The US Particle Accelerator School
Pressure Measuring Devices

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Vacuum Measurement Considerations

- Large measurement range: 760 - 10^{-13} Torr (16 orders of magnitude)
- Pressure is the descriptive term, rarely the important one
- High accuracy is impractical, ± 10% good enough
- Some gauges do not measure pressure directly
- Some gauges are gas species dependent
- Measured environment is usually a dynamic one
- Placement of gauge will influence it's response

Vacuum Measurement

- Total pressure gauges
  - *Direct measurement*
    - Liquid column level
    - Solid wall movement
  - *Indirect measurement*
    - Thermal conductivity
    - Viscosity
    - Ionization
- Partial pressure gauges
  - *Indirect* only: ionization & mass filtering

Vacuum Pressure Gauges

The pressure range measured in most vacuum systems is too broad to be measured with a single gauge!

1×10^{-10} Torr Base Vacuum Pressure	$\longleftrightarrow$	760 Torr Atmospheric Pressure

1 unit is ~11,000,000,000 [11 billion] times the other!

10 meters The dimension of a room.	$\longleftrightarrow$	10^9 km Distance between Earth and Saturn

It is not practical to measure both with the same device.

Units of Pressure Often Used in Vacuum Technology

Atmospheric Pressure (Standard) =	
760	Torr
760	mm of mercury (Hg)
29.9	inches of Hg
14.7	lbs. per square inch – abs. (psia)
0	psig (psi at gauge)
760,000	Millitorr or “microns” of Hg
101,000	Pascal (Newton/m^2)
1.01	Bar
1010	Millibar

Types of Vacuum Gauges

Direct Gauges (Displacement of a wall)

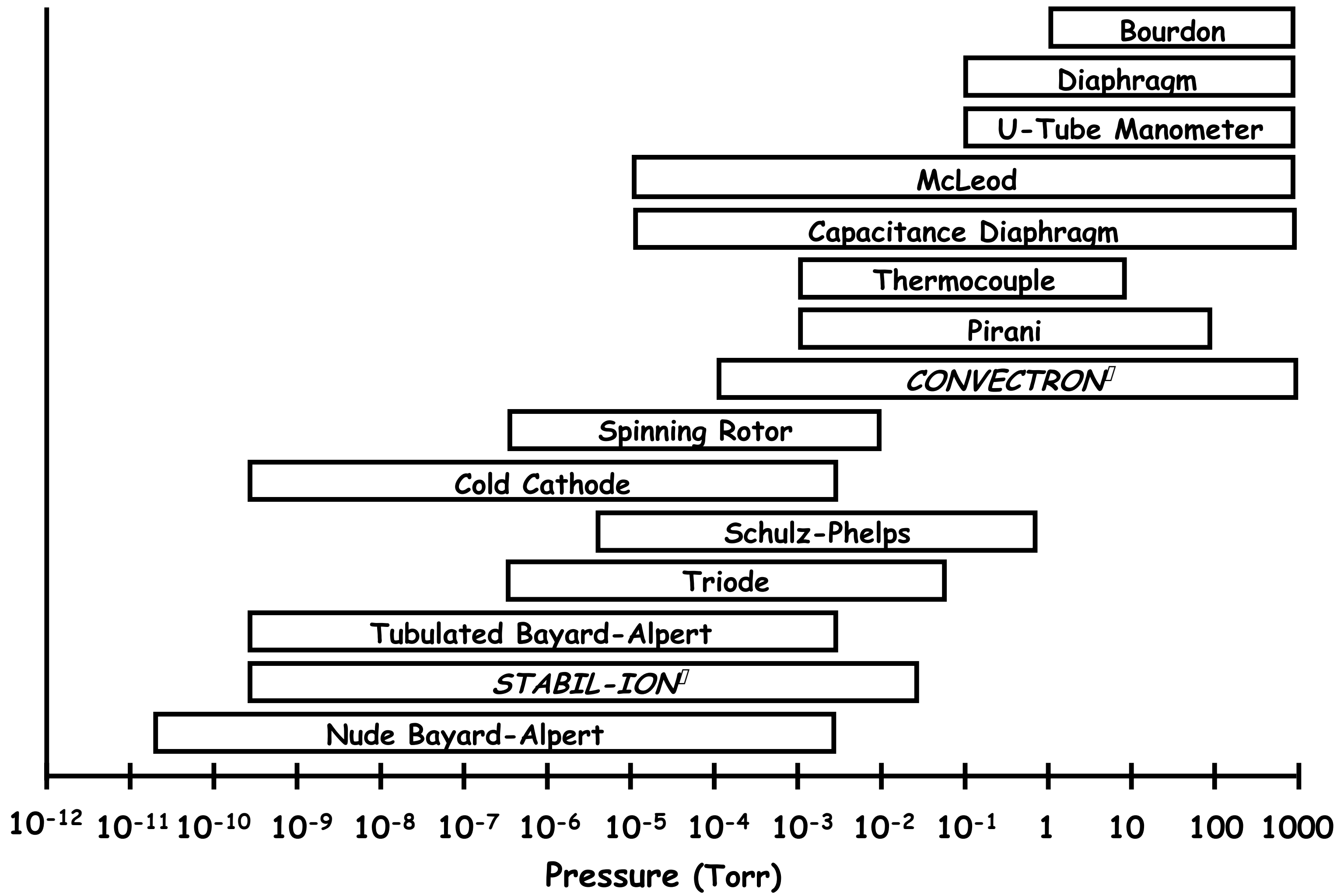
- **Solid Wall**
  - Diaphragm
  - Bourdon Type
  - Capacitance Diaphragm
- **Liquid Wall**
  - McLeod
  - U-Tube Manometer

Types of Vacuum Gauges

Indirect Gauges
(Measurement of a gas property)

- **Charge Generation (Ionization)**
  - **Cold Cathode**
    - Penning
    - Inverted Magnetron
  - **Hot Cathode**
    - Triode
    - Schulz-Phelps
    - Bayard-Alpert
    - *STABIL-ION®*
- **Energy Transfer (Heat Loss)**
  - Thermocouple
  - Pirani
  - *CONVECTRON®*
- **Momentum Transfer (Viscosity)**
  - Spinning Rotor

Range of Vacuum Gauges



Gauge Summary

Gauge	Measurement Mechanism	Operating range (Torr)	Accuracy
Bourdon tube/ diaphragm	solid wall movement	1000s-1	low
Capacitance manometer	solid wall movement	$10{,}000\text{-}10^{-6}$	high
Thermocouple	thermal conductivity	$1\text{-}10^{-3}$	medium
Pirani	thermal conductivity	$1\text{-}10^{-4}$	medium
Bayard-Alpert	ionization	$10^{-2}\text{-}10^{-11}$	medium
Penning	ionization	$10^{-2}\text{-}10^{-6}$	medium
Inverted magnetron	ionization	$10^{-3}\text{-}10^{-12}$	medium
Spinning rotor	momentum transfer	$760\text{-}10^{-7}$	high

Gauges Used on Commercial Vacuum Systems

Medium and Low Vacuum: 10^{-3} Torr to 1000 Torr

- Direct Gauges - Displacement of a Solid Wall
  - Capacitance Diaphragm Gauge
- Indirect Gauges - Heat-Loss Gauges
  - Thermocouple Gauge
  - Pirani Gauge
  - *CONVECTRON* Gauge (Convection-Enhanced Pirani)

Ultra-High and High Vacuum: 10^{-11} Torr to 10^{-3} Torr

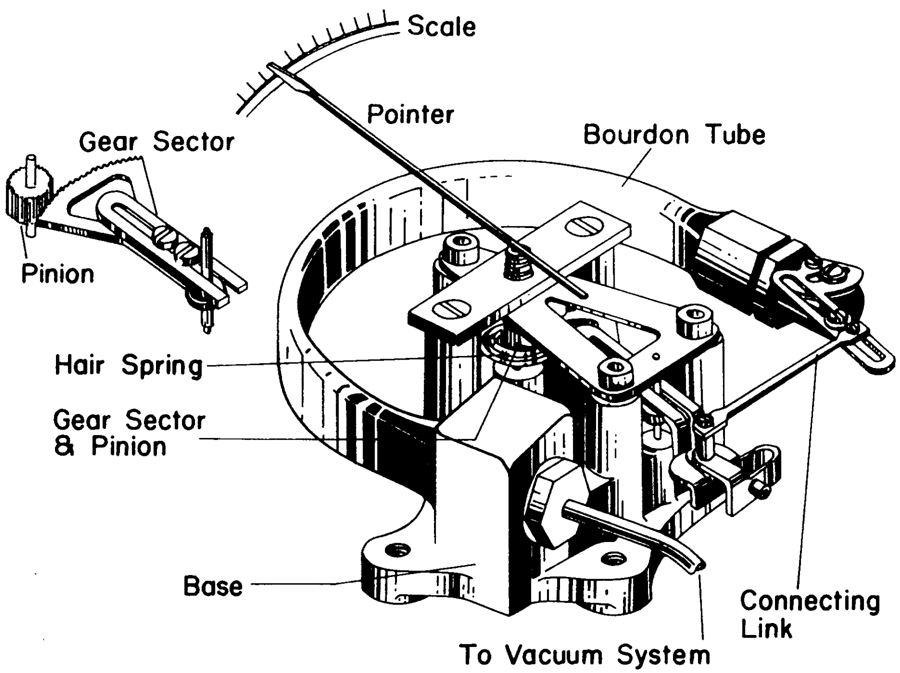
- Indirect Gauges - Ionization Gauges
  - Hot Cathode Gauge
  - Cold Cathode Gauge

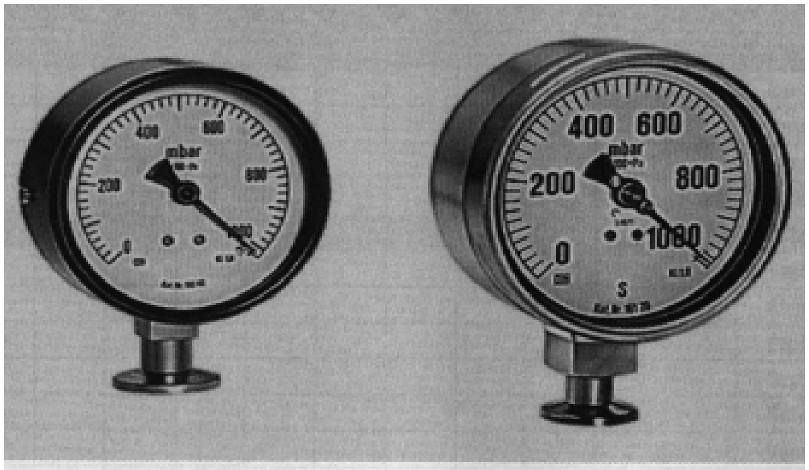
Bourdon Tube & Diaphragm Gauges

Distinguishing features & operating characteristics:

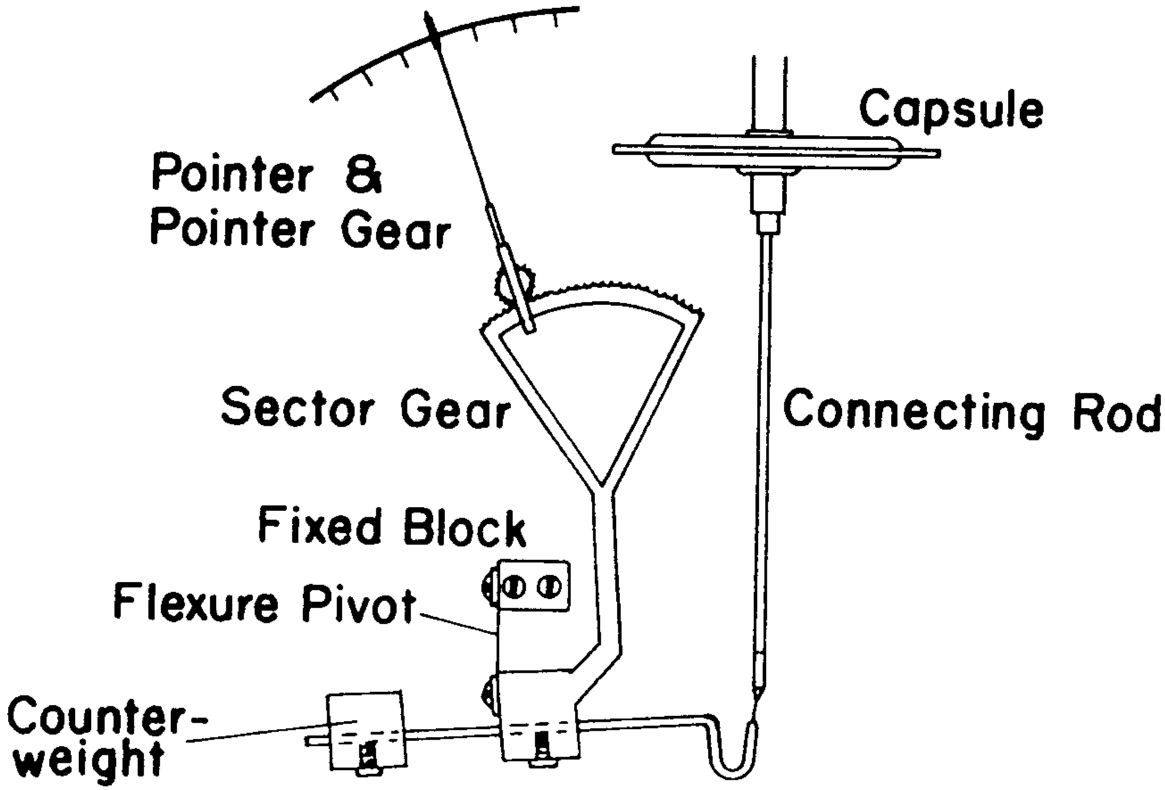
- Measures pressure directly
- Operating range above atm pressure to 1 Torr
- Indicated value is independent of gas specie being measured
- System of gears & levers transmit the movement of a small tube or wall to a pointer
- Can be constructed such that all parts exposed to vacuum are stainless steel
- Optionally configured as a compound gauge
- Bourdon tube often used as an indicator of system status
- For safety reasons: Bourdon tube recommended for most systems

Bourdon Tube Gauge Components



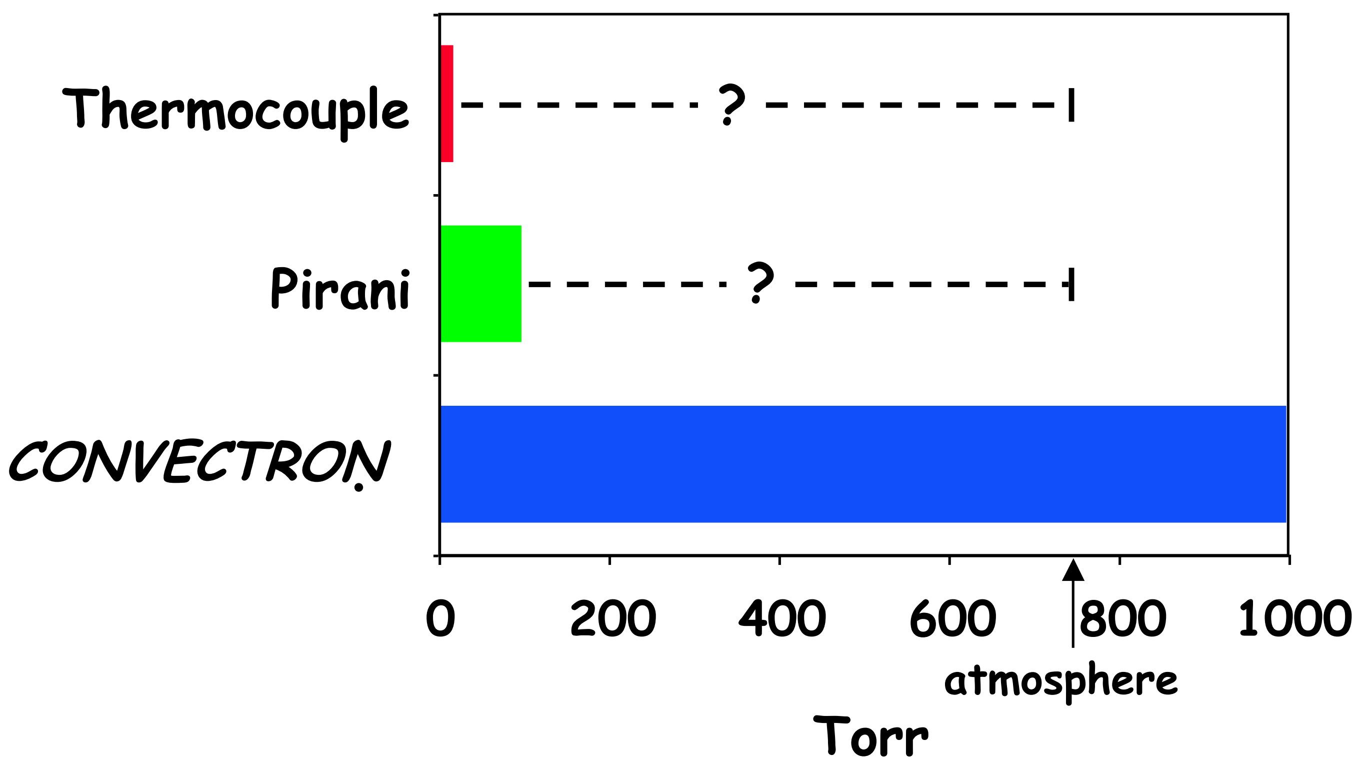


Diaphragm Gauge Components



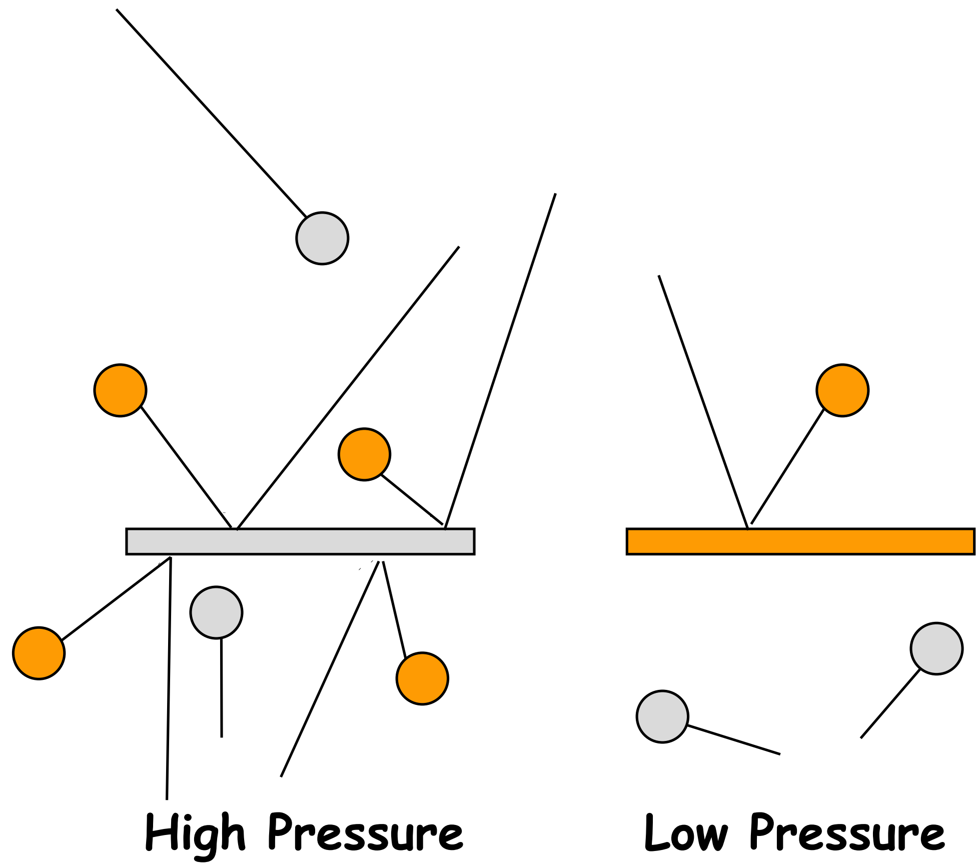
Operating Ranges for Heat-Loss Gauges

Pressure Range Comparison of Heat-Loss Sensors



Heat-Loss or Energy Transfer

- Heated element cools as molecules strike.
- Higher pressure means increased cooling of sensor.
- Gas species dependent.



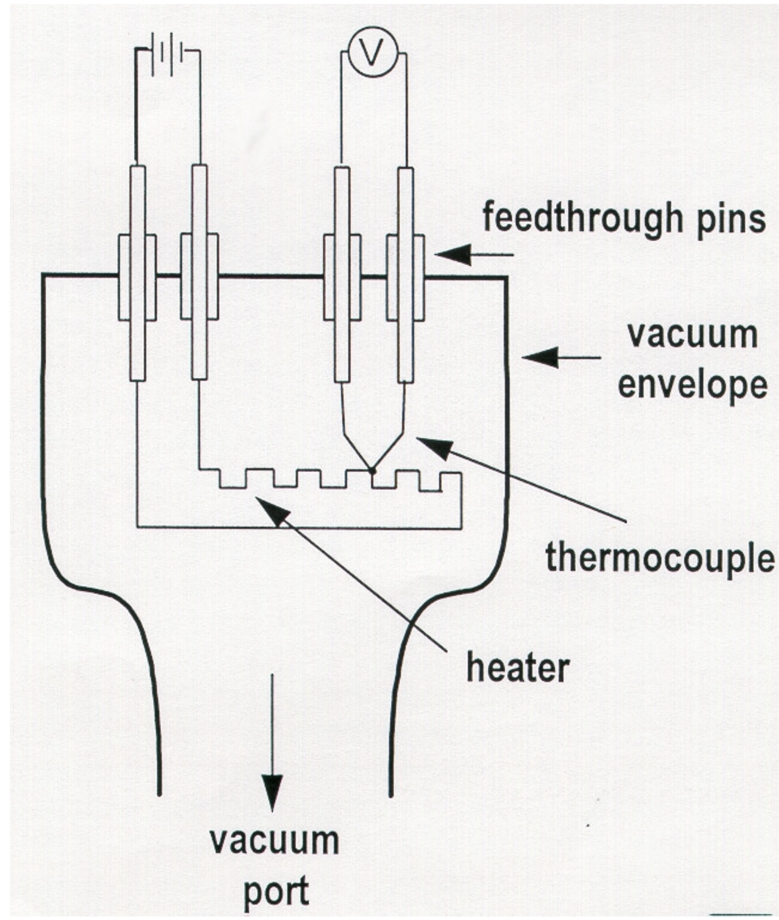
Thermocouple gauge

Distinguishing features & operating characteristics:

- Indirectly measures pressure via thermal conductivity of gases
- Operating range 1 Torr to 10^{-3} Torr
- Indicated value is gas dependent
- Constant current is delivered to a wire & it's temperature is measured by a thermocouple
- Thermocouple voltage is read on a pressure scale
- Not capable of good measurements above 1 Torr
- Rugged design, inexpensive, however somewhat inaccurate

Thermocouple Gauges

- Constant current through the heater (sensor).
- TC junction measures temperature changes.
- Slow response time.



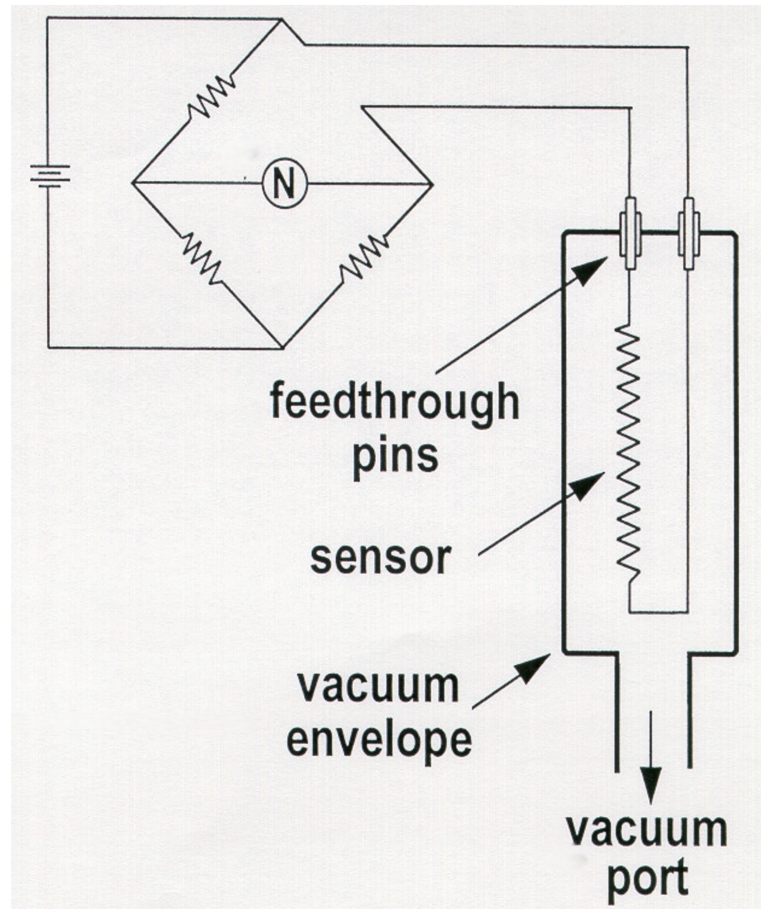
Pirani Gauges

Distinguishing features & operating characteristics:

- Indirectly measures pressure via thermal conductivity of gases
- Operating range 1 to 10^{-4} Torr
- Indicated value is gas dependent
- Resistance heated wire which is part of a Wheatstone bridge
- Pirani gauge that is sensitive to convection heat losses is available
- This gauge's operating range is 1000 to 10^{-4} Torr

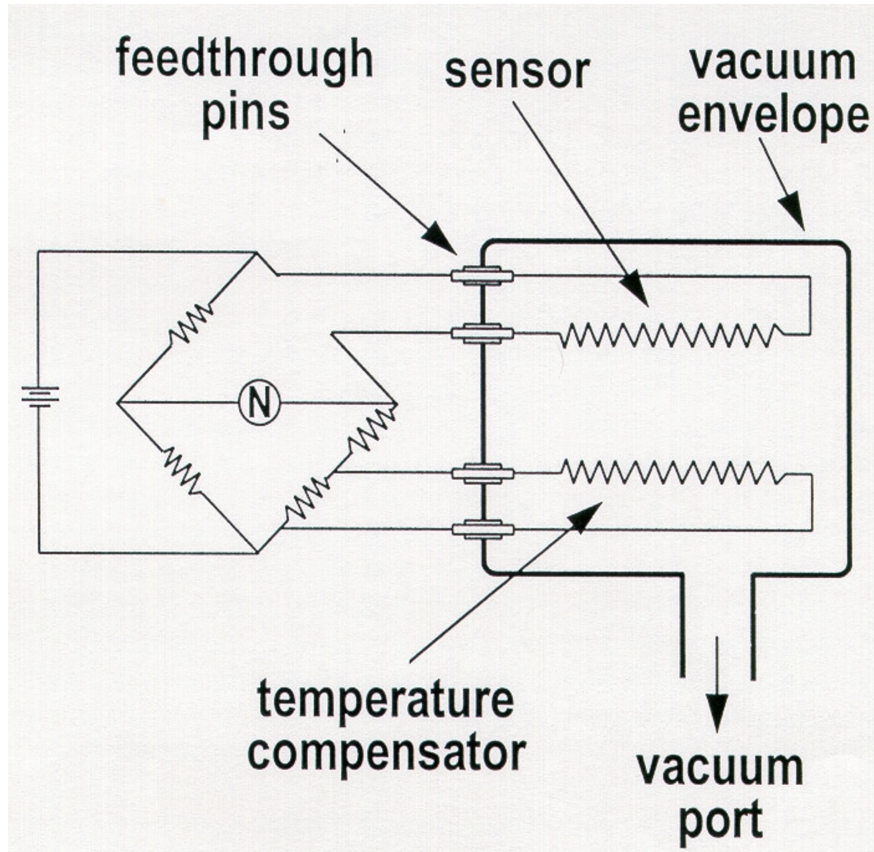
Pirani Gauge

- Wheatstone bridge with sensor as one leg of bridge.
- Current through sensor changes to maintain balance.
- Reads to ~100 Torr.



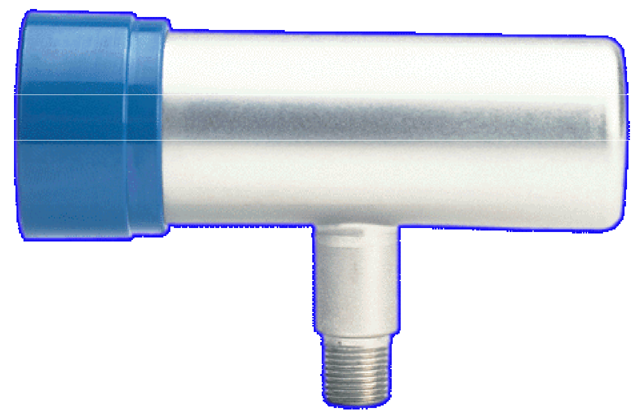
Convection Enhanced Pirani Gauge – *CONVECTRON®* Gauge

- Similar principle to pirani.
  - Conductive heat loss (10^{-3} Torr to ~100 Torr)
  - Adds convective heat loss (~100 Torr to 1000 Torr.)
- Improved temperature compensation.
- Gold plated tungsten sensor.



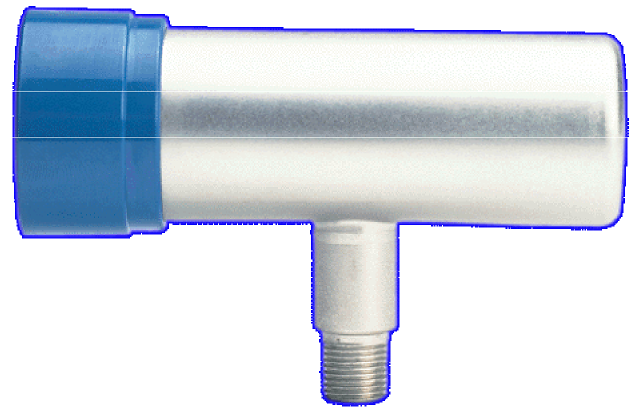
CONVECTRON Gauge Benefits

- Wide Measurement Range:
  10^{-3} Torr - 1000 Torr.
- Individual calibration.
- Accurate, fast measurement.
- Long term stability.
- Recalibrate for contaminated gauge or
- after cleaning gauge.
- Very reliable - industry standard.



CONVECTRON Gauges - Drawbacks

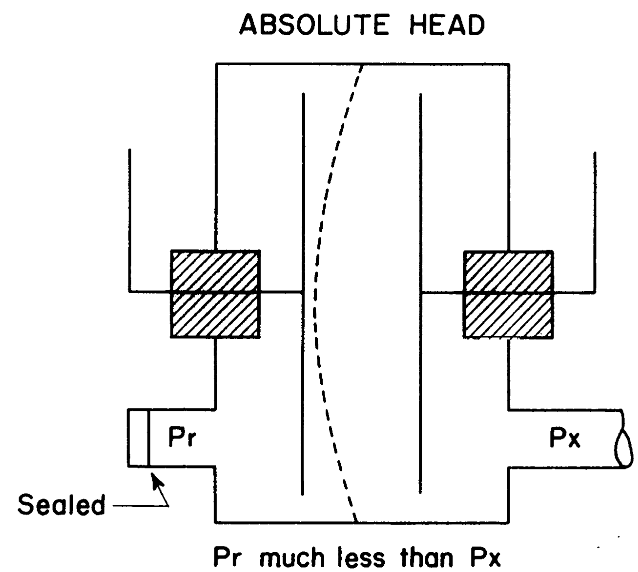
- Gas dependent
- Sensitive to orientation
- S-curve, analog output
- Fragile
- Corrosive gases - attacked by fluorine, chlorine, mercury



Capacitance Manometers

Distinguishing features & operating characteristics:

- Measures pressure directly
- Operating range 10,000 to 10^{-6} Torr, with different ranged sensors
- Indicated value is independent of gas being measured
- Diaphragm gauge that senses the change in capacitance of a circuit which contains the diaphragm wall as an active element
- Deflections of the diaphragm as small as one Å can be sensed
- Available in several ranges with differing resolution
- Measurements requiring a high degree of accuracy use heated sensors
- High precision work requires frequent "zeroing"



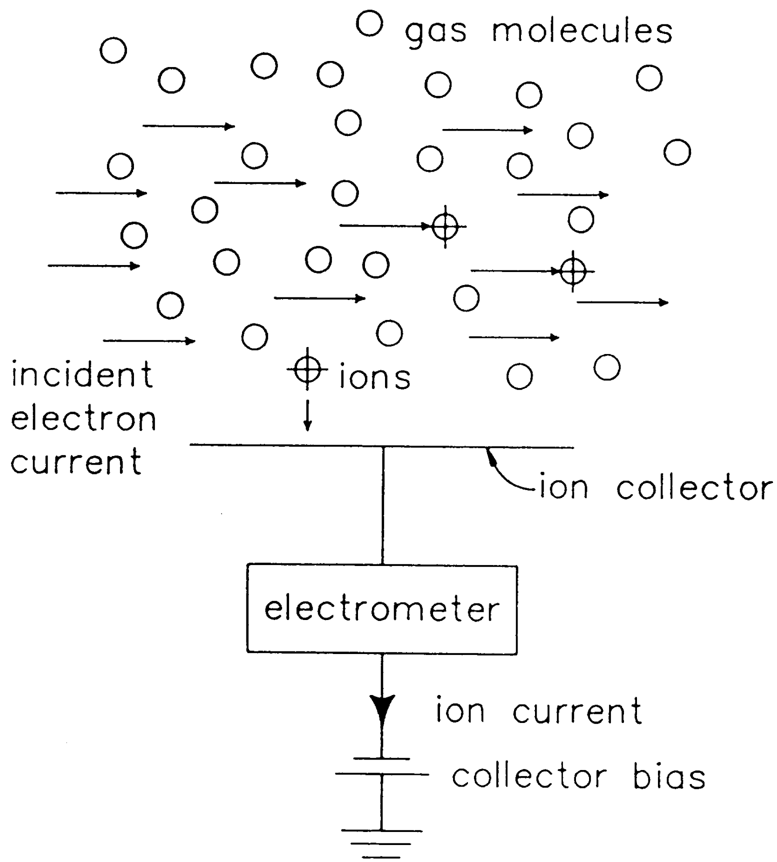
Ionization of Gases

- Gas atoms and molecules are normally without charge or "neutral", they have equal numbers of protons and electrons
- If one or more electrons are removed from an atom it becomes positively charged and we call it an ion
- Numerous processes in vacuum technology utilize energetic free electrons to strip atoms of some of their electrons, thus creating ions
- Ions, being positively charged, can be manipulated by magnetic and electrical fields
- An atom has a probability of being ionized that is dependent on the atom itself and the energy of the colliding electron. The ionization cross section quantifies the probability of ionization

Ionization Gauges

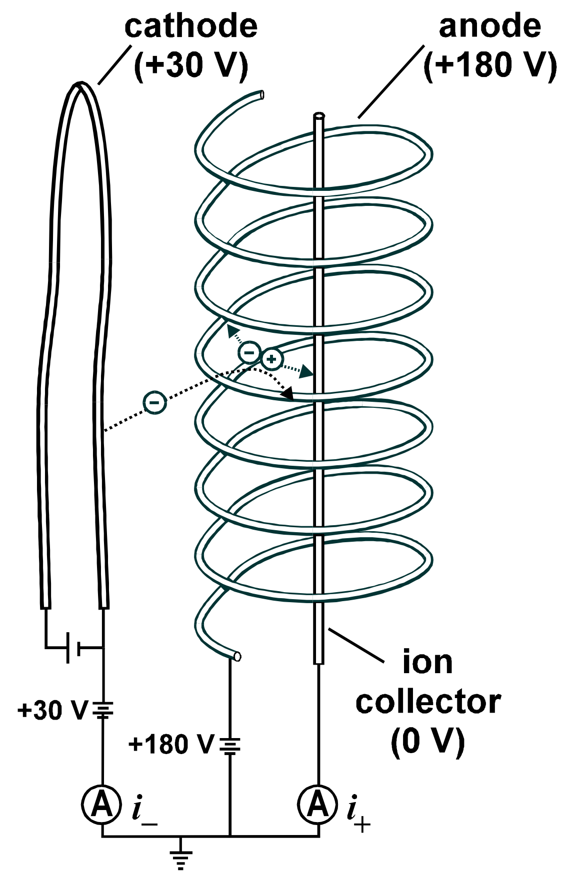
- At pressures below 10^{-5} Torr (high vacuum) direct measurement of pressure is very difficult
- Thermal conductivity gauges have exceeded their operational limits
- Primary method for pressure measurement from 10^{-4} to 10^{-12} Torr is gas ionization & ion collection/measurement
- These gauges can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

Ionization Gauge Principle of Operation



Hot Cathode Ionization Gauge, Basics

- Hot filament (cathode) emits electrons.
- Molecules are ionized and collected.
- Pressure reading is determined by the electronics from the collector current.



Gauge Sensitivity

Gauge Sensitivity: A constant that indicates how well a gauge creates ions.

- Ion gauge equation:

$$P = \frac{i_+}{i_e \cdot S}$$

where:
i_+ = ion current
i_e = emission current
S = sensitivity

- Sensitivities of B-A Gauges
  - Glass Gauge and Standard Nude Gauge ~10/Torr
  - UHV Nude Gauge ~25/Torr

Emission Current

- Emission current = Electron Current ≈ No. of electrons

- A variable controlled by the electronics

$$P = \frac{i_+}{i_e \cdot S}$$

What Emission Current Should Be Used?

- Selected, based on measurement range

- Typical emission settings for B-A gauges:
  - High pressure: i_e = 0.1 mA
  - Widest pressure range: i_e = 1 mA (default)
  - UHV range: i_e = 10 mA

- Typical problems:
  - High emission + high pressure = gauge off
  - Low emission + low pressure = “nervous” display

X-Ray Limit

- Lower limit of the gauge
- Low accuracy readings near the x-ray limit
- Select gauge with x-ray limit 5 to 10 times lower than lowest pressure
- Only an issue for UHV measurement at $P < 1 \times 10^{-9}$ Torr

Filament Selection

- Thoria-coated Iridium

  General purpose

  Operates cooler (~900° C)

  Burn-out resistant

- Tungsten

  Special purpose

  Operates hotter (~1200° C)

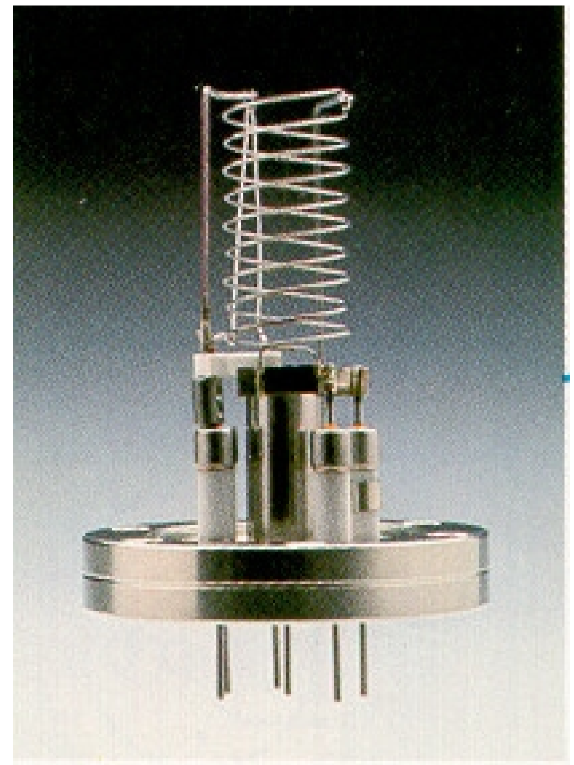
  Burns out easily and oxidizes when exposed to atmosphere

Granville-Phillips Series 274: Glass B-A Gauge

- Filaments: single thoria-coated
- iridium, or dual tungsten
- Sensitivity: 10/Torr.
- Helical grid: EB or I^2R degas.
- X-ray limit: < 3 x 10^{-10} Torr
- Port diameter: 3/4 in. or 1 in.
- Vacuum connections: straight tube, NW25, 1.33 in. ConFlat-type (16CF), 2.75 in. ConFlat-type (35CF)

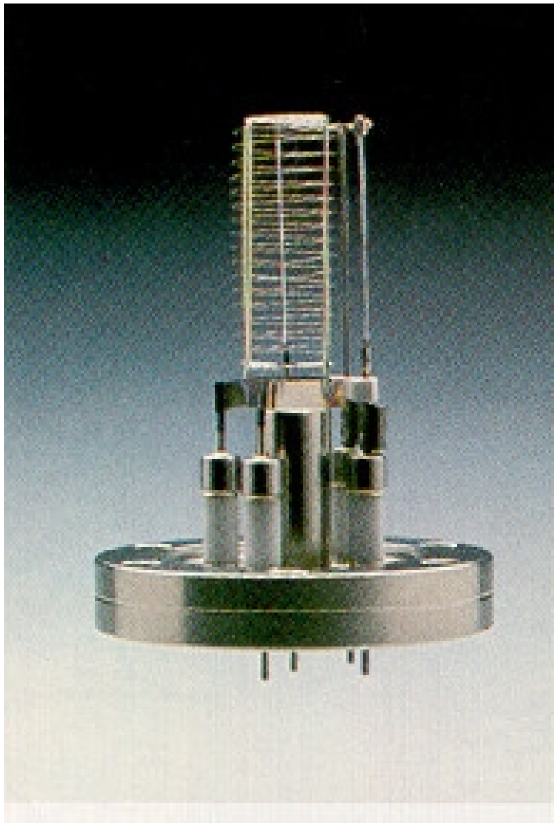
Granville-Phillips Series 274:
Nude B-A Gauge

- Filaments: single thoria-coated iridium, replaceable
- Sensitivity: 10/Torr
- Helical grid: EB or resistive degas
- X-ray limit: about 4 x 10^{-10} Torr
- Flanges: NW40, 2.75 in. ConFlat-type (35CF)
- Available with pin-guard

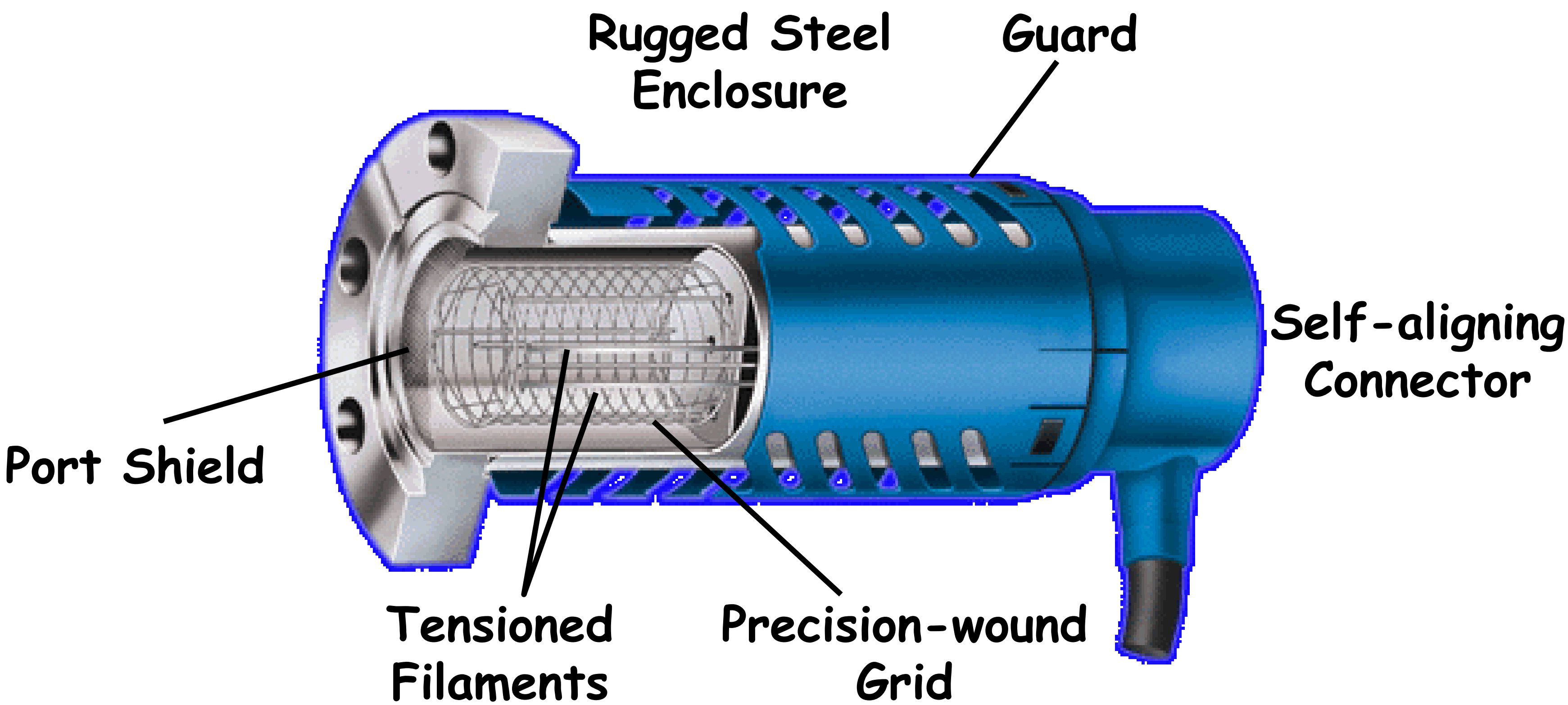


Granville-Phillips Series 274: UHV Nude B-A Gauge

- Filaments: dual thoria-coated iridium, or dual tungsten, replaceable.
- Sensitivity: 25/Torr.
- Enclosed grid: EB degas only
- X-ray limit: about 2 x 10^{-11} Torr
- Flanges: NW40, 2.75 in. ConFlat-type (35CF)
- Available with pin-guard



STABIL-ION Gauge Design



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

Only design difference is collector diameter

- Extended Range: 0.040 inches
- UHV: 0.005 inches

Advertised Accuracy of *STABIL-ION* Gauge

- 370120 with 370 controller = +/-4% of reading
- 360120 with 360 controller = +/-6% of reading [mid-scale pressures]
- 360120 with other controllers such as 347 module or older style Series 303, 307, or 350 = ~+/-15% of reading
- Independent Labs [Sandia & PTB] report better accuracy levels than the manufacturer

MICRO-ION™ Gauge Design

Electrode Assembly

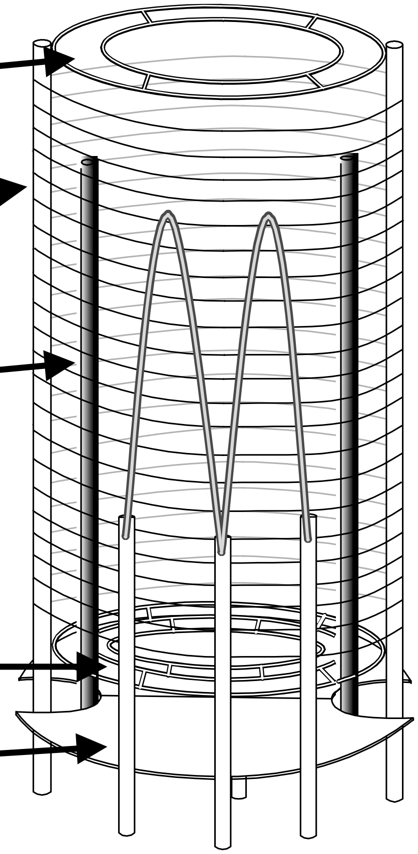
Grid Top End Cap

Grid Supports (2)

Ion Collectors (2)

Grid Bottom End Cap

Collector Shield



MICRO-ION™ Gauge: Wide Measurement Range

- X-ray limit: < 3×10^{-10} Torr (< 4×10^{-10} mbar).
- Upper pressure limit: 5×10^{-2} Torr/mbar.
- Stable behavior at pressures > 1×10^{-3} Torr/mbar.
- Useable in place of glass and nude B-A gauges.
- Good overlap with low vacuum (> 1×10^{-3} Torr/mbar) gauges such as *CONVECTRON*.

Bayard-Alpert Ionization gauge

Distinguishing features & operating characteristics:

- Measures pressure indirectly
- Operating range is 10^{-3} to 10^{-11} Torr
- Indicated value is gas dependent
- Gas ionization from electron impact & then ion collection
- Three electrode geometry
- Hot cathode (filament)
- Two configurations available, tubulated & nude

Bayard-Alpert gauge (continued)

Pressure (P) = (1/S) (i_c/i_e)

S = sensitivity of the gauge, units are reciprocal pressure

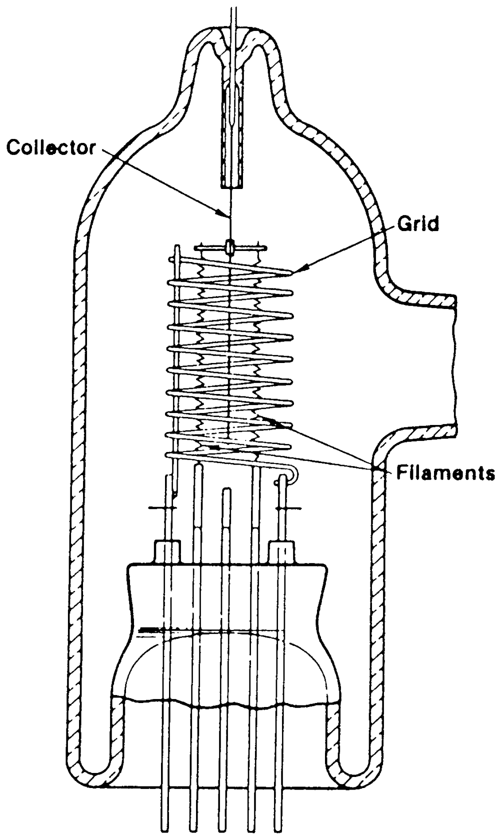
Different sensitivities for different gas species

Accurate to +/- 50%, better with calibration

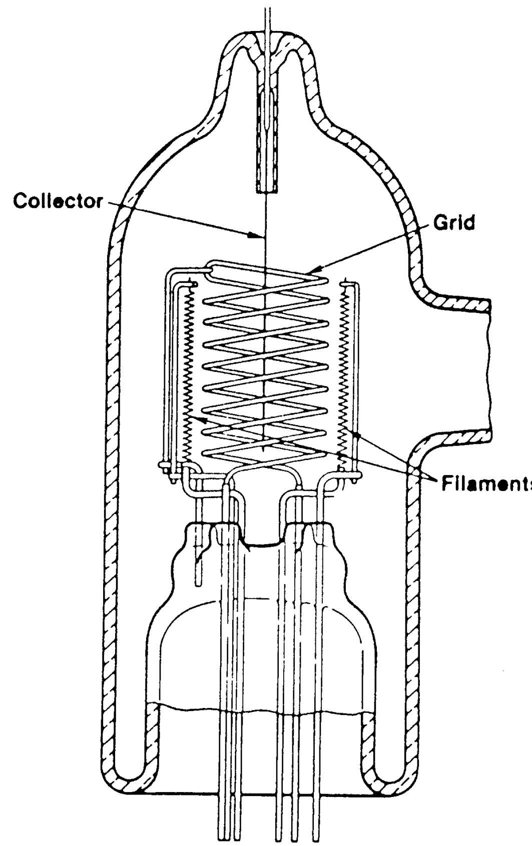
Low pressure measurement limited by residual currents

- X-ray effect
- EID
- Insulator leakage

Bayard-Alpert gauge components



Bayard-Alpert Gage
Side-By-Side Filaments



Bayard-Alpert Gage
Opposed Filaments

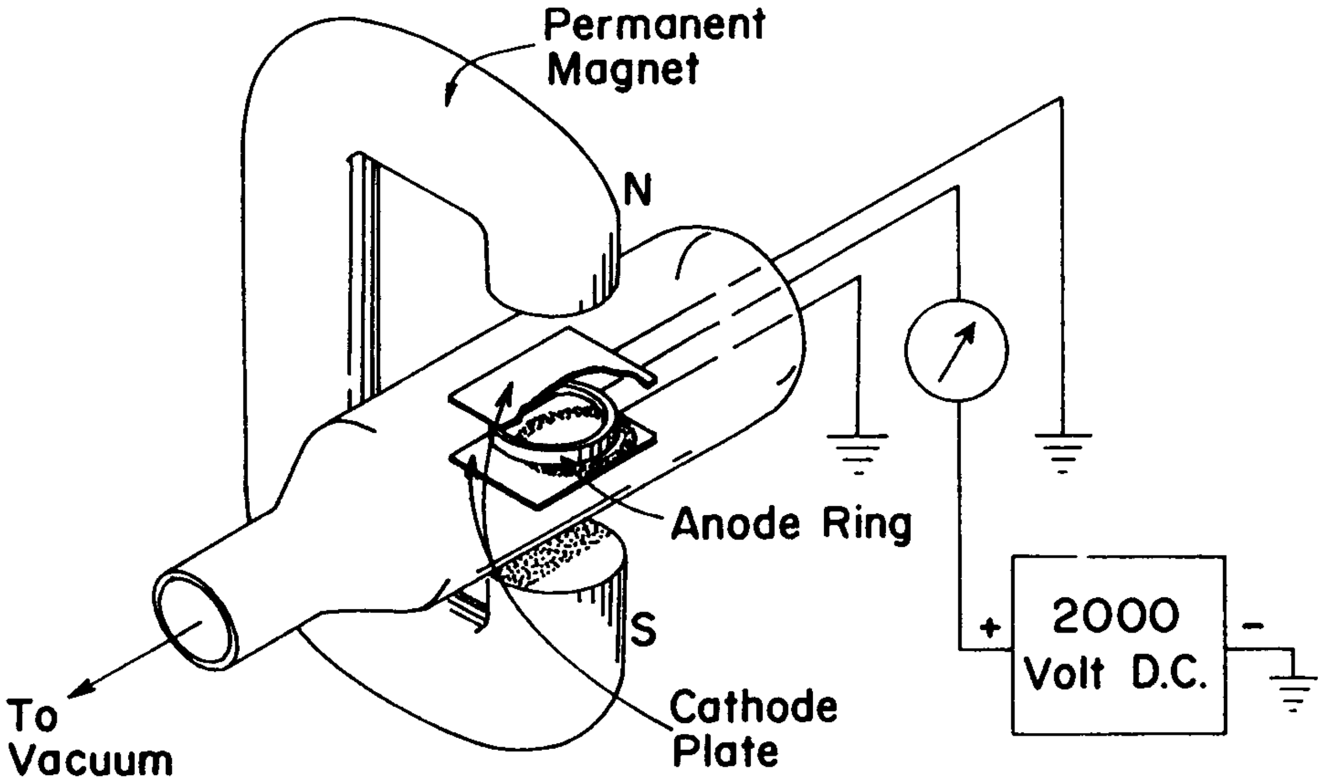
Ionization Gauges

- Glass tubulated
  - Pumping capacity can mask true pressure
  - About one third the price of a nude gauge
- Nude
  - More robust
  - Placed directly into environment, pumping is minimized
  - Filaments are replaceable
  - Higher sensitivities & can measure lower pressures (UHV)
  - Larger variation in sensitivity

Penning gauge

- Measures pressure indirectly
- Operating range 10^{-2} to 10^{-7} Torr
- Indicated value is gas dependent
- Cold cathode (no hot filament)
- Penning discharge: crossed electrical & magnetic fields to enhance ionization efficiency
- Discharge current is used as a measure of pressure
- $S = I_c/P^n$ $1.1 < n < 1.4$ pressure-current relationship is nonlinear
- Does not produce gases like a hot filament gauge
- Difficult to start & maintain discharge at pressures $<10^{-6}$ Torr
- Discharge mode "hopping" may confuse pressure indication
- Less accurate and less stable than a B-A gauge

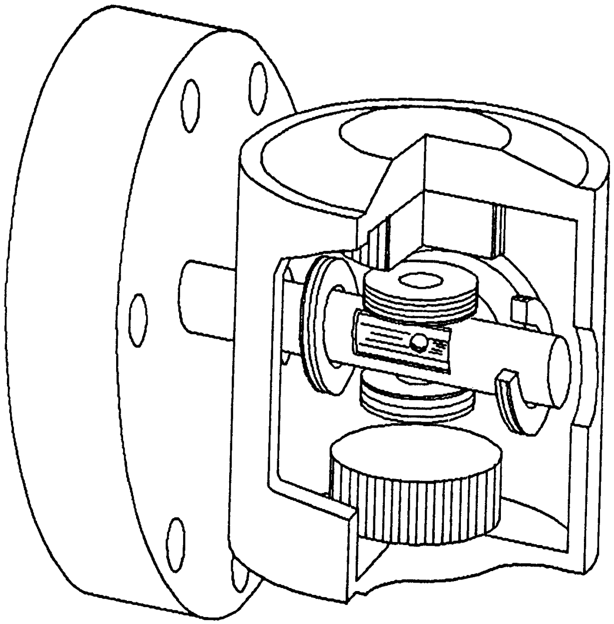
Penning gauge (cutaway and circuit)

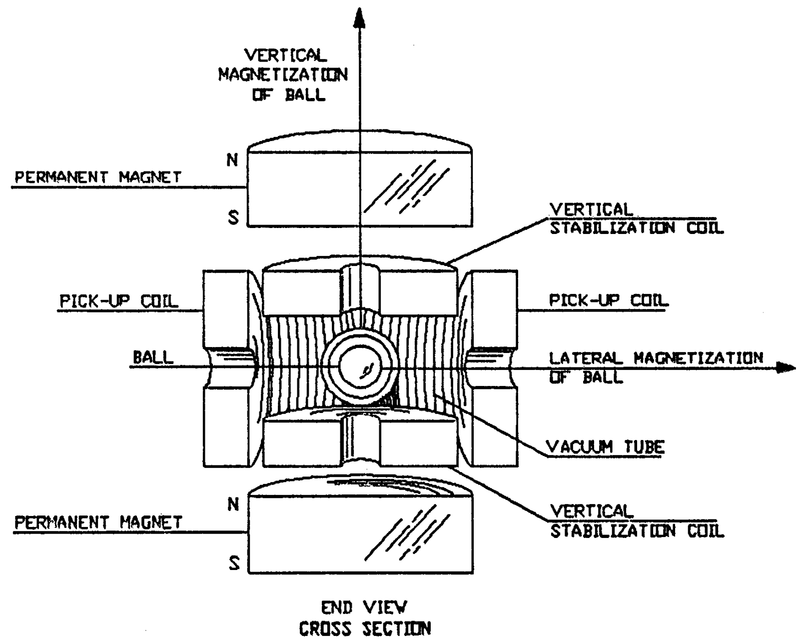


Spinning Rotor Gauge (SRG)

- Also called the molecular drag gauge (MDG)
- Measures pressure indirectly
- Operating range 10^{-2} to 10^{-7} Torr
- Indicated value is gas dependent (viscosity)
- Works by the principle of momentum transfer
- Utilizes a magnetically levitated, spinning, steel 4mm ball
- Ball rotation is slowed by gas collisions & measured
- Vibration sensitive
- Requires 30 seconds to 5 minutes to make a measurement
- Very good accuracy and linearity
- Often used in laboratories for calibration transfer standard

Spinning Rotor Gauge (SRG)



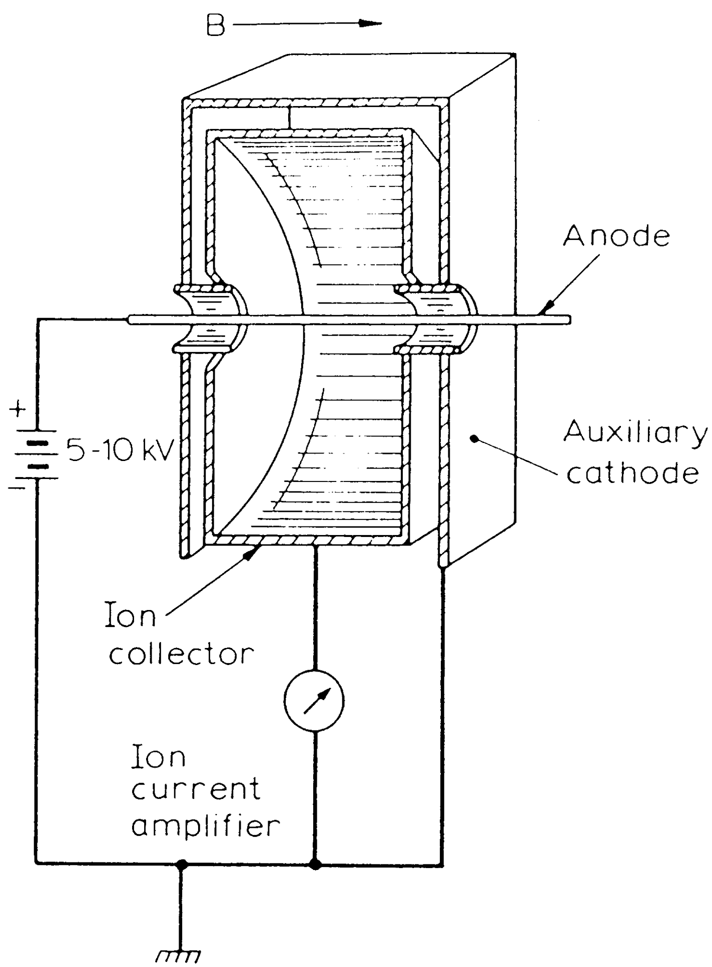


From *Handbook of Vacuum Science and Technology*, Hoffman

Inverted Magnetron Gauge

- Measures pressure indirectly
- Operating range 10^{-3} to 10^{-12} Torr (note low pressure)
- Indicated value is gas dependent
- Cold cathode (no hot filament)
- Ion current & pressure are not linearly related
- Same advantages as Penning, improvement on drawbacks
- Electrode geometry evolved from Penning configuration
- Anode changed to a rod and auxiliary (shield) cathode added
- Less accurate & reproducible than Bayard-Alpert

Inverted Magnetron Cut-away with Circuitry



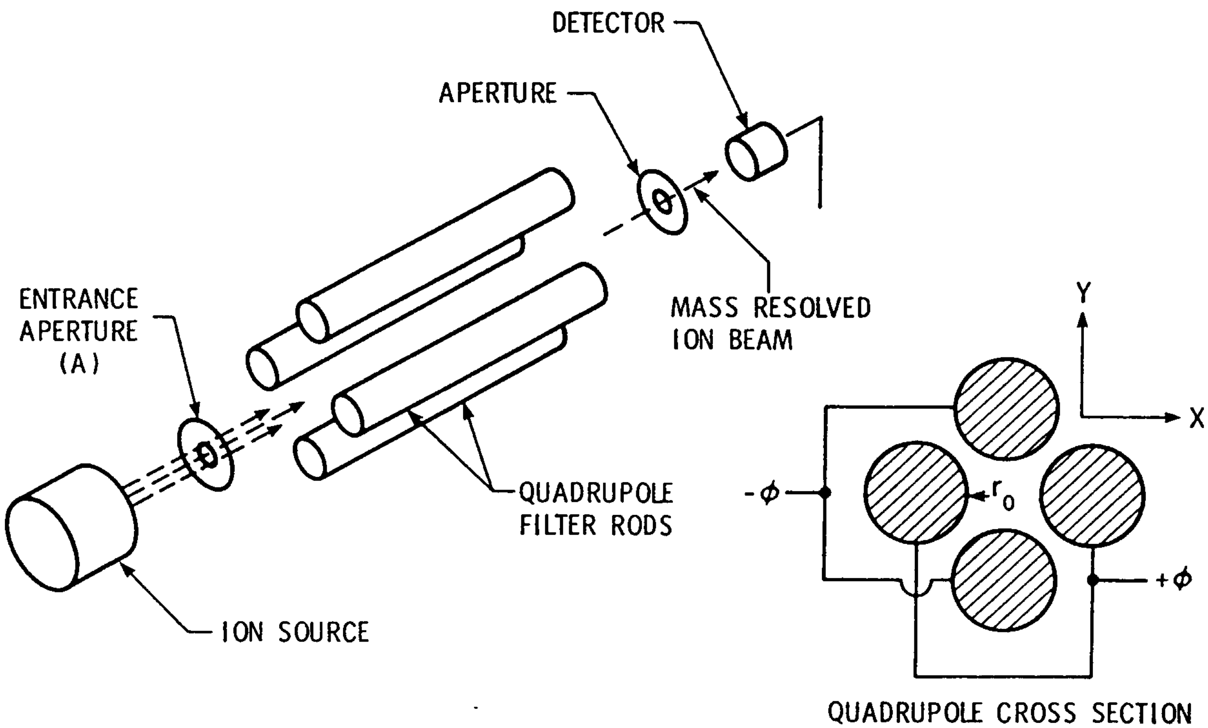
Partial Pressure Gauges

- Determine the composition of gases in a vacuum environment
- Usually qualitatively, sometimes quantitatively
- Mass spectrometer
- Amount of ions vs. mass/charge ratio (m/e or m/q)
- AMU - atomic mass unit C_{12} is exactly 12 AMU
- PPA & RGA
- Analytical mass spectrometer
- N_2^+ m/e = 28.0061 CO^+ m/e = 27.9949

Partial Pressure Gauges (continued)

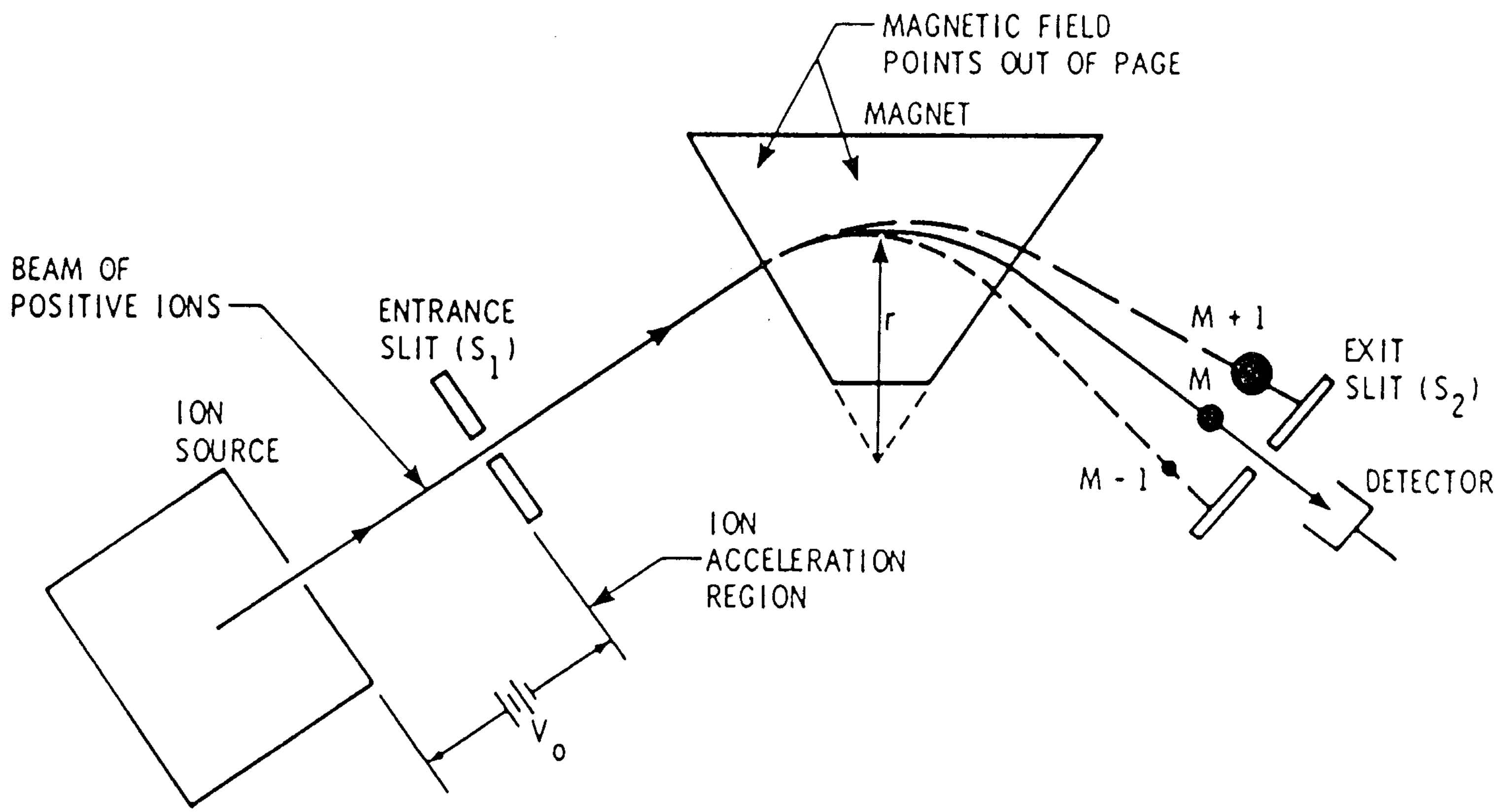
- PPA components
  - Ionizer
  - Mass filter
  - Detector
- Common types of PPAs
  - Quadrupole
  - Magnetic sector
  - Time of flight

Quadrupole Analyzer, Exploded View



Quadrupole mass filter.

Magnetic Sector Analyzer, Block Diagram



Analysis of Mass Spectra

- Fragmentation or cracking patterns
  - Dissociative ionization
  - Isotopes
  - Multiple ionization
  - Combined effects
- Cracking patterns are dependent on instrumental parameters
- Be careful with tabulated patterns
- Beware of instruments that convert ion currents to partial pressures