

This educational seminar discusses creating, measuring, and troubleshooting **High Vacuum** *(≈ $10^{-4} \rightarrow 10^{-8}$ Torr)* systems.

Specifically, today's talk will cover:

- Brief review of *Rough Vacuum* (Characteristics, Pumps & Gauges)
- Applications requiring High Vacuum
- High Vacuum Gauges & Pumps
- Troubleshooting High Vacuum applications
- *High Vacuum* summary and preview of *Ultra-High Vacuum* Webinar

Previous Webinars (***Vacuum Fundamentals*** and ***Rough Vacuum***) are available for download at:

http://www.agilent.com/en-us/training-events/eseminars/vacuum

Rough Vacuum Review: Characteristics

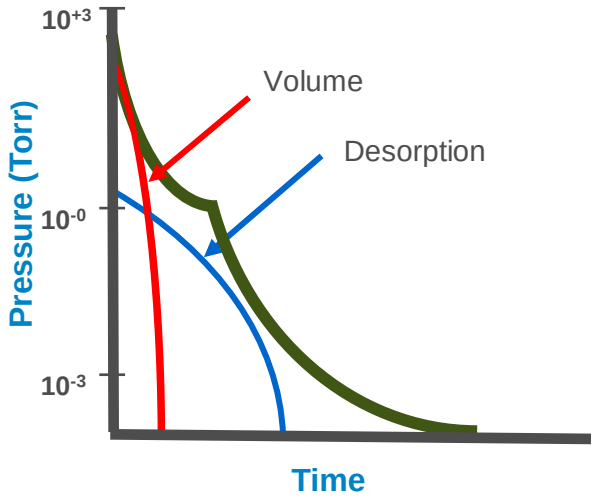
Particles are moving in *Viscous Flow*

- *Short Mean Free Path (MFP)*
- *Many more collisions with each other than with chamber walls*
- *Particles are 'motivated' to enter vacuum pumps!*



Factors governing pumpdown time:

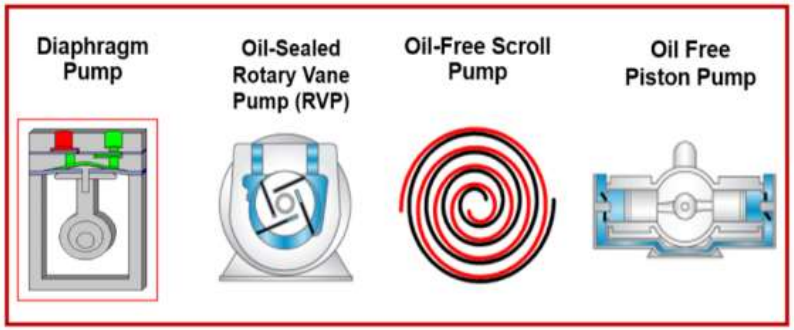
- *Dimensions of the chamber & capacity of the rough vacuum pumps (**Volume Pumping**)*
- *Chamber surface conditions (**Desorption**)*
- *Gas composition → 80% N_2 - 20% O_2 down to about **18 Torr**, then mostly H_2O down to 10^{-3} Torr*



Rough Vacuum Review: Pumps and Gauges

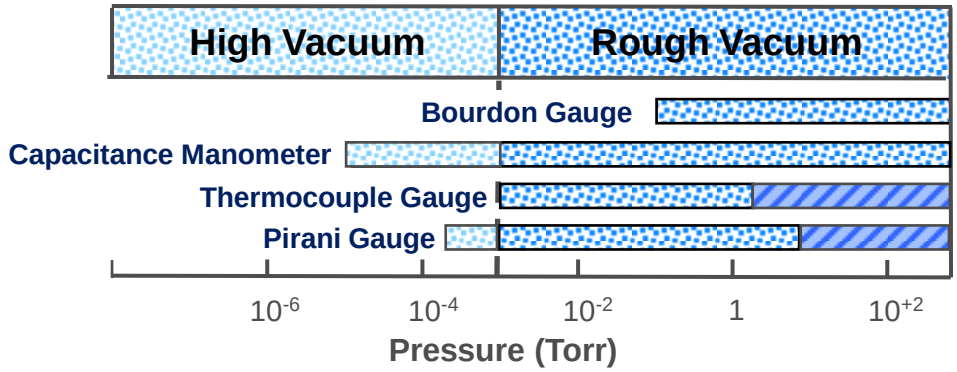
Rough Vacuum **PUMPS** require molecules to be in *Viscous Flow for effective pumping*

- Characterized by their:
  - *a) Capacity (Pumping Speed)*
  - *b) Pumping Fluid (Oil Sealed or Oil Free)*
  - *c) Base Pressure (Singe or Dual Stage)*

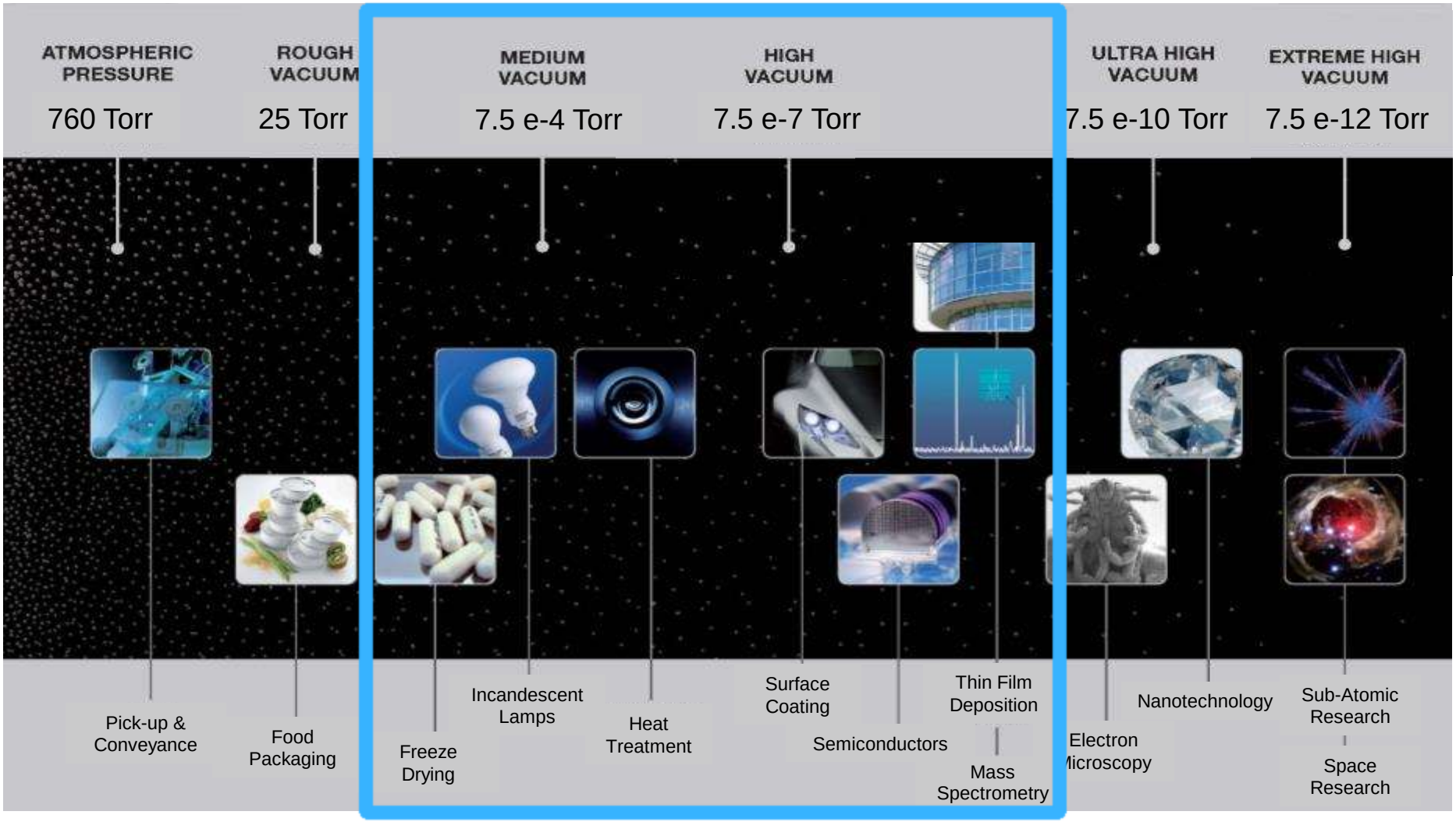


Rough Vacuum **GAUGES** rely on Mechanical Force (*Bourdon, Capacitance Manometer*) or Thermal Conductivity (*Convection, Thermocouple, Pirani*) to measure pressure

- Characterized by their:
  - *a) Accuracy*
  - *b) Response Time*
  - *c) Cost*



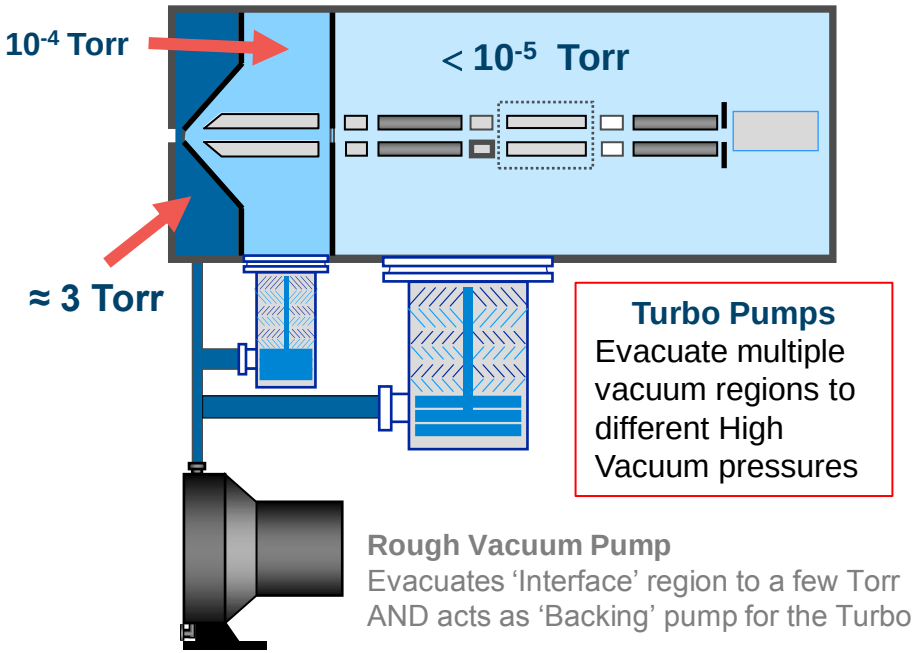
The Range of Vacuum Pressure



High Vacuum Applications

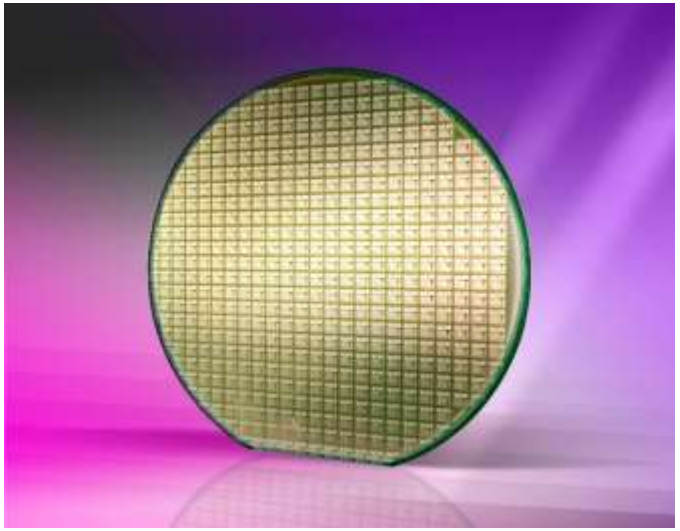
Instrumentation & Mass Spec

- 'Backing' High Vacuum Pumps
- 'Interface' Pumping (Differential Vacuum)



Vacuum Coating

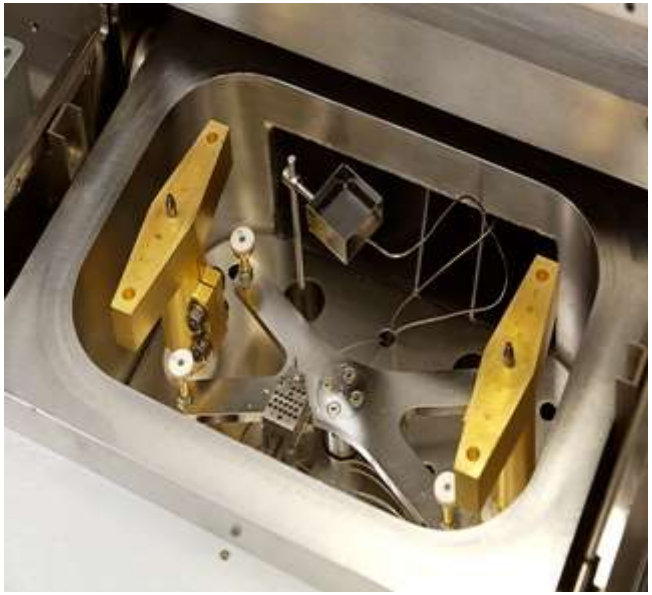
- Surface coatings for optical and semi-conductor



Rough Vacuum Applications

High Vacuum Furnaces

- Sealing and Soldering processes requiring ultra-low levels of moisture and residual gas



X-Ray Tubes

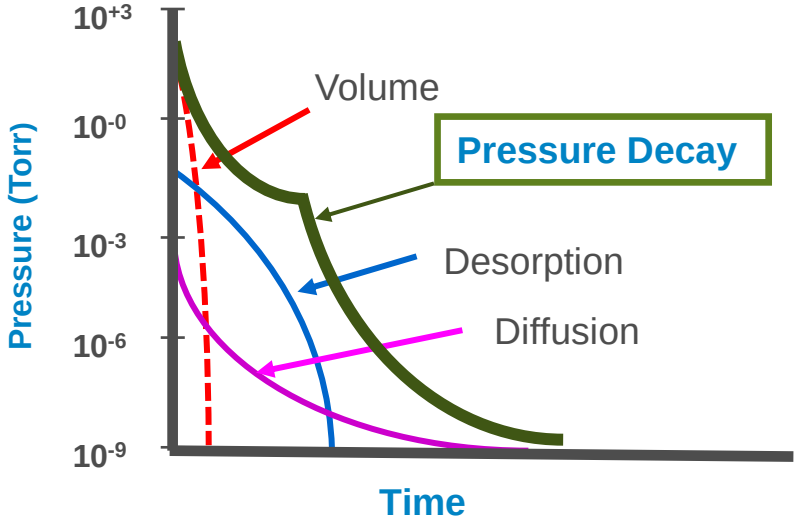
- Moisture removal and vacuum brazing



Characteristic of High Vacuum

- Gases originate from walls & surfaces
- Gases are in Molecular Flow (MFP > Chamber Dimensions)
- Gases move randomly at the Speed of Sound
- Surface Area, Material Type and Pump Speed determine ultimate pressure and pumpdown times (desorption and diffusion)
- Gas Composition is constant through High Vacuum (80% H_2O, 10% N_2, 10% CO)





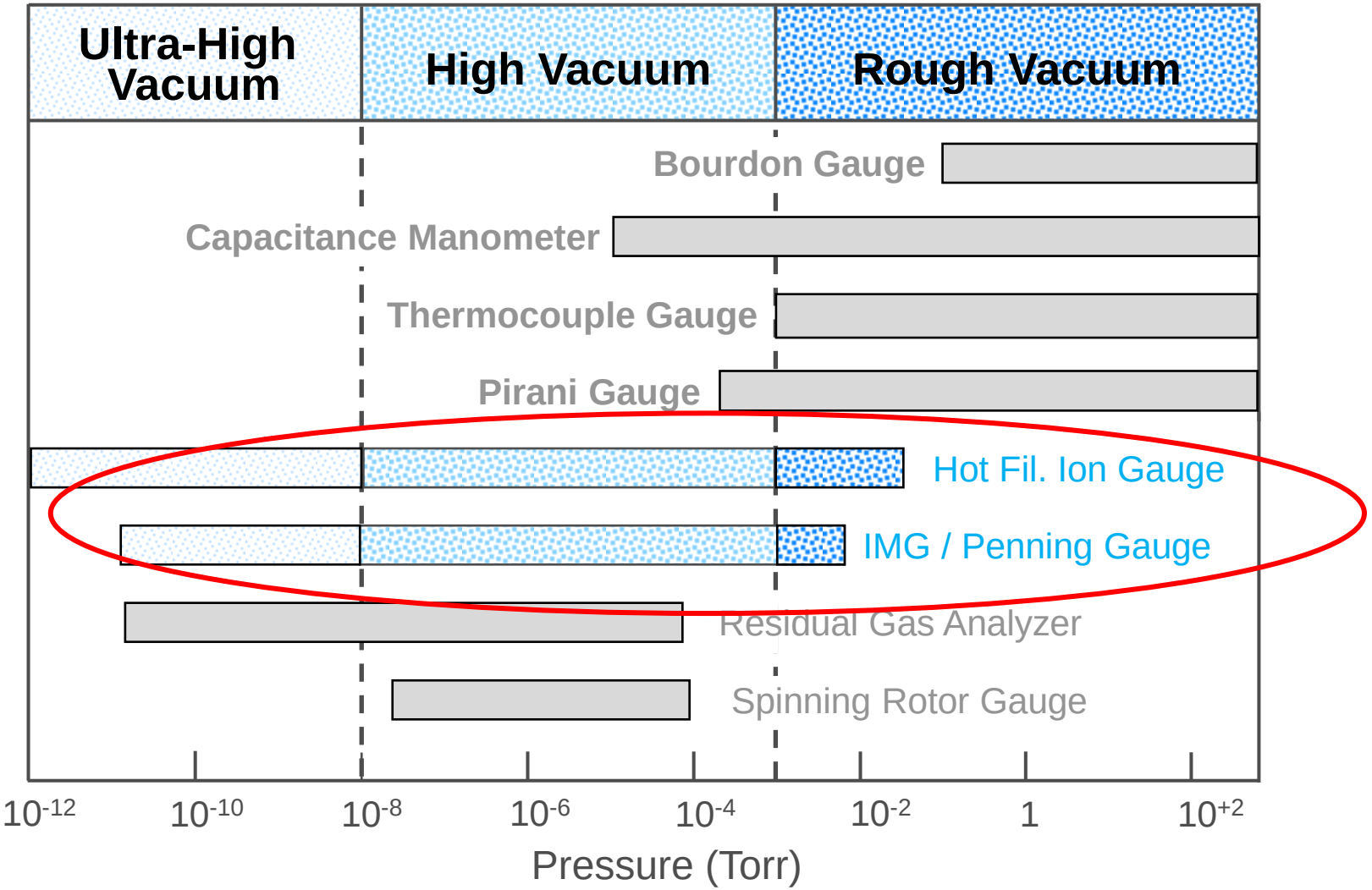
Vacuum Measurement Technologies

- Different technologies are required to measure the vacuum pressure in different vacuum regions

RANGE		GAUGE TYPE	EXAMPLES
Rough Vacuum	*Atm - 10^{-3}*	*Mechanical Deflection & Thermal Transfer Gauges*	*Bourdon Gauge Capacitance Manometer Thermocouple, Convection, Pirani*
High Vacuum	**10^{-3} - 10^{-9}**	**Mechanical Deflection & Ionization Gauges**	**Capacitance Manometer Hot Filament Gauge (BAG) IMG / Penning Gauge**
Ultra High Vacuum	*< 10^{-10}*	*Ionization Gauges & Gas Analyzers*	*UHV Ionization Gauges Ion Pump Current Residual Gas Analyzer (RGA)*

https://cds.cern.ch/record/455555/files/p75.pdf

High Vacuum Gauges



Hot Filament Ion Gauge

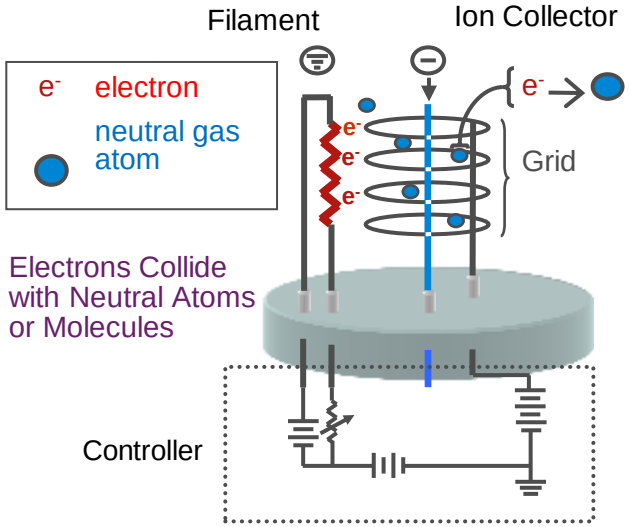


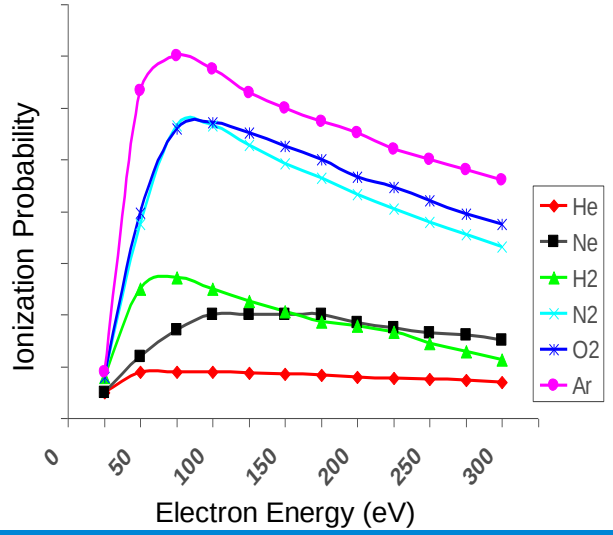
How it Works:

- Photo-electrons emitted by the filament are accelerated towards the spiral grid and strike 'background' gas molecules – creating ions
- Ions are accelerated towards the central collector – resulting current is directly proportional to the gas density (pressure!)

Characteristics:

- Gas Type Dependent (reading varies with gas species)
- **Accuracy: ± 50% (typical)**
- **10^{-2} to 10^{-9} Torr Operating Range**





Gas	Relative Sensitivity
Ar	1.2
CO	1.0 – 1.1
H_2	0.40 - 0.55
He	0.16
H_20	0.9 – 1.0
N_2	1.00
Ne	0.25
O_2	0.8 – 0.9

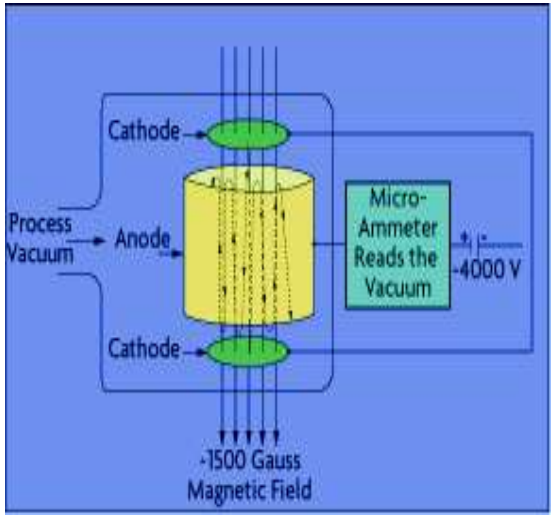
Cold Cathode Gauge

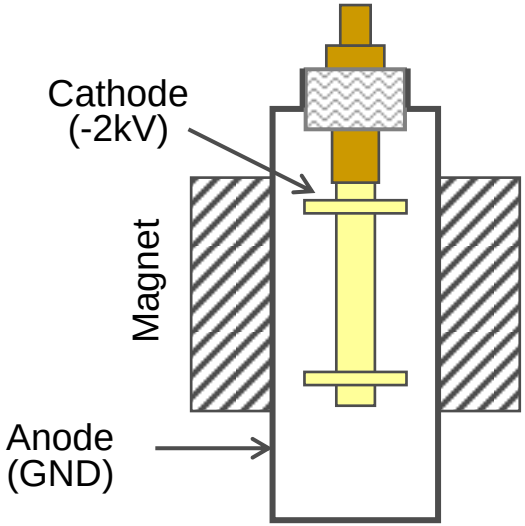
How it Works:

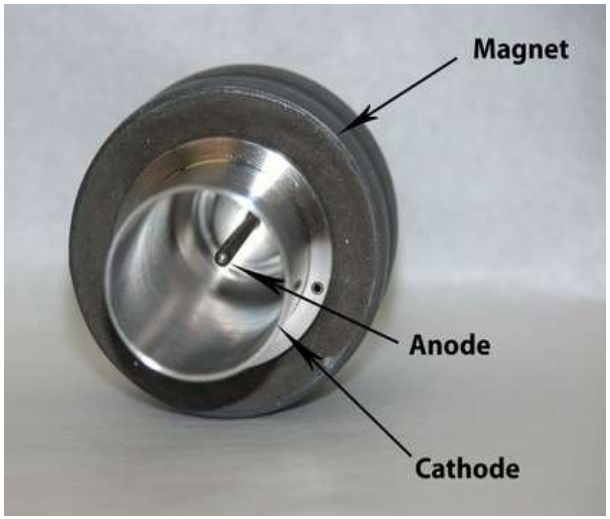
- (Cold) Electrical discharge is excited between Cathode and Anode by ≈ 2 kV field
- Discharge is sustained by magnetic field which increases MFP of electrons to increase probability of collisions with gas molecules: Ionized gas molecules strike Cathode (PαI)

Characteristics:

- Plasma ignition at low pressures can be problematic
- Discharge can lead to sputtering (Pumping Effect)
- Gas Type Dependent; 10^{-3} to 10^{-9} Torr Operating Range







Inverted Magnetron (IMG) Gauge

How it Works:

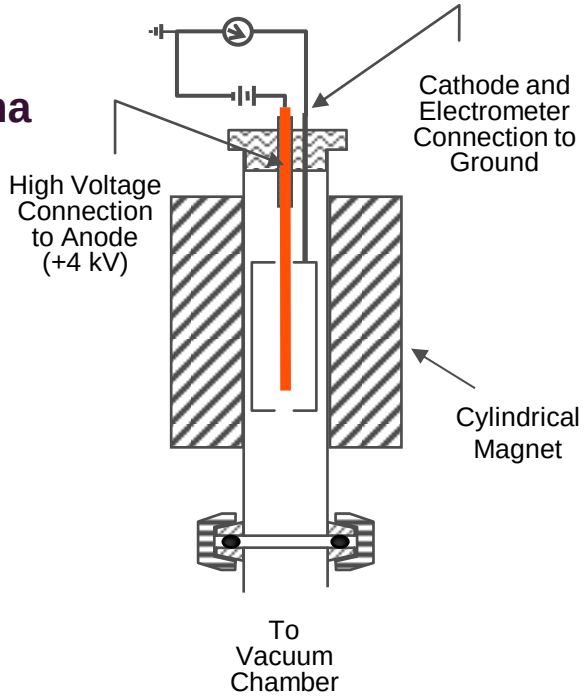
- Improvements to Cold Cathode (Penning) design made by Hobson & Redhead (1950's)
  - Guard rings at cathode potential improve plasma containment
  - Higher voltage improves probability of plasma ignition
  - Magnetic field parallel to anode axis

Characteristics:

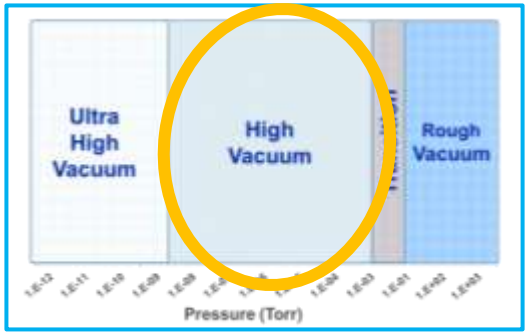
- **Improved ability to ignite and sustain a STABLE plasma**
- **10^{-3} to 10^{-11} Torr Operating Range (HV & UHV Gauge)**







Combination ('Wide-Range') Gauges



How They Work:

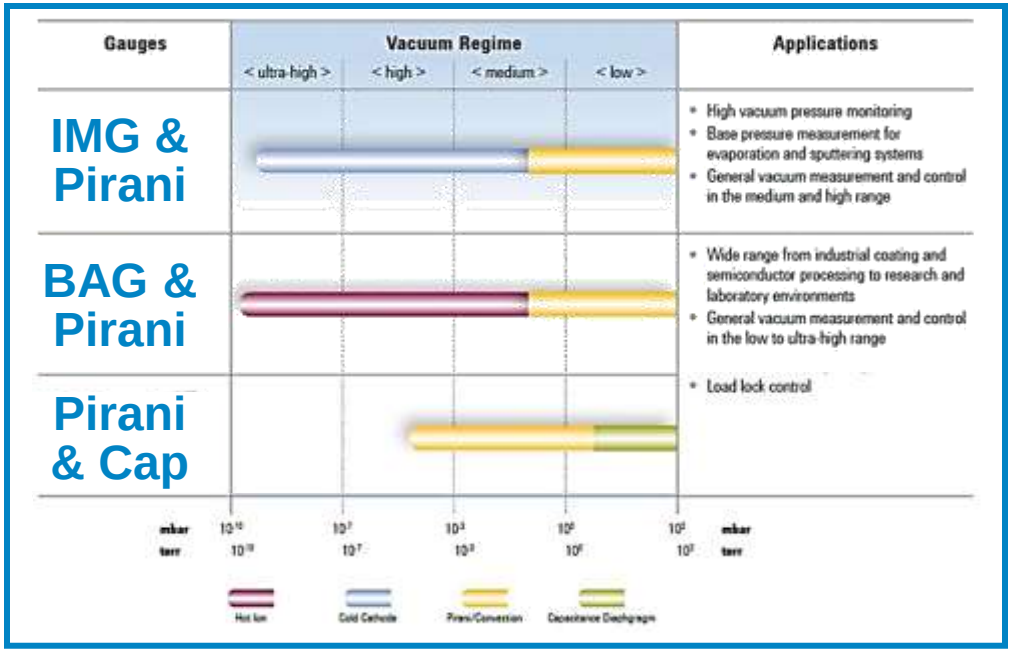
- Multiple (complimentary) gauge technologies combined in single housing: ***NO NEW PHYSICS!***



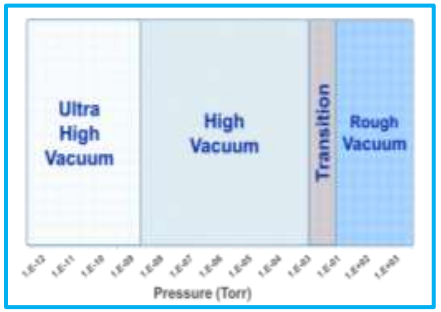
FRG-720
Full Range



PCG-750 Pirani/
Capacitance

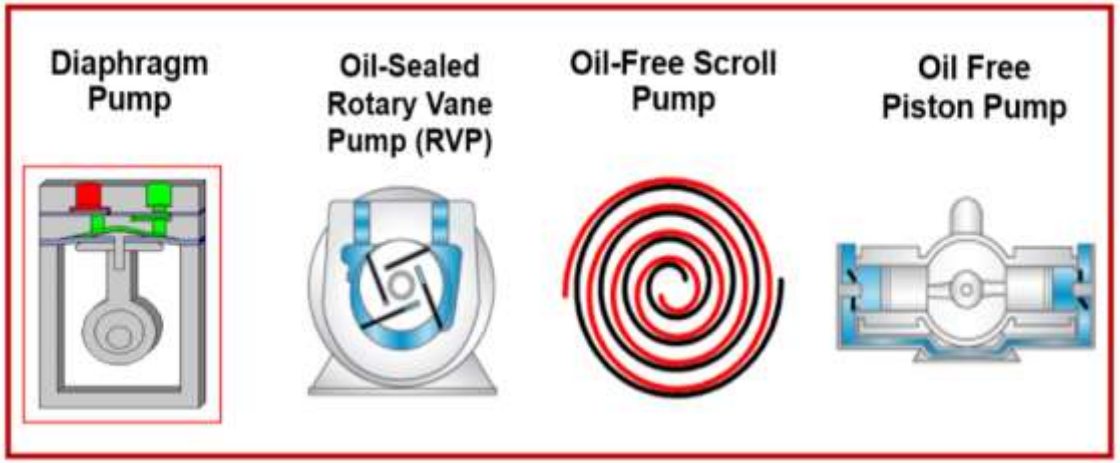


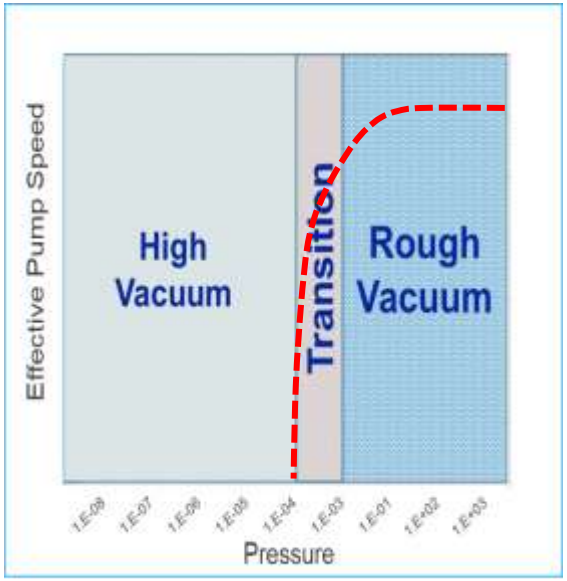
High Vacuum Pumps



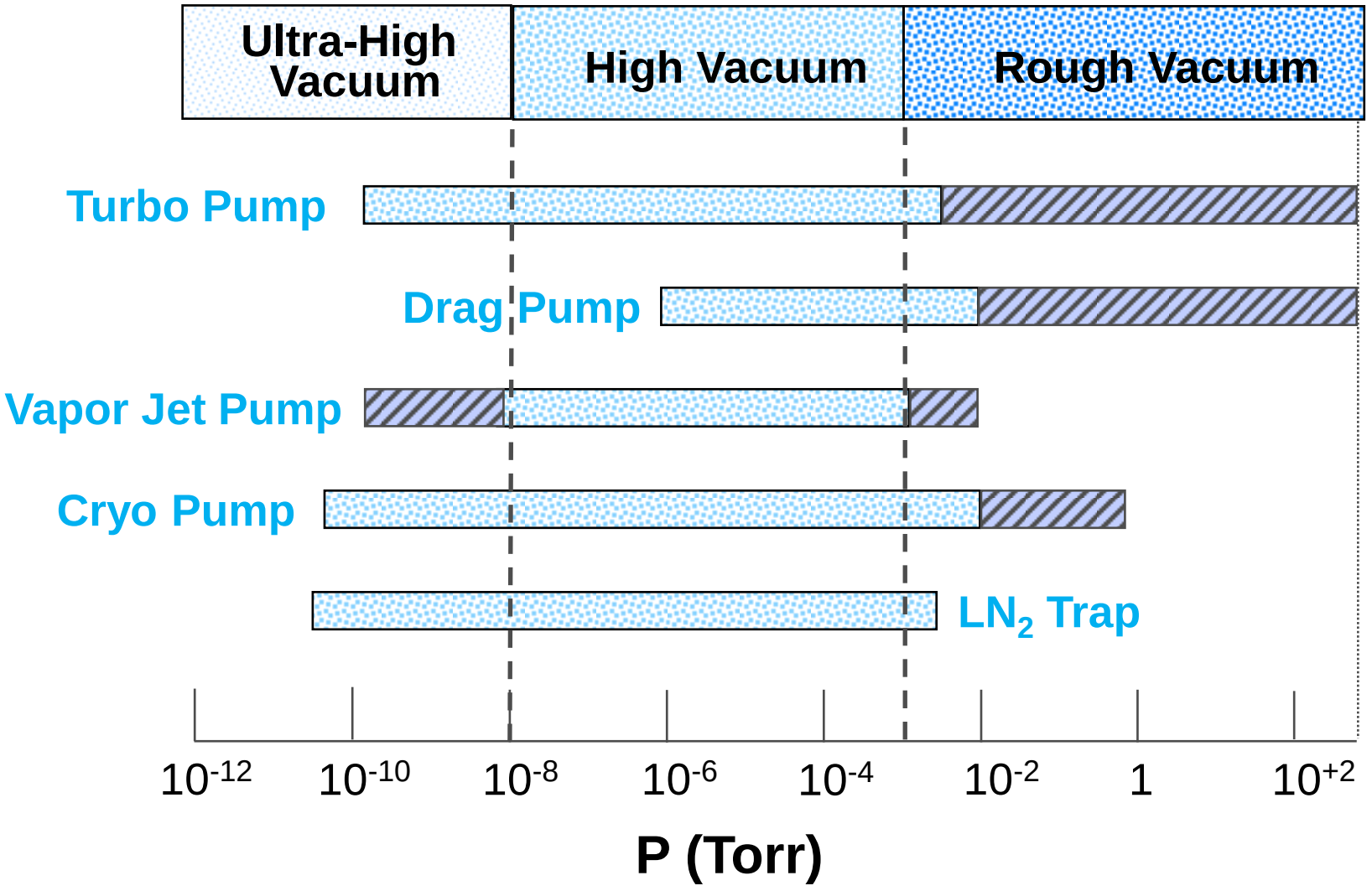
All Rough Vacuum pumps are only effective when gas is moving in **Viscous Flow**

- *Different pumping mechanisms required for High Vacuum (**Molecular Flow**)*

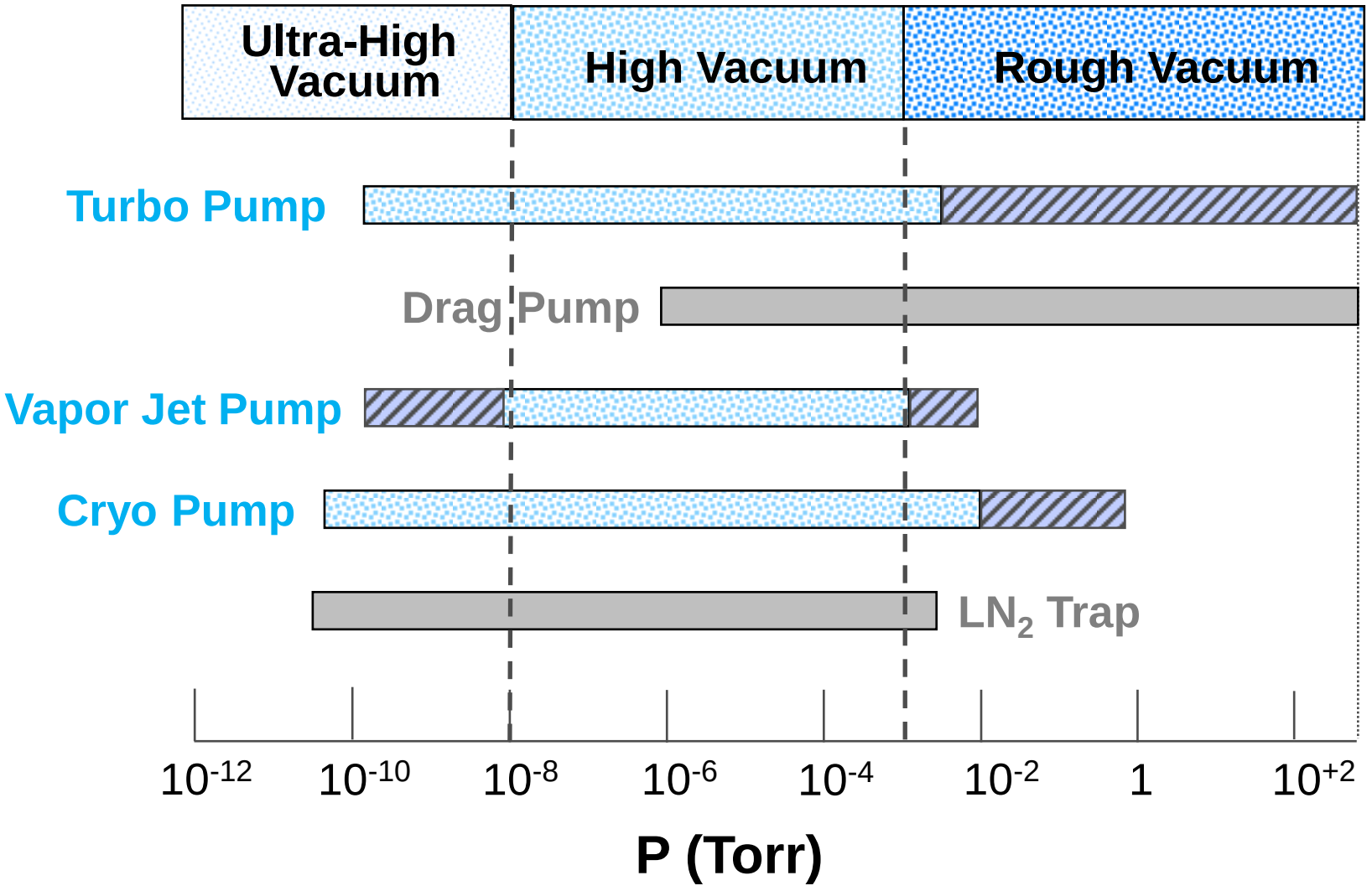




High Vacuum Pump Operating Range



High Vacuum Pump Operating Range



High Vacuum Pumps

High Vacuum pumps are described as either **Displacement** or **Capture** pumps

Displacement Pumps

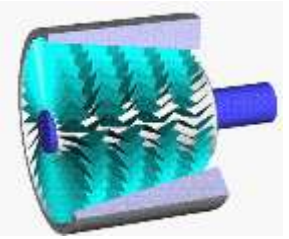




Capture Pumps

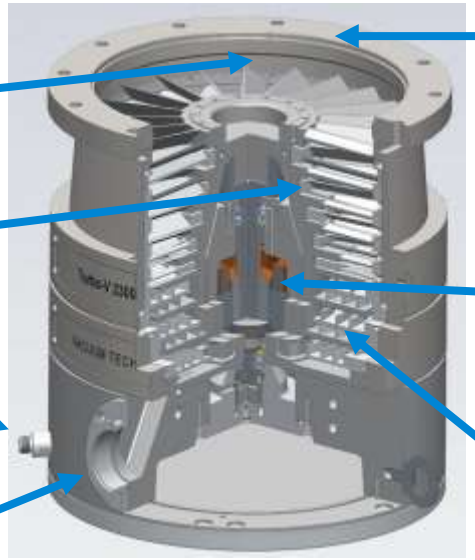


Turbo-Molecular Pump



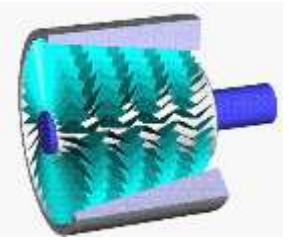
How it Works:

- **Rotating Blades** strike gas molecule entering the pump in Molecular Flow
- **Non-rotating Stators** (complementary blade angle) reflect the molecule towards exhaust
  - Increasing blade pitch prevents the molecule from travelling backwards towards the vacuum chamber
- **Drag Stage** uses momentum transfer to compress gas to higher exhaust pressure



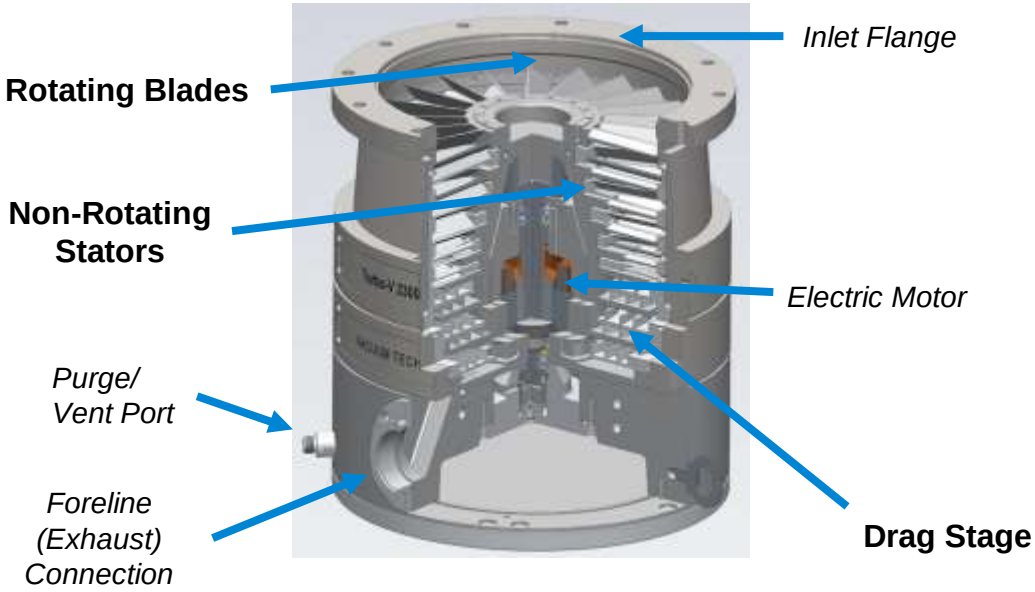


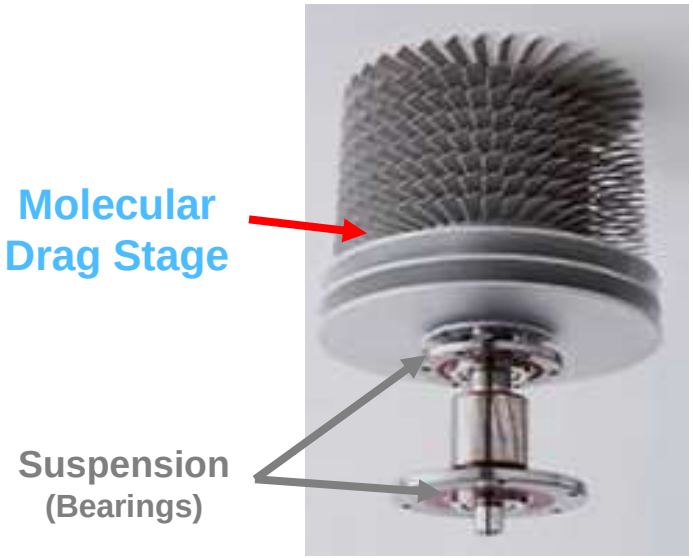
Turbo-Molecular Pump



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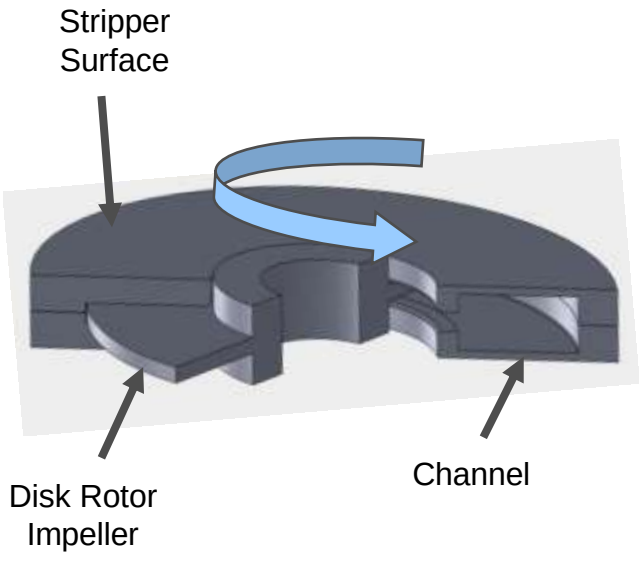


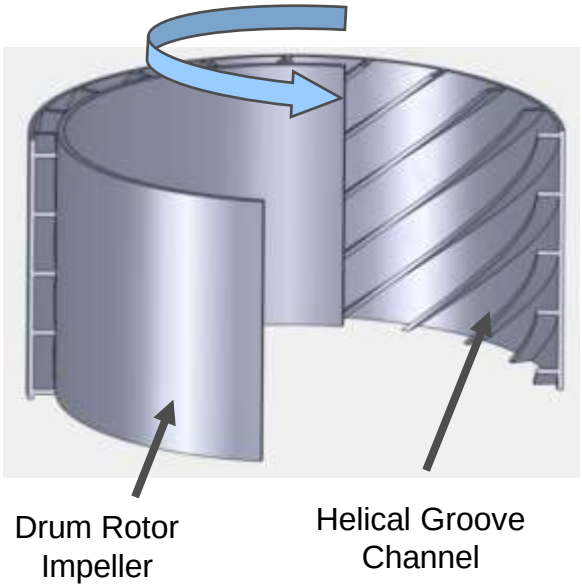


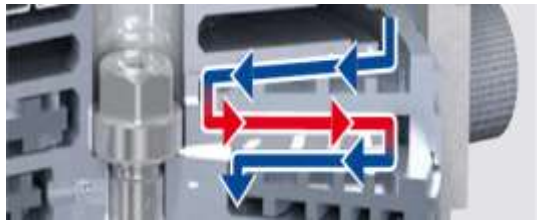
Turbo-Molecular Pump: Molecular Drag

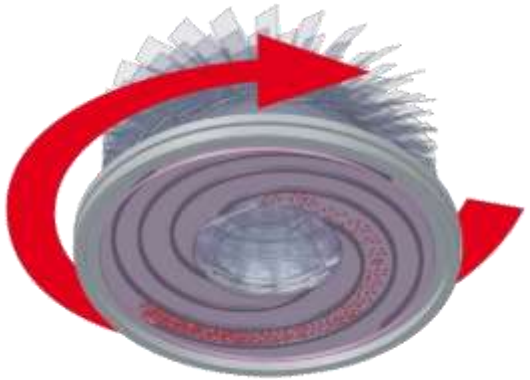
How it Works:

- Rotating blade design can only compress gas to ≈ 10^{-3} Torr (max) and result in poor pumping speeds for light gases
- **Molecular Drag Stage** transfers momentum to particles during residence time on a rotating element and **directs** the motion in a confined channel
- Gaede ('MacroTorr'), Holweck, and Siegbahn ('TwisTorr') Designs



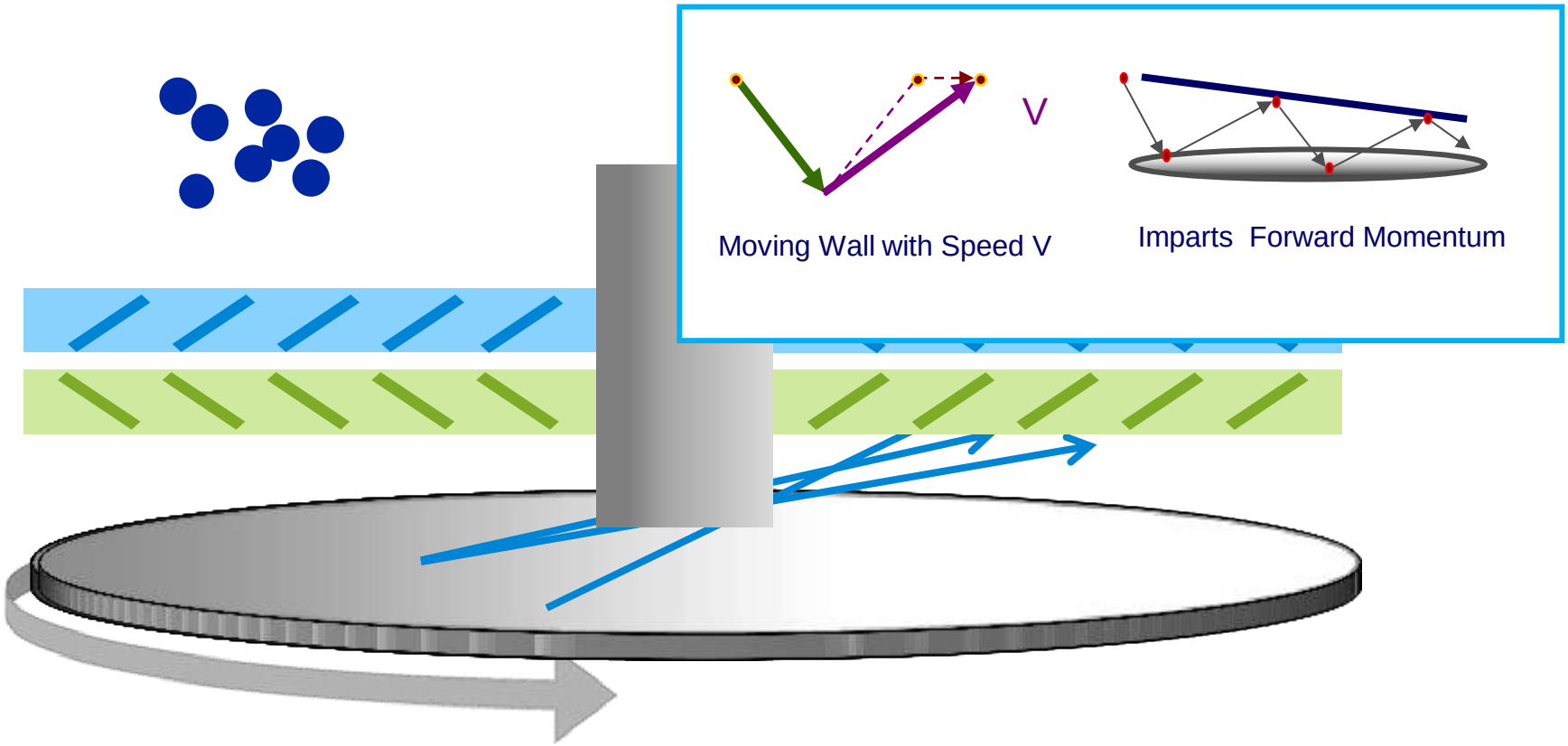






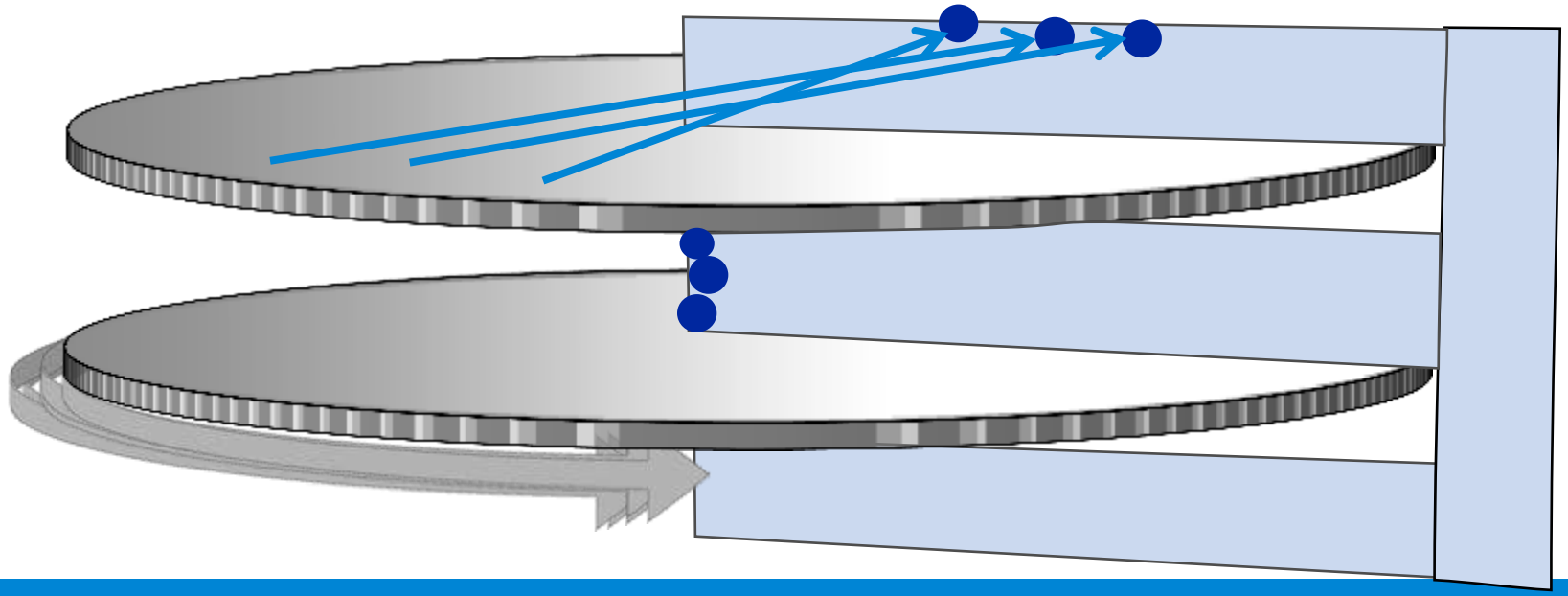
Molecular Drag Stage: Gaede (MacroTorr) Design

- After particles exit the lowest blade stage (approx. 10^{-3} Torr) **Spinning Rotor Impeller** transfers momentum to them during residence time on the disc



Molecular Drag: MacroTorr Design (cont'd)

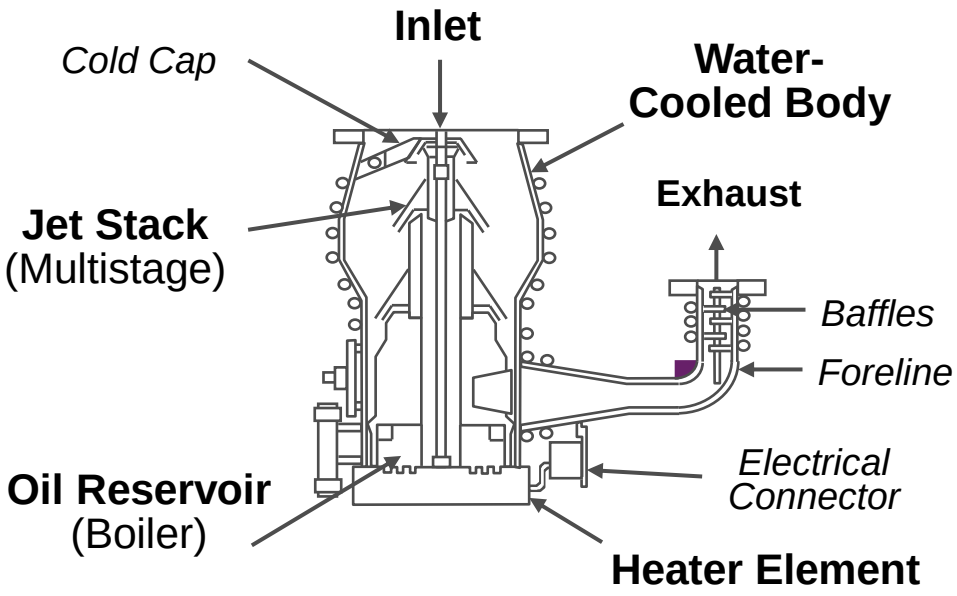
- **Stripper** directs particles from upper stage to lower stage: compressing gas ≈ 10,000x (10^{-3} to 10 Torr)
- **BENEFITS:**
  - **MUCH** greater pumping speeds for light gases
  - **SMALLER** (less expensive) backing pumps required to compress gas to atmosphere



Vapor Jet (“Diffusion”) Pump

How it Works:

- **Heating Element** vaporizes oil from the **Reservoir** forcing it up the **Jet Stack;** Oil ejected at ≈ 330 m/s (750 mph)
- Fine mist of oil strikes gas molecules entering the pump (momentum transfer) moving particles ‘down’ and towards the pump’s **Water Cooled Body**
  - Oil mist and gas condense at the cooled wall of the pump and continue moving towards pump exhaust
- Multiple oil mist ‘Curtains’ prevent molecules from travelling back towards pump **Inlet**





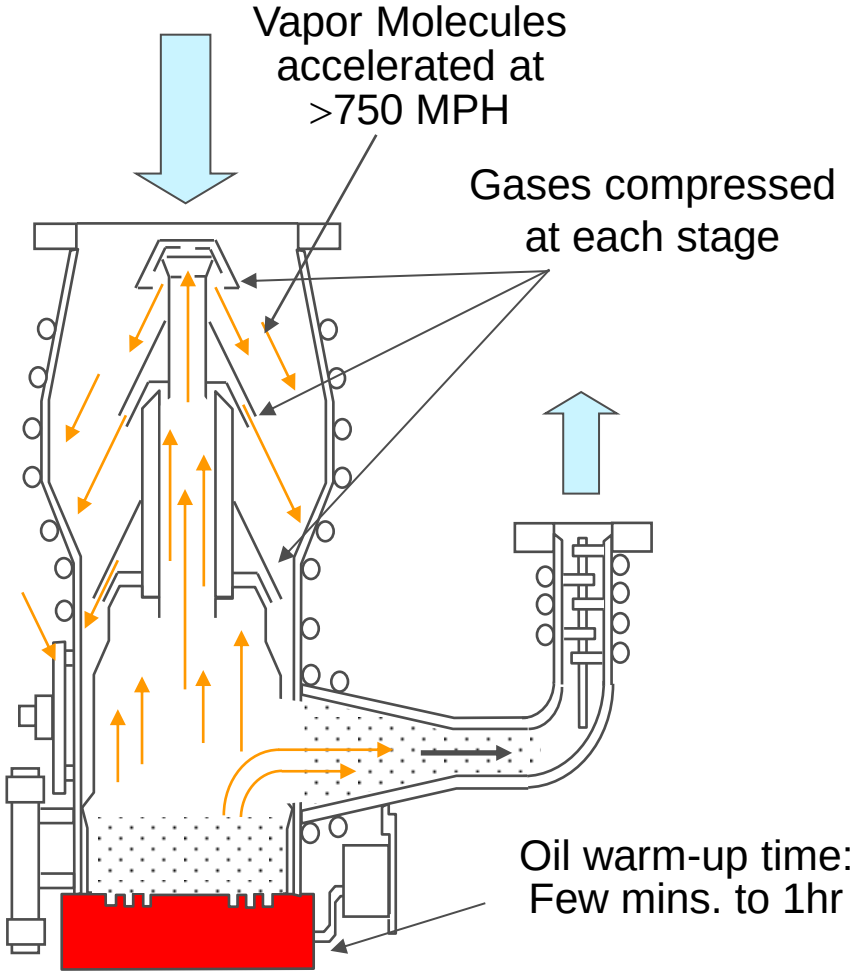
Diffusion Pump Performance

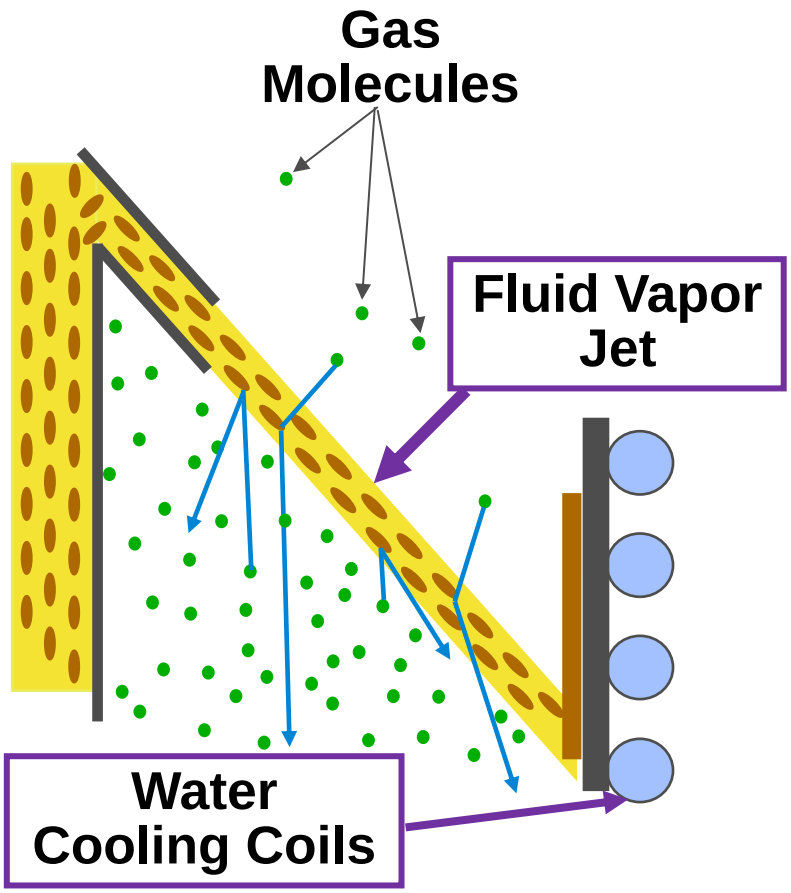
Pump Speed	12 l/s to 50,000 l/s
Ultimate Vacuum	3 x 10^{-3} to 1 x 10^{-9} Torr
Price	$800 - $30K
Oil Capacity	55 cm^3 - 3 gal
Cooling Method	air, water
Back-streaming	may require cold trap



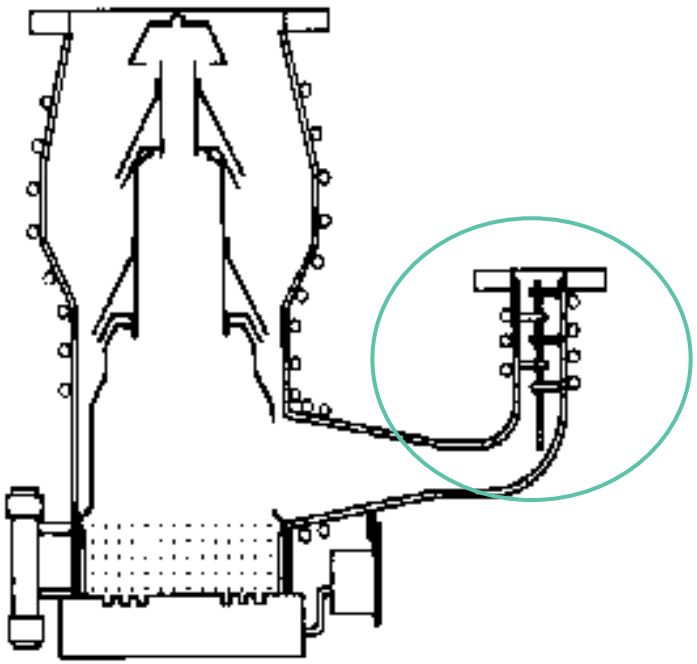


Principle of Operation



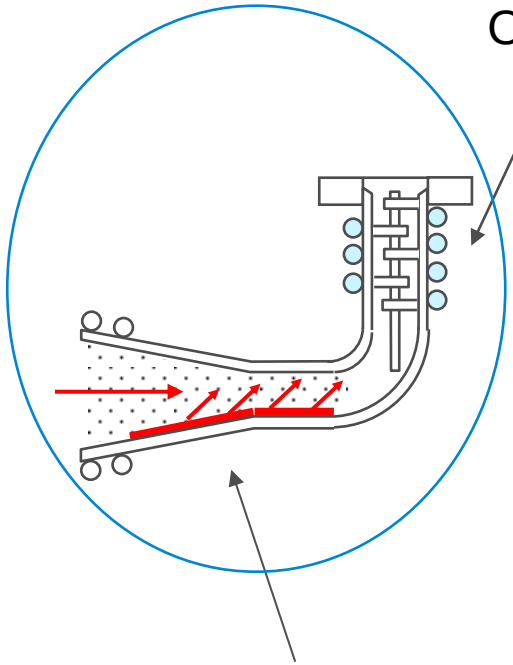


Diffusion Pump: Limiting Release of Vapors



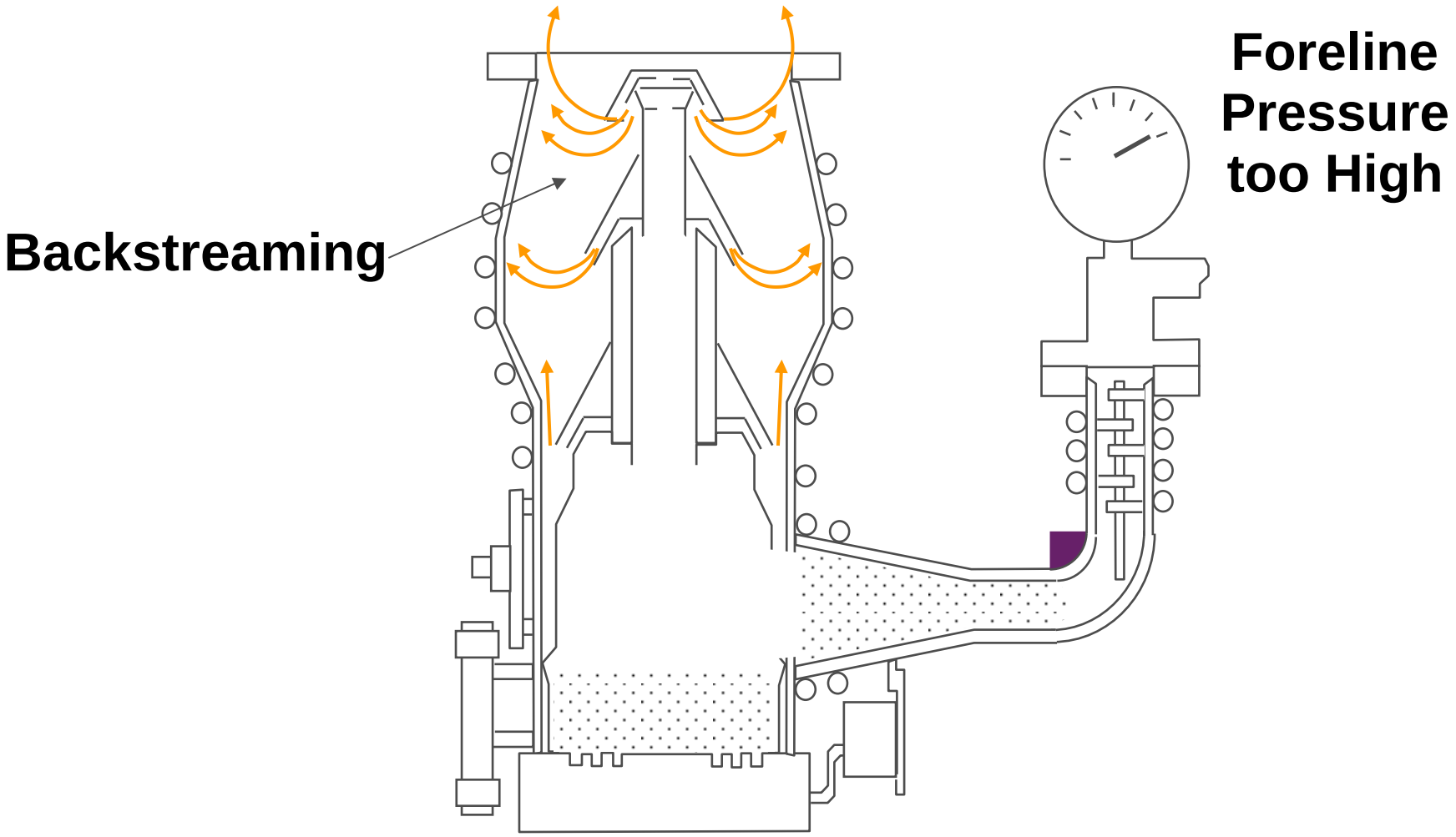
Foreline Baffle

Cooled to Condense
Oil Vapors



Kept Hot to Release Trapped Gases
From Condensed Oil

Maximum Tolerable Foreline Pressure Exceeded



Cryogenic Pump

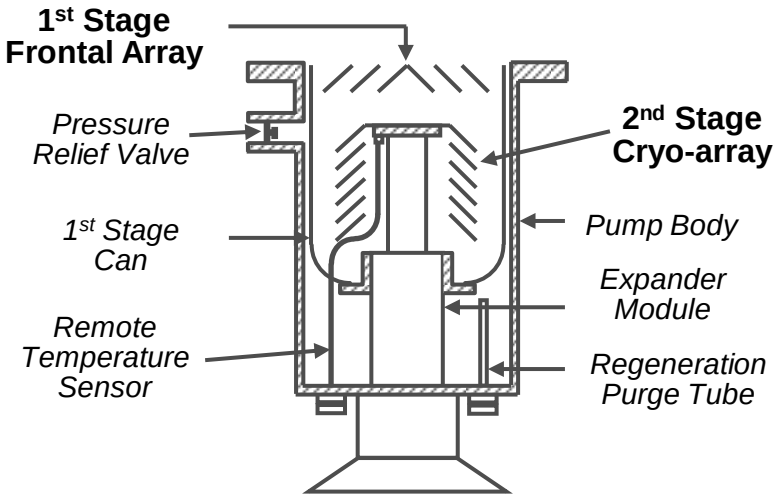


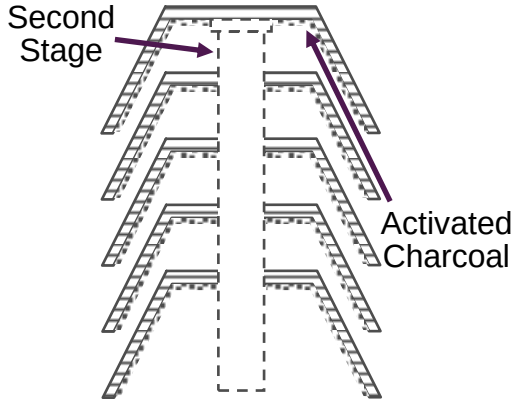
How it Works:

- Liquid He cooling circuit maintains **1st Stage Frontal Array'** at < 100K: Water
- **2nd Stage Cryo-array** maintained at < 20K to 'trap' Argon, Nitrogen, Oxygen etc
  - Activated charcoal attached to 2nd Stage forms labyrinth to 'temporarily detain' fast moving H_2 and He gases
- Requires Rough Vacuum Pump to generate 'Insulating Vacuum' so Cryo system can maintain cold head temperatures

Characteristics:

- Highest Pumping speed for H_2O
- Requires periodic re-generation (heating to room temperature) to remove trapped gases





Pump speed	**800 l/s to 60000 l/s**
Ultimate Vacuum	**1×10^{-3} to 1×10^{-10} Torr**
Price	**$4K - $60K**
Capacity	270 to 9000 T/I
Regen Method	**Hot Gas or Electric**

Cryo-Pump Regeneration

- Warm the cryopump to room temperature (290K - 300K) using heated dry nitrogen
- Rough the pump to approximately 50 millitorr
- Perform ***rate-of-rise*** test per manufacturer specification
- Rough vacuum system (insulating vacuum) then Chill pump to operating temperature

High Vacuum Pump Comparison

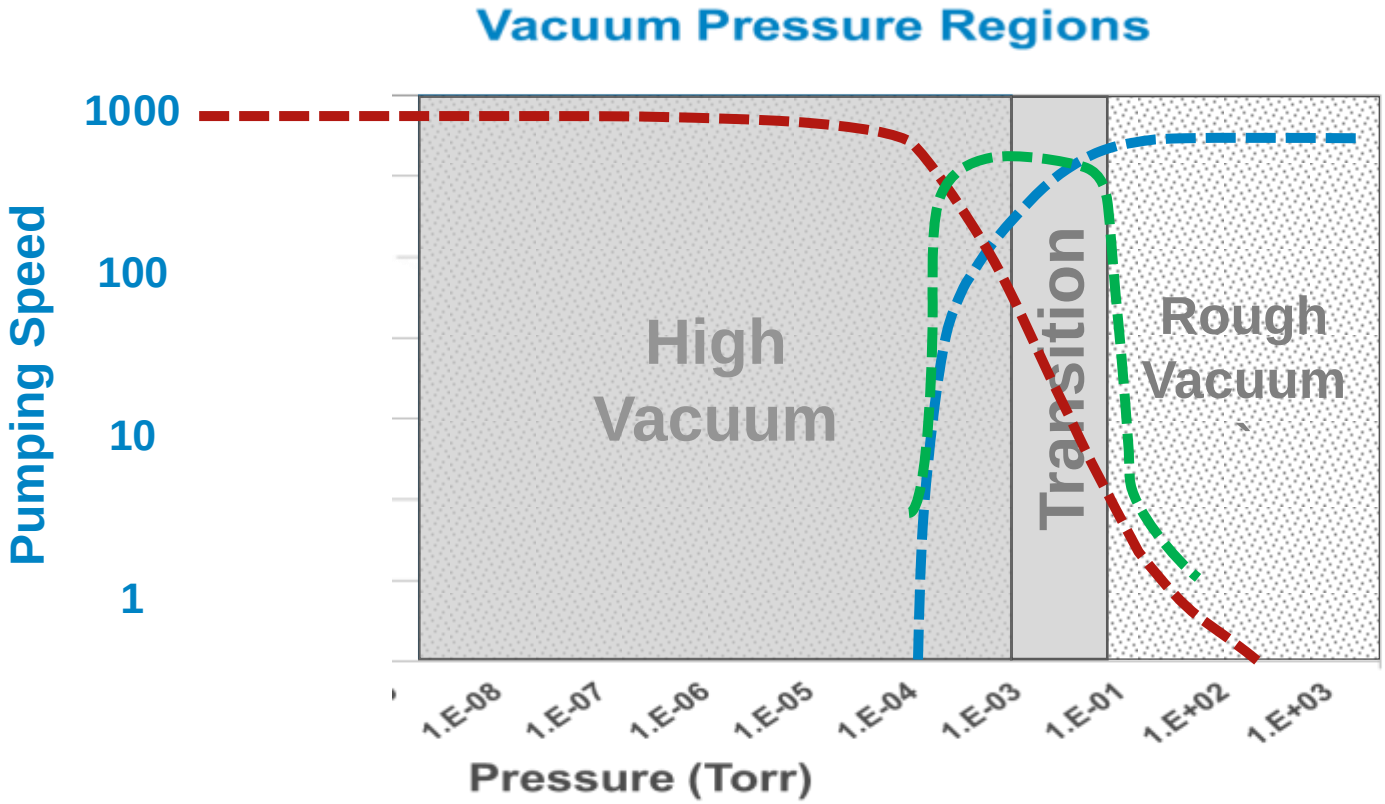
Type	Advantages	Disadvantages
Turbo-Molecular Pump (w/ drag stage)	✓ Low ultimate pressure ✓ Fast start-up & recovery ✓ Clean Continuous pumping ✓ Small forepump required ✓ No Oil!	✗ Mechanical bearing ✗ Some Noise & Vibration ✗ Lower pump speed H_2 & He
Vapor Jet (Diffusion) Pump	✓ High Throughput ✓ Lowest cost per L/sec ✓ No moving parts ✓ Low Maintenance ✓ Pumps all gasses	✗ Backstreaming ✗ No pressure tolerance ✗ Requires water cooling ✗ May require cold trap ✗ Vertical installation only ✗ No operator feedback
Cryogenic (Capture) Pump	✓ Highest H_2O pumping speed ✓ Mounts any position ✓ Clean (Oil-Free) ✓ Continuous Mechanical pumping not required	✗ Regeneration required ✗ Affected by heat ✗ Not for hazardous gases ✗ Low frequency vibration

Crossover Pressure: Rough to High Vacuum

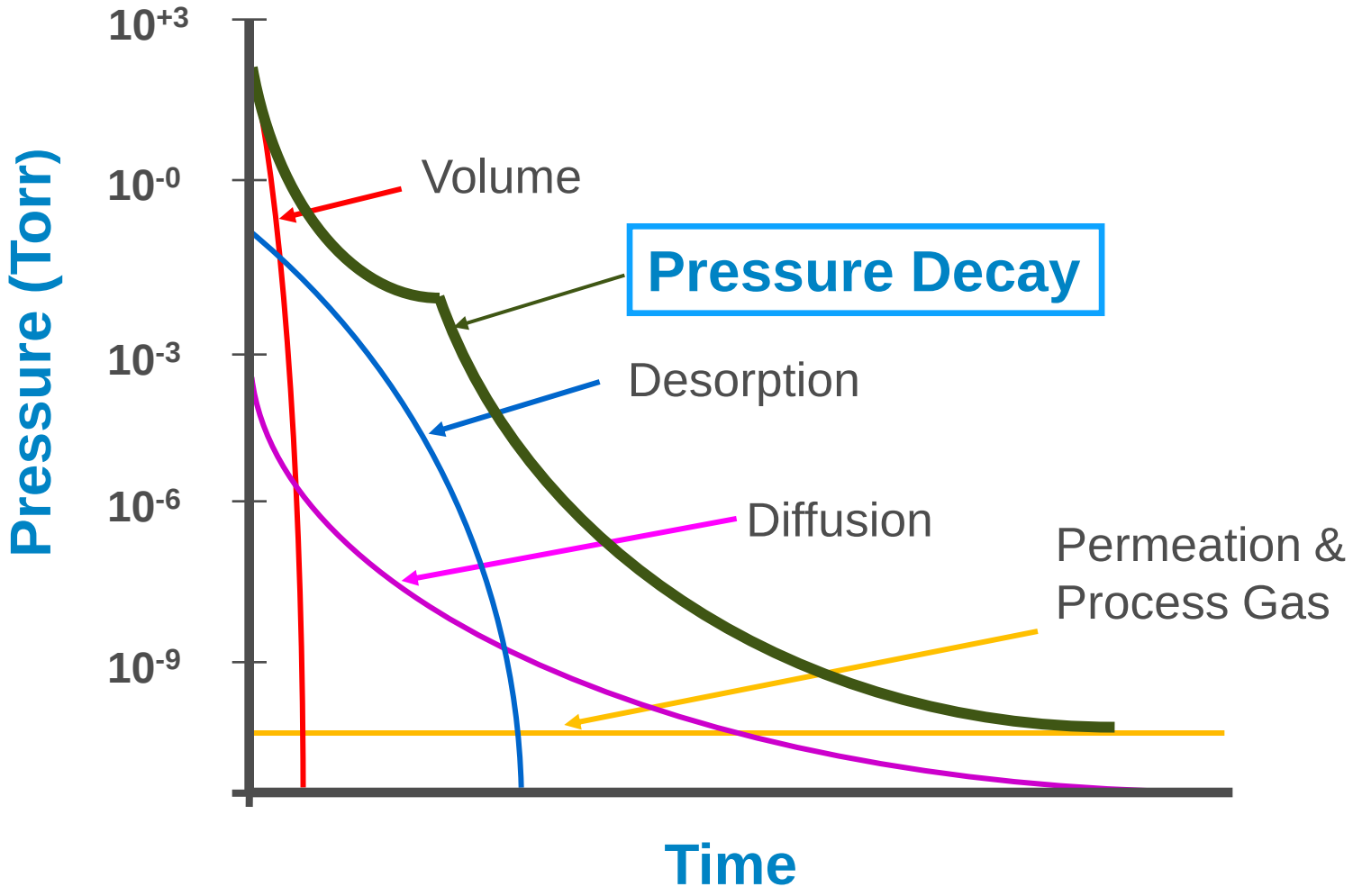


BOOSTERS: ROOTS & Claw Pumps

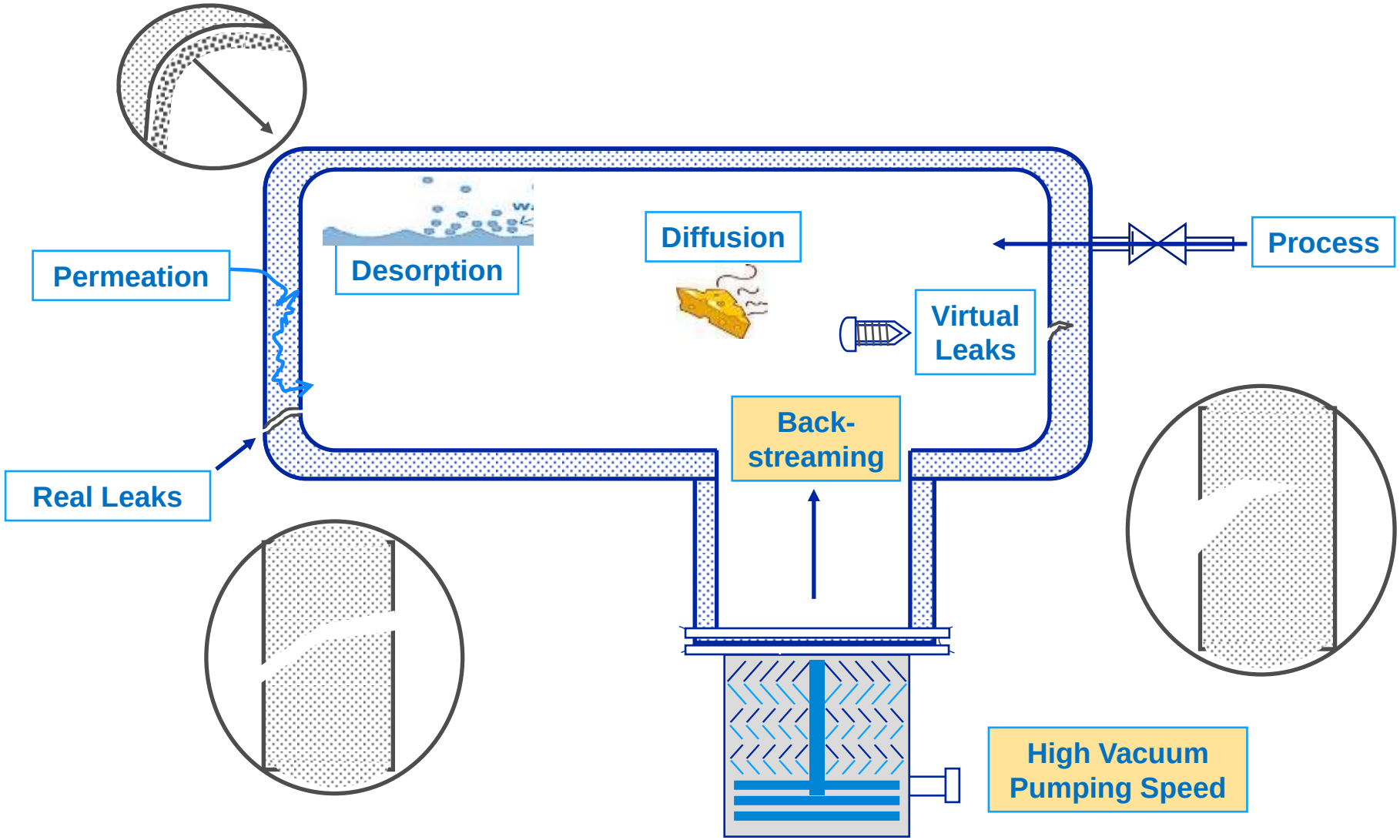
- Optimal pumping speed in **TRANSITION REGION**



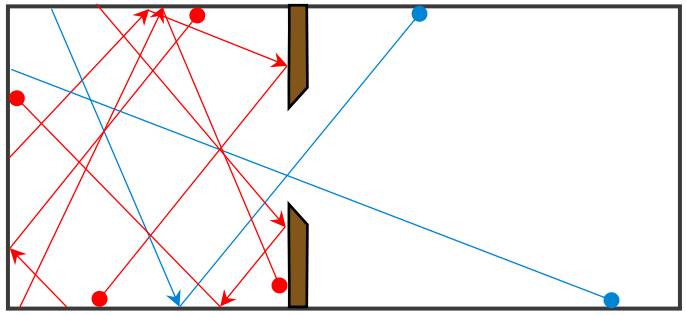
Troubleshooting High Vacuum Systems



Troubleshooting High Vacuum Systems



High Vacuum Pump Speed: Conductance



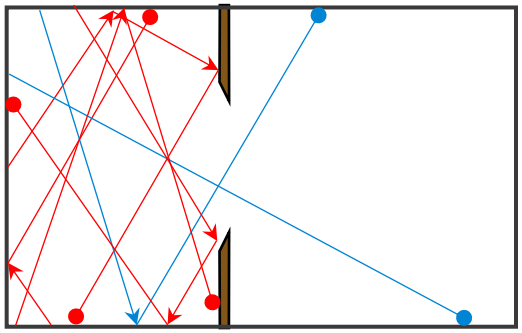
ORIFICE Conductance (for Air at Room Temperature) in MOLECULAR FLOW:

$$C = 11.6 \times A$$ (where A is in cm^2)

For Short Tubes: $$C = \frac{11.6\ D^3}{1 + L/D}$$

For Longer Tubes (L > 1.5 x D) : $$C = \frac{12.1\ D^3}{L}$$

Conductance in Molecular Flow





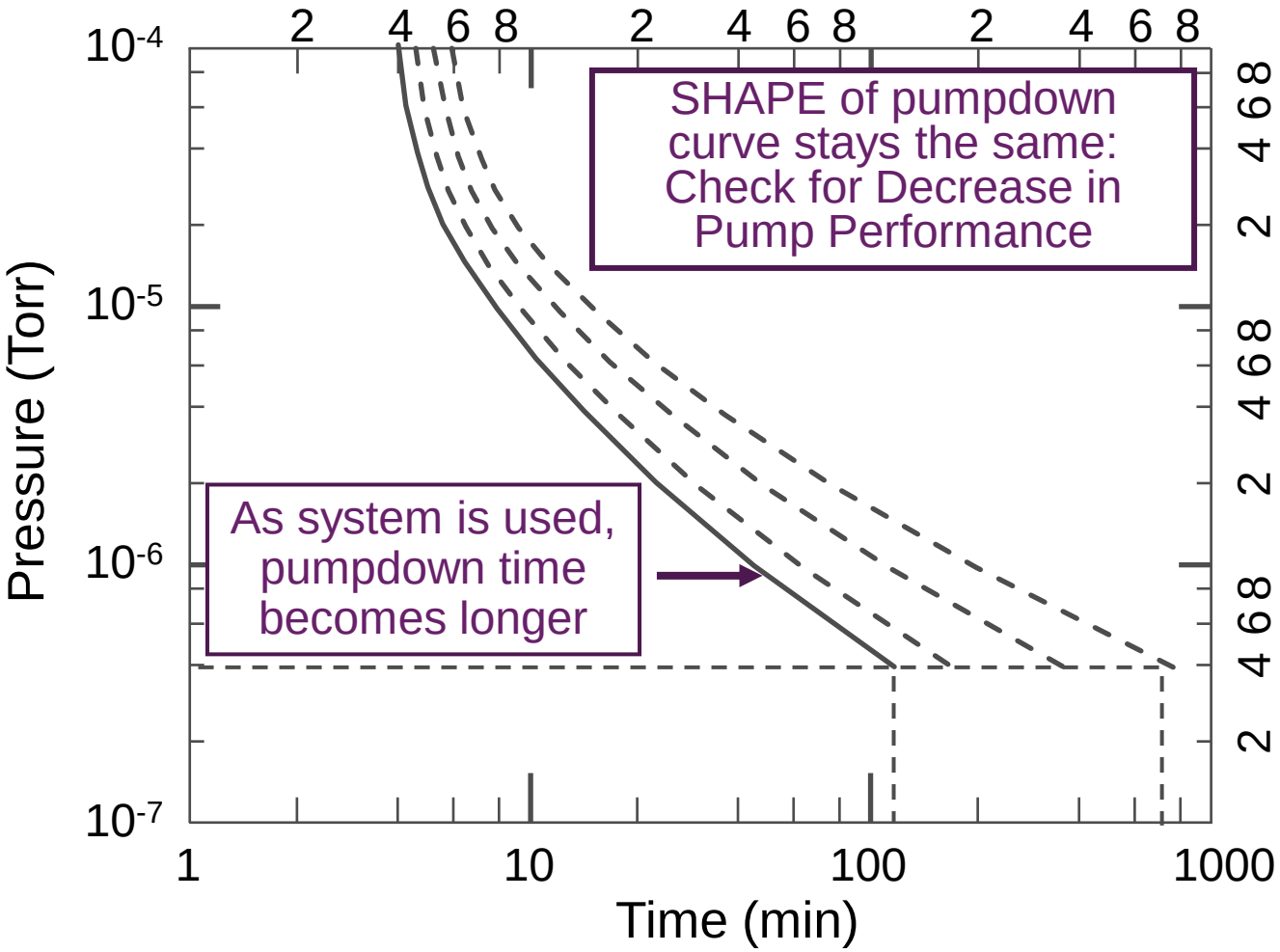


Example: 25 cm Circular Aperture $\Rightarrow$ C = $\mathbf{11.6 \times A}$ = 5691 l/s

Example: 10 cm ISO-100 Nipple $\Rightarrow$ C = $\dfrac{\mathbf{11.6\ D^3}}{\mathbf{1 + L/D}}$ = 5800 l/s

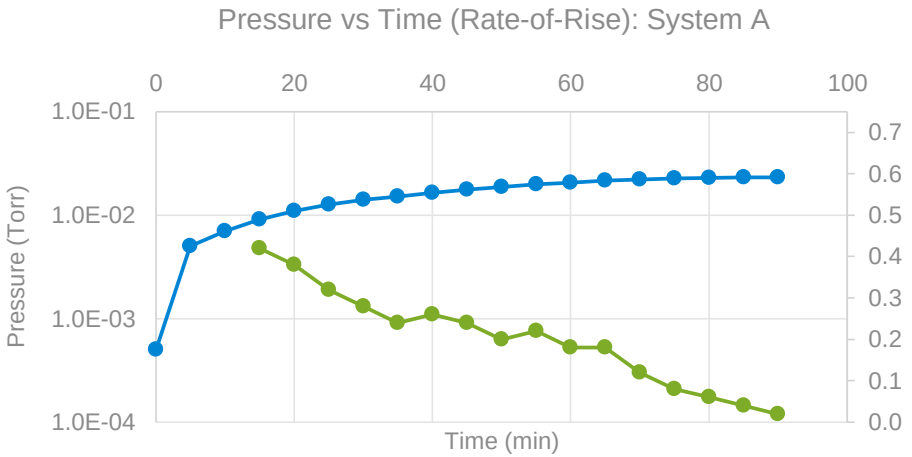
Example: 100 cm NW25 Vacuum Hose $\Rightarrow$ C = $\dfrac{\mathbf{12.1\ D^3}}{\mathbf{L}}$ = 1.9 l/s

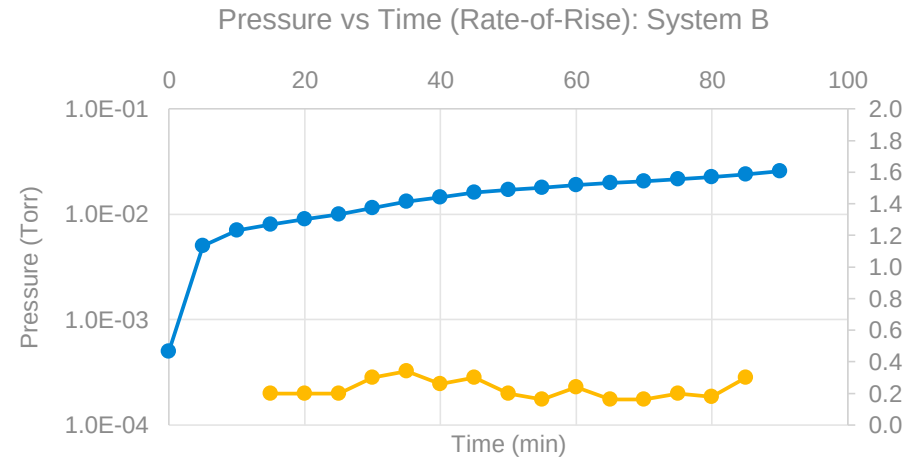
Document Vacuum System Performance!



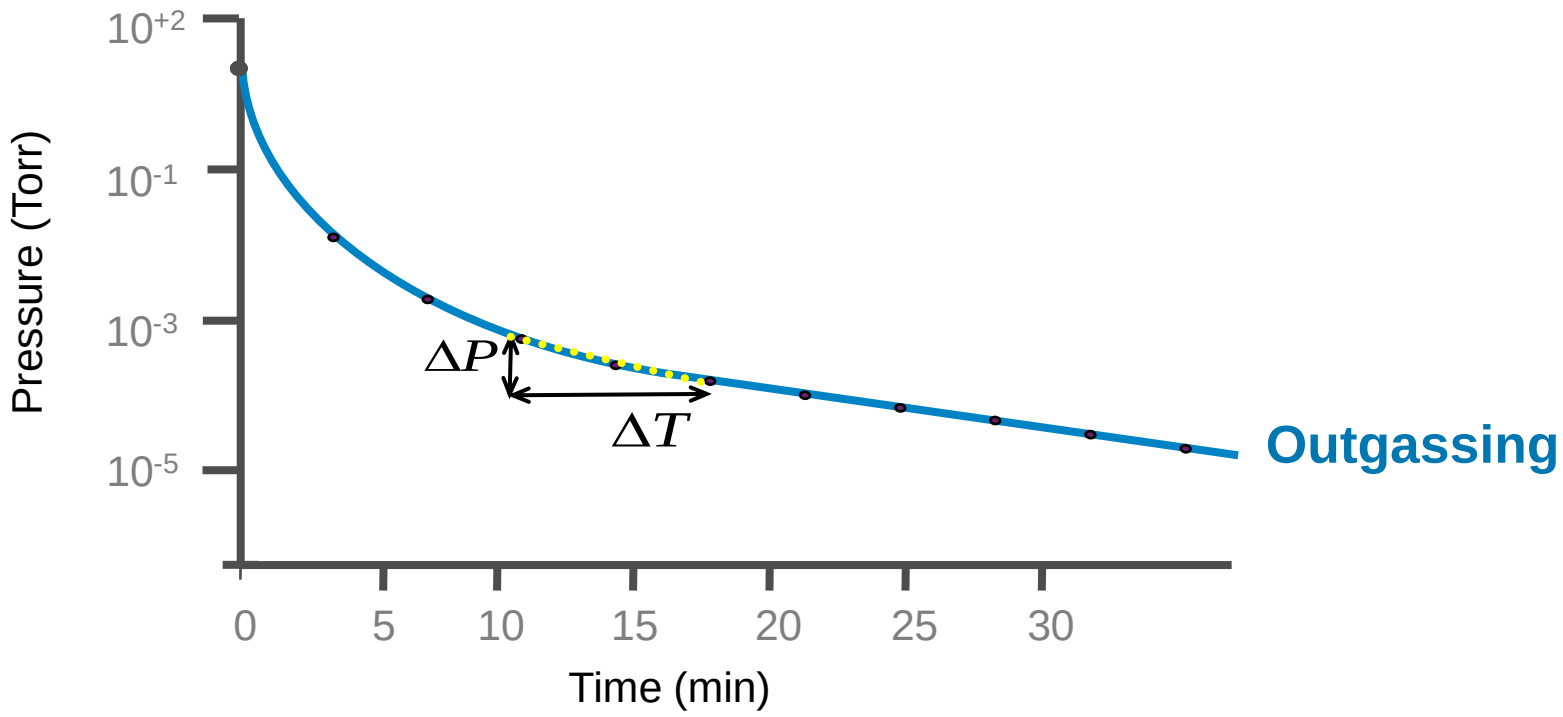
Rate-of-Rise: Virtual Leak vs Real Leak

Time	Pressure (System A)		Pressure (System B)	
0	5.00E-04		5.00E-04	
5	5.00E-03		5.00E-03	
10	7.00E-03		7.00E-03	
15	9.10E-03		8.00E-03	
20	1.10E-02		9.00E-03	
25	1.26E-02		1.00E-02	
30	1.40E-02		1.15E-02	
35	1.52E-02		1.32E-02	
40	1.65E-02		1.45E-02	
45	1.77E-02		1.60E-02	
50	1.87E-02		1.70E-02	
55	1.98E-02		1.78E-02	
60	2.07E-02		1.90E-02	
65	2.16E-02		1.98E-02	
70	2.22E-02		2.06E-02	
75	2.26E-02		2.16E-02	
80	2.29E-02		2.25E-02	
85	2.31E-02		2.40E-02	
90	2.32E-02		2.55E-02	





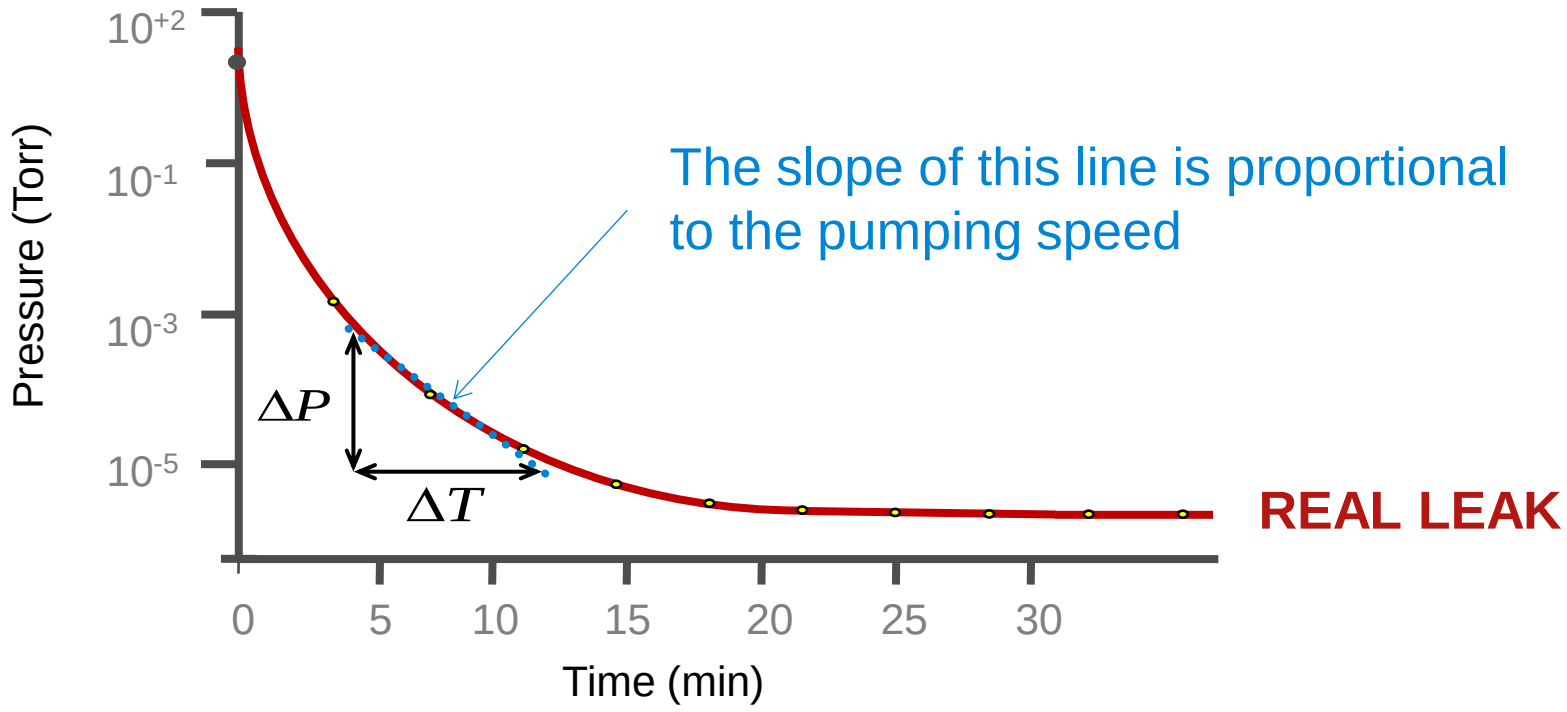
Troubleshooting High Vacuum Pumpdown



Monitoring the CHANGE in Pressure over Time can help to determine if there is a leak in the vacuum system

- A vacuum system with ***OUTGASSING*** issues will display a fairly constant rate of decrease in pressure over time

Troubleshooting High Vacuum Pumpdown



Monitoring the CHANGE in Pressure over Time can help to determine if there is a leak in the vacuum system

- A system with a REAL LEAK will display steadily ***decreasing*** slope until we reach the limits of the HIGH VACUUM pumps' ability to pump the leak

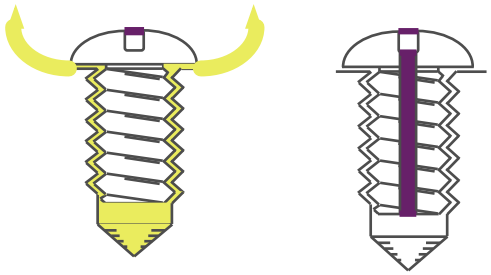
Possible Sources of Leaks

Real Leaks

- The last component you worked on!
- Components that have leaked in the past
- Seals where motion occurs
  - Sliding Seals
  - Rotating Seals
- Seals on chamber doors
- Compression fittings (Swagelok, Ultra-Torr)
- Bellows seals on valves
- Flexible tubing
- Threaded joints, plugs, etc.
- Static gasket seals on sight ports, feedtroughs, manifolds
- Welds and brazed joints

Virtual Leaks

- Residual solvents (following maintenance cleaning)
- Liquid leaks such as cooling fluids
- Trapped volumes of Gas or Liquid
- Trapped space under non-vented hardware

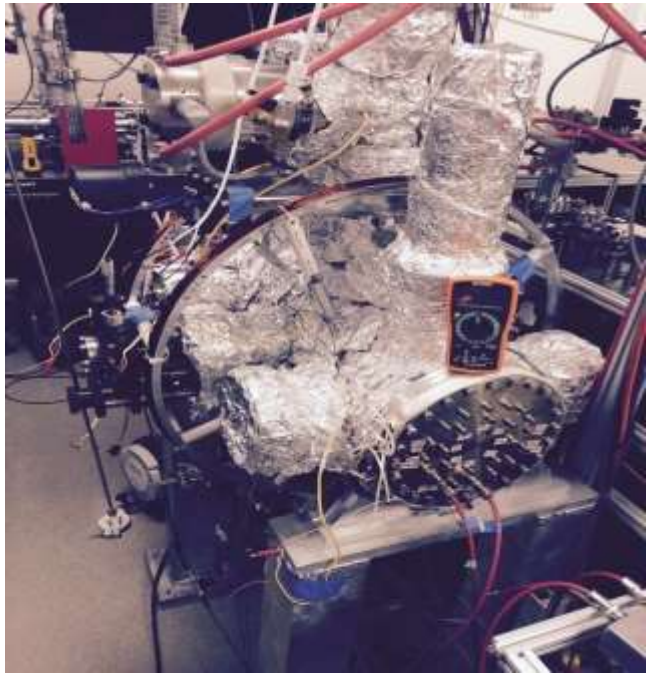


- Gasses or solvents in spaces With Poor Conductance
- High Vapor Pressure materials
- Porous materials exposed to liquid or atmosphere

Sources of Leaks: Desorption & Diffusion

Minimize Desorption & Diffusion

- **Minimize the amount of moisture entering the vacuum system, and accelerate the rate of Desorption and Diffusion of gases that ARE in the system**
  - Keep vacuum system interior CLEAN and free of moisture
  - When necessary, vent chamber with inert gas
  - Minimize exposure of clean parts to air
  - Choose materials with high bakeout temperatures
    - **EFFECTIVENESS OF BAKEOUT IS LINEAR WITH TIME BUT EXPONENTIAL WITH TEMPERATURE**



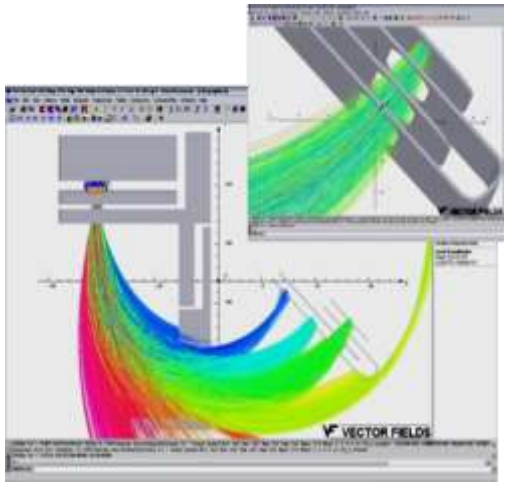
Helium Mass Spec Leak Detection

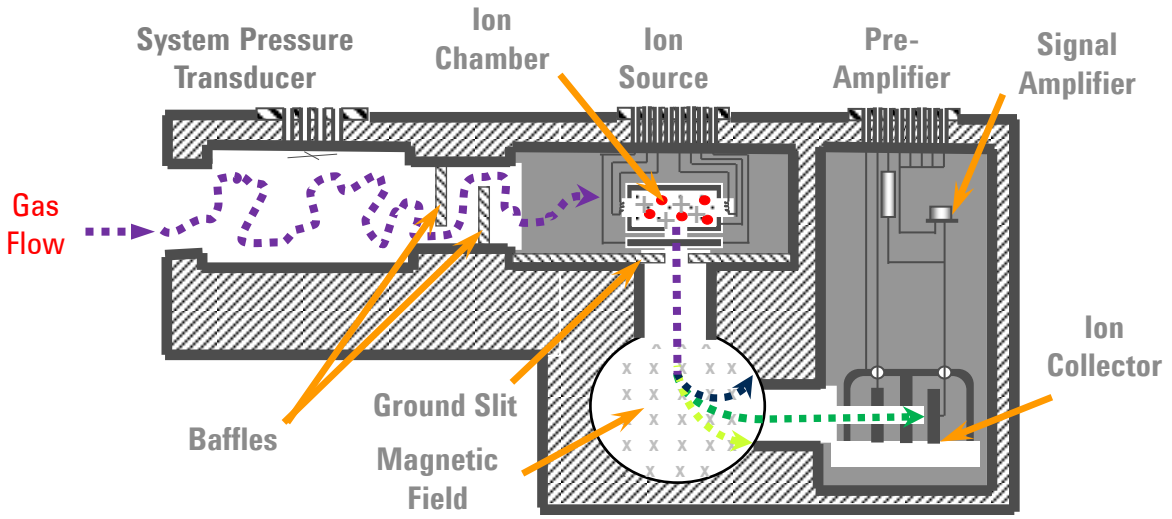


Leak Detection is usually a very sensitive technique to determine if a REAL (Outside air leaking into Vacuum System) leak exists

Theory of Operation

- Helium Leak Detector is a Mass Spectrometer 'tuned' to detect only Helium
  - Leak Detectors are NOT useful for detecting outgassing or diffusion leaks
- Why we use Helium?
  - Highly mobile, inert, (relatively) available & inexpensive, low surface absorption (easy to pump away) present in air in low quantity (≈ 5 ppm)





Summary: High Vacuum

- ✓ Molecular Flow requires pumps with high conductance inlets mounted as close as possible to the vacuum system
- ✓ High Vacuum Pump selection depends on the importance of:
  - Oil vs Oil-free Process
  - Dominant Gas Source
  - Pump Speed vs Base Pressure
  - Audible Noise & Vibration
- ✓ Ionization Vacuum Gauges are most suitable for High Vacuum; Gauges are gas type dependent
- ✓ In High Vacuum, OUTGASSING (Desorption and Diffusion) is the dominant factor (vs Chamber Volume) in determining pumpdown time and base pressure
- ✓ Techniques for troubleshooting HIGH VACUUM applications include Pumpdown Curves, Rate-of-Rise Tests and Helium Mass Spec Leak Detection
- ✓ Techniques for achieving lower base pressure include Materials Selection, System & Component Cleaning (and surface treatment) and **Bakeout**

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- Other custom training classes to fit your needs

Please e-mail Robin Arons (robin.arons@agilent.com), or call Customer Care at 800-882-7426 (Option 3) for more details on these programs

Next Live Webinar: High Vacuum (April 4)

Ultra-High Vacuum Webinar deals with the process of generating, measuring, and maintaining Ultra-High Vacuum Pressure (10^{-8} Torr to approx. 10^{-12} Torr).

Participants will learn about UHV Pumps (Ion Pumps, etc) and about modifications to High Vacuum Gauges to make them more suitable for UHV.

Considerations for constructing a vacuum system or troubleshooting leaks in the Ultra-High Vacuum regime will also be discussed

To Register, Visit:

http://www.agilent.com/en-us/training-events/eseminars/vacuum