History of Accelerator

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- History of Accelerator
  - DC accelerator
  - Cyclotron
  - Betatron
  - Synchrotron
  - Linear accelerator
  - Collider (next lecture from here)
  - Huge accelerators
- Future Accelerators
  - ILC, CLIC, plasma, etc.

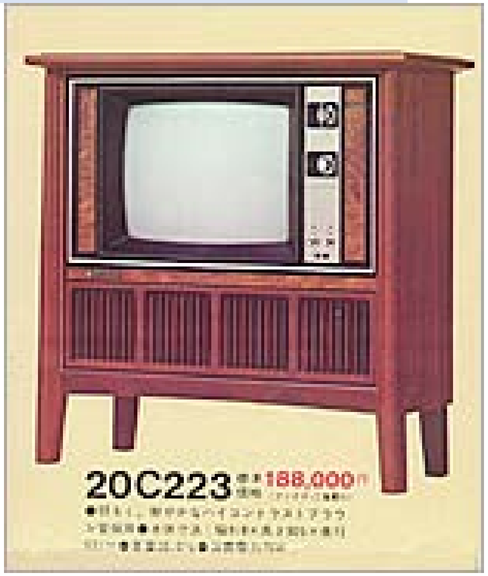
- Try to be very elementary
- Caveats: I treat only accelerators for high energy physics.
  "high energy" = "energy frontier at each time

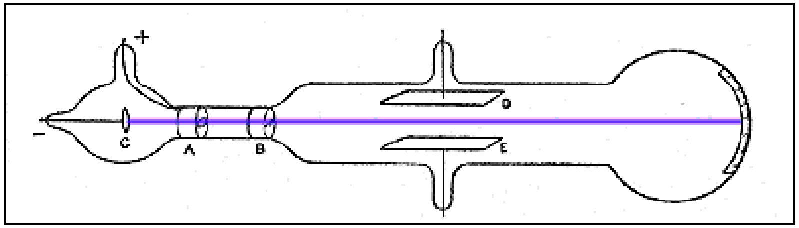
What is Accelerator?

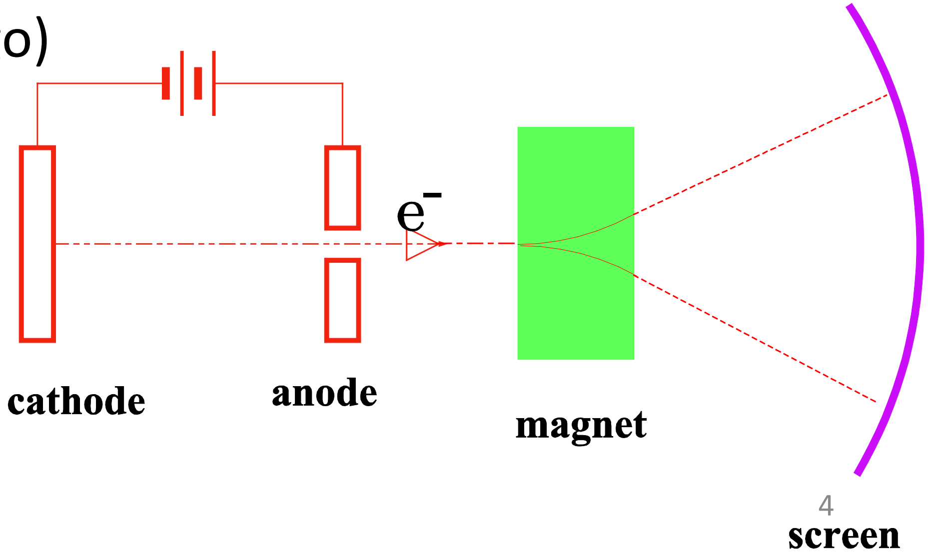
- Usually, an accelerator is a device to accelerate charged particles, such as electron and positron, to higher energies by an electro-magnetic field
- Other forces such as gravitation, nuclear force, etc.?
  - Gravitation is too weak
  - Nuclear force is too much “short-range”
- Usually electric field (not magnetic field) is used
  - Magnetic field also possible. Use dB/dt, called betatron
  - In principle, acceleration using magnetic moment is possible (e.g., neutron)

CRT: Cathode Ray Tube

- The first “accelerator”
- Electric voltage between two metallic plates
- Heat the cathode --- something emitted
- **Proved the existence of electron** in 1897 by J.J. Thomson (Cavendish lab. Cambridge)
- Measured e/m (charge-mass ratio)
  - Note that e became known by Millikan’s oil-drop experiment later in 1911
- CRT also led the discovery of X-ray by Roentgen in 1895
- TV monitor (until some years ago)





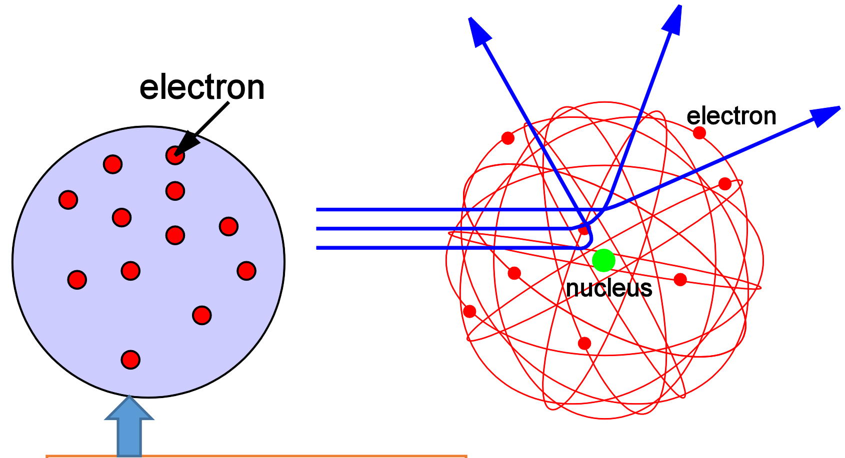


Units of Energy, Mass, Momentum etc.

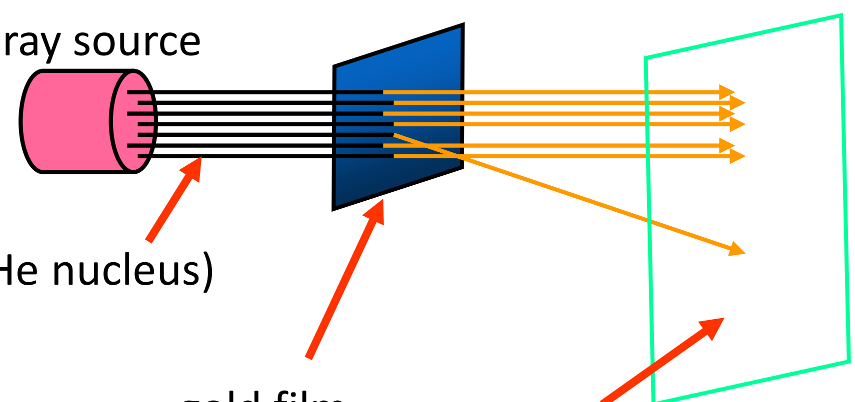
- In accelerator physics MKSA is usually used
- However, the energy, mass, etc. of particles the MKSA units, Joule, kg, etc. are seldom used
- For the energy we use
  1eV (electron volt) = the kinetic energy of electron (or positron, proton, etc, particles of charge +e or –e) accelerated by the voltage 1 Volt.
- Then, keV, MeV, GeV, TeV, etc.
- Particle mass is measured in eV/c^2
  - c = velocity of light
  - Electron mass = 0.511 MeV/c^2
  - Proton mass = 938 MeV/c^2
- Momentum is in eV/c

Experiment by Rutherford

- Earnest Rutherford (Manchester) was the first to see inside an atom (1911)
- “A particle” (alpha particle from radium) was made to collide with the atom
- Turned out there is something extremely small (now called nucleus) at the center, surrounded by electrons
    - To explain the rare events with very large angles (cannot be explained as multiple scattering)
- The particles which were made to collide came from a natural radio-active element, not from accelerator
    - A few MeV was necessary (α from ^{226}Ra ~5MeV)
    - There was no such accelerator

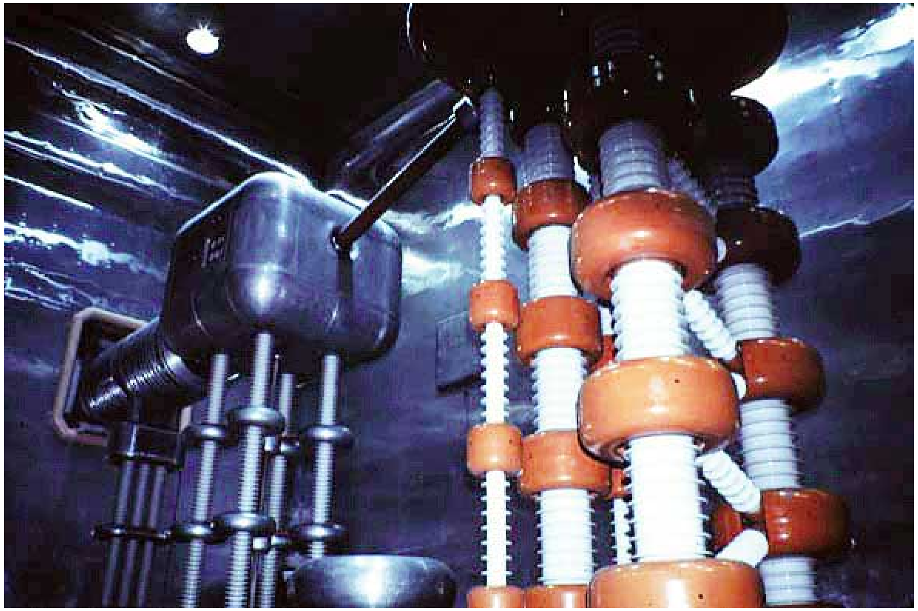


This model turned out to be wrong



Electro-Static Accelerator

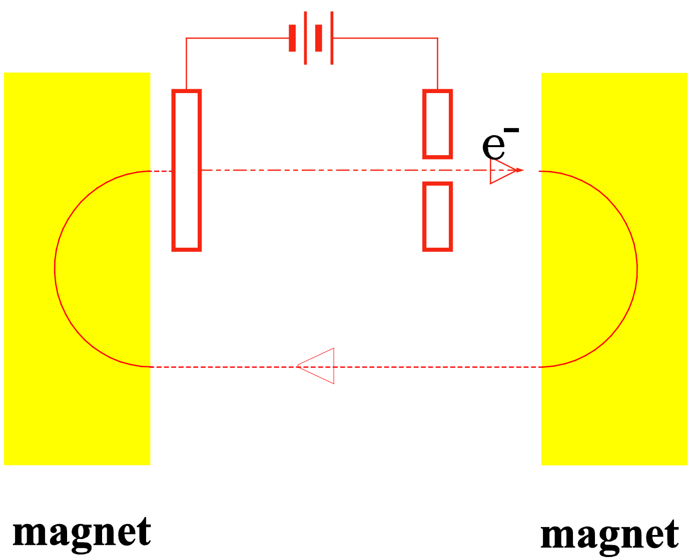
- Cockcroft-Walton
- Collect static electricity
- First nuclear transformation by accelerator
- H + Li → 2 He
  - Cavendish Institute in 1932
    - The same year as the discovery of neutron by Chadwick (also Cavendish) from beryllium irradiated by α.
  - 800keV
  - Limitation by discharge

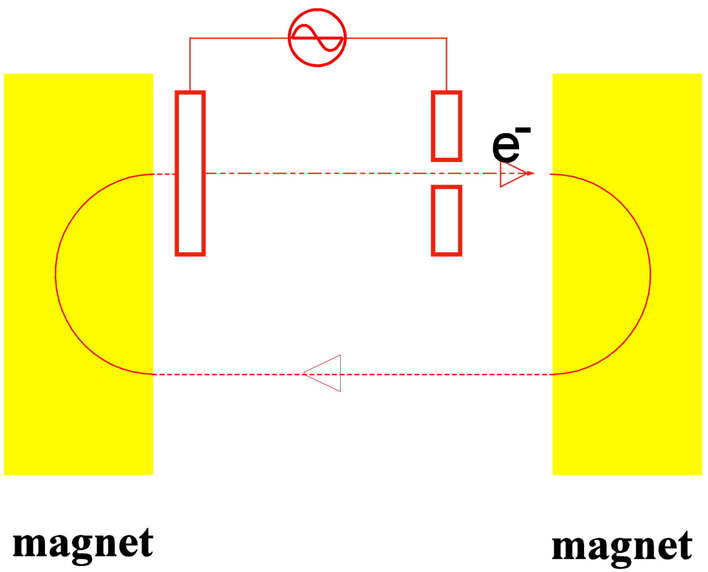


KEK 750keV Cockcroft-Walton

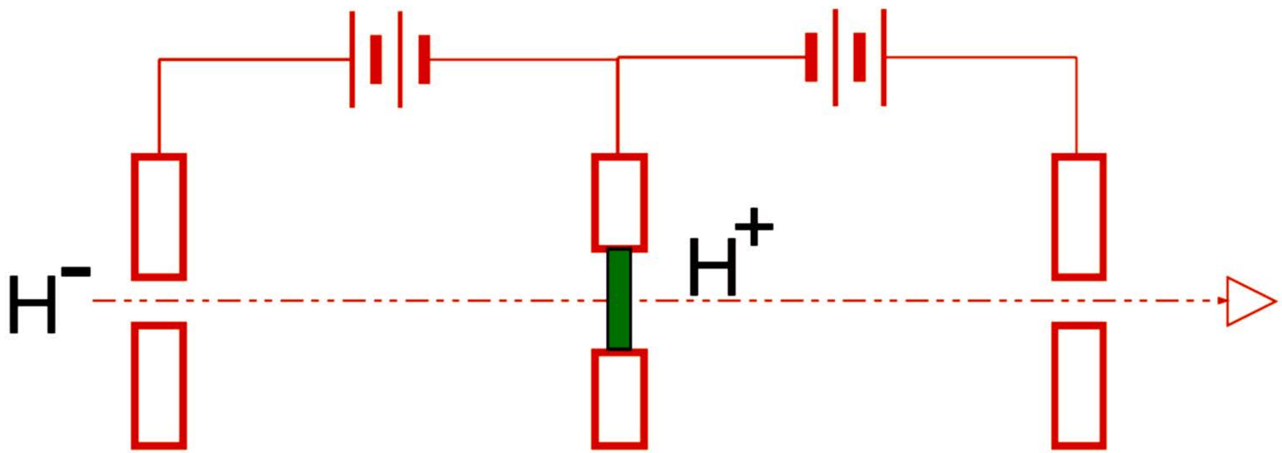
How to Go to Higher Energies

- Bend the particle after first acceleration by magnetic field
- Accelerate by the same CRT
- Does this work?
- Solution: use alternating voltage
- But high frequency is needed





- A clever (but very limited) way is the tandem (2 houses harnessed in series) accelerator

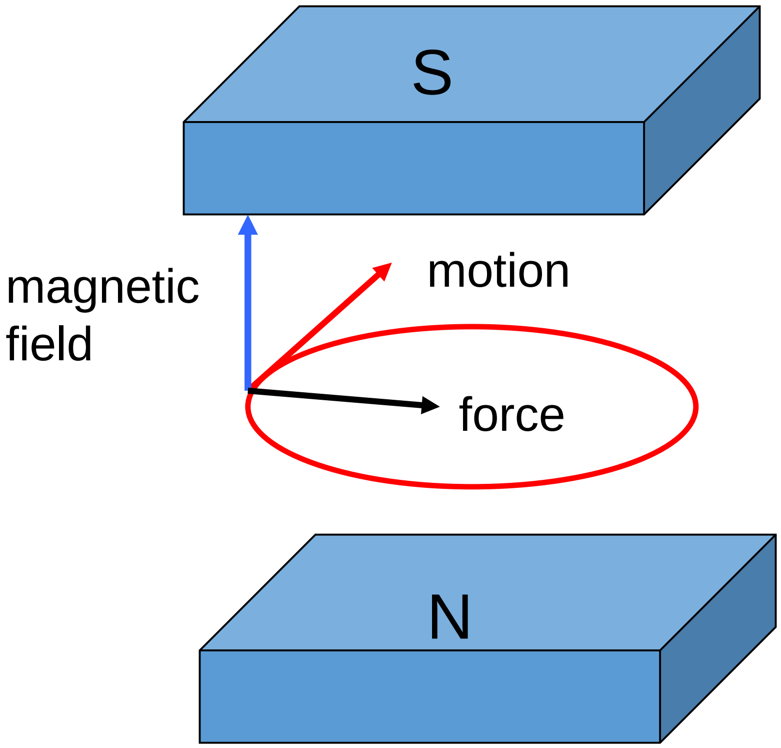


Motion in Magnetic Field

- A charged particle draws a circle
- $p = e \times B \times \rho$

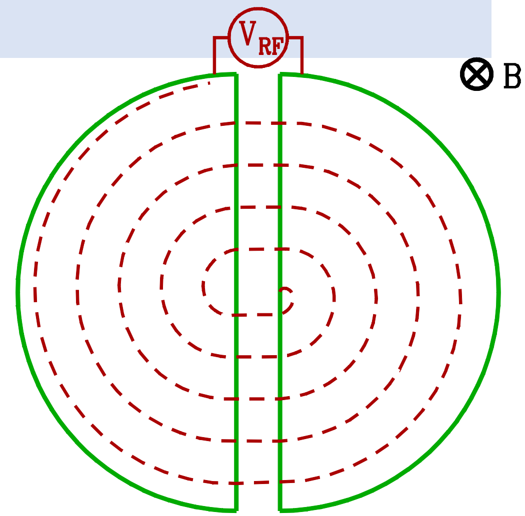
- p: particle momentum
- e: electric charge
- B: magnetic field
- ρ: orbit radius

p [GeV/c] = 0.3 x B [T] x ρ [m]

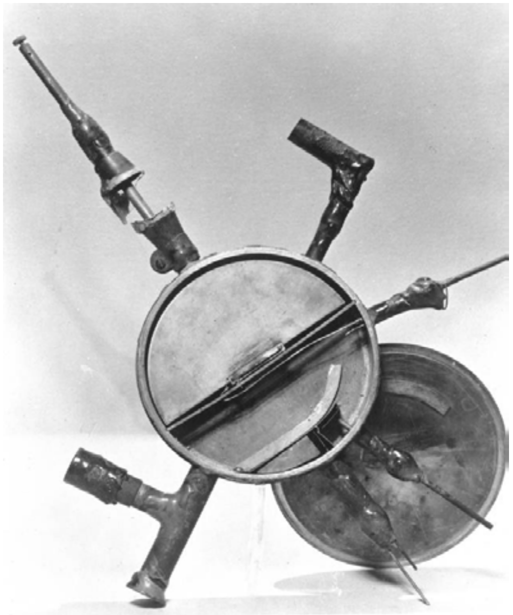


Cyclotron

- Jan. 1931
- Berkeley, California
- Lawrence & Livingston, Phys. Rev. 40, 19, 1932



First cyclotron
diameter 13cm
Proton energy 80keV
Wikipedia says ~25$



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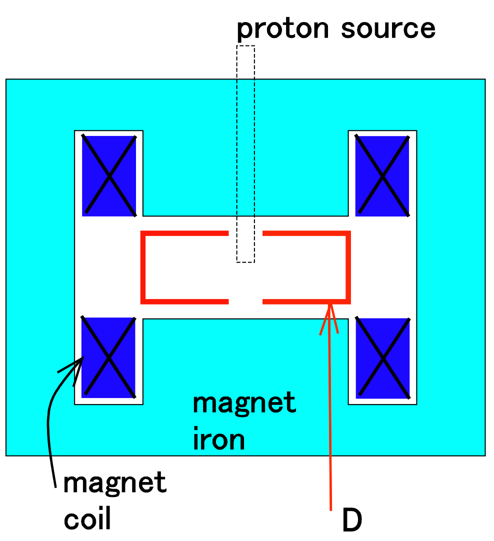


Cyclotron (2)

- Cyclotron makes use of the fact that the time for one turn is independent of the electron energy
  - $p = eB\rho$
  - $p = mv$
  - → $T = \frac{2\pi\rho}{v} = \frac{2\pi m}{eB}$

  T = time for one revolution, m : particle mass, v : velocity
- But, $p = mv$ is an approximation.
  Exact formula with the special relativity is
  $p = mv/\sqrt{1-(v/c)^2}$
- "T= independent of p" breaks down when v approaches c.
- Large difference between electron and proton

Exercise (1)

Assuming that the first cyclotron had maximum orbit diameter 13cm and reached the maximum proton energy 80keV, compute

- The magnetic field
- Frequency of the voltage

(caution: these may differ a bit from the real one.)

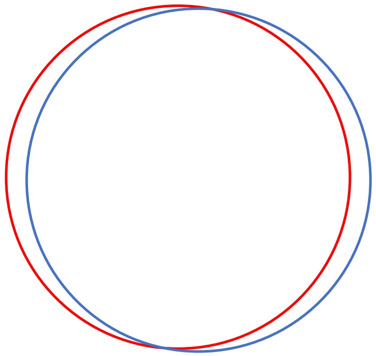
Betatron

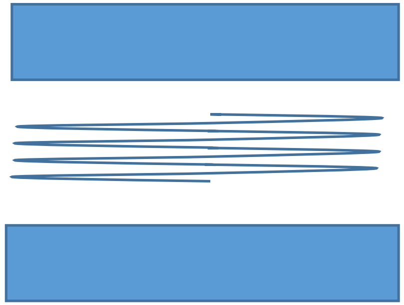
- D. W. Kerst, ~1940
- Induction accelerator (time-dependent magnetic field)

$$\text{rot}\, E = -\frac{\partial B}{\partial t} \rightarrow E_\phi = \frac{1}{2}$$

Betatron Oscillation

- If a particle velocity has an off-circle motion, the particle draws a circle with a shifted center but does not go far away (horizontal fucusing)
- But once a particle gets vertical velocity, then the particles eventually hit the magnet and is lost.
- There must be a force which gives a vertical force to the particle to bend the orbit back to the medium plane.
- Transverse motion is called “Betratron Oscillation”
- Previous figure: The magnet gap is larger outside
    - Stability of betratron oscillation

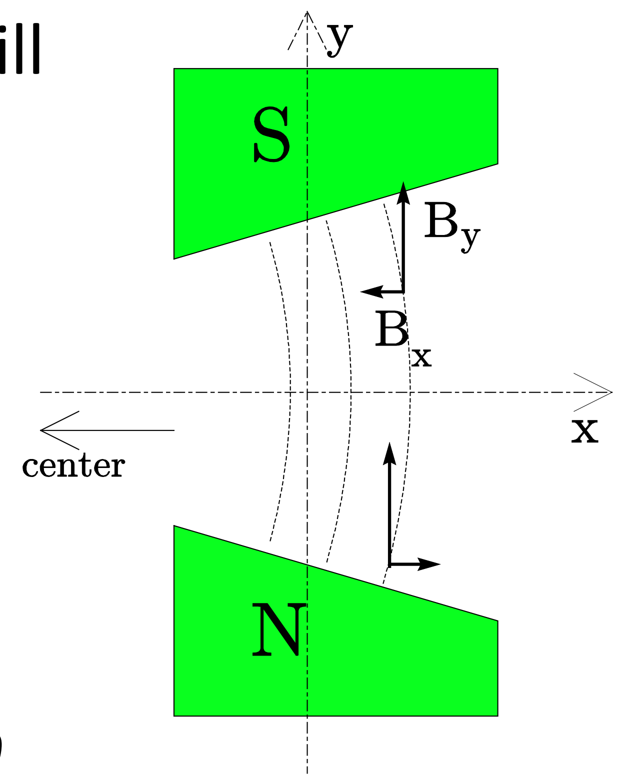




(Weak) Focusing

- Simple (vertical) magnetic field makes a circular orbit. Once a particle gets vertical velocity, it will soon hit the magnet and lost
- Use a magnet like →
  - $B_y = B_0\left(1 - \frac{nx}{r_0}\right)$
  - $B_x = -B_0\left(\frac{ny}{r_0}\right)$

Note: $\frac{\partial B_y}{\partial x} = \frac{\partial B_x}{\partial y}$



- Then,

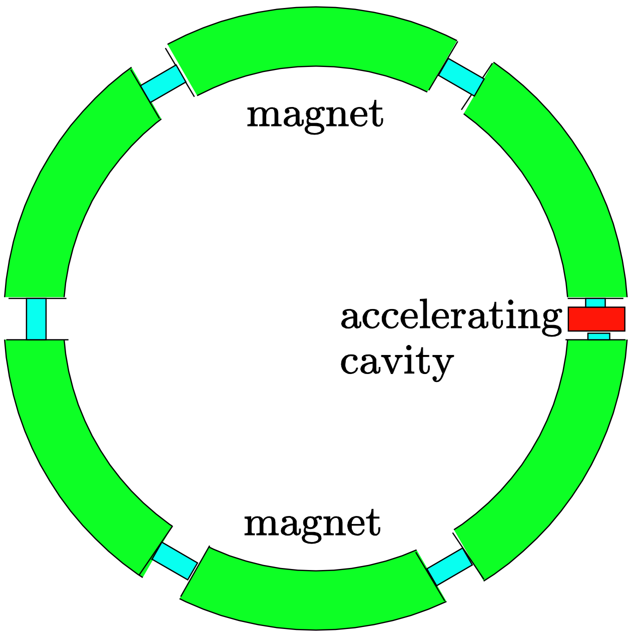
  $x \propto \sin\sqrt{1-n}\theta, \; y \propto \sin\sqrt{n}\theta$
- Stable if 0 <   < 1.

Synchrotron

- Change the magnetic field $B(t)$ so that the orbit radius does not change as energy increases
  $p(t) = eB(t)\rho$
  - Then, the magnets need not cover inside the circle. → Much smaller magnets.
  - The price to pay: Pulsed operation. No continuous beam.
- Acceleration only a few points in the ring
- High frequency needed
  - RF: radio frequency
  - $c = fRF \times \lambda_{RF}$
- Circumference must be an integer multiple of the RF wave length

$$C = h \times \lambda_{RF}$$

h is called "harmonic number"



Particle Discovery before the Era of Accelerator

- Neutron 1932 (α on beryllium)
- Neutrino ~1932 (to explain beta decay)
- positron 1932 (from cosmic ray)
- muon 1937 (cosmic ray)
- π meson 1947 (cosmic ray)

- Accelerators, improved to high energies, started to discover new particles in 1950's

GeV-class Synchrotrons

- 1950's
- A few GeV proton synchrotrons
  - Cosmotron (BNL) 3GeV
  - Bevatron (LBL) 6.2GeV
- Many new particles found
  - anti-proton, anti-neutron
  - Λ, Σ, Ξ, Ω,....
  - Systematic description introducing "Quarks" by Gell-Mann in 1964

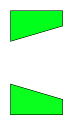
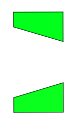
Cosmotron

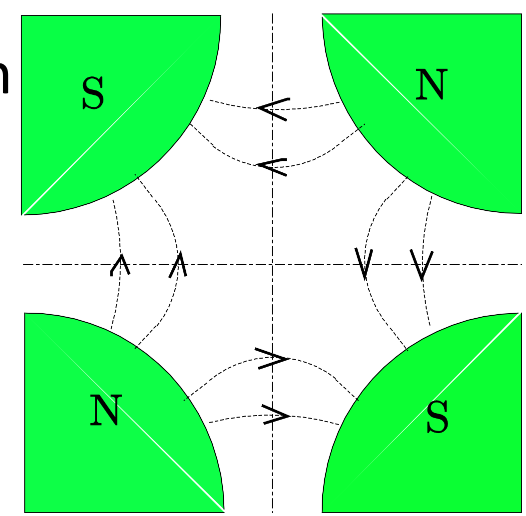
Bevatron

- Weak-focusing synchrotron
- Lawrence Berkeley Laboratory
- Start operation in 1954
- Bev.. = Billion Electron Volt
  = Giga Electron Volt (GeV)
- Discovered antiproton in 1955

http://www.lbl.gov/image-gallery/image-library.html

Principle of Strong Focusing

- Found by Earnest Courant, et.al.
- E. D. Courant, M.S. Livingston, H. S. Snyder, Phys.Rev. 88 (1952)
- Note that no single magnet can focus simultaneously in x and y.
- But arranging  and  alternately, the beam can be focused in x and y
- Two lenses with the focal length f_1, f_2 placed with the distance make a lens of focal length



$$\frac{1}{F} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}$$

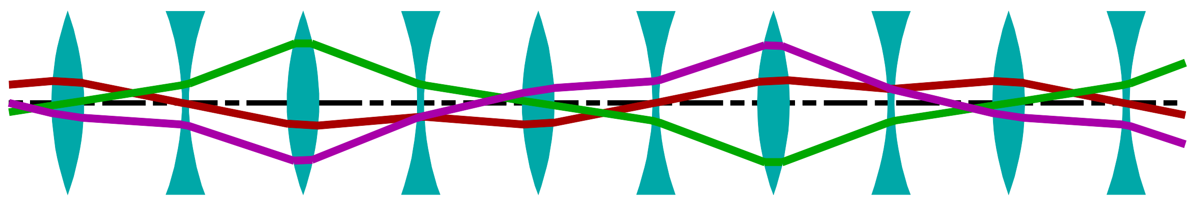
If $f_1 = -f_2 = f$, then $F = \dfrac{d}{f^2}$

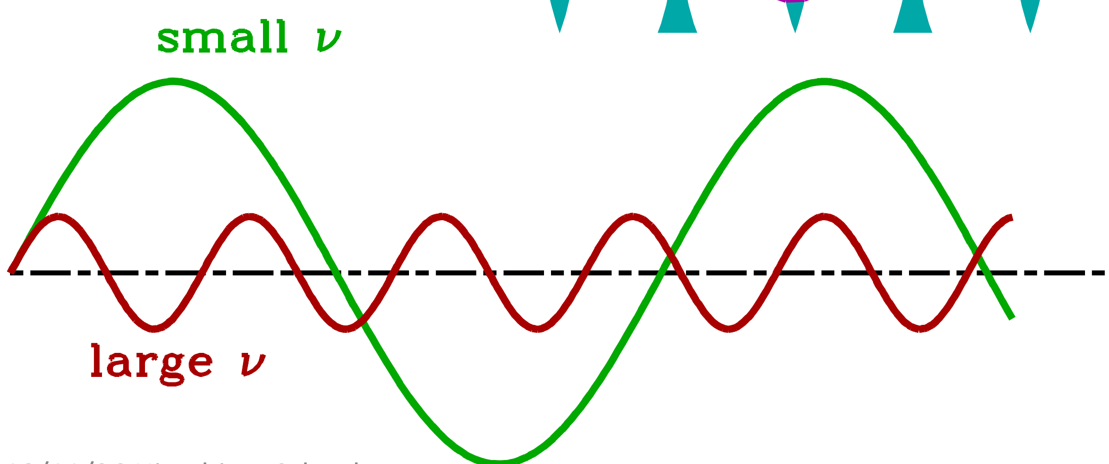
i.e., a focusing lens

- Can also be done by quadrupole magnets

Principle of Strong Focusing (2)

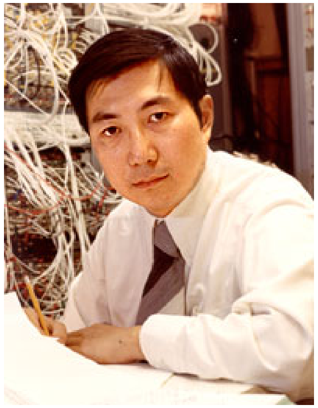
- With many focusing and defocusing lenses, the orbit oscillates many times during one turn
- The beam size becomes much smaller than weak-focusing → magnet becomes much smaller
- The price to pay was the accuracy of the field



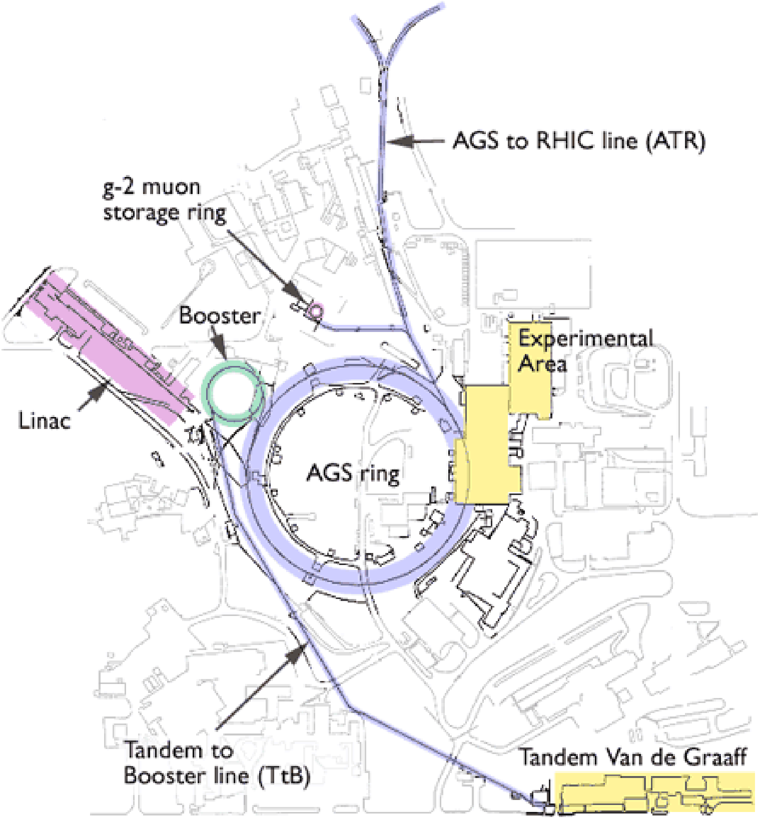


AGS: Alternating Gradient Synchrotron

- First strong-focusing synchrotron
- Brookhaven Laboratory
- Start operation in 1960, ~20GeV
- Discovery of new particles
  - J/ψ
  - ν_μ

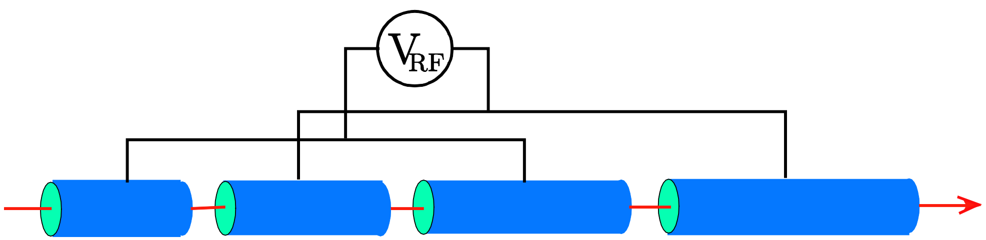


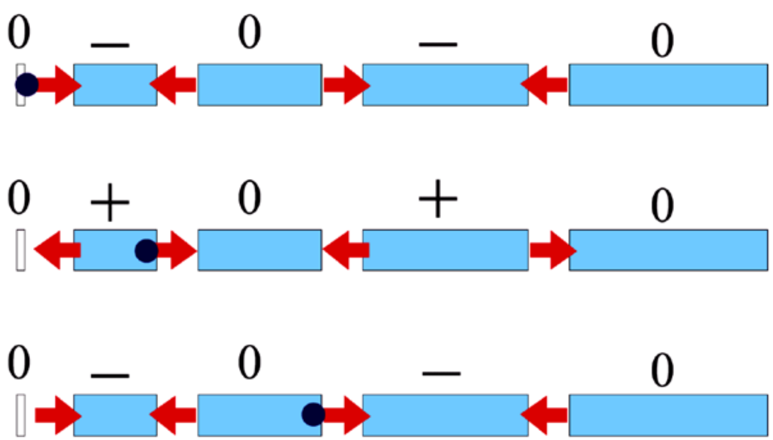
Sam Ting



Linear Accelerator

- Solve the problem of DX accelerator by another way
- Apply Alternating Voltage on the individual metallic tubes (drift-tube)
- The electric field is zero inside the tubes
- Protons at the left end are accelerated when the voltage on the first tube becomes negative
- If the voltage is flipped by the time the protons reach the exit of the first tube, they are accelerated in the gap between tube 1 and 2



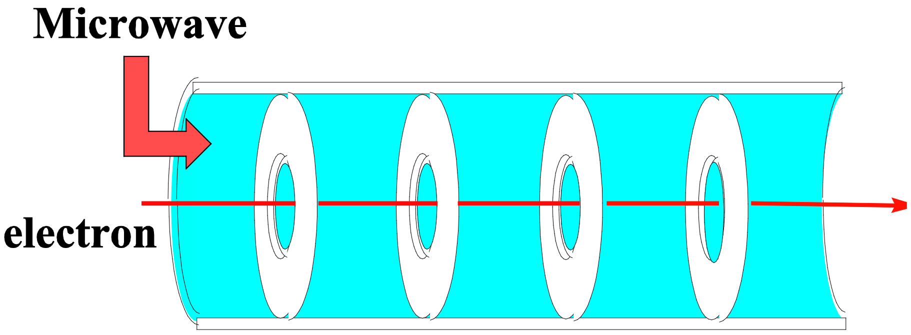


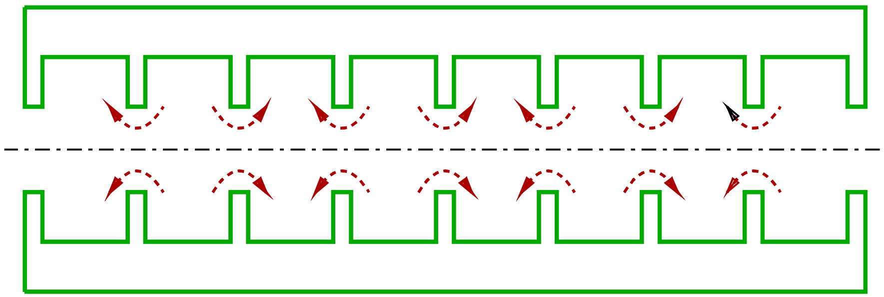
Exercise (2)

- Assume the particle is proton, the voltage is +-500kV, the length of the first drift tube is 5cm, and the gap length is negligible.
- Compute (Use non-relativistic kinematics)
  - the proton velocity in the first tube
  - required frequency
  - the length of the second tube
  - the length of the n-th tube
- One more question: how long is the tube in the limit of n→infinity (use special relativity)

Linear Accelerator (2)

- The discovery of the principle is old, but actual development much later
  - Progress of microwave technology (radar) during WW-II
- Resonator type accelerator for particles with v close to c





Stanford Linear Accelerator

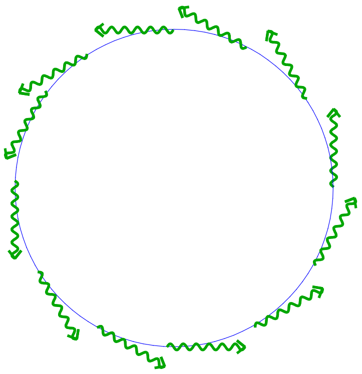
- Electron linear accelerator
- Length 2 miles
- Operation started in 1967
- ~1968 Research of deep inelastic scattering (scattering of electron and target proton, investigate structure of proton)
- This accelerator has later been used for various purposes. It is still now the highest energy linac.
  SPEAR, PEPII, SLC, LCLS, LCLSII ....

Stanford Linear Accelerator

Synchrotron Radiation

- Charged particles lose energy by synchrotron radiation
- proportional to $1/m^4$
  - Almost negligible from protons but visible in LHC
- Loss per turn (electron)

$$U = 0.088 \frac{E^4[\mathrm{GeV}]}{\rho[\mathrm{m}]} \quad [\mathrm{MeV}]$$



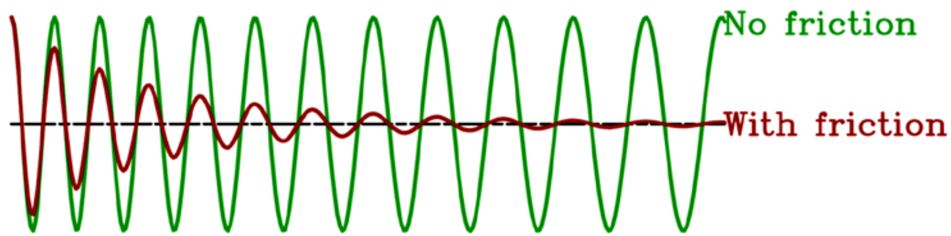
- Average photon energy

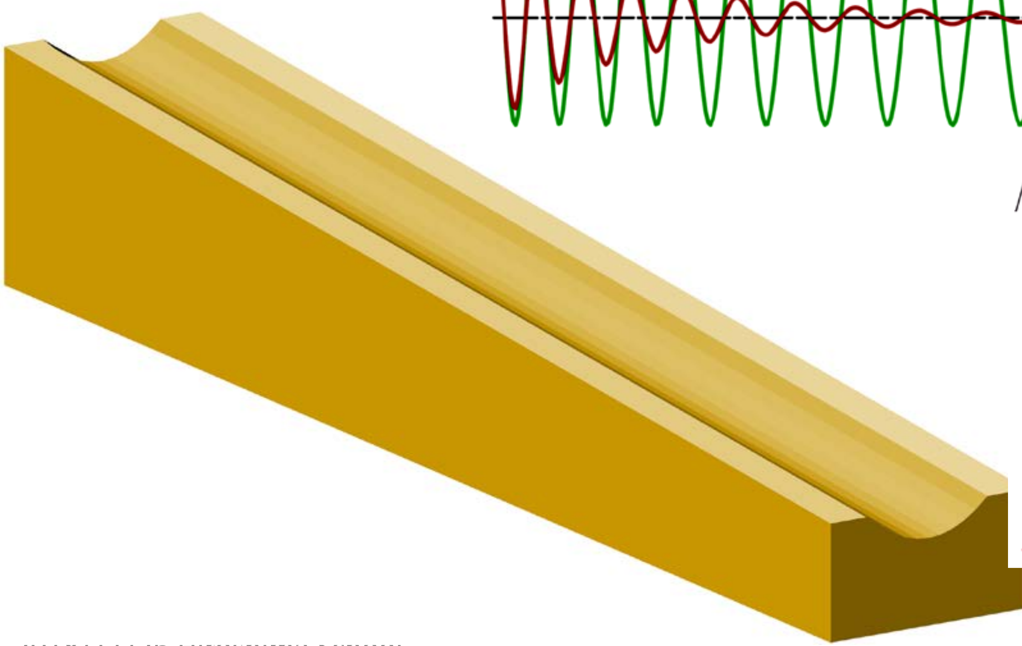
$$E_\gamma = 0.683 \frac{E^3[GeV]}{\rho[m]} \ [\mathrm{keV}]$$

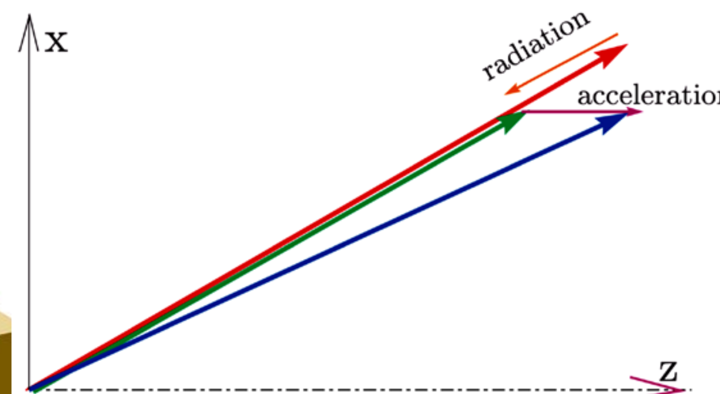
- Not only unwelcomed effects but
  - can be used as light source
  - radiation damping
    - Stabilize beam oscillation
    - Lower the emittance

Radiation Damping

- Synchrotron radiation loss is larger for higher-energy particle → damping of energy spread
- Momentum loss in the direction of motion (like frictional force) → damping of transverse oscillation

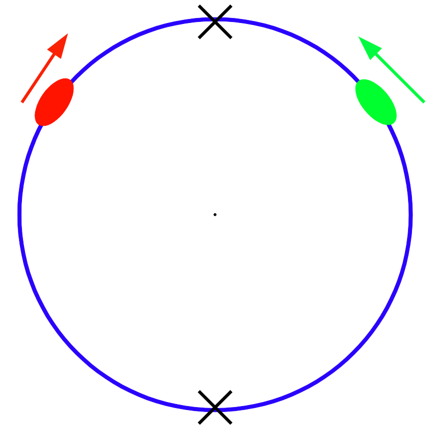


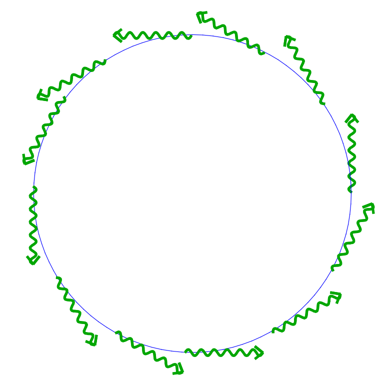




Storage Ring

- Synchrotron can be used to store beams for seconds to days
- Usage
  - Collider
  - Synchrotron light source
  - Beam manipulation
    - Low emittance
    - Buncher/debuncher
    - Stacking
- Principle same as synchrotron but
  - no need of rapid acceleration
    (even no acceleration)
  - longer beam life required (e.g., better vacuum)
  - insertion structure (colliding region, undulator, etc)





Radiation Source

- Many accelerators have been built to make use of the synchrotron radiation
- First generation: parasitic use of radiation from bending magnets of colliders
- Second generation: parasitic use of radiation from insertion magnets of colliders
  - Undulators
- Third generation: Radiation in a ring dedicated for light source
- Fourth generation?: FEL, ERL,