CAS tutorial on RGA
Essential Knowledge

Berthold Jenninger & Paolo Chiggiato

CAS on Vacuum for Particle Accelerators

A Few Bibliographic Sources

1. M. J. Drinkwine and D. Lichtman, Partial pressure analyzers and analysis, American Vacuum Society Monograph Series
2. Ph. E. Miller and M. Bonner Denton, The Quadrupole Mass Filter: Basic Operation Conceps, Journal of Chemical Education 63(7), 617, 1987
3. J. H. Gross, Mass Spectrometry: A Textbook, Springer, 2004
4. A. Lee, A Beginner's Guide to Mass Spectral Interpretation, Wiley, 1998.
5. P. H. Dawson, Quadrupole Mass Spectrometry and its Applications, American Vacuum Society Classics, 1995
6. Handbook of Vacuum Technology, Edited by K. Jousten, Wiley, 2008, p.631
7. N. Müller, Quadrupole Mass Spectrometers under UHV/XHV conditions, International Workshop on Extreme High Vacuum – Application and Technology (X-VAT), 2003
8. G. J. Peter and N. Müller, Partial pressure gauges, Proceedings of CAS, Platya de Aro, 2006 cdsweb.cern.ch/record/1047066/files/p195.pdf
9. L. Lieszkovszky et al, J. Vac. Sci. Technol. A8(1990)3838
10. P. A. Redhead, J. Vac. Sci. Technol. A10(1992)2665
11. Mesures de pressions partielles dans la technique du vide, Balzers BG 800 169 PF (8310)

Why we use residual gas analysers?

- We are not only interested in the total pressure but also in the specific gas components present in a vacuum system.

- In the specific case of particle accelerators, the kind of residual gas determines beam-gas interaction effects: for example H_2 and CO_2 are not seen by particle beams in the same way.

- More generally, the presence of N_2 in a vacuum system could be an indication of leaks, while pronounced presence of hydrocarbons indicates contamination.

How are gases identifies?

- The simplest way to detect gas components is by their masses.

- Other physical properties are also utilized, for example optical emission and absorption; however their sensitivities are lower than those obtained by mass detection.

What is the mass of a gas molecule and how we measure it?

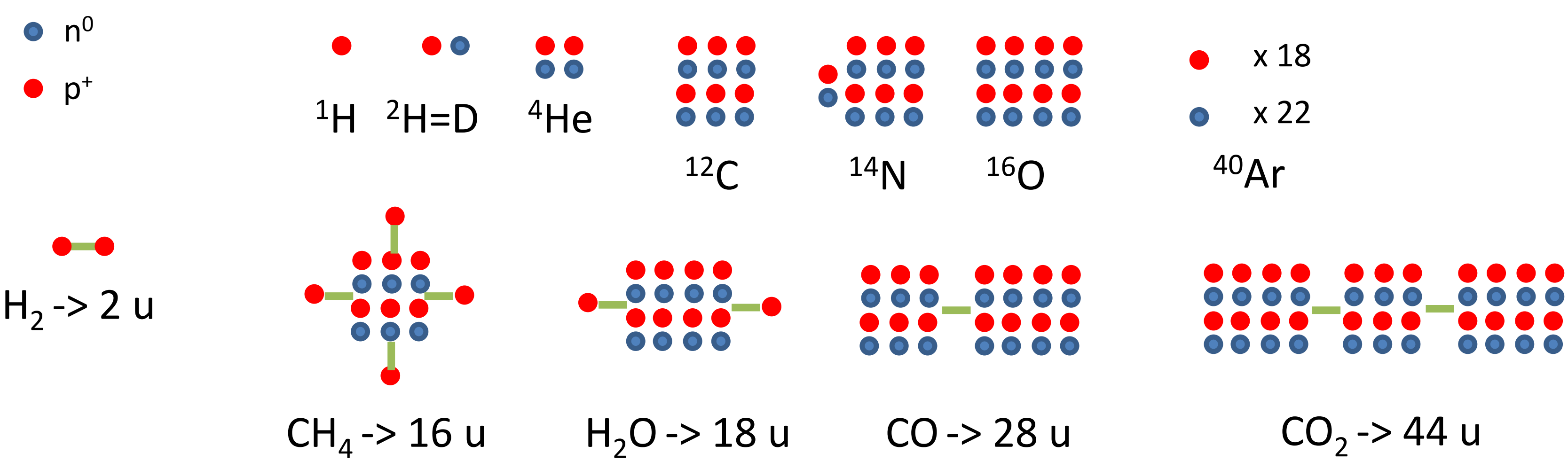
- Molecular masses are reported in ‘unified atomic mass units’ (‘u’ or Dalton, Da).

- One atomic mass unit is defined as one twelfth of the rest mass of a carbon-12 atom in its ground state.

$$1\ \text{u} = 1/12\ (^{12}\text{C mass}) = 1.66\ldots \times 10^{-27}\ \text{Kg}$$

- One unit is roughly equal to the mass of 1 proton or 1 neutron

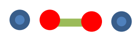
- In first approximation the atomic mass unit of a molecule can be evaluated counting its number of protons and neutrons.



What is the mass of a gas molecule and how we measure it?

- The count of protons and neutrons is only a rough estimation of the atomic mass unit, which is sufficient for UHV applications.

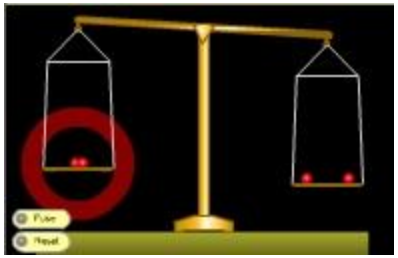
- However, this is not the case in other field, for example nuclear fusion:



D_2 -> 4.028204

^4He -> 4.0026

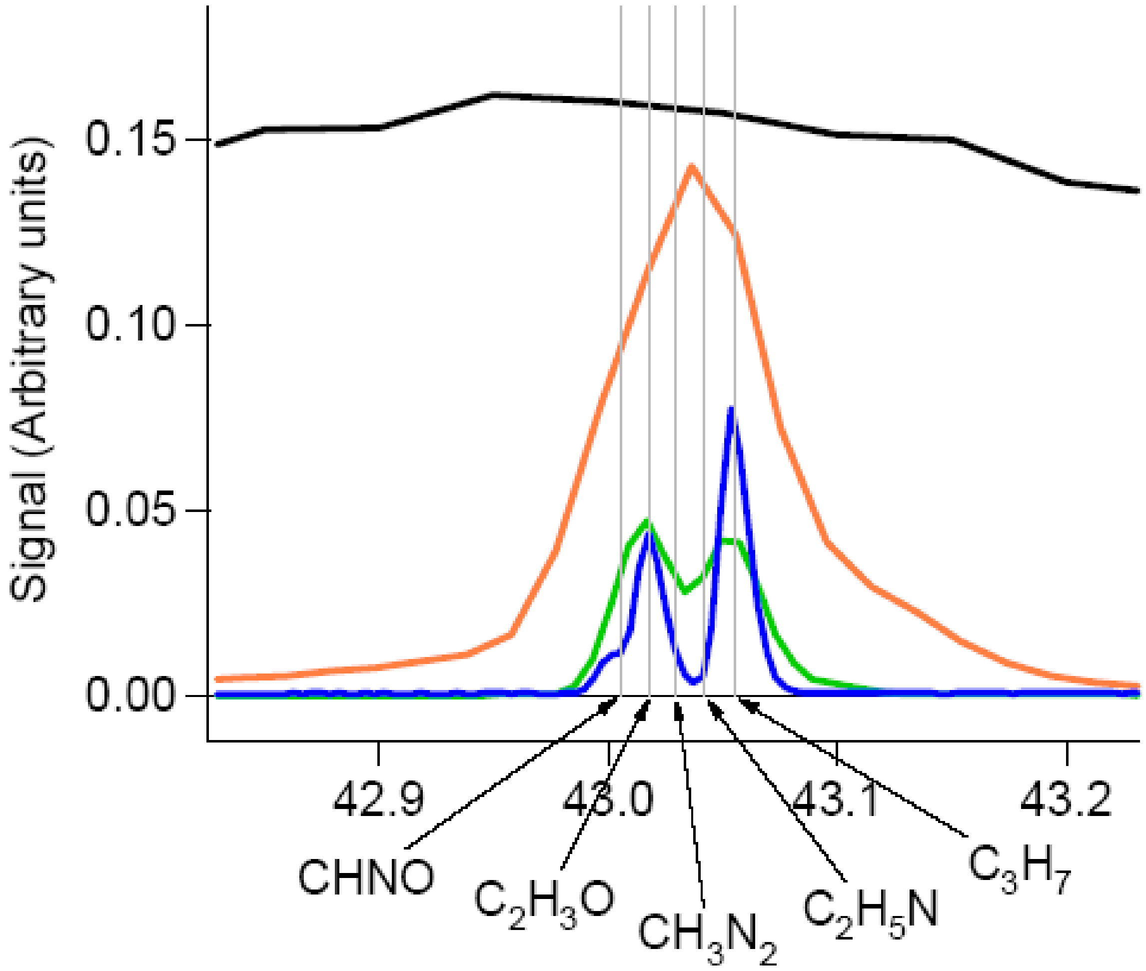
- The difference in mass is the result of the different nuclear binding state



http://www.furryelephant.com/content/radioactivity/binding-energy-mass-defect/

- Another example where neutron and proton counting is not enough: organic chemistry.

What is the mass of a gas molecule and how we measure it?



http://www.chemistry.uco.edu/Vonminden/files/MS%20Interpretation%20part%203.ppt

Molecules with atomic mass units close to 180 u

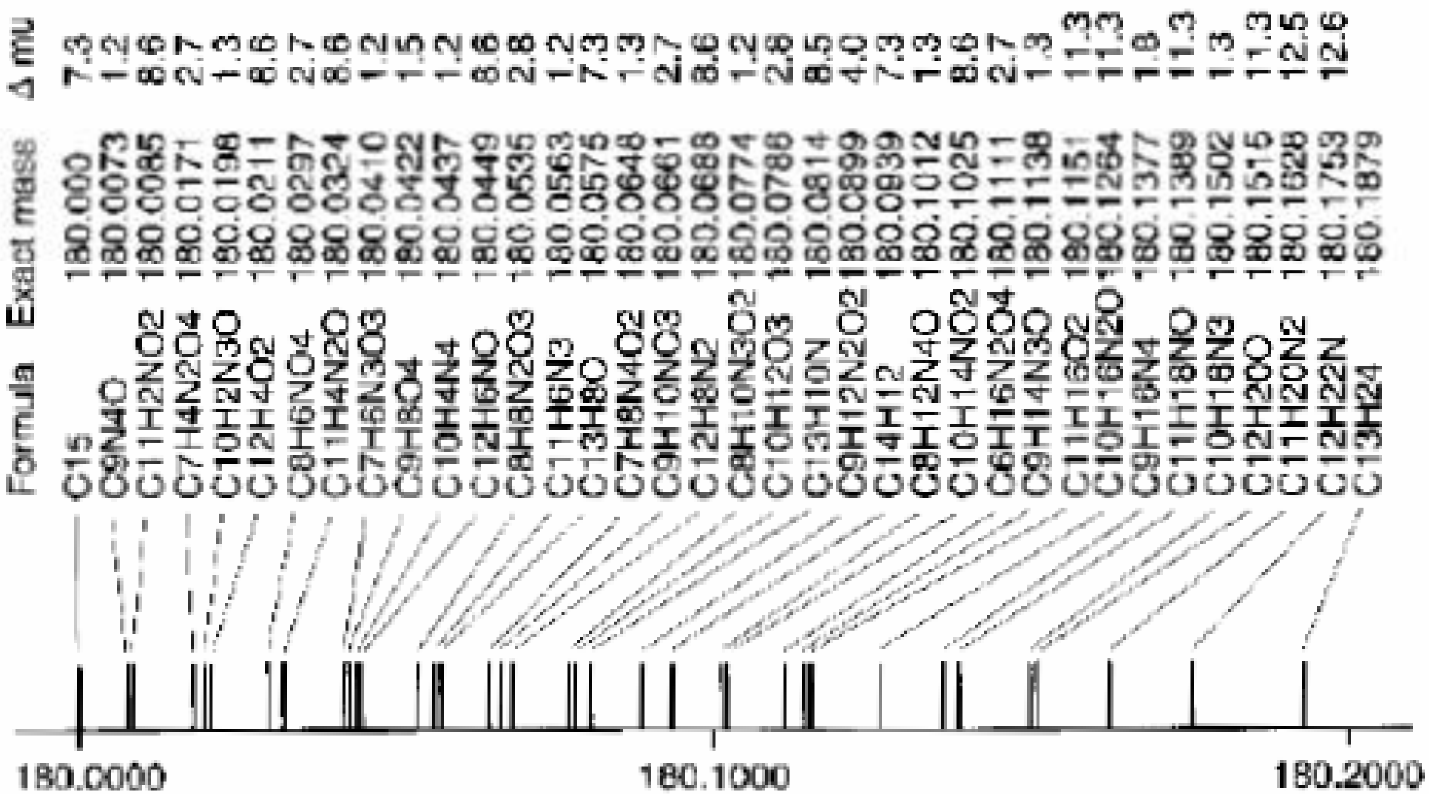


Figure 5.2
Exact masses and corresponding formulae for various possible ions of *m/z* 180 containing only carbon, hydrogen, nitrogen and oxygen atoms

http://www.chemistry.uco.edu/Vonminden/files/MS%20Interpretation%20part%203.ppt

How gas masses can be measured?

- Gas molecules are ionized by electron bombardment.
- Once ionized, gas molecules move differently in electromagnetic fields if they have different masses : they have different trajectories and velocity.
- At the exit of a selective field, the ionized molecules are collected and detected.

Ionization: The Total Ionization Cross Section

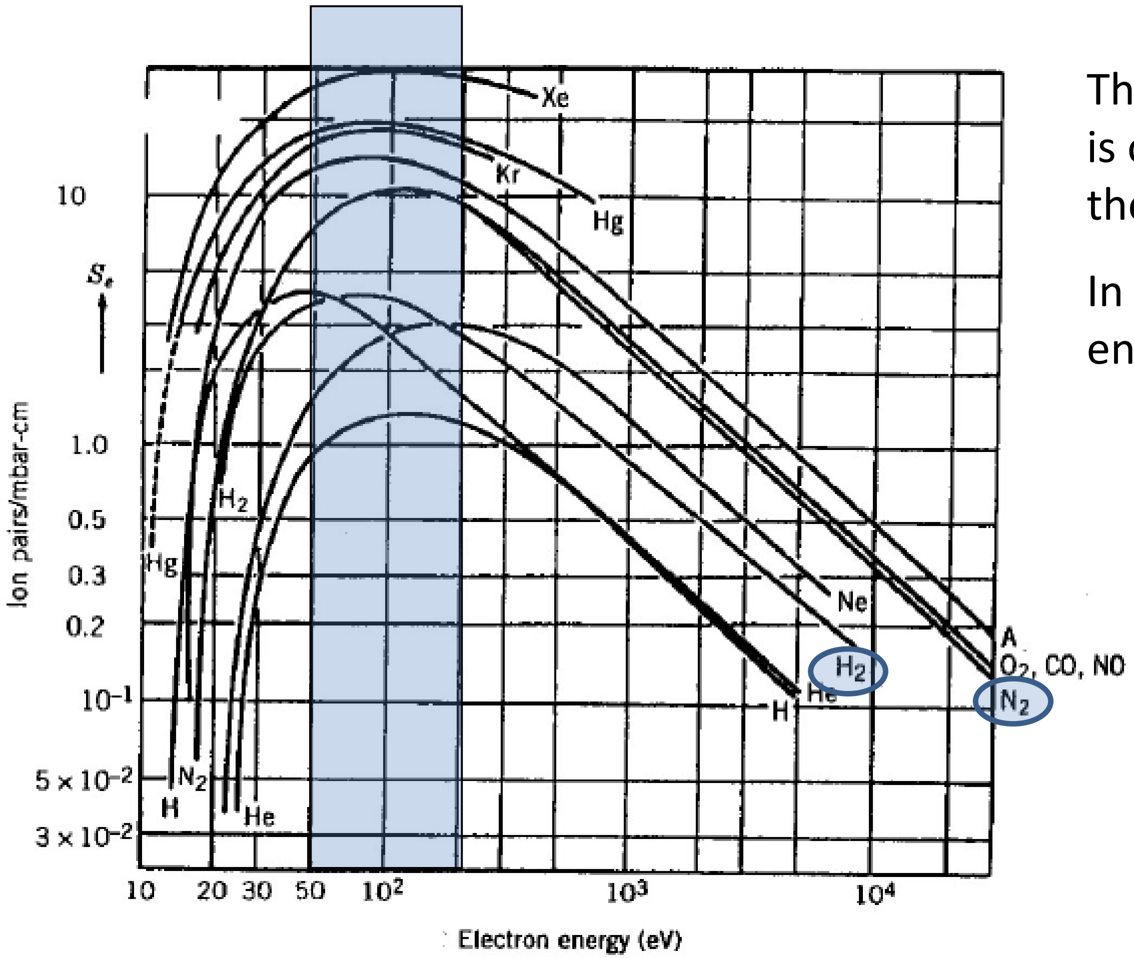


Fig. 3: Generated ions per centimetre electron path length per millibar at 20°C versus kinetic energy of incident electrons for various gases. From A. von Engel, *Ionized Gases*, AVS Classics Series.

The **maximum** of the cross section is obtained for electron energy in the range **50 to 200 eV**.

In general, in RGA the electron energy is set at 70 eV.

Ionization: Other Effects of Electron Bombardment

- Electron **bombardment causes fragmentation** of molecules in addition to ionization.

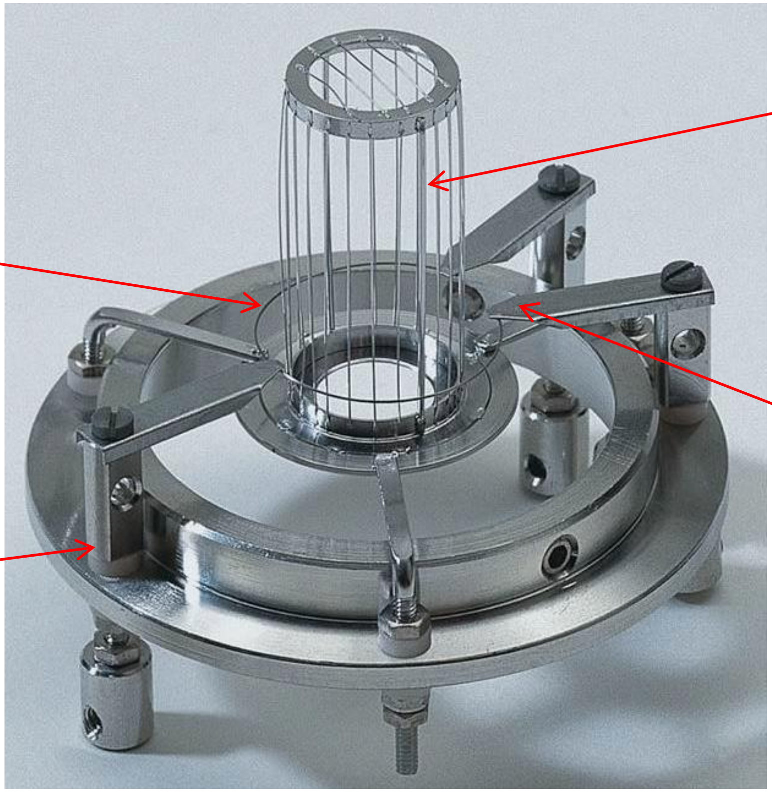
- The dissociation is not an unwanted complication. The fragmentation pattern (**cracking pattern**) facilitates the identification of gases.

- **Multiple ionization** can also occur, for example Ar^{++} in addition to Ar^{+}.

- **Electron stimulated desorption (ESD)** results in additional ions and neutral. ESD can be reduced by:
  - ✓ reducing the surface hit by the electrons
  - ✓ removing the gas adsorbed on the surface bombarded by the electrons (degassing)

- **Outgassing** of the surrounding walls caused by temperature rise induced by hot cathodes.

Ionization: The Axial Electron Source



Picture from: N. Müller, International Workshop on Extreme High Vacuum – Application and Technology (X-VAT), 2003

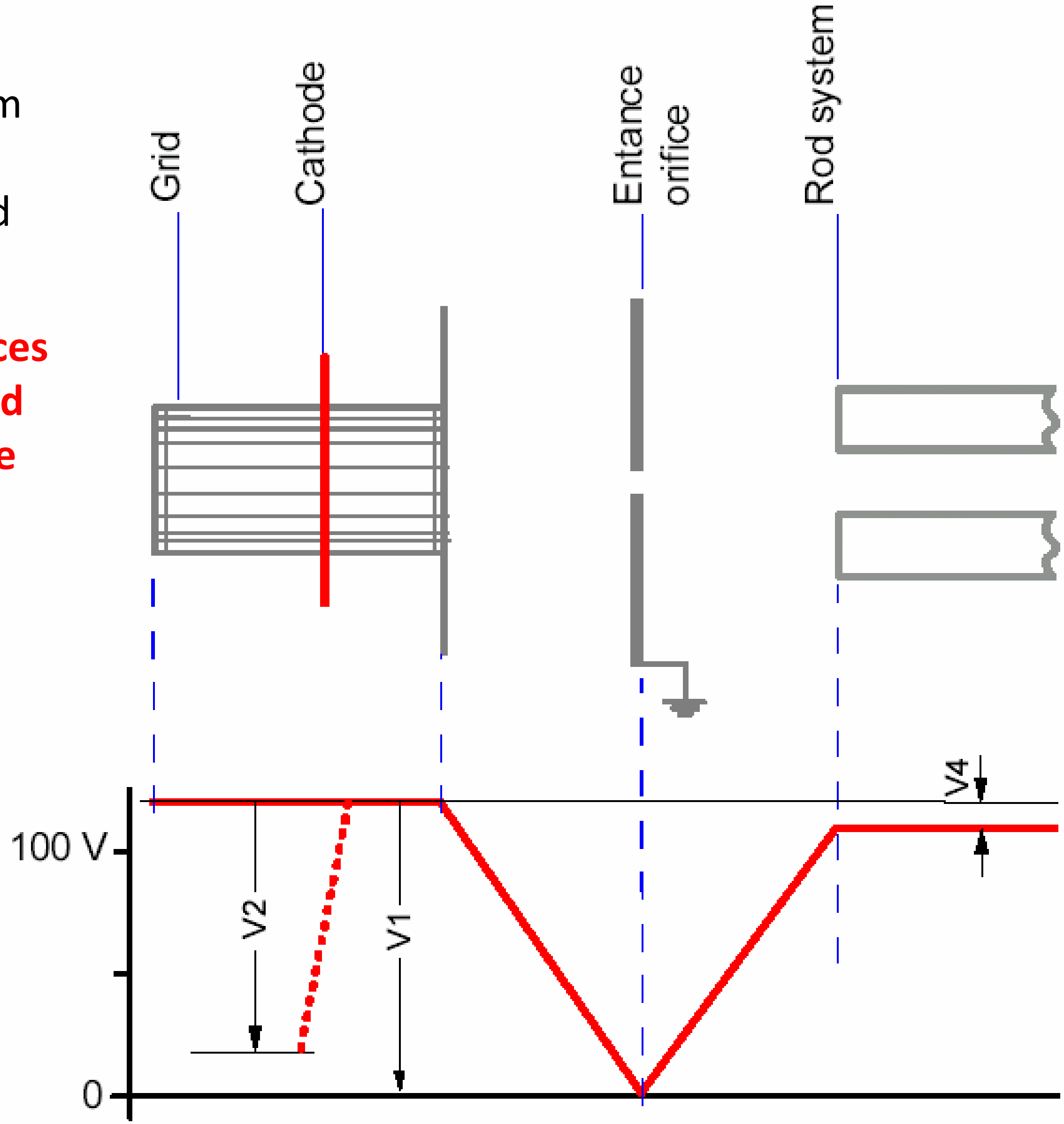
- The number of ions produced in the grid is proportional to the gas density and electron current. But for high electron current space charge can occurs: in this case positive ions can be trapped in the grid and their production rate can be reduced. In general **1 or 2 mA** are applied.

- **The electron density is higher along the grid axis-> a potential well for ions is generated: the ion density is higher along the grid axis. This improves ion extraction.**

Ionization: The Ion Extraction

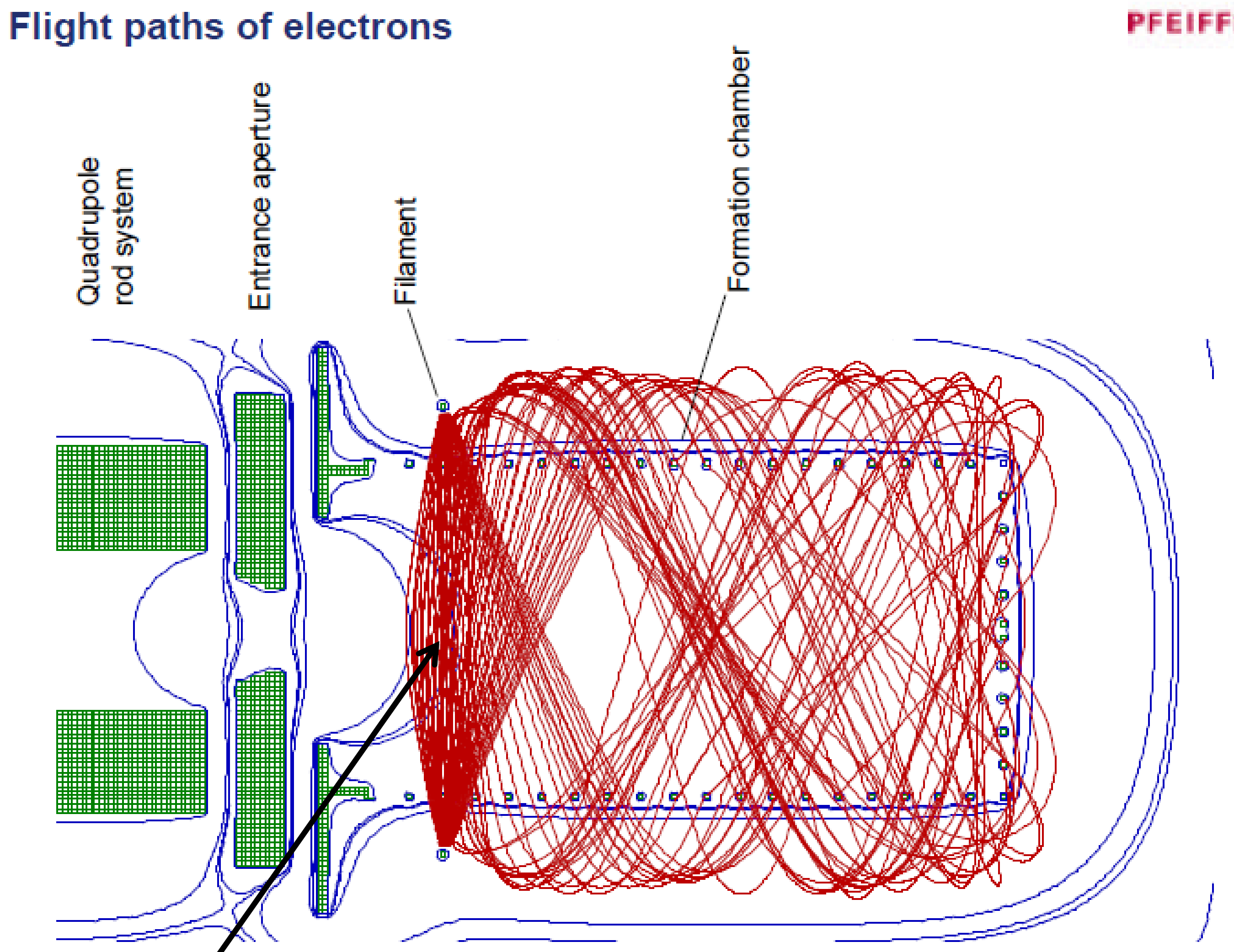
- The ions are extracted from the grid by an electrical field applied between the grid and an extractor plate.
- The **extractor plate produces field penetration into the grid which take advantages of the higher concentration of ions along the grid axis.**
- V1 : grid voltage
- V1 –V2 : filament voltage
- V1-V4: field axis voltage

INFICON
distributed by
PFEIFFER VACUUM



Drawing from: N. Müller, International Workshop on Extreme High Vacuum – Application and Technology (X-VAT), 2003

Ionization: The Ion Extraction



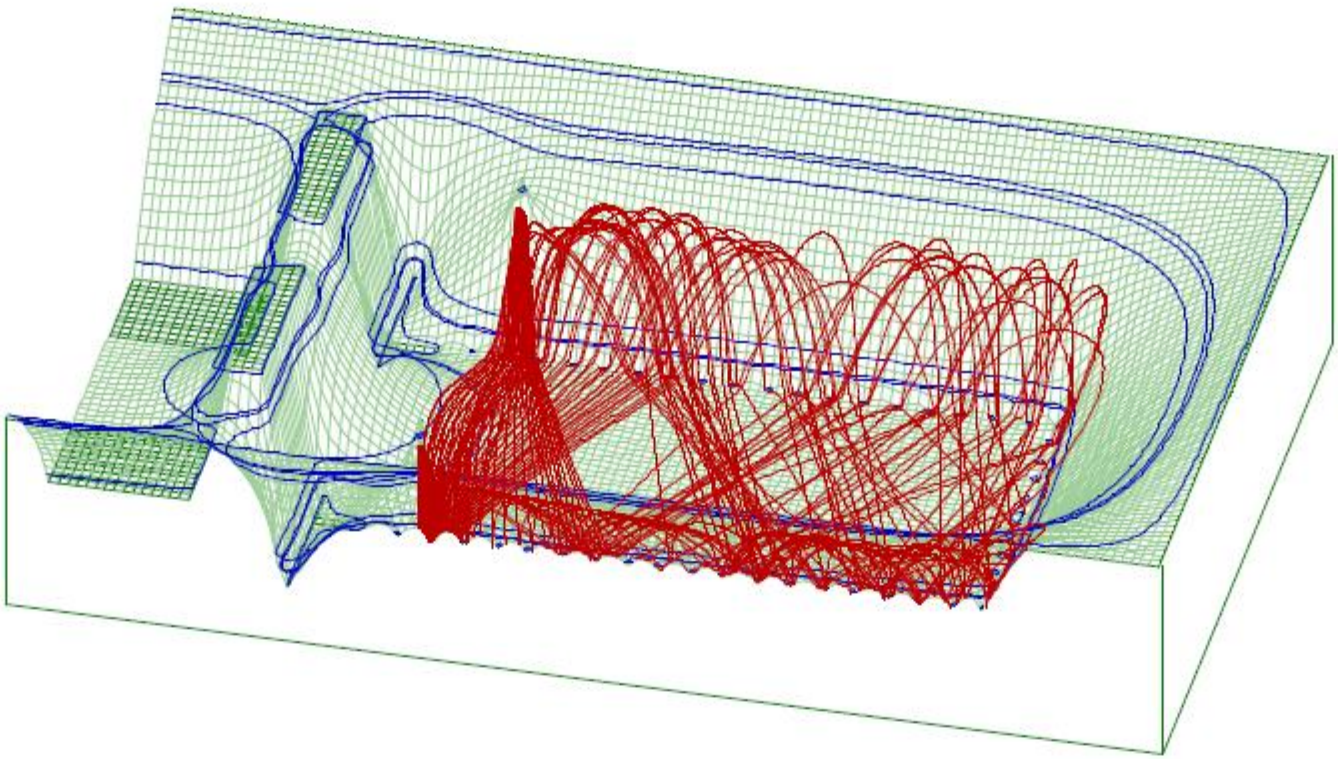
High electron density = High ion density not far from the grid exit

Drawing from: N. Müller, International Workshop on Extreme High Vacuum – Application and Technology (X-VAT), 2003

Ionization: The Ion Extraction

INFICON distributed by PFEIFFER VACUUM

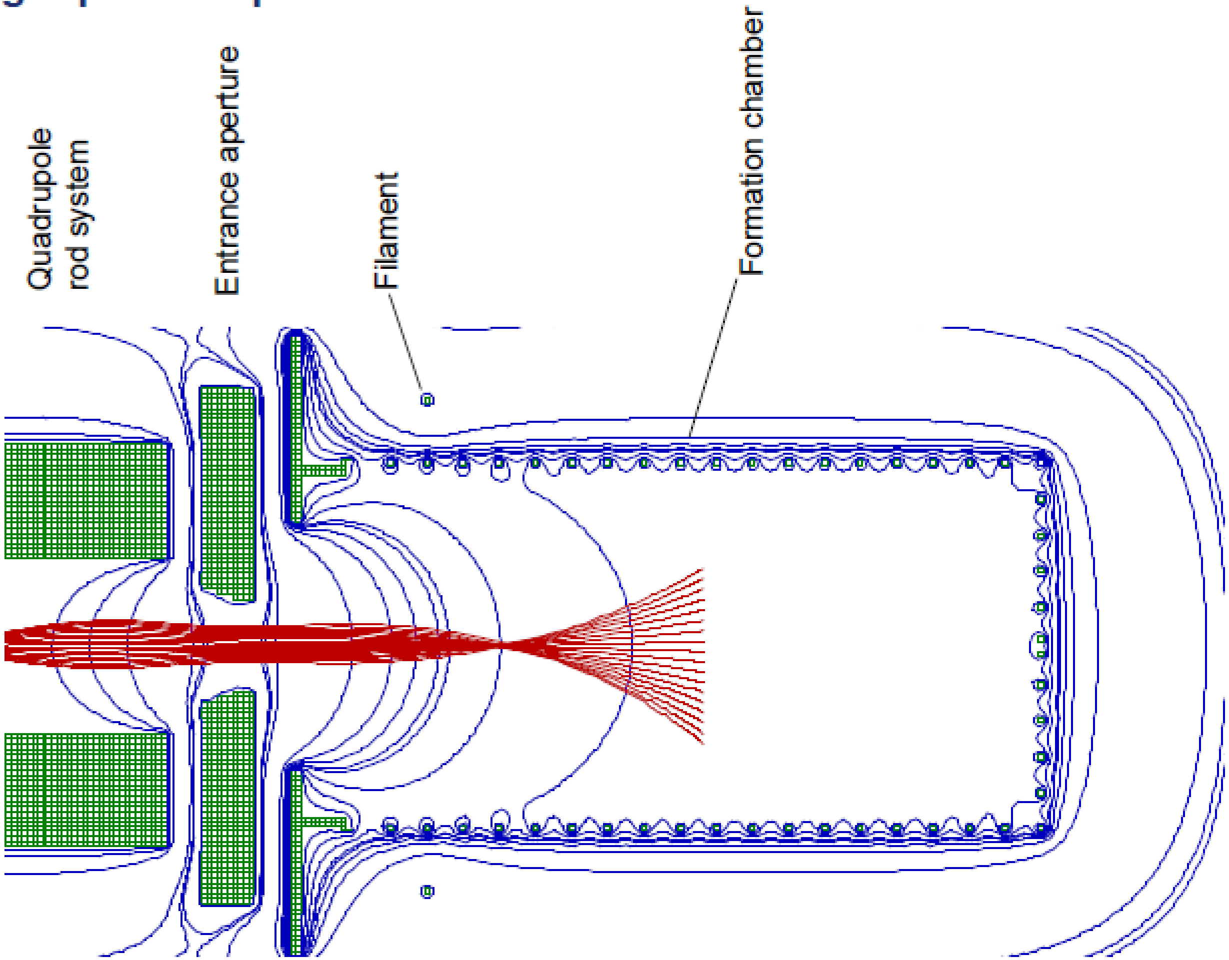
Flight paths of electrons



Drawing from: N. Müller, International Workshop on Extreme High Vacuum – Application and Technology (X-VAT), 2003

Ionization: The Ion Extraction

Flight paths of positive ions



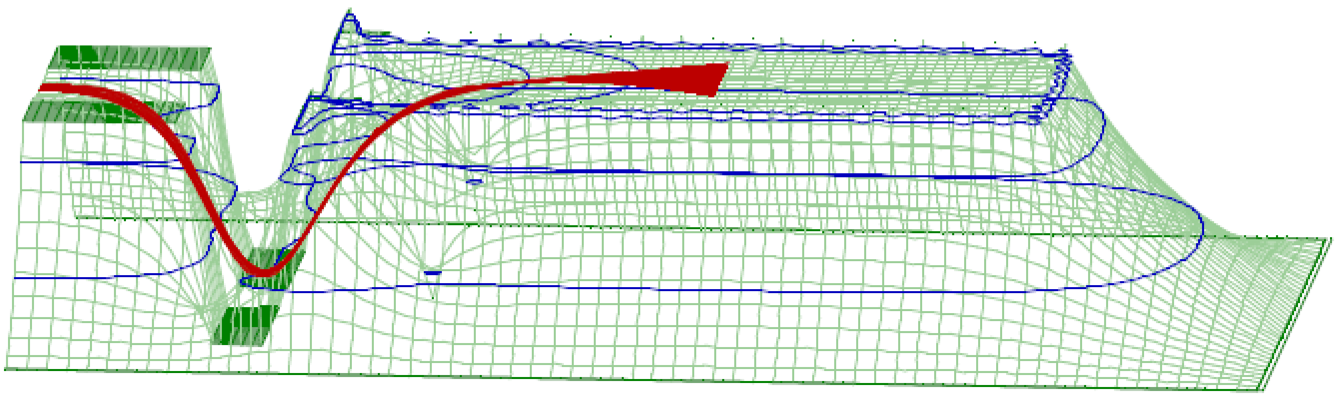
For this specific ion source (**QMxxx**), focalization electrodes are not needed

Drawing from: N. Müller, International Workshop on Extreme High Vacuum – Application and Technology (X-VAT), 2003

Ionization: The Ion Extraction

Flight paths of positive ions

➢ The field axis voltage defines the kinetic energy of the ions at the entrance of the mass filter. In other words: for a specific molecule, it defines the time the ions spend in the mass filter.



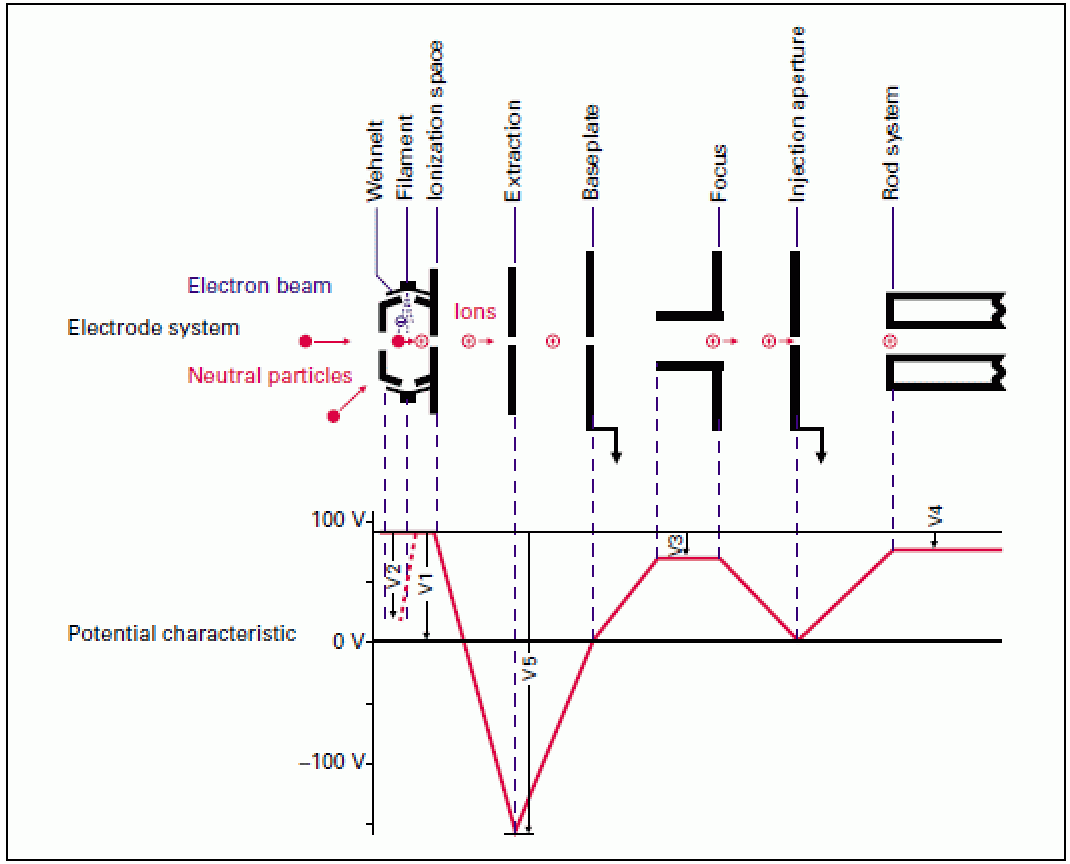
➢ For this specific ion source (**QMXXX**), ions produced in the axial grid source do not need dedicated electrodes for extraction and focusing. The **grounded base-plate is enough to create a collimated beam of ions**.

➢ This is not the case for other kind of ion sources (for example that of the Prisma).

Drawing from: N. Müller, International Workshop on Extreme High Vacuum – Application and Technology (X-VAT), 2003

Ionization: The Ion Extraction

Prisma source



Ionization: The Ion Extraction

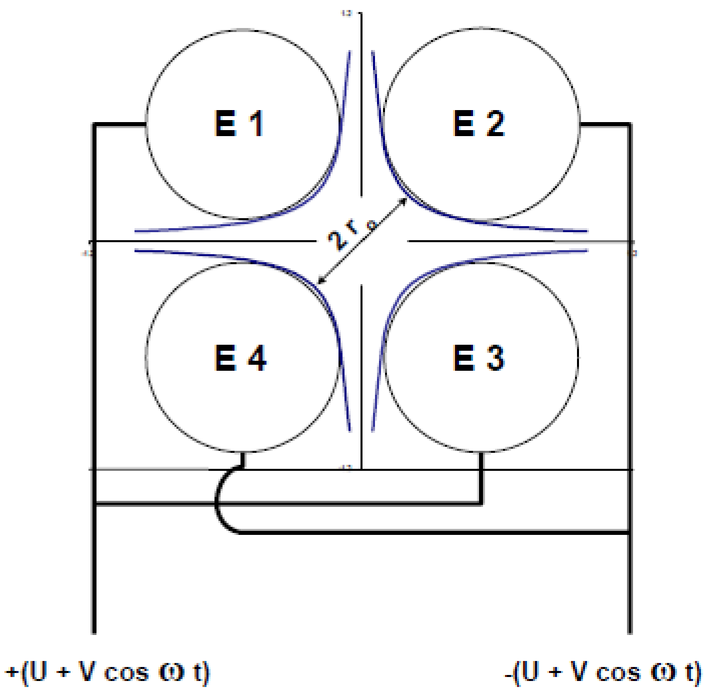
Example Hidden ???

Selection: The Quadrupole Mass Filter

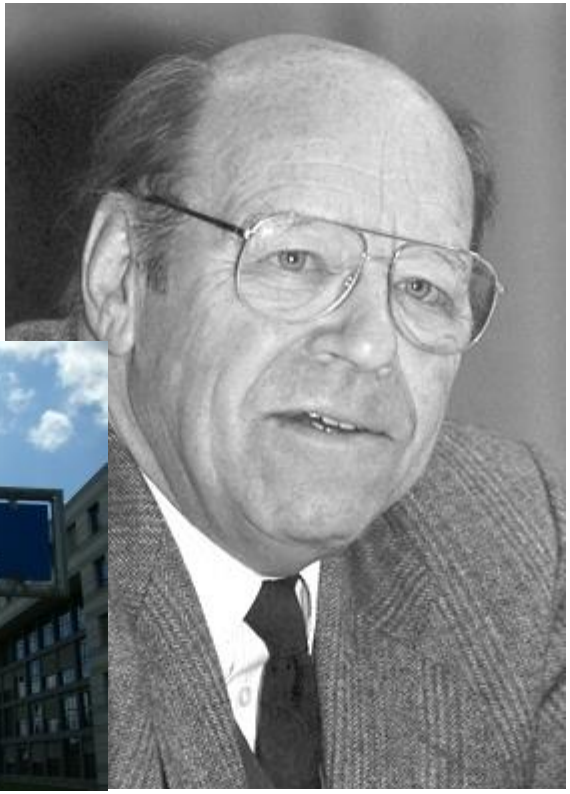
- The quadrupole mass filter was originally developed by **W. Paul**
- The filter consists of a set of **four electrodes**, ideally of **hyperbolic cross section**.
- **However, in general, they are cylinders** . The best approximation to the hyperbolic field is obtained when the radius ‘r’ of the circular cross section is:

$r= 1.148\ r_0$

$$\Phi = [U + V \cdot \cos(\omega \cdot t)] \cdot \frac{x^2 - y^2}{2 \cdot r_0^2}$$



MS basis, N. Müller, Inficon



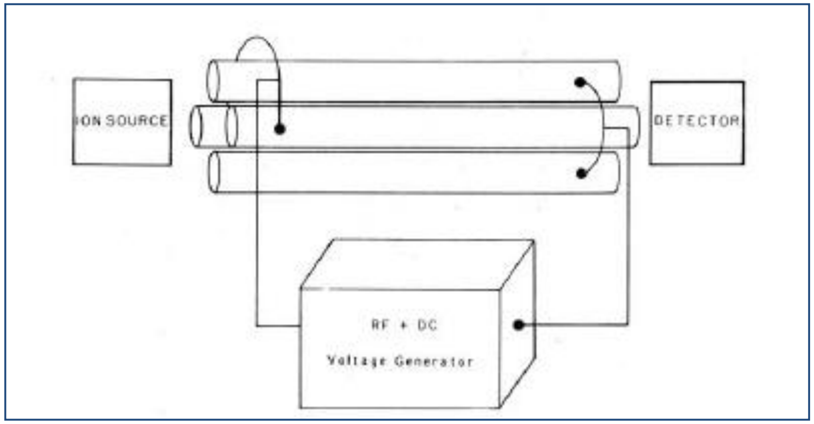
http://nobelprize.org/nobel_prizes/physics/laureates/1989/paul.html

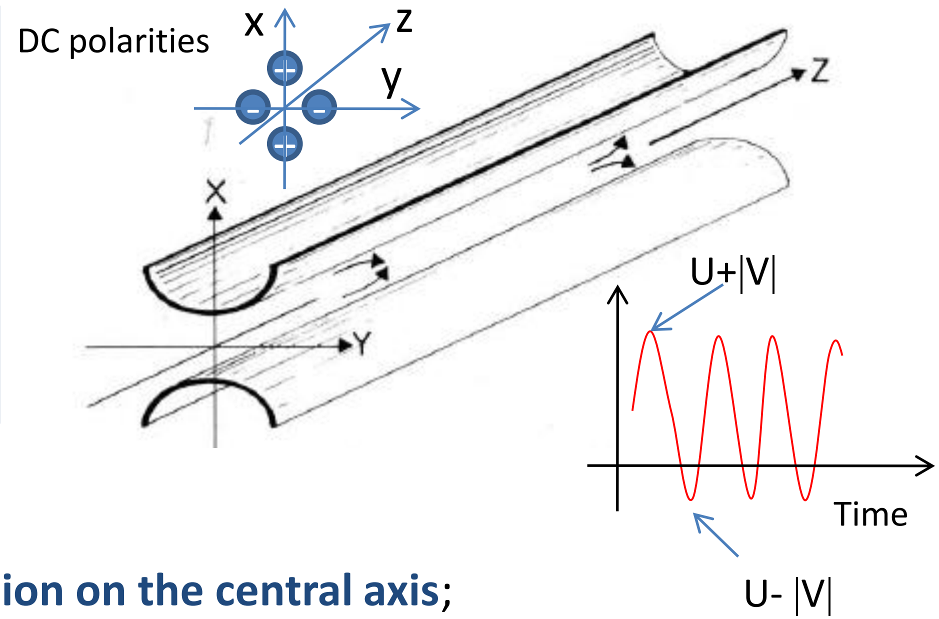
Selection: The Quadrupole Mass Filter

Ph. E. Miller and M. Bonner Denton, Journal of Chemical Education 63(7), 617, 1987

➢ The filtering action is obtained **superposing a DC to a periodic potentials**:

$U - V\cos(\omega t)$





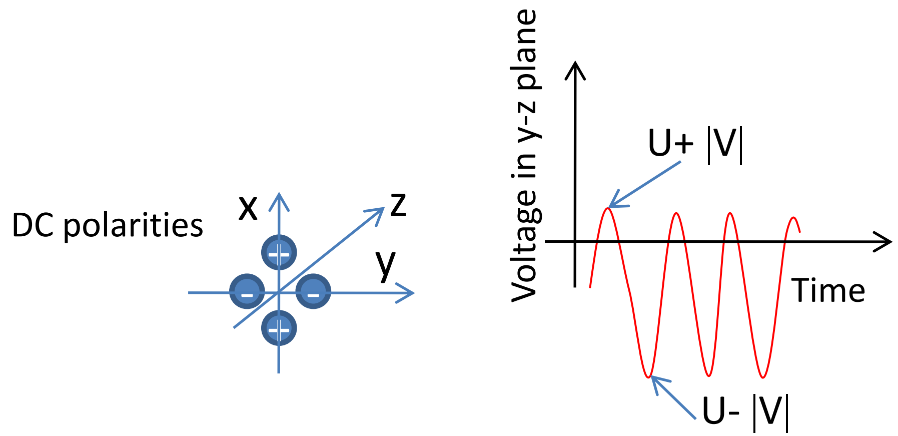
➢ In **the x-z** plane:

- the positive **DC potential focus the ion on the central axis**;
- when the **RF field is superposed**, for a certain time the two electrodes become negatively biased;
- during this time interval, **light ions can promptly react and be defocused** and possibly **lost by striking one of the two electrodes**;
- **heavy ions do not have time to react** and continue their trajectory along the axis.

<u>In the x-z plane the quadrupole is a high-pass mass filter.</u>

Selection: The Quadrupole Mass Filter

Ph. E. Miller and M. Bonner Denton, Journal of Chemical Education 63(7), 617, 1987



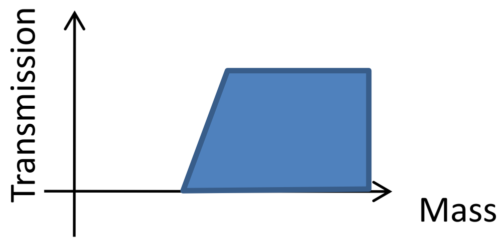
- In the **y-z** plane:
  - the **negative DC potential defocus all ions** from the central axis;
  - when the **RF field is superposed**, for a certain time the two electrodes become positively biased;
  - during this time interval, **light ions can promptly react and be focused** and possibly saved from striking one of the two electrodes;
  - **heavy ions do not have time to react**, they continue their trajectory and are lost.

In the y-z plane the quadrupole is a low-pass mass filter.

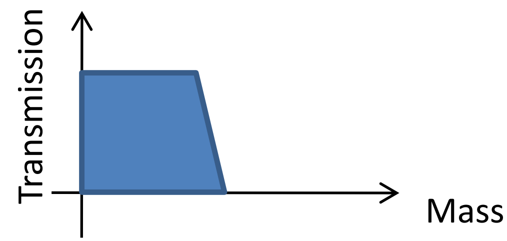
Selection: The Quadrupole Mass Filter

Ph. E. Miller and M. Bonner Denton, Journal of Chemical Education 63(7), 617, 1987

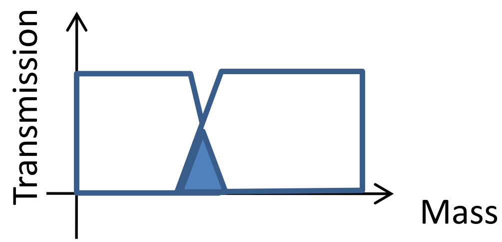
In the x-z plane the quadrupole is a high-pass mass filter.



In the y-z plane the quadrupole is a low-pass mass filter.



The quadrupole is a band-pass mass filter.

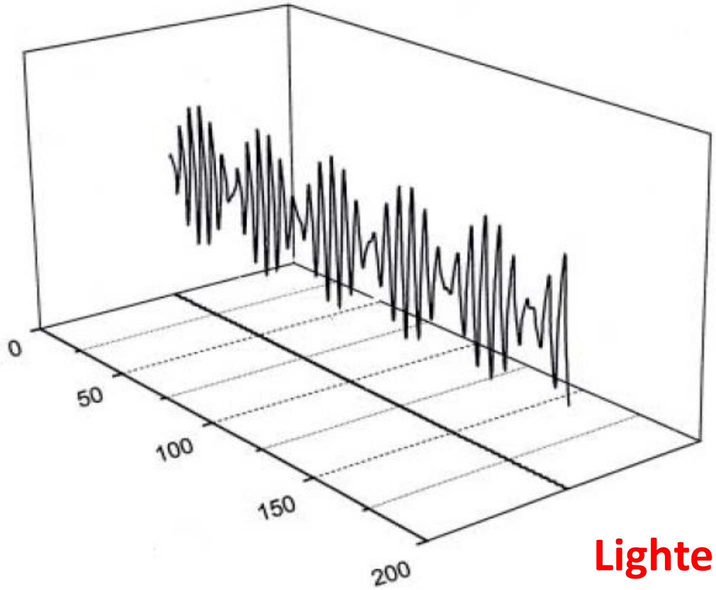


- Properties of the passing band:
  - The **width** of the band-pass region (**mass resolution**) is governed by the **V/U ratio**.
  - The **mass** at the centre of the band-pass region depends on the **magnitude** of both AD (V) and DC (U) **potentials**.

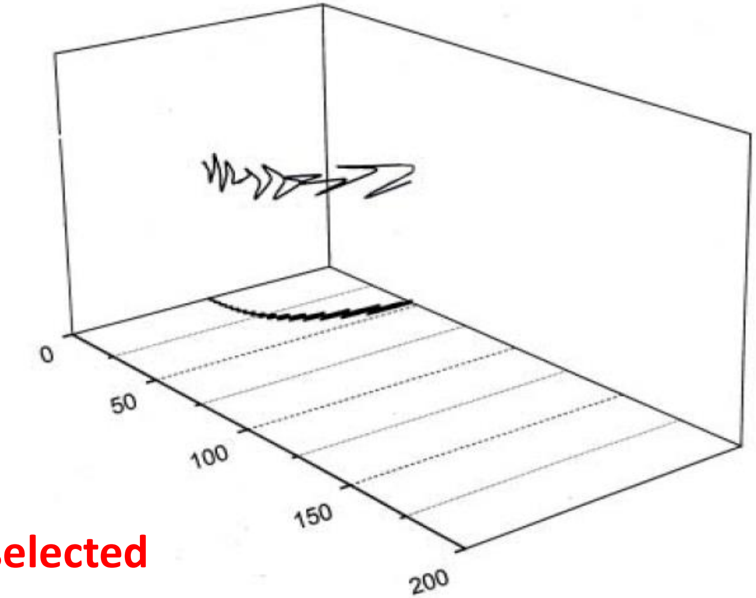
Selection: The Quadrupole Mass Filter

MS basis, N. Müller, Inficon

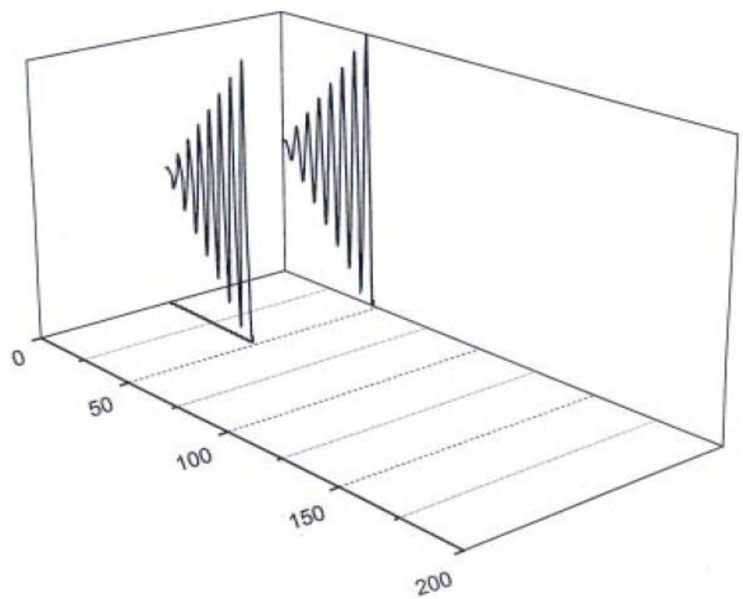
Selected ion mass

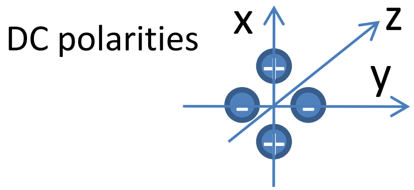


Heavier than selected



Lighter than selected





Selection: The Quadrupole Mass Filter

P. H. Dawson, Quadrupole Mass Spectrometry and its Applications, AVS Classics, p. 13-36, 1976-1995

Electrical Potential: $$\Phi = [U - V \cdot \cos(\omega \cdot t)] \cdot \frac{x^2 - y^2}{2r_0^2}$$

$$E_x = -\frac{\partial \Phi}{\partial x} = -[U - V \cdot \cos(\omega \cdot t)] \cdot \frac{x}{r_0^2}$$

Electrical Field: $$E_y = -\frac{\partial \Phi}{\partial y} = [U - V \cdot \cos(\omega \cdot t)] \cdot \frac{y}{r_0^2}$$

$$E_z = -\frac{\partial \Phi}{\partial z} = 0$$

Z = number of elementary charges of the ion

$$F_x = Ze \cdot E_x$$

$$F_x = -[U - V \cdot \cos(\omega \cdot t)] \cdot \frac{Ze \cdot x}{r_0^2}$$

Electrical Force:

$$F_y = [U - V \cdot \cos(\omega \cdot t)] \cdot \frac{Ze \cdot y}{r_0^2}$$

$$F_z = 0$$

Newton's: $$F = m \cdot a \rightarrow a = \frac{F}{m} \rightarrow \frac{d^2 x}{dt^2} = \frac{F}{m}$$

Selection: The Quadrupole Mass Filter

P. H. Dawson, Quadrupole Mass Spectrometry and its Applications, AVS Classics, p. 13-36, 1976-1995

Equation of Motion:

$$\frac{d^2x}{dt^2} + \frac{Ze \cdot x}{mr_0^2}\left[U - V \cdot \cos(\omega \cdot t)\right] = 0$$

$$\frac{d^2y}{dt^2} - \frac{Ze \cdot y}{mr_0^2}\left[U - V \cdot \cos(\omega \cdot t)\right] = 0$$

$$\frac{d^2z}{dt^2} = 0$$

First results:

1. **The ions move along the quadrupole main axis 'z' with a constant speed**, namely the initial one, which is defined by the field axis voltage. **The time of transit of H_2^+ ions** along the quadrupole is about:

$$e \cdot V = 10 \cdot 1.6 \times 10^{-19} = \frac{1}{2} m \cdot v^2 \rightarrow v = \sqrt{\frac{3.2 \times 10^{-18}}{2 \cdot 1.66 \times 10^{-27}}} \approx 3 \cdot 10^4 \frac{m}{s}$$

$$t_{tr} \approx \frac{10^{-1}}{3 \cdot 10^4} = 3 \times 10^{-6} s = 3 \mu s$$

2. The **motion along the x and y axis are independent** (thanks to the hyperbolic potential)

Selection: The Quadrupole Mass Filter

P. H. Dawson, Quadrupole Mass Spectrometry and its Applications, AVS Classics, p. 13-36, 1976-1995

$$a_u = a_x = -a_y = \frac{4 \cdot Ze \cdot U}{m \cdot \omega^2 r_0^2}$$

$$q_u = q_x = -q_y = \frac{2 \cdot Ze \cdot V}{m \cdot \omega^2 r_0^2}$$

$$\xi = \frac{\omega \cdot t}{2}$$

Note that the definition of a and q differ by a factor of 2 from those used by some authors who define U and V as half the voltage applied between opposite pairs of rods

$$\frac{d^2u}{d\xi^2} + \left[a_u - 2 \cdot q_u \cdot \cos(2\xi)\right] \cdot u = 0$$

Mathieu equation in canonical form (special case of Hill equation)

where 'u' represents either x or y

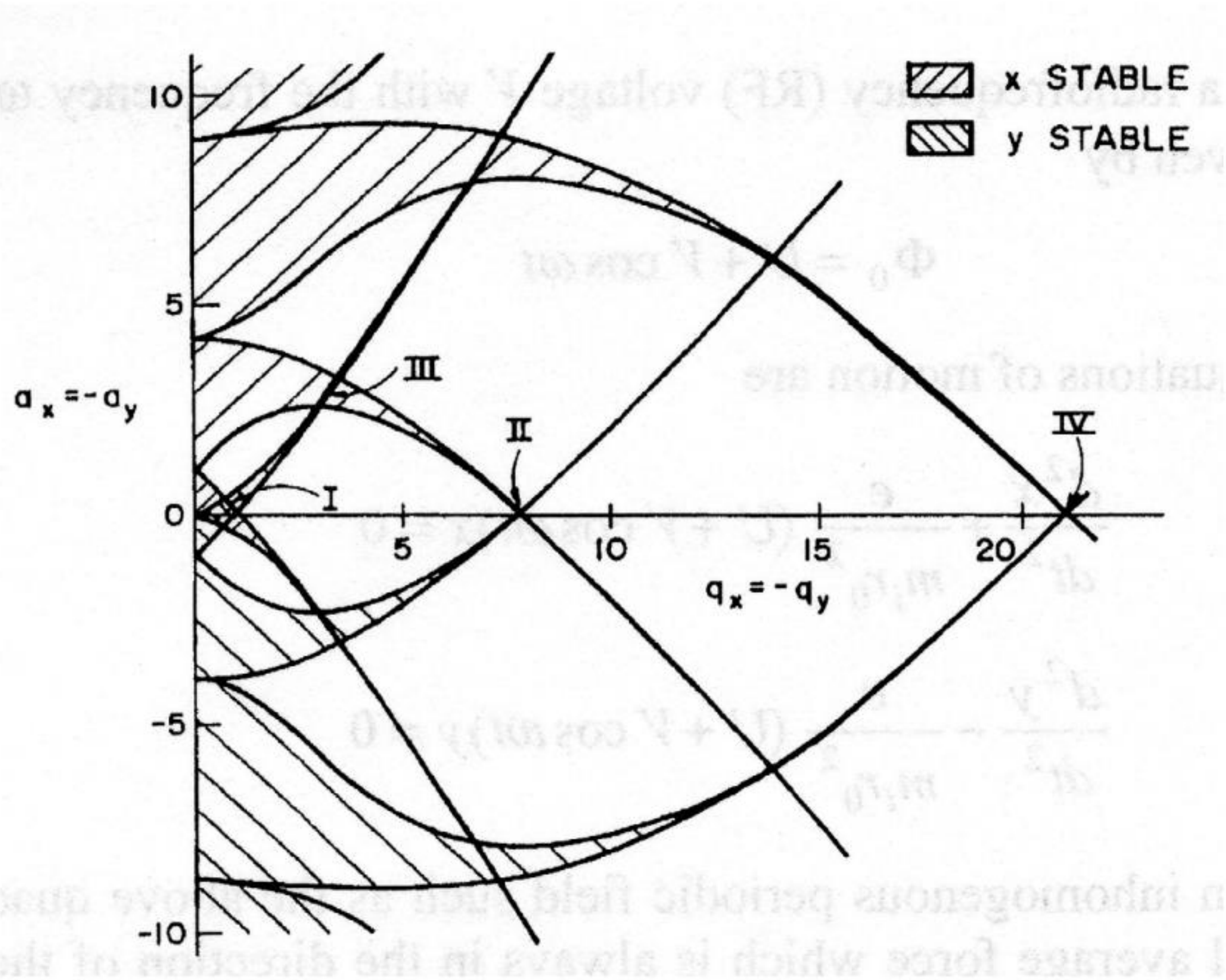
$$\frac{d^2u}{dx^2} + f(t)u = 0$$

$f(t)$: periodic

Properties of the Mathieu equation:

1. **The nature of the ion motion function does not depend on the initial condition**, i.e. velocity and position at the entrance of the quadrupole; only the amplitude depends on the entrance velocity.
2. **The solution of the equation can be stable** (t->∞, u -> finite) **or instable** (t->∞, u -> ∞)
3. The condition for stability can be represented on an **a-q diagram**.

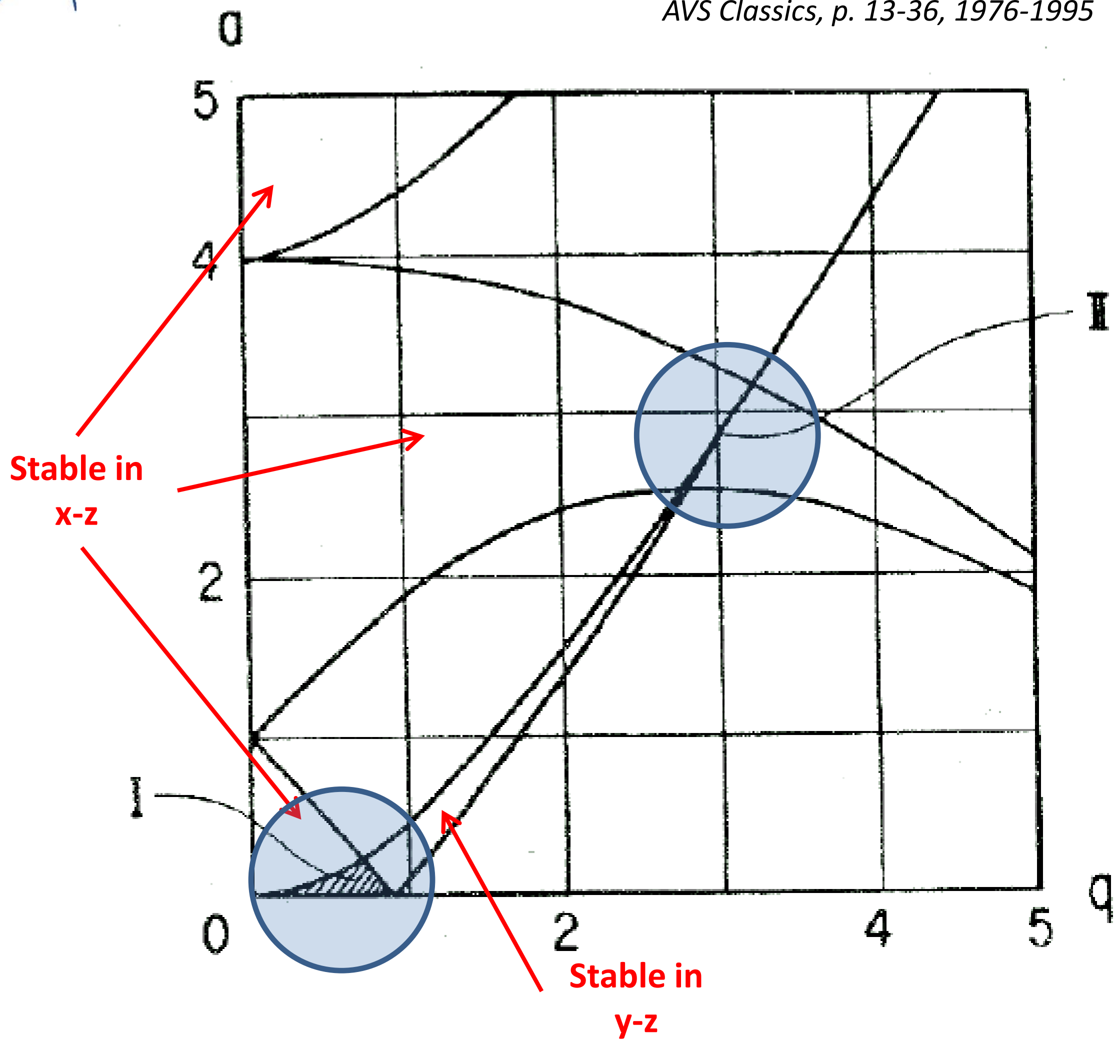
Stability Diagram



http://www.analytik.ethz.ch/vorlesungen/modernMS/Analytische_Chemie_III_Nieckarz_Oct_2010.pdf

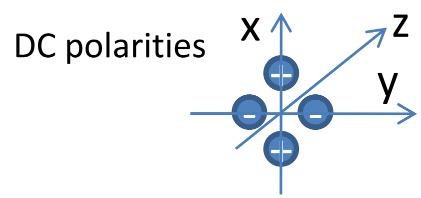
Selection: The Quadrupole Mass Filter

P. H. Dawson, Quadrupole Mass Spectrometry and its Applications, AVS Classics, p. 13-36, 1976-1995



$$a = \frac{4\,eU}{mr_0^{\ 2}\omega^2}$$

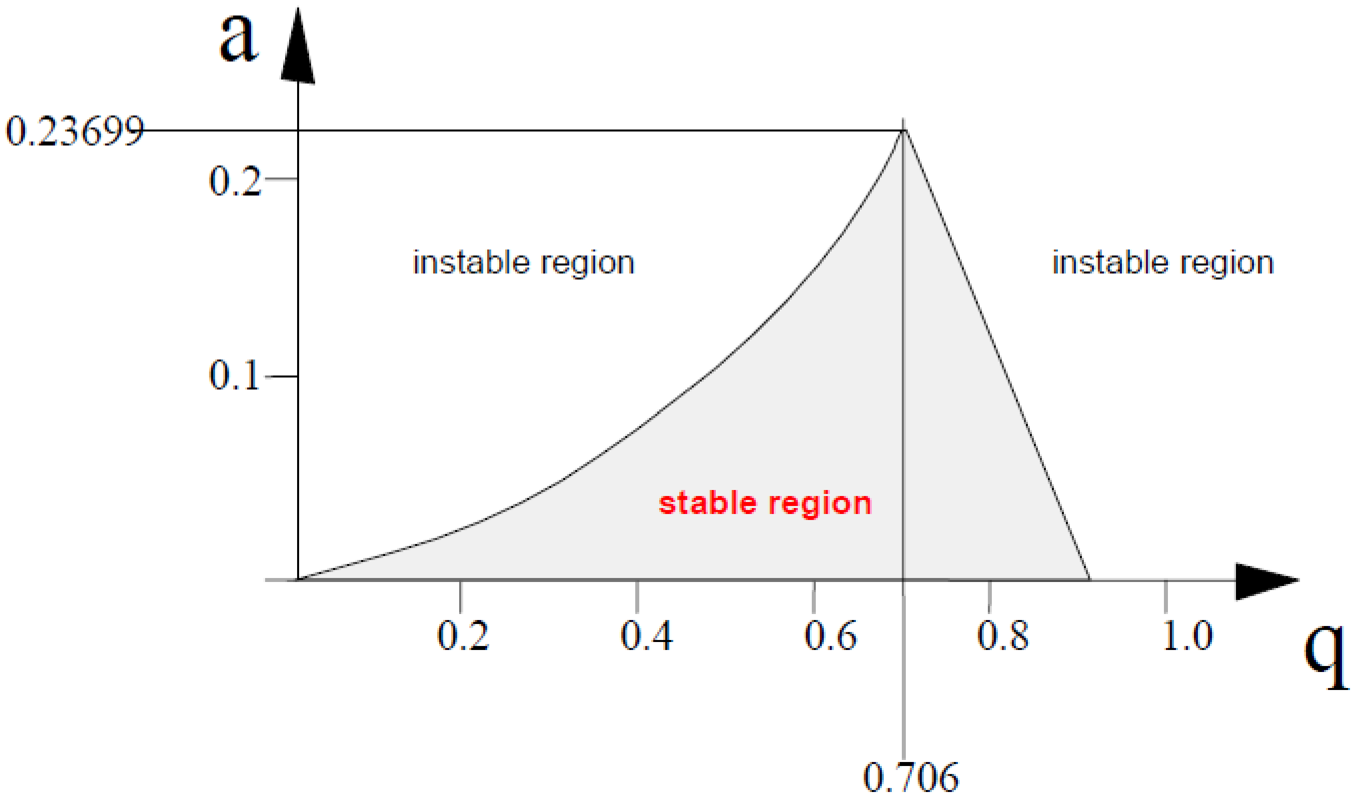
$$q = \frac{2\,eV}{mr_0^{\ 2}\omega^2}$$



The area bounded by the curves is called the '**stability triangle**' and represents the **values of U and V for which the displacement of an ion of mass m, in x and y, is less than r_0**

Selection: The Quadrupole Mass Filter

MS basis, N. Müller, Inficon

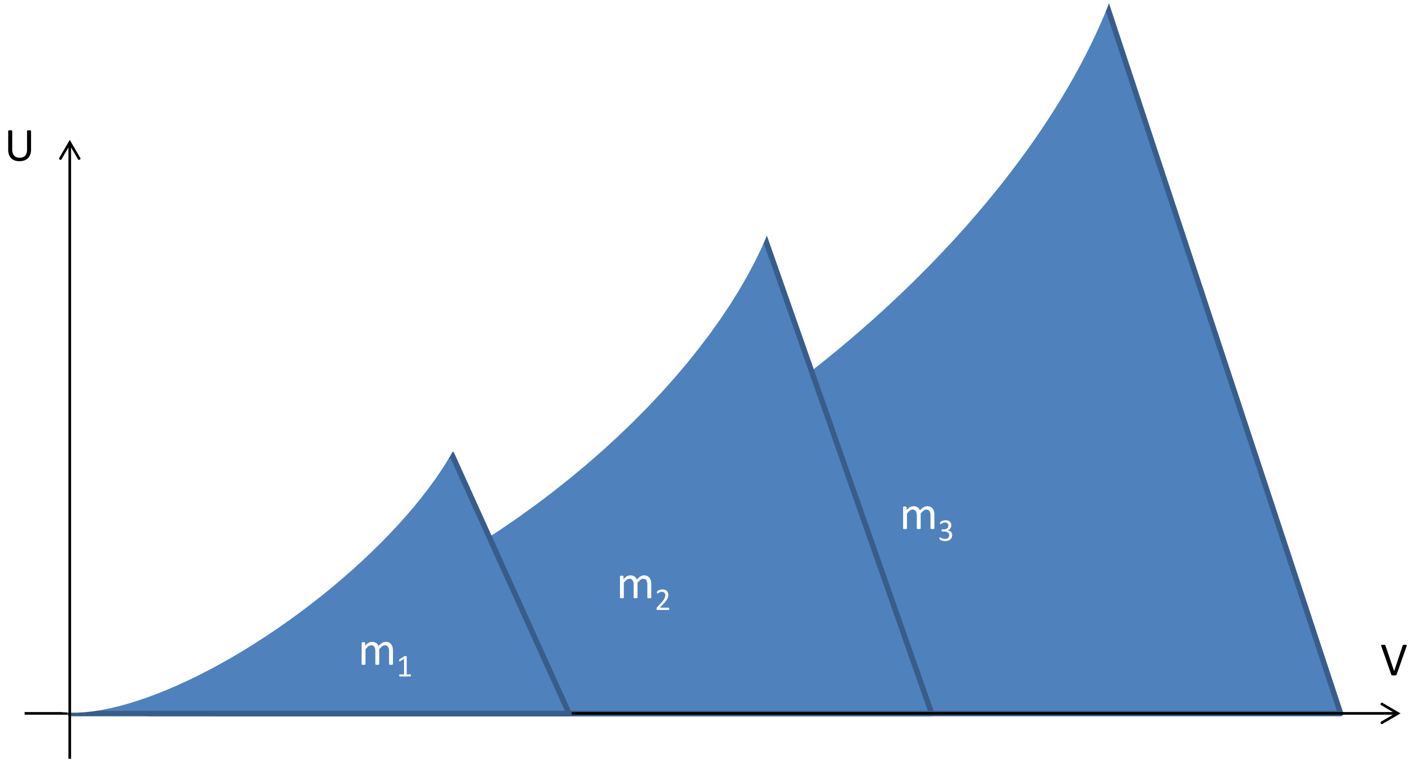


$$a = \frac{4\, eU}{m r_0^2 \omega^2}$$

$$q = \frac{2\, eV}{m r_0^2 \omega^2}$$

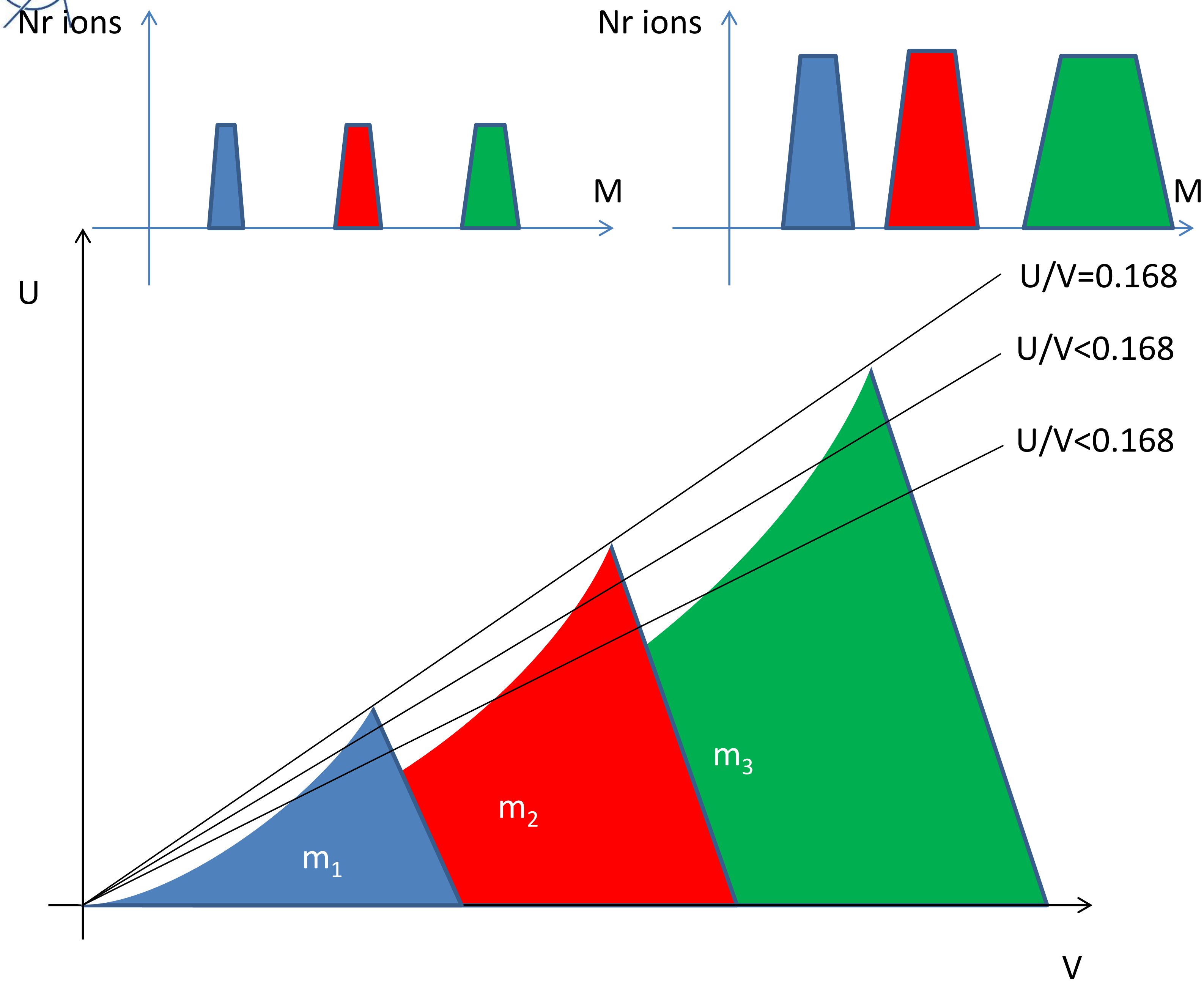
Selection: The Quadrupole Mass Filter

For a fixed value of frequency and r_0, in the **U-V plot a stability triangle for each mass is identified.**



- In principle, one could operate a quadrupole changing U and V independently of one another.
- In practice, **quadrupoles are usually operated in a manner such that the ratio U/V is held constant**, regardless of the actual magnitude of either U or V. In terms of the U-V diagram, this is equivalent to change U and V on a straight line which has a zero intercept: such a line is known as the **mass scan line**.

Selection: The Quadrupole Mass Filter



Selection: The Quadrupole Mass Filter

F. M. Ma, S. Taylor *IEE Proc.-Sci. Meas. Technol., Vol. 143, No. 1, January 1996*

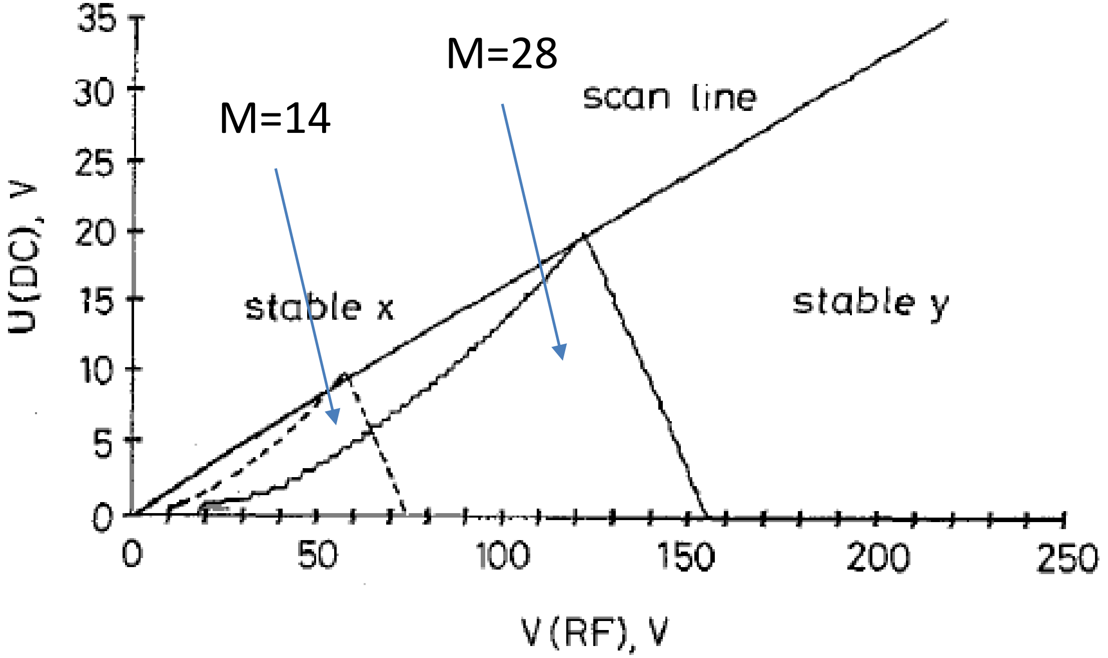
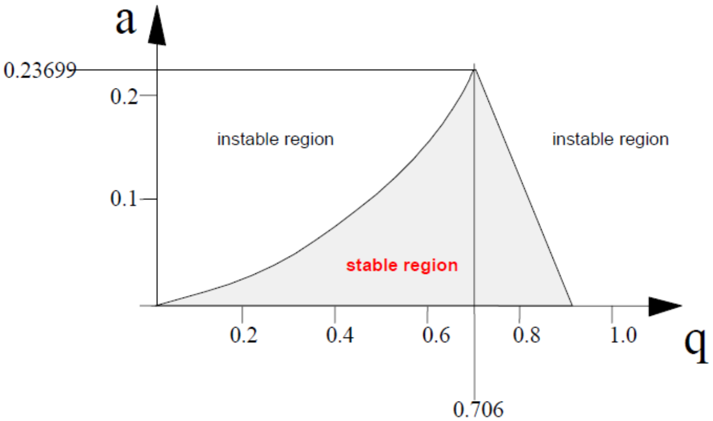


Fig.4 *Stability diagram showing peak condition for nitrogen (N_2^+) at U = 20 V and V = 123.5 V*
Filter radius (r_0) = 2.75 mm and frequency (f) = 2 MHz

Important characteristics of quadrupole mass filters:

1. Keeping U/V constant, resolution **M/ΔM is constant**.
2. Because M/ΔM is constant: **the larger the mass unit, the larger its corresponding peak.**
3. The resolution can be varied electronically adjusting U/V. In theory, there is the '*apparent possibility of an infinitely high resolution as the scan line approaches the stability tip,*' [P. H. Dawson]
4. There is a linear relationship between mass /ion charge and applied voltage.



$$\frac{m}{Ze} = \left(\frac{4}{0.706 \cdot \omega^2 r_0^2} \right) \cdot V$$

5. For a=**U=0**, i.e. no static polarisation, the quadrupole can be used as a **total pressure gauge** by scanning V in the stability range..

Selection: The Quadrupole Mass Filter Resolution; Finite Length

- Due to the **finite length of the rods,** the resolution of a quadrupole filter cannot be so high as it can be concluded by considering the stability triangle.

- Ion trajectories that would have been instable in an infinite quadrupole can reach the exit.

- It can be shown that the **upper limit to the resolution depends on the number of RF oscillations (n_0)**. :

$$\left(\frac{m}{\Delta m}\right)_{MAX} = k \cdot n_0^2 \quad \text{with } k \approx \frac{1}{20}$$

$$\Delta m = \text{width at 10\% of mass peak signa}$$

- n_0 is easily estimated considering the field axis potential V_Z:

$$e \cdot V_z = \frac{1}{2} m \cdot v_z^2 \rightarrow v_z = \sqrt{\frac{2 \cdot e \cdot V_z}{m}}$$

$$v = \frac{s}{t} = \frac{L_R}{\left(\frac{n_0}{f}\right)} \rightarrow \frac{f \cdot L_R}{n_0} = \sqrt{\frac{2 \cdot e \cdot V_z}{m}} \rightarrow n_0 = f \cdot L_R \cdot \sqrt{\frac{m}{2 \cdot e \cdot V_z}}$$

- Therefore:

$$\left(\frac{m}{\Delta m}\right)_{MAX} = k \cdot \left(f \cdot L \sqrt{\frac{m}{2 \cdot e \cdot V_z}} \right)^2 = k \frac{f^2 L^2 m}{2 \cdot e \cdot V_z} \Rightarrow (\Delta m)_{MIN} = \frac{2 \cdot e \cdot V_z}{k \cdot f^2 L^2}$$

The finite length affects in particular the lighter masses

$$(\Delta m)_{MIN} = \frac{2 \cdot e \cdot V_z}{k \cdot f^2 L^2}$$

Estimated value: L=0.1 m, f=2.5 MHz, V_z=10 eV → $(\Delta M)_{MIN}$=0.64

Selection: The Quadrupole Mass Filter, Mass Range

P. H. Dawson, Quadrupole Mass Spectrometry and its Applications, AVS Classics, p. 13-36, 1976-1995

Maximum RF amplitude

$$M_{MAX} = \frac{7 \cdot 10^6 \cdot V_{MAX}}{f^2 r_0^2}$$

Estimated value: r_0 =5 mm, f=2.5 MHz, V_{MAX}=3000 V → M_{MAX}=135

To have large mass range and high resolution:

- High RF voltage
- Low aperture -> low rod diameter
- Low frequency

- Long rods
- Low field axis voltage
- High frequency

$$\left(\frac{m}{\Delta m}\right)_{MAX} = k \frac{f^2 L^2 m}{2 \cdot e \cdot V_z}$$

But sensitivity is also important…

Mechanical errors can be the leading factor …

Selection: The Quadrupole Mass Filter, Mechanical Misalignment

Interesting paper: S. Taylor and J. R. Gibson, J. Mass Spectrom. 2008; **43**: 609–616

From the stability triangle, we have:

$$\frac{m}{e} = \left(\frac{2}{0.706 \cdot \omega^2 r_0^2} \right) \cdot V$$

If we consider frequency and voltage error-less, we can evaluate **the influence of field radius errors on the selected mass**. Differentiating…

$$dm = -\left(\frac{2eV}{0.706 \cdot \omega^2 r_0^2} \right) \cdot \frac{2dr_0}{r_0} \rightarrow \frac{dm}{m} = -\frac{2dr_0}{r_0}$$

Assume r_0=3 mm, Δr_0=30 µm -> $\frac{\Delta m}{m} = -\frac{0.06}{3} = 0.02 \rightarrow \frac{m}{\Delta m} = \left(\frac{M}{\Delta M} \right)_{MAX} = 50$

- This value shows the limitation of the 'mathematical' values obtained by the quadrupole filter theory (infinite-length filter).
- **The resolution limitation is less severe for larger r_0 -> larger rod diameter**

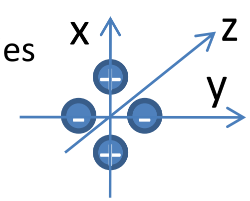
Selection: The Quadrupole Mass Filter, Mechanical Misalignment

S. Taylor and J. R. Gibson, J. Mass Spectrom. 2008; **43**: 609–616

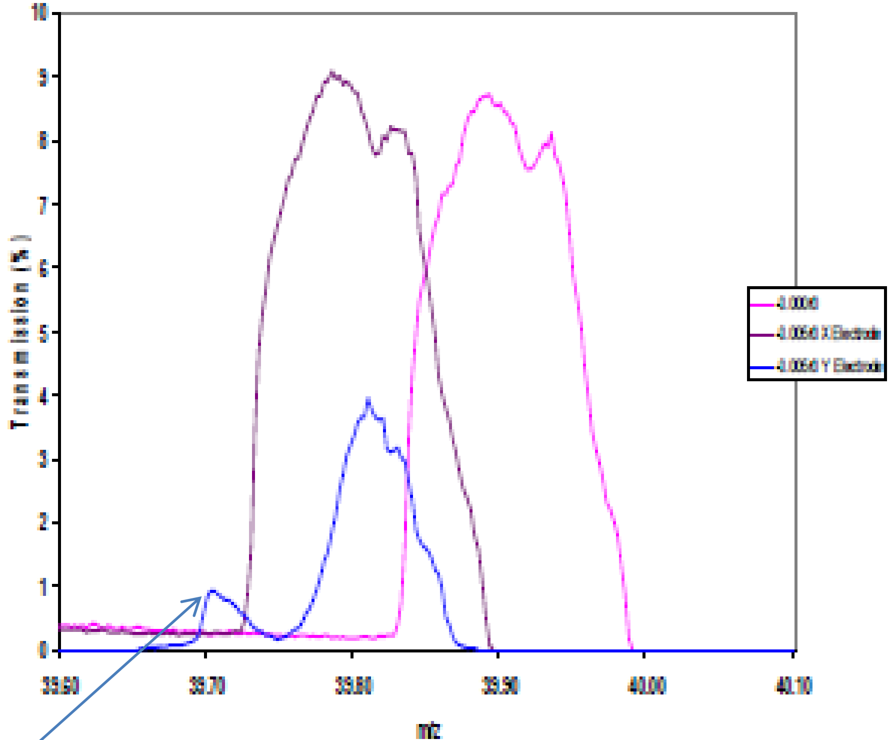
The **shape and position** of the mass peaks are strongly affected by **rod misalignment**

- **X electrode** displacement results in **shift to lower mass position** with minor change to peak shape and amplitude.
- **Y electrode** displacement results in slightly smaller shift accompanied by **significant change to peak shape** and structure.

DC polarities



Effects of manufacturing tolerance for mass 40

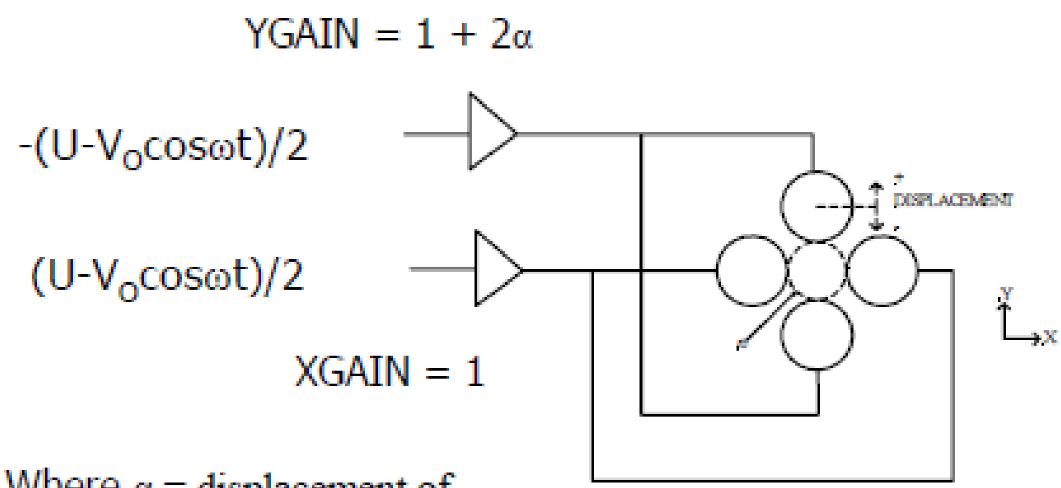


precursor peak

T.J. Hogan, RGA-8, March 13, 2008

T.J. Hogan, RGA-8, March 13, 2008

- If the poor performance is caused by a radially inward **displacement** of one rod, then this will **increase the electric field** generated by this rod.
- If the voltage on the displaced rod is slightly reduced without change to voltages on the other rods, it should be possible to compensate for the effects of the manufacturing error.



Where α = displacement of electrode as a fraction of r0

This technique is the subject of a number of patents [14].

WARNING:
The RF generators are in general tuned to a specific quadrupole filter to compensate for specific misalignment and other errors; an RF box has a unique partner…

Selection: The Quadrupole Mass Filter, Contamination of the Rods

As for the mechanical misalignment, errors in the RF and DC voltage are very critical.

- The filter is very sensitive to the **build up of electrostatic charges**. A few **mV** local variation of the DC potential can **change the sensitivity** in the percentage range.

- The build up of charges is attributed to **contaminations** (poorly conductive): the best cleanliness is needed during manipulation; assembly and operation.

- Small **ceramic particles** felt close to the quadrupole filter can provoke peak deformation and shift: this is one of the **main causes of breakdown** in our RGA.

Selection: The Quadrupole Mass Filter, Sensitivity vs. Resolution

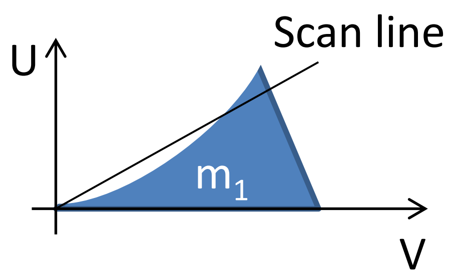
P. H. Dawson, Quadrupole Mass Spectrometry and its Applications, AVS Classics, p. 140, 1976-1995

- As U/V is increased to give **increased resolution**, a greater fraction of **the ions are lost** and hence **sensitivity is reduced**.

- The actual **relationship between resolution and sensitivity is complex** as it depends on concentration and divergence of the ion beam leaving the source.

- It is complicated further by the **defocusing action of the fringing fields** between the ion source and the analyser: low energy ions spend more time in fringe field area and are therefore transmitted less efficiently.

K. Jousten, Handbook of vacuum technology, Wiley, p.646



- In general, the product resolution-sensitivity is a constant:

$$\frac{M}{\Delta M} \cdot K\left[\frac{A}{Torr}\right] = \text{const.} \rightarrow K \propto \frac{1}{R}$$

- For P.H. Dawson: $K \propto \left(\frac{1}{R}\right)^{1-1.5}$

Selection: The Quadrupole Mass Filter, Sensitivity vs. Ion Mass

P. H. Dawson, Quadrupole Mass Spectrometry and its Applications, AVS Classics, p. 143, 1976-1995

- **The sensitivity of the quadrupole transmission should not depend on mass to charge ratio, namely no mass discrimination.**
- In theory this is possible, but **very difficult to achieve**.
- The **heavier ions spend a longer time in the fringe field and, therefore, they experience a greater dispersion in the quadrupole field**.
- **Heavier ions are transmitted less efficiently -> mass discrimination**.
- This inconvenient is more severe for high resolution

K. Jousten, Handbook of vacuum technology, Wiley, p.646

$$K \propto \frac{1}{R} = \frac{\Delta M}{M} \xrightarrow{\text{for } \Delta M \approx 1} K \propto \frac{1}{M}$$

This is far from what we regularly measure ☹.

$$\frac{K_{H_2}}{K_{N_2}} \approx 1 \div 4$$ taking ionization into account

Detection: Methods for Detecting Ions

The ion transmitted by the filter are detected:

- either by a **Faraday cup**:
  - the ion current is collected and measured directly

- or by **Secondary Electron Multiplier**:
  - the ion current is multiples by orders of magnitude by discrete or continuous dynodes.

- Our RGA are in general equipped by both detectors. The Faraday cup is used when the total pressure is in the range **$10^{-5} \div 10^{-8}$ Torr**; the ion multiplier is best suited for pressure **lower than 10^{-7} Torr**.

Detection: Faraday Cup

- The Farady cup is made in a way to recapture secondary electron.

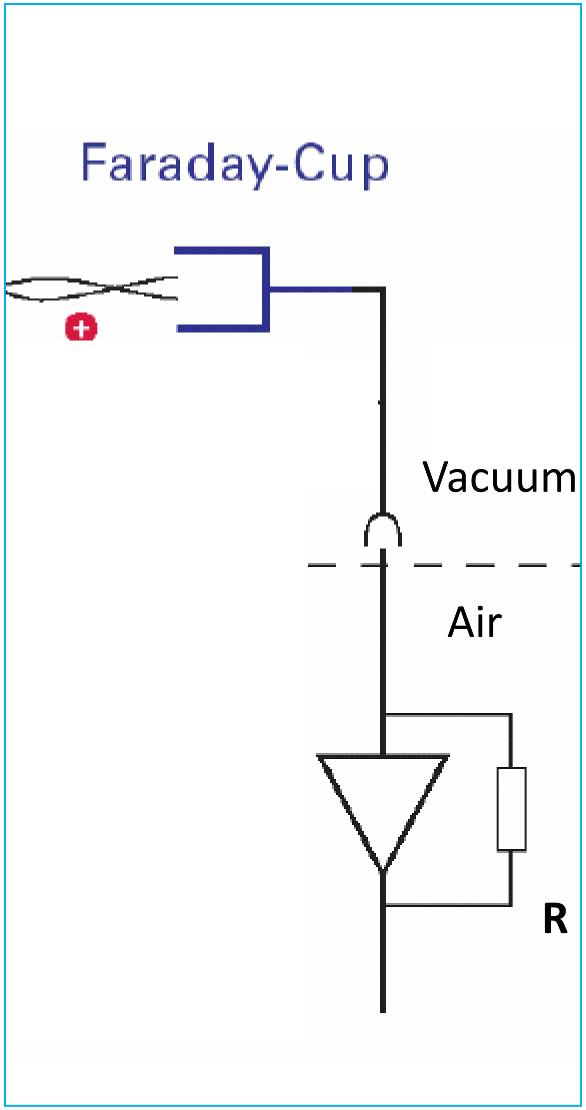
- It is always connected to an electrometer amplifier by a **short cable**:
  - reduced spurious signal pick-up
  - input capacitance low

- The resistor R is chosen in the range **$10^8 \div 10^{12}$ Ω** . Currents of the order of 10^{-15} A can be measured with a time constant of 1s.

- For a quadrupole operating in the low mass range, sensitivity of the order of **10^{-4} A/Torr** can be obtained.

- In theory a pressure detection limit in the 10^{-11} Torr could be attain.

- But in practice the **response time is too long**: R=10^{12} Ω, C=1 pF, t= 1/RC=1 s -> per each single measurement at least 3 s have to be taken-> 2.5 h for a 0-50 mass scan (60 measurements per mass unit)!



Detection: Faraday Cup

P. H. Dawson, Quadrupole Mass Spectrometry and its Applications, Tab 6.2 in p 137

Response time [s]	1	0.1	0.01	0.001
Minimum detectable signal [A]	10^{-15}	10^{-14}	10^{-13}	10^{-12}
Minimum detectable pressure [Torr]	10^{-11}	10^{-10}	10^{-9}	10^{-8}

This is what we use in general: 10 s for a 0-50 mass scan

The Faraday signal is **not affected by degradation** or mass-discrimination effects at the detector. In addition to the simple and robust design, a Faraday detector also has **long- term stability** and high thermal resistance.

Detection: Secondary Electron Multiplier

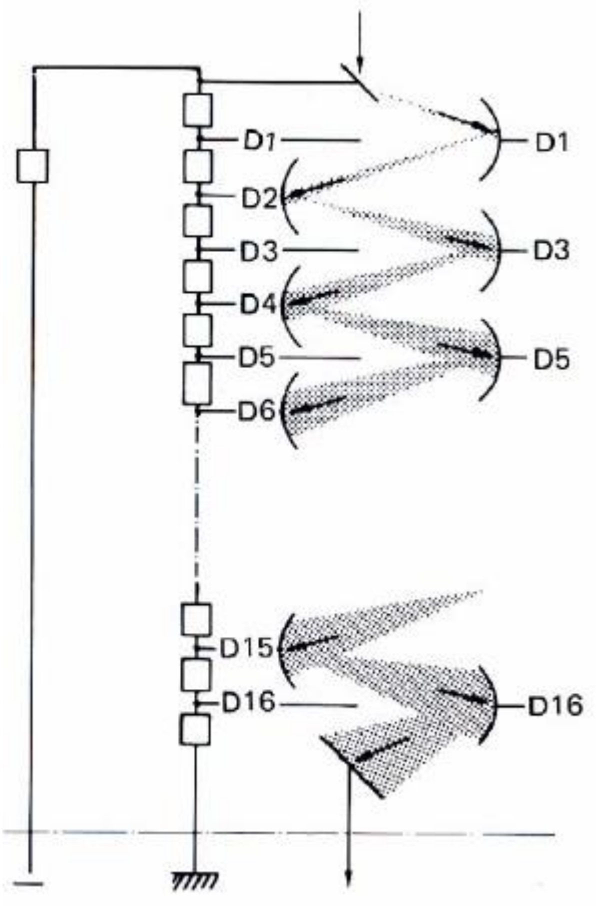
- The electron multiplier introduces a pre-amplifier with a current **gain up to $10^5 \div 10^8$** with **zero response time**. Both sensitivity and signal to noise ratio are improved.

- Both discrete and continuous dynode multiplier have a similar first step: **incident ions strikes on a high secondary electron emission surface. Here the ions impinge at low angle at about 2 KeV. A secondary electron yield > 5 is expected.**

- The electrons are then accelerated toward a second similar surface where additional electrons are emitted ; and so on. An electron avalanche is so produced and collected at the end of the multiplication steps by a Faraday cup. In between each couple of dynode about **200 V** are applied: SEY of 2 to 3 are expected:

- Gain = SEY proton at 2KeV x(SEY electron 200 eV)^N

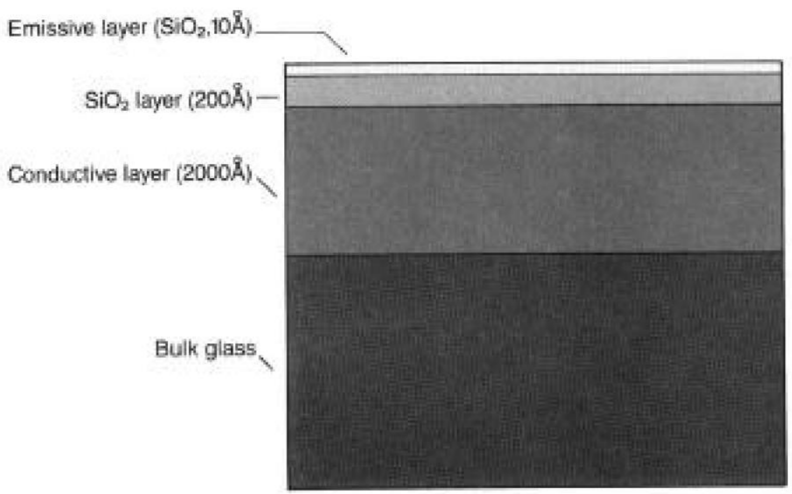
- For Pfeiffer SEM217: **N=17** -> **Max Gain =10^8** for SEY electron at 3500/17=205.9V -> SEY=2.7



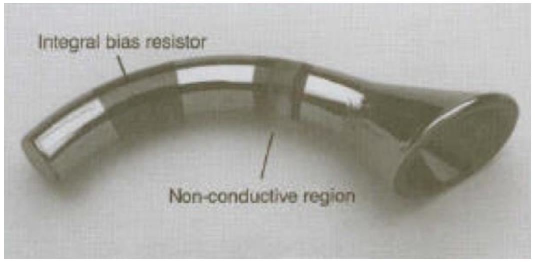
Detection: Secondary Electron Multiplier

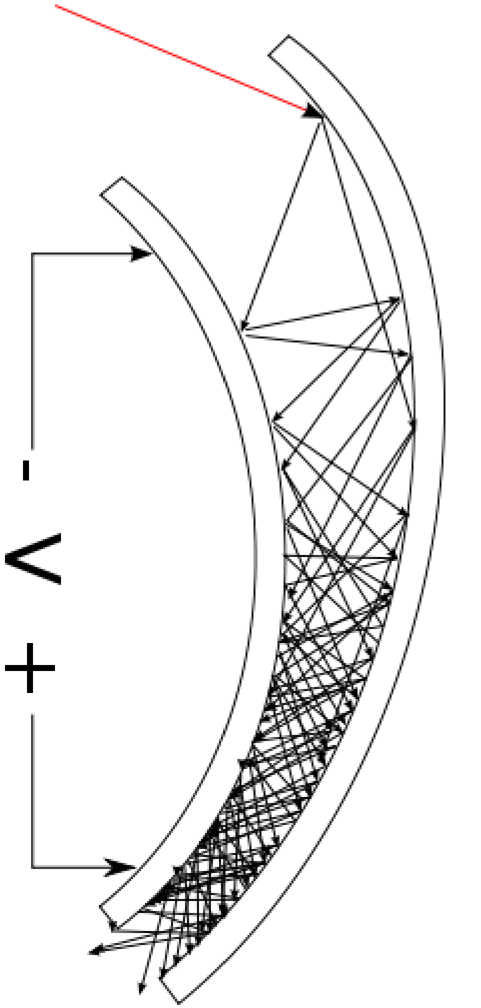
- The continuous multiplier (**channeltron**) utilizes a continuous surface made of a resistive material . The negative high voltage is applied to the whole surface producing a continuous voltage drop from the entrance to the exit.

- The shape allows multiple electron hops producing multiplication at each of them.



http://www.photonis.com/upload/industryscience/pdf/electron_multipliers/ChannelBook.pdf

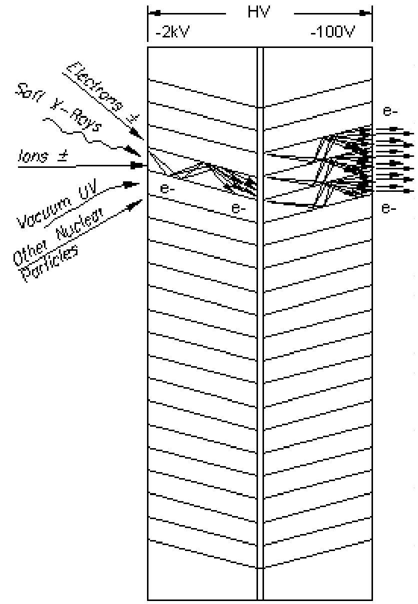




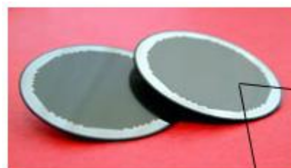
http://en.wikipedia.org/wiki/Electron_multiplier

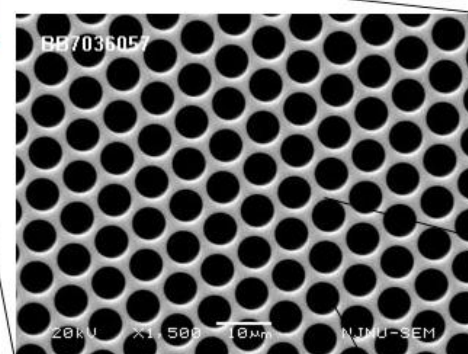
Detection: Secondary Electron Multiplier, MCP

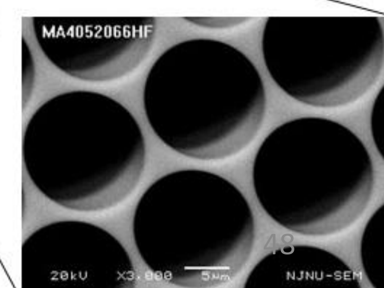
- Micro Channel plates have **gains of about 10^3-10^4**
- Instead of a single MCP, two MCPs are often sandwiched together in such a way that small angles oppose each other to obtain gains of 10^6-10^8.



http://www.amptek.com/a111.html







http://www.tectra.de/MCP.htm

Detection: Secondary Electron Multiplier

- The characteristic curve of electron multipliers is divided in two zones.
- In the first region the signal increases rapidly with the increasing voltage
- In the second it tends to saturate in a so-called plateau.

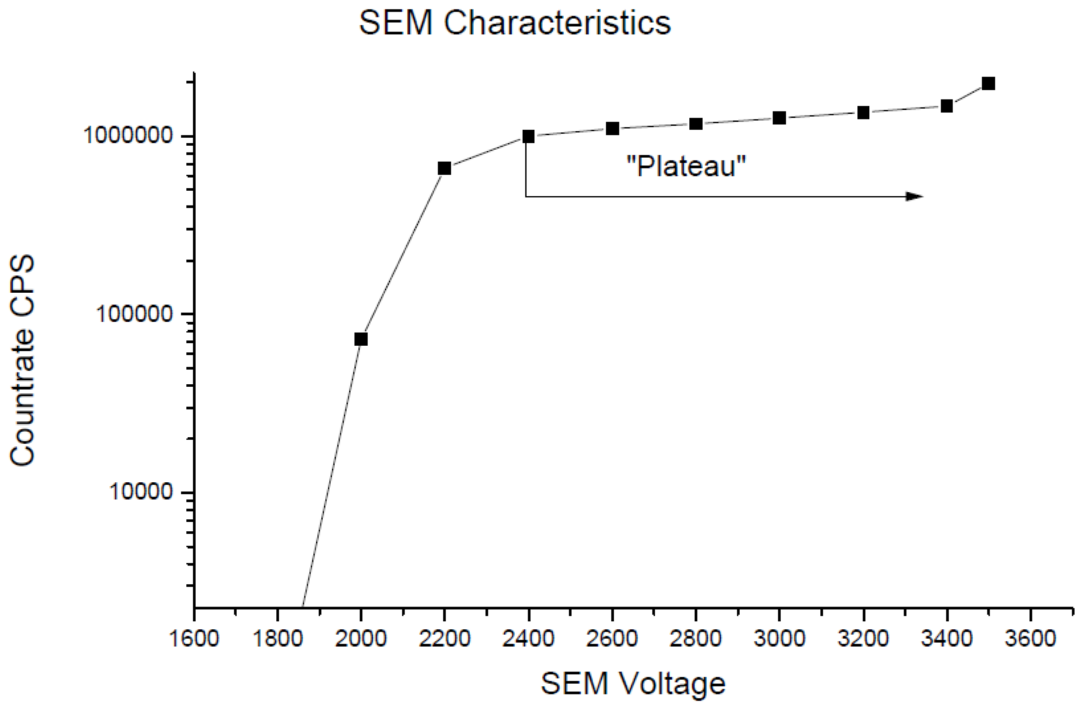
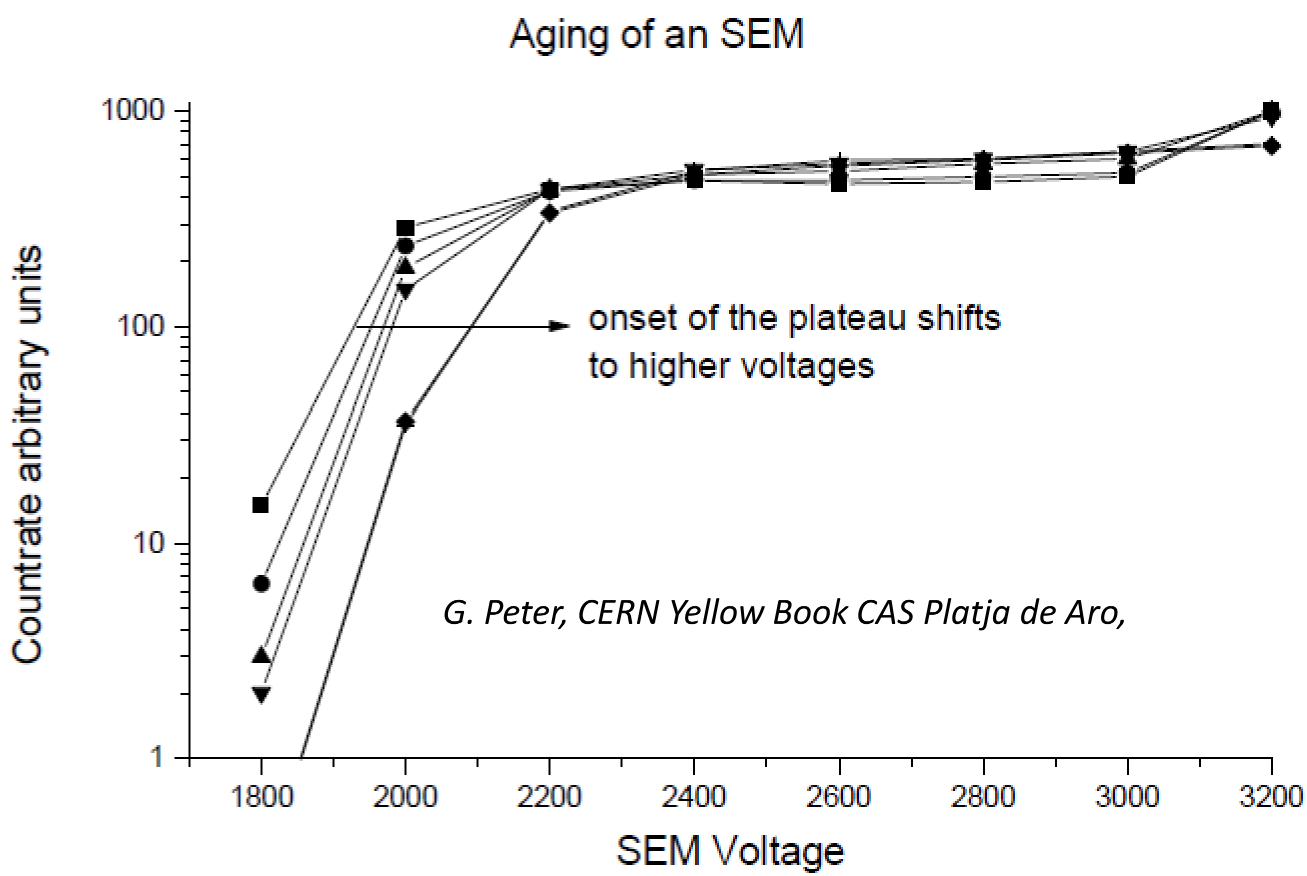


Fig. 6: Characteristics of a SEM operated in the counting mode

G. Peter, CERN Yellow Book CAS Platja de Aro,

Detection: Secondary Electron Multiplier

- **SEY and so the gain of a multiplier can change with time.**
- Long permanence in air or exposure to some gases can modify the SEY.
- **Adsorption of carbonaceous molecules leads to the formation of a C layer, with low SEY**.



It has been found that multipliers can be **rejuvenated** by baking them in 1 bar of O_2 at 300°C: carbon removal and re-oxidation of the surface.

Detection: Secondary Electron Multiplier

- The ion-electron conversion factor at the first surface of the multiplier depends on the energy and nature of the impinging ion.

- As a consequence, the **total gain of the multiplier may vary as a function of the ion mass.**

- Energetic neutrals and X-ray produced in the electron source or quadrupole can be transmitted by the quadrupole and strike the first surface of the multiplier. This phenomenon **increase the electrical noise**.

- To avoid direct line of sight from the quadrupole, the multiplier is **placed off axis**.

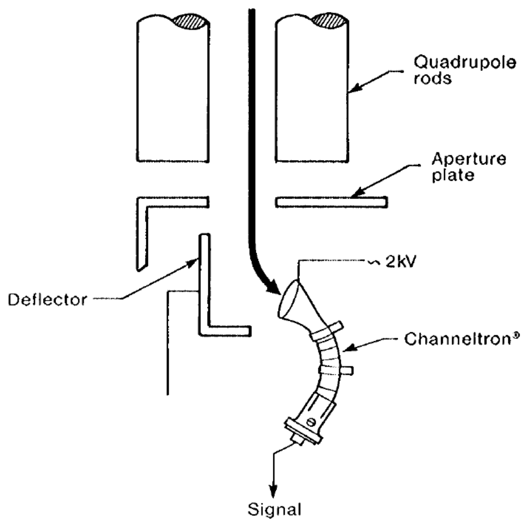
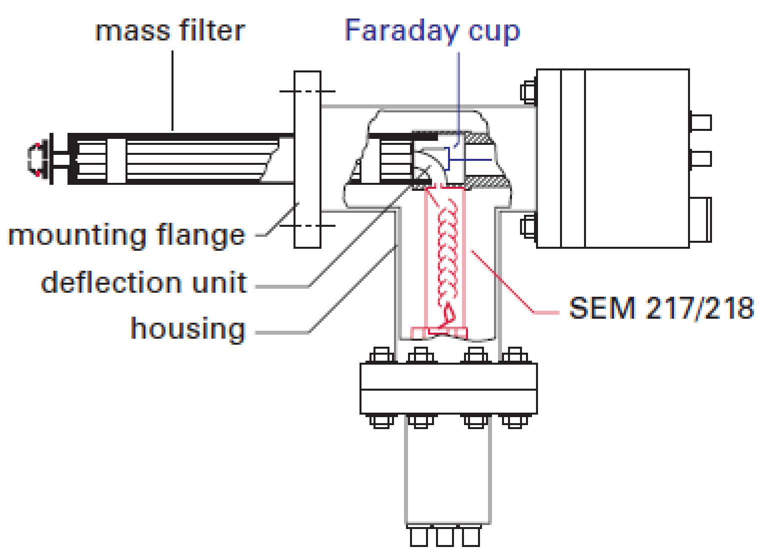
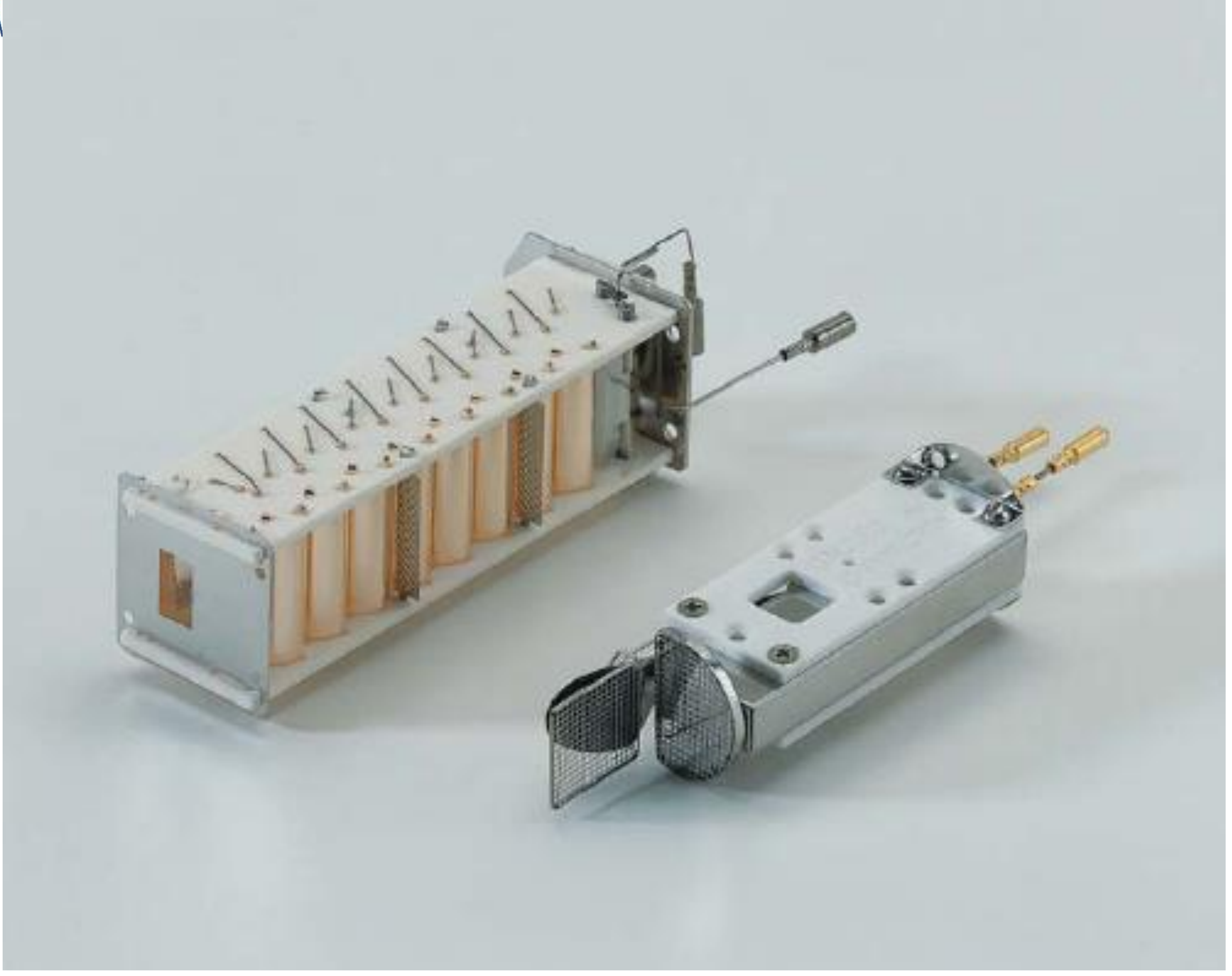


Figure 3-15 Quadrupole Mass Spectrometry (off - axis geometry)



Detection: Secondary Electron Multiplier



And now let’s put into practise…