Physics 129: Particle Physics
Lecture 5: Accelerators and Detectors (Part II)

Sept 10, 2020

Review from Last Class: Classification of particle detectors

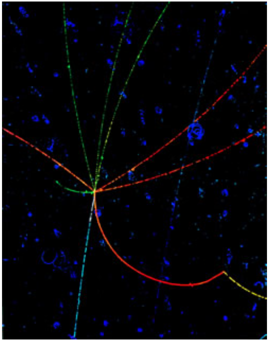
- Charged Particles
  - Momentum: Determine trajectory in B field
  - Mass: More difficult; Measurement of velocity and momentum
  - Energy: Deposited as particle stops.
    - Energy loss from ionization, bremsstrahlung
- Strongly Interacting Particles (charged or neutral)
  - Energy: Deposited where particle stops
    - Energy loss from nuclear interactions
- Photons
  - Energy: Pair production followed by ionization
- Muons
  - Momentum: As for other charged particles
  - No nuclear interactions
    - Can pass through lots of matter before stopping
    - Additional tracking detectors after calorimeter
- Neutrinos
  - Often observed by their absence: missing momentum
  - Weak interactions, eg $\nu_\mu N^Z \to \mu^- N^{Z+1}$ or $\nu_\mu N^Z \to \nu_\mu X$

Tracking Detectors

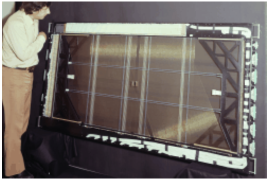
Calorimeters

Review: Types of Tracking Detectors

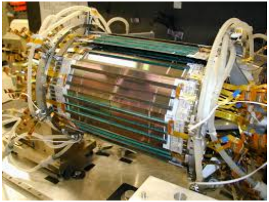
Bubble Chamber



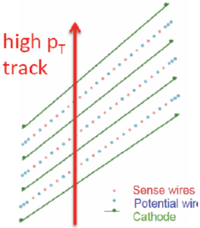
Multiwire Proportional Chamber



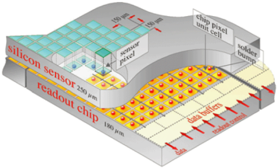
Silicon Strip Detector



Drift Chamber



Pixel Detector



Track Reconstruction

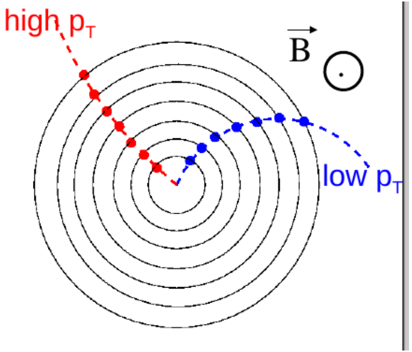
- Charged particles traverse many layers of detector
- Particle leaves an ionization "hit"
- Detectors often placed in magnetic field

  Lorenz force:

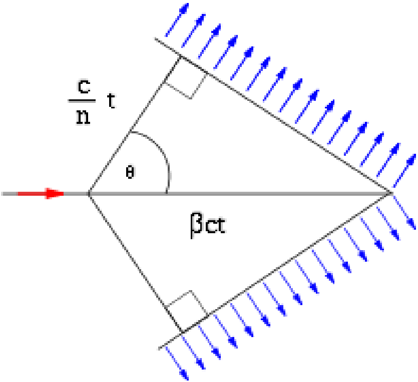
  $$\begin{aligned} F &= qv \times B \\ \Rightarrow p_T &= 0.3BR \end{aligned}$$

  $p_T \equiv$ component of momentum in plane $\perp \vec{B}$

- Hits along trajectory are "fit" to form a track
  - Deviation from straight line proportonal to momentum
  - Direction of curvature gives sign of charge



Cherenkov Radiation: Separating particle species



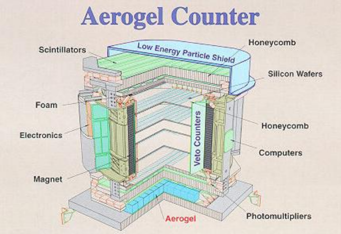
- Charged particle moving faster than light in medium produces radiation
- Wave-front is a cone of light with angle that depends on the index of refraction n of the medium

$$\cos\theta = \frac{1}{n\beta}$$

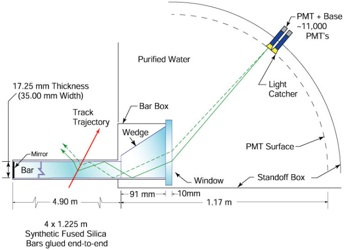
- Two types of Cherenkov detector:
  - Threshold: Separates species
    - Same p, different mass $\rightarrow$ different v
  - Ring imaging:
    - Measure θ to determine v

Examples of Cherenkov Detectors

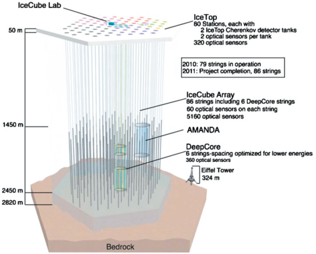
AMS Detector (International Space Station)

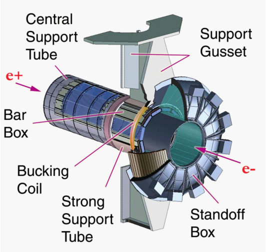


Babar DIRC

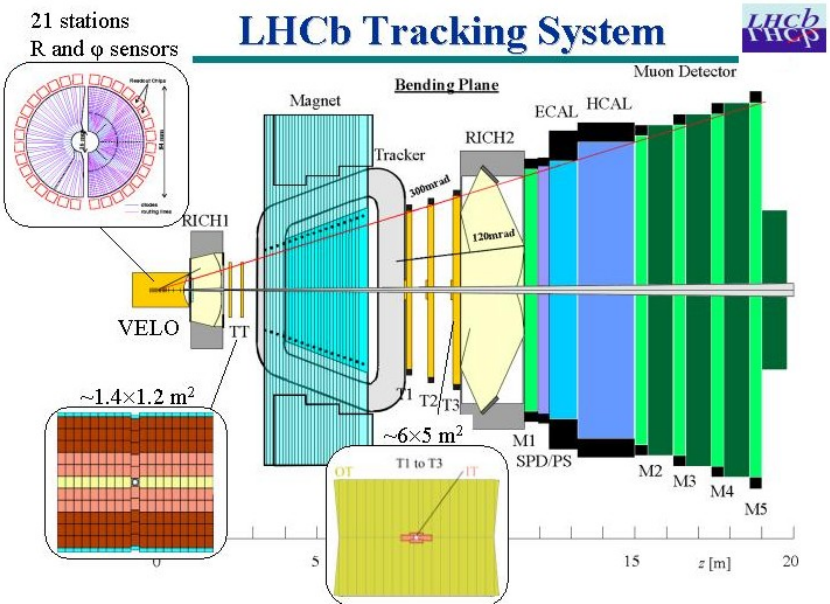


Icecube Detector (South Pole)

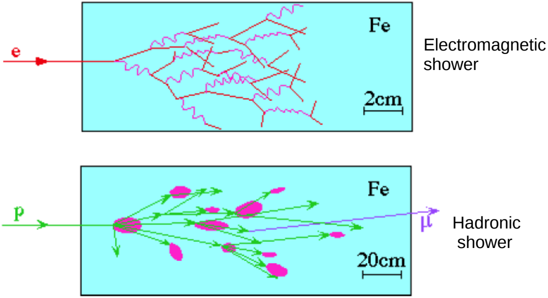




Example of Tracker with Multiple Components



Calorimeters



- Calorimeters are blocks of matter that:
  - Degrade the energy of particles through their interactions with matter
  - Are instrumented to detect the ionization and de-excitation of excited states through conversion to electronic signals
  - Measure signal of a magnitude that depends on energy of incident particle

Radiation Length

- Definition:
  - Mean distance over which a high-energy electron looses all but $1/e$ of its energy due to bremmsstahlung

    Units can be either cm or g/cm^2 (use density to convert)
- From Particle Data Group review:

$$\frac{1}{X_0} = 4\alpha r_e^2 \frac{N_A}{A} \left\{ Z^2 \left[L_{rad} - f(Z) \right] + Z L'_{rad} \right\}$$

where for $A = 1$ g/mol, $4\alpha r_e^2 \frac{N_A}{A} = 716.408$ g/cm^2; L and L' depend on the properties of the material

- A good approximation is

$$\frac{1}{X_0} = Z(Z+1) \frac{\rho}{A} \frac{\ln(287/Z^{0.3})}{716 \text{ g/cm}^3}$$

- X_0 also tells ups how long to takes for a photon to convert
  - X_0 is 7/9 of the mean free path for pair production from a high energy photon

Longitudinal and Transverse Shower Development

- Cascade due to
  - Bremsstrahlung ($e \to e\gamma$)
  - Pair production ($\gamma \to e^+e^-$)
- This continues until electrons fall below critical energy E_c
- Transverse size set by Moliere radius

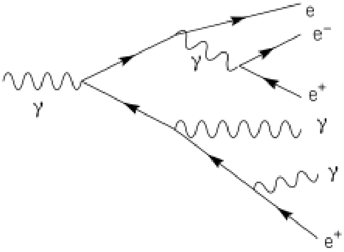
$$R_M = X_0\,(21\ \mathrm{MeV}/E_C)$$

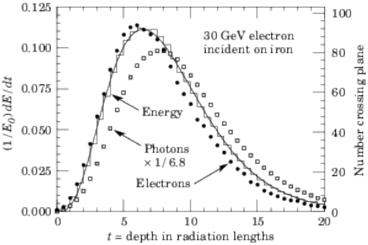
- For lead $X_0 = 0.56$ cm and $R_M = 1.53$ cm

$$\frac{dE}{dt} = E_0 b \frac{(bt)^{a-1}e^{-bt}}{\Gamma(a)}$$

where t is depth in radiation lengths

$$t_{max} = (a-1)/b$$



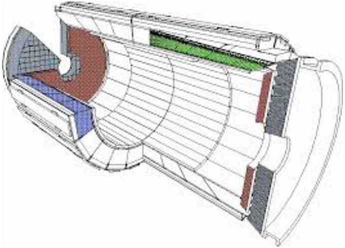


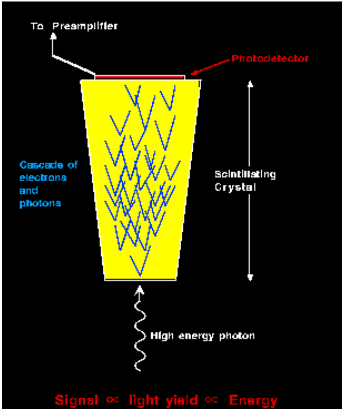
EM Calorimeters

- Total absorption calorimeter
  - Electrons and photons stop in calorimeter
  - Amount of scintillation light proportional incident energy
  - Blend of two materials: eg lead+crystal
  - Resolution typically $\propto 1/E^{1/4}$
- Sampling calorimeter
  - High Z material to induce shower: "absorber"
  - Another material to detect particles: "active material"
  - Alternating layers of absorber and active material
  - Resolution typically $\propto 1/E^{1/2}$ (more later)
  - Can be segmented longitudinally and/or transversely
- Absorber most often Pb for EM calorimeters ($Z = 82$)

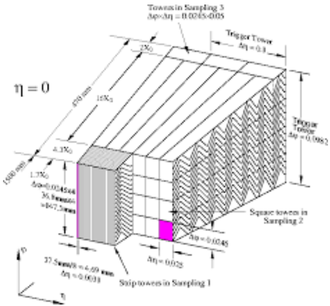
Example of Crystal (Total Absorption) Calorimeter: CMS

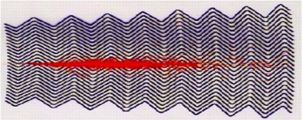
- $PbWO_4$ (lead-tungstate)
  - 22mm x 22mm x 230mm crystals in barrel
  - 75,848 crystals in total
  - 1% resolutuion at $E = 30$ GeV
  - Total depth: $25X_0$



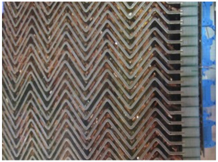


Example of Sampling Calorimeter: ATLAS Barrel Calorimeter

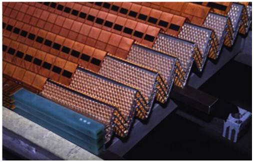




real device



radiator material



electrodes

- Accordion design
- Absorber: Pb
- Active material: liquid argon
  - Ionization electrons drift to sensors (Cu/kapton sheets)
  - Good transverse segmentation
- Resolution: 1.8% at 30 GeV
- 3 samples in depth
- Total depth: $22X_0$

Calorimeter energy resolution for sampling calorimeters

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

where

- a: “Stochastic term” (arises from fluctuations in shower)
- b: “noise term” (electronic noise)
- c: “constant term” (imperfections in calibration...)

Hadronic Showers

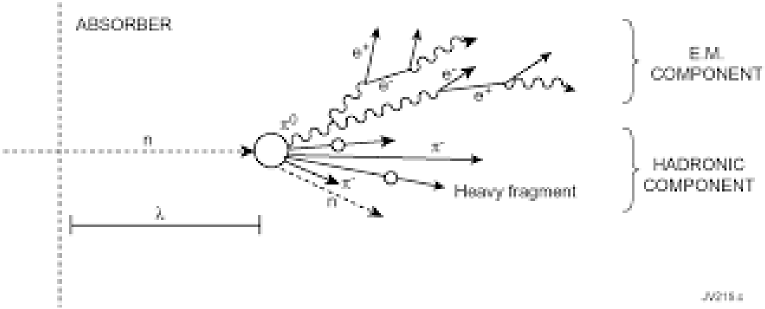
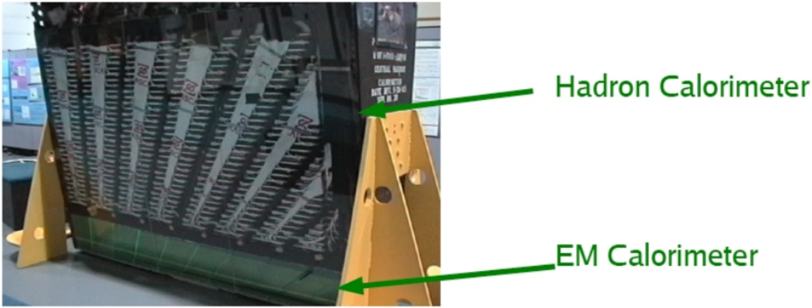


Figure 12: Schematic of development of hadronic showers.

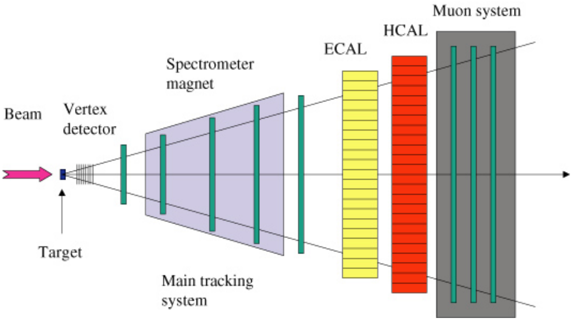
- Hadrons lose energy due to nuclear interactions in material
  - Characteristic length called "interaction length" λ
  - Depends on A rather than Z (as radiation length did)
- More complicated shower development the EM showers

Example of Combined Calorimeter Package: CDF



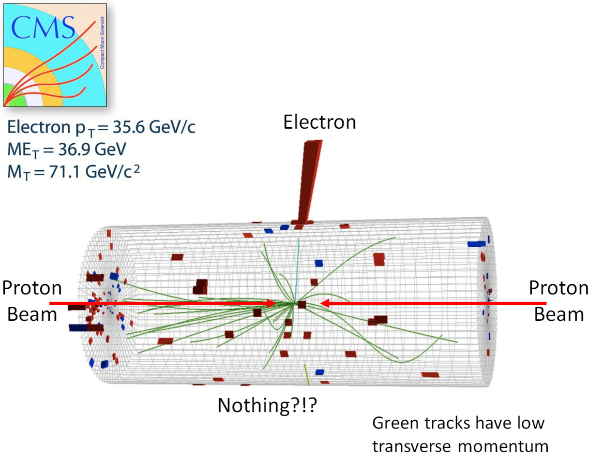
- Sampling calorimeter with sandwich structure
- EM calorimeter in front; absober is lead
- Hadronic calorimeter behind: absorber is steel
- Scintillator as active medium for both
- Projective "towers" that point to interaction region

Muon Detection



- Muon properties:
  - Muon mass more than 200 times that of electrons
    $\rightarrow$ Don't loose energy as quickly from bremsstrahlung
  - Are leptons $\rightarrow$ Don't feel strong interactions
- Energy loss dominantly from ionization $\rightarrow$ travel long distances in matter
- Detect using tracking chambers placed after lots of material
- Sometimes additional B field for a second momentum measurement

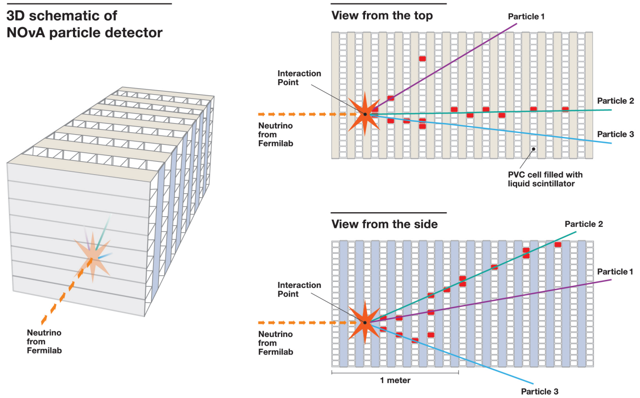
Neutrino Detection (I): via Missing Momentum



- Example of a $W^- \to e\overline{\nu}_e$ decay

Note: $m_W = 80$ GeV

Neutrino Detection (II): via weak interactions



- Charged current interactions

$$\nu_\mu + N^Z \to \mu^- + X^{Z+1}$$

- Neutral current interactions (X are hadrons produced in breakup nucleus))

$$\nu_\mu + N^Z \to \nu_\mu + X^Z$$

Accelerators: Introduction

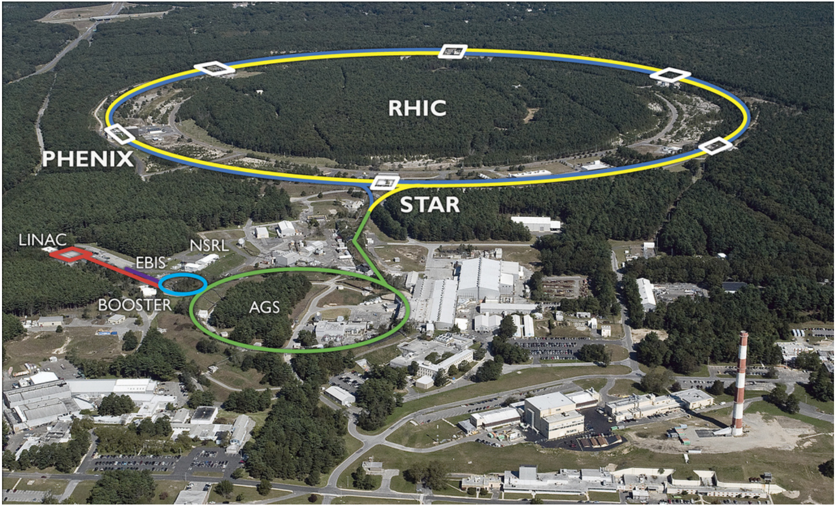
- 1^{st} accelerators not man-made
  - Radioactive sources: α, β, γ
  - Cosmic Rays
- Cosmics sources still used today
  - ν from sun, or produced in atmosphere
  - Dark matter??
- However:
  - Can't control energy or intensity
  - Can't turn them off
  - Can't select beam species
- Need for something more:

Man-made accelerators

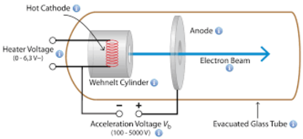
Components of an Accelerator

- Beams
  - Currents of charged particles that will be accelerated
  - Distributed in bunches (we'll see why in a few slides)
  - Transported in ultr-high vacuum
- Accelerating structures
  - Use electric fields or RF waves to accelerate particles
  - New techniques (eg laser acceleration) under study
- Magnets
  - Guide beams into well defined path
  - Focus beams to small transverse area
- To optimize performance, components usually arranged in a series of separate accelerators, each feeding the next

RHIC Heavy Ion Collider



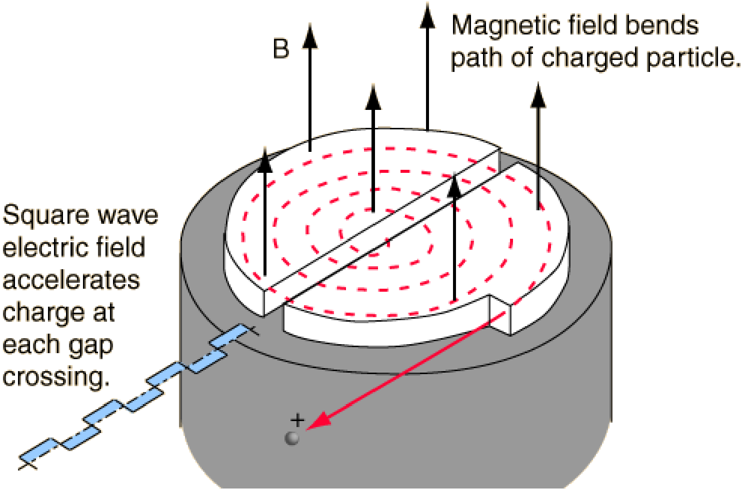
The Most Basic Accelerator: Electron Gun



- Heated wire used to spit off electrons
- HV to generate E-field: $KE = e\Delta V$
- Same idea can be used to accelerate p or $+$ ions
  - Attach electrons to atoms to make negative ions
  - Accelerate the ions
  - Strip ions of electrons by passing through foil
  - Mass spectrometer to separate
- Largest possible energy ~ 20 MeV
  - Typical energy ~ 100 KeV (Van der Graff)
  - Can we do better?

    Use AC rather than DC fields

The First AC Accelerator: The Cyclotron

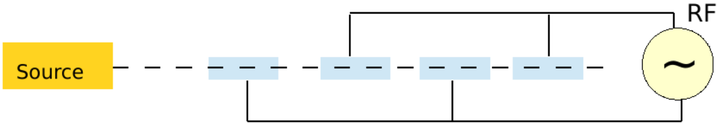


Observations about the Cyclotron

- Constant bending field B
  - Radius of curvature changes as particle accelerates
  - $p = eRB$
  - $t = 2\pi R/v = 2\pi R/(eRB/m) = 2\pi m/e$ if particle non-relativistic
- Large R needed to reach high energy if B limited
- As particle becomes relativistic, simple relationship between R and period no longer valid
- Solution
  - Change bending field as particle accelerates:

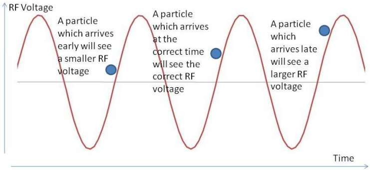
    Synchrotrons

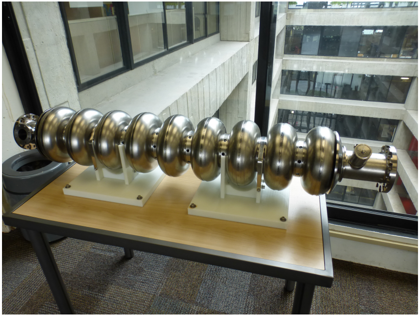
A better alternative for accelerating structures

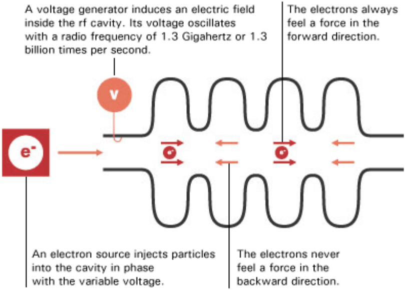


- Series of evacuated tubes with alternative tubes at opposite voltage
  - Inside tube, $E = 0$ so no acceleration
  - Between tubes ∼constant field
  - Set frequency so sign of E changes when particles in tube
  - Can get acceleration each time
- Must make tubes longer to compensate for increased velocity (until ultra-relativistic)
- Only particles with correct phase accelerated
  - Beam consists of bunches

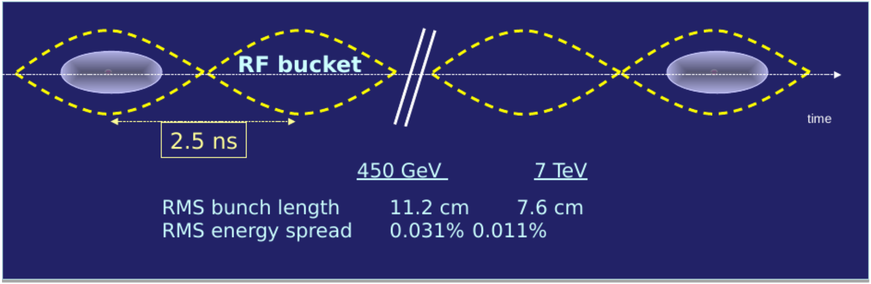
A more realistic alternative: RF Structures

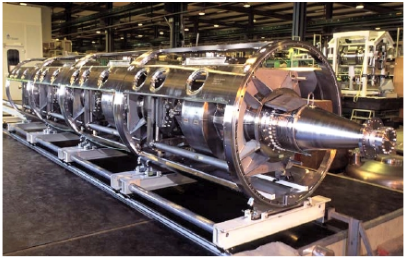






Fitting the beam into RF buckets at the LHC

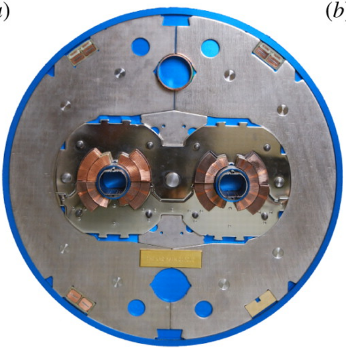




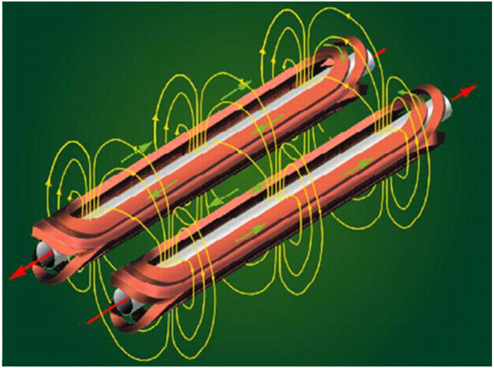
R. Assmann

Bending the beam: Dipole magnets

(a)



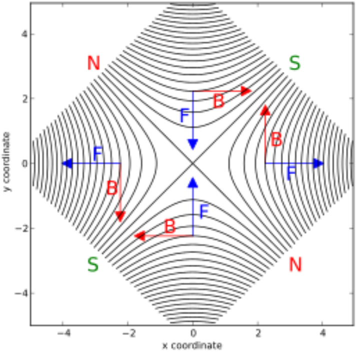
(b)



- Pictures above show LHC dipole magnets
  - Two bores since proton bunches travel in opposite directions
  - 15 m long
  - Superconducting magnets at temperature 1.9K

Focusing the beam: Quadrapoles

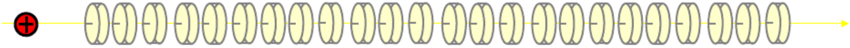
$$B_x = B'y \qquad B_y = B'x$$
$$F_x = qv_zB'x \quad F_y = -qv_zB'y$$



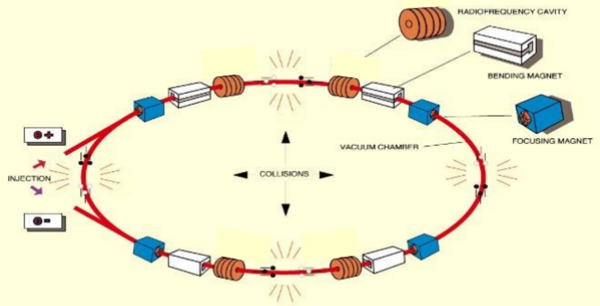
- Force is restoring in one direction, anti-restoring in the other
- Acts like a converging lens in one direction and diverging one in the other
- Several quadrapoles in series with appropriate spacing leads to overall focusing of beam in both directions

How to get to high energy: the options

LINAC (planned for several hundred GeV - but not above 1 TeV, e.g ILC)

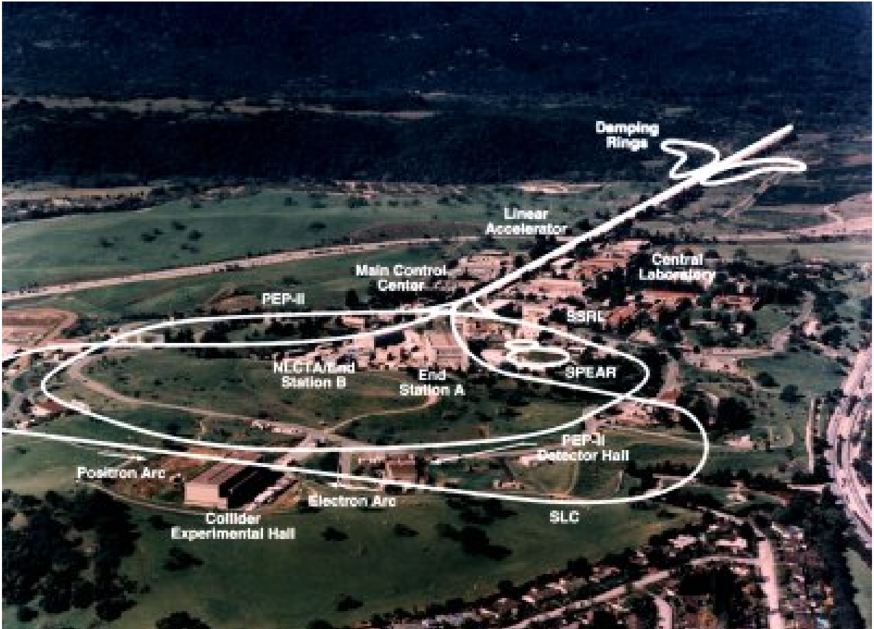


LHC **circular machine** with energy gain per turn ~0.5 MeV
acceleration from 450 GeV to 7 TeV takes about 20 minutes



...requires deflecting magnets (dipoles)

Another accelerator complex: SLAC



Event rates: Colliders

- Event rate proportional to luminosity

$$\mathcal{L} = fn\frac{N_1 N_2}{4\pi\sigma_x\sigma_y}$$

  - f: revolution frequency (LHC: 11 kHz)
  - n: number of bunches (LHC: 2808 bunches)
  - N_i: number of particles in bunch i (LHC: $\sim 10^{11}$)
  - σ: transverse size of the beam (LHC: $\sim 15\ \mu$m)

- Luminosity measured in cm^{-2}s^{-1} or pb^{-1}s^{-1}
  - Cross section per second
  - Specifies how many events per second would be observed for a process with unit cross section

$$N_{evt} = \sigma\mathcal{L}\Delta t$$

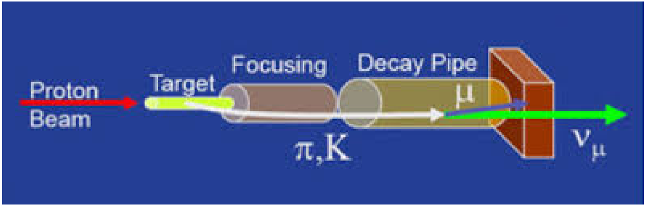
Event rates: Fixed Target

$$R = \sigma N_b n_T L$$

- R: rate (interactions per section)
- N_b: Beam rate (particles per second)
- n_T: Target number density (ρ/m_0)
- L: Target length

- Much higher rates achievable even with modest beam current and size
  - eg 1 m hydrogen target and a beam of 10^{13} particles/sec is equivalent of $\sim 10^{38}$ cm^{-2}s-1
    - LHC is 10^{34} cm^{-2}s-1

Fixed Target: Secondary and Tertiary Beams



- Primary proton beam hits target and makes secondaries
- Magnets used to select appropriate particle species and mass (π,K, etc)
- Masks and filters to removed unwanted particles
- Decay of selected particles used to create tertiary beam
  - Neutral beams (eg ν) can be created

Colliders: The past 30 years

- e^+e^-
  - LEP (CERN) 1989-2000 $\sqrt{s}$ =90-205 GeV
  - SLC (SLAC) 1989-1998 $\sqrt{s}$ =90 GeV
  - Asymmetric B-factories $\sqrt{s}$ =10 GeV:
    - PEPII (SLAC) 1999-2009
    - KEKB (KEK) 1999-present
- ep
  - HERA (DESY) $\sqrt{s}$ =920 GeV
- Hadrons
  - Tevatron (FNAL) 1986-2010 $p\bar{p}$, $\sqrt{s}$ =1.8-1.96 TeV
  - LHC (CERN) 2010-present pp, $\sqrt{s}$ =7,8,13 TeV (14 in future)
    - Also lead-lead and leap-proton collisions ~ 2.7 TeV per nucleon
  - RHIC (BNL) 2000-present Heavy ions with $\sqrt{s} = 200$ GeV per nucleon
    - Also, polarized protons with $\sqrt{s} = 500$ GeV

$\sqrt{s}$ $\equiv$center of mass energy