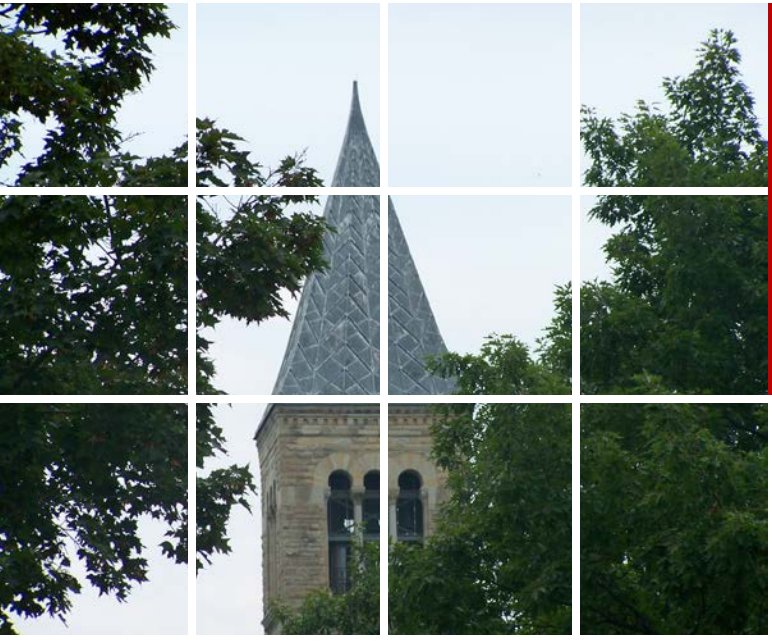


Vacuum Science and Technology for Accelerator Vacuum Systems

Yulin Li and Xianghong Liu
Cornell University, Ithaca, NY

Cornell Laboratory
for Accelerator-based Sciences
and Education (CLASSE)

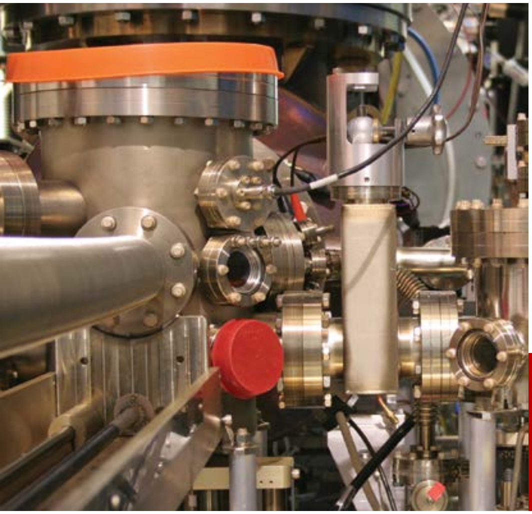


Table of Contents

SESSION 2: VACUUM INSTRUMENTATION

- Overview of total pressure gauges
- Direct pressure gauges
- Indirect pressure gauges
- Partial pressure gauges
- Gauge selection considerations

Vacuum Pressure Measurements

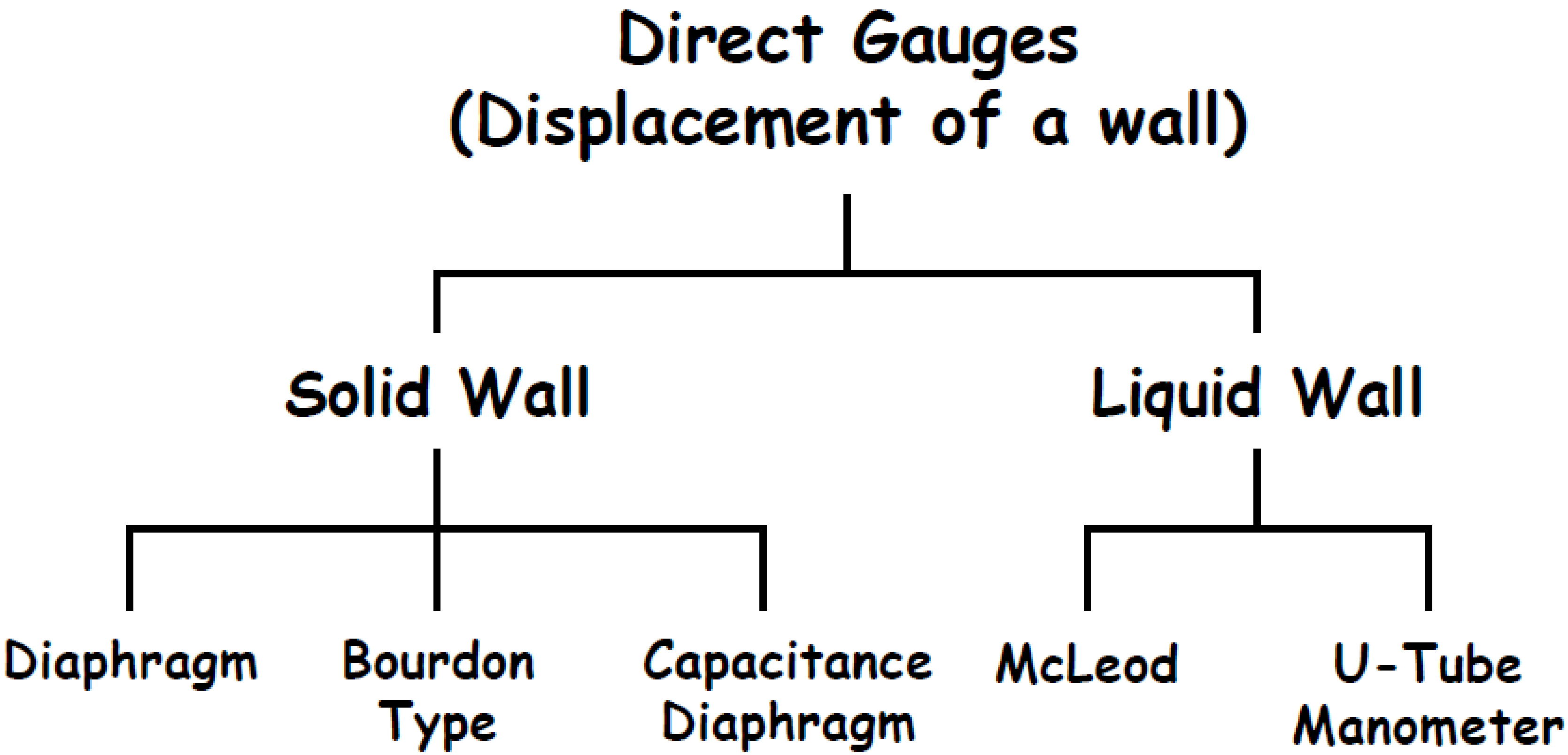
- *The Ideal Gas Law* – the foundation of vacuum measurements:

$$P = nkT$$

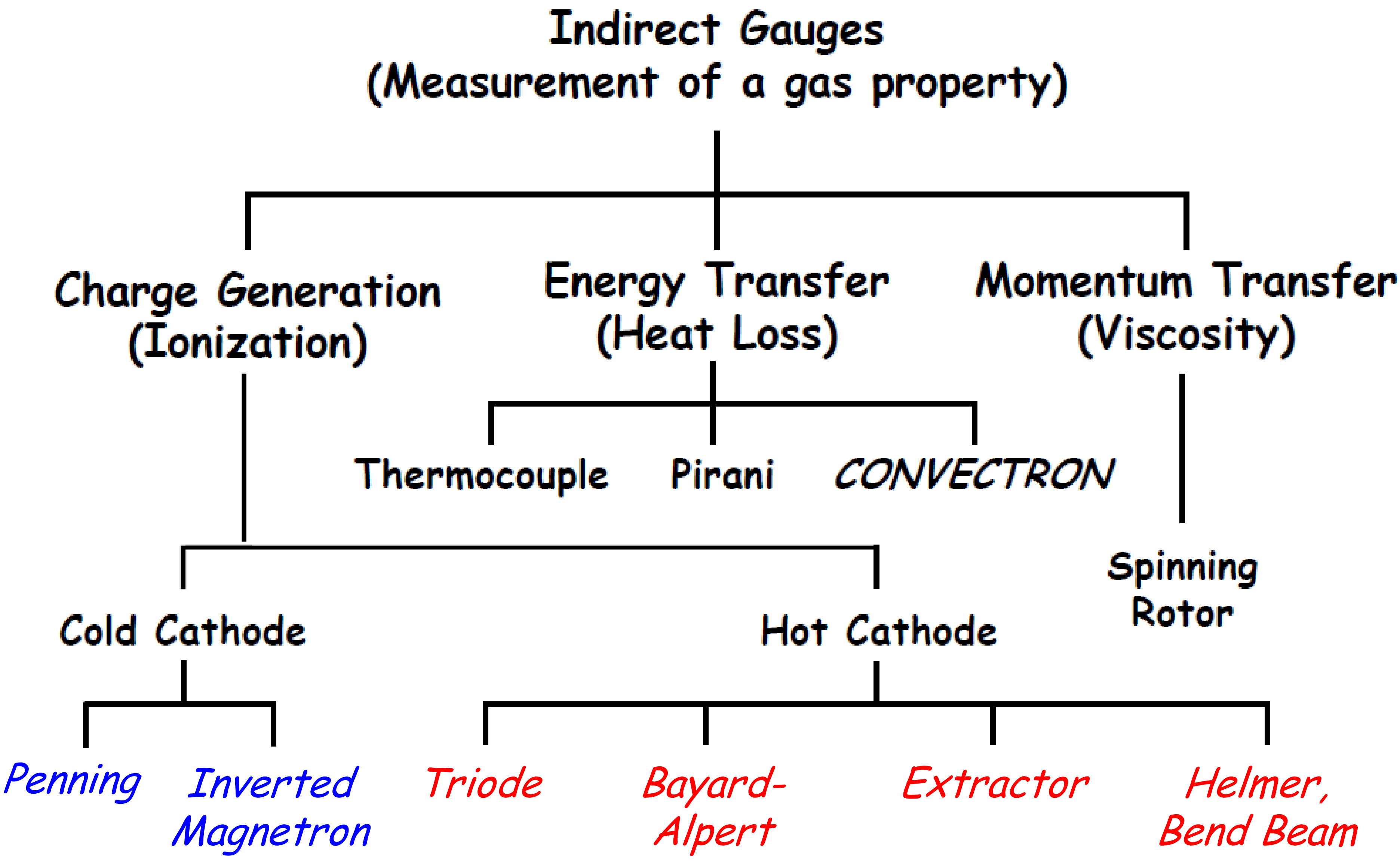
- *Direct pressure gauges* – Those gauges directly sense force per unit area. The direct gauges give 'true' measure of pressure, independent of gas types, and they may be used as primary pressure standards.
- *Indirect pressure gauges* – Those gauges explore the relations between certain physical properties (such as ionizations, viscosity, thermal energy) and the gas density. The indirect gauges are gas-type dependent, and require calibrations.

Total Pressure Gauges

Direct Gauges at a Glance

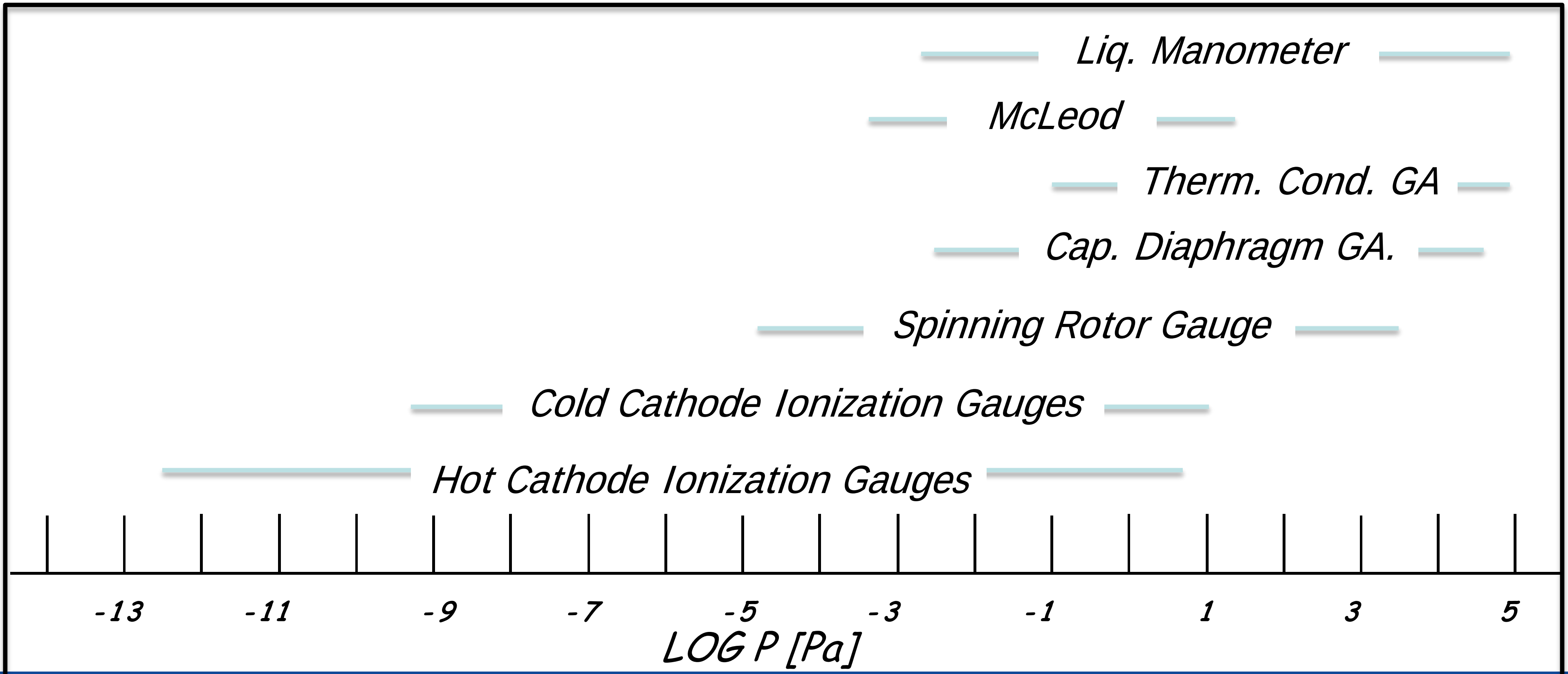


Indirect Gauges at a Glance



Vacuum Pressure Ranges

- *In today's scientific research and industrial processes, vacuum measurements cover over 17 decades of range, from atmospheric pressure (10^5 Pa) down to 10^{-12} Pa.*
- *For most applications, a combination of multiple types of gauges is needed .*



Pressure Units and Conversions

- *Mercury manometers have been used since the earliest days of vacuum technology. Thus the mmHg, or Torr is commonly used pressure unit, especially in the US.*
- *The SI unit for pressure is Pascal = 1 N/m^2.*
- *mbar is also commonly used, mostly used in Europe (and 'allowed' in SI). 1 mbar = 1.00x10^2 Pa = 0.750 Torr*

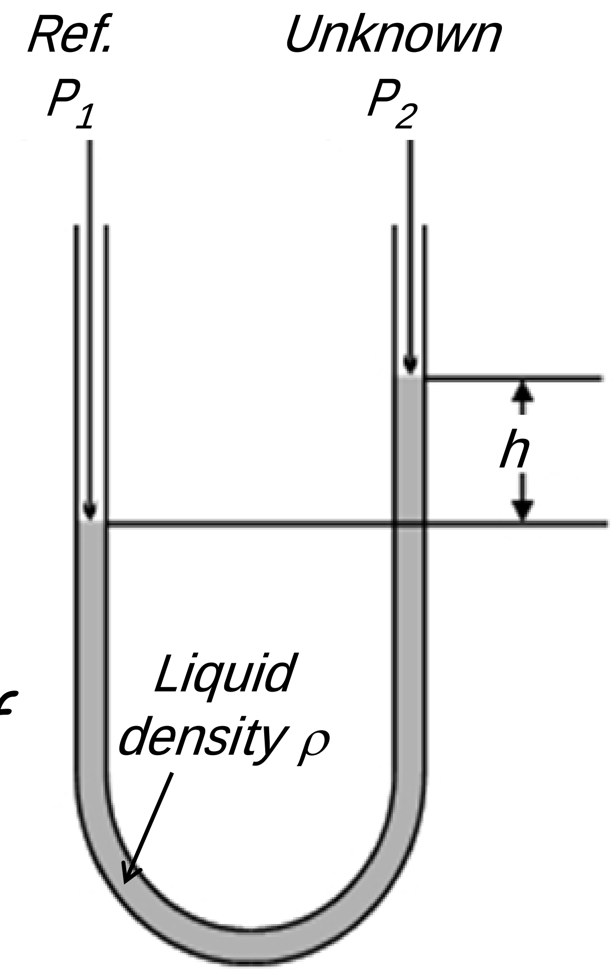
	Pa	mbar	Torr	In. Hg	PSI	atm.
Pa	1	1.00x10^2	1.33x10^2	3.39x10^3	6.89x10^3	1.01x10^5
mbar	1.00x10^{-2}	1	1.33	3.39x10^1	6.89x10^1	1.01x10^3
Torr	7.50x10^{-3}	7.50x10^{-1}	1	2.54x10^1	5.17x10^1	7.60x10^2
In. Hg	2.95x10^{-4}	2.95x10^{-2}	3.94x10^{-2}	1	2.04	2.99x10^1
PSI	1.45x10^{-4}	1.45x10^{-2}	1.93x10^{-2}	4.91x10^{-1}	1	1.47x10^1
atm.	9.87x10^{-6}	9.87x10^{-4}	1.32x10^{-3}	3.34x10^{-2}	6.80x10^{-2}	1

Liquid Manometers – U-Tubes

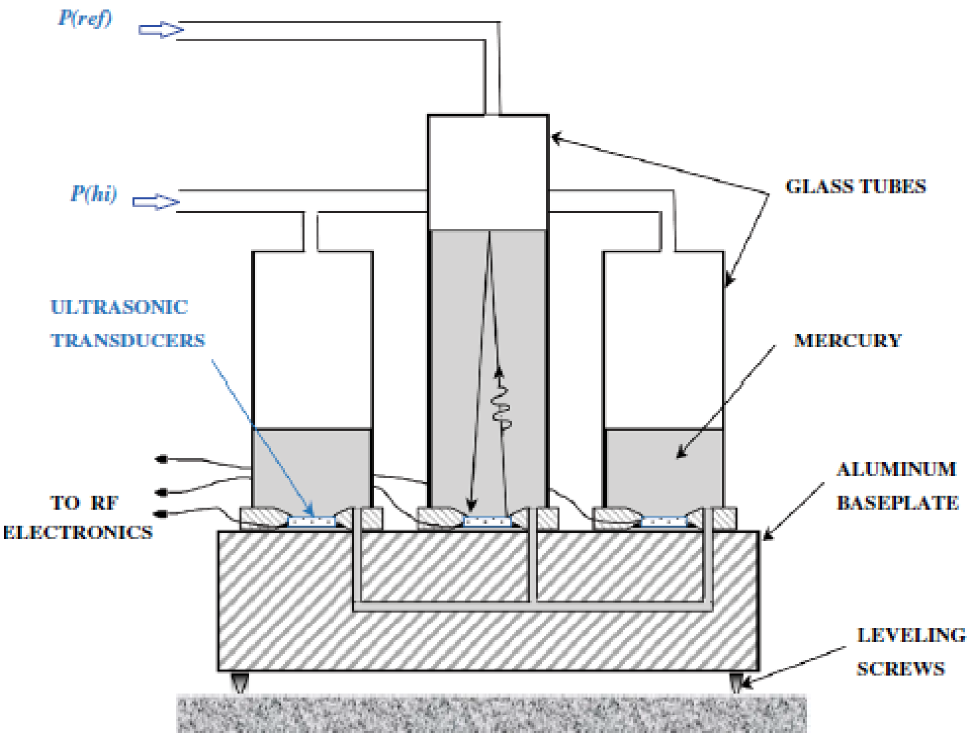
- *Simplest direct gauge.*
  Mercury or oil are often used.

$$P_1 - P_2 = h\rho g$$

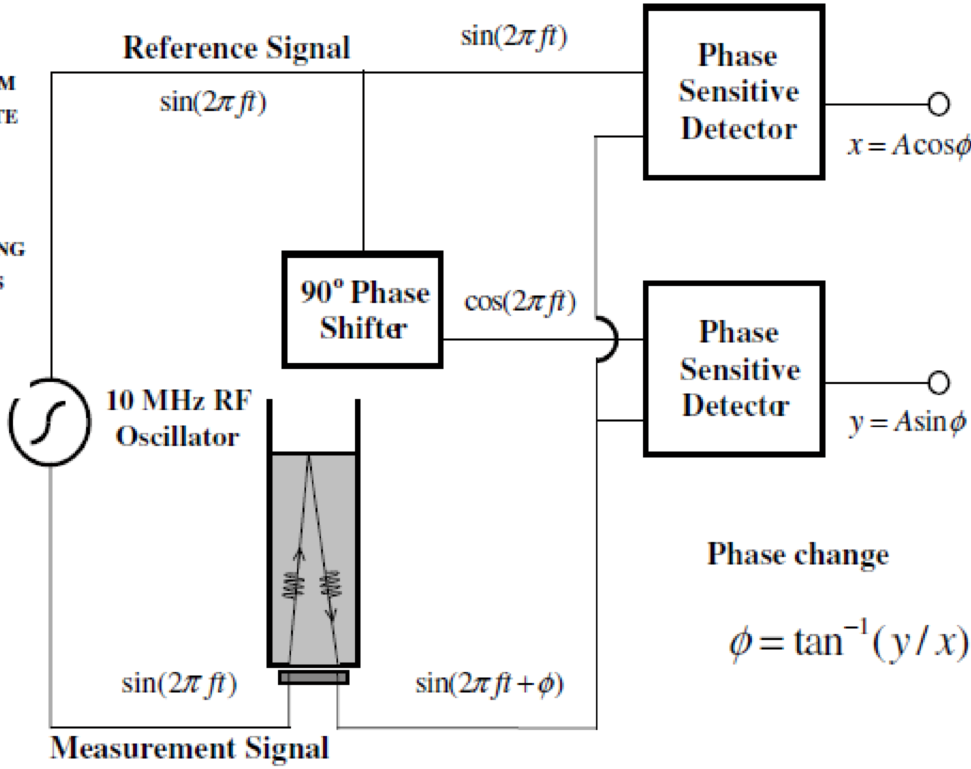
- *Main source of error is in measuring* ***h***
- *Elaborated methods developed to measure h, using optical or ultra-sonic interferometer, to achieve accuracy of 1.4 mPa in range of 1 Pa to 100 kPa in NIST, as US primary pressure standard*



NIST Ultrasonic Interferometer (UIM)



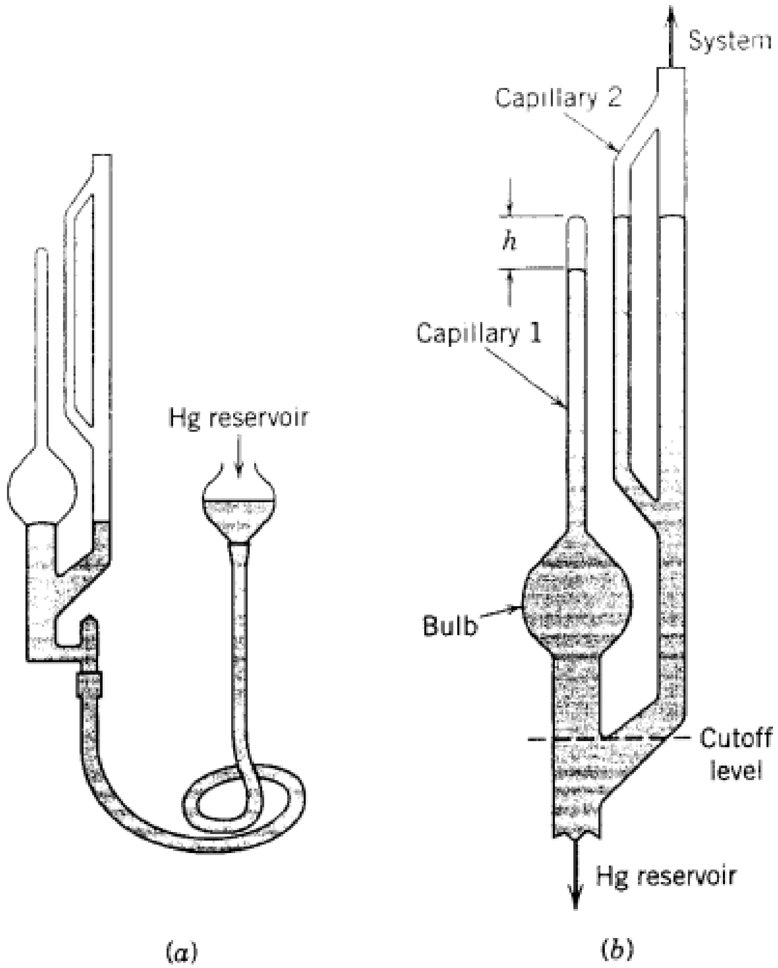
Basic NIST UIM Design



*) Jay H. Hendricks *, Douglas A. Olson, Measurement, **43** (2010) 664–674

Liquid Manometers – McLeod Gauge

- *McLeod gauge extends U-Tube manometer range using Boyle's law. It is the primary pressure standard in the range of $10^{-2} \sim 10^{3}$ Pa.*

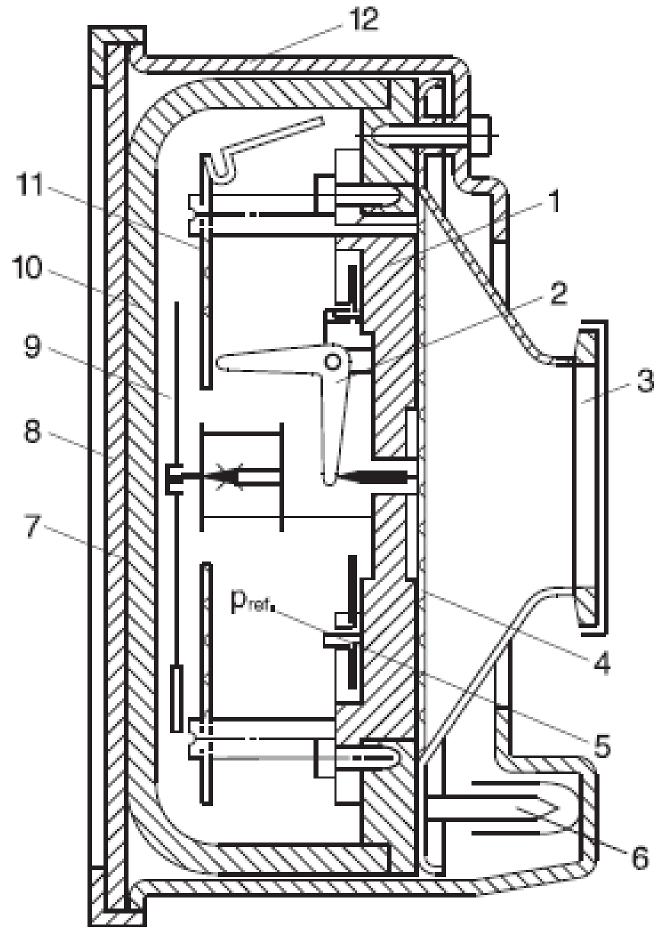


$$P = A\rho g h^2 / (V - Ah) \approx A\rho g h^2 / V$$

V – Known volume above 'cut-off'
A – Section area of capillary tubes 1&2

Mechanic Diaphragm Gauges

- *Direct gauge, independent of gas types*
- *LeyBold DIAVAC 1000*
- *Range: 1 ~ 1000 mbar*



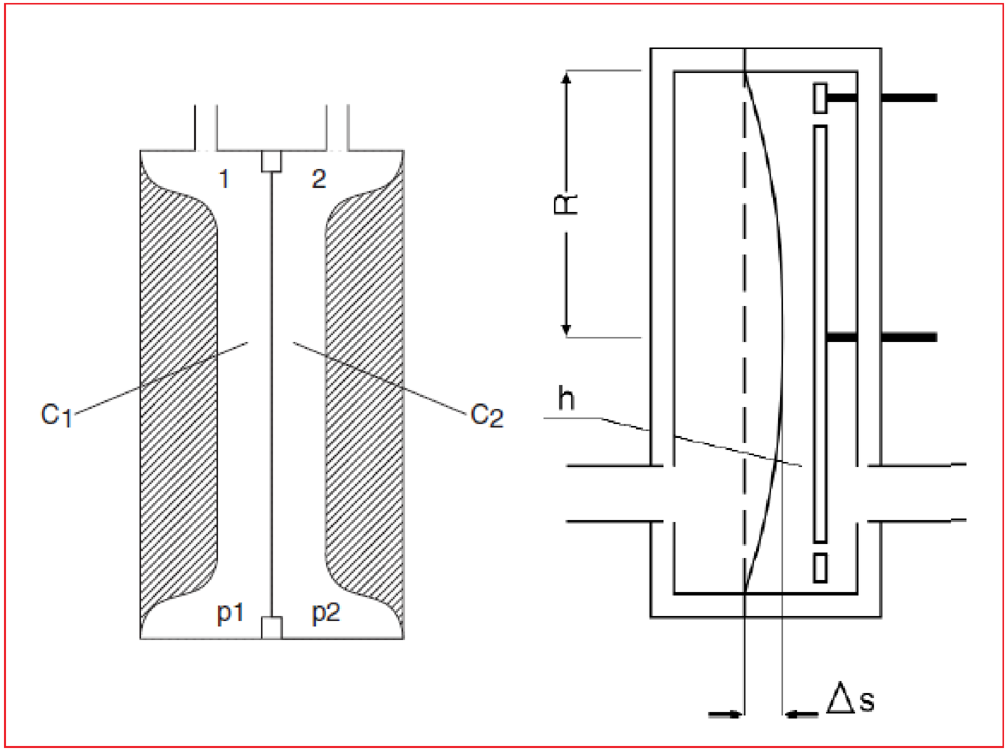
1	Base plate	7	Mirror sheet
2	Lever system	8	Plexiglass sheet
3	Connecting flange	9	Pointer
4	Diaphragm	10	Glass bett
5	Reference pressure pref	11	Mounting plate
6	Pinch-off end	12	Housing

Capacitance Diaphragm Gauges

- *Commercial CDG systems can measure pressure ranges from 0.1 ~ 10^5 Pa, independent of gas types.*
- *Usually a sensor can only cover 3~4 decades of pressure, with accuracy ±0.5%. CDG system with temperature control can provide accuracy and stability ±0.05%.*
- *CDGs are commonly used in thin film depositions.*
- *Main sources of errors are electronic drifts and diaphragm hysteresis.*

$$C = \varepsilon_0 KA/s$$

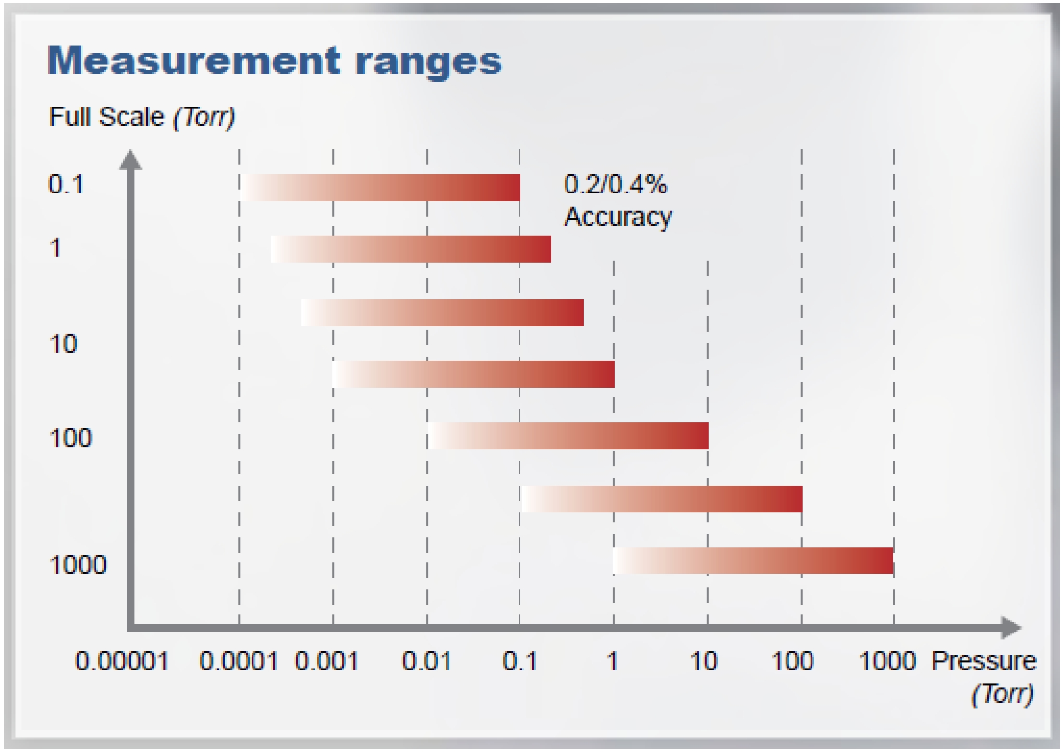
Differential pressure cause change in spacing, S.



Capacitance Diaphragm Gauge – Example

INFICON's CDGs

- All-ceramic diaphragm
- Wide ranges of pressure available
- Temperature compensated (stabilized)



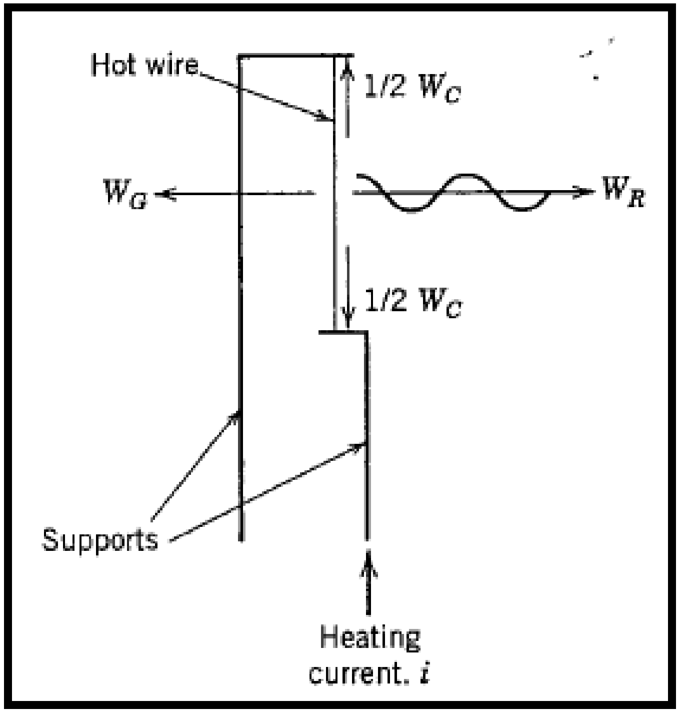
Indirect Vacuum Gauge Overview

- *Indirect gauges measure pressure by relating certain physical properties to the gas density.*
- *Three major types indirect gauges are commonly used.*
  - → *Thermal conductivity*
  - → *Viscosity*
  - → *Ionization*
- *Indirect gauges are gas type dependent*
- *Most commercially available indirect gauges are calibrated to nitrogen, thus relative calibrations of other gases to nitrogen is needed (and often supplied by the gauge manufacturers.)*

Thermal Conductivity Gauges (1)

- A hot wire in a gaseous environment loses heat (thermal energy) in three ways: (1)radiation, W_R, (2)conduction to supports, W_C, and (3) transfer by the gas molecules, W_G.

$$W_T = W_R + W_C + W_G$$

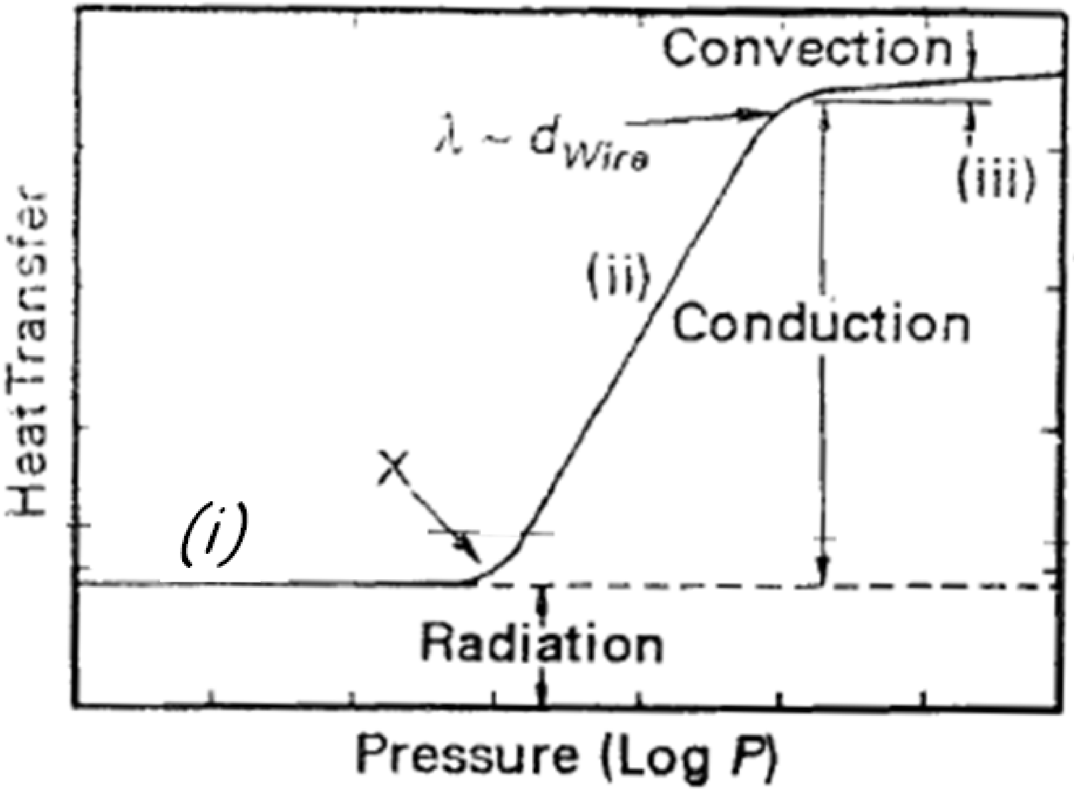


- W_G is pressure dependent, the base for these gauges.
- The heat gas transfer is approximately proportional to $m^{-1/2}$, and molecular types (atomic, diatomic, triatomic, etc.), thus is gas type dependent.
- W_R and W_C are independent of gas pressure, which determine the useful range of the gauges.

Thermal Conductivity Gauges (2)

Heat transfer may be divided into three regimes, based the pressure (mean-free length, λ)

(i) $\lambda \gg d_{wire}$; (ii) intermediate ; (iii) $\lambda \ll d_{wire}$



(i) Heat transfer insignificant as useful for pressure measurement

(ii) Linear heat transfer regime

(iii) Gas heated by the hot wire forms a hot sheath around wire

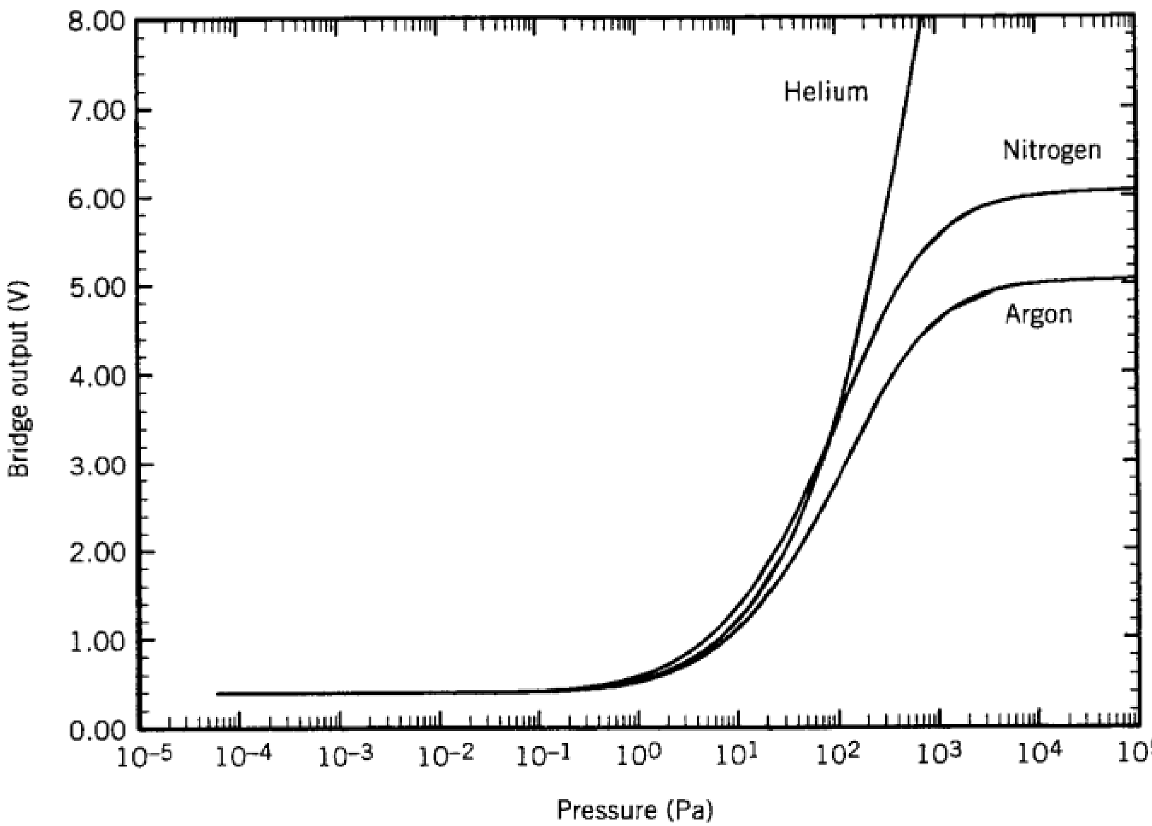
A Close Look at Heat Transfer

$$W_G = \frac{1}{4} \cdot \frac{\gamma + 1}{\gamma - 1} \cdot \alpha \cdot \sqrt{\frac{2k}{\pi m T_{wall}}} \left(T_{wire} - T_{wall}\right) P$$

α is gas accommodation coefficient,

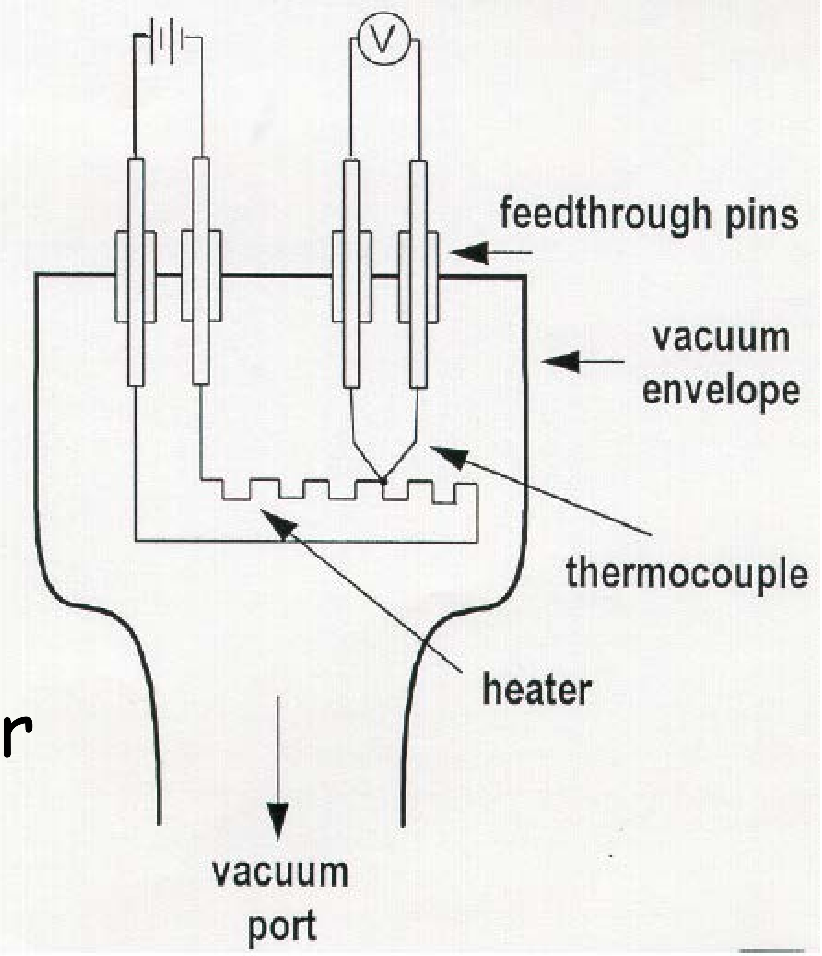
$\gamma = c_p/c_v$, c_p, and c_v are specific heat in a constant pressure and a constant volume process, respectively:

γ=1.667 (atoms)
γ≈1.40 (diatomic)
γ≈1.31 (triatomic)



Thermocouple Gauge

- Constant current through the heater (sensor).
- TC junction measures temperature changes (due to gas heat transfer).
- Working range: 10^{-2} ~ 1 torr
- Slow response time



Pirani Gauge

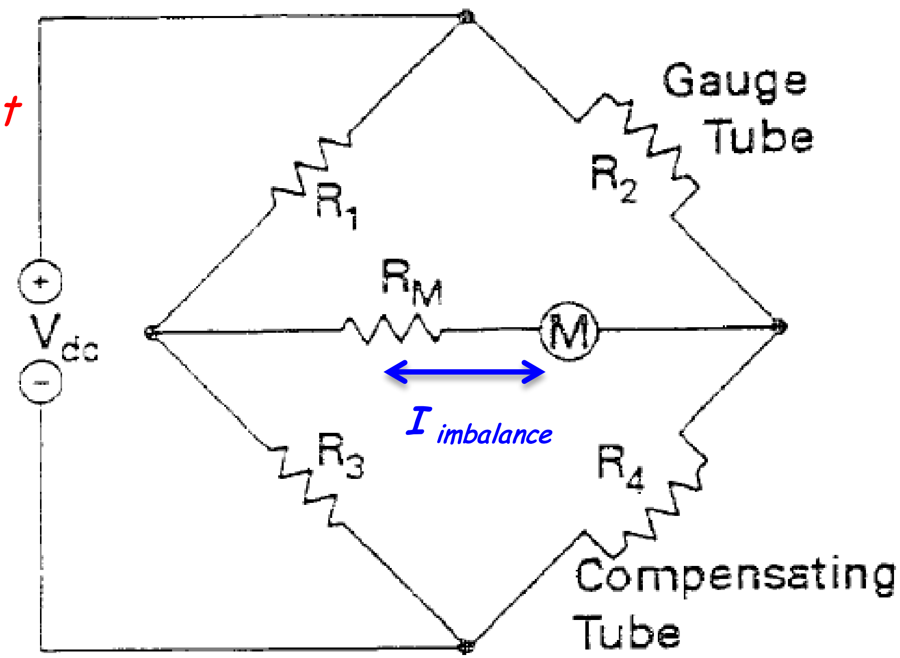
- In Pirani gauge, the heated filament constitutes an arm of a Wheatstone bridge. The Wheatstone bridge is balanced at high vacuum. Any gas heat transfer at higher pressure induces imbalance of the bridge.
- Working range: $10^{-4} \sim 100$ torr.
- There are two common modes of operations.

Constant Temperature Mode

Adjusting heating current to maintain constant temperature (thus the resistance) to keep bridge balanced. The heating current is related to the pressure.

Constant Voltage Mode

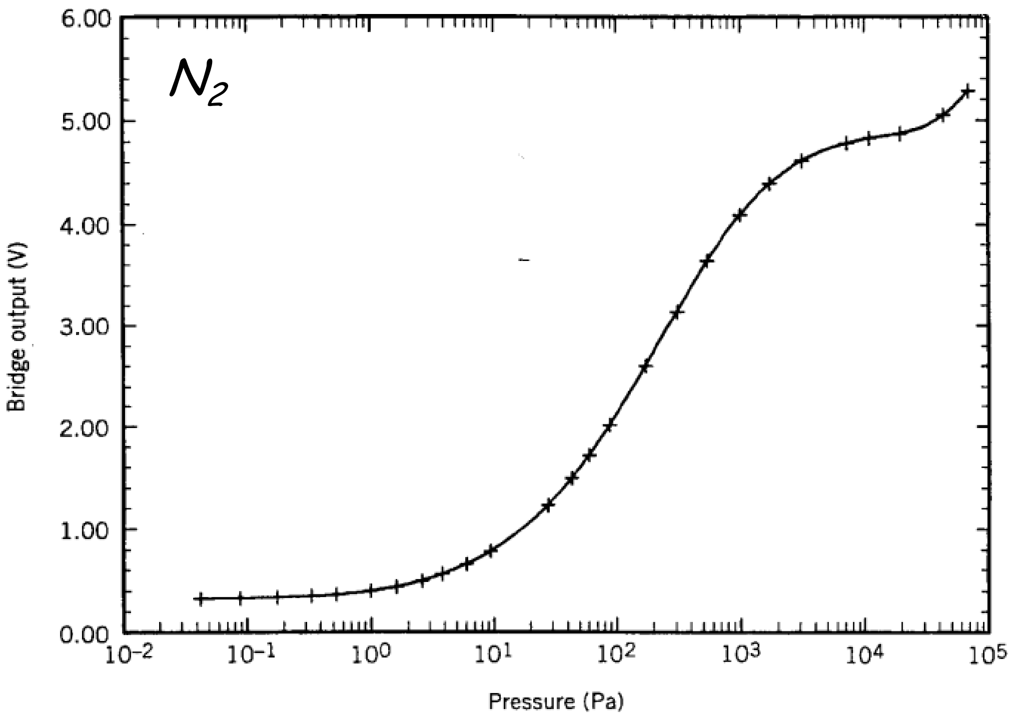
Measure pressure with the changes in the imbalance current



$I_{imbalance} = 0$ when $\frac{R_1}{R_3} = \frac{R_2}{R_4}$

Convection Enhanced Pirani Gauge

- Similar principle to Pirani gauge (but with larger tube ID)
  - →Conductive heat loss (10^{-3} to ~100 Torr)
  - →Adds convective heat loss (~100 to 1000 Torr.)
- Improved temperature compensation.
- Gold plated tungsten sensor wire (lowering emissivity and resisting contamination/corrosion).
- Sensitive to mounting orientation (at high P). (Mount horizontally!)



Commercial Convectron Gauges

Technical Data

275 Convectron Gauge

GRANVILLE-PHILLIPS

Range	From atmosphere to 10^{-4} Torr, (10^{-2} Pascal)
Sensor Material	Gold-plated tungsten
Other materials exposed to gas	304 stainless steel, borosilicate glass, Kovar, alumina, NiFe alloy, polyimide
Internal Volume	40 cm^3 (2.5 in^3)
Operating Temperature	0 °C to 50 °C ambient, non-condensing
Bakeout Temperature	150 °C maximum, non-operating, cable disconnected
Connection	1/8 inch NPT 1/2 inch tubulation
Weight	85 grams (3 ounces)

317 Convection-Enhanced Pirani Pressure Vacuum Sensors

($1.0x10^{-3}$ to 1000 Torr)

Bakeable to 250°C

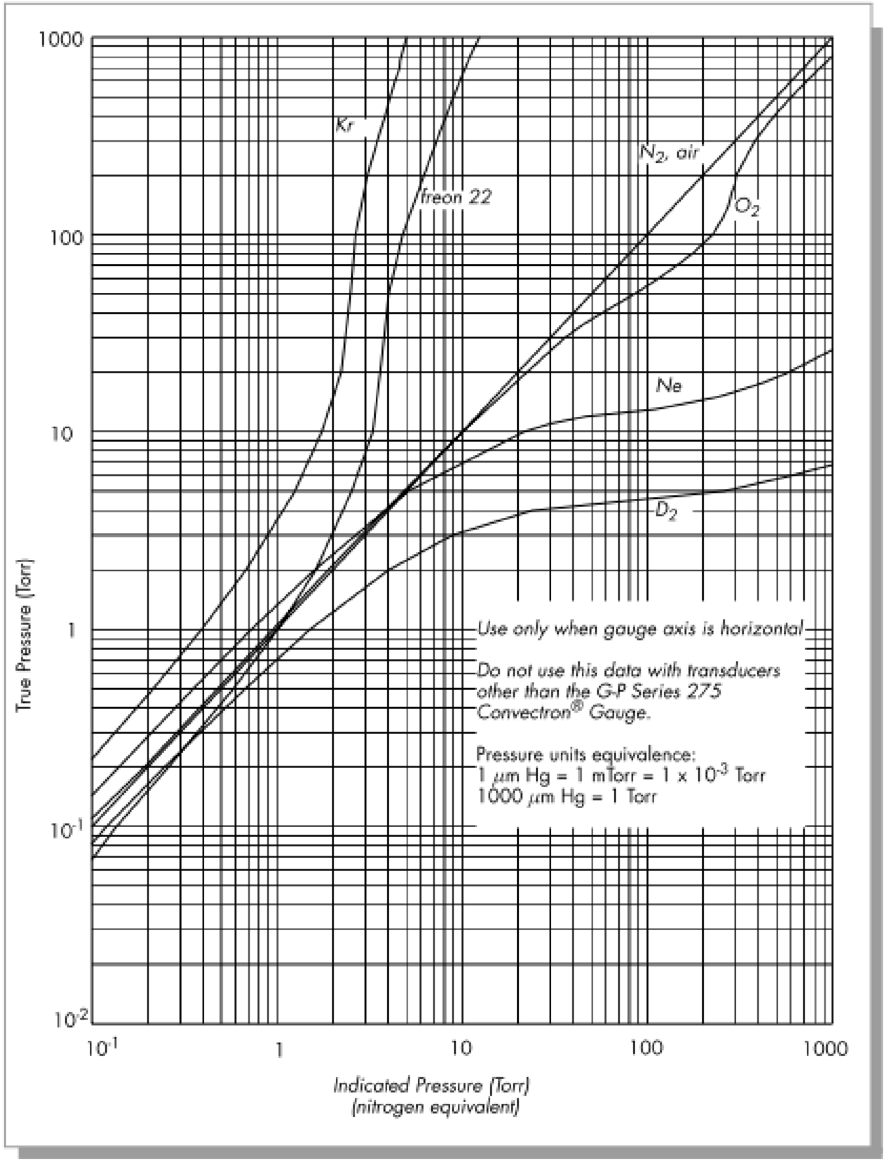
Thermal Conductivity Gauge Features

Good

- ✓ Wide measurement range
- ✓ Long-term reliability (some sensors operational over 30 years in CESR)
- ✓ Low cost, low maintenance
- ✓ Relative fast response

Not So Good

- ❖ Gas dependent, often in complicated manners, and can be potentially dangerous.
- ❖ Not suitable for corrosive applications
- ❖ Orientation dependent (>10 Torr)

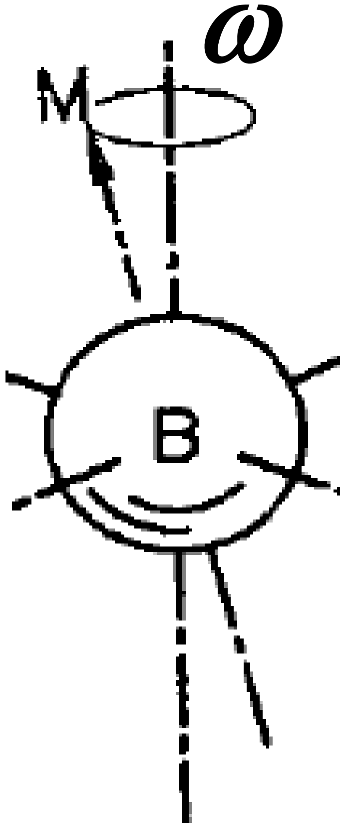


Spinning Rotor Gauge – Principle

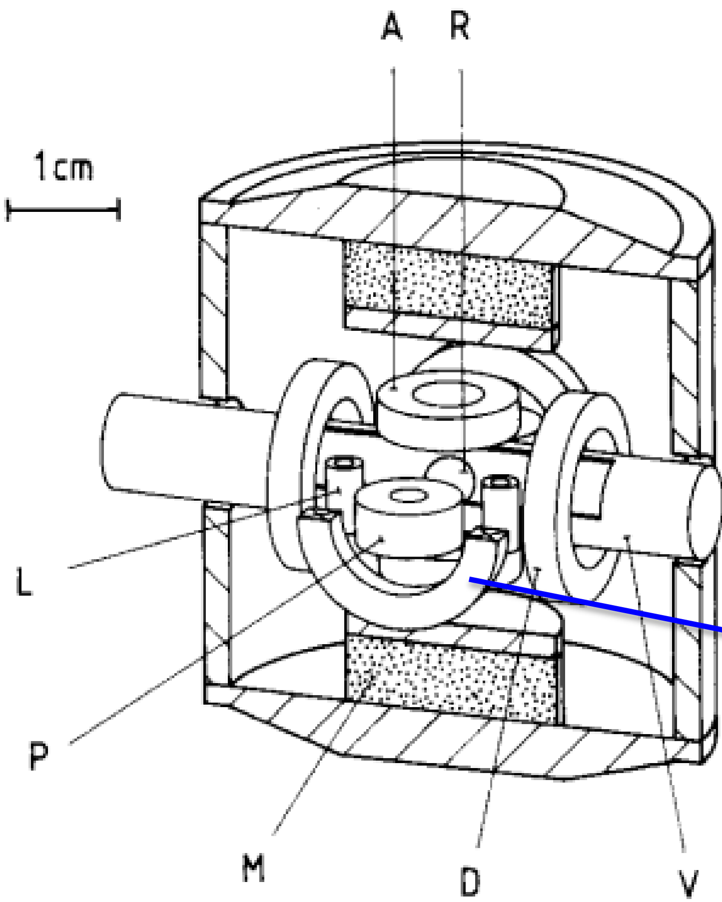
- *A spinning spherical rotor, suspended, in a gas at low pressure is slowed by interacting with the gas, through momentum transfer (or molecular drag)*
- *In the operational range (10^{-5} to 10^{-2} Pa), the deceleration by the molecular drag is proportional the molecule density.*
- *SRG is gas type dependent*

$$P = \frac{1}{5}\frac{a\rho}{\sigma}\frac{\sqrt{2\pi kT}}{\sqrt{m}}\left(-\frac{d\omega/dt}{\omega} - 2\alpha\frac{dT}{dt} - RD\right)$$

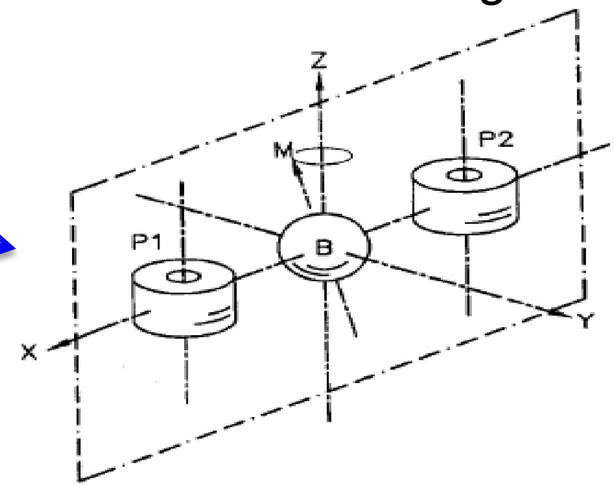
a – rotor diameter; ρ – rotor density;
σ – gas accommodation coefficient;
m – gas molecule mass; α – rotor C.T.E.
RD – residual drag (eddy current)



Spinning Rotor Gauge Structure



R *– rotor (440 stn. stl.)*
V *– vacuum enclosure*
M *– permanent magnets*
A *– 2x pickup & axial control coils*
L *– 4x lateral damping coils*
D *– 4x drive coils*
P *– 2x rotation sensing coils*



ω *= 410 – 400 rps*

- ❑ Low pressure limit: residual drags
- ❑ High pressure limit: non-linearity due to non-isotropic collisions with molecules

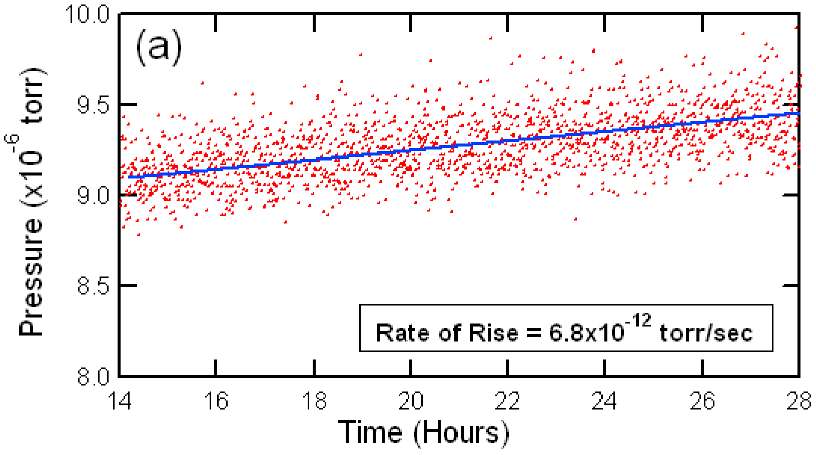
Spinning Rotor Gauge Applications

- SRG maintains long term reproducibility, better than 1% over 7-year has been demonstrated. Thus SPGs are widely used as a transferable secondary pressure standards for gauge calibrations.
- SRG does not 'alter' vacuum environment that measuring, as compared to ionization gauges.
- SRG is sensitive to shock and vibration, as well as to changes in ambient temperature.
- SRG is relatively slow in response time.

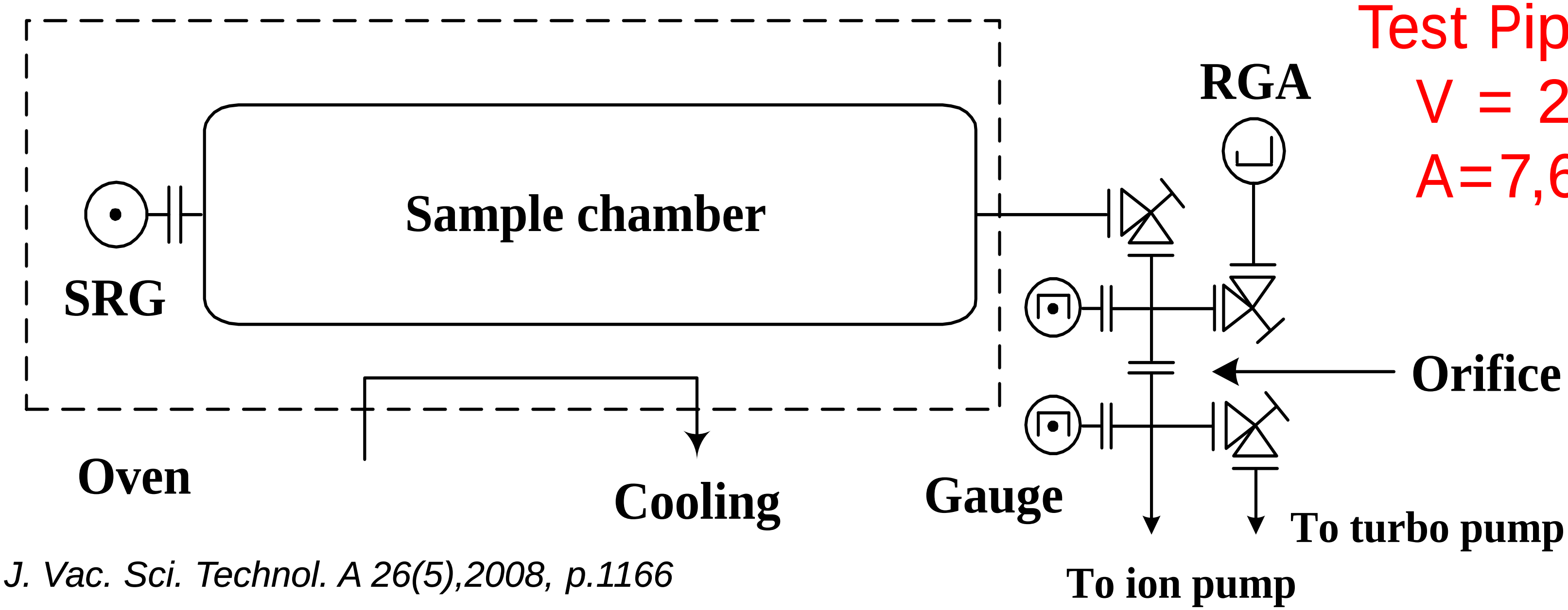
MKS SRG-3 System

SRG Application – An Example

- *Commercial SRG with easy-to-use electronics is available.*
- *We performed outgassing treatment to stainless steel to achieve ultra-low outgassing rate (<10^{-14} torr-liter/s/cm^2).*
- *This ultra-low outgassing rate can only measured by RoR method with SRG.*



Test Pipes:
V = 29-liter
A=7,600 cm^2

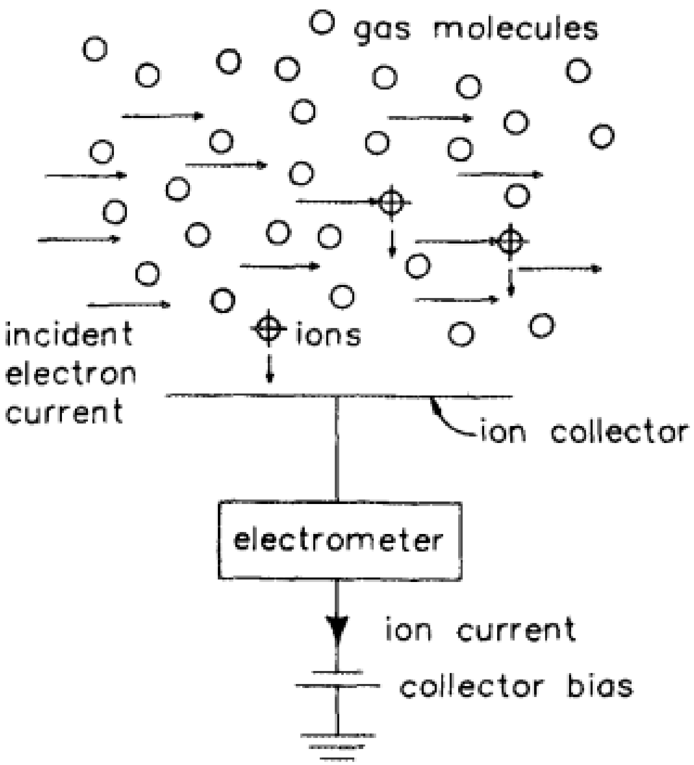


J. Vac. Sci. Technol. A 26(5),2008, p.1166

Ionization Gauges – General

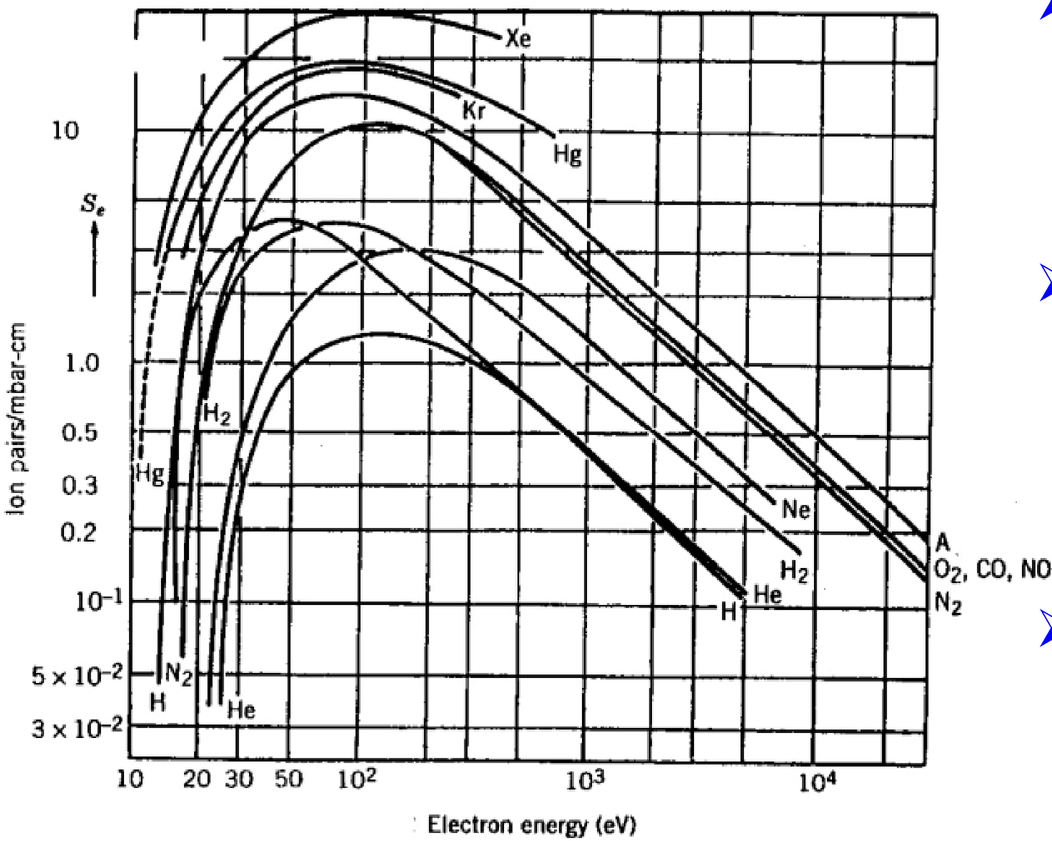
- *At pressures below 10^{-5} Torr (high vacuum) direct measurement of pressure is very difficult*
- *Thermal conductivity gauges have exceeded their operational limits*
- *Primary method for pressure measurement from 10^{-4} to 10^{-12} Torr is gas ionization & ion collection/measurement*
- *These gauges can be generally divided into hot & cold cathode types*
- *Most common high and ultra-high vacuum gauges today are the Bayard-Alpert and Inverted Magnetron*

Ionization Gauges – Principle



- *Gas atoms and molecules are normally without charge or "**neutral**", they have equal numbers of protons and electrons*
- *The neutrals may be 'ionized' via electron impact to form **ions**.*
- *Ions, being positively charged and heavy, can be manipulated by magnetic and electrical fields.*
- *The ionization rate (or the measured ion current) is usually proportional to the gas density, the base for the ion gauges.*
- *An atom has a probability of being ionized that is dependent on the atom itself and the energy of the colliding electron. Thus the ion gauges are gas type dependent.*

Electron Impact Ionization



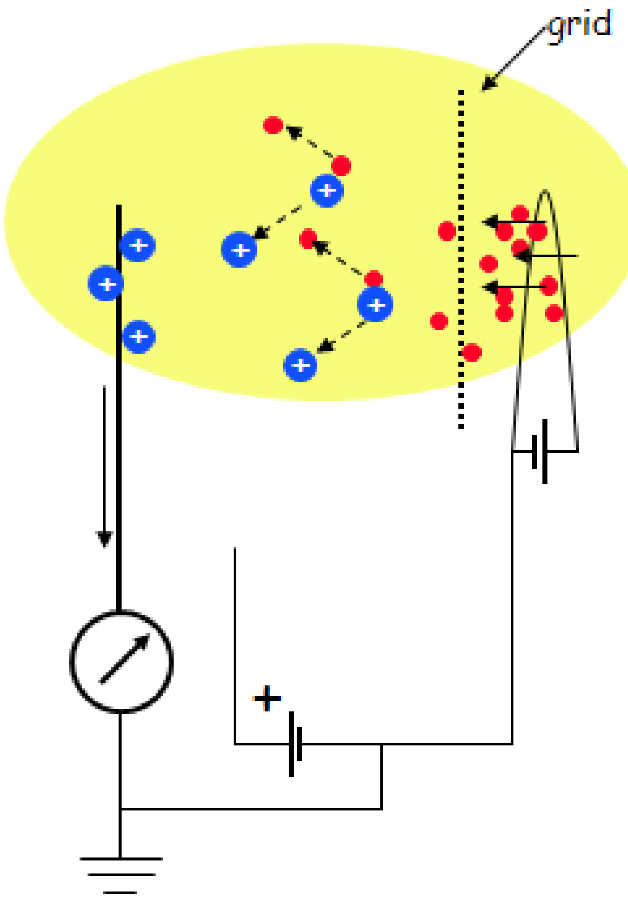
Ions per centimeter electron path length per mbar at 20°C versus energy of incident electrons for various gases

- *Electron impact ionization rate peaks at electron kinetic energy 50~200 eV for most of gases.*
- *For hot filament gauges, electrons are emitted thermionically, and accelerated by an electric field.*
- *For cold cathode gauges, electrons are initiated by field-emission (or radiations), then trapped/amplified in a cross-field (electric and magnetic fields)*

http://physics.nist.gov/PhysRefData/Ionization/Xsection.html

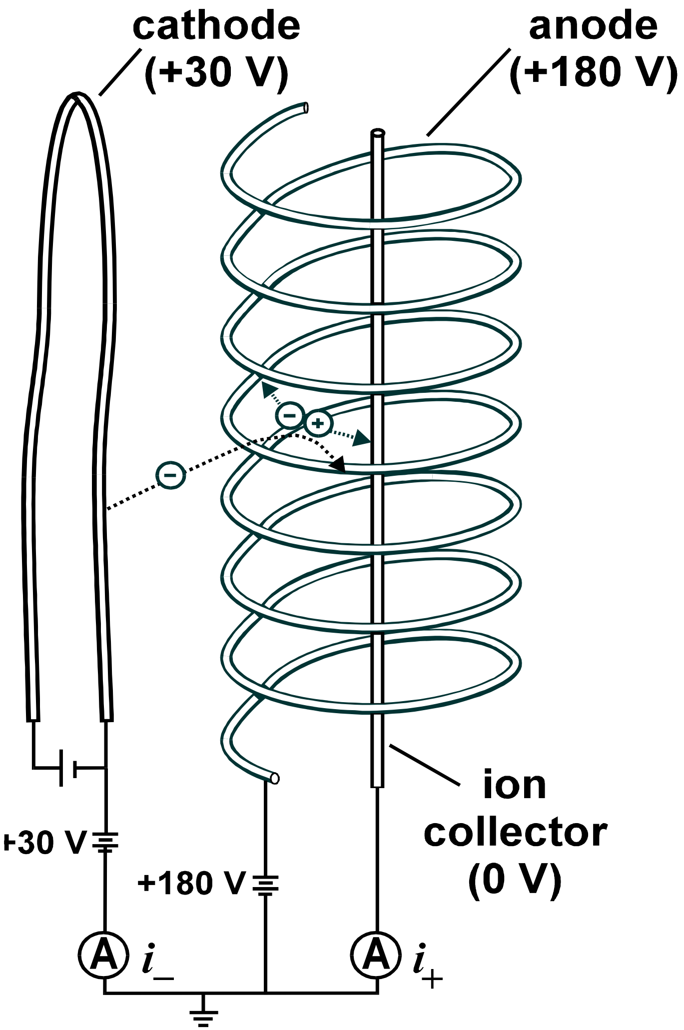
Hot Cathode Ionization Gauge – Principle

- *A hot filament (cathode) emits electrons.*
- *Electrons are accelerated by a bias grid electrode, and collide with molecules and create positive ions*
- *The positive ions that are created inside the grid volume are attracted to the collector and measured as ion current.*
- *The gauge controller electronics converts the collector ion current to a pressure reading.*



HC Ionization Gauge – Basic Parameters

- *Ionization cross section of gas molecule (size of molecule)*
- *Number of gas molecules present*
- *Number of ionizing electrons produced (emission current)*
- *Length of electron path (it is desirable to have the majority of the electron path inside the grid volume)*
- *Size of ionization (grid) volume*



HC Ionization Gauge – Sensitivity

- For an electron beam with a path length L, the ionization yield (ions generated per electron) is:

$$nL\sigma_i = \frac{\sigma_i L}{kT} P$$

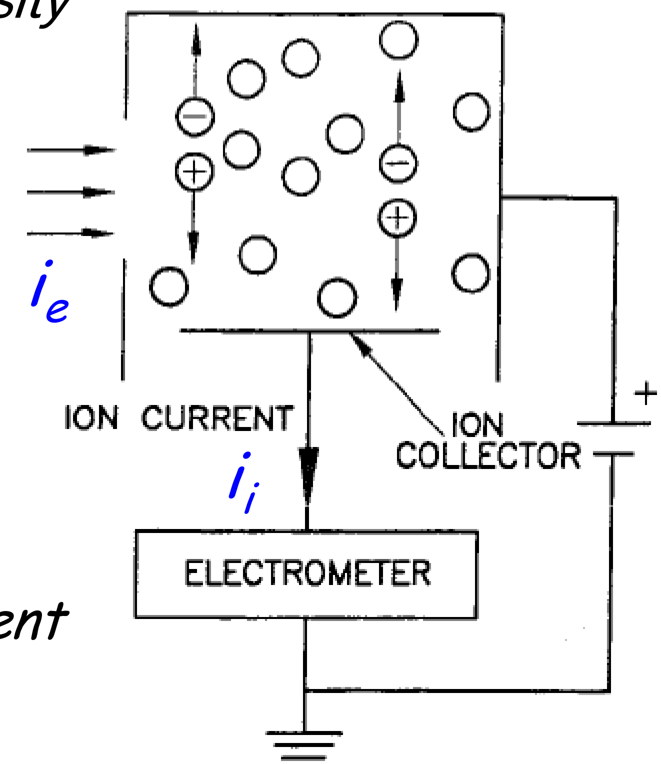
σ_i – ionization cross section
$n=P/kT$ is molecular density

- If the electron current (emission current) is i_e, the total ion current:

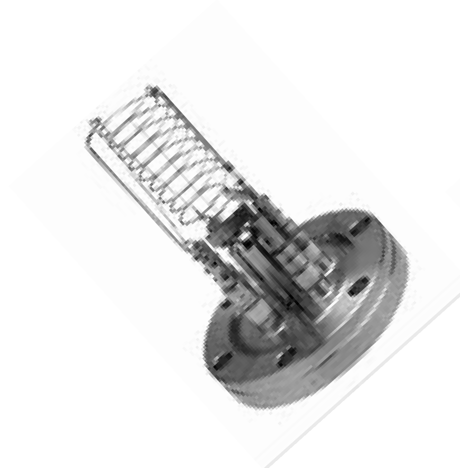
$$i_i = \frac{\sigma_i \cdot L}{kT} \cdot i_e \cdot P = K \cdot i_e \cdot P = S \cdot P$$

$$K = \frac{\sigma_i \cdot L}{kT} = \frac{i_i}{i_e} \cdot \frac{1}{P}$$ known as gauge coefficient

$S = K \cdot i_e$ is known as gauge sensitivity



Typical HC Ionization Gauge Coefficients



Gauge Type	G-P 274 Tubular	G-P 274 Nude	Leybold Extractor
Coeff. (1/Torr)	10	25	7.2

HC Ionization Gauge – Relative Sensitivity

Gas	Sensitivity
Ar	1.2
CO	1.0-1.1
H_2	0.40-0.55
He	0.16
H_2O	0.9-1.0
N_2	*1.0*
Ne	0.25
O_2	0.8-0.9
Organic Solvents	>>1

- *HCIGs are gas type dependent, mostly due to dependence on ionization cross section variations.*
- *All commercial gauges are calibrated to nitrogen.*
- *Users need to convert readings for non-N_2 gases with corresponding relative sensitivity.*

$$P_{Gas} = P_{Gauge}^{N_2} / S_{Gas}$$

HC Ionization Gauge – Limitations

- *For all HC ion gauges, the detected ion current always consists of a pressure dependent value, and a residual signal (i_r) that is not related to gas pressure.*

$$i_i = K \cdot i_e \cdot P + i_r$$

- *The residual signal (i_r) sets the lowest measurable pressure by a HC gauge.*

- *There are two major sources of the residual current:*

  → *Soft X-ray induced current*

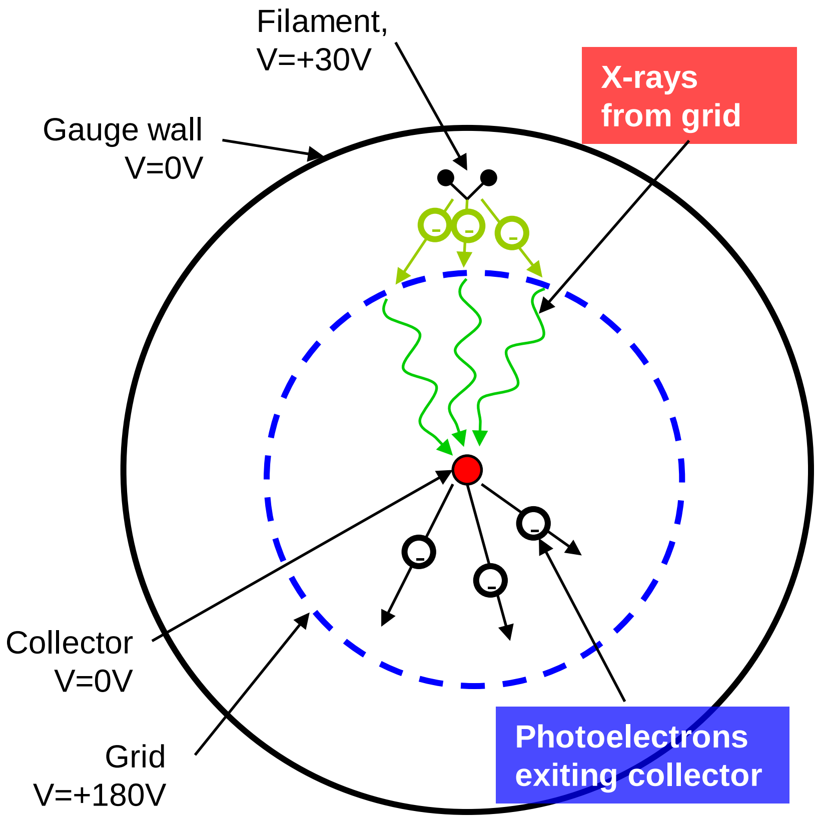
  → *Electron Stimulated Desorption (ESD)*

HC Ionization Gauge – Soft X-Ray Limit

- Some electrons emitted from the hot cathode impact the grid and produce x-rays.
- Some of the x-rays impact the collector and produce photoelectrons.
- The exiting photoelectrons

  =

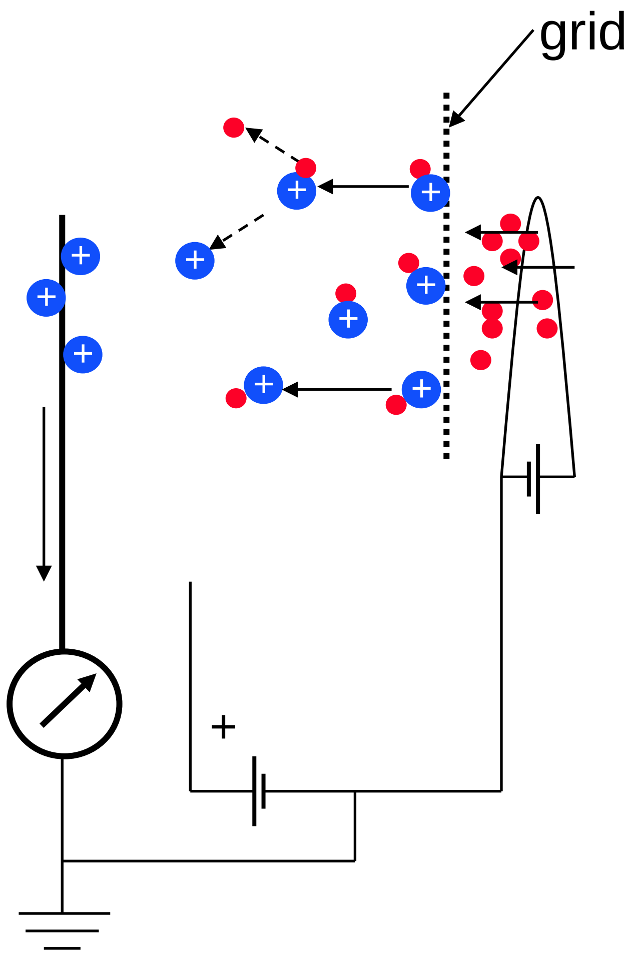
  positive ions arriving at the collector.
- The photoelectron current adds to the ion current producing an error in the pressure reading.
- Historic triode vacuum gauges had X-ray limit of 10^{-7} Pa. Modern HC gauges use much smaller anode to lower the limit below 10^{-9} Pa.



See Lafferty book P416 Fig 6.30 for triode HCG schematic

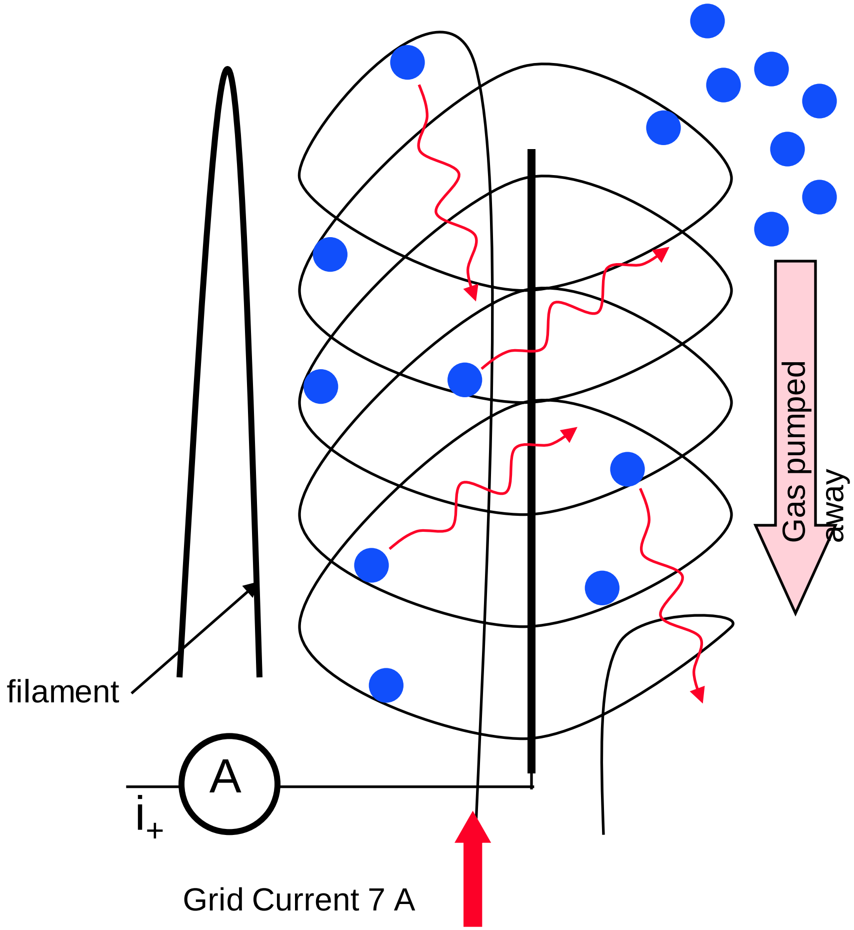
Electron Stimulated Desorption in HC Gauges

- *Gas molecules are adsorbed on the surface of the grid.*
- *Electrons emitted from the cathode strike the grid and desorb the gas molecules.*
- *The electrons also ionize some of the gas molecules on the grid when they are desorbed.*
- *The additional gas molecules and positive ions contribute to an increase in the gauge pressure reading.*



Ion Gauge Degas – Reduce ESD

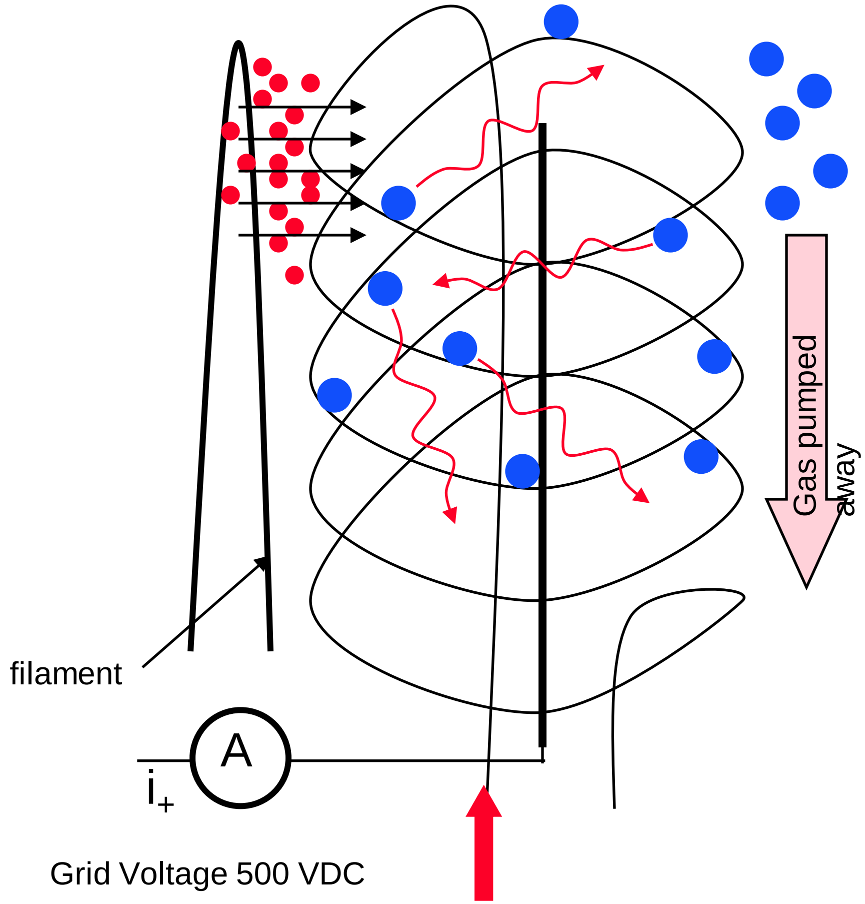
Resistive Heating



Grid Current 7 A

Grid Voltage 8 VDC

Electron Bombardment



Grid Voltage 500 VDC

Filament Emission Current 100 mA

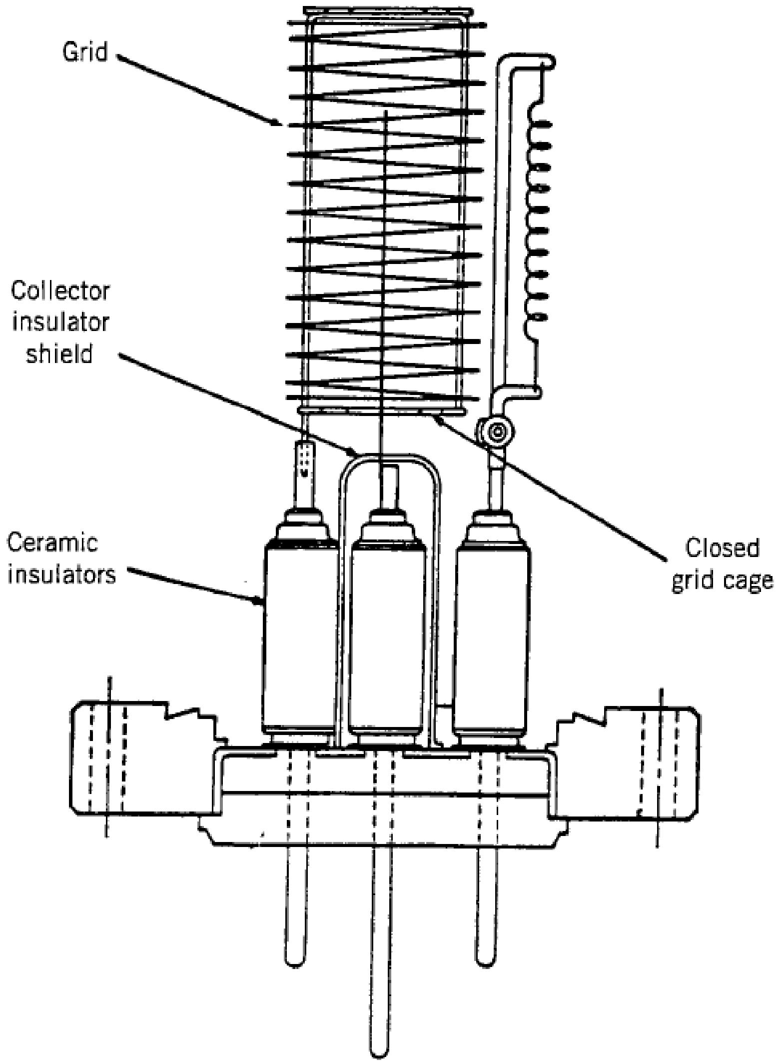
Filament Selection

- ***Thorium-coated Iridium***
  - *General purpose*
  - *Operates cooler (~900°C)*
  - *Burn-out resistant*

- ***Tungsten***
  - *Special purpose*
  - *Operates hotter (~1200°C)*
  - *Burns out easily and oxidizes when exposed to atmosphere*

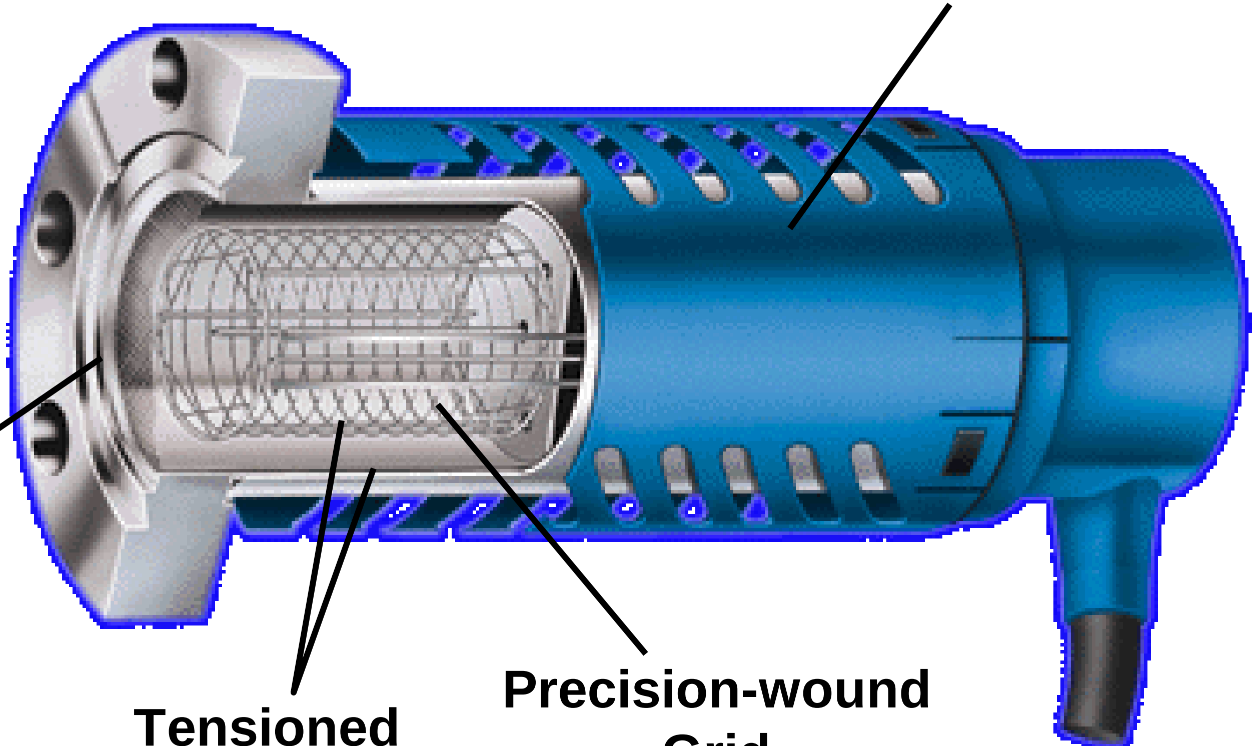
Bayard-Alpert Gauges

- *Bayard-Alpert gauge (BAG) is mostly used in high- to ultra-high vacuum ranges ($10^{-4} \sim 10^{-11}$ torr), particularly the nude style.*
- *Typical BAG sensitivity for N_2 is 5~10/Torr.*
- *The small diameter center ion collector reduces the X-ray limit to low 10^{-11} torr.*
- *The caged grid can be degassed by heating to reduce ESD.*
- *The BAGs are robust and reliable.*



STABIL-ION® BAG Design

Rugged Steel Enclosure



MKS – Granville Philips

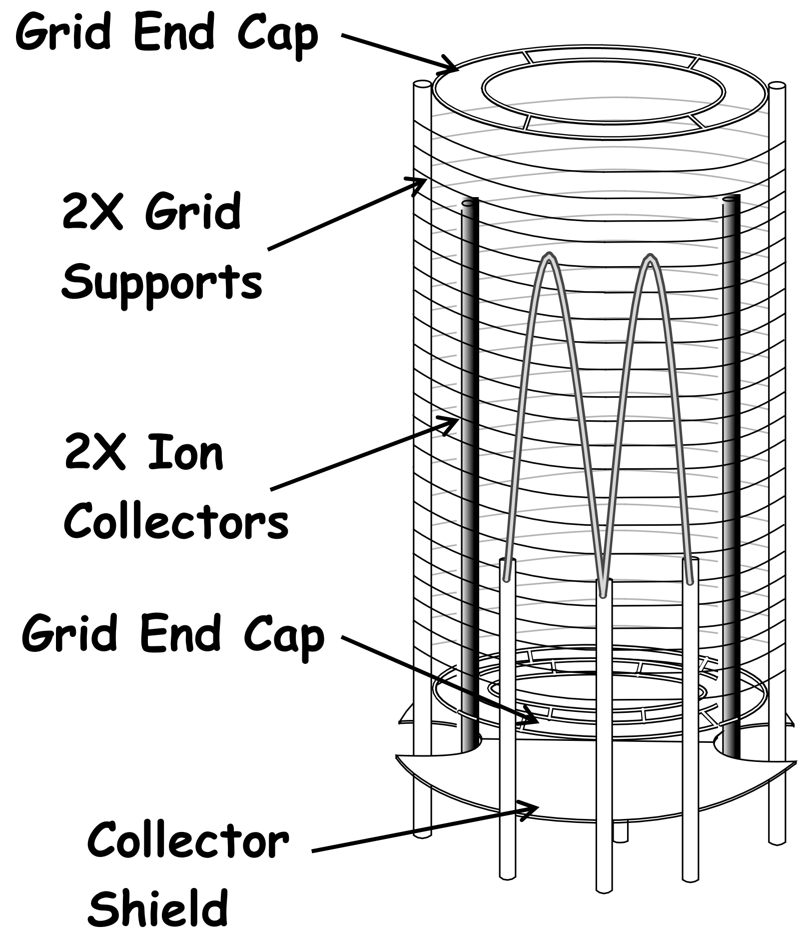
STABIL-ION® Gauge Types

- *Extended Range Gauge*
  - *1×10^{-9} to 2×10^{-2} Torr*
  - *x ray limit: < 2×10^{-10} Torr*
  - *Highest accuracy & stability*
  - *Sensitivity: 50/Torr*
- *UHV Gauge*
  - *10^{-11} to 10^{-3} Torr*
  - *x ray limit: <2×10^{-11} Torr*
  - *Less accurate & stable than Extended Range Gauge*
  - *Sensitivity: 20/Torr*

STABIL-ION gauges demonstrated excellent long-term reproducibility, many labs use them as reference calibration.

MICRO-ION™ Gauge Design

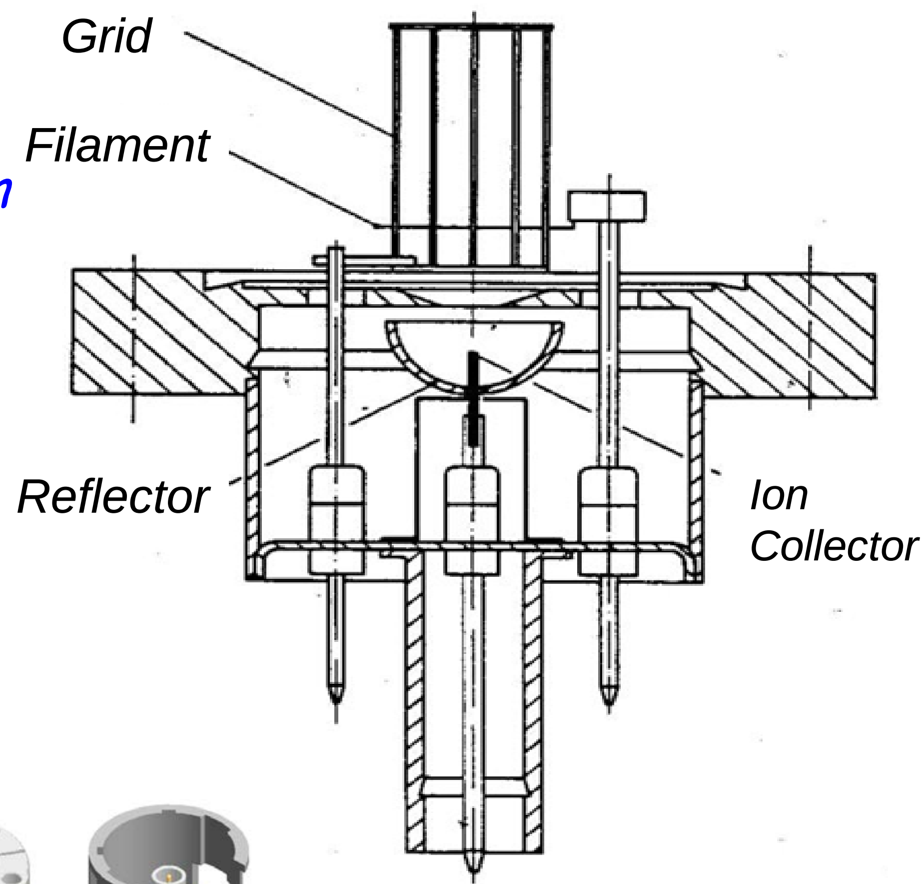
- X-ray limit: < 3 x 10^{-10} Torr
- Upper pressure limit: 5 x 10^{-2} Torr/mbar.
- Very compact, and low power.
- Good overlap with low vacuum (> 1×10^{-3} Torr) gauges such as *CONVECTRON* ®.

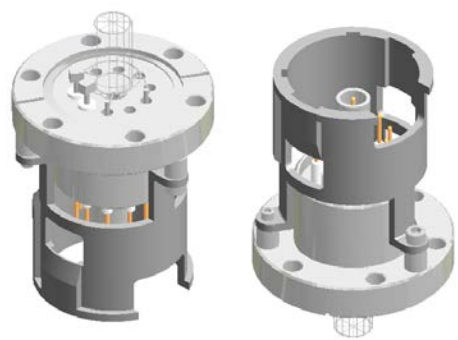


MKS – Granville Philips

Deep UHV Gauge – Extractor

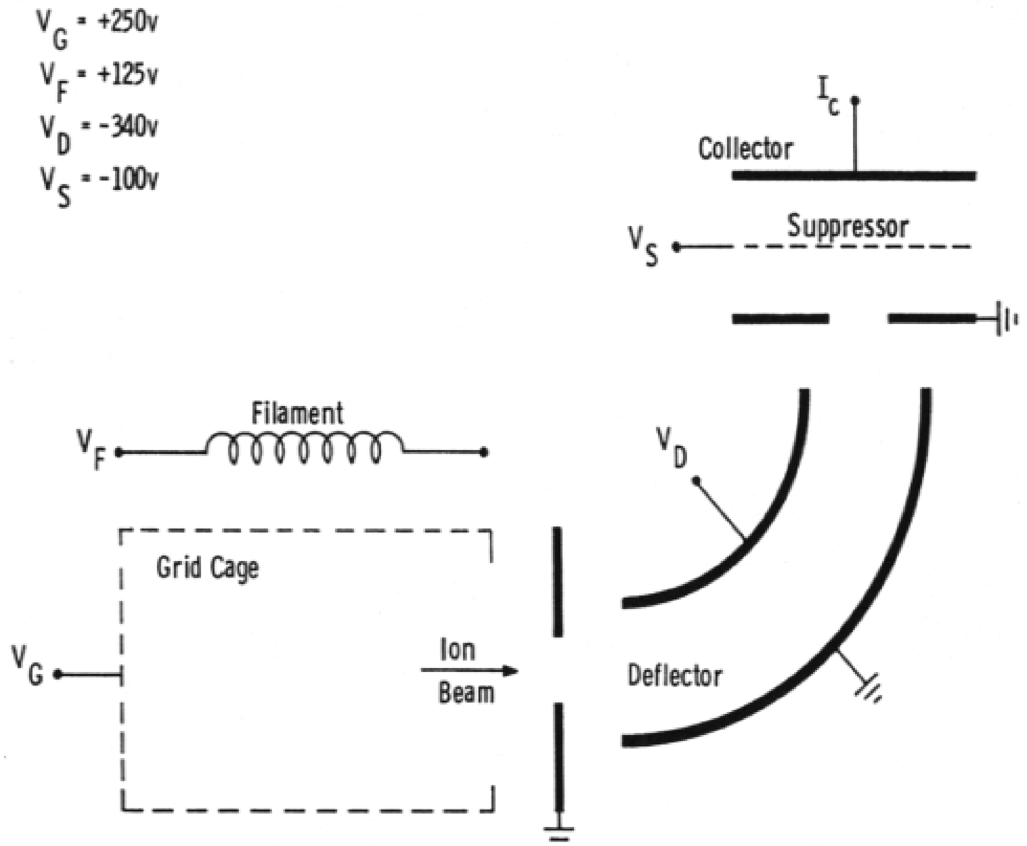
- *Most widely used commercial XHV gauge.*
- *X-ray limit: < 1 x 10^{-12} Torr as the ion collector is recessed.*
- *Discriminate against ESD ions.*
- *Has the other features of a BAG, robust, replaceable filament and can be degassed.*
- *Range: 10^{-4} to 10^{-12} torr*



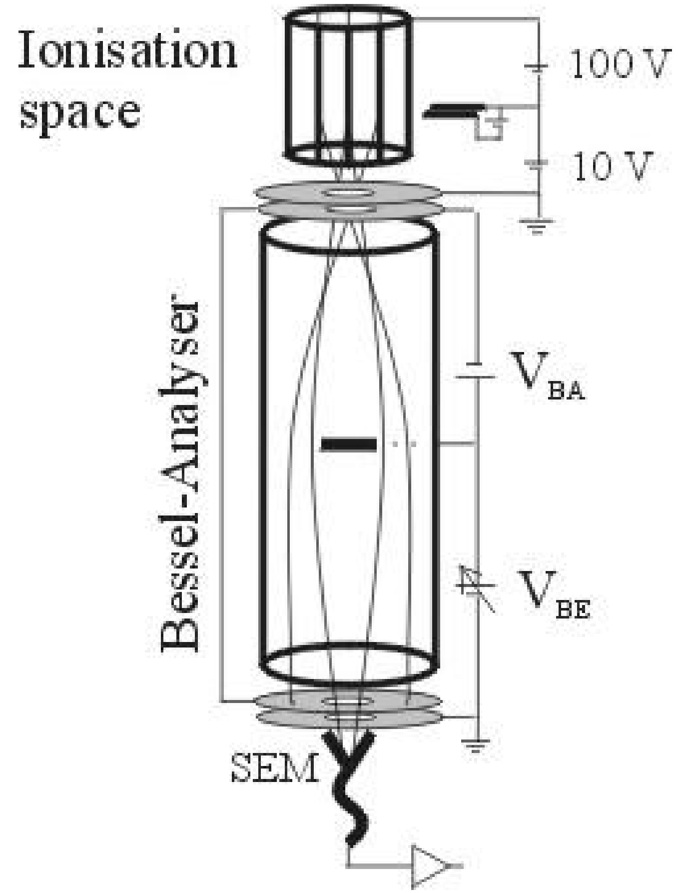


Leybold IE 514 Extractor Gauge

XHV Gauges – Energy Analyzers



Helmer Gauge
90° Bend Ion Analyzer

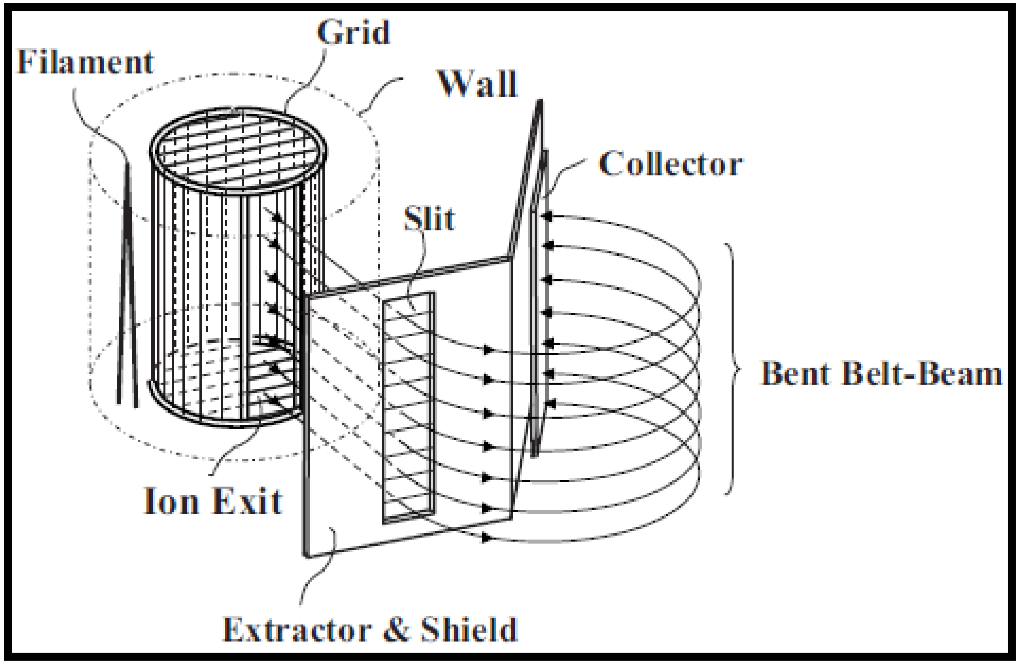


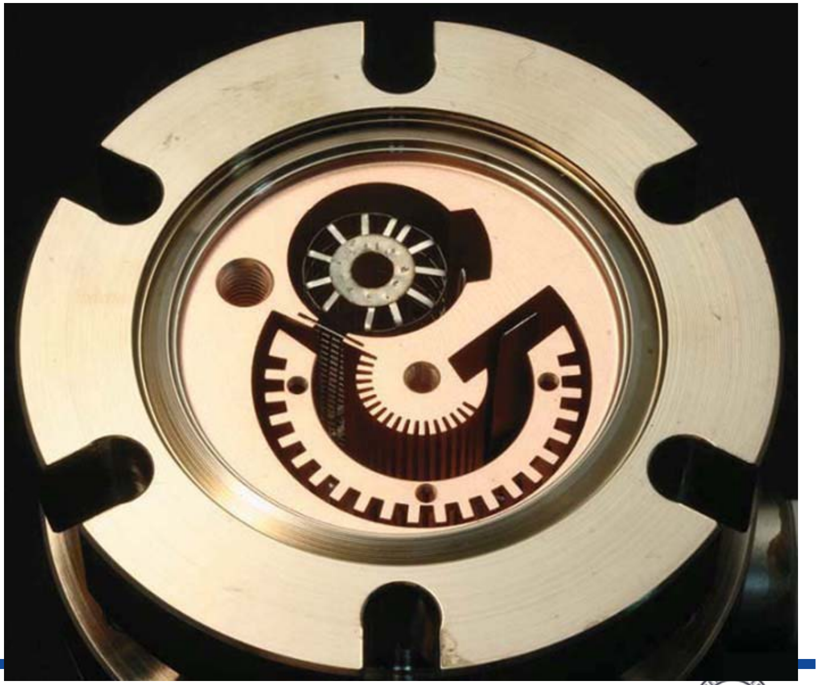
Bessel Box
Sold as Axtran® by ULVAC

Bent belt-beam (BBB) gauge

- *X-ray limit: < 4x10^{-14} Torr; S_{N2} = 2.8x10^{-4}/Torr.*
- *Completely blocks ESD ions.*
- *Use the same controller as Extractor (IE511)*

*Fumio Watanabe, J. Vac. Sci. Technol. **A 28**(3) 2010, p.486*





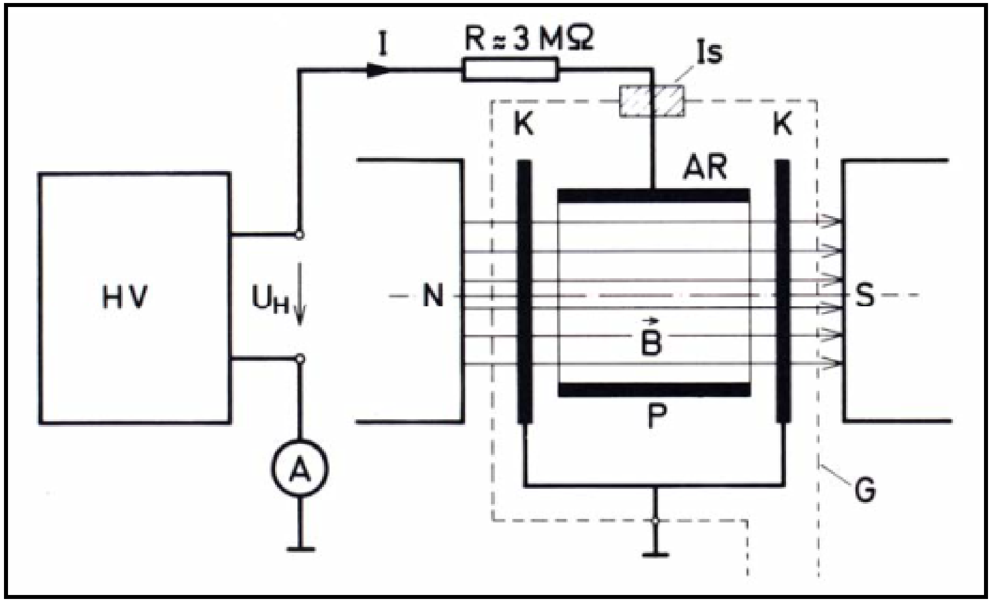
Cold Cathode Gauges

- *With a DC high voltage between a pair of electrodes in vacuum, discharge occurs. The discharge current depends on the pressure (non-linearly). However, the sustainable discharge stops around 1 Pa.*
- *In CCGs, a magnetic field is added, with the B-field 'perpendicular' to the E-field (thus the cross-field). A electron 'cloud' is created by trapping electrons in the cross-field volume. Electrons gain energy through cyclic motions in the cross-field.*
- *Ionization of gas molecules by electrons in the e-cloud extends the lower limit of CCGs.*
- *CCGs are gas-dependent in a similar way as HCGs.*
- *In a CCG, the ion current is related to pressure as:*

$$i_g = K \cdot P^n$$

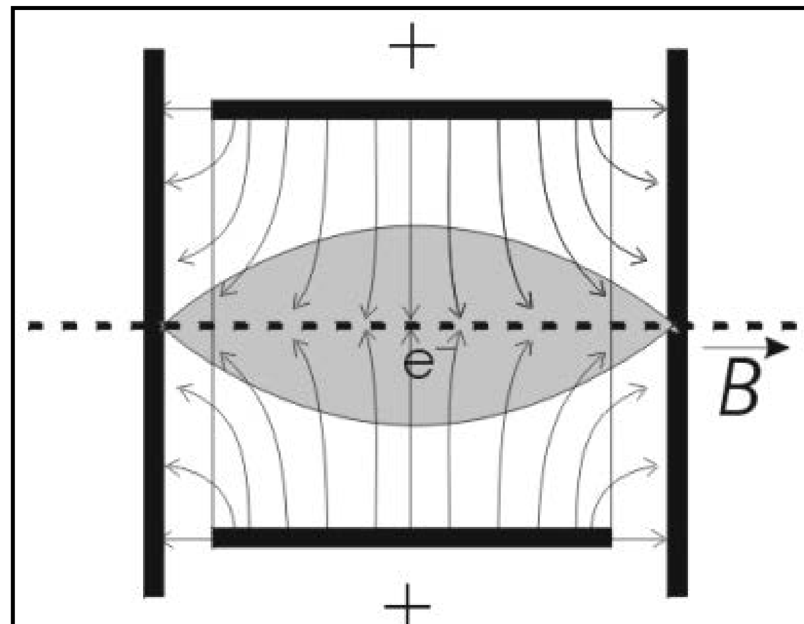
$n = 1.0 \sim 1.4$

Cold Cathode Gauges – Penning Cell



AR – anode ring
K – cathode
G – gauge case

- *At lower pressure (<10^{-2} Pa), stable electron cloud confined around axis, and ion density significantly lower than that of e-cloud.*
- *At high pressure, much higher ion density destabilize e-cloud , and plasma oscillation may occur.*



Ref. K. Jousten: Ultrahigh Vacuum Gauges

Cold Cathode Gauges – Penning Cell

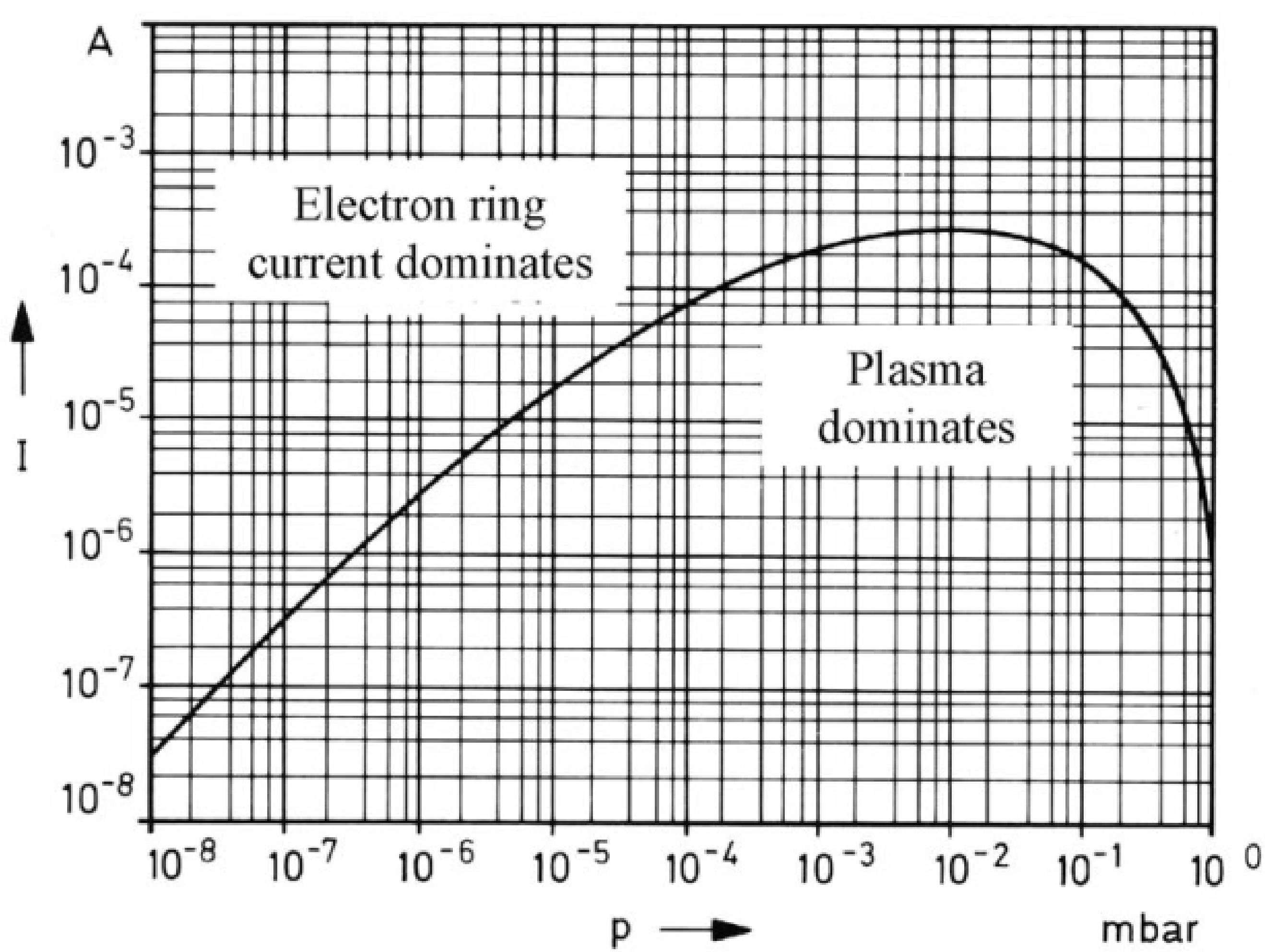
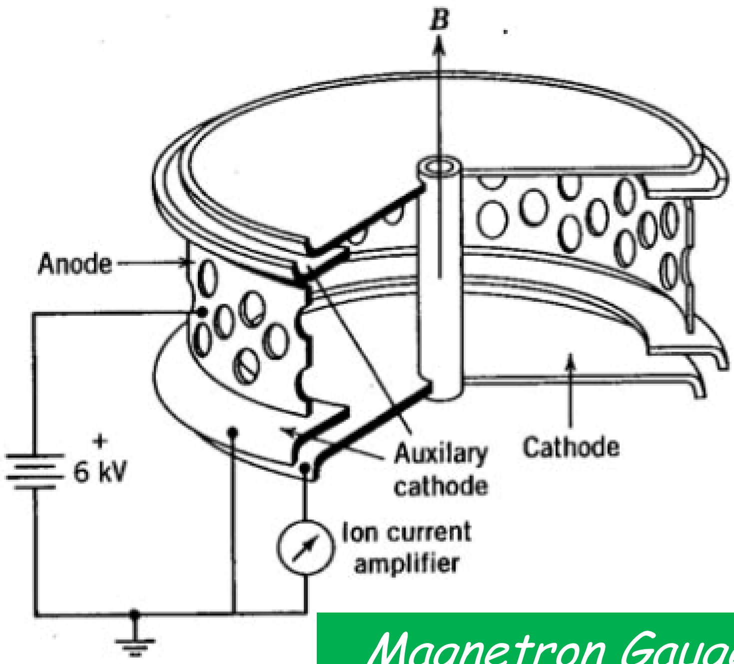
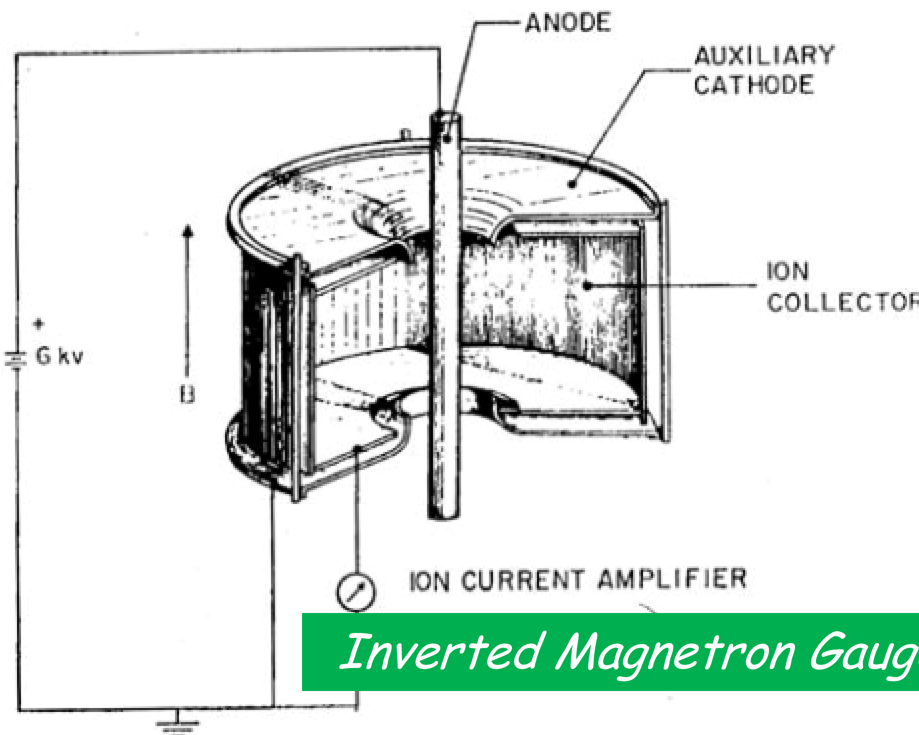


Fig. 7: Typical calibration curve of a Penning gauge. From *Wutz Handbuch Vakuumtechnik* by K. Jousten (ed.), Vieweg Verlag.

CCGs – Magnetron and inverted magnetron



Magnetron Gauge

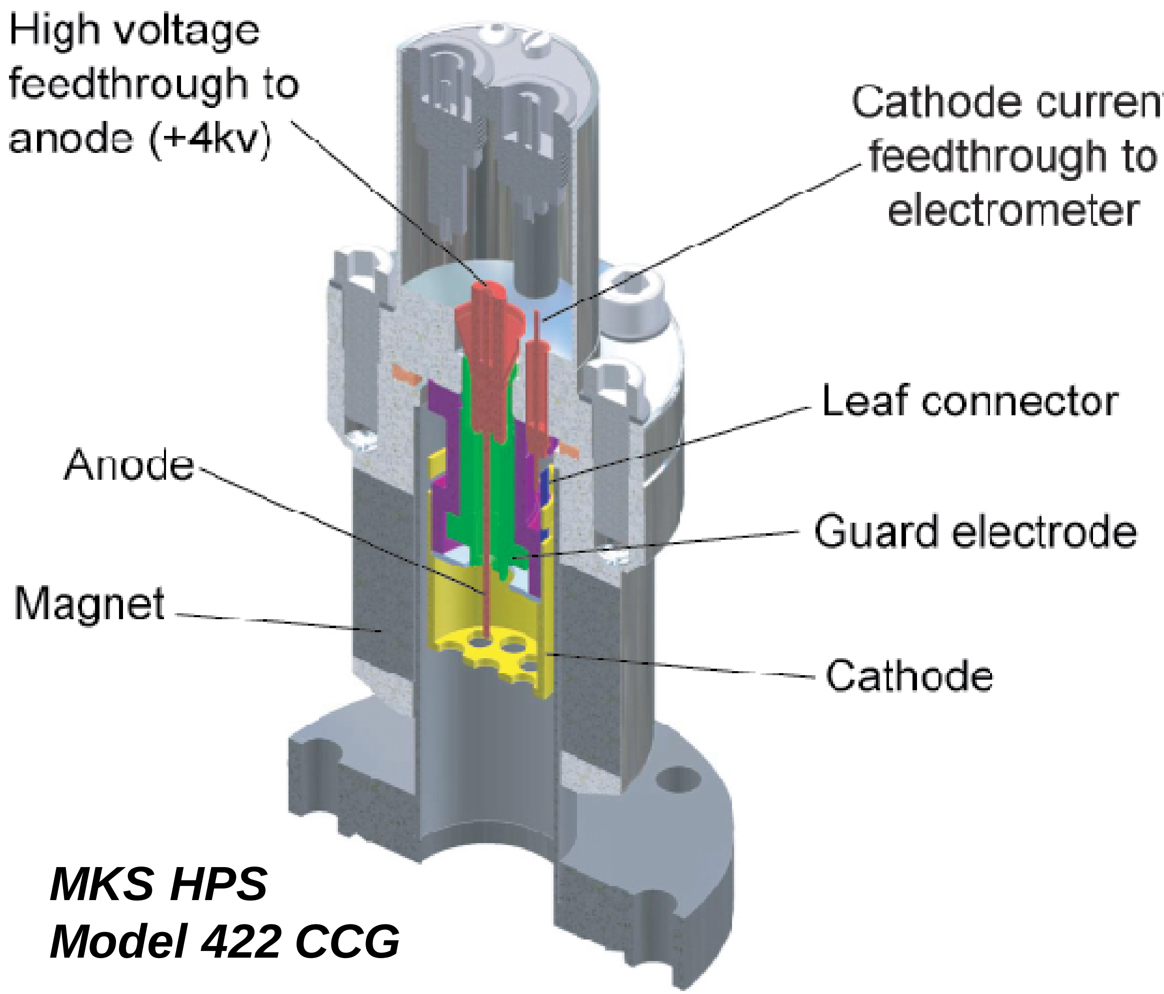


Inverted Magnetron Gauge

- *Both types were developed by Redhead and Hobson in late 50's*
- *Much more efficient electron trapping, and more stable e-cloud (no mode-jumping) over pressure range from 10^{-3} to 10^{-12} torr.*
- *With guard rings, IMG is less sensitive to field emission.*
- *MG usually has higher sensitivity, due to its larger ion collector.*

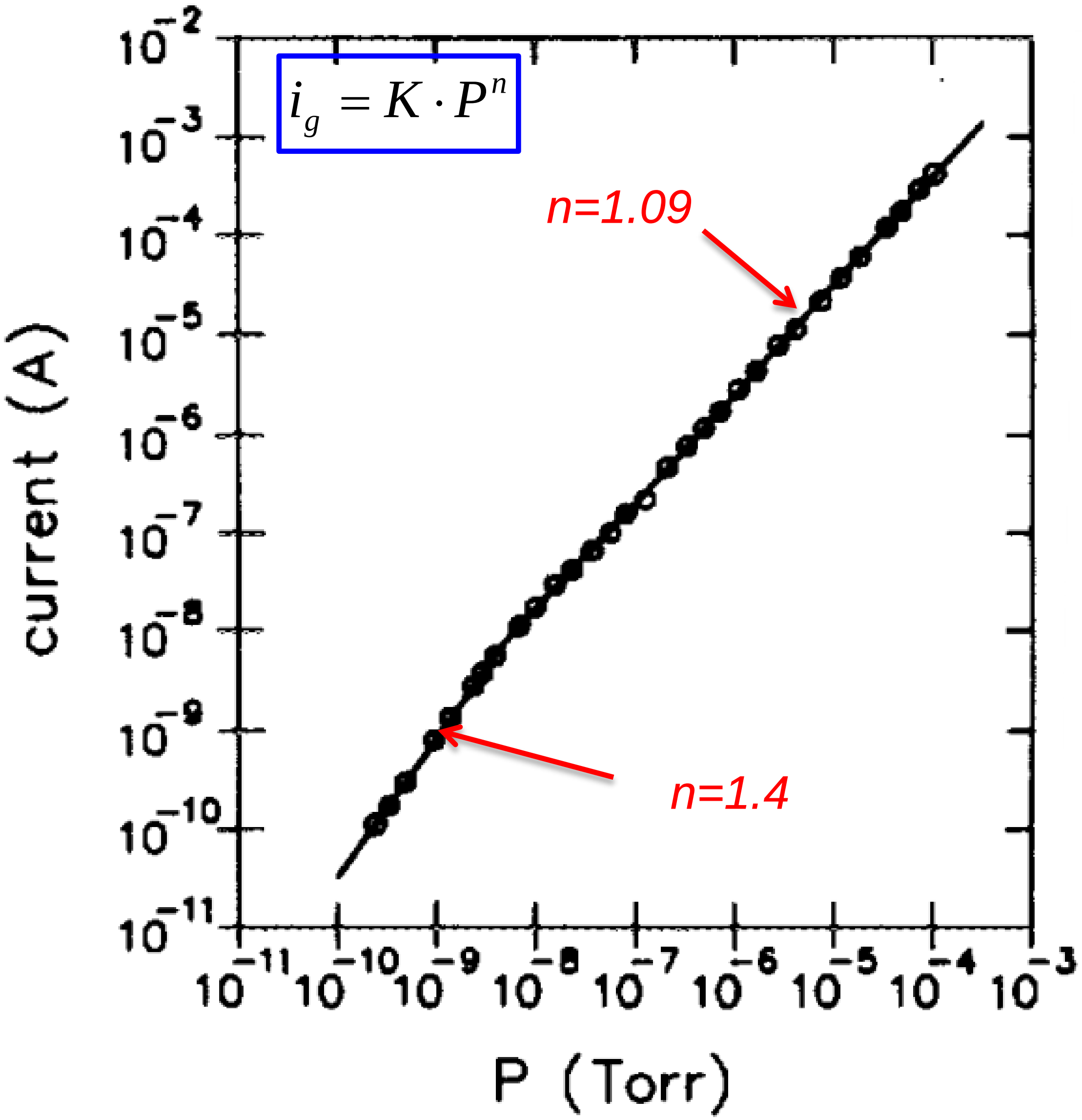
MKS-HPS Inverted Magnetron CCG

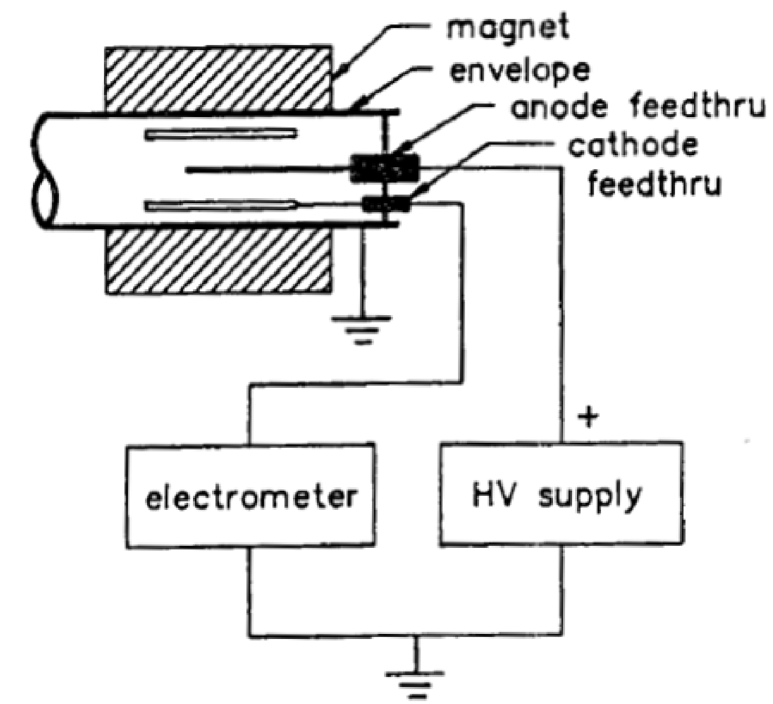
- Measuring range: 10^{-3} to 10^{-11} Torr (with Series 937 Controller)
- No X-ray limit
- Very low power, and no heating
- Very robust design
- Sensitive to contaminations, no degas option
- Be aware of stray B-field



MKS HPS Model 422 CCG

MKS-HPS Inverted Magnetron CCG (2)





CCG Circuit of Operation

With both floating anode and cathode, significantly reduce baseline current from leakages.

HCGs versus CCGs

Both HCGs and CCGs are variable gauges
in the range of 10^{-4} to 10^{-11} torr

	HCGs	CCGs
Pros	✓ Linear gauge response ✓ Higher gauge sensitivity ✓ Possible extension to XHV	✓ Inherently rugged ✓ Very low residual ion current ✓ Low power and heating ✓ Very good long-term reliability
Cons	✓ Higher X-ray and ESD limits ✓ Filament lifetime ✓ High power and heating ✓ Filament light	✓ Sensitive to contamination (oil, dielectric particulates, etc.) ✓ Discontinuity and nonlinearity ✓ Long ignition time at UHV ✓ Stray magnetic field

Partial Pressure Measurement

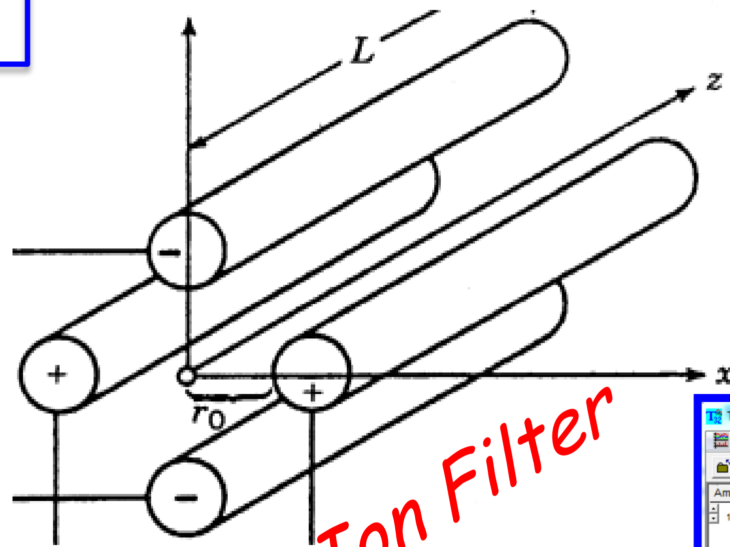
Residual Gas Analyzers

Why Residual Gas Analyzers

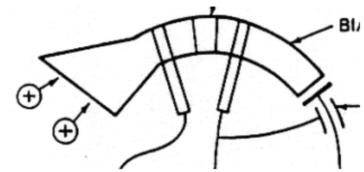
- All the gauges discussed earlier measures total gas pressure or density, no information on the gas composition.
- Residual gas analyzers are usually incorporated into critical vacuum system as vacuum diagnostic instrument.
- In most cases, qualitative mass spectral analysis is sufficient. Sometimes quantitative analysis is need, but rather difficult.
- A RGA measures relative signals verse mass-to-charge ratio (m/e), often in unit of AMU (atomic mass unit). (AMU is defined by C^{12}, that is, C^{12} has exact 12.0000 AMU)

Typical Building Blocks for a RGA System

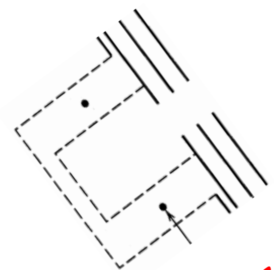
Control Electronics



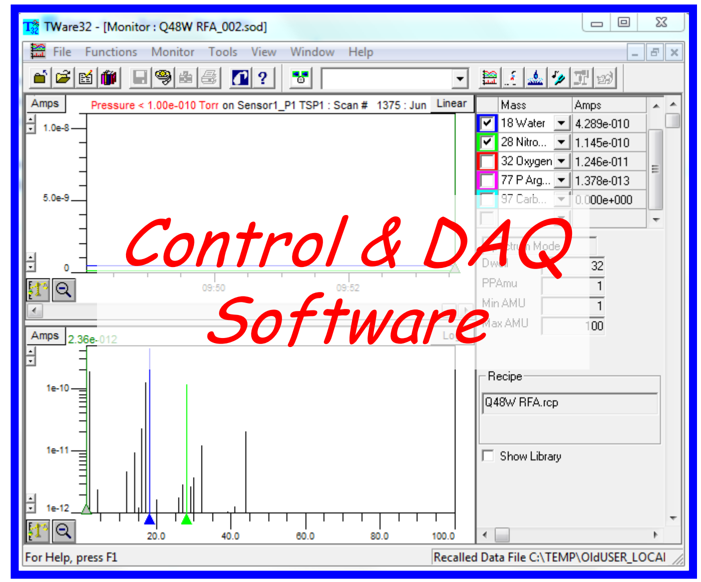
Ion Filter



Ion Detector



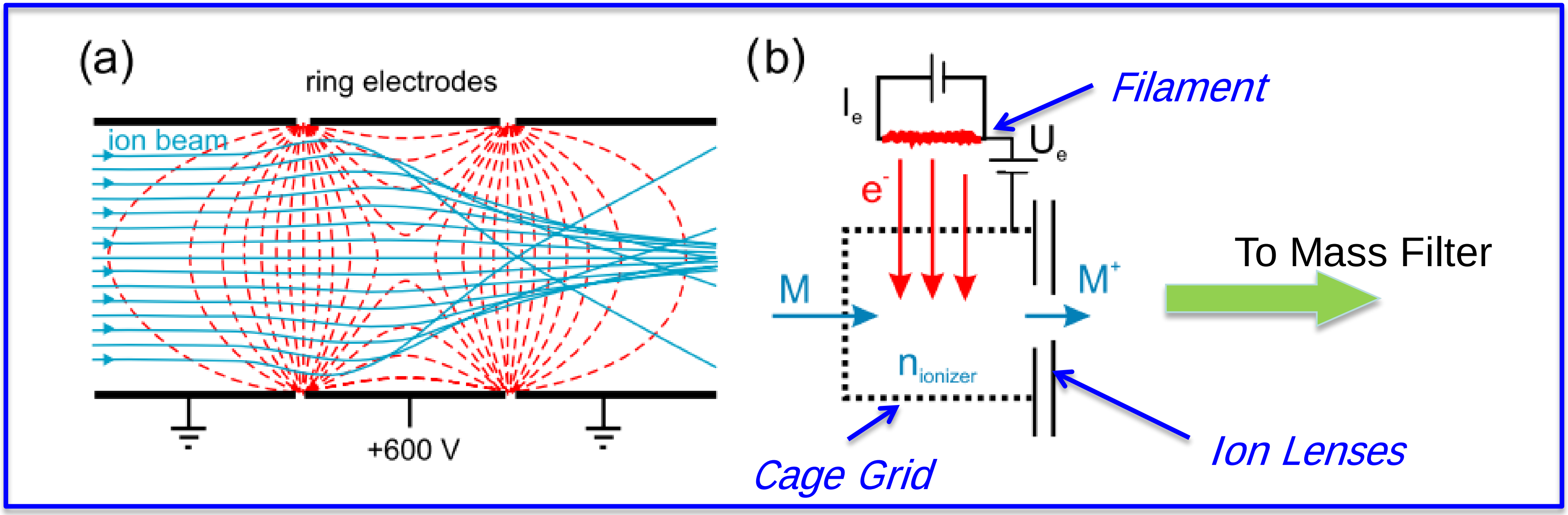
Ionizer



Control & DAQ Software

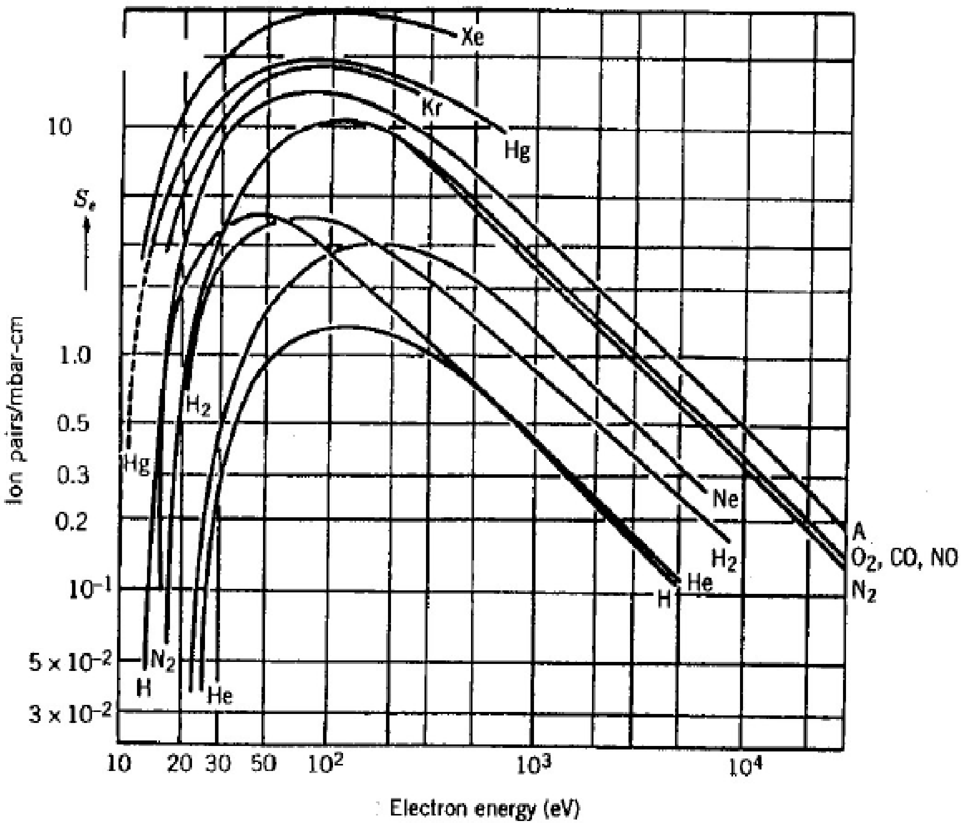
Ionizers – Types and Parameters

- *The most common ionizers are open ionizer, which is directly open to the vacuum to be monitored.*
- *Neutral gas molecules are ionized and fragmented by impact of electrons emitted from a hot filament*
- *Ions are extracted and focused into a mass filter by a set of electrostatic lenses*
- *Important ionizer parameters:* → *Electron emission current*
  → *Electron energy*
  → *Ion energy*



Electron Impact Ionization and Fragmentation

Total Ionization 'Cross-Section'



Ions per centimeter electron path length per mbar at 20C versus energy of incident electrons for various gases

Ionization & Fragmentation

$CO_2 + e \longrightarrow CO_2^+ + 2e$

$\longrightarrow CO^+ + O + 2e$

$\longrightarrow C^+ + 2O\ (O_2) + 2e$

$\longrightarrow O^+ + CO + 2e$

$\longrightarrow CO_2^{++} + 3e$

$\longrightarrow CO^{++} + O + 3e$

…, …

Three Types of Ion Filters

- Magnetic Sector

  Used mostly in leak detectors, large analytical mass spectrometers

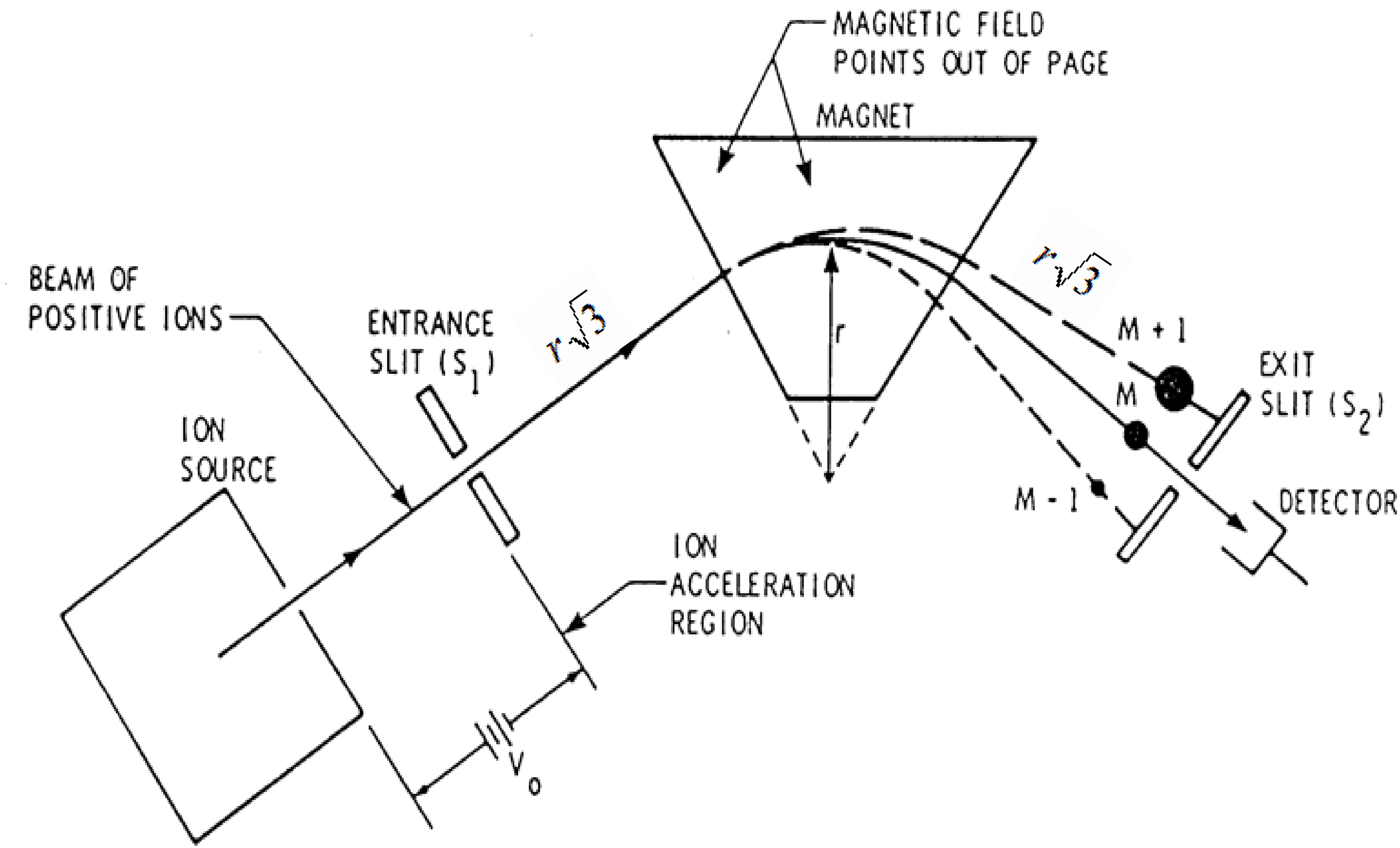
- Quadrupole

  Most widely used in RGAs

- Auto-Resonant Trap

  Relatively new, only one manufacturer

Magnetic Sector Ion Filter – Principle



Magnetic Sector – Operation

$$r = 1.44 \times 10^{-4} \frac{\sqrt{V_0}}{B} \left(\frac{M}{z} \right)^{1/2}$$

- Ion Energy V_0 in eV
- Dipole field B in Tesla
- Mass M in atomic unit
- z: degree of ionization

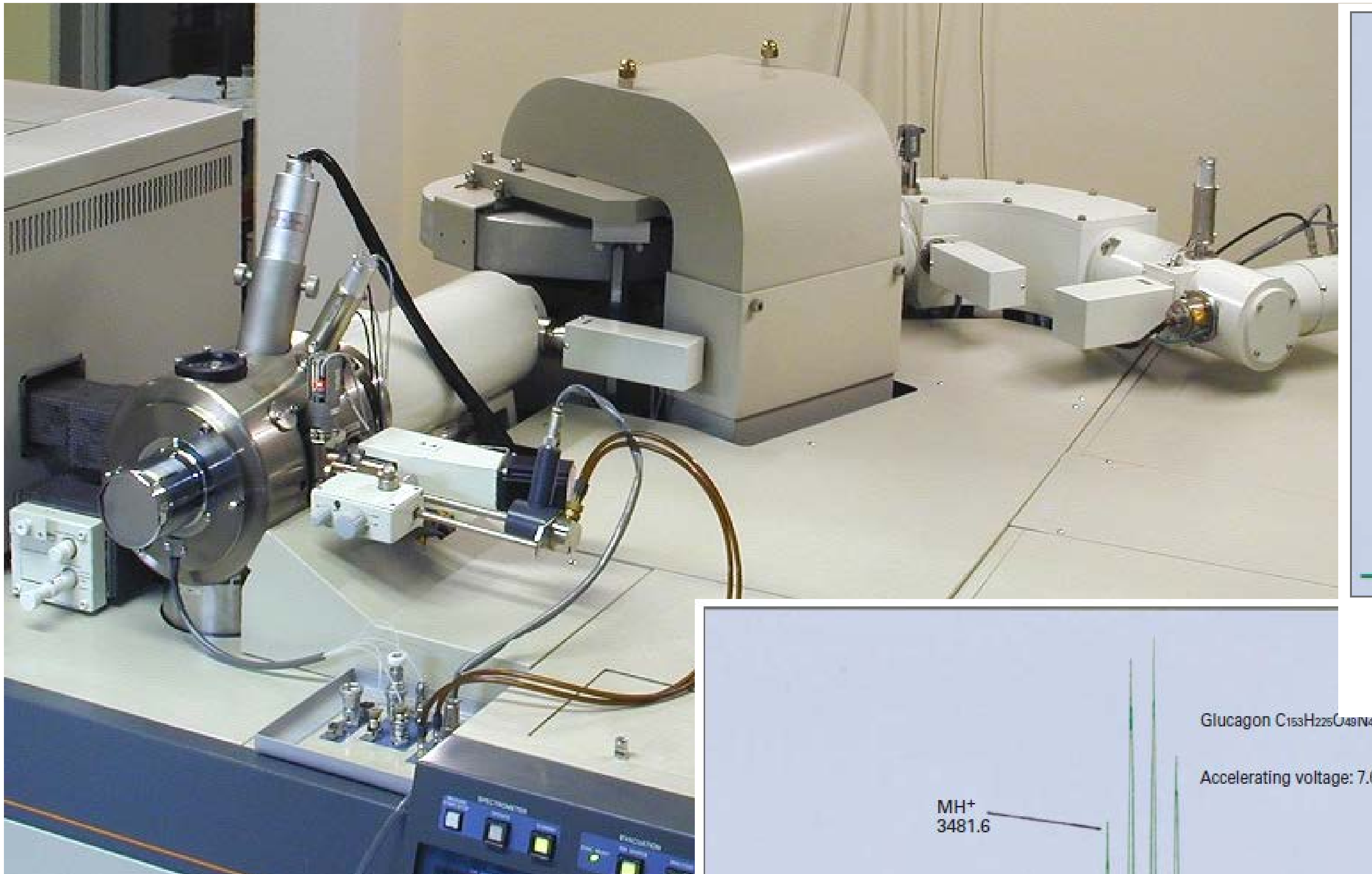
Or:

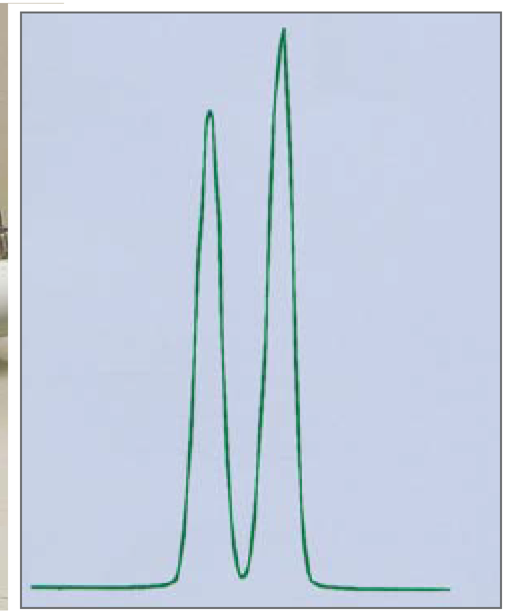
$$\frac{M}{z} = 6.94 \times 10^{3} \frac{r^2 B^2}{V_0}$$

Magnetic Sector – Operation Modes

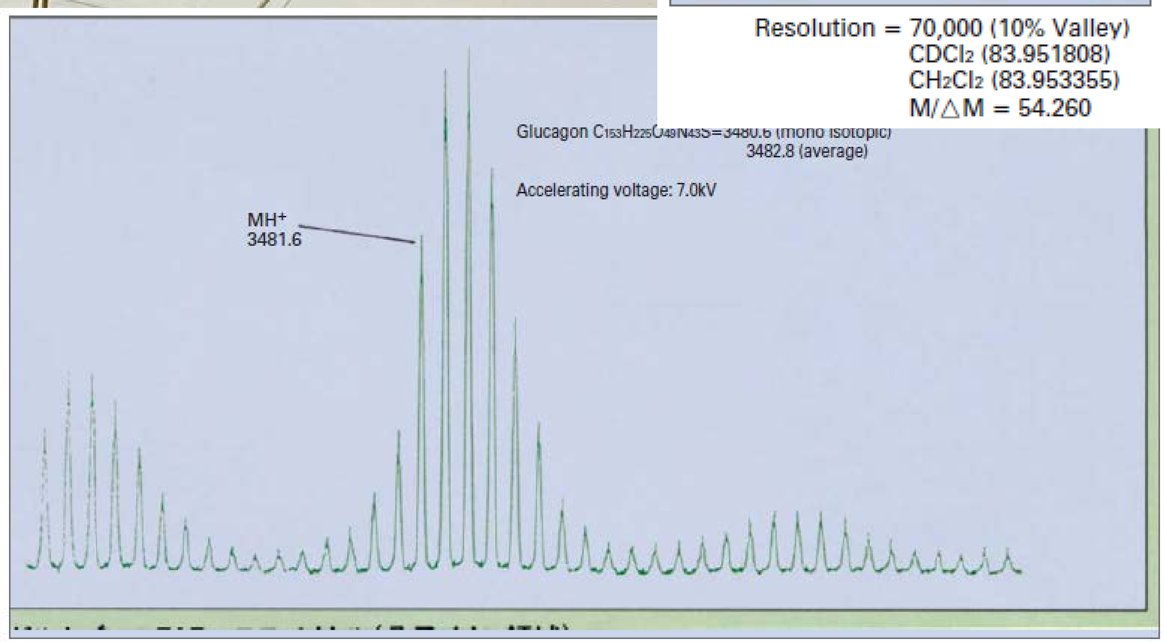
- *Use permanent magnet, varying ion accelerating voltage V_0 most used the leak detectors.*
  - ✓ *Advantages – Simple sector design, light weight, not subject to hysteresis*
  - ❖ *disadvantages – Limited mass range, sensitivity dependent of m/z*
- *Use electric sector, varying B field while holding constant ion accelerating voltage V_0. This is most commonly used.*
  - ✓ *Advantages – wide range of mass scans, with nearly constant sensitivity*
  - ❖ *disadvantages – massive and costly, hysteresis issues*

Magnetic Sector Spectrometer Station



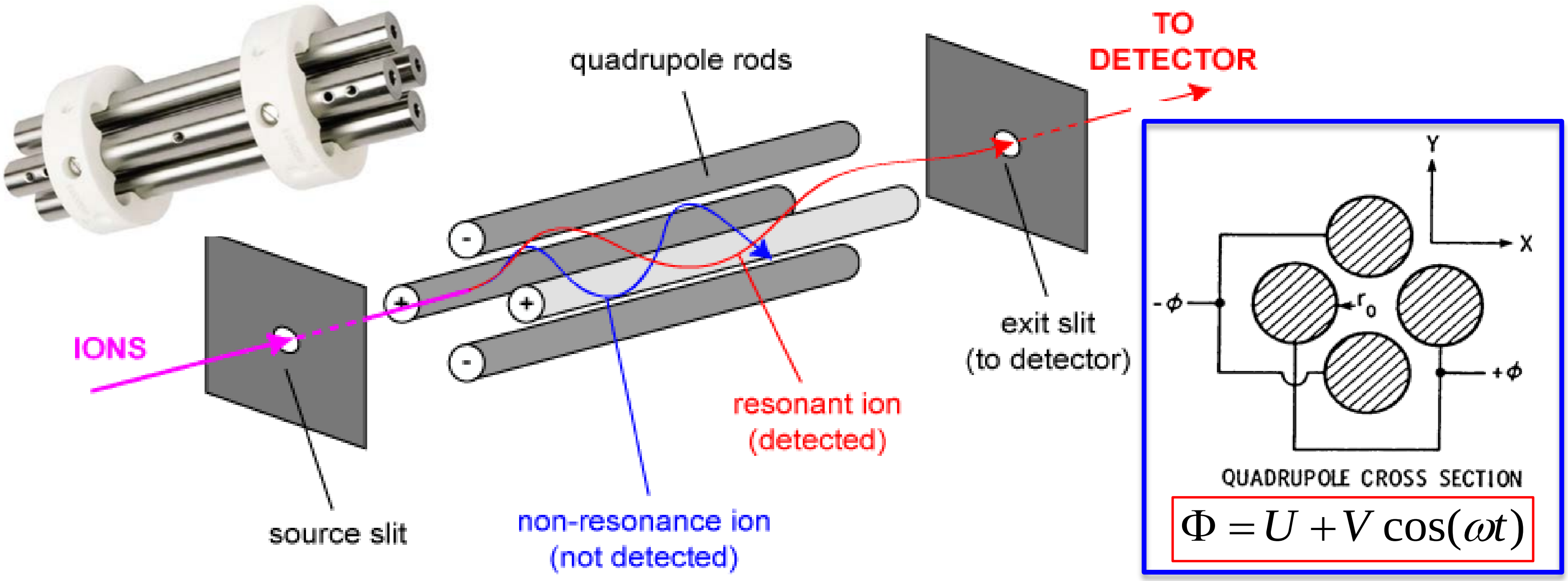


Resolution = 70,000 (10% Valley)
$CDCl_2$ (83.951808)
CH_2Cl_2 (83.953355)
M/△M = 54.260



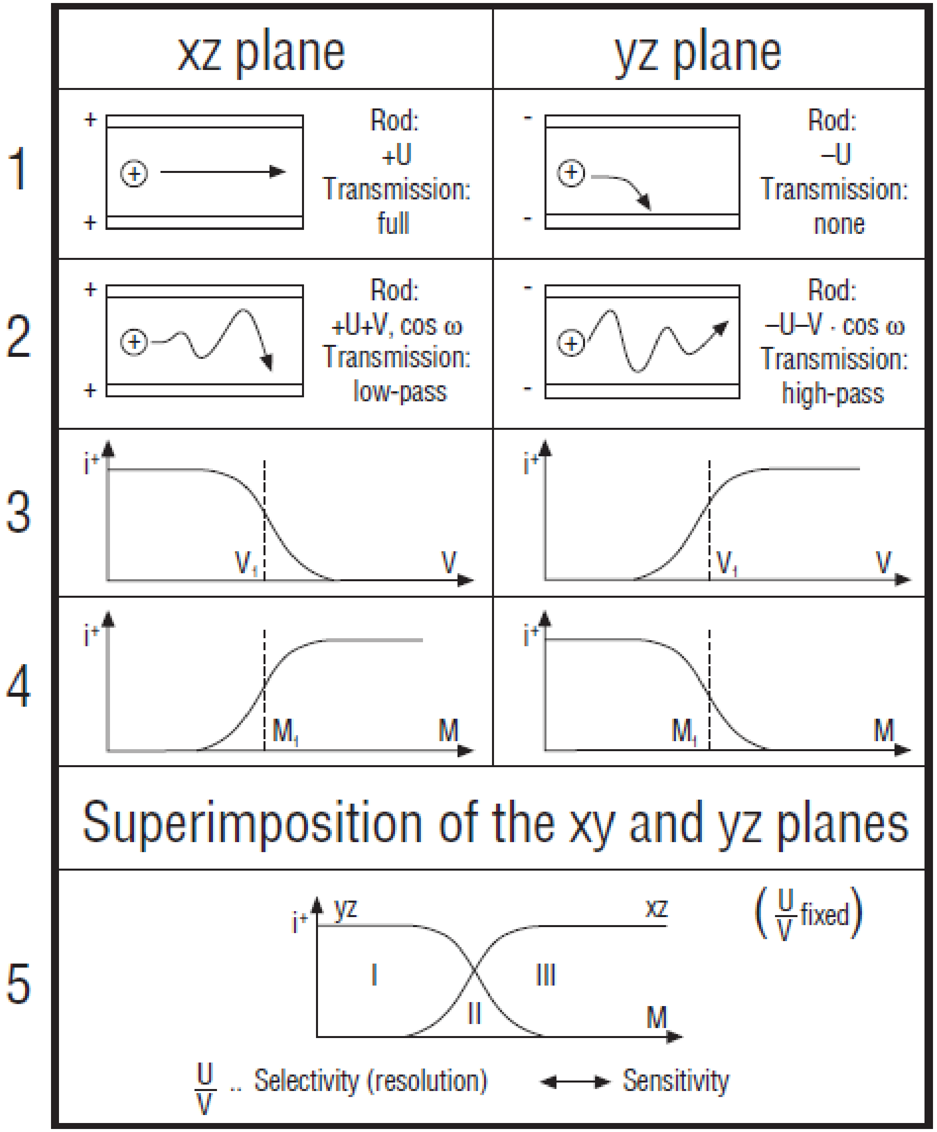
JEOL JMS-700 MStation

Quadrupole Ion Filter - Principle



- *Quadrupole Field:* $\Phi = (U + V\cos \omega t)\cdot(x^2 - y^2)/r_0^2$
- *The motion of ions in the quadrupole field can be solved using Mathieu's differential equations.*
- *Ions with certain M/z have stable trajectories to passing through exit aperture at given combination of U and V values.*

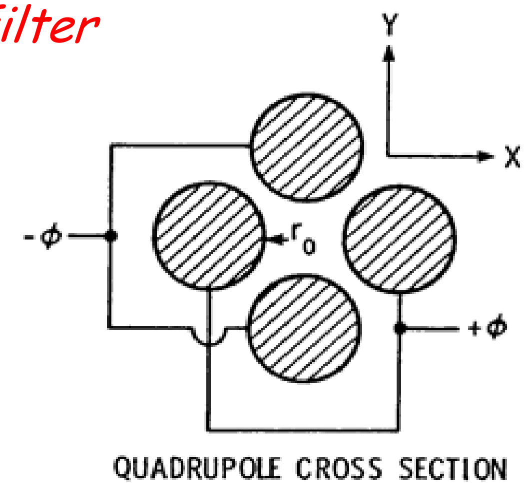
Quadrupole Ion Filter – A Non-Math Model



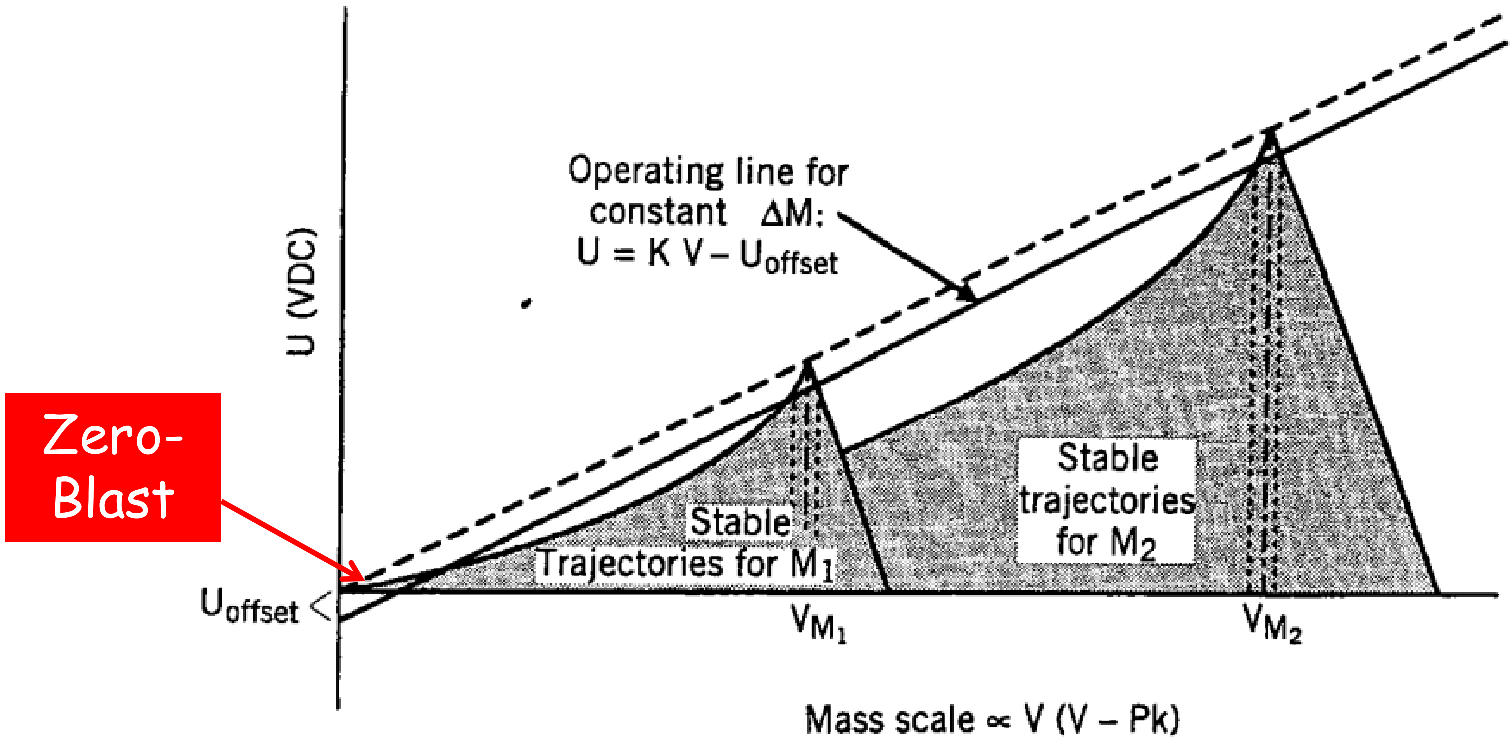
DC field stabilize ions in one plane (XZ), deflect in the other (YZ)

Superimposed RF field 'kicks' lighter ions in one plane (XZ), while 'corrects' heavy ions in the other (YZ)

Combination of both 'low-pass' and the 'high-pass' to form a 'band-pass' ion filter



Quadrupole Ion Filter - Scanning



- *Sweep V while keeping $U = KV - U_{offset}$*
- *Constant resolution over large range, $\propto U_{offset}$*

Quadrupole Ion Filter – Characteristics

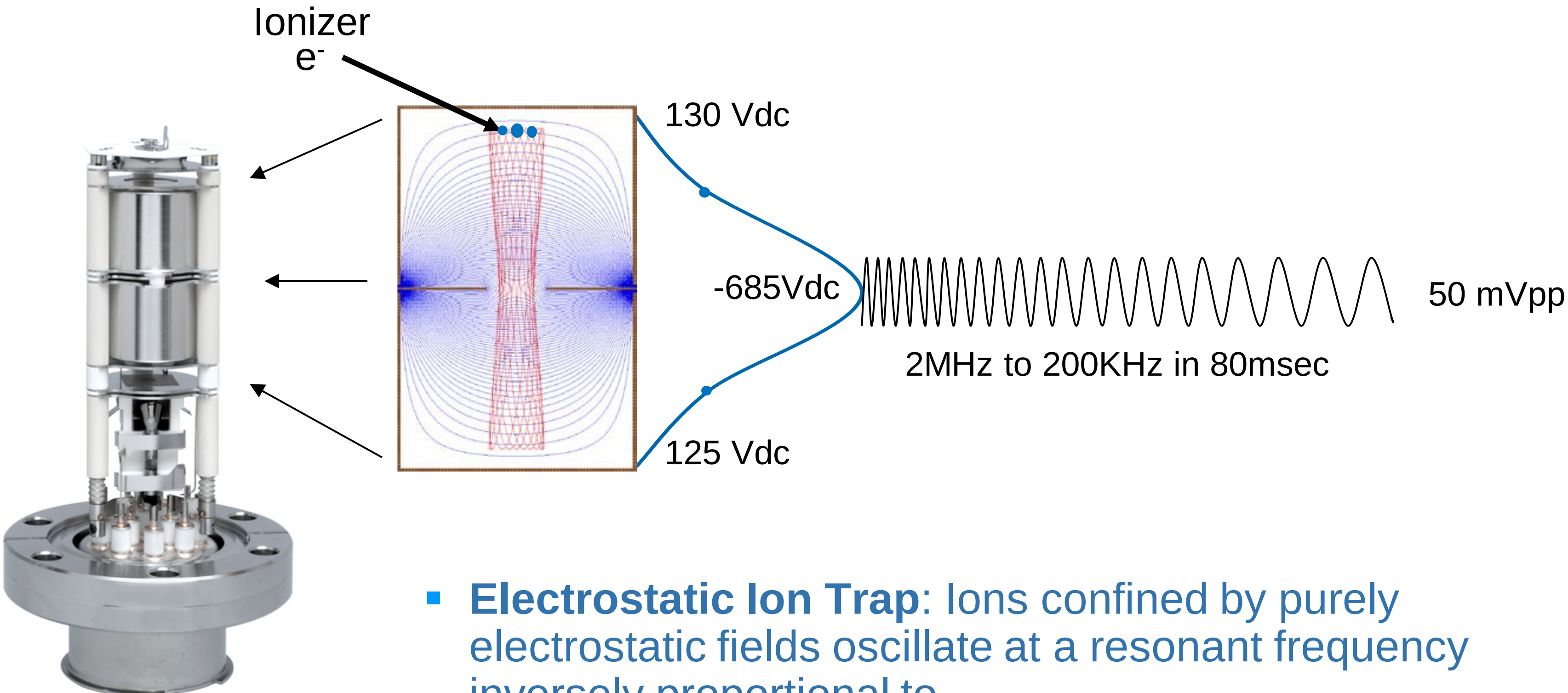
- *Linear mass scan (uniform mass separations) with constant peak width can be achieved for most commercial MQS, when properly tuned.*

- *Ion filter transmission usually depends on M/z. In many instruments, the transmission efficiency (TF) decreases in high mass (>20): $TF \propto 1/(M/z)$. Transmission factor also depends on ion energy.*

- *Resolving power (or scan range) $M/\Delta M \propto L^2$ (L filter length)*

- *Tuning and calibration is usually more difficult, must be done by experts, or in factory. In most brands, the manufacturers strongly recommend one-to-one match of the control electronic unit and the sensor head.*

Auto-Resonant Trap – Principle



- **Electrostatic Ion Trap**: Ions confined by purely electrostatic fields oscillate at a resonant frequency inversely proportional to

$$\sqrt{m/z}$$

Where, m is mass, z is the total charge of the ion

- **Autoresonance**: RF scan pushes ions when scan frequency matches ion's resonant frequency

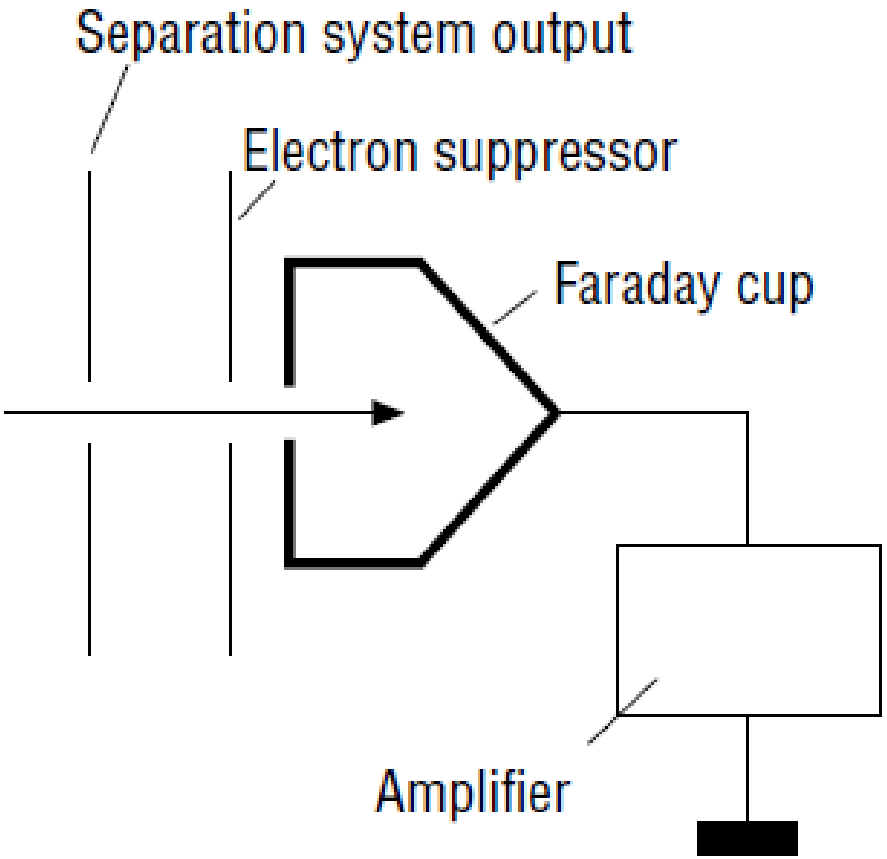
Electrostatic confinement = Ultra-low power requirements

Auto-Resonant Trap – Characteristics

- *Very fast scans (as fast as 85 ms/scan to 300 AMU)*
- *Very compact, low power and low RF power*
- *Much less artifact peaks, with very low electron emission current (as low as 5-μA)*
- *ART is ratio-matric. Need a total pressure gauge for 'true' partial pressure measurement*
- *High background ion current at high pressure (>10^{-7} torr)*
- *Relatively low spectral dynamic range*

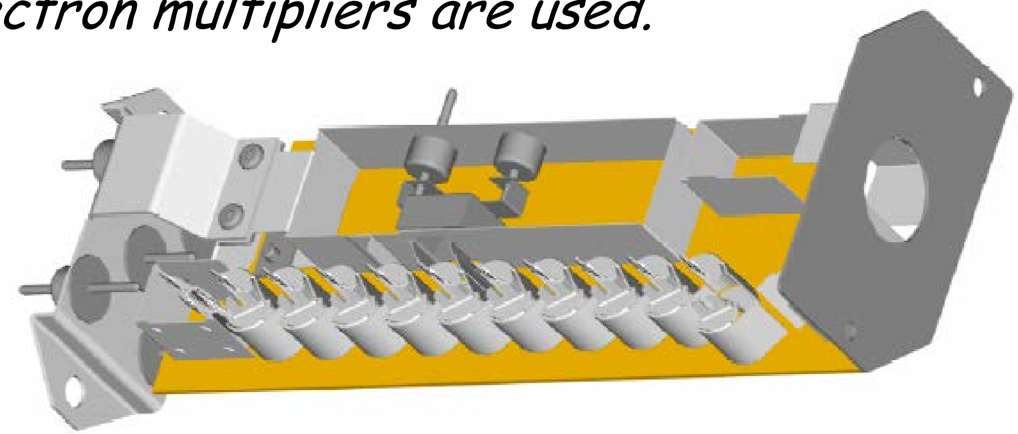
Ion Detectors – Faraday Cup

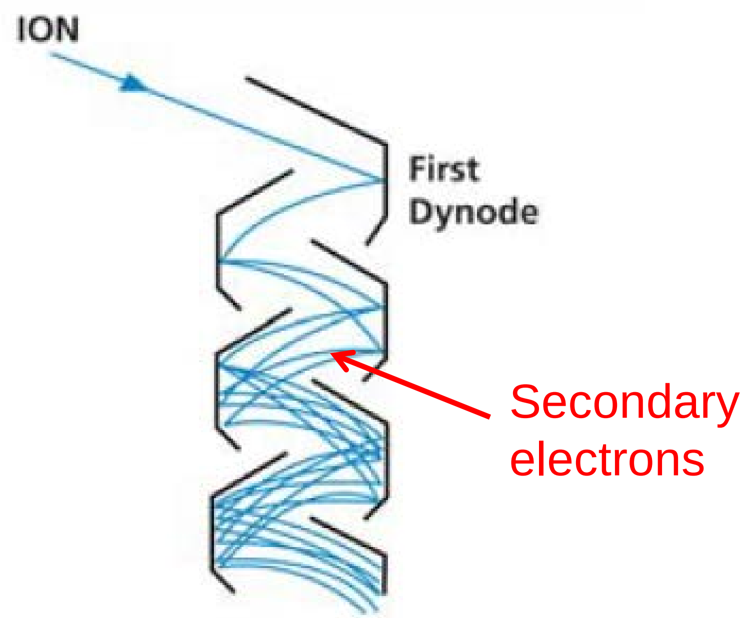
- At high-vacuum (10^{-5} to 10^{-8} torr), a Faraday cup style charge detector is sufficient.



Ion Detectors – Electron Multipliers

- At UHV conditions, the ion current becomes too small to be directly measured by a Faraday cup, electron multipliers are used.
- The electron multipliers are replying on secondary emission process on active coatings.
- To achieve sufficiently high gain, usually multiple stages of secondary emissions are employed.

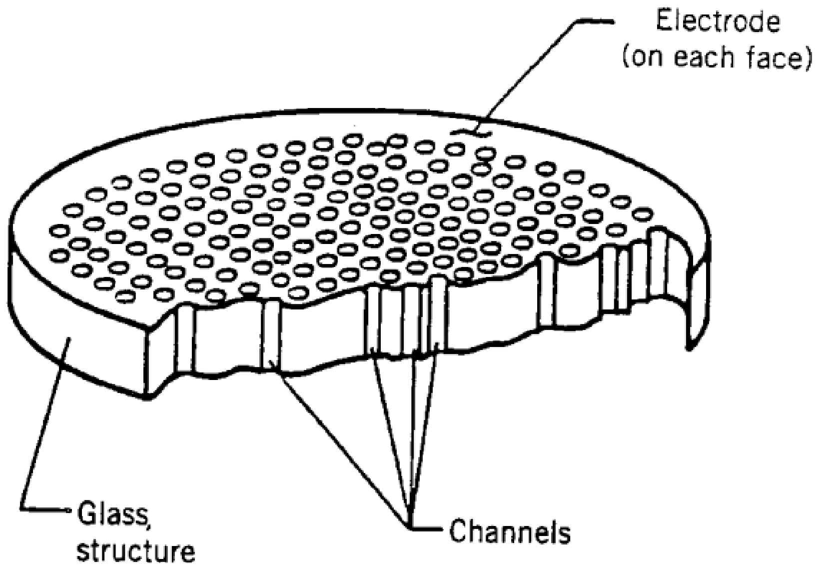


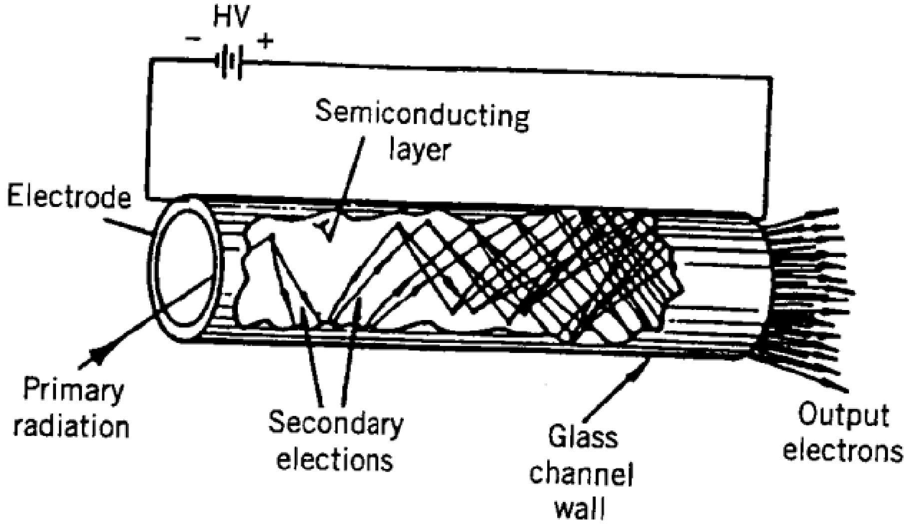


- Though discrete dynodes yield very high gain, continuous dynode multipliers are most commonly used in RGAs, as their active coatings are less sensitive to air exposure (oxidization degradation).
- Two types continuous dynode multipliers: Micro-Channel Plates and Channeltrons

Ion Detectors – Channel Plate

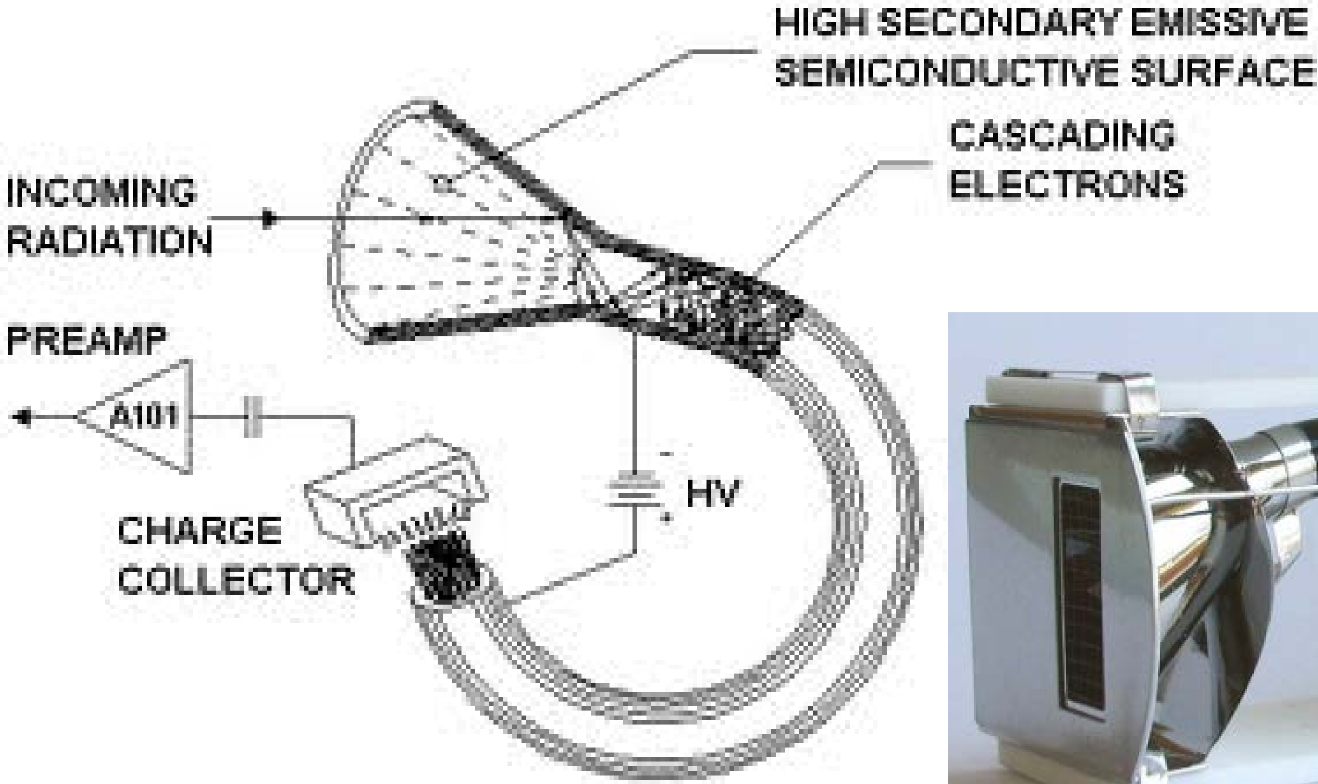
- At UHV/XHV (< 10^{-8} torr), a electron multiplier is needed.
- Micro-channel plate (MCP) is a lower cost multiplier with gain up to 10^5.





Ion Detectors – Channeltron®

- At UHV/XHV (<10^{-8} torr), a electron multiplier is needed. Channeltron® has much higher gains (>10^{7}) at higher cost.



RGA – Operational Parameters

- *Mass range – For most HV, UHV, XHV systems, 0-100 AMU is sufficient.*
- *Resolution – Normally, RGA's resolution ΔM is set ~1.0. Lower resolving power ($\Delta M>1$) may needed to gain sensitivity.*
- *Signal sensitivity – Most modern RGAs claim over-all sensitivities 10^{-14} torr. The RGA sensitivity depends on the Faraday-cup sensitivity (RGA's basic sensitivity), and the gain of electron multiplier.*
- *Mass scan speed – Most quadrupole RGAs can scan 0-100 AMU in seconds, ART-MS in <100 ms*

Some Commercial RGA Systems

Inficon Transpector 2

Range: *0 -100, 0 -200, 0 -300*
Pressure range: *<10^{-4} torr*
Sensitivity *(amp/torr):*
10^{-4} (FC), 500 (EMP)
Minimum detectable PP *(torr):*
3×10^{-13} (FC)
5×10^{-15} (EMP)

Brooks Automation VQM

Range: *0 -145, 0 -300*
Pressure range: *<10^{-5} torr*
Sensitivity *(amp/torr):*
Depend on total pressure
Minimum detectable PP *(torr):*
Depend on total pressure
(<10^{-13} torr) (always require EMP).

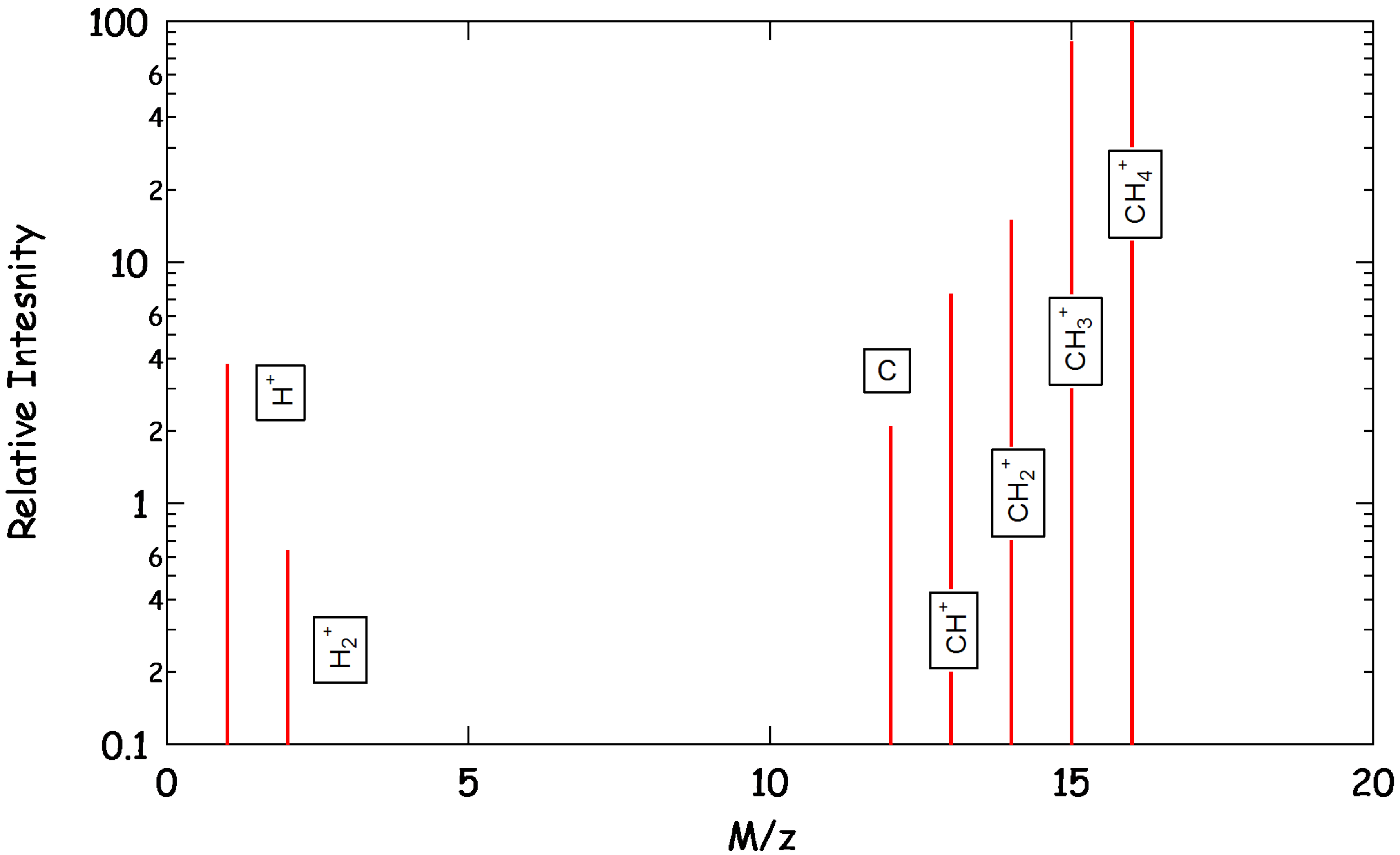
RGA with Radiation Resistance Cable

MKS's Micro-Vision Quadrupole RGA with bakeable and radiation resistance cable allows continuous operations in the accelerators. Many (100s) are used at Diamond Light Source, some has been in use in CESR for over 10 years, with no radiation induced damage, however, with higher price tags.

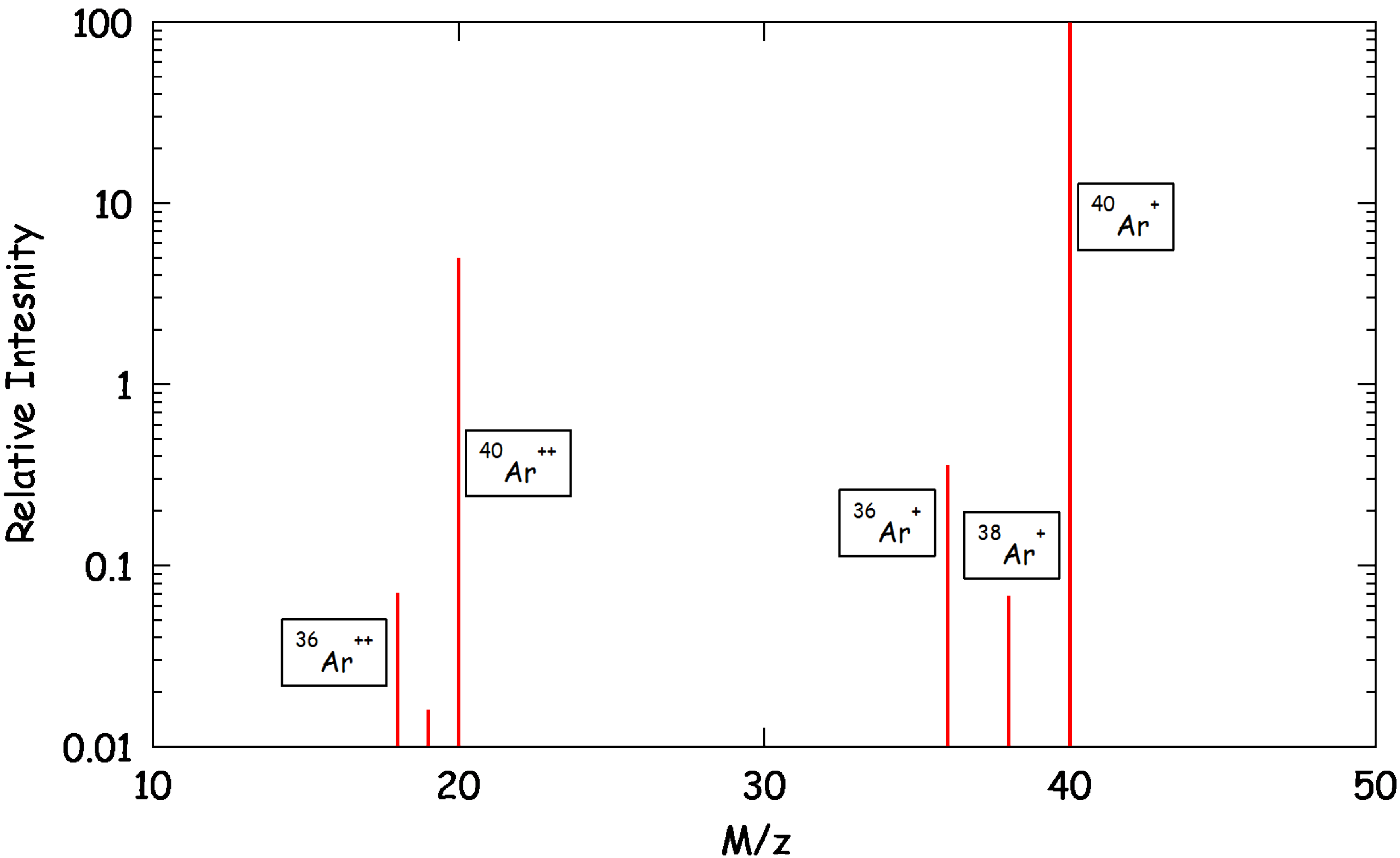
Cracking Patterns

- *When molecules of a gas or vapor are struck by electrons with sufficient kinetic energy, ionization and fragmentation of the molecules may occur, that results in ions with several mass-to-charge ratios.*
- *The mass-to-charge values are unique for each gas species, with a distribution (or pattern) of relative intensity of these M/z peaks, depending on the gas species (and the instrumental conditions).*
- *The distribution or the pattern is often referred as* ***cracking pattern*** *of the gas species.*
- *Besides singly ionization of a molecules ($CH_4 \rightarrow CH_4^+$), at least two more factors contributed to the cracking pattern: dissociative ionization (fragmentation) and isotopes*

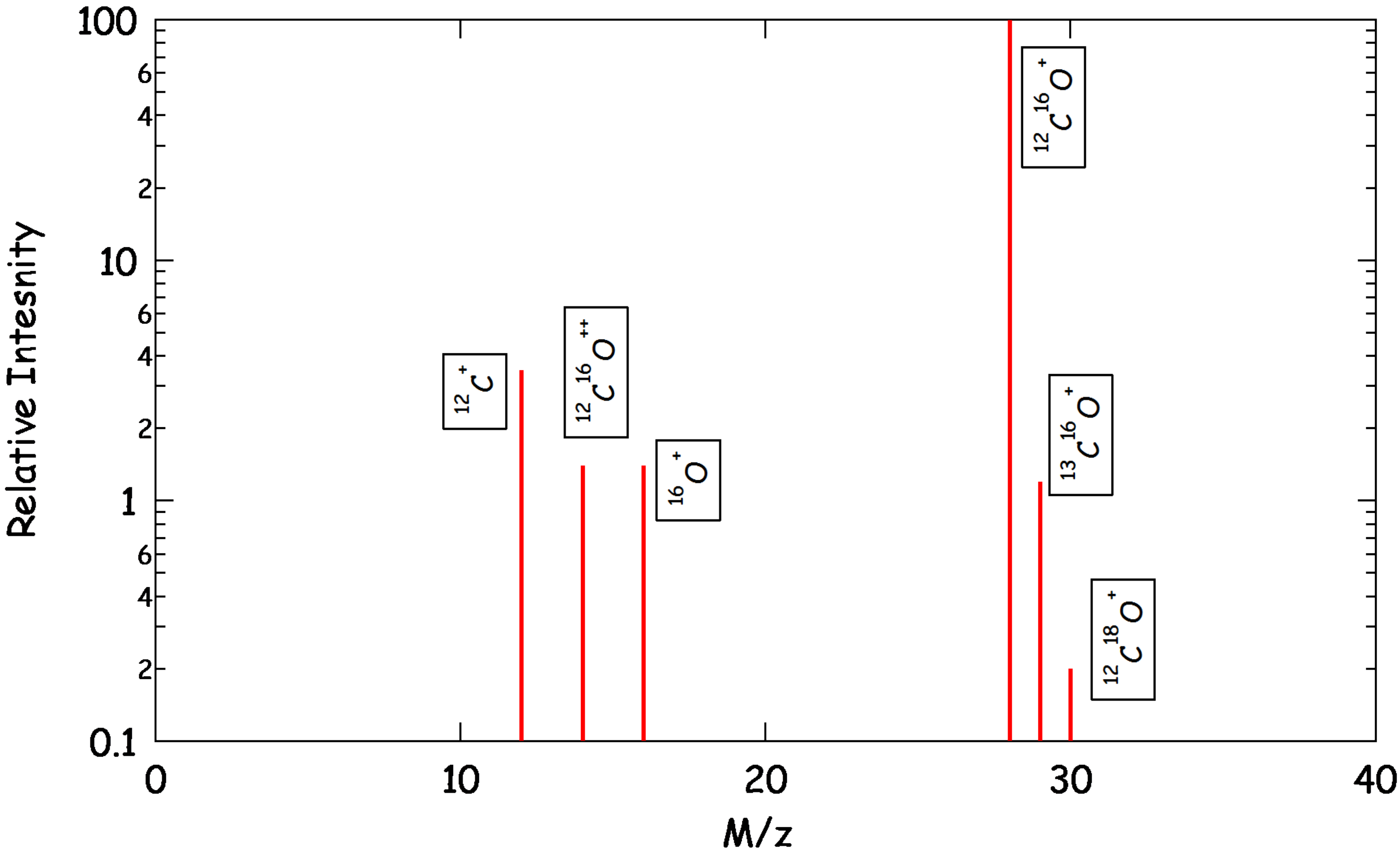
Dissociative ionization – CH_4 as example



Isotope Effect – Ar as example

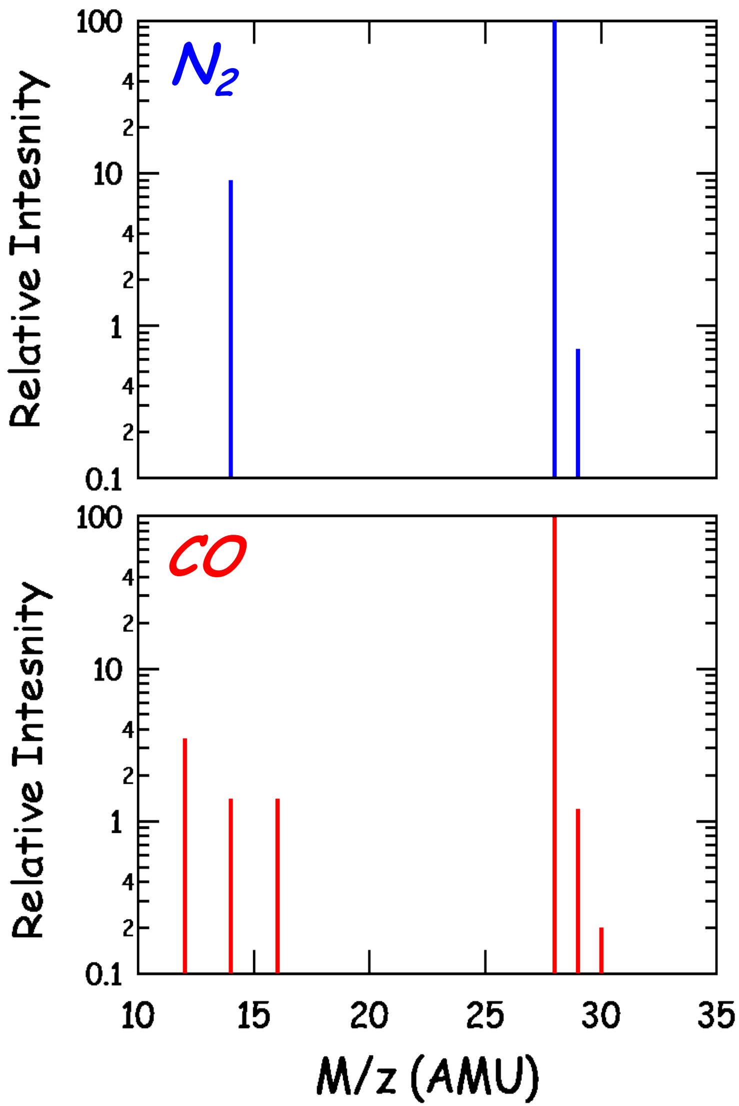


Combined Effect – CO as example



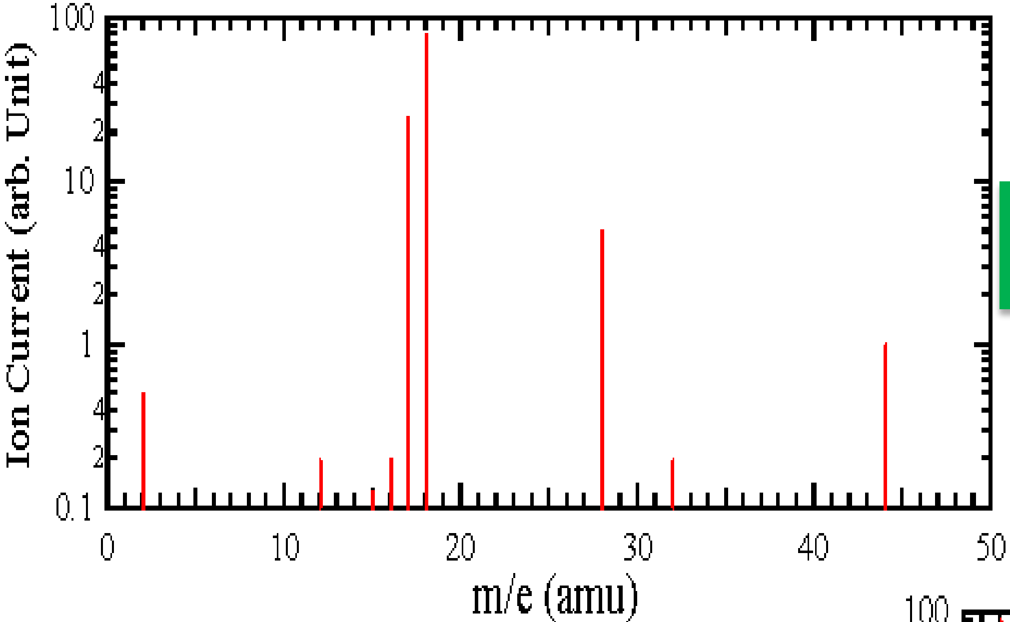
Cracking Patterns – "Fingerprints"

- *Cracking patterns are commonly used as "fingerprints" of a gas or a vapor, for qualitative gas analysis.*
- *Cracking patterns of many common gases and vapors can be found in the literatures.*
- *Published cracking patterns should be used as a guidance, and they not only depend on gas/vapor, but also vary with instrument conditions.*
- *Many commercial RGA systems have 'build-in' gas library. NIST also maintain a online mass spectrum data.*



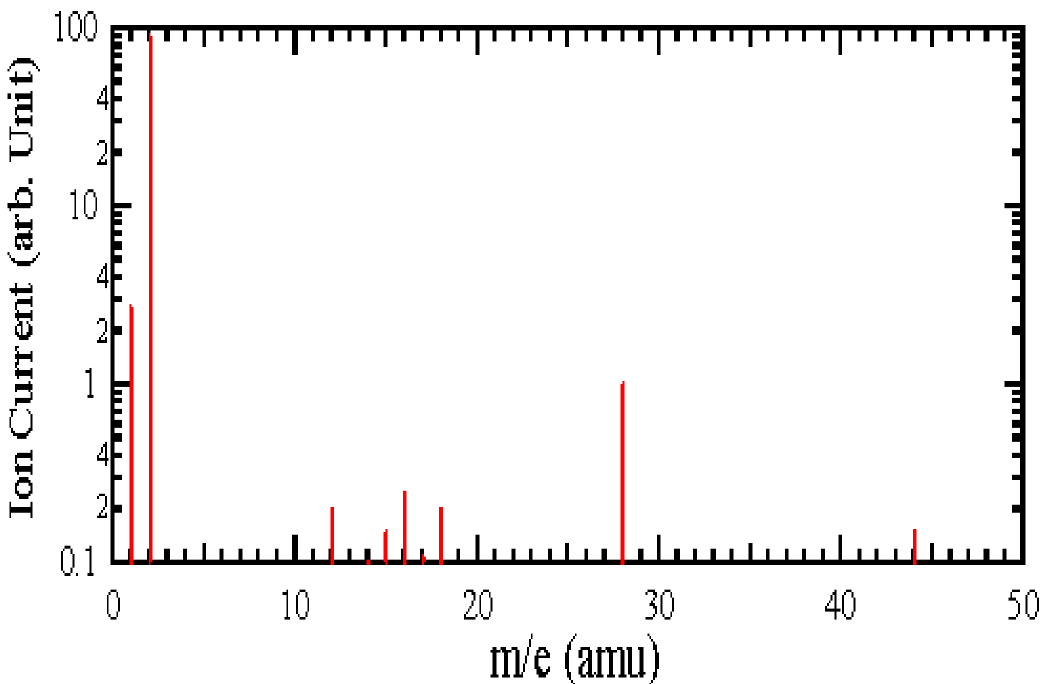
http://webbook.nist.gov/chemistry/

Qualitative Analysis – Example 1

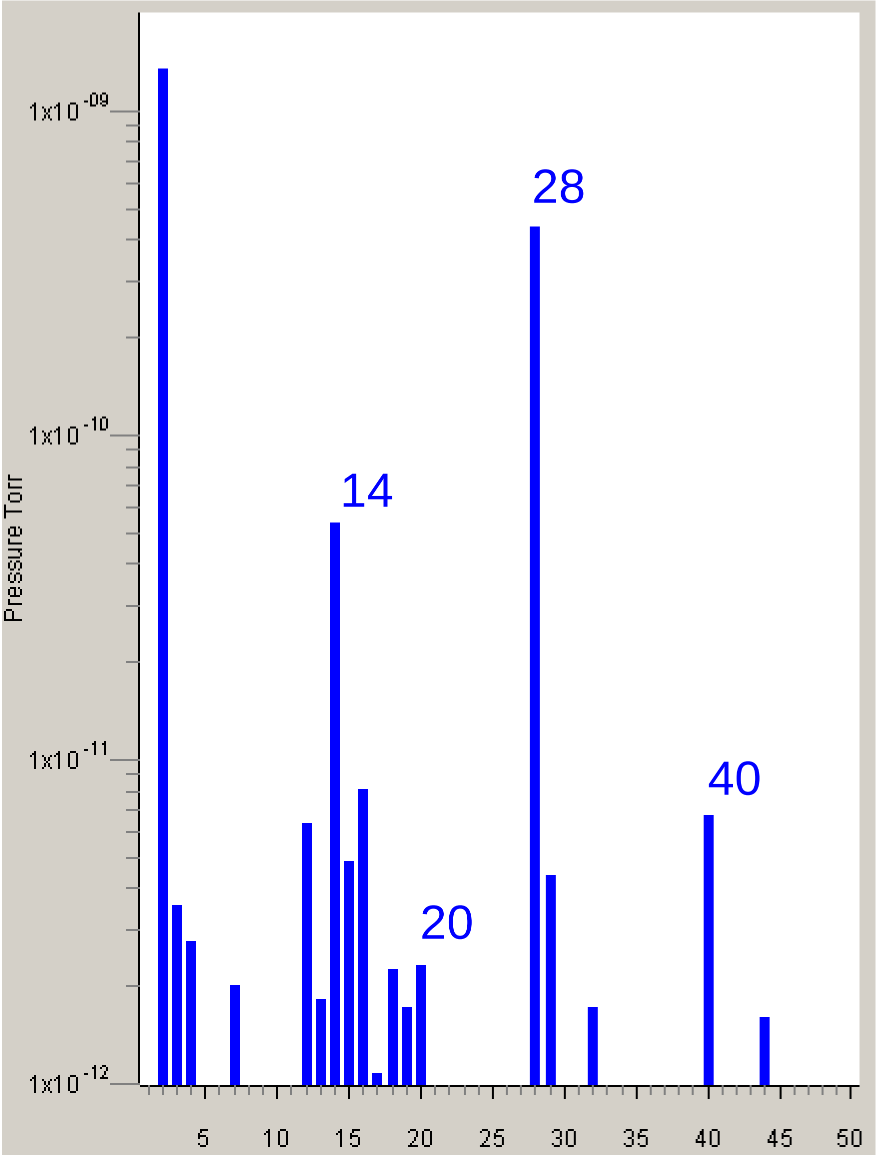


An unbaked vacuum system, H_2O dominant

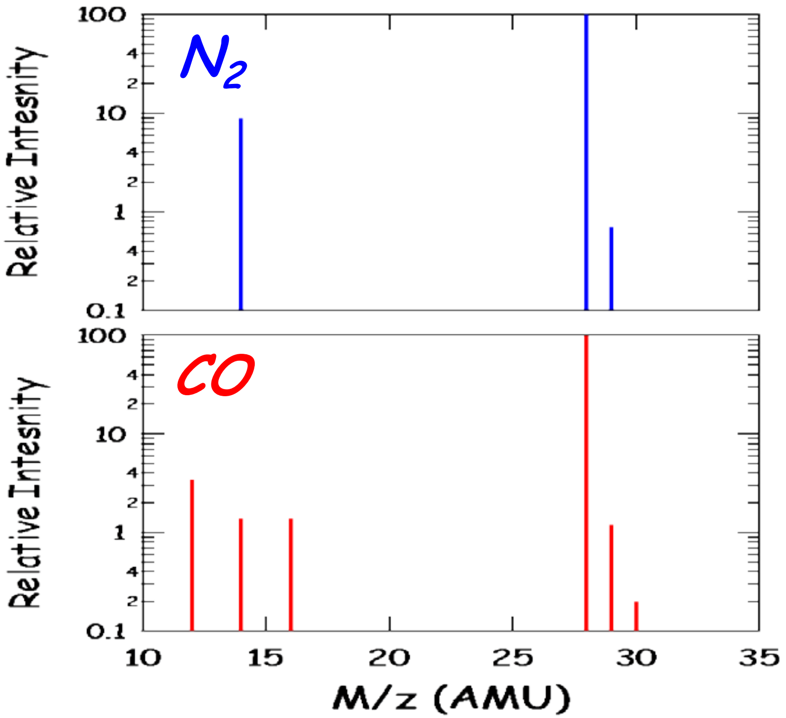
An clean UHV chamber, H_2 dominant



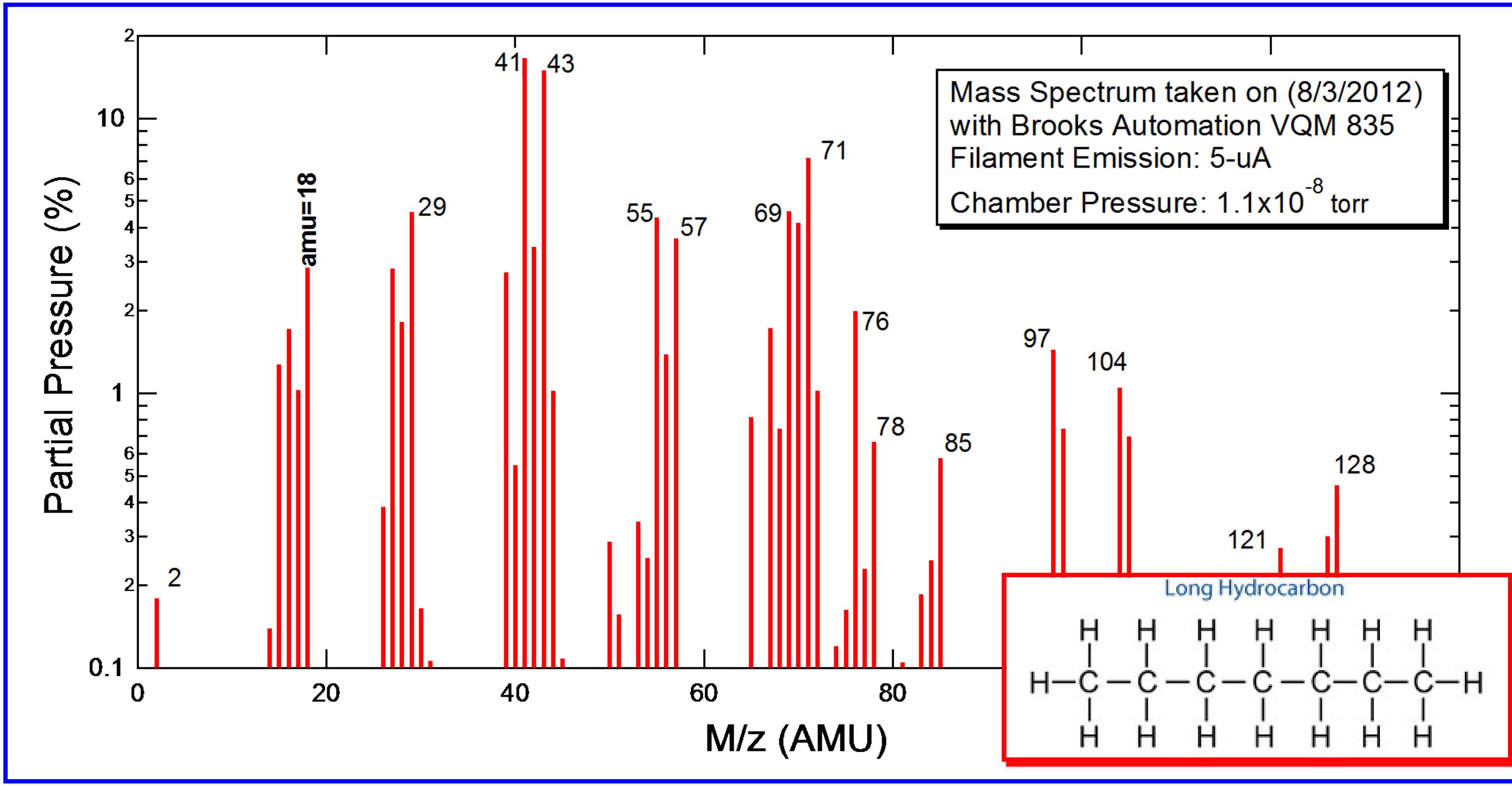
Qualitative Analysis – Example 2



Vacuum system with a small air-to-vacuum leak!

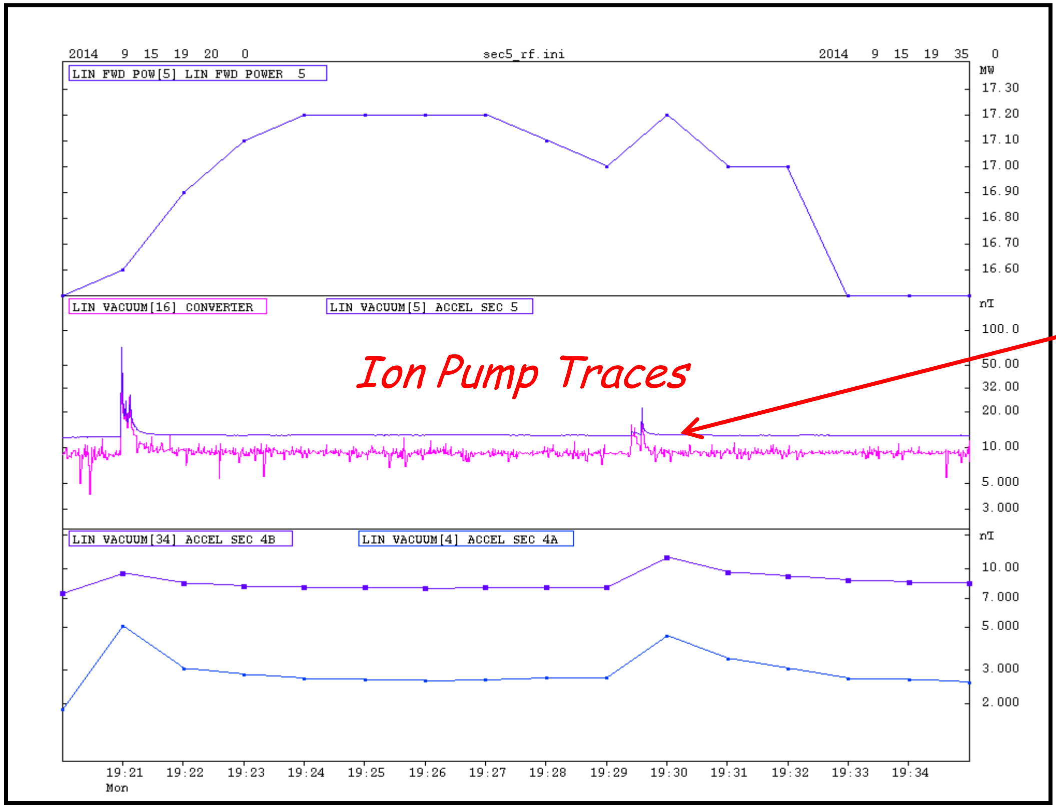


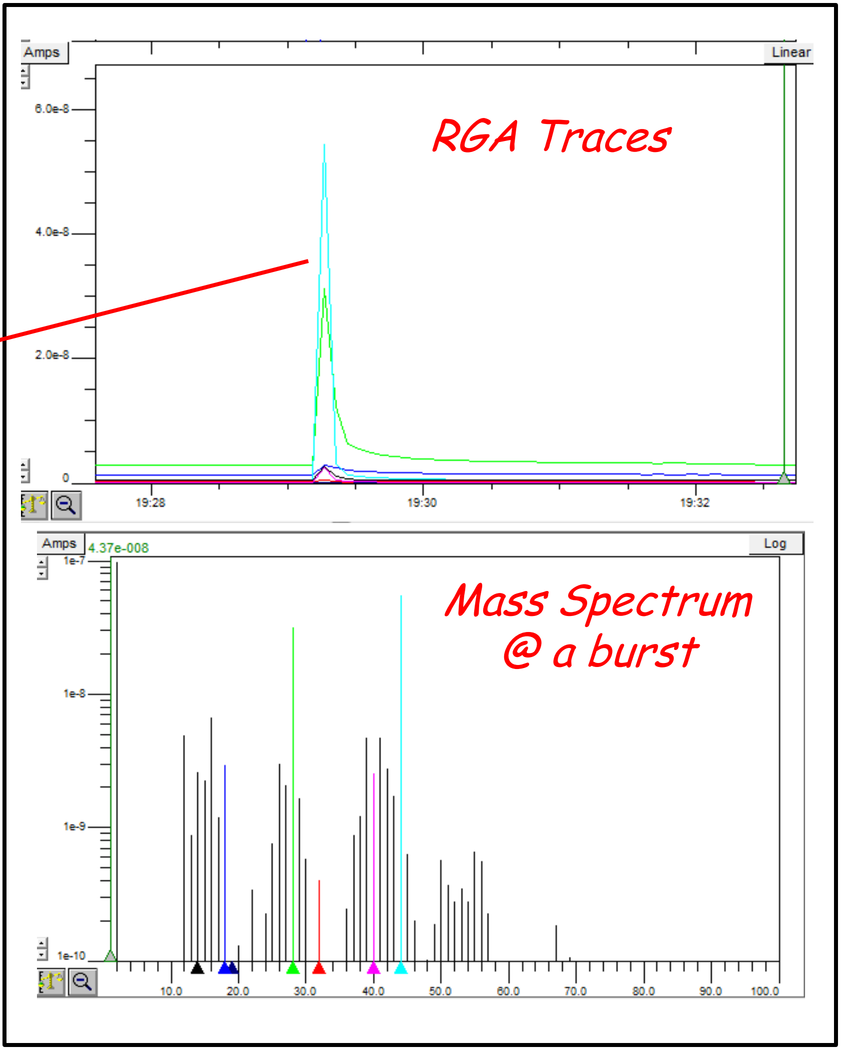
Qualitative Analysis – Example 3



A vacuum system contaminated by long-chain hydrocarbons, with peak-grouped by AMU=14, that is fragmenting by breaking a CH_2 species.

Qualitative Analysis – Example 4





- *Recently, our aging LINAC had VSWRs associated with pressure bursts.*
- *Possible leak(?): RF window (SF_6), air-to-vacuum, water-to-vacuum, …,…*
- *RGA was used to determine that these were simply due to RF arcing, as dominated by C-containing species in the 'gas-bursts'.*

RGA – Quantitative Analysis

- Quantitative analysis of partial pressures is NOT necessary in most cases, as it is very difficult and often inaccurate.
- For a system contains gases with non-overlapping peaks are relatively straightforward, by calculating PP of individual gases, using a dominant peak. Example: CO (amu:28), Ar (amu:40).

Calculating CO partial pressure using ion current at M/z=28	$PP_{CO} = \dfrac{I_{CO28}}{FF_{CO28} \cdot XF_{CO28} \cdot TF_{28} \cdot DF_{CO28} \cdot G \cdot S}$
Calculating Ar partial pressure using ion current at M/z=40	$PP_{Ar} = \dfrac{I_{Ar40}}{FF_{Ar40} \cdot XF_{Ar40} \cdot TF_{40} \cdot DF_{Ar40} \cdot G \cdot S}$

$FF_{(CO28,\ Ar40)}$: Fragmentation ratio of (CO, Ar) to M/z=(28,40) – Cracking Pattern
$XF_{(CO28,\ Ar40)}$: Relative ionization probability (to N_2) of (CO, Ar) to (CO^+, Ar^+) ions

$TF_{(28.\ 40)}$: Transmission factors for M/z=(28. 40) ions through mass filter
$DF_{(CO28,\ Ar40)}$: Detector factor of (CO^+, Ar^+) ions
G: multiplier gain; S: Instrument sensitivity for N_2, in Amp/Torr

REF: http://www.inficon.com/download/en/calcpartpress.pdf

Gauge Selection Considerations

- Gauge Range: Multiple gauges should be installed in a accelerator vacuum system to cover pressure ranges from atmospheric pressure to the working pressure.
  - → Convectron Pirani gauges are ideal for pressure atm. ~ 10^{-3} torr
  - → Ionization gauges are usually used for HV/UHV ranges.
- There are commercial 'full-range' combination gauges from many vendors.
- RGAs should be installed for UHV accelerator vacuum systems to monitor vacuum system performances and online trouble-shooting, such as potential leaks during operations, and/or unusual beam induced pressure rises.

Gauge Application to Accelerators

- *Gauges' long-term (multi-year) reliability is most important factor, as in many accelerator vacuum system, access to the gauge heads can be very limited. In this aspect, CCGs are preferred over HCGs (though stray magnetic field must be taken into consideration).*
- *Gauges with 'on-board' electronics should always be avoided, due to the radiation damage. One should also consider the long cable factor for selecting a type of gauges. Gauges require low power is always a plus.*
- *When installing a gauge to the accelerator beam pipe, one should avoid line-of-sight of the gauge port to the particle beam, to minimize the 'cross-talks' between the gauge and the beam.*

Accelerator Vacuum Gauges – A Survey

Institute Accelerator	Total Pressure Gauge		Partial Pressure Gauge	
	Type/Brand	Q'ty	QMS Brand	Q'ty
Cornell / CESR	CCG / MKS	~90	Inficon/MKS/SRS	~20
ANL / APS	CCG / MKS	~140	Spectra MKS	~120
BNL / RHIC	CCG / MKS	>100	MKS	~100
BNL / NSLS II	CCG / MKS		Hidden	
FNL / Tevtron	HCG/CCG	~100/40	SRS/Inficon/MKS	~44
CERN / LHC	BAG / CCG	~250 BAG	No fixed installation	
KEK SuperB	CCG / DIA VAC	~300		
ESRF	CCG / Pfeiffer	~200	MKS	
JLAB	HCG (EXT) for ERL-FEL CCGs for CEBAF	100s	SRS	
TLS – TPS	Extractor / Leybold	~280	Inficon	6
Diamond L.S.	CCG / MKS		MKS	
Pohang L.S.	BAG&CCG (Pfeiffer)	~80	Pfeiffer	24