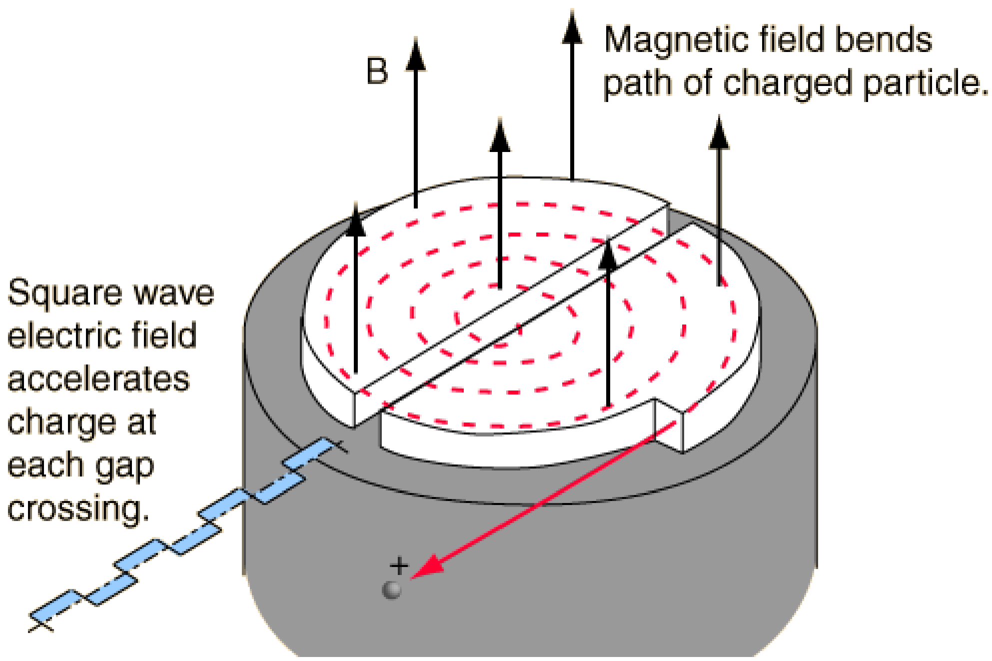
What did you learn in the last lecture?

II. Electrodynamic (Time varying E and B fields)

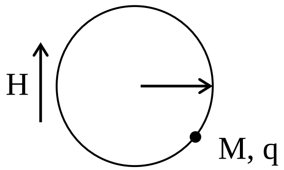
A. Cyclotron (Lawrence, 1929, Nobel Prize)

Idea: Confine the motion of the particle with a magnetic field while you accelerate it.



1. Equations of Motion for a Charged Particle in a Magnetic_Field

Particle mass: M
Charge state: qe
Magnetic field: H
radius: r



a. Trajectory is Circular path of radius r

$$F_{centripetal} = \frac{Mv^2}{r} \qquad F_{magnetic} = \frac{Hvqe}{c}$$

The two forces are balanced so equate them!

$$r = \frac{Mv^2 c}{Hvqe} = \left(\frac{Mc}{Hqe}\right) v$$

i.e. r = f(v) (classically)

b. Orbit time: v << c

$$t = \frac{2\pi r}{v} = \frac{2\pi}{v}\frac{Mcv}{Hqe} = \frac{2\pi Mc}{HqE}$$

CONSTANT!

CYCLOTRON PRINCIPLE: orbit time is independent of particle energy for classical motion

ion-cyclotron resonance

c. <u>Frequency-ω</u>

$$\omega = \frac{2\pi}{t} = \frac{Hqe}{Mc} = \left(\frac{He}{c}\right)\frac{q}{M}$$

for q/M ~ 0.5 (e.g., $^{4}He^{+2}$, $^{12}C^{+6}$),
ω ~ 10-30 MHz for H ~ 1.5 tesla.
(lower end of FM frequency.)

Notice that for a fixed magnetic field H, the cyclotron frequency is proportional to q/M of the particle.

2. Acceleration

a. Supply radiofrequency energy for each revolution
i.e., $\Delta E = qe\,\Delta V$, where ΔV ~ 50-250 kV

b. Result: velocity increases and particle spirals outward

c. Energy is limited by magnetic field H and radius r ($)

d. Total energy: defined by number of orbits required to reach maximum radius, r_{max} = n: $\therefore\ \Delta E = n\,(qe)\,\Delta V$
e.g. for n = 500, ΔV = 200 kV (q = 2) , ΔE = 200 MeV

3. <u>Classical Kinetic Energy: E_K</u>

$$E_K = \frac{1}{2}Mv^2 = \frac{1}{2}M\left(\frac{r^2H^2q^2e^2}{M^2c^2}\right) = \underbrace{\frac{1}{2}\overbrace{\left(\frac{r^2H^2e^2}{c^2}\right)}^{\text{cyclotron}}}_{K}\overbrace{\left(\frac{q^2}{A}\right)}^{\text{ion}}$$

$$E_K = K\frac{q^2}{A}$$

For v < c; limited by relativity
K is the figure of merit for the cyclotron

If we insert values for the constants we get:

$E_K = 5.05 \times 10^{-3}\ H^2\ r^2\ (q^2/A)$ $\quad$ MeV/tesla^2-cm^2

B. Properties

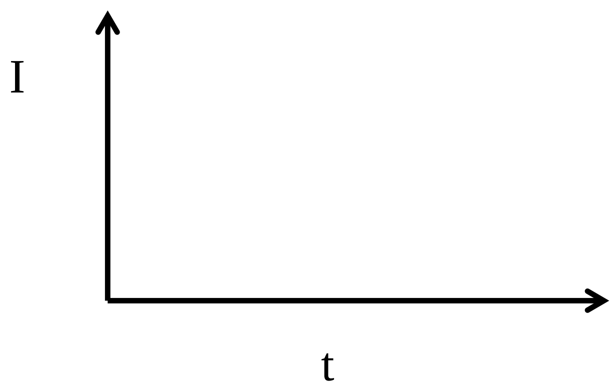
1. Ions: Most of periodic table (electron cyclotron resonance (ECR) sources yield high q) ion sources permit up to U ions

2. Higher energy, less precision than Van de Graafs

3. Energy limits: H and He: K = 215 (IU); K=500 (TRIUMF/CANADA)
Heavy ions: K = 1200 (MSU)

4. Intensity: $I \lesssim 10\mu A$

5. Time structure of beam: Pulses



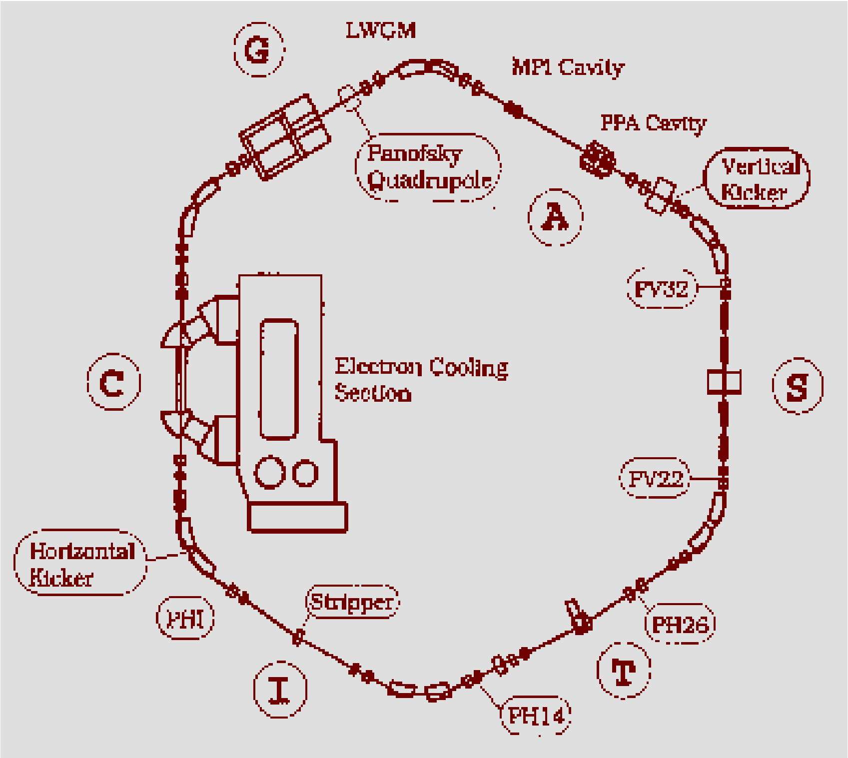
More historical information:
http://www.aip.org/history/lawrence/
Original paper on cyclotrons:
http://prola.aps.org/abstract/PR/v40/i1/p19_1
Facts about the IU cyclotron (IUCF) :
http://www.iucf.indiana.edu/whatis/facts.php

III. Synchrotron

A. Principle of Operation

1. Fixed "Circular" Path

Trajectory is controlled by magnets placed around rings;
Vary H with velocity to bend particles and keep orbit constant (ramping).
Computer-controlled process
Approach overcomes both magnet size and relativity limits.



IU Synchrotron ("Cooler")
K=500 MeV for this machine

2. Result: Maximum energy depends on radius (real estate) and strength of ring magnets; r & H = f ($)
FNAL ~ 2 TeV = 2×10^{12} eV

B. Properties

1. Ions: p , $\bar{p}$, e^- , e^+ ; up to U at RHIC (Brookhaven)

2. Energy: FNAL = 1.6 TeV (V/c ~ 0.999)

3. Storage rings: inject beam and store in ring ; unless particles collide, will circulate continually.

4. Light sources: $e^- \rightarrow \gamma \rightarrow$ biochemistry and materials science

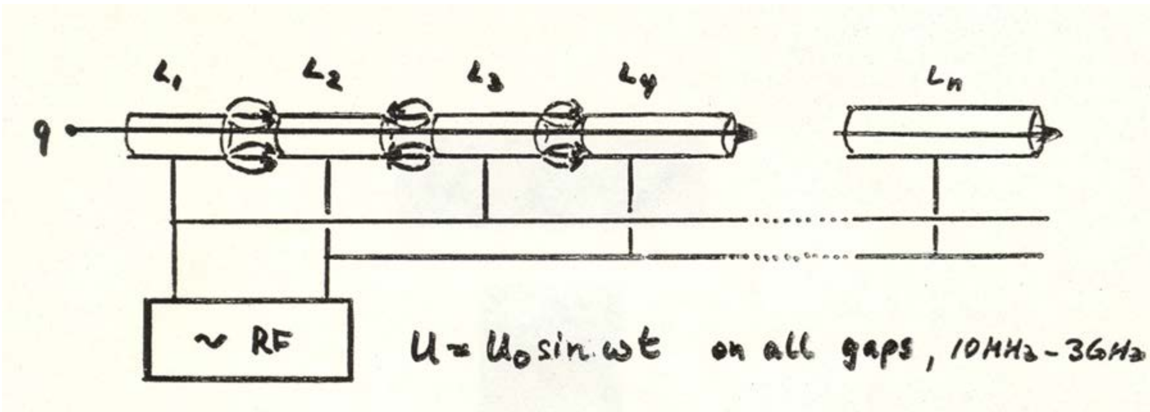
Uses: Primarily nuclear and high-energy physics (increasingly condensed matter studies)

For more on synchrotrons:
http://accelconf.web.cern.ch/AccelConf/e96/PAPERS/ORALS/FRX04A.PDF

IV. Linear Accelerators

Principle of Operation: Multiple Kicks

$\Delta E = \Delta V \; \Sigma \; q \, e \, n_i$, where n_i is the number of stages



- Inside the tubes (drift tubes) the voltage is the same i.e. no acceleration
- The voltage on the tubes is varied at radiofrequency so that as a particle moves between tubes it experiences an acceleration.
- As all the drift tubes are pulsed at the same frequency, and we want the particle to always reach the gap at the same moment, we write:

$L = V\frac{T}{2} = \beta\frac{\lambda}{2}$ where $\beta = \frac{V}{c}$ and T is the period

After n gaps,

$$\frac{1}{2}MV_n^{\,2} = n(q)U_0$$

$$V_n = \left(n\frac{2qU_0}{M} \right)^{\frac{1}{2}}$$

$$L_n = \left(n\frac{2qU_0}{M} \right)^{\frac{1}{2}} \frac{T}{2}$$

Notice that the drift tubes have to get longer as the particle accelerates so that the particle always reaches a gap at the same time.

Properties

1. Projectiles: Light ions (H) ; injector stages of FNAL and AGS
   Heavy ions: (Li –U): ATLAS, FSU
   Electrons: SLAC

2. Currents: Up to ~ 1mA
   Pulsed machines

3. Radiofrequency cavity Boosters
   IUCF $\rightarrow$ CIS
   Superconductor technology: ATLAS

V. Coupled Accelerators

Most physics accelerators today couple several different parts.

A. IUCF: RfQ + Cyclotron; RFQ + Linac

B. RHIC:

Van de Graaf and linear accelerator + synchrotron + synchrotron

C. CERN (Centre European Research Nucleaire)

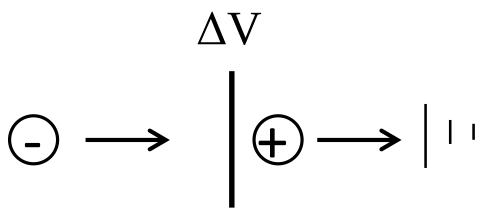
The proton source is a simple bottle of hydrogen gas. An electric field is used to strip hydrogen atoms of their electrons to yield protons. Linac 2, the first accelerator in the chain, accelerates the protons to the energy of 50 MeV. The beam is then injected into the Proton Synchrotron Booster (PSB), which accelerates the protons to 1.4 GeV, followed by the Proton Synchrotron (PS), which pushes the beam to 25 GeV. Protons are then sent to the Super Proton Synchrotron (SPS) where they are accelerated to 450 GeV.

The protons are finally transferred to the two beam pipes of the LHC. The beam in one pipe circulates clockwise while the beam in the other pipe circulates anticlockwise. It takes 4 minutes and 20 seconds to fill each LHC ring, and 20 minutes for the protons to reach their maximum energy of 4 TeV. Beams circulate for many hours inside the LHC beam pipes under normal operating conditions.

Taken From: http://home.web.cern.ch/about/accelerators

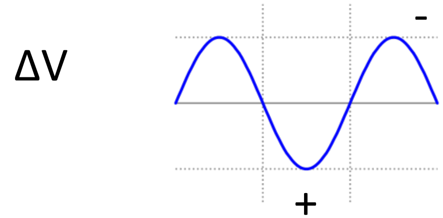
VI. Summary

Van de Graaf (tandem)



$$\Delta E = (|q_1| + |q_2|)\Delta V$$

Linear



$$E = n\Delta V$$

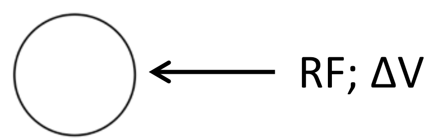
Cyclotron

B fixed

$$E = K\frac{q^2}{A}$$

t_{orbit} = constant

Synchrotron



E = f(r)

B = f(E)

INTERACTION OF RADIATION WITH MATTER

All radiation is detected through its interaction with matter!

INTRODUCTION: **What happens when radiation passes through matter?**

Emphasis on what happens to emitted particle (if no nuclear reaction and **MEDIUM** (i.e., atomic effects)

RELEVANCE:

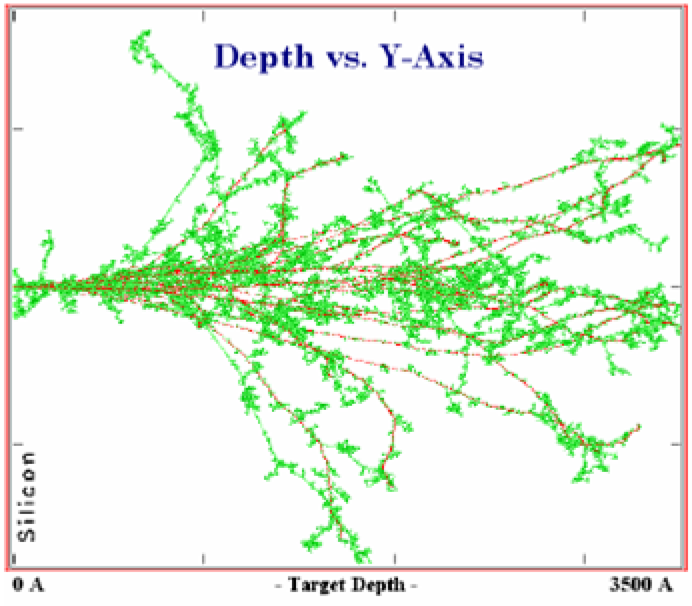
(1) Detection of Radiation
(2) Radiation Safety
(3) Environmental Hazards
(4) Biological Effects – "Radiation Hypochondria"
(5) Risk Assessment – Alternative Medicine

TYPES OF RADIATION:

(1)	Positive Ions:	X^{+q} – α, fission, cosmic rays, beams
(2)	Electrons:	$\beta^{\pm}$, IC, Auger, cosmic rays
(3)	Photons:	$\gamma \rightarrow$ x-ray $\rightarrow$ uv $\rightarrow$ visible
(4)	Neutrons:	nuclear reactors, nuclear weapons, accelerators

I. Positive Ions

Definition: Cation = ${}^{A}_{Z}X^{+q}$ where **q** = atomic ionization state



Actual SRIM calculation of energy loss as ions stop in matter.

A. Overview

1. Possible interactions:

Nuclei $\sigma \sim 10^{-24}\ \text{cm}^2$

Orbital e^{-}s $\sigma \sim 10^{-16}\ \text{cm}^2$

Since $$\frac{\sigma_{nucleus}}{\sigma_{electrons}} = 10^{-8}$$ Ion-electron collisions dominate the interactions

2. Qualitative Properties of ion-electron Collisions

a. $v_I << c$ (usually ~ 0.01 – 0.1 c)

b. Mass (ion) >> Mass (e^{-}) ; $\therefore$ Many collisions required to stop ion

c. Trajectory: straight line

Analogy: bowling ball – ping-pong ball collisions

B. Stages of Energy Loss

Electronic Stopping: $v_I >> v_e$ in atomic orbitals 95% of c

a. <u>Stripping</u>: ${}^{A}_{Z}X^{+q} \rightarrow$ [Medium] $\rightarrow {}^{A}_{Z}X^{+Z}$; e.g., ${}^{16}_{8}O^{+2} \rightarrow$ [Medium] $\rightarrow {}^{16}_{8}O^{+8}$

ion

Medium (electron sea)

i.e., ion loses all electrons (usually) in passing through matter (ΔX~100 atoms)

b. <u>Ion-Electron Collisions</u>

Multiple, sequential collisions ; straight-line trajectory

c. <u>Medium Effects</u>

(1) Ionization $\rightarrow$ Creation of multiple cations (from medium) – electron pairs

(2) Electronic Excitation: fluorescence (uv, x-rays, etc.)

(3) Molecular Dissociation (free radical formation)

2. Intermediate Stopping: $v_I \approx v_{e^-}$ (inner shells)

a. <u>Pickup</u>: Incident ion begins to pick up electrons from stopping medium. K-shell first, since they have highest velocity (binding energy).

b. <u>Moderate Directional Changes</u> (Dramatic size increase)

$$O^{+8} \xrightarrow[v(1s)]{+e^-} O^{+7} \xrightarrow{e^-} O^{+6} \xrightarrow{e^-} O^{+5} \rightarrow \rightarrow \rightarrow O^{\pm 1,0}$$

c. <u>Ion slows down</u> at each step and ionic charge is $\approx$ neutralized

3. Atomic ("nuclear") stopping: $v_I \approx v_e$ (valence shell)

a. <u>Ion charge</u> $\pm 1,0$

b. <u>Elastic ion-atom collisions</u>

$\therefore$ Mass (ion) $\approx$ Mass (medium atoms) – billiard ball collisions

c. <u>Result</u> large directional changes: Straggling

4. Summary

5. Concept of Range (R represents Range and NOT Rate)

a. Definition: The average distance traveled by an ion with a given energy **E** during stopping process.

b. Straggling: The distribution of ranges resulting from the statistical nature of the stopping process

C. Energetics

1. Maximum energy loss per collision: ΔE_{max}

   a. $\underline{\Delta E}_{max}$ is obtained when ion scatters at 180° (c.m.)

   From energy and momentum conservation (relativistic solution)

   $\Delta E_{max} = 4\ E_0\ (M_e/M_{ion}) \quad = \quad E_0/459\ A_{ion}$ (MeV)

   b. Example: 6 MeV ^{4}He ion
   $\Delta E_{max} = 6.000\ /459(4) = 0.003$ MeV
   $\therefore\ E(\alpha)' = 6.000 - 0.003 = 5.997$ MeV; i.e., long way to go

2. Average Energy Loss: $<\Delta E>$
   Average over all scattering angles,
   $<\Delta E> \approx 100$ eV for 6.000 MeV α

$$< N_{collisions} >= \frac{E_0}{< \Delta E >} = \frac{6.000}{0.0001} \approx 10^4 - 10^5$$

3. Each collision creates a cation-electron pair; creates a measurable current; basis for detectors