PHYS 3446 – Lecture #12

Monday, Mar. 7, 2005

Dr. Jae Yu

- Particle Detection
  - Ionization detectors
  - MWPC
  - Scintillators
  - Time of Flight Technique
  - Cerenkov detectors
  - Calorimeters

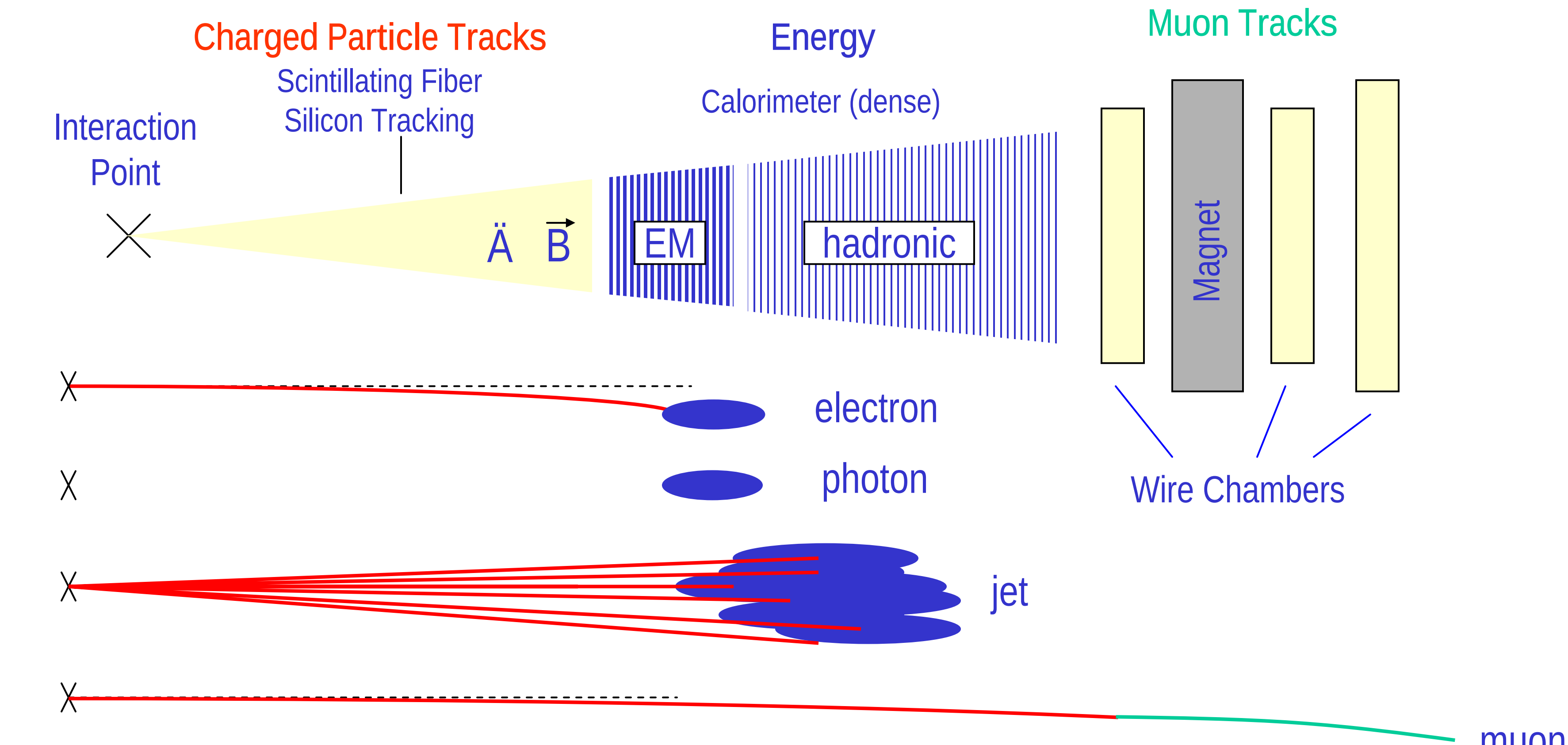
Announcements

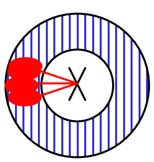
- Second term exam
  - Date and time: 1:00 – 2:30pm, Monday, Mar. 21
  - Location: SH125
  - Covers: CH4.5 – CH 8

Particle Detectors

- Subatomic particles cannot be seen by naked eyes but can be detected through their interactions within matter
- What do you think we need to know first to construct a detector?
  - What kind of particles do we want to detect?
    - Charged particles and neutral particles
  - What do we want to measure?
    - Their momenta
    - Trajectories
    - Energies
    - Origin of interaction (interaction vertex)
    - Etc
  - To what precision do we want to measure?
- Depending on the above questions we use different detection techniques

Particle Detection





neutrino -- or any non-interacting particle
missing transverse momentum

We know x,y starting momenta is zero, but along the z axis it is not, so many of our measurements are in the xy plane, or transverse

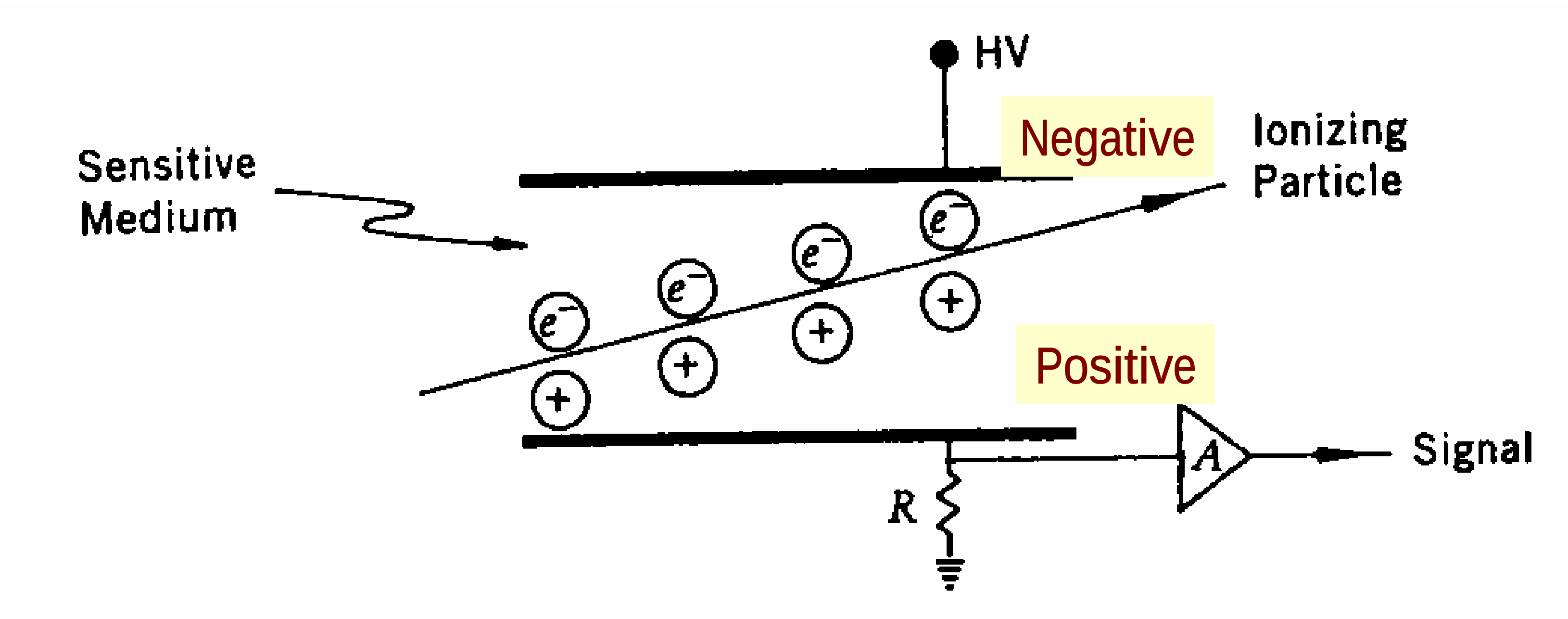
Ionization Detectors

- Measures the ionization produced when an incident particles traverses through a medium
- Can be used to
  - Trace charged particles through the medium
  - Measure the energy (dE/dx) of the incident particle
    - Must prevent re-combination of ion-electron into an atom after the ionization
    - Apply high electric field across medium
      - Separates charges and accelerates electrons

Ionization Detectors – Chamber Structure

- Basic ionization detector consists
  - A chamber with an easily ionizable medium
    - The medium must be chemically stable and should not absorb ionization electrons
    - Should have low ionization potential ($\bar{I}$) ➔ To maximize the amount of ionization produced per given energy
  - A cathode and an anode held at some large potential difference
  - The device is characterized by a capacitance determined by its geometry

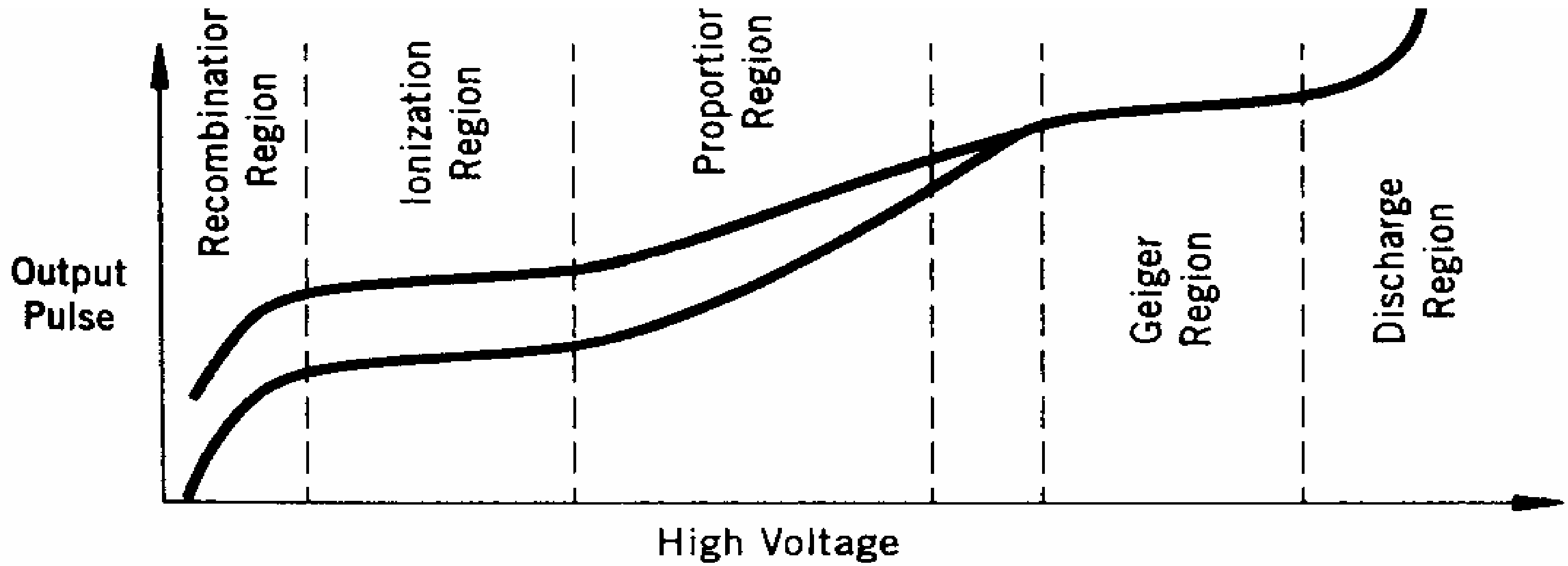
Ionization Detectors – Chamber Structure



- The ionization electrons and ions drift to their corresponding electrodes, to anode and cathode
  - Provide small currents that flow through the resistor
  - The current causes voltage drop that can be sensed by the amplifier
  - Amplifier signal can be analyzed to obtain pulse height that is related to the total amount of ionization

Ionization Detectors – HV

- Depending on the magnitude of the electric field across the medium different behaviors are expected
  - Recombination region: Low electric field
  - Ionization region: Medium voltage that prevents recombination
  - Proportional region: large enough HV to cause acceleration of ionization electrons and additional ionization of atoms
  - Geiger-operating region: Sufficiently high voltage that can cause large avalanche if electron and ion pair production that leads to a discharge
  - Discharge region: HV beyond Geiger operating region, no longer usable



Ionization Counters

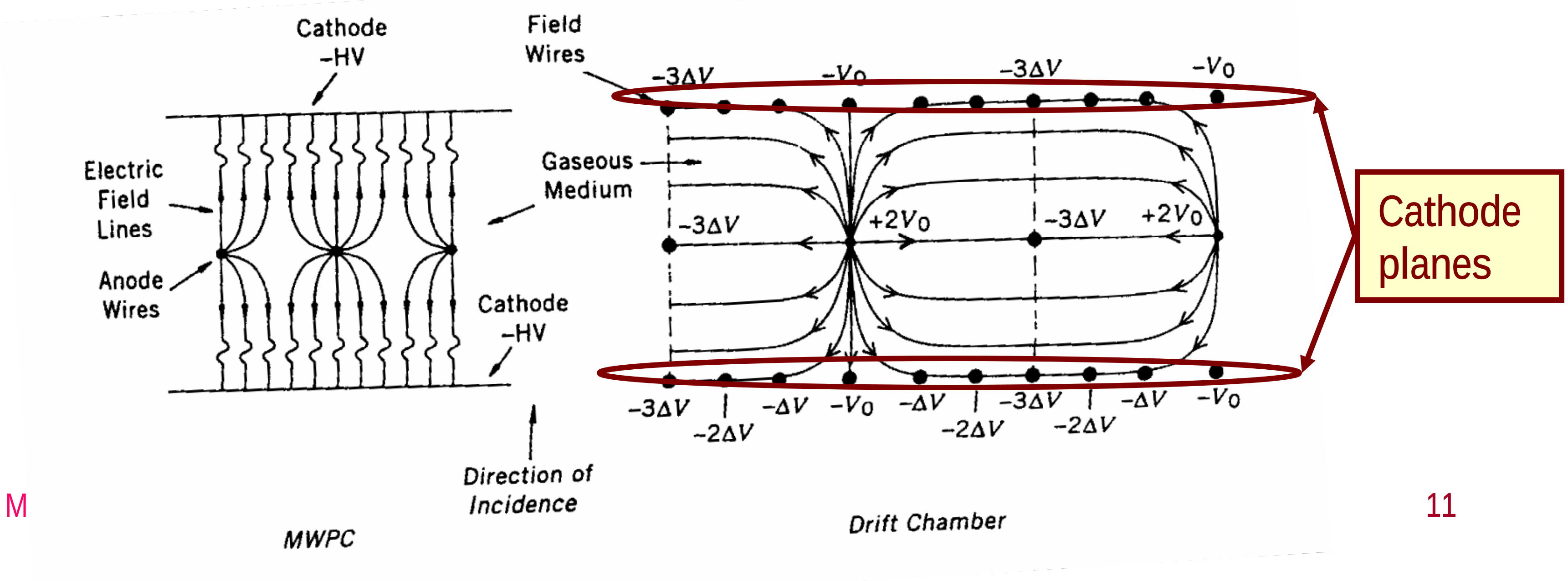
- Operate at relatively low voltage
- Generate no amplification of the original signal
- Output pulses for minimum ionizing particle is small
- Insensitive to voltage variation
- Have short recovery time → Used in high interaction rate environment
- Response linear to input signal
- Excellent energy resolution
- Liquid argon ionization chambers used for sampling calorimeters
- Gaseous ionization chambers are useful for monitoring high level of radiation, such as alpha decay

Proportional Counters

- Gaseous proportional counters operate in high electric fields ~10^4 V/cm.
- Typical amplification of factors of ~10^5
- Use thin wires (10 – 50 μm diameter) as anode electrodes in a cylindrical chamber geometry
- Multiplication occur near the anode wire where the field is strongest causing secondary ionization
- Sensitive to the voltage variation ➔ not suitable for energy measurement
- But used for tracking device

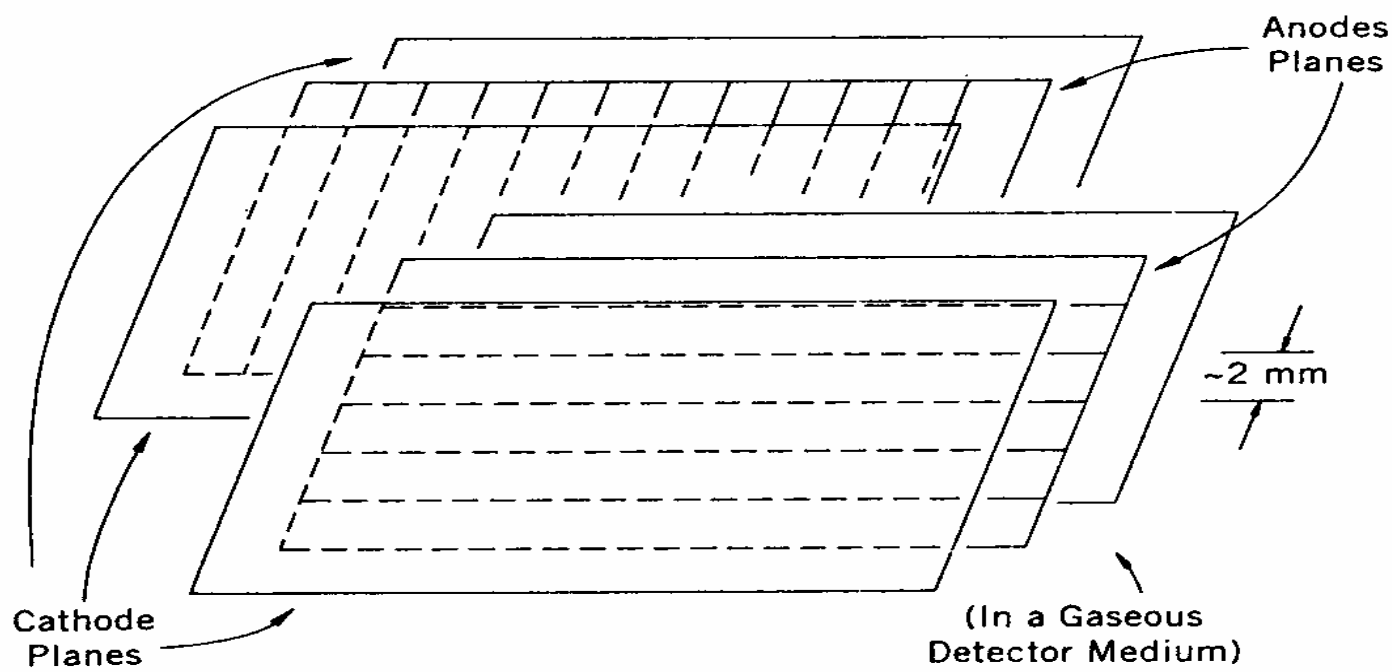
Multi-Wire Proportional Chambers (MWPC)

- G. Charpak et al developed a proportional counter in a multiwire proportional chamber
  - One of the primary position detectors in HEP
- A plane of anode wires positioned precisely w/ about 2 mm spacing
- Can be sandwiched in similar cathode planes (in <1cm distance to the anodes) using wires or sheet of aluminum



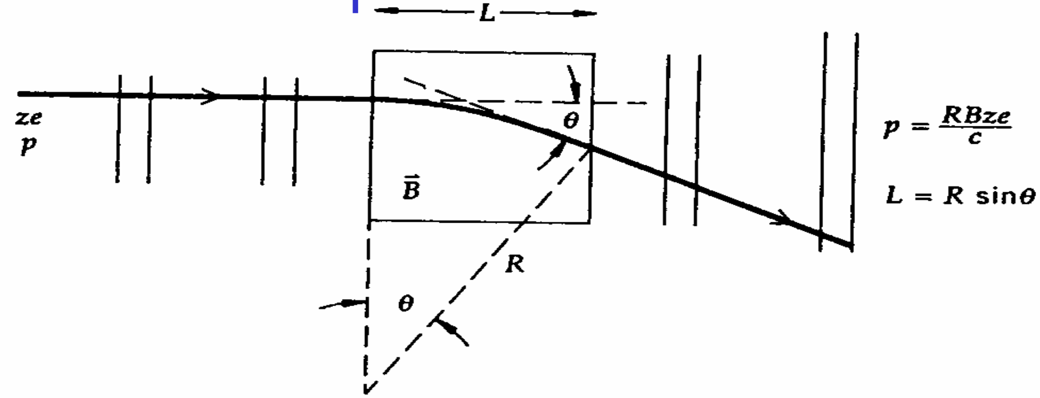
Multi-Wire Proportional Chambers (MWPC)

- These structures can be enclosed to form one plane of the detector
- Multiple layers can be placed in a succession to provide three dimensional position information



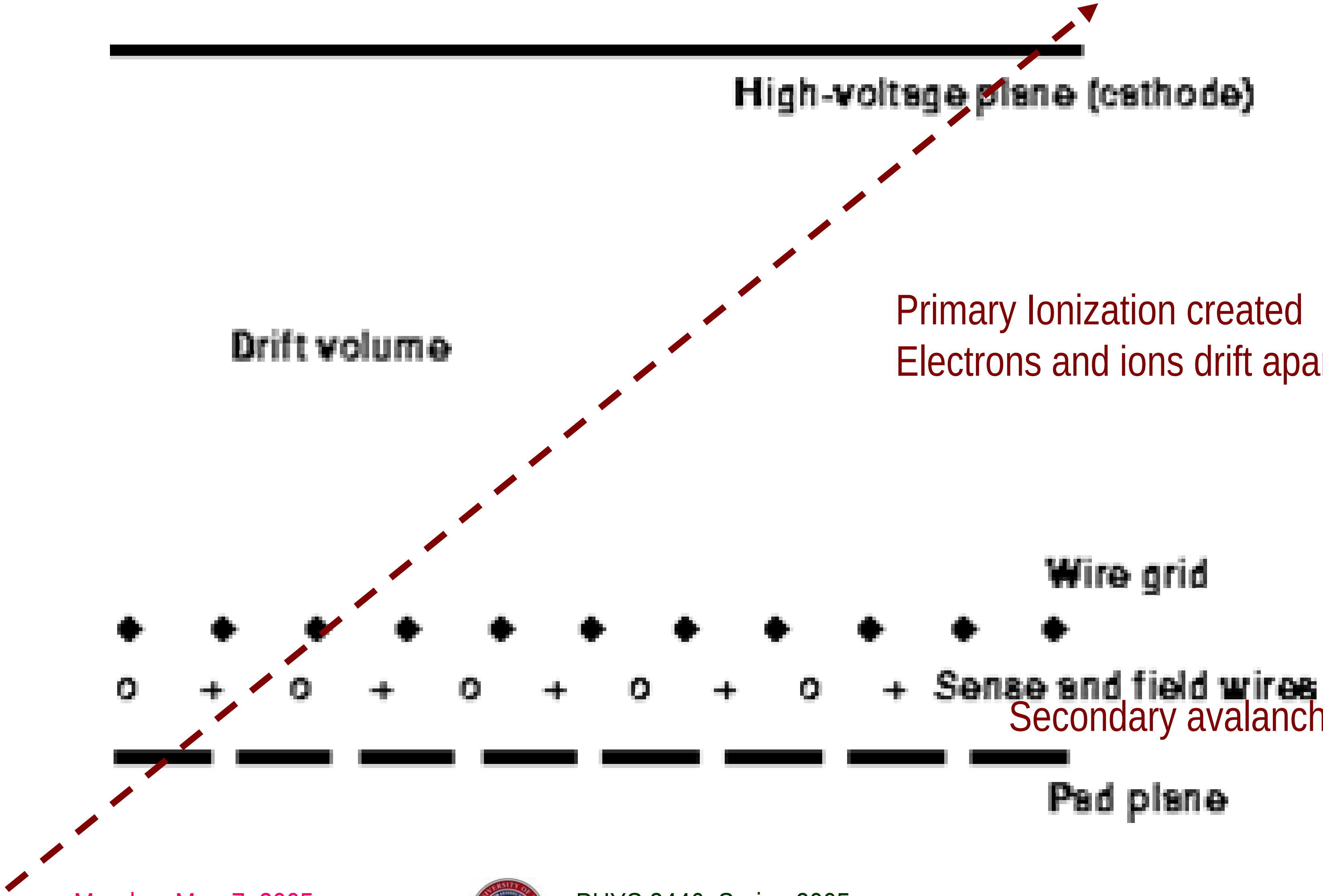
Momentum Measurements

- A set of MWPC planes placed before and after a magnetic field can be used to obtain the deflection angle which in turn provide momentum of the particle



- Multiple relatively constant electric field can be placed in each cell in a direction transverse to normal incident ➔ Drift chambers
- Typical position resolution of proportional chambers are on the order of 200 μm.

A Schematics of a Drift Chamber



Primary Ionization created
Electrons and ions drift apart

Secondary avalanche occurs

Geiger-Muller Counters

- Ionization detector that operates in the Geiger range of voltages
- For example, an electron with 0.5MeV KE that looses all its energy in the counter
- Assume that the gaseous medium is helium with an ionization energy of 42eV.
- Number of ionization electron-ion pair in the gas is $n = \frac{0.5 \times 10^6 eV}{42 eV} \approx 12,000$
- If the detector operates as an ionization chamber and has a capacitance of 1 nF, the resulting voltage signal is

$$V = \frac{Q}{C} = \frac{ne}{C} = \frac{1.2 \times 10^4 \times 1.6 \times 10^{-19} C}{1 \times 10^{-9} F} \approx 2 \times 10^{-6} V$$

- In Geiger range, the expected number of electron-ion pair is of the order 10^{10} independent of the incoming energy, giving about 1.6V pulse height

(Dis) Advantage of Geiger-Muller Counters

- Simple construction
- Insensivity to voltage fluctuation
- Used in detecting radiation
- Disadvantages
  - Insensitive to the types of radiation
  - Due to large avalanche, takes long time (~1ms) to recover
    - Cannot be used in high rate environment

Scintillation Counters

- Ionization produced by charged particles can excite atoms and molecules in the medium to higher energy levels
- The subsequent de-excitation process produces lights that can be detected and provide evidence for the traversal of the charged particles
- Scintillators are the materials that can produce lights in visible part of the spectrum

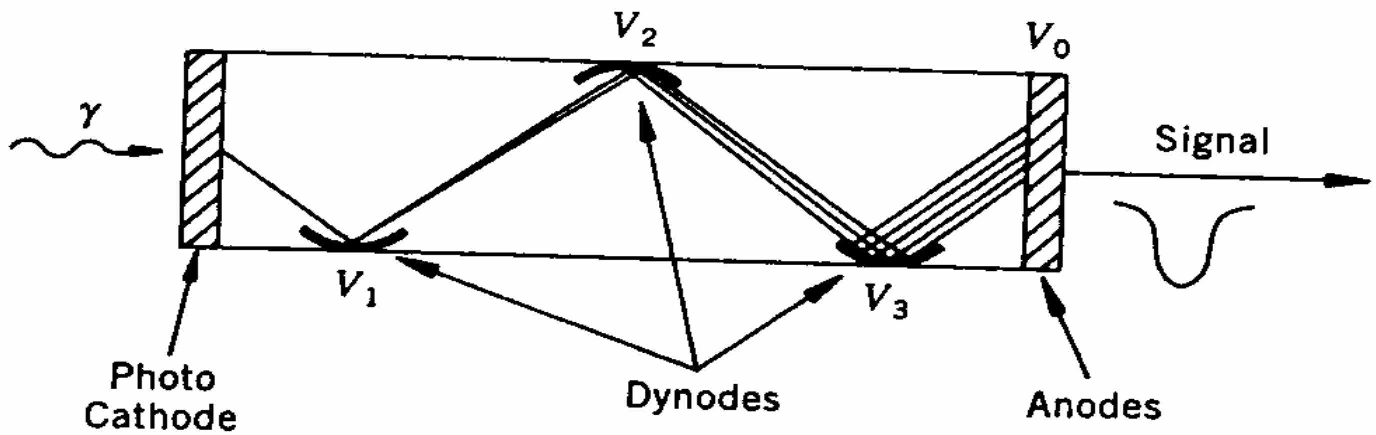
Scintillation Counters

- Two types of scintillators
  - Organic or plastic
    - Tend to emit ultra-violate
    - Wavelength shifters are needed to reduce attenuation
    - Faster decay time (10^{-8}s)
    - More appropriate for high flux environment
  - Inorganic or crystalline (NaI or CsI)
    - Doped with activators that can be excited by electron-hole pairs produced by charged particles in the crystal lattice
    - These dopants can then be deexcited through photon emission
    - Decay time of order 10^{-6}sec
    - Used in low energy detection

Scintillation Counters – Photo-multiplier Tube

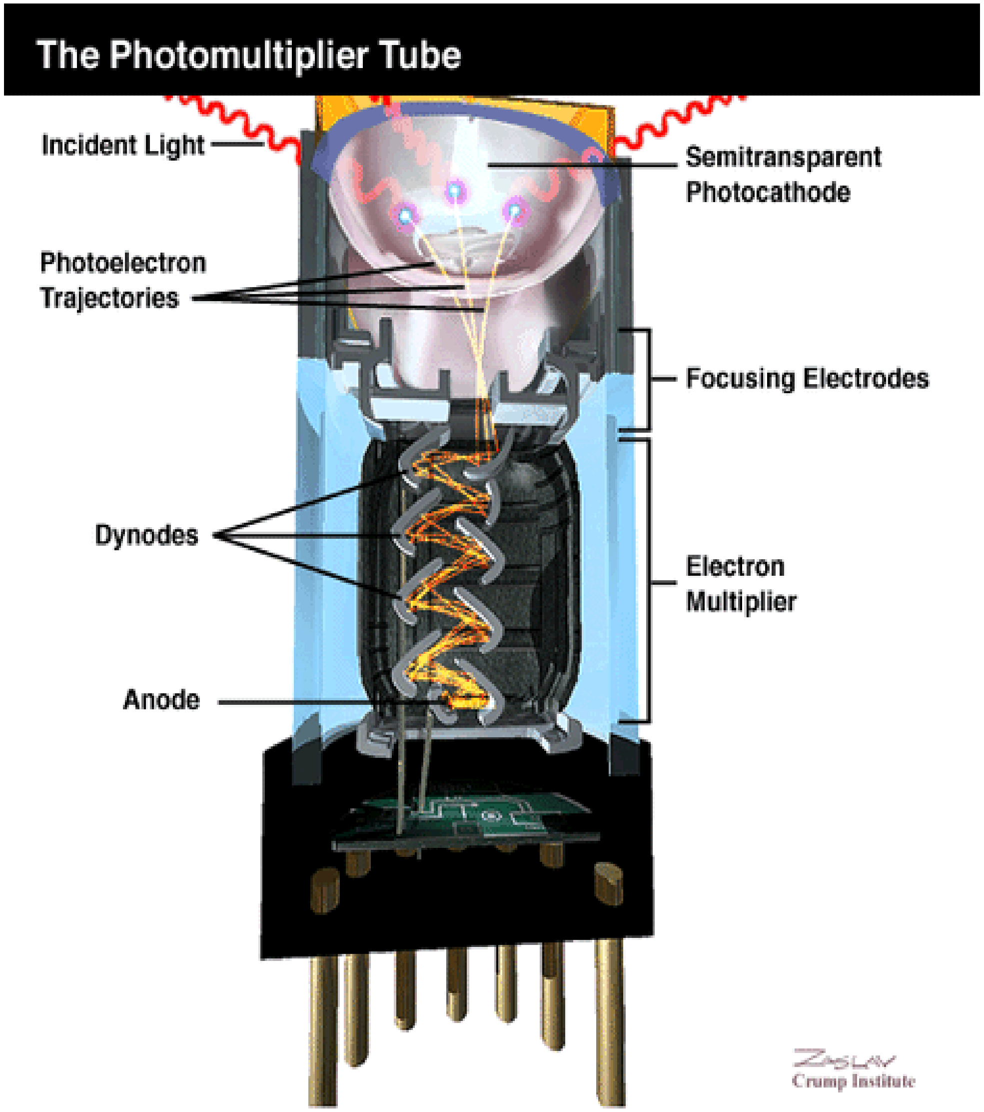
- The light produced by scintillators are usually too weak to see
  - Photon signal needs amplification through photomultiplier tubes
    - Gets the light from scintillator directly or through light guide
      - Photocathode: Made of material in which valence electrons are loosely bound and are easy to cause photo-electric effect (2 – 12 cm diameter)
      - Series of multiple dynodes that are made of material with relatively low work-function
        - » Operating at an increasing potential difference (100 – 200 V difference between dynodes

Scintillation Counters – Photo-multiplier Tube



- The dynodes accelerate the electrons to the next stage, amplifying the signal to a factor of $10^4 - 10^7$
- Quantum conversion efficiency of photocathode is typically on the order of 0.25
- Output signal is proportional to the amount of the incident light except for the statistical fluctuation
- Takes only a few nano-seconds for signal processing
- Used in as trigger or in an environment that requires fast response
- Scintillator+PMT good detector for charged particles or photons or neutrons

Some PMT's



Super-Kamiokande detector

Time of Flight

- Scintillator + PMT can provide time resolution of 0.1 ns.
  - What position resolution does this corresponds to?
    - 3cm
- Array of scintillation counters can be used to measure the time of flight (TOF) of particles and obtain their velocities
  - What can this be used for?
    - Can use this to distinguish particles with about the same momentum but with different mass
  - How?
    - Measure
      - the momentum (p) of a particle in a magnetic field
      - its time of flight (t) for reaching some scintillation counter at a distance L from the point of origin of particle
      - Determine the velocity of the particle and its mass

Time of Flight

- TOF is the distance traveled divided by the speed of the particle, t=L/v.
- Thus Δt in flight time of the two particle with m_1 and m_2 is

$$\Delta t = t_2 - t_1 = L\left(\frac{1}{v_2} - \frac{1}{v_1}\right) = \frac{L}{c}\left(\frac{1}{\beta_2} - \frac{1}{\beta_1}\right)$$

- For known momentum, p,

$$\Delta t = \frac{L}{c}\left(\frac{E_2}{pc} - \frac{E_1}{pc}\right) = \frac{L}{pc^2}\left[\sqrt{m_2^2c^4 + p^2c^2} - \sqrt{m_1^2c^4 + p^2c^2}\right]$$

- In non-relativistic limit, $\Delta t = \frac{L}{p}\left(m_2 - m_1\right) = \frac{L}{p}\Delta m$
- Mass resolution of ~1% is achievable for low energies

Assignments

1. Derive Eq. 7.10
2. Carry out computations for Eq. 7.14 and 7.17
3. Due for these assignments is Wednesday, Mar. 23.