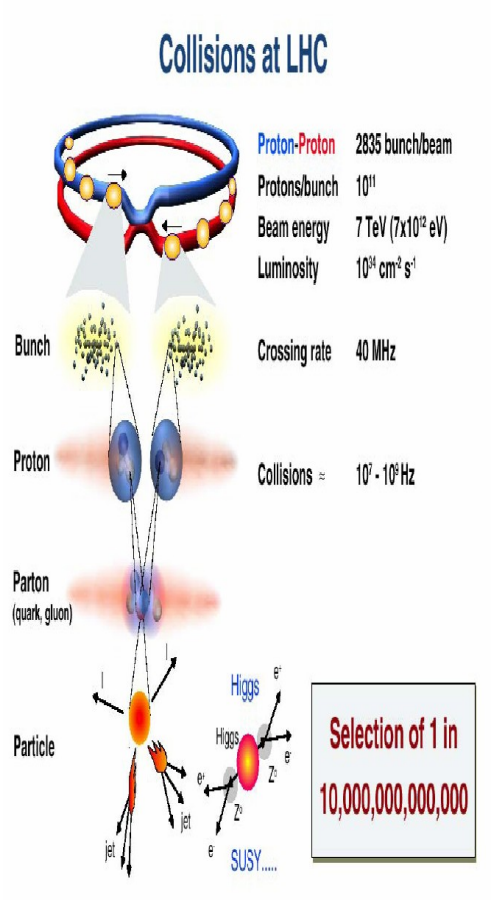
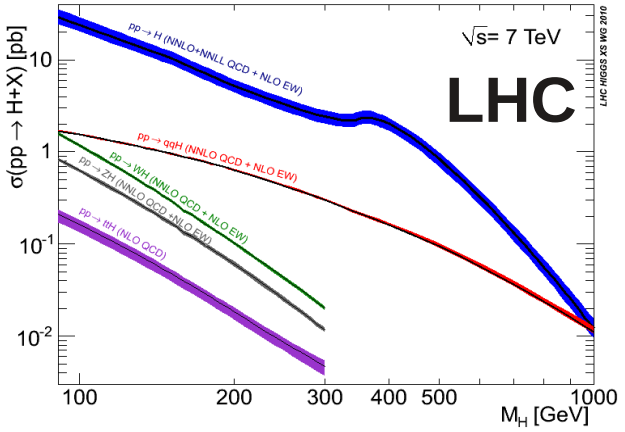
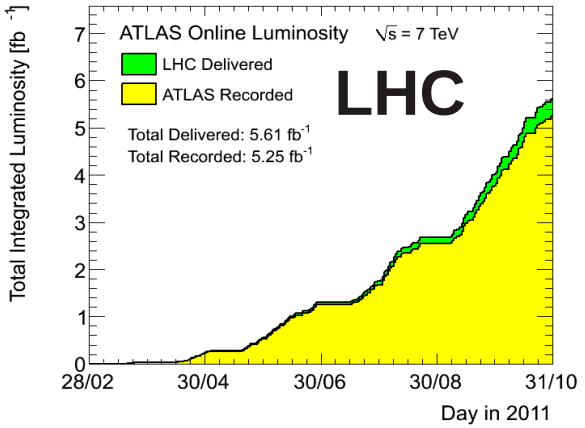
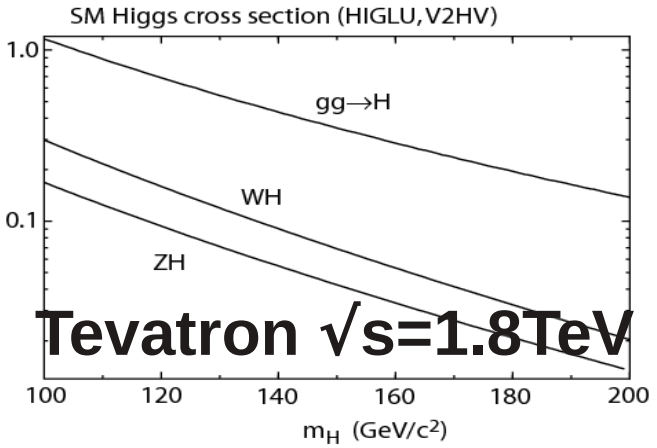
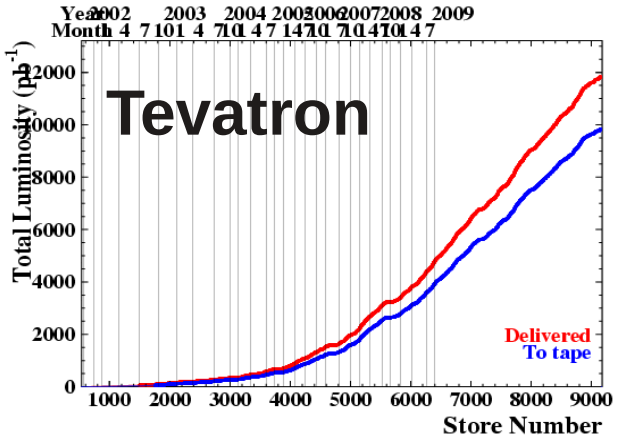
Summary of lecture 1 and 2: Main ingredients in LHC success









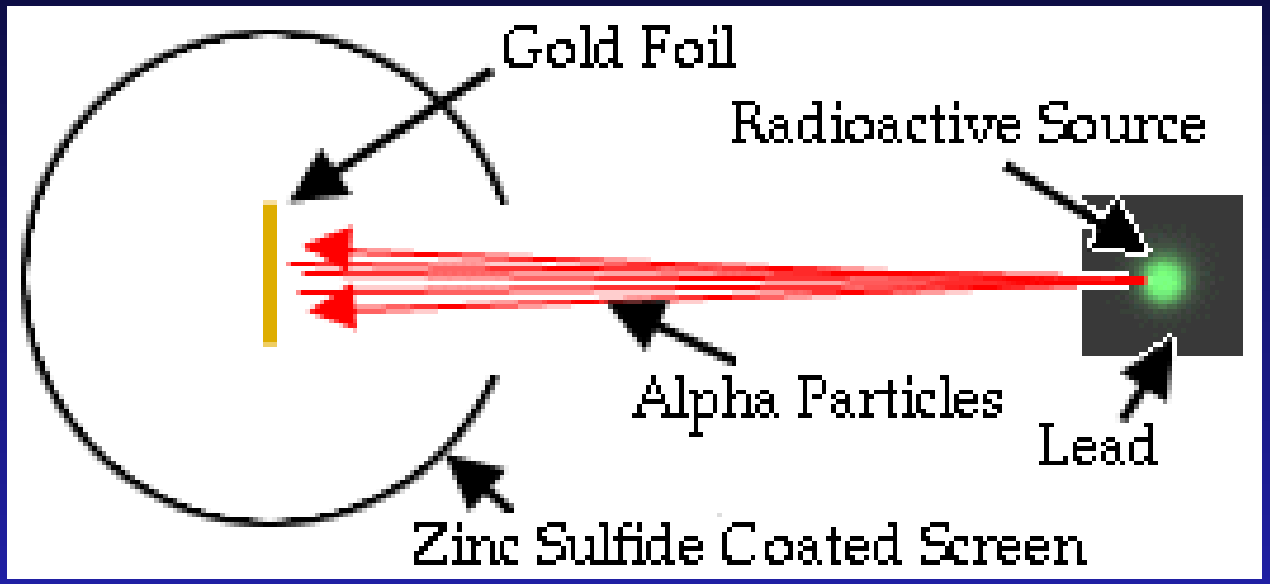


- **Energy** → 10 times higher cross section than Tevatron and integrated **luminosity** already ½ at end of 2011!

Lectures on accelerator physics

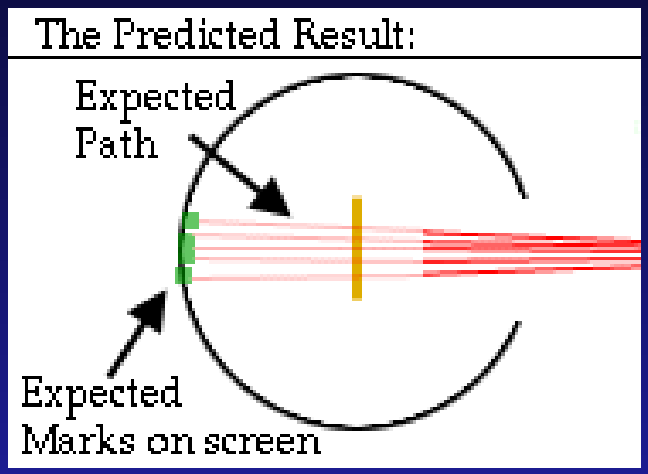
- Lecture 3 and 4: Examples
  - Examples of accelerators

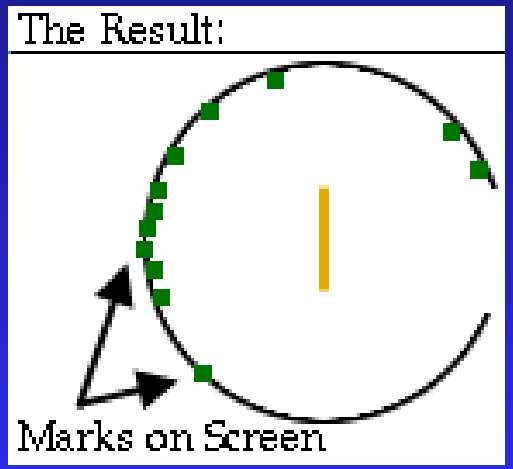
Rutherford's Scattering (1909)

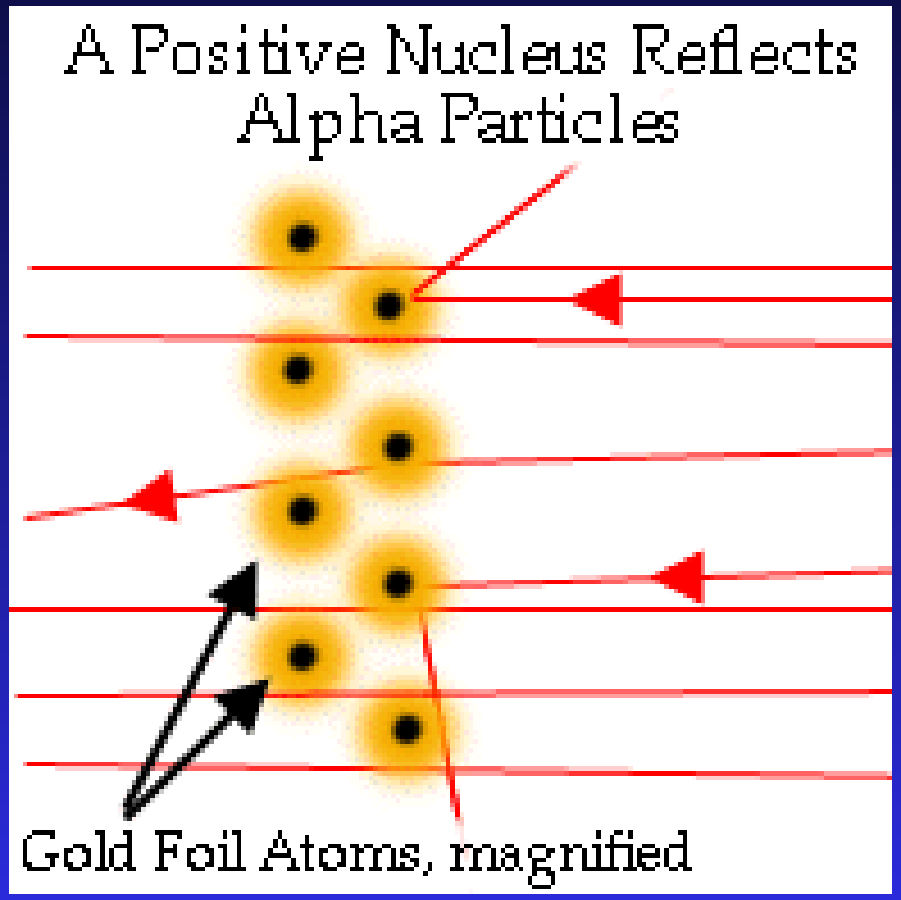


- Particle Beam
- Target
- Detector

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

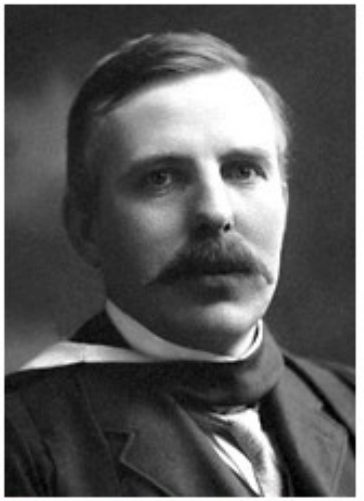
Did Rutherford get the Nobel Prize for this?

- 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 Dummies

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

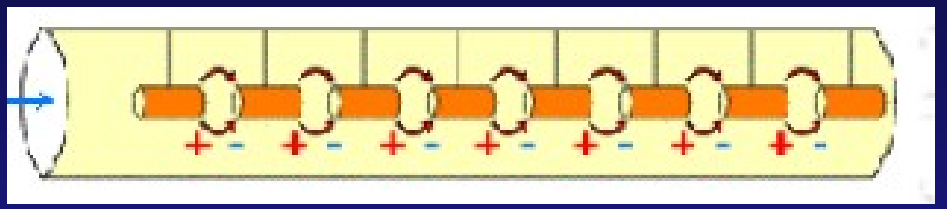
- Electric Fields

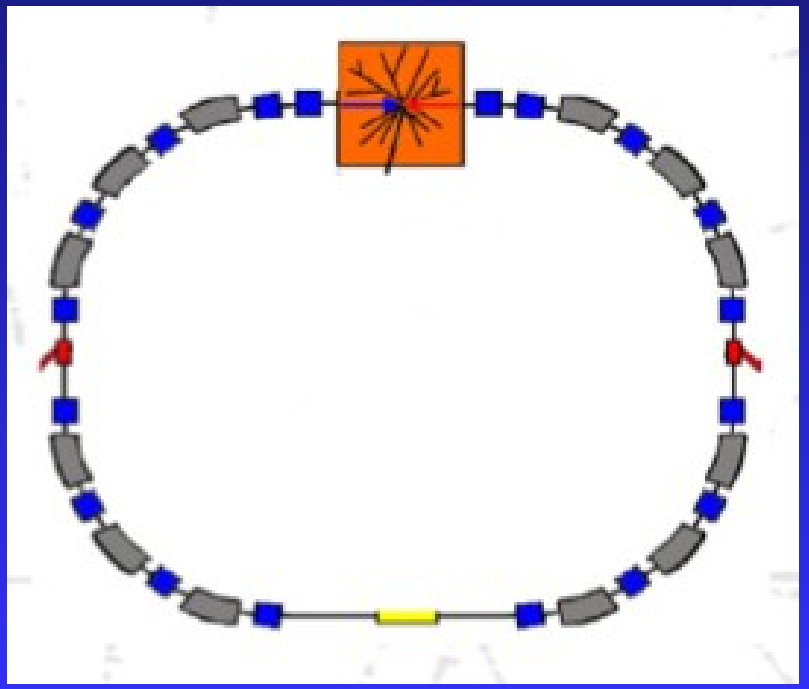
  ACCELERATES
  - Aligned with field
  - Typically need very high fields
- Magnetic Fields

  BENDS/CONFINES/FOCUSES
  - Transverse to momentum
  - Cannot change |p|

Circle or Line?

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





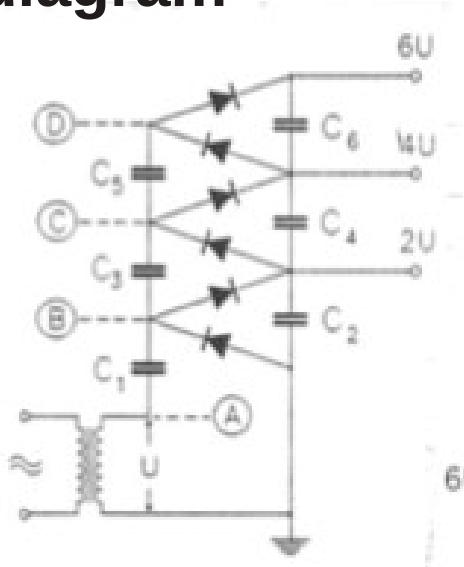
Linear accelerators

- DC
- AC

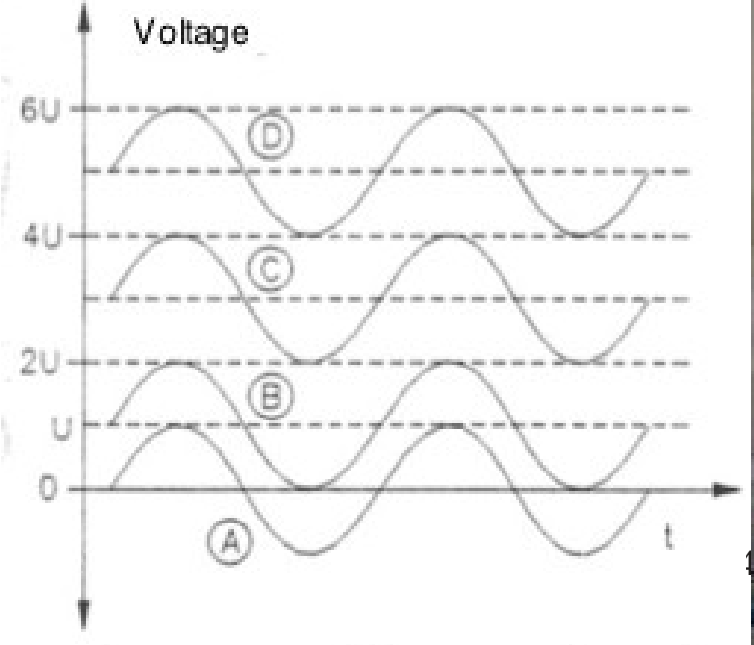
Cockroft-Walton - 1930s

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

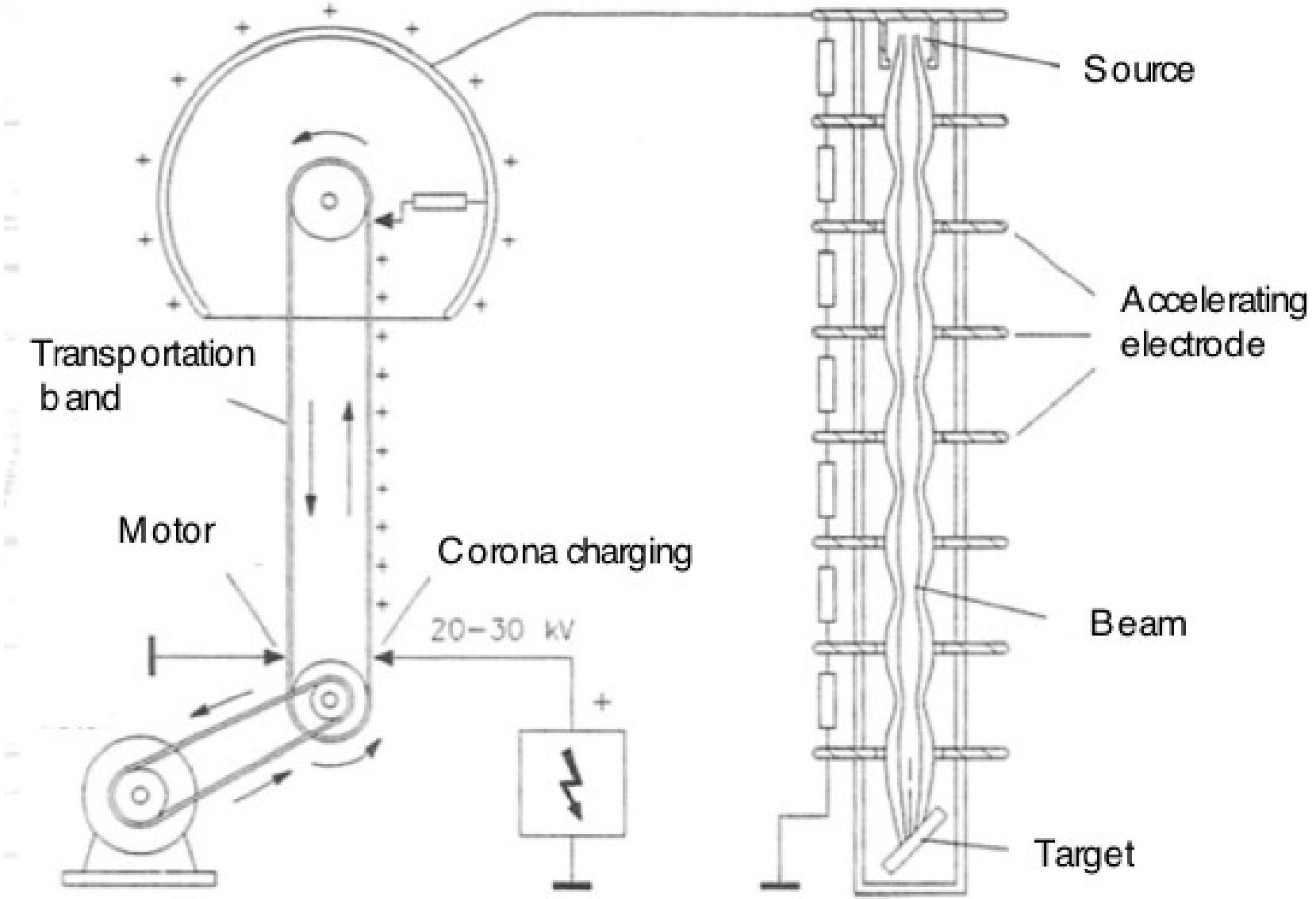
Ernest T.S. Walton

Sir John Douglas Cockcroft

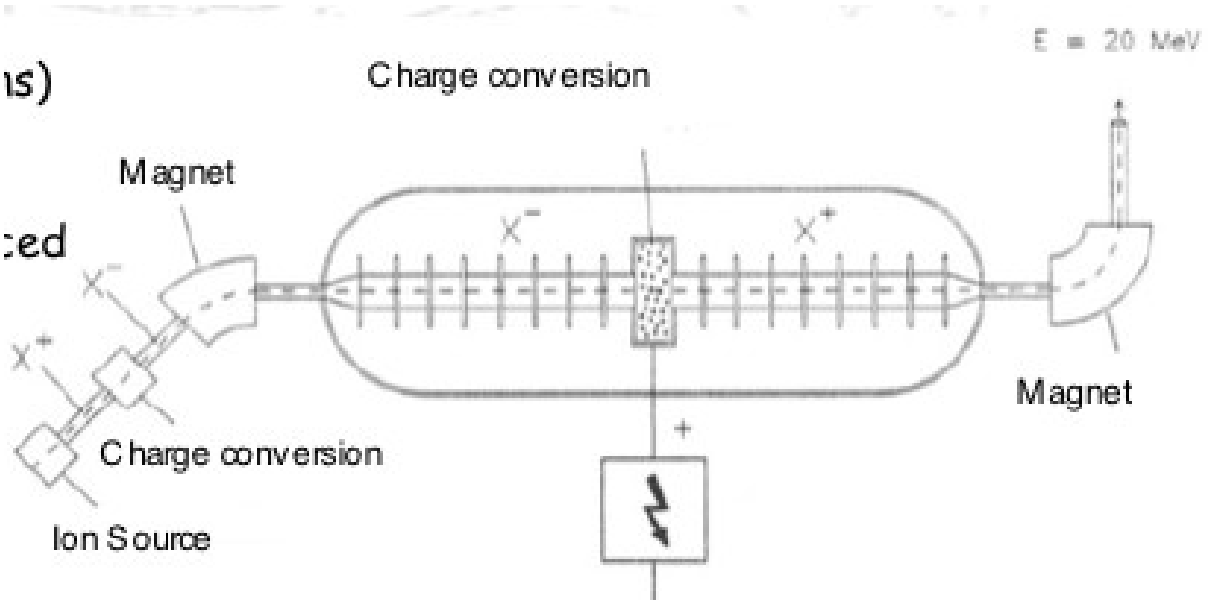
Ernest Thomas Sinton Walton

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

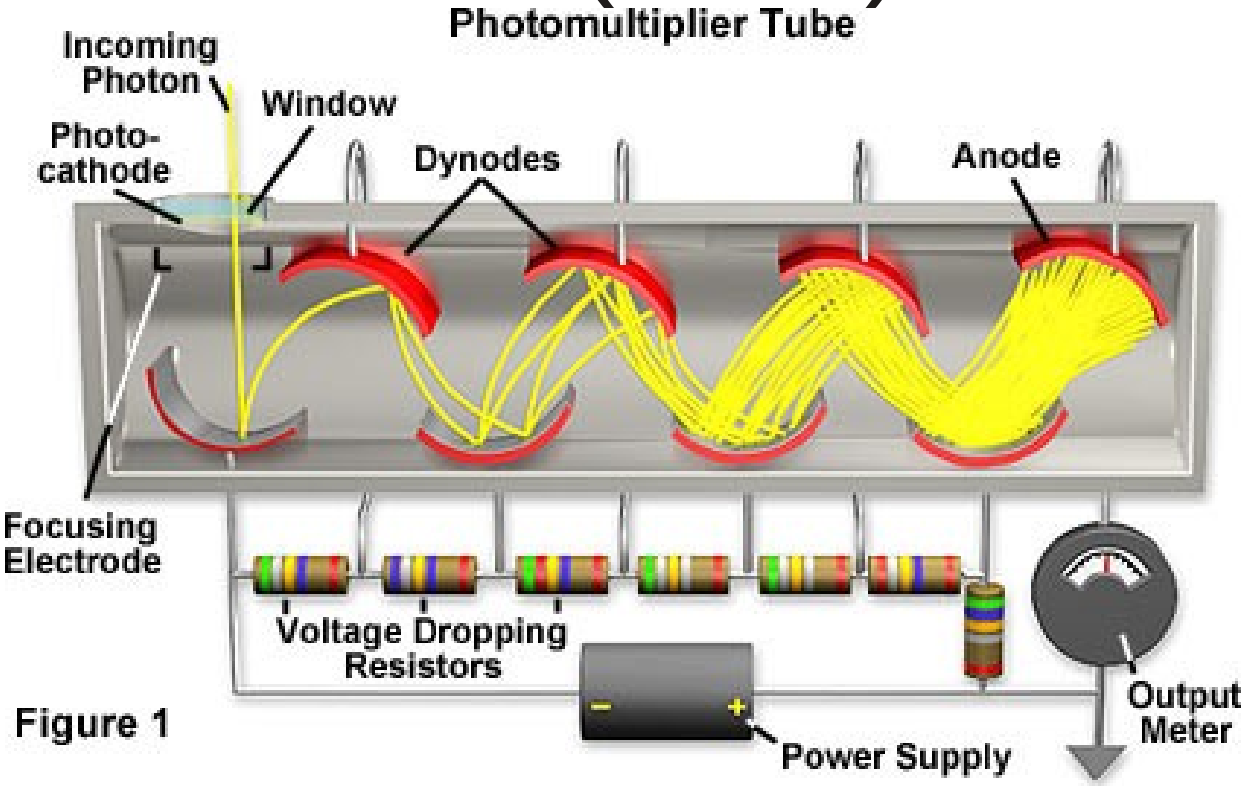


First large Van-de Graaff

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)



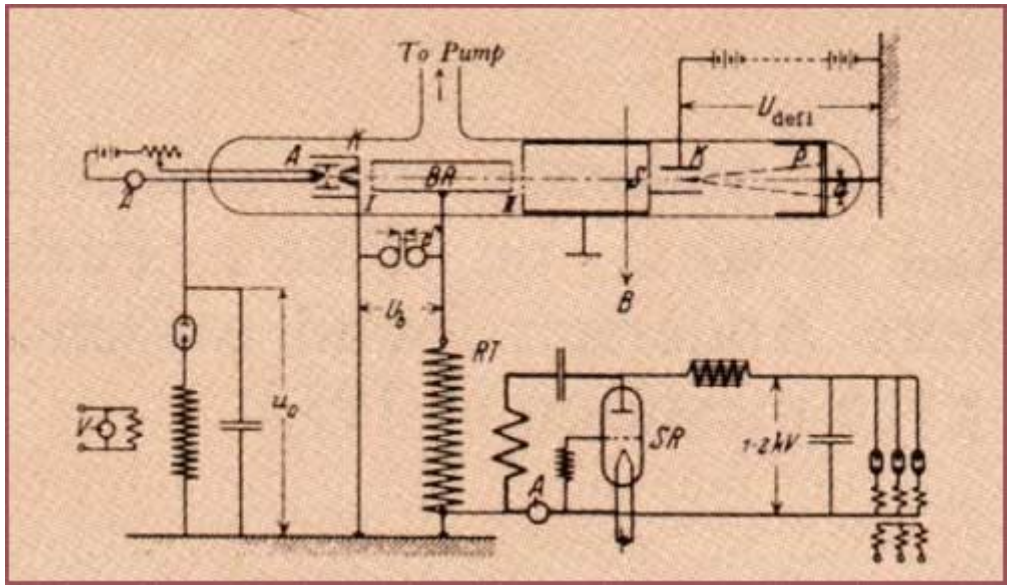
- Photons are converted (with loss) to electrons at the photocathode
- Electrons are amplified in several steps

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

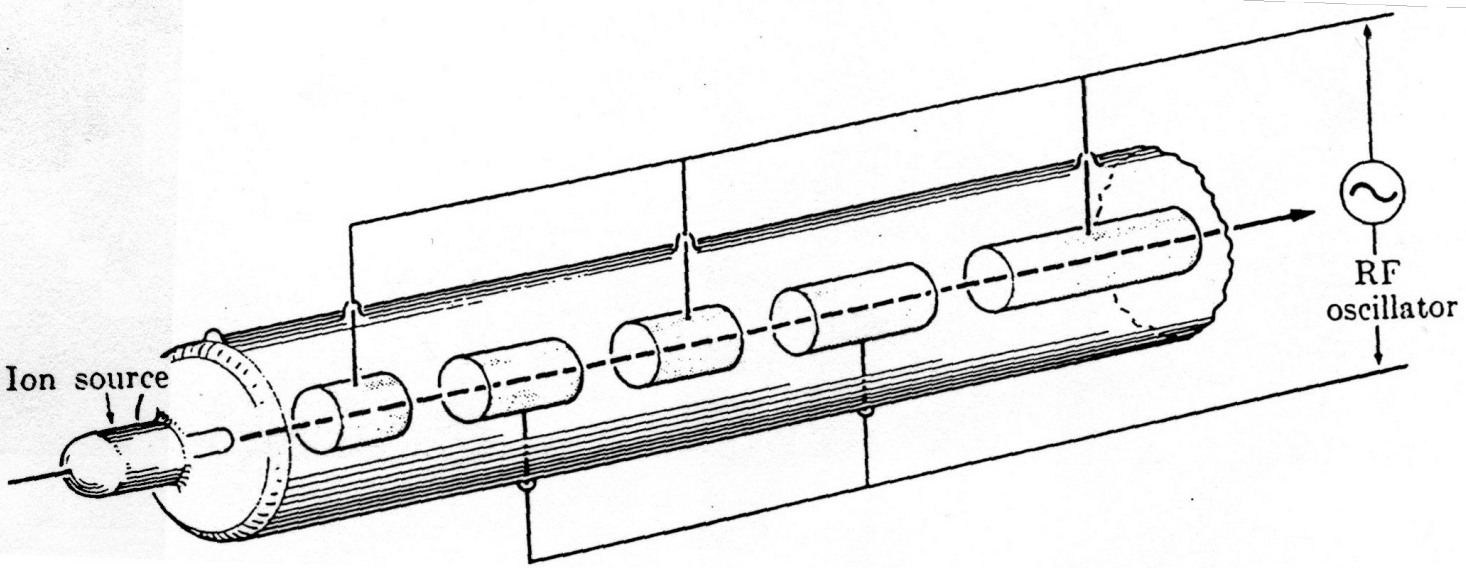
Linear Accelerators

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

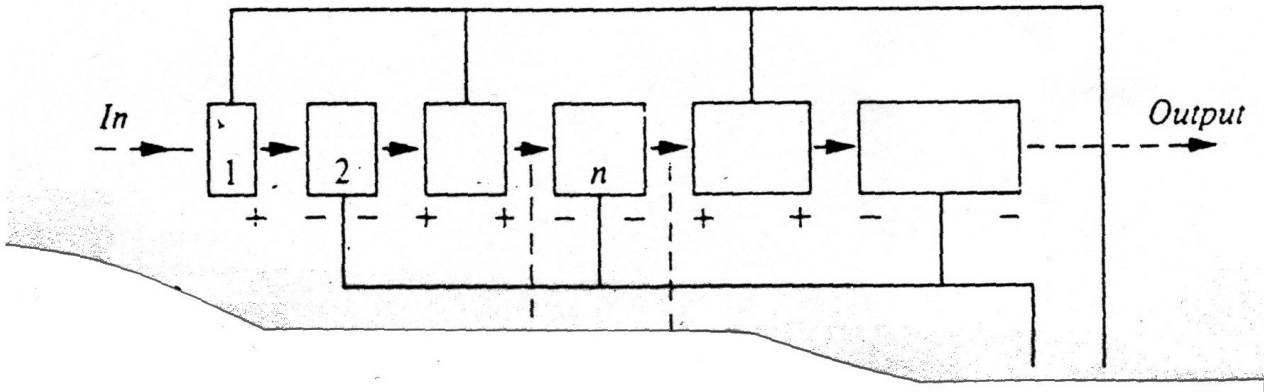


Rolf Wideröe as a young man.

LINAC principle I



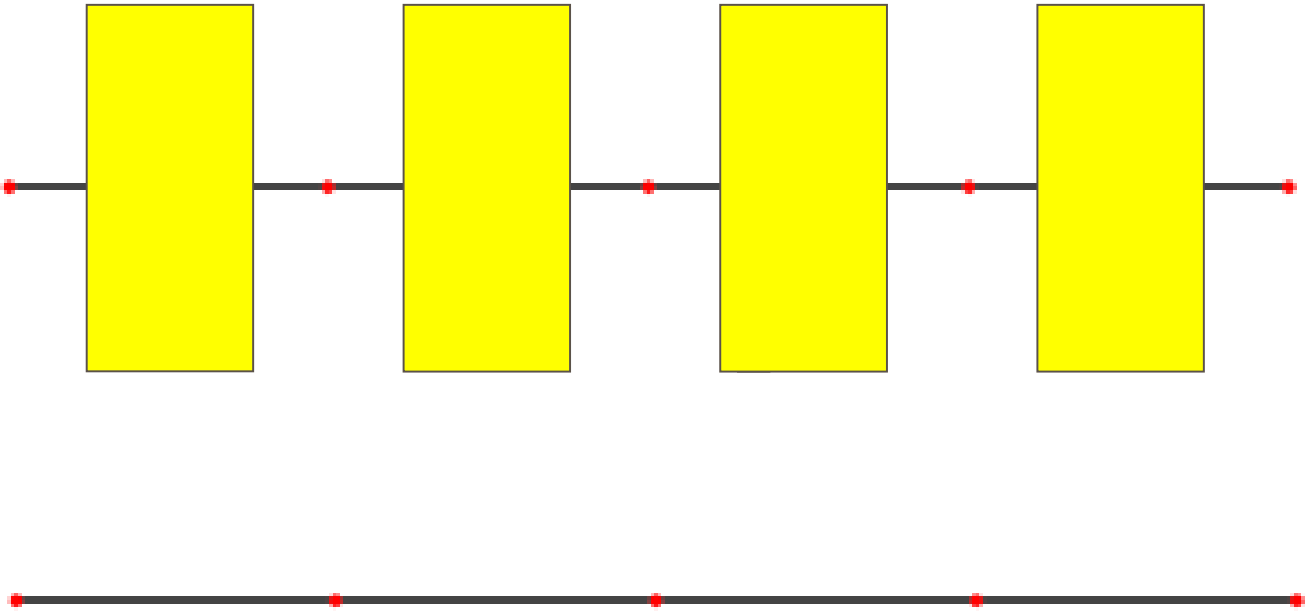
V



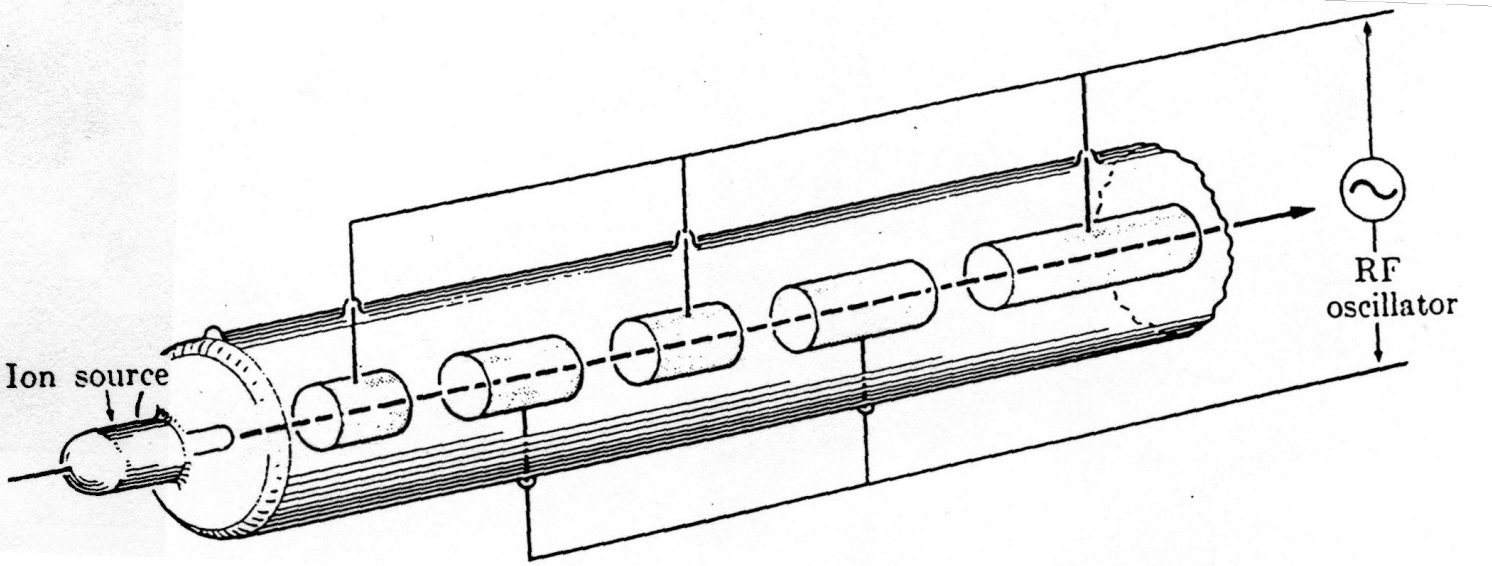
LINAC principle II

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

Standing wave



LINAC principle III



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

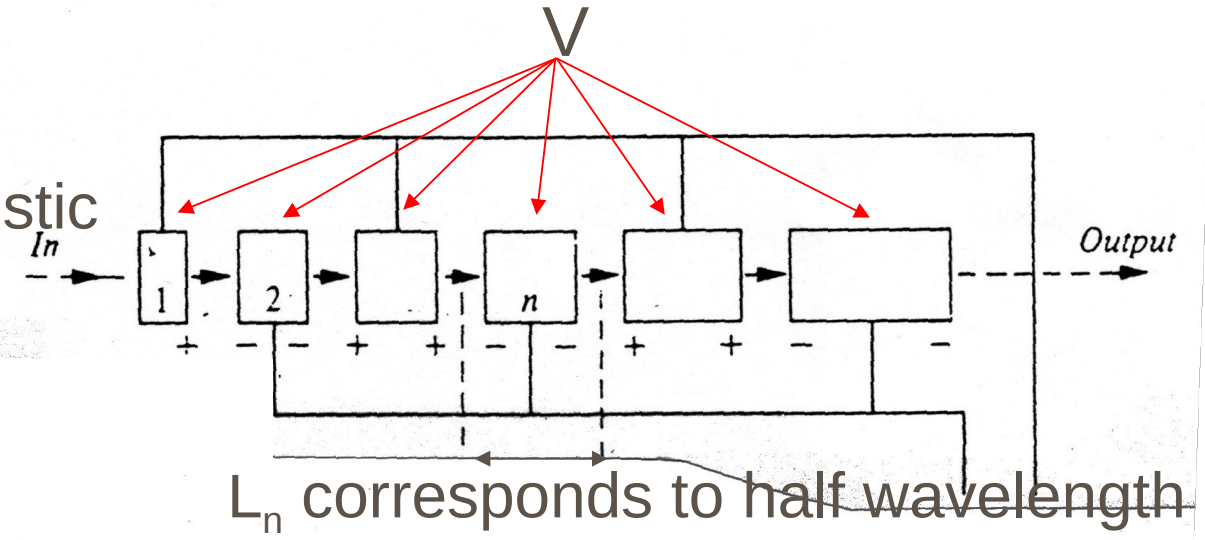
Calculate Ln assuming v(inital)=0 and vn non-relativistic and AC frequency f:

Answer:

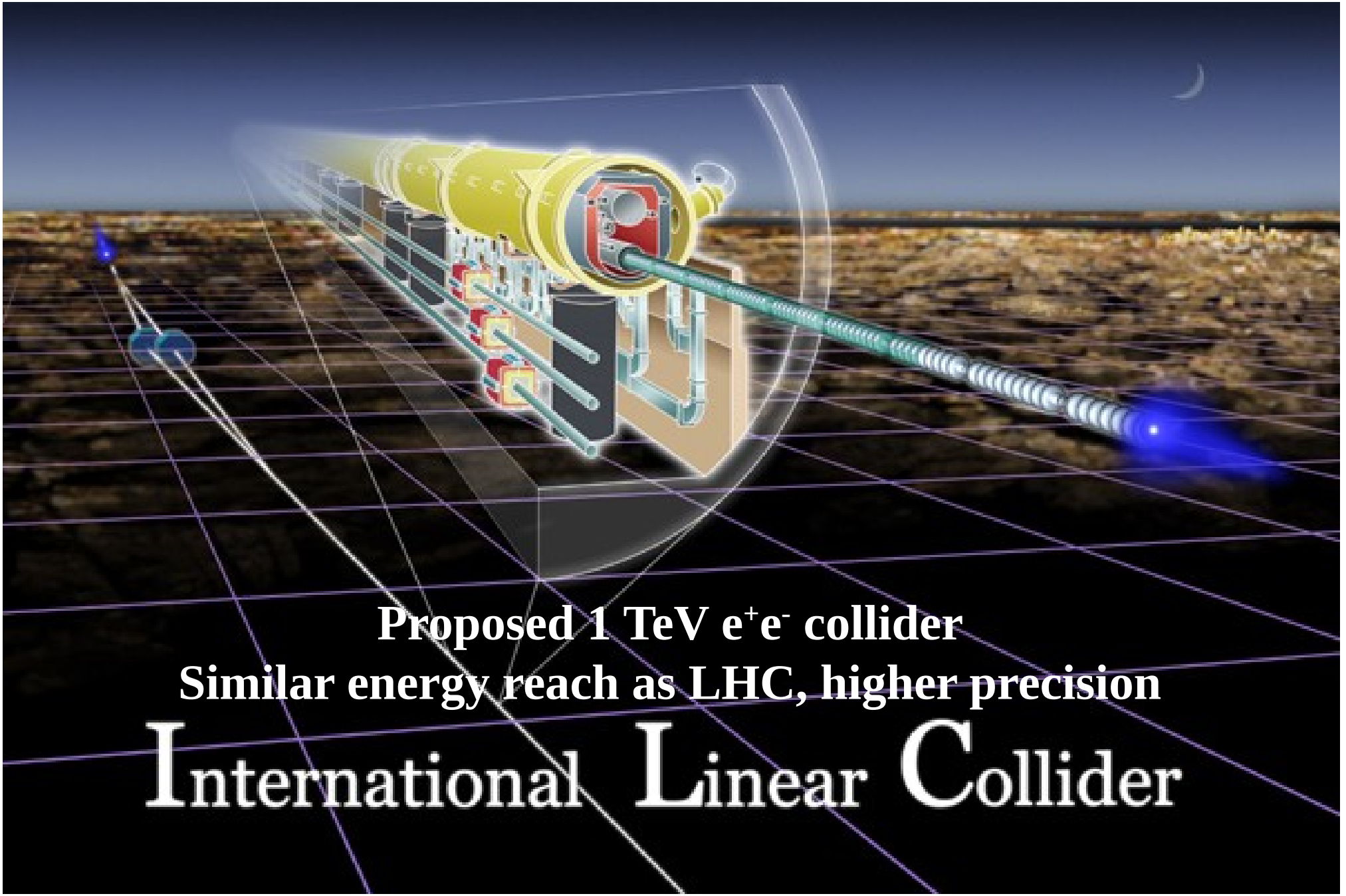
$v_n=\sqrt{2neV/m}$

$1/(2f)=L_n/v_n$ so

$L_n= 1/(2f)*v_n$



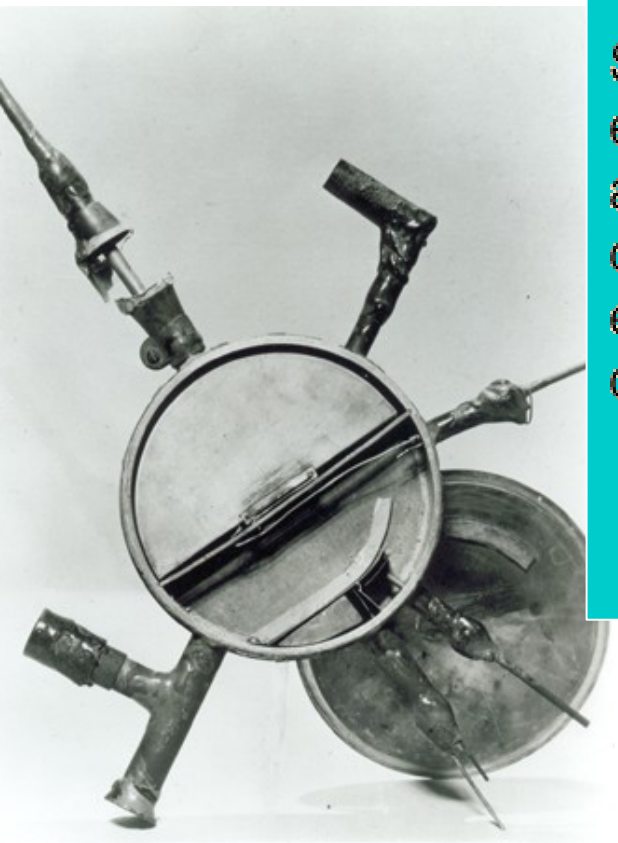
L_n corresponds to half wavelength

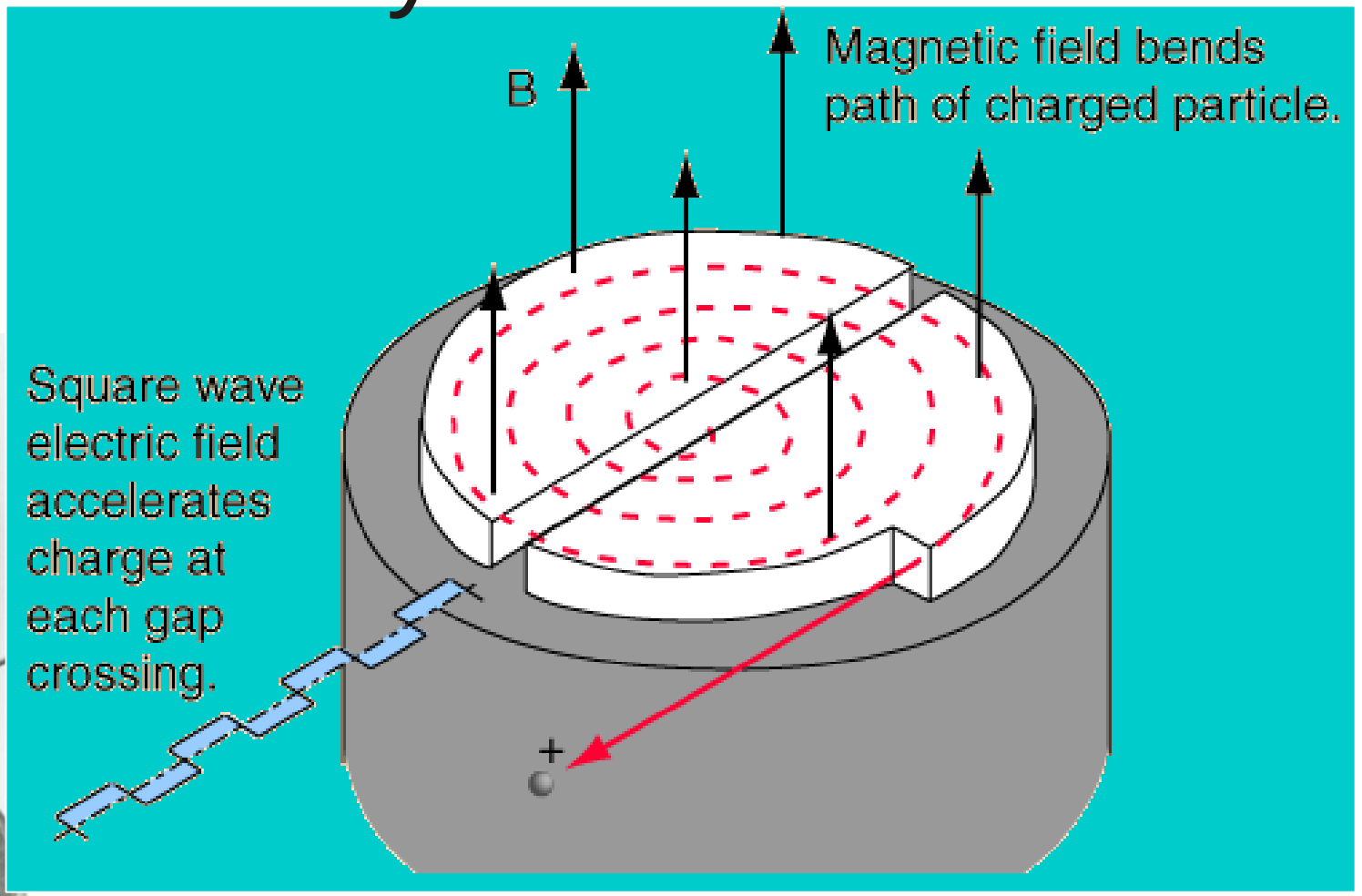

Proposed 1 TeV e^+e^- collider
Similar energy reach as LHC, higher precision
International Linear Collider

The cyclotron principle

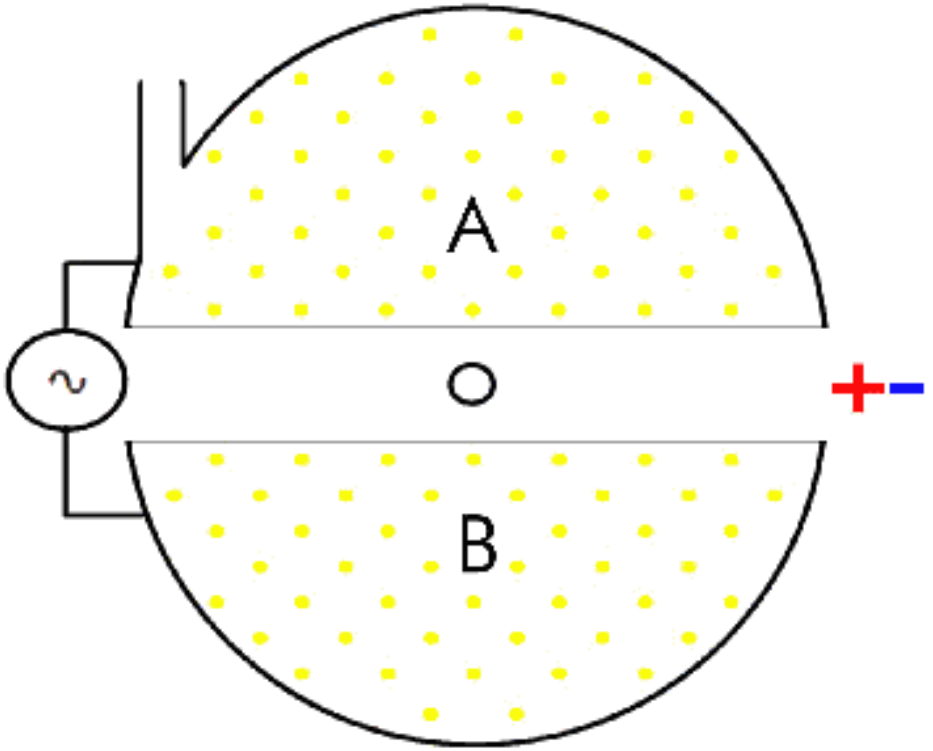
- For a non-relativistic charged particle going around in constant ring: $mv=qBR$
- What is the frequency of turns?
- Answer: $f=qB/(2\pi m)$
  - NB! does not depend on R

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

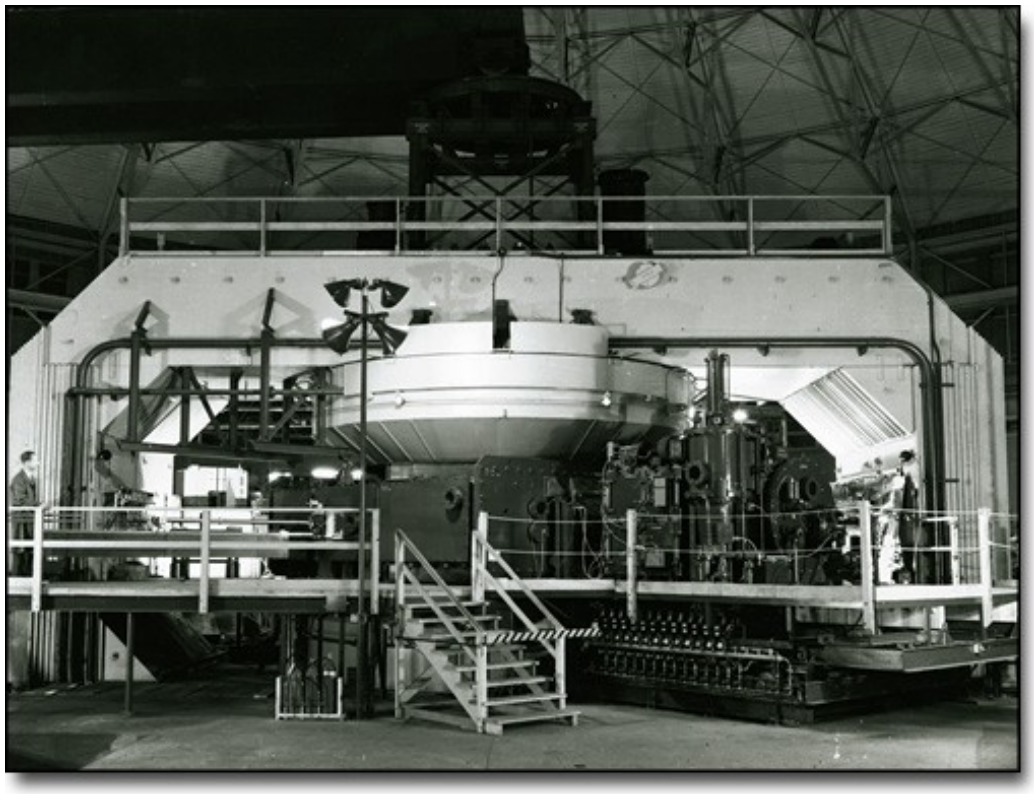
$$p[\mathrm{GeV}] = 0.3B[\mathrm{T}]\rho[\mathrm{m}]$$

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

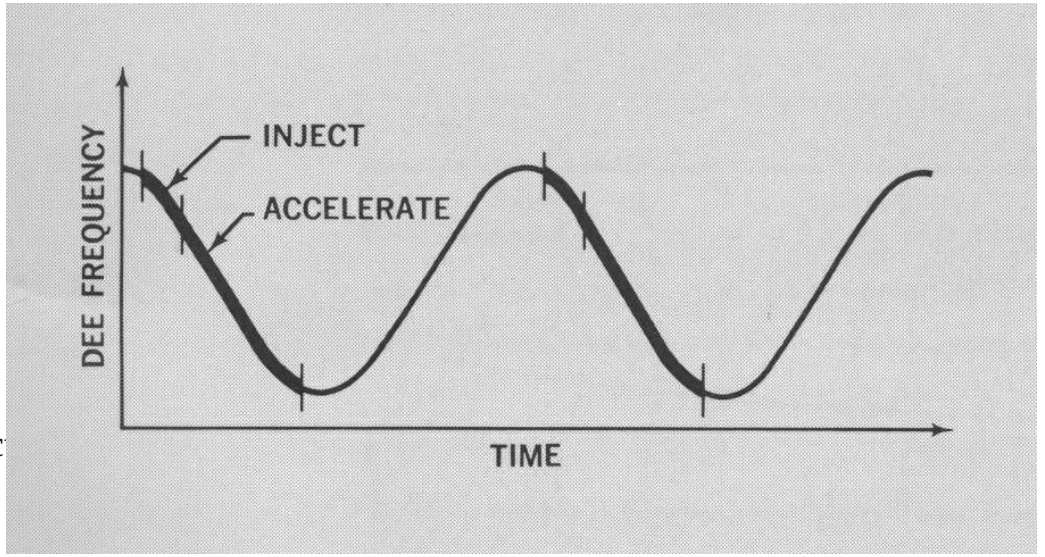
Higher energies limited by shift in revolution frequency due to relativistic effects. Cyclotrons still used extensively in hospitals.

Synchrocyclotron

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



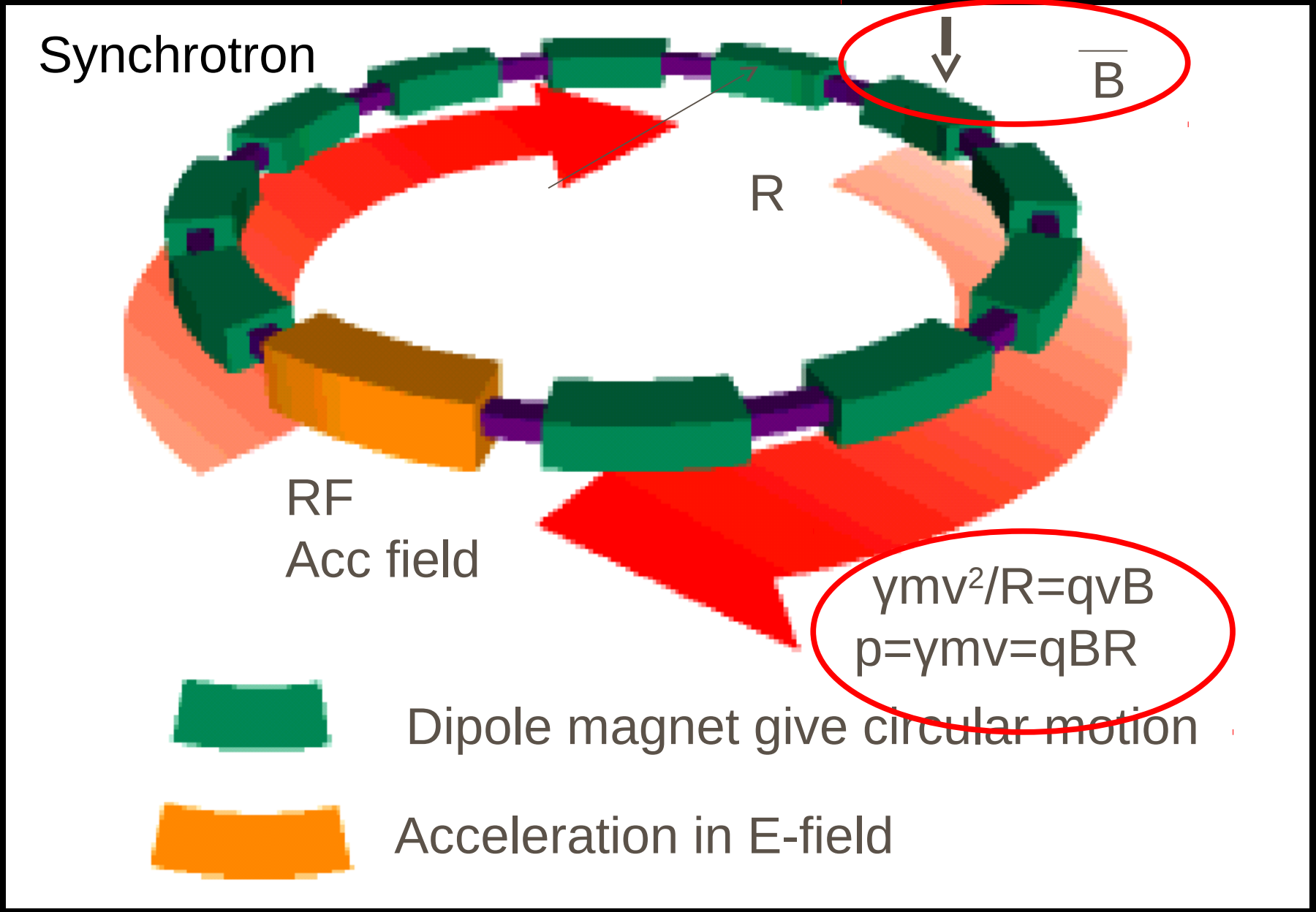
ec



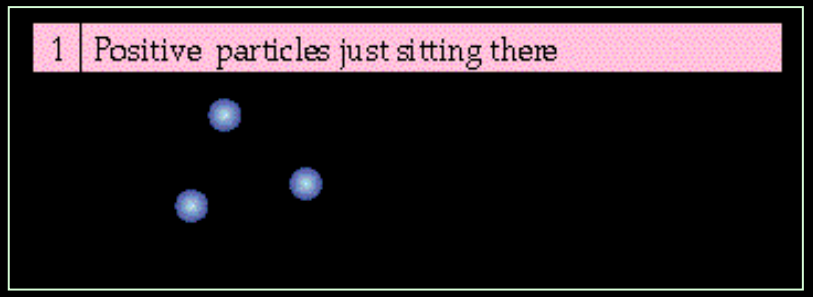
Other alternative to solve relativistic problem

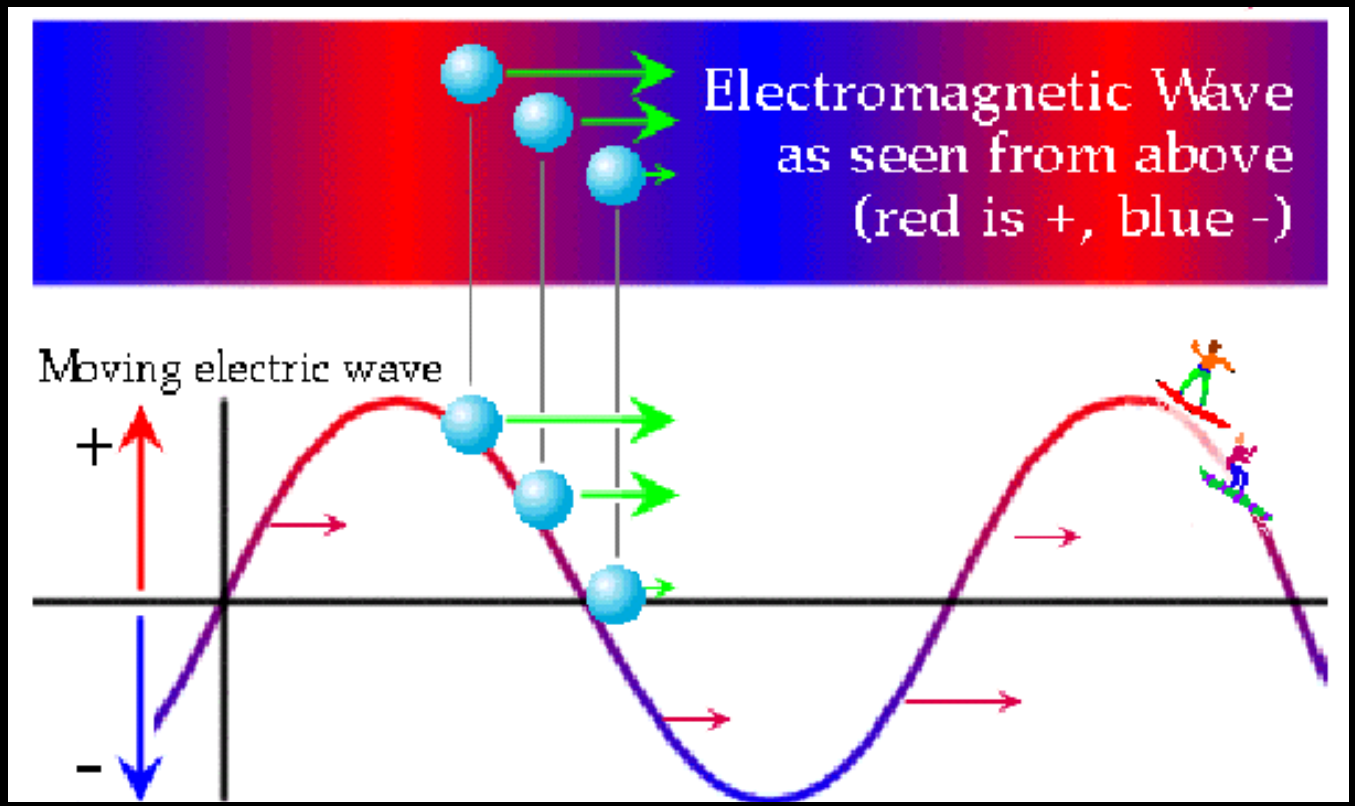
- One also has solution where one modifies B(r) to take into account relativistic effects
- The advantage is that then one can still have continuous beam

Towards the synchrotron

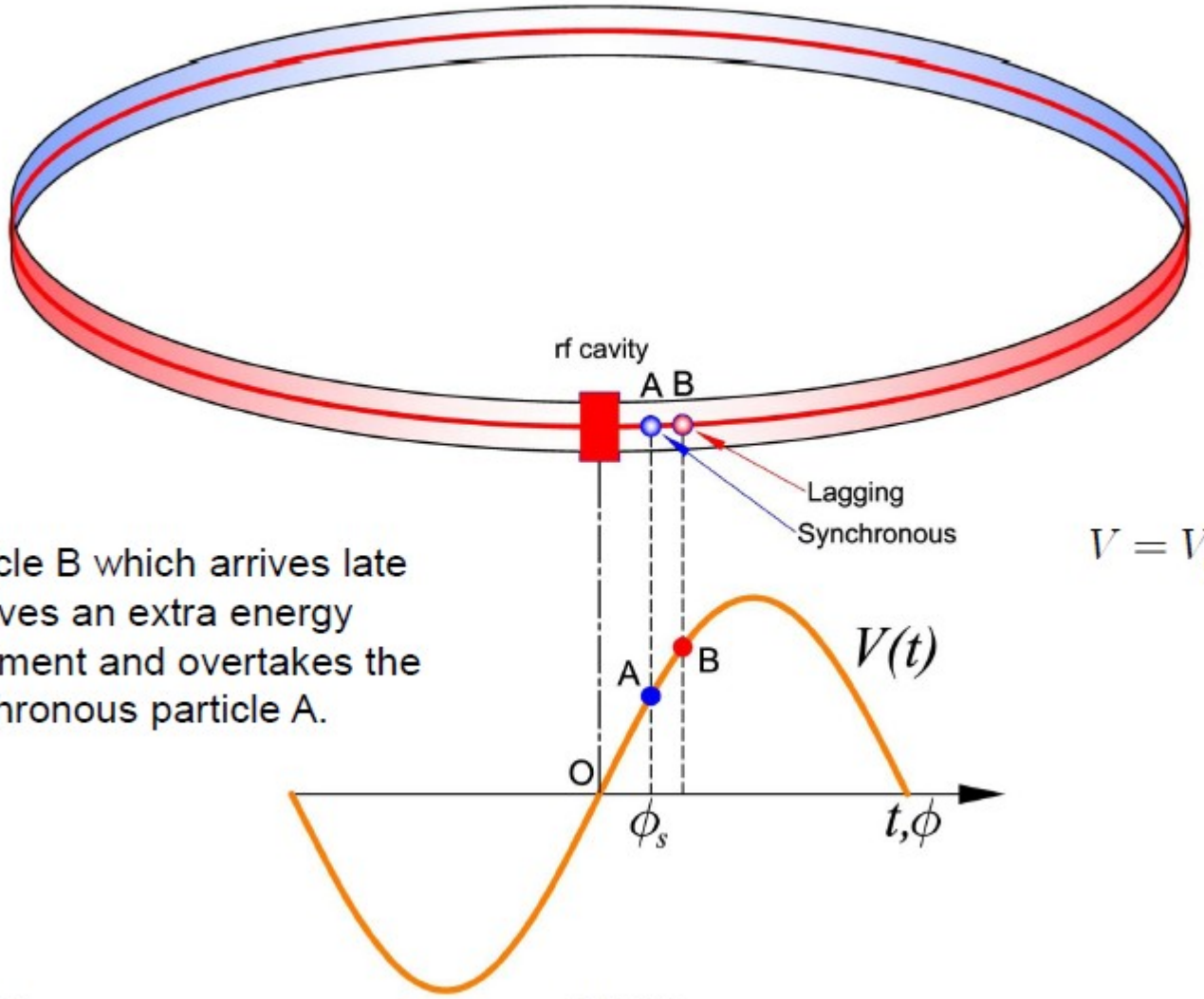


The alternating E-field keeps particles in bunches





LONGITUDINAL DYNAMICS



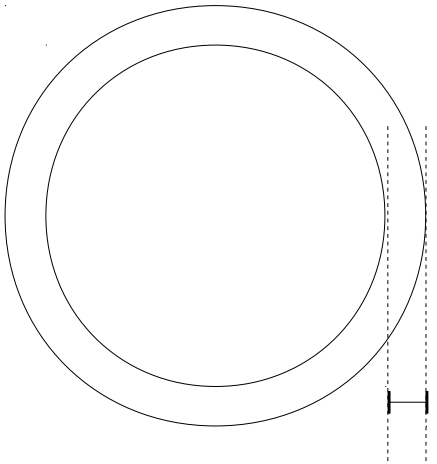
Particle B which arrives late receives an extra energy increment and overtakes the synchronous particle A.

$$V = V_0 \sin \phi_s$$

8/25/2010 D. Vranic 2

Problem

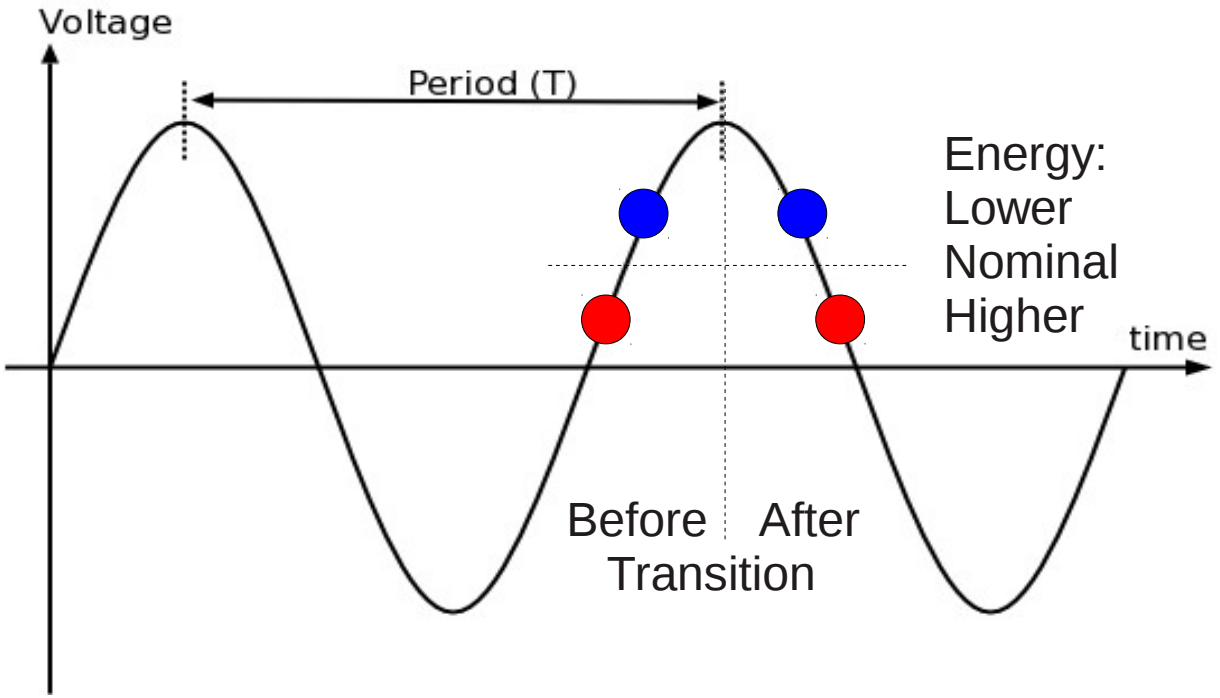
- What happens when v~c?
  - Why does the more energetic particles take longer to go around?!
- Answer:
  - Larger radius (longer path length) for same B field!
    - $R=p/(qB)$
    - $f=v/2\pi R$
      $=qBc/(2\pi p)$



$\Delta p>0 \rightarrow \Delta R>0$

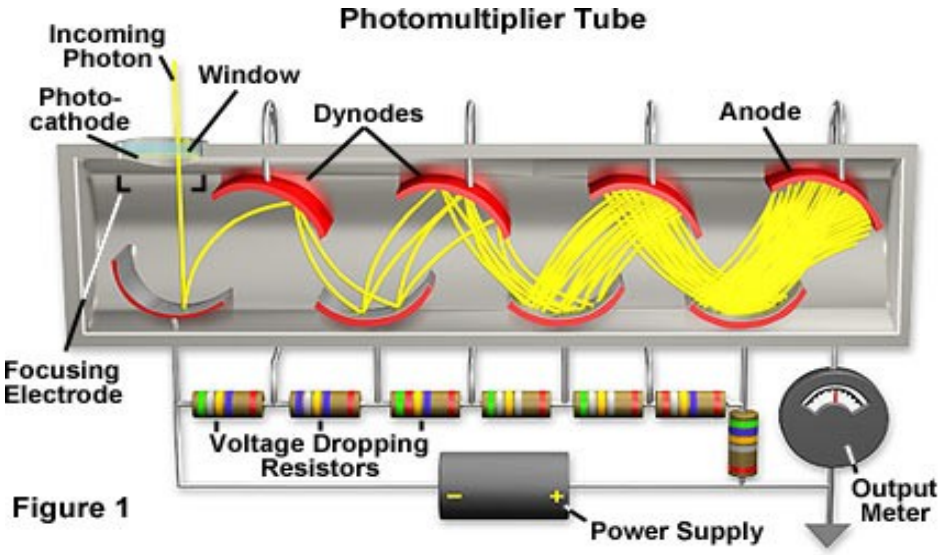
The transition energy

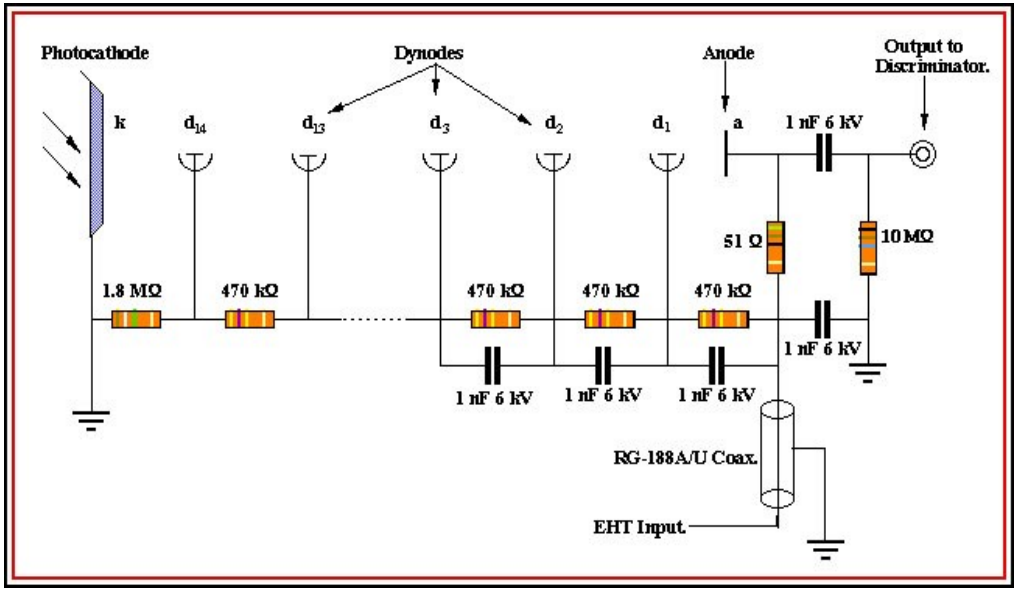
- The energy at which the higher (lower) energy particles in the beam starts to go slower (faster) around than nominal energy particles is called the transition energy
- Need to “invert” longitudinal focusing = shift half a wavelength
  - Technically challenging as beam focus diverges



Backup slides

DC acceleration in photo multiplier tube (PMT)





- The more electrons we amplify the more energy we need = capacitors or reduce resistance