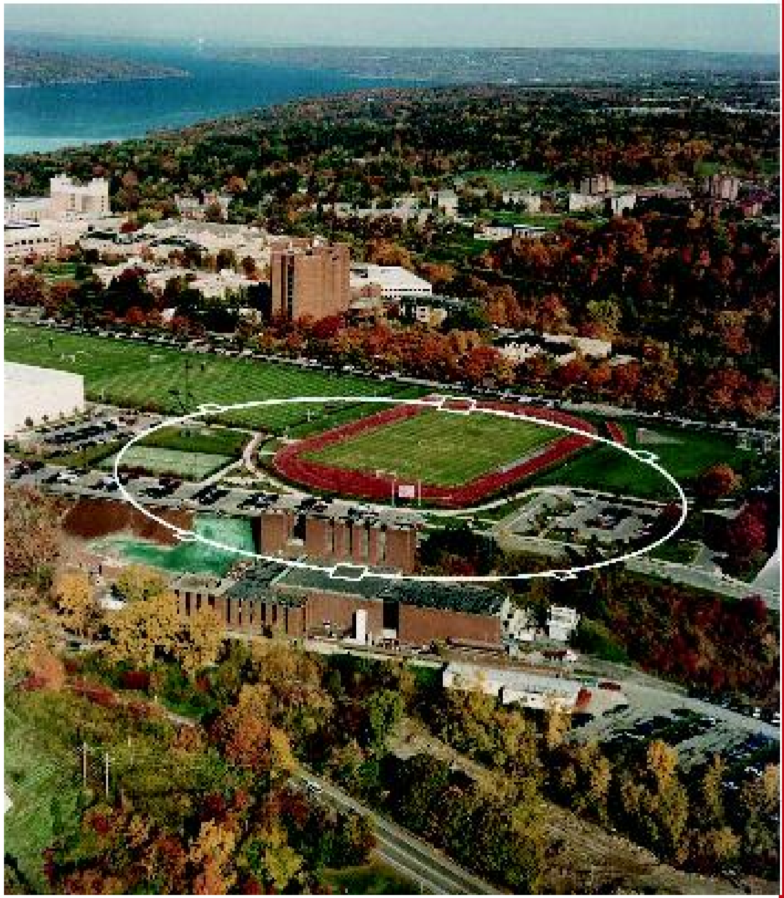
Advanced Accelerator Physics

CHESS & LEPP

Content



Literature

Required:

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

Optional:

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

Related material:

Handbook of Accelerator Physics and Engineering, Alexander Wu Chao and Maury Tigner, 2nd edition, 2002, World Scientific, ISBN: 981 02 3858 4

Particle Accelerator Physics II, Helmut Wiedemann, Springer, 2nd edition, 1999, ISBN 3 540 64504 7

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

Different accelerators

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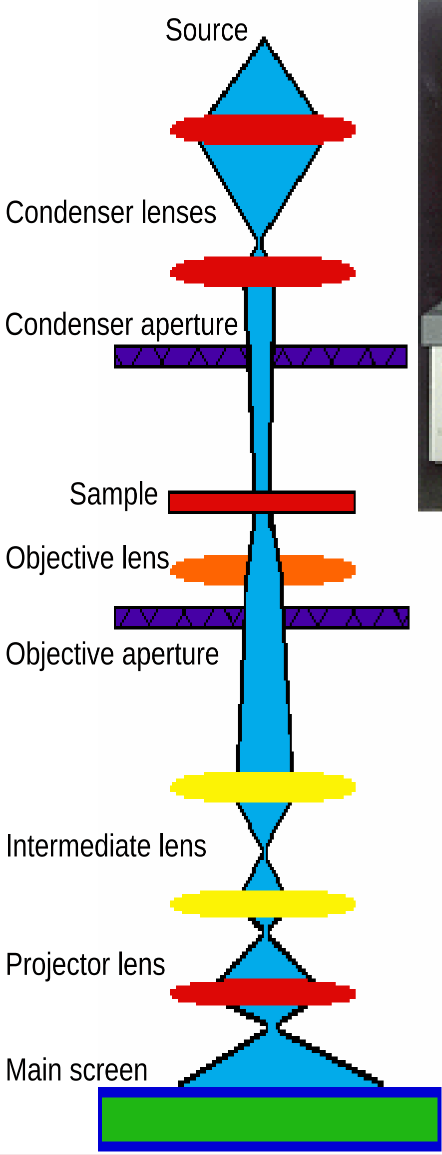

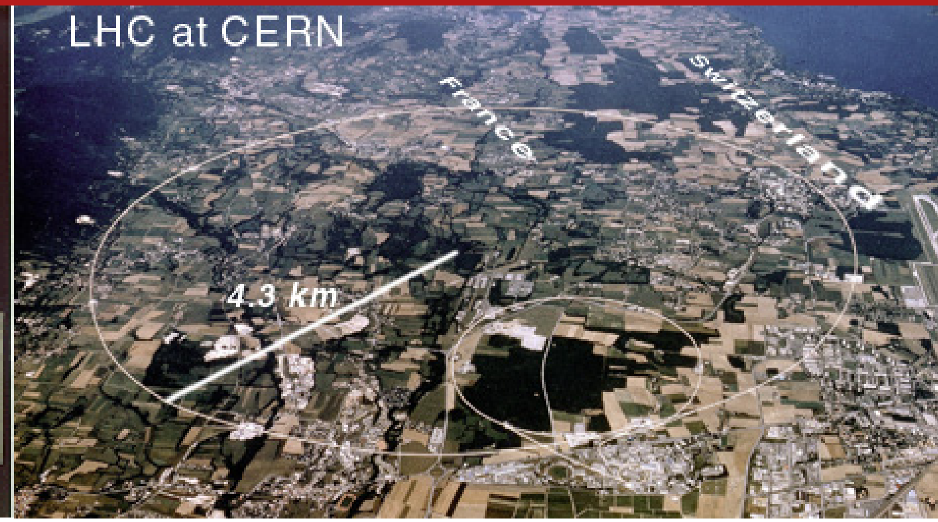

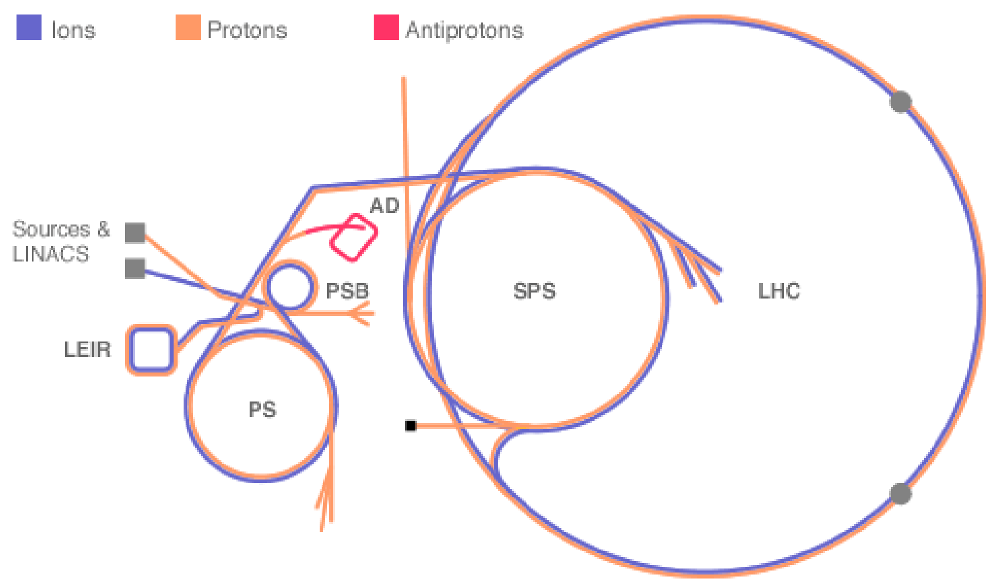

A short history of accelerators

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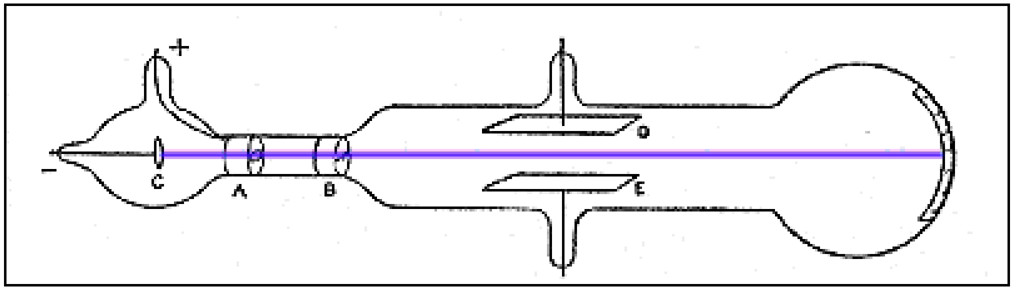
- 1862: Maxwell theory of electromagnetism
- 1887: Hertz discovery of the electromagnetic wave
- 1886: Goldstein discovers positively charged rays (ion beams)
- 1894: Lenard extracts cathode rays (with a 2.65um Al Lenard window)
- 1897: JJ Thomson shows that cathode rays are particles since they followed 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

Germany 1862-1947



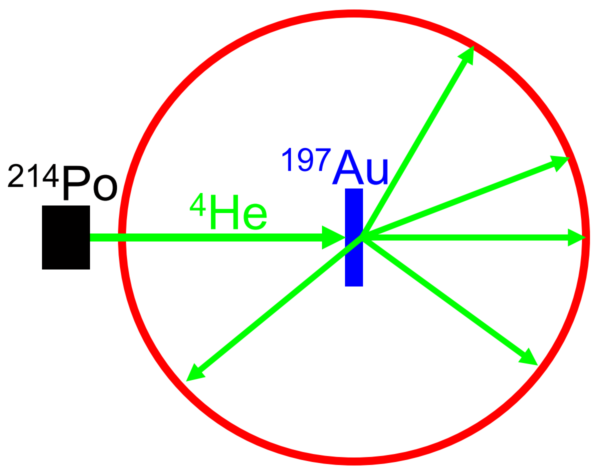
NP 1906

Joseph J. Thomson

UK 1856-1940

A short history of accelerators

- 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.



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

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

d = smalles approach for back scattering

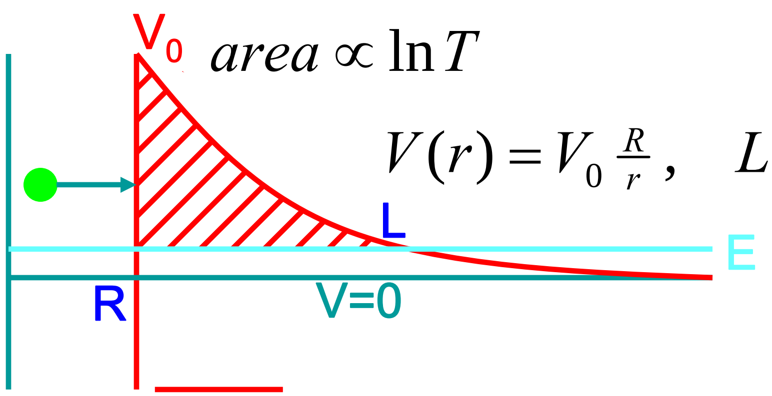
- 1919: Rutherford produces first nuclear reactions with natural ^{4}He
^{14}N + ^{4}He $\mapsto$ ^{17}O + p
- 1921: Greinacher invents the cascade generator for several 100 keV
- Rutherford is convinced that several 10 MeV are in general needed for nuclear reactions. He therefore gave up the thought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

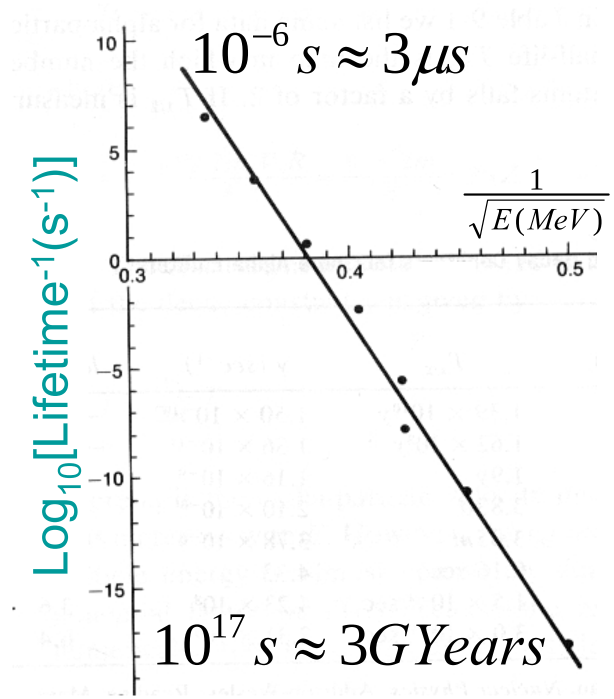
Schroedinger equation: $$\frac{\partial^2}{\partial r^2}u(r) = \frac{2m}{\hbar^2}[V(r)-E]u(r)\,,\quad T=\left|\frac{u(L)}{u(0)}\right|^2$$

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.



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

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



Three historic lines of accelerators

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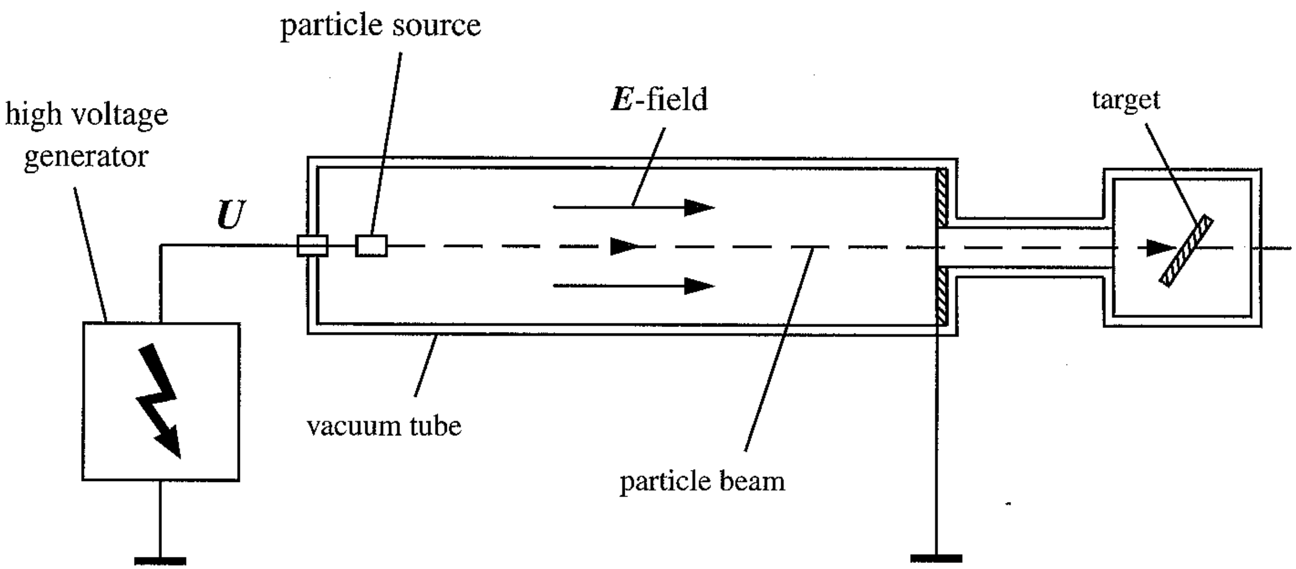
Direct Voltage Accelerators

Resonant Accelerators Transformer Accelerator

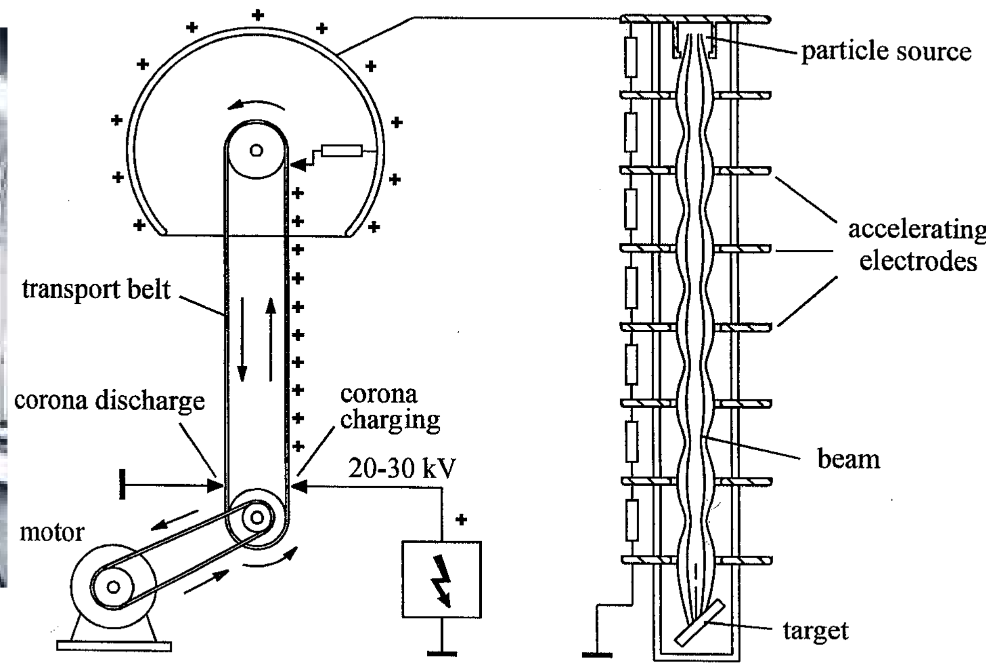


Voltage 1MV
Charge Ze
Energy Z MeV

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.

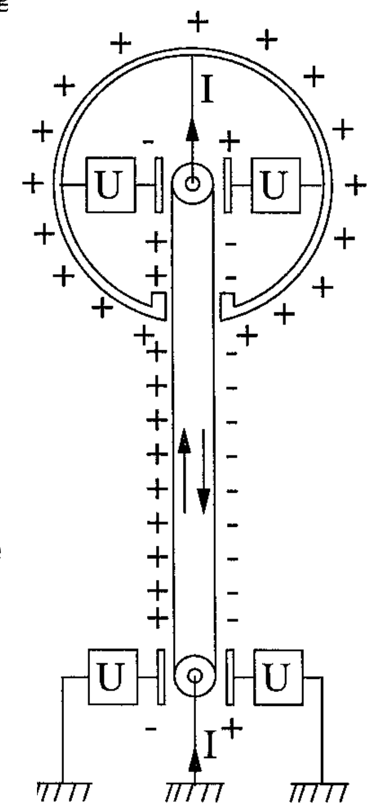
The Van de Graaff Accelerator

- 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 Accelerator

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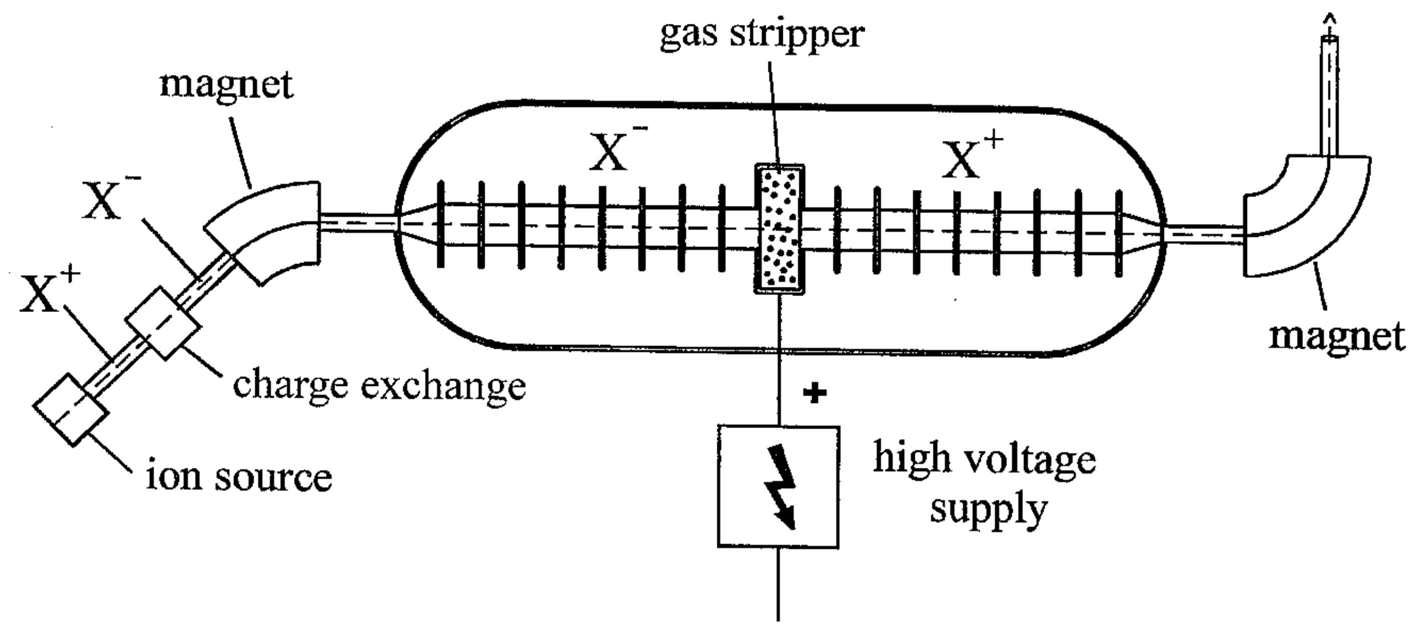
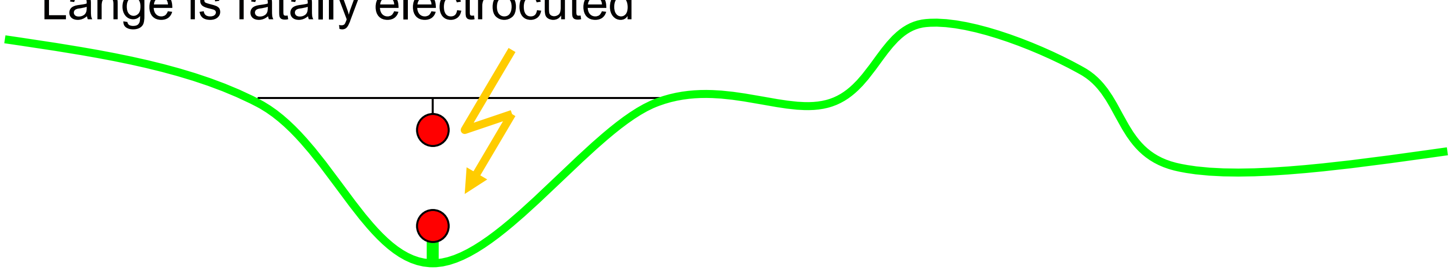
- Two Van de Graaffs, one + one –
- The Tandem Van de Graaff, highest energy 35MeV



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



The Cockcroft-Walton Accelerator

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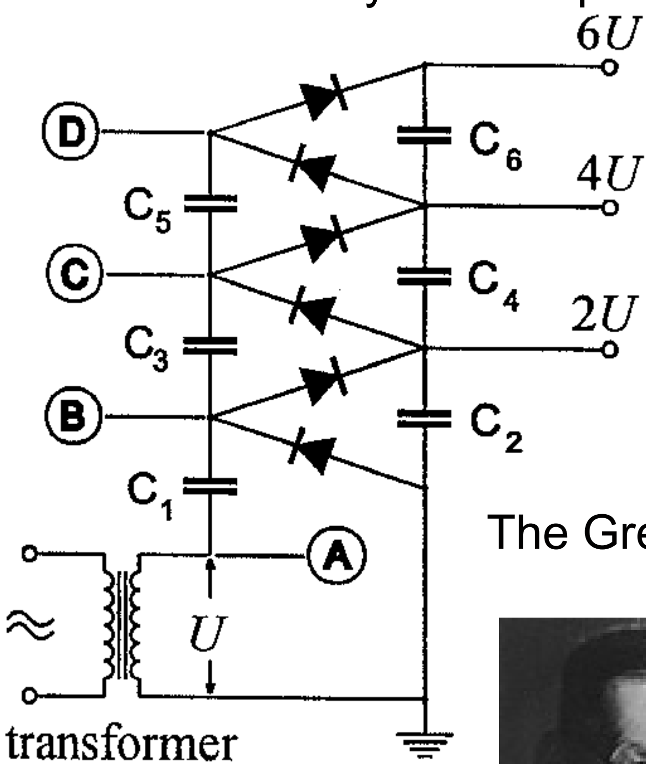
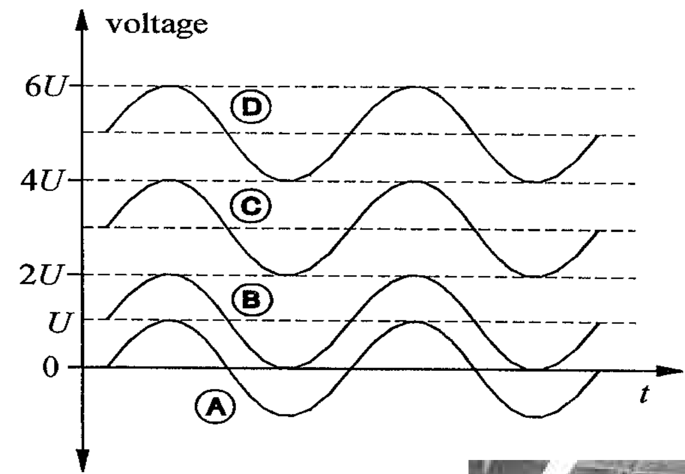
1932: Cockcroft and Walton 1932: 700keV cascate generator (planed for 800keV) and use initially 400keV protons for $^7Li + p \mapsto {}^4He + {}^4He$ and $^7Li + p \mapsto {}^7Be + n$





The Greinacker circuit

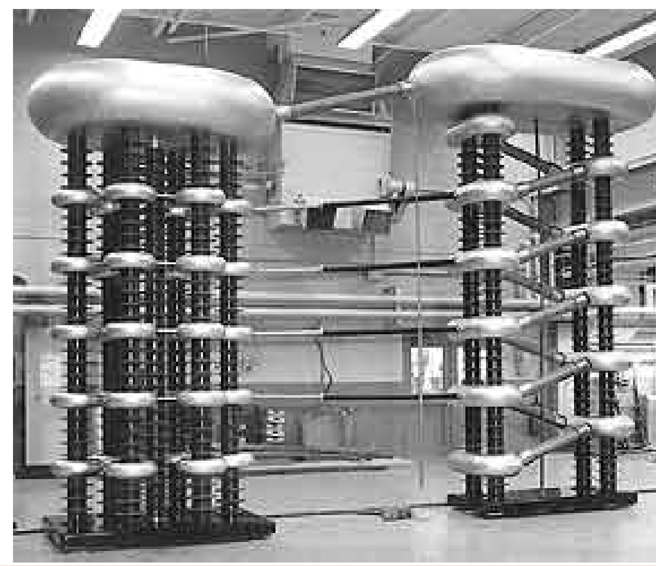
Li

Up to 4MeV, 1A

NP 1951

Sir John D Cockcrof

Ernest T S Walton



The Marx Generator

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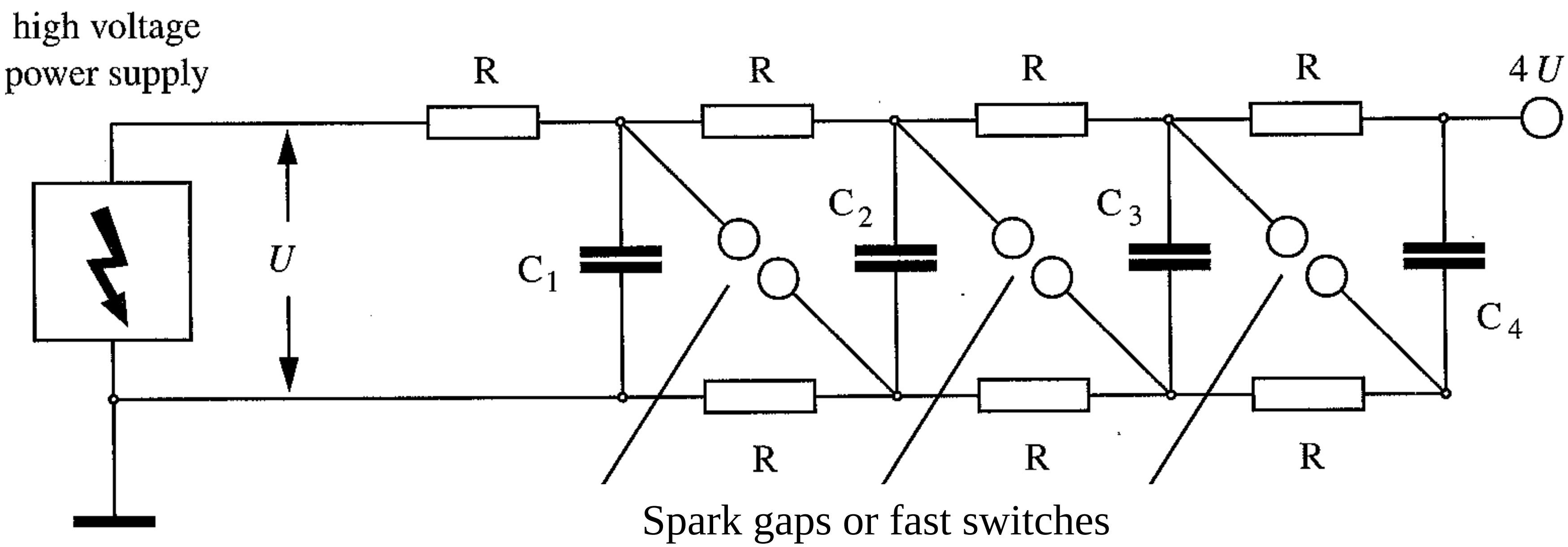
- 1932: Marx Generator achieves 6MV at General Electrics



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

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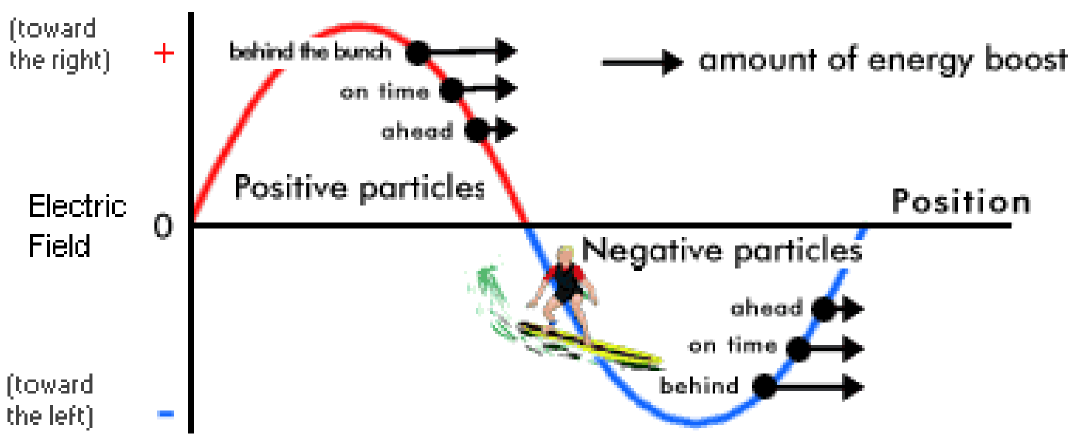
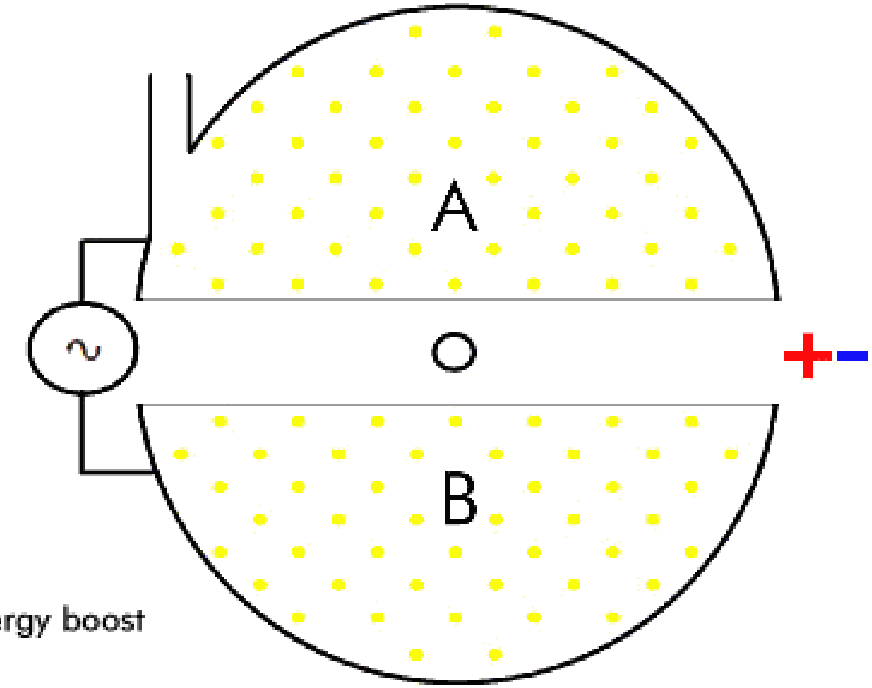
Resonant Accelerators

Direct Voltage Accelerators

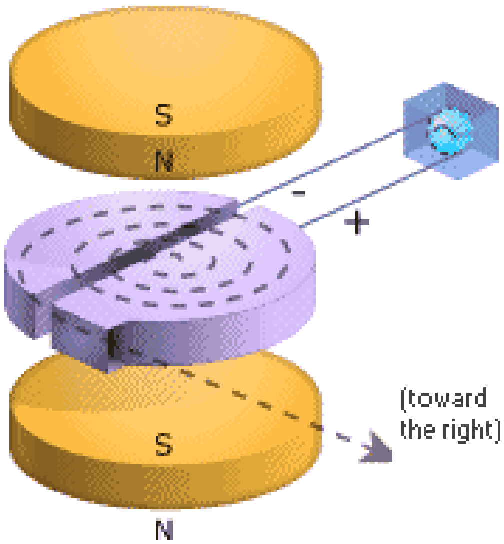
Transformer Accelerator



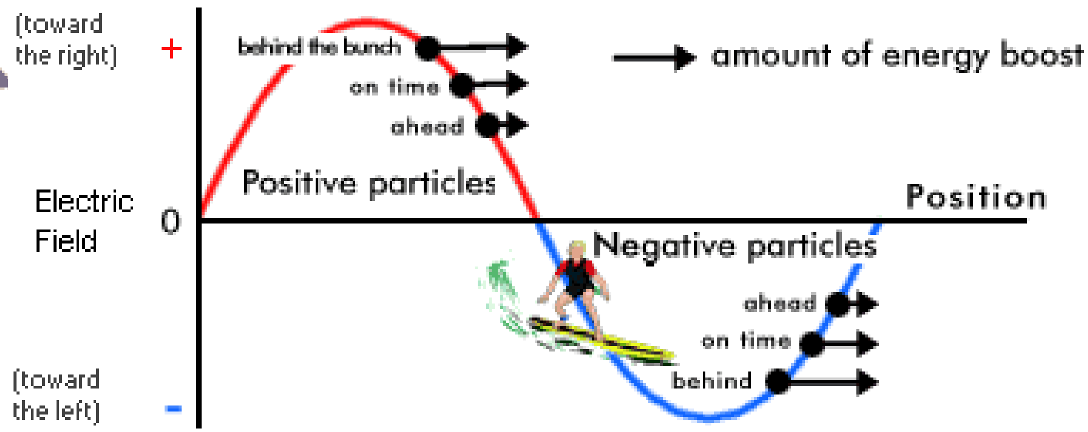


Particles must have the correct phase relation to the accelerating voltage.

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

USA 1901-1958

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

M Stanley Livingston

USA 1905-1986

The cyclotron frequency

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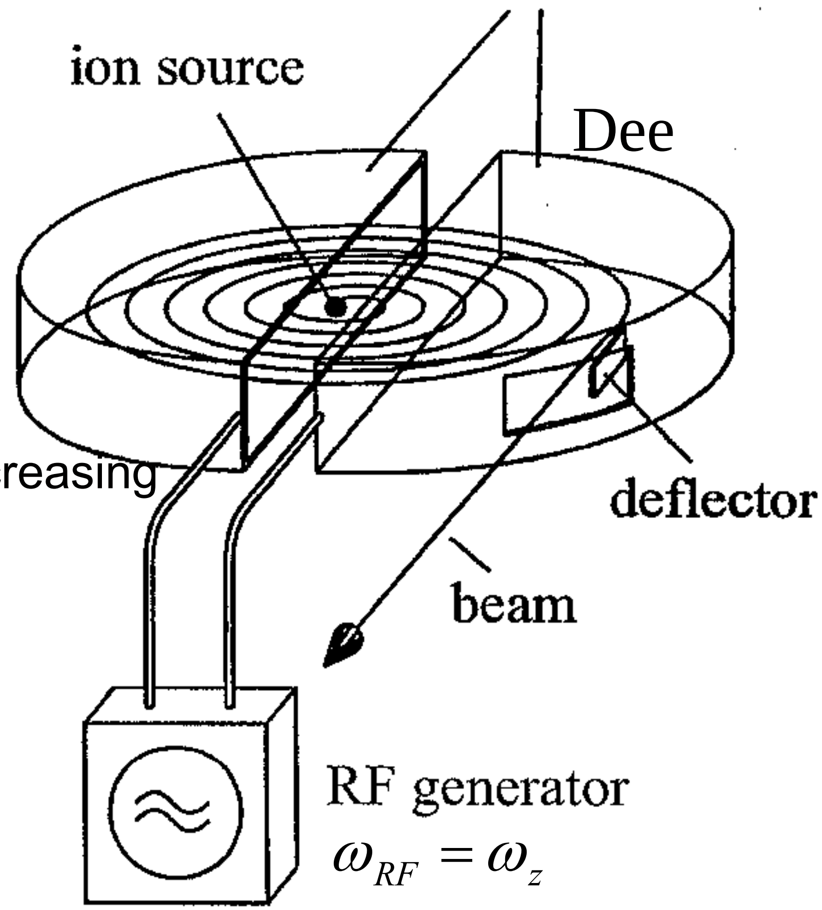
$$F_r = m_0 \gamma \omega_z v = q v B_z$$

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

Condition: Non-relativistic particles.

Therefore not for electrons.



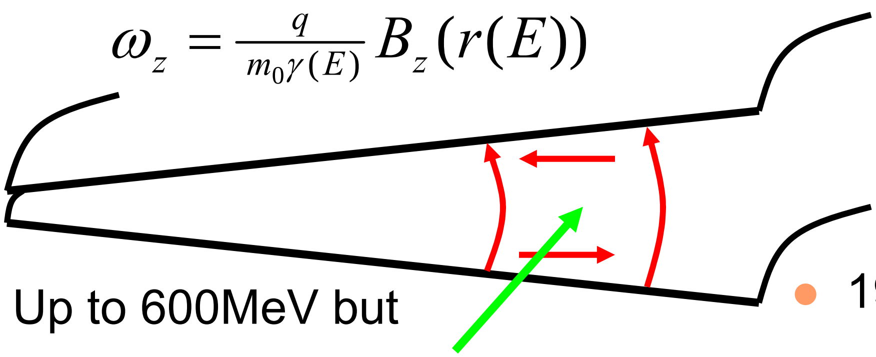
- The synchrocyclotron:

  Acceleration of bunches with decreasing

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

- 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

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

First Medical Applications

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

Modern Nuclear Therapy

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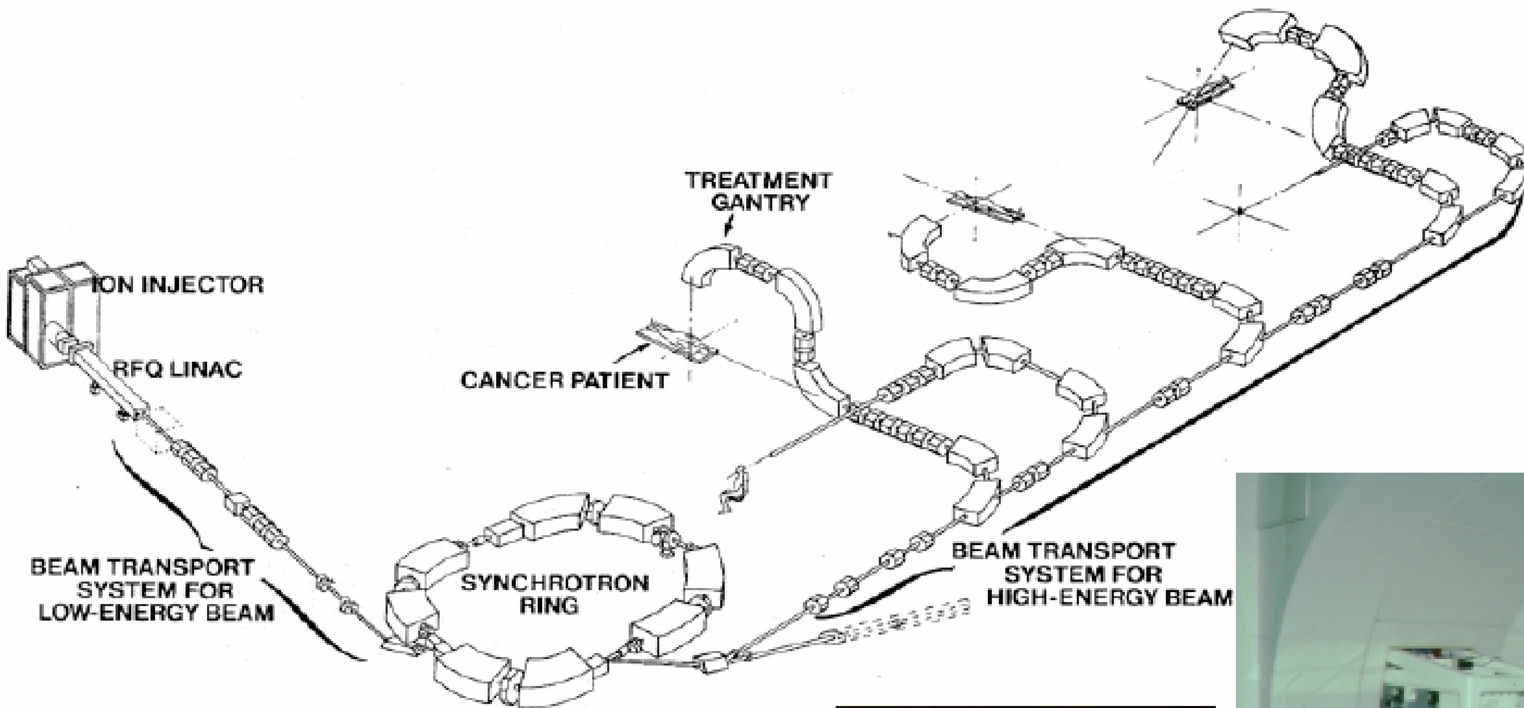
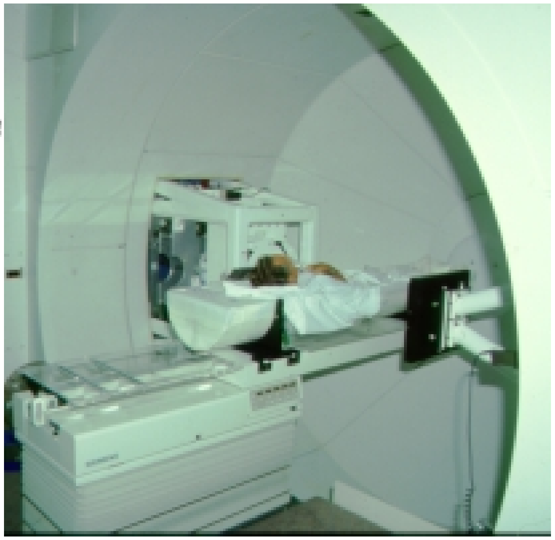
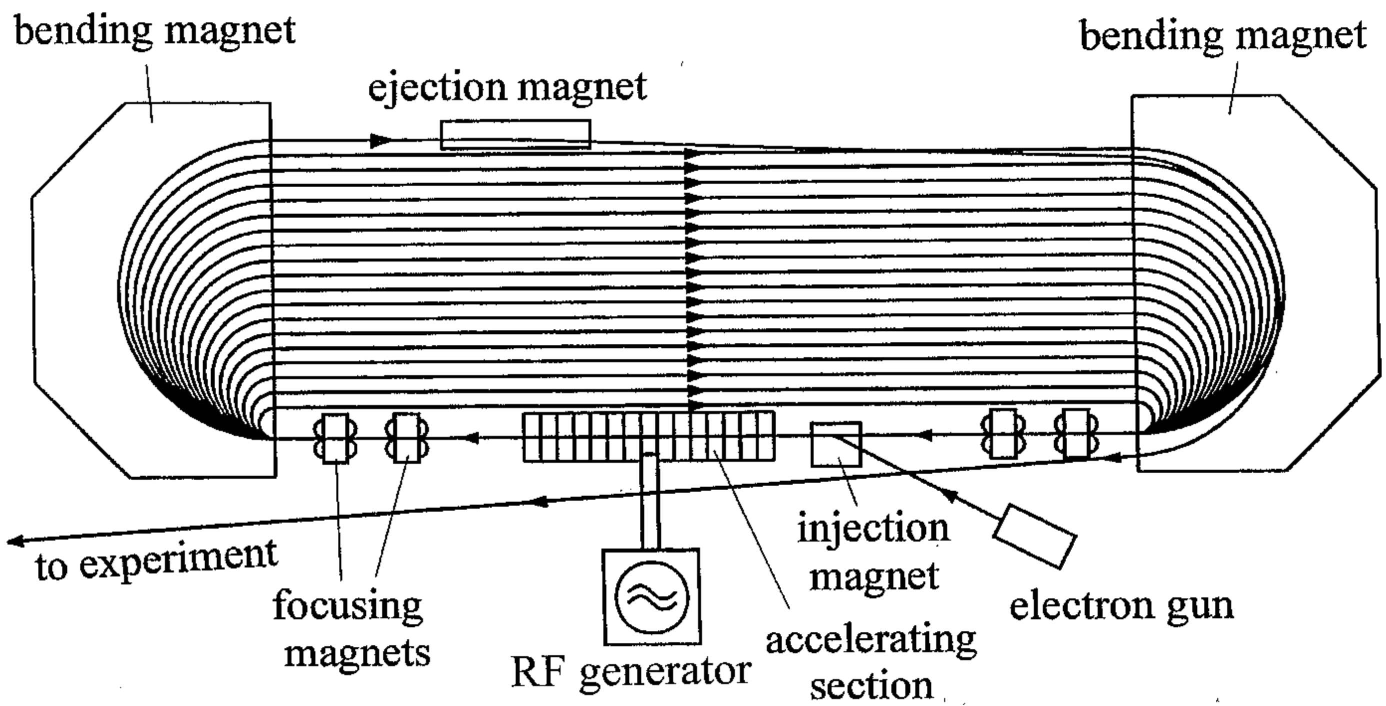
The Loma Linda proton therapy facility





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.

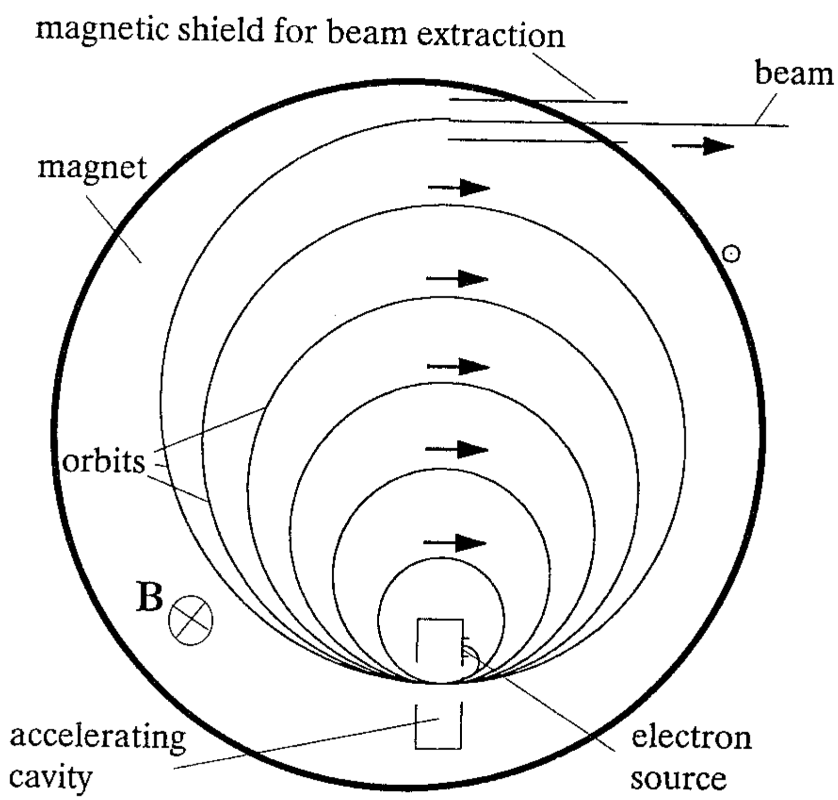


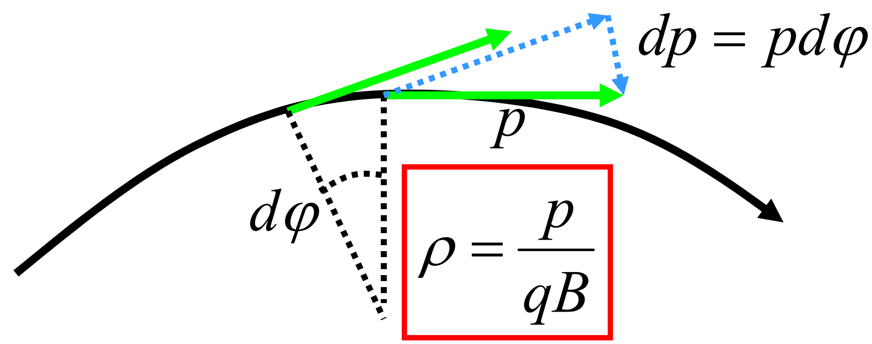
- Today: Used for medical applications with one magnet and 20MeV.
- Nuclear physics: MAMI designed for 820MeV as race track microtron.

The microtron condition

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

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





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

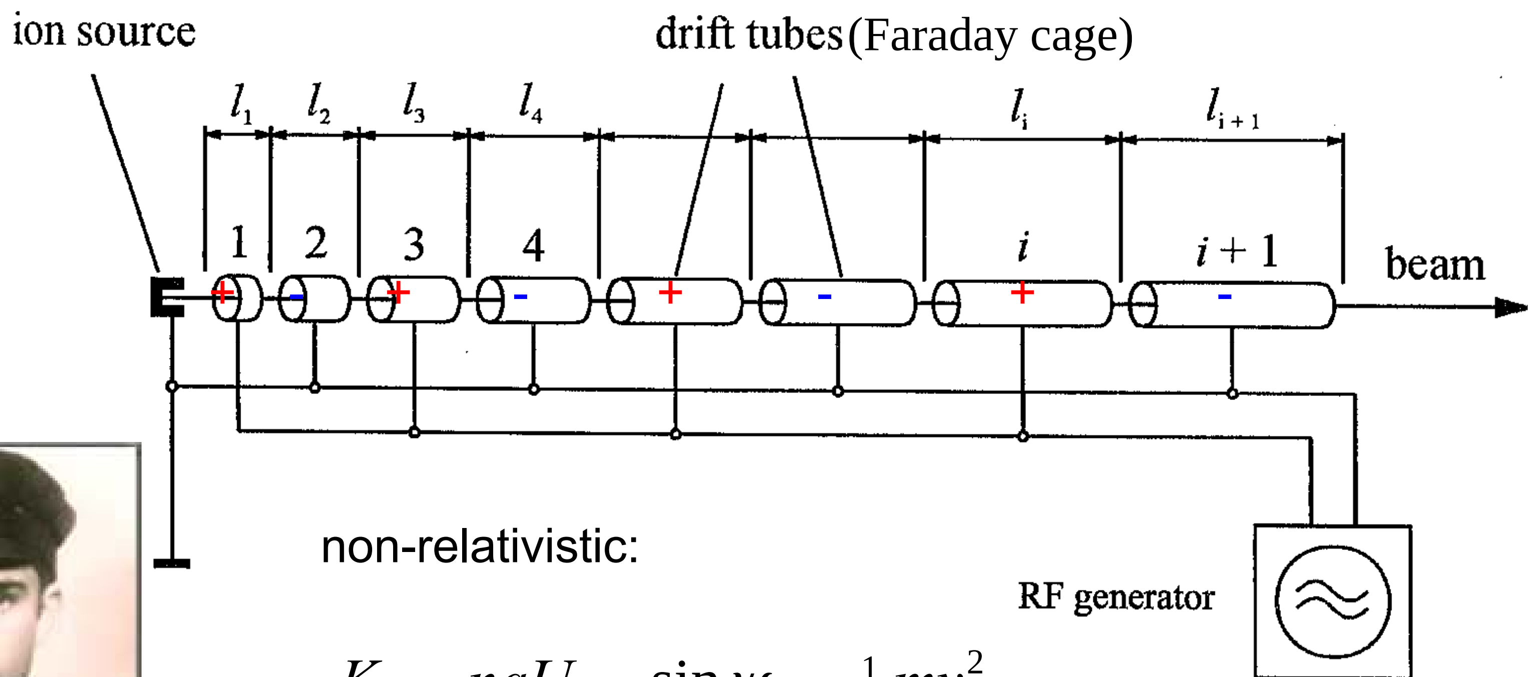
$$= \frac{2\pi}{qB}(m_0\gamma_{n+1} - m_0\gamma_n) = \frac{2\pi}{qBc^2}\Delta K$$

B=1T, n=1, and f_{RF}=3GHz leads to 4.78MeV

This requires a small linear accelerator.

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

Wideroe linear accelerator



non-relativistic:

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

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

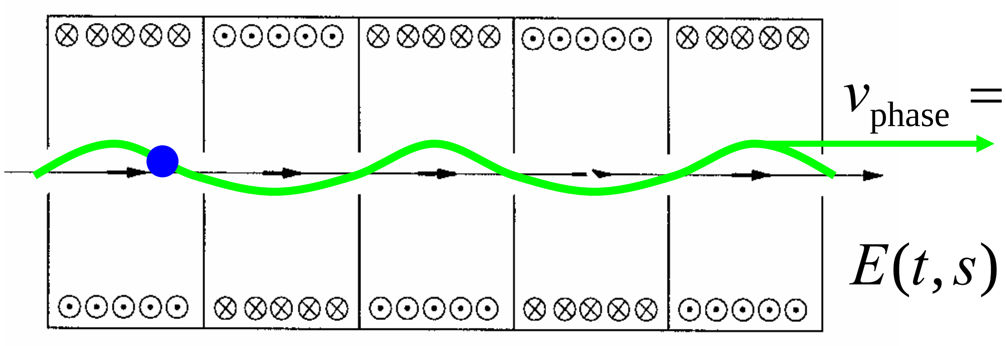
Called the π or the $1/2\beta\lambda$ mode

Wideroe

Accelerating cavities

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

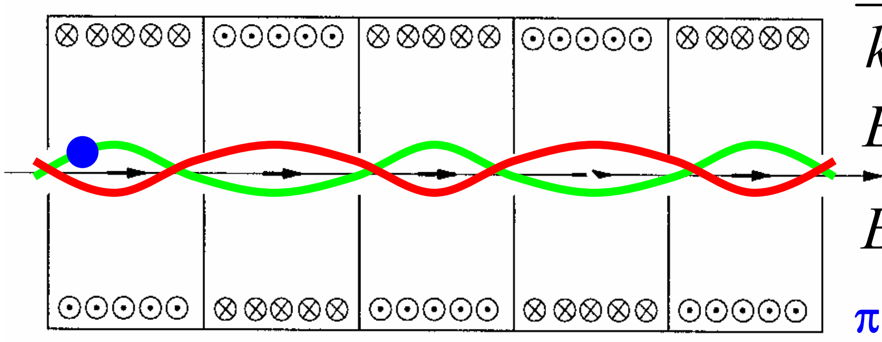
Traveling wave cavity:



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

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

Standing wave cavity:



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

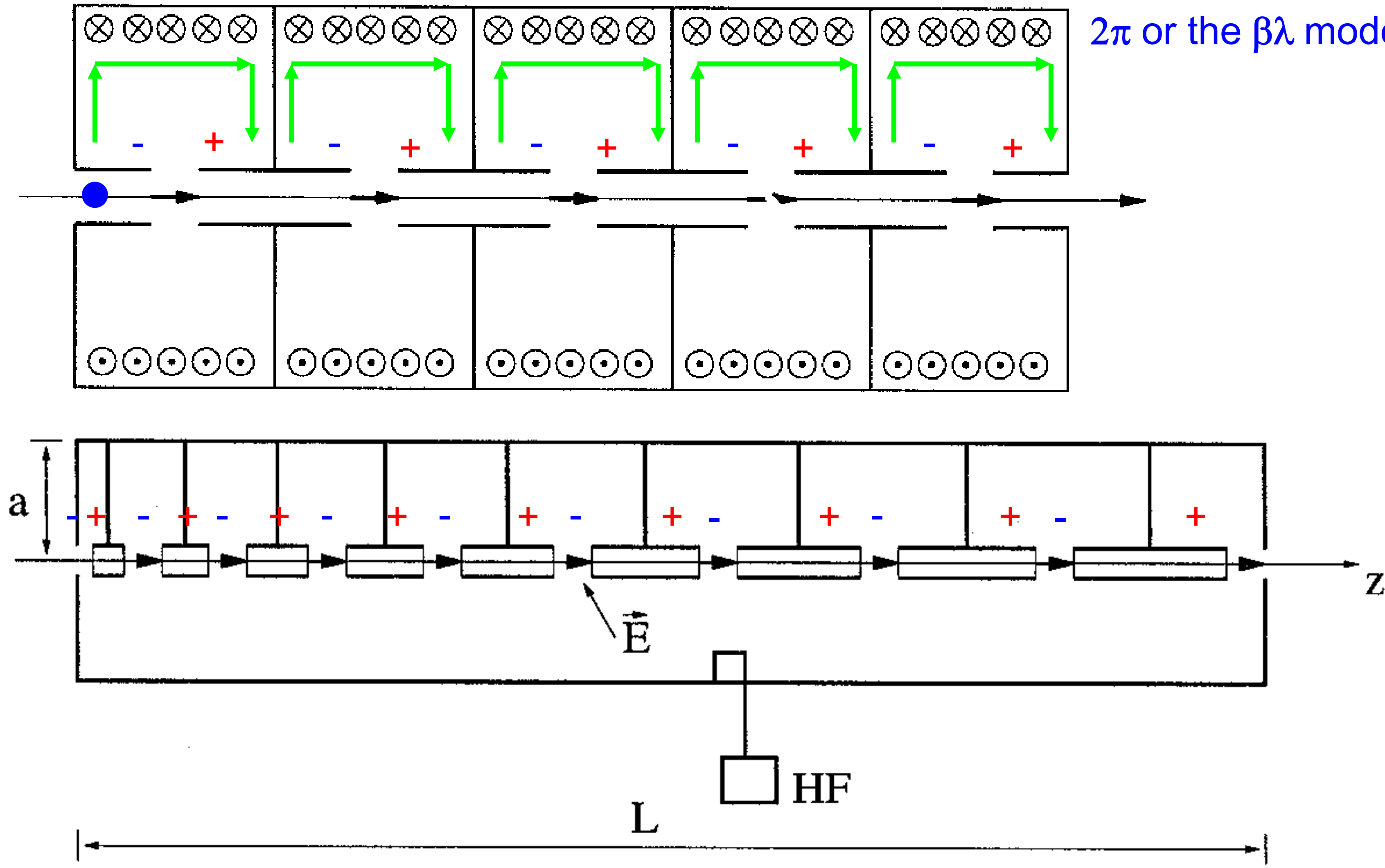
$$E(t,s) \approx E_{\max} \sin(\omega t)\sin(ks)$$

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

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 βλ mode

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

Phase focusing

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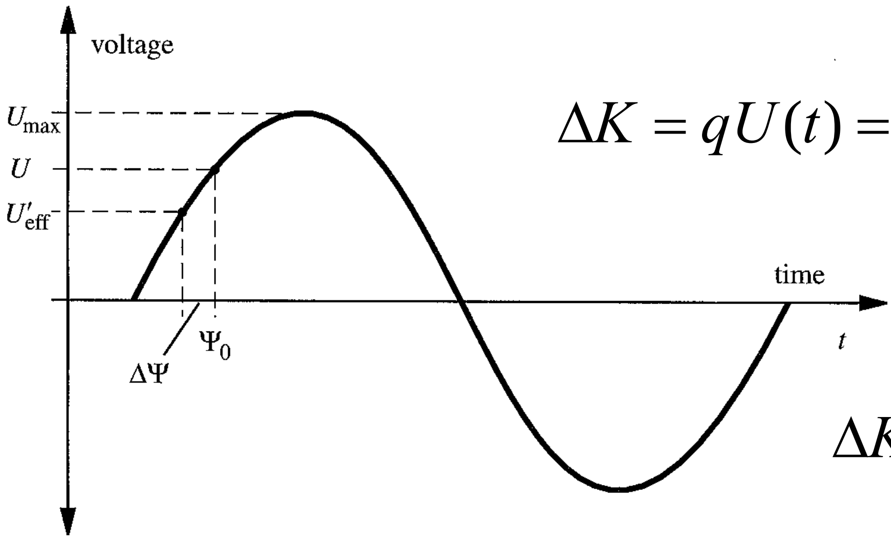
- 1945: Veksler (UDSSR) and McMillan (USA) realize the importance of phase focusing



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

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.

The RF quadrupole (RFQ)

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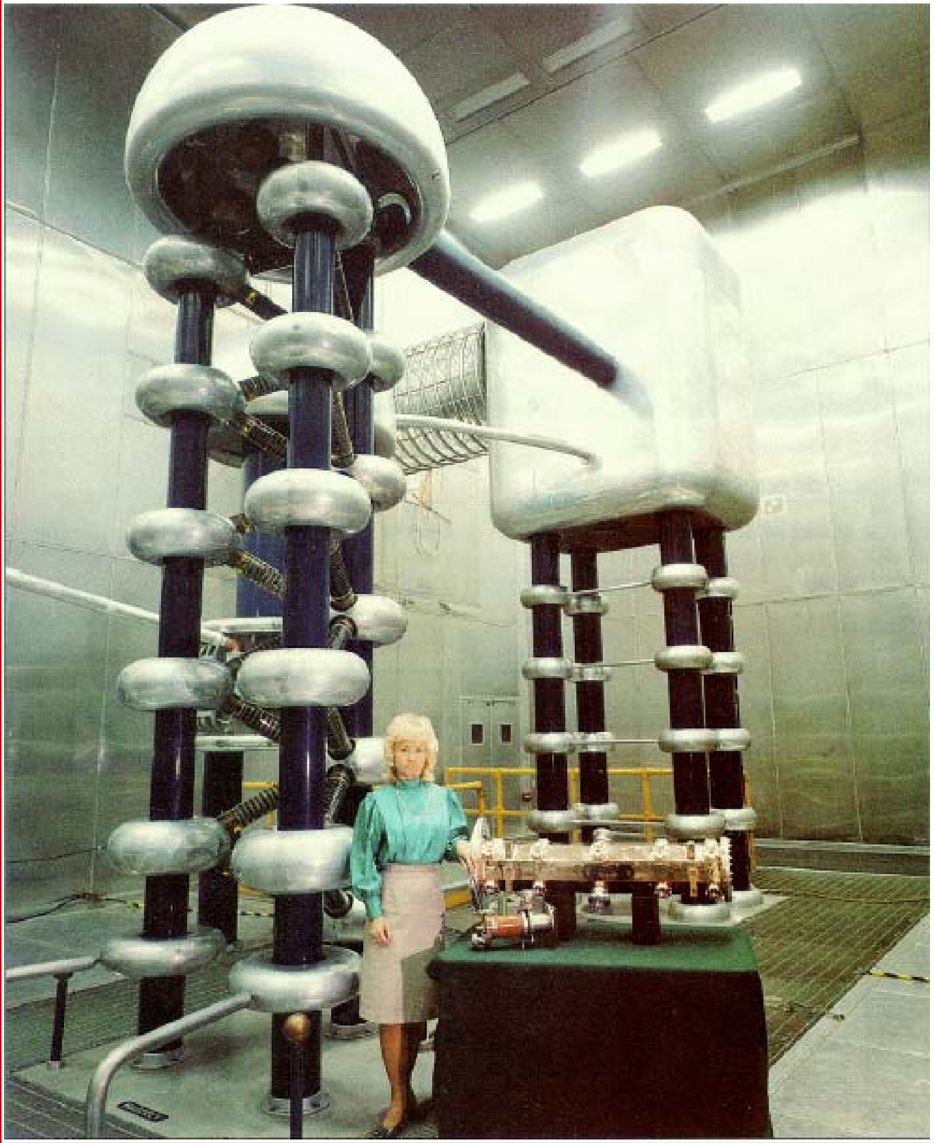
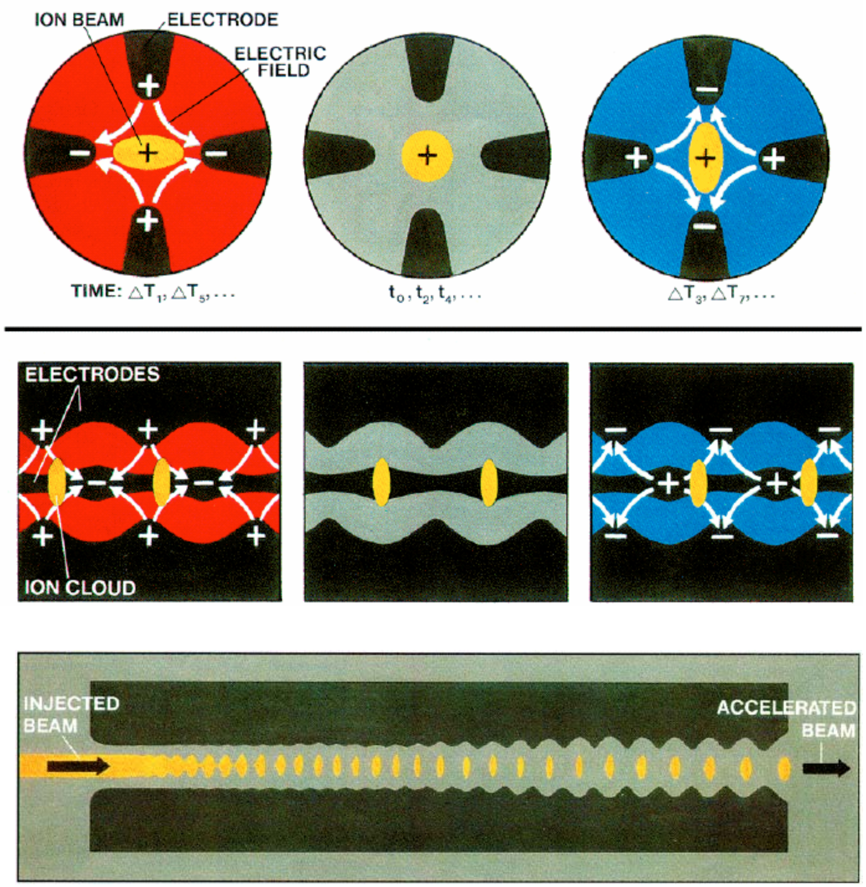


- 1970: Kapchinskii and Teplyakov invent the RFQ



Three historic lines of accelerators

Transformer Accelerator

Direct Voltage Accelerators Resonant Accelerators

- 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:

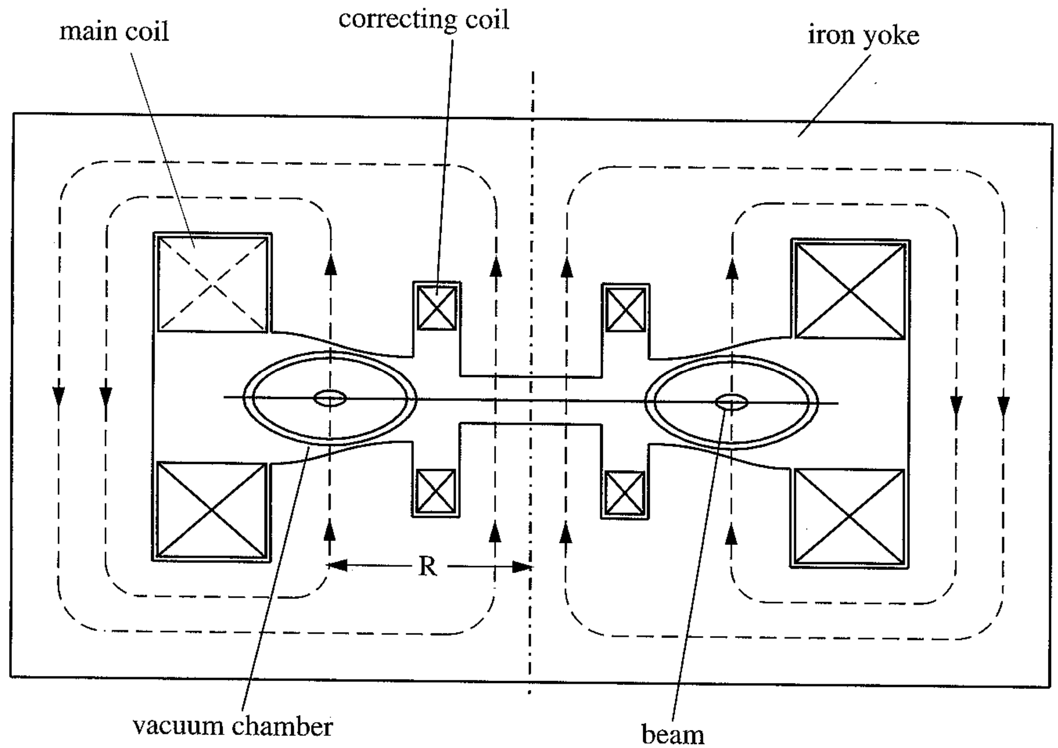
R=const, B=B(t)

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

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

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

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

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

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

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

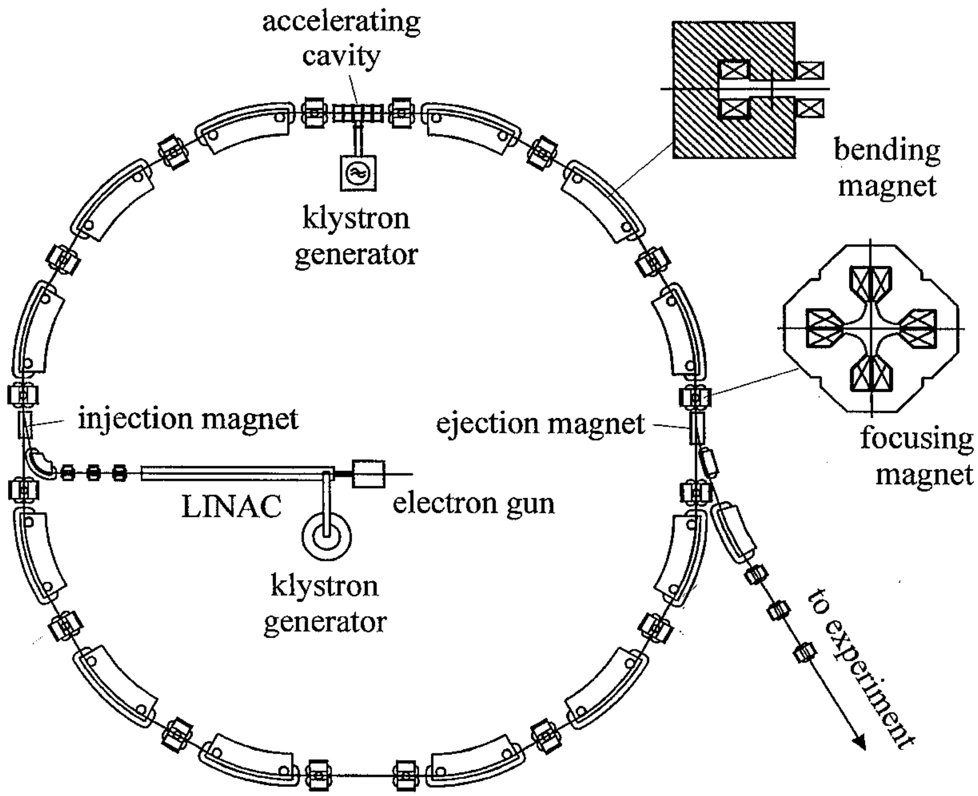
- 1945: Veksler (UDSSR) and McMillan (USA) invent the synchrotron
- 1946: Goward and Barnes build the first synchrotron (using a betatron magnet)
- 1949: Wilson et al. at Cornell are first to store beam in a synchrotron (later 300MeV, magnet of 80 Tons)
- 1949: McMillan builds a 320MeV electron synchrotron

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

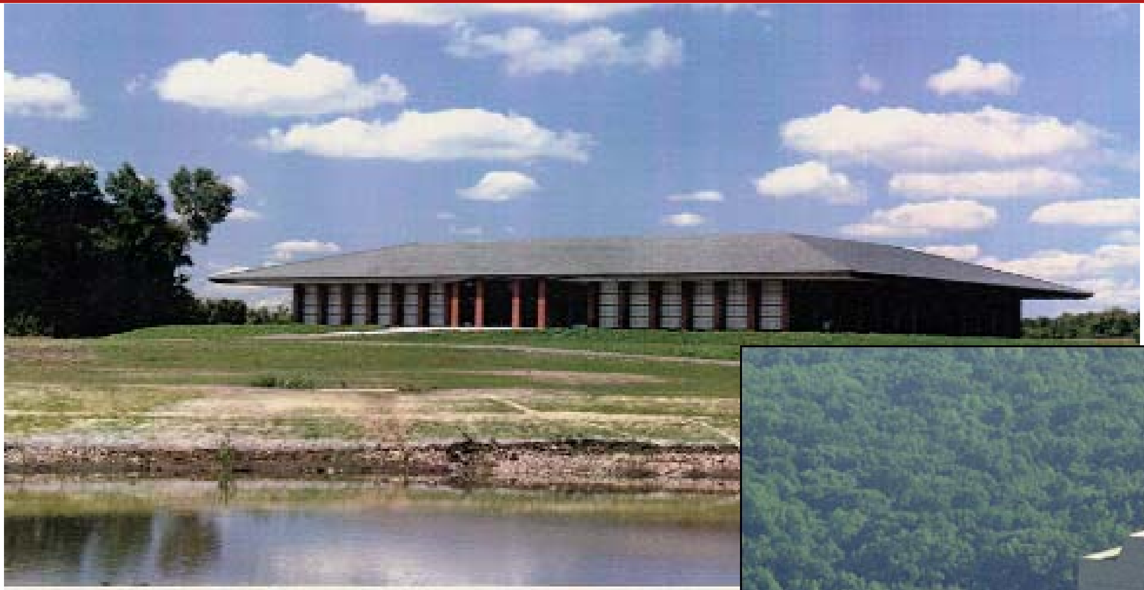
$$R = \frac{p(t)}{qB(R,t)} = \text{const.}$$

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

for an integer n called the harmonic number

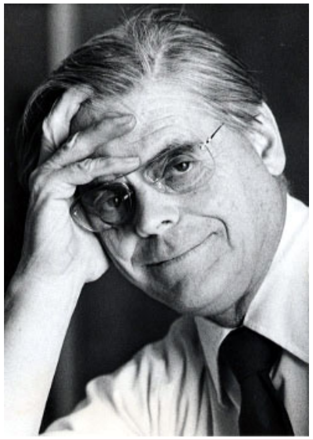


Rober R Wilson, Architecture



Science Ed Center, FNAL (1990)

Wilson Hall, FNAL

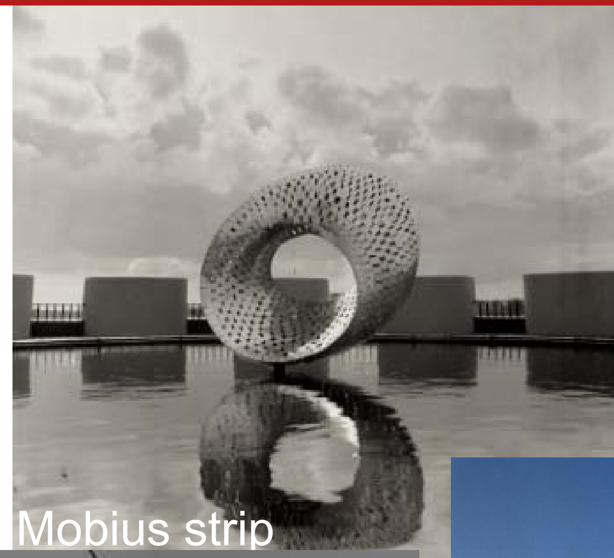


Robert R Wilson

USA 1914-2000

Rober R Wilson, Cornell & FNAL


Broken symmetry


Mobius strip


Tractricious


π lines


Hyperbolic obelisk

Weak focusing Synchrotrons

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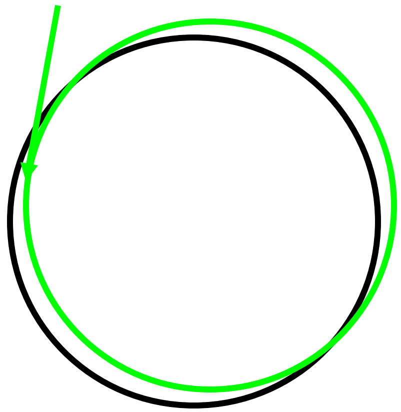
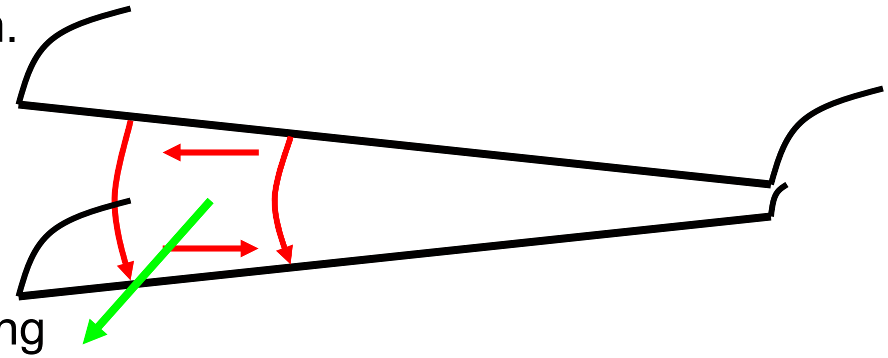
- 1952: Operation of the Cosmotron, 3.3 GeV proton synchrotron at Brookhaven: Beam pipe height: 15cm.

Natural ring focusing:



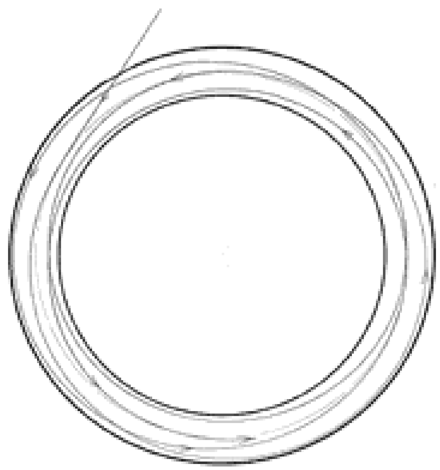


Vertical focusing

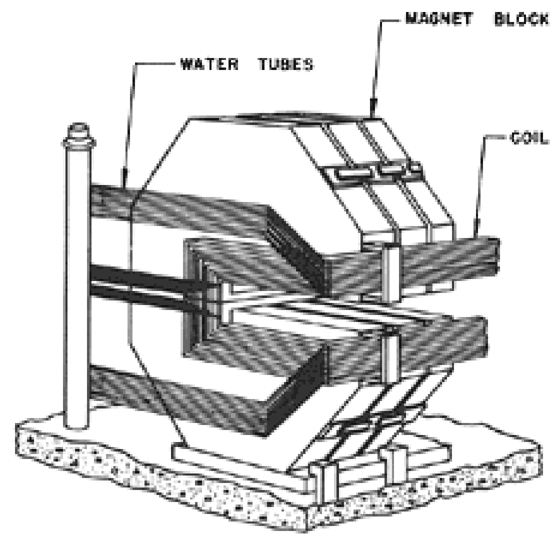
+ Horizontal defocusing + ring focusing

Focusing in both planes

The Cosmotron



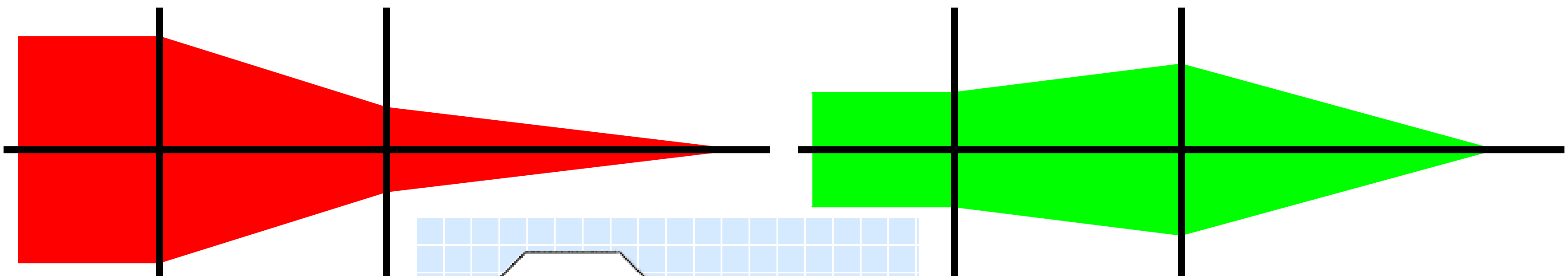
Weak focusing accelerator

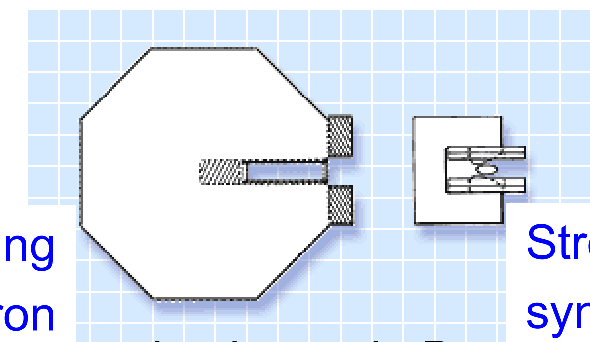


Strong focusing Synchrotrons

- 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.

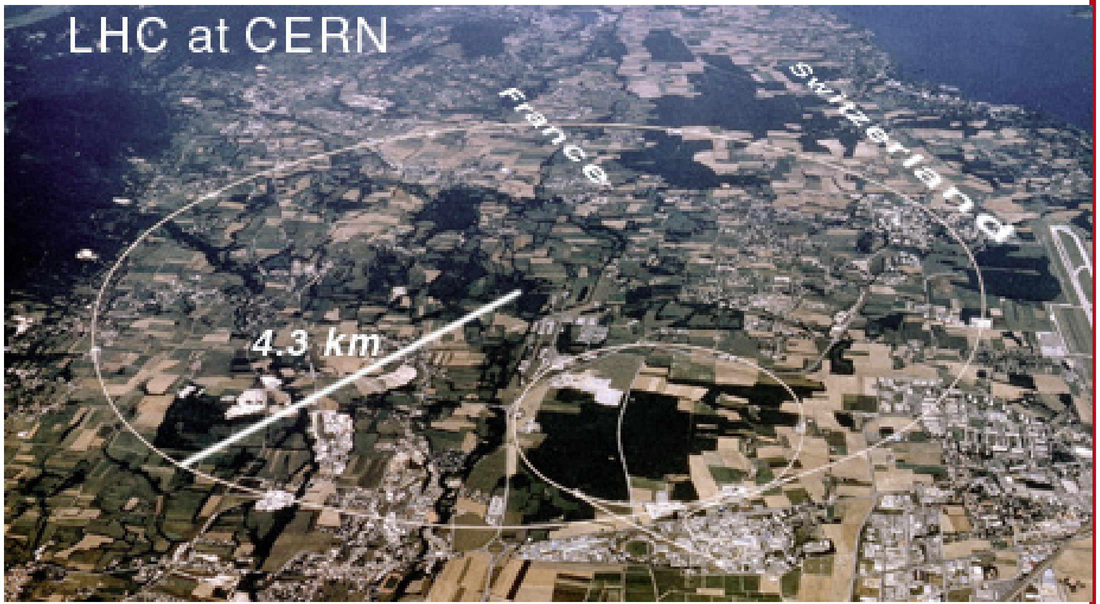
Limits of Synchrotrons

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

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



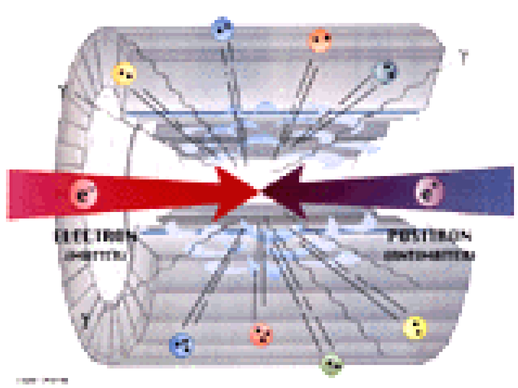
Electron beam with p = 0.1 TeV/c in CERN's 27 km LEP tunnel radiated 20 MW
Each electron lost about 4GeV per turn, requiring many of RF accelerating sections.

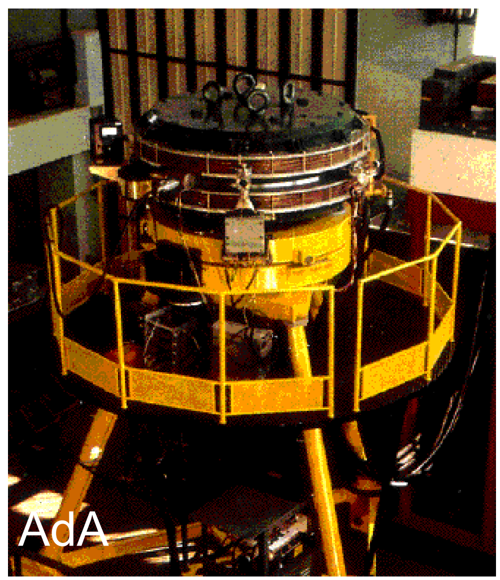
Colliding Beam Accelerators

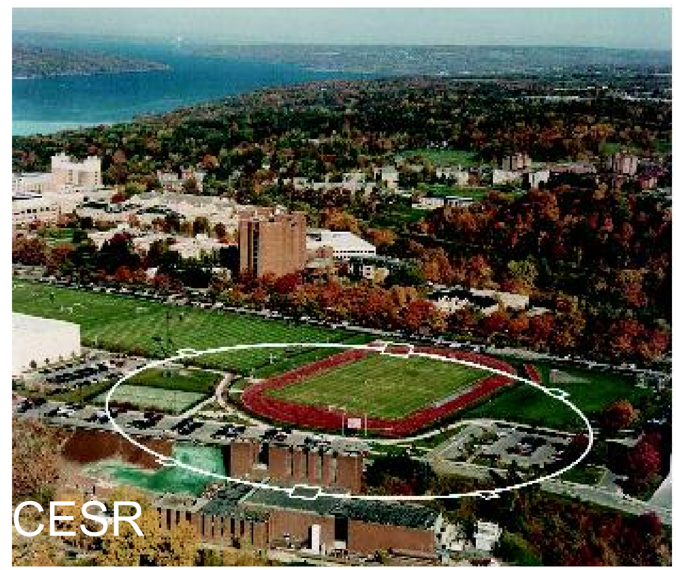
- 1961: First storage ring for electrons and positrons (AdA) in Frascati for 250MeV
- 1972: SPEAR electron positron collider at 4GeV. Discovery of the J/Psi at 3.097GeV by Richter (SPEAR) and Ting (AGS) starts the November revolution and was essential for the quarkmodel and chromodynamics.
- 1979: 5GeV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

Advantage:

More center of mass energy







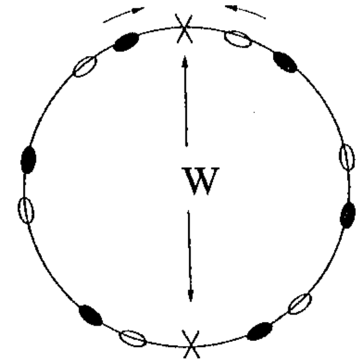
Drawback:

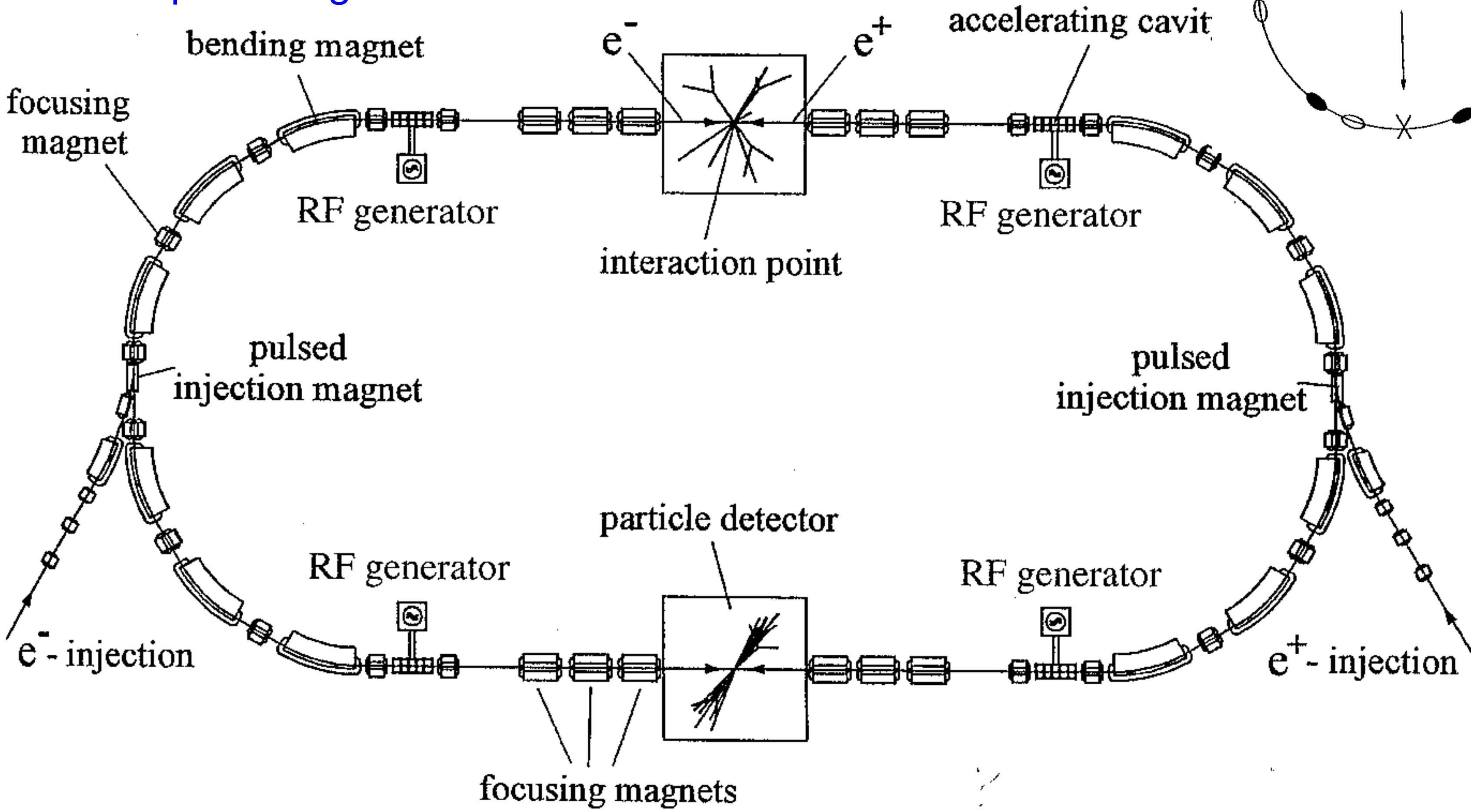
Less dense target

The beams therefore must be stored for a long time.

Ellements 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 milions of turns.

Chalenges:

- 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 Development of Colliders

CHESS & LEPP

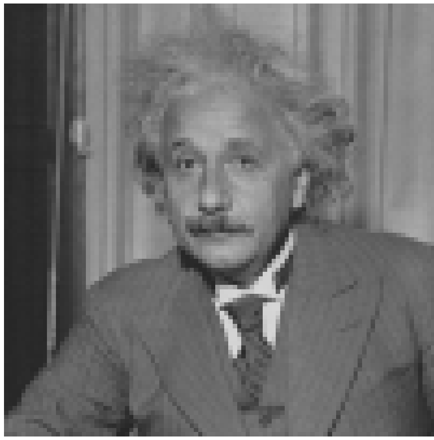
- 1981: Rubbia and van der Meer use stochastic cooling of antiportons and discover W+,W- and Z vector bosons of the weak interaction
- 1987: Start of the superconducting TEVATRON at FNAL
- 1989: Start of the 27km long LEP electron positron collider
- 1990: Start of the first asymmetric collider, electron (27.5GeV) proton (920GeV) in HERA at DESY
- 1998: Start of asymmetric two ring electron positron colliders KEK-B / PEP-II
- Today: 27km, 7 TeV proton collider LHC being build at CERN

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

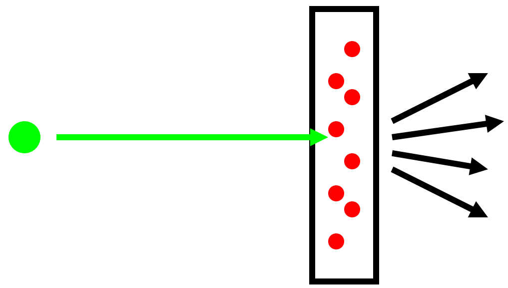
$$\frac{1}{c^2}E_{\rm cm}^2 = (P_1^\mu + P_2^\mu)_{\rm cm}(P_{1\mu} + P_{2\mu})_{\rm cm}$$

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

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

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

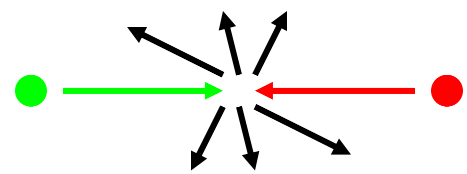
Operation of synchrotrons: fixed target experiments where some energy is in the motion of the center off mass of the scattering products



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

Operation of colliders:

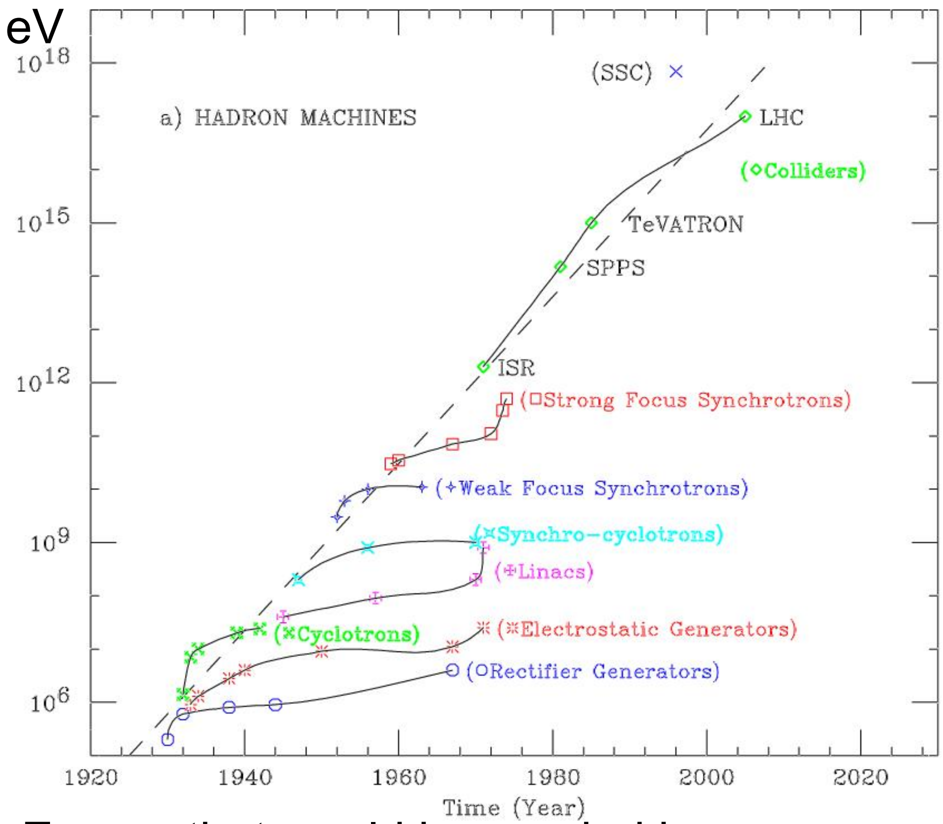
the detector is in the center of mass system



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

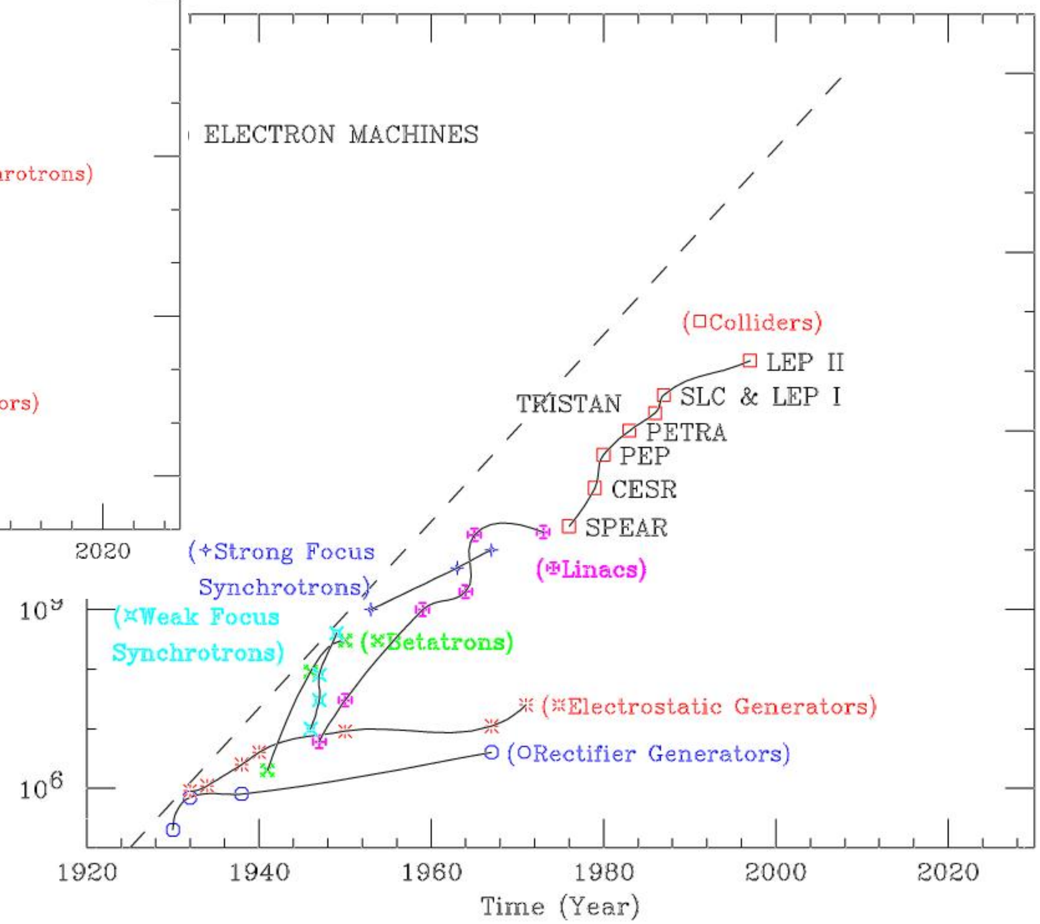
The Livingston Chart

CHESS & LEPP



Comparison:

highest energy cosmic rays have a few 10^{20}eV



Energy that would be needed in a fixed target experiment versus the year of achievement

$$E_1 = \frac{E_{\rm cm}^2}{2m_{02}c^2}$$

Example: Production of the pbar

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

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

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

$$(4m_{p0}c)^2 < \tfrac{1}{c^2} E_{\rm cm}^2 = 2\frac{E_1 m_{p0}}{c^2} + (m_{p0}c)^2 + (m_{p0}c)^2$$

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

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

NP 1959
Emilio Gino Segrè
Italy 1905 – USA 1989

NP 1959
Owen Chamberlain
USA 1920 - 2006

Example: c-cbar states

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

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

$$E_1 = E_2 \quad \Rightarrow \quad E_{\rm cm}^2 = 4E^2$$

Energy per beam: $K = E - m_0 c = 1547\text{MeV}$

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

$$K = E - m_{0e}c^2 = \frac{E_{cm}^2 - 4(m_{0e}c^2)^2}{2m_{0e}c^2} = 9.4\text{TeV}$$

NP 1976
Burton Richter
USA 1931 -

NP 1976
Samuel CC Ting
USA 1936 -

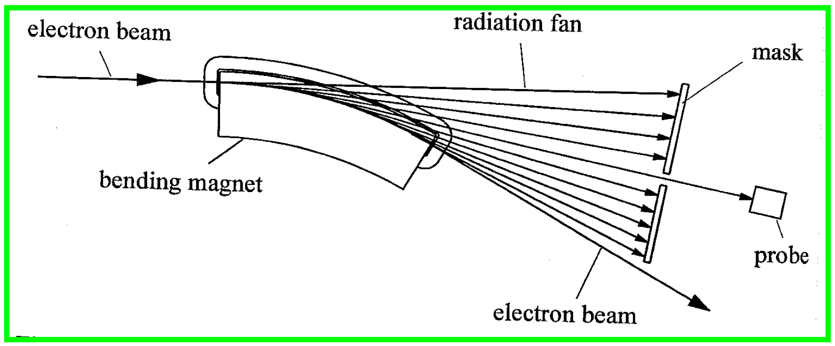
Rings for Synchrotron Radiation

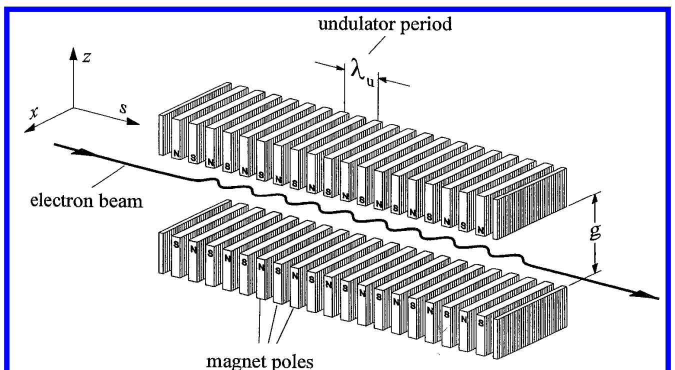
- 1947: First detection of synchrotron light at General Electrics.
- 1952: First accurate measurement of synchrotron radiation power by Dale Corson with the Cornell 300MeV synchrotron.
- 1968: TANTALOS, first dedicated storage ring for synchrotron radiation

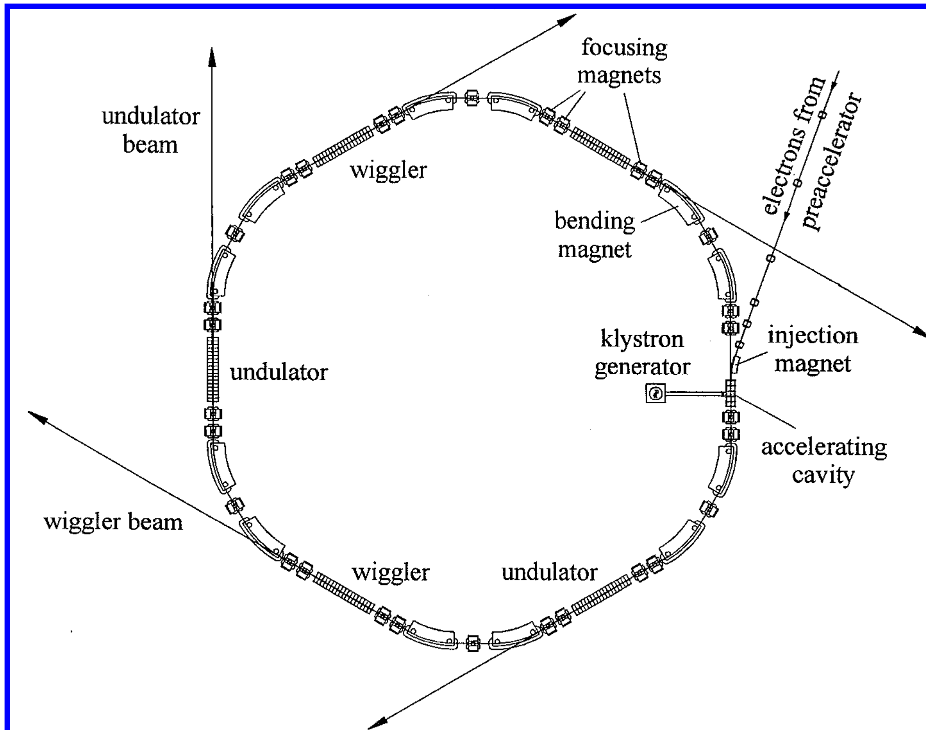
Dale Corson
Cornell's 8th president
USA 1914 –

3 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







Accelerators of the World

Sorted by Location

Europe

AGOR	Accelerateur Groningen-ORsay, KVI Groningen, Netherlands
ANKA	Ångströmquelle Karlsruhe, Karlsruhe, Germany (Forschungsgruppe Synchrotronstrahlung (FGS))
ASTRID	Aarhus Storage Ring in Denmark, ISA, Aarhus, Denmark
BESSY	Berliner Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung, Germany (BESSY I status, BESSY II status)
BINP	Budker Institute for Nuclear Physics, Novosibirsk, Russian Federation (VEPP-2M collider, VEPP-4M collider (status))
CERN	Centre Europeen de Recherche Nucleaire, Geneva, Suisse (LEP & SPS Status, LHC, CLIC, PS-Division, SL-Division)
COSY	Cooler Synchrotron, IKP, FZ Jülich, Germany (COSY Status)
CYCLONE	Cyclotron of Louvain la Neuve, Louvain-la-Neuve, Belgium
DELTA	Dortmund Electron Test Accelerator, U of Dortmund, Germany (DELTA Status)
DESY	Deutsches Elektronen Synchrotron, Hamburg, Germany (HERA, PETRA and DORIS status, TESLA)
ELBE	ELectron source with high Brilliance and low Emittance, FZ Rossendorf, Germany
ELETTRA	Trieste, Italy (ELETTRA status)
ELSA	Electron Stretcher Accelerator, Bonn University, Germany (ELSA status)
ESRF	European Synchrotron Radiation Facility, Grenoble, France (ESRF status)
GANIL	Grand Accélérateur National d'Ions Lourds, Caen, France
GSI	Gesellschaft für Schwerionenforschung, Darmstadt, Germany
IHEP	Institute for High Energy Physics, Protvino, Moscow region, Russian Federation
INFN	Istituto Nazionale di Fisica Nucleare, Italy, LNF - Laboratori Nazionali di Frascati (DAFNE, other accelerators), LNL - Laboratori Nazionali di Legnaro (Tandem, CN Van de Graaff, AN 2000 Van de Graaff), LNS - Laboratori Nazionali del Sud, Catania, (Superconducting Collider & Van de Graaff Tandem)
ISIS	Rutherford Appleton Laboratory, Oxford, U.K. (ISIS Status)
ISL	IonenStrahlLabor am HMI, Berlin, Germany
JINR	Joint Institute for Nuclear Research, Dubna, Russian Federation (U-200, U-400, U-400M, Storage Ring, LHE Synchrophasotron / Nuclotron)
JYFL	Jyväskylän Yliopiston Fysiikan Laitos, Jyväskylä, Finland
KTH	Kungl Tekniska Högskola (Royal Institute of Technology), Stockholm, Sweden (Alfén Lab electron accelerators)

Accelerators of the World

CHESS & LEPP

LMU/TUM	Accelerator of LMU and TU Muenchen, Munich, Germany
LURE	Laboratoire pour l'Utilisation du Rayonnement Electromagnétique, Orsay, France (DCI, Super-ACO status, CLIO)
MAMI	Mainzer Microtron, Mainz U, Germany
MAX-Lab	Lund University, Sweden
MSL	Manne Siegbahn Laboratory, Stockholm, Sweden (CRYRING)
NIKHEF	Nationaal Instituut voor Kernfysica en Hoge-Energie Fysica, Amsterdam, Netherlands (AmPS *closed!*)
PSI	Paul Scherrer Institut, Villigen, Switzerland (PSI status, SLS *under construction*)
S-DALINAC	Darmstadt University of Technology, Germany (S-DALINAC status)
SRS	Synchrotron Radiation Source, Daresbury Laboratory, Daresbury, U.K. (SRS Status)
TSL	The Svedberg Laboratory, Uppsala University, Sweden (CELSIUS)
TSR	Heavy-Ion Test Storage Ring, Heidelberg, Germany

North America

88" Cycl.	88-Inch Cyclotron, Lawrence Berkeley Laboratory (LBL), Berkeley, CA
ALS	Advanced Light Source, Lawrence Berkeley Laboratory (LBL), Berkeley, CA (ALS Status)
ANL	Argonne National Laboratory, Chicago, IL (Advanced Photon Source APS [status], Intense Pulsed Neutron Source IPNS [status], Argonne Tandem Linac Accelerator System ATLAS)
BNL	Brookhaven National Laboratory, Upton, NY (AGS, ATF, NSLS, RHIC)
CAMD	Center for Advanced Microstructures and Devices
CHESS	Cornell High Energy Synchrotron Source, Cornell University, Ithaca, NY
CLS	Canadian Light Source, U of Saskatchewan, Saskatoon, Canada
CESR	Cornell Electron-positron Storage Ring, Cornell University, Ithaca, NY (CESR Status)
FNAL	Fermi National Accelerator Laboratory , Batavia, IL (Tevatron)
IAC	Idaho accelerator center, Pocatello, Idaho
IUCF	Indiana University Cyclotron Facility, Bloomington, Indiana
JLab	aka TJNAF, Thomas Jefferson National Accelerator Facility (formerly known as CEBAF), Newport News, VA
LAC	Louisiana Accelerator Center, U of Louisiana at Lafayette, Louisiana
LANL	Los Alamos National Laboratory
MIT-Bates	Bates Linear Accelerator Center, Massachusetts Institute of Technology (MIT)
NSCL	National Superconducting Cyclotron Laboratory, Michigan State University
ORNL	Oak Ridge National Laboratory (EN Tandem Accelerator), Oak Ridge, Tennessee
SBSL	Stony Brook Superconducting Linac, State University of New York (SUNY)
SLAC	Stanford Linear Accelerator Center (Linac, NLC - Next Linear Collider, PEP - Positron Electron Project (finished), PEP-II - asymmetric B Factory (in commissioning), SLC - SLAC Linear electron positron Collider, SPEAR - Stanford Positron Electron Asymmetric Ring (actually SPEAR-II, see SSRL), SSRL - Stanford Synchrotron Radiation Laboratory)
SNS	Spallation Neutron Source, Oak Ridge, Tennessee
SRC	Synchrotron Radiation Center, U of Wisconsin - Madison (Aladdin Status)
SURF II	Synchrotron Ultraviolet Radiation Facility, National Institute of Standards and Technology (NIST), Gaithersburg, Maryland
TASCC	Tandem Accelerator Superconducting Cyclotron (Canada) *(closed!)*
TRIUMF	TRI-University Meson Facility / National Meson Research Facility, Vancouver, BC (Canada)

South America

LNLS	Laboratorio Nacional de Luz Sincrotron, Campinas SP, Brazil
TANDAR	Tandem Accelerator, Buenos Aires, Argentina

Asia

BEPC	Beijing Electron-Positron Collider, Beijing, China
KEK	National Laboratory for High Energy Physics ("Koh-Ene-Ken"), Tsukuba, Japan (KEK-B, PF, JLC)
NSC	Nuclear Science Centre, New Delhi, India (15 UD Pelletron Accelerator)
PLS	Pohang Light Source, Pohang, Korea
RIKEN	Institute of Physical and Chemical Research ("Rikagaku Kenkyusho"), Hirosawa, Wako, Japan
SESAME	Synchrotron-light for Experimental Science and Applications in the Middle East, Jordan (under construction)
SPring-8	Super Photon ring - 8 GeV, Japan
SRRC	Synchrotron Radiation Research Center, Hsinchu, Taiwan (SRRC Status)
UVSOR	Ultraviolet Synchrotron Orbital Radiation Facility, Japan
VECC	Variable Energy Cyclotron, Calcutta, India

Africa

NAC	National Accelerator Centre, Cape Town, South Africa

Sorted by Accelerator Type

Electrons

Stretcher Ring/Continuous Beam facilities

ELSA (Bonn U), JLab, MAMI (Mainz U), MAX-Lab, MIT-Bates, PSR (SAL), S-DALINAC (TH Darmstadt), SLAC

Accelerators of the World

Synchrotron Light Sources

ANKA (FZK), ALS (LBL), APS (ANL), ASTRID (ISA), BESSY, CAMD (LSU), CHESS (Cornell Wilson Lab), CLS (U of Saskatchewan), DELTA (U of Dortmund), ELBE (FZ Rossendorf), Elettra, ELSA (Bonn U), ESRF, HASYLAB (DESY), LURE, MAX-Lab, LNLS, NSLS (BNL), PF (KEK), UVSOR (IMS), PLS, S-DALINAC (TH Darmstadt), SESAME, SLS (PSI), SPEAR (SSRL, SLAC), SPring-8, SRC (U of Wisconsin), SRRC, SRS (Daresbury), SURF II (NIST)

Other

Alfén Lab (KTH), IAC

Protons

88" Cyclotron (LBL), CELSIUS (TSL), COSY (FZ Jülich), IPNS (ANL), ISL (HMI), ISIS, IUCF, LHC (CERN), NAC, PS (CERN), PSI, SPS (CERN)

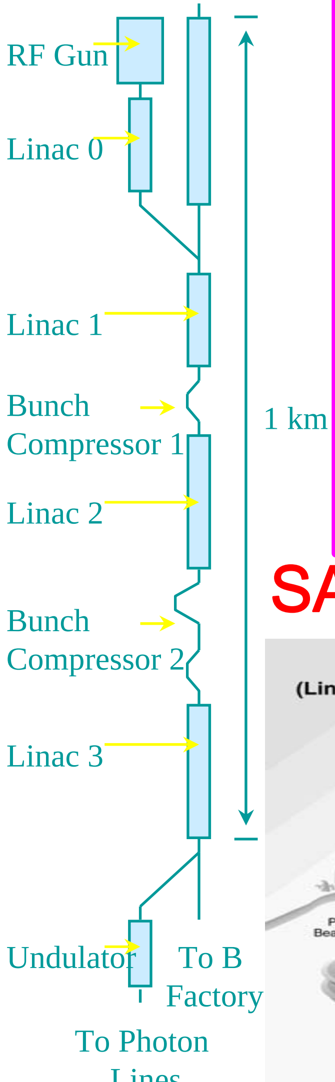
Light and Heavy Ions

88" Cyclotron (LBL), AGOR, ASTRID (ISA), ATLAS (ANL), CELSIUS (TSL), CRYRING (MSL), CYCLONE, EN Tandem (ORNL), GANIL, GSI, ISL (HMI), IUCF, JYFL, LAC, LHC (CERN), LHE Synchrophasotron / Nuclotron (JINR), LMU/TUM, LNL (INFN), LNS (INFN), NAC, NSC, PSI, RHIC (BNL), SBSL, SNS, SPS (CERN), TANDAR, TSR, U-200 / U-400 / U-400M / Storage Ring (JINR), VECC

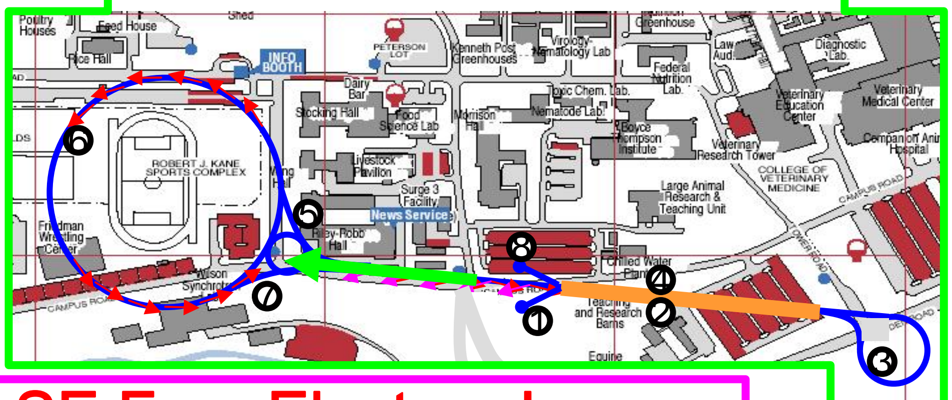
Collider

BEPC, CESR, DAFNE (LNF), HERA (DESY), LEP (CERN), LHC (CERN), PEP / PEP-II (SLAC), SLC (SLAC), KEK-B (KEK), TESLA (DESY), Tevatron (FNAL), VEPP-2M, VEPP-4M (BINP)

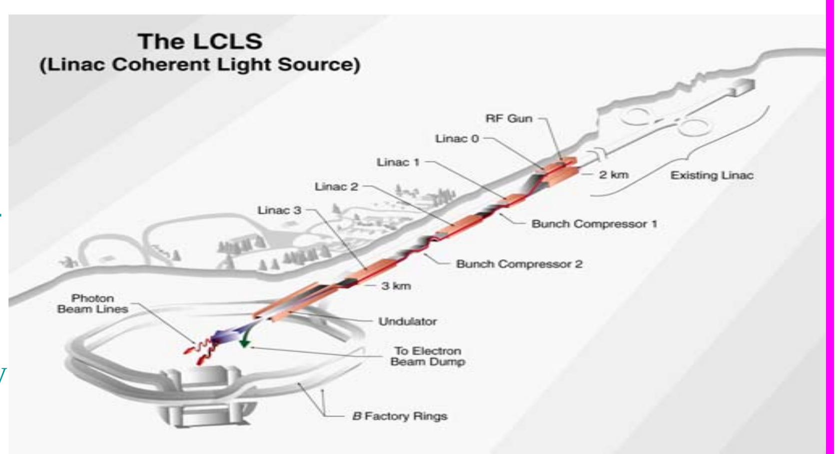
The Future



Energy Recovery Linacs



SASE Free Electron Lasers



Linear Colliders