Ion Collectors and Detectors

- Some ideal characteristics of Ion Collectors and Detectors

  1. Ideally should measure the intensity of the total ion beam
  2. Should be able to get multiple detectors without interference
  3. High Sensitivity
  4. Wide dynamic range
  5. High linearity
  6. Low Noise
  7. No changes in behavior over time
  8. Easy to Use

- Not possible to meet all of these characteristics at the same time

Ion Beam Measurement Characteristics

- Made up of individual ions arriving at the detector at an average rate that is a measure of the number of ions generated at the source
- Theoretically at least the rate of ions entering the detector is a measure of the amount of that isotope in the sample
- Theoretically if we ratio the rates of two isotope beams this ratio is the ratio of the two isotopes in the sample:

$$\frac{R_1}{R_2} = \frac{S_1}{S_2}$$

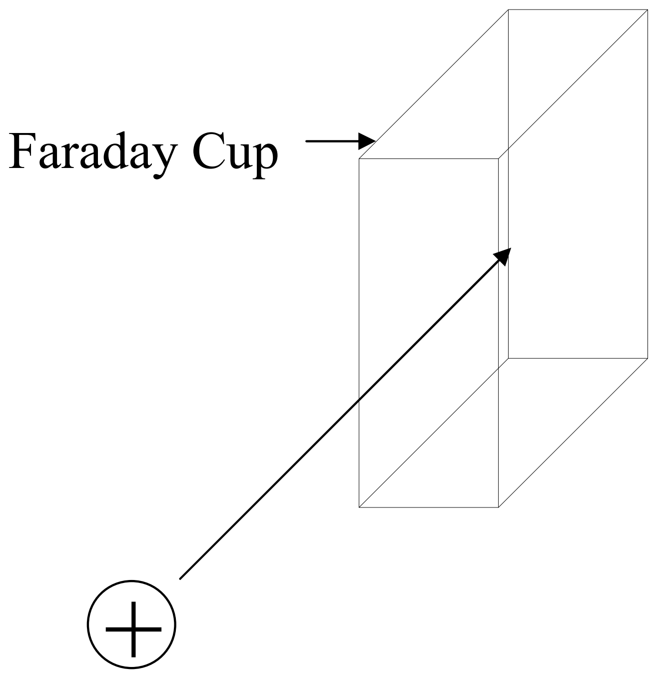
- Where R_1 is the rate of isotope 1, R_2 is the rate of isotope 2, S_1 is the amount of isotope 1 in the sample and S_2 is the amount of isotope 2 in the sample.

Measurements

- How do we measure the rates?
  - We can measure the rate directly--that is, directly count the number of ions appearing at the detector over a certain period of time
    - This is known as ion or pulse counting
  - The ion beam is an electric current
    - We can measure some parameter associated with electric currents and use this as a proxy for the rate
    - This is known as analog measurement
    - We can measure charge, current or voltage (we will discuss this in more detail when we discuss the associated electronics
- We will discuss types of detectors first

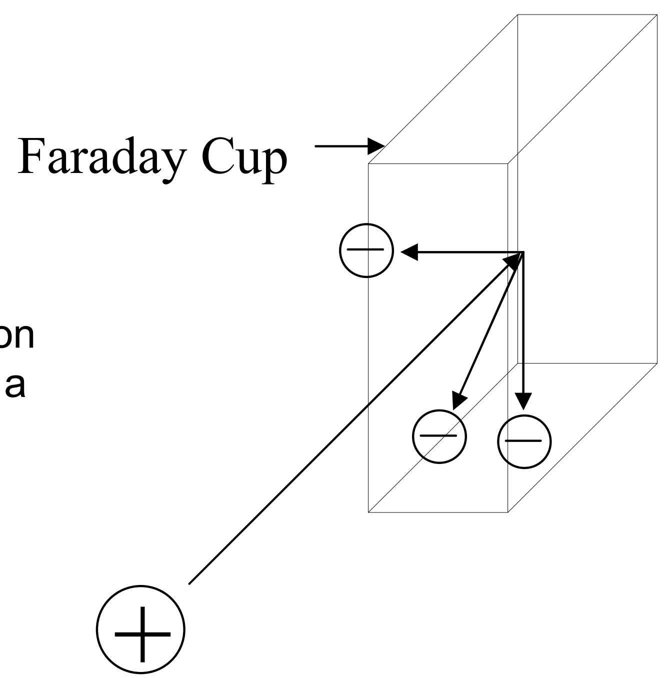
Faraday Cups

- Technically more an ion collector than detector
- Basically what the name implies: a cup the ions enter and transfer their charge to the cup
- Charge is usually tranferred to electronics outside the vacuum system
- Type of electronics determines whether measured as charge, current or voltage



Faraday Cups continued

- The faraday cup seems simple but in practice becomes quite complicated
- The first and major complication is that the ions entering have energies significantly higher than the work function of the cup material (stainless steel, carbon, graphite)
- This causes the generation of free electrons (know as secondary electrons)
- If a secondary electron leaves the cup this makes the charge on the cup look like an additional + ion has entered.



Since each ion can generate many secondary electrons, even the loss of a small portion of these electrons can cause a large error in measurement

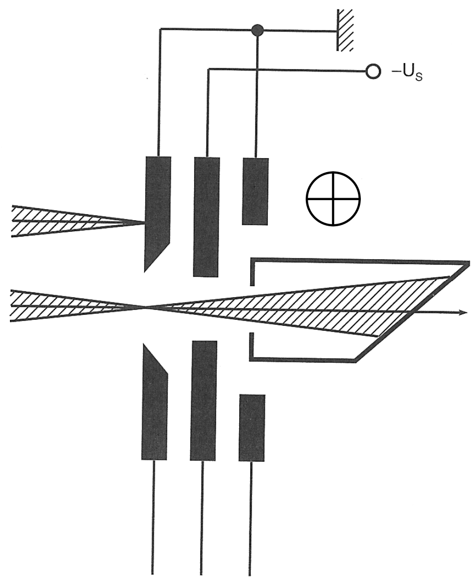
Faraday Cups continued

- What determines the number of secondary electrons?
  - Mass of ions
  - Energy of ions
  - Charge on ions
  - Angle of incidence
  - Material of cup
  - Nature of ion (monatomic vs. polyatomic)

- How can we reduce the effect of secondary electrons?
  - Passive and Active techniques

- Passive
  - Make cup of material that generates fewer secondary electrons
  - Make cup deep and narrow
- Active
  - Magnetic field to confine electrons to cup
  - Slit plate (repellor or plate) placed before cup with negative voltage, electrons that leave cup are forced back into the cup

Faraday Cups



Magnetic field plus repellor plate reduces secondary electron loss to a few hundred parts
Per million or less

Ions can also enter the cup and be reflected without giving up their charge, a positive plate
Can be placed in front of the negative repellor to reflect back these ions

More Faraday Cup

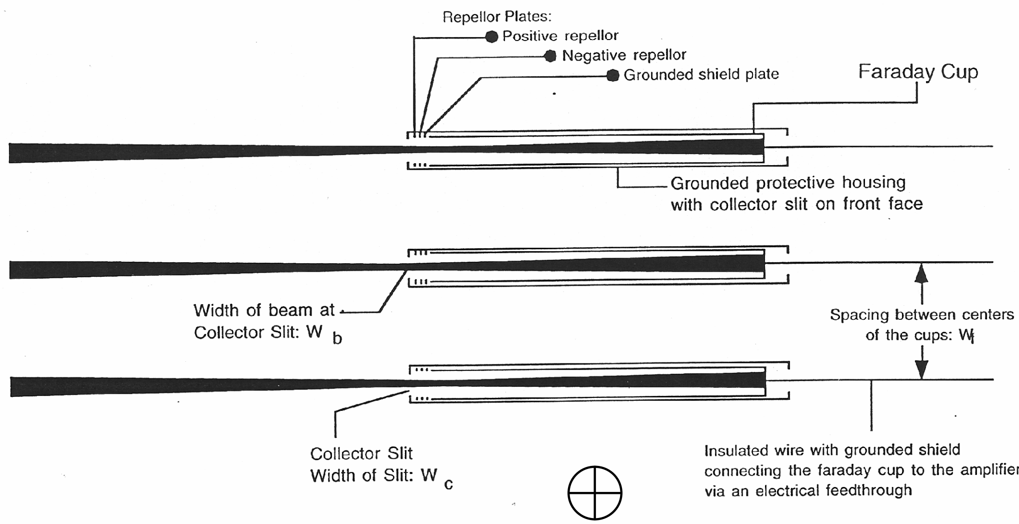


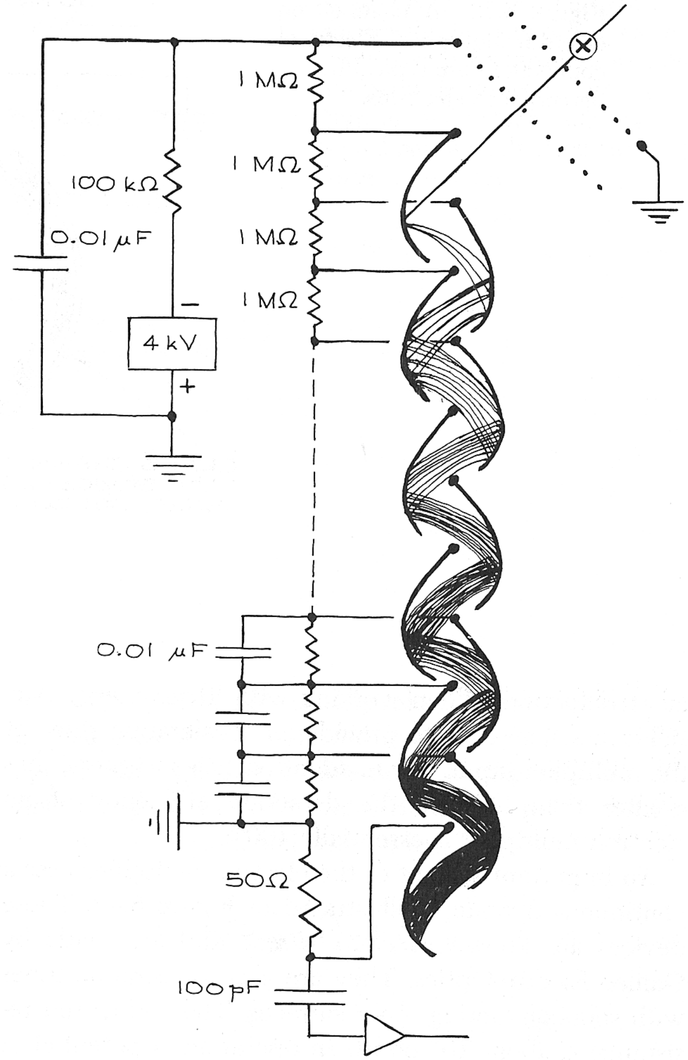
Figure 2: Diagram of three faraday cup collectors set for Sr spacing (Sr^{87} in the axial position) for a mass spectrometer with an effective radius of 54 cm. Scale: 4x. Ion beams are diverging with half-angles of 1^{o}

More more faraday cup

- Faraday Cups can go “bad”
- Material in the ion beams can be deposited on the surface of the cup (or even react with it)
- This surface layer can generate copious secondary electrons
- Coating the cup with graphite (or making it out of graphite) enhances the lifetime and also reduces secondary electron generation
- Some characteristics of faraday cups
  - Can be made thin (~2mm) so multiple cups can be placed in the MS and closely spaced peaks can be measured
  - Beam intensities of 10^{-18} A and up can be measured (depends mostly on the electronics used), typical dynamic range of 10^5 (again mainly dependent on electronics)
  - As long as secondary electron generation and ion reflection are controlled, the linearity, sensitivity and accuracy depend mainly on the electronics, although residual cup effect usually remain (generally placed under the description of cup efficiency)
  - Generally run in analog mode

Electron Multiplier

- Faraday Cups are limited in sensitivity and dynamic range
- Electron multipliers and similar devices (e.g. Daly Detector) can improve sensitivity and dynamic range
- All of these devices first use the ions to generate electrons and then amplify the electrons
- Basic electron multiplier:
  - Incoming ion generates electrons at the first dynode, the number depends on similar factors as secondary electrons in faraday cup
  - As electrons cascade to next dynode they release more electrons (typically one to two electrons, depends on voltage difference between dynodes)



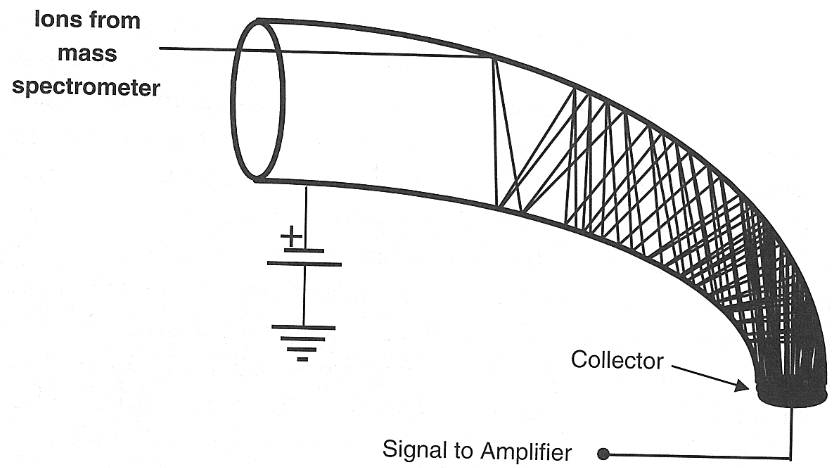
Electron Multiplier

- High gains (up to 10^7 in some cases) mean high sensitivities
- Each ion produces narrow pulse of electrons at final dynode
  - Both analog and ion counting possible
  - Number of electrons at final dynode proportional to efficiency of electron production at first dynode
- Linear response at low gains and ion rate
- Gain can be varied by adjusting voltage

- Some problems with multipliers:
  - At high gains and count rates response becomes non-linear
  - First dynode can be damaged by ions and tends to degrade over time
  - Mass dependence of electron production at first dynode
  - Spurious ions generated by electrons
  - Closely spaced pulses cannot be separated (not a problem in analog mode), known as dead time
  - Must be shielded from external magnetic and electric fields

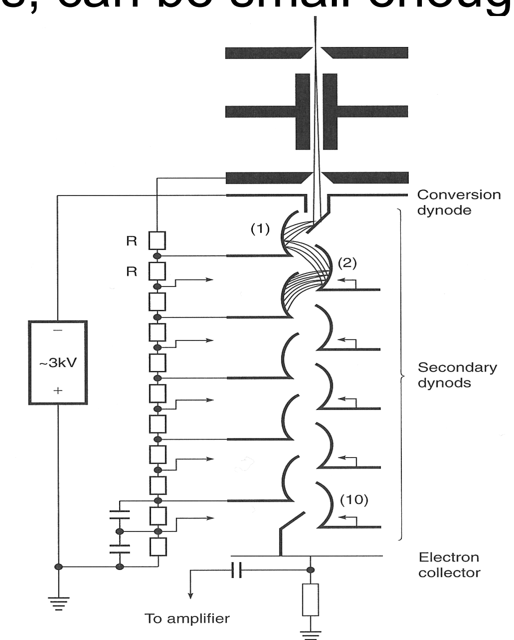
Electron Multiplier

- Variation on Electron Multiplier-the continuous dynode multiplier or channeltron:



- Can be made very small and in different shapes, can be small enough to substitute for faraday cups
- Suffers many of the same problems as EM

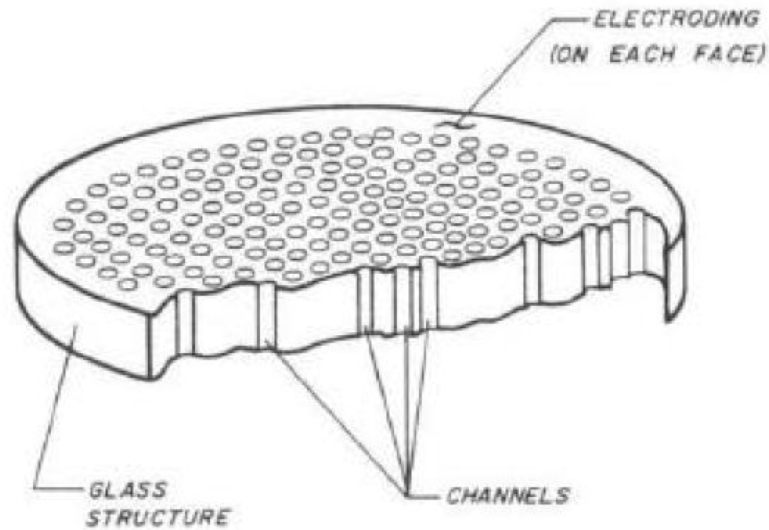
- Problems with ion damage
  can be mitigated with conversion dynode



- Channeltrons can be made very small and stacked together
- These microchannel plates can be made large and cover a wide area
- Useful in Time-of-Flight mass spectrometer and wherever the beam covers a large area

- Microchannel plates have improved time resolution over other detectors

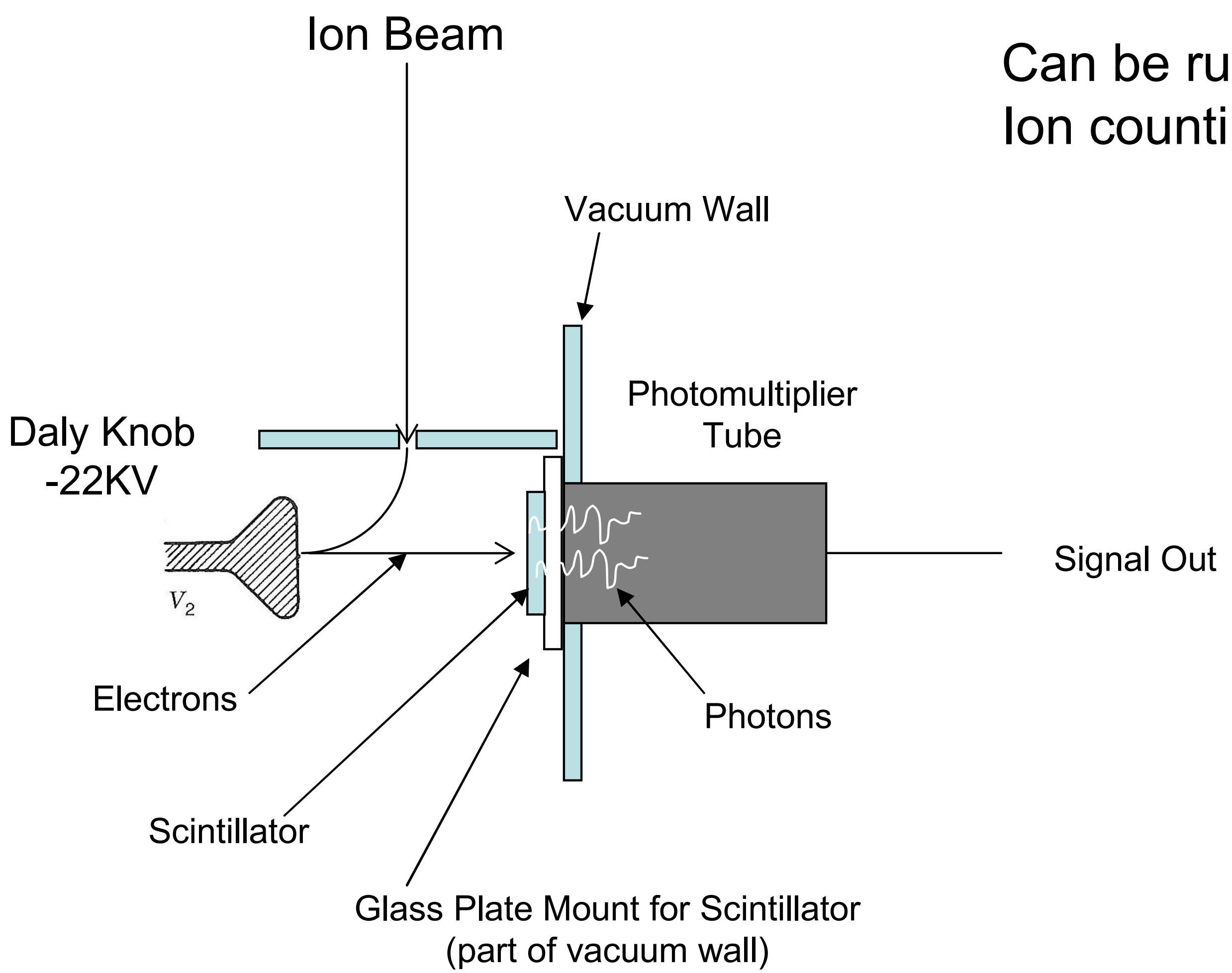
- However, they suffer from many of the same problems as other multipliers



Daly Detector

- The Daly Detectors gets around some of the problems of traditional multipliers:

Can be run in both analog and Ion counting mode



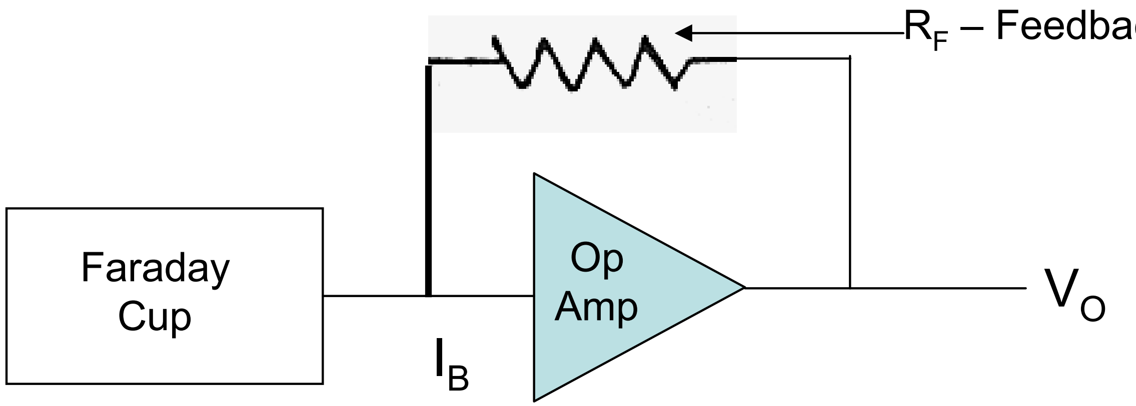
Daly Characteristic

- Advantages:
  - Knob more robust than first dynode of EM
  - Smaller mass dependence
  - Lower noise for same current gain
  - High current gains, 1 ion gives 1 to 5 electrons at knob, each electron gives 5 to 10 photons at the scintillator, each photon gives 2 to 10 electrons at the first dynode of the PM
  - Signal Pulse intensity usually well above noise intensities
  - Linear wide dynamic range (10^{-21} to 10^{-13} A)

- Disadvantages:
  - Complicated
  - Large footprint
  - Longer dead time
  - Scintillator damaged by high electron currents and heat

Electronics-Analog Mode

- Current measurement mode most common and usually involves a current to voltage converter (CVC):



$$V_O = -R_F \cdot I_B$$

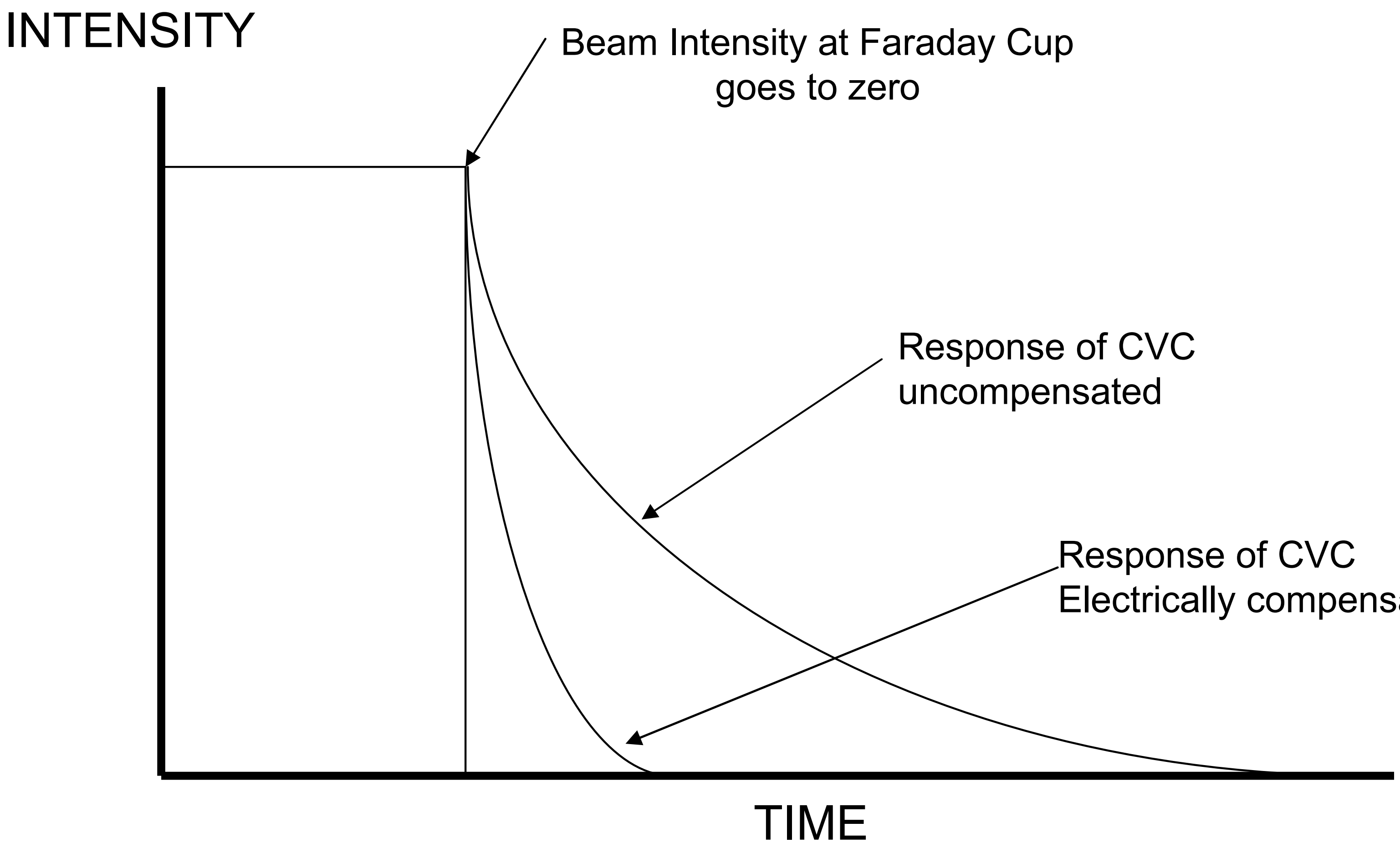
- The OpAmp must be a special one:
  - High input impedance i.e., must look like a large resistor to the beam current (>100x the feedback resistance)
  - High open loop gain (>10,000)
  - As long as the OpAmp meets these criteria the actual values are irrelevant, the converter follows the behavior defined by the equation above
- The converter behavior depends mainly on the feedback resistor:
  - To get reasonable voltage output for typical faraday current range (10^{-15} to 10^{-9} A) means we need a large value resistor, a typical value is 10^{11} ohms, so for a beam current of 10^{-11} A we would have an output voltage of 1V.

Electronics-Analog Mode-Feedback Resistor

- Such high ohm resistors have problems:
  - Sensitive to environmental factors
    - Typical temperature coefficient about 100ppm/^{o}C
    - Sensitive to humidity
    - Resistors are usually glass or epoxy encapsulated
    - CVC placed in evacuated, temperature controlled housing
  - Resistance depends on voltage across resistor
    - Voltage coefficients can range from 50 to 500 ppm/V
    - There can be step changes in the resistance
  - Small virtual capacitance across resistor slows its response to changes in voltage
    - Typical values are a few pF
    - 1/e response time = R x C = 10^{11} x 2 x 10^{-12} = 0.2 s
    - So for a step voltage change across the resistor it would take about 2.3 sec for it to get within 10ppm of the new value and this is a good response time
    - This response time means we need to wait for the CVC to respond to changes in beam current, for example when switching masses
    - This effect can be reduced by choosing fast resistors and by electrically compensating for the response time.

Schematic response curves

- The beam intensity here goes to zero instantly but in practice there is also a magnet response time that slows beam switching



Additional Comments about CVC

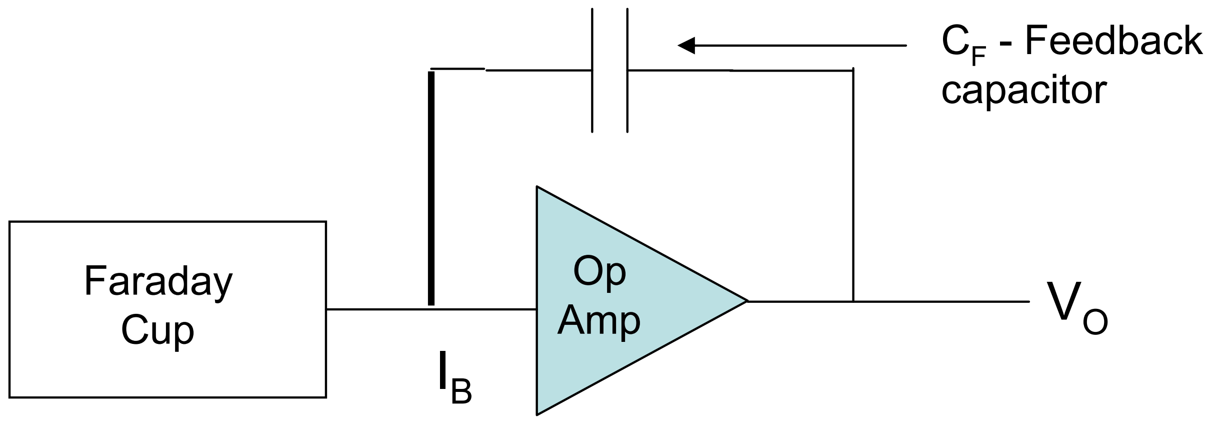
- The sensitivity of the CVC is dependent on the size of the feedback resistor
  - Increasing R_F increases the sensitivity but at a price
  - Response times and noise increase with higher R_F

- The CVC can be used for Faraday Cups and Multipliers running in analog mode
  - For multipliers in analog mode, the high current gains of the multiplier means that smaller resistors can be used (10^9 ohms is typical)
  - In this case capacitors are often added to slow the response of the CVC to filter out the high frequency noise associated with multipliers

- Because of the limitations of response times and noise Faradays combined with CVC are limited to about 10^{-17} A, CVCs combined with multipliers can give us another factor of 10 or so.

- By measuring charge directly however we can extend the faraday cup sensitivity, this is done by replacing the feedback resistor with a capacitor

Charge Measurement



$$V_O = \frac{Q}{C_F}$$

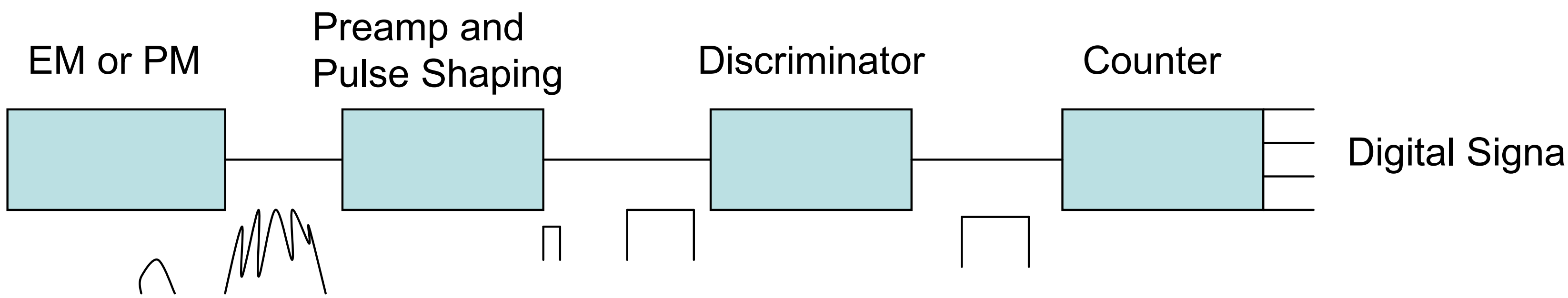
$$V_O = \frac{1}{C_F}\int I_B dt$$

•More sensitive than CVC, a 100fF capacitor and 10^{-17} A beam gives a 0.1 mv/s voltage change (same current even with 10^{12} ohm resistor gives 0.01 mv voltage output

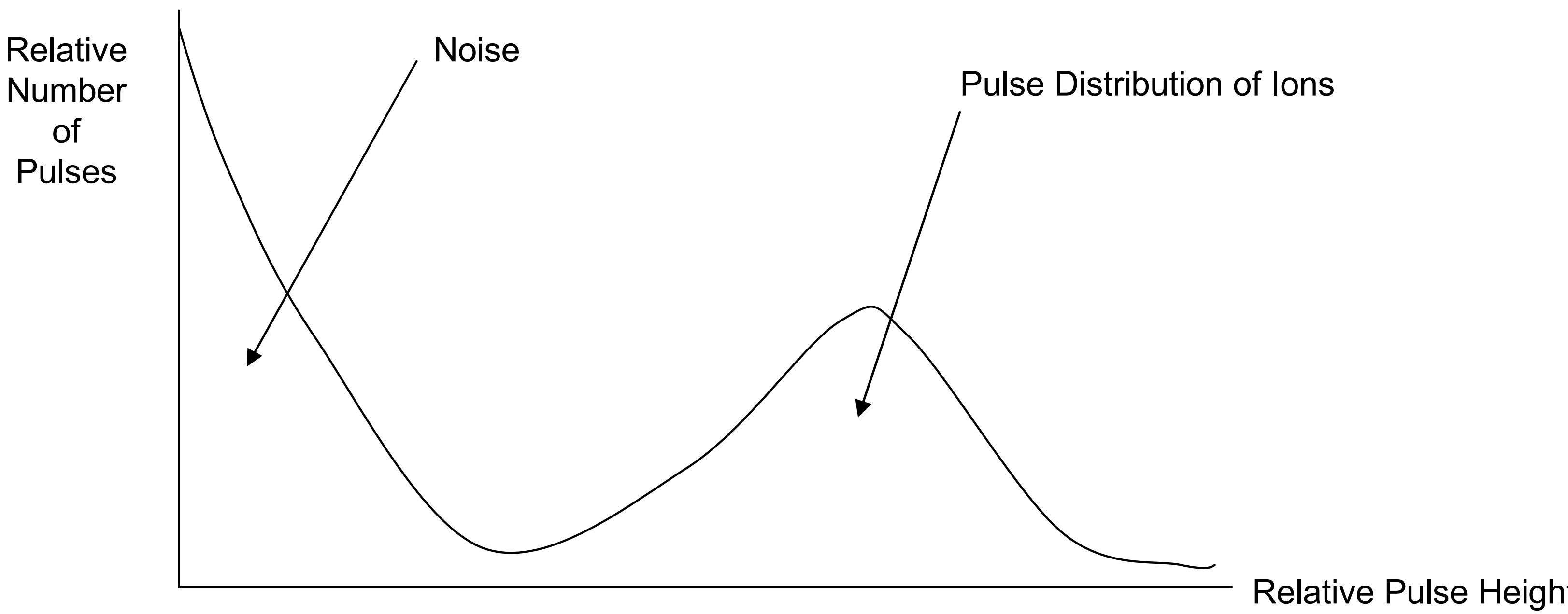
Disadvantages:

derivative of voltage needs to be measured
Capacitor needs to be reset
Small stable capacitors hard to make and need to be kept in stable environment

Pulse or Ion Counting

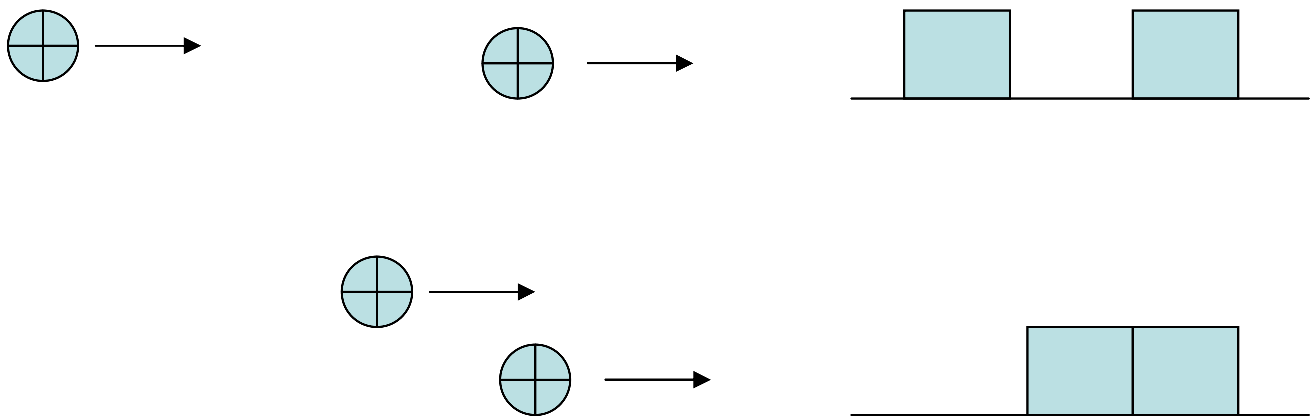


- Typical (and highly simplified) Pulse Height Spectrum for Ion Counter



Ion Counting

- Dead Time: Two or more closely spaced ions are counted as single pulse



- Can be corrected $$N_t = \frac{N_m}{1 - N_m t_d}$$

- Breaks down at high count rates

Some Final Miscellaneous Comments

- All detectors add a bias to the signal measurement that is mass dependent
- This bias is small for faradays but can be large for EMs, Channeltrons and Dalys especially for low masses
- An example:
  - MIT noble gas machine give 40Ar/36Ar for air of ~300 (accepted values = 295.5?) for faraday measurement
  - Same measurement on multiplier give ~287

- These biases can also be signal size dependent
- It can be difficult to distinguish these biases from the larger? source fractionation effects
- They are very often included as a general “fractionation” correction

- Does this limit our precision?