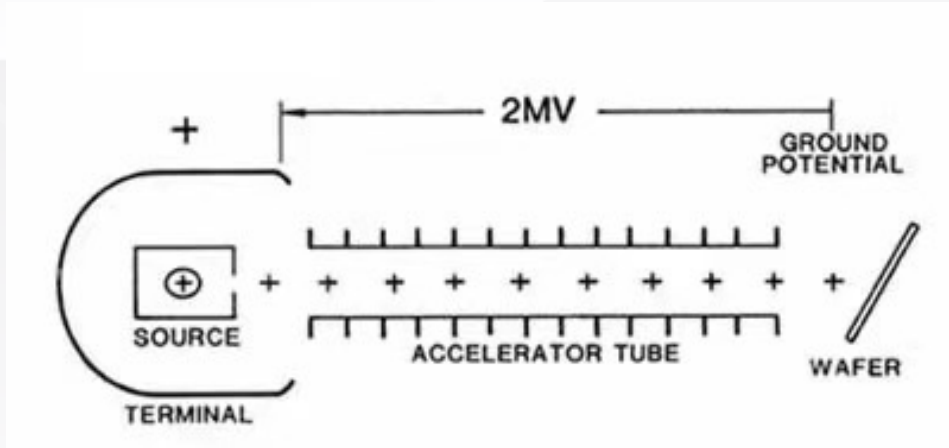
MIT

THE GENERATOR IN THE HANGAR AT ROUND HILL

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Robert J. Van De Graaff, Rhys. Rev., vol. 43, 149

▶▶ 静电加速器 Pelletron & Tandem Accelerator



静电加速器的能量上限?



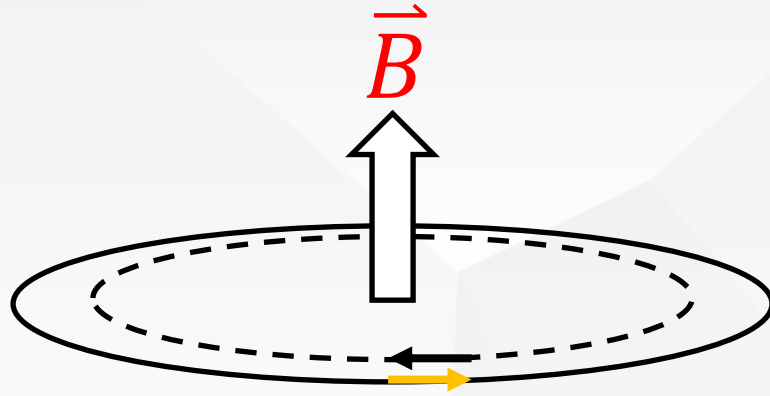
02

感应加速器

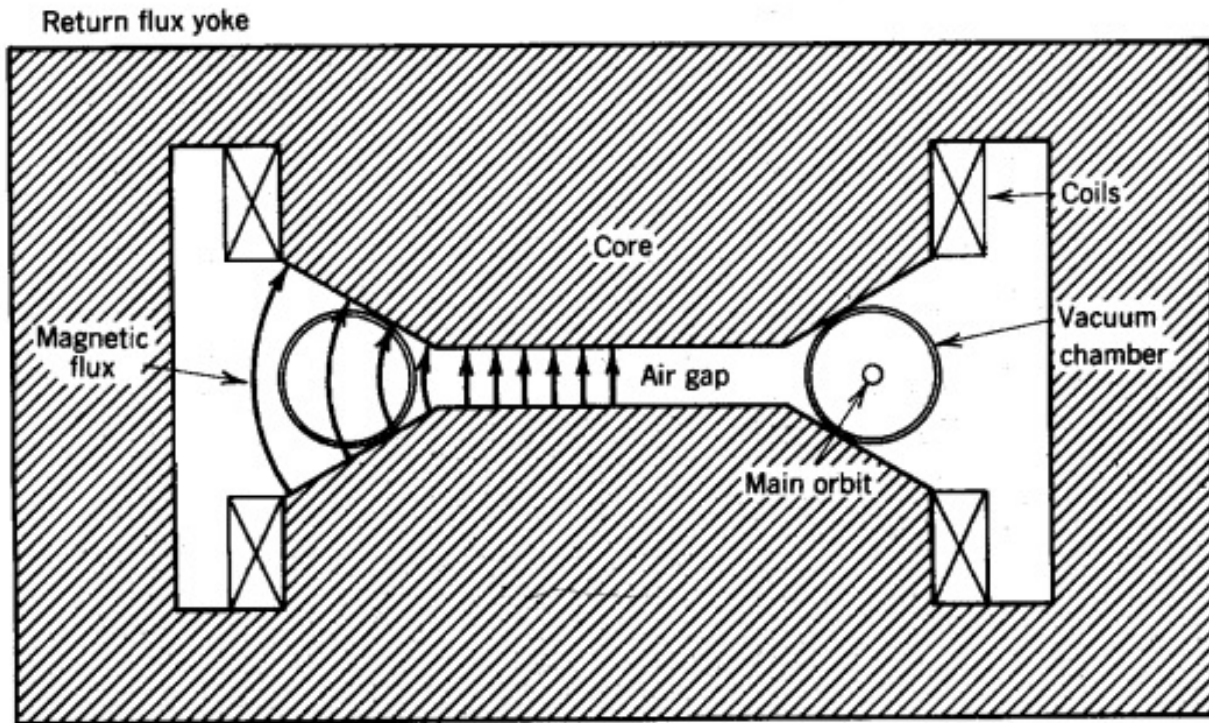
Induction Accelerators

电磁感应定律: Betatron

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$



Donald William Kerst
(1911–1993)



1939



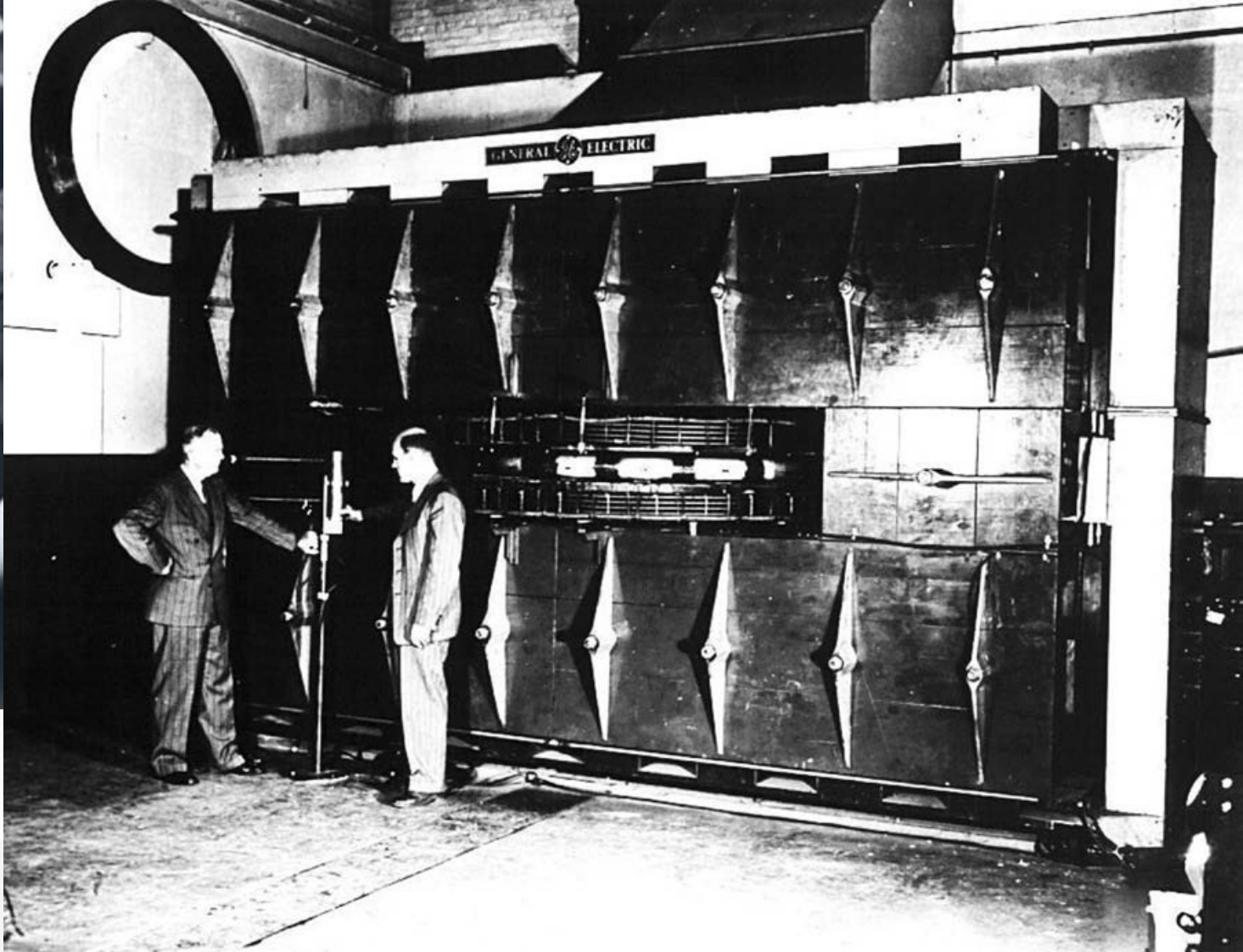
积分形式?

电磁感应定律: Betatron



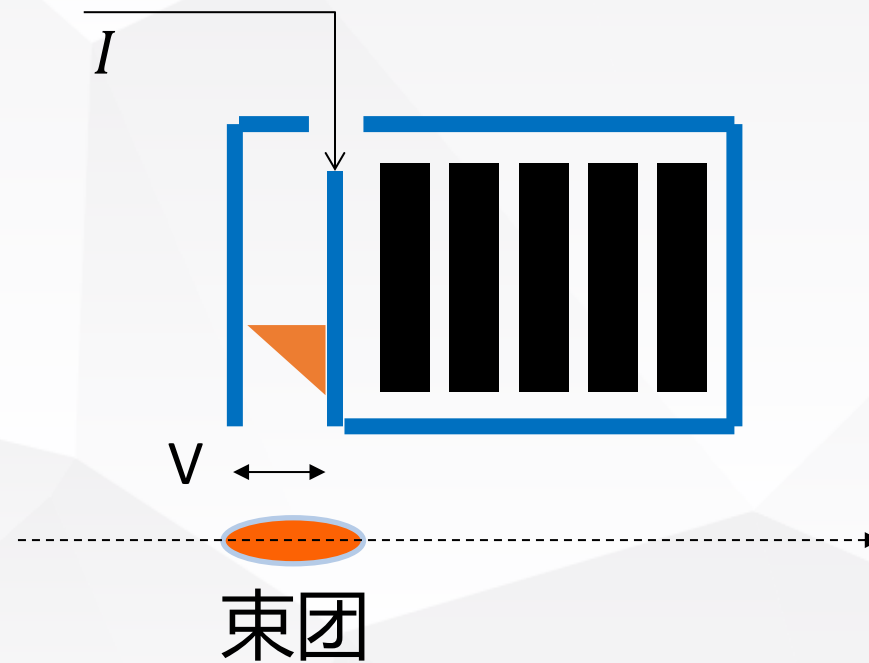
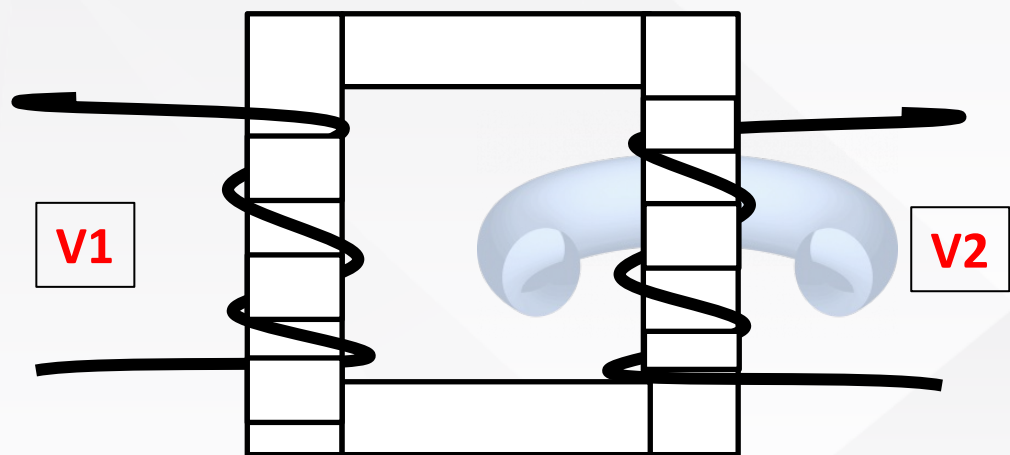
D. Kerst和第一个Betatron
伊利诺伊斯大学1940

能量上限?



100 MeV betatron, 1940s, General Electric Laboratories

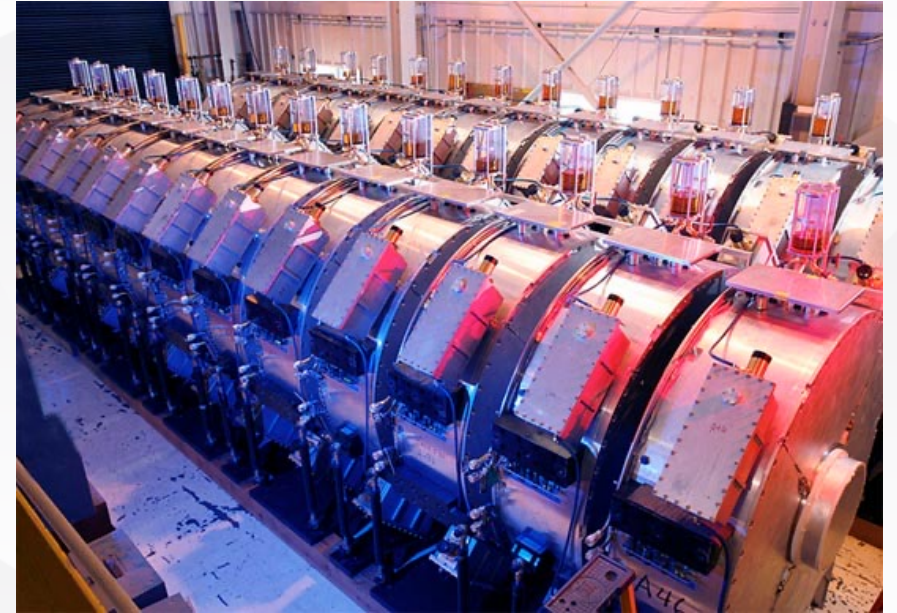
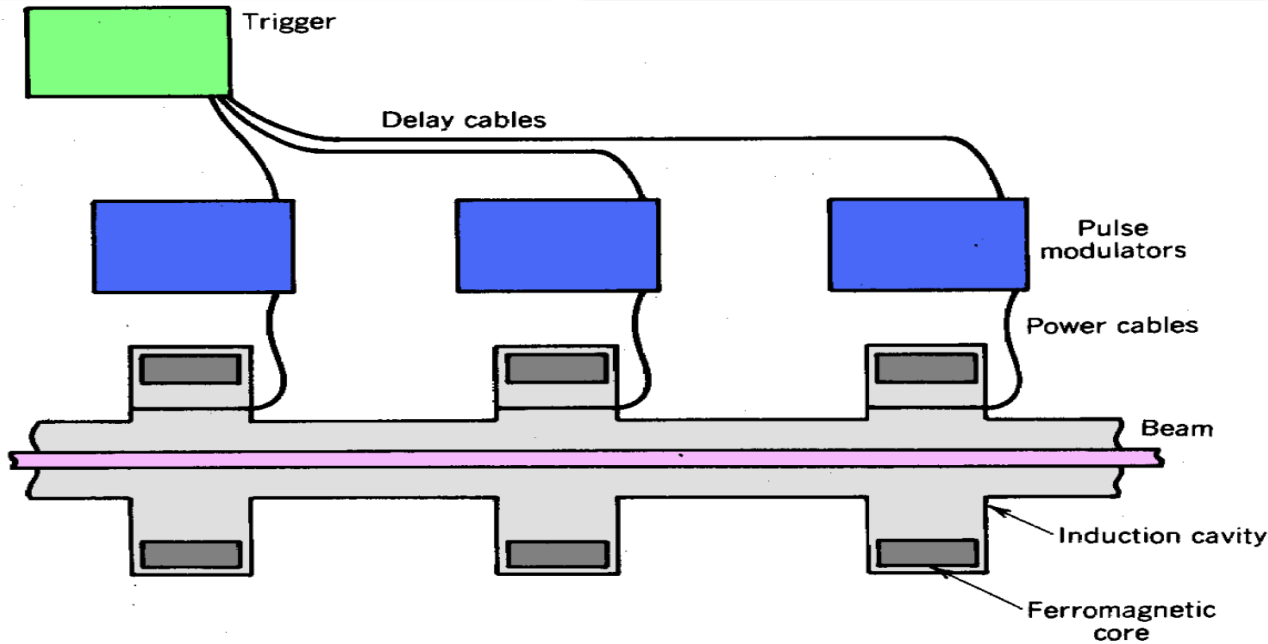
电磁感应定律：直线感应加速器 Linear Induction Accelerator



描述右侧在加速间隙产生加速电压 V 的机制？

电磁感应定律：直线感应加速器 Linear Induction Accelerator

可连续进行加速



- | | |
|----------------------------|-----------|
| 美国, LLNL, 350A 3.5MeV e-, | ~1960 |
| 美国, LLNL, 2kA, 20MeV | ~1999 |
| 法国, CEA, 1.9~3.5kA, 20MeV, | ~1999 |
| 中国, CAEP-IFP, 3kA, 20MeV, | 2005/2015 |

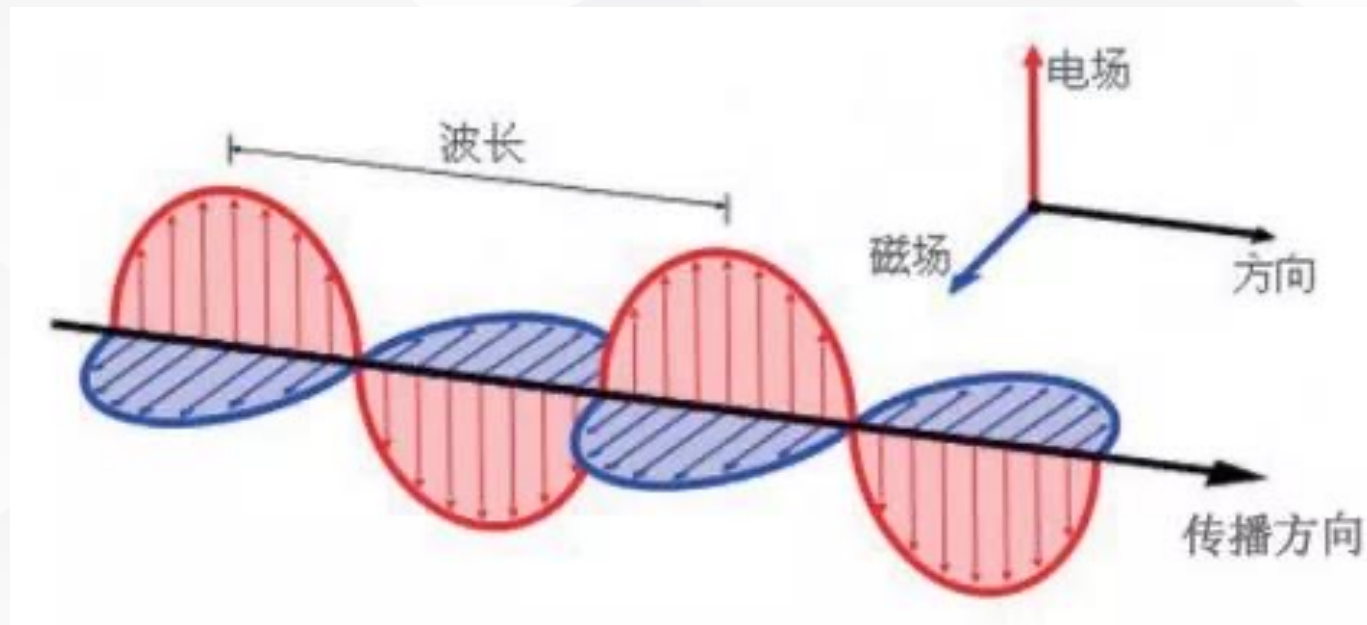
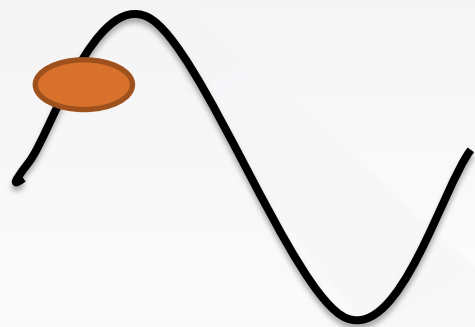


03

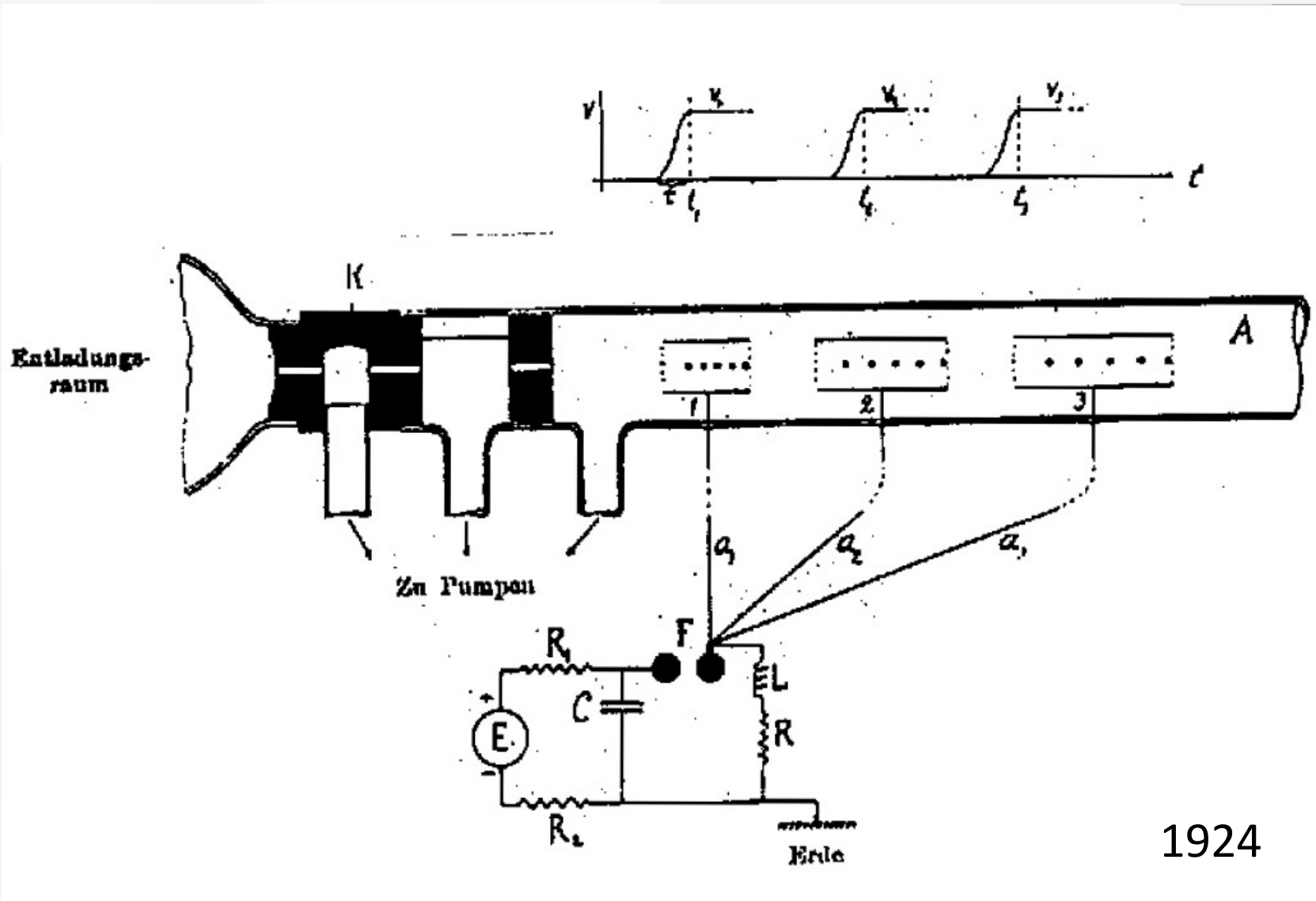
射频加速器

RF Accelerators

➤ 电磁波: Electromagnetic wave



“交变电压” AC Voltage



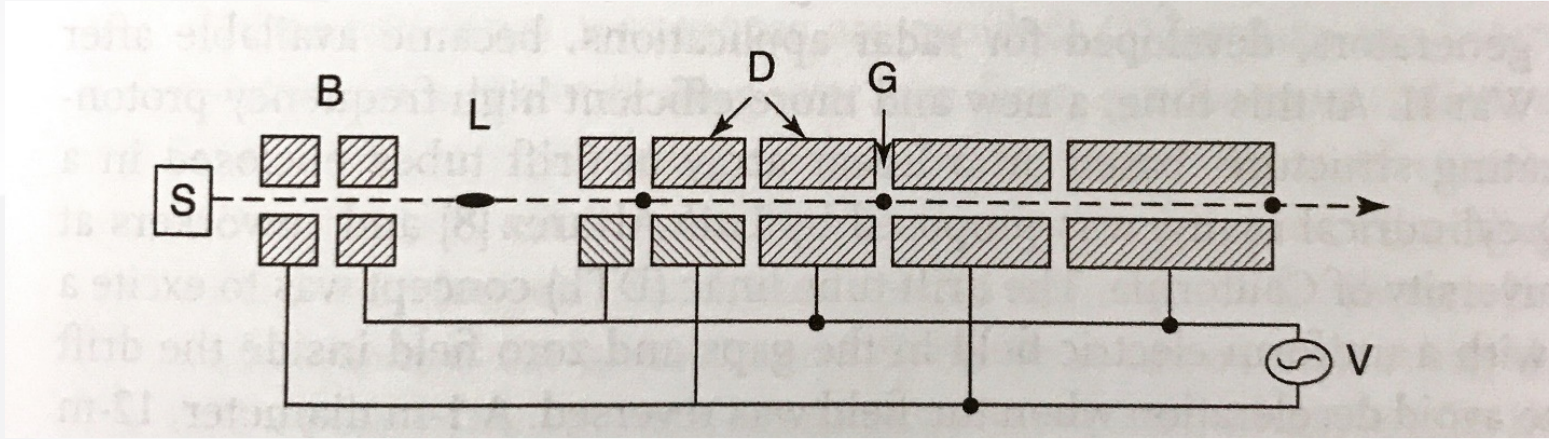
1924



GUSTAF ISING

Gustaf Ising
(1883-1960)

“交变电压” AC Voltage



Rolf Wideroe (Betatron失败了 1922-1926 柏林)

D.Sloan & E. Lorence, 90 keV – 200 keV – 1.2 MeV, 1930s

Rolf Wideroe
(1902-1996)

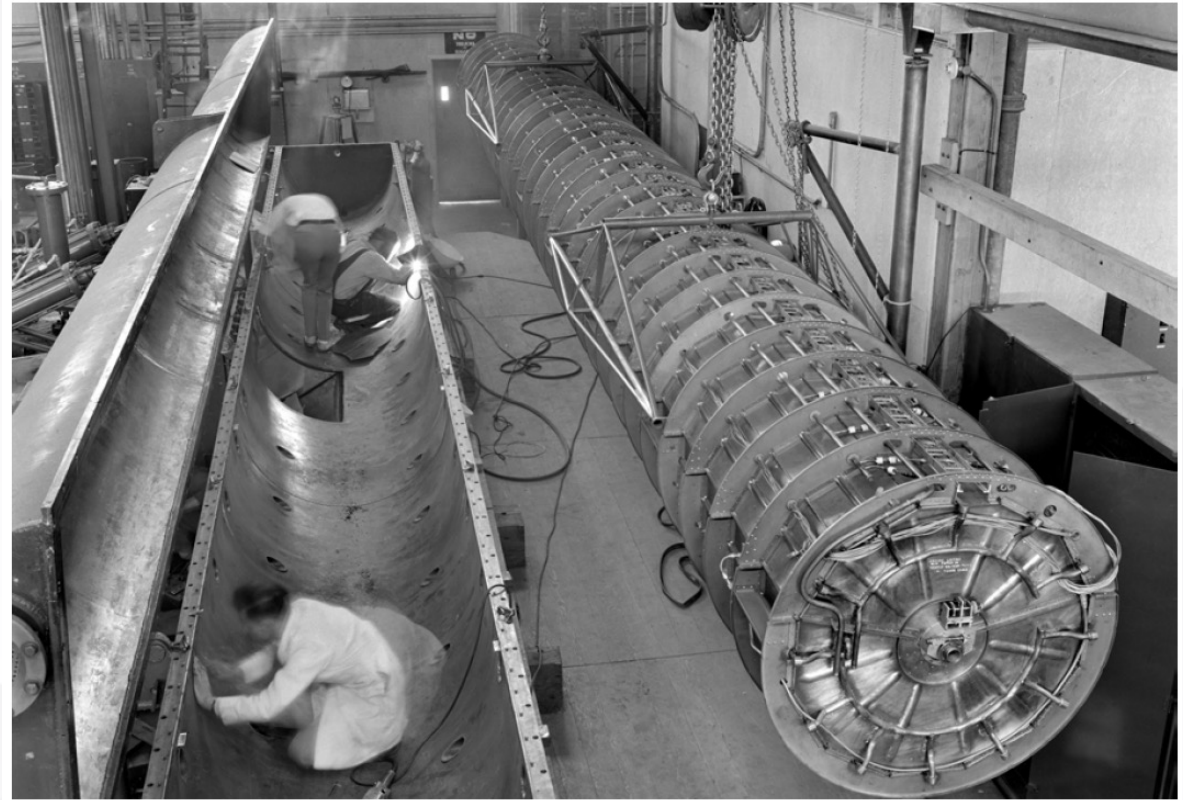
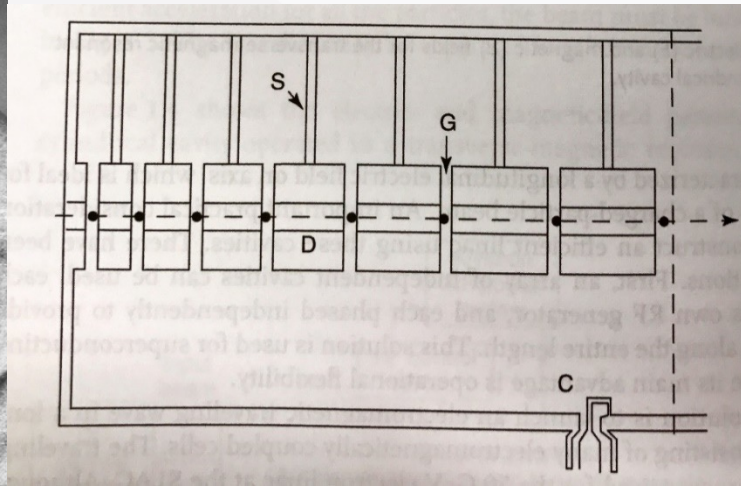


为何图上的“管子”越来越长？

▶▶ 漂移管加速器 Drifting Tube Linac



Luis W. Alvarez
(1911–1988)

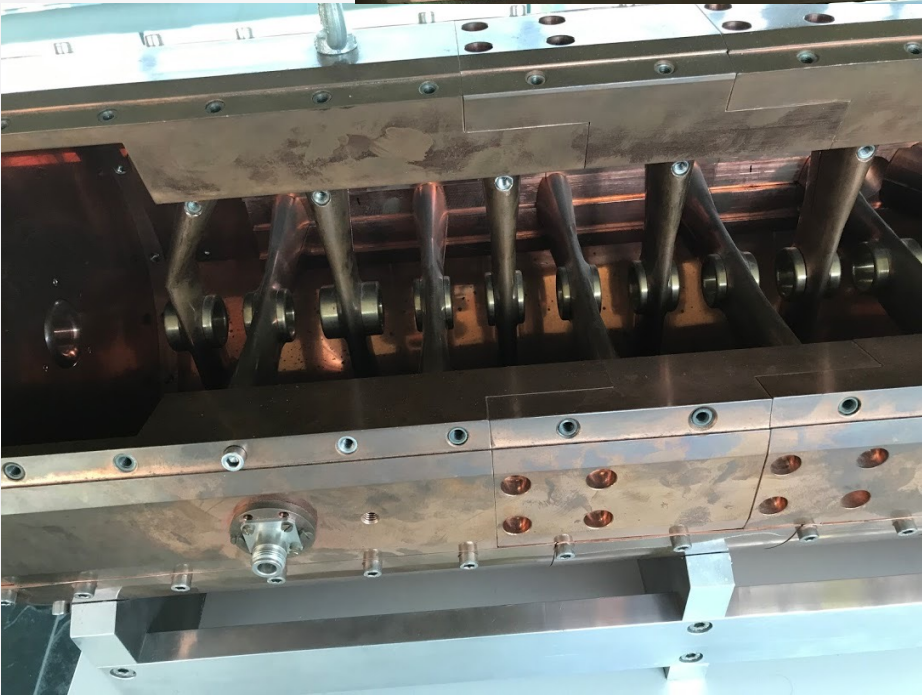
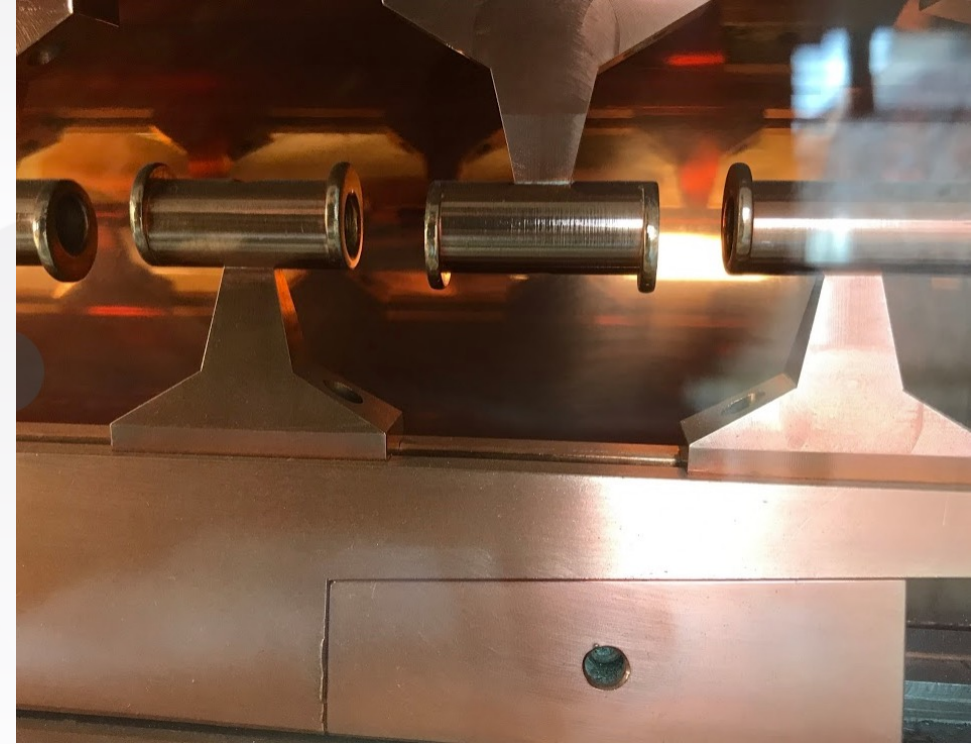


1ST Alvarez LINAC

L. Alvarez, RF resonant cavity
drift tube linac (DTL), 32 MeV proton, 1948

功率源Klystron, 1937

▶▶ 漂移管加速器 Drifting Tube Linac

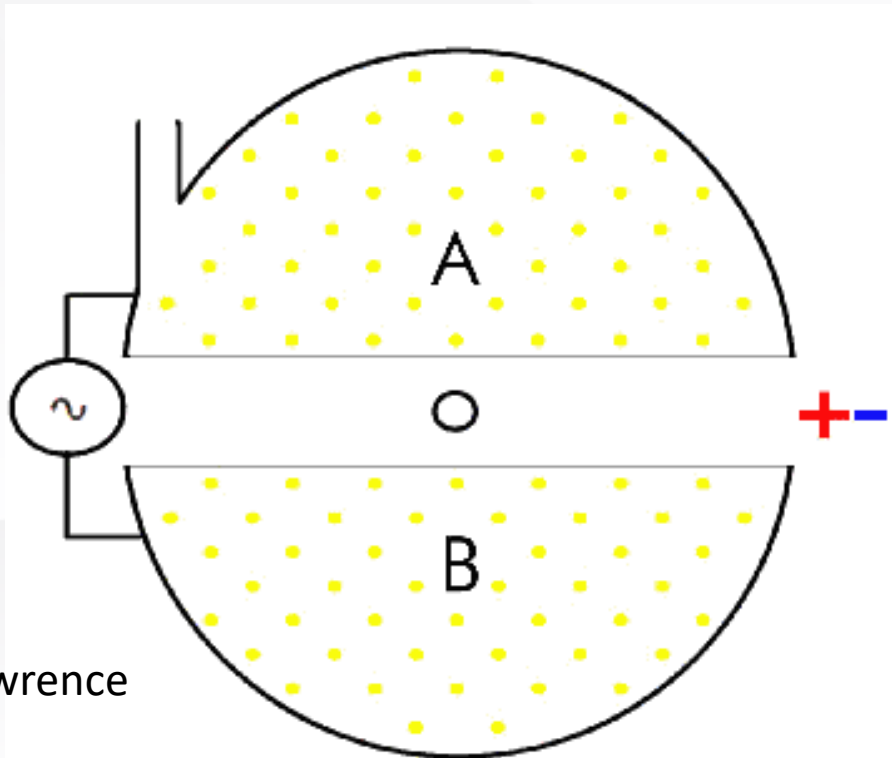


DTL的能量限制?

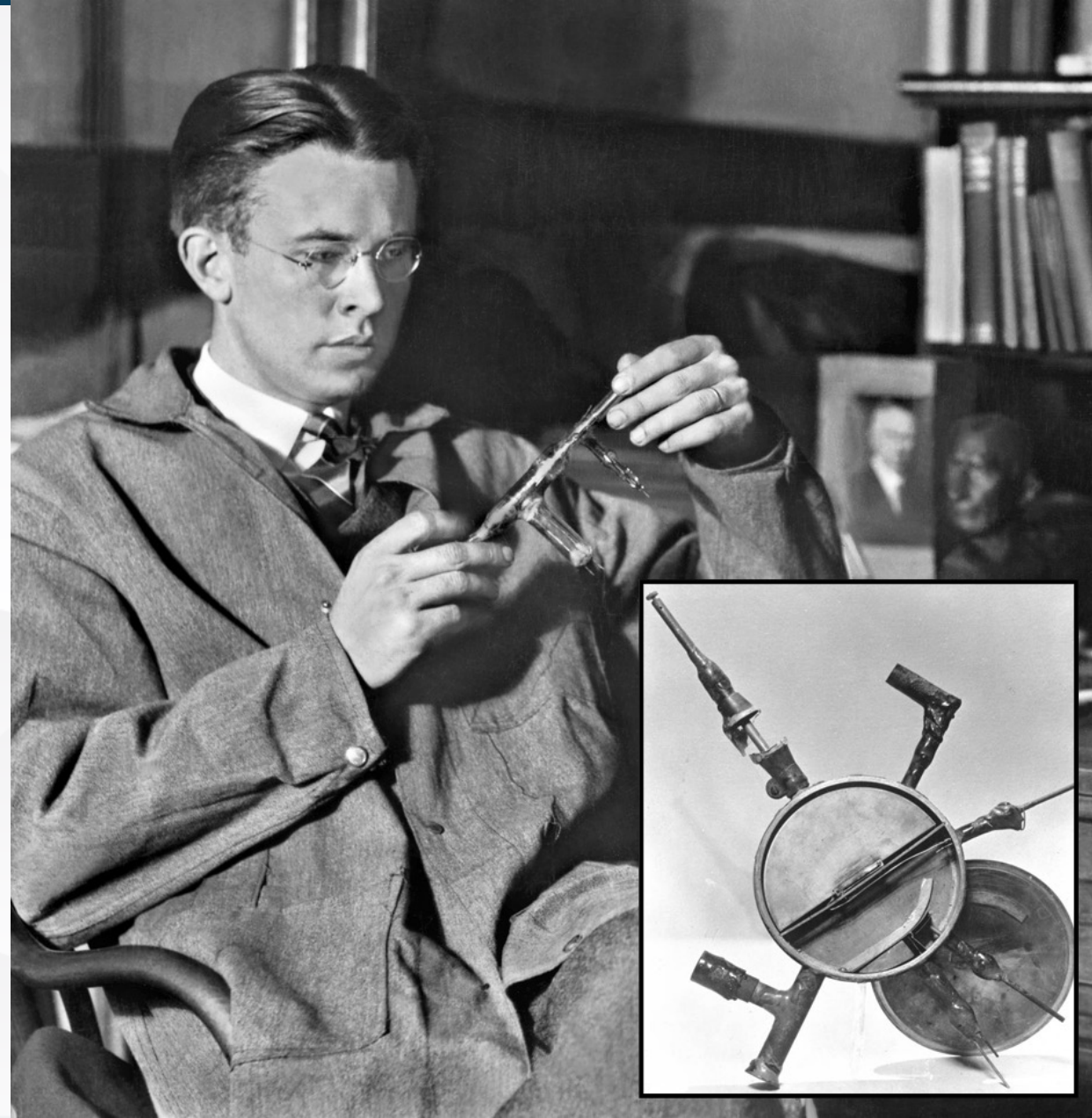
回旋加速器: Cyclotron

➤ 把直线加速器卷起来?

$$m \frac{v^2}{r} = qvB \rightarrow \omega = \frac{v}{r} = \frac{qB}{m}$$



Ernest Orlando Lawrence
(1901–1958)



➤ 回旋加速器: Cyclotron

"Lawrence was my teacher when I built the first cyclotron — he got a Nobel Prize for it — I got a PhD."

E. Lawrence

Sloan

Wideroe's idea

90 keV – 200 keV – 1.2 MeV

1930



Livingston circular idea:

80 kV(4 inch)-1.22 MeV(11 inch)-27in-37in-60in



Milton Stanley Livingston
(1905–1986)

同步加速器 Synchrotron

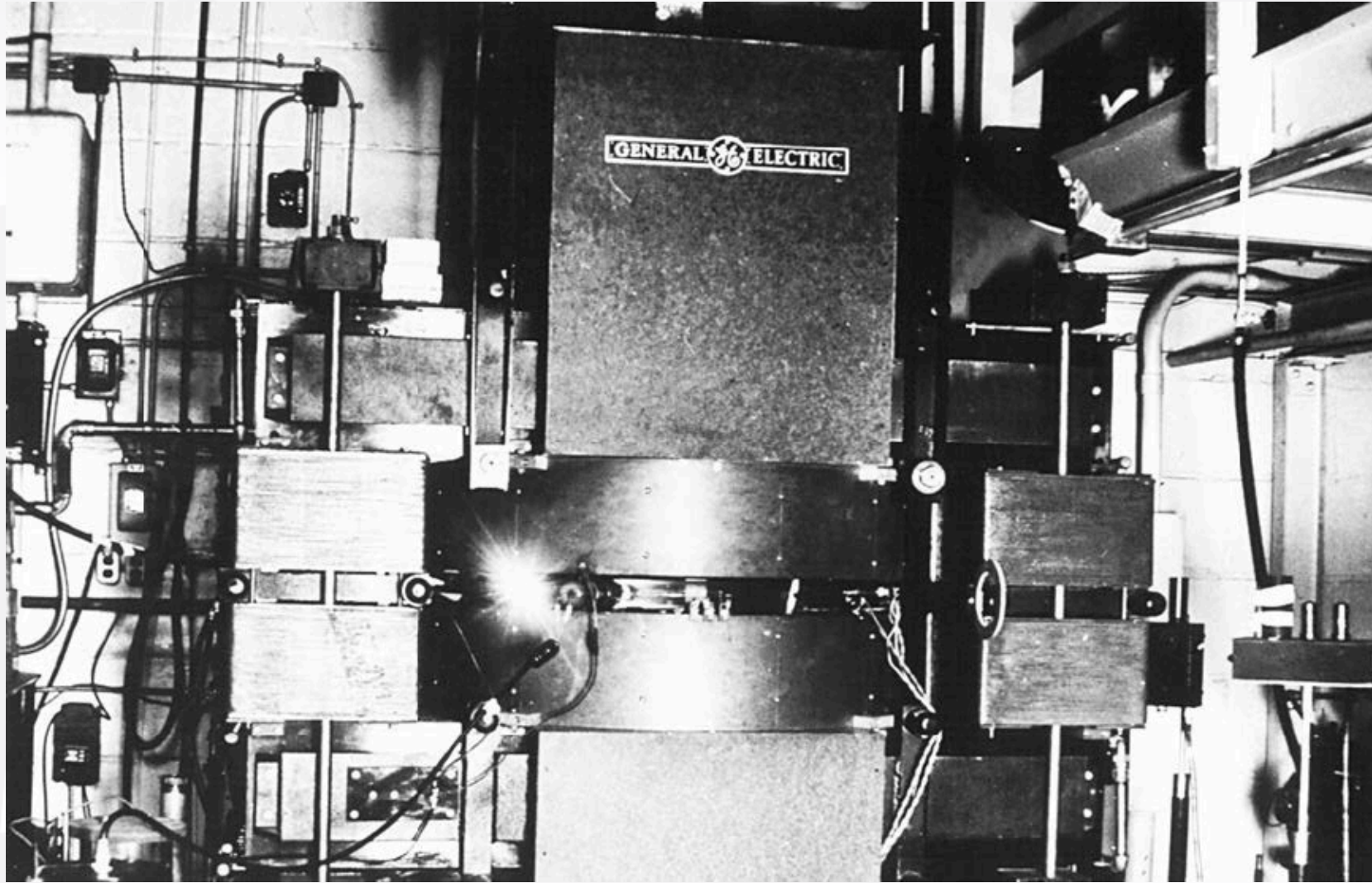
Particles should be constrained to move in a circle of constant radius thus enabling the use of an annular ring of magnetic field... which would be varied in such a way that the radius of curvature remains constant as the particles gain energy through successive accelerations by an alternating electric field applied between coaxial hollow electrodes.

$$m \frac{v^2}{r} = qvB \rightarrow r = \frac{p}{qB} \longrightarrow \begin{array}{l} \text{Synchrotrons} \\ \text{同步加速器} \end{array}$$



Marcus Oliphant
(1901–2000)

同步加速器 Synchrotron



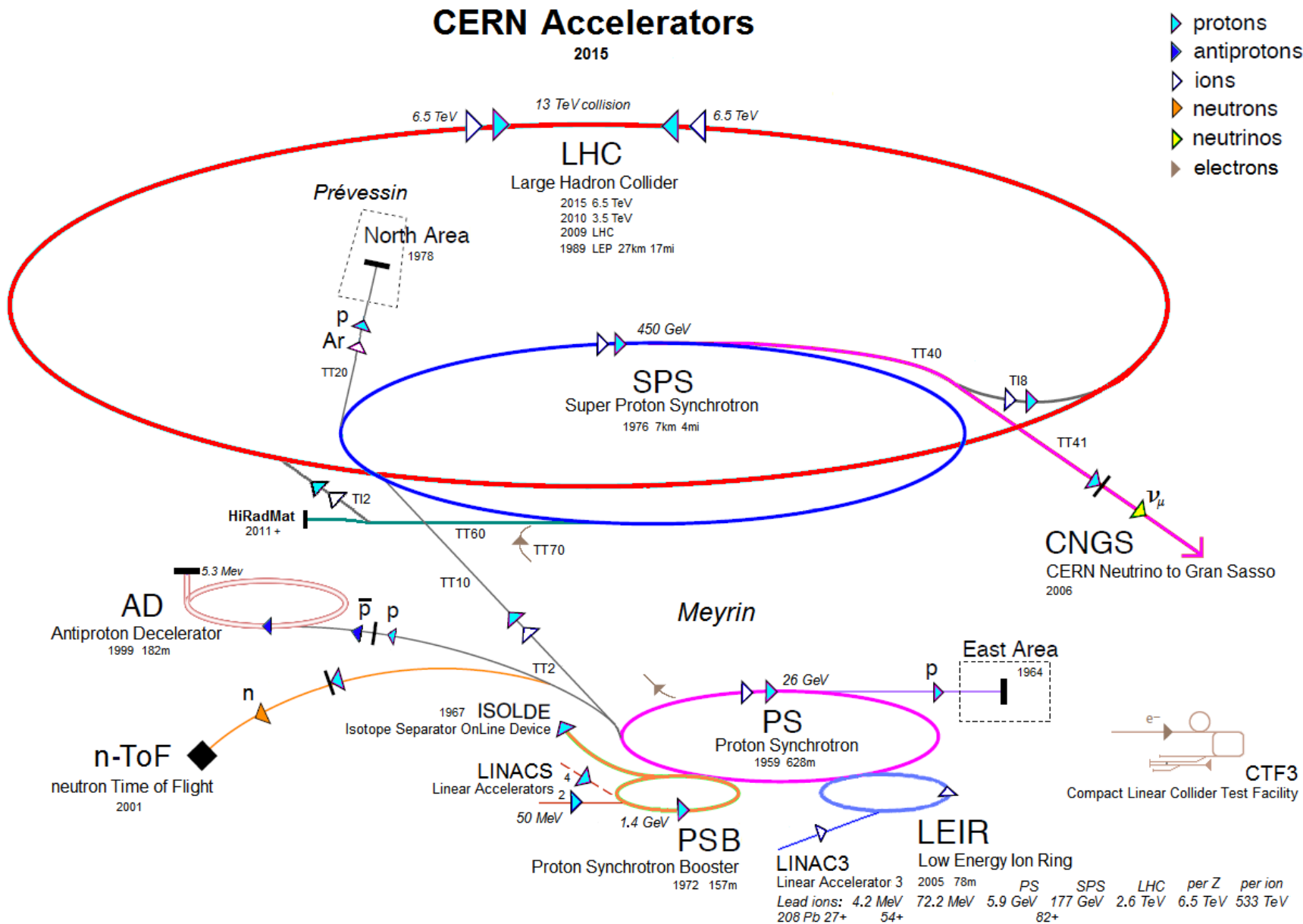
300 MeV electron synchrotron at the General Electric Co. 1940s



同步加速器的能量限制?

同步加速器 Synchrotron

级联加速





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SCHOOL OF SCIENCE, SUN YAT-SEN UNIVERSITY

04

新型加速原理

Novel Accelerators

➤ (激光) 等离子体尾场加速: Laser Plasma Wakefield Accelerator



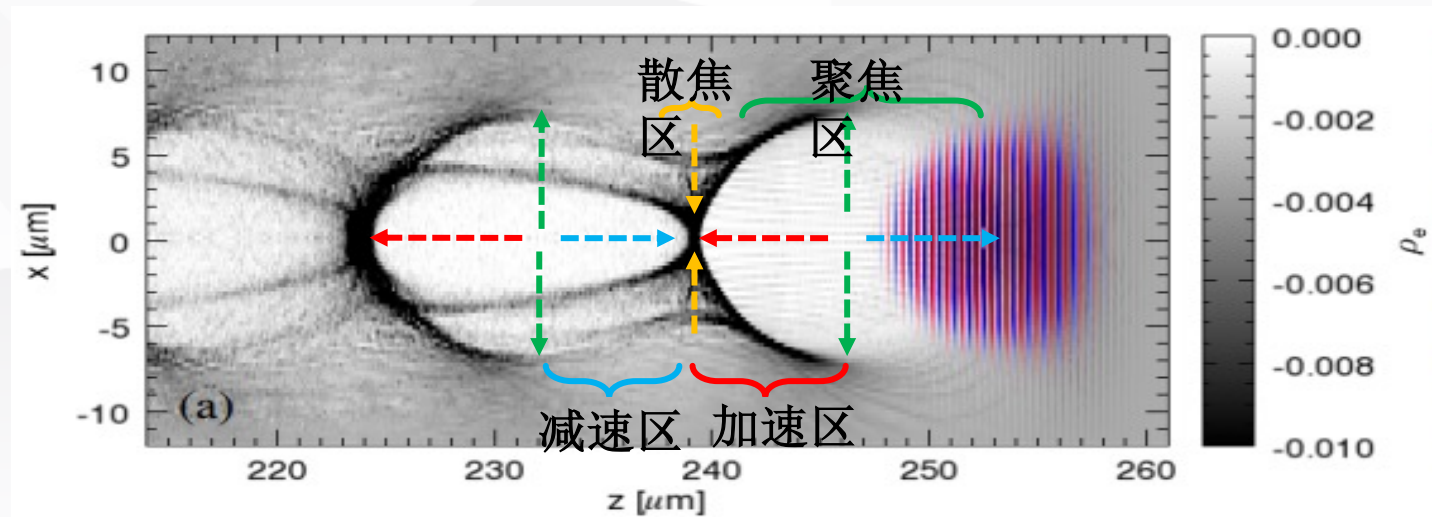
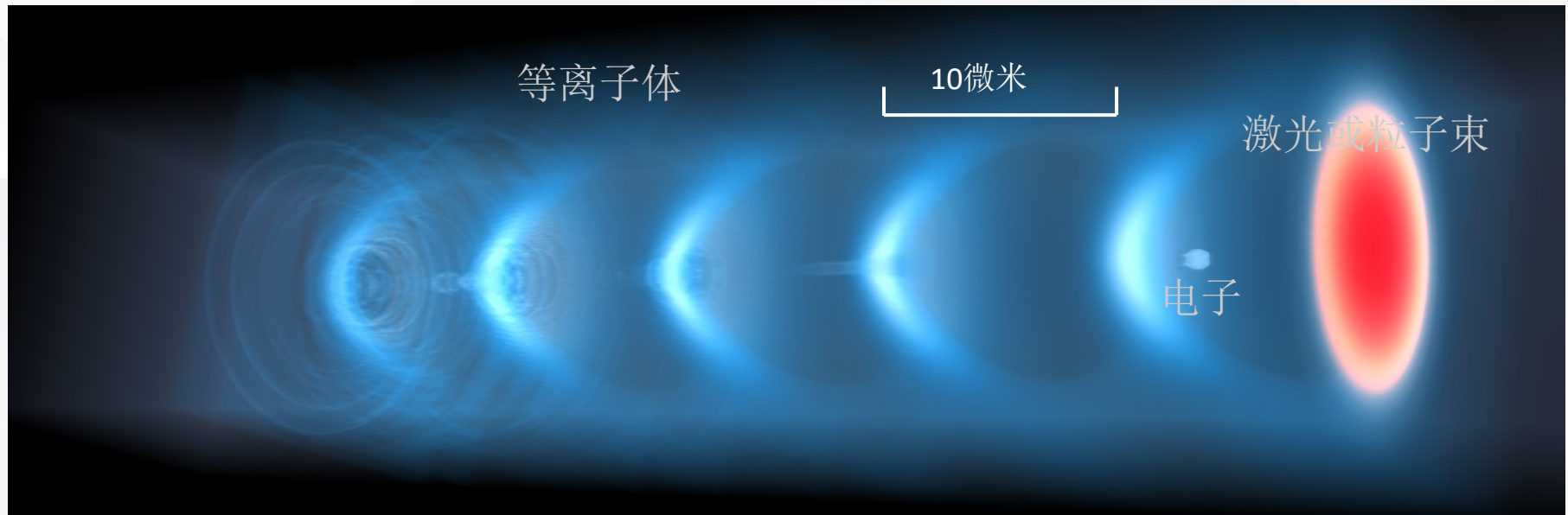
1979年, Tajima & Dawson提出LWFA;

1985年, P. Chen等人提出PWFA;

2016年, PWFA, 等离子体长度85 cm, 使42 GeV的电子束能量翻倍, 最大加速梯度52 GeV/m;

2019年, LWFA, 等离子体长度20 cm, 最大能量7.8 GeV, 5 pC。

➤ (激光) 等离子体尾场加速: Laser Plasma Wakefield Accelerator





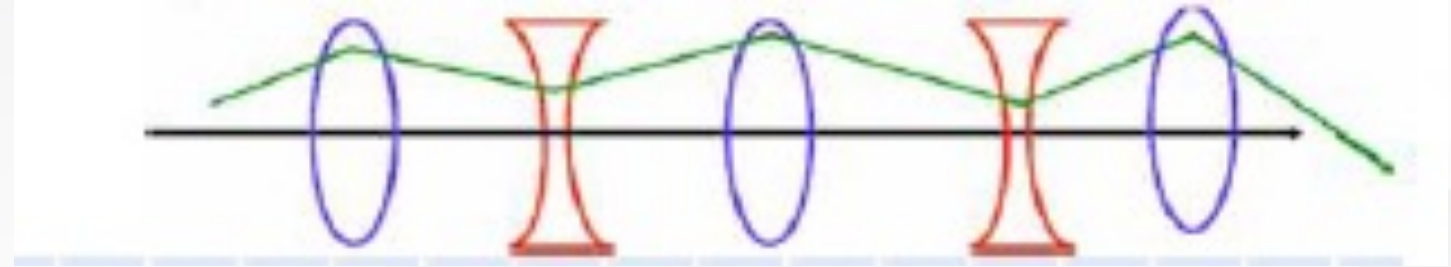
05

革命性原理

Revolutional Principles

强聚焦原理: Alternating Focusing

➤ 1952年, 美国科学家柯隆(E.D.Courant)、利文斯顿(M.S.Livingston)和史耐德(H.S.Schneider)提出



Bevatron (美国, 1954), 弱聚焦, 6.2 GeV



磁铁总重量为10000吨; 真空盒孔径超过1 m!

AGS (美国, 1960), 强聚焦, 33 GeV



磁铁总重量为4000吨

Thanks !