CRYOGENIC ENGINEERING

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Lecture No - 41

Earlier Lecture

- In the earlier lecture, we have seen non – metallic sensors like Silicon diode, Cernox and Ruthenium Oxide.

- Silicon diodes have negligible **i^2R** losses. Cernox RTDs offer high response time and have low magnetic field induced errors.

- Some of the sensors used for liquid level monitoring are Dipstick, Hydrostatic gauge, Electric Resistance/Capacitance gauge, Thermodynamic gauge and Superconducting LHe gauge.

Outline of the Lecture

Topic : Instrumentation in Cryogenics

- Pressure Measurement
- Conclusion

Thermo physical Properties

- There are various thermo physical properties that are measured or monitored in Cryogenics. They are

  - Temperature
  - Liquid Level
  - Pressure
  - Mass Flow Rate
  - Viscosity and Density
  - Electrical and Thermal Conductivity

- In this topic, only the first three properties are covered, which are very important.

Pressure Measurement

- We know that the cryogenic vessels are insulated, closed containers.

- Besides, temperature and liquid level, pressure is also a vital aspect in Cryogenic Engineering.

- Pressure measurement is needed
  - To check, whether the level of vacuum is maintained.

  - To monitor the pressure rise inside a container, as there is a continuous heat in leak.

Pressure Measurement

- Pressure measurement in Cryogenics deals with both pressures above atmosphere and pressures below atmosphere (vacuum).

- In **Cryogenic Insulations** topic, we have seen that the cryogenics and vacuum go hand in hand.

- Every cryogenic equipment needs a vacuum gauge for pressure measurement.

- Various vacuum gauges and their working principles are discussed in this topic.

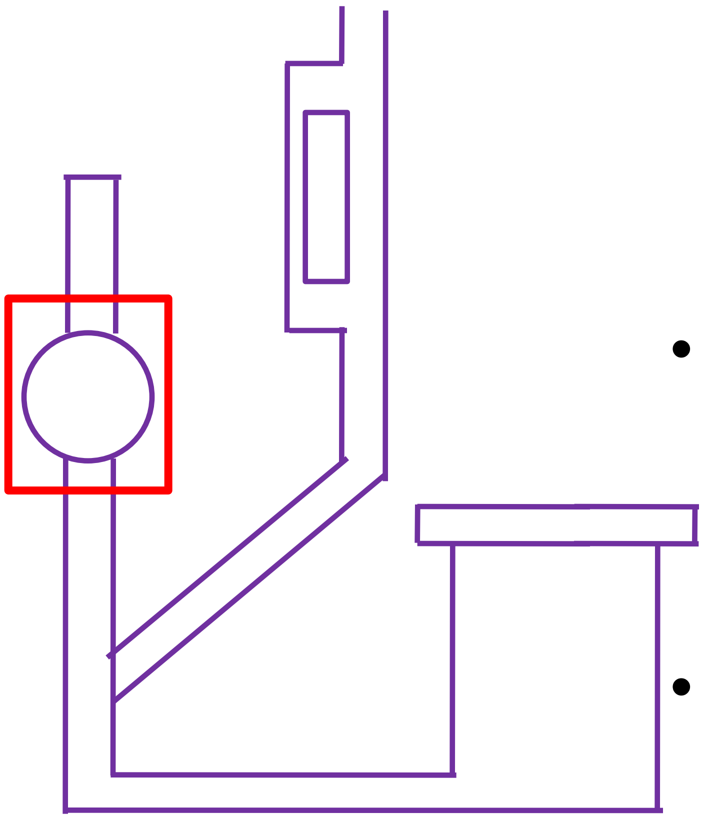
Pressure Measurement

- As seen in the earlier lecture, the levels of vacuum range from atmosphere to $\mathbf{10^{-12}}$ mbar or less.
- For different levels of vacuum, we have different gauges, working on different principles.
- For example, up to a particular level of vacuum, thermal conductivity gauges are used.
- Therefore, the choice of a gauge for a particular application or for a particular vacuum level is an important aspect.

Pressure Measurement

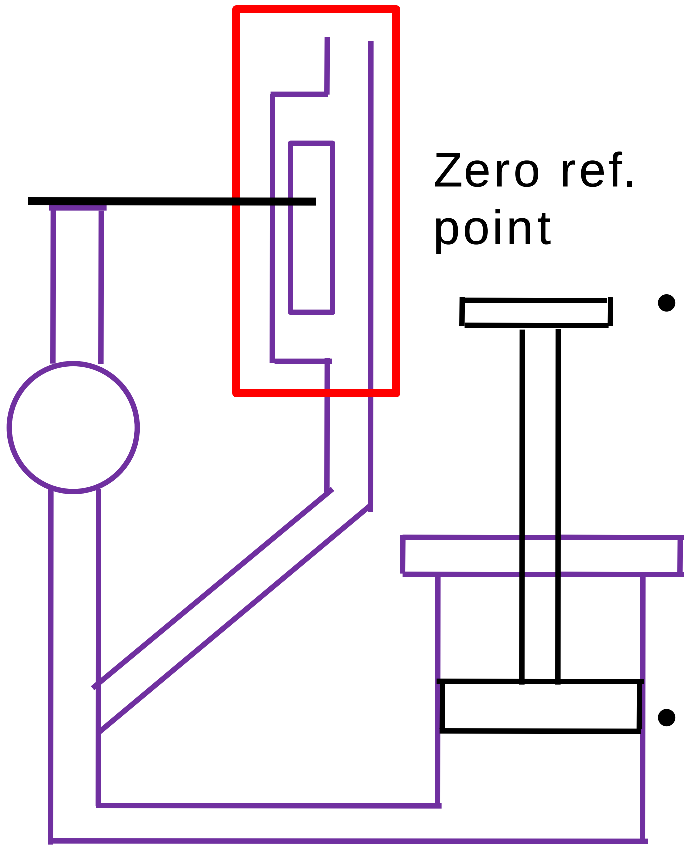
- Different pressure/vacuum gauges which could be used are
  - Hydrostatic Gauge – McLeod Gauge
  - Diaphragm Gauge – Mechanical/Electrical
  - Thermal Conductivity Gauge
  - Thermocouple Gauge
  - Ionization Gauge
    - Thermionic Ionization Gauge
    - Cold Cathode Gauge

Hydrostatic Gauge – McLeod



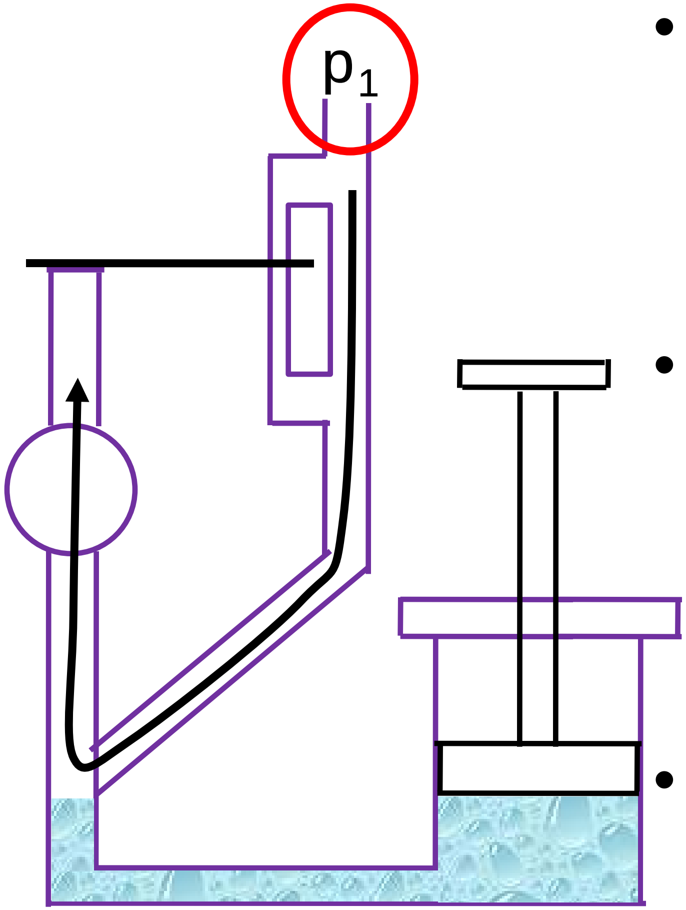
- Hydrostatic Gauge is one of the oldest type of vacuum gauges. It is also called as McLeod Gauge.
- The schematic of this gauge is as shown in the figure. It works on the principle of Boyle's Law.
- The gauge consists of a glass U – tube, whose left arm has a spherical bulb of a known volume.

Hydrostatic Gauge – McLeod



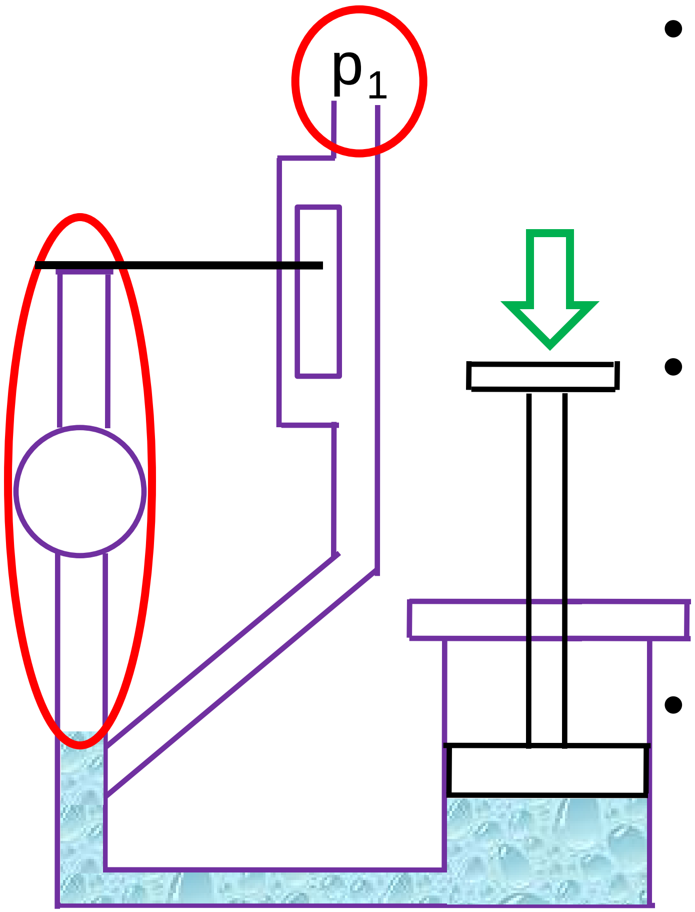
- The right arm is branched into a capillary tube, to monitor the minute changes in pressure.
- The capillary is marked with a zero reference point. It culminates back into the right arm as shown in the figure.
- The lower end of the U – tube is connected to a mercury reservoir equipped with a piston.

Hydrostatic Gauge – McLeod



- Initially, the apparatus is filled with mercury up to the indicated level.
- Let the vacuum pressure to be measured be $\mathbf{p_1}$. It is applied on the right arm as shown in the figure.
- In this situation, the pressure at any point in the system is $\mathbf{p_1}$.

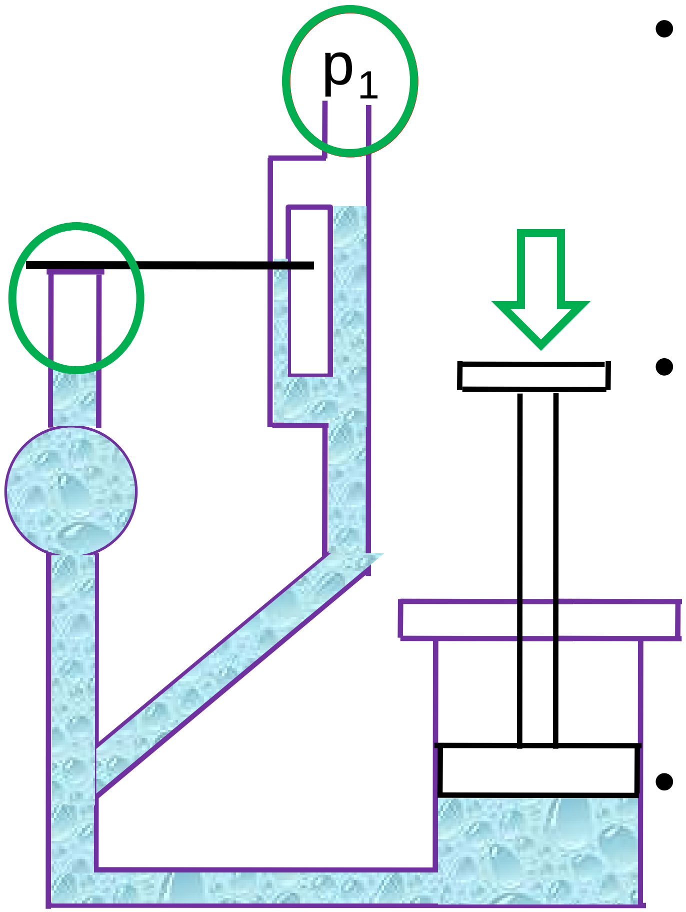
Hydrostatic Gauge – McLeod



- With the application of piston load, the mercury level in the apparatus rises.
- When the mercury crosses the junction, a known volume of gas is trapped inside bulb and tube.
- Let this volume of the gas be $\mathbf{V_1}$ as shown in the figure.
- Therefore,

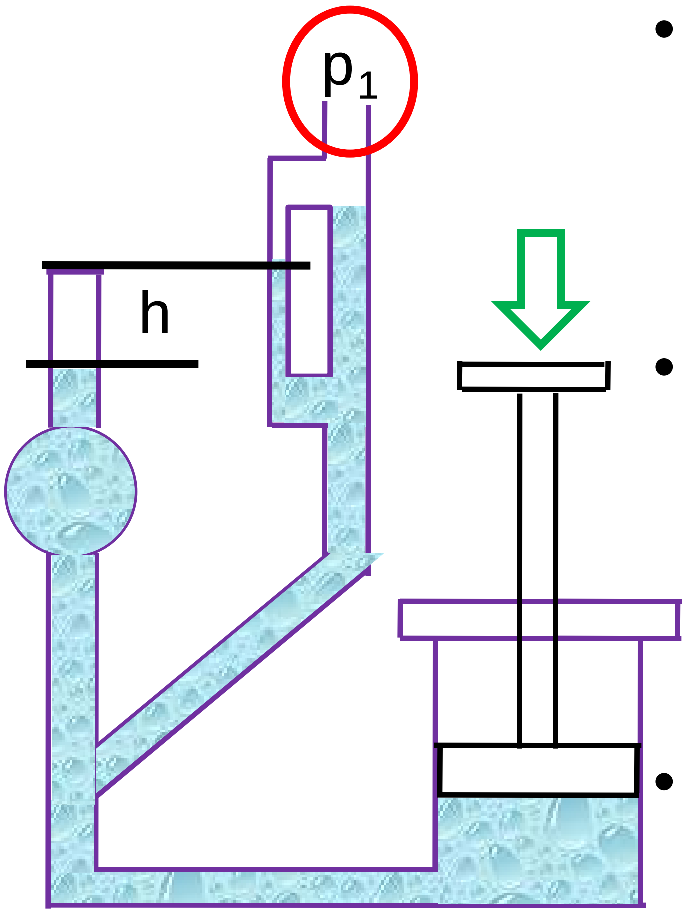
Initial Cond.	
Pressure	p_1
Volume	V_1

Hydrostatic Gauge – McLeod



- With the further application of piston load, the mercury rises to fill up both the arms.
- The load is applied until the mercury level in the capillary tube reaches the zero reference point.
- The mercury levels in the arms are adjusted to suit to
  - Applied vacuum in right arm
  - Compressed gas in left arm

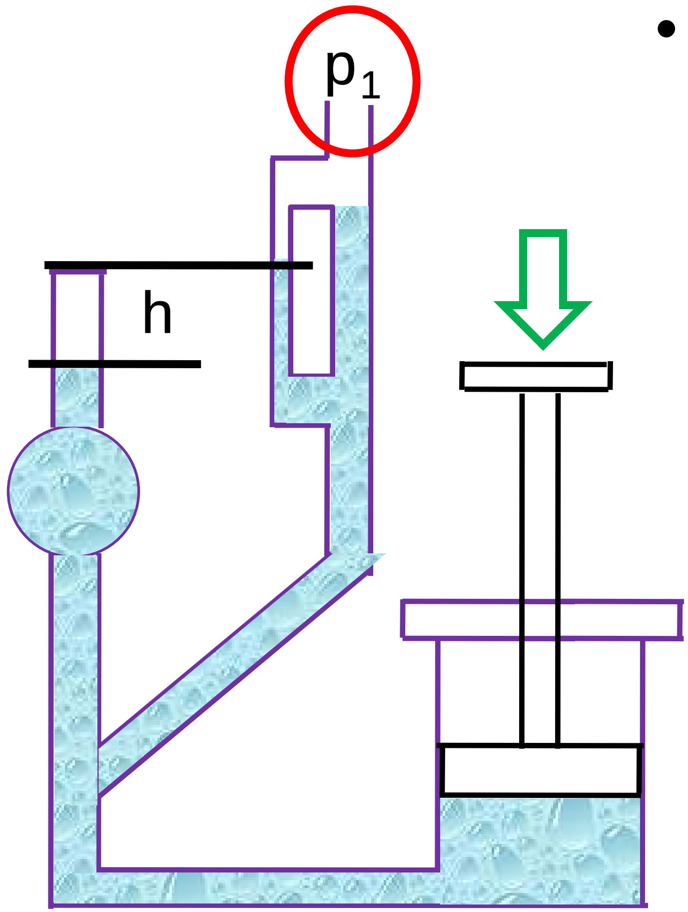
Hydrostatic Gauge – McLeod



- In this condition, the volume of the gas in left arm is read directly from the available scale.
- That is, the difference in the mercury levels in capillary and left arm represents volume and pressure of gas in left arm.
- Let **a** be the cross sectional area of the tube, we have

Final Cond.			
Pressure	p_1+h	Volume	ah

Hydrostatic Gauge – McLeod



- Hence, applying the Boyle's Law to the left arm, we have

Initial Cond.			
Pressure	p_1	Volume	V_1

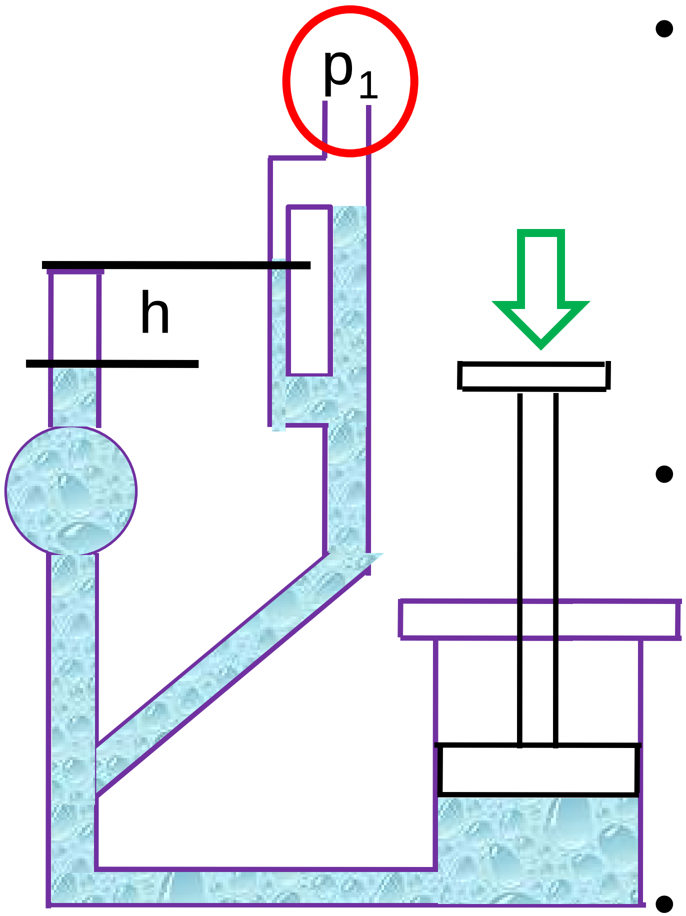
Final Cond.			
Pressure	p_1+h	Volume	ah

$$p_i V_i = p_f V_f$$

$$p_1 V_1 = \left(p_1 + h\right) ah$$

$$p_1 V_1 = p_1 ah + ah^2$$

Hydrostatic Gauge – McLeod



- Rearranging the above equation, we have

$$p_1 = \frac{ah^2}{V_1 - ah}$$

- The term, **ah**, being very small as compared to $\mathbf{V_1}$, is neglected. We have

$$p_1 = \frac{ah^2}{V_1}$$

- Therefore, the pressure $\mathbf{p_1}$ is directly proportional to $\mathbf{h^2}$.

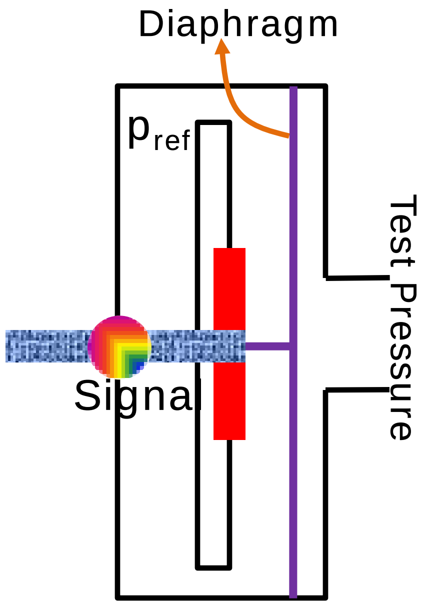
Hydrostatic Gauge – McLeod

- The advantages are
  - The gauge reading is independent of gas.
  - It serves as a reference standard to calibrate other low pressure gauges.
  - There is no need of any zero error corrections.

- The disadvantages are
  - The gas should obey the Boyle's law.
  - It does not give a continuous output.

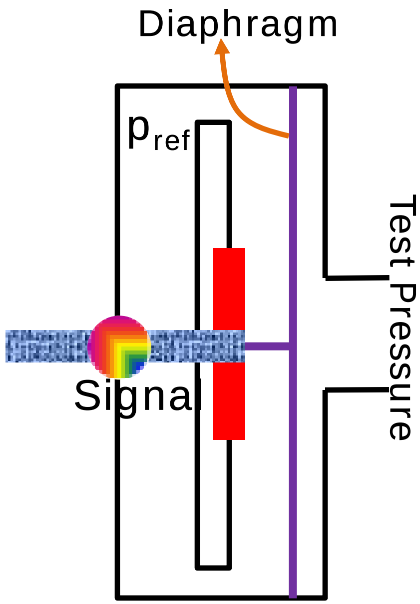
Diaphragm Gauge

- The schematic of a diaphragm gauge is as shown in the figure.



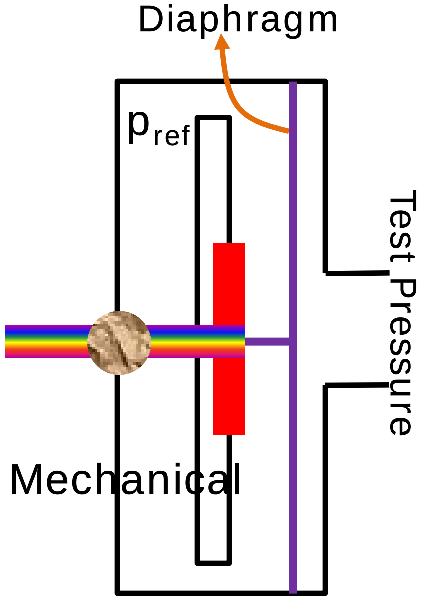
- It consists of a low stiffness corrugated Teflon diaphragm.
- On the left side of the diaphragm, a reference pressure ($\mathbf{p_{ref}}$) is maintained.
- On the right side, the diaphragm is exposed to the test pressures.

Diaphragm Gauge



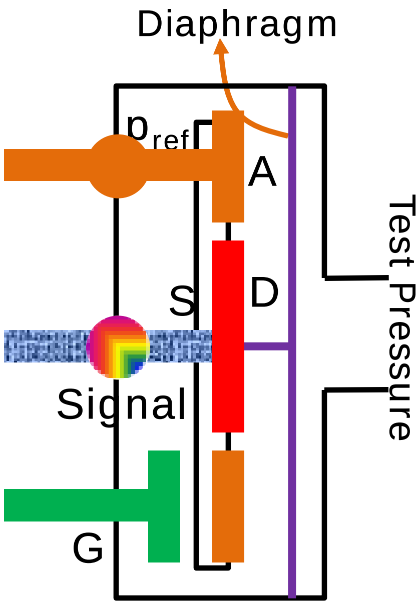
- In this device, a deflection is caused by a pressure difference across the corrugated diaphragm.
- This pressure signal or the deflection is amplified either by mechanical or electrical arrangements, to read the pressure directly.
- The amount of diaphragm's deflection decides the accuracy and sensitivity of the gauge.

Diaphragm Gauge – Mech.



- In a Mechanical Diaphragm Gauge, the diaphragm's deflection is magnified to a mechanical pointer and scale assembly.
- The scale is directly calibrated in terms of pressure for direct reading.
- The operating range of this gauge is from **1000** to **1** mbar with a good accuracy.

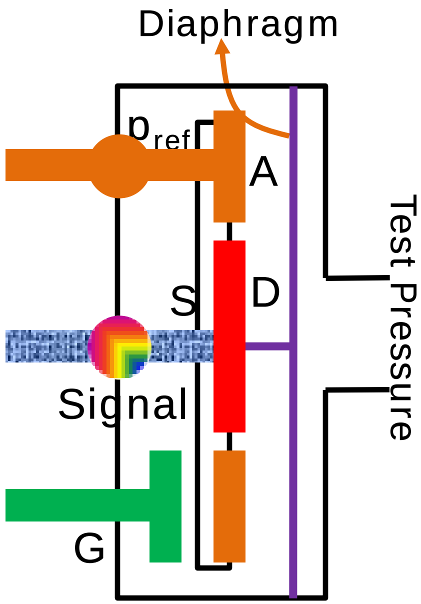
Diaphragm Gauge – Elec.



- The schematic of a Capacitance Diaphragm Gauge is as shown.
- It consists of two capacitance electrodes in the form of
  - Concentric circular disc **D**
  - Circular annulus **A**.
- These two electrodes are deposited on a ceramic substrate **S** as shown in the figure.

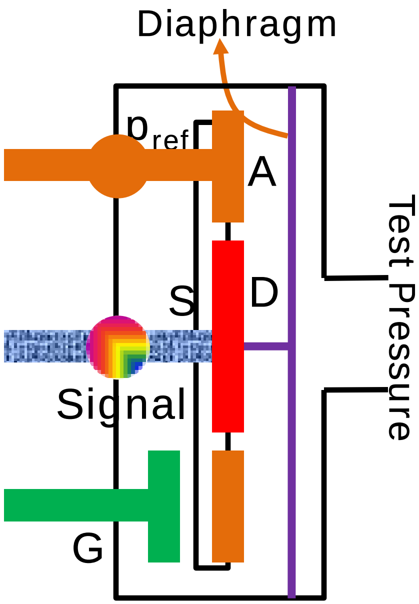
Diaphragm Gauge – Elec.

- These two electrodes are placed in the closed vicinity of an inconel diaphragm.



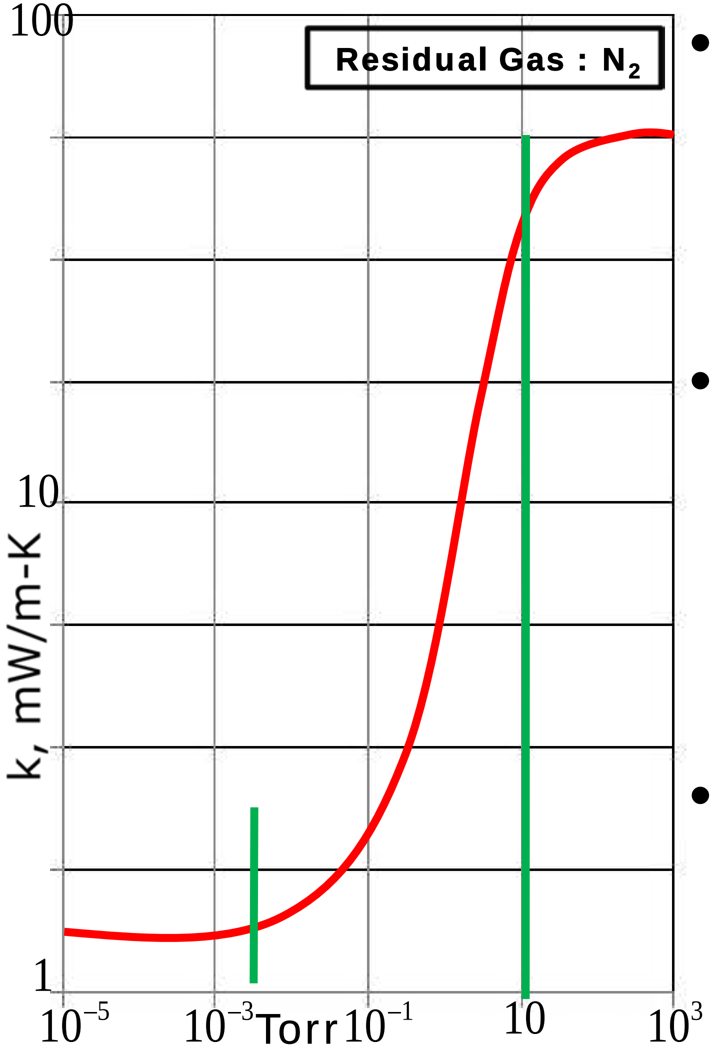
- The circular annulus capacitor is grounded at **G**.
- The whole assembly is connected to an AC electrical bridge, in which a change in capacitance is calibrated directly in terms of pressure.

Diaphragm Gauge – Elec.



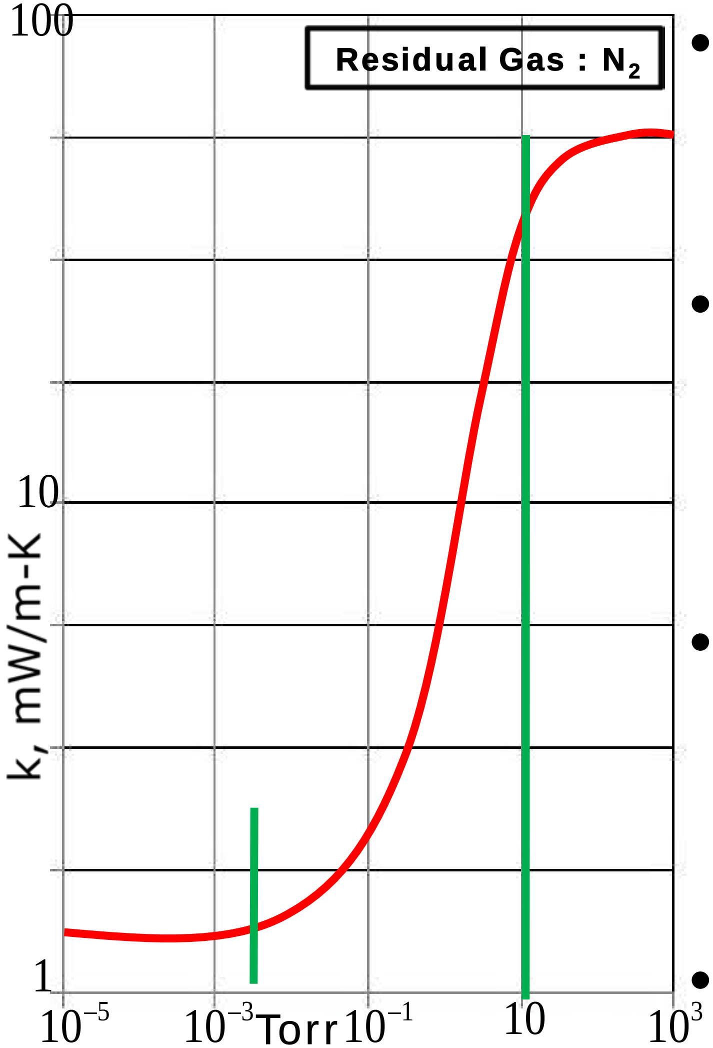
- Therefore, in an Electrical Diaphragm Gauge, the deflection is fed to movable capacitance assembly.
- These gauges are more reliable and accurate as compared to the earlier designs.
- It is important to note that the accuracy and sensitivity of the gauge is independent of the composition of the gas.

Thermal Conductivity Gauge



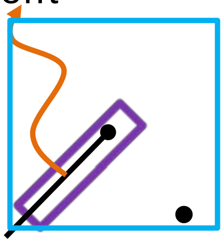
- The figure shows the variation of thermal conductivity with residual gas pressure of N_2.
- The x – axis denotes pressure in Torr and y – axis denotes logarithm of thermal conductivity.
- From the figure, it is clear that for the pressures between **10** to **10^{-2}** Torr, the thermal conductivity decreases.

Thermal Conductivity Gauge



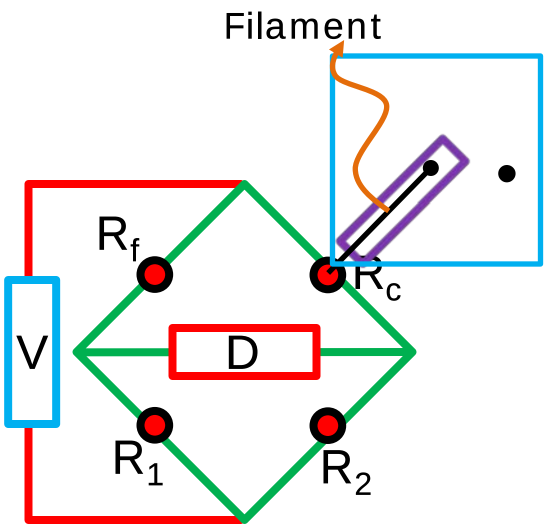
- This decrease is approximately linear for this pressure range.
- That is, $\mathbf{k_{gas}}$ is directly proportional to the pressure in this range.
- Hence, $\mathbf{Q_{cond}}$ through the gas is directly proportional to the gas pressure in this range.
- Pirani Gauge works on the above principle.

Thermal Conductivity Gauge



- In this gauge, a tungsten filament is placed inside the residual gas of which, the vacuum level is to be measured.
- It is heated to a high temperature by passing an electric current.
- The temperature of filament, thereby, its resistance, changes with $\mathbf{Q_{cond}}$.
- The $\mathbf{Q_{cond}}$ is a function of $\mathbf{k_{gas}}$, which directly represents the pressure.

Thermal Conductivity Gauge



- This filament is connected to one of the arms of the Wheatstone bridge as shown in the figure.
- With the change in resistance, the equilibrium of the bridge is disturbed at **D**, which is directly calibrated in terms of pressure.
- The bridge can either be a constant voltage type or a constant current type.

Thermocouple Gauge

- The Thermocouple Gauge functions on the same principle as that of Pirani Gauge.
- That is, the effect of residual gas in cooling a heated filament.
- The change in the temperature of the filament, due to the change in the surrounding gas pressure is measured directly by a very fine thermocouple.
- The thermocouple is attached at the center of the filament, which represents an average value.

Thermocouple Gauge

- This thermocouple voltage is magnified and it is calibrated to the denote the pressure reading.
- The operating range of this gauge is between **5** to **10^{-3}** mbar.
- The applications of thermal conductivity gauges are widely found in Rotary and Sorption pumps.
- In theses pumps, these gauges are used for a continuous monitoring of backing line pressure.

Advantages

- Some of the advantages of these gauges are
  - A fast response time offered by these gauges.
  - They offer an appropriate solution in case of control applications.
  - These gauges are often preferred due to their robustness.

Thermionic Ionization Gauge

- In an Thermionic Ionization Gauge, the residual gas molecules are ionized using an electron beam.

$$A + e^{-} \rightarrow A^{+} + 2e^{-}$$

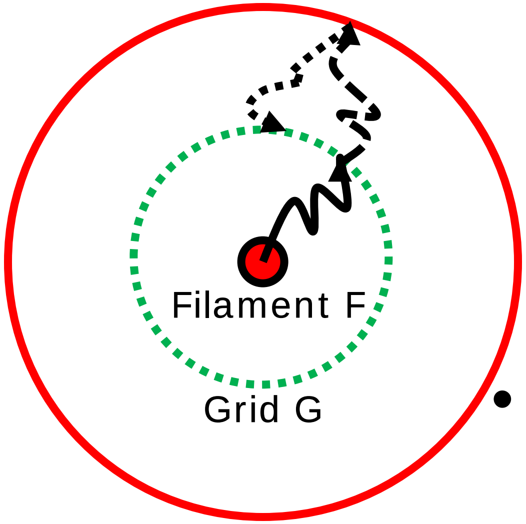
- In the above reaction, we have the following.
  - **A** is the gas molecule from the residual gas.
  - **e^{-}** is the ionization electron beam.
  - **A^{+}** is the ionized gas molecule.
  - **$2e^{-}$** are the electrons in the electric current.

- This reaction produces, two different types of current. They are **I^{+}** and **I^{-}**.

Ionization Gauges

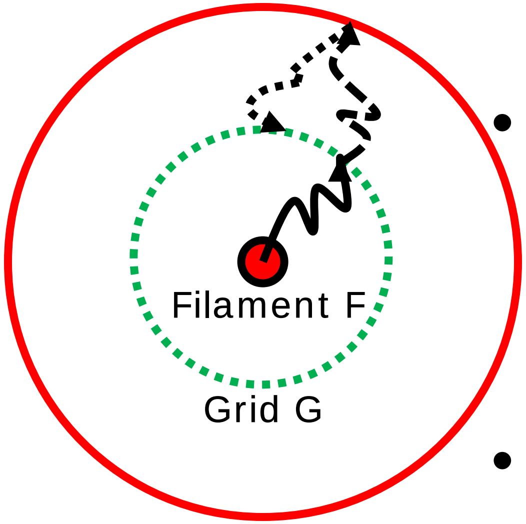
- For the measurement of vacuum pressures, there are two types of Ionization Gauges. They are
  - Thermionic Ionization Gauge
  - Cold Cathode Gauge
- These gauges operate accurately up to very low pressures, typically, in the order of $\mathbf{10^{-3}}$ to $\mathbf{10^{-10}}$ mbar.

Thermionic Ionization Gauge



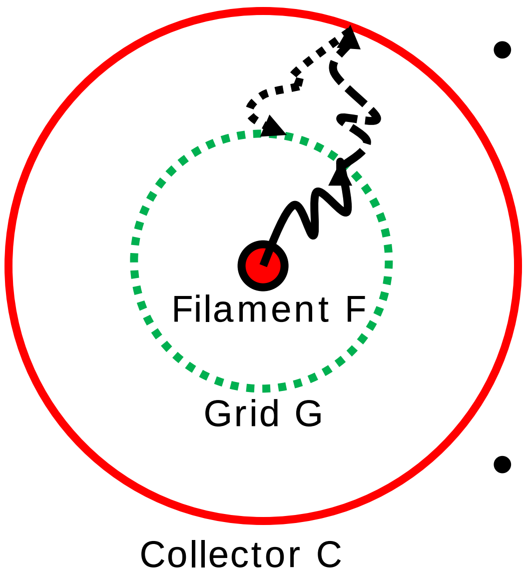
- The schematic of a Thermionic Ionization Gauge is as shown in the figure. It consists of
  - Thermionic Filament **F**
  - Cylindrical open mesh grid **G**
  - Ion collector **C**
- The Thermionic Filament **F** emits the electrons to ionize the residual gas.
- The mesh grid **G** traps the electrons to measure electronic current.

Thermionic Ionization Gauge



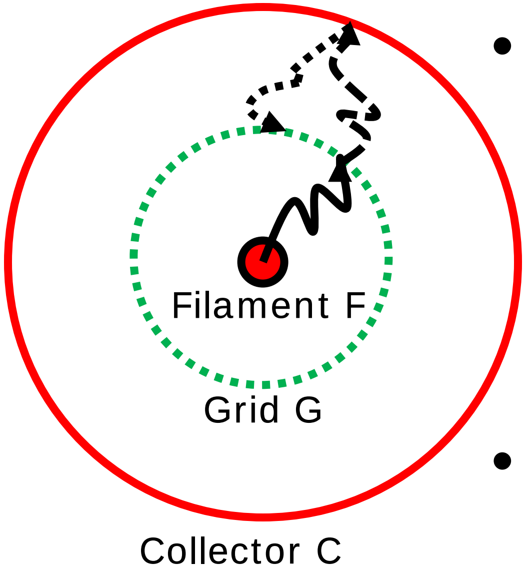
- The filament is charged with a positive potential of +30 V. The grid is maintained at +180 V.
- This large positive potential difference is required to accelerate the electrons in least possible time.
- The ion collector **C** is earthed, in order to maintain a zero potential.
- The electrons are emitted from **F** and are accelerated towards the grid.

Thermionic Ionization Gauge



- A majority of electrons strike the grid.
- However, a few of the electrons move beyond the grid, due to porosity of the grid and high velocity of electrons.
- These electrons enter a region of decelerating field in between mesh grid **G** and collector **C**.

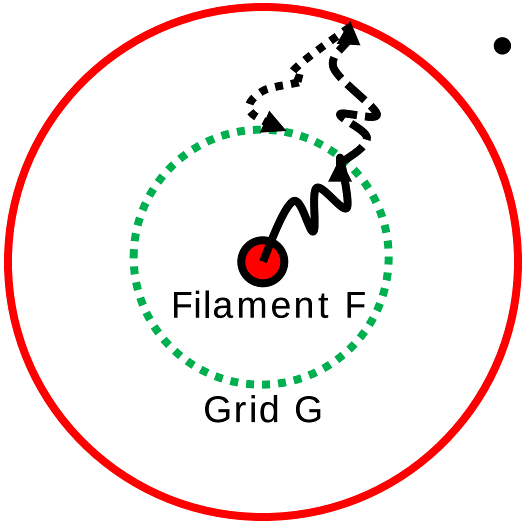
Thermionic Ionization Gauge



- They oscillate back and forth and are eventually collected on the grid.
- During this phase, the electrons have a maximum probability to hit the residual gas molecules, which produce ionic current.
- This ionization current represents the ions in residual gas. This is directly calibrated to read the gas pressure.

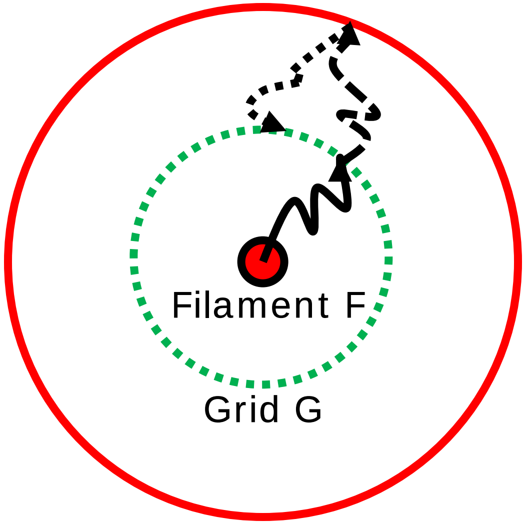
Thermionic Ionization Gauge

- These gauges are used from **10^{-3}** to **10^{-7}** mbar.



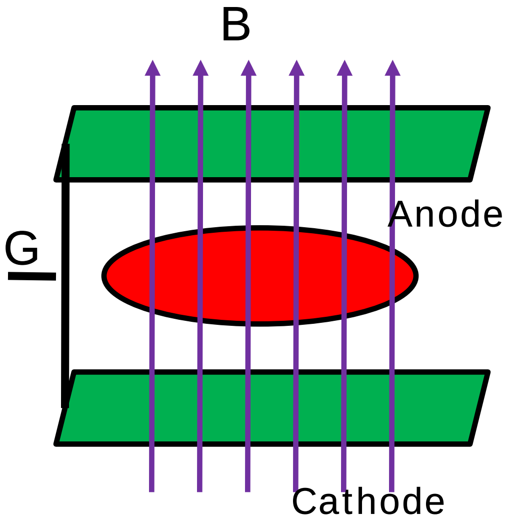
- The advantages of these gauges are
  - It offers a high reliability and ease of operation.
  - It can be easily degassed by electron bombardment (Grid power = 35 W).
  - These gauges offer a linear calibration current and pressure.

Thermionic Ionization Gauge



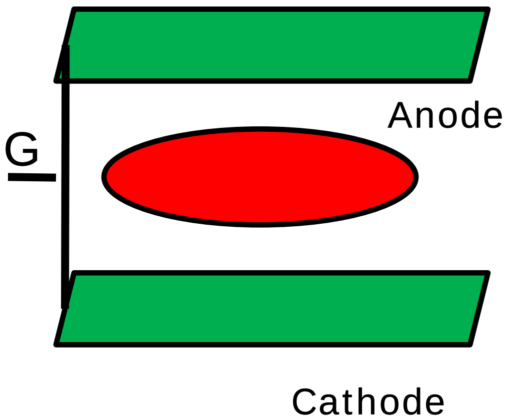
- The disadvantages are
  - The use of hot filament increases the risk of burring out, when exposed to atmospheric air.
  - As a result, an extra filament is provided as a standby.
  - The chemical reaction within the residual gas at high temperatures, produces undesirable gases.

Cold Cathode Ionization Gauge



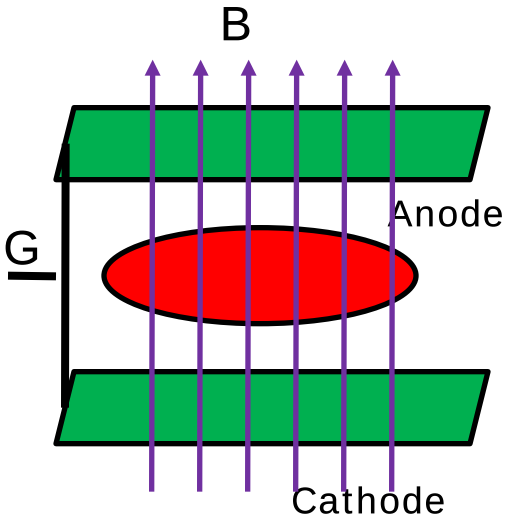
- As mentioned in the earlier slide, the Thermionic Gauges exhibit a risk of burning out of hot filament.
- This led to the development of Cold Cathode Ionization Gauges.
- These are also called as Penning Gauges, which are widely used at very low pressures.
- The schematic of Penning Gauge is as shown in the figure.

Cold Cathode Ionization Gauge



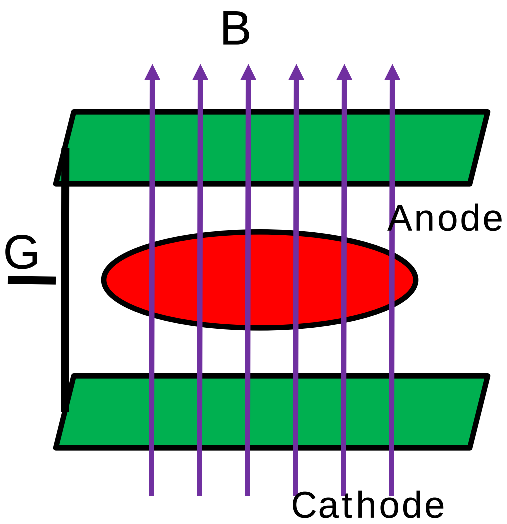
- It consists of an anode ring as shown in the figure.
- It is placed between the two symmetrical cathode plates.
- The cathode plates are grounded at **G**.
- The anode is charged with a potential difference of **2 kV**.

Cold Cathode Ionization Gauge



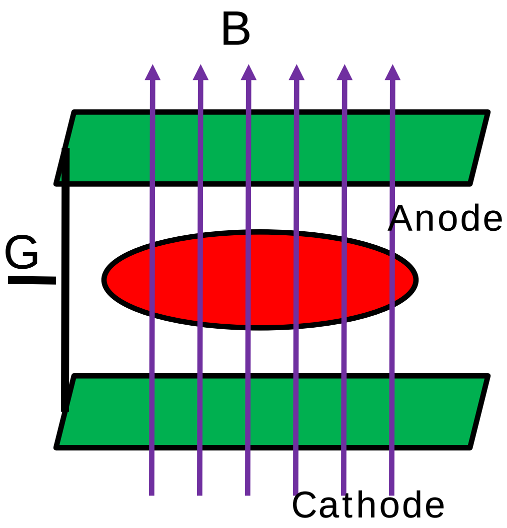
- An axial magnetic field of about **0.05 T** is maintained across the entire setup.
- Very often, permanent magnets are used to provide this field.

Cold Cathode Ionization Gauge



- The combined crossed electric and magnetic fields increase the length of travel of electrons.
- This increases the probability of ionization. The electrons are finally collected at anode.
- This ionization current represents the ions in residual gas. This is directly calibrated to read the gas pressure.

Cold Cathode Ionization Gauge



- This gauge is widely used for many scientific applications in the range of $\mathbf{10^{-3}}$ to $\mathbf{10^{-7}}$ mbar.
- The advantages of this gauge are
  - It is very robust
  - No thermionic filament
  - No thermal radiation.
- The disadvantage of this gauge is
  - It is normally less accurate than the thermionic gauge.

Conclusion

- In Cryogenics, there is a need to monitor various properties like pressure, temperature, liquid level, etc. for safe operation.
- Thermocouple works on Seebeck effect.
- PT 100, PT 1000 are some of the commonly used RTDs in Cryogenics.
- Some of the commonly used non – metallic sensors are Silicon diode, Cernox and Ruthenium Oxide.

Conclusion

- Sensors used to monitor liquid level are Dipstick, Hydrostatic gauge, Electric Resistance/Capacitance level gauge, Thermodynamic level gauge and Superconducting LHe level gauge.
- Different pressure/vacuum gauges used are McLeod Gauge, Diaphragm Gauge, Thermal Conductivity Gauge, Thermocouple Gauge, Thermionic Ionization Gauge and Cold Cathode Gauge.
- Pirani and Penning gauges are used for high vacuum levels. For less vacuum levels, other gauges are used.

- A self assessment exercise is given after this slide.

- Kindly asses yourself for this lecture.

Self Assessment

1. The hydrostatic gauge works on _____.
2. In McLeod Gauge, piston load is applied until the mercury level reaches ______.
3. In a diaphragm gauge, diaphragm is made of ____.
4. In a Capacitance diaphragm gauge, deflections alters _____.
5. In a Pirani Gauge, $\mathbf{k_{gas}}$ is proportional to ____.
6. In a Thermocouple Gauge, temperature of filament is an indication of ____.
7. In an Ionization Gauge, the filament ___ the electrons.
8. In a cold cathode gauge, the ____ is calibrated to read gas pressure.

Answers

1. Boyle's Law
2. Zero reference point
3. Teflon
4. Capacitance
5. Gas pressure
6. Gas pressure
7. Emits
8. Ionization current

Thank You!