PHYS 3446 – Lecture #13

Wednesday, Mar. 9, 2005
Dr. Jae Yu

- Particle Detection
  - Cerenkov detectors
  - Calorimeters
- Accelerators
  - Electrostatic Accelerators
  - Resonance Accelerators
  - Synchronous Accelerators (synchrotrons)
  - Colliding Beams

Announcements

- Second term exam
  - Date and time: 1:00 – 2:30pm, Monday, Mar. 21
  - Location: SH125
  - Covers: CH4.5 – CH 8

Cerenkov Detectors

- What is the Cerenkov radiation?
  - Emission of coherent radiation from the excitation of atoms and molecules
- When does this occur?
  - If a charged particle enters a dielectric medium with a speed faster than light in the medium
  - How is this possible?
    - Since the speed of light is c/n in a medium with index of refraction n, if the speed of the particle is $\beta > 1/n$, its speed is larger than the speed of light
- Cerenkov light has various frequencies but blue and ultraviolet band are most interesting
  - Blue can be directly detected w/ standard PMTs
  - Ultraviolet can be converted to electrons using photosensitive molecules mixed in with some gas in an ionization chamber

Cerenkov Detectors

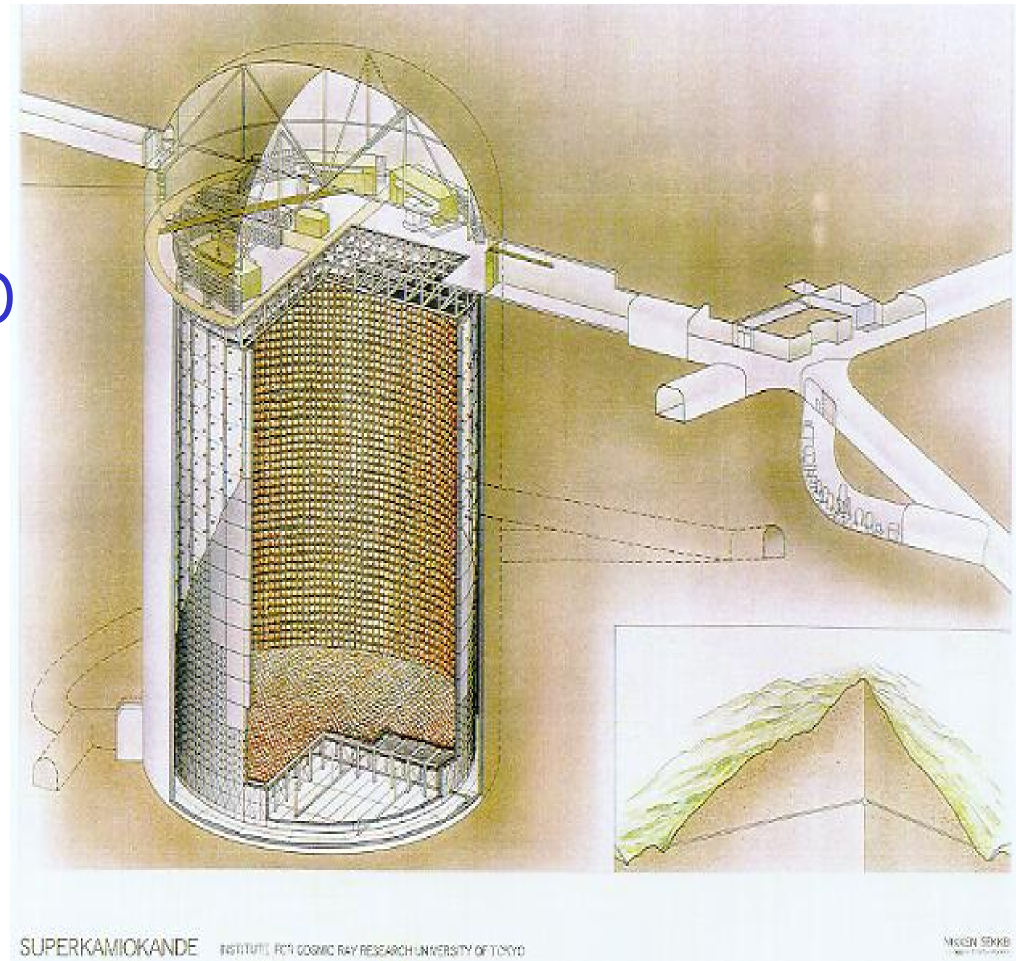
- The angle of emission is given by $\cos\theta_c = \frac{1}{\beta n}$
- The intensity of the produced radiation per unit length of radiator is proportional to $\sin^2\theta_c$.
- For $\beta n>1$, light can be emitted while for $\beta n<1$, no light can be observed.
- Thus, Cerenkov effect provides a means for distinguishing particles with the same momentum
  - One can use multiple chambers of various indices of refraction to detect Cerenkov radiation from different mass particles of the same momentum

Cerenkov Detectors

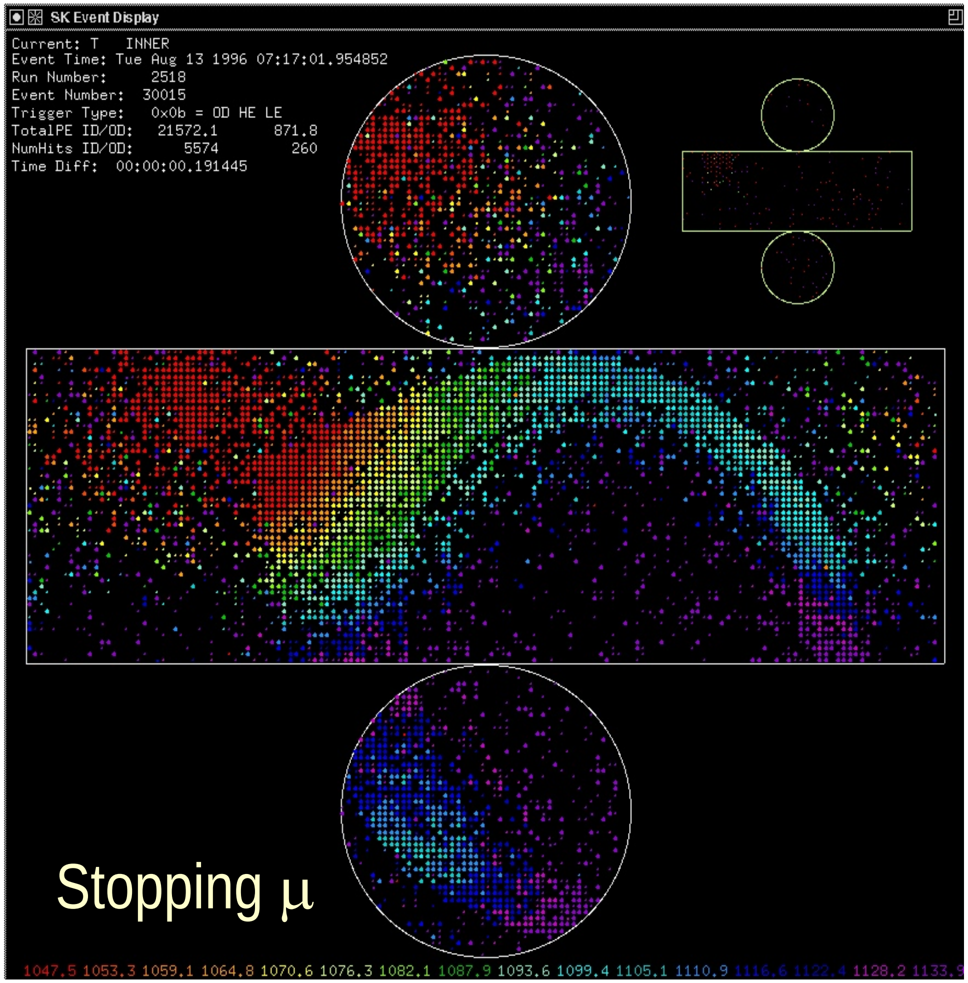
- Threshold counters
  - Particles with the same momentum but with different mass will start emitting Cerenkov light when the index of refraction is above a certain threshold
  - These counters have one type of gas but could vary the pressure in the chamber to change the index of refraction to distinguish particles
  - Large proton decay experiments use Cerenkov detector to detect the final state particles, such as $p \rightarrow e^{+}\pi^{0}$
- Differential counters
  - Measure the angle of emission for the given index of refraction since the emission angle for lighter particles will be larger than heavier ones

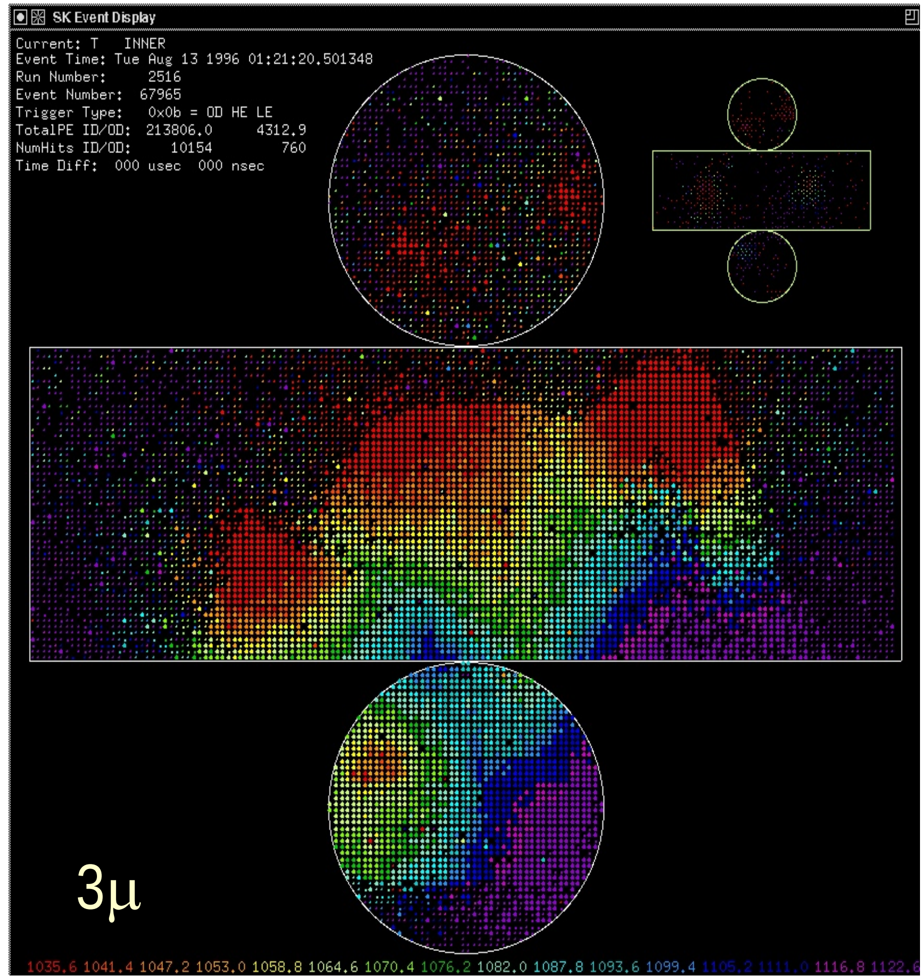
Super Kamiokande
A Differential Water Cerenkov Detector

- Kamioka zinc mine, Japan
  - 1000m underground
- 40 m (d) x 40m(h) SS
- 50,000 tons of ultra pure H_2O
- 11200(inner)+1800(outer) 50cm PMT's
- Originally for proton decay experiment
- Accident in Nov. 2001, destroyed 7000 PMT's
- Dec. 2002 resumed data taking



Super-K Event Displays





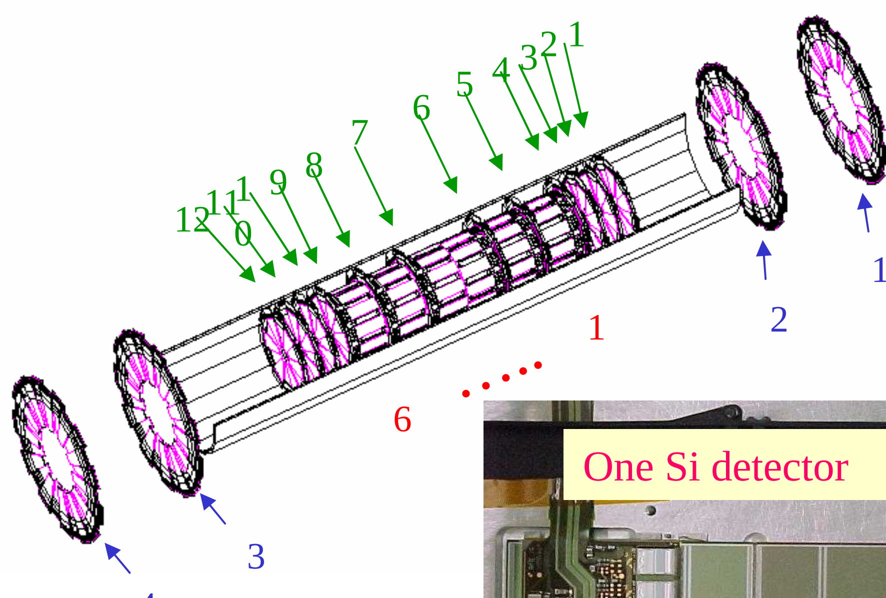
Cerenkov Detectors

- Ring-imaging Cerenkov Counters (RICH)
  - Use UV emissions
  - An energetic charged particle can produce multiple UV distributed about the direction of the particle
  - These UV photons can then be put through a photo-sensitive medium creating a ring of electrons
  - These electrons then can be detected in an ionization chamber forming a ring
  - Babar experiment at SLAC uses this detector

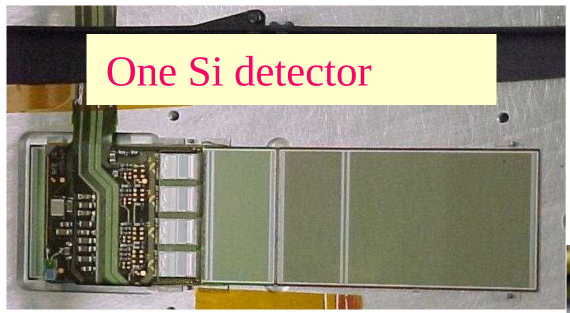
Semiconductor Detectors

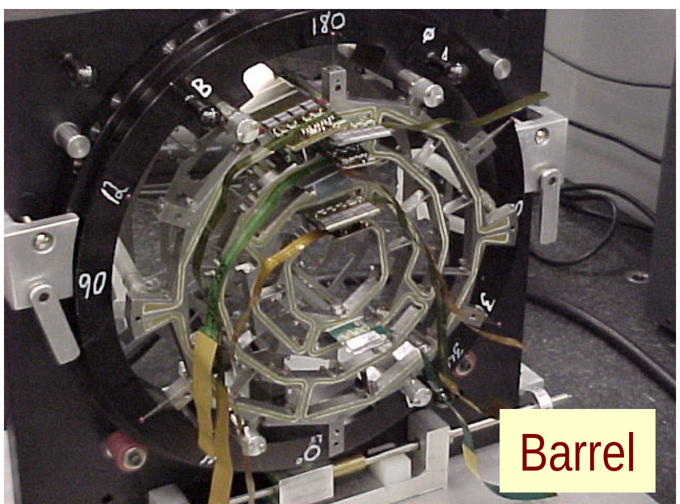
- Semiconductors can produce large signal (electron-hole pairs) with relative small energy deposit (~3eV)
  - Advantageous in measuring low energy at high resolution
- Silicon strip and pixel detectors are widely used for high precision position measurements
  - Due to large electron-hole pair production, thin layers (200 – 300 μm) of wafers sufficient for measurements
  - Output signal proportional to the ionization loss
  - Low bias voltages sufficient to operate
  - Can be deposit in thin stripes (20 – 50 μm) on thin electrode
  - High position resolution achievable
  - Can be used to distinguish particles in multiple detector configurations
- So what is the catch?
  - Very expensive ➔ On the order of \$30k/m^2

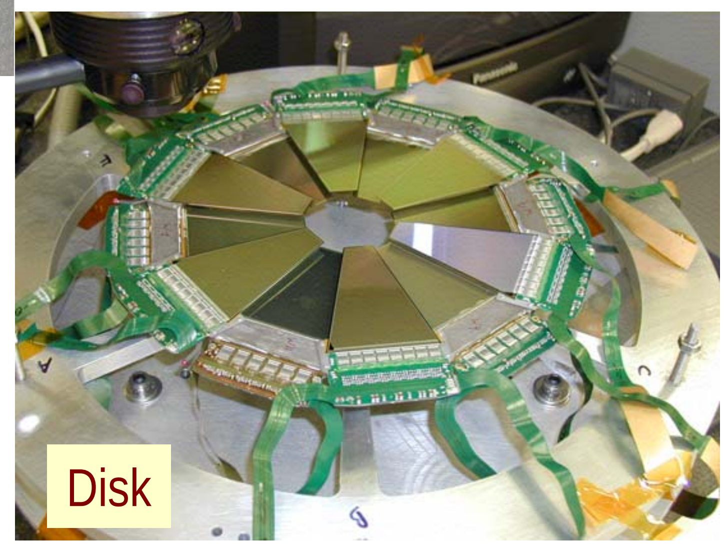
DØ Silicon Vertex Detector



	Barrels	F-Disks	H-Disks
Channels	387120	258048	147456
Modules	432	144	96
Inner R	2.7 cm	2.6 cm	9.5 cm
Outer R	9.4 cm	10.5 cm	26 cm







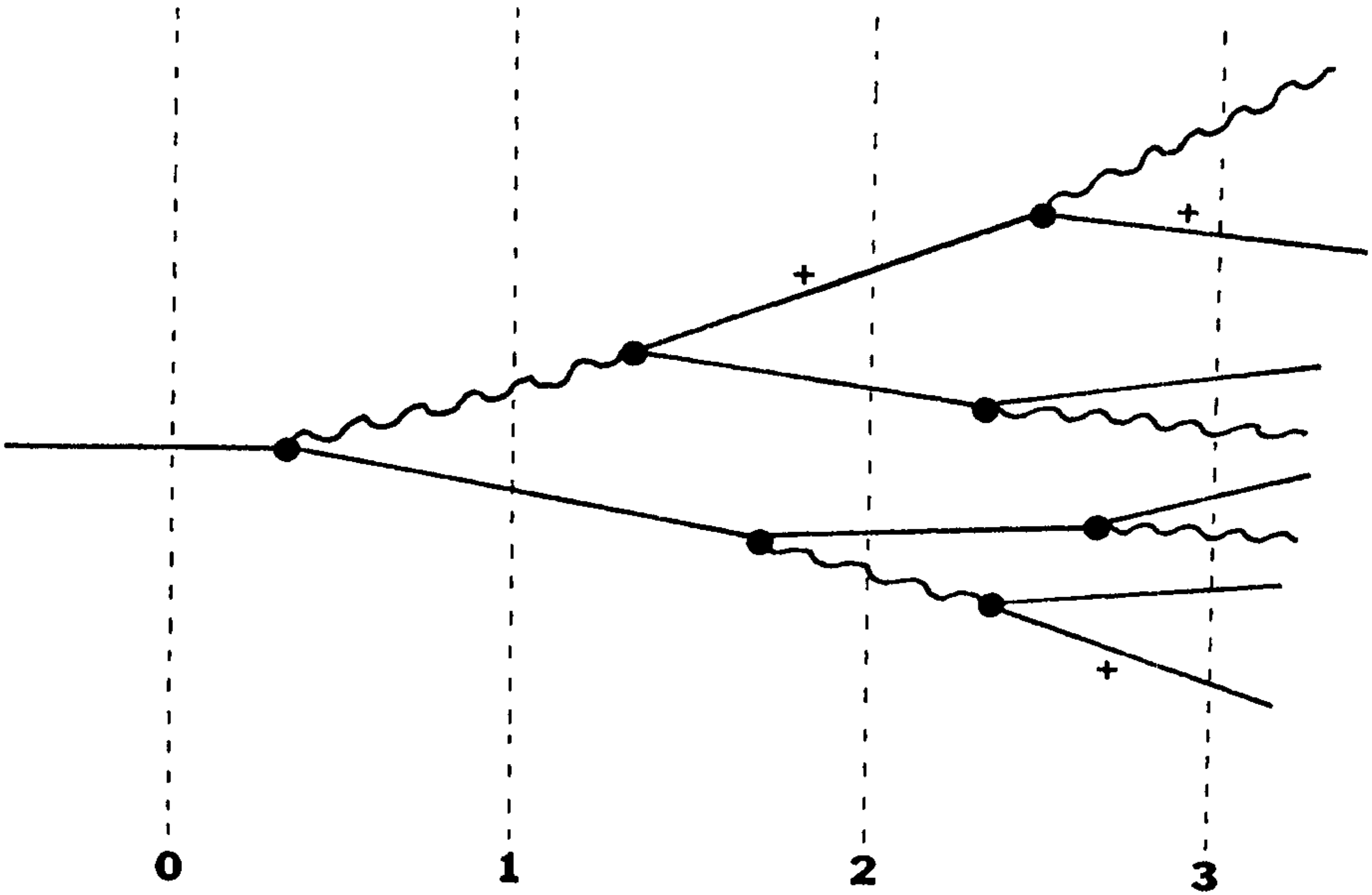
Calorimeters

- Magnetic measurement of momentum is not sufficient, why?
  - The precision for angular measurements gets worse as particles' momenta increases
  - Increasing magnetic field or increasing precision of the tracking device will help but will be expensive
  - Cannot measure neutral particle momenta
- How do we solve this problem?
  - Use a device that measures kinetic energies of particles
- Calorimeter
  - A device that absorbs full kinetic energy of a particle
  - Provides signal proportional to deposited energy

Calorimeters

- Large scale calorimeter were developed during 1960s
  - For energetic cosmic rays
  - For particles produced in accelerator experiments
- How do EM (photons and electrons) and Hadronic particles deposit their energies?
  - Electrons: via bremsstrahlung
  - Photons: via electron-positron conversion, followed by bremsstrahlung of electrons and positrons
  - These processes continue occurring in the secondary particles causing an electromagnetic shower losing all of its energy

Electron Shower Process

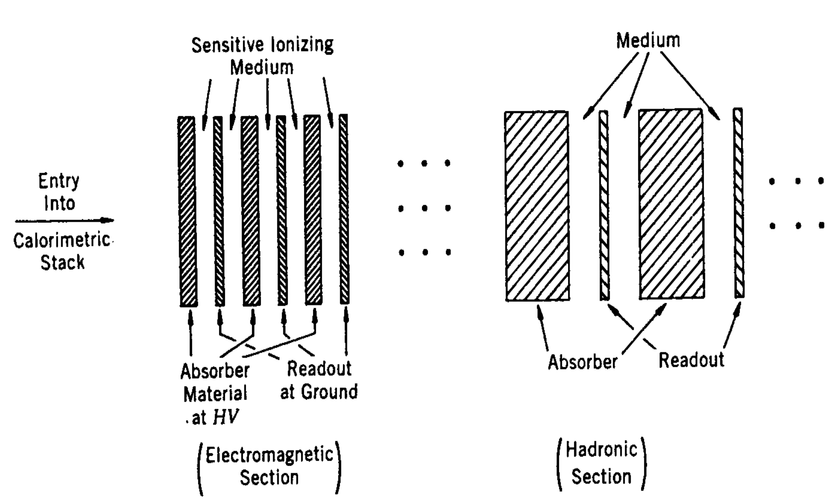


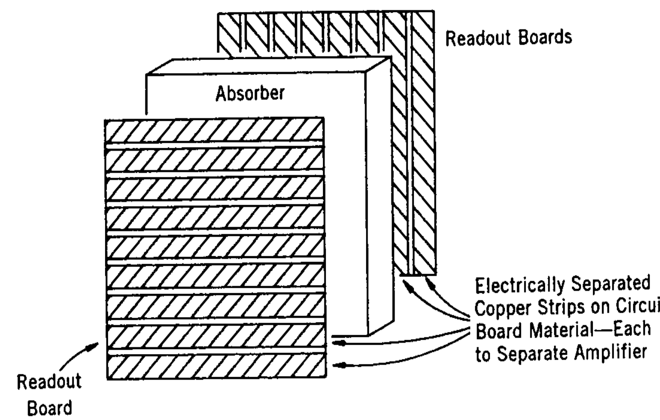
Calorimeters

- Hadrons are massive thus their energy deposit via brem is small
- They lose their energies through multiple nuclear collisions
- Incident hadron produces multiple pions and other secondary hadrons in the first collision
- The secondary hadrons then successively undergo nuclear collisions
- Mean free path for nuclear collisions is called nuclear interaction lengths and is substantially larger than that of EM particles
- Hadronic shower processes are therefore more erratic than EM shower processes

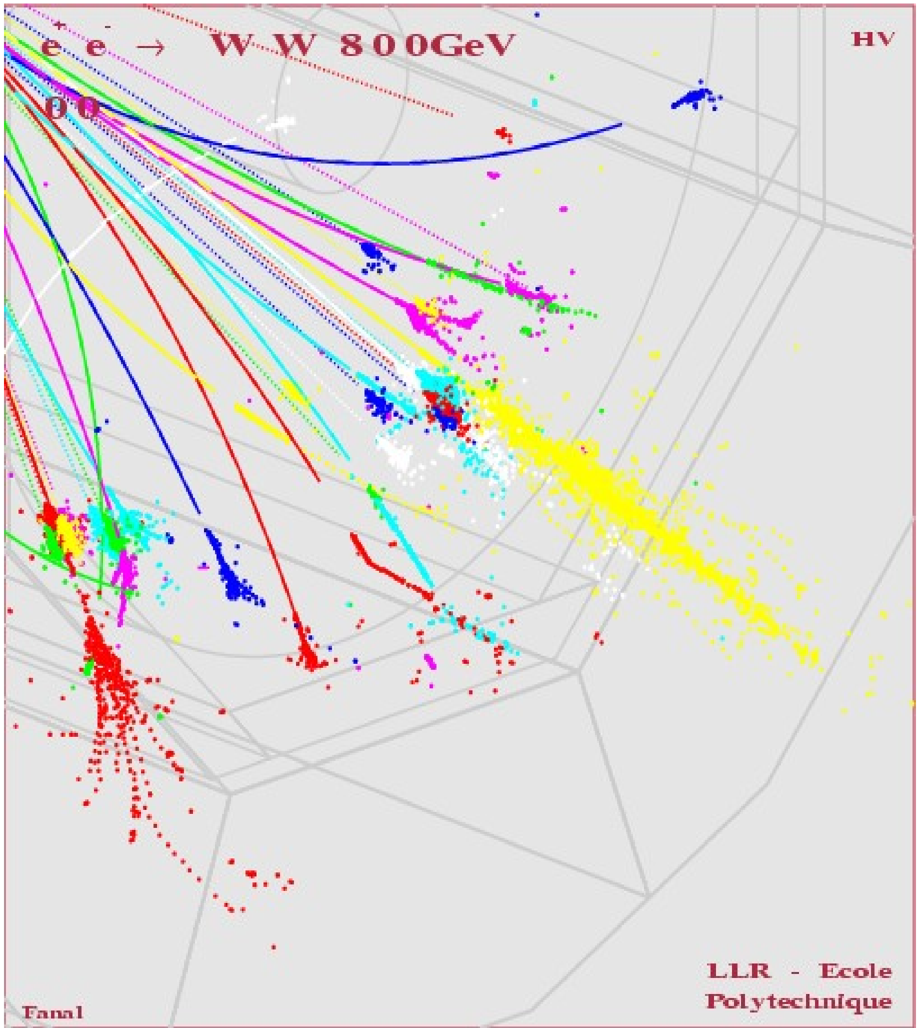
Sampling Calorimeters

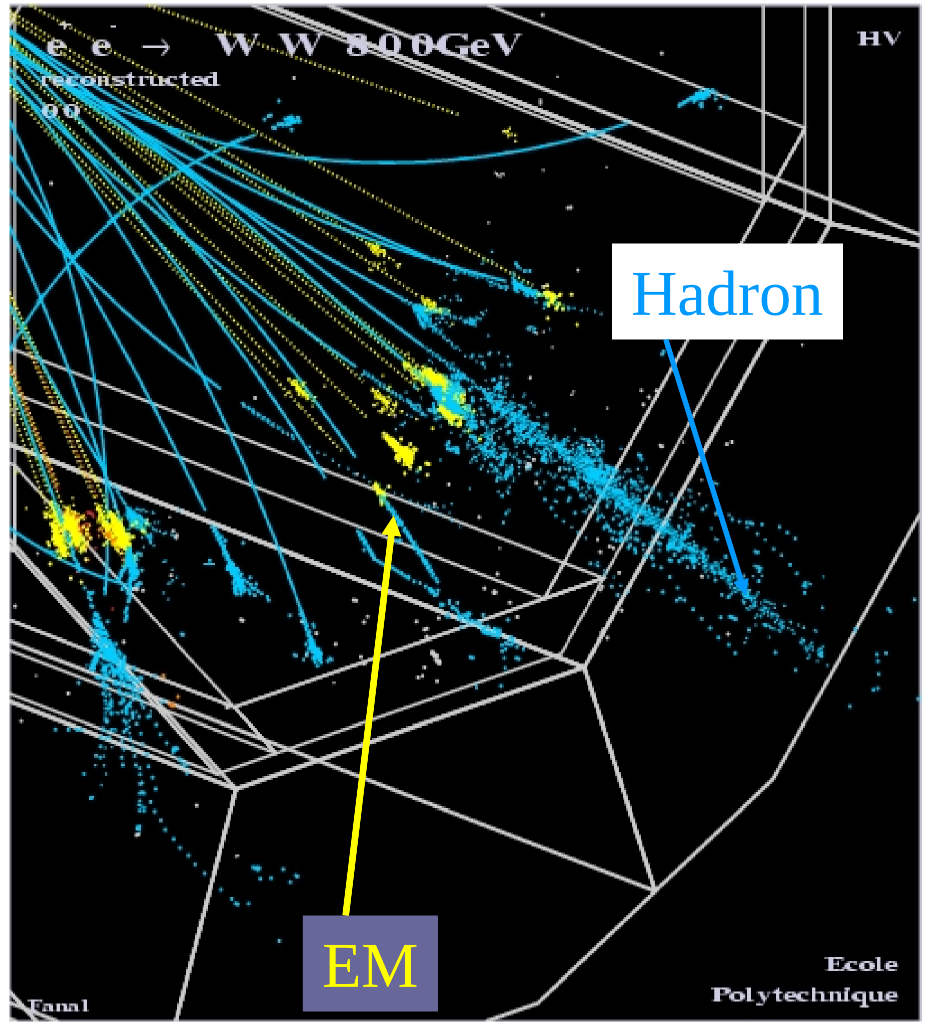
- High energy particles require large calorimeters to absorb all of their energies and measure them fully in the device (called total absorption calorimeters)
- Since the number of shower particles is proportional to the energy of the incident particles
- One can deduce the total energy of the particle by measuring only the fraction of their energy, as long as the fraction is known ➔ Called sampling calorimeters
  - Most the high energy experiments use sampling calorimeters





How particle showers look in detectors





Particle Accelerators

- How can one obtain high energy particles?
  - Cosmic ray → Sometimes we observe 1000TeV cosmic rays
    - Low flux and cannot control energies too well
- Need to look into small distances to probe the fundamental constituents with full control of particle energies and fluxes
  - Particle accelerators
- Accelerators need not only to accelerate particles but also to
  - Track them
  - Maneuver them
  - Constrain their motions on the order of 1μm
- Why?
  - Must correct particle paths and momenta to increase fluxes and control momenta

Particle Accelerators

- Depending on what the main goals of physics is, one can have various kinds of accelerators
- Fixed target experiments: Probe the nature of the nucleons ➔ Structure functions
  – Results also can be used for producing secondary particles for further accelerations
- Colliders: Probes the interactions between fundamental constituents
  – Hadron colliders: Wide kinematic ranges and high discovery potential
    - Proton-anti-proton: TeVatron at Fermilab, S$p\bar{p}$S at CERN
    - Proton-Proton: Large Hadron Collider at CERN (to turn on 2007)
  – Lepton colliders: Very narrow kinematic reach and for precision measurements
    - Electron-positron: LEP at CERN, Petra at DESY, PEP at SLAC, Tristan at KEK, ILC in the med-range future
    - Muon-anti-muon: Conceptual accelerator in the far future
  – Lepton-hadron colliders: HERA at DESY

Electrostatic Accelerators: Cockcroft-Walton

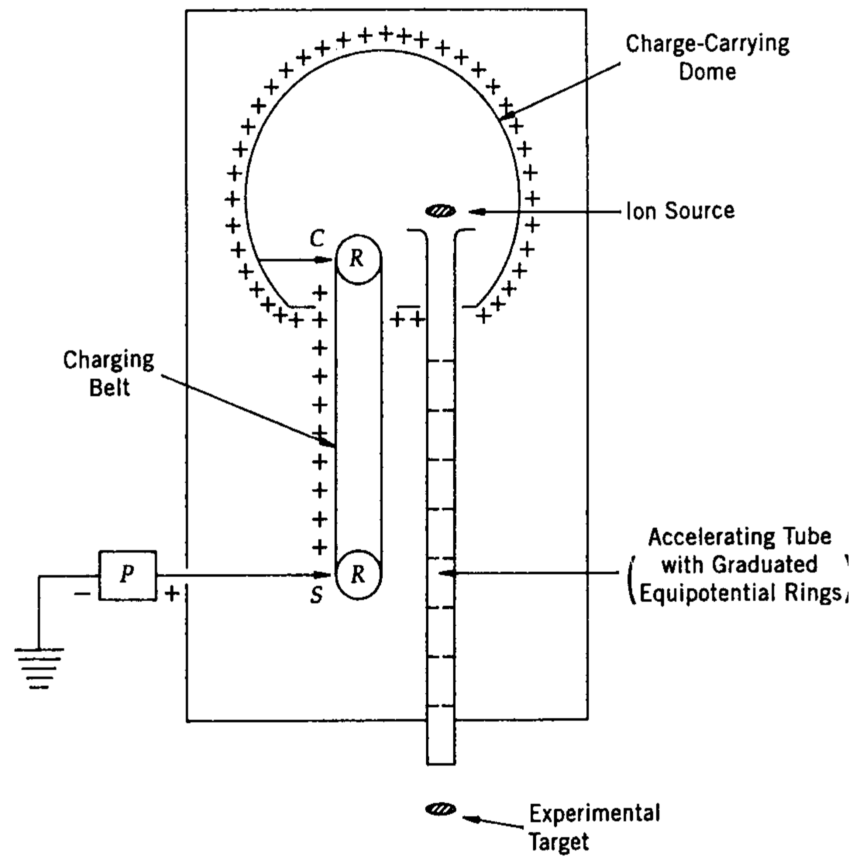
- Ckckcroft-Walton Machines
  - Pass ions through sets of aligned DC electrodes at successively increasing fixed potentials
  - Consists of ion source (hydrogen gas) and a target with the electrodes arranged in between
  - Acceleration Procedure
    - Electrons are either added or striped off of an atom
    - Ions of charge q then get accelerated through series of electrodes, gaining kinetic energy of $T=qV$ through every set of electrodes
- Limited to about 1MeV acceleration due to voltage breakdown and discharge beyond voltage of 1MV.
- Available commercially and also used as the first step high current injector (to ~1mA).

Electrostatic Accelerators: Van de Graaff

- Energies of particles through DC accelerators are proportional to the applied voltage
- Robert Van de Graaff developed a clever mechanism to increase HV
  - The charge on any conductor resides on its outermost surface
  - If a conductor carrying additional charge touches another conductor that surrounds it, all of its charges will transfer to the outer conductor increasing the charge on the outer conductor, increasing HV

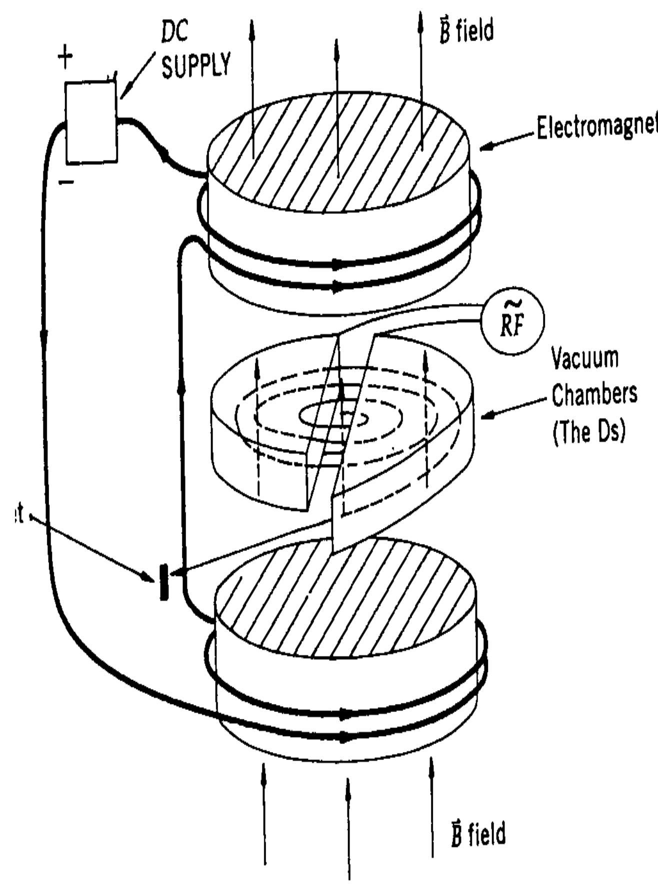
Electrostatic Accelerators: Van de Graaff

- Sprayer adds positive charge to the conveyor belt at corona points
- Charge is carried on an insulating conveyor belt
- The charges get transferred to the dome via the collector
- The ions in the source then gets accelerated to about 12MeV
- Tandem Van de Graff can accelerate particles up to 25 MeV
- This acceleration normally occurs in high pressure gas that has very high breakdown voltage



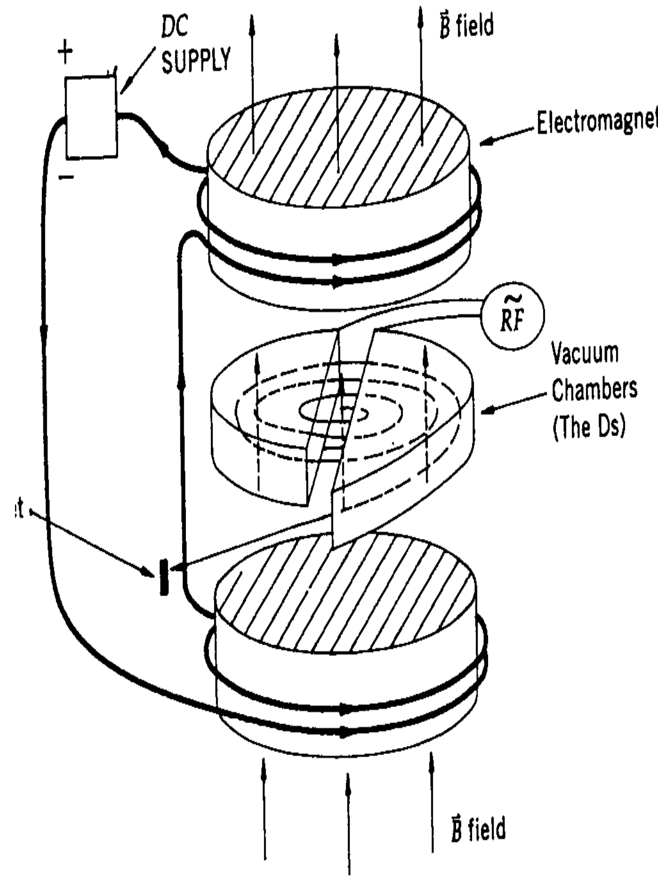
Resonance Accelerators: Cyclotron

- Fixed voltage machines have intrinsic limitations in their energy due to breakdown
- Machines using resonance principles can accelerate particles in higher energies
- Cyclotron developed by E. Lawrence is the simplest one
- Accelerator consists of
  - Two hallow D shaped metal chambers connected to alternating HV source
  - The entire system is placed under strong magnetic field



Resonance Accelerators: Cyclotron

- While the Ds are connected HV sources, there is no electric field inside the chamber due to Faraday effect
- Strong electric field exists only the gap between the Ds
- A ion source placed in the gap
- The path is circular due to the magnetic field
- Ion does not feel any acceleration in a D but bent due to magnetic field
- When the particle exits a D, the direction of voltage can be changed and the ion gets accelerated before entering into the D on the other side
- If the frequency of the alternating voltage is just right, the charged particle gets accelerated continuously until it is extracted



Resonance Accelerators: Cyclotron

- For non-relativistic motion, the frequency appropriate for alternating voltage can be calculated from the fact that the magnetic force provides centripetal acceleration for a circular orbit

$$m\frac{v^2}{r} = q\frac{vB}{c} \quad \Rightarrow \quad \frac{v}{r} = \frac{qB}{mc}$$

- In a constant speed, ω=v/r. The frequency of the motion is

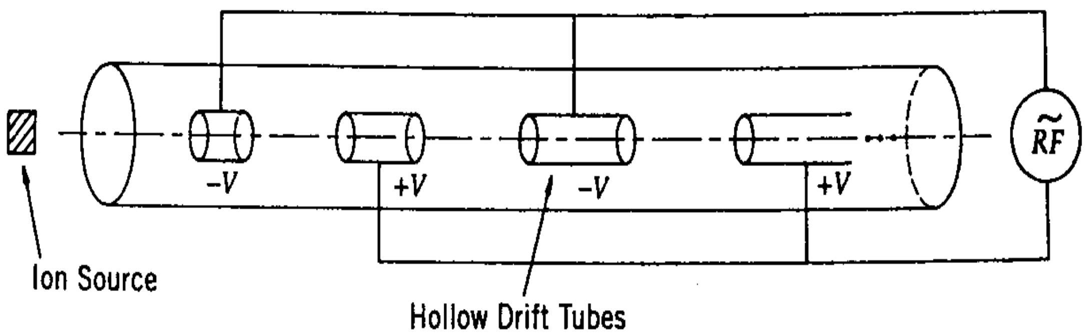
$$\nu = \frac{\varpi}{2\pi} = \frac{qB}{2\pi mc} = \frac{1}{2\pi}\left(\frac{q}{m}\right)\frac{B}{c}$$

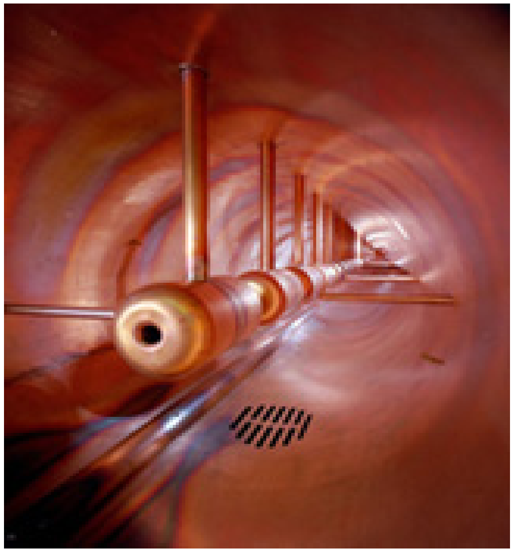
- Thus, to continue accelerate the particle the electric field should alternate in this frequency, cyclotron resonance frequency
- The maximum kinetic energy achievable for an cyclotron with radius R is

$$T_{\max} = \frac{1}{2}mv_{\max}^2 = \frac{1}{2}m\varpi^2 R^2 = \frac{(qBR)^2}{mc^2}$$

Resonance Accelerators: Linear Accelerator

- Accelerates particles along a linear path using resonance principle
- A series of metal tubes are located in a vacuum vessel and connected successively to alternating terminals of radio frequency oscillator
- The directions of the electric fields changes before the particles exits the given tube
- The tube length needs to get longer as the particle gets accelerated to keep up with the phase
- These accelerators are used for accelerating light particles to very high energies





Synchroton Accelerators

- For very energetic particles, the relativistic effect must be taken into account
- For relativistic energies, the equation of motion of a charge q under magnetic field B is $$m\gamma\frac{d\vec{v}}{dt} = m\gamma\vec{v}\times\vec{\varpi} = q\frac{\vec{v}\times\vec{B}}{c}$$
- For v ~ c, the resonance frequency becomes $$\nu = \frac{\varpi}{2\pi} = \frac{1}{2\pi}\left(\frac{q}{m}\right)\frac{1}{\gamma}\frac{B}{c}$$
- Thus for high energies, either B or ν should increase
- Machines with B is constant but ν varies are called synchrocyclotrons
- Machines there B changes independent of the change of ν is called synchrotrons

Synchroton Accelerators

- Electron synchrotrons, B varies while ν is held constant
- Proton synchrotrons, both B and ν varies
- For v ~ c, the frequency of motion can be expressed

$$\nu = \frac{1}{2\pi}\frac{v}{R} \approx \frac{c}{2\pi R}$$

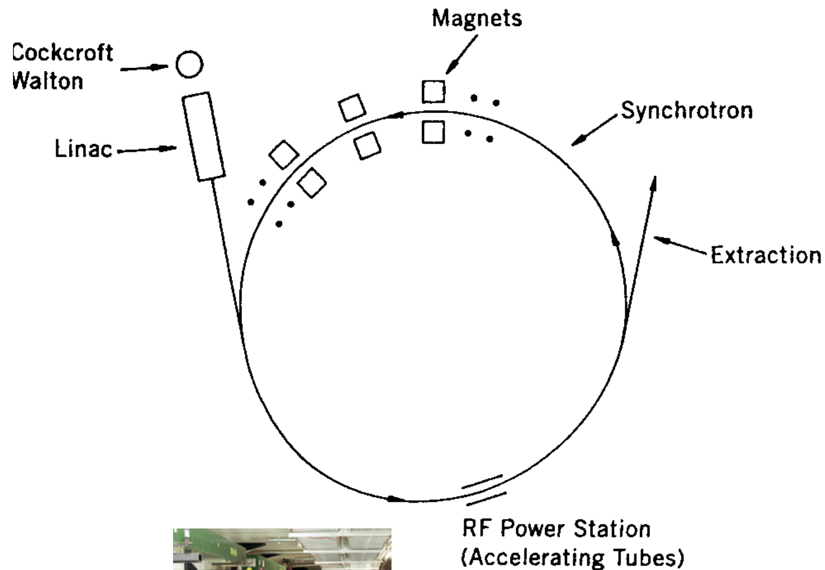
- For an electron

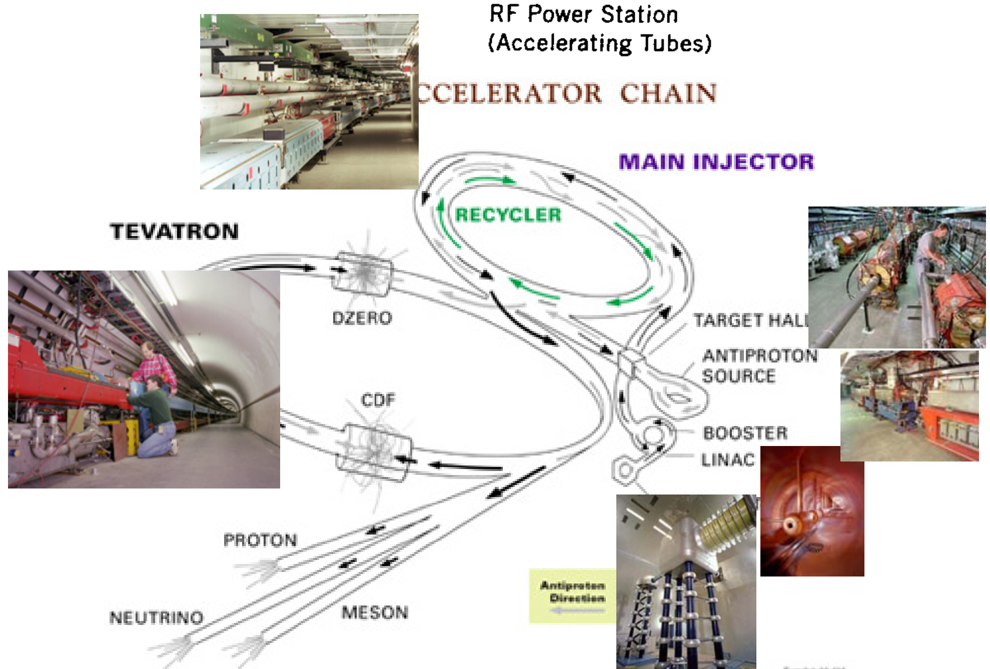
$$R(m) = \frac{pc}{qB} \approx \frac{p(GeV/c)}{0.3B(Tesla)}$$

- For magnetic field strength of 2Tesla, one needs radius of 50m to accelerate an electron to 30GeV/c.

Synchroton Accelerators

- Synchrotons use magnets arranged in a ring-like fashion.
- Multiple stages of accelerations are needed before reaching over GeV ranges of energies
- RF power stations are located through the ring to pump electric energies into the particles





Assignments

1. What are the threshold indices of refraction for protons, kaons and pions of momentum p to emit Cerenkov radiation? What are the actual values of indices of refraction for p = 1 and 10 GeV/c?
2. Compute the radius of an electron-positron synchrotron with 2T magnetic field to accelerate them to 100GeV/c.
3. Due for these assignments is Wednesday, Mar. 23.