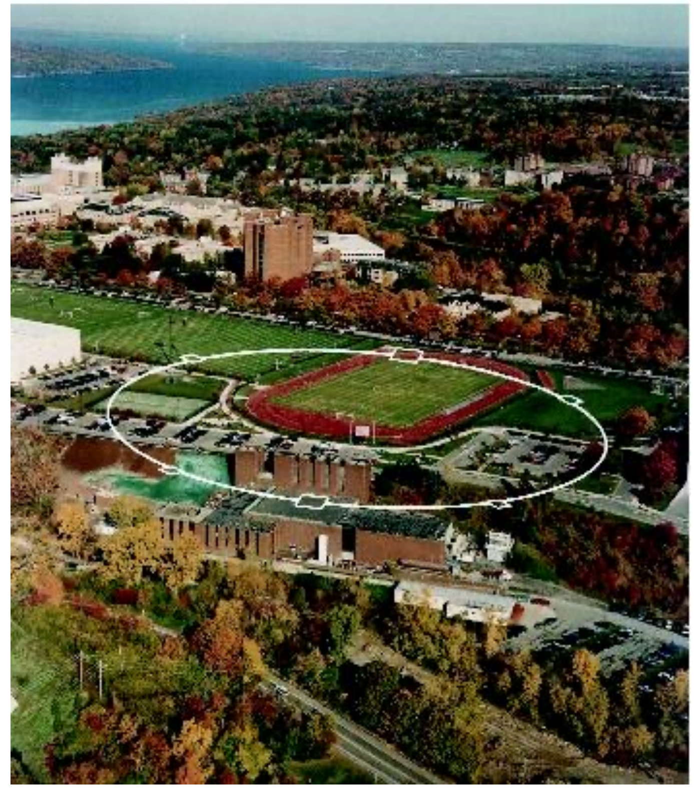
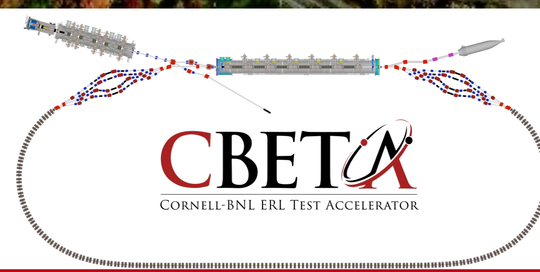
USPAS graduate Accelerator Physics

Content

1. Typical Particle Accelerators
2. Typical Accelerator Components
3. Linear Beam Optics (Circular & Straight)
4. Beam distributions
5. Nonlinear Beam Optics
6. Differential Algebra for Nonlinear Maps
7. Longitudinal Phase Space
8. Synchrotron Radiation
9. Polarization
10. Waveguides and Cavities

Accompanied by homework question and applied accelerator-optics design.





Cornell University
Brookhaven National Laboratory

Class data

Dates:

Monday – Friday June 5 – 9, 2023, 9 - 12 and 2 - 5pm, HW after 7:30pm

Monday – Thursday June 12 – 15, 2023, 9 - 12 and 2 - 5pm, HW after 7:30pm

Friday: summary and final exam, 9am - noon

Expectation:

Collaborate on homework.

Consult TAs for homework and optics design.

Co-instructor for Bmad, design, and simulation: David Sagan dcs16@cornell.edu

TAs: Ningdong Wang nw285@cornell.edu and Matthew Signorelli mgs255@cornell.edu

Lecture notes, homework, and homework solution will be on the class web page

https://www.classe.cornell.edu/~hoff/LECTURES/23USPAS/

Accelerator optics and simulations

To practice what will be learned, accelerators will be simulated with the programs Tao and Bmad.

You all have accounts to run Bmad, which will be introduced Monday afternoon.

There will be Homework of analytical nature and design / optimization / simulation assignments.

Images are taken from many sources, including:

The Physics of Particle Accelerators, Klaus Wille, Oxford University Press, 2000, ISBN: 19 850549 3

Particle Accelerator Physics I, Helmut Wiedemann, Springer, 2nd edition, 1999, ISBN 3 540 64671 x

Teilchenbeschleuniger und Ionenoptic, Frank Hinterberger, 1997, Springer, ISBN 3 540 61238 6

Introduction to Ultraviolet and X-ray Free-Electron Lasers, Martin Dohlus, Peter Schmüser, Jörg Rossbach, Springer, 2008

Various web pages, 2003 – 2023

Literature

Recommended as

Introduction

The Physics of Particle Accelerators: An Introduction, Klaus Wille, Oxford University Press

Wide selection of well explained topics

Particle Accelerator Physics, Helmut Wiedemann, Springer, (preferably 3rd edition)

Tremendous overview, with references for derivations and explanations

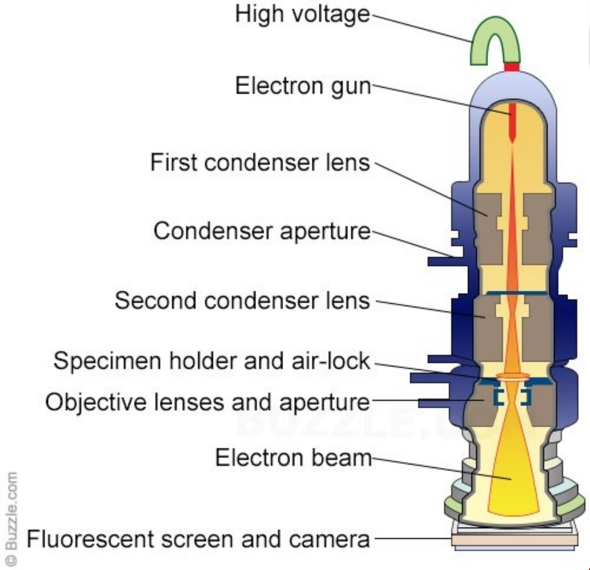
Handbook of Accelerator Physics and Engineering, Alexander Wu Cao, Maury Tigner, Hans Weise, Frank Zimmermann (3rd edition)

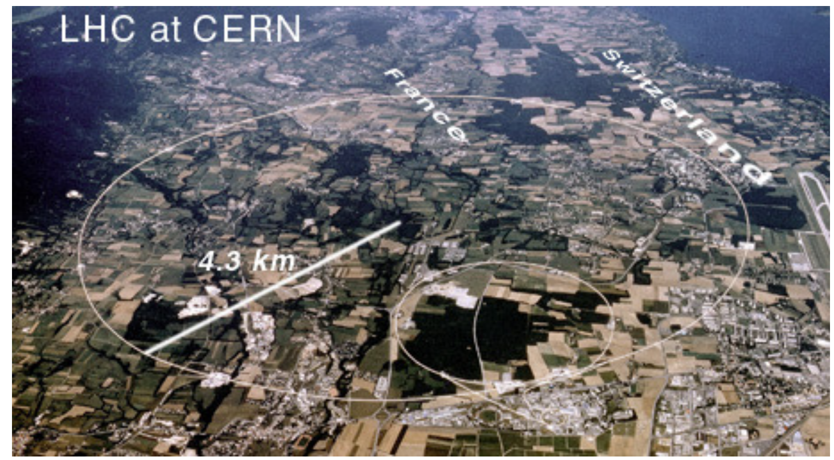
What is accelerator physics ?

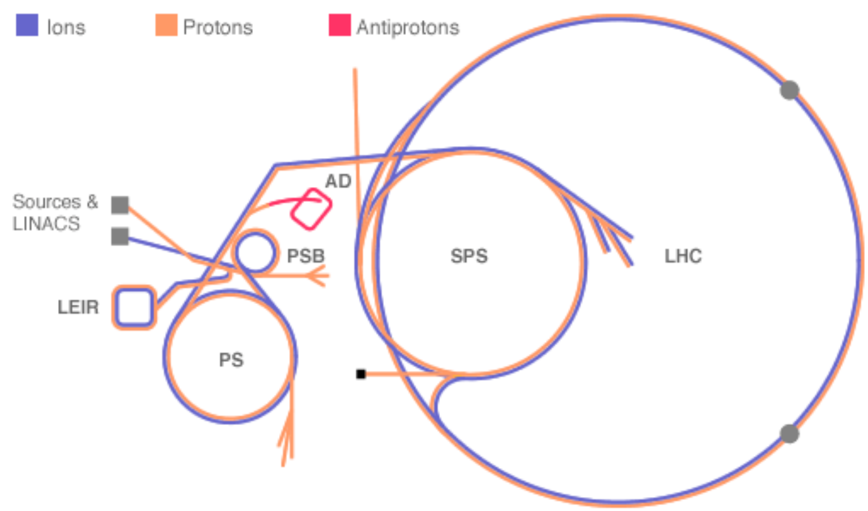
Accelerator Physics has applications in particle accelerators for high energy physics or for x-ray science, in spectrometers, in electron microscopes, and in lithographic devices. These instruments have become so complex that an empirical approach to properties of the particle beams is by no means sufficient and a detailed theoretical understanding is necessary. This course will introduce into theoretical aspects of charged particle beams and into the technology used for their acceleration.

- Physics of beams
- Physics of non-neutral plasmas
- Physics of involved in the technology:
    - Superconductivity in magnets and radiofrequency (RF) devices
    - Surface physics in particle sources, vacuum technology, RF devices
    - Material science in collimators, beam dumps, superconducting materials

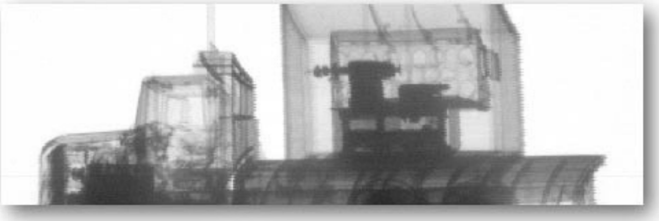
Particle accelerators, large and small



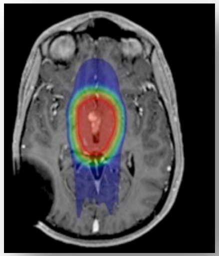




Why accelerator physics ?

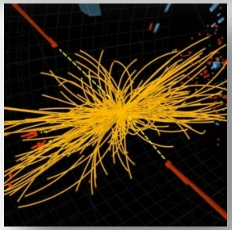


- Industry
  - Food & product safety
  - Contraband detection
  - Semiconductor fabrication
  - Bridge safety
- Medicine
  - Tumor detection and treatment.



~30,000 industrial and medical accelerators are in use, with annual sales of $3.5 B and 10% growth per year.

- Research
  - X ray sources and colliders for nuclear & particle physics
  - Electron microscopes

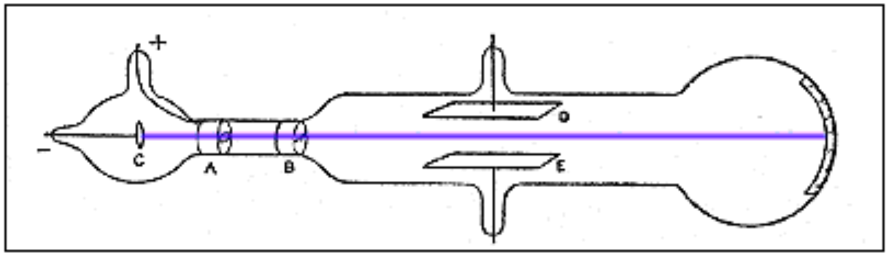


Since 1943, a Nobel Prize in **Physics** has been awarded to research benefiting from accelerators every 3 years.
Since 1997, the same has been true of **Chemistry**.

A short history of accelerators

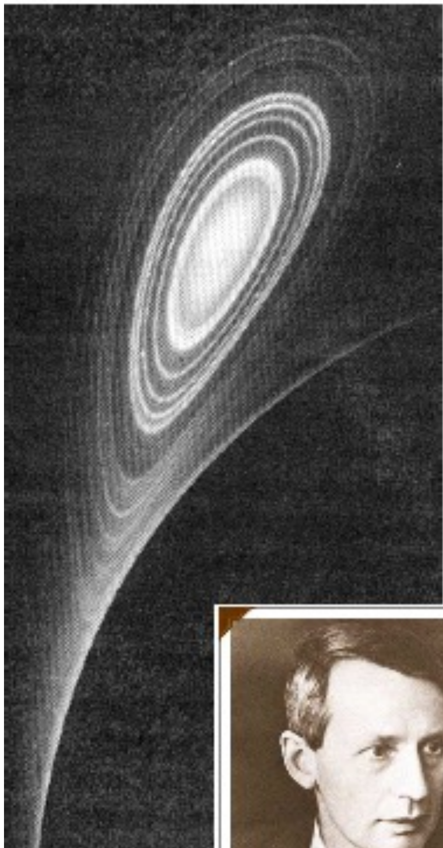
- 1862: Maxwell theory of electromagnetism
- 1887: Hertz discovery of the electromagnetic wave
- 1886: Goldstein discovers positively charged rays (ion beams)
- 1894: Lenard extracts cathode rays (with a 2.65μm Al Lenard window)
- 1897: JJ Thomson shows that cathode rays are particles since they followed the classical Lorentz force $m\vec{a} = e(\vec{E} + \vec{v} \times \vec{B})$ in an electromagnetic field
- 1926: GP Thomson shows that the electron is a wave (1929-1930 in Cornell, NP in 1937)

NP 1905, Philipp E.A. von Lenard



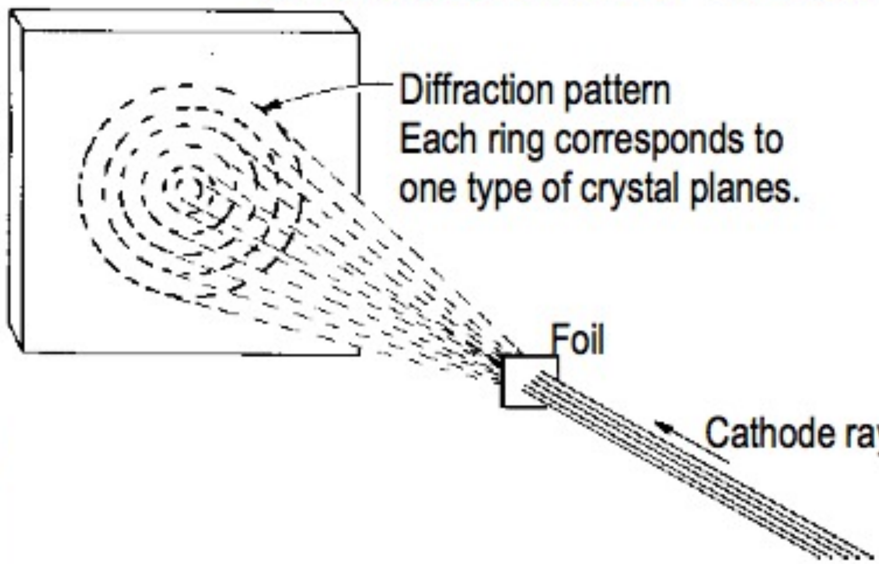
NP 1906
Joseph J. Thomson

Discoveries with accelerated beams …



George P.Thomson
(1892-1975)
1937 Nobel prize
Son of Joseph J. T.

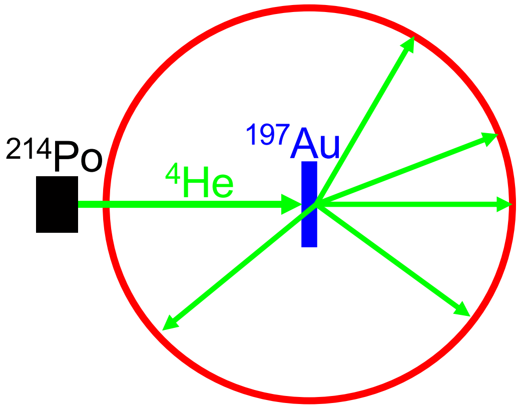
In a powdered, microcrystalline substance there is always some crystal which has the correct angle for constructive interference $2d\cos\alpha = n\lambda$



A magnetic field can change the rings, showing the the waves are associated with the electron charge.

The need for higher energies

- 1911: Rutherford discovers the nucleus with 7.7MeV ^{4}He from ^{214}Po alpha decay measuring the elastic crossection of ^{197}Au + ^{4}He $\mapsto$ ^{197}Au + ^{4}He.



$$E = \frac{Z_1 e Z_2 e}{4\pi\varepsilon_0 d} = Z_1 Z_2 m_e c^2 \frac{r_e}{d},$$

$$r_e = 2.8\mathrm{fm}, \quad m_e c^2 = 0.511\mathrm{MeV}$$

d = smalles approach for back scattering

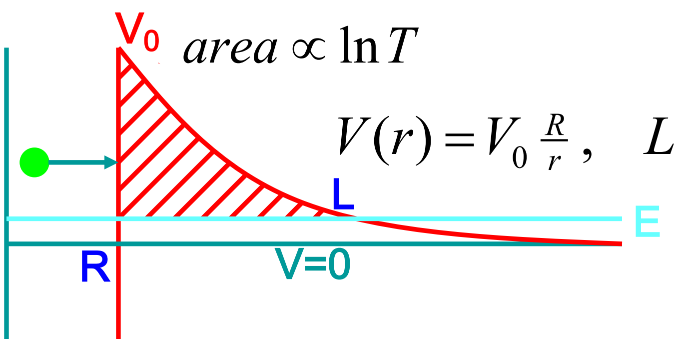
- 1919: Rutherford produces first nuclear reactions with natural ^{4}He
  ^{14}N + ^{4}He $\mapsto$ ^{17}O + p
- 1921: Greinacher invents the cascade generator for several 100 keV
- Rutherford is convinced that several 10 MeV are in general needed for nuclear reactions. He therefore gave up the thought of accelerating particles.

Tunneling allows low energies

- 1928: Explanation of alpha decay by Gamov as tunneling showed that several 100keV protons might suffice for nuclear reactions

Schroedinger equation: $\frac{\partial^2}{\partial r^2}u(r) = \frac{2m}{\hbar^2}[V(r)-E]u(r)\,,\quad T = \left|\frac{u(L)}{u(0)}\right|^2$

The transmission probability T for an alpha particle traveling from the inside towards the potential well that keeps the nucleus together determines the lifetime for alpha decay.

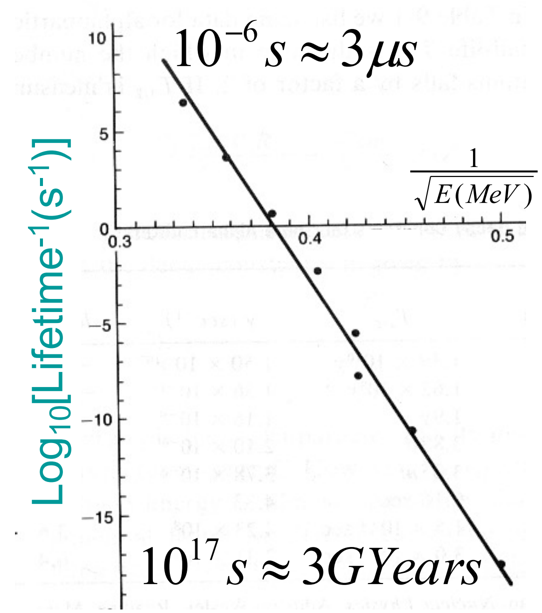


$area \propto \ln T$

$V(r) = V_0\frac{R}{r}\,,\quad L = \frac{V_0}{E}R$

$$T \approx \exp[-2\int_R^L \frac{\sqrt{2m[V(r)-E]}}{\hbar}dr]$$

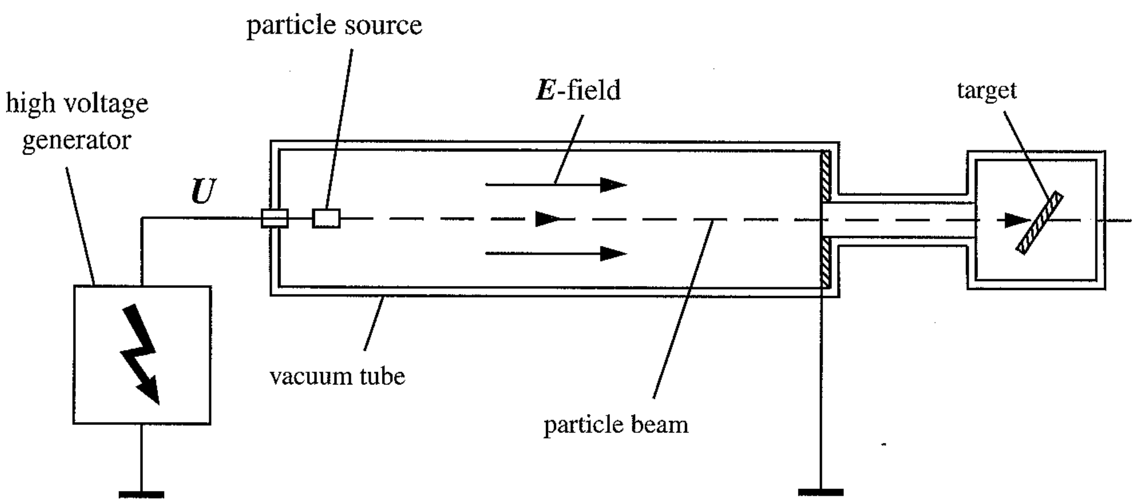
$$\ln T \approx A - \frac{C}{\sqrt{E}}$$



Three historic lines of accelerators

Direct Voltage Accelerators

Resonant Accelerators Transformer Accelerator



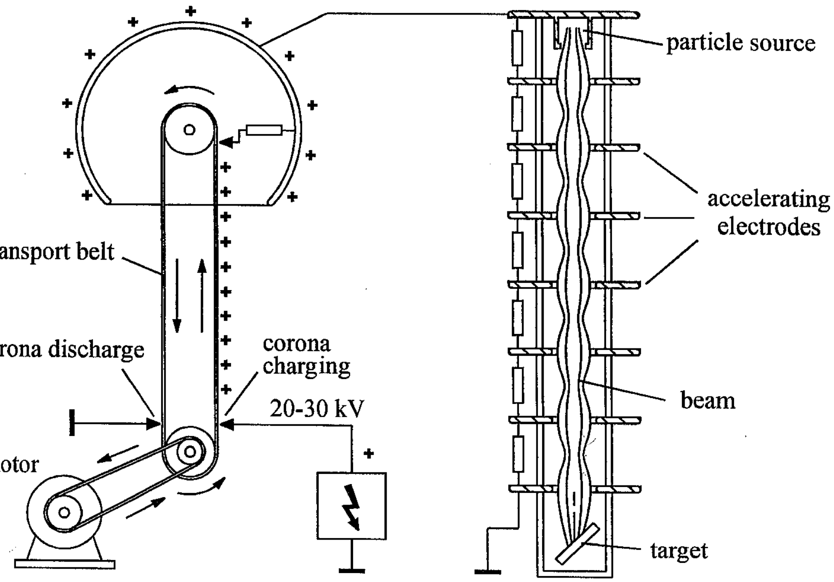
Voltage 1MV
Charge Ze
Energy Z MeV

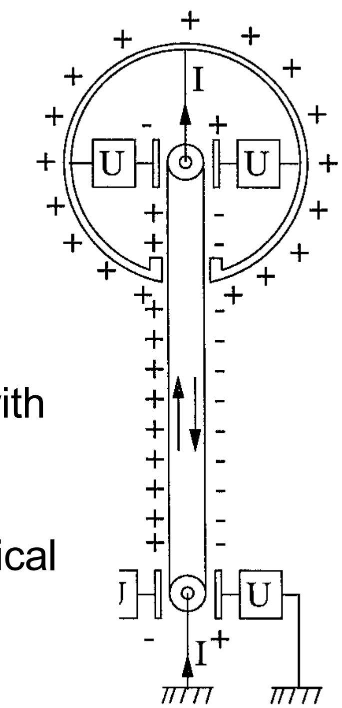
The energy limit is given by the maximum possible voltage. At the limiting voltage, electrons and ions are accelerated to such large energies that they hit the surface and produce new ions. An avalanche of charge carries causes a large current and therefore a breakdown of the voltage.

The Van de Graaff Accelerator

- 1930: van de Graaff builds the first 1.5MV high voltage generator

Van de Graaff

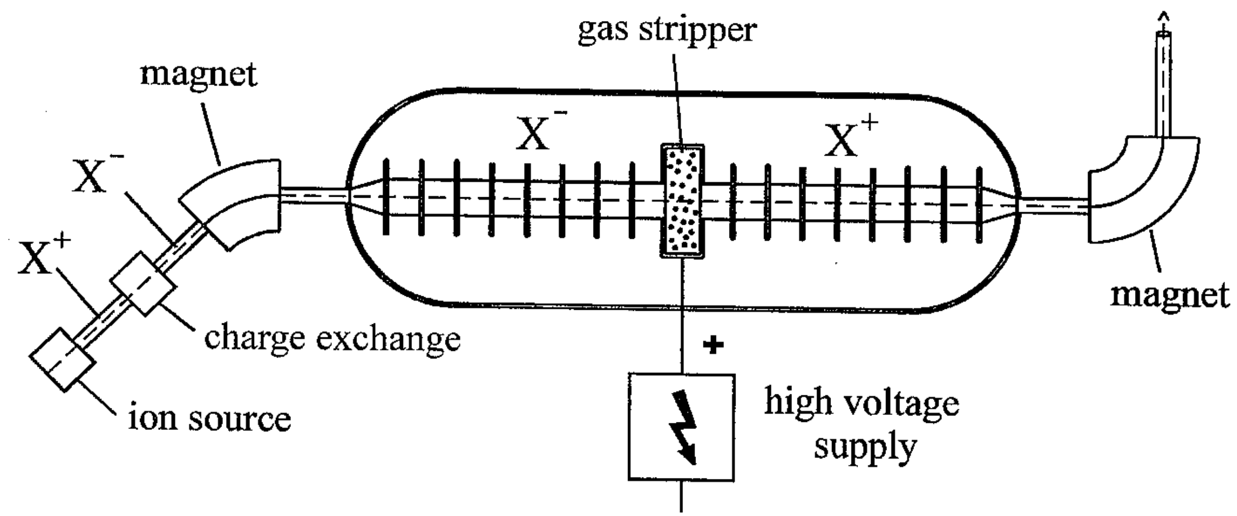




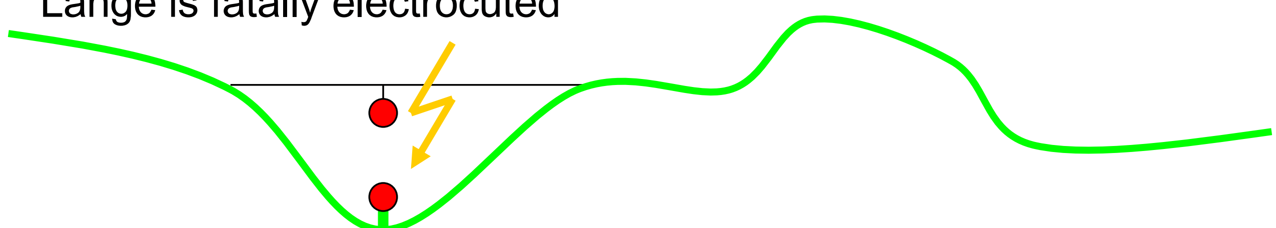
- Today Peletrons (with chains) or Laddertron (with stripes) that are charged by influence are commercially available.
- Used as injectors, for electron cooling, for medical and technical n-source via $d + t \mapsto n + \alpha$
- Up to 17.5 MV with insulating gas (1MPa SF_6)

The Tandem (Van de Graaff) Accelerator

- Two Van de Graaffs, one + one –
- The Tandem Van de Graaff, highest energy 35MeV

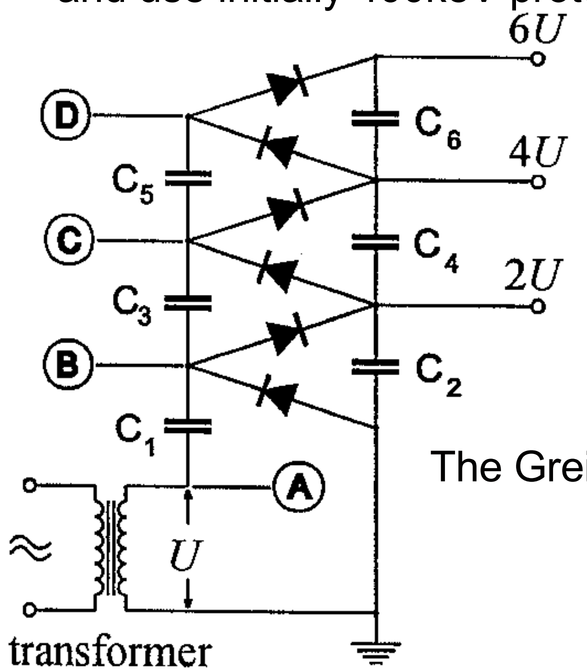


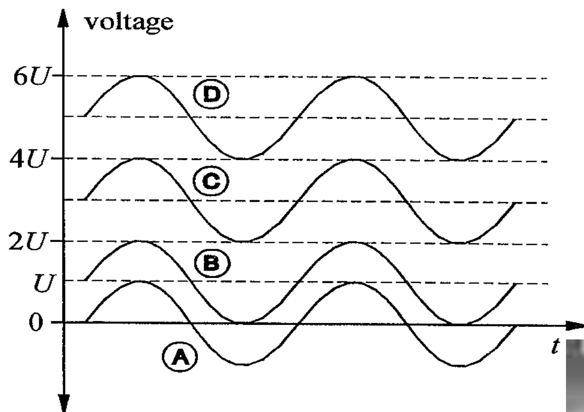
- 1932: Brasch and Lange use potential from lightening, in the Swiss Alps, Lange is fatally electrocuted



The Cockcroft-Walton Accelerator

1932: Cockcroft and Walton 1932: 700keV cascate generator (planed for 800keV) and use initially 400keV protons for ^{7}Li + p $\mapsto$ ^{4}He + ^{4}He and ^{7}Li + p $\mapsto$ ^{7}Be + n





The Greinacker circuit

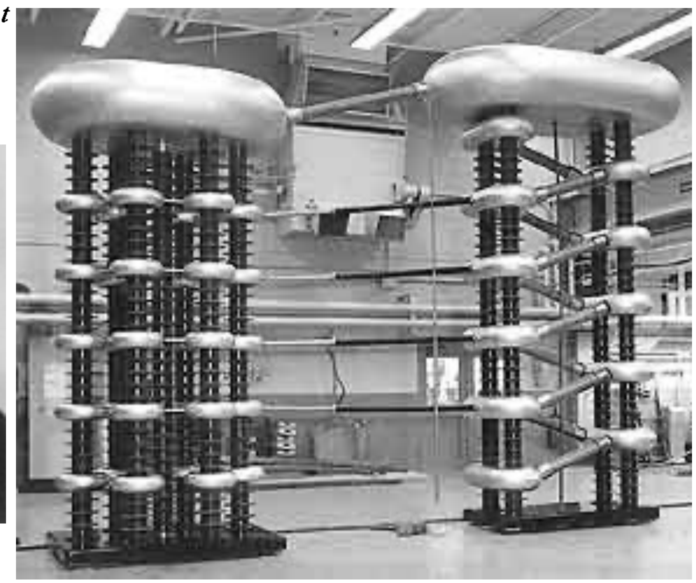
Li

Up to 4MeV, 1A

NP 1951

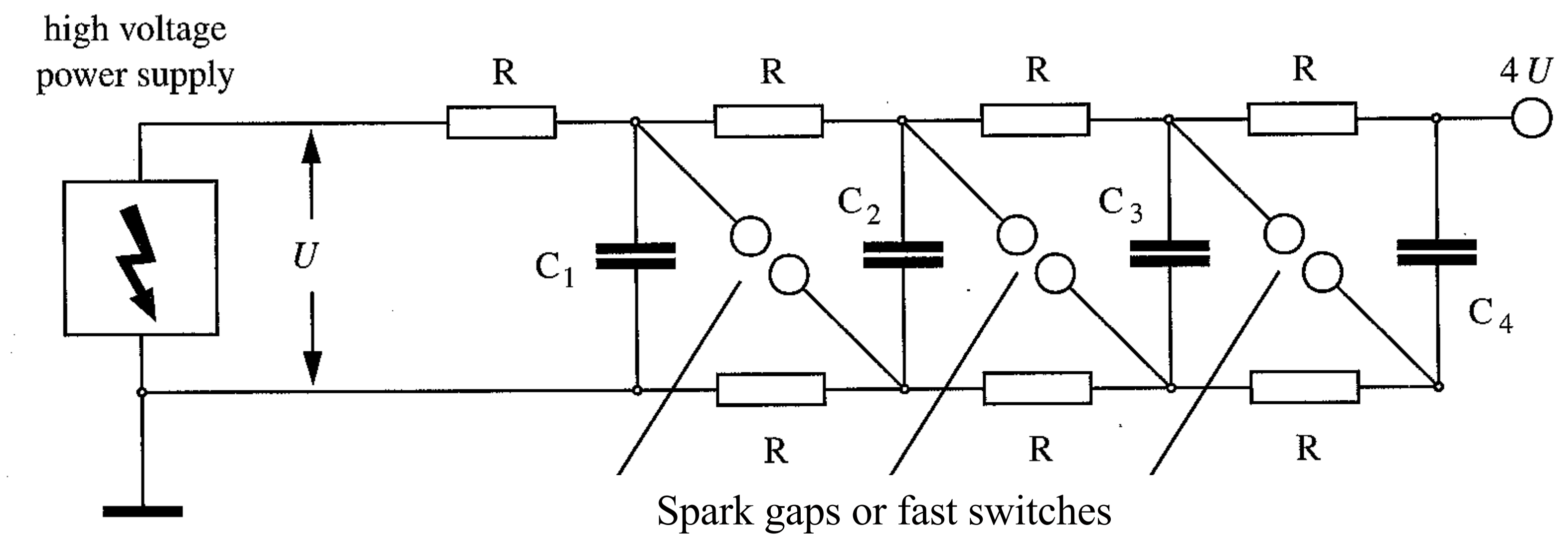
Sir John D Cockcrof

Ernest T S Walton



The Marx Generator

- 1932: Marx Generator achieves 6MV at General Electrics



After capacitors of around 2uF are filled to about 20kV, the spark gaps or switches close as fast as 40ns, allowing up to 500kA.

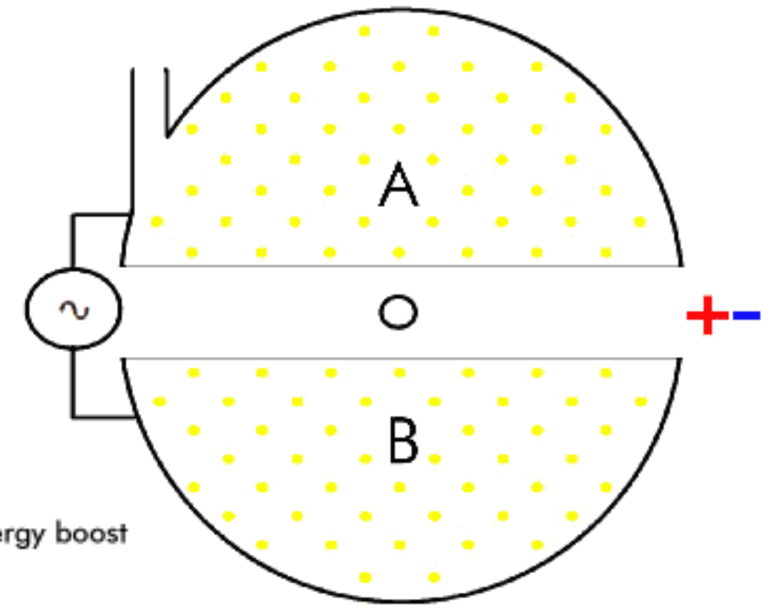
Today: The Z-machine (Physics Today July 2003) for z-pinch initial confinement fusion has 40TW for 100ns from 36 Marx generators

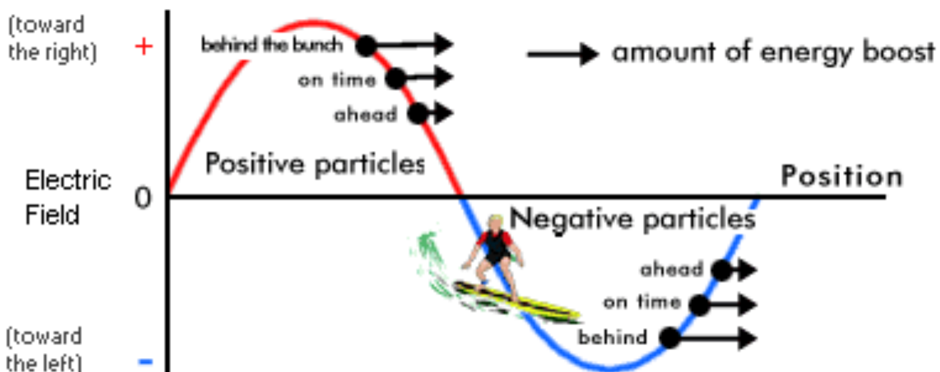
Three historic lines of accelerators

Resonant Accelerators

Direct Voltage Accelerators

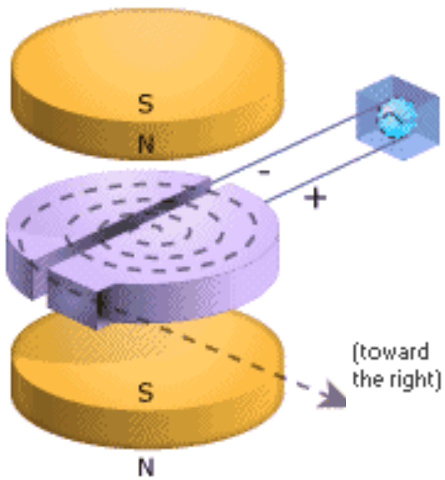
Transformer Accelerator



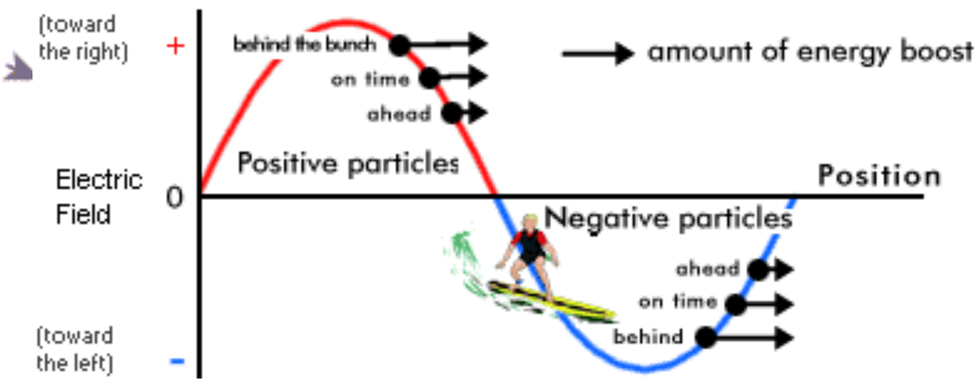


Particles must have the correct phase relation to the accelerating voltage.

The Cyclotron



- 1930: Lawrence proposes the Cyclotron
  (before he develops a workable color TV screen)
- 1932: Lawrence and Livingston use a cyclotron for
  1.25MeV protons and mention longitudinal
  (phase) focusing



NP 1939

Ernest O Lawrence

- 1934: Livingston builds the first Cyclotron
  away from Berkely (2MeV protons)
  at Cornell (in room B54)

M Stanley Livingston

The Cyclotron frequency

$$F_r = m_0\gamma\omega_z v = qvB_z$$

$$\omega_z = \tfrac{q}{m_0\gamma} B_z = \text{const}$$

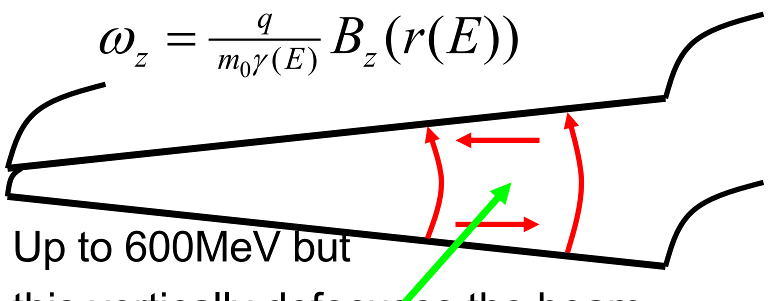
Condition: Non-relativistic particles.
Therefore, not for electrons.

- The synchrocyclotron:
  Acceleration of bunches with decreasing

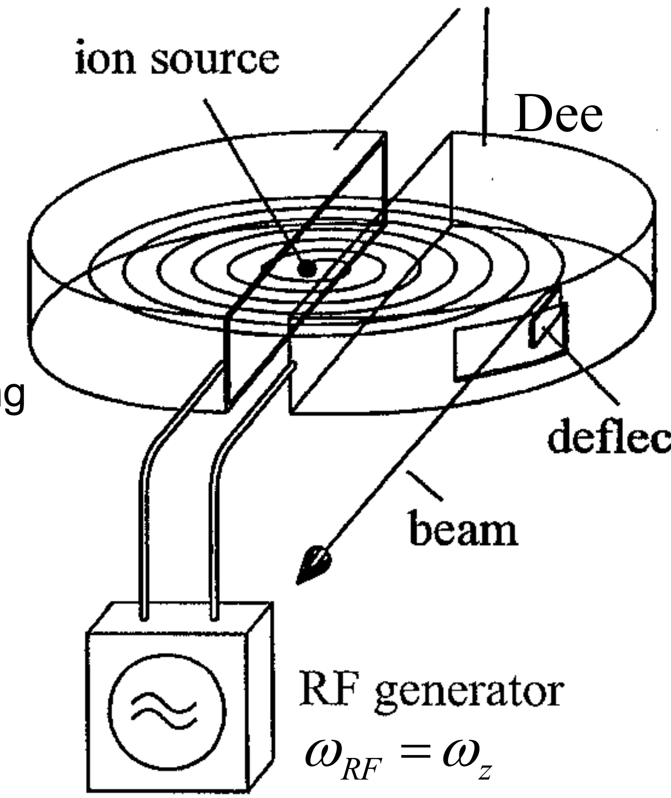
$$\omega_z(E) = \tfrac{q}{m_0\gamma(E)} B_z$$

- The isocyclotron with constant

$$\omega_z = \tfrac{q}{m_0\gamma(E)} B_z(r(E))$$

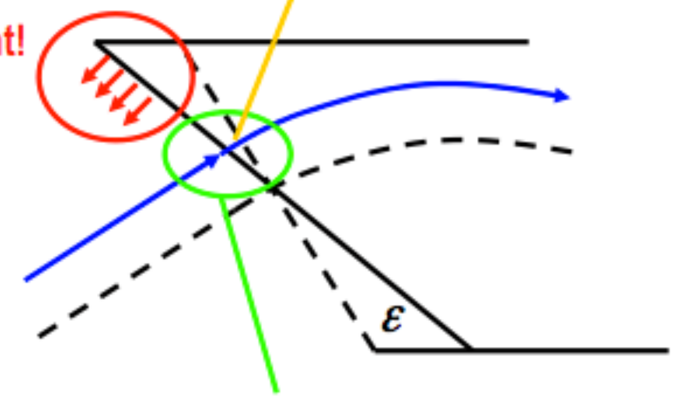


Up to 600MeV but
this vertically defocuses the beam



- 1938: Thomas proposes strong
  (transverse) focusing for a cyclotron

The Edge Focusing



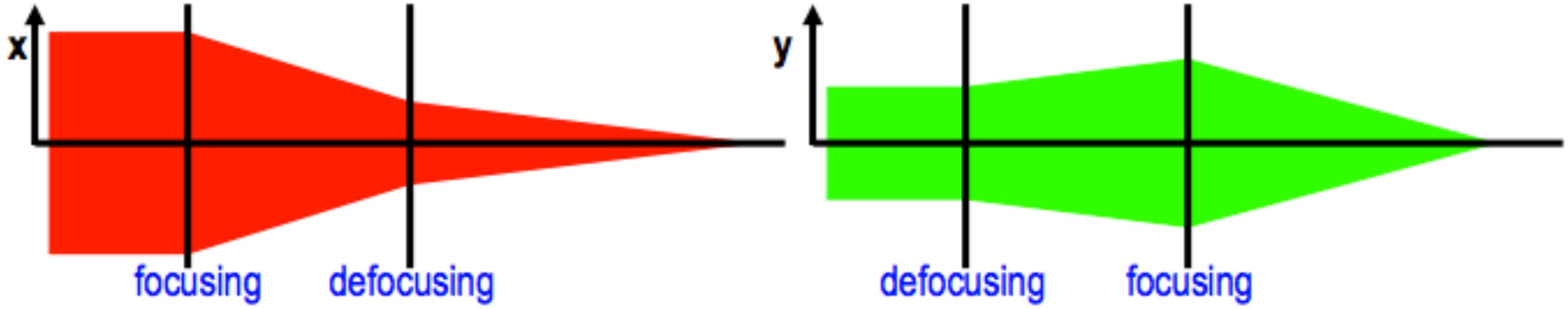
Horizontal focusing with $\Delta x' = -x\frac{\tan(\varepsilon)}{\rho}$

The longitudinal field above the enter plain defocuses, turns out to: $\Delta y' = y\frac{\tan(\varepsilon)}{\rho}$

Quadrupole effect: focusing in x and defocusing in y or
defocusing in x and focusing in y.

Quadrupole Focusing

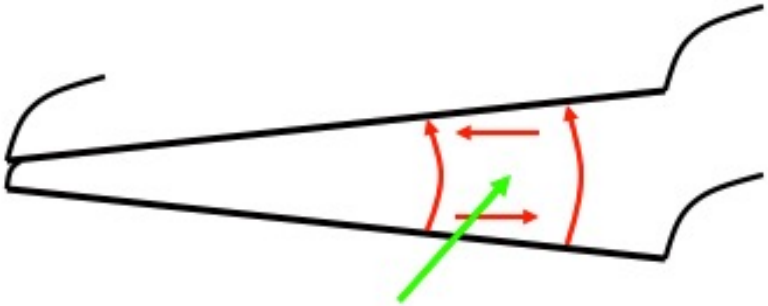
Transverse fields defocus in one plane if they focus in the other plane.
But two successive elements, one focusing the other defocusing,
can focus in both planes:



The Isocyclotron

- The isocyclotron with constant

$$\omega_z = \frac{q}{m_0\gamma(E)} B_z(r(E))$$



Up to 600MeV but

this vertically defocuses the beam.

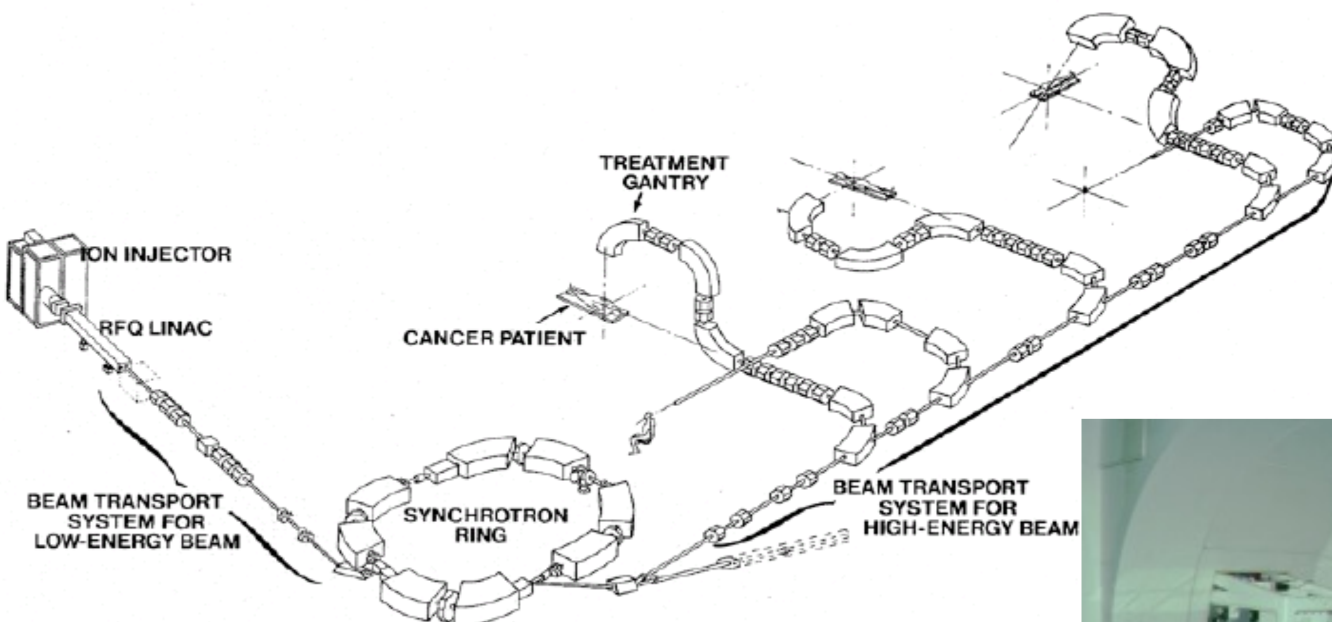
Edge focusing is therefore used.

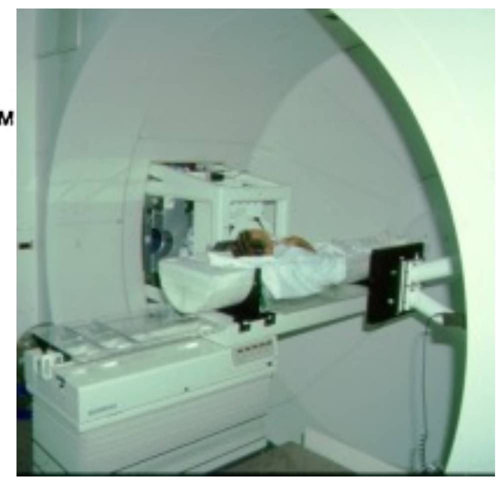
First Medical Accelerators

- 1939: Lawrence uses 60' cyclotron for 9MeV protons, 19MeV deuterons, and 35MeV 4He. First tests of tumor therapy with neutrons via d + t $\mapsto$ n + α
  With 200-800keV d to get 10MeV neutrons.

Modern Nuclear Radiation Therapy

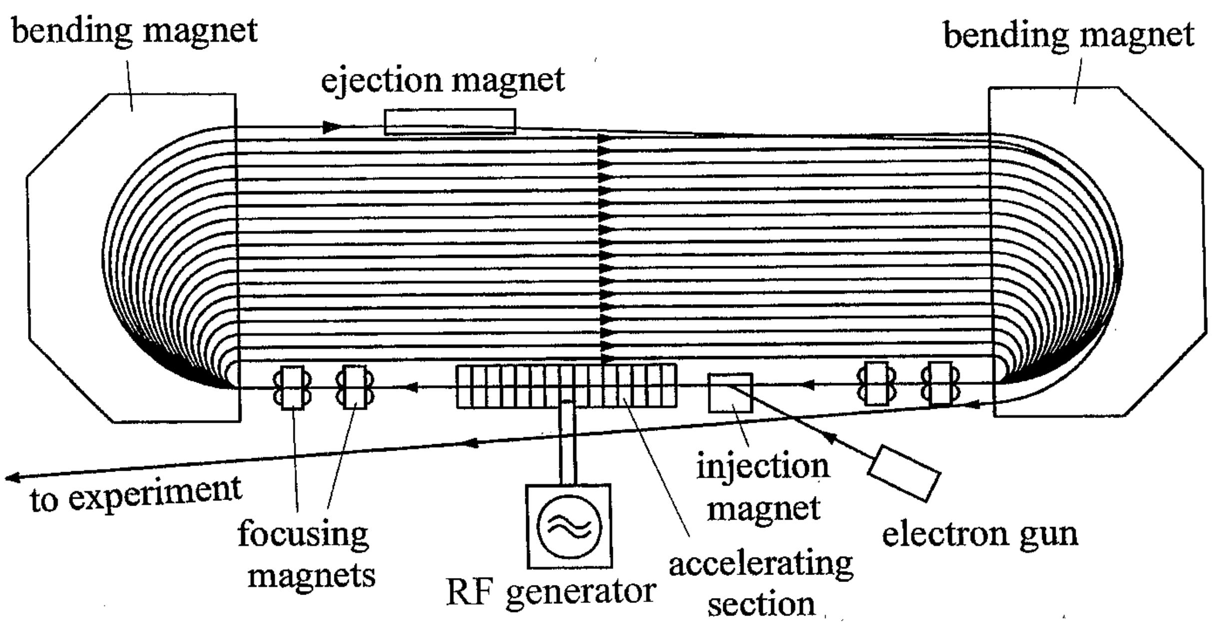
The Loma Linda proton therapy facility





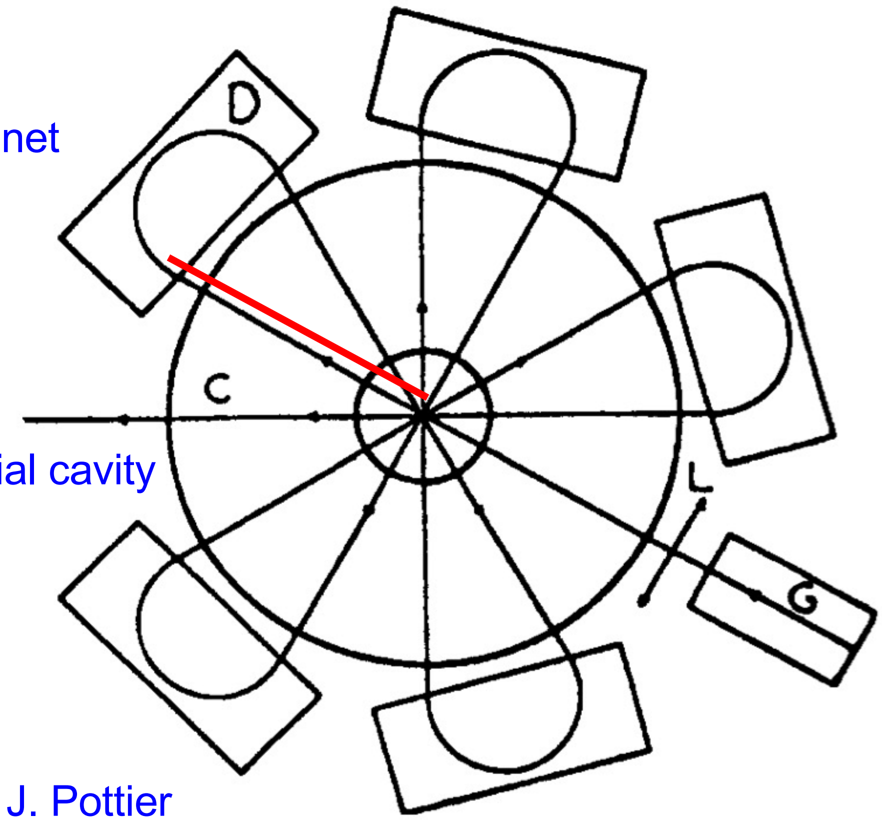
The Microtron

- Electrons are quickly relativistic and cannot be accelerated in a cyclotron.
- In a microtron the revolution frequency changes, but each electron misses an integer number of RF waves.



- Today: Used for medical applications with one magnet and 20MeV.
- Nuclear physics: MAMI designed for 820MeV as race track microtron.

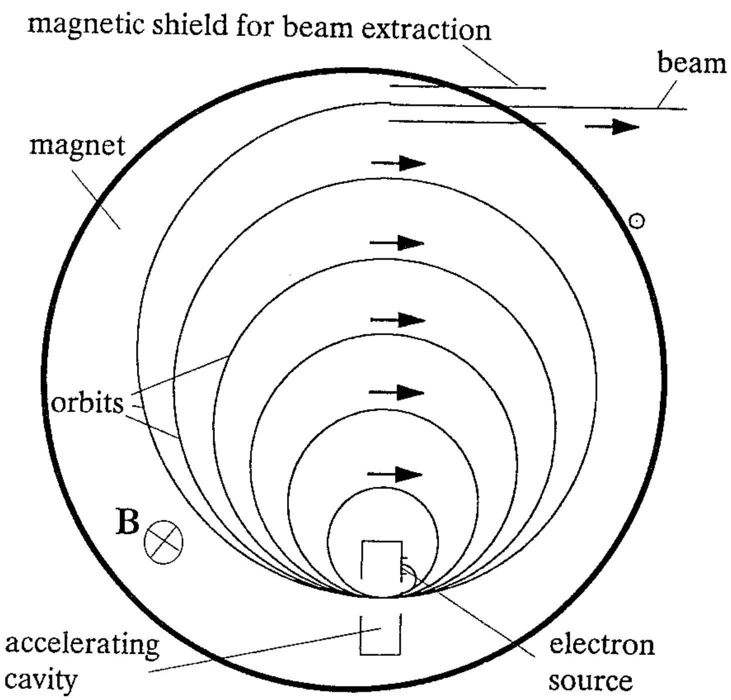
The Rhodotron



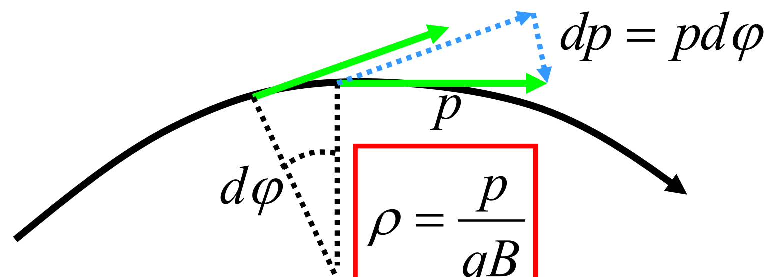
- Invented in 1989 by J. Pottier (French, CEA)

The Microtron Condition

- The extra time that each turn takes must be a multiple of the RF period.



$$\frac{dp}{dt} = qvB \Rightarrow \rho = \frac{dl}{d\varphi} = \frac{vdt}{dp/p} = \frac{p}{qB}$$



$$\rho = \frac{p}{qB}$$

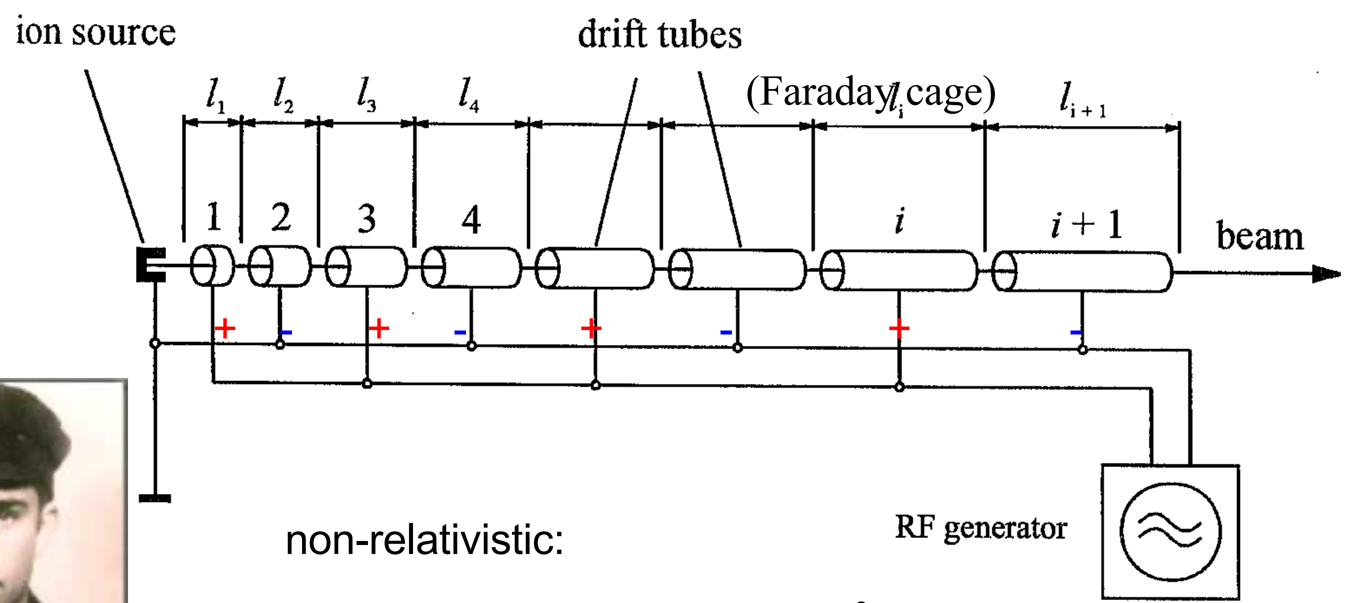
$$\Delta t = 2\pi\left(\frac{\rho_{n+1}}{v_{n+1}} - \frac{\rho_n}{v_n}\right)$$

$$= \frac{2\pi}{qB}(m_0\gamma_{n+1} - m_0\gamma_n) = \frac{2\pi}{qBc^2}\Delta K$$

$$\Delta K = n\frac{qBc^2}{\omega_{RF}}$$ for an integer n

B=1T, n=1, and f_{RF}=3GHz leads to 4.78MeV
This requires a small linear accelerator.

The Wideroe linear accelerator



Wideroe

non-relativistic:

$$K_n = nqU_{\max} \sin\psi_0 = \tfrac{1}{2} m v_n^2$$

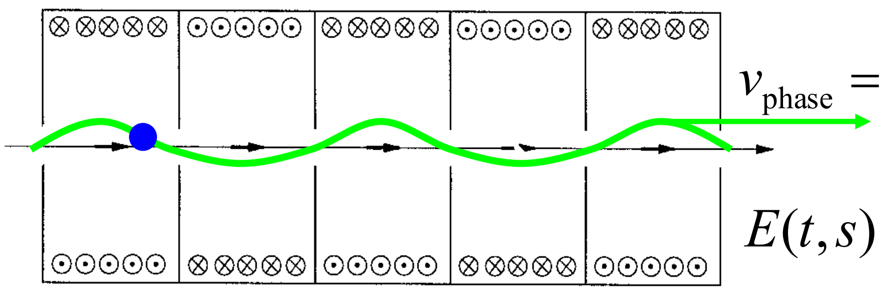
$$l_n = \tfrac{1}{2} v_n T_{RF} = \tfrac{1}{2}\beta_n \lambda_{RF} \propto \sqrt{n}$$

Called the π or the $1/2\beta\lambda$ mode

Accelerating Cavities

- 1933: J.W. Beams uses resonant cavities for acceleration

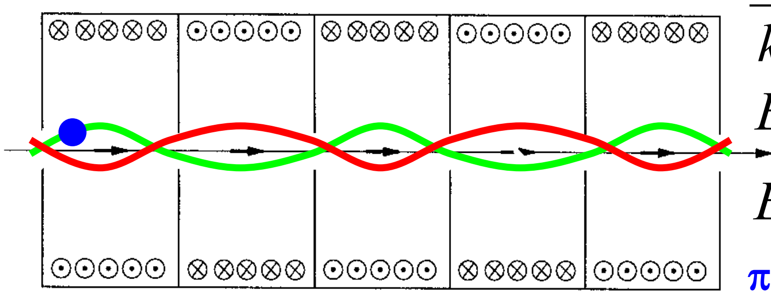
Traveling wave cavity:



$$v_{\text{phase}} = \frac{\omega}{k} = v_{\text{particle}}$$ Here v=c for electrons

$$E(t,s) \approx E_{\max} \sin(\omega t - ks)$$

Standing wave cavity:



$$\frac{\omega}{k} = v_{\text{particle}}$$

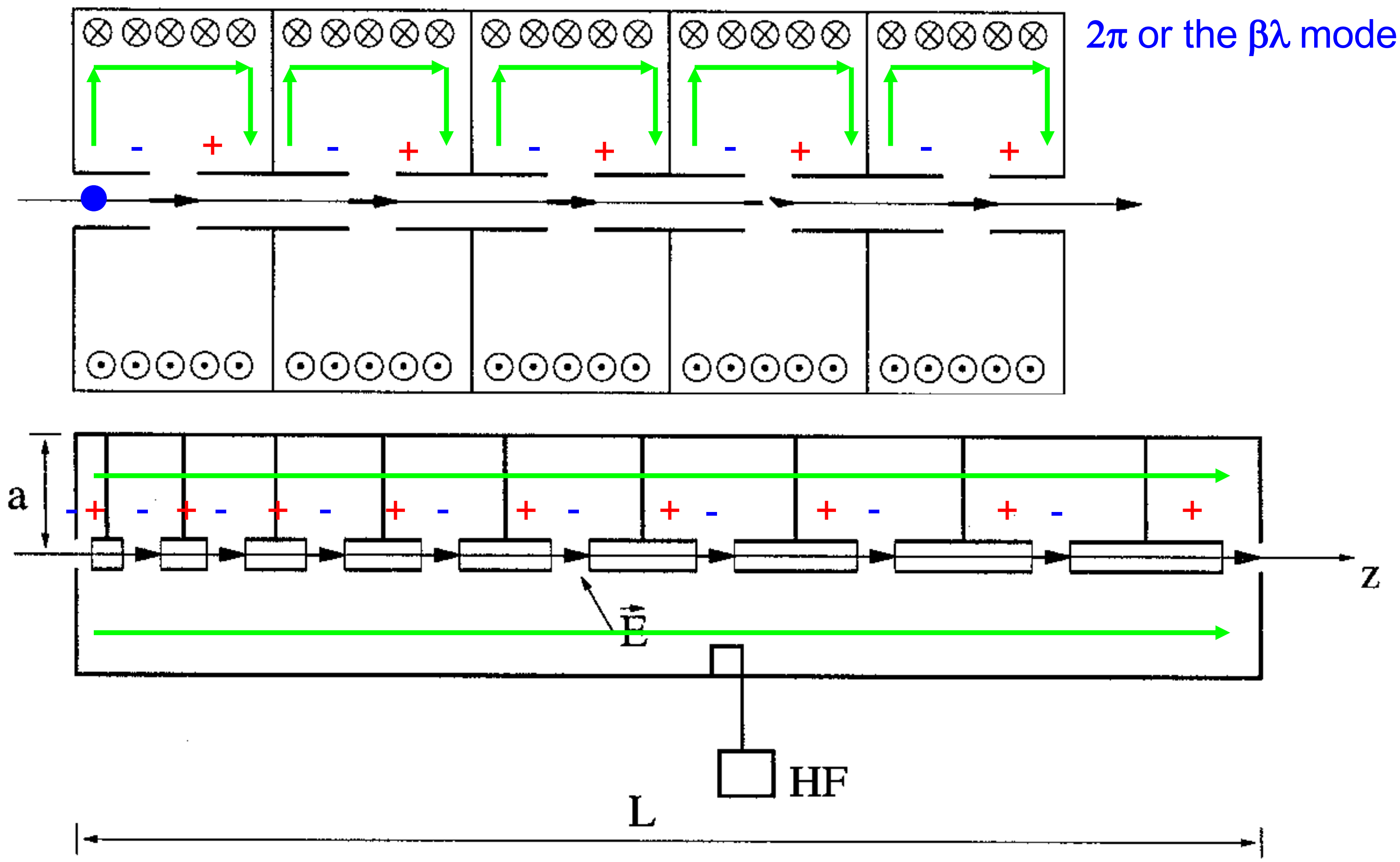
$$E(t,s) \approx E_{\max} \sin(\omega t) \sin(ks)$$

$$E(\tfrac{s}{v_{\text{particle}}}, s) \approx E_{\max} \sin^2(ks)$$

π or the 1/2βλ mode

Transit factor (for this example): $\langle E \rangle = \frac{1}{\lambda_{RF}} \int_0^{\lambda_{RF}} E(\tfrac{s}{v_{\text{particle}}}, s)\, ds \approx \tfrac{1}{2} E_{\max}$

The Alvarez Linear Accelerator

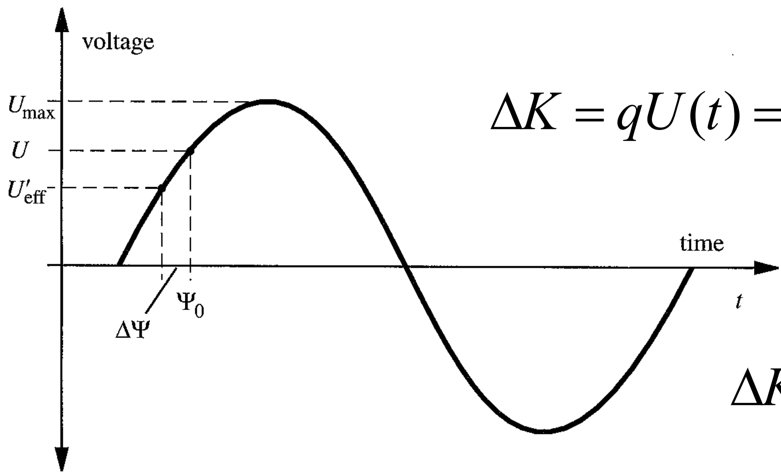


2π or the $\beta\lambda$ mode

Needs only one power input coupler and walls do not dissipate energy.

Phase Focusing

- 1945: Veksler (UDSSR) and McMillan (USA) realize the importance of phase focusing



$$\Delta K = qU(t) = qU_{\max}\sin(\omega(t-t_0)+\psi_0)$$

Longitudinal position in the bunch:

$$\sigma = s - s_0 = -v_0(t-t_0)$$

$$\Delta K(\sigma) = qU_{\max}\sin(-\tfrac{\omega}{v_0}(s-s_0)+\psi_0)$$

$$\Delta K(0) > 0$$ (Acceleration)

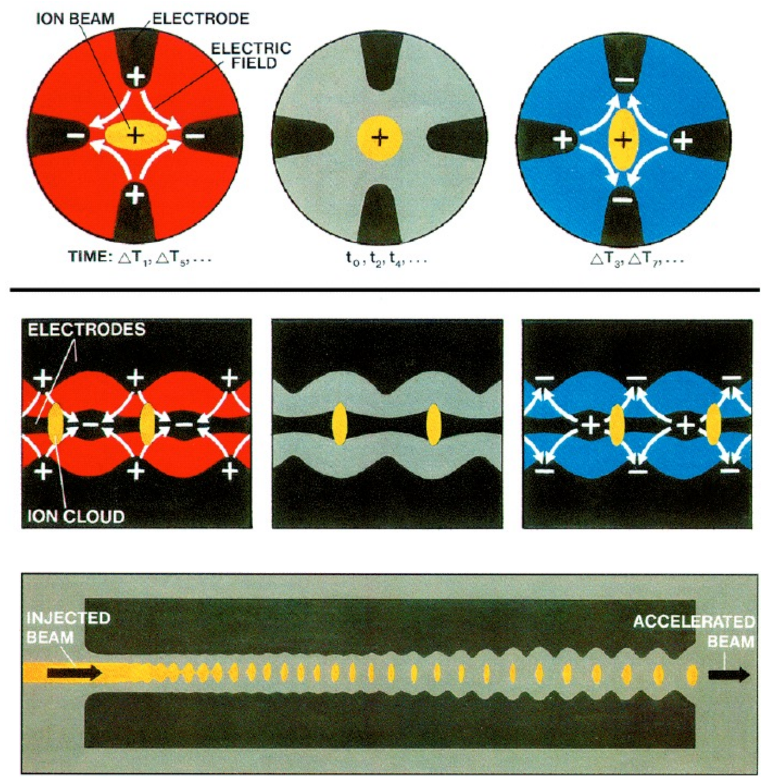
$$\Delta K(\sigma) < \Delta K(0) \text{ for } \sigma > 0 \Rightarrow \tfrac{d}{d\sigma}\Delta K(\sigma) < 0$$ (Phase focusing)

$$\left.\begin{array}{r} qU(t) > 0 \\ q\tfrac{d}{dt}U(t) > 0 \end{array}\right\} \quad \psi_0 \in (0, \frac{\pi}{2})$$

Phase focusing is required in any RF accelerator.

Radio Frequency Quadrupoles

- 1970: Kapchinskii and Teplyakov invent the RFQ



Three historic lines of accelerators

Direct Voltage Accelerators Resonant Accelerators Transformer Accelerator

- 1924: Wideroe invents the betatron
- 1940: Kerst and Serber build a betatron for 2.3MeV electrons and understand betatron (transverse) focusing (in 1942: 20MeV)

Betatron:

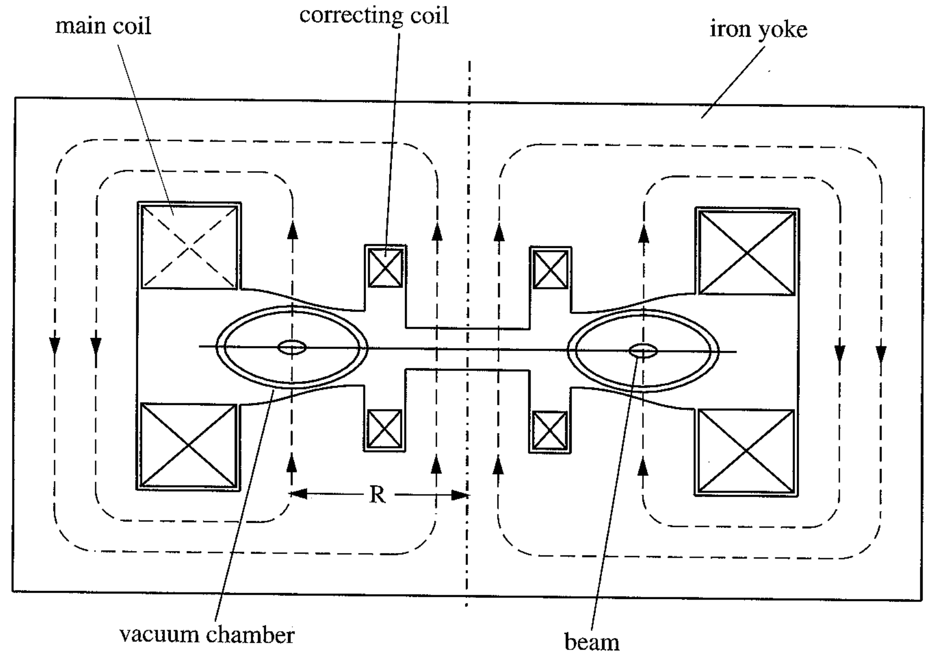
R=const, B=B(t)

Whereas for a cyclotron:

R(t), B=const

No acceleration section is needed since

$$\oint_{\partial A} \vec{E} \cdot d\vec{s} = -\iint_A \frac{d}{dt} \vec{B} \cdot d\vec{a}$$



The Betatron Condition

Condition: $R = \frac{-p_\varphi(t)}{qB_z(R,t)} = \text{const.}$ given $\oint_{\partial A} \vec{E}\cdot d\vec{s} = -\iint_A \frac{d}{dt}\vec{B}\cdot d\vec{a}$

$$E_\varphi(R,t) = -\tfrac{1}{2\pi R}\int \tfrac{d}{dt}B_z(r,t)\,r\,dr\,d\varphi = -\tfrac{R}{2}\left\langle \tfrac{d}{dt}B_z\right\rangle$$

$$\tfrac{d}{dt}p_\varphi(t) = qE_\varphi(R,t) = -q\tfrac{R}{2}\left\langle \tfrac{d}{dt}B_z\right\rangle$$

$$p_\varphi(t) = p_\varphi(0) - q\tfrac{R}{2}[\langle B_z\rangle(t) - \langle B_z\rangle(0)] = -RqB_z(R,t)$$

$$\boxed{B_z(R,t) - B_z(R,0) = \frac{1}{2}[\langle B_z\rangle(t) - \langle B_z\rangle(0)]}$$

Small deviations from this condition lead to transverse beam oscillations called betatron oscillations in all accelerators.

- Today: Betatrons with typically about 20MeV for medical applications

The Synchrotron

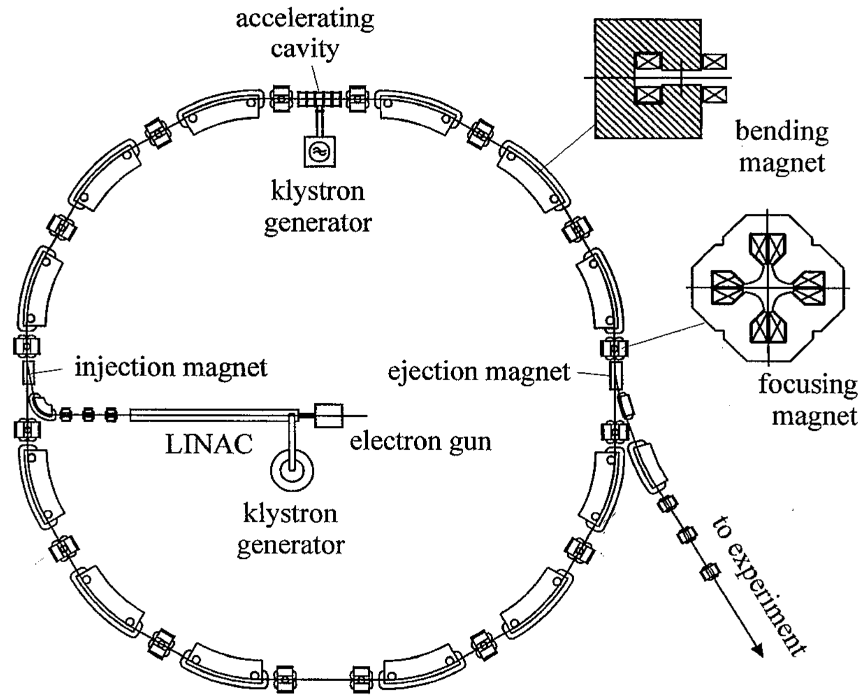
- 1945: Veksler (UDSSR) and McMillan (USA) invent the synchrotron
- 1946: Goward and Barnes build the first synchrotron (using a betatron magnet)
- 1949: Wilson et al. at Cornell are first to store beam in a synchrotron (later 300MeV, magnet of 80 Tons)
- 1949: McMillan builds a 320MeV electron synchrotron

- Many smaller magnets instead of one large magnet
- Only one acceleration section is needed, with

$$R = \frac{p(t)}{qB(R,t)} = \text{const.}$$

$$\omega = 2\pi \frac{v_{\text{particle}}}{L} n$$

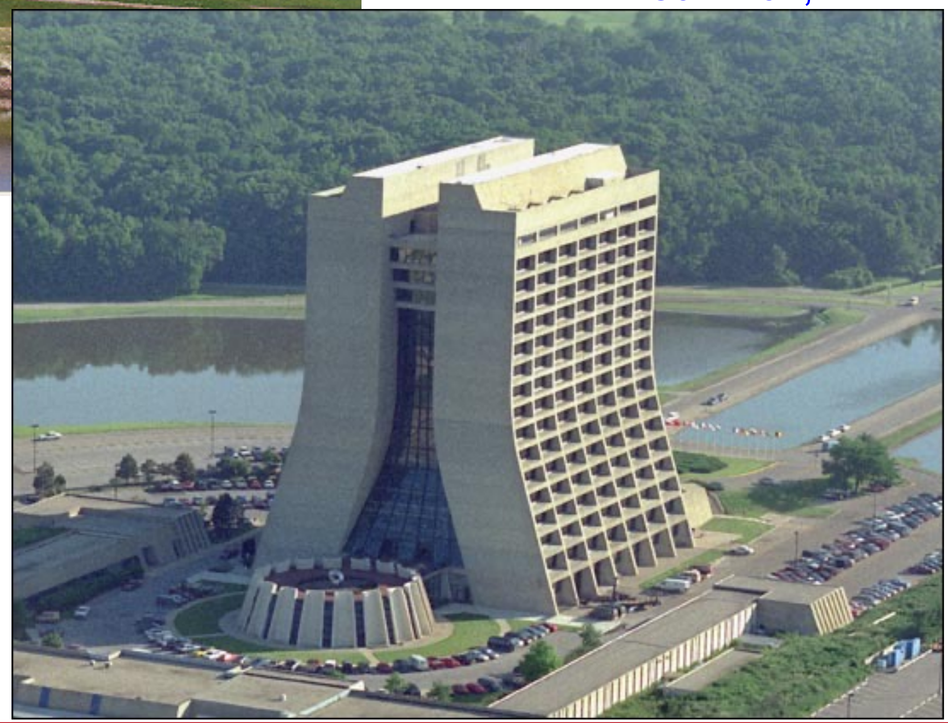
for an integer n called the harmonic number

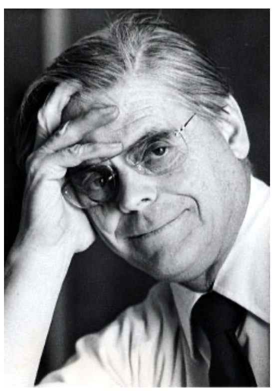


Robert Wilson, Fermilab …

Science Ed Center, FNAL (1990)

Wilson Hall, FNAL

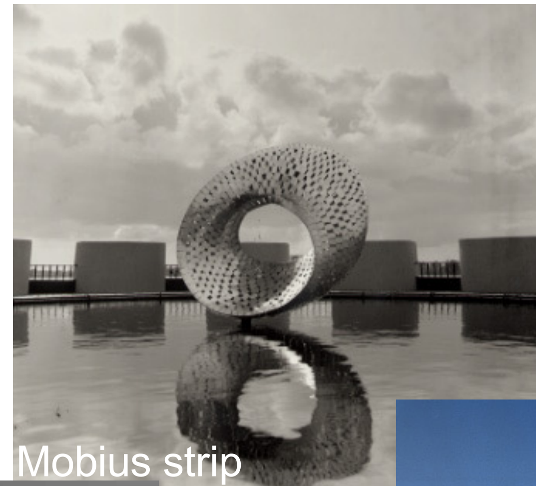




Robert R Wilson
USA 1914-2000

… art, architecture, and accelerators.

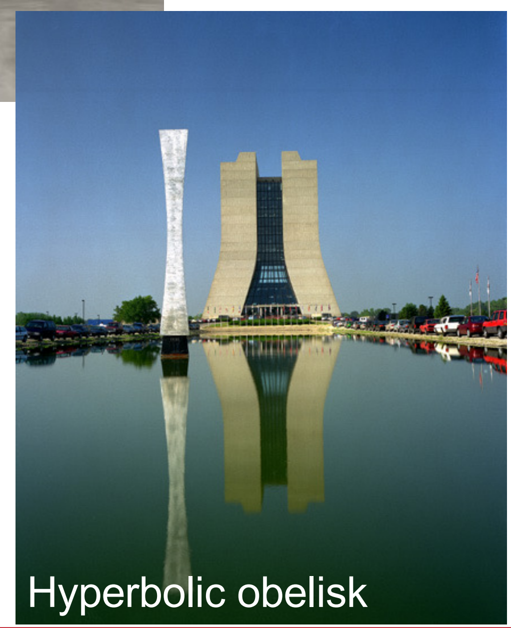
Broken symmetry



Mobius strip

Tractricious

π lines

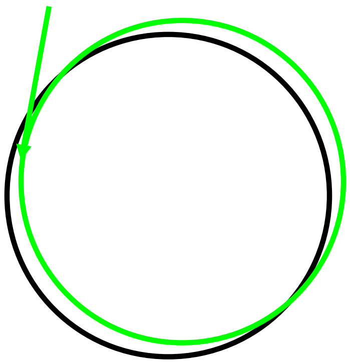


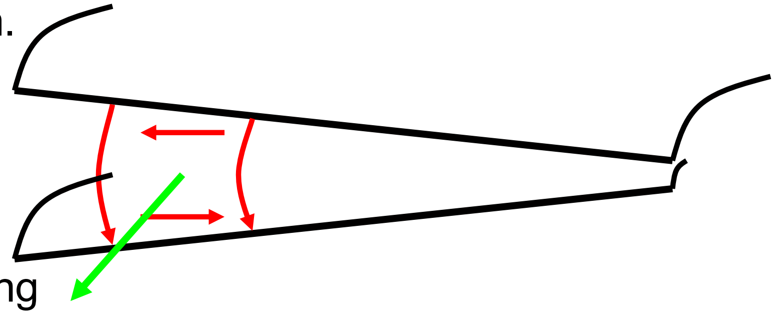
Hyperbolic obelisk

The weak focusing synchrotron

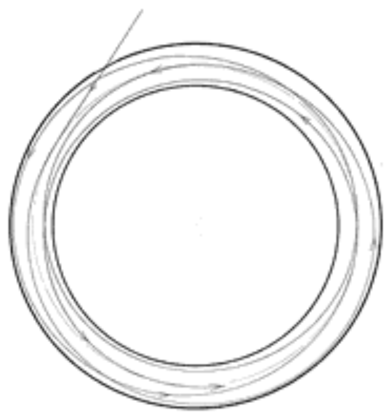
- 1952: Operation of the Cosmotron, 3.3 GeV proton synchrotron at Brookhaven: Beam pipe height: 15cm.

Natural ring focusing:

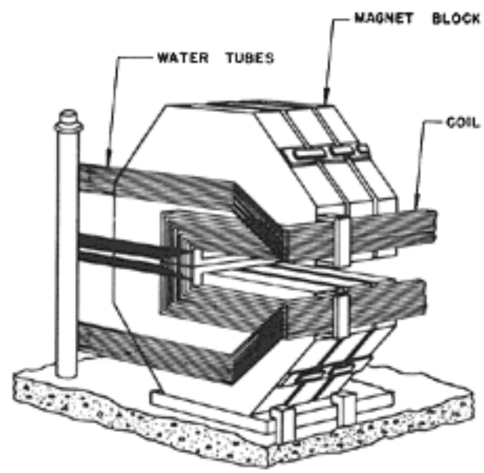




Vertical focusing
+ Horizontal defocusing + ring focusing
Focusing in both planes



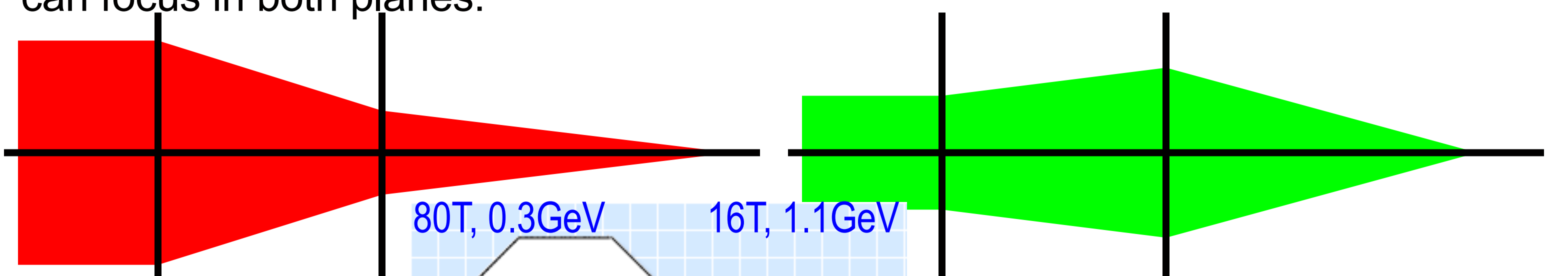
Weak focusing accelerator

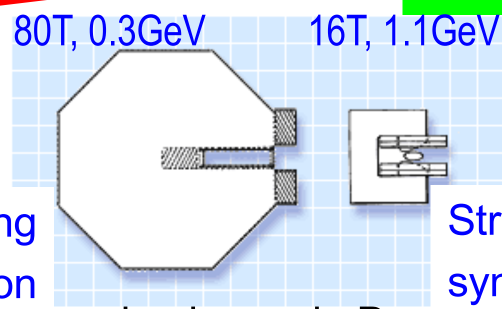


Strong focusing synchrotrons

- 1952: Courant, Livingston, Snyder publish about strong focusing
- 1954: Wilson et al. build first synchrotron with strong focusing for 1.1MeV electrons at Cornell, 4cm beam pipe height, only 16 Tons of magnets.
- 1959: CERN builds the PS for 28GeV after proposing a 5GeV weak focusing accelerator for the same cost (still in use)

Transverse fields defocus in one plane if they focus in the other plane.
But two successive elements, one focusing the other defocusing,
can focus in both planes:





Weak focusing synchrotron

Strong focusing synchrotron

- Today: only strong focusing is used. Due to bad field quality at lower field excitations the injection energy is 20-500MeV from a linac or a microtron.

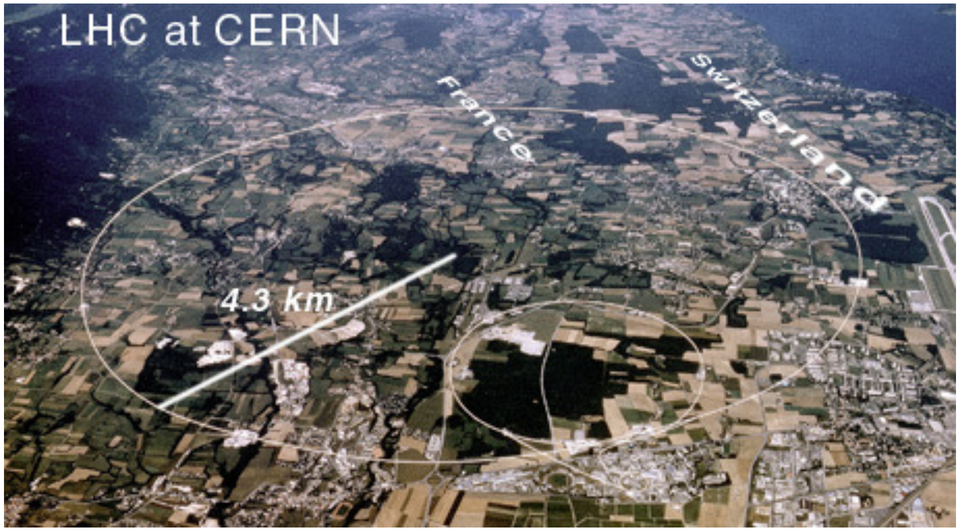
Limits of synchrotrons

$$\rho = \frac{p}{qB} \quad \Rightarrow$$ The rings become too long

Protons with p = 20 TeV/c , B = 6.8 T would require a 87 km SSC tunnel
Protons with p = 7 TeV/c , B = 8.4 T require CERN's 27 km LHC tunnel

$$P_{\text{radiation}} = \frac{c}{6\pi\varepsilon_0} N \frac{q^2}{\rho^2} \gamma^4 \quad \Downarrow$$

Energy needed to compensate
Radiation becomes too large



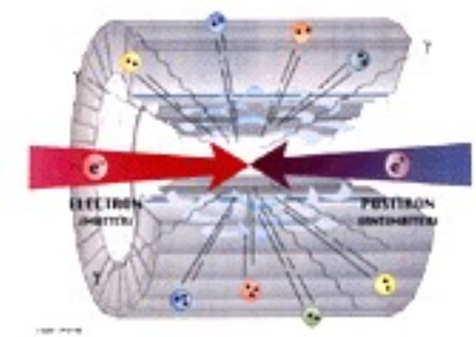
Electron beam with p = 0.1 TeV/c in CERN's 27 km LEP tunnel radiated 20 MW
Each electron lost about 4GeV per turn, requiring many RF accelerating sections.

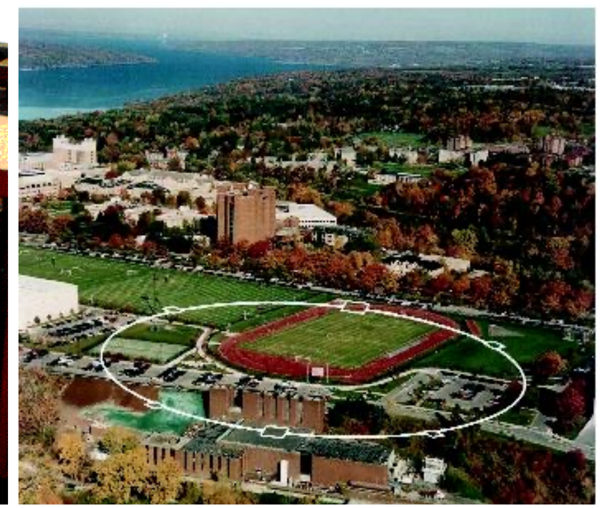
Colliding beam accelerators

- 1961: First storage ring for electrons and positrons (AdA) in Frascati for 250MeV
- 1972: SPEAR electron positron collider at 4GeV. Discovery of the J/Psi at 3.097GeV by Richter (SPEAR) and Ting (AGS) starts the November revolution and was essential for the quarkmodel and chromodynamics.
- 1979: 5GeV electron positron collider CESR (designed for 8GeV)

Advantage:

More center of mass energy





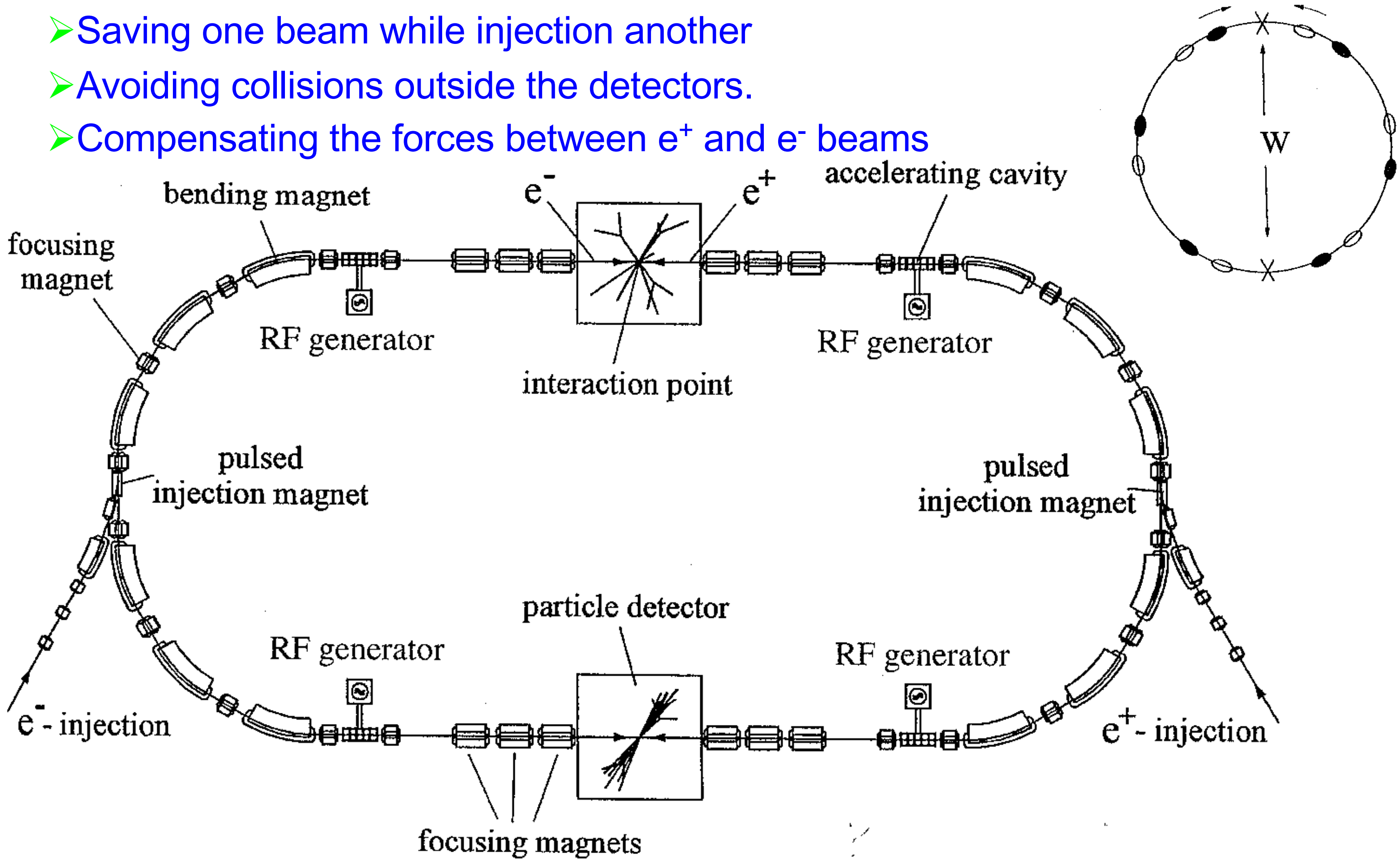
Drawback:

Less dense target

The beams therefore must be stored for a long time.

Elements of a collider

- Saving one beam while injection another
- Avoiding collisions outside the detectors.
- Compensating the forces between e^+ and e^- beams



Storage Rings

To avoid the loss of collision time during filling of a synchrotron, the beams in colliders must be stored for many millions of turns.

Challenges:

- Required vacuum of pressure below 10^{-7} Pa = 10^{-9} mbar, 3 orders of magnitude below that of other accelerators.
- Fields must be stable for a long time, often for hours.
- Field errors must be small, since their effect can add up over millions of turns.
- Even though a storage ring does not accelerate, it needs acceleration sections for phase focusing and to compensate energy loss due to the emission of radiation.

Further developments of Colliders

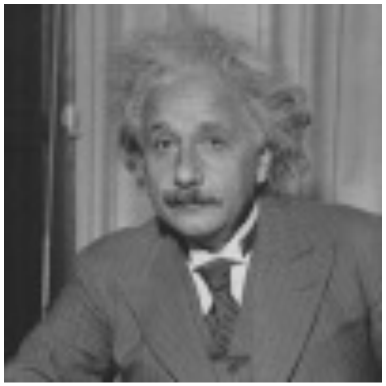
- 1981: Rubbia and van der Meer use stochastic cooling of anti-portons and discover W+,W- and Z vector bosons of the weak interaction
- 1987: Start of the superconducting TEVATRON at FNAL
- 1989: Start of the 27km long LEP electron positron collider
- 1990: Start of the first asymmetric collider, electron (27.5GeV) proton (920GeV) in HERA at DESY
- 1998: Start of asymmetric two ring electron positron colliders KEK-B / PEP-II
- Today: 27km, 6.8 TeV proton collider LHC; Higgs discovery in 2012

NP 1984
Carlo Rubbia
Italy 1934 -

NP 1984
Simon van der Meer
Netherlands 1925 -

Special Relativity

$$E = mc^2$$



Albert Einstein, 1879-1955
Nobel Prize, 1921
Time Magazine Man of the Century

Four-Vectors:
Quantities that transform according to the Lorentz transformation when viewed from a different inertial frame.

Examples:

$$X^\mu \in \{ct, x, y, z\}$$

$$P^\mu \in \{\tfrac{1}{c}E, p_x, p_y, p_z\}$$

$$\Phi^\mu \in \{\tfrac{1}{c}\phi, A_x, A_y, A_z\}$$

$$J^\mu \in \{c\rho, j_x, j_y, j_z\}$$

$$K^\mu \in \{\tfrac{1}{c}\omega, k_x, k_y, k_z\}$$

$$X^\mu \in \{ct, x, y, z\} \quad \Rightarrow \quad X^\mu X_\mu = (ct)^2 - \vec{x}^2 = \text{const.}$$

$$P^\mu \in \{\tfrac{1}{c}E, p_x, p_y, p_z\} \Rightarrow \quad P^\mu P_\mu = \left(\frac{E}{c}\right)^2 - \vec{p}^2 = (m_0 c)^2 = \text{const.}$$

Available Energy in Collisions

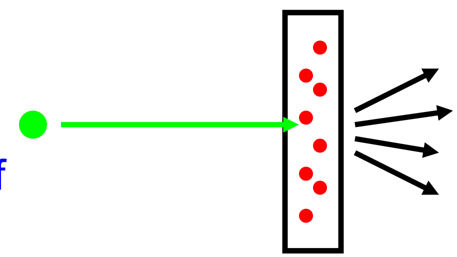
$$\frac{1}{c^2}E_{\text{cm}}^2 = (P_1^\mu + P_2^\mu)_{\text{cm}}(P_{1\mu} + P_{2\mu})_{\text{cm}}$$

$$= (P_1^\mu + P_2^\mu)(P_{1\mu} + P_{2\mu})$$

$$= \tfrac{1}{c^2}(E_1 + E_2)^2 - (p_{z1} - p_{z2})^2$$

$$= 2\left(\frac{E_1 E_2}{c^2} + p_{z1}p_{z2}\right) + (m_{01}c)^2 + (m_{02}c)^2$$

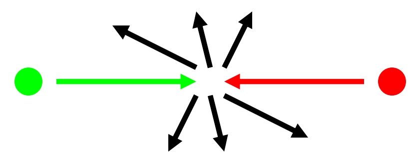
Operation of synchrotrons: fixed target experiments where some energy is in the motion of the center off mass of the scattering products



$$E_1 >> m_{01}c^2, m_{02}c^2; p_{z2} = 0; E_2 = m_{02}c^2 \quad \Rightarrow \quad E_{\text{cm}} = \sqrt{2E_1 m_{02}c^2}$$

Operation of colliders:

the detector is in the center of mass system



$$E_1 >> m_{01}c^2; E_2 >> m_{02}c^2 \quad \Rightarrow \quad E_{\text{cm}} = 2\sqrt{E_1 E_2}$$

Example: Fixed-target production of p-bar

- 1954: Operation of Bevatron, first proton synchrotron for 6.2GeV, production of the anti-porton by Chamberlain and Segrè

$$p + p \quad \mapsto \quad p + p + p + \bar{p}$$

$$\frac{1}{c^2} E_{\text{cm}}^2 = 2\left(\frac{E_1 E_2}{c^2} + p_{z1} p_{z2}\right) + (m_{01} c)^2 + (m_{02} c)^2$$

$$(4 m_{p0} c)^2 < \frac{E_{cm}^2}{c^2} = 2\, E_1 m_{p0} + (m_{po} c)^2 + (m_{po} c)^2$$

$$7 m_{p0} c^2 < E_1$$

$$K_1 = E_1 - m_0 c^2 > 6 m_{p0} c^2 = 5.628\,\text{GeV}$$

NP 1959
Emilio Gino Segrè
Italy 1905 – USA 1989

NP 1959
Owen Chamberlain
USA 1920 - 2006

Example: production of c / c-bar states

- 1974: Observation of $c-\bar{c}$ resonances (J/Ψ) at Ecm = 3095MeV at the e^+/e^- collider SPEAR

$$\frac{1}{c^2}E_{\rm cm}^2 = 2\left(\frac{E_1E_2}{c^2} + p_{z1}p_{z2}\right) + (m_{01}c)^2 + (m_{02}c)^2$$

Resonance in c/c-bar creation when $E_{cm} = 2m_{c0}c^2$ $\quad E_1 = E_2 \quad \Rightarrow \quad E_{\rm cm}^2 = 4E^2$

Energy per beam: $K = E - m_0c = 1547\text{MeV}$

Beam energy needed for an equivalent fixed target experiment: $\frac{E_{cm}^2}{c^2} = 2[Em + (mc)^2]$

$$K = E - m_{0e}c^2 = \frac{E_{cm}^2}{2m_{0e}c^2} - 2m_{0e}c^2 = 9.4\text{TeV}$$

NP 1976
Burton Richter
USA 1931 -

NP 1976
Samuel CC Ting
USA 1936 -

Rings for Synchrotron Radiation

- 1947: First detection of synchrotron light at General Electrics.
- 1952: First accurate measurement of synchrotron radiation power by Dale Corson with the Cornell 300MeV synchrotron.
- 1968: TANTALOS (U of Wisconsin), first dedicated storage ring for synchrotron radiation

Dale Corson
Cornell's 8th president
USA 1914 –

4 Generations of Light Sources

- 1st Genergation (1970s): Many HEP rings are parasitically used for X-ray production
- 2nd Generation (1980s): Many dedicated X-ray sources (light sources)
- 3rd Generation (1990s): Several rings with dedicated radiation devices (wigglers and undulators)
- Today (4th Generation): Construction of Free Electron Lasers (FELs) driven by LINACs