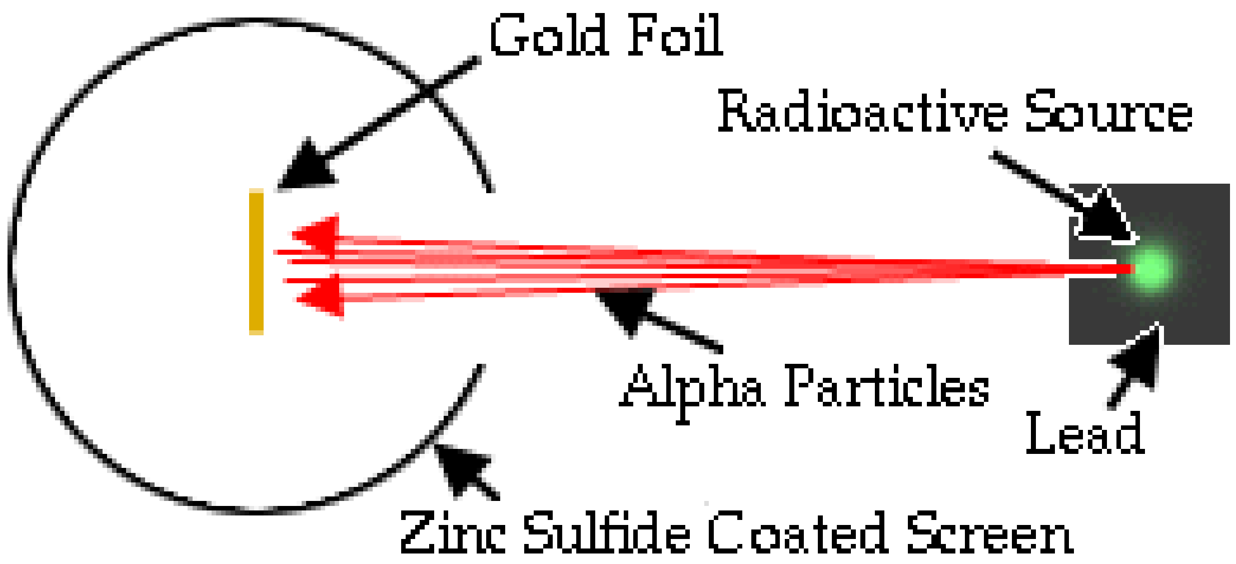
Lectures on accelerator physics

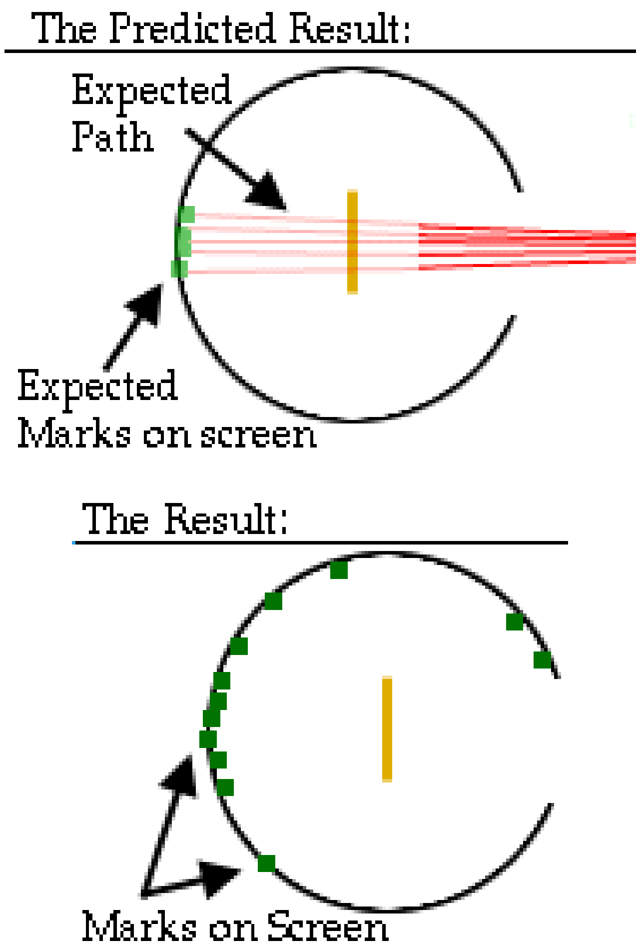
- Lecture 3 and 4: Examples
  - Examples of accelerators

Rutherford's Scattering (1909)

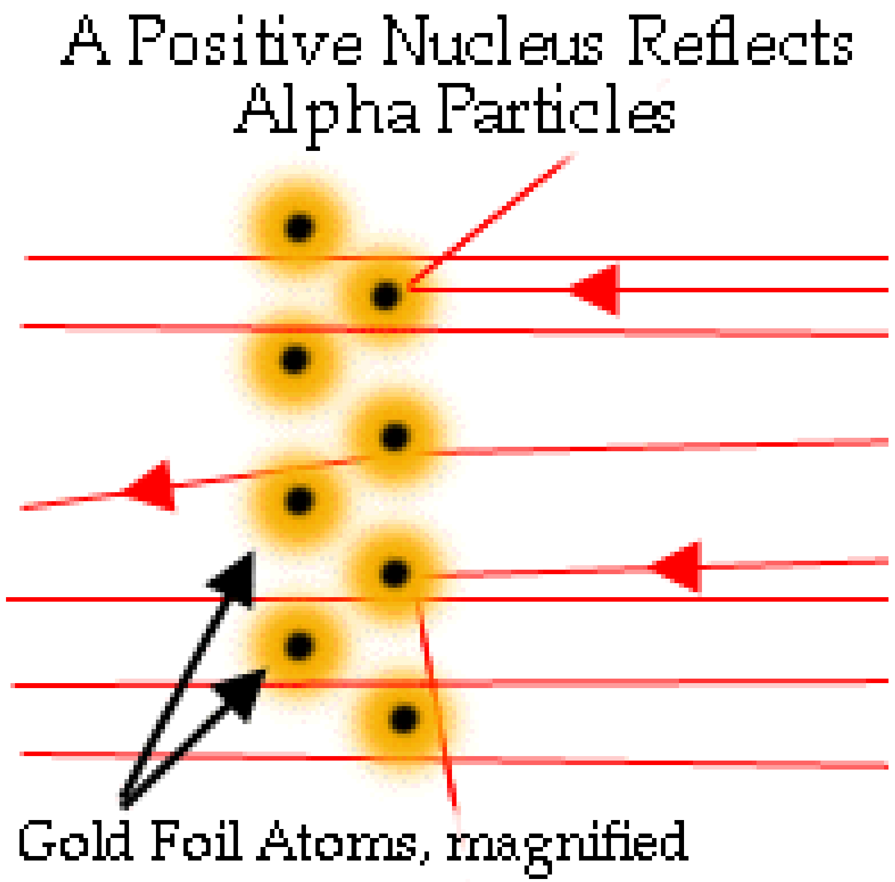


- Particle Beam
- Target
- Detector

Results



The Predicted Result:
Expected Path
Expected Marks on screen
The Result:
Marks on Screen



A Positive Nucleus Reflects Alpha Particles
Gold Foil Atoms, magnified

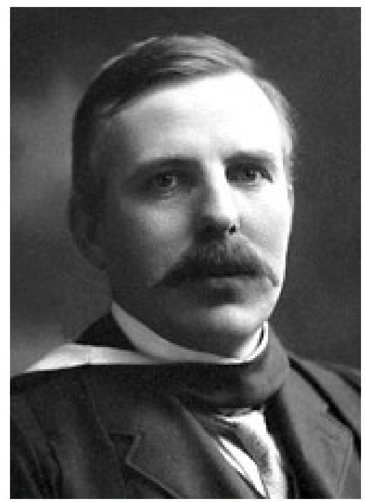
Did Rutherford get the Nobel Prize for this?

- No, he got it in Chemistry in 1908

The Nobel Prize in Chemistry 1908
Ernest Rutherford

The Nobel Prize in Chemistry 1908

Ernest Rutherford



Ernest Rutherford

The Nobel Prize in Chemistry 1908 was awarded to Ernest Rutherford *"for his investigations into the disintegration of the elements, and the chemistry of radioactive substances"*.

Sources of “Beams”

- Radioactive Decays
  - Modest Rates
  - Low Energy
- Cosmic Rays
  - Low Rates
  - High Energy
- Accelerators
  - High Rates
  - High Energy

Think time

- How to accelerate?

Accelerator Physics for Pedestrians

$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$ Lorentz Force

- Electric Fields

  ACCELERATES

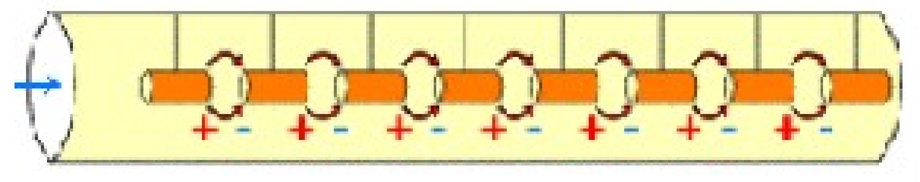
  - Aligned with field
  - Typically need very high fields
- Magnetic Fields

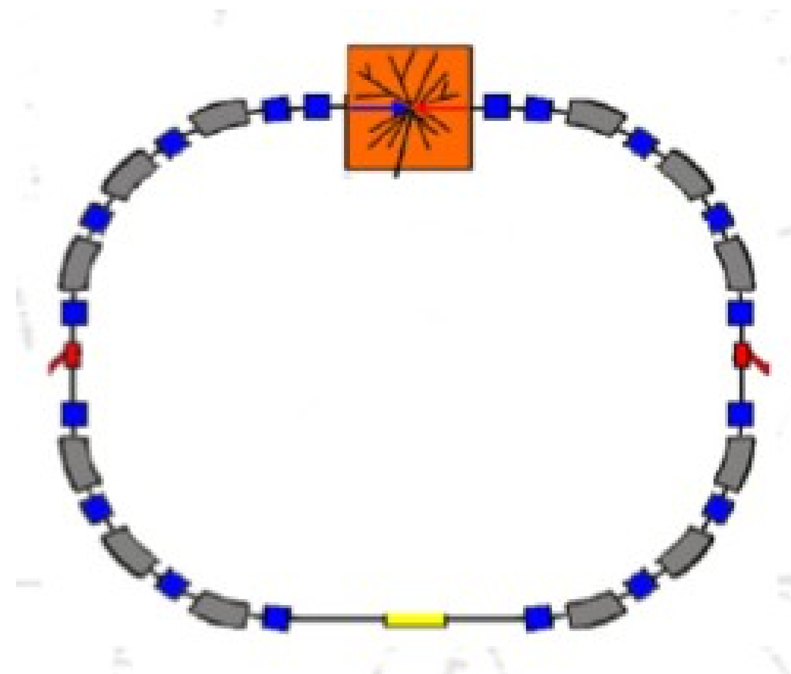
  BENDS/CONFINES/FOCUSES

  - Transverse to momentum
  - Cannot change the magnitude of the momentum

Circle or Line?

- Linear Accelerator
  - Electrostatic
  - RF linac
- Circular Accelerator
  - Cyclotron
  - Synchrotron
  - Storage Ring





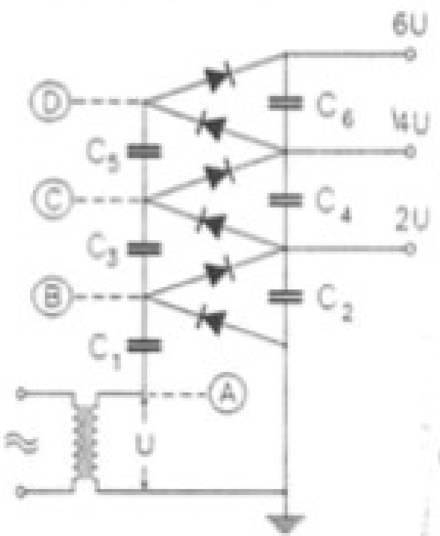
Linear accelerators

- DC
- AC

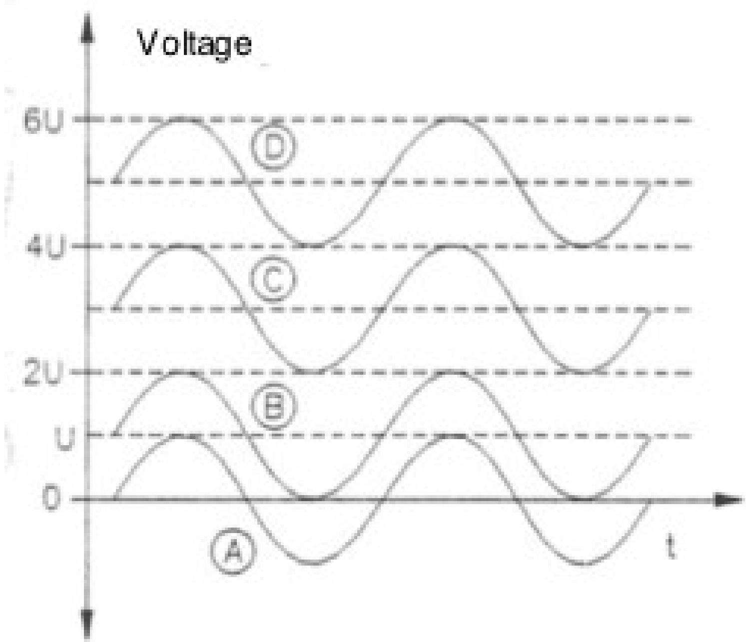
Cockroft-Walton - 1930s

Very nice flash interactive animation:
http://www-outreach.phy.cam.ac.uk/camphy/cockcroftwalton/cockcroftwalton8_1.htm

Cockroft-Walton generator diagram



Increase voltage to 800 kV
(enough for nobel prize!)



The Nobel Prize in Physics 1951
John Cockcroft, Ernest T.S. Walton

The Nobel Prize in Physics 1951

John Cockcroft

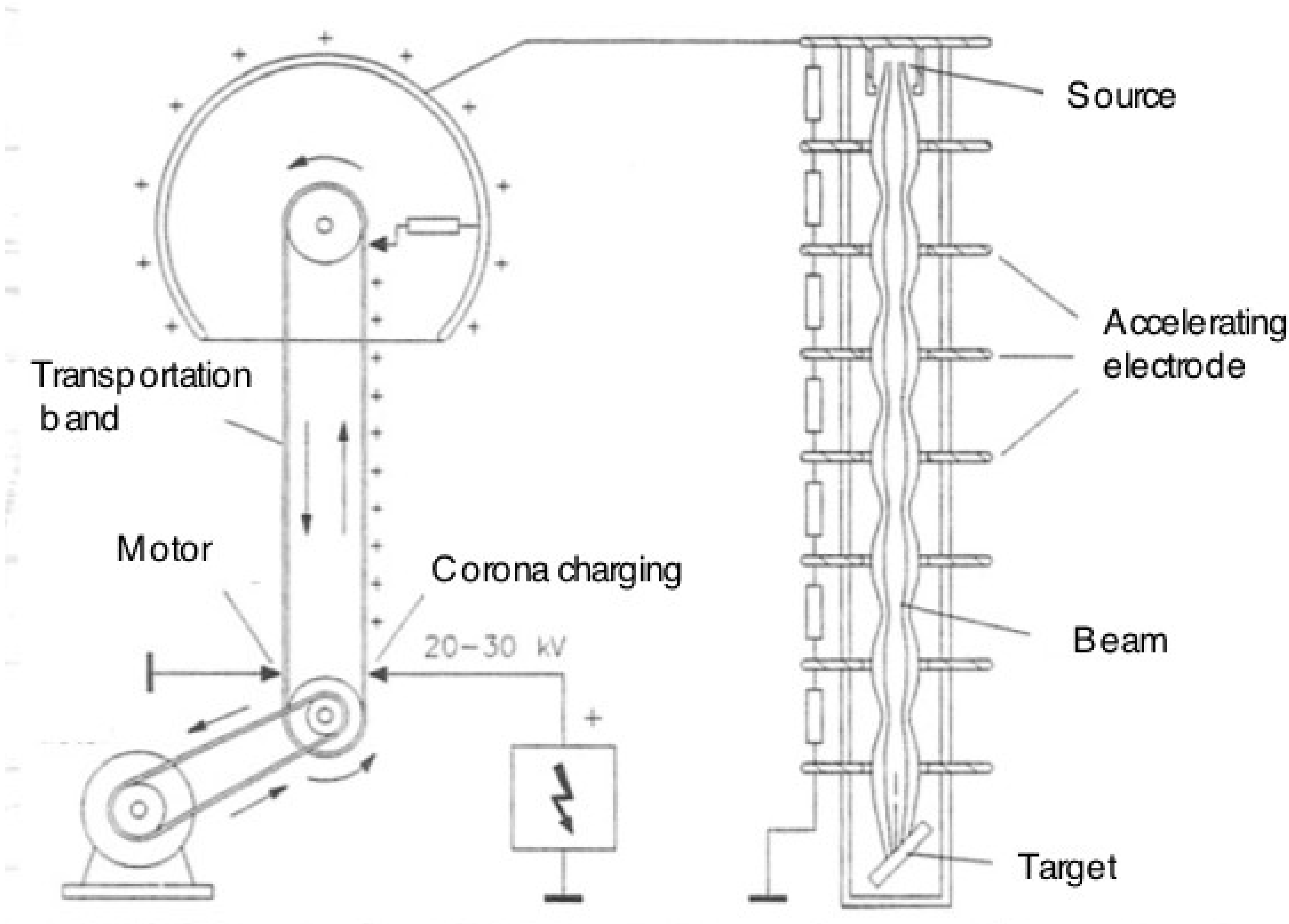
Ernest T.S. Walton

Sir John Douglas Cockcroft

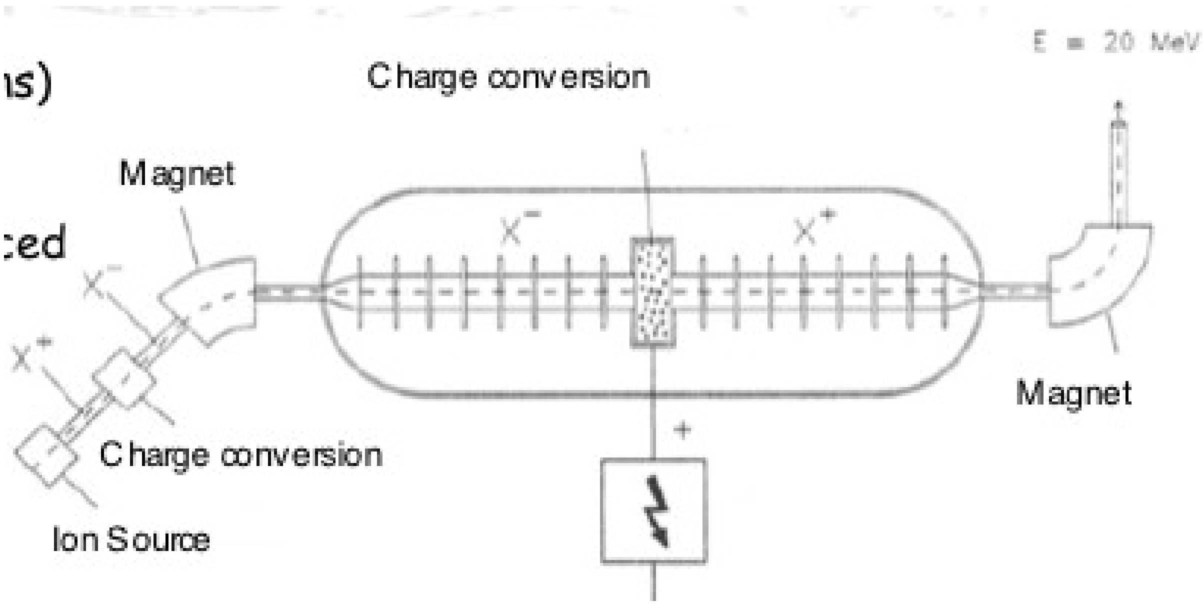
Ernest Thomas Sinton Walton

The Nobel Prize in Physics 1951 was awarded jointly to Sir John Douglas Cockcroft and Ernest Thomas Sinton Walton *"for their pioneer work on the transmutation of atomic nuclei by artificially accelerated atomic particles"*

Van-de Graaff - 1930s



Van-de Graaff II

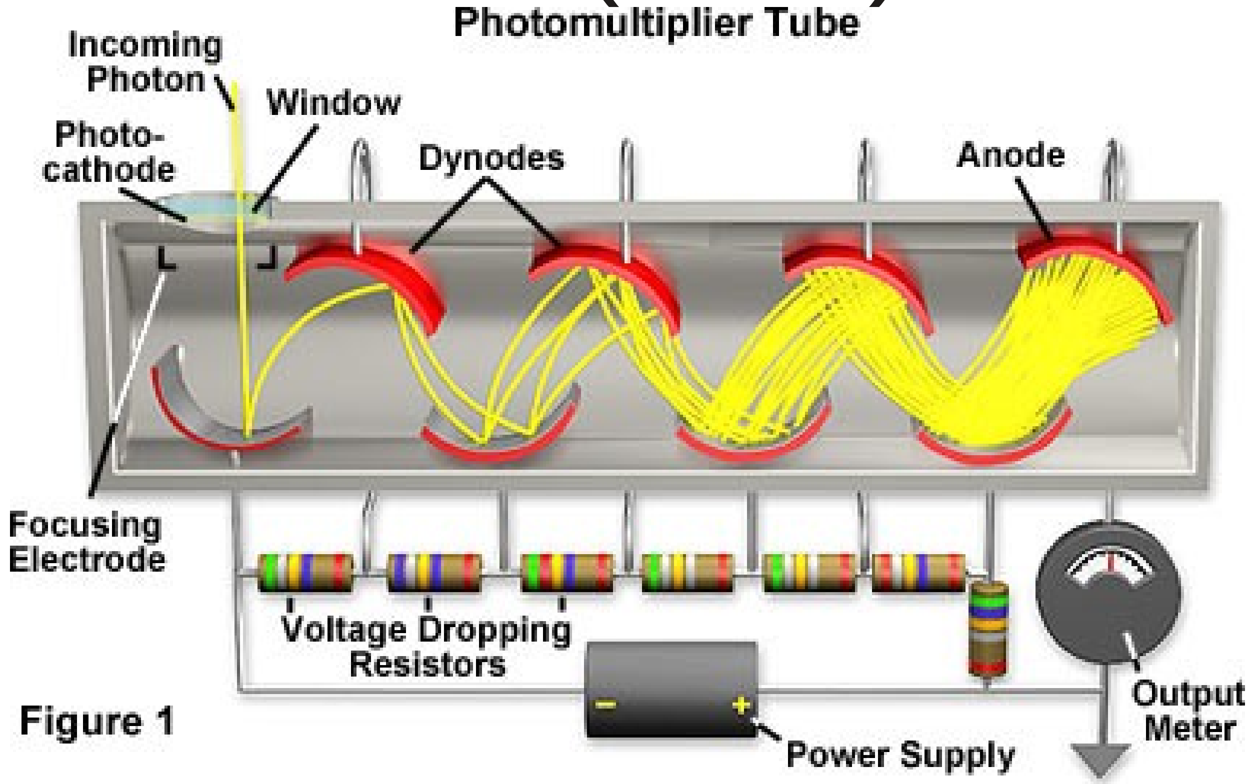


First large Van-de Graaff

Tank allows ~10 MV voltages
Tandem allows x2 from terminal voltage

20-30 MeV protons about the limit
Will accelerate almost anything (isotopes)

DC acceleration in photo multiplier tube (PMT)



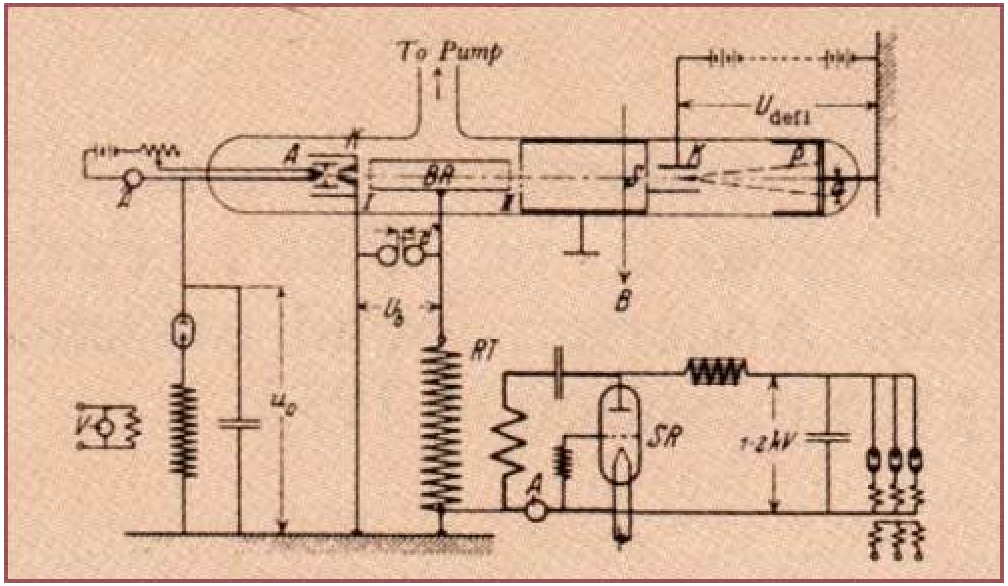
- Photons are converted (with loss) to electrons at the photocathode
- Electrons are amplified in several steps

Gustaf Ising
The “father” of AC acceleration

- “In 1924 Gustaf Ising, a Swedish physicist, proposed accelerating particles using alternating electric fields, with “drift tubes” positioned at appropriate intervals to shield the particles during the half-cycle when the field is in the wrong direction for acceleration. Four years later, the Norwegian engineer Rolf Wideröe built the first machine of this kind, successfully accelerating potassium ions to an energy of 50,000 electron volts (50 kiloelectron volts).”
  - From Britannica Academic Edition

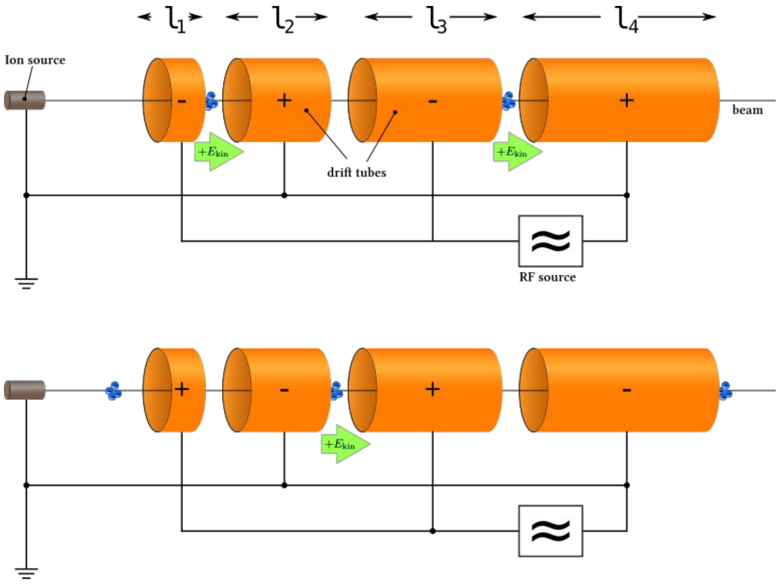
Linear Accelerators

- Proposed by Ising (Swedish) (1925)
- First built by Wideröe (Norwegian) (1928)



Rolf Wideröe as a young man.

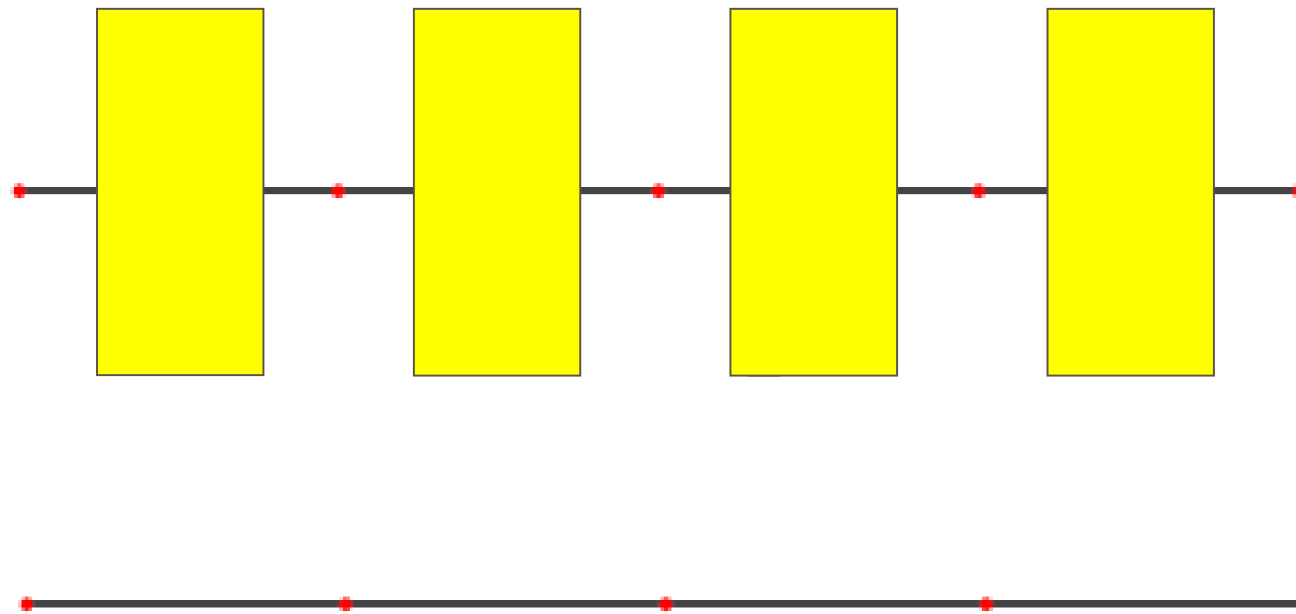
LINAC principle (1/3)



LINAC principle (2/3)

When v=c, the design is easy
For electrons this is the normal situation

Standing wave



Linac principle in action

- A small game here:
  http://www.hep.ucl.ac.uk/undergrad-projects/3rdyear/PPguide/applets/accelerator/ex.html

LINAC principle (3/3)

Can use a fixed frequency if L is made longer to match increase in velocity

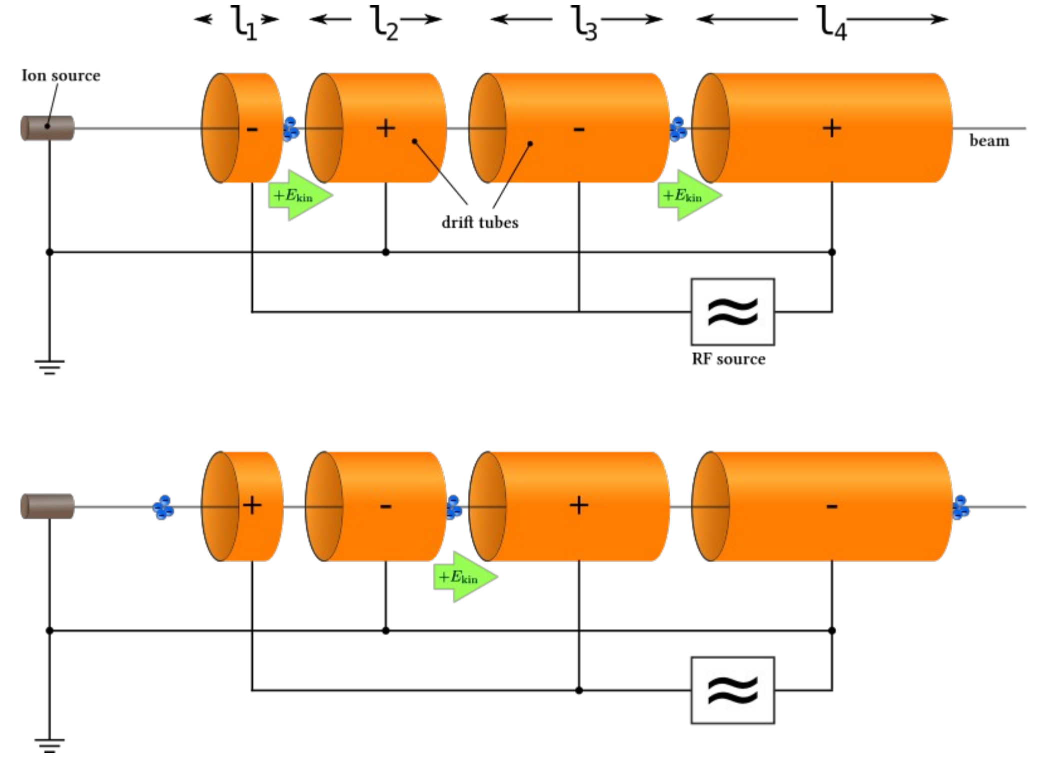
Calculate L_n assuming $v(inital)=0$ and v_n non-relativistic and AC voltage U and frequency f:

Answer:

$$v_n = \sqrt{\frac{2neU}{m}}$$

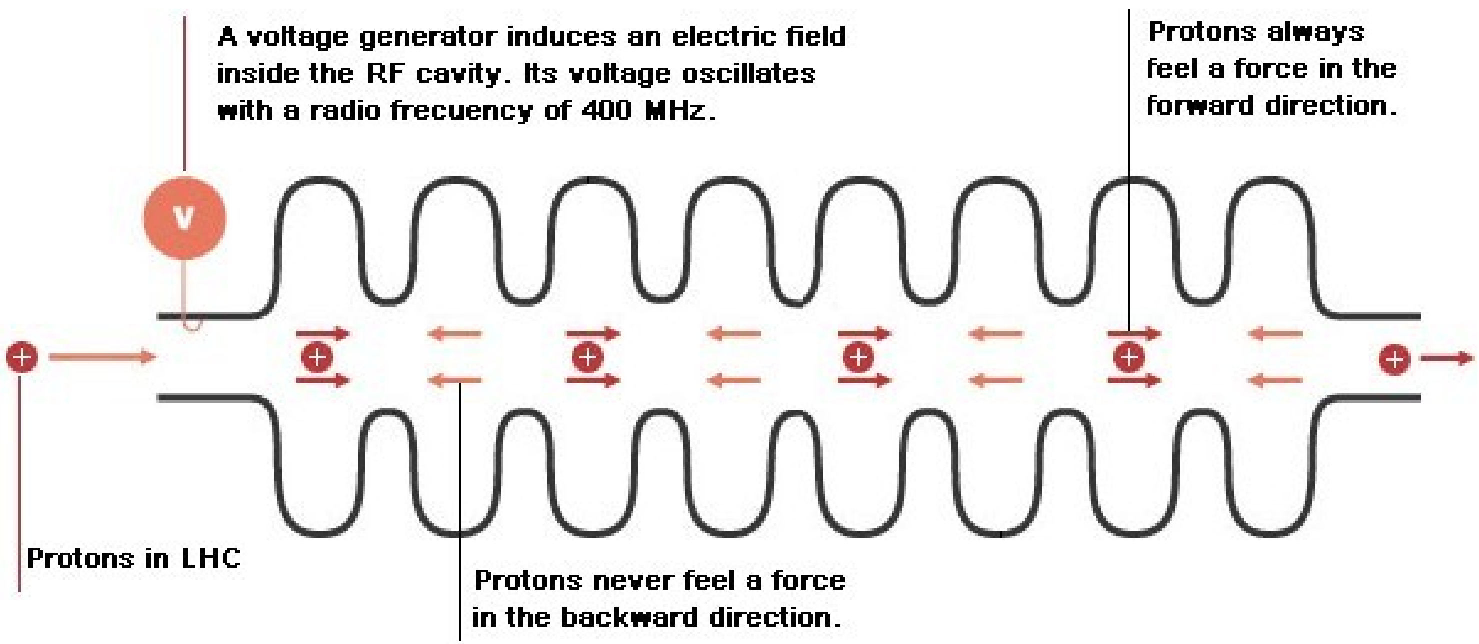
$$\frac{1}{2f} = \frac{L_n}{v_n} \rightarrow L_n = \frac{v_n}{2f}$$

L_n corresponds to half wavelength

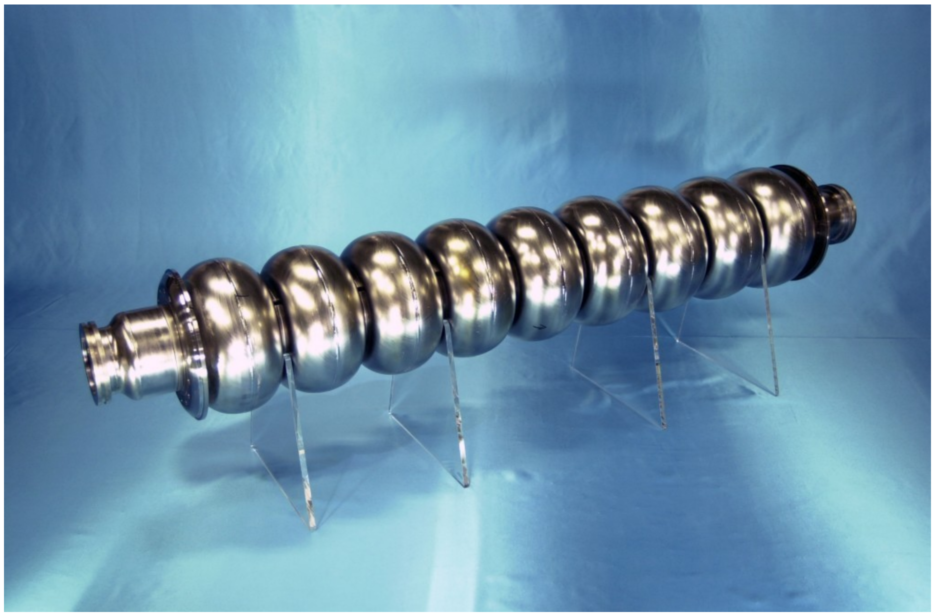


Radio Frequency (RF) cavities for linear acceleration

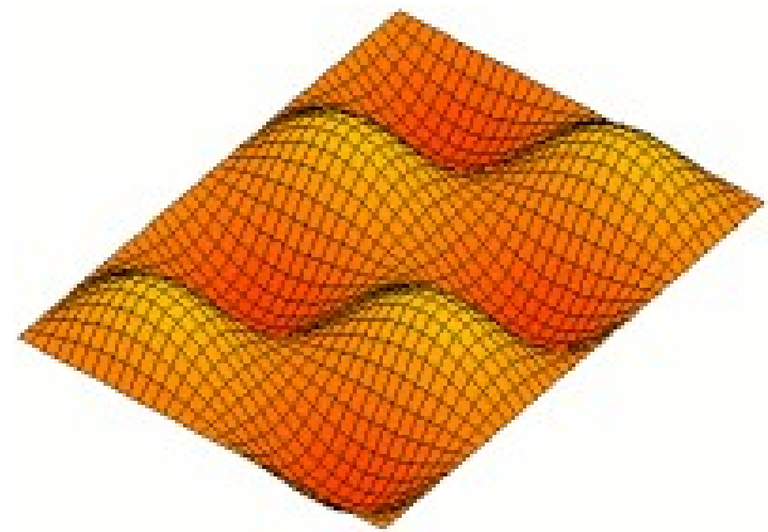
- RF cavities (sometimes also called resonance cavities) are the modern way to accelerate
- The cavity works a bit similar to a LC resonance circuit creating a strong accelartion field



Example of RF cavity from DESY



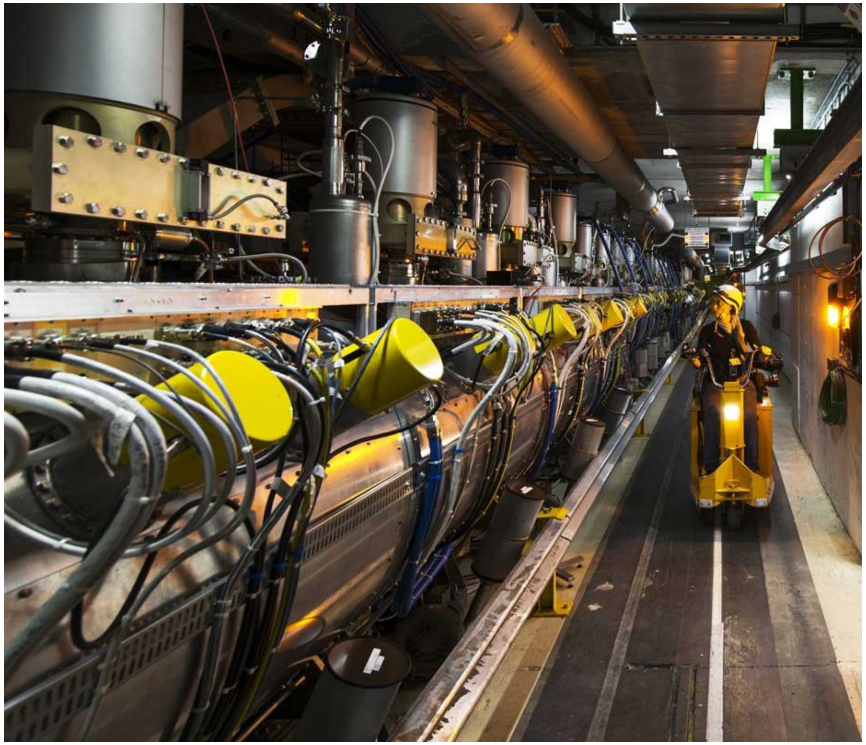
Very strong (resonant) oscillating electric field inside cavity provides acceleration



http://en.wikipedia.org/wiki/Resonator

- From http://newsline.linearcollider.org/2012/11/21/major-goal-achieved-for-high-gradient-ilc-scrf-cavities/ “We established two gradient goals: to produce cavities qualified at 35 Megavolts per metre (MV/m) in vertical tests and to demonstrate that an average gradient of 31.5 MV/m is achievable for ILC cryomodules.”

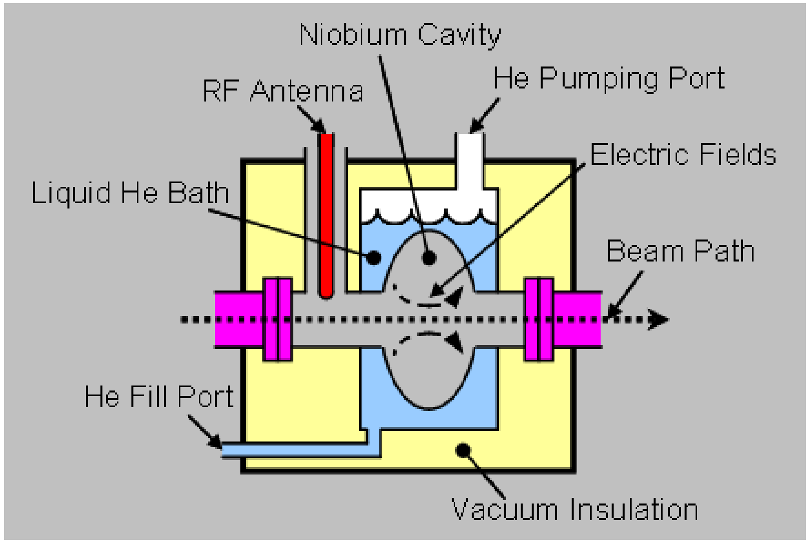
RF cavity at LHC

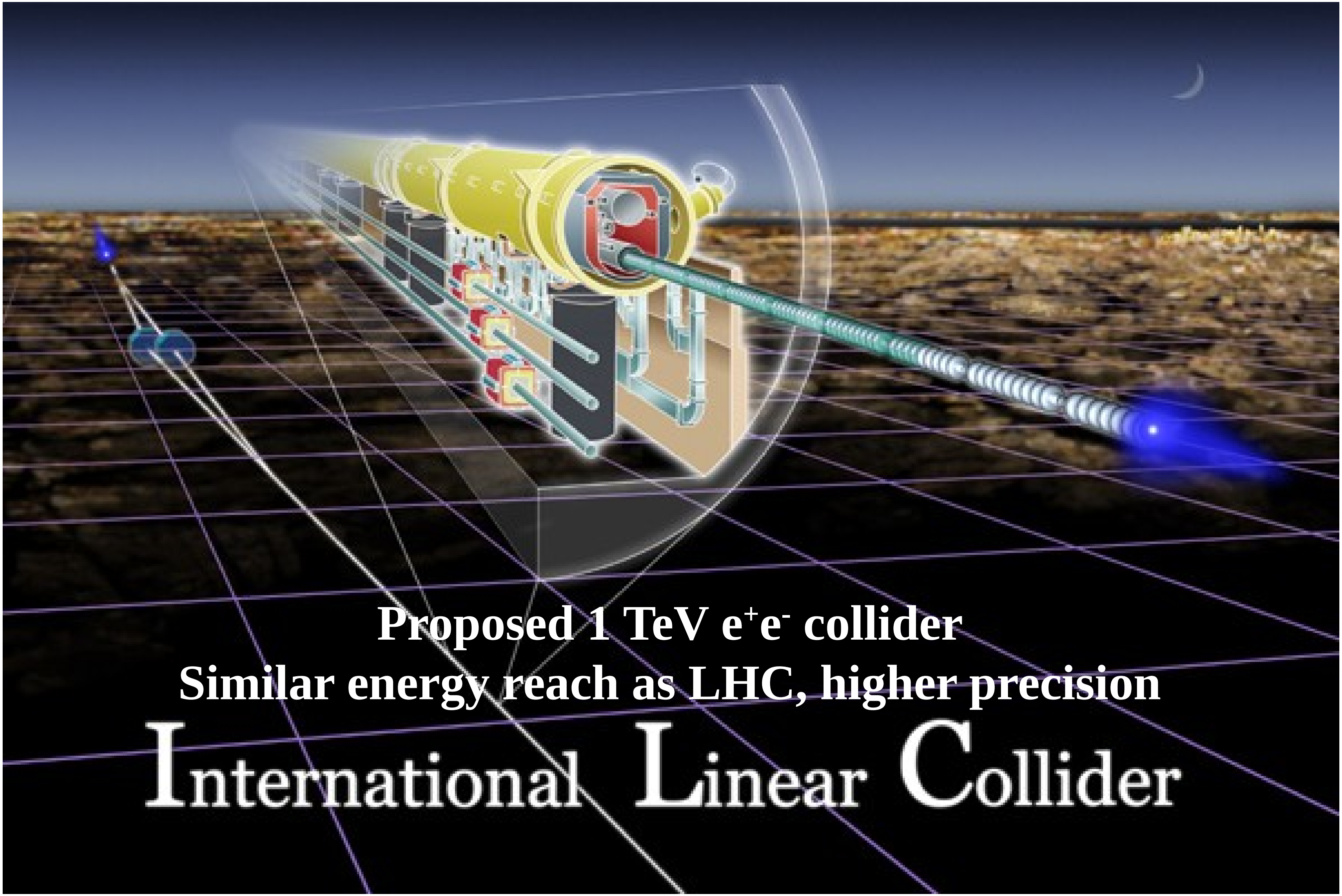


- From http://home.web.cern.ch/about/engineering/radiofrequency-cavities “High-power klystrons (tubes containing electron beams) drive each RF cavity on the LHC. A high-power electron beam inside the klystron modulates at 400 MHz. Power is extracted through a rectangular pipe of conducting metal called a waveguide, which leads to the RF cavity. Each cavity can achieve maximum voltage of 2 MV, making 16 MV per beam.”

What is super conducting in a super conducting RF cavity?

- Answer: The inside surface => no resistance => the alternating electric field is used for pure acceleration
- From http://home.web.cern.ch/about/engineering/radiofrequency-cavities "The 16 RF cavities on the LHC are housed in four cylindrical refrigerators called cryomodules – two per beam – which keep the RF cavities working in a superconducting state, without losing energy to electrical resistance."




Proposed 1 TeV e^+e^- collider
Similar energy reach as LHC, higher precision
International Linear Collider

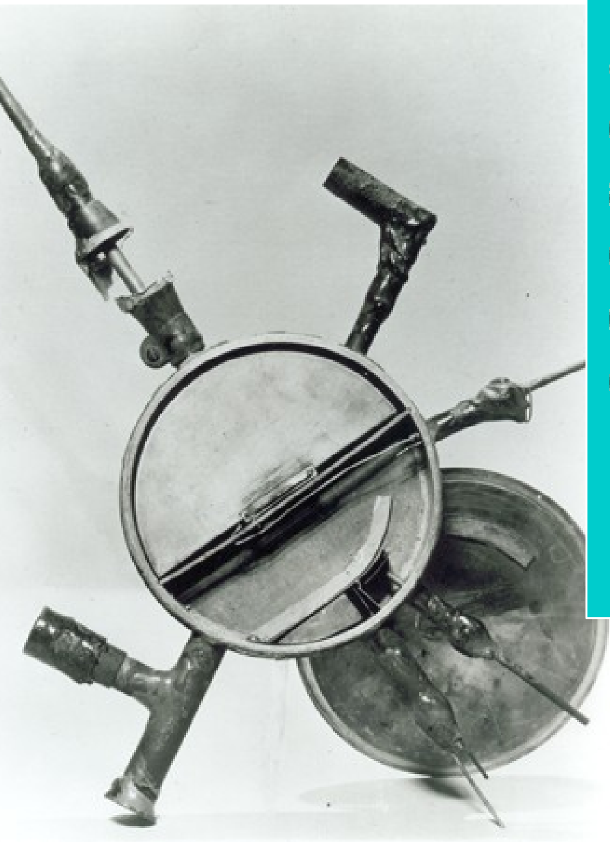
Circular accelaratos

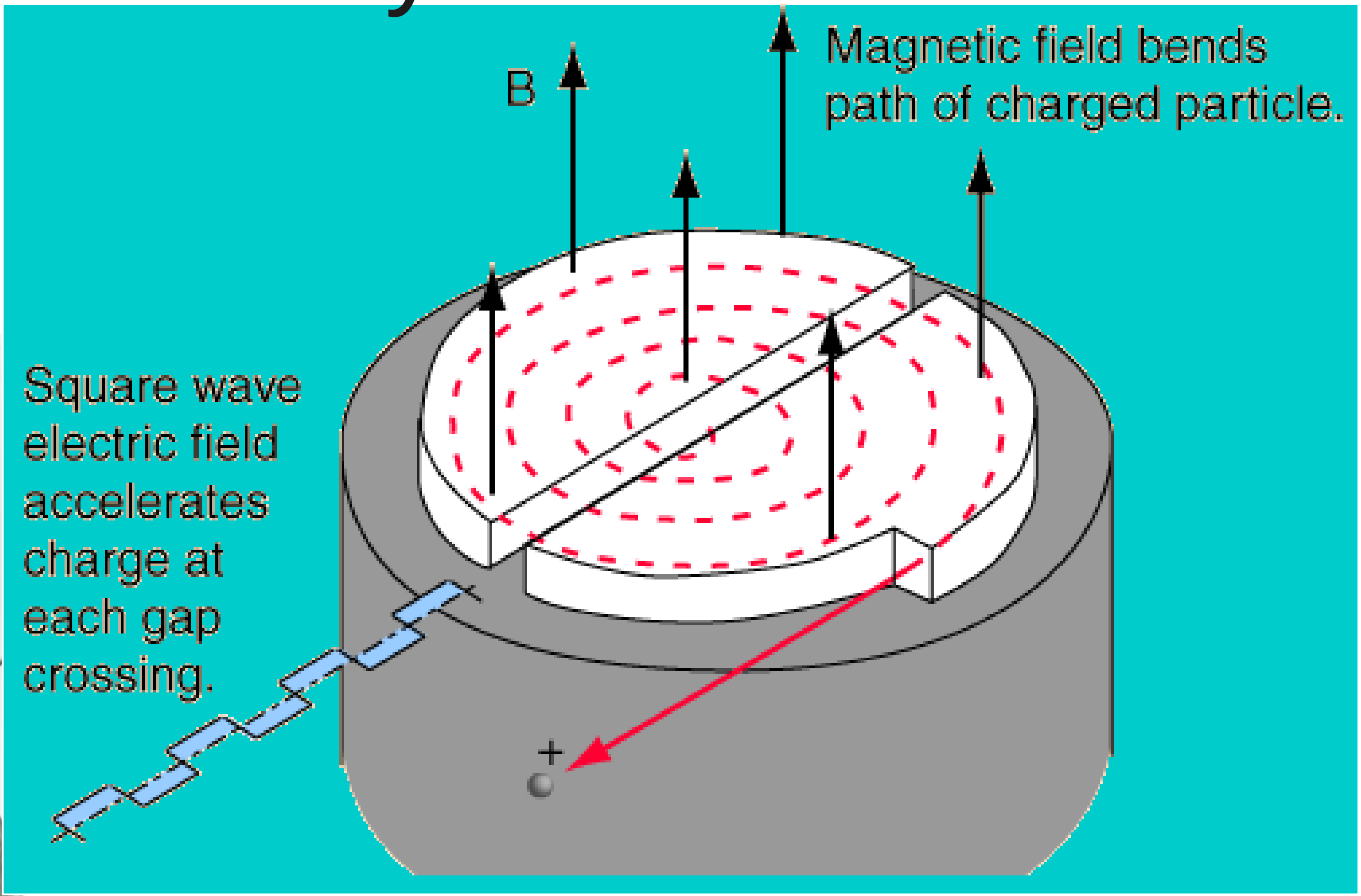
- Only AC

The cyclotron principle

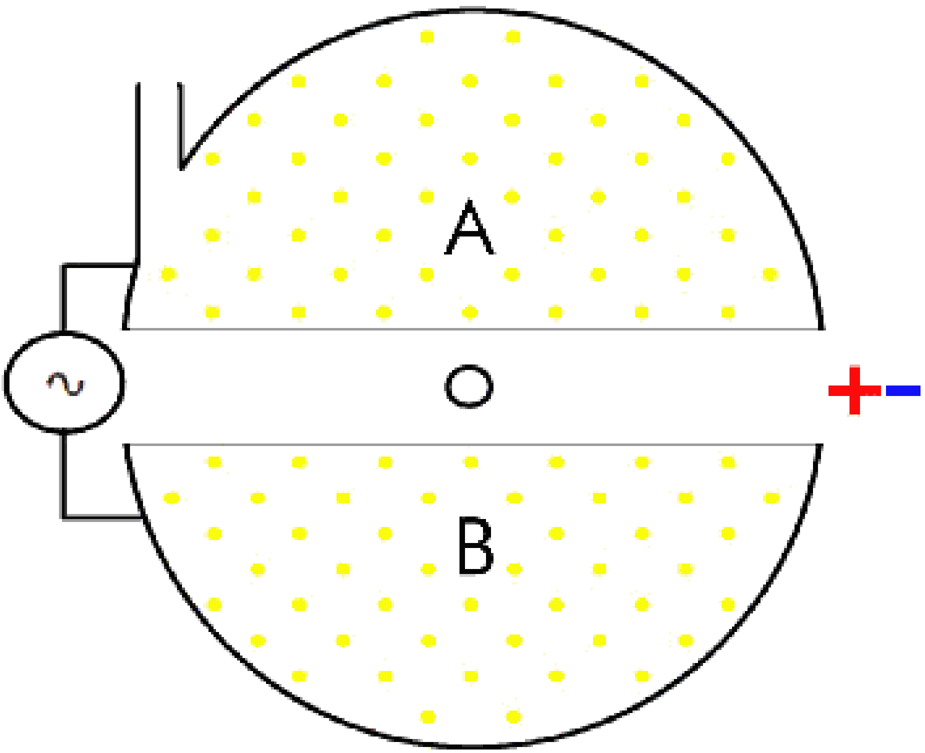
- For a non-relativistic charged particle going around in constant ring: $mv = qBR$
- What is the frequency of turns?
- Answer: $f = \frac{qB}{2\pi m}$
  - NB! does not depend on R

Cyclotron




B
Magnetic field bends
path of charged particle.
Square wave
electric field
accelerates
charge at
each gap
crossing.
+

Cyclotron animation



- http://www.aip.org/history/lawrence/images/epa-animation.gif

The Nobel Prize in Physics 1939
Ernest Lawrence

The Nobel Prize in Physics 1939

Ernest Lawrence

Ernest Orlando
Lawrence

The Nobel Prize in Physics 1939 was awarded to Ernest Lawrence *"for the invention and development of the cyclotron and for results obtained with it, especially with regard to artificial radioactive elements"*.

“Classic” Cyclotrons

Chicago, Berkeley, and others had large Cyclotrons (e.g.: 60” at LBL) through the 1950s

Protons, deuterons, He to ~20 MeV

Typically very high currents, fixed frequency

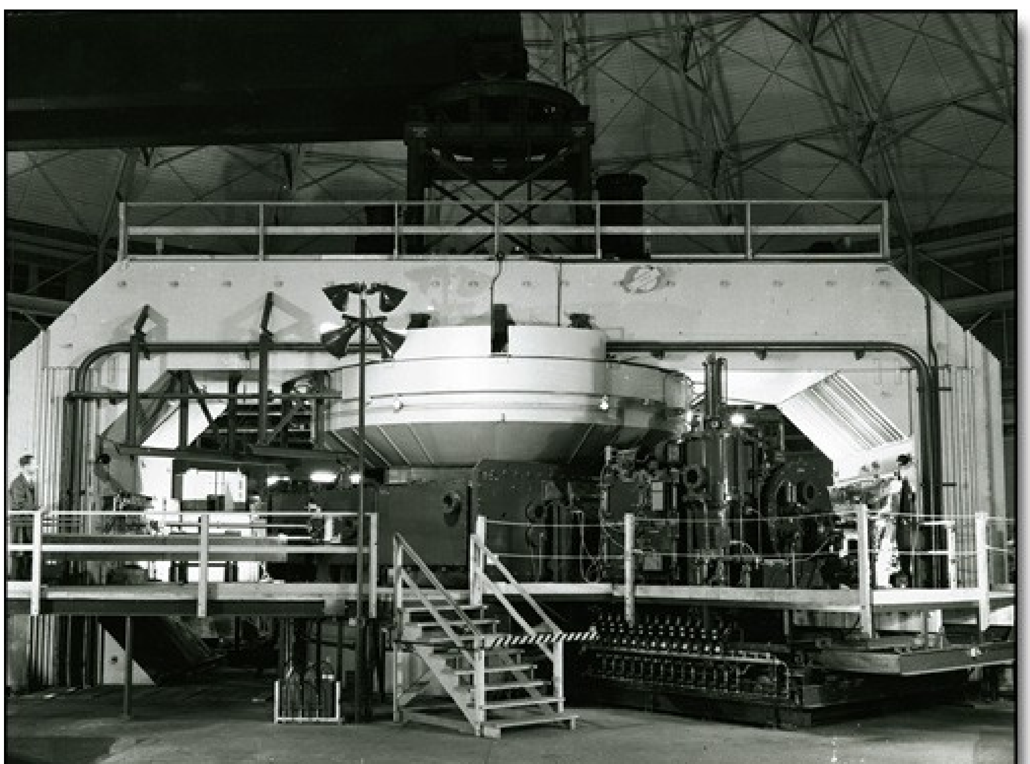
$$B[T]\cdot R[m]=0.3\cdot p[GeV/c]$$

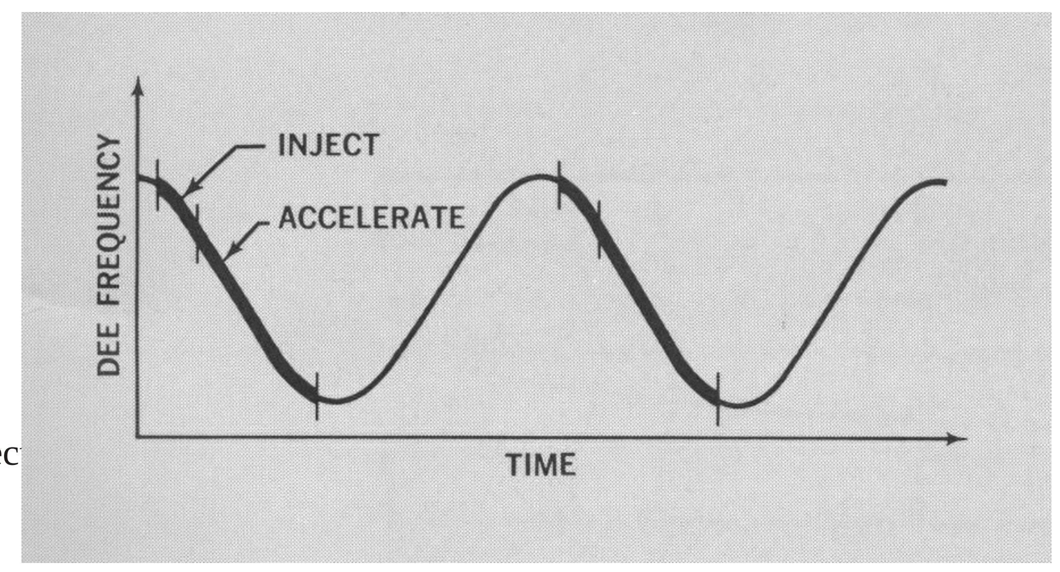
$$\omega=\frac{e}{m}\cdot B$$

Higher energies limited by shift in revolution frequency due to relativistic effects. Cyclotrons still used extensively in hospitals.

Synchrocyclotron

- Fixed "classic" cyclotron problem by adjusting "Dee" frequency.
- No longer constant beams, but rather injection+acceleration
- Up to 700 MeV eventually achieved





Other alternative to solve relativistic problem

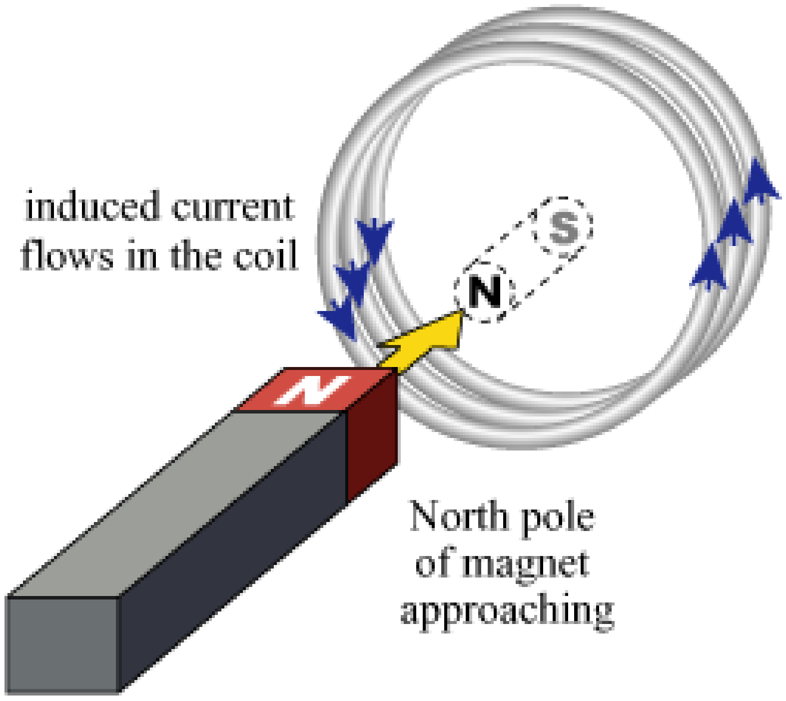
- One also has solution where one modifies B(r) to take into account relativistic effects
- The advantage is that then one can still have continuous beam

Betatron: an outsider

- The betatron was developed as a circular accelerator for electrons (where the cyclotron fails due to the relativistic effects)
- “A betatron is a cyclic particle accelerator developed by Donald Kerst at the University of Illinois in 1940 to accelerate electrons, but the concepts ultimately originate from Rolf Widerøe, whose development of an induction accelerator failed due to the lack of transverse focusing. Previous development in Germany also occurred through Max Steenbeck in the 1930s.”, http://en.wikipedia.org/wiki/Betatron

Betatron: principle

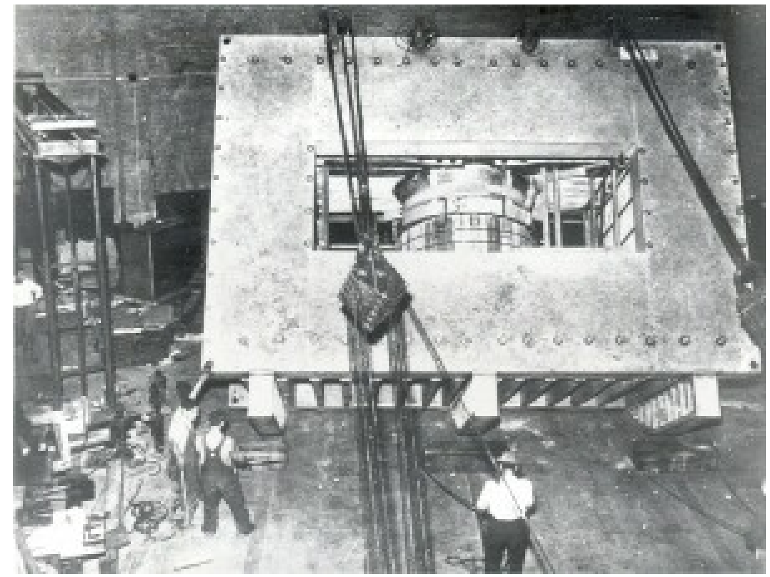
- In a betatron the acceleration field is the induced electric field from varying the magnetic field (time dependence)
- Note that the same magnetic field is used to confine the particles!



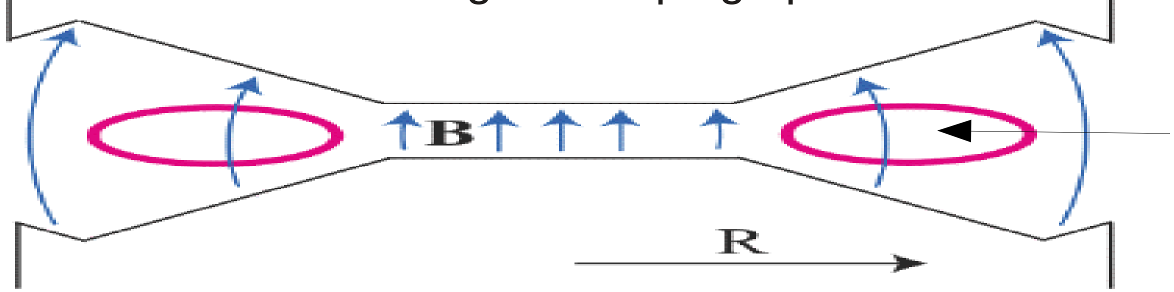
How does it look and work

Dobald Kerst with first betatron

300 MeV betatron ~1950



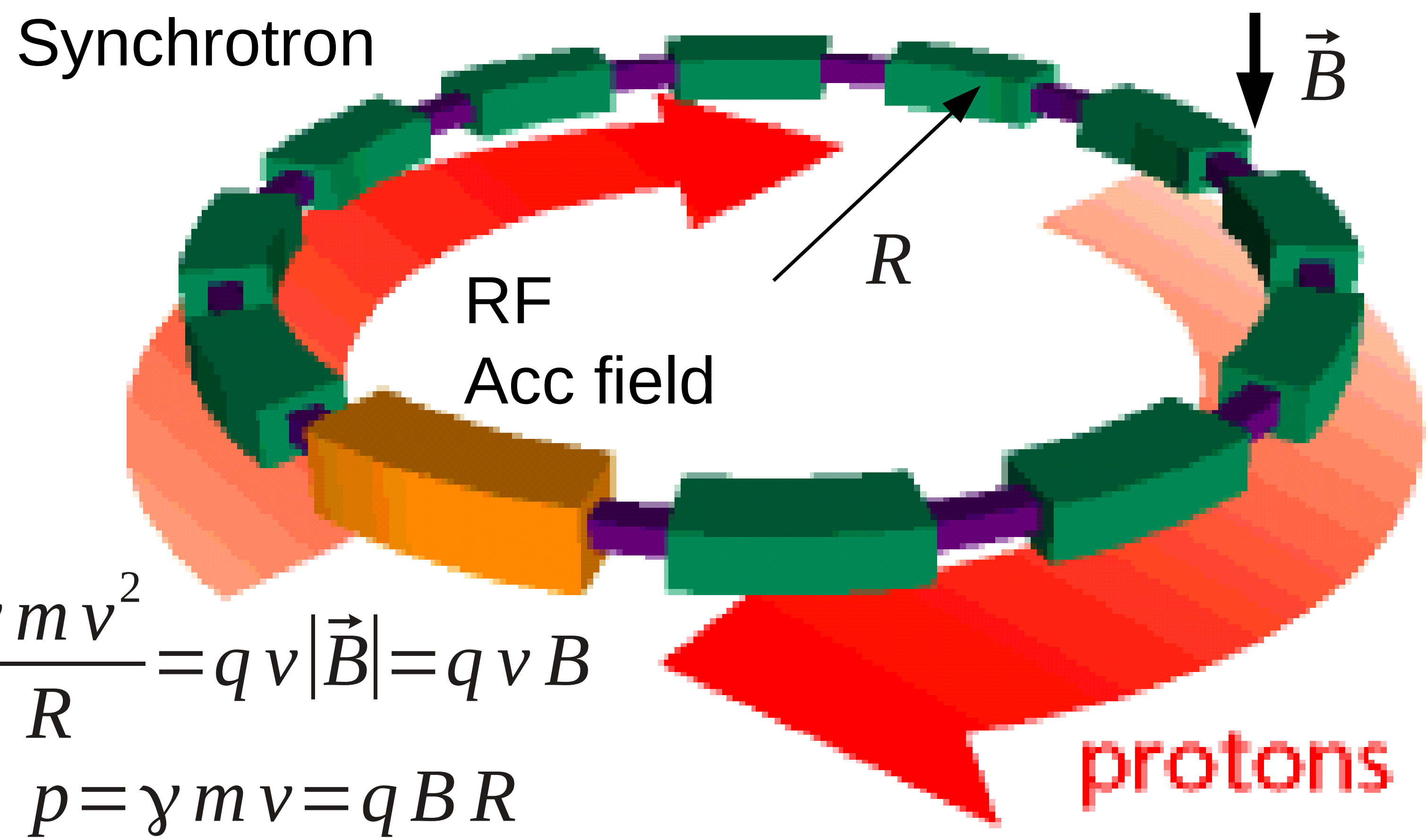
Electromagnet ramping up field



Electron tube
Circular tracjectory

Nice animation:
http://einstein1.byu.edu/~masong/emsite/S4Q50/betatron.html

Towards the Synchrotron



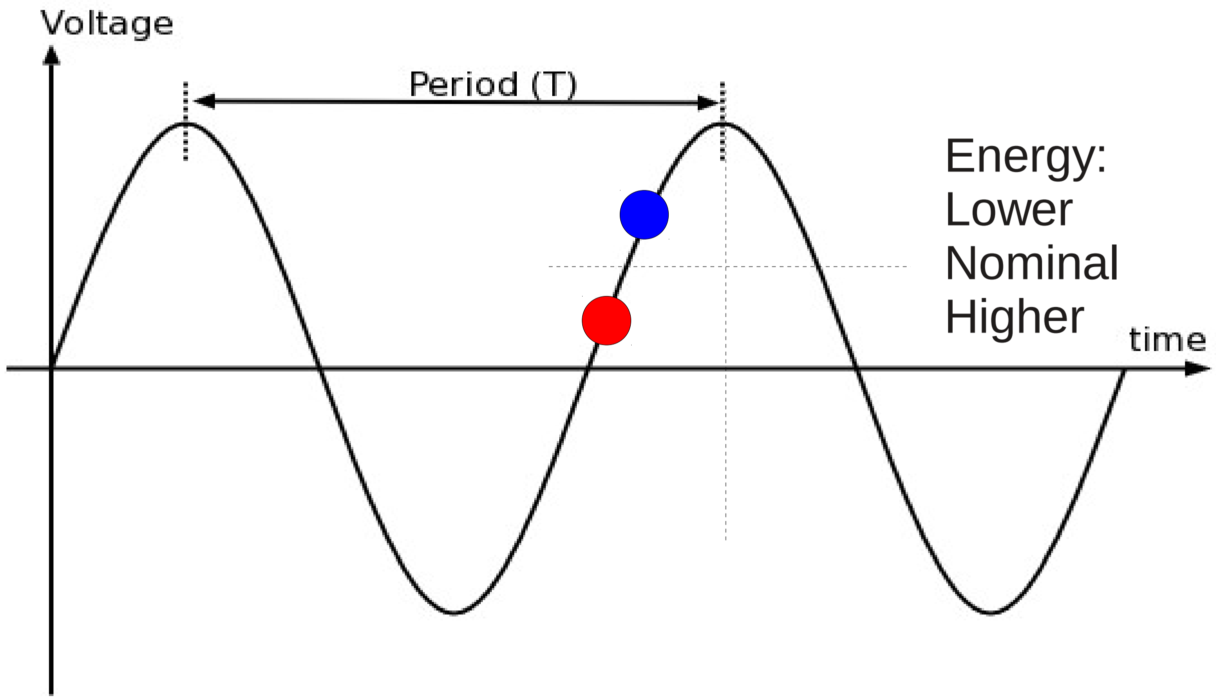
$$\frac{\gamma m v^2}{R} = q v |\vec{B}| = q v B$$

$$p = \gamma m v = q B R$$

Dipole magnet give circular motion

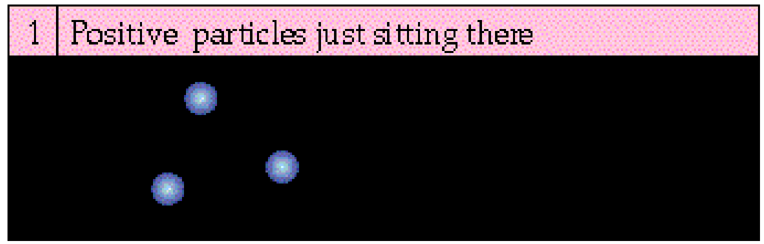
Acceleration in E-field

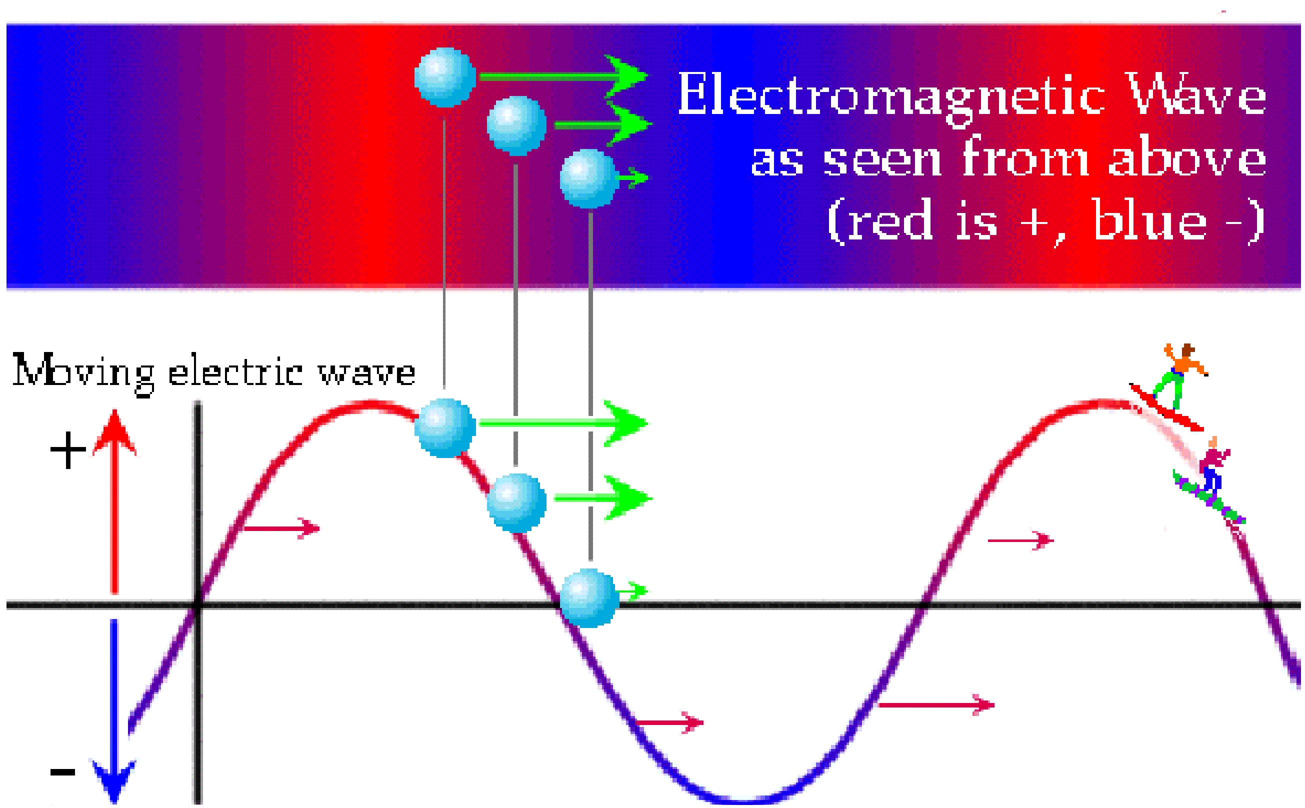
How the AC acceleration helps to focus the beam in bunches



- We want to align the beam so that slower particles sees a bigger acceleration voltage than faster particles
- In that way the longitudinal momentum dispersion in the beam will be reduced

The particles are “surfing” the acceleration wave



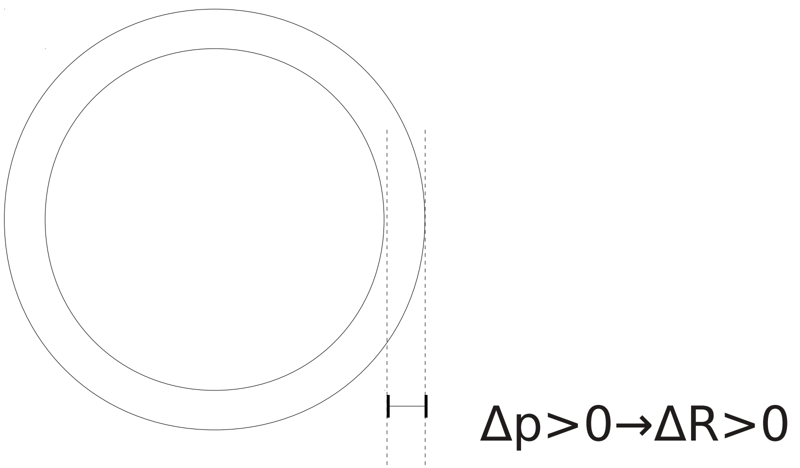


Problem

- What happens when v~c?
  - Why does the more energetic particles take longer to go around?!
- Answer:
  - Larger radius (longer path length) for same B field!

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

$$f = \frac{v}{2\pi R} = \frac{qBc}{2\pi p}$$



The transition energy

- The energy at which the higher (lower) energy particles in the beam starts to go slower (faster) around than nominal energy particles is called the transition energy
- Need to “invert” longitudinal focusing = shift half a wavelength
  - Technically challenging as beam focus diverges