Introduction and Overview of Accelerators

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29th Annual Hampton University Graduate Studies Program

HUGS 2014, Jefferson Lab, June 2-20, 2014

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Basic Definitions and Formulas

Convenient Energy & Mass Units

- We use eV to describe the energy of individual particles. The energy that a unit charge

$$e = 1.6 \times 10^{-19} \text{ Coulomb}$$

gains when it falls through a potential $\Delta\Phi$=1 volt.

$$1\text{eV} = 1.6 \times 10^{-19} \text{ Joule}$$

$$1\text{MeV} = 1.6 \times 10^{-13} \text{ J};\ \ 1\text{GeV} = 1.6 \times 10^{-10} \text{ J};\ \ 1\text{TeV} = 1.6 \times 10^{-7} \text{ J}$$

- Einstein's relation to convert rest mass to energy units

$$E_o = mc^2$$

- For electron

$$E_{o,e} = 9.1 \times 10^{-31}\text{kg} \times (3 \times 10^8 \text{ m/sec})^2 = 81.9 \times 10^{-15} \text{ Joule} = 0.512 \text{ MeV}$$

- For proton

$$E_{o,p} = 938 \text{ MeV}$$

- Momentum

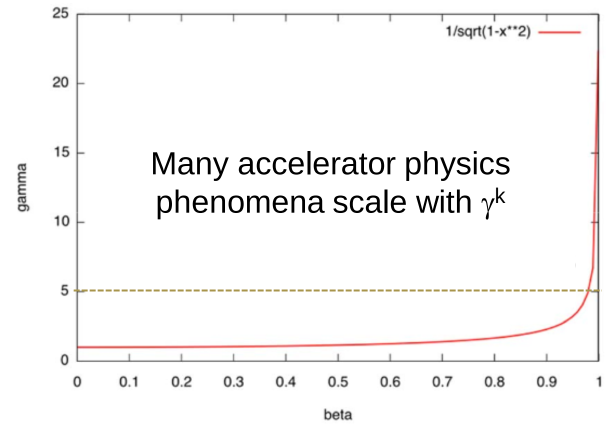
$$p : \text{eV}/c$$

Relativity Review

- Relativistic parameters:

$$\beta \equiv \frac{\upsilon}{c} \qquad \gamma \equiv \frac{1}{\sqrt{1-\beta^2}}$$

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



  - Later β and γ will also be used for other quantities, but the context should usually make them clear
  - γ=1 (classical mechanics) to ~2.05×10^5 (to date)

- Total energy E, momentum p, kinetic energy K

$$E = \gamma mc^2 \qquad p = \beta\gamma mc = \beta\left(\frac{E}{c}\right) \qquad K = (\gamma - 1)mc^2$$

- Relativity relations

$$\frac{d\beta}{\beta} = \frac{1}{\gamma^2}\frac{dp}{p} \qquad \frac{dE}{E} = \beta^2\frac{dp}{p} \qquad F = \frac{dp}{dt} = m\gamma^3\frac{dv}{dt}$$

Frames and Lorentz Transformations

- The lab frame will dominate most of our discussions
  - But not always (synchrotron radiation, space charge …)

- Invariance of space-time interval (Minkowski)

$$(ct')^2 - x'^2 - y'^2 - z'^2 = (ct)^2 - x^2 - y^2 - z^2$$

- Lorentz transformation of four-vectors
  - For example, time/space coordinates in z velocity boost

$$\begin{pmatrix} ct' \\ x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} \gamma & 0 & 0 & -\beta\gamma \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\beta\gamma & 0 & 0 & \gamma \end{pmatrix} \begin{pmatrix} ct \\ x \\ y \\ z \end{pmatrix}$$

Relativistic Electromagnetism I

- Classical electromagnetic potentials can be shown to combine to a four-potential (with c=1)

$$A^{\alpha} = (\Phi, \vec{A})$$

- The field-strength tensor is related to the four-potential

$$F^{\alpha\beta} = \partial^{\alpha} A^{\beta} - \partial^{\beta} A^{\alpha} = \begin{pmatrix} 0 & E_x & E_y & E_z \\ -E_x & 0 & -B_z & B_y \\ -E_y & B_z & 0 & -B_x \\ -E_z & -B_y & B_x & 0 \end{pmatrix}$$

  - E/B fields Lorentz transform with factor of γ, $(\beta\gamma)$

Relativistic Electromagnetism II

- The relativistic electromagnetic force equation becomes

$$\frac{dp^{\alpha}}{d\tau} = m\frac{du^{\alpha}}{d\tau} = \frac{q}{c}F^{\alpha\beta}u_{\beta}$$

  - We can write this in somewhat simpler terms

$$\frac{d(\gamma m\vec{\upsilon})}{dt} = q(\vec{E} + \vec{\upsilon}\times\vec{B})$$

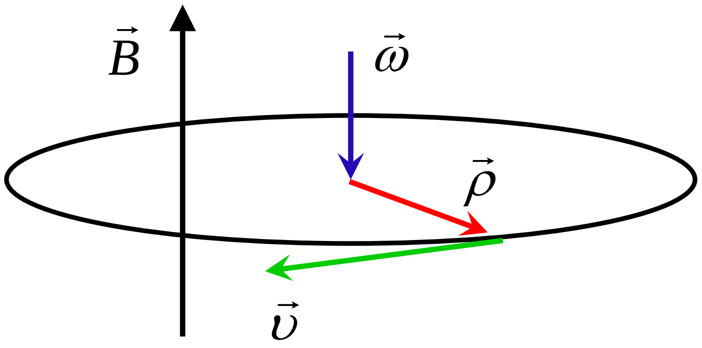
  - That is, “classical” E&M force equations hold if we treat the momentum as relativistic,

$$\vec{p} = \gamma m\vec{\upsilon} = \gamma\vec{\beta}mc$$

  - Unsurprisingly, we get
    - Energy changes from electric fields $q\vec{E}$
    - Direction changes (energy conservative) from magnetic fields $q(\vec{\upsilon}\times\vec{B})$

Constant Magnetic Field (Zero Electric Field)

- In a constant magnetic field, charged particles move in circular arcs of radius ρ with constant angular velocity ω



$$\vec{F} = \frac{d}{dt}(\gamma m\vec{\upsilon}) = \gamma m\frac{d\vec{\upsilon}}{dt} = q\vec{\upsilon}\times\vec{B}$$

$$\vec{\upsilon} = \vec{\omega}\times\vec{\rho}$$

$$\gamma m\vec{\omega}\times\frac{d\vec{\rho}}{dt} = \gamma m\vec{\omega}\times\vec{\upsilon} = q\vec{\upsilon}\times\vec{B}$$

- For $\vec{B}\perp\vec{\upsilon}$, we have

$$q\upsilon B = \frac{\gamma m\upsilon^2}{\rho} \qquad p = \gamma m(\beta c) = q(B\rho)$$

$$\frac{p}{q} = B\rho \qquad \omega = \frac{\upsilon}{\rho} = \frac{qB}{\gamma m}$$

Rigidity: Bending Radius vs Momentum

Beam $\boxed{\frac{p}{q} = B\rho}$ Accelerator (magnets, geometry)

- This is such a useful expression in accelerator physics that it has it own name: **rigidity**

- Ratio of momentum to charge
  - How hard (or easy) is a particle to deflect?
  - Often expressed in [T-m] (easy to calculate B)
  - Be careful when q≠e !!!

- A very useful expression

$$\boxed{\frac{p[GeV/c]}{q[e]} \approx 0.3B[T]\rho[m]}$$

Cyclotron Frequency

$$\boxed{\omega = \frac{\upsilon}{\rho} = \frac{qB}{\gamma m}}$$

- Another very useful expression for particle angular frequency in a constant field: **cyclotron frequency**

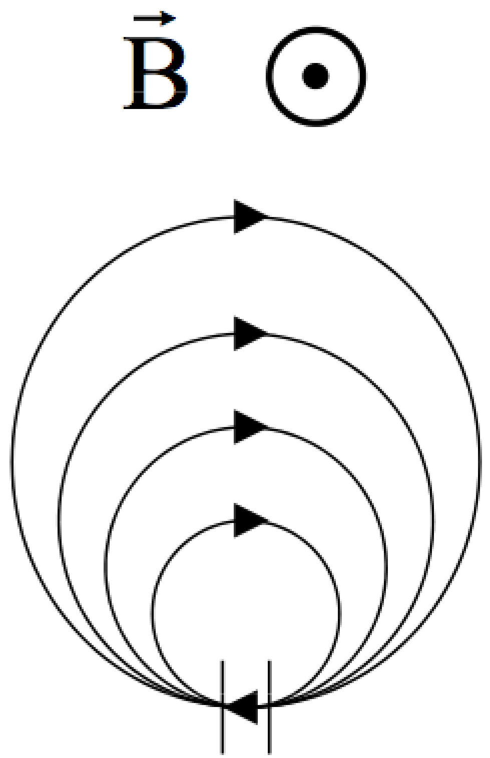
- In the nonrelativistic approximation

$$\boxed{\omega_{nonrelativistic} \approx \frac{qB}{m}}$$

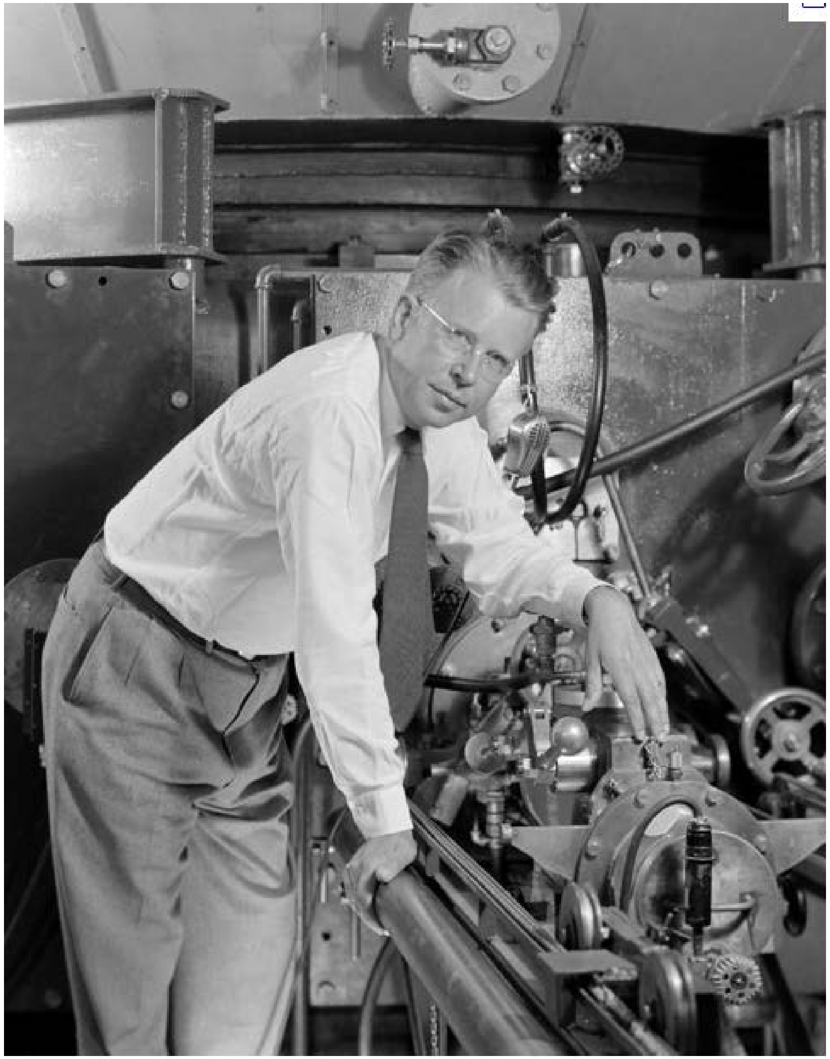
Revolution frequency is independent of radius or energy !

Lawrence and the Cyclotron

- Can we repeatedly spiral and accelerate particles through the same potential gap?



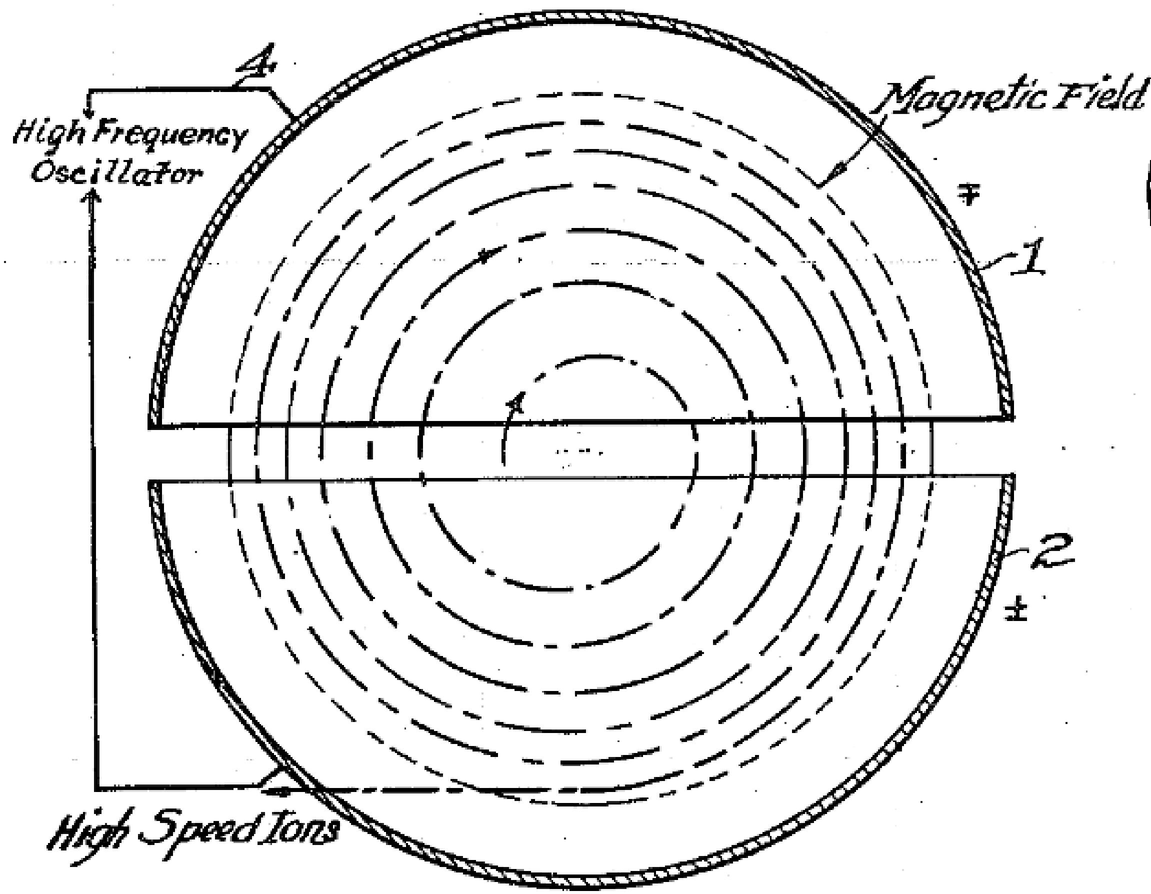
Accelerating gap $\Delta\Phi$

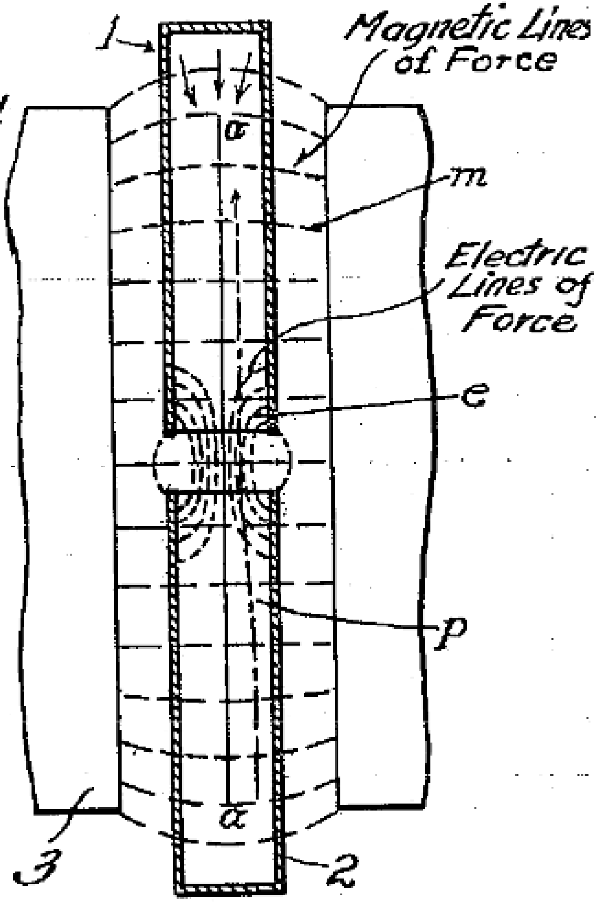


Ernest Orlando Lawrence

A Patentable Idea

- 1934 patent 1948384
  - Two accelerating gaps per turn !





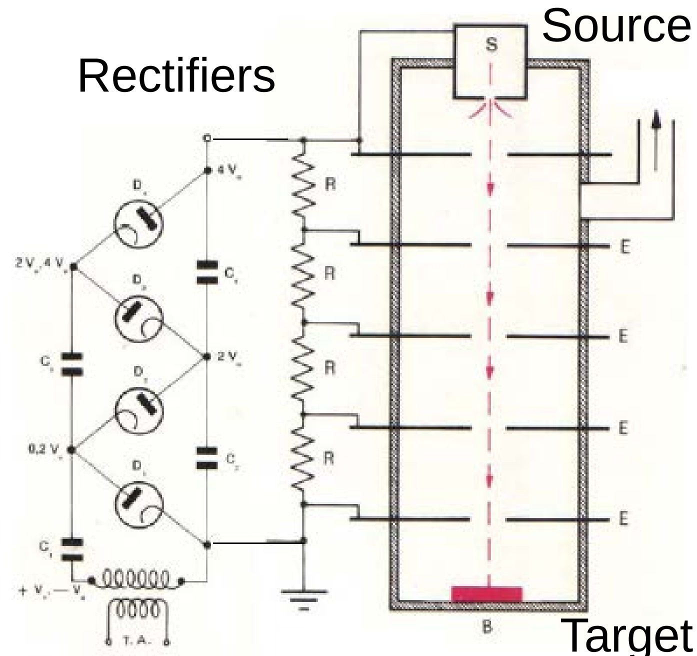
27”/69cm Cyclotron

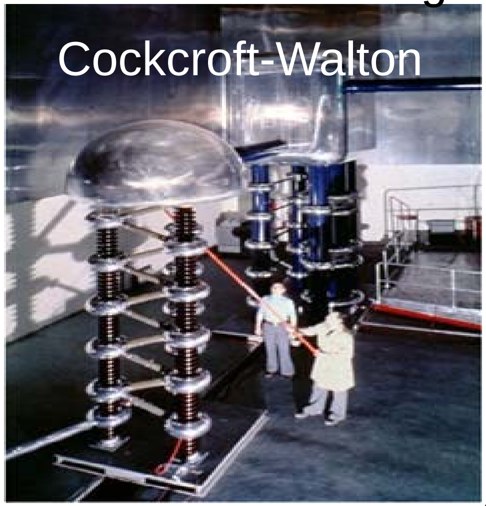
M.S. Livingston and E.O. Lawrence, 1934

Historical Hallmark of Accelerator

Electrostatic Accelerator I

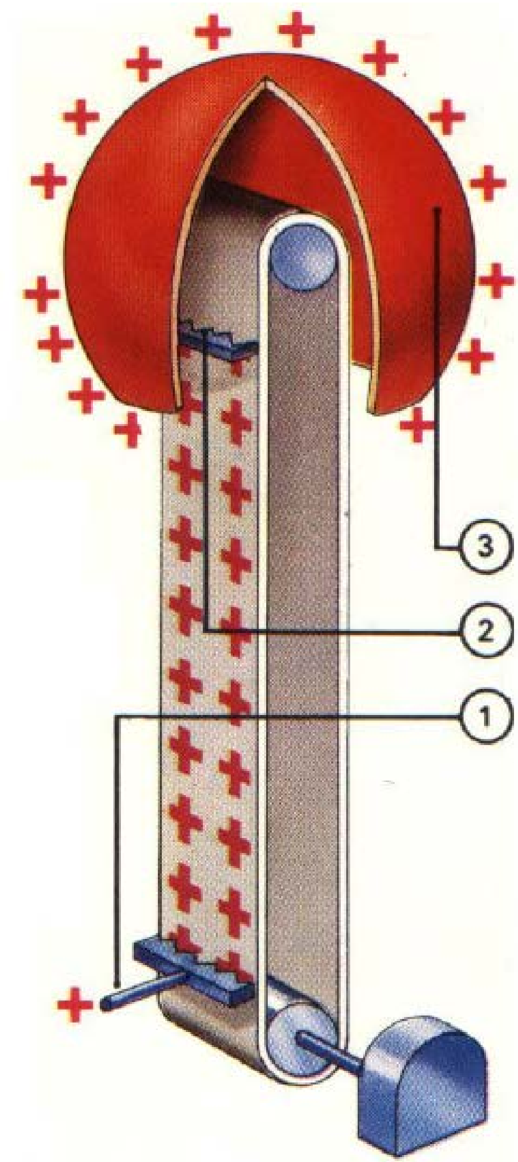
- Cockcroft-Walton
  - In 1932, John Douglas Cockcroft and Ernst Thomas Sinton Walton reached 400-kV terminal voltage to achieve the first man-made nuclear transmutation: p+7Li→2He
  - 1 MV maximum achievable voltage was limited by sparking in air
  - Cockcroft-Walton accelerators have been widely used as the first-stage ion-beam accelerator
    - H gas ionized with HV current
    - Provides high current DC beam





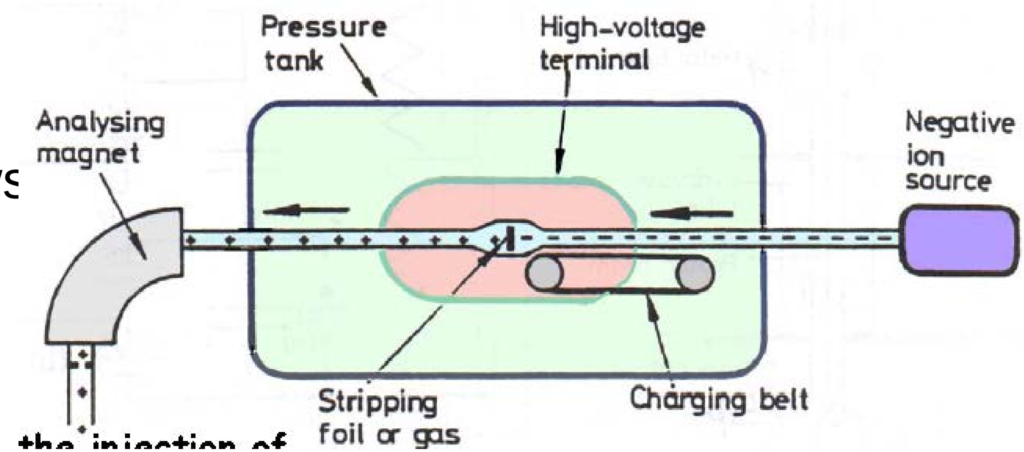
Electrostatic Accelerator II

- Van de Graaff
  - How to increase voltage?
    - 1931 R.J. Van de Graaff developed charge transporting accelerator
    - Electrode sprays HV charge onto insulated belt
    - Carried up to spherical Faraday cage
    - Removed by second electrode and distributed over sphere
  - Limited by discharge breakdown
    - ~2MV in air
    - Up to 20+ MV in tandem accelerator
    - Ancestor of Pelletrons (chains)/ Laddertrons (stripes)



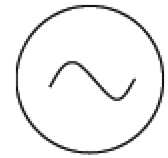
Electrostatic Accelerator III

- Tandem Van de Graaff
  - Reverse ion charge state in middle of Van de Graaff allows over twice the energy gain
  - This only works for negative ions
  - However, stripping need not be symmetric
    - Second stage accelerates more efficiently
  - BNL: two Tandems (1970, 14MV, 24m)
    - Au^{-1} to Au^{+10} /Au^{+11} /Au^{+12} to Au^{+32} for RHIC
    - About a total of 0.85MeV/nucleon total energy

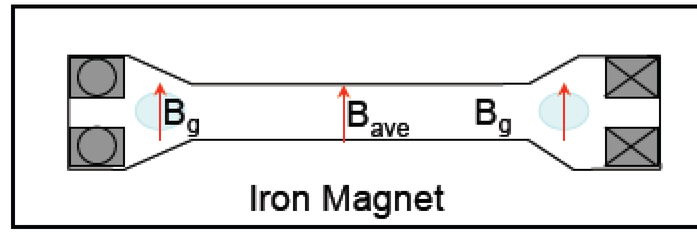


Induction Accelerator

- Betatron: first circular electron accelerator
  - Apply Faraday's law with time-varying current in coils



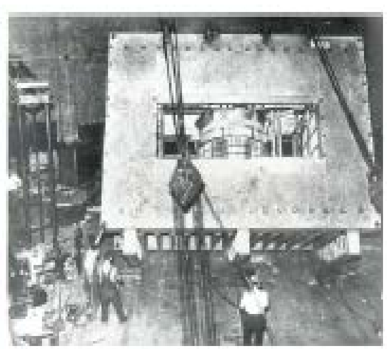
$I(t)=I_0\cos(2\pi\omega_I t)$



  - Beam sees time-varying electric field – accelerate half the time
  - Betatron: The betatron principle states that the guide field B_g is equal to 1/2 of the average field B_{av}, (**R. Wideröe** 1928).
  - Limitation: synchrotron radiation loss and transverse beam size limit due to intrinsic weak-focusing force

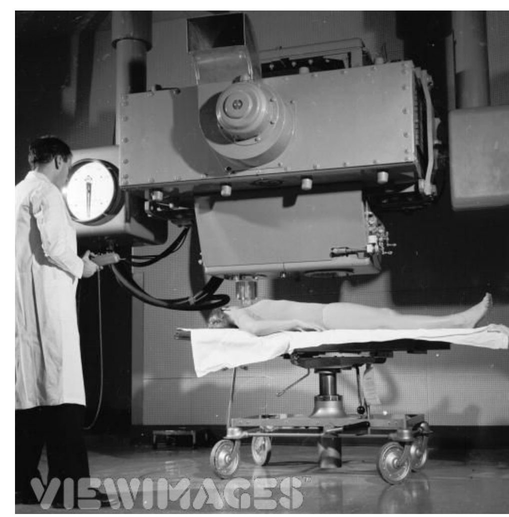
Donald Kerst
UIUC 2.5 MeV
Betatron, 1940

Don't try this at home!!



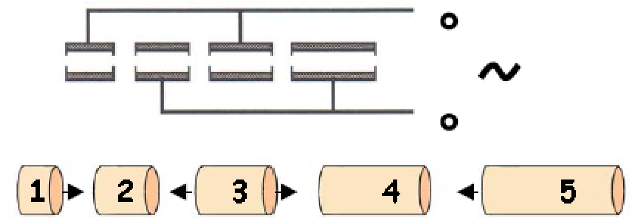
Really don't try this at home!!

UIUC 312 MeV
betatron, 1949



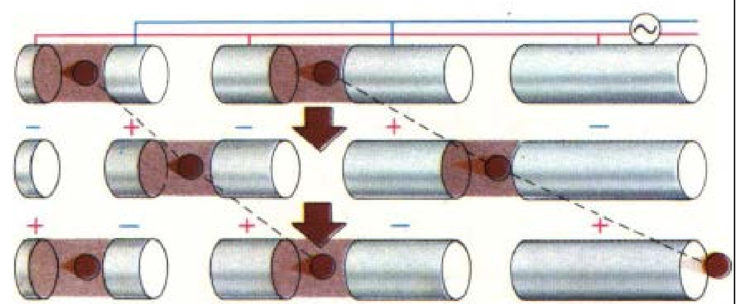
From Electrostatic to RF Acceleration

- RF accelerators
  - In 1925 G. Ising pointed out a radio-frequency field
  - In 1928 Wideroe reported the first working rf accelerator
  - In 1931 D.H. Sloan and E.O. Lawerence built a linear accelerator
  - In 1945 E.M. Mcmillan and V.Veksler discovered of the phase-focusing principle
  - In 1948 L.Alvarez and W.K.H.Panofsky constructed the first 32MV drift tube linac for proton
  - In 1970 L.M.Kapchinskij and V.A.Teplyakov invented radio-frequency quadrupole (RFQ) in a low energy accelerator

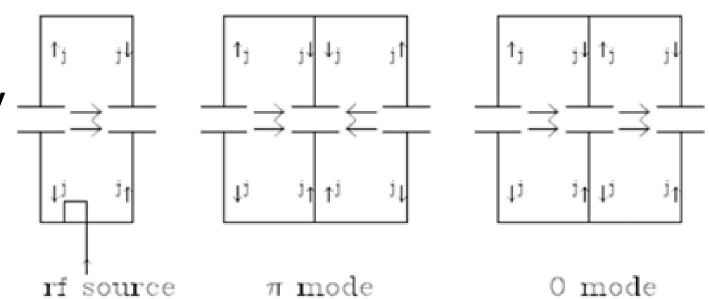


π *mode*

Wideroe linac

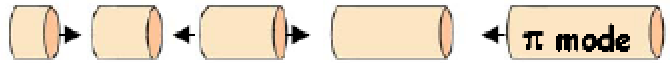


- Characteristics
  - Particles are accelerated in each gap
  - Particles are shielded in drift tubes when polarity change occurs
  - Drift tube length or RF frequency must increase at higher energies

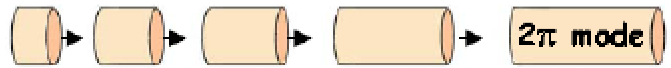


Resonant Linac Structures

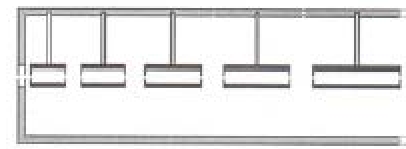
- Wideroe linac : π mode

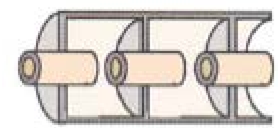


- Alvarez linac: 2π mode



- To minimize excess RF power
  - Make drift tubes/gaps resonant to RF frequency
  - In 2π mode, currents in walls separating two subsequent cavities cancel; tubes are passive





Wideroe linac

ALICE HI injector, IPN Orsay

Drift tube linac

Saturne, Saclay

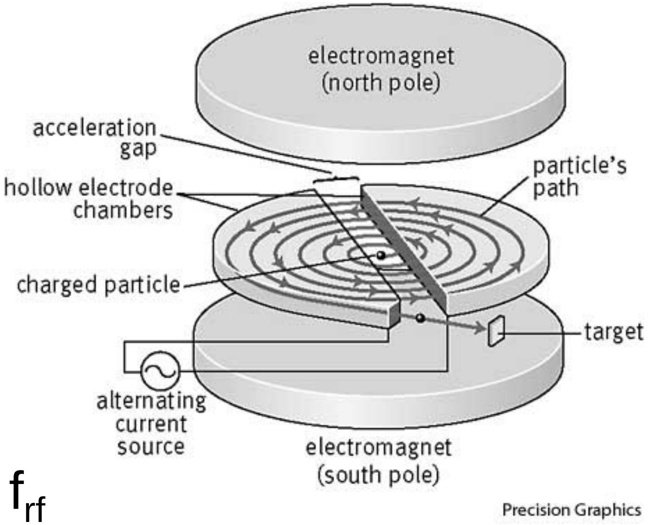
Advanced Acceleration Methods

- How far do accelerating gradients go?
  - Superconducting RF acceleration: ~40MV/m
  - CLIC: ~100MV/m
    - Two beam accelerator: drive beam couples to main beam
  - Dielectric wall acceleration: ~100MV/m
    - Induction acceleerator, very high gradient insulators
  - Dielectric wakefield acceleration: ~GV/m
  - Laser plasma acceleration: ~30GV/m
    - Electrons to 1GeV in 3.3cm
    - Particles ride in wake of plasma charge separation wave

Cyclotron Again

- Recall that for a constant B field

$$p = \gamma m(\beta c) = q(B\rho)$$



  - Radius/circumference of orbit scale with velocity $$\rho = \left(\frac{\gamma m}{qB}\right)\upsilon$$
  - Apply AC electric field in the gap at frequency f_{rf}
    - Particles accelerate until they drop out of resonance

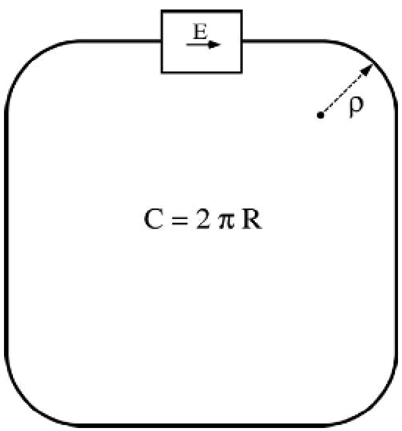
$$\omega = \frac{\upsilon}{\rho} = \frac{qB}{\gamma m} \qquad f_{rf} = \frac{\omega}{2\pi} = \frac{qB}{2\pi\gamma m}$$

  - Synchrocyclotrons: accelerate particles in bunches (not DC beam) and reduce RF frequency
  - Isochronous cyclotron: keep constant RF frequency and increase magnetic field with radius

Synchrotron

- Synchrotron is a synchronous accelerator, which has a synchronous RF phase for which the energy gain fits the increase of the magnetic field at each turn.
  - Separated magnetic fields: dipole, quadrupole, sextupole ……
  - Magnetic fields only present over the actual region of particle orbits
  - Aperture of beams is order of cm or mm
  - 1944 V.Veksler published the principle, 1945 E.McMillan constructed the first electron synchrotron, 1945 S.M Oliphant designed the first proton synchrotron

$$f_{rf} = \frac{\omega}{2\pi} = \frac{qB}{2\pi\gamma m} = \frac{f_c}{\gamma}$$



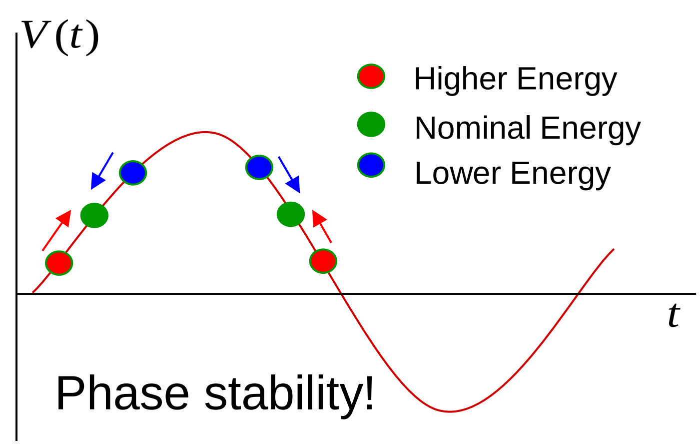
$e\hat{V}\sin\Phi \longrightarrow$ Energy gain per turn

$\Phi = \Phi_s \longrightarrow$ Synchronous particle

$\omega_{RF} = h\omega_r \longrightarrow$ RF synchronism

$\rho \quad R \longrightarrow$ Constant orbit

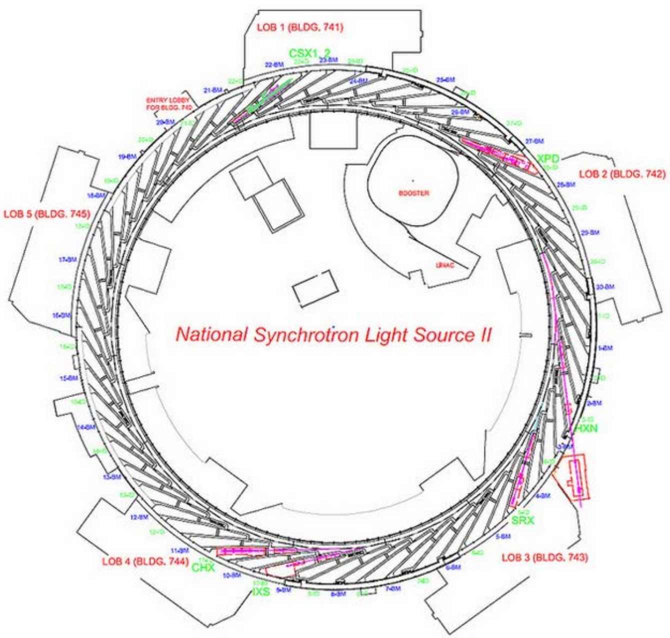
$B\rho = P/e \Rightarrow B \longrightarrow$ Variable magnetic field



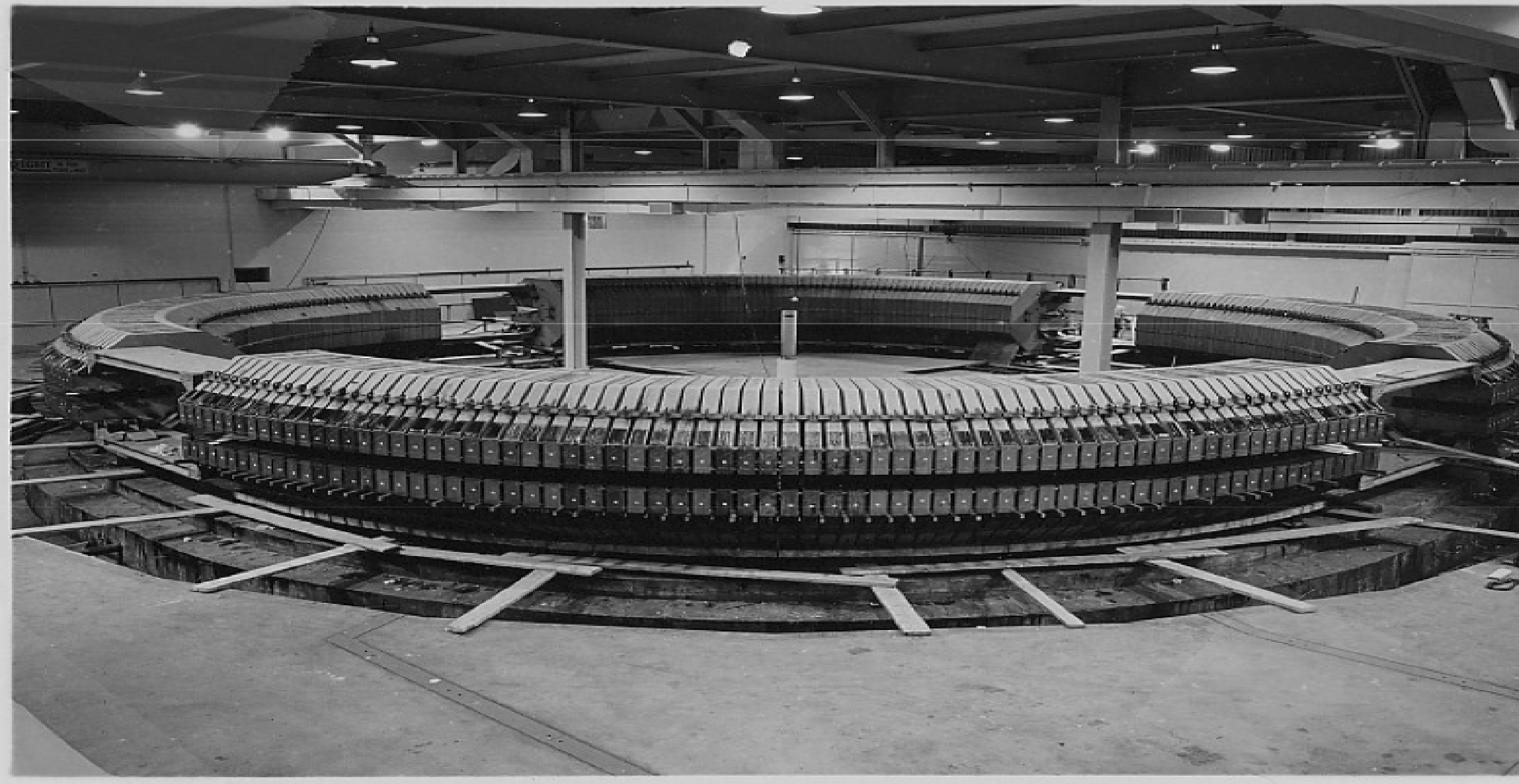
Synchrotron Radiation Source

- Synchrotron light source (a source of electromagnetic radiation)
  - Converts the high-energy electron energy into photons when the electron is directed into bending magnets and insertion devices (undulators or wigglers)
  - Applies the synchrotron light in condensed matter physics, material science, biology and medicine to probe the structure of matter from the sub-nanometer level of electron structure to the micrometer and millimeter level important in medical imaging.


Synchrotron radiation reflecting from a terbium crystal at the Daresbury Synchrotron Radiation Source, 1990



BNL Cosmotron



6/15/50 Neg. No. 6-151-0
View of Cosmotron Magnet Blocks after Leveling and Spacing

- ❖ 1953-1968, proton energy 3.3GeV, weak focusing, first external fixed target experiments

LBL Bevatron

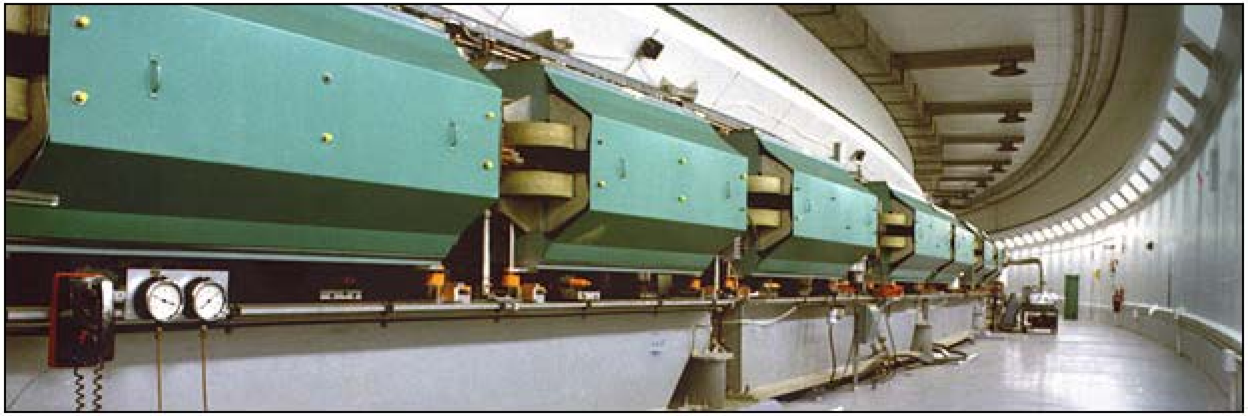
Ed McMillan and Ed Lofgren

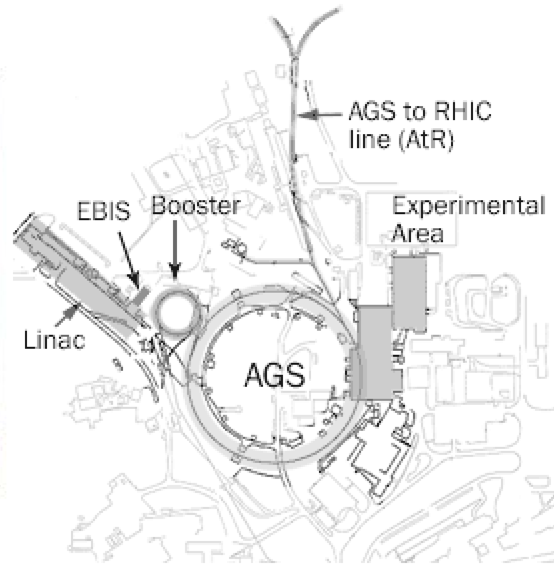
- 1954, largest weak-focusing proton synchrotron, beam energy 6.2GeV
- Discovered antiproton 1955,1959 Nobel for Segre/Chamberlain

  (became Bevelac, decommissioned 1993, demolished recently)

BNL AGS

Alternating Gradient Synchrotron





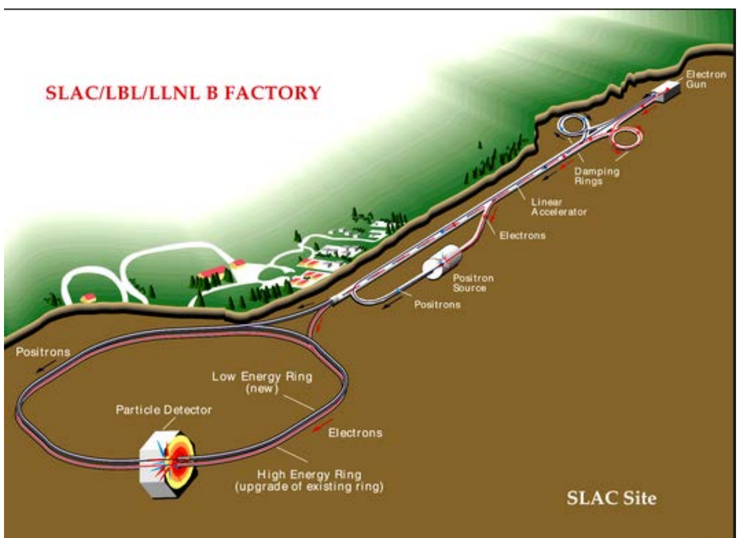
- 1960-, the first large synchrotron with alternating gradient, “strong focusing” magnets, greatly reduced the required aperture of the beam, and size and cost of the bending magnets.
- Three Nobel Prizes:
  - 1976, Samuel C.C. Ting (J part of J/Ψ and the charm quark)
  - 1980, J. Cronin and V. Fitch (CP violation by experimenting with Kaons)
  - 1962, L.Lederman, M.Schwartz and J.Steingerger (muon neutrino)

Colliders

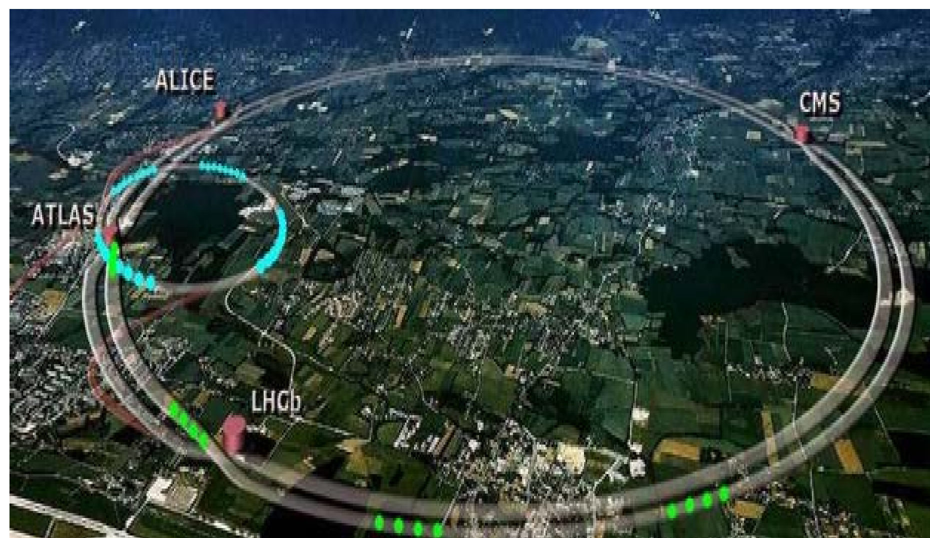
Fermilab, Chicago

The Tevatron (background) and *Main Injector* rings

Brookhaven, New York

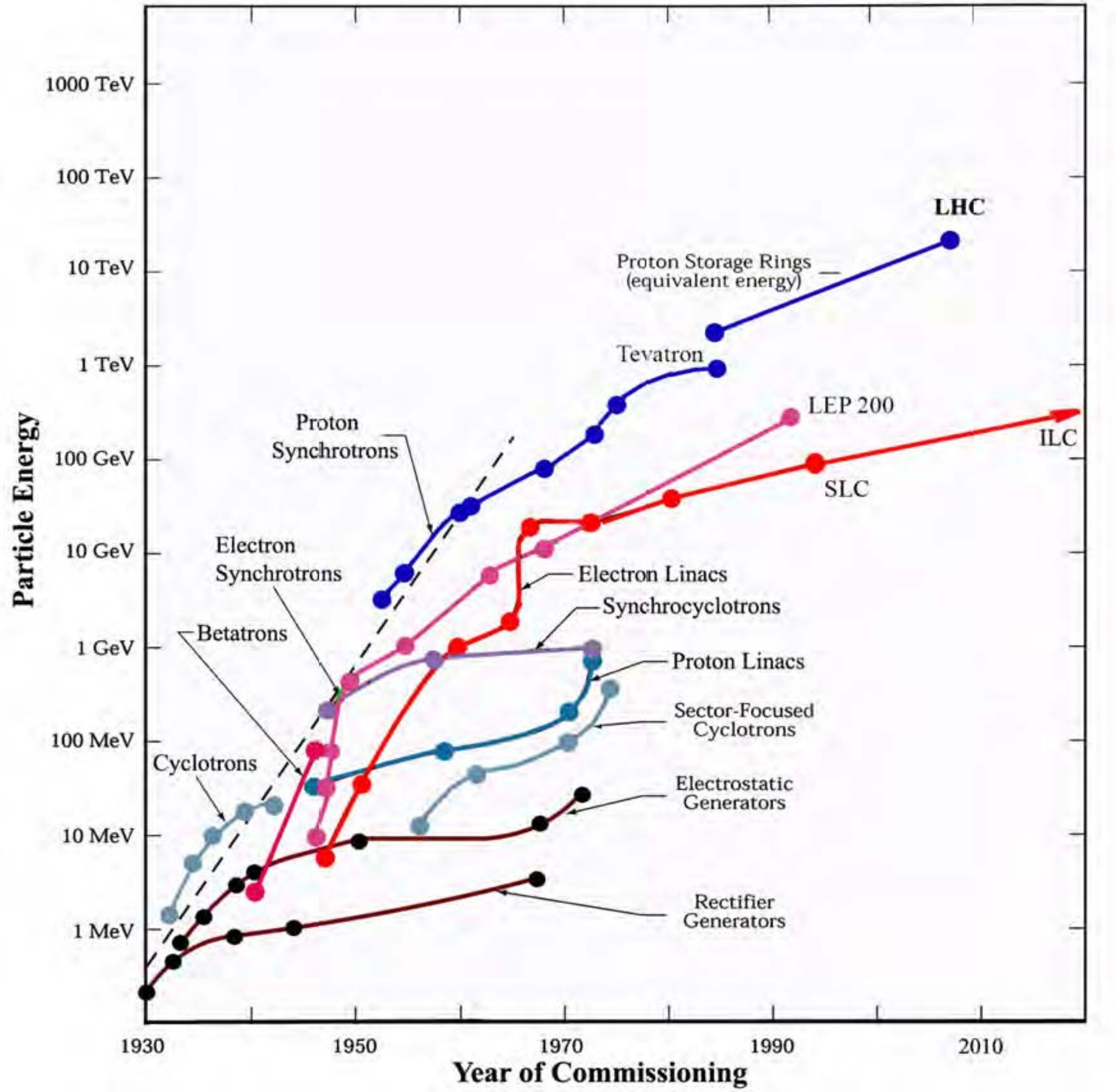


SLAC, California



CERN, Geneva, Switzerland

Energy of Beam Particles



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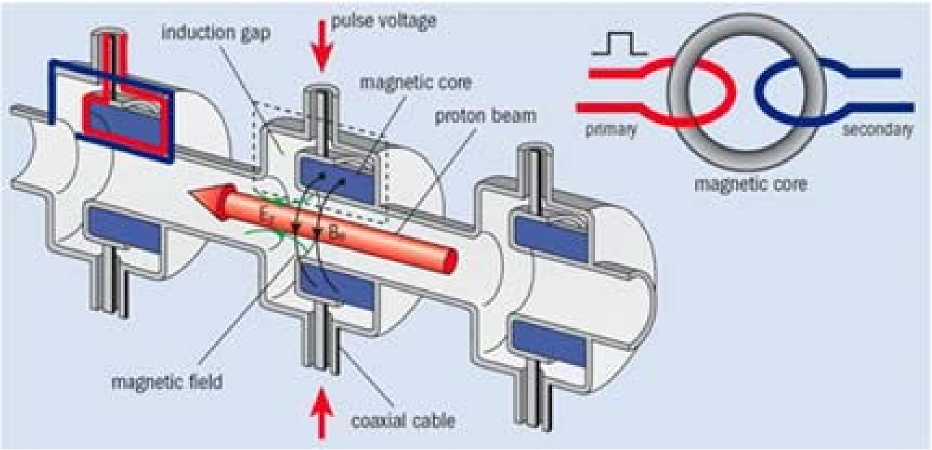
Induction Accelerators I

- Faraday's Law : $\oint_C \mathcal{E} \cdot d\vec{s} = \dot{\Phi}, \qquad \Phi = \int_S \vec{B} \cdot d\vec{S}.$

- Induction LINAC:
  - developed by N.C.Christofilos in 50's for acceleration of high-intensity beams
  - employs a ferrite core arranged in a cylindrically symmetric configuration to produce an inductive load to a voltage gap. When an external current source is discharged through the circuit, the electric field at the voltage gap along the beam axis is used to accelerate the beam
  - properly pulsed stack of modules can be used to accelerate high intensity short-pulse beams with a gradient of about 1 MeV/m and a power efficiency of about 50%.

Induction Accelerator III

❖ Induction Synchrotron



CERN Courier Mar 30, 2005

- In 2004, for the first time, a bunch of protons in the synchrotron has been accelerated by an induction method by K Takayama et al..
- The idea was to overcome shortcomings of RF synchrotron, in particular the limited longitudinal phase-space available for the acceleration of charged particles.
- The technique may overcome certain effects that normally limit intensity achieved in a synchrotron beam and could prove to be an important advance for future proton colliders